

# Search for Charginos and Sleptons in ATLAS and Identification of Pile-up with the Tile Calorimeter

Paweł Klimek







# Search for Charginos and Sleptons in ATLAS and Identification of Pile-up with the Tile Calorimeter

Pawel Klimek

Academic dissertation for the Degree of Doctor of Philosophy in Physics at Stockholm University to be publicly defended on Thursday 8 October 2015 at 14.00 in lecture room FB52, AlbaNova University Center, Roslagstullsbacken 21.

## Abstract

The standard model of particle physics (SM) describes the elementary particles and their interactions. Supersymmetry (SUSY), a symmetry beyond those included in the standard model could resolve some of the SM shortcomings. It can provide a candidate for Dark Matter and a solution to the hierarchy problem. The Large Hadron Collider (LHC) has the potential to produce the particles predicted by SUSY. This thesis presents two searches for SUSY particles in proton-proton collision data recorded by the ATLAS experiment.

The first search described in this thesis looks for direct production of chargino and slepton pairs in a final state characterized by the presence of two leptons and missing transverse energy. The second search looks for production of chargino pairs via vector boson fusion (VBF) in a final state containing of two leptons, two jets and missing transverse energy. This is the first attempt in ATLAS to search for supersymmetric particles produced via VBF. A possible observation of such process would prove that the exchanged neutralino is a Majorana particle. These analyses are done using  $\mathcal{L}=20.3 \text{ fb}^{-1}$  proton-proton collisions at  $\sqrt{s}=8 \text{ TeV}$  collected in 2012. No significant excess over background is observed. New exclusion limits at 95% confidence level on chargino, neutralino and slepton masses and cross section for chargino pair production via VBF are set.

The energy measurements of the particles created in LHC collisions are performed by the ATLAS calorimeters. Energy deposits from different collisions in the same read-out window and in the same calorimeter channel (pile-up) can spoil the energy measurements by the calorimeter. It is shown that the quality factor computed offline for each collision and for each channel in the Tile Calorimeter (TileCal) can be used to identify channels that need a special treatment to account for large energy depositions from pile-up. Efficient criteria to detect pile-up in TileCal are proposed.

**Keywords:** *ATLAS experiment, particle physics, high energy physics, supersymmetry, SUSY, beyond standard model, chargino, neutralino, slepton, vector boson fusion, VBF, Tile calorimeter, TileCal, pile-up, quality factor, Large Hadron Collider, LHC, CERN.*

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Stockholm  
University

Department of Physics

Stockholm University, 106 91 Stockholm



Paweł Klimek

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Stockholm University

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Stockholm University  
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## Abstract

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The first search described in this thesis looks for direct production of chargino and slepton pairs in a final state characterized by the presence of two leptons and missing transverse energy. The second search looks for production of chargino pairs via vector boson fusion (VBF) in a final state containing of two leptons, two jets and missing transverse energy. This is the first attempt in ATLAS to search for supersymmetric particles produced via VBF. A possible observation of such process would prove that the exchanged neutralino is a Majorana particle. These analyses are done using  $\mathcal{L} = 20.3 \text{ fb}^{-1}$  proton-proton collisions at  $\sqrt{s} = 8 \text{ TeV}$  collected in 2012. No significant excess over background is observed. New exclusion limits at 95% confidence level on chargino, neutralino and slepton masses and cross section for chargino pair production via VBF are set.

The energy measurements of the particles created in LHC collisions are performed by the ATLAS calorimeters. Energy deposits from different collisions in the same read-out window and in the same calorimeter channel (pile-up) can spoil the energy measurements by the calorimeter. It is shown that the quality factor computed offline for each collision and for each channel in the Tile Calorimeter (TileCal) can be used to identify channels that need a special treatment to account for large energy depositions from pile-up. Efficient criteria to detect pile-up in TileCal are proposed.



## Sammanfattning

Partikelfysikens standardmodell (SM) beskriver elementarpartiklarna och deras växelverkan. Supersymmetrin (SUSY), en symmetri som sträcker sig bortom standardmodellen skulle kunna ge svar på några av standardmodellens tillkortakommanden. Supersymmetrin tillhandahåller kandidatpartiklar för mörk materia och en lösning på hierarkiproblemet. Med Large Hadron Collider (LHC) har man möjlighet att producera partiklar som SUSY-modellen förutsäger. I denna avhandling presenteras två analyser av LHC data som letar efter supersymmetriska partiklar in proton-proton kollisioner i data insamlat av ATLAS-experimentet.

Den första analysen letar efter omedelbar produktion av charginos och sleptonpar där det slutliga tillståndet karakteriseras av förekomsten av två leptoner och obalanserad energi i det transversa planet. Den andra analysen letar efter chargino produktion via fusion av vektor bosoner (VBF) där det slutliga tillståndet innehåller två leptoner, två jets och obalanserad energi i det transversa planet. Detta är första gången man utfört en analys i ATLAS-experimentet där man letar efter supersymmetriska partiklar producerade via VBF. En observation av en sådan process skulle vara ett bevis för att neutralinon i processen måste vara en majoranapartikel. Dessa analyser är gjorda med  $\mathcal{L} = 20.3 \text{ fb}^{-1}$  data av proton-proton kollisioner med  $\sqrt{s} = 8 \text{ TeV}$  insamlat under 2012. Ingen signifikant signal ovanför bakgrunden observerades. Exkluderingsgränser med 95% konfidensnivå beräknades för chargino-, neutralino- och sleptonmassorna samt tvärsnitten för parproduktion av chargino via VBF.

ATLAS-kalorimetrarna mäter energin i de partiklarna som skapas i LHC-kollisionerna. Energideponeringar från skilda kollisioner som sker i samma utläsningsfönster och kalorimeterkanal (pile-up) kan försämra energimätningen. I avhandlingen klargörs hur en kvalitetsfaktor som beräknas offline för varje kollision och kanal i TileCal kalorimetern kan användas för att identifiera kanaler som behöver specialbehandling för att korrekt beräkna stora energideponeringar från pile-up. Ett effektivt kriterium för att spåra pile-up i TileCal föreslås.



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Paweł  
Stockholm, August 27, 2015



# Preface

Particle physics is the field of science which studies the properties of the smallest constituents of matter and their interactions. The goal is to advance the understanding of the universe we live in. The answers to several fundamental questions are sought: How the universe started? How has it evolved? What is matter? What is a force? How will the universe evolve?

To study the elementary particles, physicists design and build particle accelerators. Particles are accelerated to high energies and collided with a fixed target or with one another. In the collisions many new particles are produced. These particles are studied providing information about the physics at the smallest scale.

The Large Hadron Collider (LHC) located at the European Organisation for Nuclear Research (CERN) is the most powerful particle accelerator in the world in terms of collision energy and luminosity which dictates the rate of proton-proton collision events. In 2012 the LHC was producing proton-proton collisions at a centre of mass energy of  $\sqrt{s} = 8$  TeV. Its design instantaneous luminosity, a measure related to the number of proton-proton collisions per second, is  $10^{34} \text{ cm}^{-2}\text{s}^{-1}$  [1]. The ATLAS experiment is one of the two general purpose detectors designed to study processes that take place in collisions at the LHC. Its goal is to make precise measurements of fundamental quantities and search for new physics phenomena, such as new particles and new interactions.

Currently, the best description of particle physics phenomena is given by the theory called the Standard Model (SM). The SM has been extensively tested during the last four decades and has shown great predictive power. However, there are observed phenomena that are not explained by the Standard Model as discussed in Chapter 1. Therefore, a new theory is needed. One of the theories tested with ATLAS is Supersymmetry (SUSY) which is also the main subject of this thesis.

## About this thesis

This thesis presents the data analyses and detector performance studies I performed on data collected with the ATLAS detector. Part I is a theoretical overview which provides the motivation for the LHC and the ATLAS experiment. Chapter 1 is dedicated to a short presentation of the Standard Model along with its shortcomings. Supersymmetry,

a proposed theoretical extension of the SM is introduced in Chapter 2.

Experimental facilities are presented in Part II. Chapter 3 presents the LHC and the design of the ATLAS experiment along with its subsystems. Chapter 4 gives a more detailed description of the Tile Calorimeter (TileCal). The high collision frequency at LHC can lead to energy depositions from different collisions in the same read-out window and in the same calorimeter channel. This effect called pile-up can bias the energy measurement by TileCal. I studied the pile-up and a method for its identification. For this purpose I developed the simulator of pulses in the Tile Calorimeter. A method for identification of pile-up using a quality factor in each calorimeter channel of TileCal is presented in Chapter 5. The quality factor studies are also presented in **Papers I and II**.

Part III is devoted to a search for supersymmetric particles called charginos and sleptons in the case when they are directly produced in the proton-proton collisions (as opposed to secondary gauginos and sleptons produced in decays of heavier supersymmetric particles). Chapter 6 describes the physics signal and the analysis procedure. Chapter 7 discusses methods used for estimation of Standard Model backgrounds originating from the  $WW$  processes and processes containing non-prompt leptons and fake leptons. A novel element introduced in this work is the use of a jet-veto. A detailed description of the jet-veto is presented in Chapter 8. One of the main backgrounds in the presented search is the Standard Model production of a  $Z$  boson with a second associated vector boson  $W$  or  $Z$  and denoted  $ZV$ . The estimation of this background is presented in Chapter 9. Chapter 10 shows the obtained limits on chargino and slepton production. The search for chargino and slepton direct pair production is also presented in **Paper III**.

Part IV describes a search for charginos produced via vector boson fusion (VBF). This is the first attempt in ATLAS to search for supersymmetric particles produced via VBF. Moreover, a possible observation of such process would prove that the exchanged neutralino is a Majorana particle. The sought supersymmetric process and the analysis procedure is described in Chapter 11. The signal region used in the presented search is optimised to be sensitive to the VBF signatures and low mass difference between chargino and neutralino. The optimisation procedure of the signal region and its selection criteria are presented in Chapter 12 along with the definition of several regions used to validate the background estimates. Chapter 13 discusses methods used for estimation of Standard Model backgrounds originating from the processes containing non-prompt leptons and fake leptons as well as charge flip leptons. The diboson processes that involve production of  $WW$  and  $WZ$  pairs are the dominant backgrounds to the chargino VBF signal. Chapter 14 describes in detail the method developed to compute the diboson background and corresponding systematic uncertainties. The results of this analysis and obtained limits on chargino pair production via VBF are presented in Chapter 15. This analysis is the subject of an article in preparation by ATLAS collaboration and to be submitted to *Phys. Rev. D*.

This thesis is an extension of my licentiate thesis [2]. Chapter 1 and Chapters 4 - 6 are taken from the licentiate thesis with some alterations. The same is true for Chap-

ters 8 - 10.

This thesis uses the convention of natural units where  $c = \hbar = 1$ , where  $c$  is the speed of light and  $\hbar$  is the reduced Planck constant. Consequently, masses, momenta and energies are expressed in eV. For convenience GeV is used throughout this thesis.

The attached papers are:

**Paper I:** C. Clément, P. Klimek, Identification of Pile-up Using the Quality Factor of Pulse Shapes in the ATLAS Tile Calorimeter. *IEEE Nucl. Sci. Symp. Conf. Rec.* 2011:1188-1193, 2011 [3].

**Paper II:** C. Clément, P. Klimek, Identification of Pile-up Using the Quality Factor of Pulse Shapes in the ATLAS Tile Calorimeter. ATL-TILECAL-INT-2012-009, 2012 [4].

**Paper III:** The ATLAS Collaboration, Search for direct production of charginos, neutralinos and sleptons in final states with two leptons and missing transverse momentum in  $pp$  collisions at  $\sqrt{s} = 8$  TeV with the ATLAS detector. *JHEP*, 1405:071, 2014 [5].

## Author's contribution

As a PhD student at Stockholm University my first task was to study the quality factor of the pulse shapes in the ATLAS Tile Calorimeter. For this purpose I developed the TileCal pulse simulator. I implemented in this model several effects like variations in signal pulse shapes, timing miscalibrations and implemented the double Gaussian model of the calorimeter noise. I showed that the simulator was able to reproduce the quality factor distributions in collisions in absence of out-of-time pile-up. Then I included the effect of out-of-time pile-up. Using the distributions of quality factor with and without out-of-time pile-up obtained with pulse simulator I have proposed a selection criteria to identify out-of-time pile-up. This work fully performed by myself is presented in **Papers I and II**. **Paper I** contains an early stage of the study that I presented at the 2011 IEEE Nuclear Science Symposium and Medical Imaging Conference. **Paper II** presents the latest results together with the full description of the method. I presented, on behalf of the ATLAS Tile Calorimeter group, the performance of the signal reconstruction in TileCal at the 2012 CALOR International Conference on Calorimetry in High Energy Physics. This results, including also the quality factor studies I have carried out, is described in the public proceedings:

**Paper IV:** P. Klimek, Signal reconstruction performance with the ATLAS Hadronic Tile Calorimeter. *J. Phys.: Conf. Ser.* 404:012046, 2012 [6].

The pulse simulator that I developed was further developed by another Stockholm student and integrated into the official ATLAS software. The work presented in this thesis on the pulse simulator was entirely performed by me.



Next, I started to work on the analysis of ATLAS data. The goal of the work was to search for chargino and slepton direct pair production. I worked on the jet-veto constructed by the Stockholm group and developed its exact definition. I showed that the jet-veto efficiency in data is well reproduced by Monte Carlo simulation, therefore it can be utilised in the analysis without additional corrections. I also performed an estimation of the  $ZV$  background using a method the Stockholm team introduced. The  $ZV$  background is one of the dominant backgrounds in the analysis. Both my jet-veto and  $ZV$  background calculations are used in **Paper III**. Before **Paper III** was published in March 2014 we performed a first preliminary analysis of the 2012 data with preliminary object identification and background calculations. I contributed to this work presented in the paper:

**Paper V:** The ATLAS Collaboration, Search for direct-slepton and direct-chargino production in final states with two opposite-sign leptons, missing transverse momentum and no jets in  $20\text{ fb}^{-1}$  of  $pp$  collisions at  $\sqrt{s} = 8\text{ TeV}$  with the ATLAS detector. ATLAS-CONF-2013-049, 2013 [7].

Following the publication of the search for direct chargino and slepton production I started to work on the search for chargino pair production via VBF. I have been a leading analyser in this work. I performed optimisation of the signal region and defined its selection criteria. For this purpose I developed the signal region optimisation method where several variables are scanned simultaneously in order to address the correlation between the variables. I have performed the estimation of diboson background that includes the  $WW$  and  $WZ$  processes. The background is calculated using Monte Carlo with NLO normalisation extracted from dedicated fiducial regions. I have also estimated the theoretical systematic uncertainties from Monte Carlo generator, scale, PDF and parton showering. I validated all background estimations using validation regions. I calculated the event yields and estimated systematic errors in signal and validation regions. I produced plots with kinematic distributions in signal and validation regions. Finally, I have contributed to the limits calculations. This paper is at an advanced review stage by the ATLAS Collaboration and will be submitted to *Phys. Rev. D.*:

**Paper VI:** The ATLAS Collaboration, Search for electroweak production of supersymmetric particles in  $\sqrt{s} = 8\text{ TeV}$   $pp$  collisions with the ATLAS detector. In preparation to be submitted to *Phys. Rev. D.*, 2015 [8].

In summary I have worked on three analyses of ATLAS data:

- The analysis described in **Paper V** is a public conference result performed on  $\mathcal{L} = 20.7\text{ fb}^{-1}$  of 2012 data. For this analysis I have studied the jet-veto performance as described in Chapter 8 of this thesis. I also contributed to the  $ZV$ -background estimation using a method similar to the one described in Chapter 9.
- A second analysis of ATLAS 2012 data is described in **Paper III** published in *JHEP*. In this analysis a reprocessed dataset of recalculated total integrated lu-

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minosity  $\mathcal{L} = 20.3 \text{ fb}^{-1}$  is used. Jet-veto calculations using the same method as described in Chapter 8 were performed by me in order to check that the same conclusions apply there too. I also performed all calculations for the  $ZV$  background and developed the method. The  $ZV$ -background estimation method was improved by reoptimising control region definitions. This method is described in Chapter 9.

- A third analysis performed on  $\mathcal{L} = 20.3 \text{ fb}^{-1}$  of 2012 data is going to be described in **Paper VI** and submitted to *Phys. Rev. D*. The signal region is optimised by me using my own method described in Chapter 12. I have performed the diboson background estimation using Monte Carlo simulations with the normalisation extracted from NLO cross section calculators in dedicated fiducial regions. Also I have estimated the corresponding systematic uncertainties as described in Chapter 14. I performed the validation of all backgrounds estimation using validation regions. I produced plots with kinematic distributions, calculated the event yields and estimated systematic errors in signal and validation regions. I contributed to the limit calculations presented in Chapter 15.

I have presented on behalf of ATLAS collaboration the results on searches for  $R$ -parity conserving Supersymmetry at the ATLAS detector at the 2014 Lake Louise Winter Institute.

I also had the opportunity to contribute to the operation of the ATLAS detector. I have served many times as a calorimeter and data quality shifter in the ATLAS Control Room.



## Part I

# Theoretical Overview



# 1 The Standard Model of Particle Physics

The twentieth century physicists combined quantum mechanics and special relativity to create quantum field theory which became the mathematical language of the Standard Model of particle physics (SM) [9, 10, 11]. The SM is the theory describing observed elementary particle phenomena. It has been extensively tested during the last four decades and shows great predictive power [12].

A general description of matter particles in the Standard Model is given in Section 1.1. Section 1.2 gives a short introduction to fundamental interactions in the SM. The Higgs boson is briefly described in Section 1.3. Finally, shortcomings of the Standard Model are discussed in Section 1.4.

## 1.1 Elementary Matter Particles

In the Standard Model, matter consists of spin  $1/2$  fermions obeying Fermi-Dirac statistics. They are divided into quarks and leptons. Quarks are sensitive to the strong nuclear interaction in contrast to leptons which do not interact strongly. The fermions are grouped into three generations. There are two quarks, one charged lepton and one neutral lepton (called neutrino) in each generation. The visible and stable matter in our universe is made of the first generation fermions [13]. Quarks and leptons from heavier generations rapidly decay into lighter particles. The exception is neutrinos which do not decay, they oscillate between generations instead [14].

All the fermions have antiparticles differing only by the sign of the charge. In case of quarks and neutral leptons the antiparticles are denoted by the same symbol as the partners with a bar added over it. Antiparticles of charged leptons have a positive electric charge. Table 1.1 lists the fermions along with some of their properties.

## 1.2 Fundamental Interactions

Emma Noether has shown that there is symmetry associated with every conservation law. The invariance under time displacement, space translation and rotation lead to the conservation of energy, momentum and angular momentum respectively. In the Stan-

| Type                  | Name              | Symbol     | Mass [MeV]          | Electric charge [ $e$ ] |
|-----------------------|-------------------|------------|---------------------|-------------------------|
| Quarks<br>(spin=1/2)  | up                | $u$        | 2.3                 | +2/3                    |
|                       | down              | $d$        | 4.8                 | -1/3                    |
|                       | strange           | $s$        | 95                  | -1/3                    |
|                       | charm             | $c$        | 1275                | +2/3                    |
|                       | bottom            | $b$        | 4180                | -1/3                    |
|                       | top               | $t$        | $173.1 \cdot 10^3$  | +2/3                    |
| Leptons<br>(spin=1/2) | electron          | $e$        | 0.511               | -1                      |
|                       | muon              | $\mu$      | 105.7               | -1                      |
|                       | tau               | $\tau$     | 1777                | -1                      |
|                       | electron neutrino | $\nu_e$    | $< 2 \cdot 10^{-6}$ | 0                       |
|                       | muon neutrino     | $\nu_\mu$  | $< 0.19$            | 0                       |
|                       | tau neutrino      | $\nu_\tau$ | $< 18.2$            | 0                       |

Table 1.1: The Standard Model elementary fermions and their properties [15]. The electric charge is expressed in units of the elementary charge  $e$ .

Standard Model the structure of fundamental interactions are connected to the local gauge invariance. The free particle theory transforms into the interacting particle fields theory. The introduction of new vector boson fields called gauge fields accomplish the requirement of the local gauge invariance. The number of introduced vector fields corresponds to the number of independent generators of a chosen symmetry group. The Standard Model has gauge symmetry group  $SU(3) \times SU(2) \times U(1)$ . There are no particular reasons for this choice, except that it is the simplest group that reproduce the currently known features of particle interactions and it is in agreement with experiment.

In Nature four fundamental interactions have been observed: strong, electromagnetic, weak and gravitational. The first three are described by the Standard Model. Gravity is described by General Relativity. The list of fundamental interactions and their mediators is presented in Tab. 1.2. The effect of gravity on elementary particles is negligible compared to that of the other interactions and impossible to observe with present particle physics experiments. Effect of gravity becomes comparable to Standard Model interactions at very high energy, of the order of  $10^{19}$  GeV, well beyond current or planned experiments. The Standard Model describes the fundamental interactions by the exchange of spin 1 bosons obeying Bose-Einstein statistics. Table 1.3 lists the bosons along with some of their properties.

### The strong interaction

The strong force is responsible for holding the quarks together in hadrons (e.g. protons, neutrons) and nucleons in atomic nuclei and is described by the theory of Quan-

| Interaction     | Mediator<br>name | symbol         | Relative<br>strength | Flavour<br>conservation |
|-----------------|------------------|----------------|----------------------|-------------------------|
| Strong          | gluon            | $g$            | 10                   | ✓                       |
| Electromagnetic | photon           | $\gamma$       | $10^{-2}$            | ✓                       |
| Weak            | $W, Z$           | $W^{\pm}, Z^0$ | $10^{-13}$           | ✗                       |
| Gravity         | graviton*        | $G$            | $10^{-42}$           | —                       |

*\*hypothetical*

Table 1.2: The fundamental interactions of Nature with their mediators. The strong, electromagnetic and weak interactions are described by the Standard Model [13]. “✓” means the flavour is conserved, “✗” means the flavour is not conserved, “—” means the flavour conservation is not predicted by the SM.

| Type                     | Name   | Symbol    | Mass [MeV]        | Electric charge [ $e$ ] |
|--------------------------|--------|-----------|-------------------|-------------------------|
| Gauge bosons<br>(spin=1) | photon | $\gamma$  | 0                 | 0                       |
|                          | $W$    | $W^{\pm}$ | $80.4 \cdot 10^3$ | $\pm 1$                 |
|                          | $Z$    | $Z^0$     | $91.2 \cdot 10^3$ | 0                       |
|                          | gluon  | $g$       | 0                 | 0                       |
| Higgs boson<br>(spin=0)  | Higgs  | $H$       | $126 \cdot 10^3$  | 0                       |

Table 1.3: The Standard Model elementary bosons and their properties [15]. The electric charge is expressed in units of elementary charge  $e$ .



Quantum Chromodynamics (QCD) [16]. It conserves flavour and acts upon particles carrying colour charge, quarks and gluons. The strong interaction is mediated by the gluons. Gluons carry colour charge, therefore they can also interact with each other. There are eight massless, electrically neutral gluons. The quarks can carry one of three colour charges labelled: red, green and blue. Antiparticles carry inverted colour charge, “anticolour”. A free quark has never been observed. Quarks are always found in colourless bound states called hadrons. Bound states of three quarks are called baryons (e.g. proton, neutron). A quark-antiquark pair bound states is called meson (e.g. pions). The phenomenon that coloured particles cannot be isolated is called colour confinement [13]. A phenomenological explanation is that the strength of the strong force increases with the distance between coloured particles. Approximately at a distance of 1 fm (typical size of a hadron), it is energetically favourable to produce an extra quark-antiquark pair from the vacuum. This process leads to the creation of a spray of hadrons travelling approximately in the same direction as the initial quark or gluon and is called a hadronic jet.

#### The electromagnetic interaction

Electromagnetism is responsible for binding electrons into atoms and forming molecules. It is described by Quantum Electrodynamics (QED), which is one of the most accurate theories in physics. It withstands experimental tests with a precision better than  $10^{-12}$ . It acts upon particles carrying electric charge and is mediated by the electrically neutral photon. The electromagnetic interaction conserves flavour and its range is infinite.

#### The weak interaction

The weak interaction acts upon all fundamental fermions. Contrary to the strong and the electromagnetic forces, the weak interaction is mediated by massive force carriers,  $W^\pm$  and  $Z^0$ , bosons. It couples only to left-handed particles and to right-handed antiparticles. It is the only Standard Model interaction allowing to change the quark flavour. For example, it manifests itself in the  $\beta$ -decay:

$$n \rightarrow p + e^- + \bar{\nu}_e \quad (1.1)$$

In this process a  $d$ -quark in the neutron is converted to  $u$ -quark and an off-shell  $W^-$  boson is emitted, which immediately decays into an electron and an electron antineutrino. This is denoted as:

$$d \rightarrow u + W^- \rightarrow u + e^- + \bar{\nu}_e \quad (1.2)$$

Figure 1.1 illustrates this process. In the Standard Model the weak and electromagnetic interactions are combined together in a more fundamental theory, the electroweak interaction. In this model weak and electromagnetic forces are two manifestations of the same interaction.

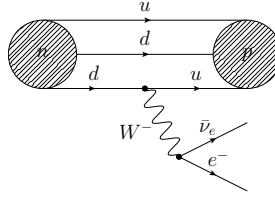


Figure 1.1: Neutron  $\beta$ -decay via the weak interaction.

### 1.3 The Higgs Boson

Without any additional ingredient the Standard Model predicts the mediators of electroweak interactions to be massless. This is wrong since the  $W^\pm$  and  $Z^0$  bosons are observed experimentally with masses of 80.4 GeV and 91.2 GeV respectively. The photon remains massless. Therefore, a mechanism to provide massive gauge bosons is included in the Standard Model. The so called BEH (Brout-Englert-Higgs) mechanism [17, 18] allows to solve this problem.

A non-zero vacuum expectation value for a scalar field caused by spontaneous symmetry breaking is postulated in the early Universe. This produces three massless Goldstone bosons with the same quantum numbers as  $W^\pm$  and  $Z^0$  bosons. The generated bosons mix with electroweak gauge bosons  $W^i$  and  $B$  giving them mass through the BEH mechanism and yielding the massive physical states  $W^\pm$  and  $Z^0$  bosons observed experimentally. The fourth gauge boson, the photon remains massless. An experimental prediction of the BEH mechanism is the existence of a so called Higgs boson.

On July 4 2012 it was announced that the Higgs boson was discovered by the ATLAS [19] and CMS [20] experiments at the LHC. Its properties are being probed in order to find out if the new particle is the Standard Model Higgs boson or an indication of beyond SM physics. Within current experimental sensitivity it is fully consistent with a Standard Model Higgs boson [21, 22].

### 1.4 Shortcomings of the Standard Model

The Standard Model has undergone a large number of rigorous experimental tests. It turns out to be the most successful theory in the history of physics since no significant tension with experiment has been found in the widest range of physics phenomena. Nevertheless, the Standard Model cannot be the final theory of Nature and is believed to be only a low energy approximation of a more fundamental theory. Reasons for that belief are several unanswered questions that are not solved by the Standard Model. A brief selection of a few of these questions is given below.

### Gravitation

Gravitation is not incorporated in the Standard Model. Despite being apparent in our daily life, at the electroweak scale gravity is so weak compared to other interactions. Therefore, it is negligible and cannot be studied experimentally together with the other interactions. The energy scale at which effects of quantum gravity are expected to become important is of the order of  $10^{19}$  GeV (Planck scale). There are no definite answers for questions like: Why is gravitation so much weaker than all other interactions? How can a quantum field theory of gravitation be formulated?

### Origin of neutrino masses

The Standard Model predicts that neutrinos are massless particles since the BEH mechanism does not give them mass unlike other fermions. Nevertheless, various measurements of solar, atmospheric and reactor neutrinos show that neutrinos have small masses and can oscillate between the generations [14]. Neutrino masses could however be incorporated to the Standard Model by adding new free parameters.

### Dark matter and dark energy

Astronomical observations of the movements of galaxies and stars inside galaxies as well as cosmological measurements [23] suggest that the visible matter constitutes only approximately 4.9% of the mass in the Universe. Another 26.8% of its mass is believed to be made up of so called dark matter [24]. It has not been detected through strong or electromagnetic interaction. It is only observed indirectly through gravitational effects, therefore it is called dark. Neutrinos were considered as potential dark matter candidates [25]. Nevertheless, they are not abundant nor heavy enough to constitute a significant part of the dark matter of the Universe. The Standard Model does not provide a good candidate of dark matter particle. The remaining 68.3% of the mass of the Universe is believed to be made up of so called dark energy [26, 27] that is even less understood than dark matter. The evidence for dark energy is indirect. It comes from the cosmological measurements indicating that the expansion of the universe is accelerating.

### Hierarchy problem

The Higgs boson mass ( $m_H$ ) can be expressed as a sum of its bare mass  $(m_H)_0$  and contributions from quantum corrections:

$$m_H^2 = (m_H^2)_0 + \frac{kg^2\Lambda^2}{16\pi^2} \quad (1.3)$$

where  $k$  is a constant and  $g$  is the coupling constant between fermions and the Higgs field. The last term corresponds to loop corrections involving virtual particles such as the top quark presented in Fig. 1.2. The factor  $\Lambda$  corresponds to the energy scale up

to which these processes are calculated. This scale is a cut-off scale above which the Standard Model is no longer valid and new physics should be taken into account. If no new physics appears before the Plank Scale then the quantity  $\Lambda$  is set to a value of the order of  $10^{19}$  GeV where quantum gravity must come into play. The mass of the Higgs boson measured by ATLAS and CMS experiments is  $m_H = 126$  GeV [19, 20]. This is 16 orders of magnitude smaller than the quantum loop corrections. Thus there must be some extraordinary cancellation between nominally uncorrected correction terms. This problem is often referred to as the hierarchy problem or fine tuning (of the correction terms) problem.

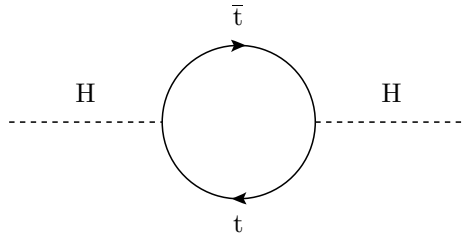


Figure 1.2: A diagram of a one-loop quantum correction to the Higgs mass.

### Beyond the Standard Model

In order to address the problems discussed above, a theory of physics beyond the Standard Model is needed. In the era of particle physics after the discovery of the Higgs boson searching for physics beyond the SM is the main goal of the experiments at the Large Hadron Collider. There are several new theories being tested. One of them is called Supersymmetry. SUSY introduces a new symmetry which leads to a new set of particles. These new particles could allow cancelation of correction terms in the Higgs mass. Also, in Supersymmetry models the Lightest Supersymmetric Particle (LSP) could be stable and weakly interacting, thus remaining undetected. Due to its predicted properties the LSP can be a good dark matter candidate, so called Weakly Interacting Massive Particle (WIMP). In Chapter 2 we discuss briefly the Supersymmetry which is also the subject of Part III and Part IV of this thesis.

Other theories beyond the Standard Model being investigated are theories of Extra Dimensions. The Large Extra Dimensions theories assumes that the Standard Model fields are confined to a four-dimensional membrane, while gravity propagates in additional extra dimensions. This would explain the weakness of gravity with respect to the other forces. A new discrete conserved Kaluza-Klein quantum number could give the phenomenology yielding new stable particles, and thereby dark matter candidate. Extra Dimensions could also solve the hierarchy problem [28]. If extra spacial dimensions are

large enough there might be phenomenological implications at the energy scale reachable by the LHC.

Other beyond Standard Model theories include compositeness, theories where some of the SM particles have a substructure.

## 2 Supersymmetry

### 2.1 Overview

In the early 1970s a symmetry that relates fermions and bosons was proposed. “Supersymmetry” (SUSY) [29, 30, 31, 32] was introduced to resolve some of the Standard Model shortcomings. A supersymmetric transformation turns a bosonic state into a fermionic one and vice versa. In this way every Standard Model particle has a supersymmetric partner called a superpartner. Some SUSY models can have more than one superpartner per standard model particle. The supersymmetric partner has all quantum numbers and couplings equal to its SM counterpart except for the spin. The spin of the SM particle and its superpartner differs by  $1/2$ . Every SM fermion (with spin  $1/2$ ) has a spin 0 superpartner. Similarly, every SM gauge boson (with spin 1) has a superpartner with spin  $1/2$ .

### 2.2 Nomenclature for Supersymmetric Particles

The nomenclature for supersymmetric particles, so called “sparticles”, adds a prefix “s” to the SM fermion names and adds a suffix “ino” to the SM boson names. The new sparticles are denoted by the same symbols as their Standard Model partners with a tilde on top. For instance, the superpartners of the leptons are called sleptons and denoted  $\tilde{\ell}^{\pm}$  (selectron -  $\tilde{e}$ , smuon -  $\tilde{\mu}$ , stau -  $\tilde{\tau}$ , sneutrino -  $\tilde{\nu}$ ). The so called left- (right-) handed sleptons are the spin zero superpartners of the left- (right-) handed leptons. A subscript  $L$  ( $R$ ) is used to denote the SUSY partners of left- (right-) handed SM particles. Superpartners of quarks are called squarks (sup -  $\tilde{u}$ , sdown -  $\tilde{d}$ , sbottom -  $\tilde{b}$ , stop -  $\tilde{t}$ ...) and superpartners of gauge bosons are called gauginos. In this thesis we use the term gaugino to designate the superpartners of the electroweak gauge bosons and Higgs bosons, while the superpartner of the gluon is called the gluino. As explained in the following sections there are four neutral gauginos called neutralinos ( $\tilde{\chi}_i^0, i = 1, 2, 3, 4$ ) and four charged gauginos called charginos ( $\tilde{\chi}_i^{\pm}, i = 1, 2$ ). They are mass eigenstates formed from the mixing of the SUSY partners of the electroweak gauge bosons  $W^i$ ,  $B$  (wino and bino) and Higgs boson (Higgsino). The superpartner of the gluon is called the gluino.

## 2.3 The Minimal Supersymmetric Standard Model

The Minimal Supersymmetric Standard Model (MSSM) [33, 34, 35, 36] is the simplest supersymmetric extension of the Standard Model. In this model each SM particle has exactly one superpartner.

### 2.3.1 Supersymmetry Breaking

If Nature was exactly supersymmetric all the superpartners would have the same mass as their Standard Model partners. This is obviously not true, since no such particles have been observed to date. The mass of the superpartners has to be larger than the mass of Standard Model partners, otherwise the superpartners would have been already observed experimentally. Therefore Supersymmetry, if it is a theory describing Nature, must be broken.

If the masses of the SUSY particles are below 2 TeV, the Supersymmetry can solve the hierarchy problem. A SUSY breaking that preserves the high energy behavior of SUSY so-called “soft breaking” is introduced [15]. Theorists have managed to construct a realistic model of spontaneously broken low energy supersymmetry where the breaking arises only from interactions of the particles of the MSSM [37]. One way to introduce the breaking of SUSY is to assume the existence of a hidden sector. The particles of these sector are completely decoupled from the MSSM. The Supersymmetry breaking occurs in this hidden sector and is transmitted to the visible sector via the messenger sector [15]. There are several models describing the SUSY breaking like gauge mediated, gravity mediated or anomaly mediated.

The soft SUSY breaking leads to the introduction of all allowed soft terms to the Lagrangian. The soft terms are mass matrices and couplings that a priori allow for flavour mixing, L-R mixing and large  $CP$  violation. This adds more than 100 new parameters to the Standard Model.

### 2.3.2 The Higgs Sector

The MSSM has an extended Higgs sector. It has to contain two Higgs doublets, since a single Higgs doublet cannot generate mass for all fermions in a way that is consistent with Supersymmetry. One Higgs doublet generates the masses of up type quarks and one generate the masses of down type quarks and charged leptons. The superpartners of the Higgs fields are called Higgsinos.

### 2.3.3 The Gaugino Sector

The neutral gauginos and neutral Higgsinos have the same quantum numbers. Therefore, they mix together into four physical mass states called neutralinos:  $\tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_3^0, \tilde{\chi}_4^0$  (where  $\tilde{\chi}_1^0$  is the lightest and  $\tilde{\chi}_4^0$  is the heaviest). The mixing is described by a  $4 \times 4$

symmetric complex mass matrix [35]:

$$M_{\tilde{\chi}^0} = \begin{pmatrix} M_1 & 0 & -M_W \tan \theta_W \cos \beta & M_W \tan \theta_W \sin \beta \\ 0 & M_2 & M_W \cos \beta & -M_W \sin \beta \\ -M_W \tan \theta_W \cos \beta & M_W \cos \beta & 0 & -\mu \\ M_W \tan \theta_W \sin \beta & -M_W \sin \beta & -\mu & 0 \end{pmatrix} \quad (2.1)$$

Similarly the charged gauginos and Higgsinos mix together into charginos:  $\tilde{\chi}_1^\pm, \tilde{\chi}_2^\pm$  (where  $\tilde{\chi}_1^\pm$  is the lighter then  $\tilde{\chi}_2^\pm$ ). The mixing is described by a  $2 \times 2$  complex mass matrix:

$$M_{\tilde{\chi}^\pm} = \begin{pmatrix} M_2 & \sqrt{2}M_W \sin \beta \\ \sqrt{2}M_W \cos \beta & \mu \end{pmatrix} \quad (2.2)$$

where  $M_1, M_2$  and  $\mu$  are the bino, wino and Higgsino mass terms respectively,  $m_W$  is the mass of the  $W$  boson,  $\theta_W$  is the weak mixing angle and  $\tan \beta$  is the ratio of vacuum expectation values of two Higgs doublets.

### 2.3.4 $R$ -parity

Lepton number  $L$  and baryon number  $B$  are conserved in the Standard Model due to gauge invariance. This prevents for instance the proton from decaying. In the MSSM interactions that violate  $L$  and  $B$  numbers are a priori allowed without additional symmetry. This seems inconsistent with the experimental lower limit on the proton mean life time of  $2.1 \cdot 10^{29}$  years [38]. For this reason a new multiplicative quantum number called  $R$ -parity is introduced:

$$R = (-1)^{3(B-L)+2S} \quad (2.3)$$

where  $S$  is the spin of the particle. All the Standard Model and Higgs particles have  $R$ -parity equal to +1, while all supersymmetric particles have  $R$ -parity equals to -1. To prevent proton decay  $R$ -parity conservation can be imposed. The conservation of  $R$ -parity has very significant phenomenological consequences:

- SUSY particles can only be produced in pairs,
- SUSY particles must have an odd number of SUSY particles in their decay products,
- the Lightest SUSY Particle (LSP) is stable.

Table 2.1 lists the MSSM sparticles and Higgs bosons with some of their properties.



| Type         | Symbol                                                                | Spin | $R$ -parity |
|--------------|-----------------------------------------------------------------------|------|-------------|
| Squarks      | $\tilde{u}_L \tilde{u}_R \tilde{d}_L \tilde{d}_R$                     | 0    | -1          |
|              | $\tilde{s}_L \tilde{s}_R \tilde{c}_L \tilde{c}_R$                     | 0    | -1          |
|              | $\tilde{t}_1 \tilde{t}_2 \tilde{b}_1 \tilde{b}_2$                     | 0    | -1          |
| Sleptons     | $\tilde{e}_L \tilde{e}_R \tilde{\nu}_e$                               | 0    | -1          |
|              | $\tilde{\mu}_L \tilde{\mu}_R \tilde{\nu}_\mu$                         | 0    | -1          |
|              | $\tilde{\tau}_1 \tilde{\tau}_2 \tilde{\nu}_\tau$                      | 0    | -1          |
| Neutralinos  | $\tilde{\chi}_1^0 \tilde{\chi}_2^0 \tilde{\chi}_3^0 \tilde{\chi}_4^0$ | 1/2  | -1          |
| Charginos    | $\tilde{\chi}_1^\pm \tilde{\chi}_2^\pm$                               | 1/2  | -1          |
| Gluino       | $\tilde{g}$                                                           | 1/2  | -1          |
| Higgs bosons | $h^0 H^0 A^0 h^\pm$                                                   | 0    | +1          |

Table 2.1: The Minimal Supersymmetric Standard Model predicted sparticles and some of their properties. The indices 1, 2 used for  $\tilde{t}$ ,  $\tilde{b}$  and  $\tilde{\tau}$  are to allow for possible large mixing between  $L$  and  $R$  states. For light flavour sfermions this mixing is small. The MSSM Higgs bosons are also listed.

### 2.3.5 The Phenomenological MSSM

MSSM introduces more than 100 additional free parameters compared to the Standard Model. Such an amount of arbitrariness makes the model difficult to constrain experimentally. Many of the parameters have to be constrained in order to form an experimentally testable theory. Therefore, the so called phenomenological Minimal Supersymmetric Standard Model (pMSSM) [39, 40] has been introduced. The pMSSM is a version of  $R$ -parity conserving MSSM. In pMSSM the number of free parameters is reduced compared to MSSM by imposing the following guiding principles:

- no additional source of CP violation compared to the SM,
- quark and lepton flavour conservation in the SUSY sector,
- no additional source of flavour changing neutral currents,
- degenerate 1st and 2nd generation sfermion masses.

The pMSSM with a neutralino as the LSP has 19 parameters. The 20<sup>th</sup> parameter is the mass of the gravitino, the hypothetical supersymmetric partner of the graviton.

### 2.3.6 Simplified Models

The experimental searches for Supersymmetry exploit the topology of the postulated signal processes in order to identify the interesting events among the billions of recorded LHC collisions. This approach is difficult, since the large number of free parameters in the SUSY theories being investigated impedes the experimental investigations. One method is to search for a single topology which can be realised in several models, i.e. several sets of model parameters can lead to that topology. It can be done using so called SUSY simplified models. These models focus on some particular decay channels rather than providing the complete description of given model. This approach allows searches for some generalised SUSY topologies. In such models additional constraints are imposed. Usually, the following simplifications are made:

- Only sparticles of interest are considered. Masses of all the other sparticles are set to very high values. This makes them not reachable by the LHC.
- All masses of the sparticles are treated as free parameters.
- The decay of interest is assumed to have 100% branching ratio.

Experimental searches for SUSY using simplified models can then be interpreted in context of multiple complete models. The topologies of simplified models may also be interpreted in the context of other models beyond Standard Model, that have the same signatures.

Parts III and IV of this thesis present searches for Supersymmetry signals using simplified models in proton-proton collisions recorded by the ATLAS experiment. Part III is dedicated to a search for direct production of chargino pairs and slepton pairs. Part IV focusses on a search for chargino pairs production via Vector Boson Fusion. The details of the simplified models used in analyses are presented in Chapter 6.1 and Chapter 11.1 respectively.

## 2.4 Motivation for Supersymmetry

Several shortcomings of the Standard Model have been discussed in Chapter 1. The SM model is believed to be a low energy approximation of a more fundamental theory. Supersymmetry was developed to extend the Standard Model in an attempt to answer questions left open by the SM.

In models with  $R$ -parity conservation the supersymmetric particles are produced in pairs. An absolutely stable LSP with no electric charge nor colour charge interacting only weakly and gravitationally, is an excellent WIMP Dark Mater candidate [41, 25]. Such particles, if produced in proton-proton collisions recorded by ATLAS, would leave the detector undetected giving rise to so called missing energy described in more details in Chapter 3.

The SM particles and their superpartners have cancelling contributions to the radiative corrections to the Higgs mass given in Eq. 1.3. An unnatural fine tuning is not needed and the hierarchy problem is elegantly solved in presence of supersymmetric particles. If the sparticle masses are not much larger than 1 TeV, Supersymmetry can still solve the hierarchy problem [42].

Another theoretical motivation for Supersymmetry is the unification of the coupling constants of the electromagnetic, weak and strong interactions. It is believed that these interactions should unify at so called Grand Unified Theory (GUT) scale [36]. In the GUT electromagnetic, weak and strong interactions are different low energy manifestations of the same fundamental force. If coupling constants are expressed as effective values with loop corrections included in the gauge boson propagator they become energy dependent running parameters. To achieve unification of the coupling constants at the GUT scale the coupling constants have to converge to a common value. The energy dependence of the coupling constants is determined by the particle content of the model. The evolution of the inverse of the gauge couplings at high energy, in the framework of the Standard Model and the Minimal Supersymmetric Standard Model is presented on Fig. 2.1. In the SM the couplings do not converge at the same point. With the particle content of SUSY they tend to converge at the same value around  $10^{16}$  GeV.

## 2.5 Supersymmetry Production at LHC

The production cross section of the supersymmetric particles depends on the masses and couplings of the SUSY particles. Figure 2.2 shows the cross section for the production

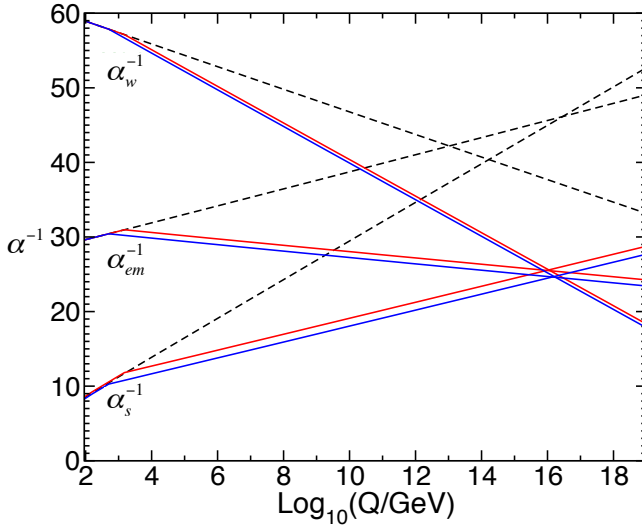


Figure 2.1: Evolution of the inverse of the gauge couplings extrapolated to the GUT scale in the framework of the Standard Model (dashed lines) and in the framework of the Minimal Supersymmetric Standard Model (solid lines) [36].

of various supersymmetric particles as a function of the sparticle mass. It can be seen that the coloured sparticles (squarks and gluinos) produced in strong interactions have significantly larger cross section than colourless sparticles (sleptons, charginos and neutralinos) of equal mass produced in weak interactions. The direct production of weakly interacting slepton pairs or gaugino pairs can be dominating at the LHC over squarks and gluinos if the masses of squarks and gluinos are much higher than masses of sleptons, charginos and neutralinos. It would be true for instance if the squark masses were above 1.3 TeV and masses of weak gauginos less than around 400 GeV. Squark masses up to  $m_{\tilde{q}} = 1.7$  TeV for neutralino mass  $m_{\tilde{\chi}_1^0} = 350$  GeV are excluded in process such as  $\tilde{q} \rightarrow q\tilde{\chi}_1^0$  [43].

ATLAS and CMS experiments perform searches for Supersymmetry production both via strong and weak interactions. Also both  $R$ -parity conserving and violating scenarios are considered. In the studies presented in this thesis only  $R$ -parity conserving models are investigated.

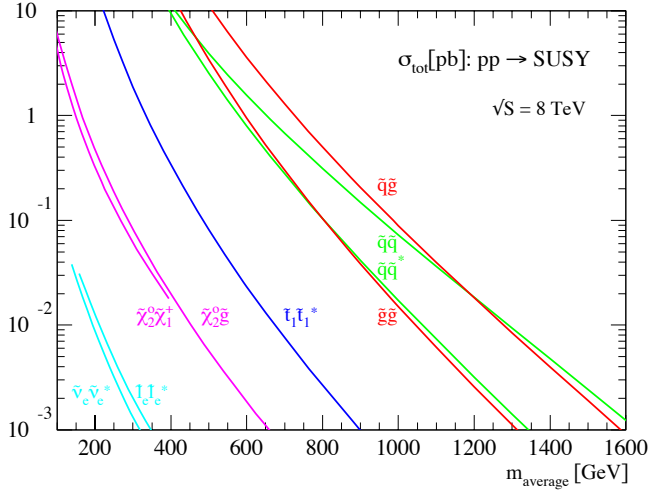


Figure 2.2: Cross sections for the production of various supersymmetric particles as a function of the particle mass in  $\sqrt{s} = 8$  TeV collisions at the LHC calculated at NLO with PROSPINO [44].

### 2.5.1 Recent Searches for Weakly Produced Supersymmetry

The searches for weakly produced Supersymmetry are performed in two main scenarios. Those are scenarios with *i*) intermediate sleptons and *ii*) with intermediate  $W/Z$  bosons in the decay chains. In the first scenario sleptons decay with 100% branching ratio to leptons. In the second scenario  $W/Z$  bosons decay to leptons with branching ratios significantly lower than 100%. The presence of leptons in the final states are of crucial importance to the experimental sensitivity to SUSY production at LHC. Therefore, the limits on the masses of SUSY particles are lower for models with  $W/Z$  bosons in the decay chains.

Figure 2.3 shows the summary of the searches for weakly produced supersymmetric particles in proton-proton collisions in ATLAS. The results of searches for different signatures are superimposed. Both scenarios with sleptons and  $W/Z$  bosons in the decay chains are considered. The experimental absence of detected SUSY particles is utilised to derive lower limits on their masses. A degenerate chargino mass ( $m_{\tilde{\chi}_1^\pm}$ ) and neutralino mass ( $m_{\tilde{\chi}_2^0}$ ) below 700 GeV is excluded for a neutralino mass below  $m_{\tilde{\chi}_1^0} = 100$  GeV at 95% confidence level in a scenario with intermediate sleptons. In a scenario with intermediate  $W/Z$  bosons the degenerate chargino mass ( $m_{\tilde{\chi}_1^\pm}$ ) and neutralino mass ( $m_{\tilde{\chi}_2^0}$ ) below 420 GeV is excluded for neutralino mass below  $m_{\tilde{\chi}_1^0} = 60$  GeV at 95% confi-

dence level. The results of CMS searches for weakly produced Supersymmetry can be found in Ref. [45, 46].

Part III of this thesis is dedicated to a search for direct  $\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp$  and direct slepton pair production. The results on  $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$  search can be found in Refs. [47, 48].

The region of parameter space with small mass splittings between  $\tilde{\chi}_1^\pm$  and  $\tilde{\chi}_1^0$  (so called compressed SUSY spectrum) is not excluded for neutralino masses above  $m_{\tilde{\chi}_1^0} = 100$  GeV. Part IV of this thesis is dedicated to a search for chargino pair production via Vector Boson Fusion in the case of a compressed spectrum with mass differences  $5 < (m_{\tilde{\chi}_1^\pm} - m_{\tilde{\chi}_1^0}) < 25$  GeV. The CMS results of search for Supersymmetry with VBF topology can be found in Ref. [49].

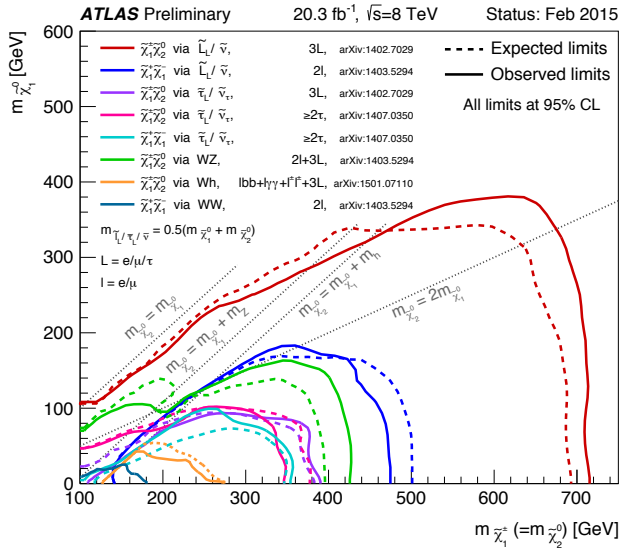


Figure 2.3: Summary of ATLAS searches for electroweak production of charginos and neutralinos based on 20.3 fb<sup>-1</sup> of proton-proton collision data at  $\sqrt{s} = 8$  TeV. Exclusion limits at 95% confidence level are shown in the  $m_{\tilde{\chi}_1^\pm} - m_{\tilde{\chi}_2^0}$  plane. The dashed and solid lines show the expected and observed limits, respectively, including all uncertainties except the theoretical signal cross section uncertainties.



## Part II

# Experimental Overview





## 3 LHC and the ATLAS Detector

### 3.1 The Large Hadron Collider

The Large Hadron Collider (LHC) [50] is a proton-proton accelerator and collider located at CERN, close to the Swiss-French border outside Geneva. The machine is housed in the circular tunnel previously used by the Large Electron Positron Collider (LEP). The tunnel is 27 km long and located approximately 100 meters underground. At the LHC, two counter rotating proton beams containing bunches of up to  $10^{11}$  protons collide at a centre of mass energy  $\sqrt{s} = 8$  TeV (and eventually  $\sqrt{s} = 14$  TeV will be reached in the period 2016-2018). The LHC beams are bent in the beam pipes by 1232 dipole magnets that produce the field of 8.33 T operating at 1.9 K. Nearly 400 quadrupole magnets are used to focus the beam. The beams intersect at four so called interaction points allowing the protons to collide.

#### 3.1.1 Luminosity

The expected number of events of a given process can be calculated as follows:

$$N = \mathcal{L} \times \sigma \quad (3.1)$$

where  $N$  is expected number of events of a given process and  $\sigma$  is the cross section for the process. The so called integrated luminosity  $\mathcal{L}$  is a measure related to the number of proton-proton collisions. Integrated luminosity is defined as:

$$\mathcal{L} = \int L dt \quad (3.2)$$

and has the unit of the inverse of a cross section. In this thesis will often be expressed in  $\text{fb}^{-1}$ . The instantaneous luminosity  $L$  is defined as:

$$L = \frac{f N_1 N_2}{4\pi \sigma_x \sigma_y} \quad (3.3)$$

where  $f$  is the bunch crossing frequency,  $N_i$  is the number of protons per bunch in each beam,  $\sigma_x$  and  $\sigma_y$  are the horizontal and vertical beam sizes at the collision point. The luminosity increases quadratically with the number of protons per bunch. This relation

can be used to increase the luminosity quickly. Nevertheless, besides difficulties to create and maintain a beam with more protons in each bunch, large  $N_i$  increases the probability for multiple collisions per bunch crossing referred to as pile-up. Pile-up is described in more details in Section 5.1.

The design instantaneous luminosity of the LHC is  $10^{34} \text{ cm}^{-2}\text{s}^{-1}$ . This makes the LHC the most powerful particle accelerator in the world in terms of collision energy and luminosity. Nominally the LHC will operate with proton bunches crossing every 25 ns. In 2012 it operated with 50 ns bunch spacing and with an expected average number of 20.7 proton-proton collisions per bunch crossing.

### 3.1.2 The Experiments at LHC

At the interaction points, four large detectors are placed in order to observe the collisions. As shown in Fig. 3.1 there are two general purpose detectors (ATLAS [51], CMS [52]) and two specialised detectors (ALICE [53], LHCb [54]):

- ATLAS (A Toroidal LHC ApparatuS) is a general purpose detector, which covers a broad field of experimental studies. The aim is to observe and study the Higgs boson and search for new phenomena involving heavy particles and very rare processes.
- CMS (Compact Muon Solenoid) is the second general purpose detector. Although CMS has the same physics goals as ATLAS, it involves different technical solutions. CMS is optimised for tracking muons. Its magnet is the largest solenoid ever built, producing a magnetic field with a strength of 4 T. The main reason to build two general purpose detectors was the requirement that any result should be independently confirmed. Additionally, two detectors give the possibility to perform statistical combination and reduce the statistical and systematic errors.
- ALICE (A Large Ion Collider Experiment) is designed to study the quark-gluon plasma [55], a state of matter in which the quarks and gluons can be considered as free particles. This state can be observed in heavy ions collisions.
- LHCb (Large Hadron Collider beauty) is designed to study B hadrons, to investigate CP violation in the  $b$  quark sector and in D meson decays.

There are additionally three smaller LHC experiments. The TOTEM (TOTAl Elastic and diffractive cross section Measurement) [56] experiment is hosted in the CMS cavern. Its purpose is to measure the total proton-proton cross section, elastic scattering and diffractive processes. It will detect particles with small transverse momentum which cannot be seen by the ATLAS nor CMS.

The second small experiment is called LHCf (Large Hadron Collider forward) [57]. This detector is installed 140 m in front of and behind ATLAS. Its purpose is to detect neutral pions  $\pi^0$  with large pseudorapidity which escape from ATLAS undetected. The

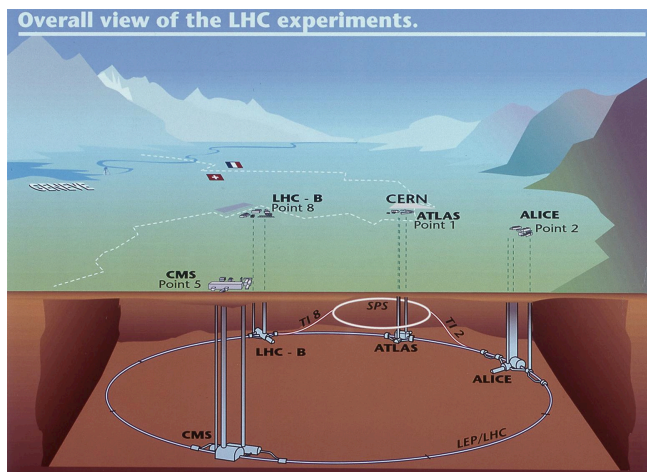


Figure 3.1: Overview of the Large Hadron Collider and its four major underground experiments: ALICE, ATLAS, CMS and LHCb.

goal is to measure the  $\pi^0$  production cross section to constrain atmospheric cosmic showers and improve our understanding of the ultra-high-energy cosmic rays.

The MoEDAL (Monopole and Exotics Detector At the LHC) [58] is the third small experiment. It shares the cavern with LHCb. Its goal is to directly search for hypothetical particles such as magnetic monopoles and other highly ionizing stable massive particles.

## 3.2 The ATLAS Detector

### 3.2.1 Introduction

ATLAS is a general purpose detector. It is designed to observe a large number of different production and decay channels. Therefore, it needs to provide a high momentum and energy resolution as well as an excellent particle identification.

The detector is 25 meters high and 44 meters long and weights approximately 7000 tons. The ATLAS detector consists of several concentric subdetectors. The goal of each component is to detect different types of particles. Figure 3.2 shows the interaction of particles with different parts of the detector. As shown in Fig. 3.3 ATLAS consists of the following subsystems:

- Inner Detector [59] - measures charge, transverse momentum and direction of charged particles. It consists of the pixel detector, Semiconductor tracker (SCT)

and Transition Radiation Tracker (TRT).

- Calorimeters [60, 61] - identify electrons, photons and hadrons, measure their energy and direction. It consists of liquid argon electromagnetic barrel and end-cap calorimeters, Tile Calorimeter and liquid argon hadronic end-cap and forward calorimeters.
- Muon Spectrometer [62] - identifies muons and measure their transverse momentum and direction. It consists of several types of muon detectors described below.

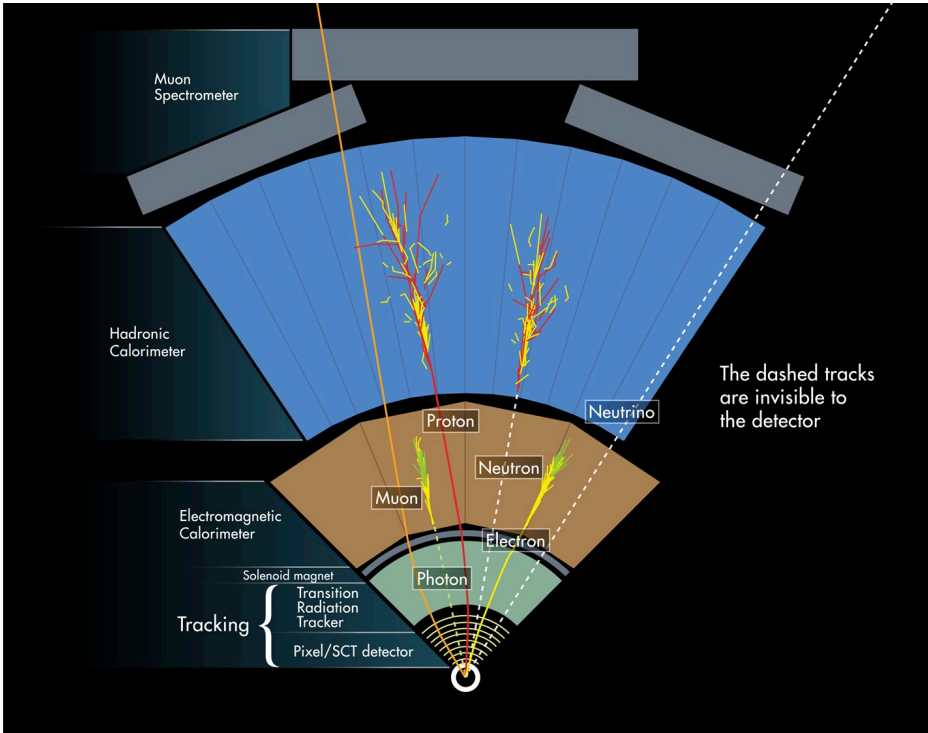


Figure 3.2: Illustration of the interaction of various particles with the different sub-detectors in a wedge of the ATLAS experiment in the plane perpendicular to the beam direction. The particles are produced in the proton-proton collision point located in the circle at the bottom of the figure. The concentric subsystems from small to large radius are: Inner Detector, calorimeters and Muon Spectrometer.

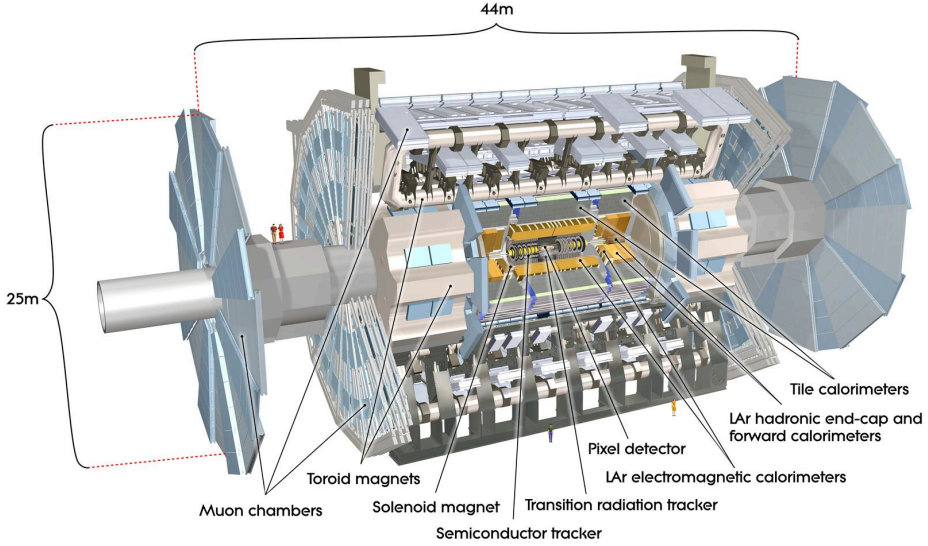


Figure 3.3: Cut-away view of the ATLAS detector and its various subdetectors [51].

### 3.2.2 Geometry and Coordinate System

The ATLAS detector has a cylindrical shape around the beam pipe axis. The coordinate system used to describe the position and direction of particles in the detector is implied by the geometry of the detector. Two coordinate systems are used in ATLAS: one right-handed cartesian and one cylindrical. In the cartesian coordinate system the  $x$ -axis points along the LHC radius towards the centre of the LHC ring in the horizontal plane. The  $y$ -axis points upwards and  $z$ -axis points along the beam axis in the counter-clockwise direction seen from above.

In the cylindrical coordinate system the polar angle  $\theta$  is measured with respect to the beam axis (along the positive  $z$ -axis) and the azimuthal angle  $\phi$  is measured with respect to the  $x$ -axis. At hadron colliders, another quantity, the pseudorapidity is used. Pseudorapidity is defined as:

$$\eta = -\ln \tan\left(\frac{\theta}{2}\right) \quad (3.4)$$

The distance between two particles or two points in the detector with coordinates  $(\eta_1, \phi_1)$

and  $(\eta_2, \phi_2)$  can be defined in pseudorapidity-azimuth space as:

$$\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2} \quad (3.5)$$

where

$$\Delta\eta = (\eta_1 - \eta_2) \quad \text{and} \quad \Delta\phi = (\phi_1 - \phi_2) \quad (3.6)$$

The initial momentum of the interacting partons inside the colliding protons in the  $z$ -direction is unknown while the initial momentum in the  $x$ - and  $y$ -direction is zero. The transverse plane is defined as the  $xy$ -plane perpendicular to the beam axis. Because of the unknown initial momentum in the  $z$ -direction transverse quantities such as transverse momentum  $p_T$  are used. Also, it is necessary to use variables that are invariant under boost along the  $z$ -axis. The pseudorapidity  $\eta$  is such a variable, thus it is preferred over the polar angle  $\theta$ .

### 3.2.3 Inner Detector

The Inner Detector [59] is the subsystem closest to the interaction point. Its goal is the precise measurement of tracks of charged particles as they pass through and interact with the material in the detector. This information is used to determine the momentum, direction and charge of particles. It also allows to identify proton-proton collision vertices and secondary vertices due to long-lived particle decays.

The solenoid magnet surrounding the Inner Detector produces a 2 T magnetic field directed along the  $z$ -axis. Charged particles that pass through the Inner Detector are bent in the transverse plane by this field. This allows a measurement of the particle momentum using the bending radius. The resolution  $\sigma_{p_T}$  of the track momentum  $p_T$  is given by:

$$\frac{\sigma_{p_T}}{p_T} = 3.4 \cdot 10^{-4} p_T \oplus 0.015 \quad (3.7)$$

where  $p_T$  is expressed in GeV and  $\oplus$  means quadratic sum. As the momentum increases, the relative effect of misalignment uncertainties increases with respect to larger radius of curvature, thus leading to a worsened resolution at high  $p_T$ .

Figure 3.4 shows a cross section of the Inner Detector with its subdetectors. The dimensions of the Inner Detector are 6.2 m in length and 2.1 m in diameter. It has to cope with very high multiplicity of particles expected in every event. The measurements are performed by three subdetectors:

- The Pixel Detector - located closest to the interaction point. The innermost layer is 50.5 mm from the  $z$ -axis. The Pixel Detector provides very high spacial resolution and high precision measurements with over 80 million silicon pixel diodes. The area of each pixel is  $40 \times 500 \mu\text{m}^2$  with a thickness of  $250 \mu\text{m}$ . The Pixel Detector has three layers and a coverage up to  $|\eta| = 1.7$  in the barrel region and five end-cap disks on each side of the barrel providing coverage up to  $|\eta| = 2.5$ .

- The Semiconductor Tracker - located immediately outside the Pixel Detector. The detector uses silicon as an active material structured in strips. Each strip has a width of  $80\ \mu\text{m}$ . The Semiconductor Tracker consists of 6.4 million read-out channels. The detector has four layers in the barrel region providing coverage up to  $|\eta| = 1.4$  and nine disks in each end-cap region with coverage up to  $|\eta| = 2.5$ . Each layer consists of two planes of strips. The planes are rotated with respect to each other with the stereo angle of  $40\ \text{mrad}$  which permits the position determination of the hit within the strip.
- The Transition Radiation Tracker - located outside the Semiconductor Tracker. It is made of thin drift straws that are  $4\ \text{mm}$  in diameter and are filled with a gas mixture. Each straw has a  $30\ \mu\text{m}$  gold plated tungsten wire at centre. The barrel part consists of about 50 000 straws parallel to the beam pipe and provide coverage up to  $|\eta| = 0.7$ . The end cap part consists of 320 000 straws, perpendicular to the beam pipe with coverage up to  $|\eta| = 2.0$ . In addition to contributing to the momentum and charge measurement the Transition Radiation Tracker can provide particle identification. The walls of the straw tubes contain polyethylene which enhances production of transition radiation photons which can be detected in Xe gas. The transition radiation occurs when a charged ultrarelativistic particle traverse a boundary between two media with different dielectric constants. The number of produced photons is proportional to the Lorentz boost factor  $\gamma = \frac{E}{m}$ . Therefore, at a given energy, a lighter particle produces more photons than a heavier particle. Electrons produce most of these photons due to their small mass. Thus, it is possible to distinguish electrons from pions.



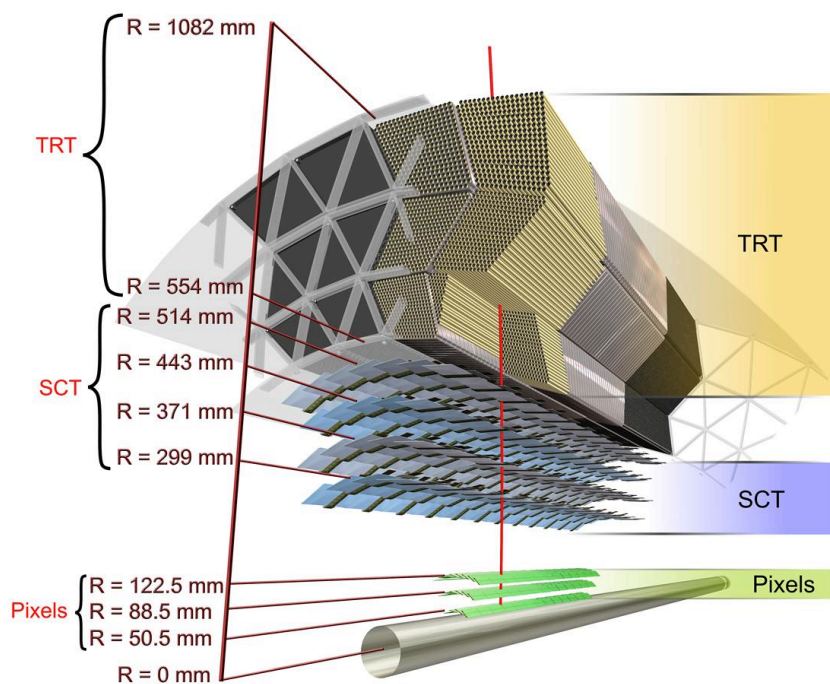


Figure 3.4: A cross section of the ATLAS Inner Detector showing its subdetectors, with their distances from the  $z$ -axis [51].

### 3.2.4 Calorimeters

The main purpose of the ATLAS Calorimeter is to measure the energy, direction and identify photons, electrons, hadrons and tau leptons in an energy range from a few GeV to a few TeV. It is also used to determine missing energy from escaping non-interacting particles such as neutrinos. Thus, it is important that the calorimeter system provides a solid angle coverage as close to  $4\pi$  as possible, so that no particles go undetected. The information from the calorimeter is also utilised by the trigger system. The calorimeter system is located outside the solenoid magnet which surrounds the Inner Detector. The calorimeter system consists of several specialised calorimeters based on different technologies: the Liquid Argon (LAr) Electromagnetic Calorimeter [60], the Tile Hadronic Calorimeter (TileCal) [61], the LAr Electromagnetic End-cap (EMEC), the LAr Hadronic End-cap (HEC) and the LAr Forward Calorimeter (FCal). Liquid argon is used in barrel electromagnetic calorimeter. It is also used in both electromagnetic and hadronic end-cap calorimeters in forward region due to high radiation environment. The layout of the calorimeter system is illustrated in Fig. 3.5.

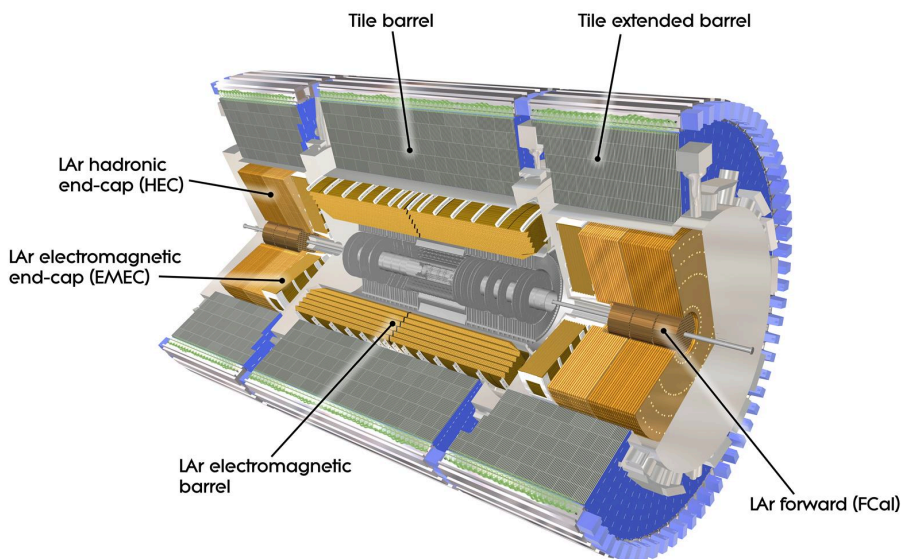


Figure 3.5: Cut-away view of the ATLAS calorimeter system [51].

The purpose of the electromagnetic calorimeter is to precisely measure the energy of electrons and photons. It exploits known interactions with matter. The ultrarelativistic electrons interact mainly by bremsstrahlung. In this process an electron loses part of its energy via Coulomb interactions with atomic nuclei and a photon is radiated. The cross section for this process is proportional to the initial energy of electron and to the square of the atomic number of the medium  $Z$ . The high energy photons mainly create electron-positron pairs. The cross section for electron-positron pair production is proportional to the square of the atomic number of the absorber and to the natural logarithm of photon energy. These processes lead to cascade of photons and electrons called “electromagnetic shower”. Calorimeters enhance and absorb the particle showers and produce a measurable electric signal or light signal. In a calorimeter a medium is selected to promote the showering and is called absorber, while the active material produces a signal when particles pass through it. Two basic types of calorimeters are distinguished, homogenous calorimeters and sampling calorimeters. A homogenous calorimeter is constructed out of a single material, acting both as absorber and active material. An example of homogenous calorimeter is the electromagnetic calorimeter of CMS. The ATLAS electromagnetic calorimeter is an example of sampling calorimeter. It means the calorimeter is build of two alternating materials, an absorber and an active material that samples the shower.

The ATLAS liquid argon calorimeter consists of lead plates with high atomic number  $Z$  as absorbers and LAr as active material. In order to be able to use LAr, the calorimeter must be housed in a cryostat. The absorber plates have an accordion geometry arranged in a cylindrical symmetry around the  $z$ -axis as shown in Fig. 3.6. The accordion shape allows a full  $\phi$  coverage without azimuthal cracks and ensures that particles pass through almost the same amount of material as a function of  $\phi$ . The energy is determined by measuring the charge created by ionisation in the active material which is itself proportional to the energy of the incident photon or electron. The measured energy is scaled by the sampling fraction to obtain the true energy deposited in absorber and active material. The energy resolution for electrons and photons is given by [63]:

$$\frac{\sigma_E}{E} = \frac{0.1}{\sqrt{E}} \oplus 0.0017 \quad (3.8)$$

where  $E$  is expressed in GeV and  $\oplus$  means quadratic sum. The relative energy resolution becomes better with increasing energy of particles, in contrast with the momentum resolution of the Inner Detector.

The barrel part of the electromagnetic calorimeter covers  $|\eta| < 1.475$ . It is divided into three longitudinal layers as shown in Fig. 3.6. It offers a fine segmentation of the read-out cells in all layers, especially in first layer where the cells are  $\Delta\eta = 0.0031$  wide. This allows to precisely measure electromagnetic shower shapes and to differentiate photons from  $\pi^0$  and other hadrons decaying to two collimated photons. The end-cap part comprises a two wheel structure that covers  $1.375 < |\eta| < 2.5$  and  $1.375 < |\eta| < 3.2$ . The electromagnetic calorimeter fills in the volume from the diame-

ter of 3 m up to a diameter of 4 m.

Calorimeters specialised in measuring the energy and direction of hadrons, hadron calorimeters, are located outside the electromagnetic calorimeters. The main task of the hadron calorimeters is to identify hadronic jets and measure their energy and direction. This is achieved by the Tile calorimeter in the range  $|\eta| < 1.7$  and by the LAr hadronic end-cap in the interval  $1.5 < |\eta| < 3.2$ . Since part of the work presented in this thesis is a study of the Tile Calorimeter, Chapter 4 is dedicated to a more detailed description of this subdetector and hadronic calorimetry.

To extend the angular coverage at large  $\eta$  the Forward Calorimeter is installed in the region  $3.1 < |\eta| < 4.9$ . Its structure is optimised to cope with a high flux of the particles in the forward region. It is divided into three longitudinal layers and uses LAr as an active material. The first layer is dedicated to the measurement of the electromagnetic component and uses copper as an absorber. The outer two layers are dedicated to the measurement of the hadronic component and utilise tungsten as an absorber.

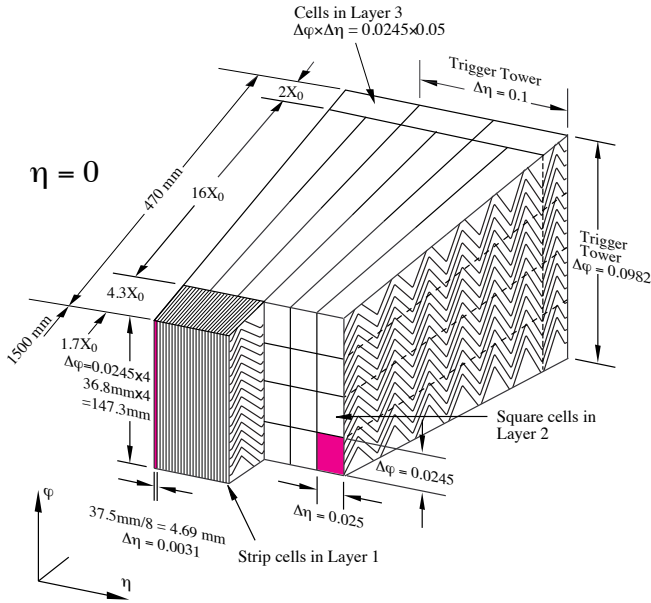


Figure 3.6: Structure of the barrel electromagnetic calorimeter with the accordion shape of the lead absorber plates. The three longitudinal layers of the calorimeter are shown [51].

### 3.2.5 Muon Spectrometer

Muons are capable of traversing the whole ATLAS calorimeters. Muons with energy higher than about 3 GeV pass through the calorimeters and have long enough lifetime not to decay in the detector. A Muon Spectrometer [62] is thus installed outside the calorimeter system. It is the largest subsystem of the ATLAS Detector. Its aim is the identification, precise momentum and direction measurement of muons with  $3 < p_T < 1000$  GeV. The Muon Spectrometer is also used by the trigger system.

Precision tracking chambers are located inside and outside eight toroidal superconducting magnet coils. Muons are bent by the magnetic field. It is sufficient to measure the radius of curvature to determine the transverse momentum of the muons. The radius can be determined by measuring at least three points along the muons trajectory. In all directions except the forward direction muons cross at least three instrumented planes.

The Muon Spectrometer consists of four subdetectors shown in Fig. 3.7 and described below:

- Monitored Drift Tube (MDT) chambers - used for precision measurements of the muon track position in the bending direction in the region of  $|\eta| < 2.7$ . For the innermost end-cap layer the coverage is up to  $|\eta| < 2.0$ .
- Cathode Strip Chambers (CSC) - used for precision measurements of the muon track position in the bending direction in region of  $2.0 < |\eta| < 2.7$ .
- Resistive Plate Chambers (RPC) - provide the muon trigger in the region of  $|\eta| < 1.05$  and muon track position measurement in the non-bending direction.
- Thin Gap Chambers (TGC) - provide the muon trigger in the region of  $1.05 < |\eta| < 2.4$  and muon track position measurement in the non-bending direction.

The core elements of the Muon Spectrometer are about 1200 MDT chambers which are used to precisely measure muon tracks. A high particle flux is expected in the forward region. In this region CSCs are used instead of the MDT, because of their higher radiation tolerance and smaller sizes which lower the pile-up. The RPCs have fast response and are used for triggering. In the forward region the TGCs are used for triggering instead of the RPCs.

The momentum resolution of the Muon Spectrometer worsens with increasing  $p_T$  of muons. It is about 2-3% for muons with a momentum of 50 GeV and about 10% for muons with a momentum of 1 TeV. For muons with momentum below 20 GeV the resolution is dominated by fluctuations of the energy loss in the calorimeters. For muons with momentum above 300 GeV the resolution is dominated by the precision of the drift radii measurements and the precision of the alignment of the chambers.

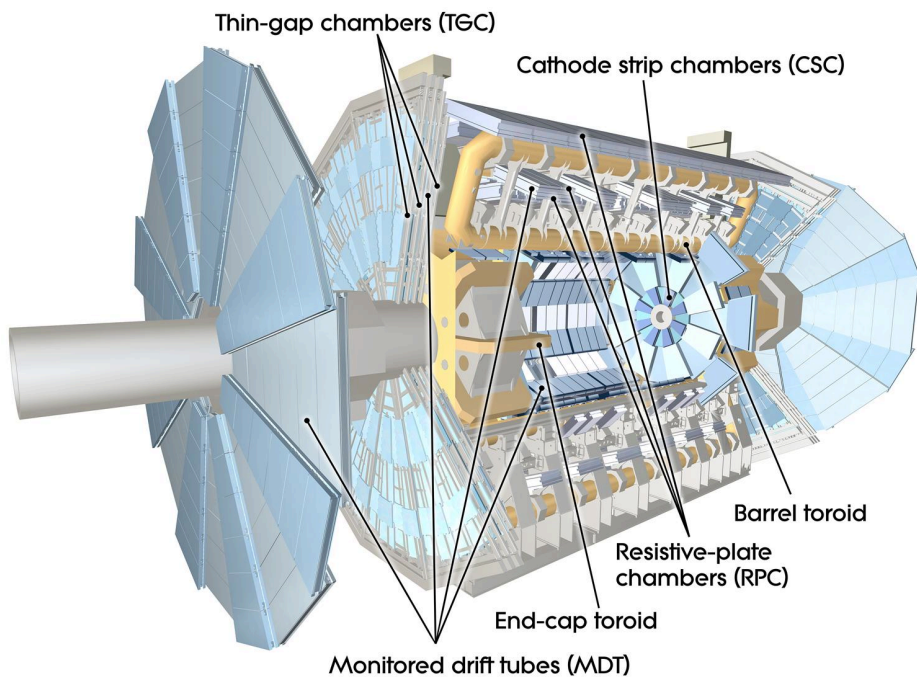


Figure 3.7: Cut-away view of the ATLAS Muon Spectrometer [51].

### 3.2.6 Magnets

A strong magnetic field is necessary to bend the trajectory of the charged particles by magnetic field in order to measure their momenta. The ATLAS Magnet system consists of two parts:

- The central solenoid
- The toroid barrel and end-cap

The central solenoid system is located between the Inner Detector and the Calorimeters. It creates a magnetic field parallel to the  $z$ -axis in the entire volume of the Inner Detector. The location of the magnet has an advantage that its size is relatively small, reducing the cost. The disadvantage is the possibility that particles start showering already in the magnet system instead of the calorimeters. The solenoid generates an axial field of 2 T that bends the path of charged particles in the Inner Detector in  $\phi$ -direction.

To minimise the material in front of the calorimeters the central solenoid magnet system is made out of a single-layer coil of superconducting NbTi 1.2 mm wire and operates at 4.5 K. Such a low temperature is provided by a cryostat which is shared with the LAr calorimeter in order to use less material. The dimensions of the central solenoid system are 2.5 m in diameter and 5.6 m in length.

The toroid magnet system provides a magnetic field of approximately 0.5 T to 1 T in the barrel and end-cap regions. The field lines form a torus around the  $z$ -axis between the radius of 9.4 and 20.1 m. The magnet system covers the area up to  $|\eta| = 2.7$ . It is made out of eight superconducting coils (the barrel region) and two toroids with eight coils each (in the two end-cap regions) symmetrically structured in  $\phi$  and spaced by  $\pi/4$ . The coils are made out of NbTiCu wire and are surrounded by air in order to minimise the effect of multiple scattering. It spans 25.3 m along the  $z$ -axis and its inner diameter is 9.4 m and outer diameter is 20.1 m in barrel region.

### 3.2.7 Trigger and Data Acquisition

At nominal LHC operation, bunches of protons cross each other every 25 ns (in 2012 the bunch spacing was 50 ns), this gives a bunch crossing frequency of 40 MHz. This frequency is used for the electronic master clock that synchronises all LHC detectors with the LHC beams. The data size of one collision event once recorded is approximately 1.5 MB. Neither the read out and data acquisition system nor the resources for offline analysis are capable to handle this event data size at a frequency of 40 MHz. Moreover only a tiny fraction of the collisions are interesting. Therefore, to select and record only important events a trigger system is used. The aim of the trigger system in ATLAS is to reduce the event rate to  $O(100 \text{ Hz})$  for final recording.

The physics processes of primary interest are characterised by large momentum transfer. This results in high  $p_T$  leptons, jets and missing transverse energy  $E_T^{\text{miss}}$ . Therefore, most of the bandwidth is assigned to triggers which rely on these features. The ATLAS trigger is based on three levels, sequentially refining the selection of the events and reducing the event rate. The first level trigger, called Level 1 (L1) trigger, is based on customised hardware. Second and third level triggers, called Level 2 (L2) trigger and Event Filter (EF) respectively, are software based implemented on a CPU farm. L2 and EF are collectively called High Level Trigger (HLT). Figure 3.8 shows a schematic overview of the trigger system.

The Level 1 trigger must decide quickly whether the event is interesting for further analysis. It reduces the event rate to a maximum of 100 kHz. Thus the L1 needs to achieve a rejection of 400 with respect to the 40 MHz bunch crossing rate. The latency of the L1 trigger is  $2.5 \mu\text{s}$ . In order to be fast it uses reduced granularity information from calorimeters and muon detectors. The tracking information is not used by L1.

The electronic modules that implement the logic of Level 1 calorimeter trigger (L1Calo) run algorithms on so called trigger towers to look for high  $p_T$  object candidates. Trigger towers are analog sums of the calorimeter signals in  $\Delta\phi \times \Delta\eta = 0.1 \times 0.1$

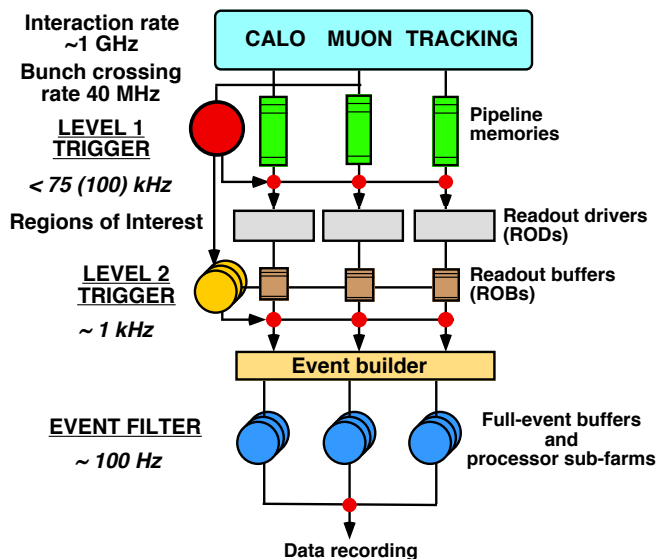


Figure 3.8: An overview of the ATLAS trigger and data acquisition system. The three levels of trigger decision, Level 1, Level 2 and Event Filter are shown on the left side with corresponding event rates. The data flows from on-detector pipeline memories on top of the sketch to Read-Out Drivers (ROD) in underground counting rooms, then further to the event builder and finally to permanent storage at the bottom of the sketch. The Event Filter sends the data out for permanent storage [64].

regions. A similar logic is implemented in the Level 1 Muon trigger (L1Muon). There the curvature of the muon candidates is approximated in order to estimate their  $p_T$ . The information about multiplicities of identified particle candidates over different threshold values is sent to the Central Trigger Processor (CTP). There the L1 decision of whether to pass on the event to the next level of trigger is taken. Detector regions of interest at L1, so called Region of Interest (RoI) are defined by the L1 system, for usage in the L2 trigger.

The information from subdetectors is stored in pipeline memories inside the detector until the L1 trigger takes its decision. As shown in Fig. 3.8 when the event is accepted by the L1 trigger the data is sent from the detector front-end electronics to the subdetector specific Read-Out Drivers (ROD) located 100 m away from the ATLAS. The RODs format digitised signals. For example the Tile Calorimeter RODs reconstruct amplitude, time, pedestal and a so called quality factor of the pulses with Optimal Filtering method described in Chapter 4. Then the data is passed to the Read-Out Buffer (ROB) where it



is stored awaiting for a Level 2 trigger decision.

The events kept by L1 are further analysed by the Level 2 trigger. The L2 latency is 40 ms. The rate of selected collisions is reduced to about 1 kHz at the output of L2, which gives a rejection factor of  $\sim 100$  with respect to the 100 kHz output rate of the L1 trigger. In order to achieve the required rejection factor at the required speed, the L2 trigger examines only RoIs that were first identified by the L1 trigger. Inside the RoIs the L2 has access to the full detector information with the full granularity of the subdetectors inside the RoIs.

Events that survive L2 go to the Event Filter for further rejection. There the rate is reduced to  $O(100 \text{ Hz})$ . The rejection factor for the EF is of the order of 10 and 400 000 for the whole trigger system. The latency of the Event Filter is 4 s. The Event Filter has access to the full event information from all subdetectors with full granularity and uses algorithms similar to those in the offline processing.

The events that survive the Event Filter are permanently recorded for offline analysis. The recorded events are sorted into several data streams, depending on what L1 trigger was fired. The most important streams used in physics analysis are `Egamma` (electrons and photons), `Muons` and `JetTauEtmis`. There are also other streams not intended to be used in physics analysis, e.g. `express` stream used for detector and data quality monitoring or calibration streams providing calibration data. The work presented in Chapter 5 and **Papers I - II** is performed with ATLAS data from the `JetTauEtmis` stream. The work performed in Part III of this thesis and **Paper III** uses the ATLAS data from the `Egamma` and `Muons` streams. The work performed in Part IV of this thesis uses the data from the `JetTauEtmis` stream.

### 3.2.8 Physics Objects Selection and Reconstruction

During proton-proton collisions a large number of particles is produced. It is crucial for the diverse physics program of ATLAS to efficiently reconstruct and identify them. The particles traversing the detector leave tracks and energy depositions in the detector medium. Different particles can be distinguished from one another by the way they interact with the detector. The raw information from ATLAS consists of energy, momentum and position measurements from specific subdetector systems. This information has to be combined in order to identify particles with assigned quantities used in physics analyses. Each of the particle candidate is subject to two levels of selections. If it passes a looser set of requirements, it is called a baseline object. Such objects are used for overlap removal and in the Matrix Method described in Section 7.2.2. A baseline object that also passes a tighter requirements is called a signal object. Such objects are used in the definition of the signal and control regions.

This section briefly describes how the ATLAS subdetectors are used to identify electrons, muons, taus, jets and missing energy for the data analyses presented in Part III and Part IV of this thesis and **Paper III**.

### Primary Vertex

The primary vertex or the interaction point is the point in space of the hard scatter interaction of two protons from the colliding beams. Points associated with particle decays are called secondary vertices. Running at high luminosity leads to multiple collisions in the same bunch crossing and multiple primary vertices in the event. This effect is called in-time pile-up. It is necessary to know which primary vertex is the origin of the identified particle in order to accurately measure its properties. The primary vertices are reconstructed using a vertex finding algorithm. The algorithm performs the extrapolation of the tracks measured in the Inner Detector to the interaction point.

Events considered in the analysis are requested to have at least five charged tracks with  $p_T > 400$  MeV associated to the primary vertex. In case of multiple primary vertices in an event, the one with the largest  $\sum p_T^2$  is selected.

### Electrons

Electrons traverse the first two ATLAS subdetector systems. They leave tracks in the Inner Detector and energy depositions in the calorimeters. The reconstruction process begins in the electromagnetic calorimeter. The energy deposits are summed longitudinally in towers of size  $\Delta\eta \times \Delta\phi = 0.025 \times 0.025$ . These regions are scanned over by a so called “sliding-window” algorithm. It locates the local  $E_T$  maxima. When the local maximum is found, a calorimeter cluster is seeded. The cluster contains  $3 \times 7$  towers in the barrel and  $5 \times 5$  towers in the end-cap. Different cluster sizes in barrel and end-cap are necessary to taken into account different geometries. Moreover, the asymmetric cluster size is a result of particle trajectories bend in  $\phi$  by the magnetic field. This effect is less prominent in the end-caps, where the cluster size is symmetric. The size of the cluster is optimised to collect as much of the electron energy as possible while limiting the electronic noise contributing to the energy measurement.

Once the cluster is defined it must be matched to a track in the Inner Detector in order to distinguish whether the energy deposition originate from electron or photon. The matching is performed by comparing the relative position of the cluster and the track. This distance is required to be within  $\Delta\eta < 0.005$  of one another. Due to the bending of the electron trajectory by the solenoidal field between the Inner Detector and the calorimeter, the requirement in the  $\phi$  direction is looser. Namely, this criterium is  $\Delta\phi < 0.005$  in the bending direction and  $\Delta\phi < 0.01$  in the other direction. Moreover, the energy deposition in the cluster must be consistent with the momentum associated to the matched track.

The information from the hadronic calorimeter is also used in order to distinguish electrons from hadrons. Electrons leave narrower shower in the calorimeter than hadrons. Therefore, the lateral shower shape is a good discriminant. Electrons deposit most of their energy in the electromagnetic calorimeter. The leakage to the hadronic calorimeter is small with respect to the fraction of energy deposited by hadrons. Thus, the relative energy deposition in electromagnetic and hadronic calorimeter as a useful discriminant.

For electron Particle Identification (PID) three working points are defined, i.e. “loose”, “medium” and “tight” [65]. This classification is based on the increasing tightness of the requirements on electron shower shape in the calorimeter, matching between the calorimeter cluster and the Inner Detector track and quality of the matched track in the Inner Detector. A tighter definition means higher purity but lower efficiency.

Once electron objects are defined, further selection is imposed at the analysis level. This selection ensures that good quality electrons are selected for use in physics analyses. Baseline electrons are required to satisfy medium requirements and reside within  $|\eta| < 2.47$ . For the analysis described in Part III of this thesis, baseline electrons must have a transverse momentum  $p_T > 10$  GeV. The analysis described in Part IV utilises soft leptons, therefore this requirement is relaxed to  $p_T > 7$  GeV.

Signal electrons are required to pass the tight criteria. Additionally, they are required to be isolated from hadronic activity as expected for leptons originating from  $W$ ,  $Z$  or gaugino and slepton decays. Therefore, signal electrons must satisfy two isolation requirements. The first one demands the sum of the transverse momentum of tracks with  $p_T > 400$  MeV observed within a cone of  $\Delta R = 0.3$  around the electron, excluding the electron candidate itself, to be less than 16% of the electron  $p_T$  ( $p_T^{\text{cone30}}/p_T < 0.16$ ). The second criteria requires isolation in the calorimeter. Namely, the sum of the transverse energy in the calorimeter clusters within the cone of  $\Delta R = 0.3$  around the electron must be less than 18% of the electron  $p_T$  ( $E_T^{\text{cone30,corr}}/p_T < 0.18$ ). Finally, the longitudinal distance between the electron and primary vertex along the beam direction must satisfy  $|z_0 \times \sin(\theta)| < 0.4$  mm while the transverse distance between the electron and primary vertex at the point of closest approach must be within five standard deviations ( $|d_0/\sigma(d_0)| < 5$ ). These requirements help reject electrons originating from the decay of long-lived particles such as  $b$ -quarks.

The electron energy scale is calibrated by comparing the mass spectra in the  $J/\psi \rightarrow ee$ ,  $Z \rightarrow ee$  and  $W \rightarrow e\nu$  samples in data and Monte Carlo. The energy resolution in MC is adjusted by smearing the energy to match the measured resolution of the detector. The same processes are used to measure the efficiency of the electron reconstruction and identification in data and simulation. A scale factor  $\mathcal{S}$  is applied to Monte Carlo in order to address the differences. The scale factor is calculated as a ratio of efficiencies in data and MC. Electron requirements are summarised in Tab. 3.1.

## Muons

Muons traverse the entire ATLAS detector, leaving evidence of their passage in all sub-detector systems. Therefore, the reconstruction and identification of muons can be performed using information from the Inner Detector, calorimeter and Muon Spectrometer. There are four different muon categories:

- Standalone muons - are reconstructed using solely tracks in the Muon Spectrometer. The track segments from different parts of the Muon Spectrometer are linked together to form a track. Then, the obtained tracks are extrapolated back to the

| Criteria                       | Description                                                                                                                                                              | Requirement    |
|--------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------|
| Baseline electron              |                                                                                                                                                                          |                |
| PID                            | Electron identification requirements                                                                                                                                     | Medium         |
| $p_T$                          | Electron transverse momentum                                                                                                                                             | $> 10$ (7) GeV |
| $ \eta $                       | Electron pseudorapidity                                                                                                                                                  | $> 2.47$       |
| Signal electron                |                                                                                                                                                                          |                |
| PID                            | Electron identification requirements                                                                                                                                     | Tight          |
| $ d_0/\sigma(d_0) $            | Significance of the transverse distance between the electron and primary vertex at the point of closest approach                                                         | $< 5$          |
| $ z_0 \times \sin(\theta) $    | Longitudinal distance between the electron and primary vertex along the beam direction                                                                                   | $< 0.4$ mm     |
| $p_T^{\text{cone30}}/p_T$      | Fraction of the transverse momenta of tracks within a cone of $\Delta R < 0.3$ surrounding the electron with respect to the electron transverse momentum                 | $< 0.16$       |
| $E_T^{\text{cone30,corr}}/p_T$ | Fraction of the transverse energy in the calorimeter cluster within a cone of $\Delta R < 0.3$ surrounding the electron with respect to the electron transverse momentum | $< 0.18$       |

Table 3.1: The definition of baseline and signal electrons. The signal electron includes also baseline requirements. The first  $p_T$  requirement is applied in the analysis described in Part III of this thesis, while the second one (in the parenthesis) is applied in the analysis presented in Part IV.

primary vertex in order to allow calculation of muon momentum. A correction addressing the energy loss in the material it traverses to reach the Muon Spectrometer is also applied.

- Combined (CB) muons - are reconstructed using information from the Inner Detector and the Muon Spectrometer. The reconstruction begins in the Muons Spectrometer where segments of tracks are linked together to form a track. Then, they are extrapolated back to the Inner Detector where a matching track is sought. The “Statistical Combination” (STACO) algorithm uses a  $\chi^2$  test to determine if the match of the tracks is significant enough to form a combined track. The momentum of the muon is calculated using a weighted combination of information from the Muon Spectrometer and the Inner Detector.

- Segment-tagged (ST) muons - are reconstructed using information from the Inner Detector and the Muon Spectrometer. The reconstruction begins in the Inner Detector where tracks not assigned to any combined muon are sought. Therefore, there is no overlap between combined muons and segment-tagged muons. Then, the tracks are extrapolated to the Muon Spectrometer and matched to at least one track segment utilising a  $\chi^2$  test. The momentum of the muon is calculated using track in the Inner Detector. This method was developed to improve the reconstruction of low  $p_T$  muons which do not reach the outer layers of the Muon Spectrometer.
- Calorimeter-tagged (CaloTag) muons - are reconstructed using information from the Inner Detector and the calorimeter. The tracks in the Inner Detector are extrapolated to the calorimeter and combined with the energy depositions. These muons are used in combination with other categories in order to improve the reconstruction of low  $p_T$  muons and muons penetrating the regions with limited coverage of the Muon Spectrometer.

In both analyses presented in this thesis combined muons and segment-tagged muons are used. Baseline muons are required to reside within  $|\eta| < 2.5$ . For the analysis described in Part III of this thesis, baseline muons must have a transverse momentum  $p_T > 10$  GeV. The analysis described in Part IV utilises soft leptons, therefore this requirement is relaxed to  $p_T > 5$  GeV.

The signal muons must satisfy additional requirements. In the analysis presented in Part III the tightened  $|\eta| < 2.4$  requirement is applied to match the covering of the muon trigger. In both analyses the longitudinal distance between the muon and primary vertex along the beam direction must satisfy  $|z_0 \times \sin(\theta)| < 1$  mm while the transverse distance between the muon and primary vertex at the point of closest approach must be within three standard deviations ( $|d_0/\sigma(d_0)| < 3$ ). Signal muons must also fulfill isolation requirements similar to those applied to electrons. The sum of the transverse momentum of tracks with  $p_T > 400$  MeV observed within a cone of  $\Delta R = 0.3$  around the muon, excluding the muon candidate itself, must be less than 12% of the muon  $p_T$  ( $p_T^{\text{cone30}}/p_T < 0.12$ ). In the analysis presented in Part IV of this thesis additional isolation requirements are applied for muons with a transverse momentum  $p_T < 15$  GeV. Namely it is required that  $p_T^{\text{cone30}}/p_T < 0.07$  and the sum of the transverse energy in the calorimeter clusters within the cone of  $\Delta R = 0.3$  around the muon must be less than 7% of the muon  $p_T$  ( $E_T^{\text{cone30,corr}}/p_T < 0.07$ ). These additional requirements are introduced in order to suppress the non-prompt muon background that is large in low  $p_T$  range.

The muon energy scale is calibrated by comparing the mass spectra in the  $J/\psi \rightarrow \mu\mu$  and  $Z \rightarrow \mu\mu$  samples in data and Monte Carlo. The muon resolution in MC is adjusted by smearing the energy to match the measured resolution of the detector. The same processes are used to measure the efficiency of the muon reconstruction and identification in data and simulation. Similarly as for electrons, scale factor  $\mathcal{S}$  is applied to

Monte Carlo in order to address the differences. Muon requirements are summarised in Tab. 3.2.

| Criteria                                                                    | Description                                                                                                                                                      | Requirement    |
|-----------------------------------------------------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------|----------------|
| Baseline muon                                                               |                                                                                                                                                                  |                |
| Reconstruction                                                              | Muon reconstruction algorithm                                                                                                                                    | CB + ST        |
| $p_T$                                                                       | Muon transverse momentum                                                                                                                                         | $> 10$ (5) GeV |
| $ \eta $                                                                    | Muon pseudorapidity                                                                                                                                              | $> 2.5$        |
| Signal muon                                                                 |                                                                                                                                                                  |                |
| $ \eta $                                                                    | Muon pseudorapidity                                                                                                                                              | $> 2.4$ (2.5)  |
| $ d_0/\sigma(d_0) $                                                         | Transverse distance between the muon and primary vertex at the point of closest approach                                                                         | $< 3$          |
| $ z_0 \times \sin(\theta) $                                                 | Significance of the longitudinal distance between the muon and primary vertex along the beam direction                                                           | $< 1$ mm       |
| $p_T^{\text{cone30}}/p_T$                                                   | Fraction of the transverse momenta of tracks within a cone of $\Delta R < 0.3$ surrounding the muon with respect to the muon transverse momentum                 | $< 0.12$       |
| Additional requirements applied for $p_T < 15$ GeV in analysis from Part IV |                                                                                                                                                                  |                |
| $p_T^{\text{cone30}}/p_T$                                                   | Fraction of the transverse momenta of tracks within a cone of $\Delta R < 0.3$ surrounding the muon with respect to the muon transverse momentum                 | $< 0.07$       |
| $E_T^{\text{cone30,corr}}/p_T$                                              | Fraction of the transverse energy in the calorimeter cluster within a cone of $\Delta R < 0.3$ surrounding the muon with respect to the muon transverse momentum | $< 0.07$       |

Table 3.2: The definition of baseline and signal muons. The signal muon includes also baseline requirements. The first  $p_T$  and  $\eta$  requirements are applied in the analysis described in Part III of this thesis, while the second ones (in the parenthesis) are applied in the analysis presented in Part IV.

### Taus

The analyses presented in this thesis consider only electron and muon final states. However, there are other SUSY searches that target processes with hadronic taus in the final state [66]. In the analyses presented in this thesis events containing hadronic taus are

rejected in order to obtain signal regions that are disjoint from the signal region used in tau-dedicated SUSY analysis. This allows to easily combine statistically the various regions.

Leptonic tau decays into electron or muon are not distinguishable from prompt electrons or muons. Therefore, leptonically decaying taus are treated as electrons or muons. Tau leptons decay 65% of the time hadronically and 35% of the time leptonically.

Hadrons from tau decays create a narrow cone jet. Comparing to quark and gluino jets, tau jets are well collimated with low track multiplicity in the Inner Detector. Also the transverse momentum of the leading track is on average higher than for quark and gluino jets. They deposit a large fraction of their energy in the electromagnetic calorimeter. Using this information, several discriminating variables are defined and combined into a Boosted Decision Tree (BDT) algorithm [67].

Baseline taus are required to satisfy loose criteria, have transverse momentum  $p_T > 20$  GeV and reside within  $|\eta| < 2.47$ . Also, one or three tracks are required and an absolute charge of one. Signal taus are required to pass additional requirements.

### Jets

Jets are collections of hadrons travelling in approximately the same direction and arising from hadronisation of a quark or a gluon. The hadrons deposit energies in the electromagnetic and hadronic calorimeter. The charged particles leave also tracks in the Inner Detector. Jets are reconstructed as follows. The calorimeter cells with significant energy deposit are grouped together into clusters [68]. The clusters are seeded by cells that have energy deposits greater than  $4\sigma$  above the cell expected noise. These are the seed-cells. If any of the neighbour cells has energy deposition greater than  $2\sigma$  above the cell's expected noise then this cell is added to the seed-cells. Finally, a single layer of cells surrounding the pre-cluster in 3-dimensions is added to it, forming a so called topological cluster (topo-cluster). The topo-clusters are input to the jet finding algorithms.

There are several algorithms used to group together calorimeter clusters into jets. In the analyses presented in this thesis jets reconstructed with the anti- $k_T$  algorithm [69, 70]. The algorithm uses the transverse momenta of the topo-clusters and their relative separation. The following distance quantity is calculated for each pair objects  $i$  and  $j$

$$d_{ij} = \min \left( p_{T,i}^{-2}, p_{T,j}^{-2} \right) \frac{\Delta R_{ij}^2}{D^2} \quad (3.9)$$

where the object  $i$  and  $j$  are either topo-clusters, or combination of several topo-clusters already combined by the algorithm. The quantities  $p_{T,i}$  and  $p_{T,j}$  are the momenta of the object  $i$  and  $j$  respectively,  $\Delta R_{ij}$  is the distance between the objects given by Eq. 3.5 and  $D$  is the distance parameter, which describes the typical size of jet. Additionally, the quantity based on the distance between an object and the beam axis is calculated:

$$d_{iB} = p_{T,i}^{-2} \quad (3.10)$$

The algorithm proceeds by identifying the smallest of the two distances  $d_{ij}$  and  $d_{iB}$ . If  $d_{ij}$  is the smallest, objects  $i$  and  $j$  are combined into a new object whose 4-vector is the sum of the 4-vectors of object  $i$  and  $j$ , and the objects  $i$  and  $j$  are removed from the list. If it is  $d_{iB}$ , object  $i$  is declared a final state jet and removed from the list of objects that proceed to the next iteration. This procedure is repeated until all objects are combined into final state jets.

In the analysis described in this thesis the anti- $k_T$  algorithm with the distance parameter of  $D = 0.4$  is used. Once calibrated, baseline jets are required to have  $p_T > 20$  GeV and  $|\eta| < 4.5$ . The signal jet selection can be tightened and a so called Jet Vertex Fraction and  $b$ -tagging algorithms are utilised. The Jet Vertex Fraction (JVF) algorithm is used to distinguish between jets associated with the hard scatter interaction from other jets from pileup interactions using vertex and track information [71]. The quantity JVF is calculated for each jet as:

$$\text{JVF}(\text{jet}_i, \text{PV}_j) = \frac{\sum_k p_T \left( \text{track}_k^{\text{jet}_i}, \text{PV}_j \right)}{\sum_n \sum_l p_T \left( \text{track}_l^{\text{jet}_i}, \text{PV}_n \right)} \quad (3.11)$$

where the numerator is the sum of the  $p_T$  of all tracks with impact parameter which is consistent with the primary vertex  $\text{PV}_j$ , while the denominator is the sum of the  $p_T$  of all tracks pointing to the jet independently of the primary vertex from which they arise. The JVF calculation relies on information from the Inner Detector, therefore JVF quantity can only be computed for jets within the Inner Detector acceptance.

Jets containing  $b$ -hadrons can be identified using so called  $b$ -tagging algorithms. A jet which is likely to contain a  $b$ -hadron is called  $b$ -jet. The  $b$ -tagging algorithms exploit the long lifetime of  $b$ - and  $c$ -hadrons inside a jet. Those hadrons travel some distance before decaying which causes the presence of displaced, secondary vertices inside the jet. A neural network based algorithm “MV1” is utilised [72]. It uses information about track impact parameters and secondary vertices. The  $b$ -tagging relies on information from the Inner Detector. Therefore, it can only be applied to jets within the Inner Detector acceptance. The signal jet selections are discussed in Section 8.1.

### Object Overlap Removal

The identification of particles in ATLAS is not always unambiguous. It is possible that a single physics object is identified as several different types of particles. In order to avoid double counting an overlap removal procedure is applied. This procedure also rejects individual objects that reside too close to each other, as they might be poorly reconstructed. Objects that are removed are not considered in subsequent steps. The overlap removal is applied on baseline electrons, muons, jets and tau leptons. The procedure is performed as follows. If two electrons lie within  $\Delta R < 0.05$ , the electron with lower transverse energy is discarded. This avoids double counting single electrons in case when a potential detector issue results in a single calorimetric cluster being



interpreted as two separate energy deposits. Also, it removes low  $p_T$  electrons created through bremsstrahlung process from the prompt electron. Then, if a jet resides within  $\Delta R < 0.2$  of the surviving electron, the jet is removed from the event. Any tau located within  $\Delta R < 0.2$  of electron or muon is removed. Electrons and muons are removed if they lie within  $\Delta R < 0.4$  of jet. If any of the remaining electrons and muons reside within  $\Delta R < 0.01$  of one another, both objects are removed. This requirement rejects the cases when muon undergo bremsstrahlung before reaching the Muon Spectrometer with the photon misidentified as electron. This can result in a badly reconstructed muon and electron on top of one another. If two muons lie within  $\Delta R < 0.05$ , both objects are removed. In the analysis presented in Part III of this thesis pairs of same flavor opposite sign (SFOS) electrons and muons with an invariant mass of  $m_{\ell\ell}^{\text{SFOS}} < 12 \text{ GeV}$  are rejected. This removes particles from photon conversions and quarkonia resonances. The analysis described in Part IV uses soft same sign leptons, therefore this requirement is modified to  $m_{\ell\ell}^{\text{SFOS}} < 2$ . Finally, if a signal tau and a jet lie within  $\Delta R < 0.2$ , the jet is removed. The object overlap removal procedure is summarised in Tab. 3.3.

| Order | Requirement                                   | Object removed            |
|-------|-----------------------------------------------|---------------------------|
| 1     | $\Delta R_{ee} < 0.05$                        | Electron with lower $E_T$ |
| 2     | $\Delta R_{ej} < 0.2$                         | Jet                       |
| 3     | $\Delta R_{e\tau} < 0.2$                      | Tau                       |
| 4     | $\Delta R_{\mu\tau} < 0.2$                    | Tau                       |
| 5     | $\Delta R_{ej} < 0.4$                         | Electron                  |
| 6     | $\Delta R_{\mu j} < 0.4$                      | Muon                      |
| 7     | $\Delta R_{e\mu} < 0.01$                      | Electron and muon         |
| 8     | $\Delta R_{\mu\mu} < 0.05$                    | Both muons                |
| 9     | $m_{\ell\ell}^{\text{SFOS}} < 12 \text{ GeV}$ | Both leptons              |
| (9)   | $m_{\ell\ell}^{\text{SFOS}} < 2 \text{ GeV}$  | Both leptons              |
| 10    | $\Delta R_{j\tau_{\text{signal}}} < 0.2$      | Jet                       |

Table 3.3: Steps in the overlap removal procedure. Objects that are removed are not considered in subsequent steps. Objects that satisfy the baseline definition are used. The one exception to this rule is step 10, which uses signal taus. Step 9 is applied in the analysis described in Part III of this thesis, while step (9) is applied in the analysis presented in Part IV.

### Missing Transverse Energy ( $E_T^{\text{miss}}$ )

The missing transverse energy is defined as the magnitude of the missing transverse momentum vector. The initial partons that participate in the hard scatter interactions carry almost no momentum in the transverse plane. Therefore, due to conservation of

momentum the missing transverse momentum should be zero if all particle momenta are measured perfectly and there are no invisible particles such as neutrinos or neutralinos from supersymmetry. The missing transverse momentum vector is given by the formula:

$$\mathbf{p}_T^{\text{miss}} = -\sum \mathbf{p}_T^e - \sum \mathbf{p}_T^\mu - \sum \mathbf{p}_T^\tau - \sum \mathbf{p}_T^\gamma - \sum \mathbf{p}_T^j - \sum \mathbf{p}_T^{\text{unclustered}} \quad (3.12)$$

where  $\sum \mathbf{p}_T^e$ ,  $\sum \mathbf{p}_T^\mu$ ,  $\sum \mathbf{p}_T^\tau$ ,  $\sum \mathbf{p}_T^\gamma$  and  $\sum \mathbf{p}_T^j$  are the vector sums of the transverse momenta of the electron, muon, tau, photon and jet respectively [73]. The baseline objects are used in the calculation.  $\sum \mathbf{p}_T^{\text{unclustered}}$  is the sum of the momenta of calorimeter energy deposits that are not associated to any of the above particles. The missing transverse energy is defined as the modulus of the missing transverse momentum vector,  $E_T^{\text{miss}} = |\mathbf{p}_T^{\text{miss}}|$ .

The  $E_T^{\text{miss}}$  ideally represent the momentum of undetected particles such as neutrinos or hypothetical particles that, like neutrinos, only interact weakly. The impossibility to measure momentum of the neutrinos or neutralinos causes a transverse momentum imbalance.

### 3.2.9 Systematic Uncertainties

Systematics uncertainties have an impact on the estimates of the background and signal event yields in the control and signal regions used in the analyses described in Parts III and IV of this thesis as well as in **Paper III**. Systematic uncertainties of experimental origin are associated to each of the identified particles and measured quantities. In order to evaluate the impact of a given source of uncertainty, the background is re-estimated after varying the uncertainty by one standard deviation. This typically requires reprocessing the relevant Monte Carlo samples in order to redo the event selection. The considered systematic uncertainties of experimental origin are as follows:

- “Leptons”: Uncertainty on the electron energy resolution and energy scale, which are provided as functions of  $p_T$  and  $\eta$  [74]. Also, it includes the uncertainty on the electron identification efficiency. Uncertainty on the muon momentum measurement in the Inner Detector and the Muon Spectrometer, which is provided as a function of  $p_T$  [75]. Also, the uncertainty on the muon identification efficiency. In the analysis presented in Part III the electron and muon trigger efficiencies are also considered as a source of systematics. Finally, the uncertainty on the number of fake electrons and muons is included.
- “Jets”: Uncertainty on the jet energy due to jet energy scale (JES) [76] calibration and jet energy resolution (JER) [77] uncertainties. They are determined from a combination of simulation, test beam and collision data. The jet energy scale uncertainty is provided as a function of  $p_T$ . The jet energy resolution uncertainty is provided as a function of  $p_T$  and  $\eta$ . They also depend on whether a jet originates from a quark or gluon, whether it was a light or heavy quark and finally depends on pile-up.

- “Missing transverse energy ( $E_T^{\text{miss}}$ )”: Uncertainties on electrons, muons, taus,  $\gamma$  and jets energies and momenta are propagated to the  $E_T^{\text{miss}}$  according to Eq. 3.12. An additional source of systematic uncertainty is considered, which arises from the uncertainty on the energy scale of the energy deposits not assigned to any identified particle (unclustered contribution in Eq. 3.12).
- “ $b$ -tagging”: Uncertainty associated with the MV1  $b$ -tagging algorithm. This category includes uncertainties on the  $b$ -jet identification efficiency for  $b$ -jets and  $c$ -jets and on the probability to wrongly  $b$ -tag a light flavour jet [78]. These uncertainties are provided as functions of  $p_T$  and  $\eta$ .
- “Luminosity”: Uncertainty on the integrated luminosity is  $\pm 2.8\%$ . It is derived, following the same methodology as that detailed in Ref. [79].

Additional sources of systematic uncertainties inherent for instance to the exact background calculation procedures are considered and discussed in Parts III and IV of this thesis.

## 4 The Tile Calorimeter

In order to measure energy and direction of hadrons ATLAS has a scintillating Tile Calorimeter (TileCal) [61]. TileCal fills the volume from an inner radius of 2.28 m to an outer radius 4.23 m. The central barrel covers an area up to  $|\eta| < 1.0$ . The extended barrel part provides a coverage of the region  $0.8 < |\eta| < 1.7$ . In this Section a description of the Tile Calorimeter is presented. The principles of hadron showers are given and the energy reconstruction in TileCal is discussed.

### 4.1 Principle of Hadron Showers

The purpose of hadronic calorimeters is to measure the energy and direction of hadrons. When a hadron passes through the calorimeter it loses energy by interaction with matter and a so called hadronic shower [80] is generated. Hadronic showers are more complex than the electromagnetic showers briefly described in Section 3.2.4, due to a large variety of nuclear processes.

A hadron can interact strongly with atomic nuclei of the medium. In this process the dominant cross section corresponds to inelastic scattering. As a result, a number of secondary hadrons are created, typically pions, protons and neutrons. These particles interact themselves with matter giving rise to a particle shower until the energy of the secondary particles is too low and energy loss becomes dominated by ionisation. Only a fraction of the incoming hadron energy is deposited in a way that is measurable. The incoming hadron energy is reconstructed using calibration constants determined in test beam studies and simulations. Some of the particles produced in the hadronic cascade, in particular  $\pi^0$ - and  $\eta$ -mesons, decay into pairs of photons and create an electromagnetic shower inside the hadronic shower.

The longitudinal size of the hadronic shower depends on the nuclear interaction length  $\lambda_{\text{int}}$ . One interaction length is the average distance required to reduce the numbers of relativistic hadrons traveling in a medium by the factor  $1/e$ . In iron, which is the absorber used in TileCal, the interaction length of protons is 16.8 cm. This is approximately ten times larger than the corresponding radiation length defined for electromagnetic-interacting particles. As a result, hadronic showers are wider and go deeper than electromagnetic showers. For this reason the hadronic calorimeter is placed around the electromagnetic calorimeter and has a larger radius. A hadronic shower

developing in the hadronic calorimeter is shown as illustration in Fig. 3.2.

## 4.2 Geometry and Read-out

The ATLAS Tile Calorimeter is a hadronic sampling calorimeter. The main task of TileCal is to identify hadronic jets and measure their energy and direction. TileCal also provides information for the Level 1 trigger and participates in the measurement of the missing energy due to non-interacting particles. It uses iron absorber and scintillating plastic tiles as active material. When a charged particle passes through the scintillating tiles, ultraviolet light is emitted and collected at the edges of each tile. The light is then transported via wavelength shifting fibers to Photomultiplier Tubes (PMT) located in a steel girder at the back of each barrel module. The girder provides the volume to house front-end read-out electronics and makes up the return yoke of the solenoid field. The scintillator tiles are grouped together into cells. The alternating layers of scintillating plastic and iron together with wavelength shifting fibers and PMTs are shown in Fig. 4.1.

TileCal is divided along the  $z$ -axis into four partitions for power distribution and data acquisition, two long barrels called LBA and LBC and two extended barrels called EBA and EBC. Each partition consists of 64 modules of equal azimuthal width  $\Delta\phi = 0.1$ . Long barrel and extended barrel modules are shown in Fig. 4.2 for  $z > 0$ . TileCal is subdivided into three separate longitudinal sampling layers, which allow to sample the shower at three different depths. The longitudinal sampling layers denoted A, BC and D have a granularity  $\Delta\eta \times \Delta\phi = 0.1 \times 0.1$  in the two innermost layers and  $\Delta\eta \times \Delta\phi = 0.2 \times 0.1$  in the outermost one. In units of nuclear interaction length the sampling layers have thickness of  $\lambda_{\text{int}} = 1.5, 4.1$  and  $1.8$  respectively at  $\eta = 0$ . It ensures that hadron showers are well contained inside the calorimeter and stopped before the Muon Spectrometer. In the space between the long and extended barrels so called crack and gap scintillators are inserted. These scintillators provide necessary corrections for energy losses in dead material in the crack regions.

Most Tile Calorimeter cells are read out by two PMTs, corresponding to two electronic read-out channels. TileCal has 9856 read-out channels in total corresponding to about 5182 cells. The PMT output is a current pulse and is read out in two gains, low and high. The ratio between the low gain and the high gain amplification is 64. The amplitude of the current pulse is proportional to the energy deposited in the associated cell. The pulse is amplified and shaped by the electronics mounted on the PMT. The shaping increases the pulse width at half-maximum to 50 ns. Then the analogue pulse is digitised with 7 samples at 25 ns intervals with 10-bit analog to digital converter (ADC). Upon a trigger accept by the Level 1 trigger the samples are sent from the front-end pipeline memories to the back-end electronics, Read-Out Drivers (ROD) located 100 m away in an underground counting room away from radiation. There Digital Signal Processors (DSP) calculate the pulse amplitude, phase and quality factor [81].

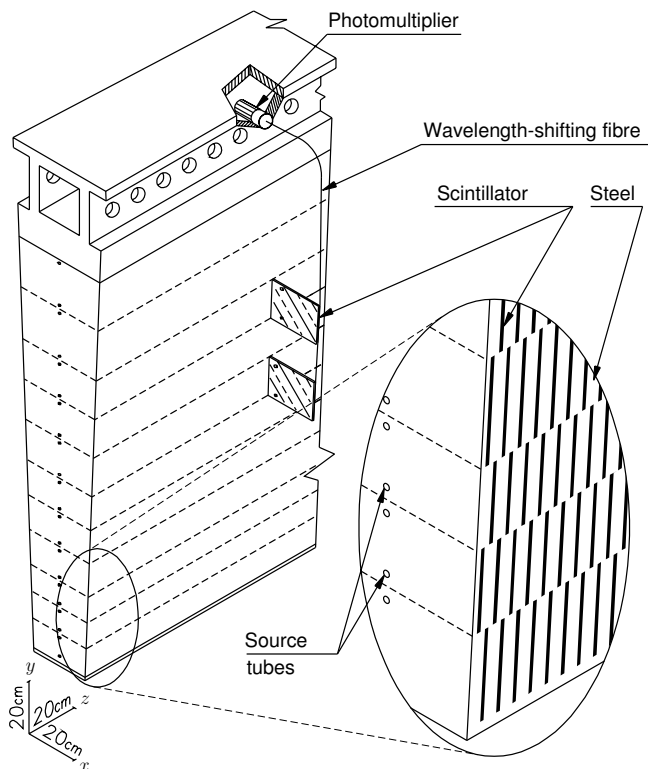


Figure 4.1: An illustration of the mechanical assembly and optical read-out of a single Tile Calorimeter module. A total of 256 such modules make up the full Tile Calorimeter. Source tubes are used to circulate a  $^{137}\text{Cs}$  radioactive source contained in a capsule for calibration purposes [51].

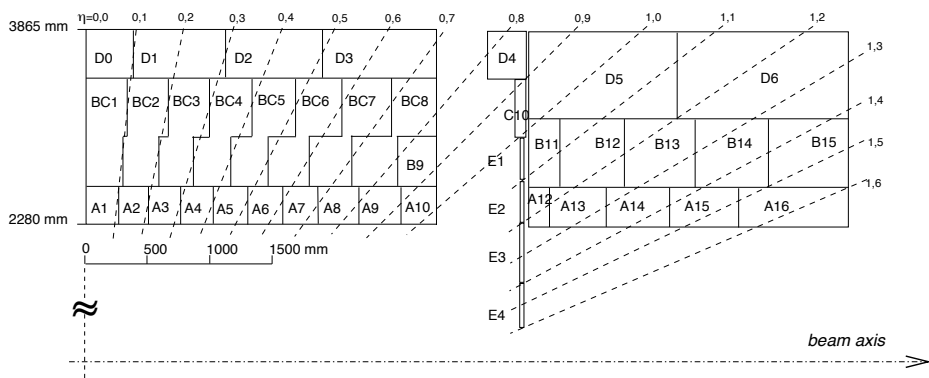


Figure 4.2: Segmentation in depth and  $\eta$  of the Tile Calorimeter modules in the central (left) and extended (right) barrels. The central barrel has a coverage up to  $|\eta| < 1.0$ . The extended barrel covers the region  $0.8 < |\eta| < 1.7$  [51].

The TileCal provides a three dimensional measurement of the energy deposited by the shower. The energy resolution  $\sigma_E$  for an incoming hadron of energy  $E$  in GeV is given by:

$$\frac{\sigma_E}{E} = \frac{0.5}{\sqrt{E}} \oplus 0.03 \quad (4.1)$$

The relative resolution becomes better with increasing energy of the incoming hadrons. The  $0.5/\sqrt{E}$  sampling term is dominated by stochastic fluctuations of energy deposited in the absorbers and fluctuations in amount of visible energy. The 0.03 term represents contributions independent on particle energy, such as material non-uniformity, radiation damage and other instrumental effects. This term is dominant at high energies.

### 4.3 Energy Reconstruction

The purpose of the energy reconstruction in the Tile Calorimeter is to calculate the energy deposited in a cell from the number of ADC counts measured in each of the two corresponding read-out channels. Seven samples at 25 ns spacing synchronised with the LHC master clock are available for each channel. These samples are referred to as  $S_i$ , where  $1 \leq i \leq 7$  and are in units of ADC counts. Depending on the amplitude of the pulse, either high or low gain is used to maximise the signal to noise ratio while avoiding saturation. For pulses with energy below  $\sim 12$  GeV high gain is used. For higher energies low gain is used. The energy  $E$  of the pulse in MeV is related to the pulse amplitude  $A$  in ADC counts by:

$$E = F_{\text{ADC} \rightarrow \text{MeV}} \cdot (A - P) \quad (4.2)$$

where  $F_{\text{ADC} \rightarrow \text{MeV}}$  is a conversion factor between ADC counts and MeV and  $P$  is the pedestal or baseline of the channel that must be subtracted. One ADC count corresponds to approximately 12 MeV and 800 MeV in high and low gain respectively. The exact correspondence is channel-dependent and requires careful calibration combining a  $^{137}\text{Cs}$  radioactive source, a laser system and injection of calibrated amounts of electric charge into the electronics [82]. The energy reconstruction is performed twice: i) in real time by the RODs (referred to as “online”) for usage in the trigger and ii) after the data has been recorded (referred to as “offline”) for usage in the data analysis. There are two main methods to derive the amplitude  $A$  of the pulse from the samples: Fit method and Optimal Filtering method (OFL) [83, 84].

#### Fit method

The Fit method uses a predefined normalized pulse shape function  $g(t)$  to reduce the bias on the reconstructed amplitude coming from the electronic noise. The following function  $f(t)$  is fitted to the measured signal samples  $S_i$ :

$$f(t) = A_{\text{fit}} \cdot g(t - t_{\text{fit}}) + P_{\text{fit}} \quad (4.3)$$



where  $A_{\text{fit}}$  is the fitted amplitude,  $P_{\text{fit}}$  is the fitted pedestal and  $t_{\text{fit}}$  is the fitted peak time. The normalized pulse shape function  $g(t)$  was determined during test beam and is normalised to a unit amplitude. Separate pulse shape functions are defined for high and low gain. The fit minimises the  $\chi^2$  expressed by:

$$\chi^2 = \sum_{i=1}^7 \left( \frac{S_i - (A_{\text{fit}} \cdot g(t - t_{\text{fit}}) + P_{\text{fit}})}{\sigma_i} \right)^2 \quad (4.4)$$

where  $\sigma_i$  is the error of sample  $S_i$  from electronic noise. The noise is estimated on a per channel basis. It is in average 1.5 ADC counts in high gain and 0.6 ADC counts in low gain.

### Optimal Digital Filtering

The Optimal Filtering (OFL) method is currently used in Tile Calorimeter. The method linearly combines the samples  $S_i$  to calculate the amplitude  $A_{\text{OFL}}$ , phase  $t_{\text{OFL}}$  with respect to the 40 MHz clock and pedestal  $P_{\text{OFL}}$  of the pulse:

$$A_{\text{OFL}} = \sum_{i=1}^7 a_i \cdot S_i \quad (4.5)$$

$$t_{\text{OFL}} = \frac{1}{A_{\text{OFL}}} \sum_{i=1}^7 b_i \cdot S_i \quad (4.6)$$

$$P_{\text{OFL}} = \sum_{i=1}^7 c_i \cdot S_i \quad (4.7)$$

where  $a_i$ ,  $b_i$  and  $c_i$  are linear coefficients optimised to minimise the bias on the reconstructed quantities introduced by the electronic noise. The same normalized pulse shape function is used as in the Fit method to determine the coefficients. The pulse shape and constants are stored in a dedicated database for calibration constants. There are two versions of the Optimal Filtering algorithm, iterative and non-iterative.

### Iterative Optimal Filtering method

The iterative Optimal Filtering method has been used for offline reconstruction of the 2012 data and is currently still in use in ATLAS. A new method called Constrained Optimal Filtering is under development and might be deployed later in 2015 or 2016. During the 2010 data taking and early 2011 the iterative Optimal Filtering method was also used online by the RODs. Due to high luminosity in 2012, only non-iterative Optimal Filtering was used.

The coefficients  $a_i$ ,  $b_i$  and  $c_i$  are functions of the pulse true phase with respect to the 40 kHz clock. This phase is known only approximately a priori before the reconstruction. The phase of the pulse in each channel is adjusted to be close to zero prior the data taking. Nevertheless, this setting is only accurate to only  $\sim 3$  ns [85]. Iterative

OFL takes the time of the maximum sample as an initial value of the phase. In next iterations, the input phase is taken to be equal to  $t_{\text{OFL}}$  calculated in the previous iteration. The algorithm converges to the actual phase value with an accuracy better than 0.5 ns in absence of pile-up pulses as shown in Fig. 3 in **Paper II**. At the end of the iteration procedure, the so called quality factor  $QF_{\text{OFL}}$  is calculated in order to verify the quality of the amplitude estimation:

$$QF_{\text{OFL}} = \sqrt{\sum_{i=1}^7 (S_i - A_{\text{OFL}} \cdot g_i - P_{\text{OFL}})^2} \quad (4.8)$$

where the  $g_i$  are the values of the normalised pulse shape function computed at the time of the 7 samples  $S_i$ . When the deviation between the true shape and pulse shape function used in reconstruction is large, then  $QF_{\text{OFL}}$  also takes large value. Therefore, the quality factor can be used to detect problems in the reconstruction procedure. This idea is developed in Chapter 5.

#### Non-iterative Optimal Filtering method

The non-iterative Optimal Filtering method performs only a single iteration of the optimal filtering method and uses as input the phase determined for each TileCal channel from prior timing calibration runs. These phases are usually close to zero due to insufficient time for processing in the DSP, the OFL reconstruction must be performed without iterations if the L1 trigger rate is above 50 kHz. Therefore, the non-iterative Optimal Filtering method is now used online by the RODs.

In the non-iterative Optimal Filtering method, during the measurement of amplitude the phase is adjusted to its value predetermined in dedicated timing runs. This is the phase expected from in-time pulses from collisions of interest. The out-of-time pile up can lead to a reconstructed phase value far from the expected one, biasing the energy measurement when the iterative method is used. By forcing the phase to its predetermined expected value, the non-iterative Optimal Filtering method better reconstructs the phase and energy of the in-time-pulse in presence of out-of-time pile-up. This method is also more robust against the electronic noise for very low signals. The next chapter and **Paper II** show a detailed study of the effect of pile-up on the quality factor and measured energy.



# 5 Out-of-Time Pile-up and Quality Factor

The detailed description of the quality factor study discussed in this chapter is presented in **Papers I** and **II**. **Paper II** contains the last developments of this work. This chapter provides an introduction to the problematic addressed in these papers. It also briefly presents the methodology and the results.

## 5.1 Pile-up

### 5.1.1 In-Time Pile-up

In 2012 the LHC was operating with proton bunches crossing each other every 50 ns (nominally the bunch spacing is designed to be 25 ns) with an expected average number of proton-proton collisions per crossing  $\langle\mu\rangle = 20.7$ . The parameter  $\mu$  is the mean value of the Poisson probability distribution describing the number of interactions per bunch crossing at a given luminosity. It is referred to as the mean number of interactions per crossing. Figure 5.1 presents the distribution of the parameter  $\mu$  in 2011 and 2012 ATLAS data. It is shown that the mean number of interaction per crossing varies significantly and can be much higher than its average value in runs when the LHC achieved particularly high luminosity. This leads to a high probability for multiple collisions to occur. It is called in-time pile-up. In this scenario, particles produced in different proton-proton interactions inside the same bunch crossing can deposit energy in the same calorimeter channel at the same time. The energy depositions from multiple interactions overlap each other thus introducing a bias in energy measurement of the collision of interest.

### 5.1.2 Out-of-Time Pile-up

Out-of-time pile-up arises because the signal acquisition time in TileCal (150 ns) is larger than the time interval between two consecutive bunch crossings (50 ns) in 2012. Therefore, there is a probability that particles originating from an earlier or later collision overlap with the current collision of interest and might deposit energy in the same

calorimeter channel.

In TileCal the long signal shaping requires a 150 ns read-out window ( $\pm 75$  ns around the signal peak time). Hardware and software delays are adjusted in such a way that the maximum amplitude of the in-time pulse is positioned around to the fourth sample,  $S_4$ . The effect of out-of-time pile-up is the superposition of pulses shifted in time. This results in anomalous pulse shapes differing from the pulse shape function used for energy reconstruction. This in general introduces a bias in the reconstructed energy. Such a situation can be detected by large values of the quality factor introduced in Section 4.3. A special treatment of the double pulses can be applied to the reconstruction of such a signal. Figure 5.2 shows an illustration of such a case. It shows a pulse centred on zero emerging from the collision of interest. A second pulse from out-of-time pile-up corresponds to the energy deposited 50 ns later in the same channel. The effect of out-of-time pile-up on the quality factor is studied in **Papers I** and **II**. Based on these studies criteria for pile-up identification have been proposed.

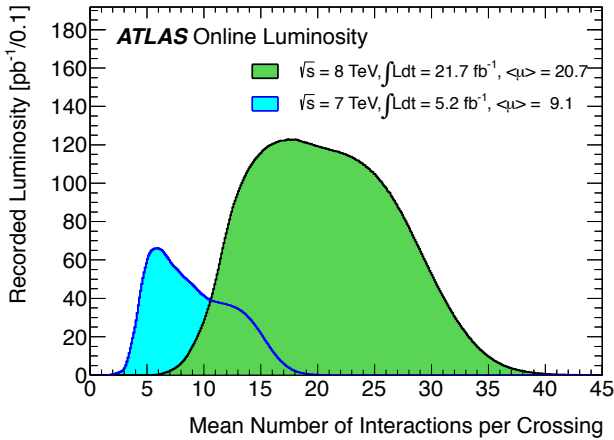


Figure 5.1: The distribution of the mean number of interactions per bunch crossing  $\mu$  for the 2011 and 2012 data [86].

## 5.2 Pulse Shape Simulator

In order to study the effect of out-of-time pile-up on quality factor distributions a numerical model of the ATLAS Tile Calorimeter pulses in the form of pulse simulator has been developed. The simulator can generate pulse shapes and corresponding quality factors with and without pile-up. It is based on a pseudo-random number generator. The seven  $S_i$  samples which determine a digitised pulse are generated.

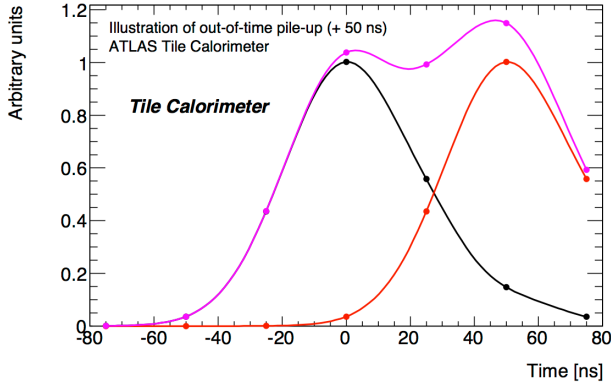


Figure 5.2: Illustration of out-of-time pile-up located at +50 ns in the ATLAS Tile Calorimeter with pulse shapes similar to those of the real detector. The black line corresponds to the in-time pulse, the red line corresponds to the out-of-time pulse, while the purple line is the superposition of those two pulses. The lines shown are functional parameterisations of actual pulse shapes, but are not actually used either in the energy reconstruction, nor in the pile-up simulation. The dots represent seven samples  $S_i$ .

The model includes electronic noise, channel-to-channel phase variations, non-ideal pulse shapes and pulse amplitude distribution from data in order to reproduce the characteristics of the digitised real pulses. A fine tuning of the model parameters to the data was performed in order to obtain a good agreement with quality factor distributions in data without pile-up. The effects included in the pulse simulator are shown in Fig. 9 in **Paper II** and briefly discussed below.

### Pulse shape

Equation 4.8 shows that the quality factor expresses the difference between the ideal pulse shape function and the real pulse shape observed in the detector. The real pulse shapes are close to the ideal pulse shape [87]. Nevertheless, even small differences between ideal and real pulses lead to a large increase of quality factor at large signal amplitude.

The normalised pulse shape function used in Optimal Filtering method is denoted  $g_i$  at the times of the samples  $S_i$ . The normalised real pulse shape observed in the detector is denoted  $h_i$ . One can write  $h_i = g_i + \delta_i$ , where  $\delta_i$  is the deviation between the pulse shape used for reconstruction and the actual pulse shape. Since the TileCal electronics is linear [81], the shape function can be scaled by the pulse amplitude. Therefore, one can write  $S_i = A \cdot h_i + P = A \cdot g_i + A \cdot \delta_i + P$ , where  $A$  is the true amplitude and  $P$  is true

pedestal of the pulse observed in the detector. Putting it to the Eq. 4.8 the quality factor can be written as:

$$Q_{F_{OFL}} = \sqrt{\sum_{i=1}^7 (A \cdot g_i + A \cdot \delta_i + P - A_{OFL} \cdot g_i - P_{OFL})^2} \quad (5.1)$$

In absence of the electronic noise and with the pedestal perfectly reconstructed,  $A = A_{OFL}$  and  $P = P_{OFL}$ , Eq. 5.1 simplifies to:

$$Q_{F_{OFL}} = A_{OFL} \cdot \sqrt{\sum_{i=1}^7 (\delta_i)^2} \quad (5.2)$$

This limit corresponds to the case of large amplitude signals where the noise and pedestal uncertainties are negligible. Therefore for large pulses there is a linear dependence of the quality factor upon the pulse amplitude and the slope depends on the difference between the pulse shape function and the real pulse shape. In case of perfect pulse shape only electronic noise and phase effects contribute to  $Q_{F_{OFL}}$  which is amplitude independent. Thus, the quality factor can be expressed as:

$$Q_{OFL} = Q_{OFL}^0 + A_{OFL} \cdot \sqrt{\sum_{i=1}^7 (\delta_i)^2} \quad (5.3)$$

where  $Q_{OFL}^0$  is the value of quality factor at low amplitude when it is dominated by noise and timing effects.

In order to make the pulse simulator able to reproduce the quality factors observed in data a different pulse shape from the ideal one must be used. This is motivated by the fact that there are small differences between the ideal pulse shape and actual pulse shapes discussed in Ref. [87].

It is achieved by modelling the real pulse shapes with an ideal shape with modified width. Widened or narrowed pulses are obtained by using a new pulse shape:

$$h(t) = g(t/\alpha) \quad (5.4)$$

where  $g$  is the ideal pulse shape used earlier and  $\alpha$  is a factor close to one.  $\alpha = 1$  gives the ideal pulse shape function used by Optimal Filtering method,  $\alpha > 1$  gives a narrower pulse while  $\alpha < 1$  gives a wider one. The factor  $\alpha$  is adjusted to the data so that pulse simulator reproduces the quality factor distribution in TileCal.  $\alpha$  is modelled with a Gaussian distribution with a mean value  $\mu_\alpha = 1.01$  and a standard deviation  $\sigma_\alpha = 0.02$ .

#### Amplitude distribution

As described above there is a strong amplitude dependence of the quality factor. Therefore, the pulse simulator has to use the same amplitude distribution as the data. In order to obtain a realistic model the amplitude is generated using a probability density function obtained (p.d.f.) from the JetTauEtmiss stream data collected by TileCal.

### Channel to channel phase variation

Ideally the peak of the pulses should be perfectly centred in the middle of the read-out window. Nevertheless, the actual peak position in the Tile Calorimeter varies slightly from channel to channel. This effect is included in the pulse simulator by randomly varying the offset of the pulses. The phase is Gaussian distributed with a mean value  $\mu_t = 0$  ns and a standard deviation  $\sigma_t = 3$  ns, as this is what is observed in the actual TileCal [85]. The distribution of channel to channel phase variation is shown in Fig. 10 in **Paper II**. Since iterative Optimal Filtering method is used for reconstruction, the effect of phase variation is small.

### Incoherent electronic noise

The incoherent electronic noise randomly modifies the measured values of the samples  $S_i$ . This effect is to first approximation uncorrelated between the samples  $S_i$ . The effect of the noise is the second most significant contribution to the quality factor, after the pulse shape, but becomes the dominant factor at low amplitudes. The incoherent electronic noise is modelled with a double Gaussian function that was found to describe the noise in the Tile Calorimeter [81]. Each channel has its own noise characteristics. Nevertheless, for simplification the present model assumes a unique noise distribution for all channels. The noise constants used to smear the  $S_i$  samples are adjusted in order to reproduce the quality factor distribution in data. The following noise constants are used:  $\sigma_{\text{noise},1} = 1.46$  ADC counts,  $\sigma_{\text{noise},2} = 3.60$  ADC,  $R = 0.07$ , where  $\sigma_{\text{noise},1}$  and  $\sigma_{\text{noise},2}$  are standard deviations of Gaussian distributions centred at zero and  $R$  is the relative normalisation between them.

### Comparison of the quality factor in TileCal data and pulse simulator

In order to validate the model the quality factor distribution obtained with the pulse simulator is compared with the one observed in data. The validation is performed to check whether the simulator is able to reproduce the quality factor distribution in data in absence of out-of-time pile-up pulses.

An integrated luminosity of  $60 \text{ nb}^{-1}$  of data taken by the ATLAS Tile Calorimeter in the JetTauEtmisss stream in March 2011 is used. During that period the LHC was operating with only 2 bunches per beam, separated by at least  $2.5 \mu\text{s}$ . This bunch spacing, much larger than the 150 ns read-out window, ensures the absence of out-of-time pile-up in this data. The data sample was acquired with high gain requiring reconstructed amplitude  $A_{\text{OFL}} > 34$  ADC counts ( $\sim 400$  MeV). The reconstructed amplitude requirement ensures that the events consist of real energy depositions in the detector, rather than noise.

A good agreement apart from small discrepancies in the high tail of the quality factor distribution in data and from the simulator is achieved as shown in Fig.12 in **Paper II**. In a range of  $0 < QF_{\text{OFL}} < 5$  ADC counts, i.e. for most events without out-of-time pile-up,



the relative difference is below 1%. The amplitude dependence of the quality factor in data is well reproduced by the simulator in the range  $200 < A_{\text{OFL}} < 1024$  ADC counts ( $2.4 < A_{\text{OFL}} < 12.4$  GeV) as shown in Fig. 11 in **Paper II**. In the range below 200 ADC counts the amplitude dependence shows non-linear behaviour in the pulse simulator. This is the transition between the region with quality factor dominated by noise and the region with quality factor dominated by amplitude.

Each TileCal channel has a slightly different pulse shapes and noise characteristics. Therefore, in order to improve the agreement between data and simulator, different pulses and noise constants should be used for different channel. The present model uses unique noise constants for all channels.

This study shows that a complex quantity such as the quality factor and its correlation with amplitude can be reproduced using the pulse simulator. It can be used to generate the distribution of quality factor in presence of out-of-time pile-up in order to derive the optimal criteria to detect out-of-time pile-up events.

### 5.3 Detection of Pile-up

The aim of this work is to predict the effect of out-of-time pile-up on the quality factor using the pulse simulator described in Section 5.2. The out-of-time pulses are unbiased by the trigger, therefore they can have arbitrarily small amplitudes. Small out-of-time pulses have a negligible effect on measured energy. There is no need to detect such cases.

If the out-of-time pulse is large enough with respect to the in-time pulse, the effect on the measured amplitude is large. Such a situation needs to be detected and special energy calculation can be applied or a flagging of the channel as unreliable can be provided. Only events with “significant” out-of-time pulses are considered. The “significant” out-of-time pulses are defined as pulses with amplitude above 34 ADC counts which corresponds to about 400 MeV. Their maximal effect on measured amplitude is 11% as shown in Fig. 14 in **Paper II**.

#### Effect of out-of-time pile-up on quality factor

Using the pulse simulator the effect of the out-of-time pile-up on quality factor has been studied in **Papers I** and **II**. The introduction of out-of-time pile-up pulse is equivalent to introducing a deviation between the ideal pulse shape function and the real pulse shape observed in TileCal channel.

Figure 5.3 black solid line shows  $QF_{\text{OFL}}$  as a function of the in-time pulse amplitude  $A_{\text{in}}$ . The  $QF_{\text{OFL}}$  was calculated using the pulse shape simulator. The lines correspond to the linear fit to the mean value of the quality factor. Different values of  $A_{\text{out}}/A_{\text{in}}$  ratios are presented. In this case the in-time pulse is dominant. The quality factor increases linearly with the amplitude for a given  $A_{\text{out}}/A_{\text{in}}$  ratio. Also the amplitude dependence gets steeper when the ratio  $A_{\text{out}}/A_{\text{in}}$  gets closer to one. The strongest amplitude depen-

dence occurs when in-time and out-of-time pulses have equal amplitude ( $A_{\text{out}} = A_{\text{in}}$ ).

Figure 5.3 purple dashed line shows  $QF_{\text{OFL}}$  as a function of the out-of-time pulse amplitude  $A_{\text{out}}$ . In this case the out-of-time pulse is dominant. It shows that there is the same effect on the quality factor regardless which pulse, in-time or out-of-time is dominant (solid black and dashed purple lines overlap each other of Fig.5.3). Nevertheless, if  $A_{\text{out}} > A_{\text{in}}$  then the iterative Optimal Filtering starts to measure the amplitude of the out-of-time pulse instead of the in-time pulse. In this situation the reconstructed energy does no longer inform us about the energy deposited in the collision under study but gives information about a completely different collision.

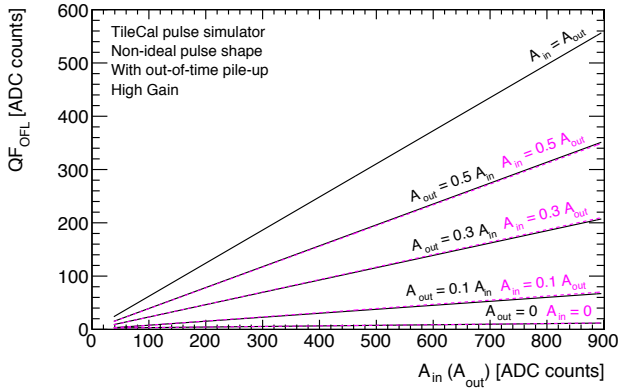


Figure 5.3: Quality factor as a function of the amplitude in different pile-up scenarios. The quality factor is calculated using TileCal pulse simulator with non-ideal pulse shapes, timing and noise effects emulated. The lines correspond to the linear fit to the mean value of the quality factor.  $A_{\text{in}}$  ( $A_{\text{out}}$ ) is the amplitude of the in-time (out-of-time) pulse. The x-axis shows the amplitude in ADC counts before channel-dependent calibration constants are applied. The calibration factor is approximately 12 MeV per ADC count.

#### Amplitude of out-of-time pulses

The average pulse amplitude for in-time pulses in TileCal is related to the trigger criteria used to record the events. Data collected in JetTauEtmisss stream are used to model the amplitude of in-time pulses.

On the other hand the out-of-time pulses are not the pulses that generate a trigger. They are collected by chance since they were close in time to a triggered proton-proton collision. Therefore, the amplitude of the out-of-time pulses must be modelled by a trigger unbiased energy distribution. This is obtained from a so called ZeroBias stream

which triggers on random collisions. This stream selects randomly a small fraction of events in coincidence with a proton bunch crossing. This allows to measure the pulse amplitude distribution in Tile Calorimeter channels without any trigger bias. The distribution of reconstructed amplitude in ZeroBias stream is shown in Fig. 15 in **Paper II**.

#### Quality factor distributions in presence of out-of-time pile-up

Figure 5.4 shows quality factor distributions in absence (black solid line) and presence (dashed purple line) of out-of-time pile-up obtained with the pulse simulator. The results are presented in three reconstructed amplitude  $A_{\text{OFL}}$  bins. Each distribution is made with 10 millions simulated pulses. A clear separation between the two cases is observed.

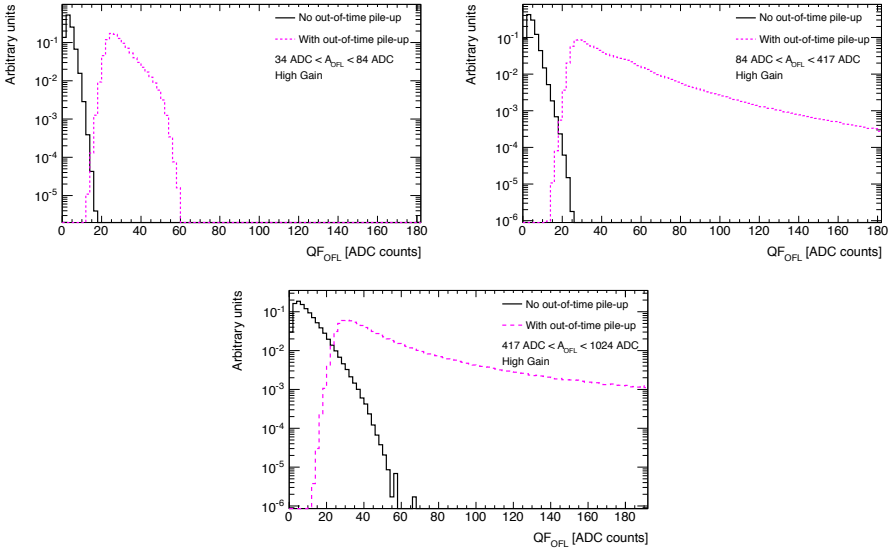


Figure 5.4: Normalised distributions of quality factor obtained with the TileCal simulator with non-ideal pulse shapes, timing and noise effects emulated. Two cases are shown: no out-of-time pile-up (black solid line) and with out-of-time pile-up (dashed purple line). Amplitude of the in-time pulse is taken from `JetTauEtm`miss. Amplitude of the out-of-time pulse is taken from ZeroBias stream. Only "significant" out-of-time pulses are considered with amplitude above 34 ADC counts ( $\sim 400$  MeV). Three measured amplitude bins are presented:  $34 < A_{\text{OFL}} < 84$  ADC ( $0.4 < E_{\text{OFL}} < 1$  GeV),  $84 < A_{\text{OFL}} < 417$  ADC ( $1 < E_{\text{OFL}} < 5$  GeV),  $417 < A_{\text{OFL}} < 1024$  ADC ( $5 < E_{\text{OFL}} < 12$  GeV).

### Optimisation of the selection to detect out-of-time pile-up

Based on the results presented in Fig. 5.4 and in **Paper II** criteria to flag TileCal channels with out-of-time pile-up are proposed. For this purpose efficiency and fake rate quantities are defined. The efficiency is the fraction of pulses containing out-of-time pile-up and correctly identified as such. The fake rate is the fraction of pulses that do not contain out-of-time pile-up that are wrongly identified as containing pile-up.

As shown in Section 5.2 the quality factor is linearly dependent on the amplitude. Therefore, three different quality factor criteria are defined for three amplitude bins. The amplitude bins presented in Fig. 5.4 correspond to the calculated amplitude  $A_{\text{OFL}}$ . Thus, these results can be used directly from the reconstructed amplitude  $A_{\text{OFL}}$ .

Table 5.1 presents the proposed cuts on the quality factor for three calculated amplitude bins. The first column shows the amplitude range in ADC counts defining the particular bin. The second column shows the corresponding energy range in GeV. In order to calculate the energy, the calibration factor of approximately 12 MeV per ADC count is used. The third column shows the proposed quality factor criteria to mark a pulse as containing out-of-time pile-up. The fourth column shows the fake rate in percent. Finally, the last column shows the efficiency in percent. Different amplitude bins can be defined based on the information presented in Fig. 5.3.

| $A_{\text{OFL}}$ [ADC] | $E_{\text{OFL}}$ [GeV] | $QF_{\text{OFL}}$ cut [ADC] | Fake rate [%]     | Efficiency [%]              |
|------------------------|------------------------|-----------------------------|-------------------|-----------------------------|
| 34 – 84                | 0.4 – 1                | $> 8.8$                     | $0.973 \pm 0.004$ | 100 ( $> 99.9\%$ at 95% CL) |
| 84 – 417               | 1 – 5                  | $> 11.6$                    | $0.985 \pm 0.006$ | 100 ( $> 99.9\%$ at 95% CL) |
| 417 – 1024             | 5 – 12                 | $> 29.7$                    | $0.99 \pm 0.01$   | $85.03 \pm 0.03$            |
| 417 – 1024             | 5 – 12                 | $> 22.9$                    | $3.75 \pm 0.03$   | $99.04 \pm 0.01$            |
| 417 – 1024             | 5 – 12                 | $> 11.7$                    | $26.55 \pm 0.06$  | 100 ( $> 99.8\%$ at 95% CL) |

Table 5.1: Proposed criteria on  $QF_{\text{OFL}}$  for three reconstructed amplitude bins, together with the corresponding fake rates and efficiencies, in different bins of the reconstructed amplitude. A set of 10 millions events was used to calculate fake rates and efficiencies. The quoted errors are statistical.

In the first bin,  $QF_{\text{OFL}} > 8.8$  ADC counts cut allows to select all pile-up events with a fake rate less than 1%. In the second bin all pile-up events can be selected with the fake rate less than 1% by applying  $QF_{\text{OFL}} > 11.6$  ADC counts cut.

In the third bin the separation between pile-up and no pile-up scenarios is slightly worse. This is due larger tails in quality factor distribution in non pile-up events as shown in Fig. 5.4 black solid line. This tail is present in the highest bin due to the amplitude dependence of quality factor as discussed in Chapter 5.2. Therefore, three different cuts on the quality factor in the third bin are proposed. More than 85% of the pulses with pile-up can be selected with fake rate less than 1% by applying  $QF_{\text{OFL}} > 29.7$  ADC counts cut. Lower  $QF_{\text{OFL}} > 22.9$  ADC counts cut increase the efficiency to

more than 99% and fake rate to 3.75%. The lowest  $QF_{\text{OFL}} > 11.7$  ADC counts cut allow to select all pile-up events with the fake rate of 26.55%.

## 5.4 Conclusions

A pulse simulator for the ATLAS Tile Calorimeter has been developed. It is shown that the simulator is able to reproduce the quality factor distributions in absence of out-of-time pile-up in data. Using this model the distribution of quality factor in presence of out-of-time pile-up is calculated. Events with an amplitude of the out-of-time pile-up large enough to affect the amplitude measurement are considered. A significant discrimination between events i) with out-of-time pile-up and ii) without out-of-time pile-up can be achieved.

## Part III

# Direct Chargino and Slepton Pair Production



# 6 Search for Direct Chargino and Slepton Pair Production

In this part of the thesis the search for direct production of weak gauginos and sleptons is discussed. In SUSY scenarios where masses of the coloured sparticles are much larger than colourless sparticles, the direct production of SUSY partners via weak interaction can be dominant at the LHC. The pMSSM allows for an arbitrary large mass difference between coloured and colourless sparticles [40, 88]. In Part III of this thesis the search for direct production of weak gauginos and sleptons is discussed.

## 6.1 Chargino and Slepton Production and Decay

In the present work direct gaugino and direct slepton production are investigated. An analysis of ATLAS data is designed to observe a signature with two opposite sign same flavour leptons, significant missing transverse energy ( $E_T^{\text{miss}}$ ) and no significant hadronic activity from the hard scatter interaction. The absence of hadrons in the decay products of charginos and sleptons is used to suppress top quark pair ( $t\bar{t}$ ) background events. Therefore, a veto on hadronic jets is introduced in this analysis. The study of jet-veto is presented in detail in Chapter 8. In this work only final states containing electrons or muons are considered, while final states with tau leptons are studied in Ref. [66]. Signal Monte Carlo samples of direct gaugino and direct slepton production are generated using HERWIG++ [89] at Leading Order (LO). The samples are normalised to Next to Leading Order (NLO) cross sections as described below.

$\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp$  direct production

One of the gaugino weak production channels with the largest cross section is  $\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp$ . In the scenarios considered here where squarks and gluons are very heavy the only allowed  $\tilde{\chi}_1^\pm$  decay channels are:

$$\tilde{\chi}_1^\pm \rightarrow \tilde{\ell}^\pm \nu, \ell^\pm \bar{\nu} \quad (6.1)$$

$$\tilde{\chi}_1^\pm \rightarrow W^\pm \tilde{\chi}_1^0 \quad (6.2)$$



where  $\ell$  is an electron, muon or tau. The sleptons can be either lighter or heavier than  $\tilde{\chi}_1^\pm$ . The decay of Eq. 6.1 occurs if the sleptons are lighter than the  $\tilde{\chi}_1^\pm$ . The final state leptons are crucial to extract the rare gaugino signal over the large Standard Model background. When the sleptons are heavier than  $\tilde{\chi}_1^\pm$ , the  $\tilde{\chi}_1^\pm$  decay proceeds via Eq. 6.2 where the  $W$  boson decays to electrons or muons in 21% of the events. By contrast when the slepton mass is between the  $\tilde{\chi}_1^0$  and  $\tilde{\chi}_1^\pm$  mass, the fraction of leptonic decays is 100%. Since processes with leptonic final states are easier to find at LHC the sensitivity to the intermediate slepton scenario in Eq. 6.1 is larger than for the scenario of Eq. 6.2.

The direct production of  $\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp$  is searched for in the two following channels:

$$pp \rightarrow \tilde{\chi}_1^\pm \tilde{\chi}_1^\mp \rightarrow \tilde{\ell} \nu_\ell (\tilde{\nu}_\ell \ell) \tilde{\ell}' \nu_{\ell'} (\tilde{\nu}_{\ell'} \ell') \rightarrow \ell \nu_\ell \tilde{\chi}_1^0 \ell' \nu_{\ell'} \tilde{\chi}_1^0 \quad (6.3)$$

$$pp \rightarrow \tilde{\chi}_1^\pm \tilde{\chi}_1^\mp \rightarrow W \tilde{\chi}_1^0 W \tilde{\chi}_1^0 \rightarrow \ell \nu_\ell \tilde{\chi}_1^0 \ell' \nu_{\ell'} \tilde{\chi}_1^0 \quad (6.4)$$

The electric charge is dropped in Eqs. 6.3 and 6.4 for simplicity, but the two final state leptons are always of opposite sign. Additionally, the neutralinos and neutrinos yield missing transverse energy  $E_T^{\text{miss}}$ . There is no final state gluon or quark in these reactions. These processes are illustrated in Fig. 6.1 top left and top right.

SUSY simplified models are used to generate  $\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp$  signal samples. In this model only the  $pp \rightarrow Z/\gamma^* \rightarrow \tilde{\chi}_1^\pm \tilde{\chi}_1^\mp$  diagrams are considered. All SUSY particles other than  $\tilde{\chi}_1^0$ ,  $\tilde{\chi}_1^\pm$  or  $\tilde{\ell}^\pm$  are assumed to be very massive in order to eliminate their contributions. The  $\tilde{\chi}_1^\pm$  is assumed to decay via sleptons or neutrinos with a branching ratio of 50% to each. The slepton branching ratios are set equal between all three lepton generations, i.e. electrons, muons and taus. The analysis selection vetoes hadronic tau decays to ensure orthogonality with a dedicated search for hadronic tau final states [66]. The lowest considered mass splitting between  $\tilde{\chi}_1^\pm$  and  $\tilde{\chi}_1^0$  is 35 GeV, since the presented analysis is not sensitive to smaller mass gaps as discussed further in Section 6.4. Figure 6.2 shows the Next to Leading Order cross section for pure wino  $\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp$  and  $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$  production in proton-proton collisions at  $\sqrt{s} = 8$  TeV as a function of  $\tilde{\chi}_1^\pm$  and  $\tilde{\chi}_2^0$  mass calculated with PROSPINO [90].

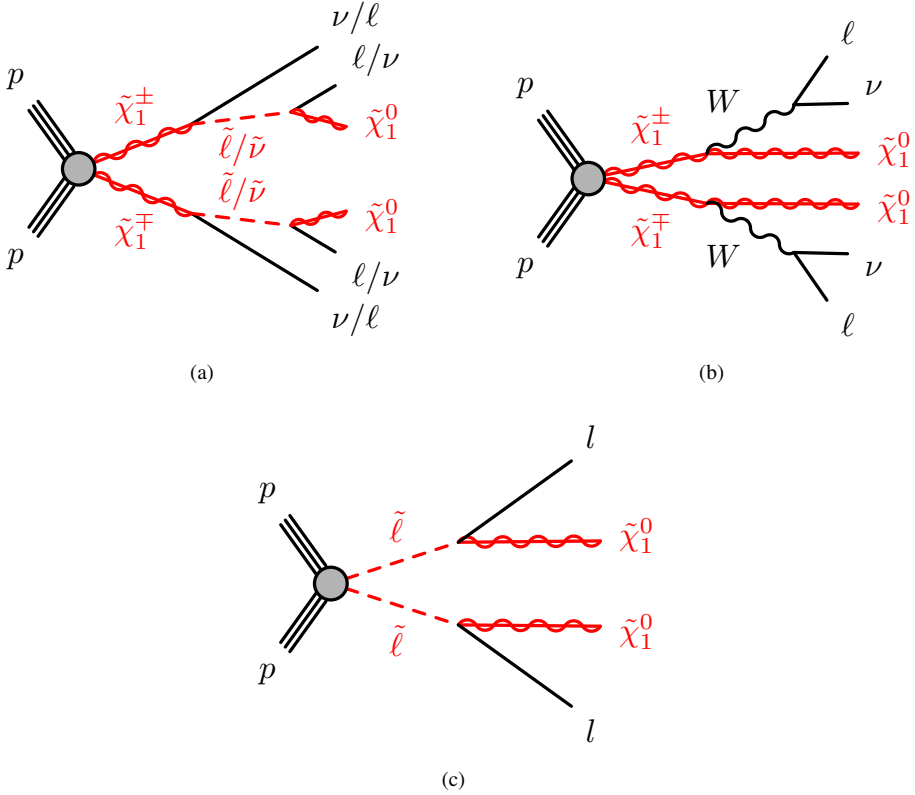


Figure 6.1: Illustration of  $\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp$  pair production and subsequent decays with intermediate light flavour charged sleptons and sneutrinos (a) and with intermediate  $W$  bosons (b) into a two-lepton final state. Illustration of direct  $\tilde{\ell}^\pm \tilde{\ell}^\mp$  pair production and subsequent decay into a two-lepton final state as shown in panel (c).

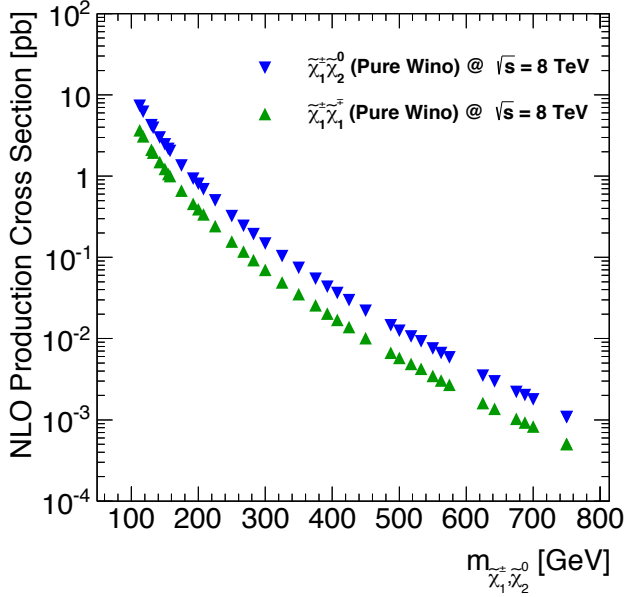


Figure 6.2: Next to Leading Order production cross sections for simplified models  $\tilde{\chi}_1^0 \tilde{\chi}_2^0$  and  $\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp$  as a function of the common  $\tilde{\chi}_1^\pm$  and  $\tilde{\chi}_2^0$  mass at  $\sqrt{s} = 8$  TeV calculated with PROSPINO [90].

### $\tilde{\ell}^\pm \tilde{\ell}^\mp$ direct production

Sleptons can be directly pair-produced in a process similar to so called Drell-Yan dilepton production at high energy [91]. In the present work only production of charged sleptons is considered. Sleptons are expected to decay into a lepton and a neutralino in 100% of the cases. Therefore, we search for  $\tilde{\ell}^\pm \tilde{\ell}^\mp$  pair production in the following channel

$$pp \rightarrow \tilde{\ell}^\pm \tilde{\ell}^\mp \rightarrow \ell^\pm \tilde{\chi}_1^0 \ell^\mp \tilde{\chi}_1^0, \quad (6.5)$$

in this channel there are exactly two opposite charge leptons and missing transverse energy  $E_T^{\text{miss}}$  due to neutralinos in the final state. Because of the absence of coloured particles in the final state, there is no hadronic activity from the final state particles. This process is illustrated at the bottom of Fig. 6.1.

To simulate  $\tilde{\ell}^\pm \tilde{\ell}^\mp$  the pMSSM [92] framework was used. Both left-handed and right-handed sleptons are considered. Squarks and gluinos are assumed to be very massive so that their contribution is completely eliminated. Heavier neutralinos and charginos are assumed to be heavy enough not to contribute to the signal. The presented analysis is

not sensitive to small mass gaps between  $\tilde{\ell}$  and  $\tilde{\chi}_1^0$  due to the challenging experimental signature arising in this situation. Therefore only models with  $m_{\tilde{\ell}} > m_{\tilde{\chi}_1^0} + 40$  GeV are considered. Figure 6.3 shows the charged slepton direct production cross section in proton-proton collisions at  $\sqrt{s} = 8$  TeV as a function of the slepton mass per slepton flavour.

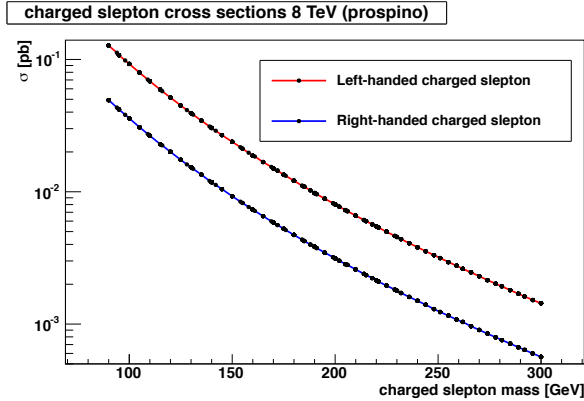


Figure 6.3: The left-handed and right-handed charged slepton pair production cross section per slepton flavour at  $\sqrt{s} = 8$  TeV obtained with PROSPINO [90]. The dots represent models that have actually been generated while the lines correspond to a polynomial interpolation.

### Analysis procedure

The first step is to define and optimise signal regions sensitive to chargino and slepton events using Monte Carlo simulations of all background processes as well as SUSY signal processes. The signal regions used in this work are described in Section 6.3. The Standard Model background in the signal regions is then finally estimated using a combination of data control regions and Monte Carlo simulations. The control regions are constructed to be enriched in the SM processes to be calculated.

Estimation of the number of background events from production of a Z boson with an associated vector boson W or Z (denoted ZV background) is presented in Chapter 9. The described method is used to perform calculations of ZV background in **Paper III**. Calculation of other SM processes is also included in this paper.

Finally, the estimated Standard Model background predictions in the signal regions are compared with data. If an excess is observed, the statistical significance is quantified. When data is in agreement with background only predictions, lower limits on chargino and slepton masses are derived. The results are presented in Chapter 10.

## 6.2 Standard Model Backgrounds

A large number of Standard Model processes can give rise to a final state with two opposite sign leptons and missing transverse energy similar to that of chargino and slepton pair production. These backgrounds need to be estimated as precisely as possible before a statement on whether the data is compatible with the background only hypothesis or with a background + SUSY signal hypothesis.

In order to develop and validate the analysis strategy and to estimate the detector acceptance and selection efficiency, fully simulated Monte Carlo (MC) event samples of each background process are generated. They are also used to determine the Standard Model backgrounds in combination with data from control regions. The MC samples include the simulation of multiple interactions per bunch crossing causing pile-up. A summary of the cross sections for different Standard Model processes measured by ATLAS is presented in Fig. 6.4.

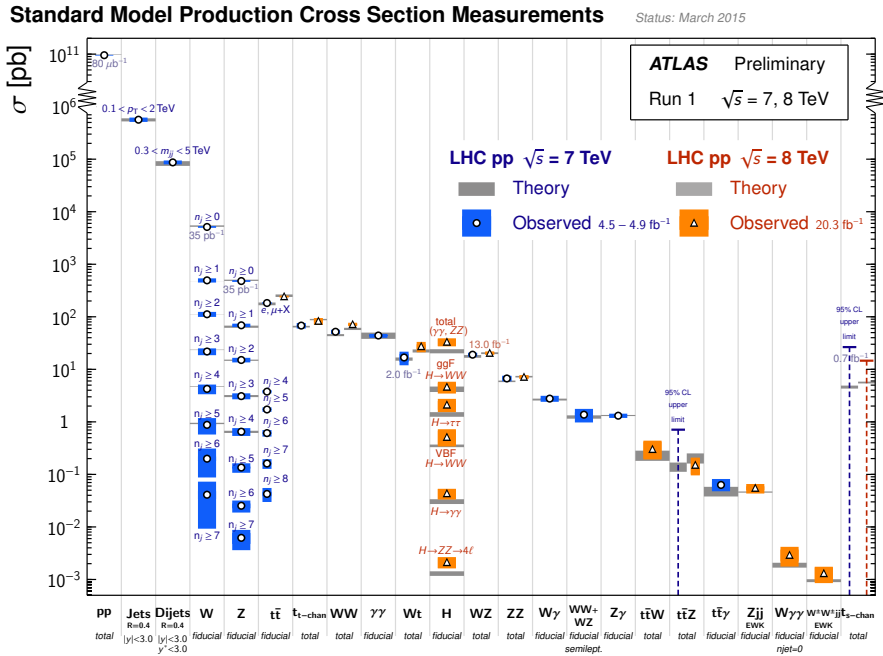


Figure 6.4: Summary of several Standard Model total and fiducial production cross section measurements compared to the corresponding theoretical expectations [93]. All theoretical expectations were calculated at NLO or higher.

The SM background processes relevant to this analysis are grouped into five categories labelled as follows:

- “WW”:  $WW$  and  $WWW$  processes. This background is estimated using a data-driven method described in Chapter 7.
- “Non-prompt leptons and fake leptons”: events where jets or photons are mis-identified as electrons or muons are mis-identified as isolated muons. This background is derived from data as described in Chapter 7.
- “Top”:  $t\bar{t}$  and single top processes. This background is estimated using a data-driven method and relies on the jet-veto study performed by the author of this thesis and presented in Chapter 8.
- “ZV”:  $Z$ +jets,  $ZW$ ,  $ZZ$ , and  $Z$ +two additional vector bosons processes. This background is estimated by the author of this thesis using the data-driven method described in Chapter 9.
- “Higgs”: production of the Standard Model Higgs boson with a mass  $m_H = 125$  GeV decaying to  $WW$  and  $ZZ$  with at least two leptons in the final state. Higgs contribution to the SM background is small and is estimated from Monte Carlo only.

The dominant Standard Model background processes are in order of decreasing importance:  $WW$ ,  $ZV$  and Top.

## 6.3 Observables for Signal Selection

In order to search for direct chargino pair and direct slepton pair production processes (Section 6.1) six signal regions are designed labeled  $SR-m_{T2,90}$ ,  $SR-m_{T2,120}$ ,  $SR-m_{T2,150}$  collectively called  $SR-m_{T2}$  and  $SR-WW_a$ ,  $SR-WW_b$ ,  $SR-WW_c$  collectively called  $SR-WW$ . Their exact definitions are provided further down. The  $SR-m_{T2}$  regions are sensitive to  $\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp$  decays with intermediate sleptons (Eq. 6.3) and direct slepton production (Eq. 6.5), while the  $SR-WW$  regions are sensitive to  $\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp$  decays with intermediate  $W$  bosons (Eq. 6.4). The variety of signal regions result from the need for different selections to accommodate a wide range of SUSY masses.

Signal regions presented in this section are utilised in the data analysis described in **Paper III**. Important observables exploited to construct the signal regions are defined below.

### 6.3.1 Stransverse Mass

Before introducing the stransverse mass ( $m_{T2}$ ) we start with a related but simpler variable, namely the transverse mass  $m_T$  [94]. The  $m_T$  variable is defined to measure the

mass of a particle decaying into a visible particle and an undetectable one. This quantity is exploited in measurements of the  $W$  boson mass. In this case the  $W$  boson decays into a visible charged lepton and an undetected neutrino. Therefore one cannot directly reconstruct the  $W$  mass from the lepton and neutrino momenta. The  $m_T$  is defined as follows:

$$m_T^2 = m_\ell^2 + m_\nu^2 + 2 \left( E_T^\ell E_T^\nu - \mathbf{p}_T^\ell \cdot \mathbf{p}_T^\nu \right) \quad (6.6)$$

where  $m_\ell$  and  $m_\nu$  are the masses,  $E_T^\ell$  and  $E_T^\nu$  are the transverse energies,  $\mathbf{p}_T^\ell$  and  $\mathbf{p}_T^\nu$  are the transverse momentum vectors of the lepton and neutrino, respectively. The neutrino transverse momentum vector is identified as the missing transverse energy vector  $\mathbf{p}_T^{\text{miss}}$  defined in Eq. 3.12. The variable  $m_T$  has an upper kinematic edge at  $m_W$ :

$$m_T^2 \leq m_W^2 \quad (6.7)$$

The  $m_{T2}$  variable also called transverse mass [95, 96, 97] builds up on  $m_T$  and is applicable to a system with two identical particles decaying to a visible particle (in our case a charged lepton) and an invisible particle (in our case a neutrino or a neutralino). This quantity is defined as follows:

$$m_{T2}^2 = \min_{\mathbf{p}_T^{\text{miss}1} + \mathbf{p}_T^{\text{miss}2} = \mathbf{p}_T^{\text{miss}}} \left\{ \max \left[ m_T^2 \left( \mathbf{p}_T^{\ell1}, \mathbf{p}_T^{\text{miss}1} \right), m_T^2 \left( \mathbf{p}_T^{\ell2}, \mathbf{p}_T^{\text{miss}2} \right) \right] \right\} \quad (6.8)$$

with the minimisation over all two momenta  $\mathbf{p}_T^{\text{miss}1}$  and  $\mathbf{p}_T^{\text{miss}2}$  such that their sum is always equal to the observed missing transverse momentum vector  $\mathbf{p}_T^{\text{miss}}$ . In case of SUSY events with well measured lepton pairs from slepton pair decays the  $m_{T2}$  has the following properties [98]:

$$m_{T2} \leq m_{T2}^{\text{max, no recoil}} = (m_\ell^2 - m_{\tilde{\chi}_1^0}^2) / m_\ell \quad (6.9)$$

More generally, the sleptons pair can be produced in association with other particles. In this case the system of sleptons recoils against these particles and the following relation applies [99]:

$$m_{T2} \leq m_{T2}^{\text{max, recoil}} = \sqrt{\left( m_\ell^2 - m_{\tilde{\chi}_1^0}^2 \right) \left( 1 - \frac{m_{\tilde{\chi}_1^0}^2}{m_{2\ell}^2} \right)} \quad (6.10)$$

In practice large recoil is required to produce  $m_{T2}$  values in this larger range. Events with large recoil are significantly suppressed by the hadronic jet-veto applied in the analysis. In absence of width effects most of the well reconstructed slepton events have  $m_{T2}$  in the range between 0 and  $m_{T2}^{\text{max, no recoil}}$ . The  $m_{T2}$  distribution calculated in  $t\bar{t}$  and  $WW$  events has a kinematic edge at the  $W$  mass. In practice imperfect momentum measurement and  $W$  width effects allow events to exceed this bound. SUSY signal events can have values of  $m_{T2}$  exceeding the  $W$  mass.

In case of chargino pair production, the  $m_{T2}$  variable has similar properties. The kinematic edge is moved to lower values because of additional invisible particles in the decay, namely neutrinos.

Figure 6.5 illustrates the shape of the  $m_{T2}$  variable for  $\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp$  and  $\tilde{\ell}^\pm \tilde{\ell}^\mp$  pair production for two sets of sparticle mass points. It shows that the kinematic edge depends on the mass splittings between the primary sparticle ( $\tilde{\chi}_1^\pm$  or  $\tilde{\ell}^\pm$ ) and the  $\tilde{\chi}_1^0$ . The  $m_{T2}$  distribution falls faster for  $\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp$  production than for  $\tilde{\ell}^\pm \tilde{\ell}^\mp$  production due to presence of neutrinos.

The  $m_{T2}$  variable provides experimental sensitivity to chargino and slepton scenarios with values of  $m_{T2}^{\text{max, no recoil}}$  exceeding the  $W$  mass.

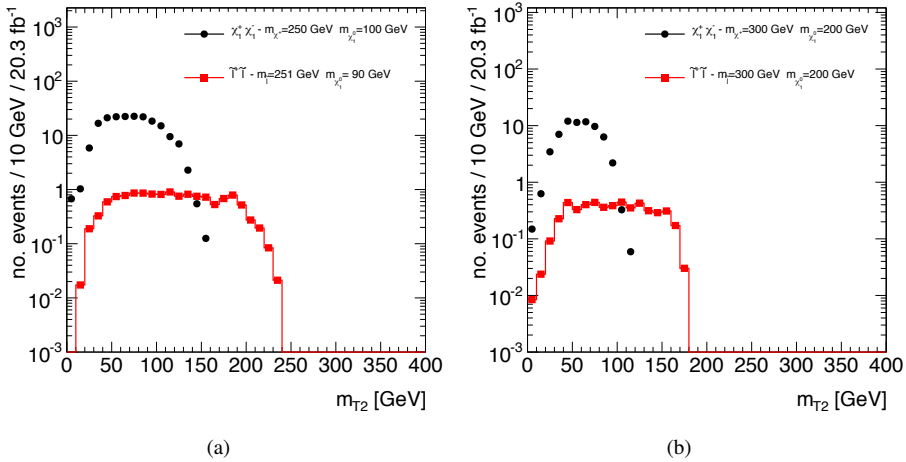


Figure 6.5: The distribution of the  $m_{T2}$  variable for  $\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp$  (black points) and  $\tilde{\ell}^\pm \tilde{\ell}^\mp$  (red squares) pair production. In panel (a) the chargino mass is  $m_{\tilde{\chi}_1^\pm} = 250$  GeV and the neutralino mass is  $m_{\tilde{\chi}_1^0} = 100$  GeV for  $\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp$  production while the slepton mass is  $m_{\tilde{\ell}^\pm} = 251$  GeV and neutralino mass is  $m_{\tilde{\chi}_1^0} = 90$  GeV for  $\tilde{\ell}^\pm \tilde{\ell}^\mp$  production. In panel (b) the chargino mass is  $m_{\tilde{\chi}_1^\pm} = 300$  GeV and the neutralino mass is  $m_{\tilde{\chi}_1^0} = 200$  GeV for  $\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp$  production while the slepton mass is  $m_{\tilde{\ell}^\pm} = 251$  GeV and the neutralino is  $m_{\tilde{\chi}_1^0} = 90$  GeV for  $\tilde{\ell}^\pm \tilde{\ell}^\mp$  production (b).



### 6.3.2 Jet-veto

The targeted signal processes do not result in jet activity apart from Initial State Radiation (ISR) jets. Therefore, a jet-veto is used to suppress the high-cross section dileptonic  $t\bar{t}$  events. The detailed description and study of the jet-veto is presented in Chapter 8.

### 6.3.3 Relative Missing Transverse Energy

The variable  $E_T^{\text{miss,rel}}$  [100] is derived from the missing transverse energy  $E_T^{\text{miss}}$  introduced in Section 3.2.8. It is designed to reduce contributions from mismeasured particle momenta to the  $E_T^{\text{miss}}$ . The variable  $E_T^{\text{miss,rel}}$  is defined as:

$$E_T^{\text{miss,rel}} = \begin{cases} E_T^{\text{miss}} & \text{if } \Delta\phi_{\ell,j} \geq \pi/2 \\ E_T^{\text{miss}} \times \sin\Delta\phi_{\ell,j} & \text{if } \Delta\phi_{\ell,j} < \pi/2 \end{cases} \quad (6.11)$$

where  $\Delta\phi_{\ell,j}$  is the azimuthal angle between the direction of  $\mathbf{E}_T^{\text{miss}}$  and that of the nearest electron, muon or jet. If a lepton or a jet is aligned with the  $\mathbf{E}_T^{\text{miss}}$  direction, it indicates that its momentum is likely to have been mismeasured. In this case only the  $\mathbf{E}_T^{\text{miss}}$  component perpendicular to the direction of associated particle is considered. This approach improves the resolution of  $E_T^{\text{miss}}$  in processes with no real missing transverse energy.

Dilepton invariant mass

The variable  $m_{\ell\ell}$  is defined as follows:

$$m_{\ell\ell} = \sqrt{(E_{\ell 1} + E_{\ell 2})^2 - |\mathbf{p}_{\ell 1} + \mathbf{p}_{\ell 2}|^2} \quad (6.12)$$

## 6.4 Signal Region Definitions

### 6.4.1 Signal Region SR- $m_{T2}$

Three signal regions SR- $m_{T2}$  are constructed to provide the sensitivity to direct slepton production. It is also used in search for direct  $\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp$  production with intermediate sleptons. The dominant sources of Standard Model background are  $WW$ ,  $ZV$  and Top events.

In SR- $m_{T2}$  two oppositely signed (OS) leptons are imposed. The leading lepton is required to have  $p_T^{\ell 1} > 35$  GeV, the subleading one must have  $p_T^{\ell 2} > 20$  GeV. The invariant mass of the lepton system is required to be  $m_{\ell\ell} > 20$  GeV. In order to suppress the  $Z/\gamma^* \rightarrow \ell\ell + \text{jet}$  background, events with  $m_{\ell\ell}$  mass away from Z mass ( $|m_{\ell\ell} - m_Z| > 10$  GeV) are selected in  $e^+e^-$  and  $\mu^+\mu^-$  channels. The jet-veto is used to suppress the high-cross section dileptonic  $t\bar{t}$  events which also results in a dilepton and  $E_T^{\text{miss}}$  final state. A  $m_{T2}$  cut is used to suppress a large fraction of the  $WW$  background and the remaining  $t\bar{t}$  background events. Different  $m_{T2}$  cut values serve a good sensitivity to SUSY scenarios with different masses of sleptons and neutralinos. In case of slepton

pair production, harder  $m_{T2}$  cuts provide better sensitivity to signals with large mass gaps between slepton and neutralino, while lower  $m_{T2}$  cuts provide better sensitivity to small mass gaps. Therefore, three signal regions with different  $m_{T2}$  cuts ( $m_{T2} > 90$  GeV,  $m_{T2} > 120$  GeV and  $m_{T2} > 150$  GeV) are defined in order to maximise sensitivity to a wide range of possible mass scenarios.

### 6.4.2 Signal Region SR-WW

Three signal regions SR-WW are optimised to provide sensitivity to direct  $\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp$  production with intermediate  $W$  bosons. Similarly to SR- $m_{T2}$  the signal regions SR-WW require oppositely signed leptons with transverse momenta  $p_T^{\ell 1} > 35$  GeV and  $p_T^{\ell 2} > 20$  GeV and  $m_{\ell\ell} > 20$  GeV. In order to suppress  $Z/\gamma^* \rightarrow \ell\ell + \text{jet}$  the cut  $|m_{\ell\ell} - m_Z| > 10$  GeV is applied. The  $t\bar{t}$  background is rejected using jet-veto.

The SR-WW<sub>a</sub> is defined for scenarios where either the chargino mass is small ( $m_{\tilde{\chi}_1^\pm} < 120$  GeV) or the mass gap between chargino and neutralino is small ( $m_{\tilde{\chi}_1^\pm} - m_{\tilde{\chi}_1^0} < 100$  GeV). In this case  $W$  bosons are produced close to the threshold ( $m_W = 80.4$  GeV). In this signal region  $E_T^{\text{miss,rel}} > 80$  GeV is imposed due to neutrinos and neutralinos. The mass of the leptons system is required to be  $m_{\ell\ell} < 120$  GeV. Only events with the transverse momentum of the dilepton system ( $p_T^{\ell\ell}$ ) larger than 80 GeV are considered.

Signal regions SR-WW<sub>b</sub> and SR-WW<sub>c</sub> are designed to be sensitive to higher chargino masses ( $m_{\tilde{\chi}_1^\pm} > 120$  GeV) and larger mass gap between chargino and neutralino ( $m_{\tilde{\chi}_1^\pm} - m_{\tilde{\chi}_1^0} > 100$  GeV). In this case the  $W$  boson is boosted. SR-WW<sub>b</sub> and SR-WW<sub>c</sub> require  $m_{T2} > 90$  GeV and  $m_{T2} > 100$  GeV respectively. Harder  $m_{T2}$  provides better sensitivity to larger chargino masses and larger  $W$  boost. Additionally, SR-WW<sub>b</sub> requires the mass of the leptons system to be  $m_{\ell\ell} < 170$  GeV in order to further suppress the Standard Model background. The definitions of the signal regions are summarised in Tab. 6.1.

## 6.5 Dataset and Trigger

The search for direct production of charginos and sleptons described in **Paper III** is performed with the entire dataset recorded by the ATLAS detector in 2012 at  $\sqrt{s} = 8$  TeV. In the jet-veto study presented in Chapter 8 a total integrated delivered luminosity of  $\mathcal{L} = 21.4 \text{ fb}^{-1}$  is used. Additional requirements that all ATLAS sub-detectors are working well reduces the luminosity by 3.1% to  $\mathcal{L} = 20.7 \text{ fb}^{-1}$ .

The estimation of the  $ZV$  background presented in Chapter 9 is performed with a reprocessed dataset of recalculated total integrated luminosity  $\mathcal{L} = 21.7 \text{ fb}^{-1}$ . The requirement that all ATLAS sub-detectors are working well reduces the luminosity by 6.5% to  $\mathcal{L} = 20.3 \text{ fb}^{-1}$ .

The dataset used in the search for direct chargino and slepton production is collected in the Egamma and Muons streams. Events have to pass one of the lepton triggers. Several triggers are used in order to select the collisions in different regions of

| Criteria                | SR- $WW_a$          | SR- $WW_b$          | SR- $WW_c$          | SR- $m_{T2,90}$    | SR- $m_{T2,120}$    | SR- $m_{T2,150}$    |
|-------------------------|---------------------|---------------------|---------------------|--------------------|---------------------|---------------------|
| OS leptons              |                     |                     |                     | ✓                  |                     |                     |
| Leptons flavour         |                     |                     |                     | $ee, e\mu, \mu\mu$ |                     |                     |
| $p_T^{\ell 1}$          |                     |                     |                     | $> 35 \text{ GeV}$ |                     |                     |
| $p_T^{\ell 2}$          |                     |                     |                     | $> 20 \text{ GeV}$ |                     |                     |
| $m_{\ell\ell}$          |                     |                     |                     | $> 20 \text{ GeV}$ |                     |                     |
| $ m_{\ell\ell} - m_Z $  |                     |                     |                     | $> 10 \text{ GeV}$ |                     |                     |
| signal central jets     |                     |                     |                     | $= 0$              |                     |                     |
| signal $b$ -jets        |                     |                     |                     | $= 0$              |                     |                     |
| signal forward jets     |                     |                     |                     | $= 0$              |                     |                     |
| $p_T^{\ell\ell}$        | $> 80 \text{ GeV}$  |                     |                     | —                  |                     |                     |
| $E_T^{\text{miss,rel}}$ | $> 80 \text{ GeV}$  |                     |                     | —                  |                     |                     |
| $m_{\ell\ell}$          | $< 120 \text{ GeV}$ | $< 170 \text{ GeV}$ |                     |                    | —                   |                     |
| $m_{T2}$                | —                   | $> 90 \text{ GeV}$  | $> 100 \text{ GeV}$ | $> 90 \text{ GeV}$ | $> 120 \text{ GeV}$ | $> 150 \text{ GeV}$ |

Table 6.1: Definitions of the signal regions SR- $WW$  and SR- $m_{T2}$ . “✓” means the cut is applied, “—” means the cut is not applied. The signal central jets are jets with specific selection to remove pile-up jets. The exact definition of these jets along with signal  $b$ -jets and signal forward jets are given in Section 8.2.

$p_T$  phase space. Symmetric triggers look for pair of electrons or muons with transverse momentum  $p_T > 14 \text{ GeV}$ . An asymmetric electron trigger requires pair of electrons with  $p_T > (25, 8) \text{ GeV}$ . An asymmetric muon trigger looks for two muons with  $p_T > (18, 8) \text{ GeV}$ . Additionally two asymmetric electron-muon triggers are used with  $(p_T^e, p_T^\mu) > (14, 8)$  and  $(8, 18) \text{ GeV}$ .

## 6.6 Conclusion

A first Monte Carlo simulation based prediction of the composition of the signal regions is presented in Tab. 6.2 - 6.6. The MC predictions are normalised using theory cross sections and luminosity and do not incorporate additional calculations from data driven methods. The tables show that the background is dominated by  $WW$  and  $ZV$  in all signal regions. The composition of SR- $WW_a$  was not studied by the author of this thesis and is therefore not listed.

| Composition of SR- $WW_b$ (Monte Carlo) |                           |                           |                           |
|-----------------------------------------|---------------------------|---------------------------|---------------------------|
| Processes                               | $e^+e^-$                  | $\mu^+\mu^-$              | $e^\pm\mu^\mp$            |
| WW                                      | $5.61 \pm 0.58 \pm 0.68$  | $8.94 \pm 0.51 \pm 1.28$  | $8.81 \pm 0.54 \pm 1.58$  |
| ZV                                      | $5.20 \pm 0.42 \pm 0.44$  | $5.92 \pm 0.39 \pm 0.76$  | $0.48 \pm 0.12 \pm 0.12$  |
| Top                                     | $0.13 \pm 0.79 \pm 0.60$  | $2.08 \pm 0.81 \pm 0.99$  | $3.83 \pm 0.99 \pm 1.33$  |
| Fakes                                   | $0.34 \pm 0.39 \pm 0.00$  | $-0.20 \pm 0.05 \pm 0.00$ | $0.21 \pm 0.35 \pm 0.00$  |
| Higgs                                   | $0.11 \pm 0.04 \pm 0.01$  | $0.13 \pm 0.04 \pm 0.03$  | $0.19 \pm 0.05 \pm 0.02$  |
| Total                                   | $11.39 \pm 1.14 \pm 1.01$ | $16.87 \pm 1.03 \pm 1.78$ | $13.52 \pm 1.19 \pm 2.07$ |

Table 6.2: Predicted sample composition based on Monte Carlo in the signal region SR- $WW_b$ . The first error is the uncertainty from limited Monte Carlo statistics, the second error is systematic uncertainty arising from all sources of systematics. The prediction correspond to a luminosity of  $20.3 \text{ fb}^{-1}$ . Fakes background is estimated using the data-driven Matrix Method described in Chapter 7.

| Composition of SR- $WW_c$ (Monte Carlo) |                           |                           |                           |
|-----------------------------------------|---------------------------|---------------------------|---------------------------|
| Processes                               | $e^+e^-$                  | $\mu^+\mu^-$              | $e^\pm\mu^\mp$            |
| WW                                      | $4.39 \pm 0.53 \pm 0.44$  | $4.84 \pm 0.39 \pm 0.84$  | $5.20 \pm 0.43 \pm 0.80$  |
| ZV                                      | $4.28 \pm 0.38 \pm 0.43$  | $5.34 \pm 0.38 \pm 0.58$  | $0.38 \pm 0.12 \pm 0.06$  |
| Top                                     | $0.10 \pm 0.70 \pm 0.78$  | $0.49 \pm 0.49 \pm 0.72$  | $0.90 \pm 0.52 \pm 0.73$  |
| Fakes                                   | $-0.12 \pm 0.21 \pm 0.00$ | $-0.05 \pm 0.02 \pm 0.00$ | $-0.09 \pm 0.19 \pm 0.00$ |
| Higgs                                   | $0.07 \pm 0.03 \pm 0.01$  | $0.08 \pm 0.03 \pm 0.01$  | $0.14 \pm 0.04 \pm 0.01$  |
| Total                                   | $8.73 \pm 0.98 \pm 1.00$  | $10.70 \pm 0.73 \pm 1.25$ | $6.54 \pm 0.71 \pm 1.09$  |

Table 6.3: Predicted sample composition based on Monte Carlo in the signal region SR- $WW_c$ . The first error is the uncertainty from limited Monte Carlo statistics, the second error is systematic uncertainty arising from all sources of systematics. The prediction correspond to a luminosity of  $20.3 \text{ fb}^{-1}$ . Fakes background is estimated using the data-driven Matrix Method described in Chapter 7.

| Composition of SR- $m_{T2,90}$ (Monte Carlo) |                           |                           |                           |
|----------------------------------------------|---------------------------|---------------------------|---------------------------|
| Processes                                    | $e^+e^-$                  | $\mu^+\mu^-$              | $e^\pm\mu^\mp$            |
| WW                                           | $8.17 \pm 0.70 \pm 0.96$  | $11.29 \pm 0.58 \pm 1.71$ | $11.93 \pm 0.63 \pm 1.96$ |
| ZV                                           | $6.22 \pm 0.48 \pm 0.48$  | $7.00 \pm 0.44 \pm 0.97$  | $0.69 \pm 0.16 \pm 0.12$  |
| Top                                          | $0.57 \pm 0.87 \pm 0.60$  | $2.33 \pm 0.86 \pm 1.00$  | $5.00 \pm 1.17 \pm 1.36$  |
| Fakes                                        | $0.08 \pm 0.40 \pm 0.00$  | $-0.22 \pm 0.05 \pm 0.00$ | $0.08 \pm 0.35 \pm 0.00$  |
| Higgs                                        | $0.11 \pm 0.04 \pm 0.01$  | $0.13 \pm 0.04 \pm 0.03$  | $0.19 \pm 0.05 \pm 0.02$  |
| Total                                        | $15.14 \pm 1.28 \pm 1.23$ | $20.52 \pm 1.13 \pm 2.21$ | $17.89 \pm 1.39 \pm 2.39$ |

Table 6.4: Predicted sample composition based on Monte Carlo in the signal region SR- $m_{T2,90}$ . The first error is the uncertainty from limited Monte Carlo statistics, the second error is systematic uncertainty arising from all sources of systematics. The prediction correspond to a luminosity of  $20.3 \text{ fb}^{-1}$ . Fakes background is estimated using the data-driven Matrix Method described in Chapter 7.

| Composition of SR- $m_{T2,120}$ (Monte Carlo) |                           |                           |                           |
|-----------------------------------------------|---------------------------|---------------------------|---------------------------|
| Processes                                     | $e^+e^-$                  | $\mu^+\mu^-$              | $e^\pm\mu^\mp$            |
| WW                                            | $1.37 \pm 0.28 \pm 0.35$  | $1.73 \pm 0.23 \pm 0.29$  | $2.46 \pm 0.29 \pm 0.23$  |
| ZV                                            | $2.22 \pm 0.26 \pm 0.25$  | $2.83 \pm 0.27 \pm 0.29$  | $0.13 \pm 0.06 \pm 0.01$  |
| Top                                           | $0.33 \pm 0.33 \pm 0.01$  | $0.00 \pm 0.00 \pm 0.00$  | $0.00 \pm 0.00 \pm 0.00$  |
| Fakes                                         | $-0.05 \pm 0.20 \pm 0.00$ | $-0.04 \pm 0.02 \pm 0.00$ | $-0.16 \pm 0.07 \pm 0.00$ |
| Higgs                                         | $0.04 \pm 0.03 \pm 0.00$  | $0.08 \pm 0.03 \pm 0.01$  | $0.11 \pm 0.04 \pm 0.01$  |
| Total                                         | $3.91 \pm 0.54 \pm 0.44$  | $4.59 \pm 0.36 \pm 0.41$  | $2.54 \pm 0.31 \pm 0.23$  |

Table 6.5: Predicted sample composition based on Monte Carlo in the signal region SR- $m_{T2,120}$ . The first error is the uncertainty from limited Monte Carlo statistics, the second error is systematic uncertainty arising from all sources of systematics. The prediction correspond to a luminosity of  $20.3 \text{ fb}^{-1}$ . Fakes background is estimated using the data-driven Matrix Method described in Chapter 7.

| Composition of SR- $m_{T2,150}$ (Monte Carlo) |                          |                           |                           |
|-----------------------------------------------|--------------------------|---------------------------|---------------------------|
| Processes                                     | $e^+e^-$                 | $\mu^+\mu^-$              | $e^\pm\mu^\mp$            |
| WW                                            | $0.36 \pm 0.14 \pm 0.28$ | $0.53 \pm 0.12 \pm 0.09$  | $0.57 \pm 0.13 \pm 0.14$  |
| ZV                                            | $0.88 \pm 0.12 \pm 0.12$ | $1.28 \pm 0.18 \pm 0.11$  | $0.03 \pm 0.02 \pm 0.01$  |
| Top                                           | $0.00 \pm 0.00 \pm 0.00$ | $0.00 \pm 0.00 \pm 0.00$  | $0.00 \pm 0.00 \pm 0.00$  |
| Fakes                                         | $0.06 \pm 0.18 \pm 0.00$ | $-0.01 \pm 0.01 \pm 0.00$ | $-0.06 \pm 0.04 \pm 0.00$ |
| Higgs                                         | $0.01 \pm 0.01 \pm 0.00$ | $0.02 \pm 0.01 \pm 0.00$  | $0.04 \pm 0.02 \pm 0.00$  |
| Total                                         | $1.31 \pm 0.26 \pm 0.30$ | $1.82 \pm 0.22 \pm 0.14$  | $0.57 \pm 0.14 \pm 0.14$  |

Table 6.6: Predicted sample composition based on Monte Carlo in the signal region SR- $m_{T2,150}$ . The first error is the uncertainty from limited Monte Carlo statistics, the second error is systematic uncertainty arising from all sources of systematics. The prediction correspond to a luminosity of  $20.3 \text{ fb}^{-1}$ . Fakes background is estimated using the data-driven Matrix Method described in Chapter 7.



# 7 $WW$ and Fake Backgrounds Estimation

The estimation of the backgrounds is the central part of any search for new physics. Several processes can mimic a SUSY signature with two leptons and missing transverse energy similar to that of chargino and slepton pair production. The background needs to be estimated as precisely as possible before a statement on whether the data is compatible with the background only hypothesis or with a background + SUSY signal hypothesis. The dominant backgrounds are  $WW$ ,  $ZV$  and Top processes. This chapter gives an overview of the methods employed to measure the  $WW$  and fake backgrounds in the signal regions  $\text{SR-}m_{T2,90}$ ,  $\text{SR-}m_{T2,120}$ ,  $\text{SR-}m_{T2,150}$ ,  $\text{SR-}WW_b$  and  $\text{SR-}WW_c$ .

## 7.1 The $WW$ Background

The  $WW$  pair production is the dominant Standard Model background. It leads to a dilepton final state when both  $W$  bosons decay leptonically. What makes the  $WW$  signature similar to SUSY is that they both contain real missing energy in the final state. In the case of  $WW$ , the missing energy comes from neutrinos while in SUSY it comes from the neutralinos and neutrinos. This background is estimated using the data-driven method described briefly below.

### 7.1.1 The $WW$ Control Region

A special region of phase space rich in  $WW$  events called a control region (CR- $WW$ ) is defined. The control region should be as close as possible to the signal region while still being dominated by the background process in question. At the same time, the control region should be disjoint from the signal region. The  $WW$  background is difficult to isolate in a control region without also collecting a substantial amount of Top and hypothetically signal. The control region CR- $WW$  is defined by selecting a slice of  $m_{T2}$  in the range  $50 < m_{T2} < 90$  GeV. This requirement positions the CR- $WW$  as close to the signal regions as possible while still keeping them disjoint. The  $m_{T2}$  requirement suppresses non- $WW$  backgrounds, mainly Top and  $Z$ +jets. The  $|m_{\ell\ell} - m_Z| < 10$  GeV requirement is not applied in order to retain enough  $WW$  events. All the other cuts are the



same as in the signal regions  $SR-m_{T2}$ . Table 7.1 gives the exact definition of the control region CR- $WW$ . Only  $e\mu$  final states are selected to estimate the  $WW$  background in the signal regions in all three channels ( $ee$ ,  $\mu\mu$  and  $e\mu$ ). The  $e\mu$  events are more pure in  $WW$  events (83%) than  $ee$  (72%) and  $\mu\mu$  (70%) due to Z+jets contamination. Although all channels produce statistically compatible estimations, the one obtained using  $e\mu$  events is considered the most reliable and less prone to systematic uncertainties, in particular from the Drell-Yan contribution.

| CR- $WW$            |                |
|---------------------|----------------|
| OS leptons          | ✓              |
| Lepton flavour      | $e\mu$         |
| $p_T^{\ell 1}$      | $> 35$ GeV     |
| $p_T^{\ell 2}$      | $> 20$ GeV     |
| $m_{\ell\ell}$      | $> 20$ GeV     |
| signal central jets | $= 0$          |
| signal $b$ -jets    | $= 0$          |
| signal forward jets | $= 0$          |
| $m_{T2}$            | $[50, 90]$ GeV |

Table 7.1: Definition of the control region (CR- $WW$ ) for the data-driven  $WW$  background calculation. “✓” means the cut is applied.

Since the signature of the SUSY processes is similar to that of  $WW$  events, the signal events could significantly contaminate the control region CR- $WW$ . This would lead to an overestimation of the  $WW$  background and result in a decrease of the sensitivity of the analysis to the signal. The SUSY scenario where the largest contamination into the  $WW$  control region occurs is chargino pair production with intermediate sleptons in the decay. The largest contribution of this signal model to the CR- $WW$  is 52%. In such a situation the  $WW$  background would be overestimated in the control region thus leading to a corresponding overestimate of  $WW$  in the signal regions. This would reduce the sensitivity to the signal. We observe that for such signal models the contribution in the signal region is large enough that it could still be excluded even if the  $WW$  background was overestimated in this way. Moreover, all the points with high contamination are already excluded with earlier searches [101]. Contamination from the chargino pair production in the scenario of intermediate  $W$  bosons in the decay is at most 14%. The majority of the signal points that are not excluded show much less than 5% contamination. All model points with high contamination remain excludable despite of the possible overestimation of the  $WW$  background in the event of signal contamination in the control region.

### 7.1.2 Method for $WW$ Background Calculation

The control region CR- $WW$  defined in the previous section is used to estimate the  $WW$  background in the signal regions SR- $m_{T2,90}$ , SR- $m_{T2,120}$ , SR- $m_{T2,150}$ , SR- $WW_b$  and SR- $WW_c$ . The data-driven prediction of the number of  $WW$  events in the signal region is given by:

$$N_{WW}^{SR} = (N_{data}^{CR} - N_{non-WW, MC}^{CR}) \times \mathcal{T}_f \quad (7.1)$$

where  $N_{WW}^{SR}$  is the data-driven estimate of the number of  $WW$  events in the signal region,  $N_{data}^{CR}$  is the observed number of events in the CR- $WW$ ,  $N_{non-WW, MC}^{CR}$  is the contribution of the non- $WW$  events in the CR- $WW$ . The non- $WW$  events need to be subtracted from the  $N_{data}^{CR}$  before extrapolation to the signal regions. The  $N_{non-WW, MC}^{CR}$  is estimated from the Monte Carlo. The  $\mathcal{T}_f$  is a transfer factor used to extrapolate from the control region to the signal region:

$$\mathcal{T}_f = \left( \frac{N_{WW}^{SR}}{N_{WW}^{CR}} \right)_{MC} \quad (7.2)$$

The transfer factor  $\mathcal{T}_f$  is the main input from the Monte Carlo in this method. Equation 7.1 may also be rewritten in term of a scale factor  $\mathcal{S}$ :

$$N_{WW}^{SR} = N_{WW, MC}^{SR} \times \mathcal{S} \quad (7.3)$$

where  $\mathcal{S}$  is defined as:

$$\mathcal{S} = \frac{N_{WW, data}^{CR} - N_{non-WW, MC}^{CR}}{N_{WW, MC}^{CR}} \quad (7.4)$$

By taking a ratio of two Monte Carlo predictions in two regions which are similar the systematic uncertainty can be reduced significantly. The scale factor  $\mathcal{S}$  allows to visualise how much the Monte Carlo needs to be scaled to reproduce the data. It takes value  $\mathcal{S} = 1$  if Monte Carlo is in perfect agreement with data in the control region.

The calculated scale factor for  $WW$  background is  $\mathcal{S} = 1.14 \pm 0.05$ . This result is in agreement with the ATLAS measurement of the  $WW$  production cross section [102]. The experimentally measured  $WW$  cross-section [102] is approximately a factor  $1.22 \pm 0.11$  above the Standard Model prediction in a somewhat different region of phase space. The final scale factor applied in **Paper III** is obtained by performing the simultaneous fit. The procedure is explained in Chapter 10.

## 7.2 Non-Prompt Leptons and Fake Leptons

### 7.2.1 Motivation

The final state searched in this analysis contains two leptons (electrons or muons) from chargino or slepton decays. Such leptons are not produced in association with hadronic

particles in the same direction. They are said to be isolated from hadronic energy and prompt because they come from the primary proton-proton interaction. These properties are similar to leptons produced in on-shell  $W$  decays and Drell-Yan production.

There are nevertheless other sources of leptons. Electrons and muons can be the result of heavy flavour secondary decays or in-flight decays of hadrons. These are so called non-prompt leptons. Electron pairs can emerge from photon conversions that can lead to the identification of fake electrons. Single pions can sometimes be mistaken for electrons, although it is rare, the rate of pions is very large. Hence, this background needs in general to be taken into account. Hadrons can also evolve early on into a pre-dominantly electromagnetic shower that can lead to the identification of fake electrons. The so-called “matrix method” used in **Paper III** to derive fake and non-prompt leptons is presented in this section.

## 7.2.2 Matrix Method

For this method it is required to use two types of leptons defined in Section 3.2.8, the loose category that fulfils the baseline criteria and tight category that fulfills the signal criteria. It is important to note that the tight leptons are a subset of the loose leptons. Additionally, the matrix method relies on a real efficiency  $r$  and a fake rate  $f$ . Both the real efficiency and the fake rate can be computed from data.

The real efficiency is defined as the probability for a prompt lepton with loose criteria to pass the tight criteria. The fake rate is the probability for a fake lepton with loose criteria to pass the tight criteria. The fake rate and real efficiency need to be determined separately for electrons and muons.

In the dilepton sample with two loose leptons the number of events is denoted  $N_{LL}$ . The two leptons can be fakes ( $N_{FF}$  is the number of such events), the two leptons can be real prompt leptons ( $N_{RR}$  is the number of such events) and finally  $N_{RF}$  ( $N_{FR}$ ) denotes the number of events where the leading (subleading) lepton is real and the subleading (leading) lepton is fake. Thus one can write:

$$N_{LL} = N_{RR} + N_{RF} + N_{FR} + N_{FF} \quad (7.5)$$

One can now look at the composition of the sample with two tight leptons. The number of such events is denoted  $N_{TT}$ . If  $r_1$  and  $r_2$  ( $f_1$  and  $f_2$ ) are the real efficiencies (fake rates) for the leading and subleading lepton, one can write:

$$N_{TT} = r_1 r_2 \cdot N_{RR} + r_1 f_2 \cdot N_{RF} + f_1 r_2 \cdot N_{FR} + f_1 f_2 \cdot N_{FF} \quad (7.6)$$

Similarly  $N_{TL}$  ( $N_{LT}$ ), the number of events where only the leading (subleading) lepton is tight, can be expressed as linear combinations of  $N_{RR}$ ,  $N_{RF}$ ,  $N_{FR}$  and  $N_{FF}$  giving a total

of four linear equations that can be expressed in the following matrix form:

$$\begin{pmatrix} N_{TT} \\ N_{TL} \\ N_{LT} \\ N_{LL} \end{pmatrix} = \begin{pmatrix} r_1 r_2 & r_1 f_2 & f_1 r_2 & f_1 f_2 \\ r_1 & r_1 & f_1 & f_1 \\ r_2 & f_2 & r_2 & f_2 \\ 1 & 1 & 1 & 1 \end{pmatrix} \begin{pmatrix} N_{RR} \\ N_{RF} \\ N_{FR} \\ N_{FF} \end{pmatrix} \quad (7.7)$$

The number of events  $N_{TT}$ ,  $N_{TL}$ ,  $N_{LT}$  and  $N_{LL}$  can simply be counted in data with all signal region selections applied. The system of equations given in Eq. 7.7 is then solved, based on measured values of the real efficiencies and fake rates. Finally, the number of events with two tight leptons arising from zero, one or two real fake leptons are given by:

$$\begin{aligned} N_{RR}^{\text{SR}} &= r_1 r_2 \cdot N_{RR} \\ N_{RF}^{\text{SR}} &= r_1 f_2 \cdot N_{RF} \\ N_{FR}^{\text{SR}} &= f_1 r_2 \cdot N_{FR} \\ N_{FF}^{\text{SR}} &= f_1 f_2 \cdot N_{FF} \end{aligned} \quad (7.8)$$

The total number of events with at least one fake lepton in the signal region is given by:

$$N_{\text{fakes}}^{\text{SR}} = N_{RF}^{\text{SR}} + N_{FR}^{\text{SR}} + N_{FF}^{\text{SR}} \quad (7.9)$$

### 7.2.3 Real Efficiencies

The real efficiency depends on the lepton  $p_T$ . The real efficiency  $r_\ell^{\text{SR}}$  in the signal region for lepton flavour  $\ell = e, \mu$  is given by:

$$r_\ell^{\text{SR}}(p_T) = \sum_i (r_i(p_T) \cdot R_i^{\text{SR}} \cdot \mathcal{S}) \quad (7.10)$$

where the sum runs on all physics processes that contribute real leptons to the signal region,  $r_i(p_T)$  is the real efficiency for each physics process computed in Monte Carlo simulation,  $R_i^{\text{SR}}$  is the fraction of events arising from process  $i$  and  $\mathcal{S}$  is a scale factor to correct for differences between simulation and data. The quantities  $R_i^{\text{SR}}$  are determined from Monte Carlo simulation. The quantities  $r_i(p_T)$  are determined by looking at truth level information in the Monte Carlo simulation. The scale factor  $\mathcal{S}$  is assumed to be the same for all processes and determined using  $Z/\gamma^* \rightarrow \ell\ell$  events in data and simulation.

### 7.2.4 Fake Rates

The fake rate depends on the lepton  $p_T$ , on the physics process in which it occurs and on the specific process generating the fake (heavy flavour, single pion, in-flight decay,

etc.) or “type of fake”. The fake rate  $f_\ell^{\text{SR}}(p_T)$  for a lepton  $\ell = e, \mu$  in a signal region is given by:

$$f_\ell^{\text{SR}}(p_T) = \sum_{i,j} (f_{ij}(p_T) \cdot R_{ij}^{\text{SR}} \cdot \mathcal{S}_j) \quad (7.11)$$

where  $i$  runs on the physics processes in which the fake occurs,  $j$  runs on the different types of fakes, the  $R_{ij}^{\text{SR}}$  is the fraction of fakes arising in physics process  $i$  of type  $j$ ,  $f_{ij}(p_T)$  is the fake rate determined in simulation and  $\mathcal{S}_j$  is the scale factor to correct for different fake rates in data and Monte Carlo for type of fake  $j$ .

## 8 Jet-Veto

### 8.1 Motivation

The chargino and slepton direct production processes do not yield hadronic activity in form of jets, but jets can still arise from Initial State Radiation (ISR). On the other hand the large  $t\bar{t}$  background can yield two leptons and two jets coming from  $b$ -quarks. The  $t\bar{t}$  process has a large cross section and results in a dilepton and  $E_T^{\text{miss}}$  final state. A jet-veto is therefore important to suppress this high-cross section background.

Another source of jets is pile-up collisions containing jets overlaid with Standard Model processes without jets. The additional jets from pile-up can equally appear overlaid over chargino and slepton pair events which would thus look background like. For this reason it is important not to simply veto all events with jets. The study described in this Chapter is included in **Paper III**.

### 8.2 Signal Jets

In order not to suppress the chargino and slepton signal it is necessary to differentiate between the jets from the primary interaction and those from pile-up. Therefore, so called signal jets are defined. The signal jet categories are designed to select jets with high probability to come from the primary vertex.

The signal jets are grouped into three disjoint categories:

- Central light jets denoted L20,
- Central  $b$ -jets denoted B20,
- Forward jets denoted F30.

The central light jets have  $|\eta| < 2.4$  and are not tagged as  $b$ -jet. They are required to have transverse momentum  $p_T > 20$  GeV. Additionally,  $\text{JVF} \neq 0$  requirement is utilised on jets with  $p_T < 50$  GeV to confirm that they come from the primary collision and not from pile-up. The JVF variable defined in Eq. 3.11 relies on information from the Inner Detector and can be defined only for jets with  $|\eta| < 2.5$ . To avoid poor accuracy near the boundary of the Semiconducting Tracker system it is used only in  $|\eta| < 2.4$ . The central light jet criteria efficiently selects jets coming from the primary vertex while

few pile-up jets survive. The L20 variable is the number of central light jets as defined above.

Jets originating from  $t\bar{t}$  production are  $b$ -jets. About 80% of these events have a  $b$ -jet with  $|\eta| < 2.4$ . Therefore, central  $b$ -jets are selected by using the MV1 algorithm, requiring  $|\eta| < 2.4$  and  $p_T > 20$  GeV. Since the  $b$ -tagging algorithm requires the tracks in a jet to come from the primary vertex, the pile-up jets are not likely to be tagged as  $b$ -jets. Therefore, no JVF cut is applied. The B20 variable is defined as the number of  $b$ -jets as defined above.

In order to improve the removal of Top events a forward jet category is defined. The forward jets are required to have  $2.4 < |\eta| < 4.5$ . Approximately 20% of  $t\bar{t}$  events have relatively forward jets. In the forward region no JVF or  $b$ -tagging requirement can be applied due to the limited acceptance of the Pixel Detector and Semiconducting Tracker. In order to avoid removing SUSY events because of pile-up jets in the forward region a higher transverse momentum cut ( $p_T > 30$  GeV) is applied, since most of pile-up jets have  $p_T < 30$  GeV. The F30 variable is defined as the number of jets fulfilling the above forward jet selections. The summary of the signal jet definitions is given in Tab. 8.1.

The jet-veto applied in this analysis requires exactly zero signal jets of the three kinds in the event:  $L20 + B20 + F30 = 0$ . The variables L20, B20 and F30 indicate both the jet category and the number of jets of a given category in the event.

| Criteria | Central light jet (L20)    | Central $b$ -jet (B20) | Forward jet (F30)    |
|----------|----------------------------|------------------------|----------------------|
| $p_T$    | $> 20$ GeV                 | $> 20$ GeV             | $> 30$ GeV           |
| $ \eta $ | $< 2.4$                    | $< 2.4$                | $2.4 <  \eta  < 4.5$ |
| $b$ -tag | ✗                          | ✓                      | —                    |
| JVF      | $\neq 0$ if $p_T < 50$ GeV | —                      | —                    |

Table 8.1: Signal jet definitions: central light jets (L20), central  $b$ -jets (B20) and forward jets (F30). “✓” means the cut is applied, “✗” means the cut is reversed, “—” means the cut is not applied.

### 8.3 Top Background Calculation and Jet-Veto

The Top background is estimated using a data-driven method. For this purpose a Top control region (CR-Top) rich in Top events is constructed. The definition of the Top control region is given in Tab. 8.2. The number of Top events in the signal region ( $N_{\text{Top}}^{\text{SR}}$ ) is calculated with the following formula:

$$N_{\text{Top}}^{\text{SR}} = \mathcal{S} \times N_{\text{Top, MC}}^{\text{SR}} \times C_{\mathcal{S}} \quad (8.1)$$

where the scale factor  $\mathcal{S}$  is the ratio between the observed number of events in the Top control region in data ( $N_{\text{Top, data}}^{\text{CR}}$ ) and in MC ( $N_{\text{Top, MC}}^{\text{CR}}$ ). The scale factor  $\mathcal{S}$  is given by:

$$\mathcal{S} = \frac{N_{\text{Top, data}}^{\text{CR}}}{N_{\text{Top, MC}}^{\text{CR}}} \quad (8.2)$$

The correction factor  $C_{\mathcal{S}}$  is used to address potential difference in the jet-veto efficiency between data and MC since the Eq. 8.2 relies implicitly on the simulation to derive the probability for Top events to survive the jet-veto. It is given by:

$$C_{\mathcal{S}} = \frac{\mathcal{E}_{\text{data}}^{\text{jet-veto}}}{\mathcal{E}_{\text{MC}}^{\text{jet-veto}}} \quad (8.3)$$

where numerator and denominator are the jet-veto efficiencies in data and MC. The jet-veto efficiency  $\mathcal{E}^{\text{jet-veto}}$  is given by:

$$\mathcal{E}^{\text{jet-veto}} = \frac{N_{\text{jet-veto}}^{\text{CR}}}{N^{\text{CR}}} \quad (8.4)$$

where  $N_{\text{jet-veto}}^{\text{CR}}$  is the number of events in CR with no signal jets while  $N^{\text{CR}}$  is the total number of all events in CR. We present the study of  $C_{\mathcal{S}}$  in two control regions. This method is used in **Paper III**.

| CR-Top                  |                    |
|-------------------------|--------------------|
| OS leptons              | ✓                  |
| Lepton flavour          | $e\mu$             |
| $p_{\text{T}}^{\ell 1}$ | $> 35 \text{ GeV}$ |
| $p_{\text{T}}^{\ell 2}$ | $> 20 \text{ GeV}$ |
| $m_{\ell\ell}$          | $> 20 \text{ GeV}$ |
| signal central jets     | $= 0$              |
| signal $b$ -jets        | $\geq 1$           |
| signal forward jets     | $= 0$              |
| $m_{\text{T}2}$         | $> 70 \text{ GeV}$ |

Table 8.2: Definition of the Top control region (CR-Top) for the data-driven Top background calculation. “✓” means the cut is applied.

## 8.4 Control Regions for Jet-Veto Validation

The jet-veto efficiency is compared between data and Monte Carlo in two control regions:  $b$ -tag control region and Z control region. The  $b$ -tag control region addresses specifically the effect of the jet-veto on  $b$ -jets, while the Z control region is dominated by light jets and forward jets.



### 8.4.1 $b$ -tag control region

The  $b$ -tag control region is constructed to be dominated by Top processes but must be different from the Top control region to be able to study the jet-veto efficiency. The  $b$ -tag control region is used to test whether the probability to pass the jet-veto in Monte Carlo matches the probability in data or if a correction is necessary. It is used to calculate the jet-veto efficiency and correction factor of Section 8.1. The definition of the  $b$ -tag control region is given in Tab. 8.3.

In order to study the jet-veto in the  $b$ -tag control region only jets with  $\Delta R > 1.0$  from the  $b$ -tagged jet are considered. The composition of the  $b$ -tag control region as a function of  $E_T^{\text{miss,rel}}$  after jet-veto is showed in Fig. 8.1 right panels and before jet-veto on the left panels. A good agreement between data and MC is observed both before and after jet-veto requirement.

| Criteria                             | $b$ -tag control region | Z control region   |
|--------------------------------------|-------------------------|--------------------|
| OS leptons                           | ✓                       |                    |
| Lepton flavour                       | $ee, \mu\mu$            |                    |
| $p_T^{\ell_1}$                       | $> 35 \text{ GeV}$      |                    |
| $p_T^{\ell_2}$                       | $> 20 \text{ GeV}$      |                    |
| $m_{\ell\ell}$                       | $> 20 \text{ GeV}$      |                    |
| $ m_{\ell\ell} - m_Z $               | $> 10 \text{ GeV}$      | $< 10 \text{ GeV}$ |
| $b$ -jets ( $p_T > 25 \text{ GeV}$ ) | $\geq 1$                | —                  |
| $E_T^{\text{miss}}$                  | $> 40 \text{ GeV}$      | —                  |

Table 8.3: Definition of the  $b$ -tag control region and Z control region for the jet-veto efficiency study. “✓” means the cut is applied, “—” means the cut is not applied.

### 8.4.2 Z control region

The Z control region is defined to be dominated by Z+jets events. It contains mostly central light jets and forward jets to a lesser extend. Therefore, the Z control region can be used to complement the checks performed in the  $b$ -tag control region. Nevertheless, the scale factor used in Eq. 8.1 is obtained using the  $b$ -tag control region because Top is by far the main background rejected by the jet-veto. The definition of Z control region is given in Tab. 8.3.

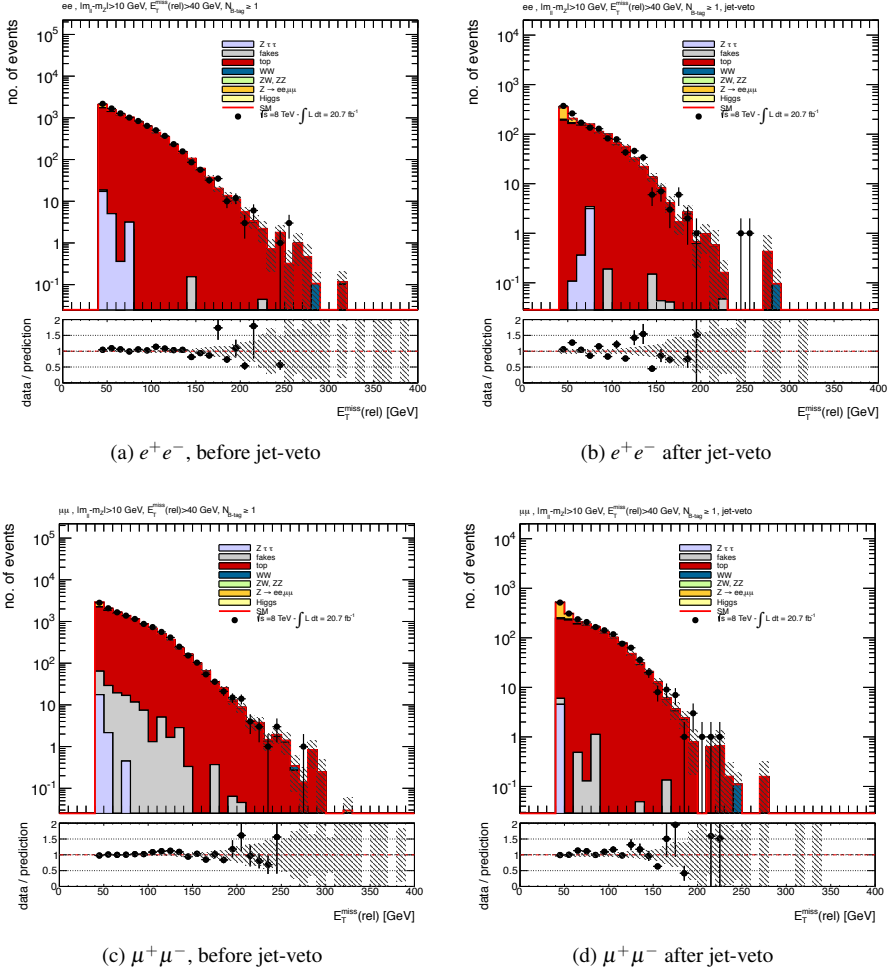


Figure 8.1: Distribution of the relative missing transverse energy in the  $ee$   $b$ -tag control region (top-left) and in the  $\mu\mu$   $b$ -tag control region (bottom-left). The top and bottom-right plots show the  $ee$  and  $\mu\mu$   $b$ -tag control regions after requiring the jet-veto ( $L20 + B20 + F30 = 0$ ). The uncertainty band represents statistical uncertainties only. The data points correspond to  $20.7 \text{ fb}^{-1}$ . The lower panel in the plots shows the ratio between observed data events over Monte Carlo predictions.

## 8.5 Results

The  $b$ -tag control region is used to compute the probability of an event to survive the jet-veto, so called jet-veto efficiency  $\mathcal{E}^{\text{jet-veto}}$  given by Eq. 8.4. This probability is showed for data and Monte Carlo as a function of the number of primary vertices in Fig. 8.2 top panels. It is presented as a function of the number of primary vertices in order to test how this probability depends on the number of primary interactions in the event and how it is modelled by MC. It is shown that less than 20% of the events in Top dominated  $b$ -tag control region survive the jet-veto. We also note that, there is no dependence of the jet-veto efficiency on the primary vertex multiplicity. The correction factor  $C_{\mathcal{J}}$  used in Eq. 8.1 is obtained by fitting a constant to the ratio shown in the data/prediction panel of the  $b$ -tag control region in Fig. 8.2. This yields  $C_{\mathcal{J}} = 0.95 \pm 0.04 \pm 0.17$  in  $ee$  channel and  $C_{\mathcal{J}} = 1.00 \pm 0.03 \pm 0.21$  in  $\mu\mu$  channel, where the first error is statistical and the second one is systematical. Jet energy scale is the largest source of systematic uncertainty.

The jet-veto efficiency studied in the Z control region is presented in Fig. 8.2 bottom panels. It is shown that the efficiency is mildly decreasing at high primary vertex multiplicities. Nevertheless, this trend is well reproduced by the Monte Carlo simulation. The same fitting procedure is applied as for the  $b$ -tag control region. The jet-veto efficiency in the Z control region is  $1.032 \pm 0.002$  in  $ee$  channel and  $1.032 \pm 0.001$  in  $\mu\mu$  channel, where error is statistical. In **Paper III** the correction factor of  $C_{\mathcal{J}} = 1.0 \pm 0.1$  is used. This is conservative and constitutes a simplifying envelope of the studies summarised in the presented chapter.

## 8.6 Conclusions

It is shown that the probability to pass the jet-veto in data is well reproduced by Monte Carlo. Therefore, MC can be used to model the jet-veto for Top events. The jet-veto correction factor is not needed for the ZV background estimation since the ZV control region (see Chapter 9) has already the jet-veto applied.

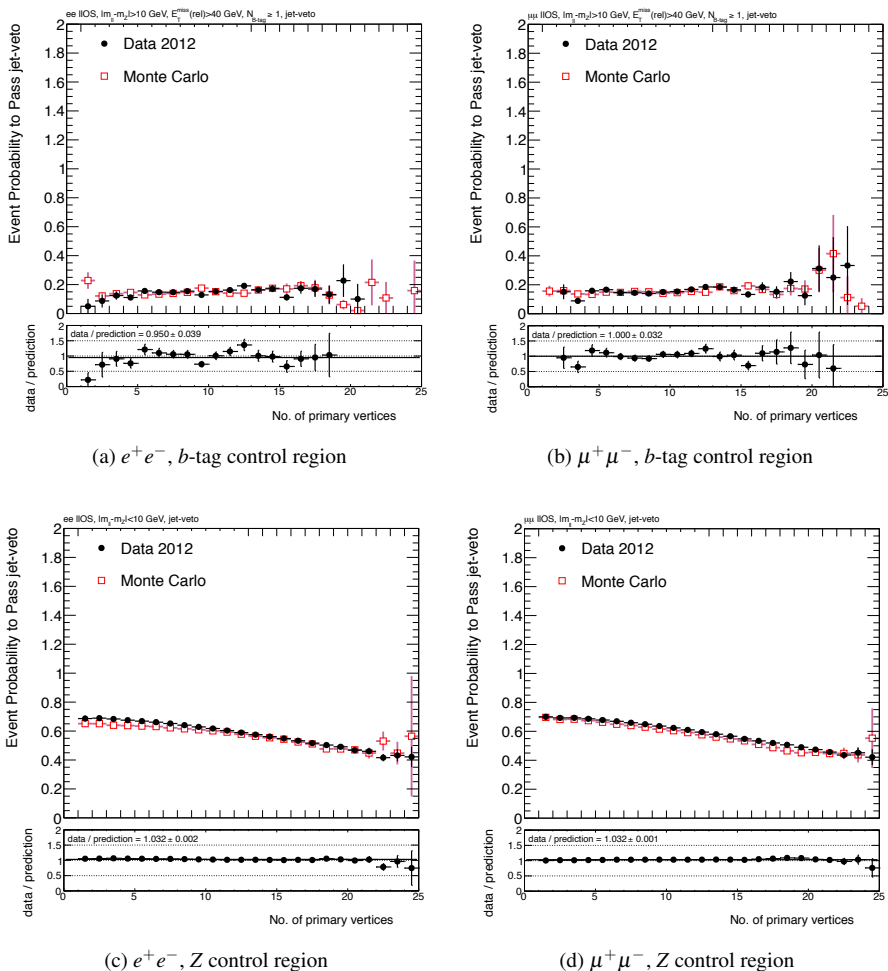


Figure 8.2: Event probability to survive the jet-veto in the  $b$ -tag control region as a function of the number of primary vertices in dielectron (a) and dimuon events (b). Event probability to pass the jet veto in the  $Z$  control region as a function of the number of primary vertices in di-electron events (c) and di-muon right events (d). The uncertainty band represents statistical uncertainty. The data points correspond to  $20.7 \text{ fb}^{-1}$ . The lower panel in the plots shows the ratio between observed data events over Monte Carlo predictions.



## 9 ZV Background Estimation

In this Chapter the data-driven estimation of  $ZV$  background is described. The presented method is used in the analysis described in **Paper III**.

### 9.1 Motivation

This Chapter is devoted to the  $Z$ +jets,  $ZW$ ,  $ZZ$  and  $Z$ +two vector bosons backgrounds determination for the opposite sign signal regions with jet-veto and  $m_{T2}$  cut:  $SR-m_{T2,90}$ ,  $SR-m_{T2,120}$ ,  $SR-m_{T2,150}$ ,  $SR-WW_b$  and  $SR-WW_c$ . The label  $ZV$  is used generically to refer to these processes. As discussed in Chapter 6,  $ZV$  is one of the dominant Standard Model backgrounds since it yields opposite sign lepton pairs and can have missing transverse energy in the final state (for instance  $ZZ \rightarrow \ell\ell\nu\nu$ ). This Chapter presents a data-driven calculation of this background in the signal regions listed above. The signal region  $SR-WW_a$  is not considered, since it requires a different type of control region selections and was not studied by the author.

### 9.2 The $ZV$ Control Region

In order to calculate the  $ZV$  background in the signal regions  $SR-m_{T2,90}$ ,  $SR-m_{T2,120}$ ,  $SR-m_{T2,150}$ ,  $SR-WW_b$  and  $SR-WW_c$  a common control region labelled  $CR-ZV$  is defined. The control region is constructed to be disjoint with all signal regions. Ideally, the control region  $CR-ZV$  should have the same selection as the signal region except the single reversed cut.  $CR-ZV$  utilises  $m_{T2} > 90$  GeV and  $|m_{\ell\ell} - m_Z| < 10$  GeV, all the other selections are the same as the signal regions mentioned earlier. The  $CR-ZV$  is rich in  $ZV$  processes. Table 9.1 gives the exact definition of the control region  $CR-ZV$ . The selection  $m_{T2} > 90$  GeV is the lowest  $m_{T2}$  cut used in signal regions. This relatively low cut provides larger data and Monte Carlo statistics lowering the statistical uncertainty. The lower  $m_{T2}$  cut also provides a smaller generator systematic uncertainty on the transfer factor  $\mathcal{T}_f$  between control and signal region. Generator uncertainty is estimated by comparing different Monte Carlo generators, POWHEG and SHERPA. For this reason the relative difference between the transfer factors obtained using these generators is calculated. The  $\mathcal{T}_f$  is further discussed in Section 9.3.

Figure 9.1 shows the  $E_T^{\text{miss,rel}}$  (top panel) and  $m_{T2}$  (bottom panel) in data and Monte

| CR-ZV                  |                    |
|------------------------|--------------------|
| OS                     | ✓                  |
| Lepton flavour         | $ee, \mu\mu$       |
| $p_T^{\ell 1}$         | $> 35 \text{ GeV}$ |
| $p_T^{\ell 2}$         | $> 20 \text{ GeV}$ |
| $m_{\ell\ell}$         | $> 20 \text{ GeV}$ |
| $ m_{\ell\ell} - m_Z $ | $< 10 \text{ GeV}$ |
| signal central jets    | $= 0$              |
| signal $b$ -jets       | $= 0$              |
| signal forward jets    | $= 0$              |
| $m_{T2}$               | $> 90 \text{ GeV}$ |

Table 9.1: Definition of the control region (CR-ZV) for the data-driven ZV background calculation. “✓” means the cut is applied.

Carlo in CR-ZV. A good agreement is observed between data and MC prediction. A very high purity of ZV events in CR-ZV is observed, 95% in  $ee$  channel and 97% in  $\mu\mu$  channel. It is observed that no Z+jets events in the Monte Carlo survive the CR-ZV selection. The Z+jets processes do not pass the  $m_{T2} < 90 \text{ GeV}$  requirement nor even looser selections and can therefore be ignored. The data in the CR-ZV is also consistent with zero Z+jets events.

### 9.3 Method

The CR-ZV defined in Section 9.2 is used to estimate the ZV background in signal regions SR- $m_{T2,90}$ , SR- $m_{T2,120}$ , SR- $m_{T2,150}$ , SR- $WW_b$  and SR- $WW_c$  with data-driven method. The number of ZV events in the signal region is calculated in the following way:

$$N_{ZV}^{\text{SR}} = (N_{\text{data}}^{\text{CR}} - N_{\text{non-Z, MC}}^{\text{CR}}) \times \mathcal{T}_f \quad (9.1)$$

where  $N_{ZV}^{\text{SR}}$  is the data-driven estimate of the number of ZV events in the signal region,  $N_{\text{data}}^{\text{CR}}$  is the observed number of events in CR-ZV. The CR-ZV can be contaminated by other Standard Model processes such as  $WW$  or Top. These events are collectively called non-Z background and their contribution to CR-ZV is labelled as  $N_{\text{non-Z, MC}}^{\text{CR}}$ . They need to be subtracted from the  $N_{\text{data}}^{\text{CR}}$  before extrapolation to the signal regions. Equation 9.1 is applied separately for the  $ee$  and  $\mu\mu$  channels. The  $N_{\text{data}}^{\text{CR}}$  is estimated from the Monte Carlo. The  $\mathcal{T}_f$  is called transfer factor and is the ratio of the number of ZV events in the signal region over the number of ZV events in the CR-ZV:

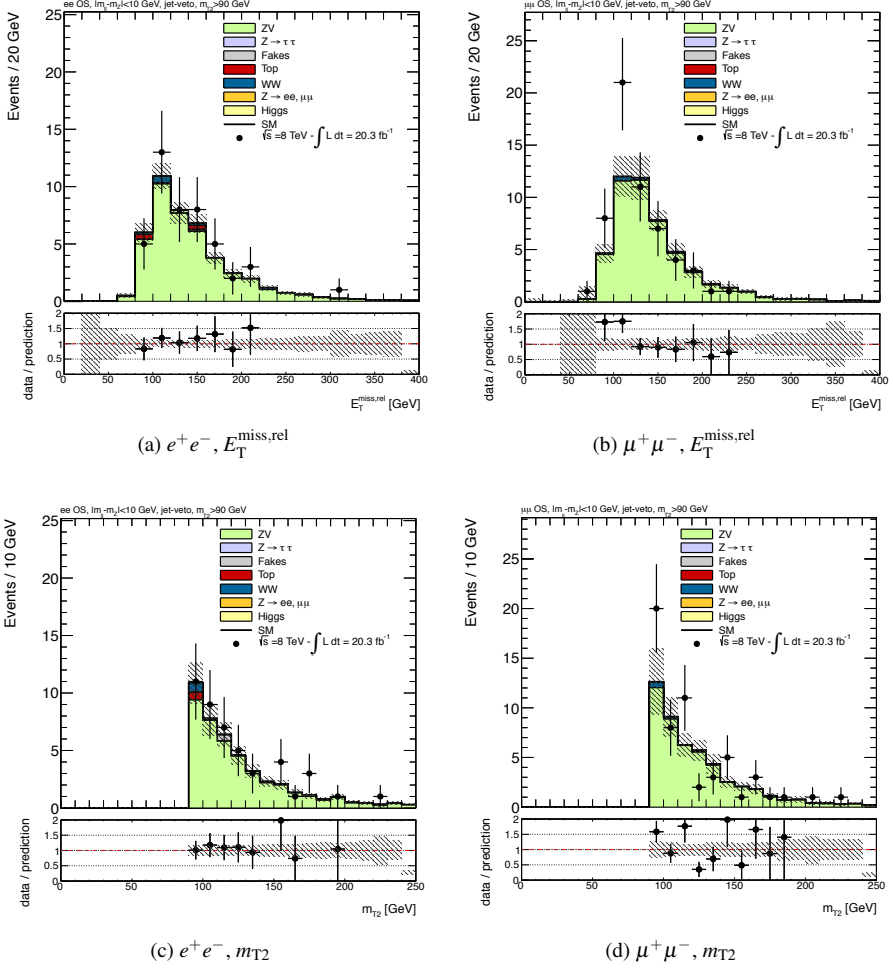


Figure 9.1: Distributions of the relative missing transverse energy (top) and the transverse mass (bottom) in the dielectron (left) and dimuon channel (right) in the CR-ZV. The uncertainty band represents the total statistical and systematic uncertainty on the Monte Carlo prediction. The data points correspond to 20.3 fb<sup>-1</sup>. The lower panel in the plots shows the ratio between observed data events over Monte Carlo predictions.



$$\mathcal{T}_f = \left( \frac{N_{ZV}^{\text{SR}}}{N_{ZV}^{\text{CR}}} \right)_{\text{MC}} \quad (9.2)$$

The  $\mathcal{T}_f$  is the main input from the Monte Carlo in this method. Equation 9.1 may also be rewritten in term of a scale factor  $\mathcal{S}$ :

$$N_{ZV}^{\text{SR}} = N_{ZV, \text{MC}}^{\text{SR}} \times \mathcal{S} \quad (9.3)$$

where  $\mathcal{S}$  is defined as:

$$\mathcal{S} = \frac{N_{ZV, \text{data}}^{\text{CR}} - N_{\text{non-Z, MC}}^{\text{CR}}}{N_{ZV, \text{MC}}^{\text{CR}}} \quad (9.4)$$

By taking a ratio of two Monte Carlo predictions in two regions which are similar, the systematic uncertainty can be reduced. The scale factor takes value  $\mathcal{S} = 1$  if Monte Carlo is in perfect agreement with data. The scaling of the ZV simulation by the factor  $\mathcal{S}$  is needed since the processes have not been measured in comparable regions in data.

## 9.4 Signal Contamination

In order to provide an accurate determination of the ZV background the CR-ZV needs to be dominated by this processes. This is indeed the case as seen in Section 9.3. Since the CR-ZV has selections similar to the signal regions it might contain some SUSY events. Therefore, the potential signal contamination from direct  $\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp$  production or from direct  $\tilde{\ell}^\pm \tilde{\ell}^\mp$  production is checked for different signal scenarios.

Figure 9.2 top panels shows the contamination in CR-ZV from  $\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp$  events in percent for different masses of the chargino  $\tilde{\chi}_1^\pm$  and the neutralino  $\tilde{\chi}_1^0$ . It shows that the highest contamination is 20%. The signal contamination can be compared to the uncertainty on the background estimate in CR-ZV. In these terms the signal contamination is  $2.2\sigma$  for the point  $(m_{\tilde{\chi}_1^\pm}, m_{\tilde{\chi}_1^0}) = (155, 5)$  GeV. Nevertheless, the sparticles mass region with high signal contamination was excluded with earlier searches [101]. Outside the previously excluded region the contamination is below 3% which corresponds to  $0.3\sigma$  significance or less and is thus completely negligible.

The contamination from the  $\tilde{\ell}^\pm \tilde{\ell}^\mp$  signal in percent for different slepton  $\tilde{\ell}^\pm$  and neutralino  $\tilde{\chi}_1^0$  masses is presented in Fig. 9.2 bottom panels. It is found to be 15% which corresponds to  $1.5\sigma$  significance at most for the points (105, 25) and (120, 0) GeV. Again, the region of high signal contamination was already excluded with earlier searches. Outside the previously excluded region the contamination is below 4% which corresponds to  $0.4\sigma$  significance or less and is thus completely negligible.

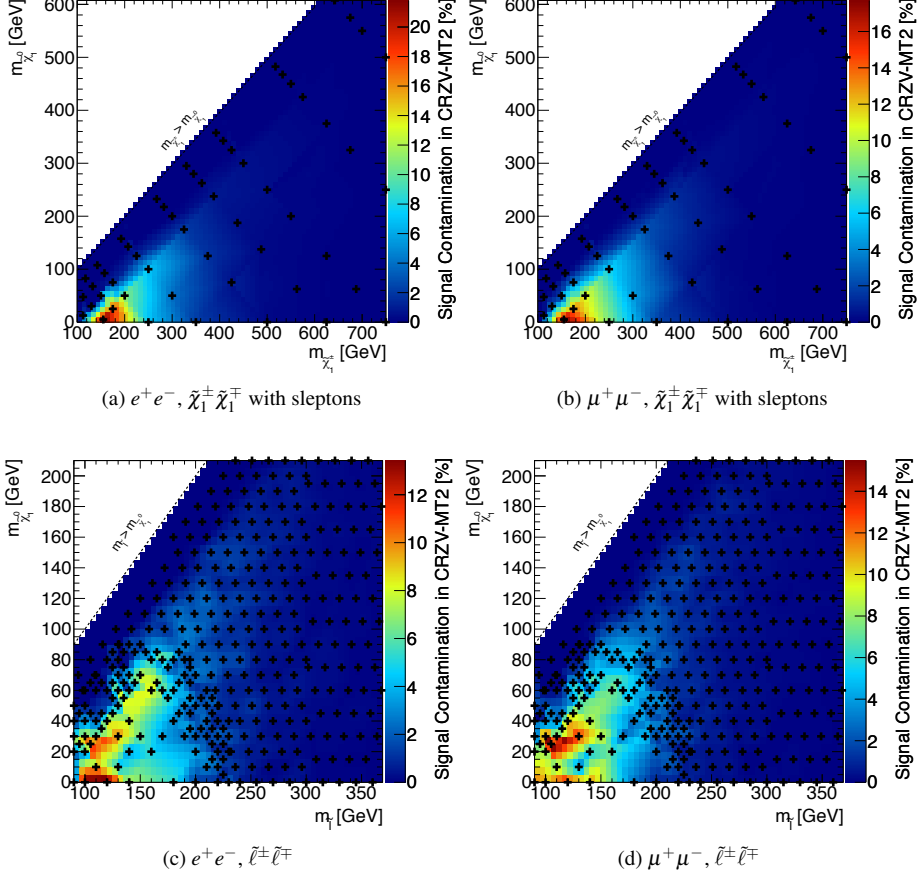


Figure 9.2: Top: signal contamination in percent ( $z$ -axis) in CR-ZV from direct chargino production with intermediate sleptons (Eq. 6.3) with respect to the chargino mass ( $x$ -axis) and to the neutralino mass ( $y$ -axis) in  $e^+e^-$  channel (a) and  $\mu^+\mu^-$  channel (b). Bottom: signal contamination in percent ( $z$ -axis) in CR-ZV from direct sleptons production (Eq. 6.5) with respect to the slepton mass ( $x$ -axis) and to the neutralino mass ( $y$ -axis) in  $e^+e^-$  channel (c) and  $\mu^+\mu^-$  channel (d). The crosses represent the probed signal points for which Monte Carlo samples have been generated. The continuous colour plain is obtained using an interpolation between the probed points. The white region on the top-left of each plot is kinematically forbidden.

## 9.5 Results

Using the CR-ZV and the method discussed in Section 9.3 the ZV background in signal regions  $\text{SR-}m_{\text{T}2,90}$ ,  $\text{SR-}m_{\text{T}2,120}$ ,  $\text{SR-}m_{\text{T}2,150}$ ,  $\text{SR-}WW_{\text{b}}$  and  $\text{SR-}WW_{\text{c}}$  is estimated. After counting the data yields in the control region the data-driven predictions for the ZV background in the signal regions was obtained. The results are presented in Table 9.2. The data-driven calculation is in good agreement with the MC based prediction. The scale factor  $\mathcal{S} = 1.025 \pm 0.084 \pm 0.070$  for  $e^+e^-$  channel and  $\mathcal{S} = 1.145 \pm 0.077 \pm 0.077$  for  $\mu^+\mu^-$  channel is applied on Monte Carlo.

|                         | $e^+e^-$                            |                                 |                                 | $\mu^+\mu^-$                        |                                 |                                 |
|-------------------------|-------------------------------------|---------------------------------|---------------------------------|-------------------------------------|---------------------------------|---------------------------------|
| Data-driven             |                                     |                                 |                                 |                                     |                                 |                                 |
| SR- $WW_{\text{b}}$     | 5.3 <sup>+0.9</sup> <sub>-0.9</sub> | <sup>+0.4</sup> <sub>-0.4</sub> | <sup>+0.7</sup> <sub>-0.7</sub> | 6.8 <sup>+1.0</sup> <sub>-1.0</sub> | <sup>+0.4</sup> <sub>-0.4</sub> | <sup>+0.8</sup> <sub>-0.8</sub> |
| SR- $WW_{\text{c}}$     | 4.4 <sup>+0.8</sup> <sub>-0.8</sub> | <sup>+0.3</sup> <sub>-0.3</sub> | <sup>+0.9</sup> <sub>-0.9</sub> | 6.1 <sup>+0.9</sup> <sub>-0.9</sub> | <sup>+0.3</sup> <sub>-0.2</sub> | <sup>+1.2</sup> <sub>-1.2</sub> |
| SR- $m_{\text{T}2,90}$  | 6.4 <sup>+1.1</sup> <sub>-1.1</sub> | <sup>+0.4</sup> <sub>-0.5</sub> | <sup>+0.8</sup> <sub>-0.8</sub> | 8.0 <sup>+1.2</sup> <sub>-1.2</sub> | <sup>+0.4</sup> <sub>-0.4</sub> | <sup>+1.0</sup> <sub>-1.0</sub> |
| SR- $m_{\text{T}2,120}$ | 2.3 <sup>+0.4</sup> <sub>-0.4</sub> | <sup>+0.3</sup> <sub>-0.3</sub> | <sup>+0.7</sup> <sub>-0.7</sub> | 3.2 <sup>+0.5</sup> <sub>-0.5</sub> | <sup>+0.2</sup> <sub>-0.2</sub> | <sup>+1.0</sup> <sub>-1.0</sub> |
| SR- $m_{\text{T}2,150}$ | 0.9 <sup>+0.2</sup> <sub>-0.2</sub> | <sup>+0.1</sup> <sub>-0.1</sub> | <sup>+0.2</sup> <sub>-0.2</sub> | 1.5 <sup>+0.3</sup> <sub>-0.3</sub> | <sup>+0.1</sup> <sub>-0.1</sub> | <sup>+0.2</sup> <sub>-0.2</sub> |
| Monte Carlo             |                                     |                                 |                                 |                                     |                                 |                                 |
| SR- $WW_{\text{b}}$     | 5.2 ±0.4                            | ±0.4                            |                                 | 5.9 ±0.4                            | ±0.8                            |                                 |
| SR- $WW_{\text{c}}$     | 4.3 ±0.4                            | ±0.4                            |                                 | 5.3 ±0.4                            | ±0.6                            |                                 |
| SR- $m_{\text{T}2,90}$  | 6.2 ±0.5                            | ±0.5                            |                                 | 7.0 ±0.4                            | ±1.0                            |                                 |
| SR- $m_{\text{T}2,120}$ | 2.2 ±0.3                            | ±0.2                            |                                 | 2.8 ±0.3                            | ±0.3                            |                                 |
| SR- $m_{\text{T}2,150}$ | 0.9 ±0.1                            | ±0.1                            |                                 | 1.3 ±0.2                            | ±0.1                            |                                 |
| Scale factor            |                                     |                                 |                                 |                                     |                                 |                                 |
| $\mathcal{S}$           | 1.025 ±0.084 ±0.070                 |                                 |                                 | 1.145 ±0.077 ±0.077                 |                                 |                                 |

Table 9.2: Data-driven and Monte Carlo prediction for the ZV background in the signal regions  $\text{SR-}m_{\text{T}2,90}$ ,  $\text{SR-}m_{\text{T}2,120}$ ,  $\text{SR-}m_{\text{T}2,150}$ ,  $\text{SR-}WW_{\text{b}}$  and  $\text{SR-}WW_{\text{c}}$ . The scale factor  $\mathcal{S}$  is also given. The first uncertainty is the combination of the uncertainty from limited Monte Carlo statistics and from control region statistics in data. The second error is the result of all other sources of systematic uncertainties except generator uncertainty. For data driven predictions the third uncertainty arises from generator systematics.

# 10 Results and Conclusions

This chapter presents the results of the search for direct chargino and slepton production. The number of events observed in the signal regions  $\text{SR-}WW_a$ ,  $\text{SR-}WW_b$ ,  $\text{SR-}WW_c$ ,  $\text{SR-}m_{T2,90}$ ,  $\text{SR-}m_{T2,120}$  and  $\text{SR-}m_{T2,150}$  is consistent with the background only predictions. Therefore exclusion limits at 95% confidence level (CL) are set. The simultaneous control region fit is described in Section 10.1. The statistical method to calculate exclusion limits is discussed in Section 10.2. The results are interpreted in the context of the SUSY simplified model in Section 10.3. These results are published in **Paper III**.

## 10.1 Simultaneous Control Region Fit

When the data driven method is applied to estimate more than one background process, the different predictions become interdependent. This is because the control region of a given background contains contributions from the other processes. If the method determines that the scale factor for a given background is different from unity, the contribution from this background in the control regions of all the other backgrounds should be rescaled appropriately. If this interdependence is taken into account, the naive approach of evaluating one background after the other results in a situation where the final result may depend on the order in which the backgrounds are evaluated. The other solution is to obtain the scale factors by fitting all backgrounds in all control regions simultaneously. This approach also ensures that systematic uncertainties that are correlated between the control regions are properly accounted for. A profile likelihood fit is performed to calculate the scale factors using the control regions  $\text{CR-}WW$ ,  $\text{CR-Top}$  and  $\text{CR-ZV}$  described in Sections 7.1.1, 8.3 and 9.2, respectively. This so called background-only fit assumes negligible signal contamination in the control regions. The method is implemented using the `HistFitter` framework [103].

The distributions in the control region are fitted with p.d.f.s that describe the expected contribution from the various Standard Model background components. A likelihood function  $\mathcal{L}$  can be expressed as a probability to observe  $n_i$  events in the control region if the expected number of events equals  $\lambda_i(\mu, b)$ . This can be described by a Poisson function:

$$\mathcal{L}(n_i|\mu, b) = P(n_i|\lambda_i(\mu, b)) = \frac{\lambda_i(\mu, b)^{n_i} e^{-\lambda_i(\mu, b)}}{n_i!} \quad (10.1)$$

where the subscript  $i$  enumerates the control regions. The  $\lambda_i(\mu, \mathbf{b})$  can be written explicitly as:

$$\lambda_i(\mu, \mathbf{b}) = \sum_j \mu_j b_{i,j} \quad (10.2)$$

where the subscript  $j$  enumerates the background processes, such that  $b_{i,j}$  is the predicted yield in the control region  $i$  from background process  $j$  and  $\mu_j$  is the normalisation of background  $j$ . There are three normalisation parameters set as free parameters:  $\mu_{WW}$ ,  $\mu_{\text{Top}}$  and  $\mu_{ZV}$ . These parameters correspond to scale factors  $\mathcal{S}$  discussed in Sections 7.1.2, 8.3 and 9.3. The normalisation parameters of other backgrounds are set to unity. The predicted yields in the control regions and the normalisation parameters are collectively called  $\mathbf{b}$  and  $\mu$ , respectively.

The impact of systematic uncertainties is modelled by including more information in the likelihood function. Each source of systematic uncertainty is parametrised by a nuisance parameter  $\theta_k$  and is described by the p.d.f.  $G(\theta_{0,k}|\theta_k, \sigma_{\theta,k})$ . The subscript  $k$  enumerates the sources of systematic uncertainties. In this notation  $\theta_{0,k}$  is the central value of the systematics around which the nuisance parameters  $\theta_k$  may be varied. Each uncertainty is subject to a Gaussian constraint term centered around its central value. The parametrisation of these terms is such that  $\theta_k$  is the nominal value of a given parameter with the  $\pm 1\sigma$  variations denoted by  $\theta_k = \pm 1$ , resulting in Gaussian terms of width  $\sigma_{\theta,k} = 1$ . When dealing with multiple sources of uncertainty, the corresponding nuisance parameters are collectively denoted  $\theta$ .

If the control regions are orthogonal and the systematic uncertainties are uncorrelated, the full likelihood can be constructed as the product of the Poisson distributed event yields from the control regions and the p.d.f. describing all associated nuisance parameters:

$$\mathcal{L}(\mathbf{n}|\mu, \mathbf{b}, \theta) = \prod_{i \in n_{\text{CR}}} \frac{\lambda_i(\mu, \mathbf{b})^{n_i} e^{-\lambda_i(\mu, \mathbf{b})}}{n_i!} \times \prod_{k \in n_{\text{syst}}} G(\theta_{0,k}|\theta_k, \sigma_{\theta,k}) \quad (10.3)$$

where  $\mathbf{n}$  denotes the set of observed event counts  $n_i$  in the control regions,  $n_{\text{CR}}$  is the number of control regions and  $n_{\text{syst}}$  is the number of sources of systematic uncertainties.

The likelihood is then maximised in order to determine the normalisation parameters  $\mu_{WW}$ ,  $\mu_{\text{Top}}$ ,  $\mu_{ZV}$  and the nuisance parameters  $\theta$ . The obtained normalisation parameters are  $\mu_{WW} = 1.14 \pm 0.05$ ,  $\mu_{\text{Top}} = 1.02 \pm 0.04$ ,  $\mu_{ZV} = 1.08 \pm 0.12$ . These values are in agreement with the scale factors  $\mathcal{S}$  calculated with the methods presented in Sections 7.1.2, 8.3 and 9.3, respectively.

## 10.2 Exclusion Methodology

The number of events observed in the signal region is described by a Poisson distribution with the number of expected events as a parameter. Under a background only hypothesis

the expected number of events is given by the total expected number of background events.

Under a signal plus background hypothesis the expected number of events is the sum of the expected number of background events  $B$  plus the expected number of signal events  $S$ .

For a given signal region and for a given SUSY model defined by the chargino ( $m_{\tilde{\chi}_1^\pm}$ ), slepton ( $m_{\tilde{\ell}^\pm}$ ) and neutralino ( $m_{\tilde{\chi}_1^0}$ ) masses a number of signal events  $S$  is expected. The probability to observe up to  $N$  events in the signal region under the signal plus background hypothesis is given by:

$$P(N|S+B) = \sum_{k=0}^N \frac{e^{-(S+B)} (S+B)^k}{k!} \quad (10.4)$$

The idea behind the model exclusion procedure is that if  $P(N|S+B)$  is small then the presence of the tested signal model is unlikely. If it is unlikely enough it is excluded at a given confidence level. For example if  $P(N|S+B) < 5\%$ , the signal is excluded at 95% CL. In practice, the quantity  $\text{CL}_{S+B}$  is calculated:

$$\text{CL}_{S+B} = 1 - P(N|S+B) = 1 - \alpha \quad (10.5)$$

where  $\alpha$  is fixed and set to 5%, i.e.  $\text{CL}_{S+B} = 95\%$ . An upper limit  $S_{\max}$  can be obtained from Eq. 10.5, where  $S_{\max}$  is the highest value of  $S$  for which  $\alpha > 5\%$  or  $1 - \alpha < 95\%$ . If a given SUSY signal model for a given set of masses  $m_{\tilde{\chi}_1^\pm}$ ,  $m_{\tilde{\ell}^\pm}$  and  $m_{\tilde{\chi}_1^0}$  has an expected value  $S$  larger than  $S_{\max}$  then this particular SUSY model is said to be excluded.

Limits on the SUSY cross section  $\sigma$  in a particular SUSY production channel can also be set. The maximum allowed cross section  $\sigma_{\max}$  consistent with data can be defined as:

$$\sigma_{\max} = \frac{S_{\max}}{\varepsilon \cdot \mathcal{L}} \quad (10.6)$$

where  $\varepsilon$  is the efficiency for selecting the SUSY signal with the signal region event selection.

In case of a downward fluctuation of the data, where less events are observed than the expected number of background events, SUSY models could be excluded even in case of absence of experimental sensitivity. To avoid this situation the ATLAS experiment uses the  $\text{CL}_s$  method [104]. In this method the following statistics is used:

$$\text{CL}_S = \frac{\text{CL}_{S+B}}{1 - p_B} \quad (10.7)$$

where  $p_B$  is the  $p$ -value of the background only hypothesis. The limits presented below use this method.

All systematic uncertainties are taken into account in limits calculation. The signal regions SR- $WW$  and SR- $m_{T2}$  are not disjoint, therefore the region with best expected exclusion limit is used at each mass point.

### 10.3 Interpretation and Conclusion

The limits on chargino pair production are set in a simplified model framework where the two important parameters are the mass of the neutralino ( $m_{\tilde{\chi}_1^0}$ ) and the mass of the chargino ( $m_{\tilde{\chi}_1^\pm}$ ). Therefore, the chargino exclusion plots are shown in the  $m_{\tilde{\chi}_1^\pm}, m_{\tilde{\chi}_1^0}$  plane.

The limits on slepton pair production are set in the framework of pMSSM in the model described in Chapter 6. The important parameters are the mass of the neutralino ( $m_{\tilde{\chi}_1^0}$ ) and the mass of the slepton ( $m_{\tilde{\ell}^\pm}$ ). Hence, the exclusion limits are presented in the  $m_{\tilde{\ell}^\pm}, m_{\tilde{\chi}_1^0}$  plane.

The results are presented in Fig. 10.1 - 10.3. In each limit plot, the dashed black line corresponds to the expected limit, while the solid red line represents observed limits. Statistical and systematic uncertainties are included. The yellow band shows the experimental uncertainties on the expected limit. The dashed red lines indicate the impact on the observed limit when the signal cross section is scaled up and down by  $1\sigma$  of theoretical uncertainties.

Figure 10.1 shows the 95% confidence level exclusion region for the direct chargino pair production with intermediate sleptons in the  $m_{\tilde{\chi}_1^\pm}, m_{\tilde{\chi}_1^0}$  plane. The results are obtained using signal regions SR- $m_{T2,90}$ , SR- $m_{T2,120}$  and SR- $m_{T2,150}$ . Chargino masses between  $m_{\tilde{\chi}_1^\pm} = 140$  GeV and  $m_{\tilde{\chi}_1^\pm} = 470$  GeV are excluded for a massless neutralino.

Figure 10.2 (a) shows the 95% confidence level exclusion region for the direct chargino pair production with intermediate  $W$  bosons in the  $m_{\tilde{\chi}_1^\pm}, m_{\tilde{\chi}_1^0}$  plane. Figure 10.2 (b) shows the observed and expected 95% upper limits on the cross section normalised to the model cross section as a function of chargino mass for a massless neutralino. The results are obtained using signal regions SR- $WW_a$ , SR- $WW_b$  and SR- $WW_c$ . Chargino masses between  $m_{\tilde{\chi}_1^\pm} = 100$  GeV and  $m_{\tilde{\chi}_1^\pm} = 180$  GeV are excluded for a massless neutralino.

Figure 10.3 shows 95% confidence level exclusion regions for the direct pair production of left-handed (a), right handed (b) and combined left- and right-handed mass degenerate (c) sleptons in the  $m_{\tilde{\ell}^\pm}, m_{\tilde{\chi}_1^0}$  plane. Signal regions SR- $m_{T2,90}$ , SR- $m_{T2,120}$  and SR- $m_{T2,150}$  are used to obtain the results. For a neutralino mass ( $m_{\tilde{\chi}_1^0} = 0$  GeV) a common value for left- and right- handed slepton mass between  $m_{\tilde{\ell}^\pm} = 90$  GeV and  $m_{\tilde{\ell}^\pm} = 330$  GeV is excluded at 95% CL. The sensitivity decreases when the mass split  $m_{\tilde{\ell}^\pm} - m_{\tilde{\chi}_1^0}$  decreases. It is caused by a lower  $m_{T2}$  kinematic edge, becoming similar to Standard Model background processes. For a neutralino mass  $m_{\tilde{\chi}_1^0} = 100$  GeV slepton mass between  $m_{\tilde{\ell}^\pm} = 160$  GeV and  $m_{\tilde{\ell}^\pm} = 320$  GeV is excluded. The presented analysis significantly improves limits compared to previous results obtained with  $\mathcal{L} = 4.7 \text{ fb}^{-1}$  of proton-proton collision data at  $\sqrt{s} = 7$  TeV recorded by ATLAS [101].

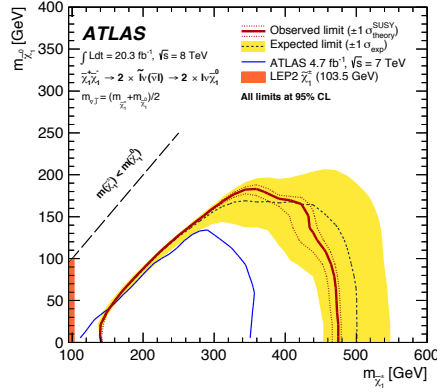
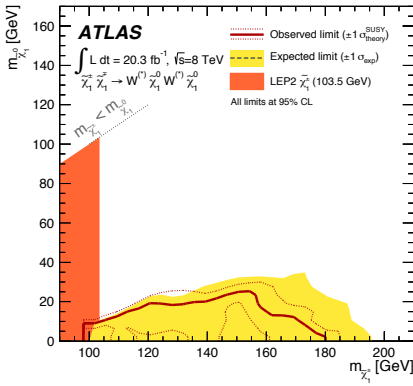
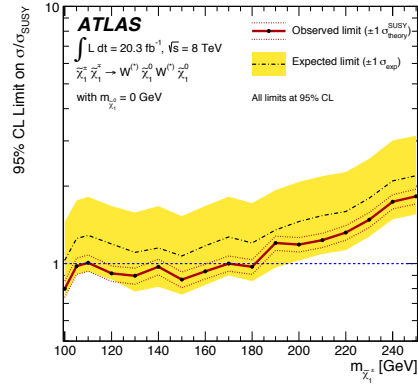


Figure 10.1: 95% CL exclusion limits for direct  $\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp$  pair production with intermediate sleptons in the decay with respect to the chargino mass ( $m_{\tilde{\chi}_1^\pm}$ ) and to the neutralino mass ( $m_{\tilde{\chi}_1^0}$ ) [5].



(a)



(b)

Figure 10.2: 95% CL exclusion limits for direct  $\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp$  pair production with intermediate  $W$  bosons in the decay (a) with respect to the chargino mass ( $m_{\tilde{\chi}_1^\pm}$ ) and to the neutralino mass ( $m_{\tilde{\chi}_1^0}$ ). 95% CL upper limits on the ratio of the cross section over expected cross section (b) as a function of chargino mass ( $m_{\tilde{\chi}_1^\pm}$ ) normalised to the simplified model cross section for a massless neutralino ( $m_{\tilde{\chi}_1^0} = 0$  GeV) [5].



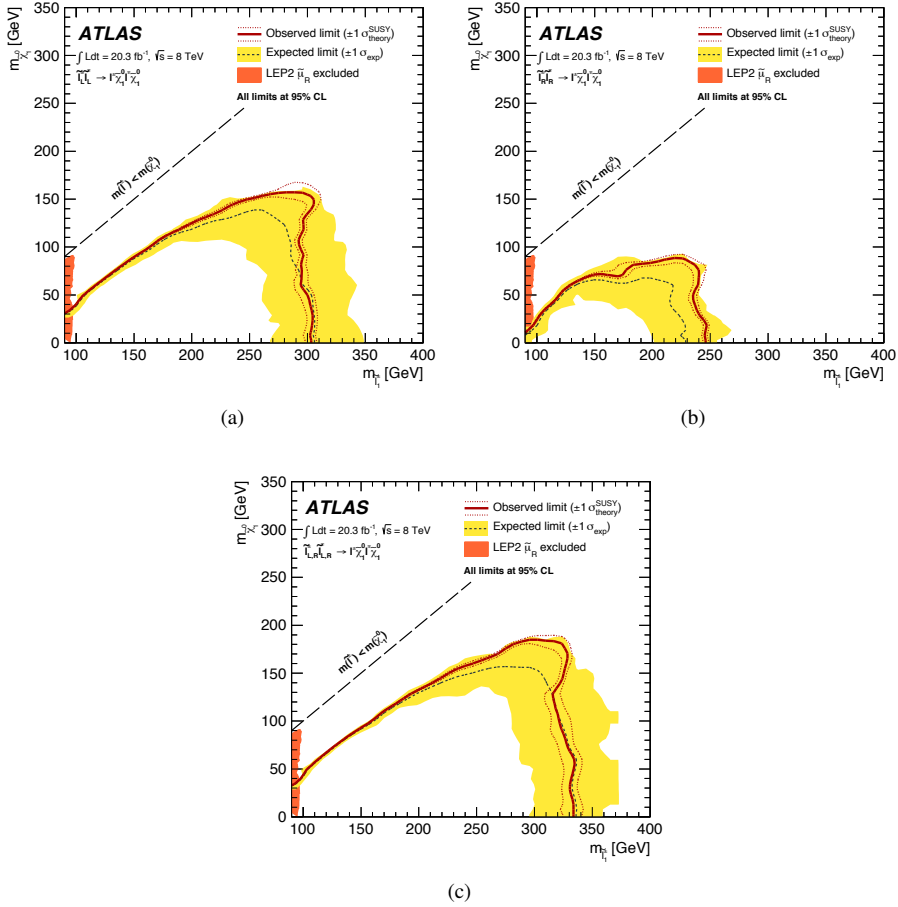


Figure 10.3: 95% CL exclusion limits for direct production of left-handed (a), right-handed (b), combination of left- and right-handed mass degenerate slepton pairs (c) with respect to the slepton mass ( $m_{\tilde{l}_{\pm}}$ ) and to the neutralino mass ( $m_{\tilde{\chi}_1^0}$ ) [5].

## Part IV

# Search for Chargino Pair Production via Vector Boson Fusion



# 11 Motivation and Strategy

This part of the thesis presents a search for same sign chargino pair production via vector boson fusion (VBF) [105, 106]. This analysis is the first in ATLAS to search for SUSY particles production via VBF. Moreover, a possible observation of such process would prove that the exchanged neutralino is a Majorana particle.

## 11.1 Chargino Pair Production via Vector Boson Fusion

In this work the same sign chargino pair production via VBF with intermediate sleptons in the decay is studied. The final state with two same sign leptons, at least two jets and  $E_T^{\text{miss}}$  is considered. In this work only final states containing electrons or muons are considered. Scenarios with small mass splittings between  $\tilde{\chi}_1^\pm$  and  $\tilde{\chi}_1^0$  (so called compressed SUSY spectrum) is investigated. The cross section for the VBF production is significantly lower than the direct production of chargino pairs. Nevertheless, the two additional forward jets characteristic of VBF provide additional handle to discriminate against the background even in the case of compressed spectrum scenario.

The preferred decay channels of the supersymmetric particles depend on the SUSY mass hierarchy. In this model  $\tilde{\chi}_1^\pm$  has to be produced in pairs and the lightest SUSY particle is a stable neutralino  $\tilde{\chi}_1^0$ . A pair of LSPs always end the supersymmetric decay chains and escapes the detector without interaction. Squarks and gluinos are assumed to be very heavy and are decoupled from the phenomenology. We consider sleptons that are lighter than  $\tilde{\chi}_1^\pm$  and  $\tilde{\chi}_2^0$  ( $m_{\tilde{\chi}_1^0} < m_{\tilde{\ell}} < m_{\tilde{\chi}_1^\pm, \tilde{\chi}_2^0}$ ). In this analysis the following  $\tilde{\chi}_1^\pm$  decay channel is considered:

$$\tilde{\chi}_1^\pm \rightarrow \tilde{\ell}^\pm \nu, \ell^\pm \tilde{\nu} \quad (11.1)$$

where  $\ell$  is an electron, muon or tau. Only left handed sleptons are considered in the model. The  $\tilde{\chi}_1^\pm$  decays directly into leptonic final states with 100% branching ratio via an on-shell slepton. The large leptonic branching ratio boosts the sensitivity of the analysis to the chargino VBF signal.

The production of  $\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp$  via VBF is searched for in the following channel:

$$pp \rightarrow \tilde{\chi}_1^\pm \tilde{\chi}_1^\mp qq' \rightarrow \tilde{\ell} \nu_\ell (\tilde{\nu}_\ell \ell) \tilde{\ell}' \nu_{\ell'} (\tilde{\nu}_{\ell'} \ell') jj \rightarrow \ell \nu_\ell \tilde{\chi}_1^0 \ell' \nu_{\ell'} \tilde{\chi}_1^0 jj \quad (11.2)$$

The electric charge is dropped from Eq. 11.2 for simplicity, but the two final state leptons are always of same sign. The neutralinos and neutrinos yield missing transverse energy  $E_T^{\text{miss}}$ . The scattered quarks create two energetic jets in the forward region. The additional final state jets are crucial to extract the rare VBF chargino signal over the large Standard Model background. This process is illustrated in Fig. 11.1.

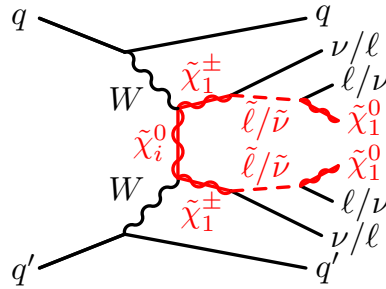


Figure 11.1: Illustration of same sign  $\tilde{\chi}_1^\pm \tilde{\chi}_1^\pm$  pair production via vector boson fusion and subsequent decay with intermediate light charged sleptons and sneutrinos. All three slepton generations are included in the definition of  $\tilde{\ell}/\tilde{\nu}$ .

### Analysis procedure

The search for same sign chargino pair production via vector boson fusion is performed in several steps. First, a signal region sensitive to signal events is developed and optimised using Monte Carlo simulations of all background processes as well as the SUSY signal processes. Experimental data in the signal region is kept blinded until the signal region, control regions and background calculation methods are fully defined and frozen. The optimisation and validation of the signal region is described in Chapter 12.

The Standard Model background in the signal regions is estimated using data and Monte Carlo driven methods. The reliability of the background estimate is probed by the use of validation regions. Estimation of the background containing non-prompt leptons and fake leptons is described in Chapter 13. Estimation of the background originating from production of two vector bosons (denoted diboson background) is presented in Chapter 14.

## 11.2 Chargino VBF Model

The SUSY simplified model is used to generate signal samples of same sign  $\tilde{\chi}_1^\pm \tilde{\chi}_1^\pm$  production via VBF. The model is defined by a set of particles and their modes of production and decay. From these parameters and the coupling constants the production

cross section as a function of particle mass is determined. It is build so that it has the minimal particle content necessary to produce SUSY-like events with the dilepton final state and is parametrised directly in terms of the sparticle masses. The parameters are chosen to be consistent with pMSSM. The results are generic and can be applied to any theories with additional SM particles, which make predictions in these topologies.

The  $\tilde{\chi}_1^\pm$  and  $\tilde{\chi}_1^0$  masses are free parameters which are varied throughout the simplified model parameter space. In the model considered here, the lightest chargino and second lightest neutralino are assumed to be pure wino and mass degenerate, i.e.  $m_{\tilde{\chi}_1^\pm} = m_{\tilde{\chi}_2^0}$ . All SUSY particles other than  $\tilde{\chi}_1^0$ ,  $\tilde{\chi}_2^0$ ,  $\tilde{\chi}_1^\pm$  and  $\tilde{\ell}$  are assumed to be very massive in order to eliminate their contributions. The  $\tilde{\chi}_1^\pm$  is assumed to decay via charged sleptons or sneutrinos with a branching ratio of 50% to each. The slepton branching ratios are set equal between electrons, muons and taus.

In this model the sleptons are light and have masses halfway between  $\tilde{\chi}_1^\pm$  and  $\tilde{\chi}_1^0$ :  $m_{\tilde{\ell}} = 0.5 m_{\tilde{\chi}_1^\pm} + 0.5 m_{\tilde{\chi}_1^0}$ . The  $\tilde{\chi}_1^\pm$  is a pure wino and  $\tilde{\chi}_1^0$  is a pure bino. Pure wino or bino state means that there is no mixing between wino, bino and higgsino states described in Chapter 2. Eight model points are generated by Monte Carlo simulations, four points with  $m_{\tilde{\chi}_1^\pm} = 110$  GeV and four points with  $m_{\tilde{\chi}_1^\pm} = 120$  GeV. For each  $\tilde{\chi}_1^\pm$  mass four small mass splittings ( $m_{\tilde{\chi}_1^\pm} - m_{\tilde{\chi}_1^0}$ ) are considered, i.e. 5, 15, 25 and 35 GeV. In this way a grid in a  $m_{\tilde{\chi}_1^\pm}, m_{\tilde{\chi}_2^0}, m_{\tilde{\chi}_1^0}$  plane is created.

Signal Monte Carlo samples are generated using Madgraph5 [107] using the Leading Order (LO) parton density function CTEQ6L1 [108] and showered in PYTHIA [109]. The detector simulation is performed using ATLFast-II. Figure 11.2 shows the LO signal cross sections calculated with Madgraph5.

## 11.3 Standard Model Backgrounds

A large number of Standard Model processes can give rise to a final state with two same sign leptons, at least two jets and missing transverse energy similar to that of chargino pair production via vector boson fusion. These backgrounds need to be estimated as precisely as possible before a statement on whether the data is compatible with the background only hypothesis or with a background + SUSY signal hypothesis.

In order to develop and validate the analysis strategy and to estimate the detector acceptance and selection efficiency, fully simulated Monte Carlo (MC) event samples of each background process relevant for this analysis are generated. The main Standard Model backgrounds are described in the following sections.

### 11.3.1 Non-Prompt Leptons and Fake Leptons

Although this analysis final state requires two same sign leptons, processes with zero or one lepton can enter the signal region. This type of background is collectively called

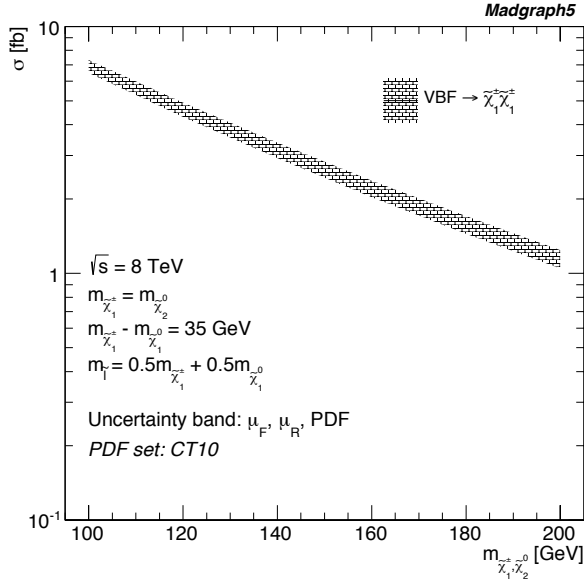


Figure 11.2: Leading Order cross sections for simplified models of same sign  $\tilde{\chi}_1^\pm \tilde{\chi}_1^\pm$  production via vector boson fusion as a function of the common  $\tilde{\chi}_1^\pm$  and  $\tilde{\chi}_2^0$  mass and  $\tilde{\chi}_1^0$  mass at  $\sqrt{s} = 8 \text{ TeV}$  calculated with Madgraph5 [107].

non-prompt lepton and fake lepton background. The physics process leading to this are described in Section 7.2.

This analysis includes low  $p_T$  leptons down to 5 GeV for muons and down to 7 GeV for electrons. For this reason the fake lepton background is the dominant one. Non-prompt leptons and fake lepton backgrounds are difficult to simulate accurately, therefore it is determined from data. All contributions to the fake backgrounds are estimated simultaneously, based on a quantity related to the probability that a lepton should pass a certain lepton definition. In this analysis the so called “fake factor” method is used to estimate the fake background. The procedure is described in Chapter 13.

### 11.3.2 Diboson Backgrounds

Pair production of leptonically decaying  $W$  bosons is the second largest background. There are two classes of processes that lead to the production of same sign  $WW$  pairs. One class involves only electroweak vertices, these are typically vector boson fusion processes. This class is labelled EWK, thus we have  $WW$ -EWK processes. The second

class of processes involve both QCD and electroweak vertices and is referred to as QCD. These are called  $WW$ -QCD processes. Figure 11.3 presents examples of EWK (a) and QCD processes (b). The opposite sign  $W^\pm W^\mp$  production is strongly suppressed by the requirement of a same sign final state used in this analysis. The same sign  $W^\pm W^\pm jj$  production via VBF has the same signature and very similar kinematics as  $\tilde{\chi}_1^\pm \tilde{\chi}_1^\pm$  production via VBF. This background is difficult to isolate in a control region without substantial potential signal and top contamination. As a result the contribution from these processes are estimated from Monte Carlo normalised to NLO cross sections. This is explained in detail in Chapter 14.

The production of  $WZ$  bosons is the third largest background in the presented analysis. The  $WZ$  production can occur via purely electroweak processes and is thus referred to as  $WZ$ -EWK. It can also occur via processes involving QCD vertices, these processes are referred to as  $WZ$ -QCD. The biggest contribution is coming from the  $WZjj$  production via vector boson scattering. This process yields three leptons, two jets and  $E_T^{\text{miss}}$ . If one lepton is not identified, the event has the same signature as the signal. This background is estimated with the same technique as  $WWjj$ . The procedure is described in Chapter 14.

The contribution from  $ZZ$  production is very small and is derived with MC.

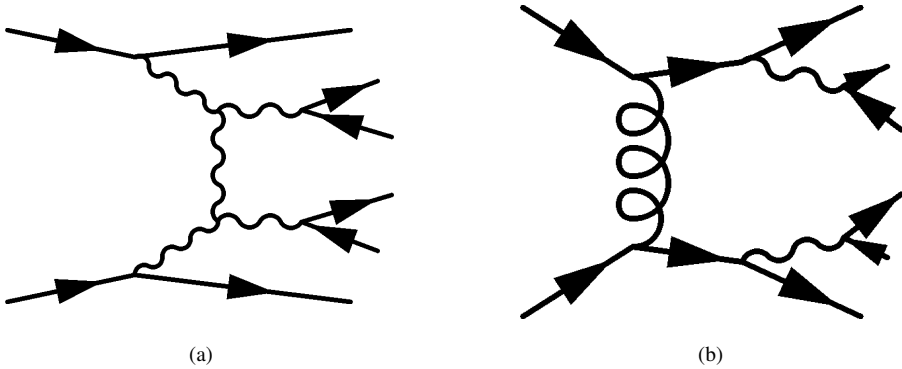


Figure 11.3: Examples of the VV-EWK process (a) and VV-QCD process (b).

### 11.3.3 Charge Flip

This analysis requires two same sign leptons. Events with two opposite sign electrons where one electron has a wrongly measured charge can appear as a same sign event and enter the signal region. This happens when an electron emits a bremsstrahlung photon, which goes through a very asymmetric decay ( $e_{\text{hard}}^\pm \rightarrow e_{\text{soft}}^\pm \gamma_{\text{hard}} \rightarrow e_{\text{soft}}^\pm e_{\text{soft}}^\pm e_{\text{hard}}^\mp$ ). The wrong electron charge is then assigned for the electron. This process is labelled



as charge flip in this thesis. All processes that yield opposite charge lepton pairs can experience the charge flip and must be taken into account.

The simulation does not model well the charge flip, since this process is very sensitive to the detector material description in the simulation. Therefore, a data driven method is used to correct the Monte Carlo prediction. This procedure is presented in Chapter 13.2.

#### 11.3.4 Top

The processes  $t\bar{t}$ ,  $tW$  and single  $t$  production contribute to the fake background. This background is therefore derived using the method described in Section 11.3.1. Top quark production in association with vector boson, i.e.  $t\bar{t}W$ ,  $t\bar{t}Z$ ,  $t\bar{t}\gamma$ ,  $t\bar{t}WW$ ,  $tZ$  are collectively called  $t\bar{t}V$ . This background can also yield two same sign leptons, at least two jets and  $E_T^{\text{miss}}$ . Although this background is irreducible, it is small and is estimated from Monte Carlo simulation.

#### 11.3.5 Higgs

This category includes production of Standard Model Higgs boson as well as Higgs production associated with vector boson ( $HW$  and  $HZ$ ). Several Higgs decays can yield at least two leptons in the final state, e.g.  $H \rightarrow WW$ ,  $H \rightarrow ZZ$ . This contribution to the SM background is small and is estimated from Monte Carlo simulation.

### 11.4 Observables for Signal Selection

Many parameters determine the kinematics of the signal process targeted in the presented work, in particular masses of chargino ( $m_{\tilde{\chi}_1^\pm}$ ), neutralino ( $m_{\tilde{\chi}_1^0}$ ), slepton ( $m_{\tilde{\ell}}$ ). The models used are characterised by two important parameters, the chargino mass and the neutralino mass. These models are labeled  $[m_{\tilde{\chi}_1^\pm}, m_{\tilde{\chi}_1^0}]$ . For instance  $[120,95]$  GeV indicates the model with  $m_{\tilde{\chi}_1^\pm} = 120$  GeV and  $m_{\tilde{\chi}_1^0} = 95$  GeV. A number of variables that aim to capture the kinematics of the events are exploited in order to obtain discrimination between the signal and the Standard Model backgrounds. In this section an overview of the main discriminating variables used in this analysis and an explanation of the type of backgrounds they help to reject are given. Characteristic distributions of some of the discussed quantities at the generator level are shown for  $WW$ -EWK,  $WW$ -QCD and  $\tilde{\chi}_1^\pm \tilde{\chi}_1^\pm$   $[120,95]$  GeV in Fig. 11.4 - 11.5. These distributions are obtained after the following selection:

- Exactly two same charge leptons (electron or muon) with  $p_T > 7$  GeV,  $|\eta| < 2.47$  for electrons and  $p_T > 5$  GeV,  $|\eta| < 2.5$  for muons. Events where any of the selected leptons originate from a  $\tau$  decay are vetoed.
- $m_{\ell\ell} > 4$  GeV

- At last two light jets ( $L20 + F30 \geq 2$ ) defined in Table 8.1
- $m_{jj} > 350$  GeV

In the case of the  $m_{jj}$  distribution in Fig. 11.4 (b), no requirement on  $m_{jj}$  was imposed.

#### Dilepton Invariant Mass ( $m_{\ell\ell}$ )

The analysis described in this part of the thesis targets the compressed SUSY spectrum. In this scenario the mass difference between  $\tilde{\chi}_1^\pm$  and  $\tilde{\chi}_1^0$  is small. Such processes yield soft leptons from the decay of charginos ( $\tilde{\chi}_1^\pm \rightarrow \ell \nu \tilde{\chi}_1^0$ ). This attribute can be used in order to discriminate between signal and background. An upper cut on the dilepton invariant mass ( $m_{\ell\ell}$ ) can be used in this case. The variable  $m_{\ell\ell}$  is defined in Eq. 6.12. This variable is beneficial in discriminating against  $WW$  and top backgrounds. In these processes leptons coming from the  $W$  decays are harder, which leads to larger invariant mass. The  $m_{\ell\ell}$  distribution is shown in Fig. 11.4 (a) for the chargino signal and the main  $WW$  background. It can be seen that the  $m_{\ell\ell}$  for the signal is significantly lower than for the  $WW$  production.

#### Number of Jets and Jet Categories

The analysis presented in this part of the thesis uses the same jet category definitions as the the analysis presented in Part III. Three types of signal jets are distinguished, i.e. central light jets (L20), central  $b$ -jets (B20) and forward jets (F30). Each jets category is defined in Chapter 8.2. The characteristic signature of the VBF production of chargino pair is the presence of two jets in its final state. Therefore, the number and type of jets are important observables. The jets in the signal process come from light quarks while  $b$ -quarks can arise in the background mainly from  $t$ -quark decays. In order to address VBF processes at least two light or forward jets are required ( $L20 + F30 \geq 2$ ). A  $b$ -jet veto is applied to reduce the high-cross section dileptonic  $t\bar{t}$  events.

#### Dijet Invariant Mass ( $m_{jj}$ )

The dijet invariant mass uses the properties of the two highest energy jets in the signal events. The  $m_{jj}$  is defined as follows:

$$m_{jj} = \sqrt{(E_{j1} + E_{j2})^2 - |\mathbf{p}_{j1} + \mathbf{p}_{j2}|^2} \quad (11.3)$$

Similarly to jet transverse momentum, dijet invariant mass reduces backgrounds with jets coming from ISR. The  $m_{jj}$  distribution is shown on Fig. 11.4 (b) and illustrates that  $m_{jj}$  is concentrated below 100 GeV for the chargino signal.

### Jet Transverse Momentum ( $p_T^j$ )

The jets in the vector boson fusion processes have usually large transverse momentum. Therefore transverse momentum of a jet ( $p_T^j$ ) is a natural variable that can be used in order to discriminate between this process and the background. This variable is effective to reduce backgrounds where jets come from initial state radiation (ISR), e.g. production of  $WW$  and  $WZ$ . Such jets have usually lower transverse momentum. The transverse momentum of the leading jet  $p_T^{j1}$  is shown on Fig. 11.4 (c). It shows that the  $p_T$  of the leading jet is generally lower for the chargino signal than for  $WW$  production.

### Missing Transverse Energy ( $E_T^{\text{miss}}$ )

The topology of the signal events targeted in this analysis contains four weakly interacting particles that escape the detector without interacting, i.e. two neutralinos ( $\tilde{\chi}_1^0$ ) and two neutrinos ( $\nu$ ). Therefore, large missing transverse energy ( $E_T^{\text{miss}}$ ) is one of the fundamental requirements for selecting the signal events. The  $E_T^{\text{miss}}$  distribution is shown on Fig. 11.4 (d). It shows that the chargino signal has significantly more  $E_T^{\text{miss}}$  than the  $WW$  background.

### $|\Delta\eta_{jj}|$

One of the characteristic signatures of vector boson fusion process is the presence of two energetic jets in the opposite hemispheres of the detector in the forward region. Thus the  $|\Delta\eta_{jj}|$  between the jets takes large values. The additional requirement of  $\eta_{j1} \cdot \eta_{j2} < 0$  can be applied in order to ensure the presence of jets in opposite hemispheres of the detector. This selection greatly reduces the QCD  $WW$  production. The  $\Delta\eta_{jj}$  distribution as well as the 2D distributions of the  $\eta$  of the leading jet versus the  $\eta$  of the subleading jet are presented on Fig. 11.5. It clearly shows that the jets are particularly forward for  $WW$ -EWK and chargino production for which it is most pronounced.

### Other Variables

The other variables useful to obtain discrimination between the signal and the Standard Model backgrounds are listed below:

- Transverse momentum of the lepton ( $p_T^\ell$ )
- Transverse momentum of the dilepton system ( $p_T^{\ell\ell}$ )
- Invariant mass of the dilepton-dijet system ( $m_{\ell\ell jj}$ )
- Transverse momentum of the dijet system ( $p_T^{jj}$ )
- Angle  $\phi$  between the two most energetic jets ( $|\Delta\phi_{jj}|$ )

- Centrality defined as:

$$C = \min(\min(\eta_{\ell 1}, \eta_{\ell 2}) - \min(\eta_{j1}, \eta_{j2}), \max(\eta_{j1}, \eta_{j2}) - \max(\eta_{\ell 1}, \eta_{\ell 2})) \quad (11.4)$$

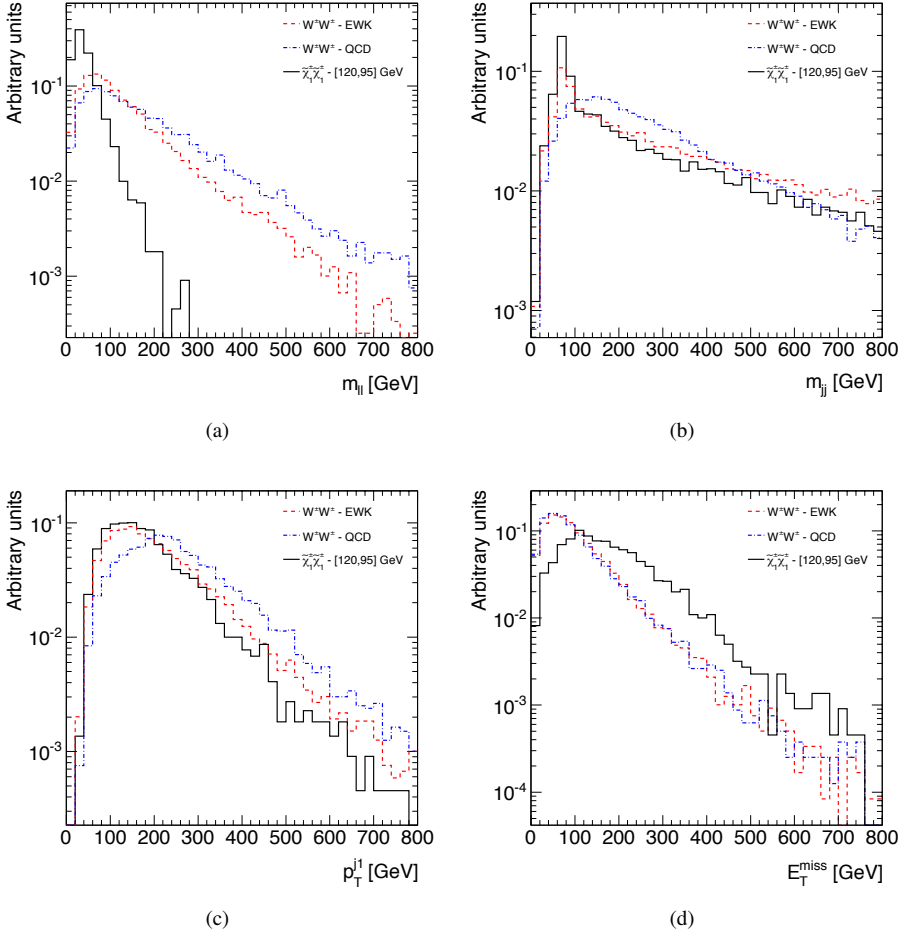


Figure 11.4: The generator level distributions of the invariant mass  $m_{\ell\ell}$  of the dilepton system (a), the invariant mass  $m_{jj}$  of the dijet system (b), the transverse momentum  $p_T$  of the leading jet (c) and the missing transverse momentum  $E_T^{\text{miss}}$  (d). The  $\tilde{\chi}_1^\pm \tilde{\chi}_1^\pm$  [120,95] GeV,  $WW$ -EWK and  $WW$ -QCD processes are compared.

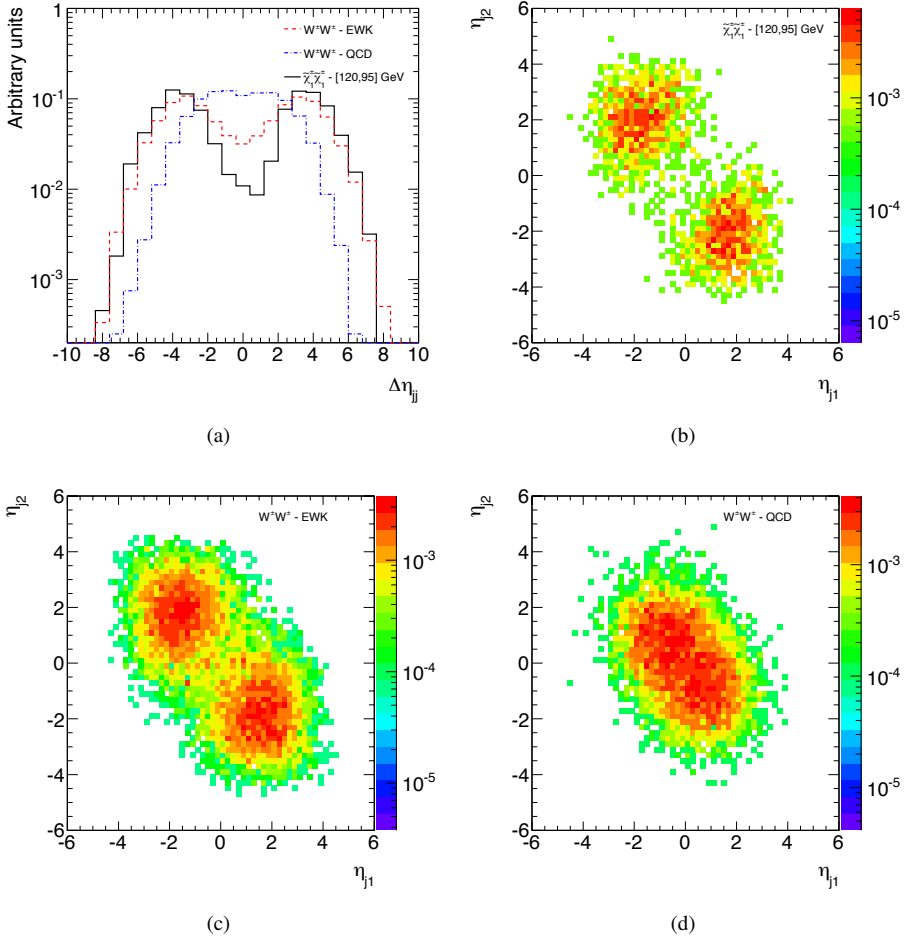


Figure 11.5: The generator level distribution of  $\Delta\eta$  between the two leading jets (a). The generator level 2D distributions of the  $\eta$  of the subleading jet versus the  $\eta$  of the leading jet for  $\tilde{\chi}_1^\pm \tilde{\chi}_1^\pm$  [120,95] GeV (b),  $WW$ -EWK (c) and  $WW$ -QCD (d).

## 11.5 ATLAS Dataset and Trigger

The search for same sign  $\tilde{\chi}_1^\pm \tilde{\chi}_1^\pm$  production via vector boson fusion is performed with the entire dataset recorded by the ATLAS detector in 2012 at a centre mass energy  $\sqrt{s} = 8$  TeV. After applying the requirement that all ATLAS sub-detectors are working well the luminosity is  $\mathcal{L} = 20.3 \text{ fb}^{-1}$  [79].

Due to the technical limitation on event readout, bandwidth, recording and storage capacity, only the most interesting proton-proton collisions can be recorded. Since the analysis is targeting the compressed SUSY spectra the applied cuts on leptons have to be as low as possible. It turns out that the ATLAS lepton trigger thresholds are too high to be used in this analysis. Instead a missing transverse energy trigger is used. The dataset used in the analysis is collected in the JetTauEtmiss stream. Events have to pass the trigger requiring  $E_T^{\text{miss}} > 80$  GeV. This is the lowest threshold unprescaled  $E_T^{\text{miss}}$  trigger used in ATLAS in 2012.

## 11.6 Conclusion

A set of discriminating variables that can be used to isolate the chargino VBF signal has been introduced. In the following Chapter 12 the exact procedure to determine the exact signal region definition is presented. The estimation of the Standard Model backgrounds is presented in Chapters 13 - 14. Finally, the results and conclusions are shown in Chapter 15.



## 12 Signal and Validation Regions

It is important to use the information characterising the targeted signal when designing the search. Kinematic variables are useful tools to pick signal processes. The signal region is constructed by a set of cuts based on the expected event kinematics of the targeted model. This chapter presents the steps of the optimisation of the signal region sensitive to the signal models described in Chapter 11. This signal region is denoted as SR-VBF.

### 12.1 Signal Candidate Preselection

Exactly two isolated same sign leptons (electrons and muons) are considered in this analysis:  $e^\pm e^\pm$ ,  $e^\pm \mu^\pm$  and  $\mu^\pm \mu^\pm$ . Moreover, the presented analysis is probing the compressed SUSY spectrum. In order to be sensitive to this scenario low transverse momentum cuts are applied:  $p_T^e > 7$  GeV and  $p_T^\mu > 5$  GeV.

A certain amount of missing transverse energy corresponding to the elusive LSP is expected in signal events. Thus it is beneficial to use the  $E_T^{\text{miss}}$  variable in order to select a signal and reduce the Standard Model background. The missing transverse energy trigger requiring  $E_T^{\text{miss}} > 80$  GeV is utilised. In order to ensure that the trigger is fully efficient in the signal region an  $E_T^{\text{miss}} > 120$  GeV requirement is applied.

The charginos are produced via VBF where two high energetic jets are present. Therefore, at least two signal central light jets or forward jets are required ( $L20 + F30 \geq 2$ ). In order to suppress the top background a veto on  $b$ -jets is imposed ( $B20 = 0$ ).

The preselection defined above is referred to as the VBF preselection.

### 12.2 Method for Signal Region Optimisation

The optimisation of the signal region is performed using pure Monte Carlo estimates for the background counts without any data driven corrections. Also the fake lepton and charge flip contribution is estimated with MC in the optimisation process. The simplified model grid described in Section 11.2 is utilised. While maximising signal acceptance is important, the expected background contribution to the signal regions is of critical consideration. Therefore, a balance must be found between keeping as many potential signal events as possible and rejecting the far larger background. The



signal region optimisation is a complex process. It requires many iterations to derive the optimal selection criteria. Since the variables are correlated, a cut on one quantity changes the optimal selection on the other ones.

The optimisation uses a flat (kinematic independent) 20% relative systematic uncertainty on the total background. This assumption is in agreement with the systematic uncertainty calculated a posteriori and shown in Tab. 15.5. The signal region remains “blinded” until the predicted background is known with confidence and validated in validation regions. In this way the background estimation remains unbiased by the level of agreement between the expected background and data in the signal region.

### 12.2.1 Figure of Merit for Sensitivity

The signal region selection is optimised using the  $p$ -value of a background only observation under a signal plus background hypothesis as a measure of the signal significance. The expected number of background events is denoted as  $b$  and the quadratic sum of the MC statistical error and its systematic error is  $\sigma_b$ . The expected number of signal events is denoted as  $s$ . Under the signal plus background hypothesis and assuming no uncertainty on signal nor background, the number of events  $N$  observed in the signal region is expected to follow a Poisson distribution with mean value  $s + b$ . This distribution is denoted as  $P(N|s + b)$ . Nevertheless, the expected number of background events has an uncertainty  $\sigma_b$  that has to be taken into account. In order to include the uncertainty  $\sigma_b$ , the Poisson distribution  $P(N|s + b)$  is convoluted with a Gaussian distribution with mean value  $b$  and standard deviation  $\sigma_b$ . This distribution is denoted  $G(B|b, \sigma_b)$  and it weights each value  $B$  of the expected number of background events. After the convolution, a new probability density function is obtained. This distribution is denoted as  $F(N|s + b, \sigma_b)$  and is given by the formula:

$$F(N|s + b, \sigma_b) = \frac{\int_0^\infty P(N|s + B)G(B|b, \sigma_b)dB}{\int_0^\infty G(B|b, \sigma_b)dB} \quad (12.1)$$

The probability that the observed number of events is less or equal than  $b$ , under the signal plus background hypothesis is called  $p$  and can be obtained by summing the probability density function from zero to  $b$ . Thus, the value of  $p$  is given by the formula:

$$p = \sum_{N=0}^b \frac{\int_0^\infty P(N|s + B)G(B|b, \sigma_b)dB}{\int_0^\infty G(B|b, \sigma_b)dB} \quad (12.2)$$

Higher sensitivity is indicated by lower values of  $p$ . If  $p < 0.05$ , it means that under the signal plus background hypothesis the probability to observe  $b$  or less events is less than 5%. In other words, if there is no excess over SM background expectation in the observed number of events, the signal plus background hypothesis is excluded at 95% confidence level (CL). Then, the investigated signal model could be excluded at 95%

CL. In order to estimate the error on the value of  $p$ ,  $b$  is varied up and down by its error ( $\sigma_b$ ) and the recalculated  $p$  is compared with the nominal value of  $p$ . In this way the variation of background expectation has influence on the uncertainty of  $p$ -value. At the level of signal region optimisation a flat 20% relative systematic uncertainty on the total background is assumed. The  $p$ -value is calculated using R00FIT package with the BinomialExpP function [110].

### 12.2.2 Signal Region Cut Optimisation

The final selection is optimised to minimise  $p$ . Additionally, at least 3.5 signal events for a grid point showing the highest sensitivity is required in order to ensure sufficient signal statistics in case of observation of a chargino VBF signal. Since the cross sections of the targeted SUSY process is very low, a tight selection has to be applied in order to suppress the Standard Model backgrounds. Since the variables are correlated, it is not sufficient to optimise a selection on single quantity at a time. Instead, an algorithm that scans variables simultaneously thus investigating all possible combinations of the cuts is used. The procedure is repeated until the optimal cut values for all variables are found. The list of variables [106] investigated in the optimisation of the signal region is presented in Tab 12.1. For each variable the interval and step of the scan is also given. Three combined channels ( $e^\pm e^\pm$ ,  $\mu^\pm \mu^\pm$ ,  $e^\pm \mu^\pm$ ) are used in the optimisation. Only variables showing significant sensitivity to the signal are utilised in the signal region. The signal region defined in this way is called SR-VBF and is used for all signal points.

Each selection requirement of the signal region SR-VBF is discussed and motivated in this section. Also a distribution of each variable used in the signal region is presented. These distributions are obtained in the VBF preselection region (panel (a) of Figs. 12.1 - 12.5). The exception is the distributions of ratio variables. Those distributions are obtained in the region where all SR-VBF (summarised in Tab. 12.2) selections are applied but not the ratio requirements themselves (panel (a) of Figs. 12.6 - 12.8).

In order to validate each cut value, the sensitivity to the signal models is studied. After all signal region selections are applied, the cut on the studied quantity is removed and the sensitivity for different cut values on this variable is studied. The sensitivity is illustrated by the value of  $p$  as a function of the cut value (panel (b) of Figs. 12.1 - 12.8).

#### Kinematics of leptons

One of the good discriminants between signal and background processes is the transverse mass of the dilepton system ( $m_{\ell\ell}$ ). The signal region SR-VBF is optimised to be sensitive to the compressed SUSY spectra models. In the investigated signal models  $\tilde{\chi}_1^\pm$  decays via a slepton into three particles (lepton, neutrino and neutralino), where the slepton has a mass halfway between  $\tilde{\chi}_1^\pm$  and  $\tilde{\chi}_1^0$ . This leads to a low transverse mass of the leptons in the final state. It turns out that the invariant mass of the dilepton system peaks at relatively low values. Figure 12.1 (a) shows that for mass  $m_{\tilde{\chi}_1^\pm} - m_{\tilde{\chi}_1^0} = 25$  GeV,

| Variable                           | Interval      | Step   |
|------------------------------------|---------------|--------|
| $E_T^{\text{miss}}$                | 120 - 200 GeV | 5 GeV  |
| $p_T^{\ell 1}$                     | 0 - 100 GeV   | 5 GeV  |
| $p_T^{\ell 2}$                     | 0 - 100 GeV   | 5 GeV  |
| $m_{T2}$                           | 0 - 100 GeV   | 5 GeV  |
| $m_{\ell\ell}$                     | 0 - 200 GeV   | 5 GeV  |
| $p_T^{j1}$                         | 0 - 200 GeV   | 5 GeV  |
| $p_T^{j2}$                         | 0 - 200 GeV   | 5 GeV  |
| $p_T^{jj}$                         | 0 - 1000 GeV  | 50 GeV |
| $m_{jj}$                           | 0 - 1000 GeV  | 50 GeV |
| $m_{\ell\ell jj}$                  | 0 - 1000 GeV  | 50 GeV |
| $ \Delta\eta_{jj} $                | 0.0 - 4.5     | 0.1    |
| $ \Delta\phi_{jj} $                | 0.0 - 3.0     | 0.1    |
| centrality                         | -2.0 - 2.0    | 0.1    |
| $p_T^{j1}/E_T^{\text{miss}}$       | 0.0 - 3.0     | 0.1    |
| $p_T^{j2}/E_T^{\text{miss}}$       | 0.0 - 3.0     | 0.1    |
| $p_T^{jj}/E_T^{\text{miss}}$       | 0.0 - 3.0     | 0.1    |
| $p_T^{\ell 1}/E_T^{\text{miss}}$   | 0.00 - 1.00   | 0.05   |
| $p_T^{\ell 2}/E_T^{\text{miss}}$   | 0.00 - 1.00   | 0.05   |
| $p_T^{\ell\ell}/E_T^{\text{miss}}$ | 0.00 - 1.00   | 0.05   |
| $p_T^{\ell 1}/p_T^{j1}$            | 0.00 - 1.00   | 0.05   |
| $p_T^{\ell\ell}/p_T^{jj}$          | 0.00 - 1.00   | 0.05   |

Table 12.1: List of variables investigated in the optimisation of signal region SR-VBF. For each variable the interval and step of the scan is given.

the  $m_{\ell\ell}$  peaks below 50 GeV.

In the diboson background, leptons come from the leptonic decays of the gauge bosons,  $WW \rightarrow \ell\nu$ ,  $WZ \rightarrow \ell\nu\ell\ell$ ,  $ZZ \rightarrow \ell\nu\nu$  ( $\ell\ell\ell\ell$ ). In these scenarios the invariant mass of the boson is shared by two particles (not into three as in the signal processes). This causes a larger tail in the  $m_{\ell\ell}$  distribution as shown in Fig 12.1 (a). Figure 12.1 (b) shows the  $p$ -value for different cuts on  $m_{\ell\ell}$ . The  $m_{\ell\ell} < 100$  GeV requirement is imposed in the signal region SR-VBF in order to suppress diboson background.

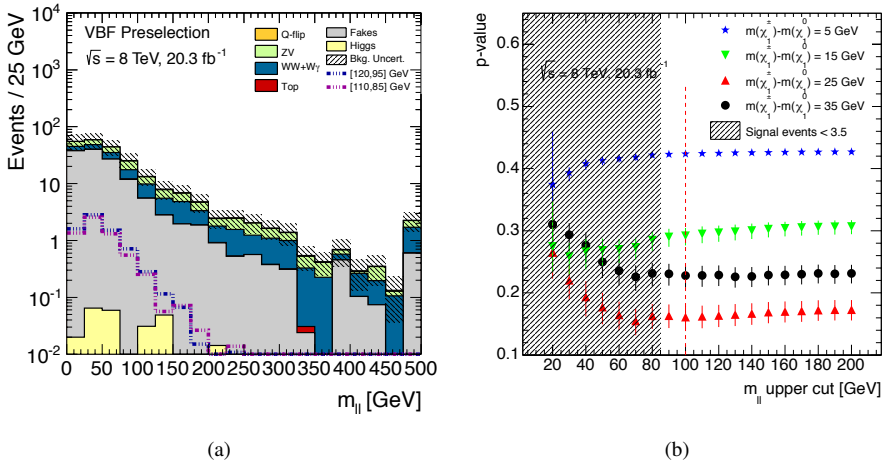


Figure 12.1: Left: distribution of invariant mass of the dilepton system in the VBF preselection region. The uncertainty band includes statistical and all systematic errors (a). Right: sensitivity to different signal points, measured with the  $p$ -value after different  $m_{\ell\ell}$  cuts. After all signal region selection requirements are applied, the cut on  $m_{\ell\ell}$  is removed and the sensitivity for different cut values on this variable is studied. A lower  $p$ -value means higher sensitivity. The error on the  $p$ -value is determined by varying the background estimate by its total uncertainty. Dashed area indicates region with too small signal statistics. The vertical red dashed line indicate the cut applied in the SR-VBF (b).

Another quantity utilising the kinematics of leptons in models with compressed spectra is  $m_{T2}$ . The  $m_{T2}$  is introduced in Section 6.3.1. This variable helps to remove a large fraction of the  $WW$  and remaining Top backgrounds that survive the  $b$ -jet veto. These backgrounds with  $W$  boson decaying leptonically have a kinematic edge at the  $W$  mass. On the other hand the signal model with compressed scenario has the kinematic edge at much lower values. This is illustrated on Fig. 12.2 (a). Figure 12.2 (b) shows the sensitivity for different  $m_{T2}$  requirements. The  $m_{T2} < 40$  GeV cut is applied in the signal region SR-VBF.

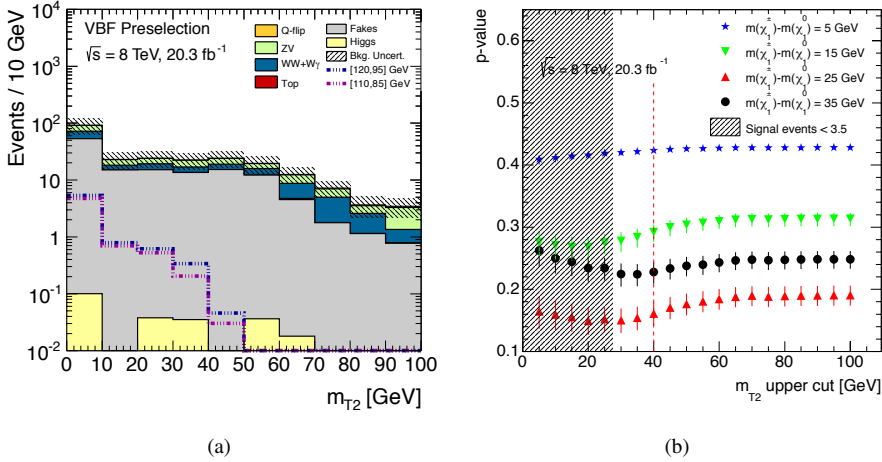


Figure 12.2: Left: distribution of transverse mass in the VBF preselection region. The uncertainty band includes statistical and all systematic errors (a). Right: sensitivity to different signal points, measured with the  $p$ -value after different  $m_{T2}$  cuts. After all signal region selection requirements are applied, the cut on  $m_{T2}$  is removed and the sensitivity for different cut values on this variable is studied. A lower  $p$ -value means higher sensitivity. The error on the  $p$ -value is determined by varying the background estimate by its total uncertainty. Dashed area indicates region with too small signal statistics. The vertical red dashed line indicate the cut applied in the SR-VBF (b).

### Kinematics of jets

In the signal events charginos are produced via Vector Boson Fusion. The VBF process is characterised by high energetic jets in the forward region coming from scattered initial quarks. These jets are characterised by a large difference in pseudorapidity ( $|\Delta\eta_{jj}|$ ) and appear in opposite hemispheres. These two additional jets in the event provide means to probe into the compress spectra SUSY scenarios. Therefore, variables utilising kinematics of jets are very helpful to separate sought signal from background events with jets coming from ISR.

The first variable based on kinematics of jets is the transverse momentum of the leading jet ( $p_T^{j1}$ ). Figure 12.3 (a) shows the  $p_T^{j1}$  for signal and backgrounds. It is shown that jets in signal events are harder than in background events. Figure 12.3 (b) shows the  $p$ -value for different cuts on  $p_T^{j1}$ . The  $p_T^{j1} > 95$  GeV requirement is imposed in the signal region SR-VBF. This cut suppresses diboson background.

Another jet kinematic variable used in the signal region is  $|\Delta\eta_{jj}|$  between the leading and subleading jet. The  $\Delta\eta_{jj}$  distribution is presented in Fig. 12.4 (a). It shows that

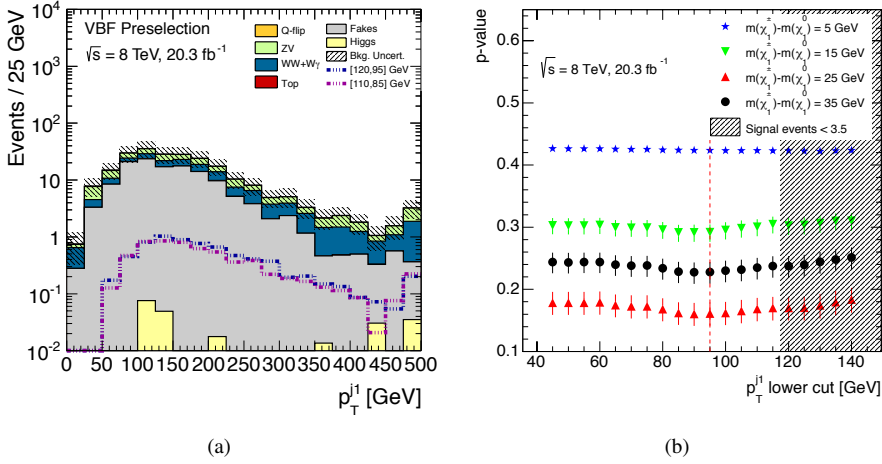


Figure 12.3: Left: distribution of transverse momentum of leading jet in the VBF pre-selection region. The uncertainty band includes statistical and all systematic errors (a). Right: sensitivity to different signal points, measured with the  $p$ -value after different  $p_T^{j1}$  cuts. After all signal region selection requirements are applied, the cut on  $p_T^{j1}$  is removed and the sensitivity for different cut values on this variable is studied. A lower  $p$ -value means higher sensitivity. The error on the  $p$ -value is determined by varying the background estimate by its total uncertainty. Dashed area indicates region with too small signal statistics. The vertical red dashed line indicate the cut applied in the SR-VBF (b).

$|\Delta\eta_{jj}|$  for ISR jets present in the background events is usually small. Whereas jets from VBF process can have large  $|\Delta\eta_{jj}|$ . Figure 12.4 (b) shows the sensitivity for different  $|\Delta\eta_{jj}|$  requirements. The  $|\Delta\eta_{jj}| > 1.6$  cut is applied in the signal region SR-VBF. In addition the jets are required to be in opposite sides of the detector ( $\eta_{j1} \cdot \eta_{j2} < 0$ ). These cuts greatly reduce the background rate, in particular Higgs and diboson events.

The last variable utilising jet kinematics is the invariant mass of the dijet system ( $m_{jj}$ ). This variable is presented in Fig. 12.5 (a). In the signal process  $m_{jj}$  can take much higher values than in the backgrounds. The  $p$ -values for different cuts on  $m_{jj}$  are presented on Fig. 12.5 (b). A hard  $m_{jj} > 350$  GeV cut is applied in the signal region SR-VBF. This requirement suppresses remaining  $WW$  events.

### Ratio variables

In order to suppress the remaining backgrounds, so called ratio variables are used. The distributions of ratio variables are presented after applying all SR-VBF selections described earlier in this section except that the selection on the ratio variables are not

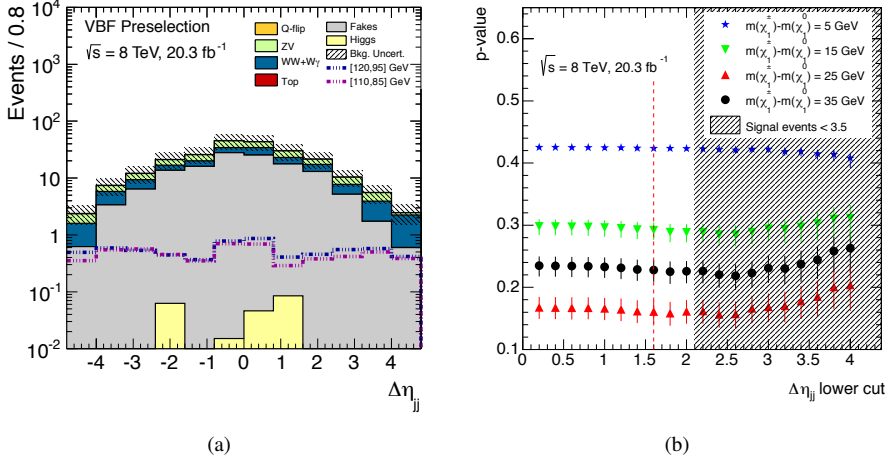


Figure 12.4: Left: distribution of  $\Delta\eta$  between leading and subleading jet in the VBF preselection region. The uncertainty band includes statistical and all systematic errors (a). Right: sensitivity to different signal points, measured with the  $p$ -value after different  $\Delta\eta_{jj}$  cuts. After all signal region selection requirements are applied, the cut on  $\Delta\eta_{jj}$  is removed and the sensitivity for different cut values on this variable is studied. A lower  $p$ -value means higher sensitivity. The error on the  $p$ -value is determined by varying the background estimate by its total uncertainty. Dashed area indicates region with too small signal statistics. The vertical red dashed line indicate the cut applied in SR-VBF (b).

applied here. As discussed earlier, the signal events contain soft leptons. On the other hand, signal is characterised by large missing transverse energy due to neutrinos and neutralinos in final state. Therefore, the ratio  $p_T^{\ell\ell}/E_T^{\text{miss}}$  takes distinctly lower values in signal events with respect to the backgrounds. It is shown in Fig. 12.6 (a). The sensitivity as a function of  $p_T^{\ell\ell}/E_T^{\text{miss}}$  is presented in Fig. 12.6 (b). A  $p_T^{\ell\ell}/E_T^{\text{miss}} < 0.4$  cut is chosen for the signal region SR-VBF.

The ratio  $p_T^{j1}/E_T^{\text{miss}}$  can help to improve the sensitivity due to large missing transverse energy in the signal. This quantity is presented on Fig. 12.7 (a). Figure. 12.7 (b) shows the value of  $p$  corresponding to different  $p_T^{j1}/E_T^{\text{miss}}$  requirements. It is chosen to require  $p_T^{j1}/E_T^{\text{miss}} < 1.9$  in the signal region SR-VBF.

The third ratio variable applied in the signal region is  $p_T^{\ell\ell}/p_T^{jj}$ . It utilises the signal property of soft leptons and hard jets. The distribution of  $p_T^{\ell\ell}/p_T^{jj}$  is presented in Fig. 12.8 (a). Figure. 12.8 (b) presents the sensitivity for different cuts on  $p_T^{\ell\ell}/p_T^{jj}$ . The  $p_T^{\ell\ell}/p_T^{jj} < 0.35$  cut is applied in the signal region SR-VBF. The requirements imposed

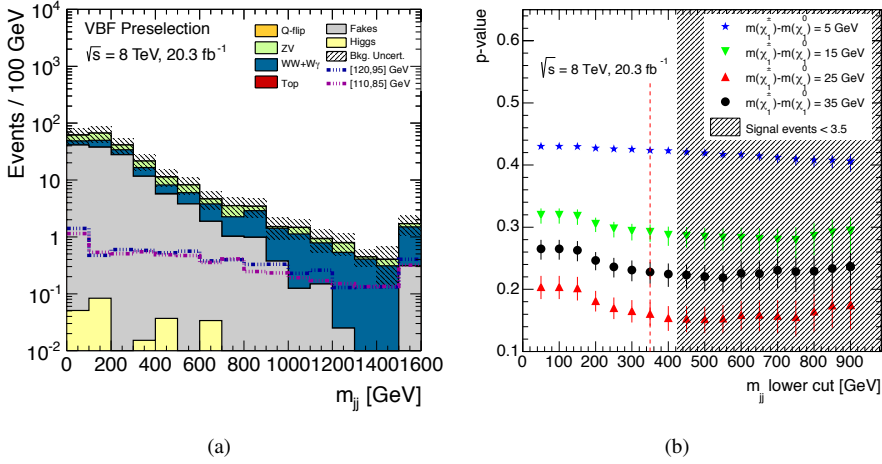


Figure 12.5: Left: distribution of invariant mass of the dijet system in the VBF preselection region. The uncertainty band includes statistical and all systematic errors (a). Right: sensitivity to different signal points, measured with the  $p$ -value after different  $m_{jj}$  cuts. After all signal region selection requirements are applied, the cut on  $m_{jj}$  is removed and the sensitivity for different cut values on this variable is studied. A lower  $p$ -value means higher sensitivity. The error on the  $p$ -value is determined by varying the background estimate by its total uncertainty. Dashed area indicates region with too small signal statistics. The vertical red dashed line indicate the cut applied in the SR-VBF (b).

on the presented ratio variables help to further reduce the remaining Top and diboson backgrounds.



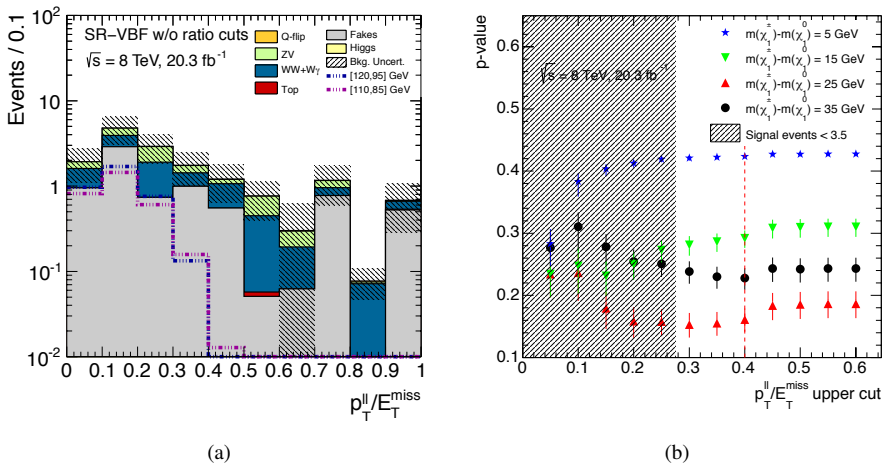


Figure 12.6: Left: distribution of  $p_T^{\ell\ell}/E_T^{\text{miss}}$  after all SR-VBF requirements (summarised in Tab. 12.2) except the ratio cuts. The uncertainty band includes statistical and all systematic errors (a). Right: sensitivity to different signal points, measured with the  $p$ -value after different  $p_T^{\ell\ell}/E_T^{\text{miss}}$  cuts. After all signal region selection requirements are applied, the cut on  $p_T^{\ell\ell}/E_T^{\text{miss}}$  is removed and the sensitivity for different cut values on this variable is studied. A lower  $p$ -value means higher sensitivity. The error on the  $p$ -value is determined by varying the background estimate by its total uncertainty. Dashed area indicates region with too small signal statistics. The vertical red dashed line indicate the cut applied in the SR-VBF (b).

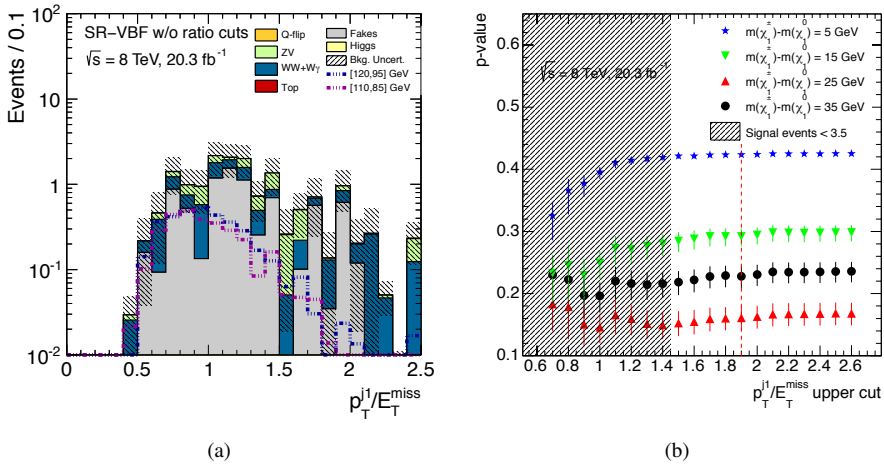


Figure 12.7: Left: distribution of  $p_T^{j1}/E_T^{\text{miss}}$  after all SR-VBF requirements (summarised in Tab. 12.2) except the ratio cuts. The uncertainty band includes statistical and all systematic errors (a). Right: sensitivity to different signal points, measured with the  $p$ -value after different  $p_T^{j1}/E_T^{\text{miss}}$  cuts. After all signal region selection requirements are applied, the cut on  $p_T^{j1}/E_T^{\text{miss}}$  is removed and the sensitivity for different cut values on this variable is studied. A lower  $p$ -value means higher sensitivity. The error on the  $p$ -value is determined by varying the background estimate by its total uncertainty. Dashed area indicates region with too small signal statistics. The vertical red dashed line indicate the cut applied in the SR-VBF (b).

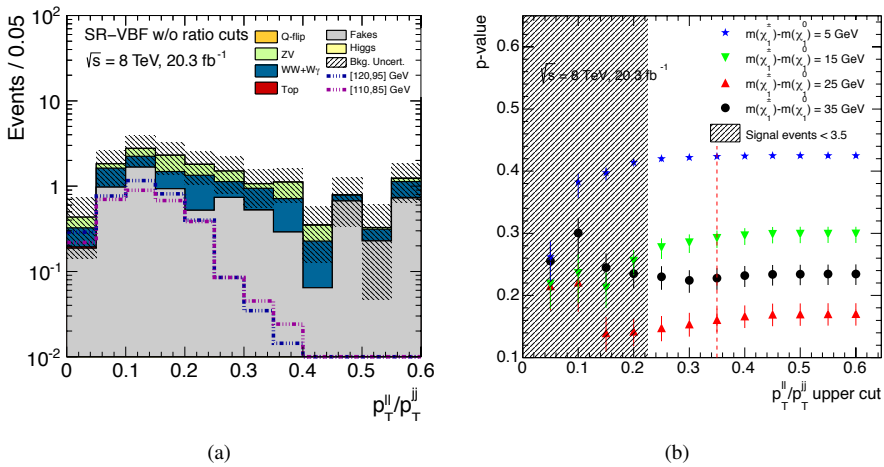


Figure 12.8: Left: distribution of  $p_T^{\ell\ell}/p_T^{jj}$  after all SR-VBF requirements (summarised in Tab. 12.2) except the ratio cuts. The uncertainty band includes statistical and all systematic errors (a). Right: sensitivity to different signal points, measured with the  $p$ -value after different  $p_T^{\ell\ell}/p_T^{jj}$  cuts. After all signal region selection requirements are applied, the cut on  $p_T^{\ell\ell}/p_T^{jj}$  is removed and the sensitivity for different cut values on this variable is studied. A lower  $p$ -value means higher sensitivity. The error on the  $p$ -value is determined by varying the background estimate by its total uncertainty. Dashed area indicates region with too small signal statistics. The vertical red dashed line indicate the cut applied in the SR-VBF (b).

## 12.3 Results of the Signal Region Optimisation

The optimised signal region SR-VBF selection is summarised in Tab. 12.2. Figure 12.9 shows the expected upper limit on the ratio of the cross section over expected cross section for same sign  $\tilde{\chi}_1^\pm \tilde{\chi}_1^\pm$  via Vector Boson Fusion with intermediate sleptons as a function of mass gap ( $m_{\tilde{\chi}_1^\pm} - m_{\tilde{\chi}_1^0}$ ). The signal point with highest sensitivity correspond to the mass difference  $m_{\tilde{\chi}_1^\pm} - m_{\tilde{\chi}_1^0} = 25$  GeV. For this point the expected excluded cross section is larger than the model cross section by a factor 1.8. A 20% flat systematic error on the expected background events is assumed. At later stages of the analysis the systematic error in the signal is estimated and this number is used in the final calculation of actual limits.

Figure 12.10 shows the acceptance (a), efficiency (b) and acceptance times efficiency (c) for the signal. The acceptance is defined as the fraction of signal events that truly fulfil the signal region requirements. The truth Monte Carlo information is used to calculate the acceptance. Then this is convoluted with the reconstruction efficiency for such events. The efficiency is calculated as the fraction of reconstructed signal events that survive signal region selection over the number of events that truly fulfil the signal region requirements. It represents the efficiency of the reconstruction of the physics objects used in the analysis. Acceptance times efficiency is the product of these, representing a measure of the fraction of signal events caught by signal region selection. It is shown that for the point with the highest sensitivity the acceptance is 9.18%, the efficiency is 43.10% and the acceptance times efficiency is 3.96%. It means that 3.96% of the signal events are selected by the signal region SR-VBF for the model with the highest sensitivity.

| SR-VBF                               |                    |
|--------------------------------------|--------------------|
| SS                                   | ✓                  |
| Lepton flavour                       | $ee, \mu\mu, e\mu$ |
| $p_T^e$ ( $p_T^\mu$ )                | $> 7$ (5) GeV      |
| $E_T^{\text{miss}}$                  | $> 120$ GeV        |
| signal light + forward jets          | $\geq 2$           |
| signal $b$ -jets                     | $= 0$              |
| $m_{\ell\ell}$                       | $< 100$ GeV        |
| $m_{T2}$                             | $< 40$ GeV         |
| $p_T^{j1}$                           | $> 95$ GeV         |
| $ \Delta\eta_{jj} $                  | $> 1.6$            |
| $\eta_{j1} \cdot \eta_{j2}$          | $< 0$              |
| $m_{jj}$                             | $> 350$ GeV        |
| $p_T^{\ell\ell} / E_T^{\text{miss}}$ | $< 0.4$            |
| $p_T^{j1} / E_T^{\text{miss}}$       | $< 1.9$            |
| $p_T^{\ell\ell} / p_T^{jj}$          | $< 0.35$           |

Table 12.2: Definition of the signal region SR-VBF. “✓” means the requirement is applied.

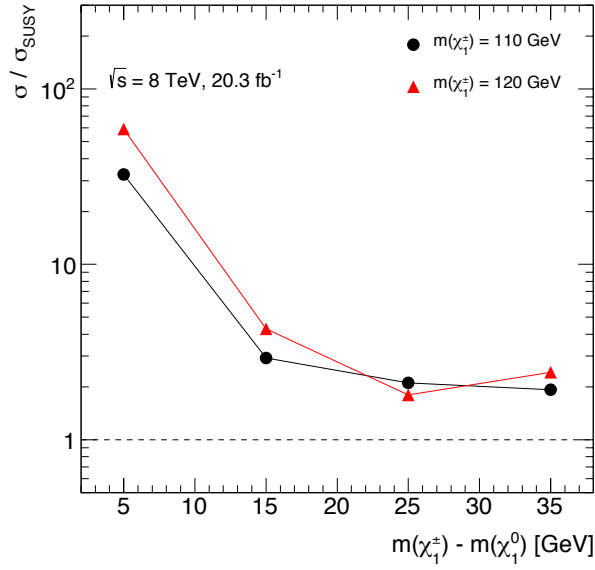
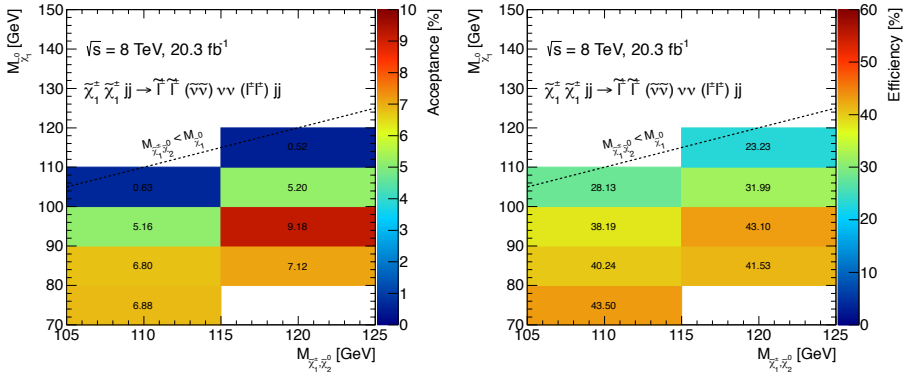
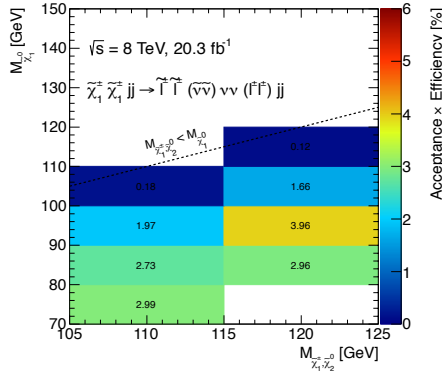


Figure 12.9: Expected upper limits on the ratio of the cross section over expected cross section for VBF  $\tilde{\chi}_1^\pm \tilde{\chi}_1^\pm$  production with intermediate sleptons as a function of mass difference ( $m_{\tilde{\chi}_1^\pm} - m_{\tilde{\chi}_2^0}$ ) normalised to the simplified model cross section for  $m_{\tilde{\chi}_1^\pm} = 110$  GeV and  $m_{\tilde{\chi}_1^\pm} = 120$  GeV.



(a) Acceptance

(b) Efficiency



(c) Acceptance × Efficiency

Figure 12.10: Acceptance (a), efficiency (b) and acceptance times efficiency (c) for a simplified model of same sign  $\tilde{\chi}_1^\pm \tilde{\chi}_1^\pm$  production via Vector Boson Fusion as a function of the common  $\tilde{\chi}_1^\pm$  and  $\tilde{\chi}_2^\pm$  mass and  $\tilde{\chi}_1^0$  mass.

## 12.4 Validation Regions

The validation of the background estimation is performed by testing the compatibility of the expected and observed events in the dedicated validation regions. The validation region is constructed to be dominated by the background processes that are addressed by the region. Three validation regions are defined:

- VR-Top to validate fakes in a Top enriched region,
- VR-Fakes to validate fakes in a light flavour jets enriched region,
- VR-VV to validate WW and WZ backgrounds.

In this section the validation regions are defined.

### 12.4.1 VR-Top

The validation region VR-Top is enriched in Top events. It is constructed in order to test the fake background estimation in a sample rich in fake background processes with heavy flavour ( $b$ - and  $c$ -) jets. It is defined in order to be close to the signal region. The requirement of at least one  $b$ -jet ( $B20 \geq 1$ ) guarantee that the VR-Top is disjoint with the signal region SR-VBF and has low signal contamination. The transverse momentum of the leading jet ( $p_T^{j1}$ ), the invariant mass of dilepton and dijet system ( $m_{\ell\ell}$  and  $m_{jj}$ ) as well as the stransverse mass ( $m_{T2}$ ) requirements are loosened with respect to SR-VBF in order to increase the statistics in the validation region. The other requirements are kept the same as in the signal region SR-VBF. The definition of the validation region VR-Top is summarised in Tab. 12.3.

### 12.4.2 VR-Fakes

The validation region VR-Fakes is constructed in order to test the fake background in a light flavour jets enriched region. It is defined by the initial preselection cuts from the signal region SR-VBF, i.e. exactly two same sign leptons (electrons or muons),  $E_T^{\text{miss}} > 120$  GeV, at least two signal central light jets or forward jets ( $L20 + F30 \geq 2$ ). The other SR-VBF cuts are not applied in the validation region. Therefore, the signal is diluted compared to the background contamination and a high statistics is ensured in the validation region. The validation region VR-Fakes selection is summarised in Tab. 12.3.

### 12.4.3 VR-VV

The validation region VR-VV is enriched in diboson ( $WW$  and  $WZ$ ) events. It is defined by requiring two same sign leptons with transverse momentum  $p_T^\ell > 40$  GeV,  $E_T^{\text{miss}} > 120$  GeV, at least two signal central light jets or forward jets ( $L20 + F30 \geq 2$ ) and no  $b$ -jets ( $B20 = 0$ ). It is constructed in order to validate the methodology em-



ployed for the calculation of the NLO normalisation of the diboson processes described in Chapter 14. The validation region VR-VV selection is summarised in Tab. 12.3.

| Criteria                           | VR-Top                | VR-Fakes              | VR-VV                 |
|------------------------------------|-----------------------|-----------------------|-----------------------|
| SS leptons                         | ✓                     | ✓                     | ✓                     |
| Lepton flavor                      | $ee, \mu\mu, e\mu$    | $ee, \mu\mu, e\mu$    | $ee, \mu\mu, e\mu$    |
| $p_T^e (p_T^\mu)$                  | $> 7 (5) \text{ GeV}$ | $> 7 (5) \text{ GeV}$ | $40 (40) \text{ GeV}$ |
| $E_T^{\text{miss}}$                | $> 120 \text{ GeV}$   | $> 120 \text{ GeV}$   | $> 120 \text{ GeV}$   |
| signal light + forward jets        | —                     | $\geq 2$              | $\geq 2$              |
| signal $b$ -jets                   | $\geq 1$              | —                     | $= 0$                 |
| signal light + forward + $b$ -jets | $\geq 2$              | —                     | —                     |
| $m_{\ell\ell}$                     | $< 150 \text{ GeV}$   | —                     | —                     |
| $m_{T2}$                           | $< 80 \text{ GeV}$    | —                     | —                     |
| $p_T^{j1}$                         | $> 55 \text{ GeV}$    | —                     | —                     |
| $ \Delta\eta_{jj} $                | $> 1.6$               | —                     | —                     |
| $\eta_{j1} \cdot \eta_{j2}$        | $< 0$                 | —                     | —                     |
| $m_{jj}$                           | $> 150 \text{ GeV}$   | —                     | —                     |
| $p_T^{\ell\ell}/E_T^{\text{miss}}$ | $< 0.4$               | —                     | —                     |
| $p_T^{j1}/E_T^{\text{miss}}$       | $< 1.9$               | —                     | —                     |
| $p_T^{\ell\ell}/p_T^{jj}$          | $< 0.35$              | —                     | —                     |

Table 12.3: Definition of the validation regions VR-Top, VR-Fakes and VR-VV. “✓” means the cut is applied, “—” means the cut is not applied.

# 13 Fake and Charge Flip Backgrounds

Searching for new physics demands that the Standard Model background processes are adequately modelled and understood. Several background processes can produce a final state with two leptons, missing transverse energy and jets, and thus can enter the signal region established in Chapter 12. These background processes were enumerated in Chapter 11. The signal region optimisation of Chapter 12 was performed using pure Monte Carlo estimates of the backgrounds. In this chapter the data-driven methods used to derive the contributions from fakes and charge flip backgrounds are described. The method to derive the fakes differs from the method used in Part III of this thesis.

## 13.1 Non-Prompt and Fake Leptons

### 13.1.1 Motivation

A number of processes can give rise to fake leptons and non-prompt leptons. These processes were described in Chapter 7. In the considered VBF signal region with two signal leptons, there can be contributions from events with one and two fake leptons, and both contributions must be estimated. Lepton transverse momenta as low 5 GeV for muons and 7 GeV for electrons are considered for the chargino VBF signal region. Because of the low momentum of the leptons the fake background is particularly large and is in fact the dominant one. Two main classes of physics processes contribute to the fakes:

- Processes with two fake leptons, essentially composed of QCD multijet background where two jets are misidentified as prompt leptons, this contribution is generically referred to as “QCD”, but also includes processes such as fully hadronic  $t\bar{t}$  decays.
- Processes with one fake lepton and one real lepton. The main component of this background is  $W$ +jets production where the  $W$  boson decays leptonically and one jet fakes the second lepton. Other processes such as  $t\bar{t}$  where one top quarks decays leptonically and one decays hadronically contribute to this category. This

contribution is generically referred to as “W+jets”.

The calculation of the fake background relies on two ingredients, first it requires the construction of control regions with loosened lepton identification criteria, disjoint from the signal lepton. In the following the superscript “id” refers to leptons which fully comply to the signal lepton criteria, and the superscript “anti-id” refers to leptons where one of the signal lepton selections has been inverted. The exact definition of the id and anti-id leptons are given in Tab. 13.1.

The number of events with zero, one and two anti-id leptons can be related to each other using a so-called “fake factor” that can be derived in data. In the following Section 13.1.2, we first describe the dilepton regions with modified lepton criteria, and in Section 13.1.3 the fake factor is introduced. Finally the various elements of the method are put together in Sec. 13.1.4.

| Criteria                       | Muon<br>id                                       | Muon<br>anti-id                                | Electron<br>id     | Electron<br>anti-id |
|--------------------------------|--------------------------------------------------|------------------------------------------------|--------------------|---------------------|
| Particle ID                    | CB + ST                                          | CB + ST                                        | Tight              | Medium              |
| Other                          | —                                                | Veto id                                        | —                  | Veto id             |
| $p_T$                          | $> 5 \text{ GeV}$                                | $> 5 \text{ GeV}$                              | $> 7 \text{ GeV}$  | $> 7 \text{ GeV}$   |
| $ d_0/\sigma(d_0) $            | $< 3$                                            | $< 3$                                          | $< 5$              | —                   |
| $ z_0 \times \sin(\theta) $    | $< 1 \text{ mm}$                                 | $< 1 \text{ mm}$                               | $< 0.4 \text{ mm}$ | $< 1 \text{ mm}$    |
| $p_T^{\text{cone30}}/p_T$      | $< 0.12$ ( $< 0.07$ for $p_T < 15 \text{ GeV}$ ) | $< 2.0$ ( $< 0.5$ for $p_T < 15 \text{ GeV}$ ) | $< 0.16$           | —                   |
| $E_T^{\text{cone30,corr}}/p_T$ | $< 0.07$ for $p_T < 15 \text{ GeV}$              | $< 0.5$ for $p_T < 15 \text{ GeV}$             | $< 0.18$           | $< 0.5$             |

Table 13.1: The definitions of id and anti-id muons and electrons. “—” means the cut is not applied. The particle ID criteria “CB”, “ST”, “Medium” and “Tight” are discussed in Chapter 3. The id lepton definitions correspond to the signal lepton definitions given in Tables 3.1 and 3.2. “Veto id” indicates that the anti-id leptons explicitly veto the leptons that fulfil the id criteria.

### 13.1.2 Fake Lepton Control Regions

Two control regions are constructed, with respectively one and two anti-id leptons,

- The single anti-id region, with exactly one anti-id and one id lepton. The number of events in this region is given by  $N^{\text{id}, \text{anti-id}}$ .
- The double anti-id region, with exactly two anti-id leptons. The number of events in this region is given by  $N^{\text{anti-id}, \text{anti-id}}$ .

Finally the chargino VBF signal region itself is part of the method and consists of two id leptons. In this section the number of events in the signal region is referred to as  $N^{\text{id}, \text{id}}$ . Apart from the lepton definitions, the single anti-id and double anti-id control regions have exactly the same selections as the signal region.

Each of these regions receives contributions from the QCD and  $W$ +jets process categories defined earlier as well as a number of events from processes with real leptons (eg.  $Z/\gamma^* \rightarrow \ell\ell$ ), labelled with the subscript “real”. The number of events in the chargino VBF signal region can thus be written as:

$$N^{\text{id, id}} = N_{W+\text{jets}}^{\text{id, id}} + N_{\text{QCD}}^{\text{id, id}} + N_{\text{real, MC}}^{\text{id, id}} \quad (13.1)$$

where  $N_{W+\text{jets}}^{\text{id, id}}$ ,  $N_{\text{QCD}}^{\text{id, id}}$  and  $N_{\text{real, MC}}^{\text{id, id}}$  are the number of events of the categories  $W$ +jets, QCD and real defined above in the signal region. Similarly the composition of the single anti-id region can be written as:

$$N^{\text{id, anti-id}} = N_{W+\text{jets}}^{\text{id, anti-id}} + N_{\text{QCD}}^{\text{id, anti-id}} + N_{\text{real, MC}}^{\text{id, anti-id}} \quad (13.2)$$

where  $N_{W+\text{jets}}^{\text{id, anti-id}}$ ,  $N_{\text{QCD}}^{\text{id, anti-id}}$  and  $N_{\text{real, MC}}^{\text{id, anti-id}}$  are the number of events of the categories  $W$ +jets, QCD and real defined above in the single anti-id region. Finally the composition of the double anti-id region can be written as:

$$N^{\text{anti-id, anti-id}} = N_{W+\text{jets, MC}}^{\text{anti-id, anti-id}} + N_{\text{QCD}}^{\text{anti-id, anti-id}} + N_{\text{real, MC}}^{\text{anti-id, anti-id}} \quad (13.3)$$

where  $N_{W+\text{jets}}^{\text{anti-id, anti-id}}$ ,  $N_{\text{QCD}}^{\text{anti-id, anti-id}}$  and  $N_{\text{real, MC}}^{\text{anti-id, anti-id}}$  are the number of events of the categories  $W$ +jets, QCD and real defined above in the double anti-id region. It should be noted that the number of events  $N^{\text{id, id}}$ ,  $N^{\text{id, anti-id}}$  and  $N^{\text{anti-id, anti-id}}$  are simply inputs from data.

### 13.1.3 Fake Factor

The fake factor is defined separately for both electrons and muons in bins of the lepton  $p_T$  and  $\eta$ , it is defined as the ratio of the number of leptons satisfying the full lepton identification ( $N^{\text{id}}$ ) over the number of lepton candidates passing the anti-id selection ( $N^{\text{anti-id}}$ ):

$$f_l = \frac{N^{\text{id}}}{N^{\text{anti-id}}} \quad (13.4)$$

where  $l = e$  or  $\mu$ . The fake factor is not a fake rate and cannot be interpreted as a probability. The fake factor is measured in data using a factor factor region. The fake factor region consists of  $Z$ +jets candidate events which contain four candidate leptons, two of which fulfil the signal lepton criteria, and labelled  $\ell_1$  and  $\ell_2$ , and presumably come from the  $Z$  boson decay and two additional baseline leptons labelled  $\ell_3$  and  $\ell_4$  that are presumably fake leptons. The fake factor region is selected in events that fired a single lepton trigger. To ensure that  $\ell_3$  and  $\ell_4$  are fake leptons the following additional selections are applied:

- For the leptons  $\ell_1$  and  $\ell_2$  coming from the  $Z$ -boson decay:

- Opposite sign and same flavor signal leptons with  $|m_{\ell_1\ell_2} - m_Z| < 15$  GeV,
- $p_T^{\ell_1} > 25$  GeV and  $p_T^{\ell_2} > 15$  GeV.
- For the fake lepton candidates  $\ell_3$  and  $\ell_4$ :
  - $|m_{\ell_3\ell_4} - m_Z| > 15$  GeV in order to remove ZZ events,
  - $\max(m_T^W) < 30$  GeV in order to remove WZ events,
  - $\min(m_{\ell_1\ell_2\ell_3} - m_Z) > 5$  GeV to remove Z with final state converted photons.

### 13.1.4 Fake Factor Method

The number of events from the QCD category in the double anti-id region is obtained as follows:

$$N_{\text{QCD}}^{\text{anti-id, anti-id}} = N^{\text{anti-id, anti-id}} - N_{W+\text{jets, MC}}^{\text{anti-id, anti-id}} - N_{\text{real, MC}}^{\text{anti-id, anti-id}} \quad (13.5)$$

where the last two contributions are estimated from Monte Carlo simulation.

The next step is to derive the composition of the single anti-id region. We start by the QCD contribution in this region, which is derived directly from the QCD contribution in the double anti-id region in Eq. 13.5 and the fake factor:

$$N_{\text{QCD}}^{\text{id, anti-id}} = f_l \times N_{\text{QCD}}^{\text{anti-id, anti-id}} \quad (13.6)$$

The remaining  $W+\text{jets}$  component of the single anti-id region can be obtained from Eq. 13.2, using the QCD estimate in Eq. 13.6 and the number of events in data in the single anti-id region  $N^{\text{id, anti-id}}$ :

$$N_{W+\text{jets}}^{\text{id, anti-id}} = N^{\text{id, anti-id}} - f_l \times N_{\text{QCD}}^{\text{anti-id, anti-id}} - N_{\text{real, MC}}^{\text{id, anti-id}} \quad (13.7)$$

where the last term represents the real lepton processes in the single anti-id region and is estimated from Monte Carlo simulation.

We can now turn to the composition of the signal region, which corresponds to the sample with two leptons fulfilling the id criteria. The number of  $W+\text{jets}$  events in the signal region is obtained from the fake factor and the number of  $W+\text{jets}$  events in the single anti-id region earlier derived in Eq. 13.7:

$$N_{W+\text{jets}}^{\text{id, id}} = f_l \times N_{W+\text{jets}}^{\text{id, anti-id}} \quad (13.8)$$

which is combined with Eq. 13.7 and yields:

$$N_{W+\text{jets}}^{\text{id, id}} = f_l \times (N^{\text{id, anti-id}} - f_l \times N_{\text{QCD}}^{\text{anti-id, anti-id}} - N_{\text{EWK, MC}}^{\text{id, anti-id}}) \quad (13.9)$$

Finally it is found that 95% of the fake lepton component in the signal region arises from processes with one fake and one real lepton (the  $W+\text{jets}$  category).

### 13.1.5 Systematic Uncertainties

The systematic uncertainties in the fake factor method come from uncertainties in the extraction of the fake factor from data as well as uncertainties on the flavor composition and  $p_T$  spectrum differences between the single anti-id, double anti-id regions and the Z+jets fake factor region. The uncertainties arising from measuring the fake factors in the Z+jets data events arises mainly from i) the data statistics in that region and ii) from the contamination of the candidate fake leptons in that region by real leptons from electroweak processes. This contamination arises mostly comes from  $WZ \rightarrow \ell\nu\ell\ell$  events and is corrected for by using Monte Carlo.

There are additional uncertainties from the application of the fake factor in the control region. These uncertainties mostly arise from differences in jet flavour composition between the fake factor region and the region where the fake factor is applied. To account for these differences, the fake factor in simulation is compared between Z+jets and W+jets events as these samples are expected to have different jet flavour composition. This uncertainty is around 30%. The anti-id definitions were selected to minimise the differences in fake factor between these samples. This means that the fake factor is more stable with respect to changes in jet flavour composition. The flavour composition is the dominant systematic for fakes with  $p_T < 25$  GeV. For larger  $p_T$ , the data statistics is the largest uncertainty.

## 13.2 Charge Flip

As discussed in Section 11.3.3 events with two opposite sign electrons where one electron has a misidentified charge can appear as a same sign event and enter into the signal region. This process is called “charge flip”. It is a rare process, happening less than 1% of the time for electrons in the presented analysis. Since it is an instrumental effect that is sensitive to the very details of the material distribution in the ATLAS detector, it is difficult to model well in simulation. For this reason a data-driven method is used to calculate this background. The charge flip for the muons is completely ignored as it is extremely low in ATLAS.

The charge flip background is estimated from opposite sign dilepton events with a weight that depends on the charge flip probability  $\varepsilon$  for electrons. This probability is measured in data as a function of electron  $p_T$  and  $\eta$  using a likelihood technique.

The probability for electrons to flip their charge is measured using  $Z \rightarrow ee$  events. This process normally yields an opposite sign electron pair. Nevertheless experimentally a same sign electron pair can occur when one of the electrons has flipped charge. A high purity  $Z \rightarrow ee$  data sample is selected using a single electron trigger with  $p_T > 24$  GeV, and using the following selections:

- Two electrons of any charge, the leading electron is required to have  $p_T > 25$  GeV to match the trigger requirement,

- The invariant mass of the two electrons is required to be within 15 GeV of the  $Z$  boson mass.

Both same sign and opposite sign dielectron pairs are selected in this way. The ratio of the number of same sign pairs to the number of all pairs (both same sign and opposite sign) gives a first estimate of the charge flip probability, which is measured to be  $\bar{\epsilon} = 0.8\%$ .

Nevertheless, the probability for charge flip depends on the amount of traversed material by the electron. There can be differences between the  $Z \rightarrow ee$  processes in which the charge flip is determined and other background processes where the charge flip is applied. Therefore, the charge flip probability is measured as a function of  $p_T$  and  $\eta$  of the electron.

For each  $Z \rightarrow ee$  event, electrons are indexed by their bin in  $p_T$  and  $\eta$ . The number of same sign pairs in each  $p_T$  and  $\eta$  bin is labeled  $N_{ij}^{SS}$ , where  $i$  and  $j$  indicate the first and second electron in the pair and, for convenience in this description, only one index is used to iterate over both  $p_T$  and  $\eta$ . The number of electron pairs without any requirement on the charge is labelled as  $N_{ij}$ . Since there are two electrons in each pair a likelihood is used to determine what weight to apply for a given event. If the charge flip probabilities in each bin are called  $\epsilon_k$  where  $k = i, j$ , and are assumed to be independent then:

$$N_{ij}^{SS} = N_{ij}(\epsilon_i + \epsilon_j) \quad (13.10)$$

If  $N_{ij}^{SS}$  is described by a Poisson distribution, the probability to observe  $N_{ij}^{SS}$  given  $N_{ij}$  total events and charge flip probabilities  $\epsilon_k$  is given by:

$$P(N_{ij}^{SS} | N_{ij}, \epsilon_i, \epsilon_j) = \frac{[N_{ij}(\epsilon_i + \epsilon_j)]^{N_{ij}^{SS}} e^{-N_{ij}(\epsilon_i + \epsilon_j)}}{N_{ij}^{SS}!} \quad (13.11)$$

Converting this into a likelihood and taking the negative natural logarithm yields:

$$-\ln L \propto - \sum_{i,j} \{ \ln [N_{ij}(\epsilon_i + \epsilon_j)] N_{ij}^{SS} - N_{ij}(\epsilon_i + \epsilon_j) \} \quad (13.12)$$

where the sum over  $i$  and  $j$  is over the  $p_T$  and  $\eta$  bins of both electrons. The charge flip probability for each bin is obtained by minimising the likelihood, this allows to derive the charge flip from data, binned in  $p_T$  and  $\eta$  of the electron.

Given the charge flip probability the estimate of the charge flip background in the signal region can be computed. The Monte Carlo simulation is used to make a full prediction of the number of events in a region where all selections are the same as the chargino VBF signal region, except that the two leptons are required to have opposite charge. Each opposite sign event is weighed with a weight  $w$  given by:

$$w = \frac{(\epsilon_1 + \epsilon_2)}{(1 - \epsilon_1)(1 - \epsilon_2)} \quad (13.13)$$

where  $\varepsilon_k$  ( $i = 1, 2$ ) is the probability for each electron to flip the their charge. The sum of the weights provides the estimate of the number of charge flip background events in the chargino VBF signal region.

When an electron undergoes the charge flip process, a small amount of energy is lost to other soft particles in the asymmetric decay. This can be observed as a shift in the invariant mass distribution  $m_{\ell\ell}$  of the two electrons coming from the  $Z$  boson decay. In order to account for this small energy loss the momentum of the charge flipped electrons in the simulation is smeared. The smearing function is derived by comparing the  $m_{\ell\ell}$  distribution in same sign dielectron pairs in data and opposite sign dielectron pairs in simulation for  $Z \rightarrow ee$  events.

The charge flip estimation is validated by performing a closure test using the same  $Z \rightarrow ee$  same sign dielectron region and by comparing the predicted and observed  $p_T$  and  $\eta$  distributions. This results in a 25% systematic uncertainty on the estimated number of charge flip background events.





# 14 Diboson Backgrounds

## 14.1 Diboson Background Contributions

The second and third largest Standard Model backgrounds in the signal region SR-VBF come from  $WW$  and  $WZ$  production respectively. The ATLAS full Monte Carlo simulation samples for  $WW$  and  $WZ$  are generated at LO with the Sherpa LO event generator. This chapter presents how these samples can be normalized using additional NLO information to achieve better accuracy on these background estimates. The NLO normalization of these backgrounds is carried out using dedicated fiducial regions [111].

The fiducial regions are regions close to the SR-VBF where normalisation at NLO can be calculated. NLO generators and cross section calculators are used in order to perform the normalisation and to apply all relevant systematic uncertainties to these predictions. The two cross section calculators available are PowhegBox [112, 113, 114, 115] and VBFNLO [116, 117, 118]. The distinction between QCD and EWK contributions to the  $WW$  and  $WZ$  processes is necessary because there is no unique NLO cross section calculator that can compute all EWK and QCD contributions from  $WW$  and  $WZ$  processes at the same time.

The expected contribution of  $ZZ$  process in the signal region is only 0.05 events which is 0.5% of a total background estimation. Since it is small this background is derived with the Sherpa event generator at LO.

## 14.2 Normalisation of the $WW$ Background

The  $WW$ -EWK and  $WW$ -QCD backgrounds are predicted using Monte Carlo Sherpa samples at LO exploiting the NLO theoretical calculations obtained with PowhegBox. The PowhegBox provides the events at particle level. Particle level means the Monte Carlo truth information for all particles (hadrons and leptons after FSR) is used. The NLO prediction is calculated in the fiducial region close to the signal region. The fiducial region is defined at the particle level by the same selections as the signal region SR-VBF except for the lepton isolation and the  $b$ -jet tagging.

Events are generated at NLO with PowhegBox and the parton showering is performed with Pythia8 [119, 120, 121]. After applying the fiducial region cuts, the remaining fraction of events is called “PowhegBox fiducial acceptance” and denoted

$A_{\text{PowhegBox}}$ . The total number of events predicted by PowhegBox at NLO in the fiducial region is  $\sigma_{\text{PowhegBox}}^{\text{NLO, incl}} \times A_{\text{PowhegBox}}$ , where  $\sigma_{\text{PowhegBox}}^{\text{NLO, incl}}$  is the  $WW$  inclusive NLO cross section calculated by PowhegBox.

The LO Sherpa samples used in the analysis are normalised to yield the same number of events in the fiducial region as the NLO PowhegBox generator. This is achieved by normalising the Sherpa samples with the cross section  $\sigma_{\text{extrap}}^{\text{NLO}}$  defined by:

$$\sigma_{\text{extrap}}^{\text{NLO}} = \sigma_{\text{PowhegBox}}^{\text{NLO, incl}} \frac{A_{\text{PowhegBox}}}{A_{\text{Sherpa}}} \quad (14.1)$$

where  $\sigma_{\text{PowhegBox}}^{\text{NLO, incl}}$  is computed with PowhegBox,  $A_{\text{PowhegBox}}$  and  $A_{\text{Sherpa}}$  are the fiducial acceptances calculated at the particle level with PowhegBox and Sherpa respectively. This procedure is applied separately to the  $WW$ -EWK and  $WW$ -QCD processes. Table 14.1 shows LO Sherpa cross sections as well as the extrapolated NLO cross sections calculated using PowhegBox for  $WW$ -EWK and  $WW$ -QCD backgrounds.

| Process        | $\sigma_{\text{Sherpa}}^{\text{LO}}$ [fb] | $\sigma_{\text{extrap}}^{\text{NLO}}$ [fb] |
|----------------|-------------------------------------------|--------------------------------------------|
| $W^+W^+$ EWK   | -                                         | $16.8 \pm 1.3$                             |
| $W^-W^-$ EWK   | -                                         | $4.7 \pm 0.4$                              |
| Total $WW$ EWK | 27.6                                      | $21.4 \pm 1.7$                             |
| $W^+W^+$ QCD   | -                                         | $10.1 \pm 2.6$                             |
| $W^-W^-$ QCD   | -                                         | $0.7 \pm 0.4$                              |
| Total $WW$ QCD | 16.1                                      | $10.8 \pm 3.0$                             |

Table 14.1: Comparison between PowhegBox LO cross sections and extrapolated NLO cross sections calculated using Sherpa for  $WW$ -EWK and  $WW$ -QCD backgrounds. The Sherpa Monte Carlo samples includes both  $W^+W^+$  and  $W^-W^-$  contributions, therefore only the total  $WW$  cross section is given. The error includes the uncertainty from the limited Monte Carlo statistics and the numerical error of the cross section calculation.

### 14.3 Normalisation of the $WZ$ background

The  $WZ$ -EWK and  $WZ$ -QCD backgrounds are predicted using Monte Carlo Sherpa samples at LO. The procedure used to normalise the Sherpa predictions is similar to the one used for  $WW$ -EWK and  $WW$ -QCD, with some additional complications as these processes are not available with PowhegBox. Instead the cross sections can be calculated at NLO using VBFNLO. VBFNLO cannot generate events at NLO, but it can calculate cross sections in the regions defined by cuts at the generator level. Most but not all of the cuts

required in the signal region can be imposed at generator level. Therefore, the fiducial region defined for VBFNLO has a looser selection than the signal region and the cuts are applied at the parton level instead of the particle level. The cuts which are not available in the VBFNLO package are the isolation requirements on the leptons, the  $b$ -jet tagging and the ratio cuts. The following selections are applied at the generator level:

- Three leptons ( $e$  or  $\mu$ ) with  $p_T^\ell > 7$  GeV and  $|\eta_\ell| < 2.5$
- $5 < m_{\ell\ell} < 100$  GeV and  $\Delta R_{\ell\ell} > 0.1$  for any pair (same sign or opposite sign)
- Two jets with  $p_T > 20$  GeV and  $|\eta| < 4.5$
- $\Delta R_{jj} > 0.4$
- $\Delta R_{\ell j} > 0.4$
- $|\Delta\eta_{jj}| > 1.6$  and  $m_{jj} > 350$  GeV
- $E_T^{\text{miss}} > 120$  GeV

The Sherpa samples are normalised so that they predict the same number of  $WZ$  events as VBFNLO in the fiducial region. This is achieved by normalising Sherpa with the following cross section:

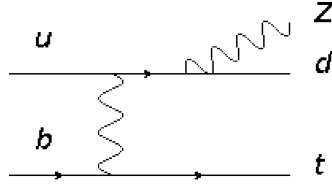
$$\sigma_{\text{extrap}}^{\text{NLO}} = \frac{\sigma_{\text{VBFNLO}}^{\text{NLO, fid}}}{A_{\text{Sherpa}}} \quad (14.2)$$

where  $\sigma_{\text{VBFNLO}}^{\text{NLO, fid}}$  is the cross section predicted by VBFNLO in the fiducial region and  $A_{\text{Sherpa}}$  is the Sherpa fiducial acceptance calculated at parton level.

The  $WZ$ -EWK production can be divided into two components. One is similar to the  $WW$ -EWK process. In this case  $W$  and  $Z$  are either radiated from light quark lines or come from the vector bosons interaction. This is referred to as “without- $b$ ” component as no  $b$ -jets are involved. The second case is the associated production of a single top quark, a  $Z$  boson and an extra jet ( $tZj$  production). Then the top quark subsequently decays to a  $W$  and a  $b$ -quark. This process involves a  $b$ -quark in the initial state as well as final state and is referred to as “with- $b$ ” component. An illustration of the  $tZj$  process is presented in Fig. 14.1.

The Sherpa  $WZ$ -EWK sample used in the analysis includes both “with- $b$ ” and “without- $b$ ” components, while VBFNLO includes only the “without- $b$ ” component. Thus, only the “with- $b$ ” component can normalised to the NLO predictions. In order to verify if a given Sherpa event is of “with- $b$ ” or “without- $b$ ” type, the matrix element information is used. The Sherpa “without- $b$ ” acceptance is calculated in the fiducial region as:

$$A_{\text{Sherpa}}^{\text{without-}b} = \frac{N_{\text{Sherpa}}^{\text{fid, without-}b}}{N_{\text{Sherpa}}^{\text{without-}b}} \quad (14.3)$$

Figure 14.1: Illustration of the  $tZj$  process.

where  $N_{\text{Sherpa}}^{\text{fid,without-}b}$  is the number of events passing fiducial region selection and not containing  $b$ -quark, while  $N_{\text{Sherpa}}^{\text{without-}b}$  is the total number of events and not containing  $b$ -quark. This acceptance is used to extrapolate the VBFNLO fiducial cross section to the total phase space of the “without- $b$ ” contribution of the Sherpa sample, similar to what was done for previous diboson processes. For the “with- $b$ ” contribution, the cross section derived using Sherpa is taken and 50% systematic uncertainty is assigned. To summarise, the Sherpa WZ-EWK sample is normalised with the following cross section:

$$\sigma_{\text{extrap}}^{\text{NLO}} = \frac{\sigma_{\text{VBFNLO}}^{\text{NLO,fid}}}{A_{\text{Sherpa}}^{\text{without-}b}} + \sigma_{\text{Sherpa}}^{\text{LO,incl}} \cdot F_{\text{Sherpa}}^{\text{with-}b} \quad (14.4)$$

where  $\sigma_{\text{VBFNLO}}^{\text{NLO,fid}}$  is the VBFNLO fiducial cross section for the “without- $b$ ” component,  $A_{\text{Sherpa}}^{\text{without-}b}$  is the Sherpa “without- $b$ ” acceptance,  $\sigma_{\text{Sherpa}}^{\text{LO,incl}}$  is the inclusive Sherpa sample cross section and  $F_{\text{Sherpa}}^{\text{with-}b}$  is the fraction of Sherpa events containing  $b$ -quark before any selection. For the used Sherpa WZ-EWK sample, the fraction  $F_{\text{Sherpa}}^{\text{with-}b}$  is 48%.

Table 14.2 shows LO Sherpa cross sections as well as extrapolated NLO cross sections calculated using VBFNLO for the WZ-EWK and the WZ-QCD backgrounds.

## 14.4 Theoretical Uncertainties

This section describes the theoretical uncertainties associated with the NLO normalisation of the diboson processes.

### 14.4.1 Generator Uncertainty

The generator uncertainty is obtained by computing the fiducial cross section  $\sigma_{\text{VBFNLO}}^{\text{NLO,fid}}$  using two different NLO generators. Then the uncertainty is calculated as the relative difference between the two cross sections. This uncertainty can only be estimated for WW-EWK which is the only process for which two NLO generators are available. Those are PowhegBox and VBFNLO. The difference between PowhegBox and VBFNLO is 1.7%. The generator uncertainty is assumed to be the same for all four WW and WZ processes.

| Process      | $\sigma_{\text{Sherpa}}^{\text{LO}}$ [fb] | $\sigma_{\text{extrap}}^{\text{NLO}}$ [fb] |
|--------------|-------------------------------------------|--------------------------------------------|
| $W^+Z$ EWK   | -                                         | $68.4 \pm 1.1$                             |
| $W^-Z$ EWK   | -                                         | $16.8 \pm 0.3$                             |
| Total WZ EWK | 82.1                                      | $85.2 \pm 1.4$                             |
| $W^+Z$ QCD   | -                                         | $9090 \pm 1230$                            |
| $W^-Z$ QCD   | -                                         | $2430 \pm 350$                             |
| Total WZ QCD | 9740                                      | $11530 \pm 1580$                           |

Table 14.2: Comparison between Sherpa LO cross sections and extrapolated NLO cross sections calculated using VBFNLO for WZ-EWK and WZ-QCD backgrounds. The Sherpa Monte Carlo samples includes both  $W^+Z$  and  $W^-Z$  contributions, therefore only the total WZ cross section is given. The error includes the uncertainty from the limited Monte Carlo statistics and the numerical error of the cross section calculation.

#### 14.4.2 Scale Uncertainty

The scale uncertainty is obtained by varying the factorisation and the renormalisation scales up and down independently by factors  $\xi_F$  and  $\xi_R$ . The cross section is calculated for several scale configurations. The factors  $\xi_F$  and  $\xi_R$  are set to the values 0.5, 1.0 and 2.0, giving nine cross section values for each of the four WW and WZ process classes. The total scale uncertainty is taken to be the maximum cross section deviation observed with respect to the nominal setting ( $\xi_F = 1$  and  $\xi_R = 1$ ). The resulting uncertainties are listed in Table 14.3. The effect of the scale variations is the largest for the QCD production. It is  $\sim 15\%$  for WW-QCD processes and  $\sim 20\%$  for the WZ-QCD processes.

| Process      | Relative error [%] |
|--------------|--------------------|
| $W^+W^+$ EWK | 6.6                |
| $W^-W^-$ EWK | 8.7                |
| $W^+W^+$ QCD | 15.2               |
| $W^-W^-$ QCD | 14.7               |
| $W^+Z$ EWK   | 1.5                |
| $W^-Z$ EWK   | 3.1                |
| $W^+Z$ QCD   | 21.6               |
| $W^-Z$ QCD   | 19.0               |

Table 14.3: The theoretical uncertainty due to renormalisation and factorisation scale variations for WW-EWK, WW-QCD, WZ-EWK and WZ-QCD.

### 14.4.3 PDF Uncertainty

The parton density function (PDF) uncertainty is calculated by varying the PDF by its uncertainties and recomputing the inclusive NLO cross section  $\sigma^{\text{NLO, incl}}$  [122]. The CT10 [123] PDF is used. It has 26 sources of uncertainties (eigenvalues) at 90% CL, each with an upward and a downward uncertainty. These uncertainties are scaled by 1/1.645 in order to obtain the 68% CL uncertainties. The uncertainty is obtained using the quadratic sum of the deviations between the nominal cross section and the recalculated cross sections with the uncertainty applied:

$$\Delta\sigma^+ = \sqrt{\sum_{i=1}^{26} \left[ \max \left( \sigma_i^{\text{NLO, incl, +}} - \sigma^{\text{NLO, incl}}, \sigma_i^{\text{NLO, incl, -}} - \sigma^{\text{NLO, incl}}, 0 \right) \right]^2} \quad (14.5)$$

$$\Delta\sigma^- = \sqrt{\sum_{i=1}^{26} \left[ \max \left( \sigma^{\text{NLO, incl}} - \sigma_i^{\text{NLO, incl, +}}, \sigma^{\text{NLO, incl}} - \sigma_i^{\text{NLO, incl, -}}, 0 \right) \right]^2} \quad (14.6)$$

where  $\Delta\sigma^+$  and  $\Delta\sigma^-$  are the upward and downward uncertainties respectively,  $\sigma^{\text{NLO, incl}}$  is the nominal inclusive NLO cross section, while  $\sigma_i^{\text{NLO, incl, +}}$  and  $\sigma_i^{\text{NLO, incl, -}}$  are the inclusive NLO cross section with the  $i$  source of uncertainty applied upward and downward respectively.

Additionally the PDF uncertainty is applied by comparing the CT10 PDF with the MSTW2008 [124] PDF. The inclusive NLO cross section  $\sigma^{\text{NLO, incl}}$  is recomputed using these PDFs and the relative difference is calculated.

The resulting PDF systematic uncertainties are given in Tab. 14.4 for  $WW$  and  $WZ$  processes. The largest relative PDF uncertainty corresponds to QCD production. It is 10.4% for  $W^+W^+$ -QCD and 26.9% for  $W^+Z$ -QCD. The uncertainty obtained by comparing CT10 PDF with the MSTW2008 PDF is negligible. The final PDF uncertainty is calculated by computing the quadratic sum of the uncertainties from CT10 and from the CT10 minus MSTW2008 difference.

### 14.4.4 Parton Shower Uncertainty

The parton shower uncertainty is obtained by comparing the cross section  $\sigma^{\text{NLO, fid}}$  calculated with different parton showering. The uncertainty is estimated only for  $WW$ -EWK and  $WW$ -QCD processes since  $WZ$  events are not generated at NLO (only the cross section is calculated) and showering cannot be performed. For  $WW$  events the same PowhegBox samples are processed with Pythia8 and Herwig++ [89] which have two different showering models. The resulting parton shower systematic uncertainties can be seen in Table 14.5. A very large relative uncertainty is observed in the case of  $W^-W^-$ -QCD process. Nevertheless, this contribution is suppressed by the VBF specific cuts in the SR-VBF. Therefore, the impact of this large uncertainty on the final estimated number of events in the signal region is negligible. Its uncertainty is negli-

| Process      | PDF error source |                 |
|--------------|------------------|-----------------|
|              | CT10 eigenvalues | CT10 - MSTW2008 |
| $W^+W^+$ EWK | +2.4%            | $\pm 0.01\%$    |
| $W^-W^-$ EWK | -2.5%            | $\pm 3.3\%$     |
| $W^+W^+$ QCD | +5.7%            | $\pm 0.2\%$     |
| $W^-W^-$ QCD | -5.0%            | $\pm 1.3\%$     |
| $W^+Z$ EWK   | +1.8%            | $\pm 3.5\%$     |
| $W^-Z$ EWK   | -4.5%            | $\pm 0.02\%$    |
| $W^+Z$ QCD   | +4.1%            | $\pm 1.4\%$     |
| $W^-Z$ QCD   | -4.8%            | $\pm 1.3\%$     |

Table 14.4: PDF eigenvalue variations and CT10 minus MSTW2008 difference for  $WW$  and  $WZ$  in the fiducial region.

ble. The relative parton shower uncertainty is 1.5% for  $WW$ -EWK processes and 9.3% for  $WW$ -QCD processes.

| Process        | $\sigma_{\text{Pythia,extrap}}^{\text{NLO}}$ [fb] | $\sigma_{\text{Herwig,extrap}}^{\text{NLO}}$ [fb] | Relative difference |
|----------------|---------------------------------------------------|---------------------------------------------------|---------------------|
| $W^+W^+$ EWK   | $16.8 \pm 1.3$                                    | $16.8 \pm 1.3$                                    | +0.2%               |
| $W^-W^-$ EWK   | $4.7 \pm 0.4$                                     | $4.3 \pm 0.4$                                     | -7.9%               |
| Total $WW$ EWK | $21.4 \pm 1.7$                                    | $21.1 \pm 1.7$                                    | -1.5%               |
| $W^+W^+$ QCD   | $10.1 \pm 2.6$                                    | $10.2 \pm 2.8$                                    | +1.2%               |
| $W^-W^-$ QCD   | $0.7 \pm 0.4$                                     | $1.6 \pm 0.7$                                     | +124.3%             |
| Total $WW$ QCD | $10.8 \pm 3.0$                                    | $11.8 \pm 3.5$                                    | +9.3%               |

Table 14.5: Comparison of the extrapolated cross sections obtained with Pythia8 and Herwig++ parton showering. The last column indicates the relative difference between the obtained cross sections.

## 14.5 Interference between electroweak and QCD processes

In order to estimate the  $WW$  background properly the interference between EWK and QCD production has to be taken into account. In this section the impact of interference effects between  $WW$ -EWK and  $WW$ -QCD on the total fiducial cross section is investigated. The interference effects in  $WZ$  and  $ZZ$  production are heavily suppressed and neglected [111].



Sherpa can produce a combined  $WW$  sample which includes both the EWK and QCD mediated production as well as their interference at LO ( $WW$ -EWK-QCD). Also, Sherpa is capable of producing the  $WW$ -EWK and  $WW$ -QCD parts separately. The sum of the separate production mechanisms can be compared to the combined sample in order to estimate the size of the interference term at LO.

Using the Sherpa samples for the complete  $WW$  process, including QCD, EWK and interference, the purely electroweak  $WW$ -EWK process and the  $WW$ -QCD process, the contribution to the cross section in the fiducial region due to interference can be calculated as:

$$\sigma_{\text{Sherpa}}^{\text{LO,fid}}(\text{INT}) = \sigma_{\text{Sherpa}}^{\text{LO,fid}}(\text{EWK+QCD}) - \sigma_{\text{Sherpa}}^{\text{LO,fid}}(\text{EWK}) - \sigma_{\text{Sherpa}}^{\text{LO,fid}}(\text{QCD}) \quad (14.7)$$

where  $\sigma_{\text{Sherpa}}^{\text{LO,fid}}(\text{INT})$  is the LO fiducial cross section due to interference between EWK and QCD productions,  $\sigma_{\text{Sherpa}}^{\text{LO,fid}}(\text{EWK+QCD})$  is the LO fiducial cross section including EWK production, QCD production and their interference,  $\sigma_{\text{Sherpa}}^{\text{LO,fid}}(\text{EWK})$  is the LO fiducial cross section for the EWK production, while  $\sigma_{\text{Sherpa}}^{\text{LO,fid}}(\text{QCD})$  is the LO fiducial cross section for the QCD production.

The extrapolated NLO cross sections for  $WW$ -EWK and  $WW$ -QCD processes calculated in Section 14.2 can be scaled by the factor  $\mathcal{S}_{\text{INT}}$  in order to include interference. The  $\mathcal{S}_{\text{INT}}$  is defined as:

$$\begin{aligned} \mathcal{S}_{\text{INT}} &= \frac{\sigma_{\text{Sherpa}}^{\text{LO,fid}}(\text{EWK}) + \sigma_{\text{Sherpa}}^{\text{LO,fid}}(\text{QCD}) + \sigma_{\text{Sherpa}}^{\text{LO,fid}}(\text{INT})}{\sigma_{\text{Sherpa}}^{\text{LO,fid}}(\text{EWK}) + \sigma_{\text{Sherpa}}^{\text{LO,fid}}(\text{QCD})} \\ &= 1 + \frac{\sigma_{\text{Sherpa}}^{\text{LO,fid}}(\text{INT})}{\sigma_{\text{Sherpa}}^{\text{LO,fid}}(\text{EWK}) + \sigma_{\text{Sherpa}}^{\text{LO,fid}}(\text{QCD})} \end{aligned} \quad (14.8)$$

The meaning if a scale factor  $\mathcal{S}_{\text{INT}}$  of 1 is that there is no interference. A factor larger than one indicates constructive interference and less than one indicates destructive interference. The scale factor  $\mathcal{S}_{\text{INT}}$  in the different regions is shown in Fig. 14.2. The first bin presents the  $\mathcal{S}_{\text{INT}}$  in the VR-Fakes. Next, the cuts from the SR-VBF are added sequentially and the corresponding scale factors are presented in subsequent bins. Finally, the last bin presents the fiducial region close to signal region SR-VBF. It shows how the interference contribution decreases when consecutive signal region cuts are applied. It can be seen that the scale factor  $\mathcal{S}_{\text{INT}}$  in the fiducial region close to the signal region equals unity within the errors. It is due to the very small fraction of the QCD component in the signal region.

The  $|\Delta\eta_{jj}|$  and  $m_{\ell\ell}$  cuts have the highest suppression power against QCD and interference terms. The dependence of the scale factor  $\mathcal{S}_{\text{INT}}$  is further studied in the regions defined by VR-Fakes selection,  $m_{\ell\ell} < 100$  GeV and various  $|\Delta\eta_{jj}|$  requirements. The scale factor  $\mathcal{S}_{\text{INT}}$  calculated in those regions is presented in Fig. 14.3. It is observed that the size of the interference decreases when a tighter  $|\Delta\eta_{jj}|$  cut is applied.

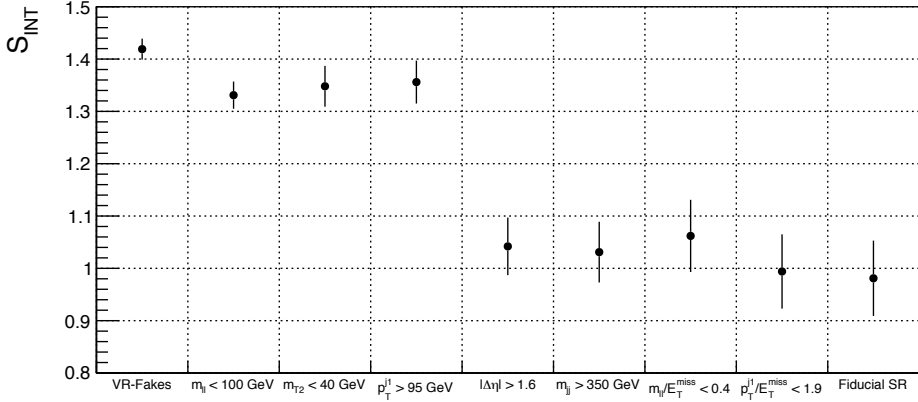


Figure 14.2: The scale factor  $\mathcal{S}_{\text{INT}}$  in the different regions. The first bin corresponds to the validation region VR-Fakes. In the following bins the remaining selections leading to the fiducial region close to SR-VBF are added sequentially. The last bin represents the fiducial region close to the signal region. The error bars are the statistical.

The interference term is suppressed in the region close to the signal region SR-VBF. Therefore, no scale factor  $\mathcal{S}_{\text{INT}}$  is applied on the  $WW$ -EWK and  $WW$ -QCD extrapolated NLO cross sections in the signal region. In the region VR-Fakes the scale factor is  $\mathcal{S}_{\text{INT}} = 1.4$ . This scale factor is applied on the  $WW$ -EWK and  $WW$ -QCD extrapolated NLO cross sections during the estimation of the  $WW$  background in VR-Fakes. In both regions the additional systematic uncertainty due to the interference is applied. A conservative uncertainty of 100% of the interference term in addition to the statistical uncertainty is used.

## 14.6 Conclusions

The second and third largest Standard Model backgrounds in the signal region SR-VBF come from  $WW$  and  $WZ$  production respectively. These backgrounds are estimated using Monte Carlo with NLO normalisation extracted using dedicated fiducial regions. The EWK and QCD contributions are considered. Relevant systematic uncertainties on the NLO normalisation are estimated. The considered sources of systematic errors are generator, scale, PDF and parton shower uncertainties. The contribution of the interference between EWK and QCD for  $WW$  production is taken into account. The LO cross sections are corrected by 22% - 30% for the  $WW$  and 5% - 18% for the  $WZ$  processes.

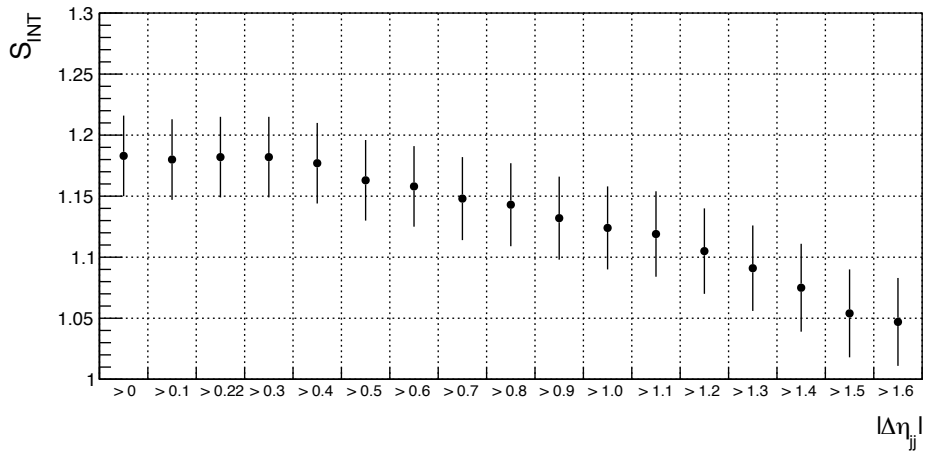


Figure 14.3: The scale factor  $\mathcal{S}_{\text{INT}}$  in the region defined by the VR-Fakes selection,  $m_{\ell\ell} < 100$  GeV and different  $|\Delta\eta_{jj}|$  requirements. The error bars are the statistical.

# 15 Results and Conclusions

In this chapter the results of the search for same sign  $\tilde{\chi}_1^\pm \tilde{\chi}_1^\pm$  pair production via VBF are presented and discussed. The results in the validation regions are presented in Section 15.1. Section 15.2 presents the event display of the signal candidate in data. Section 15.3 presents the predictions and events yields in the signal region SR-VBF. The results are interpreted in the context of the SUSY simplified model in Section 15.4.

## 15.1 Results in Validation Regions

As discussed in Chapter 13 the main Standard Model backgrounds in the signal region SR-VBF are fakes,  $WW$  and  $WZ$  processes. In this section the compatibility of the estimated background and observed events in the validation regions is presented.

### 15.1.1 VR-Top

The expected and observed numbers of events in the validation region VR-Top are presented in Tab. 15.1. It can be seen that this region is indeed dominated by fake background. The fake contamination is 89%. Figure 15.1 presents the distributions of the transverse momentum of the leading jet (a) and the missing transverse energy (b) in the validation region VR-Top. A good agreement between data and final background prediction is observed. The prediction here includes the data driven estimates.

### 15.1.2 VR-Fakes

The expected and observed numbers of events in the validation region VR-Fakes are presented in Tab. 15.2. It can be seen that this region is indeed dominated by fake background. The fraction of fakes is 65%. The second dominant background in the validation region is diboson. Its fraction is 30%. The NLO normalisation for the  $WW$  and  $WZ$  backgrounds is extracted using the dedicated fiducial region adapted to the VR-Fakes. Figure 15.2 presents the distributions of the invariant mass of the dijet system (a), the  $|\Delta\eta_{jj}|$  between the two leading jets (b), the missing transverse energy (c) and the transverse momentum of the subleading lepton (d) in the validation region VR-Fakes. A good agreement between data and final background prediction is observed. The prediction here includes the data driven estimates.

| Processes                                                                                                         | $ee$                            | $\mu\mu$                        | $e\mu$                           | $ee + \mu\mu + e\mu$             |
|-------------------------------------------------------------------------------------------------------------------|---------------------------------|---------------------------------|----------------------------------|----------------------------------|
| Fakes                                                                                                             | $5.36 \pm 0.99^{+1.77}_{-1.77}$ | $7.29 \pm 1.55^{+2.25}_{-2.25}$ | $14.74 \pm 2.52^{+5.60}_{-5.60}$ | $27.39 \pm 3.12^{+9.61}_{-9.61}$ |
| WW                                                                                                                | $0.26 \pm 0.06^{+0.04}_{-0.03}$ | $0.23 \pm 0.03^{+0.03}_{-0.03}$ | $0.89 \pm 0.39^{+0.11}_{-0.10}$  | $1.37 \pm 0.40^{+0.17}_{-0.16}$  |
| WZ                                                                                                                | $0.05 \pm 0.01^{+0.02}_{-0.06}$ | $0.39 \pm 0.18^{+0.11}_{-0.15}$ | $0.49 \pm 0.16^{+0.15}_{-0.16}$  | $0.93 \pm 0.24^{+0.25}_{-0.30}$  |
| ZZ                                                                                                                | $0.01 \pm 0.01^{+0.00}_{-0.00}$ | $< 0.01$                        | $< 0.01$                         | $0.01 \pm 0.01^{+0.00}_{-0.00}$  |
| Charge flip                                                                                                       | $0.26 \pm 0.01^{+0.26}_{-0.26}$ | $< 0.01$                        | $0.31 \pm 0.01^{+0.31}_{-0.31}$  | $0.57 \pm 0.01^{+0.57}_{-0.57}$  |
| Top                                                                                                               | $0.04 \pm 0.02^{+0.02}_{-0.01}$ | $0.25 \pm 0.12^{+0.02}_{-0.01}$ | $0.27 \pm 0.20^{+0.02}_{-0.02}$  | $0.57 \pm 0.24^{+0.02}_{-0.02}$  |
| Higgs                                                                                                             | $< 0.01$                        | $< 0.01$                        | $< 0.01$                         | $< 0.01$                         |
| Total                                                                                                             | $5.97 \pm 0.99^{+1.78}_{-1.78}$ | $8.16 \pm 1.57^{+2.25}_{-2.25}$ | $16.71 \pm 2.57^{+5.60}_{-5.60}$ | $30.84 \pm 3.17^{+9.63}_{-9.62}$ |
| $\tilde{\chi}_1^\pm \tilde{\chi}_1^\pm$ via VBF<br>( $m_{\tilde{\chi}_1^\pm}, m_{\tilde{\chi}_1^0}$ ) = (120, 95) | $0.17 \pm 0.03$                 | $0.28 \pm 0.04$                 | $0.40 \pm 0.05$                  | $0.85 \pm 0.07$                  |
| Data                                                                                                              | 6                               | 8                               | 11                               | 25                               |

Table 15.1: Observed and expected numbers of events in the validation region VR-Top. The first error is the uncertainty from limited Monte Carlo statistics. The second error is the result of all sources of systematic uncertainties. The prediction correspond to  $20.3 \text{ fb}^{-1}$ . For very small predicted event yields a conservative upper limit of 0.01 events at not less than 68% CL is given.

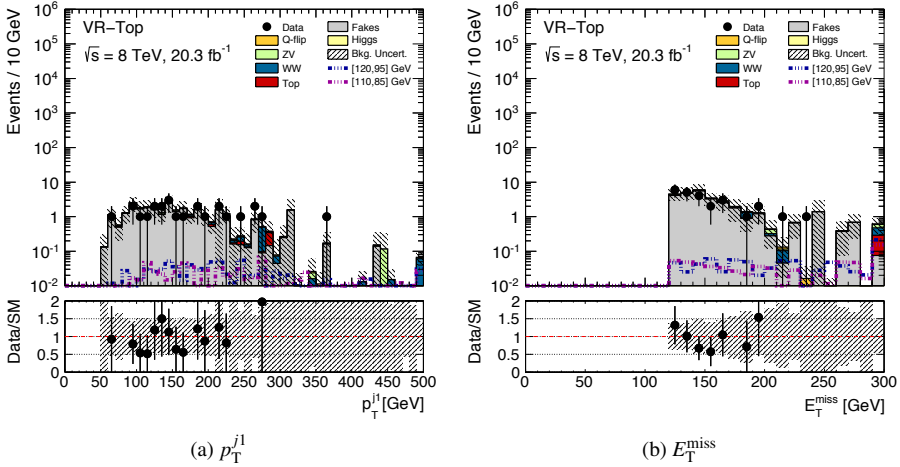


Figure 15.1: Distributions of the transverse momentum of the leading jet (a) and the missing transverse energy (b) in the validation region VR-Top. The uncertainty band represents the total statistical and systematic uncertainty on the Monte Carlo prediction. The data points correspond to  $20.3 \text{ fb}^{-1}$ . The “Q-flip” background category includes Charge Flip background. The sum of  $e^\pm e^\pm$ ,  $e^\pm \mu^\pm$  and  $\mu^\pm \mu^\pm$  events is presented.

| Processes                                                                                                     | $ee$                                | $\mu\mu$                            | $e\mu$                              | $ee + \mu\mu + e\mu$                   |
|---------------------------------------------------------------------------------------------------------------|-------------------------------------|-------------------------------------|-------------------------------------|----------------------------------------|
| Fakes                                                                                                         | $63.87 \pm 3.43^{+23.26}_{-23.26}$  | $76.46 \pm 5.72^{+24.84}_{-24.84}$  | $141.62 \pm 6.86^{+49.72}_{-49.72}$ | $281.96 \pm 9.56^{+97.82}_{-97.82}$    |
| WW                                                                                                            | $18.27 \pm 1.39^{+5.67}_{-5.86}$    | $11.23 \pm 0.24^{+3.50}_{-3.51}$    | $34.57 \pm 1.70^{+11.23}_{-10.76}$  | $64.08 \pm 2.21^{+20.41}_{-20.05}$     |
| WZ                                                                                                            | $14.01 \pm 1.15^{+3.17}_{-3.66}$    | $18.87 \pm 1.41^{+4.99}_{-4.40}$    | $32.56 \pm 1.82^{+7.66}_{-7.50}$    | $65.43 \pm 2.57^{+15.73}_{-15.35}$     |
| ZZ                                                                                                            | $0.94 \pm 0.19^{+0.03}_{-0.04}$     | $0.22 \pm 0.12^{+0.13}_{-0.12}$     | $0.53 \pm 0.17^{+0.11}_{-0.20}$     | $1.68 \pm 0.28^{+0.22}_{-0.27}$        |
| Charge flip                                                                                                   | $3.87 \pm 0.03^{+1.93}_{-1.93}$     | $< 0.01$                            | $3.89 \pm 0.03^{+1.95}_{-1.95}$     | $7.76 \pm 0.04^{+3.88}_{-3.88}$        |
| Top                                                                                                           | $2.46 \pm 0.42^{+0.44}_{-0.43}$     | $3.96 \pm 0.57^{+0.40}_{-0.43}$     | $6.50 \pm 0.79^{+0.49}_{-0.53}$     | $12.93 \pm 1.06^{+1.10}_{-1.03}$       |
| Higgs                                                                                                         | $0.07 \pm 0.04^{+0.00}_{-0.01}$     | $0.01 \pm 0.00^{+0.00}_{-0.00}$     | $0.16 \pm 0.06^{+0.04}_{-0.00}$     | $0.24 \pm 0.07^{+0.08}_{-0.01}$        |
| Total                                                                                                         | $103.49 \pm 3.90^{+24.51}_{-24.38}$ | $110.74 \pm 5.92^{+25.54}_{-25.63}$ | $219.84 \pm 7.34^{+51.55}_{-51.78}$ | $434.08 \pm 10.21^{+101.36}_{-101.61}$ |
| $\tilde{\chi}_1^+ \tilde{\chi}_1^+$ via VBF<br>( $m_{\tilde{\chi}_1^\pm}, m_{\tilde{\chi}_1^0} = (120, 95)$ ) | $1.55 \pm 0.08$                     | $2.91 \pm 0.11$                     | $3.86 \pm 0.13$                     | $8.32 \pm 0.19$                        |
| Data                                                                                                          | 112                                 | 94                                  | 194                                 | 400                                    |

Table 15.2: Observed and expected numbers of events in the validation region VR-Fakes. The first error is the uncertainty from limited Monte Carlo statistics. The second error is the result of all sources of systematic uncertainties. The prediction correspond to  $20.3 \text{ fb}^{-1}$ . For very small predicted event yields a conservative upper limit of 0.01 events at not less than 68% CL is given.

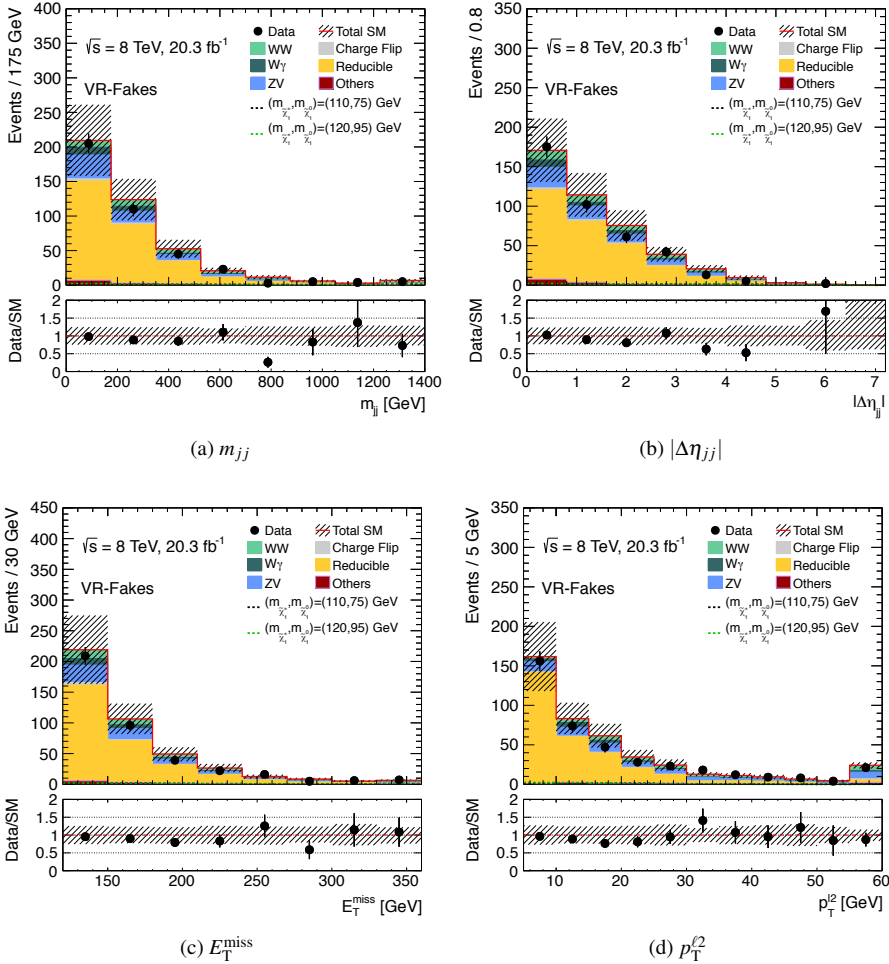


Figure 15.2: Distributions of the invariant mass of the dijet system (a), the  $|\Delta\eta_{jj}|$  between the two leading jets (b), the missing transverse energy (c) and the transverse momentum of the subleading lepton (d) in the validation region VR-Fakes. The uncertainty band represents the total statistical and systematic uncertainty on the Monte Carlo prediction. The data points correspond to  $20.3 \text{ fb}^{-1}$ . The “Reducible” background category includes fake background. The “Others” background category includes Top, Higgs and VVV processes. The  $W\gamma$  background is included in the  $WW$  category in Tab. 15.2. The sum of  $e^\pm e^\pm$ ,  $e^\pm \mu^\pm$  and  $\mu^\pm \mu^\pm$  events is presented.

## 15.1.3 VR-VV

The expected and observed numbers of events in the validation region VR-VV are presented in Tab. 15.3. It can be seen that this region is indeed dominated by the diboson backgrounds with 81% of the number of events coming from diboson processes. Figure 15.3 presents the distributions of the invariant mass of the dijet system (a), the transverse momentum of the subleading jet (b) in the validation region VR-VV. There is a fair agreement between data and prediction. The prediction here includes the data driven estimates.

| Processes                                                                                                         | $ee$                            | $\mu\mu$                         | $e\mu$                           | $ee + \mu\mu + e\mu$             |
|-------------------------------------------------------------------------------------------------------------------|---------------------------------|----------------------------------|----------------------------------|----------------------------------|
| Fakes                                                                                                             | $2.53 \pm 0.69^{+1.34}_{-1.34}$ | $0.00^{+0.13+0.08}_{-0.00-0.00}$ | $1.51 \pm 0.65^{+0.73}_{-0.73}$  | $4.04 \pm 0.96^{+1.99}_{-1.99}$  |
| WW                                                                                                                | $3.93 \pm 0.60^{+0.39}_{-0.54}$ | $2.13 \pm 0.09^{+0.17}_{-0.19}$  | $6.19 \pm 0.54^{+0.53}_{-0.49}$  | $12.25 \pm 0.81^{+0.99}_{-1.09}$ |
| WZ                                                                                                                | $2.46 \pm 0.47^{+0.65}_{-0.68}$ | $2.79 \pm 0.52^{+0.75}_{-0.72}$  | $5.75 \pm 0.75^{+1.48}_{-1.46}$  | $11.01 \pm 1.03^{+2.80}_{-2.81}$ |
| ZZ                                                                                                                | $0.52 \pm 0.16^{+0.02}_{-0.03}$ | $0.06 \pm 0.06^{+0.00}_{-0.00}$  | $0.06 \pm 0.06^{+0.04}_{-0.04}$  | $0.65 \pm 0.18^{+0.08}_{-0.05}$  |
| Charge flip                                                                                                       | $0.41 \pm 0.01^{+0.41}_{-0.41}$ | $< 0.01$                         | $0.30 \pm 0.01^{+0.30}_{-0.30}$  | $0.71 \pm 0.02^{+0.71}_{-0.71}$  |
| Top                                                                                                               | $0.04 \pm 0.01^{+0.01}_{-0.01}$ | $0.03 \pm 0.01^{+0.02}_{-0.01}$  | $0.05 \pm 0.02^{+0.01}_{-0.01}$  | $0.11 \pm 0.03^{+0.04}_{-0.03}$  |
| Higgs                                                                                                             | $0.05 \pm 0.04^{+0.00}_{-0.00}$ | $0.00 \pm 0.00^{+0.00}_{-0.00}$  | $0.02 \pm 0.01^{+0.00}_{-0.00}$  | $0.06 \pm 0.04^{+0.03}_{-0.00}$  |
| Total Bg                                                                                                          | $9.93 \pm 1.04^{+2.20}_{-2.15}$ | $5.01 \pm 0.54^{+0.80}_{-0.81}$  | $13.88 \pm 1.14^{+2.03}_{-2.04}$ | $28.83 \pm 1.63^{+4.48}_{-4.41}$ |
| $\tilde{\chi}_1^\pm \tilde{\chi}_1^\pm$ via VBF<br>( $m_{\tilde{\chi}_1^\pm}, m_{\tilde{\chi}_1^0}$ ) = (120, 95) | $0.06 \pm 0.02$                 | $0.09 \pm 0.02$                  | $0.09 \pm 0.02$                  | $0.25 \pm 0.03$                  |
| Data                                                                                                              | 10                              | 1                                | 9                                | 20                               |

Table 15.3: Observed and expected numbers of events in the validation region VR-VV. The first error is the uncertainty from limited Monte Carlo statistics. The second error is the result of all sources of systematic uncertainties. The prediction correspond to  $20.3 \text{ fb}^{-1}$ . For very small predicted event yields a conservative upper limit of 0.01 events at not less than 68% CL is given.

## 15.2 Event Display

An event candidate for  $\tilde{\chi}_1^\pm \tilde{\chi}_1^\pm$  pair production via vector boson fusion was observed in ATLAS on October 27 2012 and is visualised using the ATLAS event display package Atlantis and presented in Fig. 15.4. The event contains two muons indicated by white lines with transverse momenta of  $p_T^{\mu 1} = 19 \text{ GeV}$  and  $p_T^{\mu 2} = 7 \text{ GeV}$ . Two jets with transverse momenta of  $p_T^{j1} = 146 \text{ GeV}$  and  $p_T^{j2} = 31 \text{ GeV}$  are present in the forward region of the detector. The invariant mass of the dijet system is  $m_{jj} = 1.2 \text{ TeV}$ .



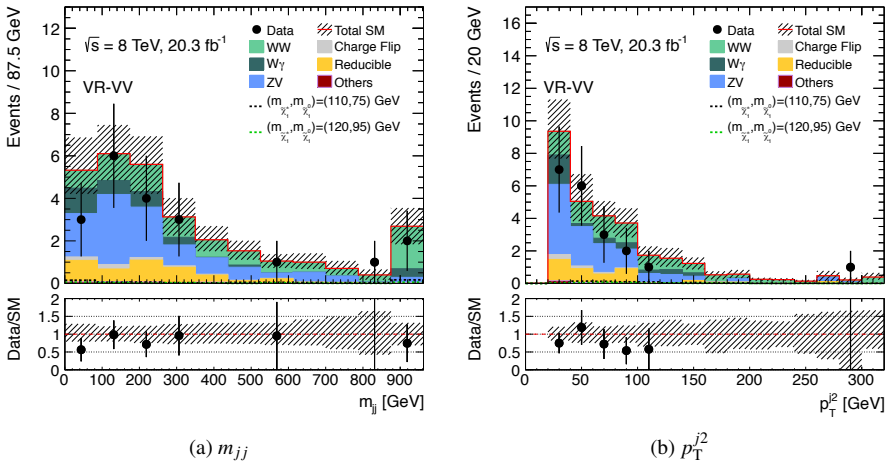


Figure 15.3: Distributions of the invariant mass of the dijet system (a), the transverse momentum of the subleading jet (b) in the validation region VR-VV. The uncertainty band represents the total statistical and systematic uncertainty on the Monte Carlo prediction. The data points correspond to  $20.3 \text{ fb}^{-1}$ . The “Reducible” background category includes fake background. The “Others” background category includes Top, Higgs and VVV processes. The  $W\gamma$  background is included in the WW category in Tab. 15.3. The sum of  $e^\pm e^\pm$ ,  $e^\pm \mu^\pm$  and  $\mu^\pm \mu^\pm$  events is presented.

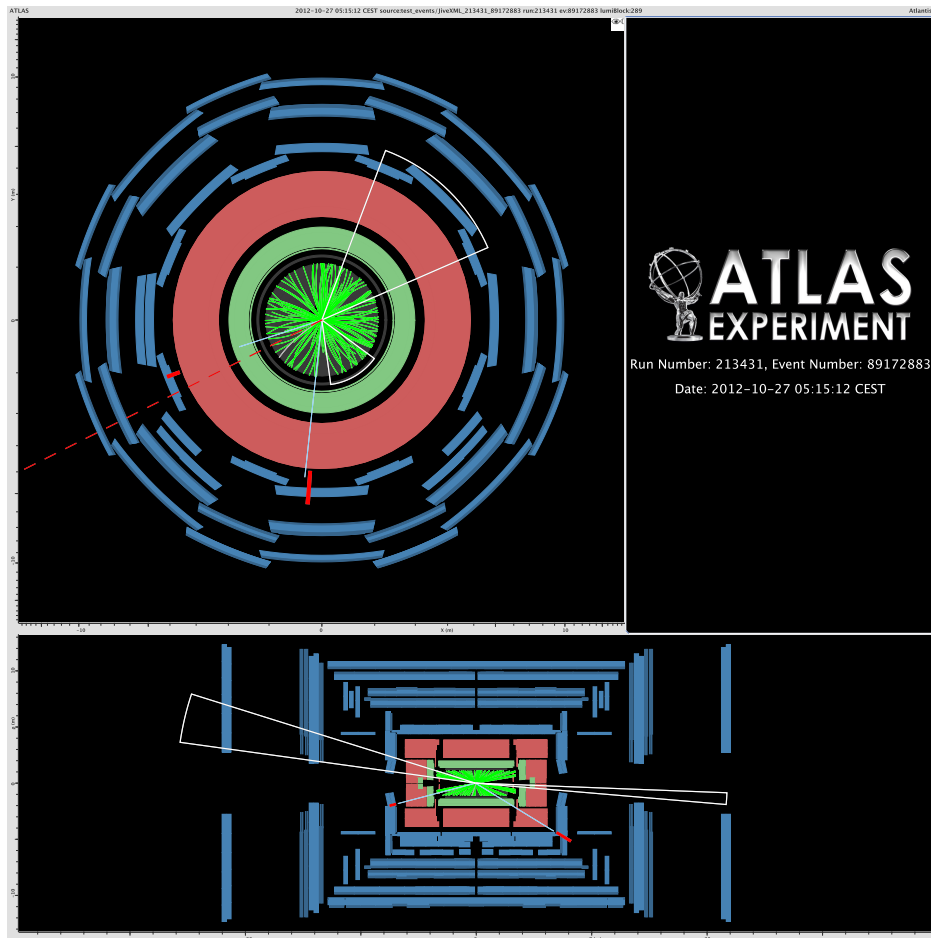


Figure 15.4: Event display of one signal-like collision event in ATLAS data from October 27, 2012. The event is visualised using ATLAS event display package Atlantis. It contains two muons with  $p_T^{\mu 1} = 19$  GeV and  $p_T^{\mu 2} = 7$  GeV indicated by white lines. Two jets  $p_T^{j1} = 146$  GeV and  $p_T^{j2} = 31$  GeV are present in the forward region of the detector. This results in  $m_{jj} = 1.2$  TeV. The jets are indicated by white cones with area proportional to the transverse momentum of the jet. The  $E_T^{\text{miss}} = 130$  GeV is represented by the red dashed line.

### 15.3 Results in the Signal Region

The expected and observed numbers of events in the signal region SR-VBF are presented in Tab. 15.4. The fake background is estimated using the data driven fake factor method. The charge flip background is estimated with its own data driven method. The  $WW$  and  $WZ$  production is estimated using Monte Carlo with NLO normalisation extracted from the fiducial regions. The other backgrounds are estimated from MC only. There is a good agreement between data and prediction and no significant excess over background is observed.

A summary of the largest systematic uncertainties for the signal region SR-VBF is presented in Tab. 15.5. The dominant uncertainty comes from the fake background estimation. The total uncertainty on all backgrounds is 21%.

Figure 15.5 shows the distributions of some selected variables in the signal region SR-VBF: the invariant mass of the dijet system (a), the  $|\Delta\eta_{jj}|$  between the two leading jets (b), the missing transverse energy (c) and the transverse momentum of the sub-leading lepton (d) are presented. Within the small statistics of the signal region the background model agrees with data within the statistical and systematics uncertainties.

| Processes                                                                                                         | $ee$                            | $\mu\mu$                        | $e\mu$                          | $ee + \mu\mu + e\mu$             |
|-------------------------------------------------------------------------------------------------------------------|---------------------------------|---------------------------------|---------------------------------|----------------------------------|
| Fakes                                                                                                             | $1.46 \pm 0.54^{+0.46}_{-0.46}$ | $1.05 \pm 0.62^{+0.25}_{-0.25}$ | $2.73 \pm 0.89^{+0.89}_{-0.89}$ | $5.24 \pm 1.21^{+1.60}_{-1.60}$  |
| $WW$                                                                                                              | $0.65 \pm 0.20^{+0.12}_{-0.05}$ | $0.57 \pm 0.05^{+0.06}_{-0.06}$ | $1.40 \pm 0.25^{+0.37}_{-0.12}$ | $2.62 \pm 0.32^{+0.49}_{-0.22}$  |
| $WZ$                                                                                                              | $0.47 \pm 0.17^{+0.19}_{-0.24}$ | $0.73 \pm 0.25^{+0.30}_{-0.22}$ | $1.11 \pm 0.30^{+0.31}_{-0.40}$ | $2.32 \pm 0.42^{+0.68}_{-0.78}$  |
| $ZZ$                                                                                                              | $< 0.01$                        | $< 0.01$                        | $0.04 \pm 0.04^{+0.10}_{-0.17}$ | $0.05 \pm 0.04^{+0.10}_{-0.17}$  |
| Charge flip                                                                                                       | $0.02 \pm 0.00^{+0.02}_{-0.01}$ | $< 0.01$                        | $0.02 \pm 0.00^{+0.02}_{-0.01}$ | $0.03 \pm 0.00^{+0.03}_{-0.02}$  |
| Top                                                                                                               | $< 0.01$                        | $0.01 \pm 0.01^{+0.00}_{-0.00}$ | $< 0.01$                        | $0.01 \pm 0.01^{+0.00}_{-0.00}$  |
| Higgs                                                                                                             | $< 0.01$                        | $< 0.01$                        | $< 0.01$                        | $0.01 \pm 0.00^{+0.00}_{-0.00}$  |
| Total                                                                                                             | $2.60 \pm 0.60^{+0.53}_{-0.52}$ | $2.36 \pm 0.67^{+0.40}_{-0.40}$ | $5.30 \pm 0.97^{+1.03}_{-1.03}$ | $10.27 \pm 1.33^{+1.88}_{-1.90}$ |
| $\tilde{\chi}_1^\pm \tilde{\chi}_1^\pm$ via VBF<br>( $m_{\tilde{\chi}_1^\pm}, m_{\tilde{\chi}_0^0} = (120, 95)$ ) | $0.63 \pm 0.05$                 | $1.16 \pm 0.07$                 | $1.69 \pm 0.09$                 | $3.47 \pm 0.12$                  |
| Data                                                                                                              | 3                               | 4                               | 3                               | 10                               |

Table 15.4: Observed and expected numbers of events in the signal region SR-VBF. The first error is the uncertainty from limited Monte Carlo statistics. The second error is the result of all sources of systematic uncertainties. The prediction correspond to  $20.3 \text{ fb}^{-1}$ . For very small predicted event yields a conservative upper limit of 0.01 events at not less than 68% CL is given.

| Dominant systematic uncertainties in SR-VBF  |     |
|----------------------------------------------|-----|
| Fake factor systematic uncertainty           | 13% |
| Fake background statistical uncertainty      | 11% |
| $WZ$ theoretical uncertainty                 | 5%  |
| $WZ$ statistical uncertainty                 | 4%  |
| Electron fake factor statistical uncertainty | 3%  |
| Jet energy resolution                        | 3%  |
| $WW$ statistical uncertainty                 | 3%  |
| $WW$ theoretical uncertainty                 | 1%  |
| Total                                        | 21% |

Table 15.5: The dominant systematic uncertainties on the background estimates for the signal region SR-VBF. The percentages show the size of the uncertainty relative to the total expected background. The total uncertainty includes all sources of systematic uncertainties.

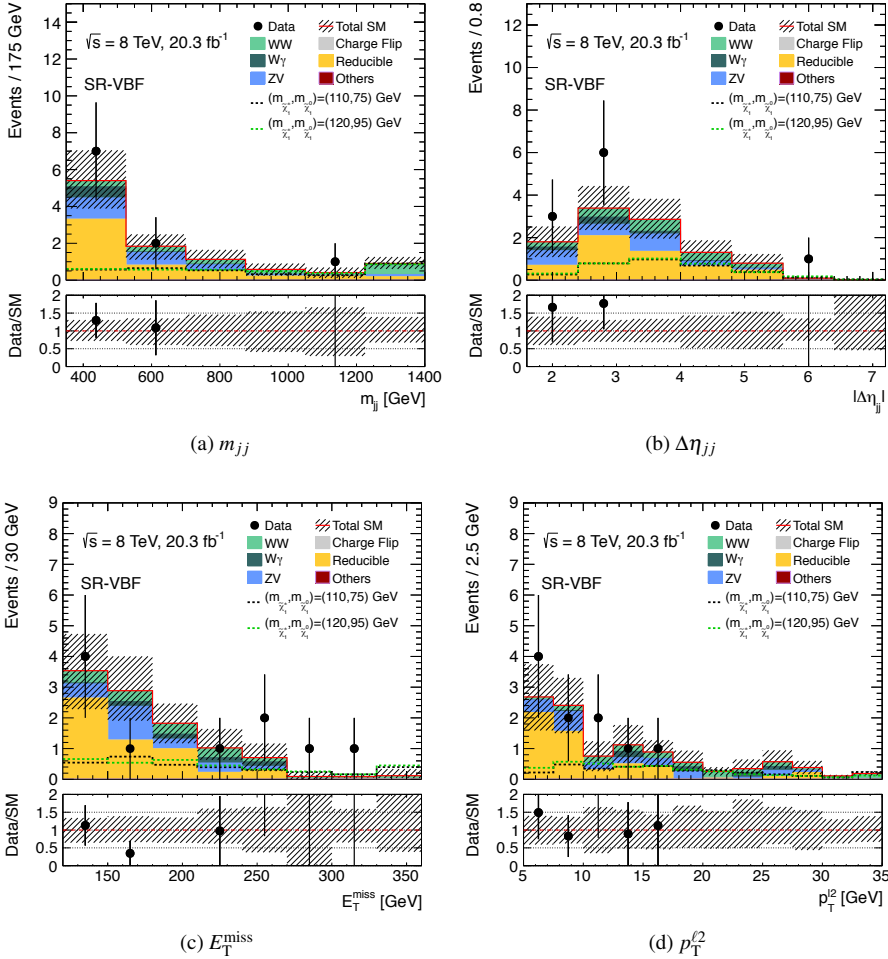


Figure 15.5: Distributions of the invariant mass of the dijet system (a), the  $|\Delta\eta_{jj}|$  between the two leading jets (b), the missing transverse energy (c) and the transverse momentum of the subleading lepton (d) in the SR-VBF. The uncertainty band represents the total statistical and systematic uncertainty on the Monte Carlo prediction. The data points correspond to  $20.3 \text{ fb}^{-1}$ . The “Reducible” background category includes fake background. The “Others” background category includes Top, Higgs and VVV processes. The  $W\gamma$  background is included in the  $WW$  category in Tab. 15.4. The sum of  $e^\pm e^\pm$ ,  $e^\pm \mu^\pm$  and  $\mu^\pm \mu^\pm$  events is presented.

## 15.4 Interpretation and Conclusion

In the signal region SR-VBF no significant excess over background is observed. Therefore, upper limits at 95% confidence level on the cross section for same sign  $\tilde{\chi}_1^\pm \tilde{\chi}_1^\pm$  pair production via VBF are derived. The methodology applied to calculate the limits is presented in Section 10.2.

In the limit plots shown in Fig. 15.6 the dashed black line corresponds to the expected limits, while the solid red line represents observed limits. Statistical and systematic uncertainties are included. The yellow band shows the experimental  $1\sigma$  uncertainties on the expected limit, while the green band shows the signal cross section scaled up and down by  $1\sigma$  of theoretical uncertainties.

The figure shows the 95% CL upper limit on the cross section for same sign  $\tilde{\chi}_1^\pm \tilde{\chi}_1^\pm$  pair production via VBF for  $m_{\tilde{\chi}_1^\pm} = 110$  GeV (a) and  $m_{\tilde{\chi}_1^\pm} = 120$  GeV (b). The limits are set with respect to the mass difference  $m_{\tilde{\chi}_1^\pm} - m_{\tilde{\chi}_1^0}$ . The best observed limit upper limit on the VBF  $\tilde{\chi}_1^\pm \tilde{\chi}_1^\pm$  production cross section is found for  $m_{\tilde{\chi}_1^\pm} = 120$  GeV and a mass difference  $m_{\tilde{\chi}_1^\pm} - m_{\tilde{\chi}_1^0} = 25$  GeV. For this model the theoretical cross section at LO is 4.33 fb and the excluded cross section is 10.9 fb. This scenario has the highest sensitivity since it was used for the optimisation of the signal region.

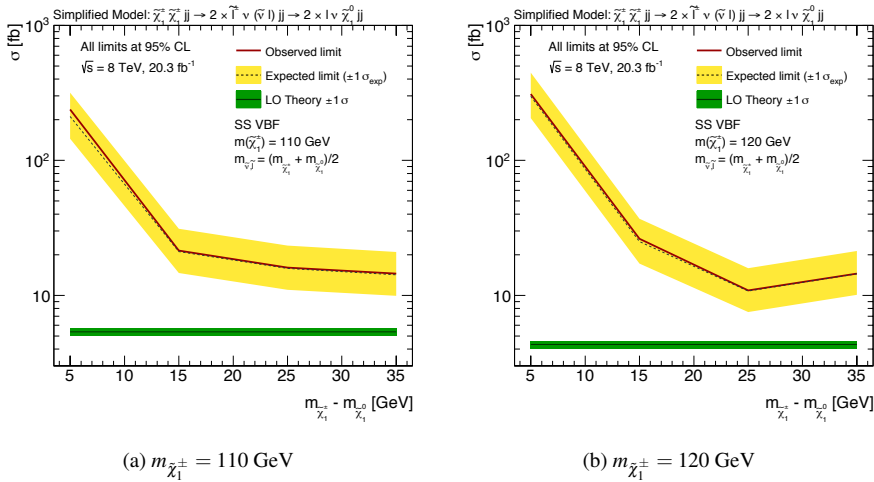


Figure 15.6: The 95% CL upper limit on the cross section for same sign  $\tilde{\chi}_1^\pm \tilde{\chi}_1^\pm$  pair production via VBF for  $m_{\tilde{\chi}_1^\pm} = 110$  GeV (a) and  $m_{\tilde{\chi}_1^\pm} = 120$  GeV (b). The limits have been set with respect to the mass difference between  $m_{\tilde{\chi}_1^\pm} - m_{\tilde{\chi}_1^0}$ .



# Conclusions

A precise energy measurement of hadronic jets is crucial both for studies of Standard Model processes and searches for physics beyond the Standard Model. In 2011-2012 the LHC was providing collisions every 50 ns. Presence of energy deposits from different collisions in the same read-out window and in the same calorimeter channel (out-of-time pile-up) can spoil the energy measurements by the calorimeter.

A pulse simulator for the ATLAS Tile Calorimeter has been developed. It is shown that the simulator is able to reproduce the quality factor distributions in absence of out-of-time pile-up in data. Using this model the distribution of quality factor in presence of out-of-time pile-up is calculated. Large out-of-time pile-up pulses that significantly affect the amplitude measurements are considered. A significant discrimination between events with out-of-time pile-up and without out-of-time pile-up is achieved. It is shown that the quality factor can be used to identify channels that received large energy deposition from pile-up and therefore require special treatment. Efficient criteria to detect pile-up in TileCal channels are proposed for three energy bins. In the first two energy bins with energies below 5 GeV, the cut on the quality factor allows to select all pile-up events with a fake rate less than 1%. In the third energy bin with energies between 5 and 12 GeV, several criteria are proposed. For instance one can successfully identify more than 99% of the events with pile-up with a fake rate of 3.75%. Since the work presented in this thesis was completed, the work with the pile-up simulator has been continued by other members of the Stockholm University ATLAS group and has been incorporated in the official ATLAS software, it is used by the entire Tile Calorimeter community.

Two searches for supersymmetric particles in proton-proton collision at  $\sqrt{s} = 8$  TeV recorded by the ATLAS experiment are presented. The full 2012 data taking period is analysed, corresponding to a total integrated luminosity of  $\mathcal{L} = 20.3 \text{ fb}^{-1}$ .

A search for production of chargino and slepton pairs in a final state characterised by the presence of two leptons and missing transverse energy is presented. The case when they are directly produced in the proton-proton collisions as opposed to secondary gauginos and sleptons produced in decays of heavier supersymmetric particles is considered.

A novel element introduced in this work and in the presented data analysis is the use of the jet-veto. The sought signal processes do not yield hadronic activity in form of jets. Nevertheless, jets can arise from initial state radiation and pile-up interactions. On



the other hand the large  $t\bar{t}$  background can yield two leptons and two jets coming from  $b$ -quarks. Another source of jets is pile-up in Standard Model processes without jets. The additional jets from pile-up can equally appear overlaid over chargino and slepton pair events which would thus look background-like. For this reason it is important to specifically veto jets from the hard proton-proton interaction but keep events with pile-up jets. A jet-veto definition was specifically developed for the search for gauginos and sleptons. The efficiency of the jet-veto is studied in a  $b$ -tag control region and a  $Z$  control region. It is shown that the probability to pass the jet-veto in data is well reproduced by Monte Carlo. Based on these studies the ATLAS simulation was used in **Paper III** to model the jet-veto for  $t\bar{t}$  events without additional corrections.

One of the dominant Standard Model backgrounds in this analysis is the production of a  $Z$  boson with an associated vector boson  $W$  or  $Z$  and denoted  $ZV$ . This background is estimated using a data-driven technique. A control region containing almost exclusively  $ZV$  processes is constructed. It is shown that its potential contamination from chargino and slepton processes is low. Using the  $ZV$  control region the number of  $ZV$  background events is estimated in the signal regions. The  $ZV$  control region is finally used for the final exclusion fits performed in **Paper III**.

In absence of significant excess over the expected Standard Model prediction, exclusion limits at 95% confidence level on chargino, neutralino and slepton production are set in the context of SUSY inspired simplified model topologies. For the direct chargino pair production with intermediate sleptons, chargino masses between  $m_{\tilde{\chi}_1^\pm} = 140$  GeV and  $m_{\tilde{\chi}_1^\pm} = 475$  GeV are excluded for a massless neutralino. For the direct chargino pair production with intermediate  $W$  bosons, the chargino mass range  $10 < m_{\tilde{\chi}_1^\pm} < 180$  GeV is excluded for a neutralino mass  $m_{\tilde{\chi}_1^0} = 0$  GeV. For a neutralino mass  $m_{\tilde{\chi}_1^0} = 0$  GeV a common value for left- and right- handed slepton mass between  $m_{\tilde{\ell}^\pm} = 90$  GeV and  $m_{\tilde{\ell}^\pm} = 325$  GeV is excluded. For a neutralino mass  $m_{\tilde{\chi}_1^0} = 100$  GeV slepton masses between  $m_{\tilde{\ell}^\pm} = 160$  GeV and  $m_{\tilde{\ell}^\pm} = 310$  GeV are excluded.

The second analysis concentrates on a previously unexplored search channel for Supersymmetry. A search for production of same charge chargino pairs via Vector Boson Fusion in a final state containing two leptons, two jets and missing transverse energy is presented in Part IV of this thesis. This is the first attempt in ATLAS to search for supersymmetric particles produced via VBF. A possible observation of such a process would prove the Majorana nature of the exchanged neutralino.

The cross section for the chargino pair production via VBF is very low. Therefore, a carefully optimised event selection has to be applied to suppress the Standard Model backgrounds while retaining enough signal. Since many kinematic variables are correlated the selections cannot be optimised one variable at a time. A signal region optimisation was performed in which several variables are scanned simultaneously in order to address the correlation issue. Using this technique a signal region is optimised for chargino VBF signatures and low mass differences between the chargino and the neutralino. The signal model for which the highest sensitivity is achieved corresponds

to a bino-wino scenario with a mass difference  $m_{\tilde{\chi}_1^\pm} - m_{\tilde{\chi}_1^0} = 25$  GeV. For this point the expected excluded cross section is above the predicted cross section by a factor 1.8.

The diboson processes that involve production of  $WW$  and  $WZ$  pairs are important backgrounds in this analysis, particularly because they can also be produced via vector boson fusion. This background is calculated using Monte Carlo simulations with NLO normalisation. The normalisation is obtained from dedicated fiducial regions using NLO generators and NLO cross section calculators. The corresponding systematic uncertainties originating from generator, scale, PDF and parton showering are also estimated. All background estimations in the search for chargino production via VBF are validated using dedicated validation regions.

No significant excess over the expected SM background is observed and exclusion limits at 95% confidence level are set on the production cross section of chargino pair production via VBF. For a mass difference  $m_{\tilde{\chi}_1^\pm} - m_{\tilde{\chi}_1^0} = 25$  GeV the excluded cross section is above the model cross section by a factor 3 at  $m_{\tilde{\chi}_1^\pm} = 110$  GeV and a factor 2 for  $m_{\tilde{\chi}_1^\pm} = 120$  GeV.

Recently, the LHC restarted its operations providing proton-proton collisions at  $\sqrt{s} = 13$  TeV. This increase in energy will allow to access higher particle masses and even rarer processes. In the new LHC run, the collisions occur every 25 ns, doubling the collision frequency with respect to LHC Run-1, thus providing a significant increase of the instantaneous luminosity. The second run of the LHC will allow to significantly increase the sensitivity to the search channels presented in this thesis, both direct chargino and sleptons searches and gaugino production via VBF. Searches for these channels will also benefit from larger cross sections at the new center of mass energy.



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I



# Identification of Pile-up Using the Quality Factor of Pulse Shapes in the ATLAS Tile Calorimeter

Christophe Clement, Pawel Klimek  
(on behalf of the ATLAS Collaboration)

**Abstract**—The ATLAS experiment records data from the proton-proton collisions produced by the Large Hadron Collider (LHC). The Tile Calorimeter is the hadronic sampling calorimeter of ATLAS in the region  $|\eta| < 1.7$ . It uses iron absorbers and scintillators as active material. The LHC will provide collisions every 25 ns, putting very strong requirements on the energy measurement in presence of energy deposits from different collisions in the same read out window and physical calorimeter channel (pile-up). In 2011 the LHC is running with filled bunches at 50 ns spacing and at intensities which yield up to about 8 proton-proton collisions per bunch crossing. We present a quality factor that can be computed online for each collision and for each calorimeter channel within the 10  $\mu$ s latency of the ATLAS first level trigger (L1 trigger), and could allow to identify calorimeter channels presenting pile-up. In presence of a poor quality factor the data from the corresponding channel is read out with additional information to allow for an offline dedicated treatment of the signals to account for pile-up.

## I. INTRODUCTION

THE Large Hadron Collider (LHC), currently under operation at CERN, with its unprecedented high energy and luminosity extends the frontier of particle physics. Bunches of up to  $10^{11}$  protons collide 40 million times per second at a center of mass energy of 7 TeV and a design luminosity of  $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ . Nominally the LHC will operate with proton bunches crossing every 25 ns, although in 2011 it has operated with 50 ns bunch spacing and with an expected average number of 8 proton-proton collisions per bunch crossing. The high interaction rates, energies, particle multiplicities, radiation doses and need for precision measurements require new standards for the design of particle detectors at LHC. ATLAS [1] is one of the major experiments designed to exploit the proton-proton data in this stringent environment.

ATLAS is a general-purpose experiment, whose goal is to cover a broad range of experimental particle physics phenomena, with the long sought Higgs boson [2] and supersymmetry [3] on top of the wanted list. The ATLAS experiment needs to be sensitive to a large number of possible decay channels and so must provide an excellent particle identification and high resolution measurements of energies, momenta and directions for the outgoing particles in the proton-proton collisions.

The Tile Calorimeter (TileCal) [4] is the hadronic sampling calorimeter of ATLAS in the region  $|\eta| < 1.7$ . The purpose of TileCal is to identify hadronic jets and measure their energy and direction. TileCal also provides vital information for the first level of trigger (L1-trigger), participates in the measurement of the missing energy due to non-interacting particles and to the identification of electrons and photons. It uses steel as an absorber and scintillating plastic tiles as an active material. Several scintillating tiles are grouped together at the read out level to form calorimeter cells. The wavelength shifting fibers couple the light from the tiles to photomultipliers (PMTs), with most TileCal cells being read out by two PMTs, corresponding to two electronic read out channels. The PMT output is a current pulse with its amplitude proportional to the energy deposited in the associated cell. Electronics mounted on the PMT amplifies and shapes the output current pulse. Pulse shaping increases the width at half-maximum to 50 ns. The analogue pulse is digitized with 7 samples at 25 ns intervals which are read out upon a trigger accept from the L1 trigger (L1A) and used to compute the pulse amplitude, phase and quality factor. 10-bit analogue to digital converters are used for the digitization.

The presence of collisions every 50 ns and the relatively large read-out window ( $\pm 75$  ns) lead to a significant fraction of calorimeter cells receiving energy from more than one bunch crossing within the same read out window and within the same physical calorimeter cell (out-of-time pile-up). Out-of-time pile-up degrades the measurement of the energy deposited in a physical cell. A quality factor is computed online for each event and for each calorimeter channel. It allows to identify calorimeter channels presenting out-of-time pile-up. In presence of a high quality factor value all 7 samples are read out to allow for a dedicated treatment of the pile-up signals offline.

A numerical model has been developed to simulate the TileCal pulse shapes and quality factors with and without out-of-time pile-up. The simulated observables are compared with actual proton-proton data in order to validate the model. The model includes electronic noise, time resolution effects and non-ideal pulse shapes. The numerical model allows to predict quality factor distributions thus permitting the optimization of the quality factor online selection criteria, under the constraints of available bandwidth while keeping a reliable out-of-time pile-up detection.

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Christophe Clement is with the Stockholm University, Sweden (telephone: +46 8 5537 8658, e-mail: clement@fysik.su.se).

Pawel Klimek is with the Stockholm University, Sweden (telephone: +46 8 5537 8152, e-mail: pawel.klimek@cern.ch).



## II. ENERGY RECONSTRUCTION AND QUALITY FACTOR DEFINITION

The goal of the energy reconstruction in TileCal is to compute the energy deposited in a TileCal cell from the number of ADC counts measured in each of the two corresponding read out channels. For each channel, 7 samples at 25 ns spacing are available, these samples are referred to as  $S_i$  with  $i = 1-7$  and are in units of ADC counts. In order to maximize the dynamic range, either a low or a high amplification (or gain) is used, depending on the pulse amplitude. The ratio between the low and the high amplification is 64. The high gain is applied to pulses up to about 12 GeV, while the low gain is applied for higher energies. One ADC count corresponds approximately to 12 MeV of deposited energy in high gain and about 800 MeV in low gain. The exact correspondence is cell-dependent and requires careful calibration [5].

The energy reconstruction combines the  $S_i$  to first obtain the amplitude in ADC counts and thereafter applies a calibration constant in MeV per ADC count. The  $S_i$  are linearly combined to provide the pulse amplitude  $A_{opt}$ , the phase with respect to the 40 MHz clock  $t_{opt}$  and the electronic pedestal  $P_{opt}$ , as follows:

$$A_{opt} = \sum_{i=1}^7 a_i \cdot S_i \quad (1)$$

$$t_{opt} = \frac{1}{A_{opt}} \sum_{i=1}^7 b_i \cdot S_i \quad (2)$$

$$P_{opt} = \sum_{i=1}^7 c_i \cdot S_i \quad (3)$$

The linear coefficients are optimized, using the autocorrelation matrix, to minimize the effect of the noise on the reconstructed quantities. This method is called Optimal Filtering. Prior knowledge of the normalized pulse shape function  $g(t)$  is required to determine the constants  $a_i$ ,  $b_i$ ,  $c_i$ . The linear coefficients are functions of the true phase of the pulse  $\tau$  with respect to the 40 MHz electronic clock. The pulse shape function as well as the linear constants are stored in a dedicated database. Further information on the use of Optimal Filtering for signal reconstruction in TileCal can be found in Ref. [6].

### A. Optimal Filtering Offline

The Optimal Filtering used in this paper is the same that is used to reconstruct offline the data of the ATLAS TileCal in proton-proton collisions. The constants  $a_i$ ,  $b_i$ ,  $c_i$  are functions of the actual phase  $\tau$  of the pulse which is only approximately known a priori. Therefore the Optimal Filtering is applied offline iteratively with an initial assumed value of the phase  $\tau$ , equal to the time of the maximum of the  $S_i$ . In later iterations, the phase is taken to be equal to  $t_{opt}$  from the previous iteration. In absence of pile-up the iterative algorithm always converges to the true value of the phase with an accuracy better than 0.5 ns (the algorithm is iterated until the difference between the input phase and  $t_{opt}$  of Eq. 2. is less than 0.5 ns or the number of iteration reaches 5) [6].

At the end of the iterative procedure, a quality factor  $Q_{opt}$  is computed to verify that the resulting  $A_{opt}$ ,  $t_{opt}$  and  $P_{opt}$  together with the pulse shape  $g(t)$  do model the data  $S_i$  accurately. In case of deviation between the actual shape and the expected shape, then  $Q_{opt}$  takes large values which can be used to detect problems in the reconstruction procedure. The quality factor is defined after convergence as follows:

$$Q_{opt} = \sqrt{\sum_{i=1}^7 (S_i - A_{opt} \cdot g_i - P_{opt})^2} \quad (4)$$

where the  $g_i$  are the values of the normalized pulse shape computed at the time of the 7 samples  $S_i$ .

### B. Optimal Filtering Online

The Optimal Filtering is also run online by the TileCal Digital Signal Processors (DSP) which perform the above linear combinations in real time. Above a trigger rate 50 kHz the Optimal Filtering must be performed without iterations due to insufficient processing time in the DSP. It was also found that in the presence of out-of-time pile-up it is better not to perform the iterations. This is due to the fact that the phase  $\tau$  needed to compute  $a_i$ ,  $b_i$ ,  $c_i$  is known from timing calibration within a few nanoseconds. On the other hand, the presence of out-of-time pile up can lead to  $t_{opt}$  values far from nominal and thus bias the energy reconstruction. For this reason only non-iterative optimal filtering is currently applied online.

## III. PILE-UP SCENARIOS

The large per bunch crossing luminosity of the LHC leads to a high probability of multiple proton-proton interactions in the same bunch crossing. This leads to in-time energy deposits from multiple collisions in the same TileCal cell from the same bunch crossing from different p-p collisions. We refer to this type of pile-up as “in-time pile-up” and it can be addressed by determining its average effect on the measured calorimeter energies. It is not discussed further in this paper.

The second type of pile-up, or “out-of-time” pile-up arises when bunch crossings are close in time, and that the signal shaping time is larger than the time between consecutive bunches. In the case of TileCal, the long signal shaping time requires a read-out window of  $\pm 75$  ns around a triggered event, to be compared with a bunch spacing of 50 ns during the 2011 data-taking. The pulse shape is adjusted in such a way that the maximum of the pulse is located close to the fourth sample,  $S_4$ . The “out-of-time” pile-up results in the superposition of pulses shifted in time resulting in anomalous pulse shapes which can be detected thanks to large values of  $Q_{opt}$ . In 2011 the LHC bunch spacing was 50 ns and therefore there are two possible pileup scenarios: the pile-up signal results from energy deposited -50 ns from the collision of interest; the pile-up signal results from energy deposited +50 ns from the collision of interest. Due to the TileCal pulse shape these have different effects on the reconstructed signal in the collision of interest. Both scenarios are studied and the expected quality factor distributions are computed in both scenarios. Fig. 1 shows an illustration of an out-of-time pile-up

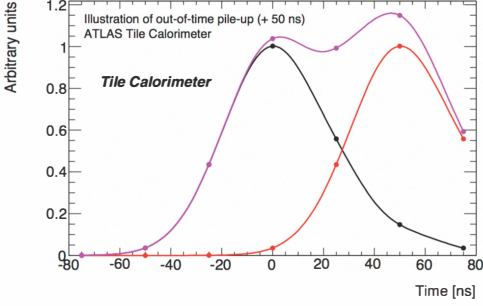


Fig. 1. Illustration of the superposition of an in-time pulse with an out-of-time pile-up pulse of equal amplitude at +50 ns in the ATLAS Tile Calorimeter. The pulse shapes shown here are approximate functional parameterizations of actual pulse shapes, but are not actually used either in the energy reconstruction, nor in the pile-up simulation.

pulse at +50 ns, in the case where the in-time and out-of-time pulses have the same amplitude.

#### IV. PULSE SHAPE SIMULATOR

##### A. Working Principle

The pulse shape simulator is based on pseudo-random number generators to generate the 7 samples  $S_i$  which constitute a digitized pulse. The pulse simulator uses a number of input probability density functions that model the electronic noise, the distribution of random pulse phases, the timing resolution and the distribution of pulse width. All these components are required to reproduce the characteristics of the digitized pulse in data. The most significant parameters of the model are the noise and the variations in pulse widths which are both adjusted such that the predicted  $Q_{opt}$  in the simulator agrees with the  $Q_{opt}$  distribution measured in data in absence of out-of-time pile-up. Thanks to the iterative procedure, the value of  $Q_{opt}$  is found to be rather independent of the timing effects. Later on in Section V the pulse simulator is used to derive the expected  $Q_F$  distribution for out-of-time pulses.

##### B. Input to the Model

The parameters of the model are the following.

1) *Pulse shape*: As shown in Eq. 4 the quality factor is a measure of the difference between the ideal pulse shape used to derive the optimal filtering coefficients and the actual pulse shapes in the real detector. It is shown on Fig. 2 that the pulse shapes in TileCal are consistent with the ideal pulse shapes. Nevertheless even small pulse shape differences will be enlarged by signal amplitudes.

The normalized ideal pulse shape used in the optimal filtering is denoted  $g(t)$ , or  $g_i$  at the times of the  $S_i$  where the pulse is sampled. The function  $h(t)$  denotes the normalized real pulse shape in an actual TileCal channel. One can thus write  $h(t) = g(t) + \delta(t)$  or  $h_i = g_i + \delta_i$  at the times of the samples  $S_i$ , where  $\delta$  quantifies the deviation between the ideal pulse shape and the actual pulse shape in the detector. In this

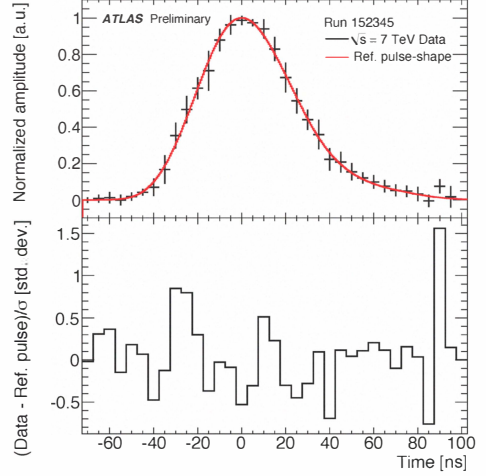


Fig. 2. Pulse shape reconstructed with the Optimal Filtering averaged over all good channels and full energy range in high gain in the TileCal from data 2010. Overlaid in red is the reference high gain pulse shape used for reconstruction. Bottom: The deviation between data and reference pulses in units of standard deviations.  $\sigma$  is the statistical spread on the data.

case one can write  $S_i = A \cdot h_i + P = A \cdot g_i + A \cdot \delta_i + P$ , where  $P$  is the actual pedestal and  $A$  is the actual amplitude. Thus the quality factor of Eq. 4 can be reexpressed as:

$$Q_{opt} = \sqrt{\sum_{i=1}^7 (A g_i + \delta_i + P - A_{opt} \cdot g_i - P_{opt})^2} \quad (5)$$

In absence of noise the amplitude and pedestal are perfectly reconstructed by the optimal filtering, thus  $P_{opt} = P$  and  $A_{opt} = A$ , which is approximately true at large amplitudes where the electronic noise becomes negligible, the equation above simplifies to

$$Q_{opt} = A \cdot \sqrt{\sum_{i=1}^7 (\delta_i)^2} \quad (6)$$

Therefore at large signal amplitudes the quality factor depends linearly upon the amplitude of the pulse and the slope depends on the difference between the ideal pulse shape and the actual pulse shape in the detector. Fig. 3 shows  $Q_{opt}$  as function of the pulse amplitude in collision data, in absence of out-of-time pile-up, for channels with signals larger than 200 ADC counts, the dependence of the quality factor on the energy appears clearly. For comparison, Fig. 4 shows the quality factor in the simulator if we assume that the measured  $S_i$  follow the ideal pulse shape. In order to reproduce the quality factor observed in data, the simulator must use a pulse shape that is different from the ideal pulse shape. The pulse shapes in data are modeled by the normalized ideal pulse shapes, with a modified width. Widened or narrowed pulses are obtained by using a new pulse shape given by  $g(\alpha t)$ , where  $g$  is the

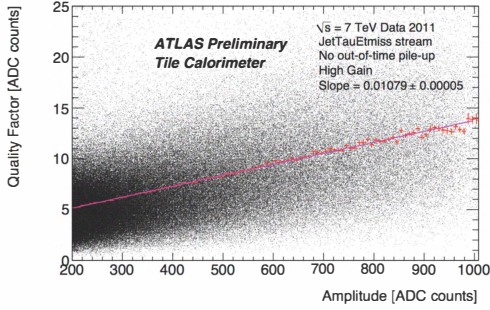


Fig. 3. Quality factor as a function of the reconstructed amplitude  $A_{opt}$  in Data 2011. This data is in high gain and was recorded while the LHC was running with only 2 bunches per beam separated by at least  $2.5 \mu s$ . The x-axis shows the amplitude in ADC counts. One ADC count corresponds approximately to 12 MeV.

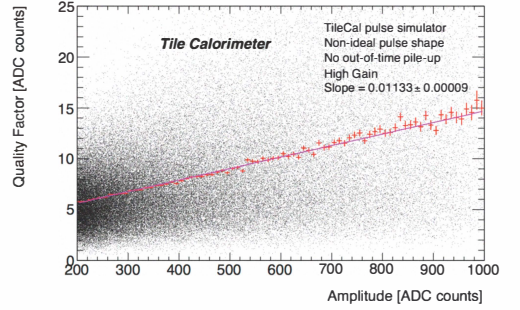


Fig. 5. Quality factor as a function of the reconstructed amplitude  $A_{opt}$  in TileCal pulse simulator with non-ideal pulse shapes, and with timing and noise effects emulated (full model of the pulse simulator). No out-of-time pile-up is present here. The x-axis shows the amplitude in ADC counts before cell-dependent calibration constants are applied. One ADC count corresponds approximately to 12 MeV.

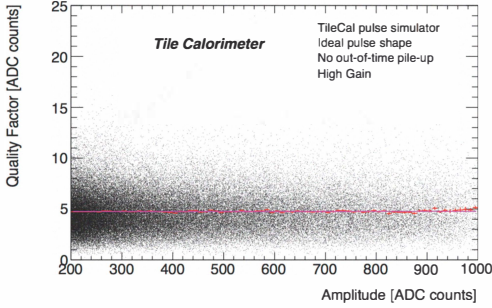


Fig. 4. Quality factor as a function of the reconstructed amplitude  $A_{opt}$  in the TileCal pulse simulator with ideal pulse shape, but with timing and noise effects emulated. No out-of-time pile-up is present here. The x-axis shows the amplitude in ADC counts before cell-dependent calibration constants are applied. One ADC count corresponds to approximately 12 MeV.

ideal pulse shape used earlier and  $\alpha$  is a factor close to one. A value of  $\alpha$  equals to one gives the ideal pulse shape, while  $\alpha < 1$  corresponds to a narrower pulse and  $\alpha > 1$  corresponds to a wider pulse. The  $\alpha$  factor is taken to follow a Gaussian distribution with a mean value of 1 and a standard deviation  $\sigma$  that is adjusted so that the quality factor distribution observed in the simulator matches that of the data.

2) *Energy distribution*: As the quality factor is dependent on the amplitude, the simulator has to use the same energy distribution as the data. The pulse shape simulator is validated by comparing its result with the data in Section IV-C using TileCal data collected with a jet or missing energy trigger. For this comparison the probability density function of the energy measured in the TileCal cells is extracted from the data and used to generate the amplitude of the pulses in the simulator. In Section V it is shown that the energy distribution in TileCal cells can be extracted without bias due to the trigger, in order to model the amplitude distribution of the out-of-time pulses.

3) *Channel to channel phase variation  $\phi_{ch}$* : Ideally the peak of the signal pulses should be perfectly centered in the middle of  $\pm 75$  ns read-out window. In the actual Tile Calorimeter the position of the pulse peak has been shown to be within 3 ns of the middle of the read-out window [4]. This effect is taken into account in the simulator by randomly offsetting the simulated pulses before reconstruction with a random phase that is Gaussian distributed with a mean of zero and a standard deviation of 3 ns.

4) *Time resolution  $\phi_{res}$* : The precision of the time  $t_{opt}$  determined with the Optimal Filtering is a known function of the pulse amplitude and has been determined in data. The resolution on  $t_{opt}$  propagates to the quality factor through equation 2 and is therefore taken into account in the simulator by randomly shifting the time of the pulse by an amount determined from a Gaussian with mean zero and with an energy dependent standard deviation, given by:

$$\sigma_T = \sqrt{p_0^2 + \left(\frac{p_1^2}{\sqrt{E}}\right)^2 + \left(\frac{p_2^2}{E}\right)^2} \quad (7)$$

where the parameters  $p_0 = 0.82 \text{ ns}$ ,  $p_1 = 0 \text{ ns} \cdot \text{GeV}^{1/2}$  and  $p_2 = 2.30 \text{ ns} \cdot \text{GeV}$  have been determined on data.

5) *Incoherent electronic noise*: The incoherent electronic noise modifies the measured values of the samples  $S_i$  randomly around the normalized pulse shape, the effect is to first approximation uncorrelated between the samples  $S_i$ . This is the second most significant contribution to the quality factor, after the pulse shape, but becomes the dominant factor at low amplitudes. The tail of high quality factor values is particularly sensitive to the noise. For this reason the simulator uses the double Gaussian noise model that was found to describe the TileCal noise data [4]. The noise constants used to smear the  $S_i$  were adjusted so that the quality factor distribution obtained with the simulator reproduces the quality factor in the data.

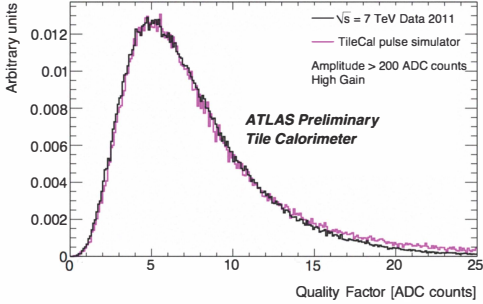


Fig. 6. Comparison of the quality factor distribution in data taken in March 2011 (black) and with the pulse simulator with non-ideal pulse shapes (purple) for pulses with amplitudes above 200 ADC counts. This data was recorded while the LHC was running with only 2 bunches per beam separated by at least  $2.5 \mu\text{s}$ .

### C. Comparison of the Quality Factor in Data and TileCal Pulse Simulator

The quality factor distribution is computed in data using an integrated luminosity of  $60 \text{ nb}^{-1}$  taken in March 2011 at a period where the LHC was operating with only 2 bunches per beam, separated by at least  $2.5 \mu\text{s}$ , therefore ensuring the absence of out-of-time pile-up. The collisions were selected to pass either a calorimeter trigger or a missing energy trigger. Fig. 3 shows the energy dependence of the quality factor in this data set. Fig. 5 shows the corresponding distribution of quality factor  $Q_{opt}$  as function of  $A_{opt}$  obtained in the pulse simulator, in absence of out-of-time pile-up as for the data of Fig. 3. The resulting quality factor distribution in data and from the simulator is shown in Fig. 6 and shows a fair agreement apart from the high tail of the quality factor distribution. This demonstrates that the pulse shapes can be simulated in such a way that a complex quantity such as the quality factor can be reproduced. The simulator can then be used to predict the quality factor distribution in presence of out-of-time pile-up in order to derive the optimal criteria to detect out-of-time pile-up while keeping the amount of read out data within the bandwidth budget of TileCal.

## V. QUALITY FACTOR SIMULATION WITH PILE-UP

### A. Amplitude of Out-of-Time Pulses

The average signal amplitude for in-time pulses is related to the trigger criteria used to record the event, since for instance requiring several highly energetic hadronic jets will certainly increase the amount of energy deposited in the calorimeter and hence the likelihood that a calorimeter channel received a large signal.

The out-of-time pulses on the other hand belong to collisions that did not pass the trigger. They are recorded by chance since they were close in time to a collision that passed the trigger. Therefore the energy distribution from pile-up is that from unbiased collisions before the trigger. This energy distribution can be extracted from data by using a

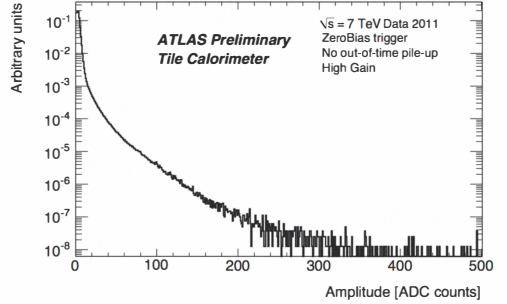


Fig. 7. Amplitude distribution of out of time pulse. Parameterization extracted from zero bias 2011 data in high gain in absence of out-of-time pile-up. This data was recorded while the LHC was running with only 2 bunches per beam separated by at least  $2.5 \mu\text{s}$ . The x-axis shows the amplitude in ADC counts before cell-dependent calibration constants are applied. The calibration factor is approximately 12 MeV per ADC count.

specific trigger. ATLAS possesses a so-called a zero bias trigger, which records a small fraction of collisions randomly selected in coincidence with the crossing of two populated proton bunches. This zero bias trigger allows to measure the energy distribution in TileCal channels without the effect of the trigger bias, and is therefore used as a model to extract the probability density function of the amplitude of the out-of-time pulses. This amplitude distribution is extracted from no pile-up ATLAS data from March 2011 at a time where the LHC was operating with only two bunches per beam, separated with at least  $2.5 \mu\text{s}$ , the corresponding distribution is shown in Fig. 7. This amplitude distribution is used as probability density function to generate out-of-time pulses in the pulse simulator and compute the quality factor in presence of pile-up in Section V-B.

### B. Quality Factor Distributions in Presence of Out-of-Time Pile-up

The effect of the out-of-time pile-up on the quality factor is first studied in absence of noise, or timing effects and for ideal pulse-shapes. In this simplified model one can study the effect of the relative sizes of the in-time and out-of-time pulses. Fig. 8 shows the dependence of the quality factor  $Q_{opt}$  as a function of the in-time pulse amplitude  $A_{in}$  given on the x-axis and for different values of the ratio between the in-time and out-of-time pulse amplitude  $A_{out}$ . It shows two important features, first that for a given ratio of  $A_{out}/A_{in}$ , the quality factor increases linearly with the amplitude of the in-time pulse, and second that the dependence on the amplitude  $A_{in}$  gets steeper when the ratio  $A_{out}/A_{in}$  gets closer to one. The worst case scenario occurs for in-time and out-of-time pulses of equal amplitude, in that case the quality factor becomes maximal. The introduction of an out-of-time pile-up pulse is equivalent to introducing a deviation between the ideal pulse shape and the real pulse shape as discussed in Sect. IV-B1. The linear dependence on the amplitude observed here is therefore

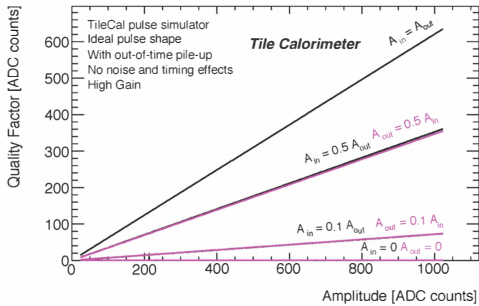


Fig. 8. Quality factor as a function of the amplitude in different pile-up scenarios in the TileCal pulse simulator with ideal pulse shape, in absence of noise or timing effects. The amplitude  $A_{in}$  ( $A_{out}$ ) is the amplitude of the in-time (out-of-time). The x-axis represents the amplitude of the in-time pulse and is given in ADC counts, before cell-dependent calibration constants are applied. One ADC count corresponds to approximately 12 MeV.

consistent with the observation of a linear dependence upon pulse amplitude made in Section. IV-B1.

In order to compute a realistic distribution of the quality factor in presence of out-of-time pile-up, the amplitude of the out-of-time pulse is modeled with the full model, and the probability density function obtained using the zero-bias data as described in Sec. IV. Fig. 9 compares the quality factor in absence (black) and in presence of out-of-time pile-up (red and purple) obtained for this model and for an in-time pulse of 1000 ADC counts, corresponding to about 12 GeV. Only the out-of-time pulses yielding an effect of more than 1% bias on the reconstructed amplitude have been retained for this figure, which occurs only for approximately 1 in  $O(10^3)$  channels per bunch crossing with an expected average number of collisions of  $\langle \mu \rangle = 3.3$ . It illustrates that for significant out-of-time pile-up pulses the distribution of quality factor is quite different in case of out-of-time compared to no out-of-time pile-up. There is a clear separation between the two cases. As it has been shown that the quality factor is linearly increasing with the amplitude of the pulses, further separation can be achieved by dividing the quality factor given in Fig. 9 and Eq. 4.

## VI. CONCLUSIONS

A numerical model of the ATLAS Tile Calorimeter pulses has been developed in the form of a pulse simulator. This model takes into account small variations in signal pulse shapes, timing resolution and small timing miscalibration effects and uses a realistic model of the calorimeter noise. The simulator is shown to be able to reproduce the quality factor distributions in collisions in absence of out-of-time pile-up for pulses with amplitudes larger than 200 ADC counts. The model is still in development and will be improved to model the data quality factor for the full range of pulse amplitude. The signal amplitude for TileCal channels is measured in zero bias triggered data and used as a model for pulses of from out-of-time pile-up collisions. Using this model of the data, the

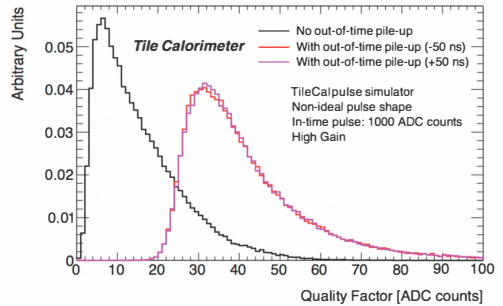


Fig. 9. Normalized distributions of quality factors in TileCal simulator with non-ideal pulse shapes for an in-time pulse of 1000 ADC counts (approximately 12 GeV), without (black) and with out-of-time pile-up (red and purple). The amplitude of the out-of-time pulse follows the distribution in the zero bias trigger and requiring additionally that the effect of the out-of-time pulse on the reconstructed amplitude is at least 1%. The two out-of-time pile-up scenarios with  $-50$  ns (red) and  $+50$  ns (purple) are shown.

distribution of quality factor in the presence of out-of-time pile-up is calculated. It shows that significant discrimination can be achieved thanks to the the quality factor between the presence and the absence of out-of-time pile-up in case the amplitude of the out-of-time pile-up large enough to affect the amplitude measurement. Using the predicted distributions of quality factor with and without out-of-time pile, the presence of significant out-of-time pile-up can be identified and a specific treatment of the double pulses can be performed.

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II





# ATLAS NOTE

December 4, 2012



## Identification of Pile-up Using the Quality Factor of Pulse Shapes in the ATLAS Tile Calorimeter

Christophe Clément and Pawel Klimek

*Stockholm University, Sweden*

### Abstract

The ATLAS experiment records data from the proton-proton collisions produced by the Large Hadron Collider (LHC). The Tile Calorimeter is the hadronic sampling calorimeter of ATLAS in the region  $|\eta| < 1.7$ . It uses iron absorbers and scintillators as active material. The LHC will provide collisions every 25 ns, putting very strong requirements on the energy measurement in presence of energy deposits from different collisions in the same read out window and physical calorimeter channel (pile-up). In 2011 the LHC was running with filled bunches at 50 ns spacing and at intensities which yield up to about 8 proton-proton collisions per bunch crossing. We present a quality factor that is computed offline for each collision and for each calorimeter channel, and provide criteria to detect pile-up in TileCal channels. The quality factor can be used to select channels that need a special treatment to account for large energy deposition from pile-up.



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# 1 Introduction

The Large Hadron Collider (LHC), currently under operation at CERN, with its unprecedented high energy and luminosity extends the frontier of particle physics. Bunches of up to  $10^{11}$  protons collide at a centre of mass energy of 7 TeV (and up to 14 TeV in nominal conditions) and a design luminosity of  $10^{34} \text{ cm}^{-2}\text{s}^{-1}$ . Nominally the LHC will operate with proton bunches crossing every 25 ns, although in 2011 it has operated with 50 ns bunch spacing and with an expected average number of 8 proton-proton collisions per bunch crossing. The high interaction rates, energies, particle multiplicities, radiation doses and need for precision measurements require new standards for the design of particle detectors at the LHC. ATLAS [1] is one of the major experiments designed to exploit the proton-proton data in this challenging environment.

ATLAS is a general-purpose experiment, whose goal is to cover a broad range of experimental particle physics phenomena, with the long sought Higgs boson [2] and supersymmetry [3] being especially important. The ATLAS experiment needs to be sensitive to a large number of possible decay channels and so must provide an excellent particle identification and high resolution measurements of energies, momenta and directions for the outgoing particles in the proton-proton collisions.

The Tile Calorimeter (TileCal) [4] is the hadronic sampling calorimeter of ATLAS in the region  $|\eta| < 1.7$ . The purpose of TileCal is to identify hadronic jets and measure their energy and direction. TileCal also provides vital information for the first level of trigger (L1 trigger) and participates in the measurement of the missing energy due to non-interacting particles. It uses iron as an absorber and scintillating plastic tiles as an active material. Several scintillating tiles are grouped together at the read out level to form calorimeter cells. The wavelength shifting fibers collect the light from the tiles to photomultipliers (PMTs), with most TileCal cells being read out by two PMTs, corresponding to two electronic read out channels. The PMT output is a current pulse whose amplitude is proportional to the energy deposited in the associated cell. Electronics mounted on the PMT amplifies and shapes the output current pulse. Pulse shaping increases the width at half-maximum to 50 ns. The analogue pulse is digitized with 7 samples at 25 ns intervals which are read out upon a trigger accept from the L1 trigger and used to compute the pulse amplitude, phase and quality factor. Ten-bit analogue to digital converters are used for the digitization.

The presence of collisions every 50 ns and the relatively large read-out window ( $\pm 75$  ns) lead to a significant fraction of calorimeter cells receiving energy from more than one bunch crossing within the same read out window and within the same physical calorimeter cell (out-of-time pile-up). Out-of-time pile-up degrades the measurement of the energy deposited in a physical cell. A quality factor is computed online for each event and for each calorimeter channel. It allows the identification of calorimeter channels with out-of-time pile-up. In the presence of a high quality factor value a dedicated treatment of the pile-up signals can be applied.

A numerical model has been developed to simulate the TileCal pulse shapes and quality factors with and without out-of-time pile-up. The simulated observables are compared with actual proton-proton data in order to validate the model. The model includes electronic noise, channel-to-channel phase variations and non-ideal pulse shapes. The model is fine tuned to the data to reproduce the quality factor distribution in data without pile-up. The numerical model is then used to predict quality factor distributions in presence of pile-up thus permitting the optimization of the quality factor selection criteria for pile-up detection, under the constraints of available bandwidth while keeping a reliable out-of-time pile-up detection. It is beyond the scope of the presented work to compare quality factor distributions with pile-up between the model and the data but is possible future development of this work.

In Section 2 the Optimal Filtering algorithm used to reconstruct the energy is briefly recalled, and the definition of the quality factor  $QF$  is given. The relevant pile-up scenarios are described in section 3. The model used to build the pulse simulator is presented in Section 4 and the impact of various effects

on the single pulse  $QF$  is studied. This Section also contains a comparison of  $QF$  distributions in data and in the simulator. The effect of the out-of-time pile-up on the quality factor is presented in Section 5. In Section 6 we present an optimisation of a cut on the quality factor to identify the out-of-time pile-up.

## 2 Energy Reconstruction and Quality Factor Definition

The goal of the energy reconstruction in TileCal is to compute the energy deposited in a TileCal cell from the number of ADC counts measured in each of the two corresponding read out channels. For each channel, 7 samples at 25 ns spacing are available, these samples are referred to as  $S_i$  with  $i = 1 - 7$  and are in units of ADC counts. In order to maximize the dynamic range, either a low or a high amplification (or gain) is used, depending on the pulse amplitude. The ratio between the low and the high amplification is 64. The high gain is applied to pulses up to about 12 GeV, while the low gain is applied for higher energies. One ADC count corresponds approximately to 12 MeV of deposited energy in high gain and about 800 MeV in low gain. The exact correspondence is channel-dependent and requires careful calibration [5]. For comparison, the most probable energy of the muon signal for projective cosmic muons entering the barrel modules for the D cells at  $0.3 < |\eta| < 0.4$  is 500 MeV [4].

The energy reconstruction combines the  $S_i$  to first obtain the amplitude in ADC counts and thereafter applies a calibration constant in MeV per ADC count. The  $S_i$  are linearly combined to provide the pulse amplitude  $A_{OFL}$ , the phase  $t_{OFL}$  with respect to the 40 MHz clock and the electronic pedestal  $P_{OFL}$ , as follows:

$$A_{OFL} = \sum_{i=1}^7 a_i \cdot S_i \quad (1)$$

$$t_{OFL} = \frac{1}{A_{OFL}} \sum_{i=1}^7 b_i \cdot S_i \quad (2)$$

$$P_{OFL} = \sum_{i=1}^7 c_i \cdot S_i \quad (3)$$

The linear coefficients are optimized, using the autocorrelation matrix, to minimize the effect of the noise on the reconstructed quantities. This method is called Optimal Filtering. Prior knowledge of the normalized pulse shape function  $g(t)$  is required to determine the constants  $a_i$ ,  $b_i$ ,  $c_i$ . The pulse shape was precisely determined from test beam data and it was verified with data from the fully installed TileCal that this function could be used for all TileCal channels [6].

The linear coefficients are functions of the true phase of the pulse with respect to the 40 MHz electronic clock. The pulse shape function as well as the linear constants are stored in a dedicated database for calibration constants (called COOL). Further information about the use of Optimal Filtering for signal reconstruction in TileCal can be found in Ref. [7].

### 2.1 Optimal Filtering Offline

The Optimal Filtering used in this note is the same as is used to reconstruct offline data of the ATLAS TileCal in proton-proton collisions. The beam data was used to adjust the average phase for each channel to be close to zero. This setting is accurate to 3 ns. During the 2010 data taking and early 2011 the Optimal Filtering was applied iteratively. Later at higher luminosity only non-iterative Optimal Filtering was used. In this work the iterative Optimal Filtering is studied. The constants  $a_i$ ,  $b_i$ ,  $c_i$  are functions of the actual phase of the pulse which is only approximately known a priori. Therefore the Optimal Filtering is applied offline iteratively with an initial assumed value of the phase, equal to the time of the maximum

of the  $S_i$ . In later iterations, the phase is taken to be equal to  $t_{OFL}$  from the previous iteration. In absence of pile-up the iterative algorithm always converges to the true value of the phase with an accuracy better than 0.5 ns<sup>1</sup>[7].

At the end of the iterative procedure, a quality factor  $QF_{OFL}$  is computed to verify that the resulting  $A_{OFL}$ ,  $t_{OFL}$  and  $P_{OFL}$  together with the pulse shape  $g(t)$  do model the data  $S_i$  accurately. In case of deviation between the actual shape and the expected shape, then  $QF_{OFL}$  takes large values which can be used to detect problems in the reconstruction procedure. The quality factor is defined after convergence as follows:

$$QF_{OFL} = \sqrt{\sum_{i=1}^7 (S_i - A_{OFL} \cdot g_i - P_{OFL})^2} \quad (4)$$

where the  $g_i$  are the values of the normalized pulse shape computed at the time of the 7 samples  $S_i$ . Figure 1 shows the relative difference between reconstructed  $A_{OFL}$  and true amplitude  $A_{True}$  as a function of true amplitude. In this plot  $A_{True}$  was varied with step of one ADC count. Figure 2 shows the relative difference between reconstructed  $t_{OFL}$  and true time  $t_{True}$  as a function of a true time. In this plot  $t_{True}$  was varied with step of one nanosecond. Figure 3 shows the absolute difference between reconstructed  $t_{OFL}$  and true time  $t_{True}$  as a function of a true amplitude. In this plot  $A_{True}$  was varied with step of one ADC count. In these histograms each bin consists of 1000 entries. Figures 1, 2 and 3 show that amplitude and time reconstructed well by the Optimal Filtering. One can also note that the precision of the reconstructed amplitude and time deteriorate as expected at low amplitudes where the analog noise and sampling accuracy become important. These plots were obtained with full model of the TileCal pulse simulator described in Section 4. Figures presenting bias and resolution of amplitude and time reconstruction with Optimal Filtering are included in Appendix A. Number of iterations to converge as a function of true time of the pulse is shown on Fig. 4. Iterative Optimal Filtering reconstructs the phase with an initial assumed value equal to the time of the maximum of the  $S_i$ . Therefore, if the phase is equal to the time of any sample (0,  $\pm 25$ ,  $\pm 50$ ,  $\pm 75$  ns) only one iteration is needed. If the phase takes values different than the samples, larger number of iterations is performed.

## 2.2 Optimal Filtering Online

The Optimal Filtering is also run online by the TileCal Digital Signal Processors (DSP) which perform the above linear combinations in real time. Above a trigger rate of 50 kHz the Optimal Filtering must be performed without iterations due to insufficient processing time in the DSP. It was also found that in the presence of out-of-time pile-up it is better not to perform the iterations. This is due to the fact that the phase needed to compute  $a_i$ ,  $b_i$ ,  $c_i$  is known from timing calibration within a few nanoseconds. On the other hand, the presence of out-of-time pile up can lead to  $t_{OFL}$  values far from nominal and thus bias the energy reconstruction when iterative method is used. The non-iterative Optimal Filtering method reconstructs better the phase of in-time-pulse. The noise width becomes smaller using non-iterative method. Therefore, the reconstruction is more robust against the noise for very low amplitudes. For this reasons only non-iterative Optimal Filtering is currently applied online.

## 3 Pile-up Scenarios

The large per bunch crossing luminosity of the LHC leads to a high probability that multiple proton-proton interactions may take place in same bunch crossing where the trigger interaction occurred (in-time pile-up). Due to the presence of the in-time pile-up the signal collected in a single TileCal cell integrate

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<sup>1</sup>The algorithm is iterated until the difference between the input phase and  $t_{OFL}$  of Eq. 2 is less than 0.5 ns or the number of iteration reaches 5.

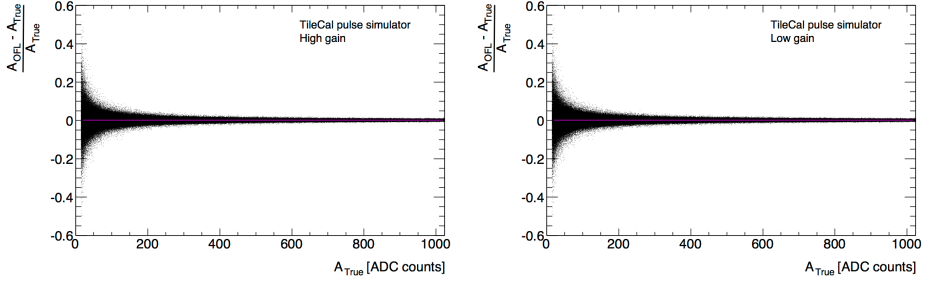


Figure 1: Relative difference between reconstructed and true amplitude as a function of true amplitude in TileCal pulse simulator. This is shown for high gain (left) and low gain (right). Amplitude is reconstructed with Optimal Filtering with iterations in absence of out-of-time pile-up. The purple line corresponds to the linear fit to mean value of the relative difference.

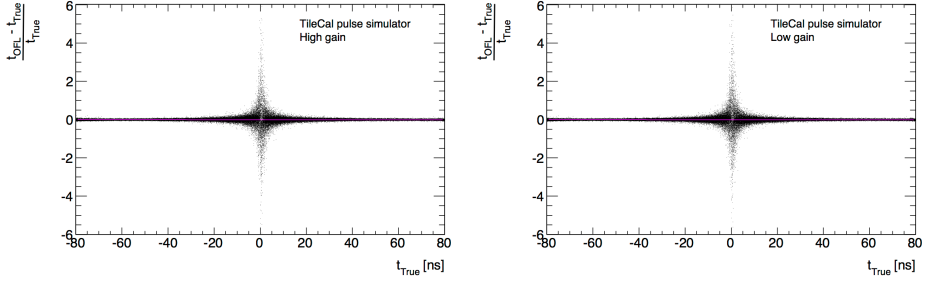


Figure 2: Relative difference between reconstructed and true time as a function of true time in TileCal pulse simulator. This is shown for high gain (left) and low gain (right). Time is reconstructed with Optimal Filtering with iterations in absence of out-of-time pile-up. The purple line corresponds to the linear fit to mean value of the relative difference.

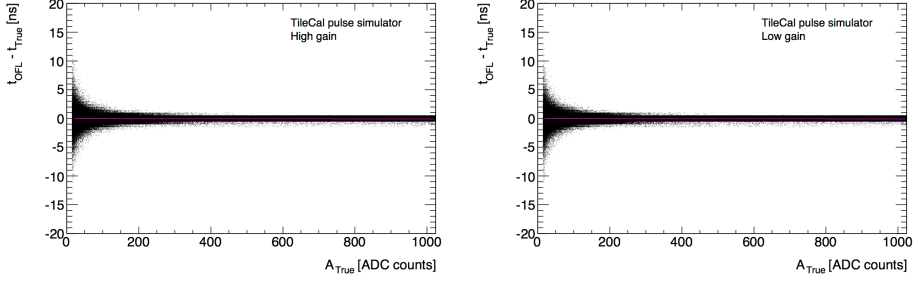


Figure 3: Absolute difference between reconstructed and true time as a function of true amplitude in TileCal pulse simulator. This is shown for high gain (left) and low gain (right). Time is reconstructed with Optimal Filtering with iterations in absence of out-of-time pile-up. The purple line corresponds to the linear fit to mean value of the relative difference.

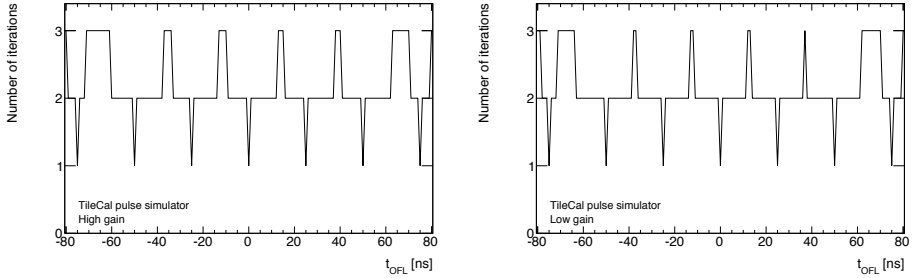


Figure 4: Number of iterations to convergence in iterative Optimal Filtering as a function of true time of the pulse in TileCal pulse simulator with ideal pulse shapes, in absence of emulation of noise and timing effects. This is shown for high gain (left) and low gain (right). Time is reconstructed with Optimal Filtering with iterations in absence of out-of-time pile-up. This result was obtained by reconstruction of the pulse with amplitude of 84 ADC counts (1 GeV).

the contributions from multiple interactions. The effect of the “in-time pile-up” can be evaluated by determining its average effect on the measured TileCal cell energies. It is not discussed further in this paper.

The second type of pile-up, or “out-of-time” pile-up arises because the signal integration time is larger than the distance between two consecutive bunch crossings. In this case collisions from protons belonging to bunch crossings close in time to the one where the trigger occurred also contribute to the signal a TileCal cell. In the case of TileCal, the long signal shaping time requires a read-out window of  $\pm 75$  ns around a triggered event, to be compared with a bunch spacing of 50 ns during the 2011 and 2012 data-taking. The hardware delays are adjusted in such a way that the maximum amplitude of the in-time pulses is located close to the fourth sample,  $S_4$ . The “out-of-time” pile-up results in the superposition of pulses shifted in time resulting in anomalous pulse shapes which can be detected thanks to large values of  $QF_{OFL}$ . Figure 5 shows an illustration of an out-of-time pile-up pulse having the maximum amplitude located at +50 ns, in the case where the in-time and out-of-time pulses have the same amplitude.

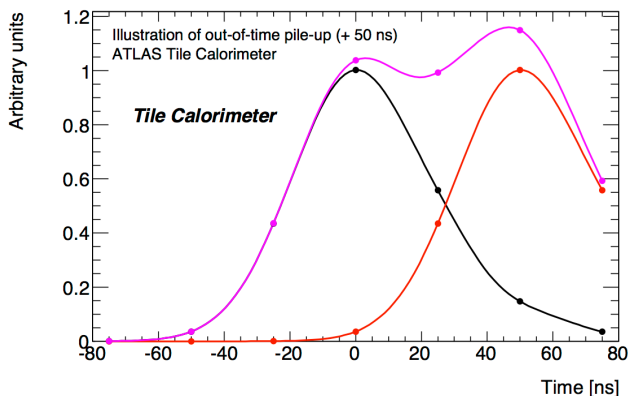


Figure 5: Illustration of out-of-time pile-up (+50 ns) in ATLAS Tile Calorimeter with pulse shapes similar to those in the real detector. The pulse shapes shown here are approximate functional parameterizations of actual pulse shapes, but are not actually used either in the energy reconstruction, nor in the pile-up simulation.

## 4 Pulse Shape Simulator

### 4.1 Working Principle

The pulse shape simulator is based on pseudo-random number generators to generate the 7 samples  $S_i$  which constitute a digitized pulse. The pulse simulator uses a number of input distribution functions such as the electronic noise, width of the pulse shapes, random time phases and amplitudes in order to reproduce the characteristics of the digitized pulse in data. The model is adjusted to reproduce the electronic high frequency noise, channel to channel phase variations, pulse shape variations, quality factor, correlation between quality factor and pulse amplitude observed in the data. In Section 5 the pulse simulator is used to derive the expected  $QF_{OFL}$  distribution for out-of-time pulses.

## 4.2 Input to the Model

### 4.2.1 Pulse shape

As shown in Eq. 4 the quality factor is a measure of the difference between the ideal pulse shape used to derive the Optimal Filtering coefficients and the actual pulse shapes in the real detector. It is shown in Fig. 6 that the pulse shapes in TileCal are consistent with the ideal pulse shapes [6]. Nevertheless, even small pulse shape differences will be enlarged by signal amplitudes causing higher quality factor.

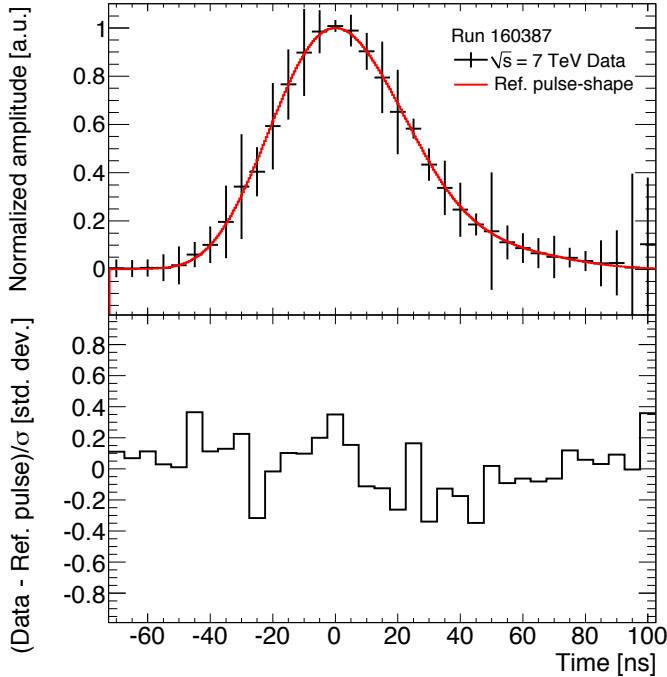


Figure 6: Pulse shape reconstructed with the Optimal Filtering averaged over all good channels and full energy range in high gain in the TileCal from 2010 data. Overlaid in red is the reference high gain pulse shape used for reconstruction. Bottom: Deviation between data and reference pulses in units of standard deviations.  $\sigma$  is the standard deviation of the data [6].

The normalized ideal pulse shape used in the Optimal Filtering is denoted  $g(t)$ , or  $g_i$  at the times of the  $S_i$  where the pulse is sampled. The function  $h(t)$  denotes the normalized real pulse shape in an actual TileCal channel. One can thus write  $h(t) = g(t) + \delta(t)$  or  $h_i = g_i + \delta_i$  at the times of the samples  $S_i$ , where  $\delta$  quantifies the deviation between the ideal pulse shape and the actual pulse shape in the detector. The TileCal electronics is linear and no deviations from linearity has been observed in data or test beam [4]. Therefore the shape functions describing the pulses can simply be scaled by the pulse amplitude. In this case one can write  $S_i = A \cdot h_i + P = A \cdot g_i + A \cdot \delta_i + P$ , where  $P$  is the actual pedestal and  $A$  is the actual



amplitude. Thus the quality factor of Eq. 4 can be reexpressed as:

$$QF_{OFL} = \sqrt{\sum_{i=1}^7 (A \cdot g_i + A \cdot \delta_i + P - A_{OFL} \cdot g_i - P_{OFL})^2} \quad (5)$$

In the absence of noise and with the pedestal perfectly reconstructed,  $P_{OFL} = P$  and  $A_{OFL} = A$ . In this case Eq. 5 reduces to

$$QF_{OFL} = A_{OFL} \cdot \sqrt{\sum_{i=1}^7 (\delta_i)^2} \quad (6)$$

This limit corresponds to large signals where the electronic noise and pedestal uncertainties are negligible. Therefore at large signal amplitudes one can expect the quality factor to depend linearly upon the amplitude of the pulse and the slope depends on the difference between the ideal pulse shape and the actual pulse shape in the detector. A deviation from a linear dependence between the quality factor and the amplitude could be used to detect deviations from linearity. Figure 7 left panel shows  $QF_{OFL}$  as function of the pulse amplitude in collision data, in absence of out-of-time pile-up. The purple line corresponds to the linear fit to mean value of the quality factor. The dependence of the quality factor on the amplitude appears clearly. In the 2004 test beam analysis a quadratic trend of the  $\chi^2$  of the fit method was observed as function of the amplitude [8]. This observation is also compatible, since there is a square root in the formula of quality factor which gives linear amplitude dependence. For comparison, Fig. 7 right panel shows the quality factor in the simulator if we assume that the measured  $S_i$  follow the ideal pulse shape. In the case of perfect pulse shape only the timing and noise effects contribute to  $QF_{OFL}$  which takes a constant value as a function of the amplitude as shown in the right panel of Fig. 7. Therefore the quality factor can be written as:

$$Q_{OFL} = Q_{OFL}^0 + A_{OFL} \cdot \sqrt{\sum_{i=1}^7 (\delta_i)^2} \quad (7)$$

where  $Q_{OFL}^0$  is the value of the quality factor at low amplitude when it is dominated by noise and timing effects. The value of  $Q_{OFL}^0$  was determined from data i.e. using the linear fit (the purple line in left the panel of Fig. 7) the value of quality factor at  $A_{OFL} = 0$  ADC was calculated. Figure 8 left panel shows  $(QF_{OFL} - Q_{OFL}^0)/A_{OFL}$  in collision data. The purple line corresponds to the linear fit to mean value. The distribution is flat as a function of amplitude with a mean value around zero (purple line). This is consistent with Eq. 7.

In order to reproduce the quality factor observed in data, the simulator must use a pulse shape that is different from the ideal pulse shape. The pulse shapes in data are modeled by the normalized ideal pulse shapes, with a modified width. Widened or narrowed pulses are obtained by using a new pulse shape given by:

$$h(\alpha t) = g(t) \quad (8)$$

where  $g$  is the ideal pulse shape used earlier and  $\alpha$  is a factor close to one. A value of  $\alpha$  equals to one gives the ideal pulse shape, while  $\alpha < 1$  corresponds to a narrower pulse and  $\alpha > 1$  corresponds to a wider pulse. During the early studies the  $\alpha$  factor was taken to follow a Gaussian distribution with a mean value of 1 and a standard deviation of  $\sigma = 0.01$ . These values were observed during previous studies of pulse shape in TileCal [6]. Nevertheless, the simulator showed not adequate agreement between data and simulator. Therefore, the factor  $\alpha$  was adjusted to the data so that the quality factor distribution

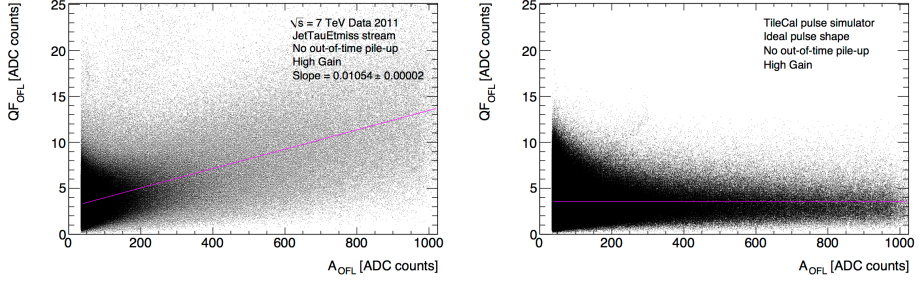


Figure 7: Left: Quality factor as a function of reconstructed amplitude in 2011 data. The data consists of runs: 177531, 177539, 177540, 177593, 177682 from March 2011 ( $\langle\mu\rangle = 3.3$ ). This data was recorded while the LHC was running with only 2 bunches per beam separated by at least  $2.5 \mu\text{s}$ . Right: Quality factor as a function of reconstructed amplitude in TileCal pulse simulator with ideal pulse shape, but timing and noise effects emulated. No out-of-time pile-up. One can observe that with ideal pulse shapes the quality factor is not amplitude-dependent. The x-axis shows the amplitude in ADC counts before channel-dependent calibration constants are applied. The calibration factor is approximately 12 MeV per ADC count. The purple line corresponds to the linear fit to mean value of the quality factor.

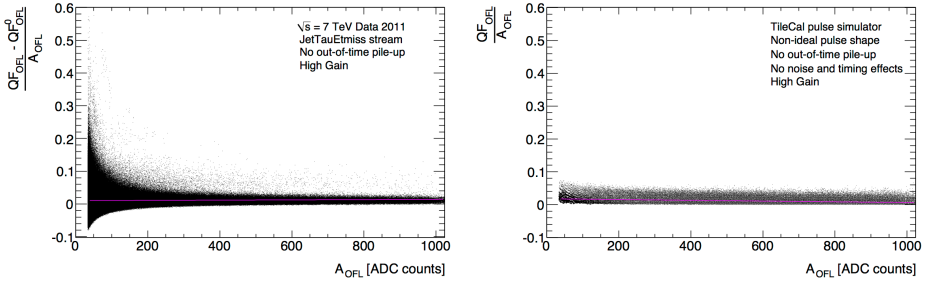


Figure 8: Left:  $(QF_{OFL} - Q_{OFL}^0)/A_{OFL}$  as a function of reconstructed amplitude ( $A_{OFL}$ ) in 2011 data. The data consists of runs: 177531, 177539, 177540, 177593, 177682 from March 2011 ( $\langle\mu\rangle = 3.3$ ). This data was recorded while the LHC was running with only 2 bunches per beam separated by at least  $2.5 \mu\text{s}$ . Right:  $QF_{OFL}/A_{OFL}$  as a function of reconstructed amplitude in TileCal pulse simulator in absence of emulation of noise and timing effects but using stretched pulse shapes according to  $g(at)$ . No out-of-time pile-up. The x-axis shows the amplitude in ADC counts before channel-dependent calibration constants are applied. The calibration factor is approximately 12 MeV per ADC count. The purple line corresponds to the linear fit to mean value.

observed in the simulator matches that of the data. It is found that  $\alpha$  modeled with a Gaussian with a mean value of 1.01 and a standard deviation of  $\sigma = 0.02$  provides a good model of the data. Figure 8 right panel shows  $QF_{OFL}/A_{OFL}$  in the simulator with widened pulse shapes. In this particular case no noise or timing effects are emulated so  $Q_{OFL}^0$  can be assumed to be equal to zero. The distribution is flat as a function of amplitude with a mean value around 0 (purple line) and is consistent with the observation in collision data (Fig. 8 left panel).

#### 4.2.2 Amplitude distribution

Fig. 9 top left panel shows the effect of amplitude variation with ideal pulse shape, while top right panel shows the effect of amplitude variation with widened pulse shape. The amplitude is modeled with the probability density function obtained using JetTauEtmis data. It confirms what was showed in Section 4.2.1 that in presence of non-ideal pulse shape there is a strong amplitude dependence on quality factor. As the quality factor is dependent on the amplitude, the simulator has to use the same amplitude distribution as the data. The pulse shape simulator is validated by comparing its result with the data in Section 4.3 using TileCal data collected in JetTauEtmis stream. For this comparison the probability density function of the amplitude measured in the TileCal cells is extracted from the data and used to generate the amplitude of the pulses in the simulator. In Section 5 it is shown that the amplitude distribution in TileCal cells can be extracted without bias due to the trigger, in order to model the amplitude distribution of the out-of-time pulses.

#### 4.2.3 Channel to channel phase variation $\phi_{ch}$

Ideally the peak of the signal pulses should be perfectly centered in the middle of  $\pm 75$  ns read-out window. In the actual Tile Calorimeter the position of the pulse peak has been shown to be within 3 ns of the middle of the read-out window [4]. This effect is taken into account in the simulator by randomly offsetting the simulated pulses before reconstruction with a random phase that is Gaussian distributed with a mean of zero and a standard deviation of  $\sigma = 3$  ns, as this is what is observed in the actual TileCal [9]. The corresponding distribution of reconstructed phase in pulse simulator is shown in Fig. 10. The effect of channel to channel phase variation on quality factor is showed on bottom left panel of Fig. 9. Since iterative Optimal Filtering method was used for reconstruction, the effect of phase variation is small.

#### 4.2.4 Incoherent electronic noise

The incoherent electronic noise modifies the measured values of the samples  $S_i$  randomly around the normalized pulse shape. This effect is to first approximation uncorrelated between the samples  $S_i$ . Figure 9 shows the impact of different effects on quality factor i.e. the quality factor distribution with amplitude variation (top left panel), with amplitude and pulse shape variation (top right), with channel to channel phase offsets (bottom left panel), and finally with a double Gaussian noise model (bottom right). It appears that the effect of the timing is very small while the effect of the noise is the second most significant contribution to the quality factor, after the pulse shape, but becomes the dominant factor at low amplitudes. Since most of the events have low amplitude they form a peak in quality factor distribution. Therefore, the position of the peak of quality factor values is particularly sensitive to the noise. For this reason the simulator uses the double Gaussian noise model that was found to describe the TileCal noise data [4]. During early studies the mean values of the noise constants stored in COOL data base were used in simulator. Nevertheless, the results showed not adequate agreement between data and simulator. Therefore, the noise constants used to smear the  $S_i$  were adjusted so that the quality factor distribution obtained with the simulator reproduces the quality factor in the data. The following noise constants are

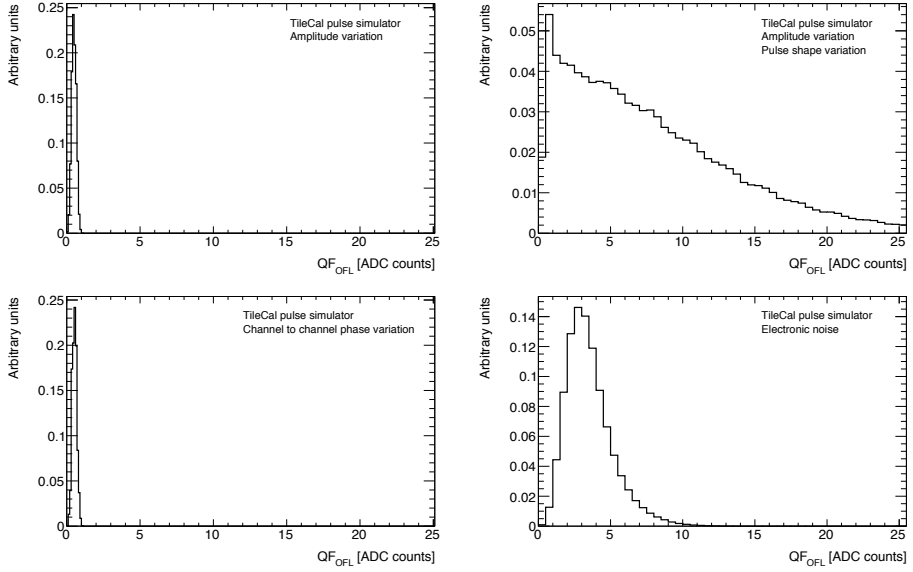


Figure 9: Top left: Quality factor with smeared amplitude. Top right: Quality factor with smeared amplitude and widened pulse shapes. Bottom left: Quality factor with smeared channel to channel time offsets. Bottom right: Quality factor with double Gaussian electronic noise.

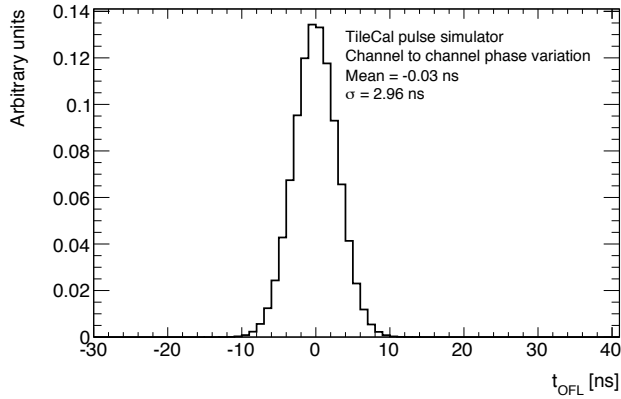


Figure 10: Channel to channel time offset distribution.

used:  $\sigma_1 = 1.46$  ADC,  $\sigma_2 = 3.60$  ADC counts and the relative normalization of the two Gaussians  $R = 0.07$ .

### 4.3 Comparison of the Quality Factor in Data and TileCal Pulse Simulator

All the presented results for both collision data and simulator consist of events acquired with high gain with reconstructed amplitude  $A_{OFL} > 34$  ADC counts (400 MeV). The reconstructed amplitude requirement ensure that the studied events consist of real energy depositions in the detector. Pedestal events are not considered in this study.

The quality factor distribution is computed in data using an integrated luminosity of  $60 \text{ nb}^{-1}$  taken in March 2011 at a period where the LHC was operating with only 2 bunches per beam, separated by at least  $2.5 \mu\text{s}$  (runs 177531, 177539, 177540, 177593, 177682), therefore ensuring the absence of out-of-time pile-up. The collisions were collected in JetTauEtmiss stream. The quality factor distribution is also computed in simulator using the model described in Section 4.2 and compared with collision data.

To obtain optimal agreement between data and pulse simulator, one would have to use different noise constants in different channels, since all channels in the real detector have slightly different noise and pulse characteristics. The events from different channels would enter to the histograms with different frequencies dependent on  $\eta$  and layer. Also, the pulse shapes would have to be widened differently in different channels. The simulator results presented here are obtained with the simplified model introduced earlier, using the averaged noise and pulse shape variation constants adjusted to data.

Figure 11 left panel shows the reconstructed amplitude dependence on quality factor in collision data while right panel shows the corresponding distribution of quality factor obtained in the pulse simulator, in absence of out-of-time pile-up. The amplitude dependence of the quality factor in data is well reproduced by the simulator in the range 200 – 1024 ADC counts, as attested by the similar fitted slopes in the right panel of Fig. 11. In the range below 200 ADC counts the amplitude dependence shows non-linear behaviour in the pulse simulator. Therefore, the fit was performed in the linear region only. In order to obtain a good agreement in whole amplitude range one would have to apply a treatment described above. The resulting quality factor distribution in data and from the simulator is shown in top panels of Fig. 12, while the bottom panel shows a relative difference between distributions. A good agreement apart from a small discrepancies in the high tail of the quality factor distribution is shown. In a range of  $0 < QF_{OFL} < 5$  ADC counts, i.e. for most events w/o out-of-time pile-up the relative difference is below 1%. Figure 13 shows  $QF_{OFL}/A_{OFL}$  distribution in data and from the simulator. Also here a fair agreement is observed.

This demonstrates that the pulse shapes can be simulated in such a way that a complex quantity such as the quality factor and its correlation with amplitude can be reproduced. The simulator can then be used to predict the quality factor distribution in presence of out-of-time pile-up in order to derive the optimal criteria to detect out-of-time pile-up while keeping the amount of read out data within the bandwidth budget of TileCal.

## 5 Quality Factor Simulation with Pile-up

### 5.1 Strategy

The goal of this section is to determine the effect of out-of-time pile-up on the quality factor in the pile-up scenarios presented in Section 3. The out-of-time pulses in a TileCal cell can be of arbitrary small sizes. For a small enough amplitude of the out-of-time pulse compared to the in-time pulse, the effect on the reconstructed energy in the cell will be negligible. When the effect of the out-of-time pulse on the reconstructed energy is negligible there is no need to detect the out-of-time pulse.

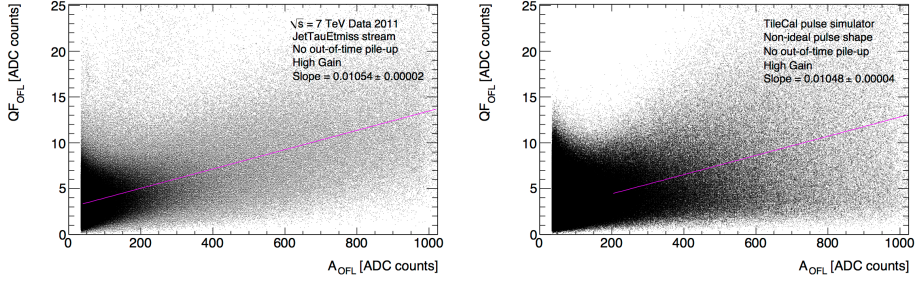


Figure 11: Left: Quality factor as a function of reconstructed amplitude in 2011 data. The data consists of runs: 177531, 177539, 177540, 177593, 177682 from March 2011 ( $\langle\mu\rangle = 3.3$ ). This data was recorded while the LHC was running with only 2 bunches per beam separated by at least  $2.5\ \mu\text{s}$ . Right: Quality factor as a function of reconstructed amplitude in TileCal pulse simulator with non-ideal pulse shapes, timing and noise effects emulated (full model of the pulse simulator). No out-of-time pile-up. There is amplitude dependence of quality factor. The x-axis shows the amplitude in ADC counts before channel-dependent calibration constants are applied. The calibration factor is approximately 12 MeV per ADC count. The purple line corresponds to the linear fit to mean value of the quality factor.

On the other hand when the out-of-time pulse is large enough with respect to the in-time pulse, its effect on the reconstructed energy will be large. Therefore, it is important to detect such a situation so that proper action can be taken, for instance by performing a special energy reconstruction or flagging the cell as providing an unreliable energy measurement.

The strategy presented in this note is therefore that small out-of-time pulses are simply ignored. The amplitude for which the out-of-time pulse becomes non-negligible referred here as “significant” pulses, is determined in bins of the amplitude of the in-time pulse amplitude.

While the average energy distribution in cells due to in-time pulse is related to the trigger item which triggered the recording of the event, the out-of-time pulses on the other hand belong to events that did not fire the trigger therefore the energy distribution of the out-of-time pulses correspond to the energy distribution in a ZeroBias trigger randomly distributed in coincidence with the crossing of populated bunch pairs. So the energy distribution for the significant pulses will be taken from the energy observed in ZeroBias events, and passing the energy threshold that makes the pulse giving a significant bias on the energy reconstruction.

## 5.2 Effect of Pile-up on the Reconstructed Amplitude

In this section we determine what is a “significant” out-of-time pulse by looking at its effect on the reconstructed amplitude. The amplitude of the in-time pulse is referred to as  $A_{in}$ . For a given value of  $A_{in}$  the amplitude of the out-of-time pulse referred to as  $A_{out}$  is varied. For each value of  $A_{in}$  and  $A_{out}$  the amplitude is recomputed with the iterative Optimal Filtering and compared to the true in-time pulse amplitude. Figure 14 gives the size of the deviation of reconstructed amplitude  $A_{OLF}$  from the true in-time amplitude as function of the amplitude of out-of-time pulse in the case of out-of-time pile-up located 50 ns earlier than in-time pulse and  $A_{out} < A_{in}$ . The purple line corresponds to the 9th order polynomial fit to mean value of relative difference. This Figure shows for instance that the maximal average effect on the reconstructed amplitude is 11% in all  $A_{in}$  bins. The observed shape is invariant if plotted as a function of  $A_{out}/A_{in}$  and indicates that the bias increases with  $A_{out}$  up to some point. After the extremum is reached

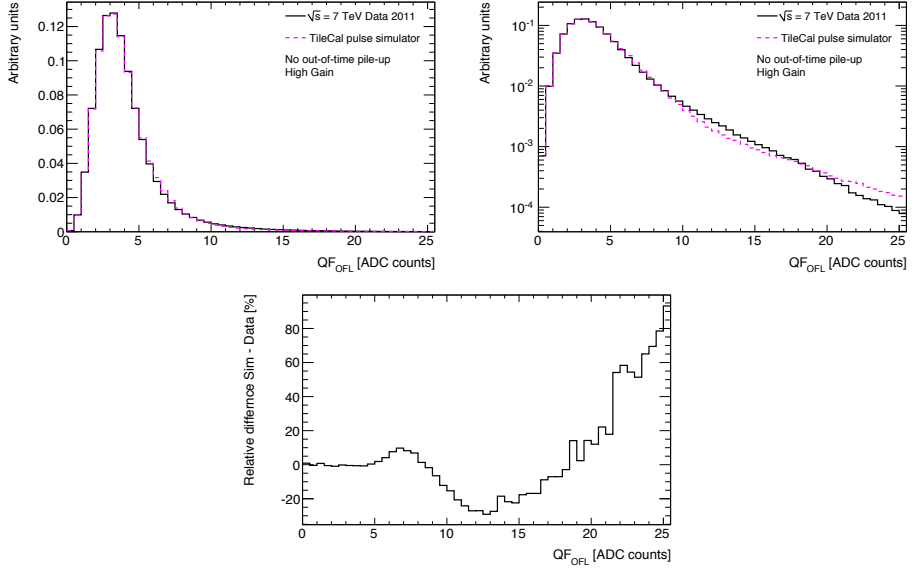


Figure 12: Comparison of quality factor distribution in 2011 data and in TileCal pulse simulator with non-ideal pulse shapes, timing and noise effects emulated (full model of the pulse simulator). The data consists of runs: 177531, 177539, 177540, 177593, 177682 from March 2011 ( $\langle\mu\rangle = 3.3$ ). This data was recorded while the LHC was running with only 2 bunches per beam separated by at least  $2.5 \mu\text{s}$ . Plot on left side has y axis in linear scale, plot on right side has y axis in logarithmic scale, plot on the bottom shows relative difference between simulator and data.

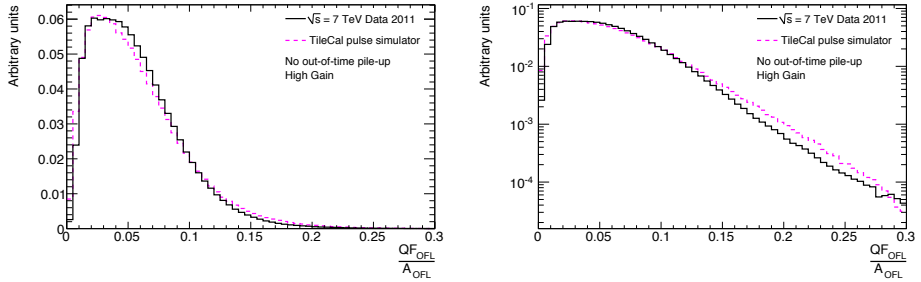


Figure 13: Comparison of quality factor divided by reconstructed amplitude distribution in 2011 data and in TileCal pulse simulator with non-ideal pulse shapes, timing and noise effects emulated (full model of the pulse simulator). The data consists of runs: 177531, 177539, 177540, 177593, 177682 from March 2011 ( $\langle\mu\rangle = 3.3$ ). This data was recorded while the LHC was running with only 2 bunches per beam separated by at least  $2.5 \mu\text{s}$ . Plot on left side has y axis in linear scale while plot on right side has y axis in logarithmic scale.

the bias decreases back. It can be understood in terms of pulse shapes (Fig. 5). The reconstructed phase increases with the ratio  $A_{out}/A_{in}$ . It takes the value  $t_{OFL} = 0$  ns for  $A_{out} = 0$  ADC counts and  $t_{OFL} = 25$  ns (lies in the middle between the pulses) for  $A_{in} = A_{out}$ . Since in the reconstruction of amplitude with Optimal Filtering method the largest constant  $a_{max}$  correspond to the reconstructed phase, one has to look at the purple line presenting the sum of two pulses in the time region 0 – 25 ns on Fig. 5. The shape of this line shows the similar behaviour to the shapes observed on Fig. 14. In the reconstruction of pedestal first and last constants ( $c_1$  and  $c_7$ ) are the largest. Therefore, in case of no out-of-time pile-up the pedestal is determined mainly from the samples with little or no signal. In presence of pile-up out-of-time signal is added to either first or last sample. Therefore, the reconstructed pedestal is overestimated while the amplitude is underestimated. Maximal average effect on reconstructed amplitude of out-of-time pulses of amplitude  $A_{out} = 34$  ADC (400 MeV) or below is 11% for  $A_{in} = 34$  ADC, 8.8% for  $A_{in} = 84$  ADC, 2.2% for  $A_{in} = 417$  ADC and 0.9% for  $A_{in} = 1000$  ADC. When  $A_{out} > A_{in}$  the out of time pulse becomes dominant. In this case, since iterative the Optimal Filtering method is used the out-of-time amplitude is reconstructed.

We conclude that the “significant” out-of-time pulses are those with amplitude above 34 ADC since their maximal average effect on reconstructed amplitude is 11%. Only these pulses are considered in studies described in Section 4.2.1.

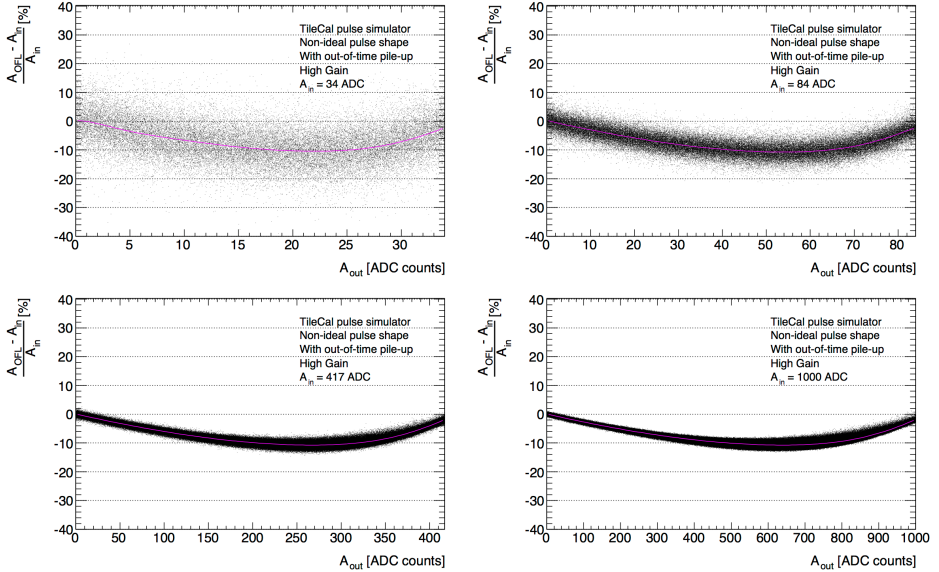


Figure 14: Relative difference between reconstructed amplitude and true in-time pulse amplitude as a function of true out-of-time pulse amplitude in TileCal pulse simulator with non-ideal pulse shapes, timing and noise effects emulated (full model of the pulse simulator). Four cases:  $A_{in} = 34$  ADC ( $A_{in} = 0.4$  GeV),  $A_{in} = 84$  ADC ( $A_{in} = 1$  GeV),  $A_{in} = 417$  ADC ( $A_{in} = 5$  GeV),  $A_{in} = 1000$  ADC ( $A_{in} = 12$  GeV). The purple line corresponds to the 9th order polynomial fit to mean value of relative difference.



### 5.3 Amplitude of Out-of-Time Pulses

The average signal amplitude for in-time pulses is related to the trigger criteria used to record the event, since for instance requiring several highly energetic hadronic jets will certainly increase the amount of energy deposited in the calorimeter and hence the likelihood that a calorimeter channel received a large signal.

The out-of-time pulses on the other hand belong to collisions that did not pass the trigger. They are recorded by chance since they were close in time to a collision that passed the trigger. Therefore the energy distribution from pile-up is that from unbiased collisions before the trigger. This energy distribution can be extracted from data by using a specific trigger. ATLAS possesses a so-called a ZeroBias trigger, which records a small fraction of collisions randomly selected in coincidence with the crossing of two populated proton bunches. This ZeroBias trigger allows to measure the energy distribution in TileCal channels without the effect of the trigger bias, and is therefore used as a model to extract the probability density function of the amplitude of the out-of-time pulses. This amplitude distribution is extracted from no pile-up ATLAS data from March 2011 at a time where the LHC was operating with only two bunches per beam, separated with at least  $2.5 \mu\text{s}$ . The corresponding distribution of amplitude before channel-dependent calibration constants are applied is shown in Fig. 15. This amplitude distribution is used as probability density function to generate out-of-time pulses in the pulse simulator and compute the quality factor in presence of pile-up in Section 5.4. Additionally, a lower cut of 34 ADC counts described in Section 5.2 is applied.

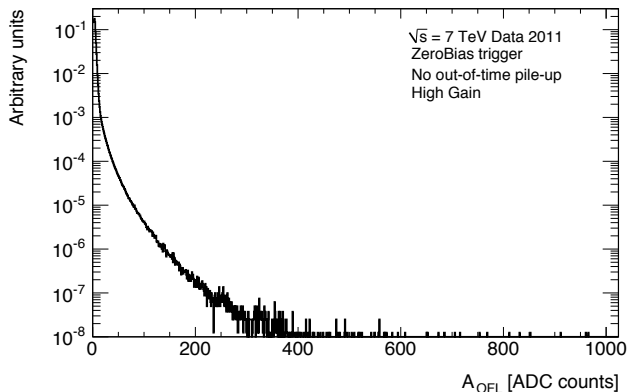


Figure 15: Distribution of reconstructed amplitude in 2011 data ZeroBias stream, in absence of out-of-time pile-up. The data consists of runs: 177531, 177539, 177540, 177593, 177682 from March 2011 ( $\langle\mu\rangle = 3.3$ ). This data was recorded while the LHC was running with only 2 bunches per beam separated by at least  $2.5 \mu\text{s}$ . The x-axis shows the amplitude in ADC counts before channel-dependent calibration constants are applied. The calibration factor is approximately 12 MeV per ADC count. The electronic noise is approximately 1.5 ADC counts.

### 5.4 Quality Factor Distributions in Presence of Out-of-Time Pile-up

In this Section the effect of the out-of-time pile-up on the quality factor is studied. Using TileCal pulse simulator model one can study the effect of the relative sizes of the in-time and out-of-time pulses. Fig. 16

shows the dependence of the quality factor  $QF_{OFL}$  as a function of the in-time pulse amplitude  $A_{in}$  (out-of-time pulse  $A_{out}$ ) given on the x-axis and for different values of the ratio between the in-time and out-of-time pulse amplitude. The lines correspond to the linear fit to mean value of the quality factor. It shows two important features, first that for a given ratio of  $A_{out}/A_{in}$ , the quality factor increases linearly with the amplitude, and second that the dependence on the amplitude  $A_{in}$  gets steeper when the ratio  $A_{out}/A_{in}$  gets closer to one. The worst case scenario occurs for in-time and out-of-time pulses of equal amplitude, in that case the quality factor becomes maximal. The introduction of an out-of-time pile-up pulse is equivalent to introducing a deviation between the ideal pulse shape and the real pulse shape. The linear dependence on the amplitude observed here is therefore consistent with the observation of a linear dependence upon pulse amplitude made in Section. 4.2.1. In iterative Optimal Filtering method the reconstructed phase  $t_{OFL}$  is proportional to the ratio  $A_{out}/A_{in}$ . It takes the value  $t_{OFL} = 0$  ( $t_{OFL} = 50$ ) ns for  $A_{out} = 0$  ( $A_{in} = 0$ ) ADC counts and  $t_{OFL} = 25$  ns (lies in the middle between the pulses) for  $A_{in} = A_{out}$ . Therefore, there is the same effect on quality factor regardless which pulse, in-time or out-of-time is dominant (on Fig. 16 black and purple lines are overlapping).

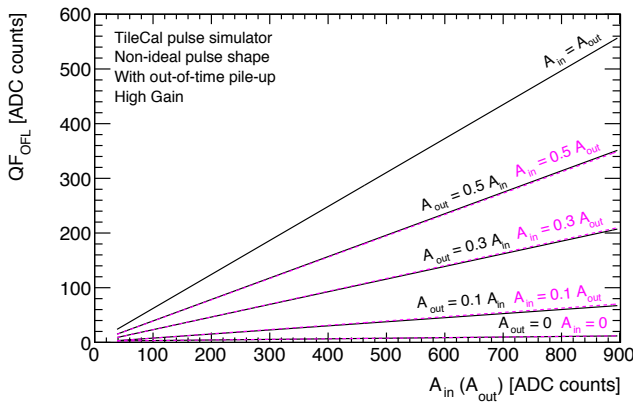


Figure 16: Quality factor as a function of the amplitude in different pile-up scenarios in TileCal pulse simulator with non-ideal pulse shapes, timing and noise effects emulated (full model of the pulse simulator).  $A_{in}$  ( $A_{out}$ ) is the amplitude of the in-time (out-of-time) pulse. The x-axis shows the amplitude in ADC counts before channel-dependent calibration constants are applied. The calibration factor is approximately 12 MeV per ADC count.

In order to compute a realistic distribution of the quality factor in presence of out-of-time pile-up, the pulses are generated with the simulator using all effects described earlier in Section 4. The amplitude of the out-of-time pulse is modeled with the probability density function obtained using the ZeroBias data as described in Section 4 and 5.4. The amplitude of in-time pulse is modeled with the probability density function obtained using JetTauEtmis data. In both cases, in-time and out-of-time pulse, there is lower cut 34 ADC counts (400 MeV) imposed on the actual amplitude. Figure 17 compares the quality factor in the absence (black) and presence of out-of-time pile-up (purple) obtained for this model in three reconstructed amplitude bins. In order to get the distributions presented in this Figure, a large set of 10 million in-time pulses without out-of-time pile-up was generated using pulse simulator. These events correspond to the black line distributions. Then, the same number of events with out-of-time pile-up were generated. These events correspond to the purple line distributions. Figure 17 illustrates

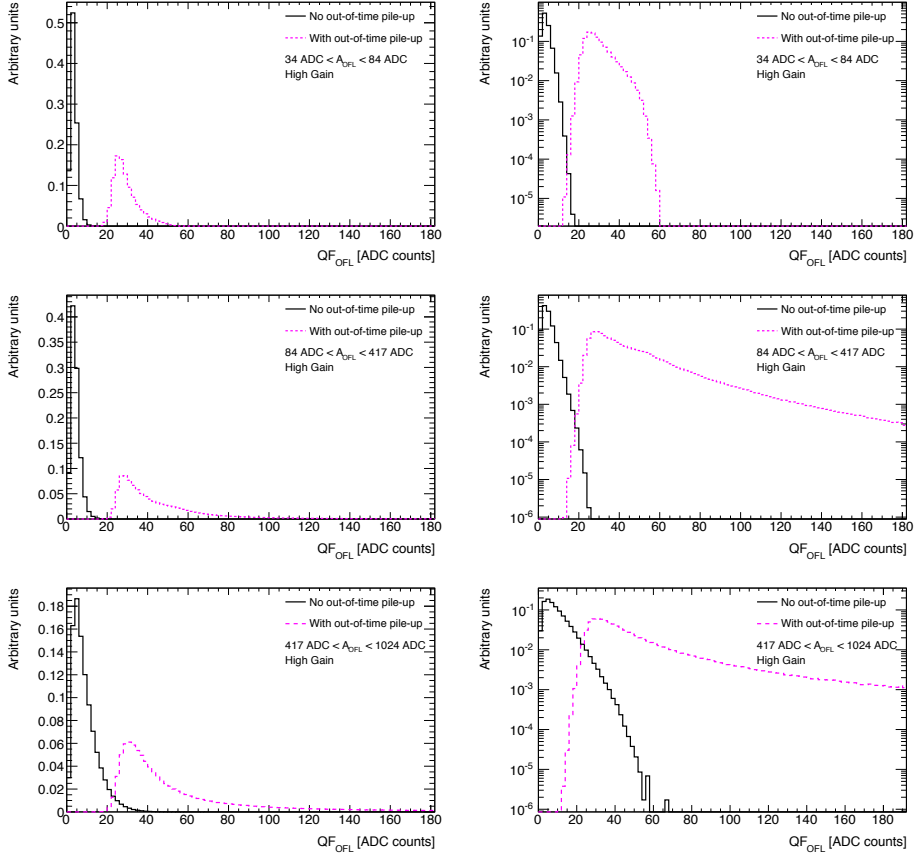


Figure 17: Normalized distributions of quality factor in TileCal simulator with non-ideal pulse shapes, timing and noise effects emulated (full model of the pulse simulator). Two cases: no out-of-time pile-up (black) and with out-of-time pile-up (purple). Amplitude of in-time pulse follows the distribution in JetTauEtmisss stream with cut corresponding to the bin. Amplitude of the out-of-time pulse follows the distribution in ZeroBias stream with a cut on 34 ADC counts (0.4 GeV). Three reconstructed amplitude bins:  $34 < A_{OFL} < 84 \text{ ADC}$  ( $0.4 < E_{OFL} < 1 \text{ GeV}$ ),  $84 < A_{OFL} < 417 \text{ ADC}$  ( $1 < E_{OFL} < 5 \text{ GeV}$ ),  $417 < A_{OFL} < 1000 \text{ ADC}$  ( $5 < E_{OFL} < 12 \text{ GeV}$ ). The JetTauEtmisss and ZeroBias data was recorded while the LHC was running with only 2 bunches per beam separated by at least  $2.5 \mu\text{s}$  and corresponds to the runs: 177531, 177539, 177540, 177593, 177682 from March 2011 ( $\langle\mu\rangle = 3.3$ ). Plots on left side have y axis in linear scale while plots on right side have y axis in logarithmic scale.

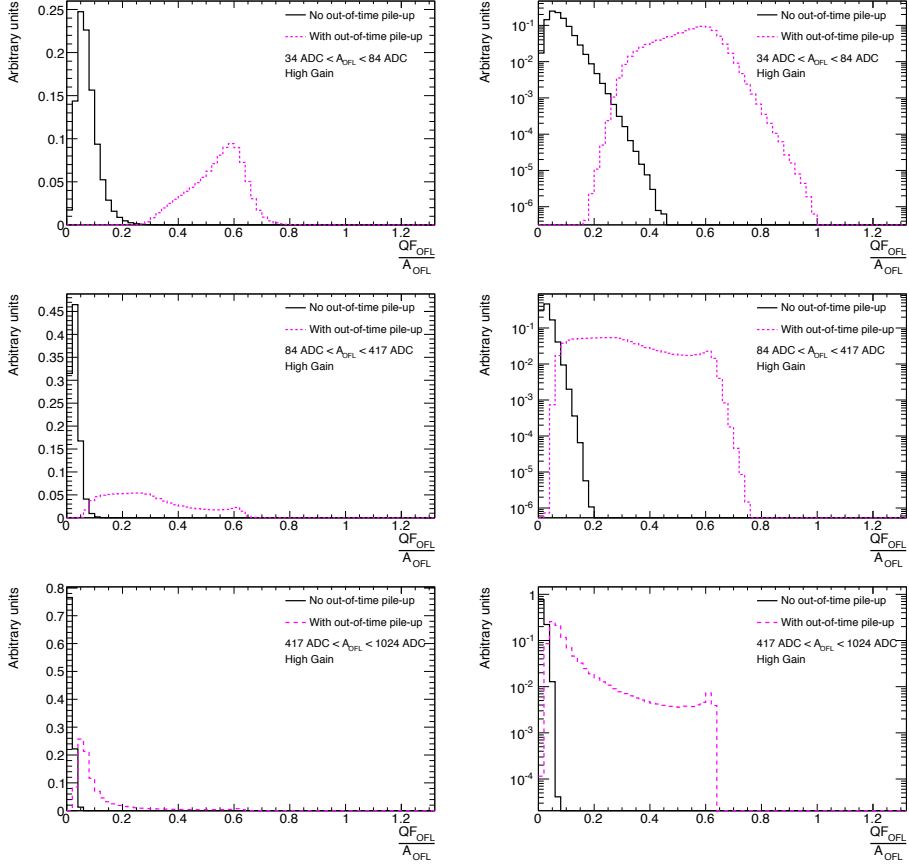


Figure 18: Normalized distributions of quality factor divided by reconstructed amplitude in TileCal simulator with non-ideal pulse shapes, timing and noise effects emulated (full model of the pulse simulator). Two cases: no out-of-time pile-up (black) and with out-of-time pile-up (purple). Amplitude of in-time pulse follows the distribution in JetTauEtmisss stream with cut corresponding to the bin. Amplitude of the out-of-time pulse follows the distribution in ZeroBias stream with a cut on 34 ADC counts (0.4 GeV). Three reconstructed amplitude bins:  $34 < A_{OFL} < 84$  ADC ( $0.4 < E_{OFL} < 1$  GeV),  $84 < A_{OFL} < 417$  ADC ( $1 < E_{OFL} < 5$  GeV),  $417 < A_{OFL} < 1000$  ADC ( $5 < E_{OFL} < 12$  GeV). The JetTauEtmisss and ZeroBias data was recorded while the LHC was running with only 2 bunches per beam separated by at least  $2.5 \mu\text{s}$  and corresponds to the runs: 177531, 177539, 177540, 177593, 177682 from March 2011 ( $\langle \mu \rangle = 3.3$ ). Plots on left side have y axis in linear scale while plots on right side have y axis in logarithmic scale.

that for significant out-of-time pile-up pulses the distribution of quality factor is quite different in case of out-of-time compared to no out-of-time pile-up. There is a clear separation between the two cases.

As it has been shown that the quality factor is linearly increasing with the amplitude of the pulses, further studies of quality factor divided by amplitude ( $QF_{OFL}/A_{OFL}$ ) were performed. For this purpose exactly the same simulation model was used. Fig. 18 compares  $QF_{OFL}/A_{OFL}$  in the absence (black) and presence of out-of-time pile-up (purple) obtained for this model in three reconstructed amplitude bins. In this case, also good separation is observed. Nevertheless, the best separation between the pile-up and non-pile-up scenarios is obtained by using the quality factor, rather than the quality factor divided by the amplitude as can be seen in Fig. 17. Based on these results possible criteria to select pile-up channels is proposed in the next section.

## 6 Optimization of the Selection to Detect Pile-up

Using the quality factor distributions presented in Fig. 17 one can propose selections to detect out-of-time pile-up based on a cut on quality factor. Since there is a linear dependence of the amplitude of out-of-time pulse on quality factor, three different selection criteria are defined for three different amplitude bins. The amplitude bins presented in Fig. 17 correspond to the reconstructed amplitude  $A_{OFL}$ . Therefore, these results can be used directly to propose the cuts on the quality factor.

Table 1 shows proposed cuts on the quality factor for three reconstructed amplitude bins. The first column shows reconstructed amplitude range in ADC counts in particular bin, second column shows reconstructed energy in MeV in each bin (the calibration factor is approximately 12 MeV per ADC count), third column shows proposed cuts on quality factor, fourth column shows fake rate in per cent and last column shows the efficiency in per cent. A fake rate is defined as a fraction of non out-of-time pile-up events that were wrongly selected as a pile-up events. The efficiency is defined as a fraction of out-of-time pile-up events correctly selected as pile-up events. If necessary, one can apply different reconstructed amplitude bins based on the information from Fig. 16.

In case of the first bin ( $34 < A_{OFL} < 84$  ADC) a cut of  $QF_{OFL} > 8.8$  ADC counts allows the selection of all pile-up events with less than 1% of non-pile-up events wrongly selected. The same result can be obtained in second bin ( $84 < A_{OFL} < 417$  ADC) with cut of  $QF_{OFL} > 11.6$ . In case of third bin ( $417 < A_{OFL} < 1024$  ADC) the separation becomes slightly worse due to larger tail in distribution of quality factor in non-pile-up events. The tail is present in highest amplitude bin due to quality factor amplitude dependence described in Section 4.2.1. Therefore, three different cuts on quality factor are presented. Cut of  $QF_{OFL} > 29.7$  ADC allows to limit fake rate to less than 1% with 85.03% efficiency. Lower cut of  $QF_{OFL} > 22.9$  ADC increase efficiency to 99.04% and fake rate to 3.75%. Using cut of  $QF_{OFL} > 11.7$  ADC one can select all pile-up events with fake rate of 26.55%. Depending on the constraints of available bandwidth one of the proposed cut can be chosen in this amplitude bin.

| $A_{OFL}$ [ADC] | $E_{OFL}$ [GeV] | $QF_{OFL}$ cut [ADC] | Fake rate [%]     | Efficiency [%]            |
|-----------------|-----------------|----------------------|-------------------|---------------------------|
| 34 — 84         | 0.4 — 1         | 8.8                  | $0.973 \pm 0.004$ | 100.0 (> 99.9% at 95% CL) |
| 84 — 417        | 1 — 5           | 11.6                 | $0.985 \pm 0.006$ | 100.0 (> 99.9% at 95% CL) |
| 417 — 1024      | 5 — 12          | 29.7                 | $0.99 \pm 0.01$   | $85.03 \pm 0.03$          |
| 417 — 1024      | 5 — 12          | 22.9                 | $3.75 \pm 0.03$   | $99.04 \pm 0.01$          |
| 417 — 1024      | 5 — 12          | 11.7                 | $26.55 \pm 0.06$  | 100.0 (> 99.8% at 95% CL) |

Table 1: Proposed cuts on  $QF_{OFL}$  for three reconstructed amplitude bins, together with the corresponding fake rates and efficiencies, in different bins of the reconstructed amplitude. A set of 10 millions events was used to calculate fake rates and efficiencies. The quoted errors are statistical.

## 7 Conclusions

A numerical model of the ATLAS Tile Calorimeter pulses has been developed in the form of a pulse simulator. This model takes into account small variations in signal pulse shapes, small timing miscalibration effects and uses double Gaussian model of the calorimeter noise. The simulator is shown to be able to reproduce the quality factor distributions in collisions in absence of out-of-time pile-up. The variation in pulse shapes from cell to cell is a crucial effect that has to be taken into consideration to model the quality factor at high pulse amplitude. The modeling of the electronic noise is crucial to correctly describe the low energy part of the quality factor distribution. The signal amplitude for TileCal channels is measured in ZeroBias triggered data and used as a model for pulses from out-of-time pile-up collisions. Using this model of the data, the distribution of the quality factor in the presence of out-of-time pile-up is calculated. It shows that when amplitude of the out-of-time pile-up is large enough to affect the amplitude measurement, significant discrimination between the presence and the absence of out-of-time pile-up can be achieved thanks to the quality factor. Using the predicted distributions of quality factor with and without out-of-time pile-up, the presence of significant out-of-time pile-up can be identified and a specific treatment of the double pulses can be performed. For this purpose adequate cuts on quality factor in three various reconstructed amplitude bins are proposed. In particular in the lowest energy bins it is possible to achieve 100% efficiency for significant pile-up pulses while keeping a fake rate of 1%. The presented results have been obtained using iterative Optimal Filtering reconstruction method. In the next step the quality factor calculated with non-iterative method needs to be studied. This would allow to implement identification of pile-up using quality factor online in DSP.

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## Appendices

### A Bias and Resolution of Optimal Filtering Reconstruction

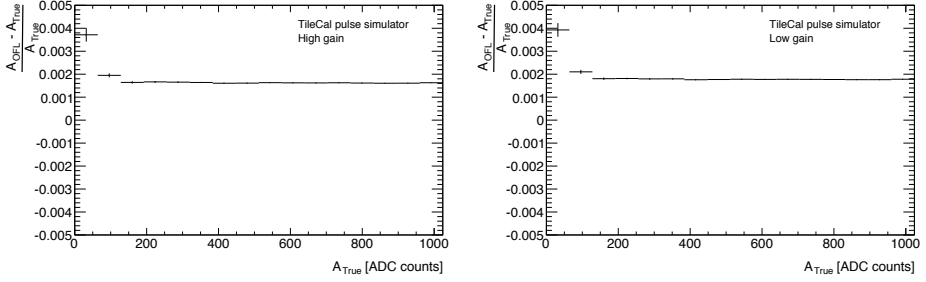


Figure 19: The bias in reconstruction of amplitude as a function of true amplitude in TileCal pulse simulator. This is shown for high gain (left) and low gain (right). Amplitude is reconstructed with Optimal Filtering with iterations in absence of out-of-time pile-up.

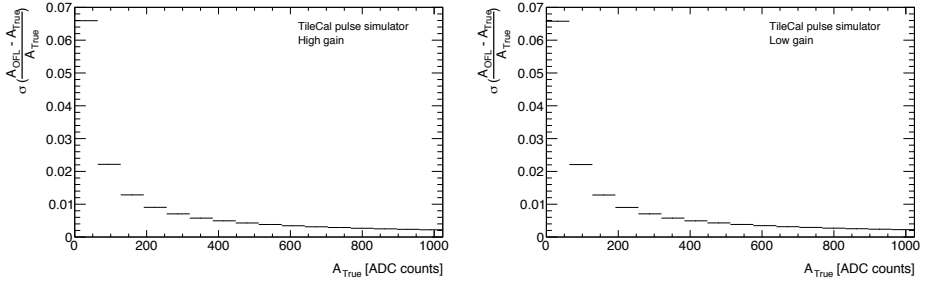


Figure 20: The resolution of amplitude reconstruction as a function of true amplitude in TileCal pulse simulator. This is shown for high gain (left) and low gain (right). Amplitude is reconstructed with Optimal Filtering with iterations in absence of out-of-time pile-up.

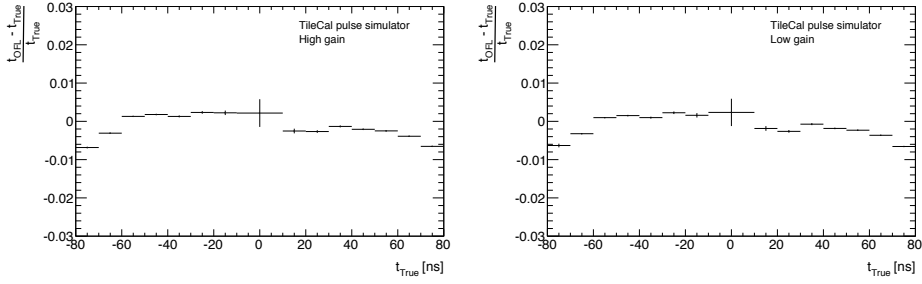


Figure 21: The bias in reconstruction of time as a function of true time in TileCal pulse simulator. This is shown for high gain (left) and low gain (right). Time is reconstructed with Optimal Filtering with iterations in absence of out-of-time pile-up.

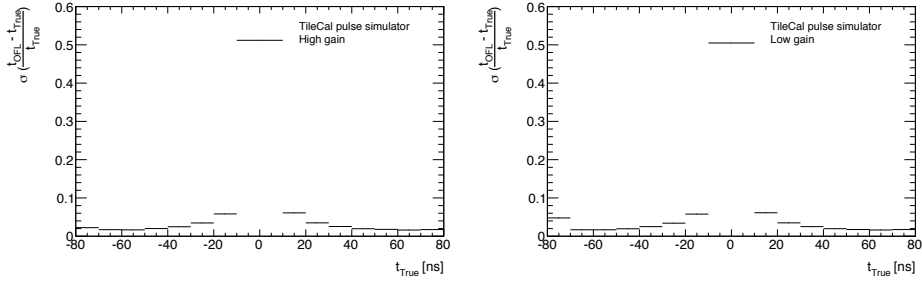


Figure 22: The resolution of time reconstruction as a function of true time in TileCal pulse simulator. This is shown for high gain (left) and low gain (right). Time is reconstructed with Optimal Filtering with iterations in absence of out-of-time pile-up.

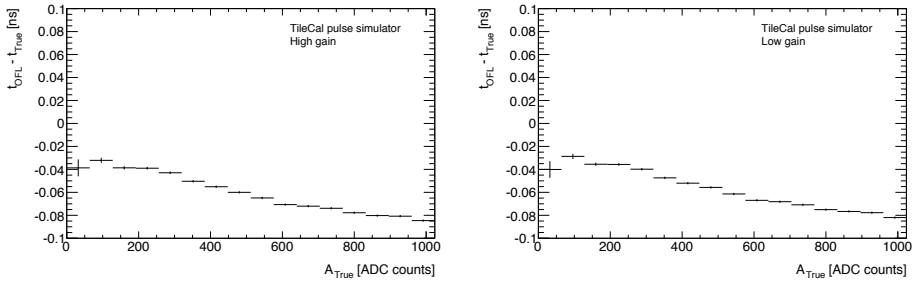


Figure 23: The bias in reconstruction of time as a function of true amplitude in TileCal pulse simulator. This is shown for high gain (left) and low gain (right). Time is reconstructed with Optimal Filtering with iterations in absence of out-of-time pile-up.



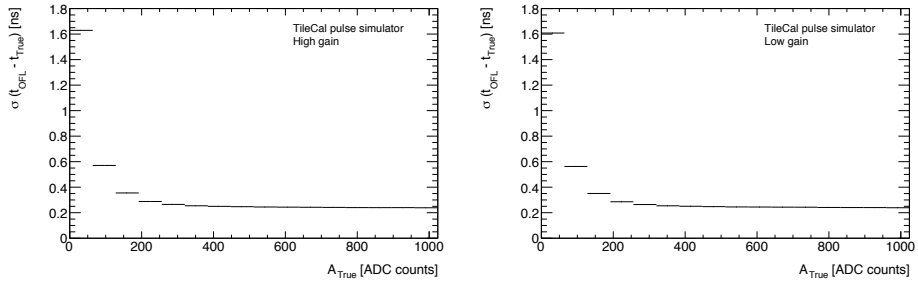


Figure 24: The resolution of time reconstruction as a function of true time in TileCal pulse simulator. This is shown for high gain (left) and low gain (right). Time is reconstructed with Optimal Filtering with iterations in absence of out-of-time pile-up.

III



# Search for direct production of charginos, neutralinos and sleptons in final states with two leptons and missing transverse momentum in $pp$ collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector



## The ATLAS collaboration

*E-mail:* [atlas.publications@cern.ch](mailto:atlas.publications@cern.ch)

**ABSTRACT:** Searches for the electroweak production of charginos, neutralinos and sleptons in final states characterized by the presence of two leptons (electrons and muons) and missing transverse momentum are performed using  $20.3\text{ fb}^{-1}$  of proton-proton collision data at  $\sqrt{s} = 8$  TeV recorded with the ATLAS experiment at the Large Hadron Collider. No significant excess beyond Standard Model expectations is observed. Limits are set on the masses of the lightest chargino, next-to-lightest neutralino and sleptons for different lightest-neutralino mass hypotheses in simplified models. Results are also interpreted in various scenarios of the phenomenological Minimal Supersymmetric Standard Model.

**KEYWORDS:** Supersymmetry, Hadron-Hadron Scattering

**ARXIV EPRINT:** [1403.5294](https://arxiv.org/abs/1403.5294)

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## 1 Introduction

Supersymmetry (SUSY) [1–9] is a spacetime symmetry that postulates for each Standard Model (SM) particle the existence of a partner particle whose spin differs by one-half unit. The introduction of these new particles provides a potential solution to the hierarchy problem [10–13]. If  $R$ -parity is conserved [14–18], as is assumed in this paper, SUSY particles are always produced in pairs and the lightest supersymmetric particle (LSP) emerges as a stable dark-matter candidate.

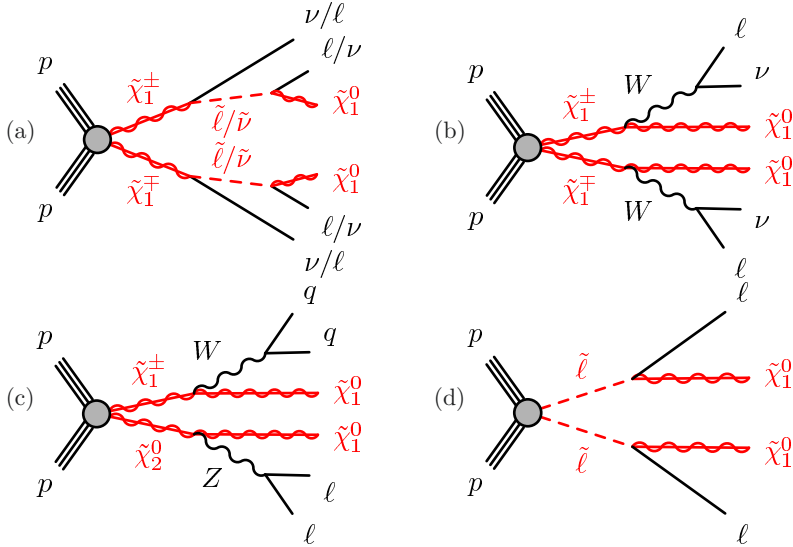
The charginos and neutralinos are mixtures of the bino, winos and higgsinos that are superpartners of the  $U(1)$ ,  $SU(2)$  gauge bosons and the Higgs bosons, respectively. Their mass eigenstates are referred to as  $\tilde{\chi}_i^\pm$  ( $i = 1, 2$ ) and  $\tilde{\chi}_j^0$  ( $j = 1, 2, 3, 4$ ) in the order of increasing masses. Even though the gluinos and squarks are produced strongly in  $pp$  collisions, if the masses of the gluinos and squarks are large, the direct production of charginos, neutralinos and sleptons through electroweak interactions may dominate the production of SUSY particles at the Large Hadron Collider (LHC). Such a scenario is possible in the general framework of the phenomenological minimal supersymmetric SM (pMSSM) [19–21]. Naturalness suggests that third-generation sparticles and some of the charginos and neutralinos should have masses of a few hundred GeV [22, 23]. Light sleptons are expected in gauge-mediated [24–29] and anomaly-mediated [30, 31] SUSY breaking scenarios. Light sleptons could also play a role in the co-annihilation of neutralinos, allowing a dark matter relic density consistent with cosmological observations [32, 33].

This paper presents searches for electroweak production of charginos, neutralinos and sleptons using  $20.3\text{ fb}^{-1}$  of proton-proton collision data with a centre-of-mass energy  $\sqrt{s} = 8\text{ TeV}$  collected at the LHC with the ATLAS detector. The searches target final states with two oppositely-charged leptons (electrons or muons) and missing transverse momentum. Similar searches [34, 35] have been performed using  $\sqrt{s} = 7\text{ TeV}$  data by the ATLAS and CMS experiments. The combined LEP limits on the selectron, smuon and chargino masses are  $m_{\tilde{e}} > 99.9\text{ GeV}$ ,  $m_{\tilde{\mu}} > 94.6\text{ GeV}$  and  $m_{\tilde{\chi}_1^\pm} > 103.5\text{ GeV}$  [36–41]. The LEP selectron limit assumes gaugino mass unification and cannot be directly compared with the results presented here.

## 2 SUSY scenarios

Simplified models [42] are considered for optimization of the event selection and interpretation of the results. The LSP is the lightest neutralino  $\tilde{\chi}_1^0$  in all SUSY scenarios considered, except in one scenario in which it is the gravitino  $\tilde{G}$ . All SUSY particles except for the LSP are assumed to decay promptly. In the electroweak production of  $\tilde{\chi}_1^+ \tilde{\chi}_1^-$  and  $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ ,  $\tilde{\chi}_1^\pm$  and  $\tilde{\chi}_2^0$  are assumed to be pure wino and mass degenerate, and only the  $s$ -channel production diagrams,  $q\bar{q} \rightarrow (Z/\gamma)^* \rightarrow \tilde{\chi}_1^+ \tilde{\chi}_1^-$  and  $q\bar{q}' \rightarrow W^{\pm*} \rightarrow \tilde{\chi}_1^\pm \tilde{\chi}_2^0$ , are considered. The cross-section for  $\tilde{\chi}_1^+ \tilde{\chi}_1^-$  production is 6 pb for a  $\tilde{\chi}_1^\pm$  mass of 100 GeV and decreases to 10 fb at 450 GeV. The cross-section for  $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$  production is 11.5 pb for a degenerate  $\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$  mass of 100 GeV, and 40 fb for 400 GeV.

In the scenario in which the masses of the sleptons and sneutrinos lie between the  $\tilde{\chi}_1^\pm$  and  $\tilde{\chi}_1^0$  masses, the  $\tilde{\chi}_1^\pm$  decays predominantly as  $\tilde{\chi}_1^\pm \rightarrow (\tilde{\ell}^\pm \nu \text{ or } \ell^\pm \bar{\nu}) \rightarrow \ell^\pm \nu \tilde{\chi}_1^0$ . Figure 1(a) shows direct chargino-pair production,  $pp \rightarrow \tilde{\chi}_1^+ \tilde{\chi}_1^-$ , followed by the slepton-mediated decays. The final-state leptons can be either of the same flavour (SF =  $e^+e^-$  or  $\mu^+\mu^-$ ), or of different flavours (DF =  $e^\pm\mu^\mp$ ). In this scenario, the masses of the three left-handed sleptons and three sneutrinos are assumed to be degenerate with  $m_{\tilde{\ell}} = m_{\tilde{\nu}} = (m_{\tilde{\chi}_1^0} + m_{\tilde{\chi}_1^\pm})/2$ . The  $\tilde{\chi}_1^\pm$  is assumed to decay with equal branching ratios (1/6) into  $\tilde{\ell}^\pm \nu$  and  $\ell^\pm \bar{\nu}$  for three lepton flavours, followed by  $\tilde{\ell}^\pm \rightarrow \ell^\pm \tilde{\chi}_1^0$  or  $\bar{\nu} \rightarrow \nu \tilde{\chi}_1^0$  with a 100% branching ratio.



**Figure 1.** Electroweak SUSY production processes of the considered simplified models.

In the scenario in which the  $\tilde{\chi}_1^\pm$  is the next-to-lightest supersymmetric particle (NLSP), the  $\tilde{\chi}_1^\pm$  decays as  $\tilde{\chi}_1^\pm \rightarrow W^\pm \tilde{\chi}_1^0$ . In direct  $\tilde{\chi}_1^+ \tilde{\chi}_1^-$  production, if both  $W$  bosons decay leptonically as shown in figure 1(b), the final state contains two opposite-sign leptons, either SF or DF, and large missing transverse momentum.

Another scenario is considered in which  $\tilde{\chi}_1^\pm$  and  $\tilde{\chi}_2^0$  are mass degenerate and are co-NLSPs. The direct  $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$  production is followed by the decays  $\tilde{\chi}_1^\pm \rightarrow W^\pm \tilde{\chi}_1^0$  and  $\tilde{\chi}_2^0 \rightarrow Z \tilde{\chi}_1^0$  with a 100% branching fraction. If the  $Z$  boson decays leptonically and the  $W$  boson decays hadronically, as shown in figure 1(c), the final state contains two opposite-sign leptons, two hadronic jets, and missing transverse momentum. The leptons in this case are SF and their invariant mass is consistent with the  $Z$  boson mass. The invariant mass of the two jets from the  $W$  decay gives an additional constraint to characterize this signal.

A scenario in which the slepton is the NLSP is modelled according to ref. [43]. Figure 1(d) shows direct slepton-pair production  $pp \rightarrow \tilde{\ell}^+ \tilde{\ell}^-$  followed by  $\tilde{\ell}^\pm \rightarrow \ell^\pm \tilde{\chi}_1^0$  ( $\ell = e$  or  $\mu$ ), giving rise to a pair of SF leptons and missing transverse momentum due to the two neutralinos. The cross-section for direct slepton pair production in this scenario decreases from 127 fb to 0.5 fb per slepton flavour for left-handed sleptons, and from 49 fb to 0.2 fb for right-handed sleptons, as the slepton mass increases from 100 to 370 GeV.

Results are also interpreted in dedicated pMSSM [44] scenarios. In the models considered in this paper, the masses of the coloured sparticles, of the CP-odd Higgs boson, and of the left-handed sleptons are set to high values to allow only the direct production of charginos and neutralinos via  $W/Z$ , and their decay via right-handed sleptons, gauge bosons and the lightest Higgs boson. The lightest Higgs boson mass is set close to 125 GeV [45, 46] by tuning the mixing in the top squark sector. The mass hierarchy, com-

position and production cross-section of the charginos and neutralinos are governed by the ratio  $\tan\beta$  of the expectation values of the two Higgs doublets, the gaugino mass parameters  $M_1$  and  $M_2$ , and the higgsino mass parameter  $\mu$ . Two classes of pMSSM scenarios are studied on a  $\mu$ - $M_2$  grid, distinguished by the masses of the right-handed sleptons  $\tilde{\ell}_R$ . If  $m_{\tilde{\ell}_R}$  lies halfway between  $m_{\tilde{\chi}_1^0}$  and  $m_{\tilde{\chi}_2^0}$ ,  $\tilde{\chi}_2^0$  decays preferentially through  $\tilde{\chi}_2^0 \rightarrow \tilde{\ell}_R \ell \rightarrow \tilde{\chi}_1^0 \ell \ell$ . The parameter  $\tan\beta$  is set to 6, yielding comparable branching ratios into each slepton generation. To probe the sensitivity to different  $\tilde{\chi}_1^0$  compositions, three values of  $M_1 = 100, 140$  and  $250$  GeV are considered. If, on the other hand, all sleptons are heavy,  $\tilde{\chi}_1^\pm$  and  $\tilde{\chi}_2^0$  decay via  $W$ ,  $Z$  and Higgs bosons. The remaining parameters are fixed to  $\tan\beta = 10$  and  $M_1 = 50$  GeV so that the relic dark-matter density is below the cosmological bound across the entire  $\mu$ - $M_2$  grid. The lightest Higgs boson has a mass close to 125 GeV and decays to both SUSY and SM particles where kinematically allowed.

In addition, the gauge-mediated SUSY breaking (GMSB) model proposed in ref. [47] is considered. In this simplified model, the LSP is the gravitino  $\tilde{G}$ , the NLSP is the chargino with  $m_{\tilde{\chi}_1^\pm} = 110$  GeV, and in addition there are two other light neutralinos with masses  $m_{\tilde{\chi}_1^0} = 113$  GeV and  $m_{\tilde{\chi}_2^0} = 130$  GeV. All coloured sparticles are assumed to be very heavy. The  $\tilde{\chi}_1^+ \tilde{\chi}_1^-$  production cross-section is not large ( $\sim 1.4$  pb), but the same final state is reached via production of  $\tilde{\chi}_1^\pm \tilde{\chi}_1^0$  ( $\sim 2.5$  pb),  $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$  ( $\sim 1.0$  pb) and  $\tilde{\chi}_1^0 \tilde{\chi}_2^0$  ( $\sim 0.5$  pb). The  $\tilde{\chi}_1^0$  decays into  $\tilde{\chi}_1^\pm W^\mp$ , and the  $\tilde{\chi}_2^0$  decays either into  $\tilde{\chi}_1^\pm W^\mp$  or  $\tilde{\chi}_1^0 Z$ . Because of the small mass differences, decay products of the off-shell  $W$  and  $Z$  bosons are unlikely to be detected. As a result, all of the four production channels result in the same experimental signature, and their production cross-sections can be added together for the purpose of this search. Each  $\tilde{\chi}_1^\pm$  then decays via  $\tilde{\chi}_1^\pm \rightarrow W^\pm \tilde{G}$ , and leptonic decays of the two  $W$  bosons produce the same final-state as in the other scenarios.

### 3 The ATLAS detector

The ATLAS detector [48] is a multi-purpose particle physics detector with a forward-backward symmetric cylindrical geometry and nearly  $4\pi$  coverage in solid angle.<sup>1</sup> It contains four superconducting magnet systems, which include a thin solenoid surrounding the inner tracking detector (ID), and barrel and end-cap toroids as part of a muon spectrometer (MS). The ID covers the pseudorapidity region  $|\eta| < 2.5$  and consists of a silicon pixel detector, a silicon microstrip detector, and a transition radiation tracker. In the pseudorapidity region  $|\eta| < 3.2$ , high-granularity liquid-argon (LAr) electromagnetic (EM) sampling calorimeters are used. An iron-scintillator tile calorimeter provides coverage for hadron detection over  $|\eta| < 1.7$ . The end-cap and forward regions, spanning  $1.5 < |\eta| < 4.9$ , are instrumented with LAr calorimeters for both EM and hadronic measurements. The

<sup>1</sup>ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the centre of the detector, and the  $z$ -axis along the beam line. The  $x$ -axis points from the IP to the centre of the LHC ring, and the  $y$ -axis points upwards. Cylindrical coordinates  $(r, \phi)$  are used in the transverse plane,  $\phi$  being the azimuthal angle around the  $z$ -axis. Observables labelled ‘transverse’ are projected into the  $x$ - $y$  plane. The pseudorapidity is defined in terms of the polar angle  $\theta$  by  $\eta = -\ln \tan(\theta/2)$ .



MS surrounds the calorimeters and consists of a system of precision tracking chambers ( $|\eta| < 2.7$ ), and detectors for triggering ( $|\eta| < 2.4$ ).

## 4 Monte Carlo simulation

Monte Carlo (MC) simulated event samples are used to develop and validate the analysis procedure and to evaluate the subdominant SM backgrounds as well as the expected signal yields. The dominant SM background processes include  $t\bar{t}$ , single-top, and diboson ( $WW$ ,  $WZ$  and  $ZZ$ ) production. The predictions for the most relevant SM processes are normalized to data in dedicated control regions, as detailed in section 7. MC samples are produced using a GEANT4 [49] based detector simulation [50] or a fast simulation using a parameterization of the performance of the ATLAS electromagnetic and hadronic calorimeters [51, 52] and GEANT4 elsewhere. The effect of multiple proton-proton collisions from the same or different bunch crossings is incorporated into the simulation by overlaying minimum bias events generated using PYTHIA [53] onto hard scatter events. Simulated events are weighted to match the distribution of the number of interactions per bunch crossing observed in data, which averaged 20.7.

Production of top-quark pairs is simulated at next-to-leading order (NLO) with MC@NLO v4.06 [54–56], assuming a top-quark mass of 172.5 GeV. Additional samples generated with POWHEG-BOX v1.0 [57] and AcerMC v3.8 [58] are used for the evaluation of systematic uncertainties. The  $t\bar{t}$  cross-section is normalized to the next-to-next-to-leading order (NNLO) calculation including resummation of next-to-next-to-leading logarithmic (NNLL) soft gluon terms obtained with Top++ v2.0 [59]. Single top production is modelled with MC@NLO v4.06 for  $Wt$  and  $s$ -channel production, and with AcerMC v3.8 for  $t$ -channel production. Production of  $t\bar{t}$  associated with a vector boson is simulated with the leading-order (LO) generator MADGRAPH 5 v1.3.33 [60] and normalized to the NLO cross-section [61–63].

Diboson ( $WW$ ,  $WZ$  and  $ZZ$ ) production is simulated with POWHEG-BOX v1.0, with additional gluon-gluon contributions simulated with gg2WW v3.1.2 [64] and gg2ZZ v3.1.2 [65]. Additional diboson samples are generated at the particle level with aMC@NLO v2.0 [66] to assess systematic uncertainties. The diboson cross-sections are normalized to NLO QCD predictions obtained with MCFM v6.2 [67, 68]. Triple-boson ( $WWW$ ,  $ZWW$  and  $ZZZ$ ) production is simulated with MADGRAPH 5 v1.3.33 [69], and vector-boson scattering ( $WWjj$  and  $WZjj$ ) is simulated with SHERPA v1.4.1 [70].

Samples of  $W \rightarrow \ell\nu$  and  $Z/\gamma^* \rightarrow \ell\ell$  produced with accompanying jets (including light and heavy flavours) are obtained with a combination of SHERPA v1.4.1 and ALPGEN v2.14 [71]. The inclusive  $W$  and  $Z/\gamma^*$  production cross-sections are normalized to the NNLO cross-sections obtained using DYNLLO v1.1 [72]. QCD production of  $b\bar{b}$  and  $c\bar{c}$  is simulated with PYTHIA v8.165.

Finally, production of the SM Higgs boson with  $m_H = 125$  GeV is considered. The gluon fusion and vector-boson fusion production modes are simulated with POWHEG-BOX v1.0, and the associated production ( $WH$  and  $ZH$ ) with PYTHIA v8.165.

Fragmentation and hadronization for the MC@NLO and ALPGEN samples are performed either with HERWIG v6.520 [73] using JIMMY v4.31 [74] for the underlying event, or with

PYTHIA v6.426. PYTHIA v6.426 is also used for MADGRAPH samples, whereas PYTHIA v8.165 is used for the POWHEG-BOX samples. For the underlying event, ATLAS tune AUET2B [75] is used. The CT10 NLO [76] and CTEQ6L1 [77] parton-distribution function (PDF) sets are used with the NLO and LO event generators, respectively.

Simulated signal samples are generated with HERWIG++ v2.5.2 [78] and the CTEQ6L1 PDF set. Signal cross-sections are calculated to NLO using PROSPINO2.1 [79]. They are in agreement with the NLO calculations matched to resummation at the next-to-leading logarithmic accuracy (NLO+NLL) within  $\sim 2\%$  [80–82].

## 5 Event reconstruction

Events are selected in which at least five tracks, each with transverse momentum  $p_T > 400$  MeV, are associated to the primary vertex. If there are multiple primary vertices in an event, the one with the largest  $\sum p_T^2$  of the associated tracks is chosen. In each event, ‘candidate’ electrons, muons, hadronically-decaying  $\tau$  leptons, and jets are reconstructed. After resolving potential ambiguities among objects, the criteria to define ‘signal’ electrons, muons and jets are refined. Hadronically-decaying  $\tau$  leptons are not considered as signal leptons for this analysis, and events containing them are removed (see section 6) so that the data sample is distinct from that used in the ATLAS search for electroweak SUSY production in the three-lepton final states [83].

Electron candidates are reconstructed by matching clusters in the EM calorimeter with tracks in the ID. The magnitude of the momentum of the electron is determined by the calorimeter cluster energy. They are required to have  $p_T > 10$  GeV,  $|\eta| < 2.47$ , and satisfy shower-shape and track-selection criteria analogous to the ‘medium’ criteria in ref. [84].

Muon candidates are reconstructed by matching an MS track to an ID track [85]. They are then required to have  $p_T > 10$  GeV and  $|\eta| < 2.4$ .

Jet candidates are reconstructed from calorimeter energy clusters using the anti- $k_t$  jet clustering algorithm [86, 87] with a radius parameter of 0.4. The jet candidates are corrected for the effects of calorimeter response and inhomogeneities using energy- and  $\eta$ -dependent calibration factors based on simulation and validated with extensive test-beam and collision-data studies [88]. Energy deposition due to pile-up interactions is statistically subtracted based on the area of the jet [89]. Only jet candidates with  $p_T > 20$  GeV and  $|\eta| < 4.5$  are subsequently retained. Events containing jets that are likely to have arisen from detector noise or cosmic rays are removed [88].

A  $b$ -jet identification algorithm [90] is used to identify jets containing a  $b$ -hadron decay inside a candidate jet within  $|\eta| < 2.4$ , exploiting the long lifetime of  $b$ - and  $c$ -hadrons. The mean nominal  $b$ -jet identification efficiency, determined from simulated  $t\bar{t}$  events, is 80%. The misidentification (mis-tag) rates for  $c$ -jets and light-quark/gluon jets are approximately 30% and 4%, respectively. Small differences in the  $b$ -tagging performance observed between data and simulation are corrected for as functions of  $p_T$  of the jets.

Hadronically-decaying  $\tau$  leptons are reconstructed by associating tracks with  $p_T > 1$  GeV passing minimum track quality requirements to calorimeter jets with  $p_T > 10$  GeV and  $|\eta| < 2.5$ . A multivariate discriminant is used to identify the jets as hadronic  $\tau$

decays [91]. Their energy is determined by applying a simulation-based correction to the reconstructed energy in the calorimeter [92], and  $p_T > 20$  GeV is required.

Object overlaps are defined in terms of  $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$ , where  $\Delta\eta$  and  $\Delta\phi$  are separations in  $\eta$  and  $\phi$ . Potential ambiguities among objects are resolved by removing one or both of nearby object pairs in the following order: if two electron candidates are within  $\Delta R = 0.05$  of each other, the electron with the smaller  $p_T$  is removed; any jet within  $\Delta R = 0.2$  of an electron candidate is removed; any  $\tau$  candidate within  $\Delta R = 0.2$  of an electron or a muon is removed; any electron or muon candidate within  $\Delta R = 0.4$  of a jet is removed; if an electron candidate and a muon candidate are within  $\Delta R = 0.01$  of each other, both are removed; if two muon candidates are within  $\Delta R = 0.05$  of each other, both are removed; if the invariant mass of a SF opposite-sign lepton pair has an invariant mass less than 12 GeV, both are removed; and finally any jet within  $\Delta R = 0.2$  of a  $\tau$  candidate is removed.

Signal electrons are electron candidates satisfying the ‘tight’ criteria [84] placed on the ratio of calorimetric energy to track momentum, and the number of high-threshold hits in the transition radiation tracker. They are also required to be isolated. The  $p_T$  scalar sum of tracks above 400 MeV within a cone of size  $\Delta R = 0.3$  around each electron candidate (excluding the electron candidate itself) and associated to the primary vertex is required to be less than 16% of the electron  $p_T$ . The sum of transverse energies of the surrounding calorimeter clusters within  $\Delta R = 0.3$  of each electron candidate, corrected for the deposition of energy from pile-up interactions, is required to be less than 18% of the electron  $p_T$ . The distance of closest approach of an electron candidate to the event primary vertex must be within five standard deviations in the transverse plane. The distance along the beam direction,  $z_0$ , must satisfy  $|z_0 \sin \theta| < 0.4$  mm.

Signal muons are muon candidates satisfying the following criteria. The  $p_T$  scalar sum of tracks above 400 MeV within a cone of size  $\Delta R = 0.3$  around the muon candidate and associated to the primary vertex is required to be less than 16% of the muon  $p_T$ . The distance of closest approach of a muon candidate to the event primary vertex must be within three standard deviations in the transverse plane, and  $|z_0 \sin \theta| < 1$  mm along the beam direction.

The efficiencies for electrons and muons to pass the reconstruction, identification and isolation criteria are measured in samples of  $Z$  and  $J/\psi$  leptonic decays, and corrections are applied to the simulated samples to reproduce the efficiencies in data.

Signal jets are jet candidates that are classified in three exclusive categories. Central  $b$ -jets satisfy  $|\eta| < 2.4$  and the  $b$ -jet identification criteria. Central light-flavour jets also satisfy  $|\eta| < 2.4$  but do not satisfy the  $b$ -jet identification criteria. If a central light-flavour jet has  $p_T < 50$  GeV and has tracks associated to it, at least one of the tracks must originate from the event primary vertex. This criterion removes jets that originate from pile-up interactions. Finally, forward jets are those with  $2.4 < |\eta| < 4.5$  and  $p_T > 30$  GeV.

The missing transverse momentum,  $\mathbf{p}_T^{\text{miss}}$ , is defined [93] as the negative vector sum of the total transverse momenta of all  $p_T > 10$  GeV electron, muon and photon candidates,  $p_T > 20$  GeV jets, and all clusters of calorimeter energy with  $|\eta| < 4.9$  not associated to such objects, referred to hereafter as the ‘soft-term’. Clusters associated with electrons, photons and jets make use of calibrations of the respective objects, whereas clusters not associated with these objects are calibrated using both calorimeter and tracker information.

The quantity  $E_T^{\text{miss,rel}}$  is defined from the magnitude,  $E_T^{\text{miss}}$ , of  $\mathbf{p}_T^{\text{miss}}$  as

$$E_T^{\text{miss,rel}} = \begin{cases} E_T^{\text{miss}} & \text{if } \Delta\phi_{\ell,j} \geq \pi/2 \\ E_T^{\text{miss}} \times \sin \Delta\phi_{\ell,j} & \text{if } \Delta\phi_{\ell,j} < \pi/2 \end{cases},$$

where  $\Delta\phi_{\ell,j}$  is the azimuthal angle between the direction of  $\mathbf{p}_T^{\text{miss}}$  and that of the nearest electron, muon, central  $b$ -jet or central light-flavour jet. Selections based on  $E_T^{\text{miss,rel}}$  aim to suppress events where missing transverse momentum arises from significantly mis-measured jets or leptons.

## 6 Event selection

Events are recorded using a combination of two-lepton triggers, which require identification of two lepton (electron or muon) candidates with transverse momenta exceeding a set of thresholds. For all triggers used in this measurement, the  $p_T$  thresholds are 18–25 GeV for the higher- $p_T$  lepton and 8–14 GeV for the other lepton. After event reconstruction, two signal leptons of opposite charge, with  $p_T > 35$  GeV and  $> 20$  GeV, are required in the selected events. No lepton candidates other than the two signal leptons are allowed in the event. The two signal leptons are required to match those that triggered the event. The trigger efficiencies with respect to reconstructed leptons with  $p_T$  in excess of the nominal thresholds have been measured using data-driven techniques. For events containing two reconstructed signal leptons with  $p_T > 35$  GeV and  $> 20$  GeV, the average trigger efficiencies are approximately 97% in the  $e^+e^-$  channel, 75% in the  $e^\pm\mu^\mp$  channels, and 89% in the  $\mu^+\mu^-$  channel.

The dilepton invariant mass  $m_{\ell\ell}$  must be greater than 20 GeV in all flavour combinations. Events containing one or more  $\tau$ -jet candidates are rejected.

Seven signal regions (SRs) are defined in this analysis. The first three, collectively referred to as SR- $m_{T2}$ , are designed to provide sensitivity to sleptons either through direct production or in chargino decays. The next three, SR- $WW$ , are designed to provide sensitivity to chargino-pair production followed by  $W$  decays. The last signal region, SR- $Z$ jets, is designed specifically for chargino and second lightest neutralino associated production followed by hadronic  $W$  and leptonic  $Z$  decays. The SF and DF event samples in each SR are considered separately. When a scenario that contributes to both SF and DF final states is considered, a simultaneous fit to the SF and DF samples is employed. All SRs of the same lepton flavour combination, except for SR- $Z$ jets, overlap with each other and are not statistically independent. Table 1 summarizes the definitions of the SRs.

Five of the SRs exploit the ‘transverse’ mass  $m_{T2}$  [94, 95], defined as

$$m_{T2} = \min_{\mathbf{q}_T} \left[ \max \left( m_T(\mathbf{p}_T^{\ell 1}, \mathbf{q}_T), m_T(\mathbf{p}_T^{\ell 2}, \mathbf{p}_T^{\text{miss}} - \mathbf{q}_T) \right) \right],$$

where  $\mathbf{p}_T^{\ell 1}$  and  $\mathbf{p}_T^{\ell 2}$  are the transverse momenta of the two leptons, and  $\mathbf{q}_T$  is a transverse vector that minimizes the larger of the two transverse masses  $m_T$ . The latter is defined by

$$m_T(\mathbf{p}_T, \mathbf{q}_T) = \sqrt{2(p_T q_T - \mathbf{p}_T \cdot \mathbf{q}_T)}.$$

For SM  $t\bar{t}$  and  $WW$  events, in which two  $W$  bosons decay leptonically and  $\mathbf{p}_T^{\text{miss}}$  originates from the two neutrinos, the  $m_{T2}$  distribution has an upper end-point at the  $W$  mass. For signal events, the undetected LSP contributes to  $\mathbf{p}_T^{\text{miss}}$ , and the  $m_{T2}$  end-point is correlated to the mass difference between the slepton or chargino and the lightest neutralino. For large values of this difference, the  $m_{T2}$  distribution for signal events extends significantly beyond the distributions of the  $t\bar{t}$  and  $WW$  events.

## 6.1 SR- $m_{T2}$

SR- $m_{T2}$  targets  $\tilde{\chi}_1^+ \tilde{\chi}_1^-$  production followed by slepton-mediated decays (figure 1a) and direct slepton pair production (figure 1d). Events are required to contain two opposite-sign signal leptons and no signal jets. Only SF channels are used in the search for direct slepton production, while the chargino-to-slepton decay search also uses DF channels. In the SF channels, the dilepton invariant mass  $m_{\ell\ell}$  must be at least 10 GeV away from the  $Z$  boson mass.

The dominant sources of background are diboson and top production ( $t\bar{t}$  and  $Wt$ ). Three signal regions, SR- $m_{T2}^{90}$ , SR- $m_{T2}^{120}$  and SR- $m_{T2}^{150}$ , are defined by requiring  $m_{T2} > 90$  GeV, 120 GeV and 150 GeV, respectively. Low values of  $m_{T2}$  threshold provide better sensitivity to cases in which the  $\tilde{\ell}$  or  $\tilde{\chi}_1^\pm$  mass is close to the  $\tilde{\chi}_1^0$  mass, and high values target large  $\tilde{\ell}-\tilde{\chi}_1^0$  or  $\tilde{\chi}_1^\pm-\tilde{\chi}_1^0$  mass differences.

## 6.2 SR- $WW$

Direct  $\tilde{\chi}_1^+ \tilde{\chi}_1^-$  production followed by  $W$ -mediated decays (figure 1b) is similar to the slepton-mediated scenario, but with smaller visible cross-sections due to the  $W \rightarrow \ell\nu$  branching fraction. Three signal regions, SR- $WWa$ , SR- $WWb$  and SR- $WWc$ , are designed to provide sensitivities to this scenario for increasing values of  $\tilde{\chi}_1^\pm-\tilde{\chi}_1^0$  mass difference. Events are required to contain two opposite-sign signal leptons and no signal jets. Both SF and DF channels are used in these signal regions. In the SF channels, the dilepton invariant mass  $m_{\ell\ell}$  must be at least 10 GeV away from the  $Z$  boson mass.

For large  $\tilde{\chi}_1^\pm-\tilde{\chi}_1^0$  mass splitting, the  $m_{T2}$  variable provides good discrimination between the signal and SM background. Two signal regions, SR- $WWb$  and SR- $WWc$ , are defined by  $m_{T2} > 90$  GeV and 100 GeV, respectively. The  $m_{T2}$  thresholds are lower than in SR- $m_{T2}$  because the smaller visible cross-sections limit the sensitivity to large  $\tilde{\chi}_1^\pm$  masses. For SR- $WWb$ , an additional requirement of  $m_{\ell\ell} < 170$  GeV is applied to further suppress the SM background.

For cases in which the  $\tilde{\chi}_1^\pm-\tilde{\chi}_1^0$  mass splitting is close to the  $W$  boson mass, the  $m_{T2}$  variable is not effective in distinguishing signal from the SM  $WW$  production. The signal region SR- $WWa$  is defined by  $E_T^{\text{miss,rel}} > 80$  GeV,  $p_{T,\ell\ell} > 80$  GeV and  $m_{\ell\ell} < 120$  GeV, where  $p_{T,\ell\ell}$  is the transverse momentum of the lepton pair. These selection criteria favour events in which the di-lepton opening angle is small, which enhances the difference in the  $E_T^{\text{miss,rel}}$  distribution between the signal and the background due to the two LSPs in the signal.

| SR                            | $m_{T2}^{90}$ | $m_{T2}^{120}$ | $m_{T2}^{150}$ | WWa     | WWb     | WWc     | Zjets     |
|-------------------------------|---------------|----------------|----------------|---------|---------|---------|-----------|
| lepton flavour                | DF,SF         | DF,SF          | DF,SF          | DF,SF   | DF,SF   | DF,SF   | SF        |
| central light jets            | 0             | 0              | 0              | 0       | 0       | 0       | $\geq 2$  |
| central $b$ -jets             | 0             | 0              | 0              | 0       | 0       | 0       | 0         |
| forward jets                  | 0             | 0              | 0              | 0       | 0       | 0       | 0         |
| $ m_{\ell\ell} - m_Z $ [GeV]  | $> 10$        | $> 10$         | $> 10$         | $> 10$  | $> 10$  | $> 10$  | $< 10$    |
| $m_{\ell\ell}$ [GeV]          | —             | —              | —              | $< 120$ | $< 170$ | —       | —         |
| $E_T^{\text{miss,rel}}$ [GeV] | —             | —              | —              | $> 80$  | —       | —       | $> 80$    |
| $p_{T,\ell\ell}$ [GeV]        | —             | —              | —              | $> 80$  | —       | —       | $> 80$    |
| $m_{T2}$ [GeV]                | $> 90$        | $> 120$        | $> 150$        | —       | $> 90$  | $> 100$ | —         |
| $\Delta R_{\ell\ell}$         | —             | —              | —              | —       | —       | —       | [0.3,1.5] |
| $m_{jj}$ [GeV]                | —             | —              | —              | —       | —       | —       | [50,100]  |

**Table 1.** Signal region definitions. The criteria on  $|m_{\ell\ell} - m_Z|$  are applied only to SF events. The two leading central light jets in SR-Zjets must have  $p_T > 45$  GeV.

### 6.3 SR-Zjets

The last signal region, SR-Zjets, differs from the previous six in that it requires the presence of at least two central light jets. This signal region is designed to target the  $pp \rightarrow \tilde{\chi}_1^\pm \tilde{\chi}_2^0 \rightarrow W^\pm \tilde{\chi}_1^0 Z \tilde{\chi}_1^0$  process in which the  $W$  boson decays hadronically and the  $Z$  boson decays leptonically (figure 1c).

The two highest- $p_T$  central light jets must have  $p_T > 45$  GeV, and have an invariant mass in the range  $50 < m_{jj} < 100$  GeV. There must be no central  $b$ -jet and no forward jet in the event. The two opposite-sign leptons must be SF, and their invariant mass must be within 10 GeV of the  $Z$  boson mass.

To suppress large background from the SM  $Z$  + jets production,  $E_T^{\text{miss,rel}} > 80$  GeV is required. Events are accepted only if the reconstructed  $Z$  boson is recoiling against the rest of the event with a large transverse momentum  $p_{T,\ell\ell} > 80$  GeV, and the separation  $\Delta R_{\ell\ell}$  between the two leptons must satisfy  $0.3 < \Delta R_{\ell\ell} < 1.5$ .

## 7 Background estimation

For SR- $m_{T2}$  and SR- $WW$ , the SM background is dominated by  $WW$  diboson and top-quark ( $t\bar{t}$  and  $Wt$ ) production. Contributions from  $ZV$  production, where  $V = W$  or  $Z$ , are also significant in the SF channels. The MC predictions for these SM sources are normalized in dedicated control regions (CR) for each background, as described in section 7.1. For SR-Zjets, the dominant sources of background are  $ZV$  production and  $Z/\gamma^* + \text{jets}$ . The former is estimated from simulation, validated using  $ZV$ -enriched control samples, and the latter is estimated by a data-driven technique, as described in section 7.2. The top-quark background in SR-Zjets is estimated using a dedicated CR. Background due to hadronic jets mistakenly reconstructed as signal leptons or real leptons originating from heavy-flavour

| SR                            | $m_{T2}$ and $WWb/c$ |          |        | $WWa$      |          |        | Zjets        |
|-------------------------------|----------------------|----------|--------|------------|----------|--------|--------------|
| CR                            | $WW$                 | Top      | $ZV$   | $WW$       | Top      | $ZV$   | Top          |
| lepton flavour                | DF                   | DF       | SF     | DF         | DF       | SF     | SF           |
| central light jets            | 0                    | 0        | 0      | 0          | 0        | 0      | $\geq 2$     |
| central $b$ -jets             | 0                    | $\geq 1$ | 0      | 0          | $\geq 1$ | 0      | $\geq 1$     |
| forward jets                  | 0                    | 0        | 0      | 0          | 0        | 0      | 0            |
| $ m_{\ell\ell} - m_Z $ [GeV]  | —                    | —        | $< 10$ | —          | —        | $< 10$ | $> 10$       |
| $m_{\ell\ell}$ [GeV]          | —                    | —        | —      | $< 120$    | $< 120$  | —      | —            |
| $E_T^{\text{miss,rel}}$ [GeV] | —                    | —        | —      | $[60, 80]$ | $> 80$   | $> 80$ | $> 80$       |
| $p_{T,\ell\ell}$ [GeV]        | —                    | —        | —      | $> 40$     | $> 80$   | $> 80$ | $> 80$       |
| $m_{T2}$ [GeV]                | $[50, 90]$           | $> 70$   | $> 90$ | —          | —        | —      | —            |
| $\Delta R_{\ell\ell}$         | —                    | —        | —      | —          | —        | —      | $[0.3, 1.5]$ |

**Table 2.** Control region definitions. The top CR for SR-Zjets requires at least two jets with  $p_T > 20$  GeV in  $|\eta| < 2.4$ , at least one of which is  $b$ -tagged.

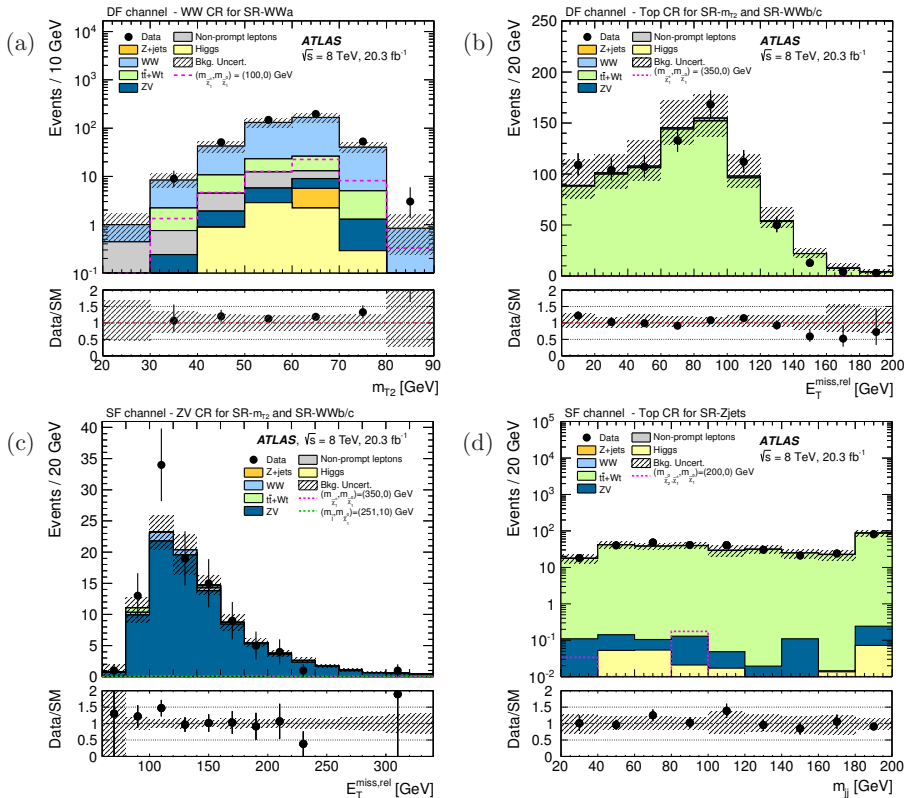
decays or photon conversions, referred to as ‘non-prompt leptons’, is estimated using a data-driven method described in section 7.3. Contributions from remaining sources of SM background, which include Higgs production and  $Z/\gamma^* + \text{jets}$  (except in SR-Zjets), are small and are estimated from simulation. Table 2 summarizes the definitions of the control regions.

## 7.1 Background in SR- $m_{T2}$ and SR- $WW$

The normalization factors for the background in SR- $m_{T2}$  and SR- $WW$  due to the SM  $WW$ , top and  $ZV$  production are constrained using dedicated CRs for each background. Each CR is dominated by the background of interest and is designed to be kinematically as close as possible to a corresponding signal region. The normalization factors are obtained from the likelihood fit described in section 7.4.

The  $WW$  control region for SR- $m_{T2}$  and SR- $WWb/c$  is defined by requiring  $50 < m_{T2} < 90$  GeV and the events must contain no jets. Only the DF sample is used in this CR because the corresponding regions in the SF samples suffer from contamination from  $Z/\gamma^* + \text{jets}$  background. Appropriate ratios of electron and muon efficiencies are used to obtain the SF background estimations from the corresponding DF CR. For SR- $WWa$ , the CR is defined by lowering the  $E_T^{\text{miss,rel}}$  and  $p_{T,\ell\ell}$  requirements so that  $60 < E_T^{\text{miss,rel}} < 80$  GeV and  $p_{T,\ell\ell} > 40$  GeV. Figure 2(a) shows the  $m_{T2}$  distribution in this CR. The normalization factors are not applied to the MC predictions in all four plots of figure 2. Predicted signal contamination in this CR is less than 10% for the signal models  $\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp \rightarrow W^\pm W^\mp \tilde{\chi}_1^0 \tilde{\chi}_1^0$  with  $m_{\tilde{\chi}_1^\pm} > 100$  GeV.

The top control region for SR- $m_{T2}$  and SR- $WWb/c$  is also defined using the DF sample, and by requiring at least one  $b$ -tagged jet and vetoing central light jets and forward jets. The events must also satisfy  $m_{T2} > 70$  GeV. Figure 2(b) shows the  $E_T^{\text{miss,rel}}$  distribution in this CR. For SR- $WWa$ , the CR is defined using the DF sample and requiring at least



**Figure 2.** Distributions of (a)  $m_{T2}$  in the WW CR for SR-WWa, (b)  $E_T^{\text{miss,rel}}$  in the top CR for SR-WWb/c and SR- $m_{T2}$ , (c)  $E_T^{\text{miss,rel}}$  in the ZV CR for SR-WWb/c and SR- $m_{T2}$ , and (d)  $m_{jj}$  in the top CR for SR-Zjets. No data-driven normalization factor is applied to the distributions. The hashed regions represent the total uncertainties on the background estimates. The rightmost bin of each plot includes overflow. The lower panel of each plot shows the ratio between data and the SM background prediction.

one  $b$ -tagged jet, with all the other SR criteria unchanged. The predicted contamination from SUSY signal is negligible for the models considered.

The ZV control region for SR- $m_{T2}$  and SR-WWb/c is defined identically to the SF SR- $m_{T2}^{90}$ , but with the Z veto reversed. Figure 2(c) shows the  $E_T^{\text{miss,rel}}$  distribution in this CR. The contamination due to non-ZV sources is dominated by WW events (4.5%). For SR-WWa, the CR is defined by reversing the Z veto in the SF sample. The predicted contamination from SUSY signal is less than 5% in these CRs.

## 7.2 Background in SR-Zjets

The top CR for SR-Zjets is defined by reversing the Z veto and requiring at least one  $b$ -tagged jet. To increase the statistics of the sample, the  $p_T$  threshold for the central jets



is lowered to 20 GeV, and no cut on  $m_{jj}$  is applied. Figure 2(d) shows the  $m_{jj}$  distribution in this CR. The predicted contamination from SUSY signal is negligible.

The  $ZV$  background in SR-Zjets consists of diboson production accompanied by two light-flavour jets, that is,  $WZjj \rightarrow \ell\nu\ell'\ell'jj$ , where the lepton from the  $W$  decay was not reconstructed, and  $ZZjj \rightarrow \ell\nu\nu jj$ . The contribution from  $ZV \rightarrow \ell\ell q\bar{q}$  is strongly suppressed by the  $E_T^{\text{miss,rel}}$  requirement. This background is estimated from simulation, and validated in control samples of  $WZjj \rightarrow \ell\nu\ell'\ell'jj$  and  $ZZjj \rightarrow \ell\ell\ell'\ell'jj$  where all leptons are reconstructed. The  $WZjj$  enriched control sample consists of events with three leptons, at least two of which make up a SF opposite-sign pair with an invariant mass within 10 GeV of the  $Z$  boson mass. In addition, events must have  $E_T^{\text{miss}} > 30$  GeV,  $m_T > 40$  GeV computed from the  $\mathbf{p}_T^{\text{miss}}$  and the lepton that was not assigned to the  $Z$  boson, at least two central light jets, and no central  $b$ -jet. The predicted contamination from SUSY signal is less than 10% in this region. The  $ZZjj$  enriched control sample consists of events with two pairs of same-flavour opposite-sign leptons, each with an invariant mass within 10 GeV of the  $Z$  boson mass,  $E_T^{\text{miss}} < 50$  GeV, at least two central light jets, and no signal  $b$ -jet. The data in these control samples are compared with the simulation to assess the systematic uncertainties of the  $ZV$  background estimation, as reported in section 8.

In SR-Zjets,  $Z/\gamma^* + \text{jets}$  events are an important source of background, where significant  $E_T^{\text{miss}}$  arises primarily from mis-measurement of jet transverse momentum. A data-driven approach called the ‘jet smearing’ method is used to estimate this background. In this method, a sample enriched in  $Z/\gamma^* + \text{jets}$  events with well-measured jets is selected from data as seed events. The seed events are selected by applying the SR-Zjets event selection, but reversing the  $E_T^{\text{miss,rel}}$  cut. To ensure that the events only contain well measured jets, the ratio  $E_T^{\text{miss}}/\sqrt{E_T^{\text{sum}}}$ , where  $E_T^{\text{sum}}$  is the scalar sum of the transverse energies of the jets and the soft-term, is required to be less than  $1.5 (\text{GeV})^{1/2}$ . Each seed event is smeared by multiplying each jet four-momentum by a random number drawn from the jet response function, which is initially estimated from simulation and adjusted after comparing the response to data in a photon + jet sample. In addition, the contribution to  $E_T^{\text{miss}}$  due to the soft-term is also modified by sampling randomly from the soft-term distribution measured in a  $Z \rightarrow \ell\ell$  sample with no reconstructed jets. The smearing procedure is repeated 10,000 times for each seed event. The resulting pseudo-data  $E_T^{\text{miss,rel}}$  distribution is then normalized to the data in the region of  $E_T^{\text{miss,rel}} < 40$  GeV, and the migration into the signal region is evaluated.

To validate the jet-smearing method, a control sample is selected with the same selection criteria as SR-Zjets but reversing the  $p_{T,\ell\ell}$  requirement, and removing the  $\Delta R_{\ell\ell}$  and  $m_{jj}$  criteria to increase the number of events. The seed events are selected from the control region events by requiring  $E_T^{\text{miss,rel}} < 40$  GeV and  $E_T^{\text{miss}}/\sqrt{E_T^{\text{sum}}} < 1.5 (\text{GeV})^{1/2}$ . Results are validated in a region with  $40 < E_T^{\text{miss,rel}} < 80$  GeV, which is dominated by  $Z/\gamma^* + \text{jets}$ . The method predicts  $750 \pm 100$  events, where both statistical and systematic uncertainties are included, in agreement with the 779 events observed in data.

### 7.3 Non-prompt lepton background estimation

The term ‘non-prompt leptons’ refers to hadronic jets mistakenly reconstructed as signal leptons or leptons originating from heavy-flavour decays or photon conversions. In this context, ‘prompt leptons’ are leptons produced directly in decays of sparticles or weak bosons. The number of non-prompt lepton events is estimated using the matrix method [96], which takes advantage of the difference between the prompt efficiency  $\epsilon_p$  and non-prompt efficiency  $\epsilon_n$ , defined as the fractions of prompt and non-prompt candidate leptons, respectively, that pass the signal-lepton requirements.

The prompt and non-prompt efficiencies are evaluated as functions of the  $p_T$  of the lepton candidate in simulated events using MC truth information. Differences between data and MC are corrected for with normalization factors measured in control samples. Since the efficiencies depend on the production process, average  $\epsilon_p$  and  $\epsilon_n$  values are calculated for each SR and CR using the fraction of each process predicted by the simulation as the weights. The data/MC normalization factors for  $\epsilon_p$  are derived from  $Z \rightarrow \ell\ell$  events. The normalization factors for  $\epsilon_n$  depend on whether the non-prompt lepton originated from jets or from photon conversion. The normalization factors for misidentified jets or leptons from heavy-flavour decays are measured in a control region enriched in  $b\bar{b}$  production. Events are selected with two candidate leptons, one  $b$ -tagged jet and  $E_T^{\text{miss,rel}} < 40$  GeV. One of the two lepton candidates is required to be a muon and to lie within  $\Delta R = 0.4$  of the  $b$ -tagged jet, while the other lepton candidate is used to measure the non-prompt efficiency. For measuring the normalization factor for photon conversions, a  $Z \rightarrow \mu\mu\gamma$  control sample is defined by selecting events with two muons,  $E_T^{\text{miss,rel}} < 50$  GeV, at least one candidate electron (which is the conversion candidate) with  $m_T < 40$  GeV, and requiring that the invariant mass of the  $\mu^+\mu^-e^\pm$  system is within 10 GeV of the  $Z$  boson mass.

Using  $\epsilon_n$  and  $\epsilon_p$ , the observed numbers of events in each SR and CR with four possible combinations (signal-signal, signal-candidate, candidate-signal and candidate-candidate) of leptons are expressed as weighted sums of the numbers of events with four combinations of prompt and non-prompt leptons. Solving these equations allows determination of the non-prompt lepton background. The contribution of non-prompt-lepton background in the signal regions is less than 5% of the total background in all signal regions.

### 7.4 Fitting procedure

For each SR, a simultaneous likelihood fit to the corresponding CRs is performed to normalize the top,  $WW$  and  $ZV$  (in the case of SR- $Z$ jets only top is fitted) background estimates. The inputs to the fit are the numbers of observed events in the CRs, the expected contributions of top,  $WW$  and  $ZV$  from simulation, and the expected contributions of other background sources determined as described in sections 7.1–7.3.

The event count in each CR is treated as a Poisson probability function, the mean of which is the sum of the expected contributions from all background sources. The free parameters in the fit are the normalization of the top,  $WW$  and  $ZV$  contributions. The systematic uncertainties on the expected background yields are included as nuisance parameters, constrained to be Gaussian with a width determined from the size of the uncertainty.

| SR                | $m_{T2}$ and $WWb/c$ |       |       | $WWa$ |       |       | $Zjets$ |
|-------------------|----------------------|-------|-------|-------|-------|-------|---------|
| CR                | $WW$                 | Top   | $ZV$  | $WW$  | Top   | $ZV$  | Top     |
| Observed events   | 1061                 | 804   | 94    | 472   | 209   | 175   | 395     |
| MC prediction     | 947                  | 789   | 91    | 385   | 215   | 162   | 399     |
| Normalization     | 1.14                 | 1.02  | 1.08  | 1.12  | 0.97  | 1.04  | 0.99    |
| Statistical error | 0.05                 | 0.04  | 0.12  | 0.08  | 0.08  | 0.12  | 0.06    |
| Composition       |                      |       |       |       |       |       |         |
| $WW$              | 84.6%                | 1.4%  | 5.0%  | 86.8% | 1.7%  | 10.5% | 1.3%    |
| Top               | 10.4%                | 98.5% | <0.1% | 7.3%  | 98.1% | 2.8%  | 98.0%   |
| $ZV$              | 2.0%                 | 0.1%  | 94.9% | 1.9%  | <0.1% | 82.9% | 0.3%    |
| Non-prompt lepton | 1.9%                 | <0.1% | <0.1% | 2.7%  | <0.1% | <0.1% | <0.1%   |
| Other             | 1.1%                 | <0.1% | 0.1%  | 1.3%  | <0.1% | 3.7%  | 0.3%    |

**Table 3.** Numbers of observed and predicted events in the CRs, data/MC normalization factors and composition of the CRs obtained from the fit. Systematic errors are described in section 8.

Correlations between control and signal regions, and background processes are taken into account with common nuisance parameters. The free parameters and the nuisance parameters are determined by maximizing the product of the Poisson probability functions and the constraints on the nuisance parameters.

Table 3 summarizes the numbers of observed and predicted events in the CRs, data/MC normalization and CR composition obtained from the simultaneous fit. The normalization factors agree within errors between different SRs for each of the  $WW$ , Top and  $ZV$  contributions. Results of the background estimates in the SRs can be found in tables 5, 6 and 7.

## 8 Systematic uncertainties

Systematic uncertainties affect the estimates of the backgrounds and signal event yields in the control and signal regions. A breakdown of the different sources of systematic uncertainties and their size is shown in table 4.

The ‘CR statistics’ and ‘MC statistics’ uncertainties arise from the number of data events in the CRs and simulated events in the SRs and CRs, respectively. The largest contributions are due to the simulated background samples in the signal regions.

The dominant experimental systematic uncertainties, labelled ‘Jet’ in table 4, come from the propagation of the jet energy scale calibration [97] and resolution [98] uncertainties. They were derived from a combination of simulation, test-beam data and in situ measurements. Additional uncertainties due to differences between quark and gluon jets, and light and heavy flavour jets, as well as the effect of pile-up interactions are included. The ‘Lepton’ uncertainties include those from lepton reconstruction, identification and trigger efficiencies, as well as lepton energy and momentum measurements [84, 85]. Uncertainties due to  $\tau$  reconstruction and energy calibration are negligible. Jet and lepton

|                   | $m_{T2}^{90}$ |    | $m_{T2}^{120}$ |    | $m_{T2}^{150}$ |    | WWa |    | WWb |    | WWc |    | Zjets |
|-------------------|---------------|----|----------------|----|----------------|----|-----|----|-----|----|-----|----|-------|
|                   | SF            | DF | SF             | DF | SF             | DF | SF  | DF | SF  | DF | SF  | DF | SF    |
| CR statistics     | 5             | 3  | 6              | 4  | 8              | 4  | 5   | 5  | 5   | 3  | 6   | 4  | 1     |
| MC statistics     | 5             | 7  | 7              | 12 | 10             | 23 | 3   | 4  | 5   | 8  | 6   | 10 | 14    |
| Jet               | 4             | 1  | 2              | 1  | 5              | 7  | 3   | 6  | 4   | 2  | 4   | 3  | 11    |
| Lepton            | 1             | 2  | 1              | 1  | 4              | 1  | 1   | 3  | 2   | 3  | 1   | 8  | 4     |
| Soft-term         | 3             | 4  | 1              | 1  | 2              | 8  | < 1 | 2  | 3   | 5  | 1   | 6  | 5     |
| b-tagging         | 1             | 2  | <1             | <1 | <1             | <1 | 1   | 1  | 1   | 2  | <1  | 1  | 2     |
| Non-prompt lepton | <1            | 1  | <1             | <1 | 1              | <1 | 1   | 1  | 1   | 2  | <1  | 1  | <1    |
| Luminosity        | <1            | <1 | <1             | <1 | <1             | <1 | <1  | <1 | <1  | <1 | <1  | <1 | 2     |
| Modelling         | 11            | 13 | 21             | 31 | 18             | 40 | 6   | 6  | 8   | 10 | 15  | 19 | 42    |
| Total             | 13            | 16 | 24             | 34 | 23             | 47 | 9   | 11 | 12  | 14 | 17  | 24 | 47    |

**Table 4.** Systematic uncertainties (in %) on the total background estimated in different signal regions. Because of correlations between the systematic uncertainties and the fitted backgrounds, the total uncertainty can be different from the quadratic sum of the individual uncertainties.

energy scale uncertainties are propagated to the  $E_T^{\text{miss}}$  evaluation. An additional ‘Soft-term’ uncertainty is associated with the contribution to the  $E_T^{\text{miss}}$  reconstruction of energy deposits not assigned to any reconstructed objects [93].

The ‘ $b$ -tagging’ row refers to the uncertainties on the  $b$ -jet identification efficiency and charm and light-flavour jet rejection factors [99]. The ‘Non-prompt lepton’ uncertainties arise from the data-driven estimates of the non-prompt lepton background described in section 7.3. The dominant sources are  $\eta$  dependence of the non-prompt rates, differences between the light and heavy flavour jets, and the statistics of the control samples. The uncertainty on the integrated luminosity is  $\pm 2.8\%$ , and affects the normalization of the background estimated with simulation. It is derived following the methodology detailed in ref. [100].

The ‘Modelling’ field of table 4 includes the uncertainties on the methods used for the background estimate, as well as the modelling uncertainties of the generators used to assist the estimate. For SR-Zjets an additional 20% uncertainty is assigned to the ZV background estimate to account for the variations between data and simulation in the ZV control regions with two or more jets, as described in section 7.2. Uncertainties on the  $Z/\gamma^* + \text{jets}$  background estimate in SR-Zjets include the systematic uncertainties associated with the jet smearing method due to the fluctuations in the non-Gaussian tails of the response function and the systematic uncertainty associated with the cut value on  $E_T^{\text{miss}}/\sqrt{E_T^{\text{sum}}}$  used to define the seed region. The effect of using each seed event multiple times is also taken into account. Generator modelling uncertainties are estimated by comparing the results from POWHEG and MC@NLO generators for top events, and POWHEG and aMC@NLO for WW events, using HERWIG for parton showering in all cases. Parton showering uncertainties are estimated in top and WW events by comparing POWHEG plus HERWIG with POWHEG plus PYTHIA. Both generator modelling and parton showering uncertainties are es-

timated in  $ZV$  events by comparing POWHEG plus PYTHIA to SHERPA. Special  $t\bar{t}$  samples are generated using AcerMC with PYTHIA to evaluate the uncertainties related to the amount of initial and final-state radiation [101]. Impact of the choice of renormalization and factorization scales is evaluated by varying them between 0.5 and 2 times the nominal values in POWHEG for top events and aMC@NLO for diboson events. The uncertainties due to the PDFs for the top and diboson events are evaluated using 90% C.L. CT10 PDF eigenvectors. Effects of using different PDF sets have been found to be negligible. The dominant contribution among the ‘Modelling’ uncertainties comes from the difference between POWHEG and aMC@NLO for diboson production.

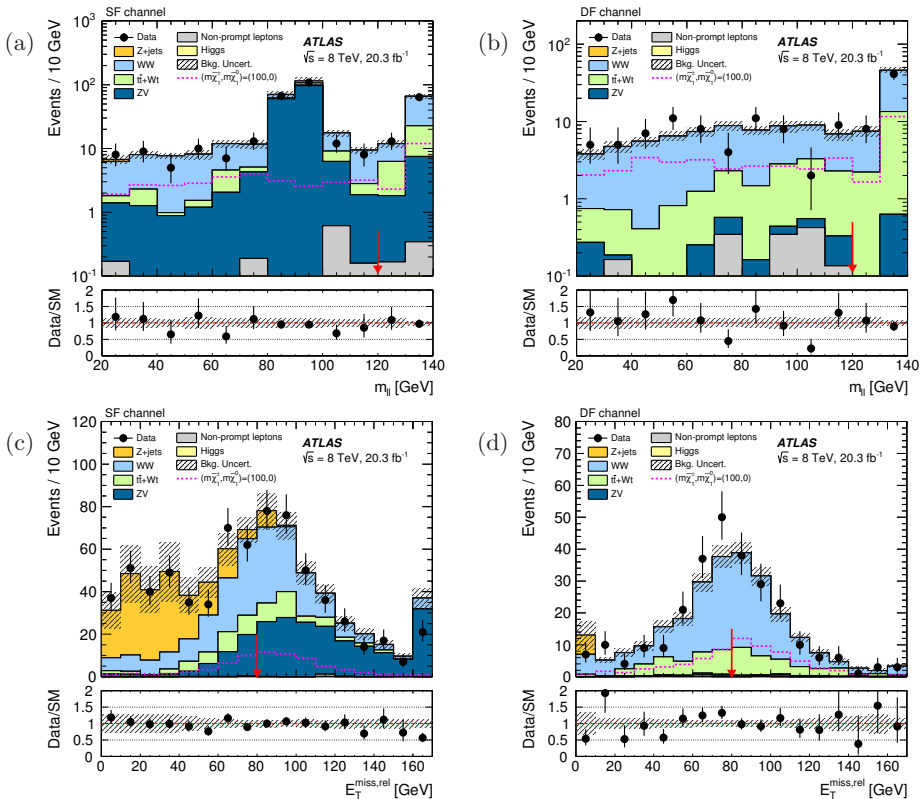
Signal cross-sections are calculated to NLO in the strong coupling constant. Their uncertainties are taken from an envelope of cross-section predictions using different PDF sets and factorization and renormalization scales, as described in ref. [102]. Systematic uncertainties associated with the signal selection efficiency include those due to lepton trigger, reconstruction and identification, jet reconstruction and  $E_{\text{T}}^{\text{miss}}$  calculation. Uncertainties on the integrated luminosity affect the predicted signal yield. The total uncertainty on the predicted signal yield is typically 9–13% for SUSY scenarios to which this measurement is sensitive.

## 9 Results

Figures 3 and 4 show the comparison between data and the SM prediction for key kinematic variables in different signal regions. In each plot, the expected distributions from the  $WW$ ,  $t\bar{t}$  and  $ZV$  processes are corrected with data-driven normalization factors obtained from the fit detailed in section 7. The hashed regions represent the sum in quadrature of systematic uncertainties and statistical uncertainties arising from the numbers of MC events. The effect of limited data events in the CR is included in the systematic uncertainty. All statistical uncertainties are added in quadrature whereas the systematic uncertainties are obtained after taking full account of all correlations between sources, background contributions and channels. The rightmost bin of each plot includes overflow. Illustrative SUSY benchmark models, normalized to the integrated luminosity, are superimposed. The lower panel of each plot shows the ratio between data and the SM background prediction.

Tables 5, 6 and 7 compare the observed yields in each signal region with those predicted for the SM background. The errors include both statistical and systematic uncertainties. Good agreement is observed across all channels.

For each SR, the significance of a possible excess over the SM background is quantified by the one-sided probability,  $p_0$ , of the background alone to fluctuate to the observed number of events or higher, using the asymptotic formula [103]. This is calculated using a fit similar to the one described in section 7.4, but including the observed number of events in the SR as an input. All systematic uncertainties and their correlations are taken into account via nuisance parameters. The accuracy of the limits obtained from the asymptotic formula was tested for all SRs by randomly generating a large number of pseudo data sets and repeating the fit. Upper limits at 95% CL on the number of non-SM events for each SR are derived using the  $\text{CL}_s$  prescription [104] and neglecting any possible contamination

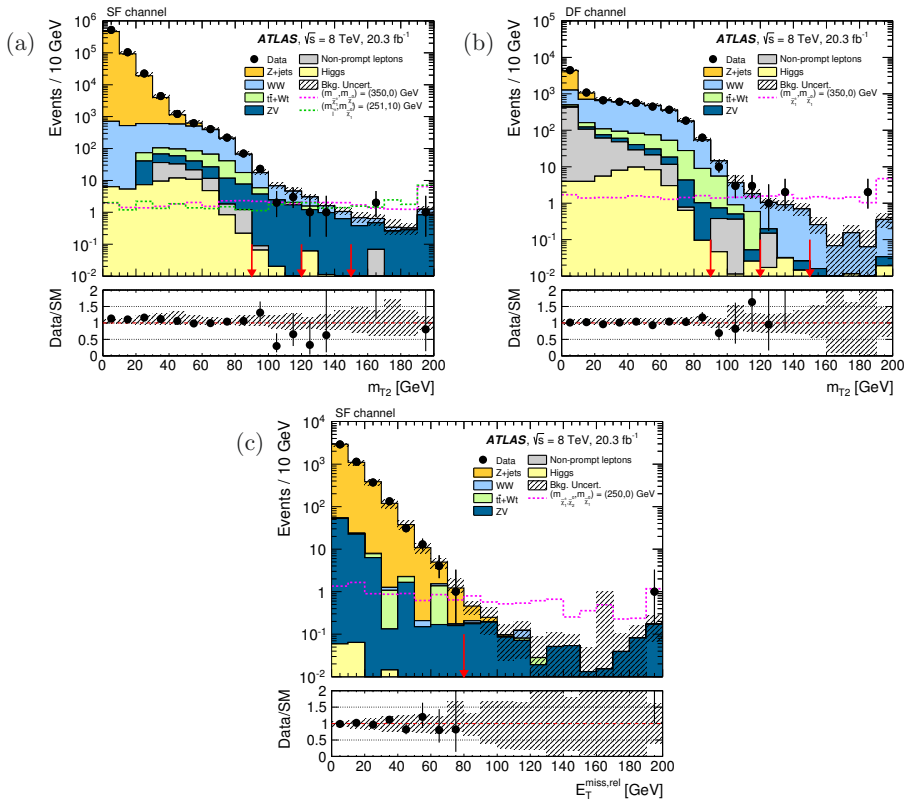


**Figure 3.** Distributions of  $m_{\ell\ell}$  in the (a) SF and (b) DF samples that satisfy all the SR-WW selection criteria except for the one on  $m_{\ell\ell}$ , and of  $E_T^{\text{miss,rel}}$  in the (c) SF and (d) DF samples that satisfy all the SR-WW selection criteria except for the ones on  $m_{\ell\ell}$  and  $E_T^{\text{miss,rel}}$ . The lower panel of each plot shows the ratio between data and the SM background prediction. The hashed regions represent the sum in quadrature of systematic uncertainties and statistical uncertainties arising from the numbers of MC events. Predicted signal distributions in a simplified model with  $m_{\tilde{\chi}_1^\pm} = 100$  GeV and  $m_{\tilde{\chi}_1^0} = 0$  are superimposed. Red arrows indicate the SR-WW selection criteria. In (a), the region  $81.2 < m_{\ell\ell} < 101.2$  GeV is rejected by the Z boson veto.

in the CRs. Normalizing these by the integrated luminosity of the data sample they can be interpreted as upper limits,  $\sigma_{\text{vis}}^{95}$ , on the visible non-SM cross-section, defined as the product of acceptance, reconstruction efficiency and production cross-section of the non-SM contribution. The results are given in tables 5, 6 and 7.

## 10 Interpretation

Exclusion limits at 95% confidence-level are set on the slepton, chargino and neutralino masses within the specific scenarios considered. The same CLs limit-setting procedure as in



**Figure 4.** Distributions of  $m_{T2}$  in the (a) SF and (b) DF samples that satisfy all the SR- $m_{T2}$  selection criteria except for the one on  $m_{T2}$ , and of (c)  $E_T^{\text{miss,rel}}$  in the sample that satisfies all the SR-Zjets selection criteria except for the one on  $E_T^{\text{miss,rel}}$ . The lower panel of each plot shows the ratio between data and the SM background prediction. The hashed regions represent the sum in quadrature of systematic uncertainties and statistical uncertainties arising from the numbers of MC events. Predicted signal distributions in simplified models with  $m_{\tilde{\chi}_1^\pm} = 350$  GeV,  $m_{\tilde{\ell}} = m_{\tilde{\nu}} = 175$  GeV and  $m_{\tilde{\chi}_1^0} = 0$  are superimposed in (a) and (b),  $m_{\tilde{\ell}} = 251$  GeV and  $m_{\tilde{\chi}_1^0} = 10$  GeV in (a), and  $m_{\tilde{\chi}_1^\pm} = m_{\tilde{\chi}_2^0} = 250$  GeV and  $m_{\tilde{\chi}_1^0} = 0$  in (c). Red arrows indicate the selection criteria for SR- $m_{T2}$  and SR-Zjets.

section 9 is used, except that the SUSY signal is allowed to populate both the signal region and the control regions as predicted by the simulation. Since the SRs are not mutually exclusive, the SR with the best expected exclusion limit is chosen for each model point.

The results are displayed in figures 5 through 9. In each exclusion plot, the solid (dashed) lines show observed (expected) exclusion contours, including all uncertainties except for the theoretical signal cross-section uncertainty arising from the PDF and the renormalization and factorization scales. The solid band around the expected exclusion contour shows the  $\pm 1\sigma$  result where all uncertainties, except those on the signal cross-sections, are

|                                                             | SR- $m_{T2}^{90}$      |                        | SR- $m_{T2}^{120}$     |                        | SR- $m_{T2}^{150}$     |                        |
|-------------------------------------------------------------|------------------------|------------------------|------------------------|------------------------|------------------------|------------------------|
|                                                             | SF                     | DF                     | SF                     | DF                     | SF                     | DF                     |
| Expected background                                         |                        |                        |                        |                        |                        |                        |
| $WW$                                                        | $22.1 \pm 4.3$         | $16.2 \pm 3.2$         | $3.5 \pm 1.3$          | $3.3 \pm 1.2$          | $1.0 \pm 0.5$          | $0.9 \pm 0.5$          |
| $ZV$                                                        | $12.9 \pm 2.2$         | $0.8 \pm 0.2$          | $4.9 \pm 1.6$          | $0.2 \pm 0.1$          | $2.2 \pm 0.5$          | $< 0.1$                |
| Top                                                         | $3.0 \pm 1.8$          | $5.5 \pm 1.9$          | $0.3^{+0.4}_{-0.3}$    | $< 0.1$                | $< 0.1$                | $< 0.1$                |
| Others                                                      | $0.3 \pm 0.3$          | $0.8 \pm 0.6$          | $0.1^{+0.4}_{-0.1}$    | $0.1 \pm 0.1$          | $0.1^{+0.4}_{-0.1}$    | $0.0^{+0.4}_{-0.0}$    |
| Total                                                       | $38.2 \pm 5.1$         | $23.3 \pm 3.7$         | $8.9 \pm 2.1$          | $3.6 \pm 1.2$          | $3.2 \pm 0.7$          | $1.0 \pm 0.5$          |
| Observed events                                             | 33                     | 21                     | 5                      | 5                      | 3                      | 2                      |
| Predicted signal                                            |                        |                        |                        |                        |                        |                        |
| $(m_{\tilde{\chi}_1^\pm}, m_{\tilde{\chi}_1^0}) = (350, 0)$ | $24.2 \pm 2.5$         | $19.1 \pm 2.1$         | $18.1 \pm 1.8$         | $14.7 \pm 1.7$         | $12.0 \pm 1.3$         | $10.1 \pm 1.3$         |
| $(m_{\tilde{\ell}}, m_{\tilde{\chi}_1^0}) = (251, 10)$      | $24.0 \pm 2.7$         | —                      | $19.1 \pm 2.5$         | —                      | $14.3 \pm 1.7$         | —                      |
| $p_0$                                                       | 0.50                   | 0.50                   | 0.50                   | 0.27                   | 0.50                   | 0.21                   |
| Observed $\sigma_{\text{vis}}^{95}$ [fb]                    | 0.63                   | 0.55                   | 0.26                   | 0.36                   | 0.24                   | 0.26                   |
| Expected $\sigma_{\text{vis}}^{95}$ [fb]                    | $0.78^{+0.32}_{-0.23}$ | $0.62^{+0.26}_{-0.18}$ | $0.37^{+0.17}_{-0.11}$ | $0.30^{+0.13}_{-0.09}$ | $0.24^{+0.13}_{-0.08}$ | $0.19^{+0.10}_{-0.06}$ |

**Table 5.** Observed and expected numbers of events in SR- $m_{T2}$ . Also shown are the one-sided  $p_0$  values and the observed and expected 95% CL upper limits,  $\sigma_{\text{vis}}^{95}$ , on the visible cross-section for non-SM events. The ‘Others’ background category includes non-prompt lepton,  $Z/\gamma^* + \text{jets}$  and SM Higgs. The numbers of signal events are shown for the  $\tilde{\chi}_1^+ \tilde{\chi}_1^- \rightarrow (\tilde{\ell}\nu \text{ or } \ell\tilde{\nu})\tilde{\chi}_1^0 (\tilde{\ell}'\nu' \text{ or } \ell'\tilde{\nu}')\tilde{\chi}_1^0$  scenario and for the  $\tilde{\ell}^+ \tilde{\ell}^- \rightarrow \ell^+ \tilde{\chi}_1^0 \ell^- \tilde{\chi}_1^0$  scenario with different  $\tilde{\chi}_1^\pm$ ,  $\tilde{\chi}_1^0$  and  $\tilde{\ell}$  masses in GeV.

considered. The dotted lines around the observed exclusion contour represent the results obtained when varying the nominal signal cross-section by  $\pm 1\sigma$  theoretical uncertainty. All mass limits hereafter quoted correspond to the signal cross-sections reduced by  $1\sigma$ .

Figure 5 shows the 95% CL exclusion region obtained from SR- $m_{T2}$  on the simplified model for direct  $\tilde{\chi}_1^+ \tilde{\chi}_1^-$  pair production followed by slepton-mediated decays. For  $m_{\tilde{\chi}_1^0} = 0$ , chargino masses between 140 GeV and 465 GeV are excluded. The exclusion in this scenario depends on the assumed slepton mass, which is chosen to be halfway between the  $\tilde{\chi}_1^\pm$  and  $\tilde{\chi}_1^0$  masses in this analysis. Studies performed with particle-level signal MC samples show that the signal acceptance in SR- $m_{T2}$  depends weakly on  $m_{\tilde{\ell}}$ , and the choice of  $m_{\tilde{\ell}} = (m_{\tilde{\chi}_1^\pm} + m_{\tilde{\chi}_1^0})/2$  minimizes (maximizes) the acceptance for small (large)  $\tilde{\chi}_1^\pm - \tilde{\chi}_1^0$  mass splitting.

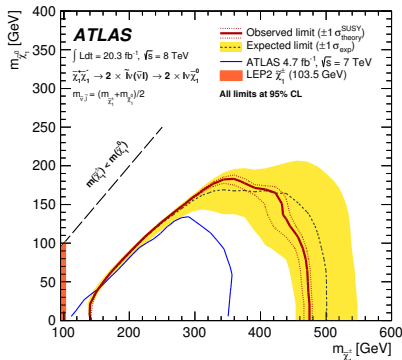
Figure 6(a) shows the 95% CL exclusion regions obtained from SR- $WW$  on the simplified-model  $\tilde{\chi}_1^+ \tilde{\chi}_1^-$  production followed by  $W$ -mediated decays. Figure 6(b) shows the observed and expected 95% CL upper limits on the SUSY signal cross-section normalized by the simplified-model prediction as a function of  $m_{\tilde{\chi}_1^\pm}$  for a massless  $\tilde{\chi}_1^0$ . For  $m_{\tilde{\chi}_1^0} = 0$ , chargino mass ranges of 100–105 GeV, 120–135 GeV and 145–160 GeV are excluded at 95% CL.

Figure 7(a) shows the 95% CL exclusion region obtained from SR- $Z\text{jets}$  in the simplified-model  $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$  production followed by  $W$  and  $Z$  decays. For  $m_{\tilde{\chi}_1^0} = 0$ , degenerate  $\tilde{\chi}_1^\pm$  and  $\tilde{\chi}_2^0$  masses between 180 GeV and 355 GeV are excluded. Figure 7(b) shows the exclusion region obtained by combining this result with results from the relevant signal regions (SR0a/SR1a/SR1SS/SR2a) in the ATLAS search for electroweak SUSY



|                                                              | SR-WW <sup>a</sup>     |                        | SR-WW <sup>b</sup>     |                        | SR-WW <sup>c</sup>     |                        |
|--------------------------------------------------------------|------------------------|------------------------|------------------------|------------------------|------------------------|------------------------|
|                                                              | SF                     | DF                     | SF                     | DF                     | SF                     | DF                     |
| Background                                                   |                        |                        |                        |                        |                        |                        |
| $WW$                                                         | $57.8 \pm 5.5$         | $58.2 \pm 6.0$         | $16.4 \pm 2.5$         | $12.3 \pm 2.0$         | $10.4 \pm 2.7$         | $7.3 \pm 1.9$          |
| $ZV$                                                         | $16.3 \pm 3.5$         | $1.8 \pm 0.5$          | $10.9 \pm 1.9$         | $0.6 \pm 0.2$          | $9.2 \pm 2.1$          | $0.4 \pm 0.2$          |
| Top                                                          | $9.2 \pm 3.5$          | $11.6 \pm 4.3$         | $2.4 \pm 1.7$          | $4.3 \pm 1.6$          | $0.6^{+1.2}_{-0.6}$    | $0.9 \pm 0.8$          |
| Others                                                       | $3.3 \pm 1.5$          | $2.0 \pm 1.1$          | $0.5 \pm 0.4$          | $0.9 \pm 0.6$          | $0.1^{+0.5}_{-0.1}$    | $0.4 \pm 0.3$          |
| Total                                                        | $86.5 \pm 7.4$         | $73.6 \pm 7.9$         | $30.2 \pm 3.5$         | $18.1 \pm 2.6$         | $20.3 \pm 3.5$         | $9.0 \pm 2.2$          |
| Observed events                                              | 73                     | 70                     | 26                     | 17                     | 10                     | 11                     |
| Predicted signal                                             |                        |                        |                        |                        |                        |                        |
| $(m_{\tilde{\chi}_1^\pm}, m_{\tilde{\chi}_1^0}) = (100, 0)$  | $25.6 \pm 3.3$         | $24.4 \pm 2.2$         |                        |                        |                        |                        |
| $(m_{\tilde{\chi}_1^\pm}, m_{\tilde{\chi}_1^0}) = (140, 20)$ |                        |                        | $8.3 \pm 0.8$          | $7.2 \pm 0.8$          |                        |                        |
| $(m_{\tilde{\chi}_1^\pm}, m_{\tilde{\chi}_1^0}) = (200, 0)$  |                        |                        |                        |                        | $5.2 \pm 0.5$          | $4.6 \pm 0.4$          |
| $p_0$                                                        | 0.50                   | 0.50                   | 0.50                   | 0.50                   | 0.50                   | 0.31                   |
| Observed $\sigma_{\text{vis}}^{95}$ [fb]                     | 0.78                   | 1.00                   | 0.54                   | 0.49                   | 0.29                   | 0.50                   |
| Expected $\sigma_{\text{vis}}^{95}$ [fb]                     | $1.13^{+0.46}_{-0.32}$ | $1.11^{+0.44}_{-0.31}$ | $0.66^{+0.28}_{-0.20}$ | $0.53^{+0.23}_{-0.16}$ | $0.52^{+0.23}_{-0.16}$ | $0.41^{+0.19}_{-0.12}$ |

**Table 6.** Observed and expected numbers of events in SR-WW. Also shown are the one-sided  $p_0$  values and the observed and expected 95% CL upper limits,  $\sigma_{\text{vis}}^{95}$ , on the visible cross-section for non-SM events. The ‘Others’ category includes non-prompt lepton,  $Z/\gamma^* + \text{jets}$  and SM Higgs. The numbers of signal events are shown for the  $\tilde{\chi}_1^+ \tilde{\chi}_1^- \rightarrow W^+ \tilde{\chi}_1^0 W^- \tilde{\chi}_1^0$  scenario with different  $\tilde{\chi}_1^\pm$  and  $\tilde{\chi}_1^0$  masses in GeV.

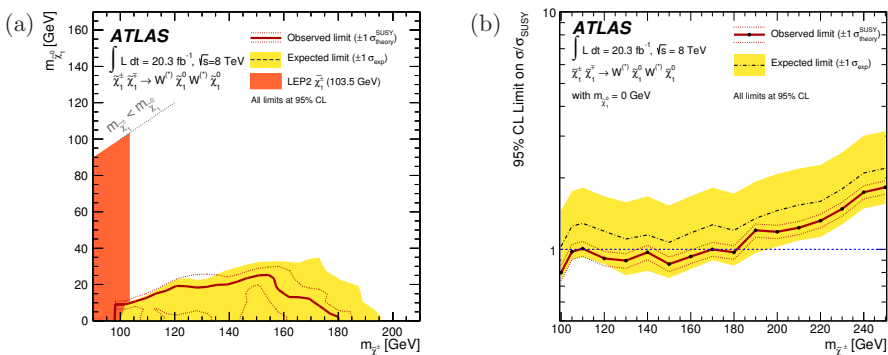


**Figure 5.** Observed and expected 95% CL exclusion regions in the  $(m_{\tilde{\chi}_1^\pm}, m_{\tilde{\chi}_1^0})$  plane for simplified-model  $\tilde{\chi}_1^+ \tilde{\chi}_1^-$  pair production with common masses of sleptons and sneutrinos at  $m_{\tilde{e}} = m_{\tilde{\nu}} = (m_{\tilde{\chi}_1^\pm} + m_{\tilde{\chi}_1^0})/2$ . Also shown is the LEP limit [36, 37] on the mass of the chargino. The blue line indicates the limit from the previous analysis with the 7 TeV data [34].

production in the three-lepton final states [83]. The fit is performed on the combined likelihood function using all signal regions. The uncertainties are profiled in the likelihood

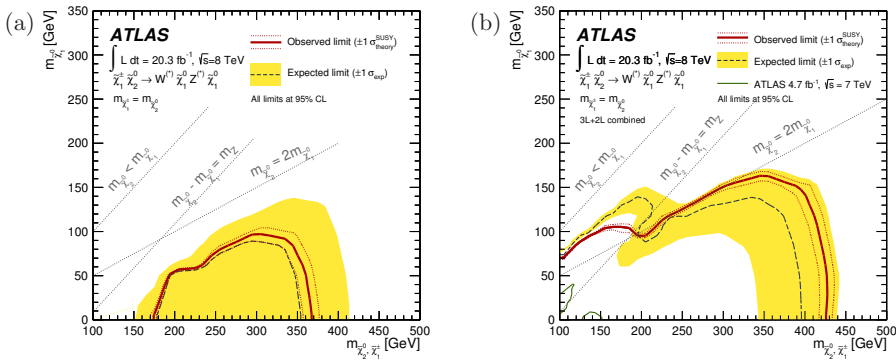
|                                                                                | SR-Zjets               |
|--------------------------------------------------------------------------------|------------------------|
| Background                                                                     |                        |
| $WW$                                                                           | $0.1 \pm 0.1$          |
| $ZV$                                                                           | $1.0 \pm 0.6$          |
| Top                                                                            | $< 0.1$                |
| $Z + \text{jets and others}$                                                   | $0.3 \pm 0.2$          |
| Total                                                                          | $1.4 \pm 0.6$          |
| Observed events                                                                | 1                      |
| Predicted signal                                                               |                        |
| $(m_{\tilde{\chi}_2^0, \tilde{\chi}_1^\pm}, m_{\tilde{\chi}_1^0}) = (250, 0)$  | $6.4 \pm 0.8$          |
| $(m_{\tilde{\chi}_2^0, \tilde{\chi}_1^\pm}, m_{\tilde{\chi}_1^0}) = (350, 50)$ | $3.7 \pm 0.2$          |
| $p_0$                                                                          | 0.50                   |
| Observed $\sigma_{\text{vis}}^{95}$ [fb]                                       | 0.17                   |
| Expected $\sigma_{\text{vis}}^{95}$ [fb]                                       | $0.19^{+0.11}_{-0.06}$ |

**Table 7.** Observed and expected numbers of events in SR-Zjets. Also shown are the one-sided  $p_0$  value and the observed and expected 95% CL upper limits,  $\sigma_{\text{vis}}^{95}$ , on the visible cross-section for non-SM events. The numbers of signal events are shown for the  $\tilde{\chi}_1^\pm \tilde{\chi}_2^0 \rightarrow W^\pm \tilde{\chi}_1^0 Z \tilde{\chi}_1^0$  scenario with different  $\tilde{\chi}_1^\pm$ ,  $\tilde{\chi}_2^0$  and  $\tilde{\chi}_1^0$  masses in GeV.



**Figure 6.** (a) Observed and expected 95% CL exclusion regions in the  $(m_{\tilde{\chi}_1^\pm}, m_{\tilde{\chi}_1^0})$  plane for simplified-model  $\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp$  production followed by  $W$ -mediated decays. Also shown is the LEP limit [36, 37] on the mass of the chargino. (b) Observed and expected 95% CL upper limits on the cross-section normalized by the simplified-model prediction as a function of  $m_{\tilde{\chi}_1^\pm}$  for  $m_{\tilde{\chi}_1^0} = 0$ .

and correlations between channels and processes are taken into account. The combination significantly improves the sensitivity. As a result, degenerate  $\tilde{\chi}_1^\pm$  and  $\tilde{\chi}_2^0$  masses between 100 GeV and 415 GeV are excluded at 95% CL for  $m_{\tilde{\chi}_1^0} = 0$ .

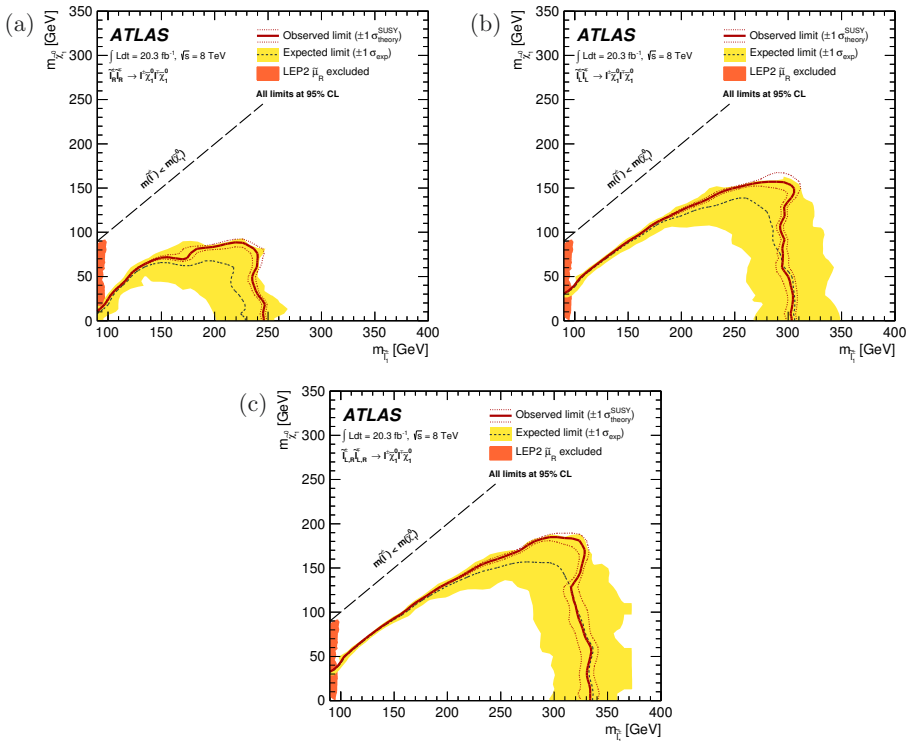


**Figure 7.** (a) Observed and expected 95% CL exclusion regions in the  $(m_{\tilde{\chi}_2^0}, m_{\tilde{\chi}_1^\pm})$  plane for simplified-model  $\tilde{\chi}_1^0 \tilde{\chi}_2^0$  production followed by  $W$  and  $Z$ -mediated decays obtained from SR-Zjets; and (b) the exclusion regions obtained by combining with the ATLAS three-lepton search [83]. The green lines in (b) indicate the regions excluded by ATLAS using 4.7 fb $^{-1}$  of  $\sqrt{s} = 7$  TeV data [105].

Figure 8 shows the 95% CL exclusion regions obtained from SR- $m_{T2}$  for the direct production of (a) right-handed, (b) left-handed, and (c) both right- and left-handed selectrons and smuons of equal mass in the  $m_{\tilde{\chi}_1^0} - m_{\tilde{\ell}}$  plane. For  $m_{\tilde{\chi}_1^0} = 0$ , common values for left and right-handed selectron and smuon mass between 90 GeV and 325 GeV are excluded. The sensitivity decreases as the  $\tilde{\ell} - \tilde{\chi}_1^0$  mass splitting decreases because the  $m_{T2}$  end point of the SUSY signal moves lower towards that of the SM background. For  $m_{\tilde{\chi}_1^0} = 100$  GeV, common left and right-handed slepton masses between 160 GeV and 310 GeV are excluded. The present result cannot be directly compared with the previous ATLAS slepton limits [34], which used a flavour-blind signal region and searched for a single slepton flavour with both right-handed and left-handed contributions.

Figure 9(a)–(c) show the 95% CL exclusion regions in the pMSSM  $\mu - M_2$  plane for the scenario with right-handed sleptons with  $m_{\tilde{\ell}_R} = (m_{\tilde{\chi}_1^0} + m_{\tilde{\chi}_2^0})/2$ . The  $M_1$  parameter is set to (a) 100 GeV, (b) 140 GeV and (c) 250 GeV, and  $\tan\beta = 6$ . At each model point, the limits are obtained using the SR with the best expected sensitivity. Figure 9(d) shows the exclusion region for  $M_1 = 250$  GeV obtained by combining the results of this analysis with the ATLAS three-lepton results [83]. Figure 10(a) shows the 95% CL exclusion region in the pMSSM  $\mu - M_2$  plane for the scenario with heavy sleptons,  $\tan\beta = 10$  and  $M_1 = 50$  GeV, using the SR with the best expected sensitivity at each model point. The island of exclusion near the centre of figure 10(a) is due to SR-Zjets, and is shaped by the kinematical thresholds of the  $\tilde{\chi}_1^\pm \rightarrow W \tilde{\chi}_1^0$  and  $\tilde{\chi}_2^0 \rightarrow Z \tilde{\chi}_1^0$  decays. Figure 10(b) shows the exclusion region obtained by combining the results from SR-Zjets with the three-lepton results. These results significantly extend previous limits in the pMSSM  $\mu - M_2$  plane.

The  $\text{CL}_s$  value is also calculated from SR- $WWa$  for the GMSB model point where the chargino is the NLSP with  $m_{\tilde{\chi}_1^\pm} = 110$  GeV,  $m_{\tilde{\chi}_1^0} = 113$  GeV and  $m_{\tilde{\chi}_2^0} = 130$  GeV [47]. The observed and expected  $\text{CL}_s$  values are found to be 0.19 and 0.29, respectively. The

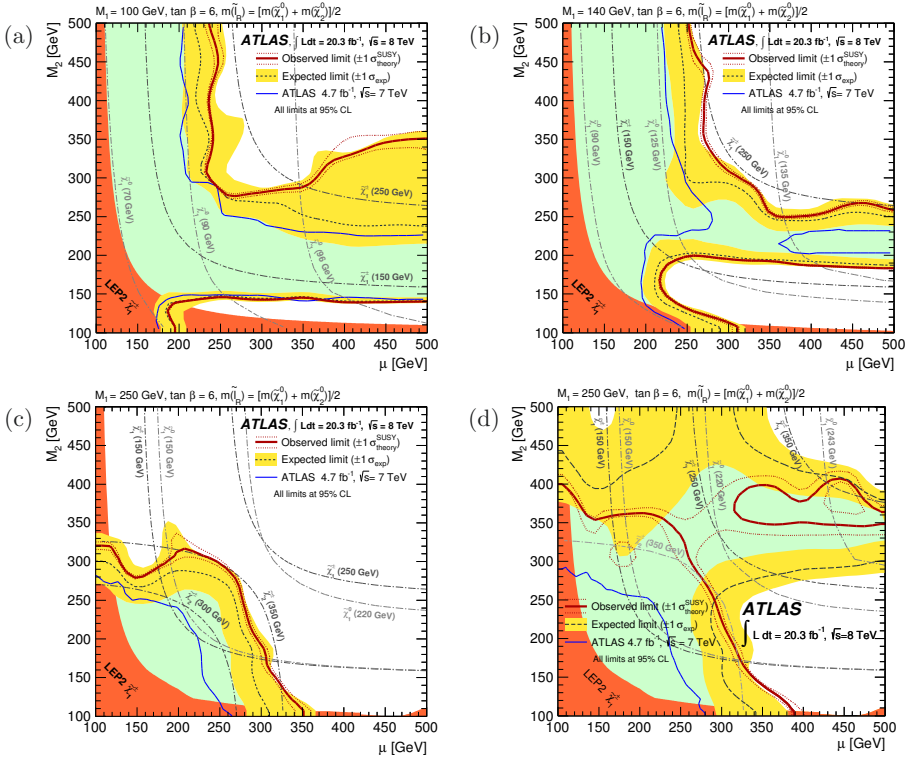


**Figure 8.** 95% CL exclusion regions in the  $(m_{\tilde{L}}, m_{\tilde{\chi}_1^0})$  plane for (a) right-handed, (b) left-handed, and (c) both right- and left-handed (mass degenerate) selectron and smuon production. Also illustrated are the LEP limits [36, 37] on the mass of the right-handed smuon  $\tilde{\mu}_R$ .

observed and expected 95% CL limits on the signal cross-section are 1.58 and 1.90 times the model prediction, respectively.

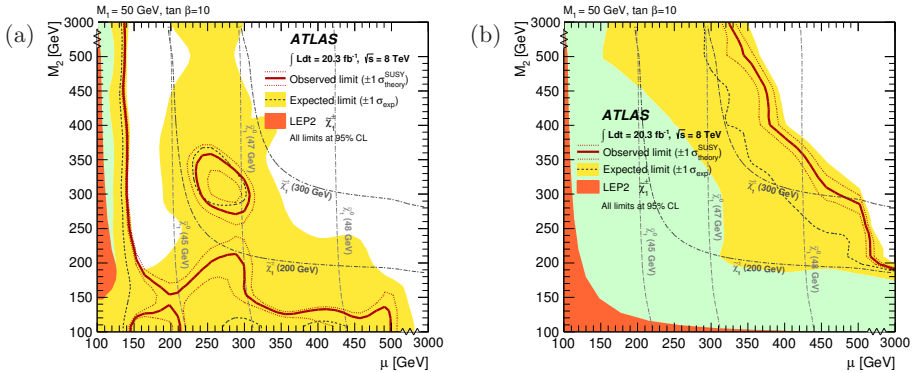
## 11 Conclusion

Searches for the electroweak production of charginos, neutralinos and sleptons in final states characterized by the presence of two leptons (electrons and muons) and missing transverse momentum are performed using  $20.3 \text{ fb}^{-1}$  of proton-proton collision data at  $\sqrt{s} = 8 \text{ TeV}$  recorded with the ATLAS experiment at the Large Hadron Collider. No significant excess beyond Standard Model expectations is observed. Limits are set on the masses of the lightest chargino  $\tilde{\chi}_1^\pm$ , next-to-lightest neutralino  $\tilde{\chi}_2^0$  and sleptons for different masses of the lightest neutralino  $\tilde{\chi}_1^0$  in simplified models. In the scenario of  $\tilde{\chi}_1^+ \tilde{\chi}_1^-$  pair production with  $\tilde{\chi}_1^\pm$  decaying into  $\tilde{\chi}_1^0$  via an intermediate slepton with mass halfway between the  $\tilde{\chi}_1^\pm$  and  $\tilde{\chi}_1^0$ ,  $\tilde{\chi}_1^\pm$  masses between 140 GeV and 465 GeV are excluded at 95% CL for a massless  $\tilde{\chi}_1^0$ . In the scenario of  $\tilde{\chi}_1^+ \tilde{\chi}_1^-$  pair production with  $\tilde{\chi}_1^\pm$  decaying into  $\tilde{\chi}_1^0$  and a  $W$  boson,  $\tilde{\chi}_1^\pm$  masses



**Figure 9.** 95% CL exclusion regions in the  $\mu$ - $M_2$  mass plane of the pMSSM with right-handed slepton mass  $m_{\tilde{e}_R} = (m_{\tilde{\chi}_1^0} + m_{\tilde{\chi}_2^0})/2$ . The areas covered by the  $-1\sigma$  expected limit are shown in green. The  $M_1$  parameter is (a) 100 GeV, (b) 140 GeV and (c) 250 GeV, and  $\tan\beta = 6$ . The exclusion region for  $M_1 = 250$  GeV (d) is obtained by combining the results of this analysis with those from the ATLAS three-lepton search [83]. The dash-dotted lines indicate the masses of  $\tilde{\chi}_1^\pm$  and  $\tilde{\chi}_1^0$ . Also shown are the previously reported exclusion regions by ATLAS [105] and the LEP limits [36, 37] on the mass of the chargino.

in the ranges 100–105 GeV, 120–135 GeV and 145–160 GeV are excluded at 95% CL for a massless  $\tilde{\chi}_1^0$ . This is the first limit for this scenario obtained at a hadron collider. Finally, in the scenario of  $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$  production with  $\tilde{\chi}_1^\pm$  decaying into  $W \tilde{\chi}_1^0$  and  $\tilde{\chi}_2^0$  decaying into  $Z \tilde{\chi}_1^0$ , common  $\tilde{\chi}_1^\pm$  and  $\tilde{\chi}_2^0$  masses between 180 GeV and 355 GeV are excluded at 95% CL for a massless  $\tilde{\chi}_1^0$ . Combining this result with those from ref. [83] extends the exclusion region to between 100 GeV and 415 GeV. In scenarios where sleptons decay directly into  $\tilde{\chi}_1^0$  and a charged lepton, common values for left and right-handed slepton masses between 90 GeV and 325 GeV are excluded at 95% CL for a massless  $\tilde{\chi}_1^0$ . Improved exclusion regions are also obtained in the pMSSM  $\mu$ - $M_2$  plane for four sets of slepton mass,  $M_1$  and  $\tan\beta$  values.



**Figure 10.** (a) 95% CL exclusion regions in the  $\mu$ - $M_2$  mass plane of the pMSSM with very large slepton masses,  $M_1 = 50$  GeV and  $\tan \beta = 10$ . (b) The exclusion region obtained by combining the results from SR-Zjets with those from the ATLAS three-lepton search [83]. The areas covered by the  $-1\sigma$  expected limit are shown in green. The dash-dotted lines indicate the masses of  $\tilde{\chi}_1^\pm$  and  $\tilde{\chi}_1^0$ . Also shown are the LEP limits [36, 37] on the mass of the chargino.

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## The ATLAS collaboration

G. Aad<sup>84</sup>, B. Abbott<sup>112</sup>, J. Abdallah<sup>152</sup>, S. Abdel Khalek<sup>116</sup>, O. Abdinov<sup>11</sup>, R. Aben<sup>106</sup>, B. Abi<sup>113</sup>, M. Abolins<sup>89</sup>, O.S. AbouZeid<sup>159</sup>, H. Abramowicz<sup>154</sup>, H. Abreu<sup>137</sup>, R. Abreu<sup>30</sup>, Y. Abulaiti<sup>147a,147b</sup>, B.S. Acharya<sup>165a,165b,a</sup>, L. Adamczyk<sup>38a</sup>, D.L. Adams<sup>25</sup>, J. Adelman<sup>177</sup>, S. Adomeit<sup>99</sup>, T. Adye<sup>130</sup>, T. Agatonovic-Jovin<sup>13b</sup>, J.A. Aguilar-Saavedra<sup>125f,125a</sup>, M. Agustoni<sup>17</sup>, S.P. Ahlen<sup>22</sup>, A. Ahmad<sup>149</sup>, F. Ahmadov<sup>64,b</sup>, G. Aielli<sup>134a,134b</sup>, T.P.A. Åkesson<sup>80</sup>, G. Akimoto<sup>156</sup>, A.V. Akimov<sup>95</sup>, G.L. Alberghi<sup>20a,20b</sup>, J. Albert<sup>170</sup>, S. Albrand<sup>55</sup>, M.J. Alconada Verzini<sup>70</sup>, M. Aleksa<sup>30</sup>, I.N. Aleksandrov<sup>64</sup>, C. Alexa<sup>26a</sup>, G. Alexander<sup>154</sup>, G. Alexandre<sup>49</sup>, T. Alexopoulos<sup>10</sup>, M. Alhroob<sup>165a,165c</sup>, G. Alimonti<sup>90a</sup>, L. Alio<sup>84</sup>, J. Alison<sup>31</sup>, B.M.M. Allbrooke<sup>18</sup>, L.J. Allison<sup>71</sup>, P.P. Allport<sup>73</sup>, S.E. Allwood-Spiers<sup>53</sup>, J. Almond<sup>83</sup>, A. Aloisio<sup>103a,103b</sup>, A. Alonso<sup>36</sup>, F. Alonso<sup>70</sup>, C. Alpigiani<sup>75</sup>, A. Altheimer<sup>35</sup>, B. Alvarez Gonzalez<sup>89</sup>, M.G. Alviggi<sup>103a,103b</sup>, K. Amako<sup>65</sup>, Y. Amaral Coutinho<sup>24a</sup>, C. Amelung<sup>23</sup>, D. Amidei<sup>88</sup>, S.P. Amor Dos Santos<sup>125a,125c</sup>, A. Amorim<sup>125a,125b</sup>, S. Amoroso<sup>48</sup>, N. Amram<sup>154</sup>, G. Amundsen<sup>23</sup>, C. Anastopoulos<sup>140</sup>, L.S. Ancu<sup>49</sup>, N. Andari<sup>30</sup>, T. Andeen<sup>35</sup>, C.F. Anders<sup>58b</sup>, G. Anders<sup>30</sup>, K.J. Anderson<sup>31</sup>, A. Andreazza<sup>90a,90b</sup>, V. Andrei<sup>58a</sup>, X.S. Anduaga<sup>70</sup>, S. Angelidakis<sup>9</sup>, I. Angelozzi<sup>106</sup>, P. Anger<sup>44</sup>, A. Angerami<sup>35</sup>, F. Anghinolfi<sup>30</sup>, A.V. Anisenkov<sup>108</sup>, N. Anjos<sup>125a</sup>, A. Annovi<sup>47</sup>, A. Antonaki<sup>9</sup>, M. Antonelli<sup>47</sup>, A. Antonov<sup>97</sup>, J. Antos<sup>145b</sup>, F. Anulli<sup>133a</sup>, M. Aoki<sup>65</sup>, L. Aperio Bella<sup>18</sup>, R. Apolle<sup>119,c</sup>, G. Arabidze<sup>89</sup>, I. Aracena<sup>144</sup>, Y. Arai<sup>65</sup>, J.P. Araque<sup>125a</sup>, A.T.H. Arce<sup>45</sup>, J-F. Arguin<sup>94</sup>, S. Argyropoulos<sup>42</sup>, M. Arik<sup>19a</sup>, A.J. Armbruster<sup>30</sup>, O. Arnaez<sup>82</sup>, V. Arnal<sup>81</sup>, H. Arnold<sup>48</sup>, O. Arslan<sup>21</sup>, A. Artamonov<sup>96</sup>, G. Artoni<sup>23</sup>, S. Asai<sup>156</sup>, N. Asbah<sup>94</sup>, A. Ashkenazi<sup>154</sup>, S. Ask<sup>28</sup>, B. 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Barberio<sup>87</sup>, D. Barberis<sup>50a,50b</sup>, M. Barbero<sup>84</sup>, T. Barillari<sup>100</sup>, M. Barisonzi<sup>176</sup>, T. Barklow<sup>144</sup>, N. Barlow<sup>28</sup>, B.M. Barnett<sup>130</sup>, R.M. Barnett<sup>15</sup>, Z. Barnovska<sup>5</sup>, A. Baroncelli<sup>135a</sup>, G. Barone<sup>49</sup>, A.J. Barr<sup>119</sup>, F. Barreiro<sup>81</sup>, J. Barreiro Guimarães da Costa<sup>57</sup>, R. Bartoldus<sup>144</sup>, A.E. Barton<sup>71</sup>, P. Bartos<sup>145a</sup>, V. Bartsch<sup>150</sup>, A. Bassalat<sup>116</sup>, A. Basye<sup>166</sup>, R.L. Bates<sup>53</sup>, L. Batkova<sup>145a</sup>, J.R. Batley<sup>28</sup>, M. Battistin<sup>30</sup>, F. Bauer<sup>137</sup>, H.S. Bawa<sup>144,e</sup>, T. Beau<sup>79</sup>, P.H. Beauchemin<sup>162</sup>, R. Beccherle<sup>123a,123b</sup>, P. Bechtel<sup>21</sup>, H.P. Beck<sup>17</sup>, K. Becker<sup>176</sup>, S. Becker<sup>99</sup>, M. Beckingham<sup>139</sup>, C. Becot<sup>116</sup>, A.J. Beddall<sup>19c</sup>, A. 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D.P. Benjamin<sup>45</sup>, J.R. Bensinger<sup>23</sup>, K. Benslama<sup>131</sup>, S. Bentvelsen<sup>106</sup>, D. Berge<sup>106</sup>, E. Bergeaas Kuutmann<sup>16</sup>, N. Berger<sup>5</sup>, F. Berghaus<sup>170</sup>, E. Berglund<sup>106</sup>, J. Beringer<sup>15</sup>, C. Bernard<sup>22</sup>, P. Bernat<sup>77</sup>, C. Bernius<sup>78</sup>, F.U. Bernlochner<sup>170</sup>, T. Berry<sup>76</sup>, P. Berta<sup>128</sup>, C. Bertella<sup>84</sup>, F. Bertolucci<sup>123a,123b</sup>, M.I. Besana<sup>90a</sup>, G.J. Besjes<sup>105</sup>, O. Bessidskaia<sup>147a,147b</sup>, N. Besson<sup>137</sup>, C. Betancourt<sup>48</sup>, S. Bethke<sup>100</sup>, W. Bhimji<sup>46</sup>, R.M. Bianchi<sup>124</sup>, L. Bianchini<sup>23</sup>, M. Bianco<sup>30</sup>, O. Biebel<sup>99</sup>, S.P. Bieniek<sup>77</sup>, K. Bierwagen<sup>54</sup>, J. Biesiada<sup>15</sup>, M. Biglietti<sup>135a</sup>, J. Bilbao De Mendizabal<sup>49</sup>, H. Bilokon<sup>47</sup>, M. Bindi<sup>54</sup>, S. Binet<sup>116</sup>, A. Bingul<sup>19c</sup>, C. Bini<sup>133a,133b</sup>, C.W. Black<sup>151</sup>, J.E. Black<sup>144</sup>, K.M. Black<sup>22</sup>, D. Blackburn<sup>139</sup>, R.E. Blair<sup>6</sup>, J.-B. Blanchard<sup>137</sup>, T. Blazek<sup>145a</sup>, I. Bloch<sup>42</sup>, C. Blocker<sup>23</sup>, W. Blum<sup>82,\*</sup>, U. Blumenschein<sup>54</sup>, G.J. Bobbink<sup>106</sup>, V.S. Bobrovnikov<sup>108</sup>, S.S. Bocchetta<sup>80</sup>, A. Bocci<sup>45</sup>, C.R. Boddy<sup>119</sup>, M. Boehler<sup>48</sup>, J. Boek<sup>176</sup>, T.T. Boek<sup>176</sup>, J.A. Bogaerts<sup>30</sup>, A.G. Bogdanchikov<sup>108</sup>, A. Bogouch<sup>91,\*</sup>, C. Bohm<sup>147a</sup>, J. Bohm<sup>126</sup>, V. Boisvert<sup>76</sup>, T. Bold<sup>38a</sup>, V. Boldea<sup>26a</sup>, A.S. Boldyrev<sup>98</sup>, M. Bomben<sup>79</sup>, M. Bona<sup>75</sup>, M. Boonekamp<sup>137</sup>, A. Borisov<sup>129</sup>, G. Borissov<sup>71</sup>, M. Borri<sup>83</sup>, S. Borroni<sup>42</sup>, J. Bortfeldt<sup>99</sup>, V. Bortolotto<sup>135a,135b</sup>, K. Bos<sup>106</sup>, D. Boscherini<sup>20a</sup>, M. Bosman<sup>12</sup>, H. Boterenbrood<sup>106</sup>, J. Boudreau<sup>124</sup>, J. Bouffard<sup>2</sup>, E.V. Bouhova-Thacker<sup>71</sup>, D. Boumediene<sup>34</sup>, C. Bourdarios<sup>116</sup>, N. Bousson<sup>113</sup>, S. Boutouil<sup>136d</sup>, A. Boveia<sup>31</sup>, J. Boyd<sup>30</sup>, I.R. Boyko<sup>64</sup>, I. Bozovic-Jelisavcic<sup>13b</sup>, J. Bracinik<sup>18</sup>, P. Branchini<sup>135a</sup>, A. Brandt<sup>8</sup>, G. Brandt<sup>15</sup>, O. Brandt<sup>58a</sup>, U. Bratzler<sup>157</sup>, B. Brau<sup>85</sup>, J.E. Brau<sup>115</sup>, H.M. Braun<sup>176,\*</sup>, S.F. Brazzale<sup>165a,165c</sup>, B. Brelier<sup>159</sup>, K. Brendlinger<sup>121</sup>, A.J. Brennan<sup>87</sup>, R. Brenner<sup>167</sup>, S. Bressler<sup>173</sup>, K. Bristow<sup>146c</sup>, T.M. Bristow<sup>46</sup>, D. Britton<sup>53</sup>, F.M. Brochu<sup>28</sup>, I. Brock<sup>21</sup>, R. Brock<sup>89</sup>, C. Bromberg<sup>89</sup>, J. Bronner<sup>100</sup>, G. Brooijmans<sup>35</sup>, T. Brooks<sup>76</sup>, W.K. Brooks<sup>32b</sup>, J. Brosamer<sup>15</sup>, E. Brost<sup>115</sup>, G. Brown<sup>83</sup>, J. Brown<sup>55</sup>, P.A. Bruckman de Renstrom<sup>39</sup>, D. Bruncko<sup>145b</sup>, R. Bruneliere<sup>48</sup>, S. Brunet<sup>60</sup>, A. Bruni<sup>20a</sup>, G. Bruni<sup>20a</sup>, M. Bruschi<sup>20a</sup>, L. Bryngemark<sup>80</sup>, T. Buanes<sup>14</sup>, Q. Buat<sup>143</sup>, F. Bucci<sup>49</sup>, P. Buchholz<sup>142</sup>, R.M. Buckingham<sup>119</sup>, A.G. Buckley<sup>53</sup>, S.I. Buda<sup>26a</sup>, I.A. Budagov<sup>64</sup>, F. Buehrer<sup>48</sup>, L. Bugge<sup>118</sup>, M.K. Bugge<sup>118</sup>, O. Bulekov<sup>97</sup>, A.C. Bundock<sup>73</sup>, H. Burckhart<sup>30</sup>, S. Burdin<sup>73</sup>, B. Burghgrave<sup>107</sup>, S. Burke<sup>130</sup>, I. Burmeister<sup>43</sup>, E. Busato<sup>34</sup>, D. Büscher<sup>48</sup>, V. Büscher<sup>82</sup>, P. Bussey<sup>53</sup>, C.P. Buszello<sup>167</sup>, B. Butler<sup>57</sup>, J.M. Butler<sup>22</sup>, A.I. Butt<sup>3</sup>, C.M. Buttar<sup>53</sup>, J.M. Butterworth<sup>77</sup>, P. Butti<sup>106</sup>, W. Buttinger<sup>28</sup>, A. Buzatu<sup>53</sup>, M. Byszewski<sup>10</sup>, S. Cabrera Urbán<sup>168</sup>, D. Caforio<sup>20a,20b</sup>, O. Cakir<sup>4a</sup>, P. Calafiura<sup>15</sup>, A. Calandri<sup>137</sup>, G. Calderini<sup>79</sup>, P. Calfayan<sup>99</sup>, R. Calkins<sup>107</sup>, L.P. Caloba<sup>24a</sup>, D. Calvet<sup>34</sup>, S. Calvet<sup>34</sup>, R. Camacho Toro<sup>49</sup>, S. Camarda<sup>42</sup>, D. Cameron<sup>118</sup>, L.M. Caminada<sup>15</sup>, R. Caminal Armadans<sup>12</sup>, S. Campana<sup>30</sup>, M. Campanelli<sup>77</sup>, A. Campoverde<sup>149</sup>, V. Canale<sup>103a,103b</sup>, A. Canepa<sup>160a</sup>, J. Cantero<sup>81</sup>, R. Cantrill<sup>76</sup>, T. Cao<sup>40</sup>, M.D.M. Capeans Garrido<sup>30</sup>, I. Caprini<sup>26a</sup>, M. Caprini<sup>26a</sup>, M. Capua<sup>37a,37b</sup>, R. Caputo<sup>82</sup>, R. Cardarelli<sup>134a</sup>, T. Carli<sup>30</sup>, G. Carlino<sup>103a</sup>, L. Carminati<sup>90a,90b</sup>, S. Caron<sup>105</sup>, E. Carquin<sup>32a</sup>, G.D. Carrillo-Montoya<sup>146c</sup>, A.A. Carter<sup>75</sup>, J.R. Carter<sup>28</sup>, J. Carvalho<sup>125a,125c</sup>, D. Casadei<sup>77</sup>, M.P. Casado<sup>12</sup>, E. Castaneda-Miranda<sup>146b</sup>, A. Castelli<sup>106</sup>, V. Castillo Gimenez<sup>168</sup>, N.F. Castro<sup>125a</sup>, P. Catastini<sup>57</sup>, A. Catinaccio<sup>30</sup>, J.R. Catmore<sup>118</sup>, A. Cattai<sup>30</sup>, G. Cattani<sup>134a,134b</sup>, S. Caughron<sup>89</sup>, V. Cavaliere<sup>166</sup>, D. Cavalli<sup>90a</sup>, M. Cavalli-Sforza<sup>12</sup>, V. Cavasinni<sup>123a,123b</sup>, F. Ceradini<sup>135a,135b</sup>, B. Cerio<sup>45</sup>, K. Cerny<sup>128</sup>, A.S. Cerqueira<sup>24b</sup>, A. Cerri<sup>150</sup>, L. Cerrito<sup>75</sup>,

F. Cerutti<sup>15</sup>, M. Cerv<sup>30</sup>, A. Cervelli<sup>17</sup>, S.A. Cetin<sup>19b</sup>, A. Chafaq<sup>136a</sup>, D. Chakraborty<sup>107</sup>, I. Chalupkova<sup>128</sup>, K. Chan<sup>3</sup>, P. Chang<sup>166</sup>, B. Chapleau<sup>86</sup>, J.D. Chapman<sup>28</sup>, D. Charfeddine<sup>116</sup>, D.G. Charlton<sup>18</sup>, C.C. Chau<sup>159</sup>, C.A. Chavez Barajas<sup>150</sup>, S. Cheatham<sup>86</sup>, A. Chegwiddden<sup>89</sup>, S. Chekanov<sup>6</sup>, S.V. Chekulaev<sup>160a</sup>, G.A. Chelkov<sup>64</sup>, M.A. Chelstowska<sup>88</sup>, C. Chen<sup>63</sup>, H. Chen<sup>25</sup>, K. Chen<sup>149</sup>, L. Chen<sup>33d,g</sup>, S. Chen<sup>33c</sup>, X. Chen<sup>146c</sup>, Y. Chen<sup>35</sup>, H.C. Cheng<sup>88</sup>, Y. Cheng<sup>31</sup>, A. Cheplakov<sup>64</sup>, R. Cherkaoui El Moursli<sup>136e</sup>, V. Chernyatin<sup>25,\*</sup>, E. Cheu<sup>7</sup>, L. Chevalier<sup>137</sup>, V. Chiarella<sup>47</sup>, G. Chiefari<sup>103a,103b</sup>, J.T. Childers<sup>6</sup>, A. Chilingarov<sup>71</sup>, G. Chiodini<sup>72a</sup>, A.S. Chisholm<sup>18</sup>, R.T. Chislett<sup>77</sup>, A. Chitan<sup>26a</sup>, M.V. Chizhov<sup>64</sup>, S. Chouridou<sup>9</sup>, B.K.B. Chow<sup>99</sup>, I.A. Christidi<sup>77</sup>, D. Chromek-Burckhart<sup>30</sup>, M.L. Chu<sup>152</sup>, J. Chudoba<sup>126</sup>, J.C. Chwastowski<sup>39</sup>, L. Chytka<sup>114</sup>, G. Ciapetti<sup>133a,133b</sup>, A.K. Ciftci<sup>4a</sup>, R. Ciftci<sup>4a</sup>, D. Cinca<sup>62</sup>, V. Cindro<sup>74</sup>, A. Ciocio<sup>15</sup>, P. Cirkovic<sup>13b</sup>, Z.H. Citron<sup>173</sup>, M. Citterio<sup>90a</sup>, M. Ciubancan<sup>26a</sup>, A. Clark<sup>49</sup>, P.J. Clark<sup>46</sup>, R.N. Clarke<sup>15</sup>, W. Cleland<sup>124</sup>, J.C. Clemens<sup>84</sup>, C. Clement<sup>147a,147b</sup>, Y. Coadou<sup>84</sup>, M. Cobal<sup>165a,165c</sup>, A. Coccaro<sup>139</sup>, J. Cochran<sup>63</sup>, L. Coffey<sup>23</sup>, J.G. Cogan<sup>144</sup>, J. Coggeshall<sup>166</sup>, B. Cole<sup>35</sup>, S. Cole<sup>107</sup>, A.P. Colijn<sup>106</sup>, C. Collins-Tooth<sup>53</sup>, J. Collot<sup>55</sup>, T. Colombo<sup>58c</sup>, G. Colon<sup>85</sup>, G. Compostella<sup>100</sup>, P. Conde Muiño<sup>125a,125b</sup>, E. Coniavitis<sup>167</sup>, M.C. Conidi<sup>12</sup>, S.H. Connell<sup>146b</sup>, I.A. Connelly<sup>76</sup>, S.M. Consonni<sup>90a,90b</sup>, V. Consorti<sup>48</sup>, S. Constantinescu<sup>26a</sup>, C. Conta<sup>120a,120b</sup>, G. Conti<sup>57</sup>, F. Conventi<sup>103a,h</sup>, M. Cooke<sup>15</sup>, B.D. Cooper<sup>77</sup>, A.M. Cooper-Sarkar<sup>119</sup>, N.J. Cooper-Smith<sup>76</sup>, K. Copic<sup>15</sup>, T. Cornelissen<sup>176</sup>, M. Corradi<sup>20a</sup>, F. Corriveau<sup>86,i</sup>, A. Corso-Radu<sup>164</sup>, A. Cortes-Gonzalez<sup>12</sup>, G. Cortiana<sup>100</sup>, G. Costa<sup>90a</sup>, M.J. Costa<sup>168</sup>, D. Costanzo<sup>140</sup>, D. Côté<sup>8</sup>, G. Cottin<sup>28</sup>, G. 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A. Zoccoli<sup>20a,20b</sup>, M. zur Nedden<sup>16</sup>, G. Zurzolo<sup>103a,103b</sup>, V. Zutshi<sup>107</sup> and L. Zwalinski<sup>30</sup>

<sup>1</sup> *Department of Physics, University of Adelaide, Adelaide, Australia*

<sup>2</sup> *Physics Department, SUNY Albany, Albany NY, United States of America*

<sup>3</sup> *Department of Physics, University of Alberta, Edmonton AB, Canada*

<sup>4</sup> <sup>(a)</sup> *Department of Physics, Ankara University, Ankara;* <sup>(b)</sup> *Department of Physics, Gazi University, Ankara;* <sup>(c)</sup> *Division of Physics, TOBB University of Economics and Technology, Ankara;* <sup>(d)</sup>

*Turkish Atomic Energy Authority, Ankara, Turkey*

<sup>5</sup> *LAPP, CNRS/IN2P3 and Université de Savoie, Annecy-le-Vieux, France*

<sup>6</sup> *High Energy Physics Division, Argonne National Laboratory, Argonne IL, United States of America*

<sup>7</sup> *Department of Physics, University of Arizona, Tucson AZ, United States of America*

- <sup>8</sup> *Department of Physics, The University of Texas at Arlington, Arlington TX, United States of America*
- <sup>9</sup> *Physics Department, University of Athens, Athens, Greece*
- <sup>10</sup> *Physics Department, National Technical University of Athens, Zografou, Greece*
- <sup>11</sup> *Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan*
- <sup>12</sup> *Institut de Física d'Altes Energies and Departament de Física de la Universitat Autònoma de Barcelona, Barcelona, Spain*
- <sup>13</sup> <sup>(a)</sup> *Institute of Physics, University of Belgrade, Belgrade;* <sup>(b)</sup> *Vinca Institute of Nuclear Sciences, University of Belgrade, Belgrade, Serbia*
- <sup>14</sup> *Department for Physics and Technology, University of Bergen, Bergen, Norway*
- <sup>15</sup> *Physics Division, Lawrence Berkeley National Laboratory and University of California, Berkeley CA, United States of America*
- <sup>16</sup> *Department of Physics, Humboldt University, Berlin, Germany*
- <sup>17</sup> *Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern, Switzerland*
- <sup>18</sup> *School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom*
- <sup>19</sup> <sup>(a)</sup> *Department of Physics, Bogazici University, Istanbul;* <sup>(b)</sup> *Department of Physics, Dogus University, Istanbul;* <sup>(c)</sup> *Department of Physics Engineering, Gaziantep University, Gaziantep, Turkey*
- <sup>20</sup> <sup>(a)</sup> *INFN Sezione di Bologna;* <sup>(b)</sup> *Dipartimento di Fisica e Astronomia, Università di Bologna, Bologna, Italy*
- <sup>21</sup> *Physikalisches Institut, University of Bonn, Bonn, Germany*
- <sup>22</sup> *Department of Physics, Boston University, Boston MA, United States of America*
- <sup>23</sup> *Department of Physics, Brandeis University, Waltham MA, United States of America*
- <sup>24</sup> <sup>(a)</sup> *Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro;* <sup>(b)</sup> *Federal University of Juiz de Fora (UFJF), Juiz de Fora;* <sup>(c)</sup> *Federal University of Sao Joao del Rei (UFSJ), Sao Joao del Rei;* <sup>(d)</sup> *Instituto de Fisica, Universidade de Sao Paulo, Sao Paulo, Brazil*
- <sup>25</sup> *Physics Department, Brookhaven National Laboratory, Upton NY, United States of America*
- <sup>26</sup> <sup>(a)</sup> *National Institute of Physics and Nuclear Engineering, Bucharest;* <sup>(b)</sup> *National Institute for Research and Development of Isotopic and Molecular Technologies, Physics Department, Cluj Napoca;* <sup>(c)</sup> *University Politehnica Bucharest, Bucharest;* <sup>(d)</sup> *West University in Timisoara, Timisoara, Romania*
- <sup>27</sup> *Departamento de Física, Universidad de Buenos Aires, Buenos Aires, Argentina*
- <sup>28</sup> *Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom*
- <sup>29</sup> *Department of Physics, Carleton University, Ottawa ON, Canada*
- <sup>30</sup> *CERN, Geneva, Switzerland*
- <sup>31</sup> *Enrico Fermi Institute, University of Chicago, Chicago IL, United States of America*
- <sup>32</sup> <sup>(a)</sup> *Departamento de Física, Pontificia Universidad Católica de Chile, Santiago;* <sup>(b)</sup> *Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso, Chile*
- <sup>33</sup> <sup>(a)</sup> *Institute of High Energy Physics, Chinese Academy of Sciences, Beijing;* <sup>(b)</sup> *Department of Modern Physics, University of Science and Technology of China, Anhui;* <sup>(c)</sup> *Department of Physics, Nanjing University, Jiangsu;* <sup>(d)</sup> *School of Physics, Shandong University, Shandong;* <sup>(e)</sup> *Physics Department, Shanghai Jiao Tong University, Shanghai, China*
- <sup>34</sup> *Laboratoire de Physique Corpusculaire, Clermont Université and Université Blaise Pascal and CNRS/IN2P3, Clermont-Ferrand, France*
- <sup>35</sup> *Nevis Laboratory, Columbia University, Irvington NY, United States of America*
- <sup>36</sup> *Niels Bohr Institute, University of Copenhagen, Kobenhavn, Denmark*
- <sup>37</sup> <sup>(a)</sup> *INFN Gruppo Collegato di Cosenza, Laboratori Nazionali di Frascati;* <sup>(b)</sup> *Dipartimento di Fisica, Università della Calabria, Rende, Italy*
- <sup>38</sup> <sup>(a)</sup> *AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, Krakow;* <sup>(b)</sup> *Marian Smoluchowski Institute of Physics, Jagiellonian University, Krakow, Poland*
- <sup>39</sup> *The Henryk Niewodniczanski Institute of Nuclear Physics, Polish Academy of Sciences, Krakow,*

Poland

- 40 *Physics Department, Southern Methodist University, Dallas TX, United States of America*
- 41 *Physics Department, University of Texas at Dallas, Richardson TX, United States of America*
- 42 *DESY, Hamburg and Zeuthen, Germany*
- 43 *Institut für Experimentelle Physik IV, Technische Universität Dortmund, Dortmund, Germany*
- 44 *Institut für Kern- und Teilchenphysik, Technische Universität Dresden, Dresden, Germany*
- 45 *Department of Physics, Duke University, Durham NC, United States of America*
- 46 *SUPA - School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom*
- 47 *INFN Laboratori Nazionali di Frascati, Frascati, Italy*
- 48 *Fakultät für Mathematik und Physik, Albert-Ludwigs-Universität, Freiburg, Germany*
- 49 *Section de Physique, Université de Genève, Geneva, Switzerland*
- 50 <sup>(a)</sup> *INFN Sezione di Genova;* <sup>(b)</sup> *Dipartimento di Fisica, Università di Genova, Genova, Italy*
- 51 <sup>(a)</sup> *E. Andronikashvili Institute of Physics, Iv. Javakhishvili Tbilisi State University, Tbilisi;* <sup>(b)</sup> *High Energy Physics Institute, Tbilisi State University, Tbilisi, Georgia*
- 52 *II Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen, Germany*
- 53 *SUPA - School of Physics and Astronomy, University of Glasgow, Glasgow, United Kingdom*
- 54 *II Physikalisches Institut, Georg-August-Universität, Göttingen, Germany*
- 55 *Laboratoire de Physique Subatomique et de Cosmologie, Université Grenoble-Alpes, CNRS/IN2P3, Grenoble, France*
- 56 *Department of Physics, Hampton University, Hampton VA, United States of America*
- 57 *Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge MA, United States of America*
- 58 <sup>(a)</sup> *Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg;* <sup>(b)</sup> *Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg;* <sup>(c)</sup> *ZITI Institut für technische Informatik, Ruprecht-Karls-Universität Heidelberg, Mannheim, Germany*
- 59 *Faculty of Applied Information Science, Hiroshima Institute of Technology, Hiroshima, Japan*
- 60 *Department of Physics, Indiana University, Bloomington IN, United States of America*
- 61 *Institut für Astro- und Teilchenphysik, Leopold-Franzens-Universität, Innsbruck, Austria*
- 62 *University of Iowa, Iowa City IA, United States of America*
- 63 *Department of Physics and Astronomy, Iowa State University, Ames IA, United States of America*
- 64 *Joint Institute for Nuclear Research, JINR Dubna, Dubna, Russia*
- 65 *KEK, High Energy Accelerator Research Organization, Tsukuba, Japan*
- 66 *Graduate School of Science, Kobe University, Kobe, Japan*
- 67 *Faculty of Science, Kyoto University, Kyoto, Japan*
- 68 *Kyoto University of Education, Kyoto, Japan*
- 69 *Department of Physics, Kyushu University, Fukuoka, Japan*
- 70 *Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata, Argentina*
- 71 *Physics Department, Lancaster University, Lancaster, United Kingdom*
- 72 <sup>(a)</sup> *INFN Sezione di Lecce;* <sup>(b)</sup> *Dipartimento di Matematica e Fisica, Università del Salento, Lecce, Italy*
- 73 *Oliver Lodge Laboratory, University of Liverpool, Liverpool, United Kingdom*
- 74 *Department of Physics, Jožef Stefan Institute and University of Ljubljana, Ljubljana, Slovenia*
- 75 *School of Physics and Astronomy, Queen Mary University of London, London, United Kingdom*
- 76 *Department of Physics, Royal Holloway University of London, Surrey, United Kingdom*
- 77 *Department of Physics and Astronomy, University College London, London, United Kingdom*
- 78 *Louisiana Tech University, Ruston LA, United States of America*
- 79 *Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France*
- 80 *Fysiska institutionen, Lunds universitet, Lund, Sweden*
- 81 *Departamento de Física Teórica C-15, Universidad Autónoma de Madrid, Madrid, Spain*
- 82 *Institut für Physik, Universität Mainz, Mainz, Germany*
- 83 *School of Physics and Astronomy, University of Manchester, Manchester, United Kingdom*

- 84 CPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France  
 85 Department of Physics, University of Massachusetts, Amherst MA, United States of America  
 86 Department of Physics, McGill University, Montreal QC, Canada  
 87 School of Physics, University of Melbourne, Victoria, Australia  
 88 Department of Physics, The University of Michigan, Ann Arbor MI, United States of America  
 89 Department of Physics and Astronomy, Michigan State University, East Lansing MI, United States of America  
 90 <sup>(a)</sup> INFN Sezione di Milano; <sup>(b)</sup> Dipartimento di Fisica, Università di Milano, Milano, Italy  
 91 B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk, Republic of Belarus  
 92 National Scientific and Educational Centre for Particle and High Energy Physics, Minsk, Republic of Belarus  
 93 Department of Physics, Massachusetts Institute of Technology, Cambridge MA, United States of America  
 94 Group of Particle Physics, University of Montreal, Montreal QC, Canada  
 95 P.N. Lebedev Institute of Physics, Academy of Sciences, Moscow, Russia  
 96 Institute for Theoretical and Experimental Physics (ITEP), Moscow, Russia  
 97 Moscow Engineering and Physics Institute (MEPhI), Moscow, Russia  
 98 D.V.Skobeltzyn Institute of Nuclear Physics, M.V.Lomonosov Moscow State University, Moscow, Russia  
 99 Fakultät für Physik, Ludwig-Maximilians-Universität München, München, Germany  
 100 Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München, Germany  
 101 Nagasaki Institute of Applied Science, Nagasaki, Japan  
 102 Graduate School of Science and Kobayashi-Maskawa Institute, Nagoya University, Nagoya, Japan  
 103 <sup>(a)</sup> INFN Sezione di Napoli; <sup>(b)</sup> Dipartimento di Fisica, Università di Napoli, Napoli, Italy  
 104 Department of Physics and Astronomy, University of New Mexico, Albuquerque NM, United States of America  
 105 Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands  
 106 Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam, Netherlands  
 107 Department of Physics, Northern Illinois University, DeKalb IL, United States of America  
 108 Budker Institute of Nuclear Physics, SB RAS, Novosibirsk, Russia  
 109 Department of Physics, New York University, New York NY, United States of America  
 110 Ohio State University, Columbus OH, United States of America  
 111 Faculty of Science, Okayama University, Okayama, Japan  
 112 Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman OK, United States of America  
 113 Department of Physics, Oklahoma State University, Stillwater OK, United States of America  
 114 Palacký University, RCPTM, Olomouc, Czech Republic  
 115 Center for High Energy Physics, University of Oregon, Eugene OR, United States of America  
 116 LAL, Université Paris-Sud and CNRS/IN2P3, Orsay, France  
 117 Graduate School of Science, Osaka University, Osaka, Japan  
 118 Department of Physics, University of Oslo, Oslo, Norway  
 119 Department of Physics, Oxford University, Oxford, United Kingdom  
 120 <sup>(a)</sup> INFN Sezione di Pavia; <sup>(b)</sup> Dipartimento di Fisica, Università di Pavia, Pavia, Italy  
 121 Department of Physics, University of Pennsylvania, Philadelphia PA, United States of America  
 122 Petersburg Nuclear Physics Institute, Gatchina, Russia  
 123 <sup>(a)</sup> INFN Sezione di Pisa; <sup>(b)</sup> Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy  
 124 Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh PA, United States of America  
 125 <sup>(a)</sup> Laboratório de Instrumentação e Física Experimental de Partículas - LIP, Lisboa; <sup>(b)</sup> Faculdade

- de Ciências, Universidade de Lisboa, Lisboa; <sup>(c)</sup> Department of Physics, University of Coimbra, Coimbra; <sup>(d)</sup> Centro de Física Nuclear da Universidade de Lisboa, Lisboa; <sup>(e)</sup> Departamento de Física, Universidade do Minho, Braga; <sup>(f)</sup> Departamento de Física Teórica y del Cosmos and CAFPE, Universidad de Granada, Granada (Spain); <sup>(g)</sup> Dep Física and CEFITEC of Faculdade de Ciências e Tecnologia, Universidade Nova de Lisboa, Caparica, Portugal
- 126 Institute of Physics, Academy of Sciences of the Czech Republic, Praha, Czech Republic  
 127 Czech Technical University in Prague, Praha, Czech Republic  
 128 Faculty of Mathematics and Physics, Charles University in Prague, Praha, Czech Republic  
 129 State Research Center Institute for High Energy Physics, Protvino, Russia  
 130 Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom  
 131 Physics Department, University of Regina, Regina SK, Canada  
 132 Ritsumeikan University, Kusatsu, Shiga, Japan  
 133 <sup>(a)</sup> INFN Sezione di Roma; <sup>(b)</sup> Dipartimento di Fisica, Sapienza Università di Roma, Roma, Italy  
 134 <sup>(a)</sup> INFN Sezione di Roma Tor Vergata; <sup>(b)</sup> Dipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italy  
 135 <sup>(a)</sup> INFN Sezione di Roma Tre; <sup>(b)</sup> Dipartimento di Matematica e Fisica, Università Roma Tre, Roma, Italy  
 136 <sup>(a)</sup> Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Energies - Université Hassan II, Casablanca; <sup>(b)</sup> Centre National de l'Energie des Sciences Techniques Nucleaires, Rabat; <sup>(c)</sup> Faculté des Sciences Semlalia, Université Cadi Ayyad, LPHEA-Marrakech; <sup>(d)</sup> Faculté des Sciences, Université Mohamed Premier and LPTPM, Oujda; <sup>(e)</sup> Faculté des sciences, Université Mohammed V-Agdal, Rabat, Morocco  
 137 DSM/IRFU (Institut de Recherches sur les Lois Fondamentales de l'Univers), CEA Saclay (Commissariat à l'Energie Atomique et aux Energies Alternatives), Gif-sur-Yvette, France  
 138 Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz CA, United States of America  
 139 Department of Physics, University of Washington, Seattle WA, United States of America  
 140 Department of Physics and Astronomy, University of Sheffield, Sheffield, United Kingdom  
 141 Department of Physics, Shinshu University, Nagano, Japan  
 142 Fachbereich Physik, Universität Siegen, Siegen, Germany  
 143 Department of Physics, Simon Fraser University, Burnaby BC, Canada  
 144 SLAC National Accelerator Laboratory, Stanford CA, United States of America  
 145 <sup>(a)</sup> Faculty of Mathematics, Physics & Informatics, Comenius University, Bratislava; <sup>(b)</sup> Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice, Slovak Republic  
 146 <sup>(a)</sup> Department of Physics, University of Cape Town, Cape Town; <sup>(b)</sup> Department of Physics, University of Johannesburg, Johannesburg; <sup>(c)</sup> School of Physics, University of the Witwatersrand, Johannesburg, South Africa  
 147 <sup>(a)</sup> Department of Physics, Stockholm University; <sup>(b)</sup> The Oskar Klein Centre, Stockholm, Sweden  
 148 Physics Department, Royal Institute of Technology, Stockholm, Sweden  
 149 Departments of Physics & Astronomy and Chemistry, Stony Brook University, Stony Brook NY, United States of America  
 150 Department of Physics and Astronomy, University of Sussex, Brighton, United Kingdom  
 151 School of Physics, University of Sydney, Sydney, Australia  
 152 Institute of Physics, Academia Sinica, Taipei, Taiwan  
 153 Department of Physics, Technion: Israel Institute of Technology, Haifa, Israel  
 154 Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel  
 155 Department of Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece  
 156 International Center for Elementary Particle Physics and Department of Physics, The University of Tokyo, Tokyo, Japan  
 157 Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo, Japan

- 158 *Department of Physics, Tokyo Institute of Technology, Tokyo, Japan*  
 159 *Department of Physics, University of Toronto, Toronto ON, Canada*  
 160 <sup>(a)</sup> TRIUMF, Vancouver BC; <sup>(b)</sup> *Department of Physics and Astronomy, York University, Toronto*  
 ON, Canada  
 161 *Faculty of Pure and Applied Sciences, University of Tsukuba, Tsukuba, Japan*  
 162 *Department of Physics and Astronomy, Tufts University, Medford MA, United States of America*  
 163 *Centro de Investigaciones, Universidad Antonio Narino, Bogota, Colombia*  
 164 *Department of Physics and Astronomy, University of California Irvine, Irvine CA, United States of*  
 America  
 165 <sup>(a)</sup> INFN Gruppo Collegato di Udine, Sezione di Trieste, Udine; <sup>(b)</sup> ICTP, Trieste; <sup>(c)</sup>  
 Dipartimento di Chimica, Fisica e Ambiente, Università di Udine, Udine, Italy  
 166 *Department of Physics, University of Illinois, Urbana IL, United States of America*  
 167 *Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden*  
 168 *Instituto de Física Corpuscular (IFIC) and Departamento de Física Atómica, Molecular y Nuclear*  
 and Departamento de Ingeniería Electrónica and Instituto de Microelectrónica de Barcelona  
 (IMB-CNM), University of Valencia and CSIC, Valencia, Spain  
 169 *Department of Physics, University of British Columbia, Vancouver BC, Canada*  
 170 *Department of Physics and Astronomy, University of Victoria, Victoria BC, Canada*  
 171 *Department of Physics, University of Warwick, Coventry, United Kingdom*  
 172 *Waseda University, Tokyo, Japan*  
 173 *Department of Particle Physics, The Weizmann Institute of Science, Rehovot, Israel*  
 174 *Department of Physics, University of Wisconsin, Madison WI, United States of America*  
 175 *Fakultät für Physik und Astronomie, Julius-Maximilians-Universität, Würzburg, Germany*  
 176 *Fachbereich C Physik, Bergische Universität Wuppertal, Wuppertal, Germany*  
 177 *Department of Physics, Yale University, New Haven CT, United States of America*  
 178 *Yerevan Physics Institute, Yerevan, Armenia*  
 179 *Centre de Calcul de l'Institut National de Physique Nucléaire et de Physique des Particules*  
 (IN2P3), Villeurbanne, France  
<sup>a</sup> Also at Department of Physics, King's College London, London, United Kingdom  
<sup>b</sup> Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan  
<sup>c</sup> Also at Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom  
<sup>d</sup> Also at TRIUMF, Vancouver BC, Canada  
<sup>e</sup> Also at Department of Physics, California State University, Fresno CA, United States of America  
<sup>f</sup> Also at Novosibirsk State University, Novosibirsk, Russia  
<sup>g</sup> Also at CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France  
<sup>h</sup> Also at Università di Napoli Parthenope, Napoli, Italy  
<sup>i</sup> Also at Institute of Particle Physics (IPP), Canada  
<sup>j</sup> Also at Department of Physics, St. Petersburg State Polytechnical University, St. Petersburg,  
 Russia  
<sup>k</sup> Also at Department of Financial and Management Engineering, University of the Aegean, Chios,  
 Greece  
<sup>l</sup> Also at Louisiana Tech University, Ruston LA, United States of America  
<sup>m</sup> Also at Institutio Catalana de Recerca i Estudis Avancats, ICREA, Barcelona, Spain  
<sup>n</sup> Also at CERN, Geneva, Switzerland  
<sup>o</sup> Also at Ochadai Academic Production, Ochanomizu University, Tokyo, Japan  
<sup>p</sup> Also at Manhattan College, New York NY, United States of America  
<sup>q</sup> Also at Institute of Physics, Academia Sinica, Taipei, Taiwan  
<sup>r</sup> Also at LAL, Université Paris-Sud and CNRS/IN2P3, Orsay, France  
<sup>s</sup> Also at School of Physics and Engineering, Sun Yat-sen University, Guangzhou, China  
<sup>t</sup> Also at Academia Sinica Grid Computing, Institute of Physics, Academia Sinica, Taipei, Taiwan  
<sup>u</sup> Also at Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université  
 Paris-Diderot and CNRS/IN2P3, Paris, France

- <sup>v</sup> Also at School of Physical Sciences, National Institute of Science Education and Research, Bhubaneswar, India
- <sup>w</sup> Also at Dipartimento di Fisica, Sapienza Università di Roma, Roma, Italy
- <sup>x</sup> Also at Moscow Institute of Physics and Technology State University, Dolgoprudny, Russia
- <sup>y</sup> Also at section de Physique, Université de Genève, Geneva, Switzerland
- <sup>z</sup> Also at Department of Physics, The University of Texas at Austin, Austin TX, United States of America
- <sup>aa</sup> Also at Institute for Particle and Nuclear Physics, Wigner Research Centre for Physics, Budapest, Hungary
- <sup>ab</sup> Also at International School for Advanced Studies (SISSA), Trieste, Italy
- <sup>ac</sup> Also at Department of Physics and Astronomy, University of South Carolina, Columbia SC, United States of America
- <sup>ad</sup> Also at Faculty of Physics, M.V.Lomonosov Moscow State University, Moscow, Russia
- <sup>ae</sup> Also at Physics Department, Brookhaven National Laboratory, Upton NY, United States of America
- <sup>af</sup> Also at Moscow Engineering and Physics Institute (MEPhI), Moscow, Russia
- <sup>ag</sup> Also at Department of Physics, Oxford University, Oxford, United Kingdom
- <sup>ah</sup> Also at Institut für Experimentalphysik, Universität Hamburg, Hamburg, Germany
- <sup>ai</sup> Also at Department of Physics, The University of Michigan, Ann Arbor MI, United States of America
- <sup>aj</sup> Also at Discipline of Physics, University of KwaZulu-Natal, Durban, South Africa
- <sup>\*</sup> Deceased