

DISSERTATION

The quest for the top squark in semi-leptonic and hadronic final states with the ATLAS Experiment

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*Non sapevo esattamente cosa potesse voler dire scrivere un ritratto e adesso lo so.
C'è un modo di farlo che ha un senso. Poi magari ti può venire meglio o peggio,
ma è una cosa che esiste. Non sta solo nella mia testa.*

Mr Gwyn, Alessandro Baricco

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Introduction

Physicists have always been very interested in studying the fundamental components of matter and in understanding how they interact. The Standard Model of Particle Physics (SM) is the theory that describes the fundamental particles and their interactions. It was developed as a consistent theory based on the principles of quantum mechanics and quantum field theory in the 1960s and 1970s, and experimental measurements confirmed its predictions through the decades, e.g. with the discovery of the W and Z bosons in 1983 [1, 2, 3, 4]. At the end of the twentieth century, the only missing particle needed for the SM to be complete was the Higgs boson. Its search was one of the most important reasons to build a particle collider, the Large Hadron Collider (LHC), that could reach collision energies more than five times higher than those reached until then. Another motivation for the LHC was the search for new particles predicted by theories that extend the SM, especially those predicted by Supersymmetry (SUSY). Despite delivering precise predictions confirmed by experimental measurements, the SM cannot be regarded as the final theory of particle physics since it has in the order of 20 free parameters and does not include a theory of gravity together with the theory of the electroweak and strong interactions. Moreover, the SM has no particle that could be a good candidate for the dark matter of the universe, which is measured by cosmological observations.

Supersymmetry is a very promising extension of the SM which, by introducing a symmetry between bosons and fermions, assigns a partner to each SM particle and introduces additional Higgs bosons. A natural candidate for dark matter is provided by SUSY models where the R-parity is conserved, a condition that is needed to ensure that, as observed experimentally, the proton does not decay on universal time scales. This candidate is the Lightest Supersymmetric Particle (LSP), which should be massive, electrically neutral, and interact only via the weak force. Furthermore, in these scenarios, the SUSY particles are produced in pairs and always decay to an odd number of LSPs.

The LHC started colliding protons at the end of 2009 at a centre-of-mass energy, $\sqrt{s}$, of 900 GeV and 2.7 TeV. During 2010 and 2011 the proton–proton (pp) centre-of-mass collision energy was raised to 7 TeV, and in 2012 the pp collision energy was brought to $\sqrt{s} = 8$ TeV. On the 4th of July 2012 it was announced that the ATLAS and CMS collaborations observed, in the data produced by the LHC pp collisions at $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV, a new particle compatible with the SM Higgs boson and with a mass of about 125 GeV [5, 6]. As more data were analysed, the properties of the new boson were investigated and showed so far no deviations from the SM expectations for the Higgs boson.

The discovery of a Higgs boson with mass of 125 GeV makes the searches for supersymmetric particles even more important. Especially the searches for the supersymmetric partners of the bot-

tom and top quarks, the sbottom and the stop, are of great interest because they are required to be light, i.e. have a mass not larger than about 1 TeV, so that the Higgs boson mass hierarchy problem can be solved.

The focus of this thesis is on two searches for the direct pair production of light stops, one performed with the data recorded by the ATLAS experiment at a centre-of-mass energy of 7 TeV in 2011, the other with the data recorded at $\sqrt{s} = 8$ TeV in 2012. The events that are searched for may contain leptons, have many jets, some of which arising from b -quarks, and have a large amount of missing energy in the transverse plane to the beam axis because of the LSPs, which leave the experiment undetected. These searches are particularly challenging because of the small stop production cross section and the very similar signature of stop events compared to that of pair-produced top-quarks events.

Since the measurement and performance of the missing transverse energy is essential for the search for supersymmetry, a study of the resolution of its Soft component was performed to complete the research work done for this dissertation.

The thesis is structured as follows. The theoretical foundation for the research work is introduced in Chapter 2, where the SM is discussed and its successes and drawbacks are listed, followed by the theory of supersymmetry presented as a possible extension. At the end of the chapter, the phenomenology of hadron-hadron interactions is also briefly discussed and the Monte Carlo event generation is summarised. The LHC and the ATLAS experiment, with its subdetectors and the data acquisition model, are presented in Chapter 3. The role of the Worldwide Computing Grid and the detector simulation algorithms are also discussed. The reconstruction and performance of the physics objects needed in the analyses are described in Chapter 4 for the data recorded at centre-of-mass energies of 7 and 8 TeV. In the next chapter, Chapter 5, as a part of the personal contributions to this thesis, in-depth studies of the resolution of the Soft component of the missing transverse energy and of possible parameterizations to describe it are presented. Then, in the first part of Chapter 6, the programme of the searches for supersymmetry within the ATLAS collaboration is introduced, followed by the elements needed to design and interpret a search for new physics processes. The signal models used in the analyses are introduced, the analysis strategy is explained and the experimental and theoretical uncertainties that affect the searches are presented. Finally, an overview of the statistical methods used to interpret the analysis results is given. A search for direct stop production in final states with jets, b -jets, a lepton and missing transverse energy performed with the data recorded at a centre-of-mass energy of 7 TeV is presented in Chapter 7. This search is optimised for a light stop with mass below or around the mass of the top-quark. Major contributions, within the work for this thesis, are in the optimisation of the method to reconstruct the $t\bar{t}$ semi-leptonic decay, in the estimation of the background processes and the systematic uncertainties associated to them. A second search for the direct pair-production of light stops performed with the dataset recorded at $\sqrt{s} = 8$ TeV is presented in Chapter 8. This analysis targets scenarios where the stop is heavier than the top quark and decays in all-hadronic final states containing jets, b -jets and large missing transverse energy. The contributions to this analysis, within the work for this thesis, are in the optimisation of the analysis sensitivity to models where the stop decays in a top and a neutralino, the design and optimisation of a method to reconstruct the hadronic decay of $t\bar{t}$ pairs, as well as the estimation of the $t\bar{t}$ background contribution. Finally, the summary of the obtained results is given in Chapter 9.

Theory Overview

The theory that describes the elementary particles, their interactions, and the simulation of the interactions at hadron colliders via Monte Carlo techniques are presented in this chapter.

The Standard Model (SM) of particle physics is described in Section 2.1. In particular the particle content of the theory and the fundamental interactions are discussed. Some open questions of the theory are also presented. Supersymmetry (SUSY) is then introduced in Section 2.2 as possible extension of the SM. The focus is on R-parity conserving models and on the properties of the third generation SUSY partners, objects of the searches presented in Chapters 7 and 8. The phenomenology of the interactions at hadron colliders and their modelling with Monte Carlo (MC) techniques are presented in Section 2.3.

2.1 The Standard Model of Particle Physics

The Standard Model of particle physics is the quantum field theory (see for example Ref. [7]) that describes the elementary matter particles and their fundamental interactions. It was developed in the 1960s and 1970s and, since then, experimental measurements confirmed its predictions by discovering the predicted particles and by measuring their properties. The driving factor in building the SM is the connection, given by Noether's theorem, between conservation laws and symmetries of the Lagrangian [8]. The physics laws are invariant under time and space translation giving the conservation of energy and momentum, and under rotation giving the conservation of the angular momentum. These are space-time symmetries, but also internal symmetries exist such as gauge transformations that lead to the conservation of a charge, e.g. the electric charge.

The SM Lagrangian can be written as the sum of five terms, as

$$\mathcal{L}_{\text{SM}} = \mathcal{L}_K + \mathcal{L}_{QCD} + \mathcal{L}_{EW} + \mathcal{L}_Y + \mathcal{L}_H. \quad (2.1)$$

These are a kinetic term $\mathcal{L}_K$, where the kinematics of the matter particles (fermions) is described, the terms where the strong and electroweak interactions are introduced, $\mathcal{L}_{QCD}$ and $\mathcal{L}_{EW}$, the Yukawa term $\mathcal{L}_Y$, which contains the fermion mass expressions, and the Higgs interaction and potential term $\mathcal{L}_H$.

The SM is not regarded as the ultimate theory since it has 19 free parameters and cannot explain the cosmological observation of the energy-matter content of the universe. The free parameters are the fermion masses, the CKM mixing angles and a CP violating phase, the strength of the interaction coupling constants, the QCD vacuum angle, the vacuum expectation value of the Higgs field and the Higgs boson mass.

In the next paragraphs the particles of the SM and their interactions are presented in order to achieve a better understanding of the Lagrangian and of the meaning of its parameters.

In particular the particle content of the SM, differentiating fermions and bosons, is discussed first. Then the different interactions, electromagnetic, strong, and electroweak are presented together with the Higgs mechanism. Finally some open questions of the SM, such as the hierarchy problem and the presence of dark matter in the universe, are introduced.

The information for this summary has been extracted based on the Refs. [7, 9, 10, 11, 12], from which a broader overview of quantum field theories, gauge theories and the SM can be gained.

2.1.1 Particle Content

The particles of the Standard Model are divided primarily in fermions and bosons, based on their spin, and are characterised by quantum numbers. Fermions have half integer spin, in $\hbar$ units, while bosons have integer spin. The fermions are identified as the matter constituents and the bosons as the force carriers.

The known fermions are divided in two classes depending on the interactions they are sensitive to. These are leptons and quarks, where leptons do not interact via the strong force. Both leptons and quarks have six members, subdivided in three generations or families. The two particles belonging to each generation have a relative electric charge difference of one, in units of the electron charge e , and particles of a higher generation are heavier than their corresponding particles in a lower one. The fermion generations, their electric charge and interactions are summarised in Table 2.1.

Particle Type	1 st Gen.	2 nd Gen.	3 rd Gen.	Charge (Q/e)	Interactions
Leptons	ν_e	ν_μ	ν_τ	0	weak
	e	μ	τ	-1	electromagnetic and weak
Quarks	u	c	t	$+2/3$	electromagnetic, weak and strong
	d	s	b	$-1/3$	

Table 2.1: The SM fermions: leptons and quarks divided in three generations, their electric charges and interactions.

The lepton generations are formed by a neutrino with zero electric charge, that interacts only via the weak force, and a charged lepton with $Q/e = -1$, that interacts both via the electromagnetic and the weak force. The quantum number that identifies leptons is the *lepton flavour*, which is conserved separately for the three generations in electroweak interactions, and assumes the value +1 for leptons, and -1 for anti-leptons. In the SM neutrinos are assumed to be massless. However, at the end of the 1990s and begin of the 2000s neutrino oscillations were observed [13, 14, 15, 16, 12] giving evidence that also neutrinos have a mass, even if very small. In the following, the SM ansatz is pursued, since for the scope of this work neutrino masses do not play any role; in general the masses of the presented particles are taken from Ref. [12].

The electron, e , with a mass of 511 keV, and the electron neutrino, ν_e , are the leptons of the first generation. The second generation is composed by the muon, μ , with mass of 105.66 MeV, and its neutrino ν_μ . Finally the tau lepton, τ , with mass of 1.78 GeV, and its neutrino, ν_τ , form the third generation. While the electron and the muon were discovered at the end of the nineteenth century and in 1936, the tau lepton was discovered in 1975 [17]. Analogously, the electron neutrino was discovered in 1956 and in 1962 it was observed that the muon neutrino is a different particle than ν_e , whereas the tau neutrino was first observed in 2000 [18].

The quarks have fractional electric charge, the up-type quarks (u, c, t) have charge $+\frac{2}{3}e$ and the down-type quarks (d, s, b) $-\frac{1}{3}e$. They interact via the electromagnetic, weak and strong forces. Each quark has an own flavour quantum number that is conserved in strong interactions and violated in weak interactions. The up, u , and the down, d , quarks belong to the first quark generation and have a mass of few MeV. The charm, c , and the strange, s , quarks are the second generation quarks with masses of 1.3 GeV and of order of 100 MeV, respectively. Finally, the quarks of the third generation are the top, t , and the bottom, b , that have masses of 173 GeV and 4.2 GeV. The bottom quark was discovered in 1977 at Fermilab [19] while the top quark was discovered in 1995 by the CDF and D0 collaborations at Tevatron [20, 21]. Due to its very short lifetime of about 5×10^{-25} s, which is shorter than the strong force typical interaction time of 10^{-23} s, no top bound states can be observed, and it can then decay through weak interaction essentially only in a W boson and a b quark.

The bosons of the SM are summarised in Table 2.2 with the information about the interaction they mediate, their mass, their electric charge and the coupling strength of the force they are mediating at an energy corresponding to the Z boson mass. The mediators of the electromagnetic, weak and strong forces are vector bosons (spin $s = 1$), while the SM Higgs boson is a scalar particle.

Interaction	Mediator	Mass (GeV)	Charge (Q/e)	Coupling Strength at $m(Z) = 91.2$ GeV
Electromagnetic	Photon (γ)	0	0	$1/127.94 \sim 10^{-2}$
Weak	$\begin{pmatrix} W^\pm \\ Z \end{pmatrix}$	$\begin{pmatrix} 91.1876 \pm 0.0021 \\ 80.385 \pm 0.015 \end{pmatrix}$	$\begin{pmatrix} \pm 1 \\ 0 \end{pmatrix}$	$\sim 1/29.5 \sim 0.034$
Strong	8 gluons (g)	0	0	0.1185 ± 0.0006
Mass	Higgs (H)	125.4 ± 0.4	0	

Table 2.2: The SM bosons are summarised together with the force for which they act as mediators, their mass - taken from the 2014 PDG review [12] - their electric charge and their coupling strength at $m(Z) = 91.2$ GeV.

The photon, γ , is massless, mediates the electromagnetic interaction and it is its own antiparticle. The mediators of the weak force are the $W^\pm$ and the Z^0 bosons. The W bosons have an electric charge of ± 1 and are each other's antiparticle; the Z boson has zero electric charge and is its own antiparticle. They were discovered in 1983 at the UA1 and UA2 experiments at the SPS at CERN [1, 2, 3, 4], while their interaction strength with fermions and the mass of the Z boson were determined precisely at the LEP experiments in the 1990s. The current world average is 80.385 ± 0.015 GeV for the W boson mass, and 91.1876 ± 0.0021 GeV for the Z boson mass [12]. The weak vector bosons can interact among themselves and the $W^\pm$ bosons can interact also with the photon.

The gluons, g , are the massless mediators of the strong force. They exchange the *colour charge* and, being themselves colour charged, trilinear and quartic self couplings are allowed.

Finally, the Higgs boson is the mediator of the field that, through the Higgs mechanism, gives masses to the vector bosons and to the fermions. It was the last missing particle of the SM and was discovered in 2012 by the ATLAS and CMS collaborations [5, 6]. The most recent values of its mass are $m_H = 125.36 \pm 0.37(\text{stat}) \pm 0.18(\text{syst})$ GeV as measured by the ATLAS experiment [22], and $m_H = 125.02^{+0.26}_{-0.27}(\text{stat})^{+0.14}_{-0.15}(\text{syst})$ GeV as measured by CMS experiment [23].

2.1.2 Particle Interactions

The Lagrangian for a free fermion can be written, from the Dirac equation of motion for spin-1/2 particles, as

$$\mathcal{L}_{\text{free}} = \bar{\psi}(i\gamma_\mu\partial^\mu - m)\psi. \quad (2.2)$$

Here ψ is the spinor representing the matter field, $\bar{\psi}$ is its spinorial adjoint, γ_μ , with $\mu = 0, 1, 2, 3$, are the four Dirac γ matrices, and m is the mass of the fermion.

The SM is based on the $\text{SU}_C(3) \times \text{SU}_L(2) \times \text{U}_Y(1)$ gauge symmetry structure.

$\text{SU}_C(3)$ is the symmetry group that governs the strong interaction, mediated by the gluons, $\text{SU}_L(2) \times \text{U}_Y(1)$ is the symmetry group of the electroweak interaction, which is mediated by the photon and the $W^\pm$ and Z bosons.

The mass term, as written in the free particle Lagrangian, is not invariant under transformations of the $\text{SU}_L(2) \times \text{U}_Y(1)$ symmetry group of the electroweak interactions. This is the reason why the Higgs mechanism and the Yukawa couplings have to be introduced in order to have fermions with a non-zero mass in the SM Lagrangian.

Electromagnetic Interaction

The quantum field theory of electromagnetic interactions is quantum electrodynamics (QED). It can be obtained from classical electrodynamics by quantising the Maxwell equations for the electric and magnetic fields.

QED can be considered as the prototype of gauge-interaction theories. Its internal symmetry is $\text{U}_Q(1)$, which gives a local gauge invariance with the electric charge as the quantity conserved.

To obtain the QED Lagrangian, the free-particle Lagrangian of equation 2.2, which is invariant under global gauge transformations of the Dirac field $\psi \rightarrow e^{i\alpha}\psi$, has to be transformed to become invariant under local gauge transformations of the form $\psi \rightarrow e^{i\alpha(x)}\psi$.

To promote the global gauge invariance of the Lagrangian to a local gauge invariance with $\alpha = \alpha(x)$, a gauge field A_μ has to be introduced, which couples to the Dirac field with a strength proportional to its charge q . The partial derivative can be then transformed in a covariant derivative containing the field A_μ , $\partial_\mu \rightarrow D_\mu = \partial_\mu - iqA_\mu$, and the local gauge invariance can be achieved.

The field A_μ can be identified with the photon by adding a kinetic term $F_{\mu\nu}F^{\mu\nu}$ for the field A_μ to the Lagrangian, where $F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$.

The QED Lagrangian has, thus, the form:

$$\mathcal{L}_{\text{QED}} = \mathcal{L}_{\text{free}} + e\bar{\psi}\gamma_\mu A^\mu\psi - \frac{1}{4}F_{\mu\nu}F^{\mu\nu}, \quad (2.3)$$

where the second term represents the interaction of the field A_μ with the Dirac field ψ of charge e , electric charge of the electron, and the third term represents the photon kinetic energy.

As introduced above, the coupling strength of the field A_μ with a fermion spinor ψ is proportional to the electric charge of the electron e . In natural units, the relation $e = g_e = \sqrt{4\pi\alpha}$ between e and the fine-structure constant α can be written, and α can be then regarded as the QED coupling constant.

The photon–fermions vertex is shown in Fig. 2.1 using the Feynman diagram technique¹ with the convention that the time flows from left to right. Here the strength of the interaction vertex is highlighted.

¹ Feynman diagrams permit to depict particle interactions and associate to each line and vertex a mathematical expression, given by the Feynman rules, that is then used e.g. in cross section computations. The rules on how to work and compute processes with Feynman diagrams can be found e.g. in Ref. [7].

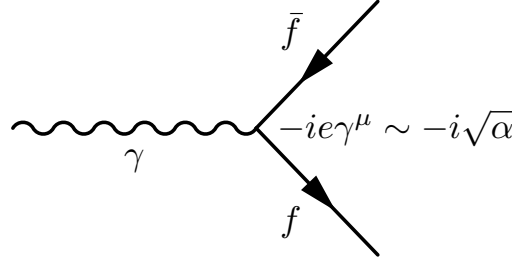


Figure 2.1: QED vertex

Strong Interaction

Quantum Chromodynamics is the theory that describes strong interactions. Its gauge symmetry group is $SU_C(3)$ which introduces colour as a new quantum number. The colour states are three, red, green and blue. There are eight generators of the group, which are represented by the Gell-Mann λ^a matrices. This means that there are eight mediator vector bosons, identified with the gluons, which are massless and carry a colour charge. Since the gluons are “coloured”, trilinear and quartic gauge self couplings are possible. Both the colour charge and the quark flavour are conserved in strong interactions.

QCD has a coupling strength which is small at high energies, or equivalently at short distances, and that increases at low energies (large distances). This behaviour can be modelled by a potential of the form

$$V_{QCD} = -\frac{a}{r} + br, \quad (2.4)$$

where r is the distance between two particles interacting via the strong force. The first term dominates at small distances and the parameter a is proportional to the strong coupling constant α_s , whereas the second term dominates at large distances. This behaviour gives, on one side, the QCD asymptotic freedom observed at high energy, which makes it possible to describe high energy QCD with perturbation theory and have solid predictions, and, on the other side, colour confinement, which is responsible for the fact that no free coloured states exist.

In the energy regime where perturbative QCD (pQCD) can be used, the predictions are obtained as a function of the strong coupling constant α_s . Since the strength of the strong interaction varies with the energy of the process under study, $\alpha_s(\mu_R^2)$ is defined as a renormalisable quantity which depends on the energy scale μ_R used for its renormalisation. This unphysical energy scale is generally chosen to be similar to the scale of the momentum transfer Q of the studied interaction. This dependence on an energy scale gives the so-called running of the strong coupling constant.

The formula of the strong running coupling constant $\alpha_s(Q^2)$ at the first order of perturbation theory is given by

$$\alpha_s(Q^2) = \frac{\alpha_s(\mu^2)}{1 + \frac{\alpha_s(\mu^2)}{12\pi} (11n_c - 2n_f) \ln \frac{Q^2}{\mu^2}}, \quad (2.5)$$

where Q is the energy scale at which α_s is computed, μ is a reference scale for which the value of α_s is known, n_c is the number of the colours of the model (three in the SM), and n_f is the number of flavours taking part in the interaction, which depends on the interaction energy itself and in the SM can be up to six for energies above that of the top-quark mass. The Z boson mass is often taken as the reference scale μ , where the world average value of $\alpha_s(M_Z^2) = 0.1185 \pm 0.0006$ is obtained [12].

By defining $\Lambda_{QCD} \sim 200$ MeV as the typical QCD energy scale where the strong coupling constant diverges, the running of α_s can be rewritten as

$$\alpha_s(Q^2, \Lambda_{QCD}^2) = \frac{12\pi}{(11n_c - 2n_f) \ln \frac{Q^2}{\Lambda_{QCD}^2}}. \quad (2.6)$$

With the running of α_s written in this form, it can be easily seen that α_s becomes large for energy scales of the order of Λ_{QCD}^2 . The regime known as asymptotic freedom is, instead, reached for an energy scale Q^2 much larger than Λ_{QCD}^2 where α_s becomes small.

The Feynman diagram of the gluon–quarks QCD vertex is drawn in Fig. 2.2 with the coupling strength of the vertex. The colour of the depicted states is also given in a simplified way.

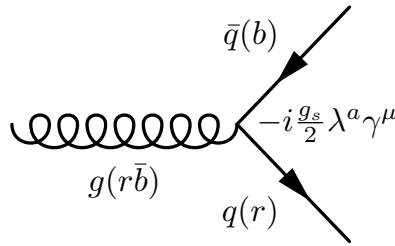


Figure 2.2: Gluon-quarks QCD vertex with colour exchange

The phenomenology of proton–proton scattering, necessary to have an understanding of the interactions at hadron colliders, is presented in Section 2.3.

Electroweak Interaction

The theory of electroweak (EW) interactions is the underlying theory that includes as low energy limits QED and the theory of weak interactions. The theory of weak interactions evolved from the Fermi effective field theory of β decay. It is the only interaction that also involves neutrinos, it was found to violate parity, and is a short range interaction because of the large mass of its mediators, the $W^\pm$ and Z^0 vector bosons.

The symmetry group of charged current processes, which are mediated by the W bosons, is $SU_L(2)$, where L stands for left, to indicate that the interaction involves only the left-handed fermion component and does not transform their right-handed component.

The left, ψ_L , and right, ψ_R , chiral components of a fermion spinor $\psi = \psi_L + \psi_R$ can be defined as

$$\psi_{L/R} = \frac{1}{2} (1 \mp \gamma^5) \psi, \quad (2.7)$$

where γ^5 is the matrix $\gamma^5 = i\gamma^0\gamma^1\gamma^2\gamma^3$.

Charged current interactions transform the elements of weak isospin doublets into each other. The weak isospin, τ_3 , is a new quantum number, which is conserved in weak interactions. Considering the leptons, the weak isospin doublet of the first generation is composed by electron-neutrino and electron, with the neutrino having $\tau_3 = +1/2$, and the electron $\tau_3 = -1/2$. The same scheme can be applied to the other lepton generations and also to the quark families, which means that an up-type quark can be transformed into a down-type quark violating the quark flavour quantum number.

The W boson–fermions vertex and its coupling strength can be seen in Fig. 2.3a, where $g_W = \sqrt{4\pi\alpha_W}$ is the weak coupling strength of the W boson defined, through the Fermi constant G_F , as

$$\frac{G_F}{\sqrt{2}} = \frac{g_W^2}{8m_W^2}, \quad (2.8)$$

with $G_F = 1.166 \times 10^{-5} \text{ GeV}^{-2}$ and m_W being the mass of the W boson.

The EW - or GWS - model was proposed in the 1960s by Glashow, Weinberg and Salam [24, 25, 26]. The symmetry group describing this interaction is $SU_L(2) \times U_Y(1)$ where Y is the hypercharge defined in relation to the electric charge of the fermion Q , in units of e , and its weak isospin τ_3 as

$$Q = \tau_3 + \frac{Y}{2}. \quad (2.9)$$

The gauge vector bosons of the $SU_L(2)$ group are the W_μ^a , $a = 1, 2, 3$ bosons, which belong to an isospin vector. B_μ^0 is the gauge boson of the $U_Y(1)$ group, which is an isospin scalar. The W_μ^a bosons transform only the left handed component of fermions, while B_μ couples to both the left- and the right-handed component.

The W_μ^a and B_μ^0 bosons couple to the fermions with coupling strengths g and g' , respectively, and they are massless in order to keep the theory invariant under gauge transformations. The gauge-boson mass terms can then be added through the Higgs mechanism, as described in the next subsection, and since the W_μ^a bosons interact only with left-handed fermion states, the classical fermion mass term $m\bar{\psi}\psi$, which is not invariant under the $SU_L(2)$ transformations, cannot appear in the SM Lagrangian.

The $W^\pm$ bosons are obtained as linear combination of W_μ^1 and W_μ^2 , which have $\tau_3 = \pm 1$, as

$$W_\mu^\pm = \frac{1}{\sqrt{2}} (W_\mu^1 \mp iW_\mu^2). \quad (2.10)$$

The two gauge bosons with $\tau_3 = 0$, W_μ^3 and B_μ^0 , mix to give the real fields propagators Z_μ^0 and A_μ , defined as

$$\begin{pmatrix} Z_\mu^0 \\ A_\mu^0 \end{pmatrix} = \begin{pmatrix} \cos \theta_w & -\sin \theta_w \\ \sin \theta_w & \cos \theta_w \end{pmatrix} \begin{pmatrix} W_\mu^3 \\ B_\mu^0 \end{pmatrix} \quad (2.11)$$

where θ_w is the weak mixing angle (or Weinberg angle) defined by $\sin^2 \theta_w = 0.23155 \pm 0.00005$ [12].

Since the Z boson is a mixture of the W_μ^3 and B_μ^0 bosons, it interacts with both the left- and right-handed fermion components. This gives a more complicated expression of the coupling strength of the vertex with respect to the W boson–fermions vertex. The Feynman diagram of the Z boson–fermions vertex is shown in Fig. 2.3b. The parameters $c_{V/A}^f$ depend on the fermion coupling to the boson and g_Z , the Z coupling strength, relates to g_W as

$$g_Z = \frac{g_W}{\cos \theta_w}. \quad (2.12)$$

By imposing the condition that the coupling strength of the photon with fermions is e , the relation between the couplings g , g' , e and the weak mixing angle

$$g \sin \theta_w = g' \cos \theta_w = e \quad (2.13)$$

can be obtained.

The fermion eigenstates of the electroweak interaction differ from the mass eigenstates. These are defined for each lepton generation as an isospin doublet, formed with the left-handed fermions, and a right-handed isospin singlet, which exists only for the charged leptons.

Considering the quark sector, the electroweak eigenstates of the down-type quarks are a mixture of the d , s , and b quarks according to the mechanism explained first by Cabibbo [27], for the first two quarks generations, and then extended by Kobayashi and Maskawa [28]. The transition probability coefficients V_{ij} , with $i = u, c, t$ and $j = d, s, b$, which define the down-type quarks admixtures, are collected in the CKM matrix. The probability of the quark of flavour i to decay in the quark of flavour j is, hence, given by $|V_{ij}|^2$. So, for example, the down-quark eigenstate of the electroweak interaction is defined as $d' = V_{ud} \cdot d + V_{us} \cdot s + V_{ub} \cdot b$. The CKM matrix contains also a small CP violating phase that can explain the CP violation observed in the kaon system [29].

As for the leptons, the quark electroweak eigenstates are defined as isospin doublets, formed with the left-handed quarks, and isospin singlets for the right-handed one. The down-type quarks are, though, defined by their admixture d' , s' , and b' given by the CKM matrix.

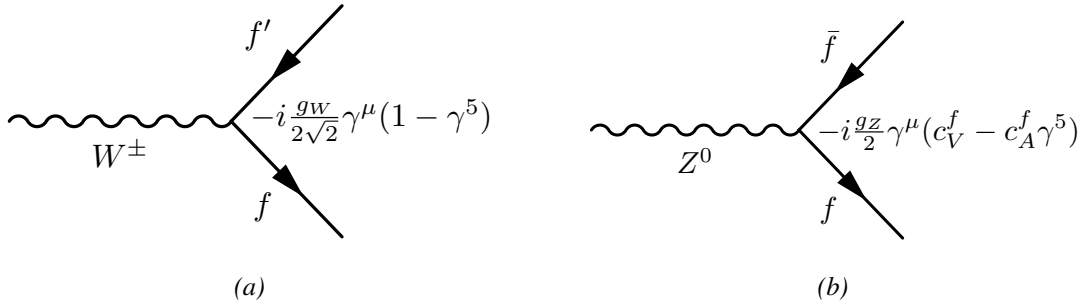


Figure 2.3: Weak interaction vertices with fermions, (a) charged current mediated by the W boson, (b) neutral current mediated by the Z boson.

The Higgs Mechanism

The Higgs mechanism was proposed in 1964, almost simultaneously, by six theorists: Higgs, Brout and Englert, and Guralnik, Hagen and Kibble [30, 31, 32, 33]. This mechanism, through the spontaneous breaking of the $SU(2)$ symmetry, introduces a massive scalar boson in the theory, the Higgs boson, and gives mass to the vector bosons but keeps the theory renormalisable [34]. The Higgs boson had been, for almost fifty years, the most important missing piece to make the SM a complete theory consistent with the experimental observation of the masses of fermions and vector bosons.

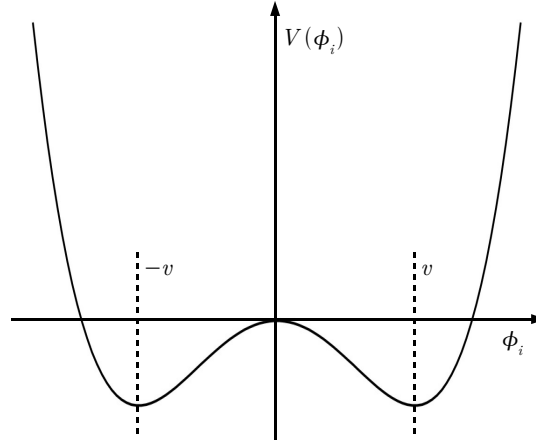
The Lagrangian associated to the Higgs field ϕ , a $SU(2)$ doublet of complex scalar fields, is

$$\mathcal{L}_H = (D_\mu \phi)^\dagger (D^\mu \phi) - V(\phi^\dagger \phi), \quad (2.14)$$

where the first term gives the kinetic energy of the field and its interaction with the $SU_L(2)$ and $U_Y(1)$ vector bosons of the GWS theory, and the second term is the Higgs potential.

The terms of the Higgs Lagrangian can be written explicitly as

$$\begin{cases} D_\mu \phi = \left(i\partial_\mu - g\tau_a W_\mu^a - \frac{Y}{2} g' B_\mu \right) \phi \\ V(\phi^\dagger \phi) = -\mu^2 (\phi^\dagger \phi) + \lambda (\phi^\dagger \phi)^2 \end{cases} \quad (2.15)$$


 Figure 2.4: Higgs potential for a field ϕ_i , with stable minima at $\pm v$

In order to have the right sign for the mass term in the potential both μ^2 and λ are set to be positive. The typical form of the Higgs potential is shown in Fig. 2.4 as a one-dimensional projection for the component i of the Higgs field ϕ .

Considering the component ϕ_i of the Higgs field, the value of the minima of the potential can be extracted by computing its first derivative with respect to ϕ_i and by requiring it to vanish. The value that is obtained for the minima is $\pm |\phi_0| = \pm v = \pm \sqrt{\frac{\mu^2}{\lambda}}$ and the symmetry of the Lagrangian is spontaneously broken when one of the possible minima is explicitly chosen. A sensible choice for the field ϕ and for the breaking of the symmetry is then given by

$$\phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} \phi_1 + i\phi_2 \\ \phi_3 + i\phi_4 \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ |\phi_0| + h(x) \end{pmatrix} = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + h(x) \end{pmatrix}, \quad (2.16)$$

where ϕ^+ and ϕ^0 are the two complex scalar fields belonging to the Higgs SU(2) doublet, and $h(x)$ is the variation of the field, after the spontaneous symmetry breaking, with respect to its minimum found in v . The minimum energy state $\phi_0 = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix}$ is the ground state of the Higgs field and v is its *vacuum expectation value* (VEV).

After the spontaneous symmetry breaking, the masses of the vector bosons can be extracted by computing the interaction terms between the Higgs field and the $W^\pm$, Z^0 and γ bosons at the minimum of the Higgs potential. This gives for the W boson $m_W = g \frac{v}{2}$, and for the Z boson, identified as $Z_\mu^0 = \frac{1}{\sqrt{g^2 + g'^2}} (g' W_\mu^3 + g B_\mu)$ - see equations 2.11 and 2.13, $m_Z = \sqrt{g^2 + g'^2} \frac{v}{2}$, while it is found that, also after the symmetry breaking, the photon field remains massless.

The combination of these results gives the relation between the W and Z boson masses and the weak mixing angle:

$$\frac{m_W}{m_Z} = \frac{g}{\sqrt{g^2 + g'^2}} = \cos \theta_w. \quad (2.17)$$

Moreover, by replacing the mass of the W boson as a function of v in equation 2.8 it is possible to

extract the value of the vacuum expectation value as $v = (\sqrt{2}G_F)^{-1/2} \simeq 246$ GeV. The mass of the Higgs boson is found to be $m_H = \sqrt{2}\mu = \sqrt{2}\lambda v$. The fact that it is non-zero means that the Higgs boson itself couples to the Higgs field.

To introduce the fermion mass terms, the so-called Yukawa couplings have to be also introduced. The electron mass term in the Lagrangian takes the form of $-\lambda_e \bar{E}_L \cdot \phi e_R + \text{hermitian conjugate}$, where E_L is the SU(2) electron doublet, e_R is the SU(2) right handed electron singlet, and λ_e is the dimensionless parameter that represents the Yukawa coupling for the electron. By computing this term at the minimum of the Higgs potential one gets $m_e = \frac{1}{\sqrt{2}}\lambda_e v$. The masses for the muon and tau leptons, as well as those for the quarks, can be extracted analogously.

The couplings of the Higgs boson are shown in Fig. 2.5 for the interaction vertices with the W and Z bosons, with fermions, and with itself. The strength of the coupling is proportional to the mass of the particle interacting with the Higgs boson, i.e. the heavier the particle, the stronger its coupling to the Higgs boson.

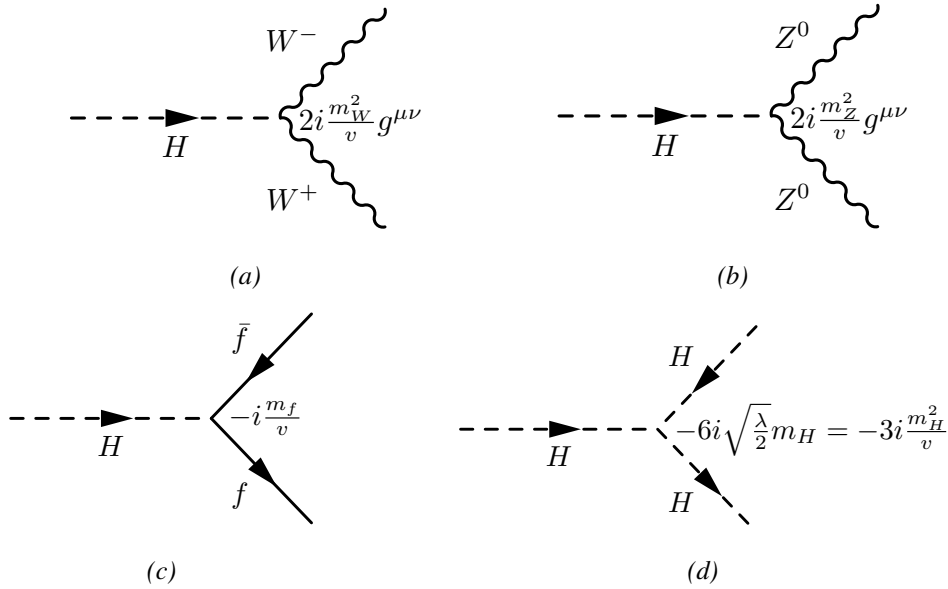


Figure 2.5: Higgs interaction vertices with bosons (a) for the $W^\pm$ and (b) for the Z^0 , fermions (c) and itself (d). The strength of the coupling at the vertex is shown.

2.1.3 Open Questions of the Standard Model

Despite being able to give very precise predictions of the processes it describes, the SM cannot explain a number of observations and has some theoretical limitations. The main phenomena that have no explanation in the SM are the presence of dark matter and dark energy in the universe which contribute to 95% of its energy-mass content - see e.g. Refs. [35, 36] and references therein, the matter anti-matter asymmetry, and the masses of the neutrinos. Moreover, within the SM the Higgs mass hierarchy problem cannot be solved, the coupling constants of the strong, weak and electromagnetic interactions do not unify at any energy scale, and a quantum description of gravity, that has only a classical description provided by Einstein's theory of general relativity [37], is not included.

In the following paragraphs only the SM problems that can be solved by extending it with a super-

symmetric model, see Section 2.2, are described in more details. These are the lack of a force unification within the SM, the Higgs mass hierarchy problem and the presence of dark matter in the universe.

Forces Unification

The SM can explain very well the particle physics processes up to the 100 GeV – 1 TeV scale. Since the electromagnetic and the weak interaction unify at a scale of 100 GeV, one could try to achieve also a unification of the electroweak and strong forces. This should happen possibly at a lower energy than the Planck mass scale, $M_P = 10^{19}$ GeV, i.e. before the gravitational effects among elementary particles become of the same order of magnitude of the effects of the electroweak and strong interactions.

The running of the inverse of the coupling constants of the fundamental interactions is shown as a function of the interaction energy in Fig. 2.6, on the left for the SM and on the right for a minimal supersymmetric extension of the Standard Model, see Section 2.2.1. In the figures the three coupling constants shown are α_1 for the $U_Y(1)$ symmetry group, α_2 for the $SU_L(2)$ symmetry group, and α_3 for the $SU_C(3)$ symmetry group.

It can be observed that in the SM no unification of the coupling constants can be achieved, while this can be realised at a scale of about 10^{16} GeV if the SM is extended to include supersymmetric particles, which are connected to the SM ones via a new symmetry between fermions and bosons.

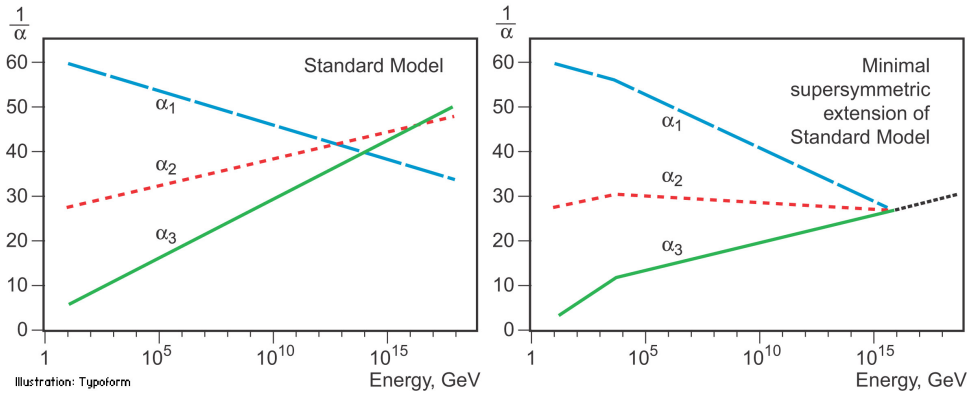


Figure 2.6: Running of the coupling constants in the SM and in a minimal supersymmetric extension of the SM. In this figure α_1 represents the coupling constant of the $U_Y(1)$ group, α_2 the one of $SU_L(2)$ and α_3 the one of $SU_C(3)$ [38].

Hierarchy Problem

In the previous section the mass of the Higgs boson was given in relation to the parameters of the Higgs potential. The value $m_H = \sqrt{2}\mu = \sqrt{2\lambda} v$ is, however, only the tree level prediction. In order to have a result with higher precision, the radiative corrections to the squared mass parameter μ^2 have to be computed. These contributions are divergent and the introduction of a cutoff scale is needed to remove the infinities.

The first order loop corrections diagrams to the μ^2 parameter, that can give such divergences, are shown in Fig. 2.7 for a fermionic and a scalar particle loop.

The value of the μ^2 mass parameter can be written as the sum of the tree level contribution μ_0^2 and of the first order corrections due to scalar and fermionic particles as

$$\mu^2 = \mu_0^2 - \frac{\lambda_s}{16\pi^2} \Lambda_c^2 + \frac{\kappa y_f^2}{8\pi^2} \Lambda_c^2, \quad (2.18)$$



Figure 2.7: Loop corrections to the Higgs mass parameter from a fermion (a) and from a scalar (b) [39].

where λ_s is the coupling of the Higgs boson with the scalar particle, y_f is the Higgs boson Yukawa coupling with the fermion, κ is the colour factor parameter that takes the value $\kappa = 1$ for leptons and $\kappa = 3$ for quarks, and Λ_c is the cutoff scale.

The cutoff scale can be identified with the scale up to which the SM theory is valid. Above this scale new physics processes should be seen and the upper bound for Λ_c is the Plank mass. If new particles are indeed observed at a scale Λ_c this scale becomes a real physics scale. If these particles interact with the Higgs field, they will give contributions to its mass parameter of the type presented above, with sign dependent on them being scalar or fermionic particles.

From the Higgs boson discovery at the ATLAS and CMS experiments, it is known that $m_H \simeq 125$ GeV. This means that μ^2 is of the order of $(100 \text{ GeV})^2$. In order for the radiative corrections to be cancelled, the only solution would be to have a bare mass $\mu_0^2 \sim \Lambda_c^2$. If the choice $\Lambda_c = 10^{16}$ GeV is made, taking this as the possible grand unification scale, relative cancellations at the level $m_H^2/\Lambda_c^2 = 10^4/10^{32} = 10^{-28}$ are required, which does not seem to be very natural.

What can be noted is that the corrections from fermion loops have an opposite sign with respect to those from scalar loops. If scalar particles would exist with a similar mass as those of the SM fermions, there would be a natural compensation of the terms for every Λ_c , and the problem of unnatural large cancellations would be overcome.

Dark Matter

The amount of baryonic matter, originating from the Standard Model fermions, measured by cosmological observations sums up to about 5% of the total energy-matter content of the universe [35, 36, 12, 40, 41, 42]. The remaining energy is split in dark energy and dark matter (DM), with contributions of about 69% and 26% respectively. Dark energy is needed to explain the expansion of the universe and very little is known about its origin and properties. Dark matter must be composed by massive and only weakly interacting particles, that are also required to be stable on cosmological time scales.

The first evidence of the presence of dark matter in the universe came from the measurement of the rotation curves of the galaxies. It was found that the rotation velocity is constant with the distance from the galaxy center, instead of decreasing. This hints at the presence of a halo of non electromagnetically interacting matter with mass distribution $M(r) \propto r$, where r is the distance from the center of the galaxy. In the SM the only particles that could be dark matter candidates are the neutrinos, which have, however, a too low energy density to explain the total amount of estimated dark matter. It has been calculated that they can, at most, contribute to 5% of the measured dark matter density.

The most compelling candidates for dark matter are the weakly interacting massive particles (WIMPs). Many direct and indirect searches for these particles have been performed and are ongoing at hadron colliders and at dedicated experiments. The coverage of past direct dark matter detection experiments and the sensitivity of future detectors are shown in Fig. 2.8 where the limits on the WIMP–nucleon

scattering cross section are shown as a function of the mass of the WIMP, and the preferred areas for different theory models are also shown [43]. The results are shown for experiments that are designed to detect the interaction of dark matter with SM particles in cases where their spin orientation does not affect the scattering amplitude. Large areas of the parameter space have been already excluded for WIMP particles with mass above 10 GeV and for WIMP–nucleon scattering cross sections above 10^{-8} pb. Even though some experiments, e.g. the DAMA experiment at the Gran Sasso national laboratories, observed hints of dark matter signals in their searches [44] - shaded closed contours in the figure - no confirmation of an observation of DM particles could be claimed, so far, by any collaboration. Future direct DM detection searches are expected to extend the sensitivity to lower WIMP–nucleon scattering cross sections and to WIMP masses below 10 GeV. The sensitivity of some proposed experiments is already expected to be limited by the neutrino scattering background.

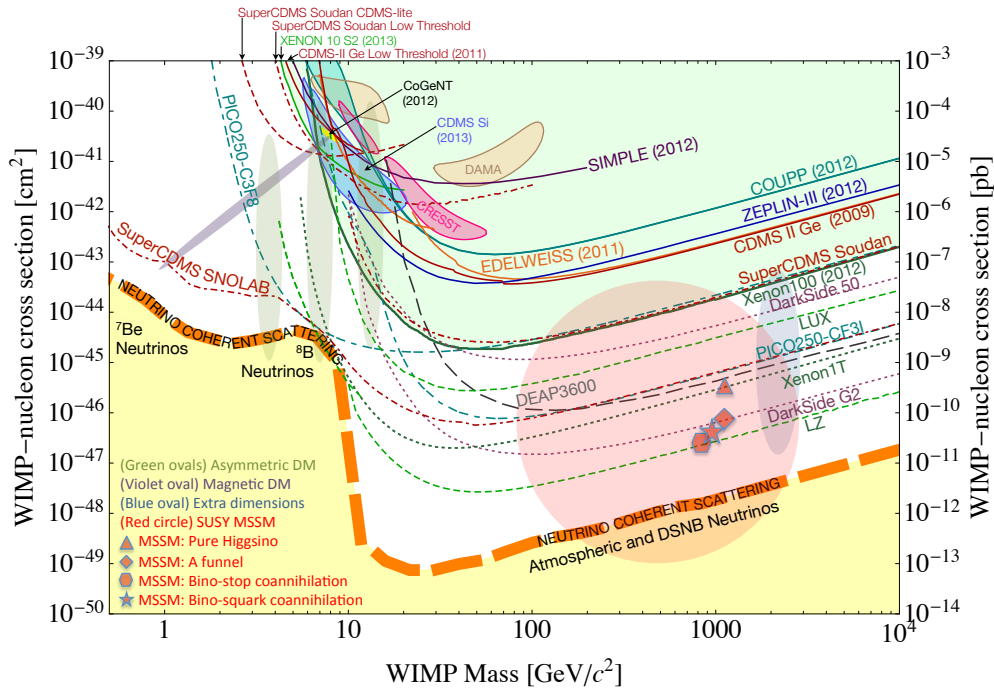


Figure 2.8: Cross section limits for WIMP–nucleon spin independent searches as a function of the WIMP mass. The solid lines represents the limits set by the experiments, the shaded contours represents the areas where hints of dark matter signal were observed, and the dashed lines are the projections of the sensitivity of future experiments. The shaded areas are drawn to show the preferred WIMP mass and cross section in different dark matter theory models. The neutrino coherent scattering contour represents the limit for which the experimental sensitivity to WIMPs will be strongly affected by the neutrino scattering background [43].

2.2 Supersymmetry

In this section supersymmetry, and in particular the minimal supersymmetric Standard Model (MSSM), is introduced. A more complete description, as well as the mathematical derivation of the SUSY prop-

erties and Lagrangian, can be found in Refs. [39, 45].

Some of the problems and inconsistencies presented in the previous section can have a simple and elegant solution if the SM is extended by introducing a new symmetry. Supersymmetry establishes a transformation that relates fermions and bosons. Its generator Q is an anti-commuting spinor, i.e. a spin-1/2 object, that transforms each SM fermion in a boson and vice versa:

$$\begin{aligned} Q|\text{Fermion}\rangle &\propto |\text{Boson}\rangle \\ Q|\text{Boson}\rangle &\propto |\text{Fermion}\rangle \end{aligned} \quad (2.19)$$

The commutation and anti-commutation rules satisfied by the supersymmetry generator Q and its hermitian conjugate $Q^\dagger$ are presented in equation 2.20. In particular, the first condition relates Q and $Q^\dagger$ with the generator of time and space translations P^μ .

$$\begin{cases} \{Q, Q^\dagger\} = P^\mu \\ \{Q, Q\} = \{Q^\dagger, Q^\dagger\} = 0 \\ [P^\mu, Q] = [P^\mu, Q^\dagger] = 0 \end{cases} \quad (2.20)$$

The particles are organised in supermultiplets which contain the same number of fermionic and bosonic degrees of freedom, $n_F = n_B$. The fermions and bosons belonging to a supermultiplet can be transformed one into the other by a linear combination of the generators Q and $Q^\dagger$. From the commutation of the SUSY generators with P^μ , follows the commutation with the mass operator P^2 , therefore all the particles in a supermultiplet are mass degenerate. They also have the same quantum numbers under the SM gauge transformations $SU_c(3) \times SU_L(2) \times U_Y(1)$, since the generators of these groups also commute with the SUSY generators. Given these conditions, to each SM particle a supersymmetric partner is assigned, which shares the same supermultiplet and the same quantum numbers up to the 1/2 unit of spin difference.

The possible supermultiplets are summarised below. Instead of using the Dirac spinor representation, the Weyl chiral representation is chosen for the fermionic states and for the operators Q and $Q^\dagger$.

- A *chiral or Weyl supermultiplet* contains one fermion with two helicity states ($n_F = 2$) and two real scalar bosons that can be written as a single complex scalar field. Left handed Weyl spinors are used to represent the chiral supermultiplets, therefore for the right handed particles their conjugate is chosen as fundamental representation.
- A *gauge supermultiplet* contains a vector boson (spin-1), which has to be massless before spontaneous symmetry breaking and has, hence, two bosonic degrees of freedom, and a massless fermion (spin-1/2) which has the same gauge transformations for the left and the right handed component.
- If the gravity is included with the spin-2 graviton as gauge boson, which has two degrees of freedom, its supermultiplet contains the massless spin-3/2 gravitino as superpartner.

The naming convention used for the supersymmetric particles is:

- *Partners of the SM fermions* are spin-zero particles called scalar fermions or *sfermions*. In general a “s” is added as a prefix to the name of the SM fermion to indicate its SUSY partner.
- *Partners of the SM bosons* are spin-1/2 particles and their name is built from the SM name by adding the suffix “ino”, so that the gauge boson partners are the gauginos and the Higgs boson partners the Higgsinos.

The symbol used to identify SUSY particles is the tilde: the partner of a left handed SM fermion f_L is $\tilde{f}_L$, and analogously the partner of a SM boson B is $\tilde{B}$.

The SUSY particles interact via the electroweak and strong forces as their SM partners. In particular this means that only the scalar partners of the left-handed fermions interact with the partners of the $W^\pm$ bosons. Since the handedness is an ill-defined quantity for scalar particles, a left-handed sfermion indicates simply the partner of a left-handed fermion and has no further connections to the original chirality.

In supersymmetric theories at least two Higgs doublets are needed to give mass to the up- and down-type quarks and charged leptons and to keep the theory renormalisable. The Higgs doublets are embedded in chiral supermultiplets, where the Higgsinos are left-handed $SU_L(2)$ Weyl spinors.

Finally, since no SUSY particles have been observed so far, supersymmetry must be a broken symmetry. The Lagrangian of the theory can then be written as the sum of a supersymmetric invariant term and a supersymmetry breaking term, $\mathcal{L}_{\text{soft}}$, as

$$\mathcal{L} = \mathcal{L}_{\text{SUSY}} + \mathcal{L}_{\text{soft}} = \mathcal{L}_{\text{free}} + \mathcal{L}_{\text{int}} + \mathcal{L}_{\text{soft}} . \quad (2.21)$$

The SUSY invariant term of the Lagrangian contains a free term, with the kinetic terms of the scalar and fermionic fields, and an interaction term which includes Yukawa interaction terms, terms for the interactions among the particles of the supermultiplets, and gauge interaction terms. In the $\mathcal{L}_{\text{soft}}$ term, the mass of the SUSY particles and additional SUSY breaking terms are introduced. This means that the SUSY particles can have a mass independent from the electroweak symmetry breaking.

2.2.1 The Minimal Supersymmetric Standard Model

The model that, on top of the SM, introduces the minimal number of additional particles and no additional gauge interactions is the minimal supersymmetric Standard Model (MSSM). The particle content of the MSSM is summarised in Table 2.3, for the chiral supermultiplets, and in Table 2.4, for the gauge supermultiplets. The lepton and quark supermultiplets are presented only once in the table, since they have the same structure for all the three generations, index $i = 1, 2, 3$. As in the SM, it is assumed that only left-handed neutrinos exist, therefore no right handed electrically neutral lepton supermultiplets are added.

Particle Name	Supermultiplet Symbol	Spin-1/2	Spin-0
Quarks, Squarks	Q_i	(u_L, d_L)	$(\tilde{u}_L, \tilde{d}_L)$
	$\bar{u}_i$	$u_R^\dagger$	$\tilde{u}_R^*$
	$\bar{d}_i$	$d_R^\dagger$	$\tilde{d}_R^*$
Leptons, Sleptons	L_i	(ν, e_L)	$(\tilde{\nu}, \tilde{e}_L)$
	$\bar{e}_i$	$e_R^\dagger$	$\tilde{e}_R^*$
Higgsinos, Higgs	H_u	$(\tilde{H}_u^+, \tilde{H}_u^0)$	(H_u^+, H_u^0)
	H_d	$(\tilde{H}_d^0, \tilde{H}_d^-)$	(H_d^0, H_d^-)

Table 2.3: SUSY chiral supermultiplets represented by their gauge eigenstates. For the quark and lepton supermultiplet the index i represent the generation and can take the values 1,2,3.

Differently than in the SM, two Higgs SU(2) doublets are needed to give mass to the up- and down-type fermions [39]. The two Higgs doublets have in total eight degrees of freedom (two complex scalar fields per doublet) of which three are used to give mass to the $W^\pm$ and Z^0 bosons through the electroweak symmetry breaking, and the others give five physical mass eigenstates, which are:

- two neutral CP even scalars h^0 and H^0
- one neutral CP odd pseudo-scalar A^0
- two charged scalars $H^\pm$

Both the two Higgs doublets must acquire a non-zero vacuum expectation value: v_u for H_u and v_d for H_d . The squared sum of v_u and v_d gives the vacuum expectation value of the SM Higgs boson v . The ratio between the two VEVs is defined as $\tan\beta = \frac{v_u}{v_d}$.

The Higgsino mass term is identified with μ , given that $|\mu|^2$ represents the Higgs field squared mass parameter. The squared mass terms of the mass eigenstates of the scalar Higgses can be then written as a function of $|\mu|$, m_{H_u} and m_{H_d} . Usually the squared mass terms of the CP even and of the charged Higgses are written as function of the A^0 and Z squared mass terms. This can be done because the mass of the Z boson can also be written as a combination of the $|\mu|$, m_{H_u} and m_{H_d} terms plus $\tan\beta$.

It is then found that the mass of the lightest CP even Higgs m_{h^0} is strongly constrained by the tree level relation between the Z and the H_u squared mass terms $m_Z^2 = -2(|\mu|^2 + m_{H_u}^2)$, which gives for m_{h^0} the tree level constraint

$$m_{h^0}^2 \leq m_Z^2 \cos^2(2\beta). \quad (2.22)$$

The limit on the squared mass parameter of h^0 has to be modified by adding the radiative corrections. At first order, the main contribution comes from the top and stop loops because of the large top Yukawa coupling. In the limit of large $\tan\beta$, of very large masses of the other Higgs bosons (decoupling limit $m_{A^0} \gg m_Z$, $m_{A^0} \sim m_{H^0} \sim m_{H^\pm}$) and of large stop mixing, the limit $m_{h^0} \lesssim 135$ GeV is obtained [39]. In the decoupling limit the light Higgs h^0 has properties that are almost indistinguishable from those of the SM Higgs boson.

From the large top, bottom and tau lepton Yukawa couplings follows a non negligible mixing between the sfermion gauge eigenstates that, in turn, results in mass eigenstates that are a mixture of the left- and right-handed sfermions. The properties of the third generation supermultiplets are of great interest in general for supersymmetry and in particular for the searches presented in Chapters 7 and 8 and are therefore discussed more extensively below (Paragraph “Third Generation”). On the other hand, the effect of the mass mixing for the lepton and quark supermultiplets of the first and second generations is expected to be small due to their small Yukawa couplings. It can be also assumed that the masses of the squarks of the first two generations are almost degenerate, that they are heavier than the sleptons, and in MSSM models it is likely that the right-handed states are lighter than the left-handed ones [39].

The SUSY partners of the electrically neutral W boson, $\widetilde{W}^3$, and the bino mix, after electroweak symmetry breaking, with the same transformation as the W^3 and B^0 in the SM, see equation 2.11, to give the SUSY partners of the Z boson, the zino, and of the photon, the photino.

In general the SUSY fermions, partners of the SM gauge bosons and of the Higgs bosons, mix to give mass eigenstates. The gluinos are the only SUSY fermions that do not mix since they are an octet with colour charge and none of the other gauginos have this property.

The gaugino mass eigenstates are:

Gauge Group	Particle Name	Spin-0	Spin-1/2
$SU_c(3)$	gluon, gluinos	g	$\tilde{g}$
$SU_L(2)$	W bosons, winos	$W^\pm, W^3$	$\tilde{W}^\pm, \tilde{W}^3$
$U_Y(1)$	B boson, bino	B^0	$\tilde{B}^0$

Table 2.4: SUSY gauge supermultiplets with the gauge group they represent.

- Four *neutralinos*, $\tilde{\chi}_i^0$, $i = 1, 2, 3, 4$, which result from the mixing of the neutral gauginos $\tilde{B}^0$ and $\tilde{W}^3$, and the neutral Higgsinos $\tilde{H}_u^0$ and $\tilde{H}_d^0$.
- Two *chargino* mass eigenstates each with electric charge ± 1 , $\tilde{\chi}_i^\pm$, $i = 1, 2$, which arise from the mixing of the charged gauginos $\tilde{W}^\pm$, and of the charged Higgsinos $\tilde{H}_u^\pm$ and $\tilde{H}_d^\pm$.

In many models under the hypothesis of gaugino universality, see below “Supersymmetry Breaking and Models”, the mass of the lightest chargino is set to be twice the mass of the lightest neutralino.

R-Parity Conservation

In the supersymmetric Lagrangian it is possible to write gauge invariant terms that represent interactions between SUSY and SM particles. In this way scalar SUSY particles can “mediate” interactions leading to baryon (B) or lepton (L) number violation. There are, though, extremely strong experimental limits on these processes. In particular these terms would allow for the decay of the proton, which is observed to be stable on universal time scales [46].

To avoid having lepton and baryon number violating terms, a new symmetry, called *matter parity* [47, 48, 49, 50] or *R-parity* [51], can be added. This provides a new conserved multiplicative quantum number, the matter parity, defined as

$$P_M = (-1)^{3(B-L)}, \quad (2.23)$$

or analogously the *R-parity*, defined as

$$P_R = (-1)^{3(B-L)+2s}, \quad (2.24)$$

with s being the spin of the particle.

Matter and *R-parity* quantum numbers are equivalent. While the same matter quantum number is shared by all particles in a supermultiplet, the *R-parity* is not: all SUSY particles have $P_R = -1$ and all SM particles $P_R = 1$.

The conservation of *R-parity* implies that:

- The lightest supersymmetric particle (LSP) must be stable and, if it is electrically neutral and interacts only weakly with matter, it is a good dark matter candidate.
- Each SUSY particle must decay in an odd number of SUSY particles, meaning that at the end of a decay chain an odd number of LSPs will be produced.
- At colliders, SUSY particles are produced in pairs.

Supersymmetry Breaking and Models

The need of writing SUSY breaking terms in the MSSM Lagrangian introduces 105 free parameters corresponding to SUSY masses, mixing angles and CP violating phases. In particular these are the gaugino mass terms (M_1, M_2, M_3) and the trilinear couplings of the interaction terms between scalar particles, matrices with dimension of mass (a_u, a_d, a_e), that should have a value similar to the soft breaking scale $m_{\text{soft}} \sim 1$ TeV, and the squared mass matrices of the chiral supermultiplets and Higgs mass terms that should assume a scale similar to m_{soft}^2 . These parameters can be greatly reduced ($O(30)$ parameters) if experimental constraints on CP violating processes and phenomena implying flavour changing currents are applied. In particular, to suppress mixing among scalar particles of different generations, it is sensible to assume that the a_i couplings are proportional to the Yukawa coupling matrices, which have non negligible off-diagonal terms only for third generation SM fermions.

Since with supersymmetry the unification of the coupling constants is achieved at a scale of $\sim 10^{16}$ GeV it is reasonable to assume that the mass terms of the gauginos unify around this scale at a value $m_{1/2}$, this hypothesis is labelled as *gaugino universality*. This also gives the approximate relation $M_3 : M_2 : M_1 \approx 6 : 2 : 1$ at the TeV scale.

Little is known about the mechanism of supersymmetry breaking. It is generally assumed that the breaking happens in a hidden sector, that cannot be directly investigated, and, in the most common models, it is transferred to the visible sector via flavour blind either gravitational or SM gauge interactions. These models allow to further reduce the number of free parameters of the SUSY Lagrangian.

- Gravity mediated SUSY breaking models are in general indicated as mSUGRA (minimal supergravity) and have five free parameters, that in constrained MSSM models are identified with: the masses of the SUSY scalars and gauginos, $m_{1/2}$ and m_0^2 , and the common trilinear parameter, A_0 , at the gauge unification scale, $\tan\beta$, and the sign of the Higgsino mass parameter μ . The evolution of the mass parameters up to the unification scale for a mSUGRA model is shown in Fig. 2.9. In general the LSP is the lightest neutralino.
- Gauge mediated SUSY breaking models (GMSB) have a much lower scale of the hidden sector, that is estimated to be of a few TeV, and in most models the LSP is a very light gravitino.

A different approach used to have models with few free parameters (19), with less theoretical prejudices, and that are easy to test experimentally is that of the phenomenological models within the MSSM (pMSSM). In this case no particular assumptions are made on the supersymmetry breaking mechanism and, in general, the models are used to test a defined mass hierarchy or specific processes, where the particles that are not of interest are set to a much higher scale to which the experiment is not sensitive (simplified models [52]).

Third Generation

Third generation squarks and leptons have a particular role within supersymmetric models. Since all SUSY particles enter in the radiative corrections to the Higgs squared mass parameter proportionally to the Yukawa coupling of their SM partner, it follows that the stops, sbottoms and staus give a much larger contribution than all the other squarks and sleptons. Since the Yukawa couplings of the first two generations are negligible they are often approximated to be zero.

The naturalness principle [53] requires a low level of fine tuning of the theory, which means that the radiative contributions to the Higgs squared mass parameter should be smaller or, at most, of the same

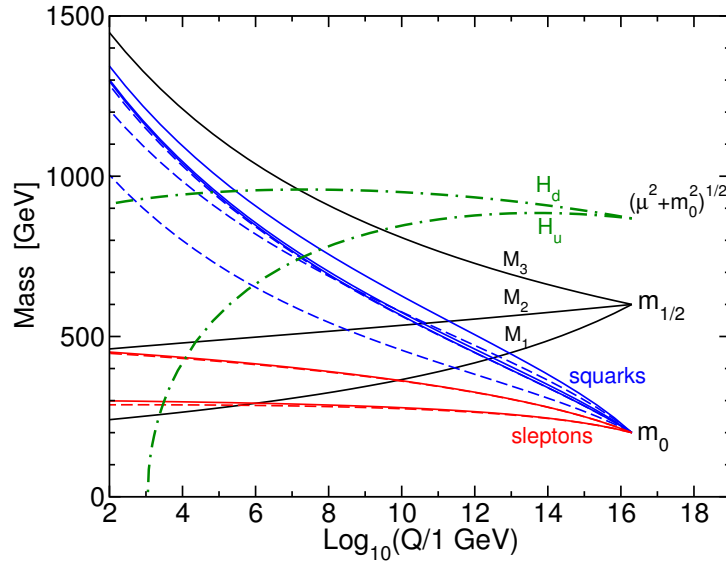


Figure 2.9: Evolution of the mass parameters of the SUSY particles in a mSUGRA model. The mass of the particles is shown as a function of the logarithm of the energy scale. The mass parameters of the Higgs doublet unify at the value $\sqrt{\mu^2 + m_0^2}$, the gaugino mass parameters unify at $m_{1/2}$ and the scalar mass parameters unify at m_0 . The dashed lines for the leptons and squarks represent the parameter of the third generation particles [39].

order of magnitude of m_h^2 . This is one of the strongest principles to constrain theoretically the stop and gluino masses (the gluinos contribute through radiative corrections to the stop mass parameters), that should be found at an energy smaller than or of the order of 1 TeV and 2 TeV, respectively, to not exceed a fine-tuning of the theory of the order of 10% [53]. The left bottom squark must also be light since it shares the Q_3 doublet with the stop left. A typical mass spectrum for a natural simplified model is shown in Fig. 2.10a.

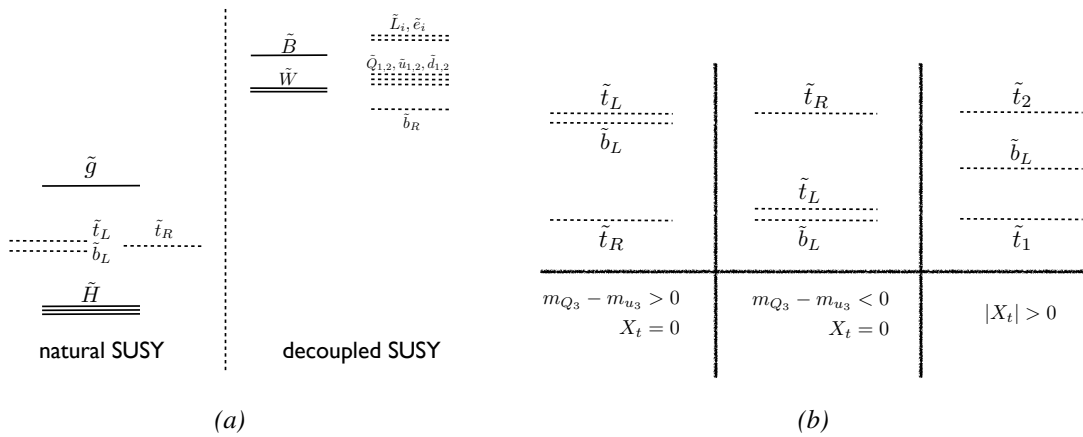


Figure 2.10: (a) Typical mass spectrum of a simplified model with light Higgsinos, stops, sbottom left and gluinos. The other particles are decoupled at a much higher scale. (b) Different stop splitting and mixing and relation to the sbottom left [53].

The variation to the Higgs squared mass parameter given by the top and the stop loops is given by

$$\delta m_h^2 = \frac{3G_F}{\sqrt{2}\pi^2} m_t^4 \left(\log \left(\frac{\bar{m}_{\tilde{t}}^2}{m_t^2} \right) + \frac{X_t^2}{\bar{m}_{\tilde{t}}^2} \left(1 - \frac{X_t^2}{12\bar{m}_{\tilde{t}}^2} \right) \right). \quad (2.25)$$

Here $X_t = A_t - \mu \cot \beta$, with A_t as soft trilinear coupling parameter and μ as Higgsino mass, and $\bar{m}_{\tilde{t}} = \sqrt{m_{\tilde{t}_1} m_{\tilde{t}_2}}$ average stop mass.

The left and right stop gauge eigenstates mix with the mass matrix

$$\mathbf{m}_{\tilde{t}}^2 = \begin{pmatrix} m_{Q_3}^2 + m_t^2 + t_L m_Z^2 & m_t X_t \\ m_t X_t & m_{\tilde{u}_3}^2 + m_t^2 + t_R m_Z^2 \end{pmatrix} \quad (2.26)$$

to give the mass eigenstates $\tilde{t}_1$ and $\tilde{t}_2$. The soft mass parameters for the third generation squark doublet and for the right handed stop are m_{Q_3} and $m_{\tilde{u}_3}$, respectively. The parameter that directly governs the mixing is X_t , and the terms t_L and t_R represent the contributions from quartic interactions terms of the $SU_L(2)$ and $U_Y(1)$ groups of the form (squark)²(Higgs)², which give $t_L = \left(\frac{1}{2} - \frac{2}{3} \sin^2 \theta_w \right) \cos(2\beta)$ and $t_R = \left(\frac{2}{3} \sin^2 \theta_w \right) \cos(2\beta)$.

Since at tree level the Higgs mass parameter is bounded by the Z boson mass, and the Higgs boson discovered in 2012 has a mass of 125 GeV, considering a large $\tan \beta$ the radiative corrections should contribute for about 30 GeV. The stop contribution can be maximised for large stop average mass $\bar{m}_{\tilde{t}}$, and maximal mixing, i.e. $X_t = \sqrt{6} \bar{m}_{\tilde{t}}$, for which the lightest stop mass eigenstate, $\tilde{t}_1$, becomes almost a pure $\tilde{t}_R$ [39]. Possible scenarios of stop mass splittings and mixings are shown in Fig. 2.10b [53].

2.3 Hadron–Hadron Interactions

At hadron colliders the colliding particles are composite objects and the perturbative QCD theory, presented in Section 2.1.2, is not sufficient to describe the interactions that occur between them. In this section the theory of hadron interactions is briefly presented together with how Monte Carlo generators implement the theory predictions to be compared with the data collected by the experiments. A more complete description of these topics can be found in Refs. [54, 55, 56, 57].

At the LHC (see Chapter 3) two proton beams collide at the interaction points where the experiments are placed. The beams are made of proton bunches, containing of the order of 10^{11} protons, that as they collide can give origin to hard scattering interactions but mostly to soft elastic or inelastic scattering where only a small momentum is transferred. In particular, the minimum bias events arise from inelastic scattering and are the process with the largest production cross section at the LHC, which corresponds to 71.5 mb at a centre-of-mass energy, $\sqrt{s}$, of 7 TeV, and to 73 mb at $\sqrt{s} = 8$ TeV. In hard interactions, where large momentum transfers are involved, the partons, i.e. the valence and sea quarks and the gluons within the proton, and not the protons themselves interact. This type of interactions can be described by perturbative QCD, while this is not possible for the soft collisions because of α_s becoming large.

Thanks to the factorisation theorem, the hadronic cross section for two objects A and B interacting to give the decay product X can be written as

$$\sigma_{AB \rightarrow X} = \sum_{a,b} \int f_{a/A}(x_a, Q^2) f_{b/B}(x_b, Q^2) \hat{\sigma}_{ab \rightarrow X} dx_a dx_b. \quad (2.27)$$

In this formula a and b are the two interacting partons, which belong to the composite objects A and B, respectively. The functions $f_{j/J}$ are density functions of the parton j in the object J , which depend on

x_j , the fraction of the momentum of the object J carried by the parton j , and on the energy scale of the hard interaction Q^2 . Finally, $\hat{\sigma}_{ab \rightarrow X}$ is the partonic cross section of $ab \rightarrow X$ that can be computed using pQCD.

The density functions are proton structure functions named parton distribution functions (PDFs). They can be measured in lepton–hadron deep inelastic scattering experiments and in lepton–lepton production cross section measurements in hadron–hadron collisions, especially in Drell–Yan processes, while the study of events involving jet production is of particular importance for the determination of the gluon PDFs.

The PDFs depend on the energy scale Q^2 of the interaction under study. The DGLAP, or Altarelli–Parisi, equations [58, 59, 60] are used to evolve the PDFs from a known distribution at the energy scale Q_1^2 , $f(x, Q_1^2)$, to a new one at the scale Q_2^2 , $f(x, Q_2^2)$. The evolution equations are written in terms of splitting functions, that at first order can be derived by QCD vertices, and can be expanded in powers of the strong running coupling constant $\alpha_s(Q^2)$. Thanks to these equations, it is possible to combine measurements done at different energy scales to have a prediction of the PDFs that can be used e.g. for hadron interactions at LHC energies.

Many groups, CTEQ, MSTW, NNPDF, HeraPDF [61, 62, 63, 64, 65, 66], work to extract the PDFs by fitting the results from different experiments and measurements. An example of PDFs from the NNPDF collaboration is shown in Fig. 2.11 for two interaction energy scales $Q^2 = 10 \text{ GeV}^2$ and $Q^2 = 10^4 \text{ GeV}^2$.

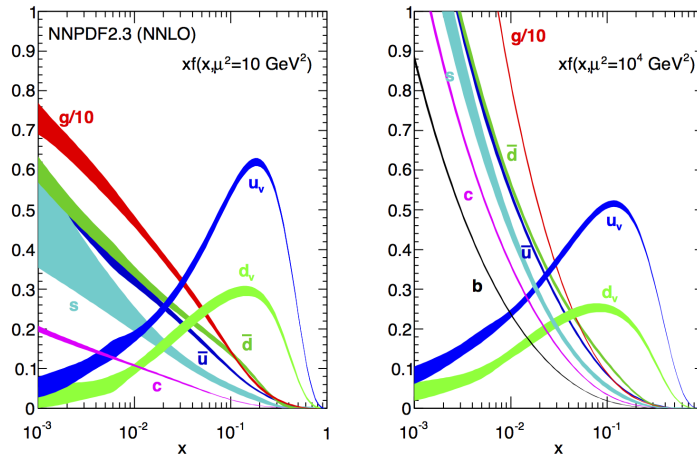


Figure 2.11: PDFs distribution at $Q^2 = 10 \text{ GeV}^2$ and $Q^2 = 10^4 \text{ GeV}^2$ computed by the NNPDF collaboration [67].

The scale Q^2 of equation 2.27 is called factorisation scale, μ_F . The partonic cross section, $\hat{\sigma}_{ab \rightarrow X}$, also depends on an energy scale, the renormalisation scale, μ_R , needed for its perturbative expansion in terms proportional to increasing orders of α_s . The cross section obtained with different choices of μ_F and μ_R may differ. Often the two energy scales are set to be equal and the scale chosen is that of a typical energy scale of the hard interaction under study.

The scale dependence can be mitigated by computing the cross section at next-to-leading order (NLO). This means that the radiation of a quark or a gluon by one of the particles taking part in the interaction is taken into account as well as the contributions from loops of virtual particles. The radiation may be real, giving an additional jet in the final state, or virtual in the case of the loops. An example of the production of a W boson at leading order with no additional radiation (LO), with the radiation of a real gluon and with a virtual gluon loop contribution is shown in Fig. 2.12.

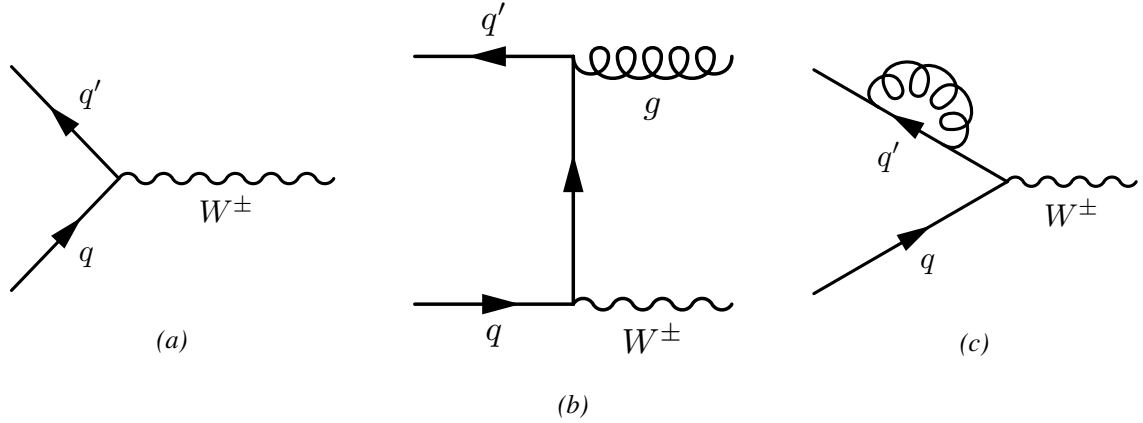


Figure 2.12: W boson production by the interaction of two quarks q and q' (a) at leading order, (b) with the emission of a real gluon, and (c) with the radiation of a virtual gluon.

2.3.1 Monte Carlo Generators

A Monte Carlo (MC) generator [56, 57] serves to simulate a complete event that may happen in a collision between elementary or composite particles. The scheme of such an event is shown in Fig. 2.13. The first step for its simulation is the computation of the cross section of the relevant process with the PDFs information. For this, the theoretical calculation of the matrix element of the hard process is needed. The following steps are those of the parton showering, and of the hadronisation of the shower products and their decay. Finally, the underlying soft event is added to the hard process. These steps are explained in more detail in the next paragraphs together with a list of the MC generators used to produce simulated events for the analyses presented in Chapters 7 and 8.

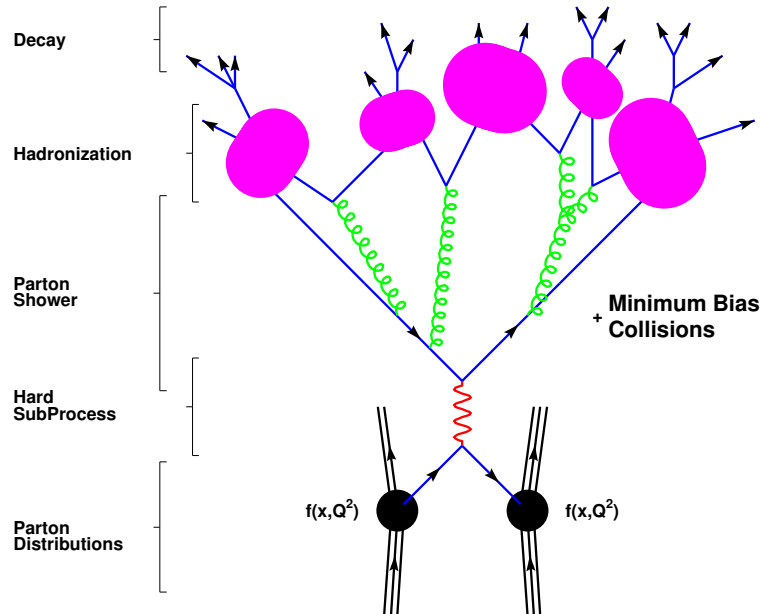


Figure 2.13: Scheme of an event generated by a full MC simulation with showering and hadronisation [57].

Hard Scattering

The simulation of the hard scattering part of the event makes use of the cross section of the process calculated with the formula 2.27. The events are generated taking into account the probability distribution of the possible final state configurations for the interaction process under study. Only few generators can simulate events with a NLO description and only for some specific processes. If a LO MC generator is used, additional radiation jets can be added by the parton showering process.

Even if it is not possible to simulate events at NLO, the theory prediction for the cross section at NLO may exist. In these cases the cross section of the generated events is multiplied by a so-called K – *factor*, which is the ratio of the inclusive cross sections at next-to-leading to leading order:

$$K = \frac{\sigma_{NLO}}{\sigma_{LO}} . \quad (2.28)$$

This is allowed because the ratio is in general quite independent of the energy scale and of the applied selections.

A summary of the cross sections of some important processes at hadron colliders is shown in Fig. 2.14, where the collision energies of the Tevatron and of the LHC are highlighted.

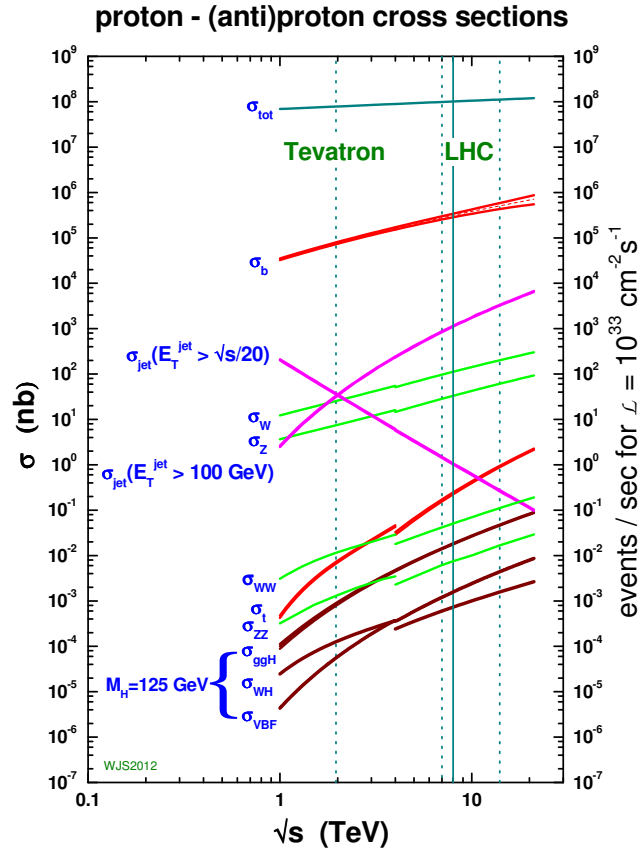


Figure 2.14: Standard Model cross sections as a function of the collider energy, with a 125 GeV Higgs boson. The green vertical full line indicates the cross sections of the centre-of-mass energy of the LHC at $\sqrt{s} = 8$ TeV [68].

Parton Showering and Hadronisation

The parton showering allows to evolve, by using the DGLAP equations, the partons produced in the hard interactions to the Λ_{QCD} scale where the partons combine to form the known hadrons. The high energy quarks are allowed to split into quark-gluon pairs, while gluons can split into quark-quark or gluon-gluon pairs. The probability for a parton to branch is assessed with the Sudakov form factors that are weighted for the PDFs at the appropriate energy scale. The parton showering model describes especially well the parameter regions of soft and collinear gluon emission. The radiation of a new parton can happen both in the initial (ISR) and in the final (FSR) state.

When the parton cascades get to the Λ_{QCD} scale, the partons recombine to colour singlet hadrons, that can decay if unstable. This process is called hadronisation and it combines not only the partons coming from the showering, but also the remnants of the protons after the hard interaction. Since the formation of hadrons happens at a scale where pQCD cannot be used, the hadronisation models are phenomenological models that have to be tuned with experimental data.

In many cases it is the parton shower that adds to a LO matrix element the additional radiation jets. If a NLO matrix element is used for the hard scattering the overlaps and double counting have to be eliminated when it is matched to the parton shower. The matching procedure [69] in general resolves the overlaps by dividing the available phase space in two regions, one dominated by the hard emission of radiation, which is better described by the matrix element, as it also takes correctly into account possible interferences between processes with the same final state, and the other dominated by soft emissions, best described by the parton shower, and by assigning new weights to the events.

Underlying Event and Pileup

Given a hadron-hadron interaction which gives origin to an hard collision event between two partons, the underlying event is the set of soft interactions happening on top of the hard process between the remaining partons of the involved hadrons. It is described by phenomenological models (tunes) that are highly dependent on data. Tunes were produced for the MC used by the ATLAS experiment for PYTHIA [70, 71, 72, 73] and for HERWIG/JIMMY [70, 74, 75]. The underlying event is independent from the description of the hard interaction part and it is added to it when the simulation of this latter part has been completed.

The pile-up of an events is due to the soft scattering of protons belonging to the same bunches of the protons that gave origin to the hard scattering (in-time pile-up) and to interactions happening in the collisions of the previous or next bunches (out-of-time pile-up). This interactions are simulated by parameterizing the amount of hadrons for each colliding bunch and the time separation between bunches.

Showering and Hadronisation Leading Order Generators

The showering and hadronisation generators are multi-purpose generators that cover a wide range of physics processes. They are leading order generators that can produce a complete event from the definition of the hard scattering, to the showering and the addition of the underlying event. They can, thus, be used either standalone or in combination with generators that deal only with the generation of the hard process, but do not have either the parton showering, or the hadronisation implemented.

These generators are:

- PYTHIA [76, 77], used e.g. for the simulation of jet processes.
- HERWIG and HERWIG++ [78, 79], used e.g. for the simulation of SUSY processes.

- SHERPA [80], in this thesis used e.g. for the W and Z bosons production simulations.

Leading Order Generators

The leading order generators generate only the LO matrix element of the hard interaction for specific processes. They are then interfaced usually to PYTHIA or HERWIG for the parton showering, the hadronisation, and the addition of the underlying event.

The ones used to simulate samples considered in this work are:

- ALPGEN [81]: it generates SM processes from hadron collisions by evaluating exactly the tree level matrix elements. Moreover, the real emission of up to six additional partons can be exactly simulated, which, however, requires the correct matching with the parton shower in order to eliminate possible double counting. It has been used especially for the generation of samples of electroweak processes with additional jets.
- ACER MC [82]: it is optimised to produce SM background processes in pp interactions where heavy-flavour jets or an high lepton multiplicity are involved. Moreover, the amount of initial and final state radiation of an hard process can be easily modified to assess the theoretical uncertainties related to these variations.
- MadGraph [83]: it is a multi-purpose generator used e.g. for the simulation of diboson production and for some SUSY processes.

Next To Leading Order Generators

The next to leading order generators, that in general should give a more appropriate description of the processes they simulate w.r.t. the LO generators, used for the analyses presented in this thesis are:

- MC@NLO [84]: it includes the full NLO QCD corrections for hard processes at hadron colliders. It is generally matched to HERWIG and it has been used especially for $t\bar{t}$ and single top samples. As a consequence of the matching with the parton shower generator the events acquire positive and negative weights, that have to be taken into account when working with the sample.
- PowHeg [85, 86]: it has been used to simulate SM processes such as $t\bar{t}$ and single top production and it is usually matched to PYTHIA. The weights obtained from the matching procedure are always positive.

The LHC and the ATLAS Experiment

Situated at CERN near Geneva, Switzerland, the Large Hadron Collider (LHC) is the world largest proton–proton collider. The ATLAS experiment (A Toroidal LHC ApparatuS) is one of the two multipurpose detectors designed to investigate the physics produced by the LHC pp collisions. The LHC and the ATLAS experiment are presented in this chapter in Section 3.1 and Section 3.2, respectively. The Worldwide LHC Computing Grid, Section 3.3, and the detector simulations used by the ATLAS experiment, Section 3.4, are also shortly discussed.

3.1 The Large Hadron Collider

The LHC [87] is the largest and most powerful proton–proton collider ever built to study high energy physics processes. It is situated in the almost 27 km long tunnel built for the LEP (Large Electron Positron) machine, which was an electron–positron collider in operation between 1989 and 2000 and then dismantled to allow the assembly of the LHC. The LHC was designed to reach a centre-of-mass energy of $\sqrt{s} = 14$ TeV for proton–proton collisions and a maximum instantaneous luminosity of $\mathcal{L} = 10^{34} \text{ cm}^{-2}\text{s}^{-1}$. It can also accelerate and collide ion beams and a dedicated experiment, ALICE (A Large Ion Collider Experiment), has been designed to study heavy-ions physics; even if not optimised for this task, also ATLAS and CMS (Compact Muon Solenoid), which is the other LHC multipurpose experiment, can analyse heavy ion collisions.

Due to an accident on 19 September 2008 when commissioning the first beams, an additional year was needed before the machine could start operation. Thus, when the machine was restarted at the end of 2009, the first collisions took place with a reduced luminosity and beam energy. In 2010 and 2011 data was collected using a beam energy of 3.5 TeV; in 2012 the beam energy was raised to 4 TeV and an instantaneous peak luminosity of $\mathcal{L}_{\text{peak}} = 7.73 \cdot 10^{33} \text{ cm}^{-2}\text{s}^{-1}$ was reached. The complete dataset collected in these three years is identified as Run 1 dataset. The dataset analysed for this thesis corresponds to the total pp collision data collected in 2011 and 2012 at centre-of-mass energies of $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV, respectively.

The LHC is divided in octants. The multi-purpose experiments ATLAS and CMS are placed at the Interaction Points (IP) 1 and 5, respectively, ALICE is placed at IP2 and LHCb, optimised for the study of b-physics, at IP8. The beams injection-lines are in the second and eighth octants. The two beams, circulating in opposite directions, are accelerated by two separate superconducting Radio Frequency

(RF) systems, placed in the fourth octant, from the injection energy of 450 GeV up to the final design beam energy of 7 TeV. The magnets used to dump the beams, the so called kickers, are in the sixth octant and again separate systems for the two beams are provided.

The two beam pipes are integrated in a single structure with the superconducting magnets. Overall, more than 9000 magnets are used in the LHC ring. To keep the proton beams on a circular orbit 1232 superconducting dipoles are exploited. They are cooled to 1.9 K with superfluid helium and can reach a magnetic field of 8.33 T. To focus and collimate the beams, quadrupoles are used, while higher order magnetic poles serve mainly to correct for beam instabilities.

Nominally 2808 proton bunches, containing each of the order of 10^{11} protons, with a 25 ns spacing can be stored in and accelerated by the LHC. For the LHC Run 1 pp collisions, the chosen bunch spacing was of 150 ns in 2010 and 50 ns in 2011 and 2012.

The protons are brought to the LHC injection energy of 450 GeV using the CERN accelerator complex, shown schematically in Fig. 3.1. The protons are extracted by ionising hydrogen gas and are first accelerated to 50 MeV by the Linac2. Then in the Proton Synchrotron Booster (PSB) they reach the energy of 1.4 GeV and are injected in the PS, Proton Synchrotron, where the energy is taken to 25 GeV. Finally the SPS, Super Proton Synchrotron, accelerates the proton bunches to 450 GeV. The minimum LHC filling time is of 16 minutes and at least 20 minutes are needed for the energy ramp-up from the injection energy to the final desired beam collision energy. This is also the minimum time needed to ramp the magnets down after a beam abort.

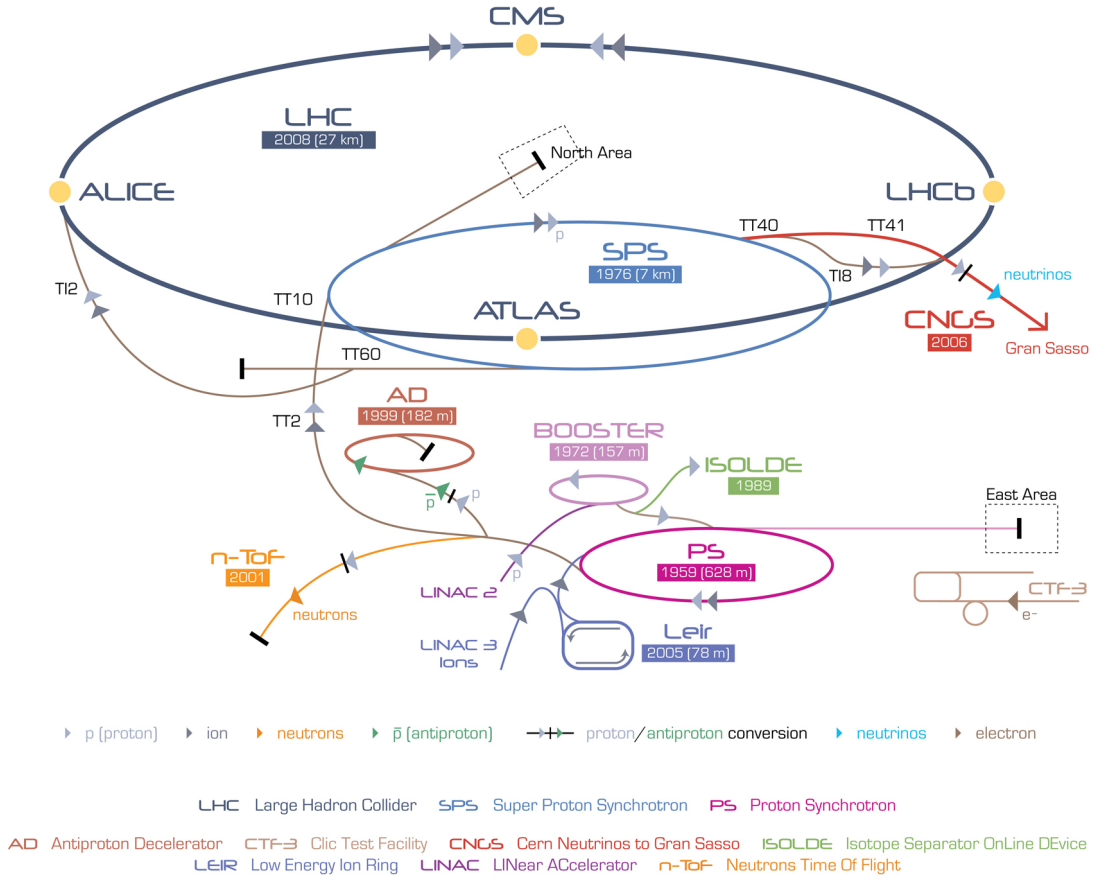


Figure 3.1: The CERN accelerator complex [88] with its main four experiments ALICE, ATLAS, CMS and LHCb, and the pre-accelerators Linac2, Booster, PS and SPS. Minor experiments and the heavy-ions pre-accelerators are also shown.

3.2 The ATLAS Detector

In order to optimally detect and study the products of the LHC pp collisions the ATLAS detector, a complex multi-purpose experiment, was designed. The detector schematic picture can be seen in Fig. 3.2. The ATLAS detector is 44 m long, has a diameter of 25 m and a weight of about 7000 tons. Each of its sub-systems has been developed to match tight requirements, such as high resolution for the momentum measurement of leptons and photons, for the energy measurement of jets and a good vertex resolution to be able to tag tau leptons and b -jets.

The detector has to be fast, have a high granularity, a high coverage in the polar and azimuthal angles and be radiation hard, since a high number of underlying events is expected for each interesting hard scattering event.

The sub-systems developed to achieve the best performance for the detector are a tracker, an electromagnetic and a hadronic calorimeter and a muon spectrometer. For the charge and momentum measurements, magnetic fields are provided by a solenoid and a barrel and two endcaps toroids. These elements are introduced in the following paragraphs, while the very forward detectors (LUCID, ALFA and ZDC), used to determine the luminosity delivered to the experiment, are not described; a more detailed description of the ATLAS detector and its sub-detectors can be found in Ref. [89].

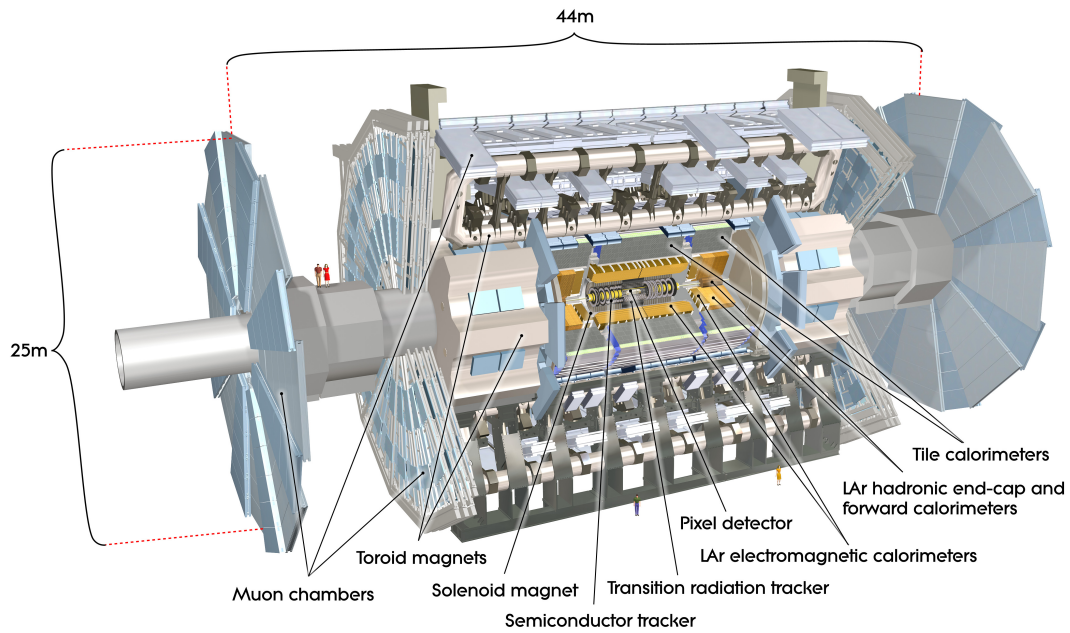


Figure 3.2: Cut view of the ATLAS detector. The detector is 44 m long, with a diameter of 25 m and a weight of 7000 tons [89].

The ATLAS Coordinate System

The ATLAS experiment has a cylindrical symmetry around the nominal interaction point, set as the origin of its coordinate system. The z -axis is in the beam direction, the x -axis points to the centre of the LHC ring and the y -axis points upwards. The x - y plane is, hence, the transverse plane to the beam where the transverse quantities such as p_T , E_T and E_T^{miss} are defined. The azimuthal angle ϕ is defined around the beam axis, while the angle from the beam axis is the polar angle θ . The pseudorapidity η , defined as

$$\eta = -\ln \tan(\theta/2), \quad (3.1)$$

is often used instead of the polar angle to describe the angular distance to the z axis. The distance ΔR in the $(\eta - \phi)$ angular plane is defined as

$$\Delta R = \sqrt{\Delta\eta^2 + \Delta\phi^2}. \quad (3.2)$$

3.2.1 The Magnet System

The ATLAS detector makes use of four superconducting magnets: one solenoid and three toroids, two for the endcaps and one for the barrel.

The solenoid provides a 2 T axial magnetic field in the volume of the inner detector. It is placed between the inner detector and the electromagnetic calorimeter (ECAL); it is 5.8 m long, has an inner diameter of 2.46 m and is 5 cm thick. The solenoid and the ECAL share a vacuum vessel to minimise the dead material before the calorimeter.

The toroids produce the magnetic field for the measurement of the muon tracks, 0.5 T in the central region and 1 T in the endcaps of the muon spectrometer. Each of them consists of eight coils assembled in radial symmetry around the beam axis; each coil of the barrel toroid has an individual vacuum vessel, while the endcaps toroid systems have a single integrated cooling system each. The barrel toroid system, shown during the detector assembly phase in Fig. 3.3, has a length of 25 m, an inner radius of 4.7 m and an outer radius of 10.05 m. The endcap toroids are rotated by 22.5° with respect to the barrel toroid to give a radial overlap and to optimise the bending power in the transition region between the two.

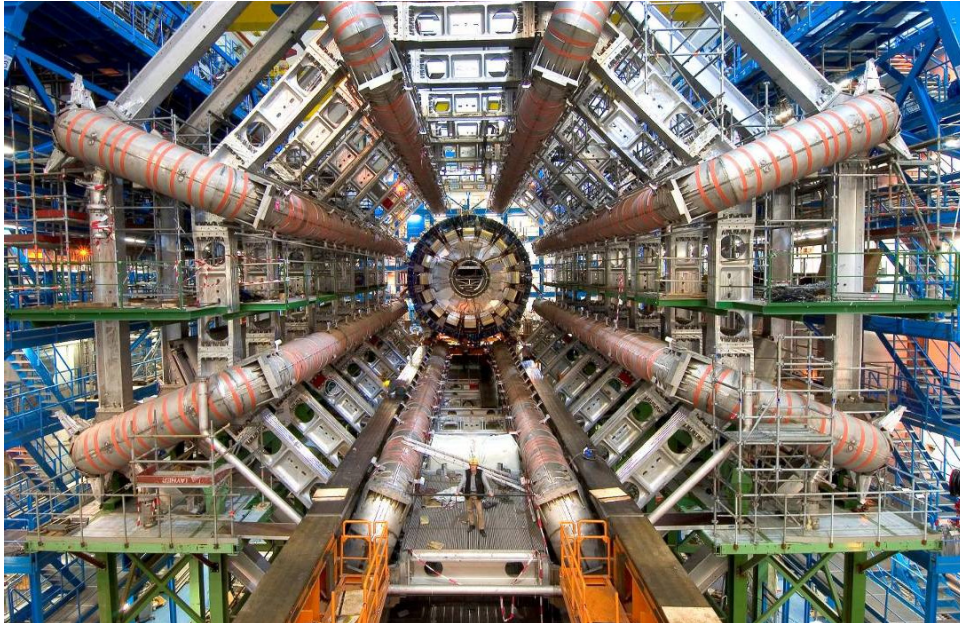


Figure 3.3: The barrel toroid of the ATLAS detector during the installation. The person in the picture can be used to have an idea of the scale of the experiment [89].

3.2.2 The Inner Detector

The ATLAS Inner Detector (ID) is an integrated system of three sub-detectors: the pixel and silicon microstrip precision trackers and a straw-tube tracking detector (TRT). The ID is immersed in the 2 T magnetic field of the solenoid and is composed of concentric cylinders in the barrel and disks perpendicular to the beam axis in the endcaps, as schematically presented in Fig. 3.4. It has a very high granularity, necessary to achieve the high momentum and vertex resolution required by the physics studies in a dense track environment, and its coverage reaches $|\eta| = 2.5$. The design momentum resolution of the inner detector is

$$\sigma_{p_T}/p_T = 0.05\% p_T \oplus 1\%.$$

The interplay of the pixel and strip precision trackers with the TRT ensures a very good pattern recognition and accurate measurements both in the transverse plane ($R - \phi$) and along the z axis. The high granularity of the pixel detector and its vicinity to the interaction point are used to precisely determine the impact parameters and primary and secondary vertices, necessary for the identification of τ leptons and heavy flavour jets. The straw-tube hits have a lower spacial resolution but are nevertheless important for the momentum measurements, thanks to the high number of hits and to the long track length, and for the electron identification, since the TRT can detect transition-radiation photons.

The inner detector must resist the high irradiation expected by the operation at design luminosity for ten years.

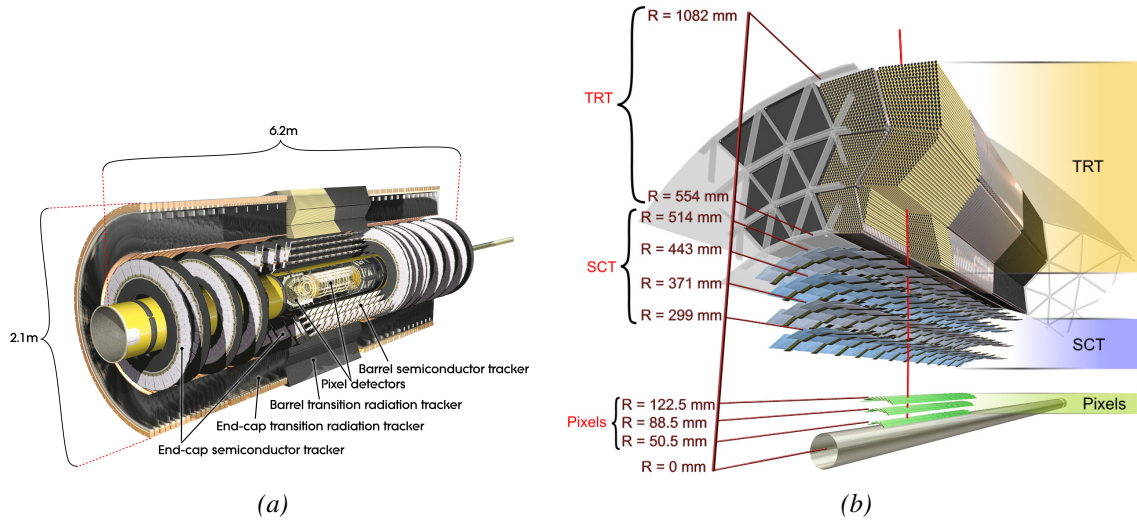


Figure 3.4: (a) Cut view of the inner detector with overall size. (b) ID sub-detectors and distance of each layer from the beam axis [89].

Pixel detector

The pixel detector, which operates at a temperature between -5 and -10°C , has the highest granularity. Most of the approximately 80 millions pixels have a size of $40 \times 400 \mu\text{m}^2$, they are segmented in the transverse and longitudinal planes and grouped into 1744 modules. Three pixel layers are installed both in the barrel and in the endcaps disks; in the barrel region, the first layer is 5.05 cm apart from the beam axis, the third 12.25 cm.

Primary and secondary vertices can be identified. The accuracy of the measurement of the primary

vertex is of the order of $10\ \mu\text{m}$ in the transverse plane and $115\ \mu\text{m}$ in the longitudinal direction. During the 2013-2014 shutdown an additional high granularity pixel layer, the insertable b-layer (IBL), has been installed at a distance of 3.3 cm to the beam axis [90]. This additional layer improves the vertex measurement and the tracking performance for instantaneous luminosities up to three times the original design luminosity.

Semiconductor Tracker

The semiconductor tracker (SCT) is a silicon microstrip detector installed externally to the pixel detector, working, as the latter, at a temperature in the range -5 to -10°C . In total 6.3 millions strips grouped in 4088 modules form the SCT.

In the barrel, the strips have a pitch of $80\ \mu\text{m}$ and a length of 12.8 cm; each of them contains two 6.4 cm long sensors with the readout cables located in the 2 mm gap between the sensors. In the endcaps the strip pitch varies between 57 and $94\ \mu\text{m}$ and the length between 5.4 and 6.5 cm. The SCT has four layers in the barrel and nine in the endcap disks allowing for at least four space measurements per track. Each layer has two sets of strips, one parallel to the beam (barrel) or radial (disks) and one tilted by 40 mrad, to allow a precise measurement also along the z axis.

The achieved accuracy is $17\ \mu\text{m}$ in the transverse plane and $580\ \mu\text{m}$ in the longitudinal direction. The SCT has a coverage up to $|\eta| = 2.5$, like the pixel detector, and together with it allows for the identification of secondary vertices of long-lived particles.

Transition Radiation Tracker

The transition radiation tracker is the outermost part of the ID and, differently from the pixel and SCT detectors, is operated at room temperature. It is formed by straw-tubes filled with a Xenon based gas mixture interleaved with transition radiation material. The tubes have a 4 mm diameter and a length of 144 cm in the barrel and of 37 cm in the endcaps. In the barrel the tubes are aligned to the beam direction and their wires are divided at $\eta = 0$; in the endcaps the straws are arranged radially.

The TRT, with its 351000 readout channels, covers up to $|\eta| = 2.0$ and can provide only $(R - \phi)$ plane information with an accuracy of $130\ \mu\text{m}$. The poorer precision is counterbalanced by the high number of measured hits per track: for a track with $p_T > 0.5\ \text{GeV}$ at least 36 points are measured giving a precise momentum measurement. Moreover, the TRT provides efficient electron identification for $|\eta| < 2.0$ and energies ranging from 0.5 to 150 GeV.

3.2.3 The Calorimeter System

The calorimeters are placed externally to the inner detector and the solenoid. An electromagnetic (ECAL) and a hadronic (HCAL) calorimeter are integrated in the experiment to measure, in the most efficient way, the energy deposited by electrons, photons and hadronic jets. The calorimeter design is summarised in Fig. 3.5. Both ECAL and HCAL are sampling calorimeters, meaning that layers of active material alternate with layers of absorber plates, and extend to $|\eta| < 4.9$. In the ECAL the η region up to 2.5 has a very fine granularity to allow for a precise measurement of electrons and photons and to be able to distinguish between the decay in two photons of the neutral pion and of the Higgs boson ($\pi^0 \rightarrow \gamma\gamma$ and $H \rightarrow \gamma\gamma$), while between $|\eta| = 2.5$ and $|\eta| = 3.2$ the segmentation in η becomes coarser. The HCAL has, in general, a coarser granularity than the ECAL, which is sufficient for the measurement of jets and missing transverse energy. The calorimeters must also ensure a good containment of the electromagnetic and hadronic showers and limit the punch through into the muon spectrometer (Section 3.2.4). This is achieved thanks to the 22 to 24 radiation lengths of the ECAL and the ~ 10 interaction lengths

of the HCAL. In the following paragraphs the main characteristics of the electromagnetic, hadronic and forward calorimeters are presented.

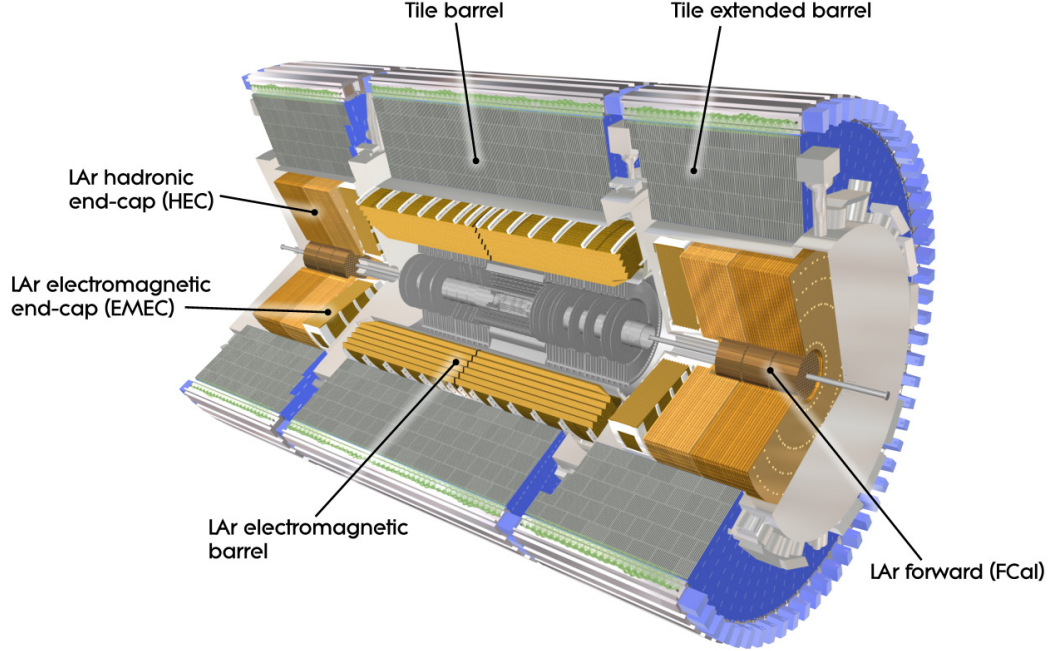


Figure 3.5: Cut-away view of the ATLAS calorimeter system [89].

The Electromagnetic Calorimeter

The electromagnetic calorimeter is built of three parts, one in the barrel and one in each of the endcaps, each with its own cryostat. It measures especially electron and photon showers. The active material used is Liquid Argon (LAr) because of its radiation hardness, stability of response over time and linear behaviour while lead is used as absorber. An accordion geometry is chosen, which guarantees a complete ϕ symmetry without crack regions. The coverage extends to $|\eta| < 3.2$, but electrons and photons can be selected by dedicated triggers only up to a η of about 2.5 (see Section 3.2.5). The performance in terms of energy resolution of the ECAL is

$$\sigma_E/E = \frac{10\%}{\sqrt{E}} \oplus 0.7\%.$$

The barrel extends to $|\eta| = 1.475$ and it is formed by two identical 3.2 m long half-barrels that leave a gap of 4 mm at $\eta = 0$; two coaxial wheels are in the endcaps (EMEC), the outer covering $1.375 < |\eta| < 2.5$ and the inner $2.5 < |\eta| < 3.2$. Three sections in depth are provided in the region matching the ID, $|\eta| < 2.5$, while the inner wheel has only two. The first and second layer are finely segmented in η and ϕ with cells with $\Delta\eta \times \Delta\phi = 0.003 \times 0.1$ in the most central region of layer 1, $\Delta\eta \times \Delta\phi = 0.025 \times 0.025$ in the central region of layer 2, and up to $\Delta\eta \times \Delta\phi = 0.1 \times 0.1$ above $\eta = 2.5$. The fine segmentation in η of the first two layers ensures the good determination of the direction and angular separation of photons needed to identify the decay of the π^0 .

In the region $|\eta| < 1.8$ a presampler has been installed in front of the ECAL. This has the role of

correcting for the energy loss of electrons and photons upstream of the calorimeter and its cell have dimensions of $\Delta\eta \times \Delta\phi = 0.025 \times 0.1$.

The Hadronic Calorimeter

The hadronic calorimeter measures the energy and stops neutral and charged hadronic particles. It makes use of different technologies in the central and in the endcap regions.

The tile calorimeter covers the region $|\eta| < 1.7$ and it is composed by a 5.8 m long barrel, up to $|\eta| = 1.0$, and two extended barrels, each 2.6 m long, covering $0.8 < |\eta| < 1.7$. Scintillating tiles are used as active material and steel as absorber. In the gaps between the barrel and the extended barrels special steel-scintillator sandwich modules are used in order to recover part of the energy otherwise lost in the crack region. The tiles produce ultraviolet scintillation light which is transported to photomultipliers by wavelength shifting fibres. The expected light emission loss after 10 years of machine operation at design luminosity is of 10%. Also the tile calorimeter has three layers, the first two have a segmentation $\Delta\eta \times \Delta\phi = 0.1 \times 0.1$, the third $\Delta\eta \times \Delta\phi = 0.2 \times 0.1$.

The hadronic endcaps (HEC) are copper-LAr calorimeters that cover $1.5 < |\eta| < 3.2$. Each endcap has two wheels with two segments in depth, sharing the same cryostat as the EMEC. The η coverage overlaps with the tile coverage on one side, and with the FCAL (see next paragraph) coverage on the other, to guarantee good calorimeter measurements and to reduce the background reaching the muon spectrometer. The chosen readout cells segmentation is $\Delta\eta \times \Delta\phi = 0.1 \times 0.1$ up to $|\eta| = 2.5$ and $\Delta\eta \times \Delta\phi = 0.2 \times 0.2$ above.

The expected performance of the hadronic calorimeter is

$$\sigma_E/E = \frac{50\%}{\sqrt{E}} \oplus 3\%.$$

The Forward Calorimeter

The forward calorimeter (FCAL) covers the higher η range $3.1 < |\eta| < 4.9$ and it is integrated in the endcaps cryostat together with the EMEC and the HEC. The extension of the coverage to such high pseudorapidity is of particular importance for the correct reconstruction of the missing transverse momentum. The FCAL has three layers the first acts as electromagnetic calorimeter and the other serve for the measurements of the hadronic showers. It has a coarser granularity with respect to the other part of the calorimetric system and, like the ECAL and the HEC, it exploits LAr as active medium interleaved with copper (first layer) or tungsten absorber plates. For the hadronic part the measurement of the energy has a lower precision than in the HCAL giving

$$\sigma_E/E = \frac{100\%}{\sqrt{E}} \oplus 10\%.$$

3.2.4 The Muon Spectrometer

The muon spectrometer (MS) is intended to measure the momentum and the charge of the muons that cross the rest of the detector losing only a small fraction of their energy in the calorimeters. The measurement of the muon properties is achieved thanks to the magnetic field of the toroids, which bend the muon trajectories. The system can measure muons up to $|\eta| = 2.7$ and trigger on them for $|\eta| < 2.4$, with a gap at $\eta = 0$ needed for the services for the ID, solenoid and calorimeters. Both in the barrel and in the endcaps there are three layers of chambers, cylindrical and wheels perpendicular to the beam,

respectively. In the barrel the distance of the layers from the beam axis is 5, 7.5 and 10 m. The required accuracy in the alignment of the chambers in order to get to the design performance is of $30\text{ }\mu\text{m}$ and the magnetic field of the toroids has to be known at the per mil level.

Two classes of chambers are used in the experiment, one to have precision tracking, the other for triggering and to provide a second position coordinate. In the barrel region, up to $|\eta| = 2$, Monitored Drift Tubes (MDT) are used for the tracking. They provide a measurement of the track position in the bending direction of the magnetic field with a $35\text{ }\mu\text{m}$ precision. In the wheels in the region $2 < |\eta| < 2.7$ Cathode Strip Chambers (CSC) are used, instead. They can withstand higher particles rates and have a good time resolution and, thanks to their design, they provide a measurement both in the bending plane, $40\text{ }\mu\text{m}$ precision, and in the transverse plane, 5 mm precision.

For the trigger system Resistive Plate Chambers (RPC) are used in the barrel ($|\eta| < 1.05$) and Thin Gap Chambers (TGC) are used in the endcaps (up to $|\eta| = 2.4$). The trigger chambers provide p_T thresholds, the possibility to identify the bunch-crossing thanks to their time resolution, and the measurement of the track coordinate in the ϕ plane with a precision ranging between 2 and 10 mm.

In standalone measurements the spectrometer has 10% resolution for a 1 TeV muon track, and muon tracks can be measured with good precision in the p_T range from 3 GeV to 3 TeV.

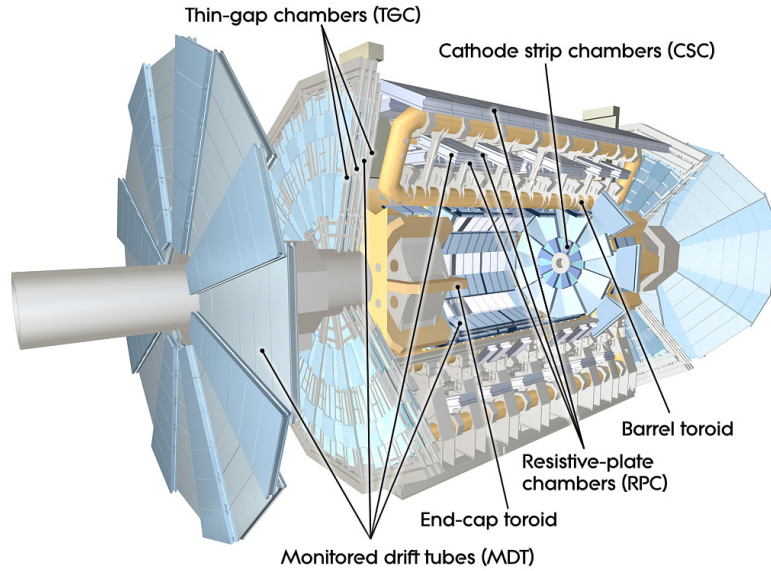


Figure 3.6: Cut-away view of the ATLAS muon system [89].

3.2.5 Trigger and Data Acquisition

The trigger and data acquisition (TDAQ) system manages the triggering and storage of the interesting collision data. The trigger is divided in three levels L1, L2 and Event Filter (EF), these latter grouped in the High Level Trigger (HLT). Each level refines the decision of the previous and may add additional event selections or requirements. The scheme of the ATLAS trigger system is shown in Fig. 3.7.

The Level 1 Trigger uses only a limited amount of detector information - only calorimeters and muon trigger chambers - to determine Regions Of Interest (ROI) where particular features are identified and criteria as energy thresholds are fulfilled. On average the processing time per event is of $2.5\text{ }\mu\text{s}$ and the event rate from about 40 MHz is reduced to 75 kHz.

The Level 2 Trigger uses the information from all detectors to inspect the ROI selected by L1; in

particular, the use of the tracker allows for better particle identification. With refined selections the rate is reduced to 3.5 kHz for a mean processing time per event of 40 ms.

Finally the Event Filter (EF), run after the event reconstruction, analyses events based on the L2 selection using software algorithms similar to offline analysis procedures. The processing time is, therefore, much higher than for the previous levels reaching 4 s per event on average. The final rate of events, selected by the EF, that are saved permanently is of 200 to 400 Hz.

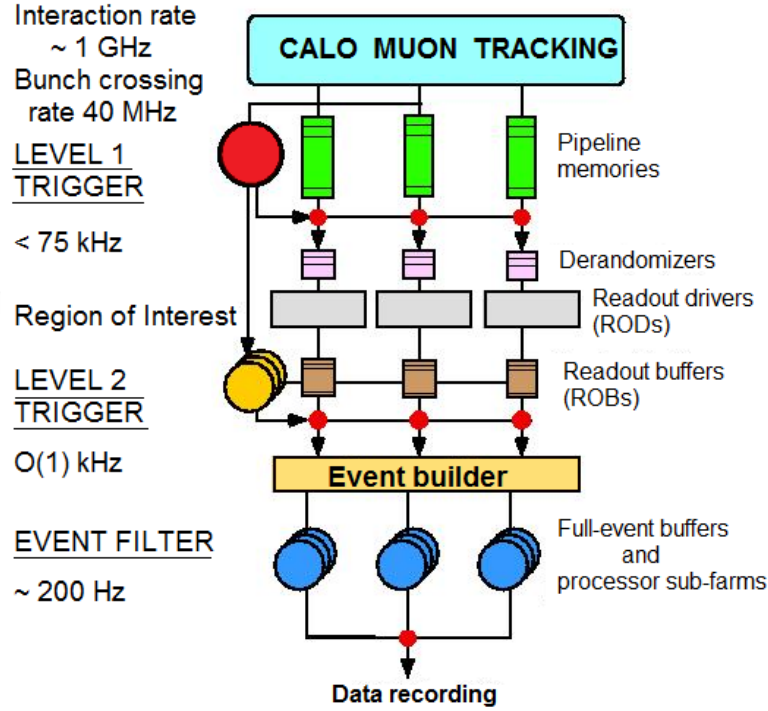


Figure 3.7: Diagram of the ATLAS trigger system: the three trigger levels are displayed with the reduction in the event rate achieved from 40 MHz bunch crossing rate to 200-400 Hz kept for recording [91].

The data acquisition stores the information long enough for the L1 trigger to take the ROI decisions with the aid of Read Out Drivers (ROD) and passes the full detector data of the ROI to the L2 trigger. During data taking, the detector hardware and software are controlled and monitored by the data acquisition system. The Detector Control System (DCS), instead, ensure the safe operation of the detector hardware providing a unique interface to all sub-detectors and communicating with other systems that have a separate control system such as the LHC accelerator or the ATLAS magnet system.

3.2.6 Luminosity and Data Taking

The amount of integrated luminosity delivered to the ATLAS experiment by the LHC in 2011 and 2012, and analysed for the SUSY searches presented in Chapters 7 and 8, at $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV, respectively, is shown against time in Fig. 3.8a. The green histogram represents the luminosity delivered by the LHC, in yellow is shown the luminosity recorded by the ATLAS detector and in blue the amount of data with good quality for physics analyses. The difference in luminosity delivered to and recorded by the ATLAS experiment is due to different data acquisition inefficiencies, among these the “warm start”, that is the time needed to ramp up the voltage of the inner detector and of the muon spectrometer and to turn on the pixel preamplifiers when stable beams are declared. The average data taking efficiency

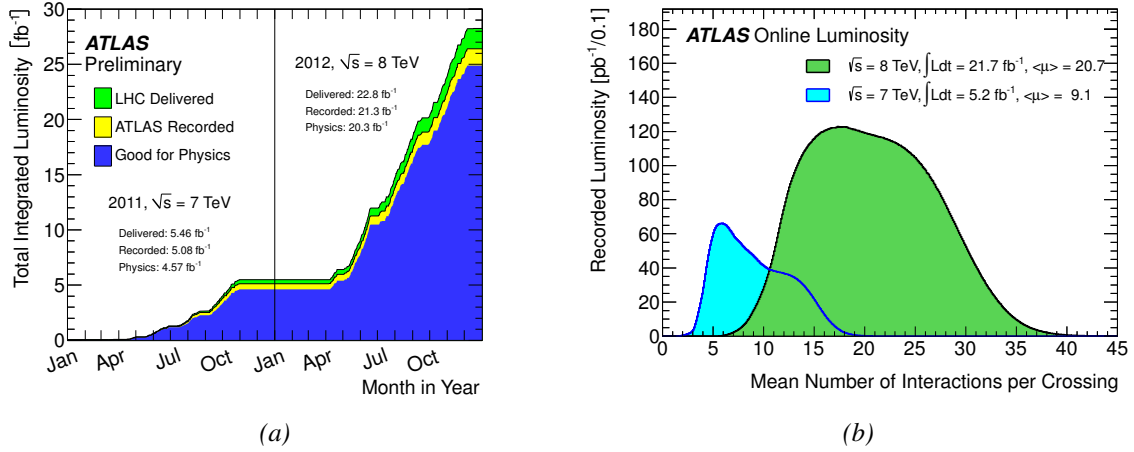


Figure 3.8: (a) Total integrated luminosity in fb⁻¹ delivered in 2011 and 2012 by the LHC (green), recorded by the ATLAS experiment (yellow) and good for physics analyses (blue). (b) Distribution of the recorded luminosity as a function of the average number of interactions per bunch crossing, $\langle\mu\rangle$, for the 7 (light blue) and 8 (green) TeV ATLAS datasets [92].

over the full Run 1 was at the level of 93%.

The luminosity can be defined based on machine and beam parameters. The instantaneous luminosity, $\mathcal{L}$, is in fact an important specification of a collider. It is the quantity that multiplied by the cross section of a process, σ , gives the rate of events expected from it, R_{ev} :

$$R_{ev} = \mathcal{L} \cdot \sigma \quad (3.3)$$

The luminosity depends on the beam parameters and it is defined as

$$\mathcal{L} = \frac{N_p^2 \cdot n_b}{4\pi \cdot \sigma_x \sigma_y} \cdot f \text{ [cm}^{-2}\text{s}^{-1}\text{]}, \quad (3.4)$$

where N_p is the number of protons per bunch, n_b the number of bunches per beam, f is the revolution frequency and, assuming Gaussian shaped beams, $\sigma_{x/y}$ is the transverse width of the beam at the interaction point.

The luminosity decreases during a LHC run primarily due to loss of protons in the collisions and secondarily for particle scattering on the residual gas in the beam pipes and for the intra beam scattering. The estimated luminosity lifetime is $\tau_{\mathcal{L}} = 14.9$ h.

The integrated luminosity

$$\mathcal{L}_{int} = \int \mathcal{L} dt \text{ [cm}^{-2}\text{]}, \quad (3.5)$$

represents the recorded data integrated over a given amount of time, usually a so-called luminosity block in which the instantaneous luminosity can be regarded as being constant. Assuming optimal LHC machine efficiency, nominal luminosity and 200 days of data taking per year, the total integrated luminosity per year would amount to 100 fb⁻¹.

The luminosity can be measured via bunch-by-bunch measurements, exploiting the very forward detectors dedicated to the luminosity measurements, see Section 3.2, or with so-called van der Meer scans, which are beam-beam separation scans that allow the direct measurement of the transverse dimensions of the beams $\sigma_{x/y}$ [93].

The number of mean interactions per bunch crossing $\langle\mu\rangle$ in 2011 and 2012, which is a measure of the

amount of pile-up in the events, is summarised in Fig. 3.8b. It amounts to $\langle\mu\rangle = 9$ and $\langle\mu\rangle = 21$ in 2011 and 2012 respectively, while in 2010 $\langle\mu\rangle$ was smaller than 3. The peak number of interactions per bunch crossing in Run 1 is, instead, shown in Fig. 3.9.

In 2010 the highest measured instantaneous luminosity was $2 \cdot 10^{32} \text{ cm}^{-2}\text{s}^{-1}$, in 2011 the value $3.6 \cdot 10^{33} \text{ cm}^{-2}\text{s}^{-1}$ was reached and in 2012 the highest instantaneous luminosity measured was of $7.73 \cdot 10^{33} \text{ cm}^{-2}\text{s}^{-1}$.

The total integrated luminosity recorded by the ATLAS experiment in 2010 is of 45 pb^{-1} (47 pb^{-1} delivered) with a final uncertainty of $\pm 3.5\%$, in 2011 5.1 fb^{-1} (delivered 5.5 fb^{-1}) with a final uncertainty of $\pm 1.8\%$, and in 2012 21.3 fb^{-1} (delivered 22.8 fb^{-1}) with an uncertainty of $\pm 2.8\%$. The key parameters of the datasets recorded in 2011 and 2012 are summarised in Table 3.1. The detailed description of the methods used to determine the final integrated luminosity recorded by the experiment can be found in Refs. [93, 94].

	2011	2012
$\sqrt{s}$ [TeV]	7	8
σ_{inel} [mb]	71.5	73
Peak Luminosity [$\text{cm}^{-2}\text{s}^{-1}$]	$3.6 \cdot 10^{33}$	$7.73 \cdot 10^{33}$
$\langle\mu\rangle$	9	21
Delivered Luminosity [fb^{-1}]	5.5	22.8
Recorded Luminosity [fb^{-1}]	5.1	21.3
Luminosity after Data Quality [fb^{-1}]	4.6	20.3
Uncertainty on Luminosity	$\pm 1.8\%$ ($\pm 3.9\%$)	$\pm 3.6\%$ ($\pm 2.8\%$)
Data Taking Efficiency	93%	93.4%

Table 3.1: Summary of the most important data taking and luminosity parameters of the 2011 and 2012 ATLAS datasets [92, 93, 94]. The luminosity uncertainty quoted in brackets is the one used in the analyses.

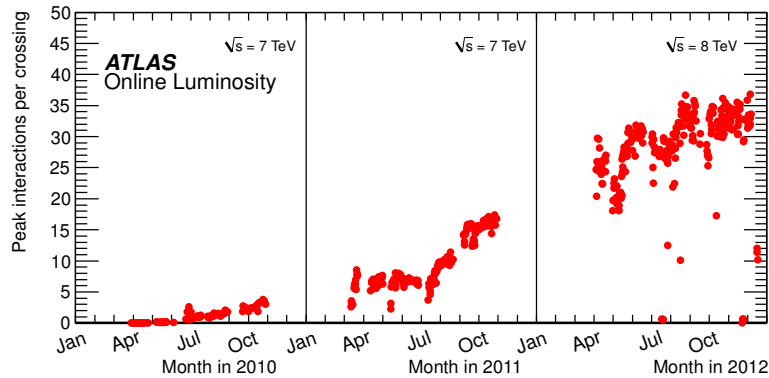


Figure 3.9: Distribution of the maximum number of interactions per single bunch crossing (peak interactions per crossing) as a function of the month of data taking in the period 2010-2012 [92].

3.3 The Worldwide LHC Computing Grid

At design luminosity, the collision rate within the ATLAS detector is of the order of 40 MHz. Trigger decisions lower this rate to 400 Hz of interesting events, see Section 3.2.5, which corresponds in average

to 600 MB/s of data to be saved for the analyses [95, 96]. The total amount of data collected by the ATLAS experiment during LHC Run 1 sums up to about 8 PB. On top of the real data a huge amount of simulated data have to be prepared and stored for the physics analyses [95, 97].

Given this huge amount of data to be stored, distributed, processed and analysed, a flexible and efficient computing infrastructure is essential.

The Worldwide LHC Computing Grid (WLCG) is the collaboration, founded in 2001, that provides the computing infrastructure both in term of storage and of processing power for the LHC experiments [96]. It has to handle the data volume coming from the experiments at a rate of hundreds of Hertz, to allow the users of the experiments to access the data for their analyses in a stable and reliable way and to archive these data for the long term.

Since this cannot be provided by a single computing centre, the solution was to build a distributed system that, combining the resources of multiple centres and creating an authentication and authorisation infrastructure, could match the experimental requirements. This was achieved by using the technology of grid computing that also allows users from all over the world to access and process the stored data.

The WLCG has a hierarchical structure, three main layers of computer centres form its infrastructure: one Tier 0, at CERN, eleven Tier 1, of which seven are in Europe, and more than 100 Tier 2 organised in management federations.

The Tier 0 coordinates the tiers, the tasks distribution to the sites and the operation of the grid. Being the nearest to the experiments, it receives the raw data directly from the experiments and archives it immediately to tape, to ensure that it remains available to the users on the long term. As a safety measure a second copy of the data is distributed among the Tier 1 centres by mean of a dedicated connection that allows a data transfer of 10 GB/s. The big Tier 0 computing cluster is used primarily for the tasks of detector calibration and alignment and for the first data reconstruction.

Each of the Tier 1 sites is responsible for the MC production and the data (re)processing, it archives an agreed amount of raw, reconstructed and simulated data. They provide computing clusters used for large scale analysis, such as data reprocessing, and support a group of Tier 2 sites. The Tier 2 clusters are used mainly for the user data analysis and for Monte Carlo simulation; they pledge computing power and disk space to the experiments but they do not have to archive data. Their resources are accessible to all the members of an experiment, who must be able to run their analysis at any Tier location.

In order to allow an easy and correct access and manipulation of the data, the following services are guaranteed by the grid.

- Storage elements with implemented mechanisms of data transfer and retrieval as well as database with file catalogs, detector conditions and metadata of the experiments.
- Computing services such as job submission and monitoring based on share and distribution of the workload to the sites and the possibility to use the application software of the experiments.

3.4 Detector Simulation

Simulated data is used in many ATLAS performance and physics studies to have a prediction of the expected behaviour and response of a particular process. In order to have reliable simulated samples, it is important not only the Monte Carlo generation of the physics processes, see Section 2.3.1, but also the correct detector simulation. For example, depending on its lifetime, a particle may be decayed directly by the generator or during detector simulation. The ATLAS collaboration uses as baseline tool for the detector simulation the GEANT4 toolkit [98, 99] interfaced to Athena, the ATLAS software framework [95, 100]. Faster simulations have also been developed to decrease the simulation running time.

ATLFAST-II (AFII) [101] found broad use in the collaboration thanks to its possibility of combining full GEANT simulation for parts of the detector with parameterized simulation for others.

The full detector simulation makes use of the proper description of the geometry and conditions of the detector. It gives a complete description of the decays and the interaction of the particles with the detector by propagating every generated particle through the detector material. This process is very CPU intensive and, in average, just for the simulation step more than 30 minutes are needed for a single $t\bar{t}$ event; of this time around 80% is needed for the propagation and the showering of the particles in the calorimeters. The slowness of the simulation can be a showstopper when a very high number of simulated events is needed for a single process or when, as in the case of the SUSY searches, hundreds of different physics processes have to be simulated.

The ATLFAST-II simulation with FastCaloSim [101] is a valid alternative to the full simulation. The inner detector and the muon spectrometer are simulated with the full detector description, while for the response of the calorimeters a parameterization of the energy profile of the showers in the longitudinal and transverse plane is used. The parameterization depends strongly on the particle generating the shower: photons are chosen as exemplification for the electromagnetic showers and charged pions for the hadronic ones. After event reconstruction, the differences between full and AFII simulation amounts to no more than 5% that can be further reduced by applying objects calibration corrections. Since the AFII simulation is in average between 20 and 40 times faster than full simulation, as can be seen from Fig. 3.10, and its performance in terms of physics description of an event maintains a high level, it has been used extensively for Run 1 ATLAS MC production for rare and very busy processes such as the decays of SUSY particles.

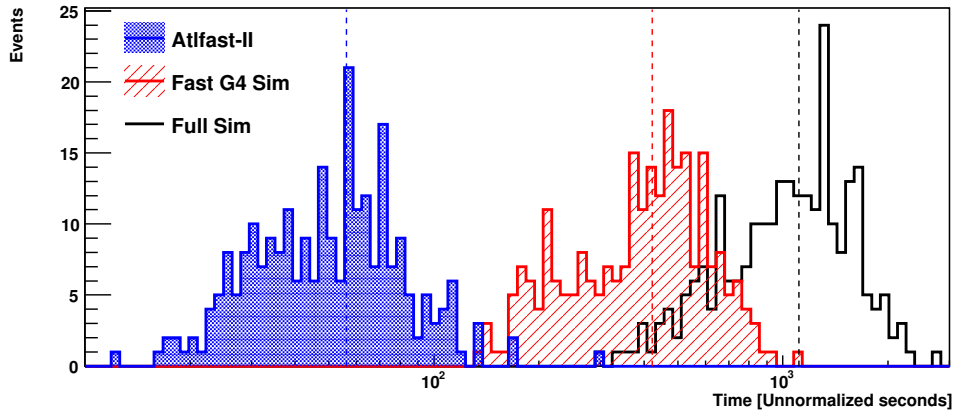


Figure 3.10: Distribution of the number of events per simulation time for full, Fast G4 and ATLFAST-II detector simulations. The reconstruction and detector simulation was run on 250 $t\bar{t}$ events. The dashed lines represent the mean of the distributions [98].

Physics Objects Reconstruction and Performance

In this chapter the reconstruction and identification of the physics objects at the ATLAS experiment, together with their performance, is discussed. Only the objects relevant to the analyses described in Chapters 7 and 8 are presented; these are tracks and vertices, Section 4.1, electrons, Section 4.2, muons, Section 4.3, jets together with the tagging of heavy flavour jets, Section 4.4, and missing transverse momentum, E_T^{miss} , Section 4.5.

4.1 Track and Vertex Reconstruction and Performance

The reconstruction of tracks is necessary to be able to identify charged particles and the hard interaction vertex as opposed to the pile-up vertices. In a low pile-up environment the tracking reconstruction algorithms perform well and the data-MC agreement is good [102]. With the increase of the mean number of interactions per bunch crossing a balance has to be found between tighter requirements, to decrease the number of fake tracks and vertices, and the loss in reconstruction efficiency [103].

To reconstruct tracks three algorithms are used:

- *Inside-out* algorithm: the track is reconstructed starting from three seed hits in the silicon detectors, then other compatible hits are added and finally the track is extended to the TRT. This is the baseline algorithm and it is used to reconstruct the tracks of primary particles, i.e. particles with a mean life time $\tau_L > 3 \times 10^{-11}$ s. A minimum p_T threshold of $p_T > 0.4$ GeV is required for a track to be retained.
- *Back-tracking* algorithm: starts from track fragments reconstructed in the TRT and extends them towards the interaction point by adding silicon hits. This algorithm identifies the tracks coming from the decay products of primary particles, the so called secondaries.
- *TRT-standalone* tracks are tracks with no associated segment in the pixel and or in the SCT detector.

The baseline requirements for a good track are 7 hits in the pixel + SCT detectors and not more than two holes in the pixel detector, where a hit is a measured point belonging to a track and a hole is a missing point that, given the track trajectory, would have been expected to be measured. The “robust”

requirements used to minimise the number of reconstructed fake tracks, are 9 hits in the silicon detectors and no holes in the pixels.

The track reconstruction efficiency for primary particles versus the track p_T is shown in Fig. 4.1a. The efficiency is defined as the fraction of reconstructed tracks matched to a primary particle and it is stable in different pile-up conditions with the tight as well as with the baseline track requirements. A 5% loss in efficiency is observed when applying the robust selection. The robust requirements, though, are very effective in eliminating the pile-up dependency of the ratio of secondaries and combinatorial fake tracks over the primary tracks by rejecting most of the fake tracks. This ratio as a function of the track p_T is shown in Fig. 4.1b for the different pile-up conditions studied and the two reconstruction selections, baseline and robust.

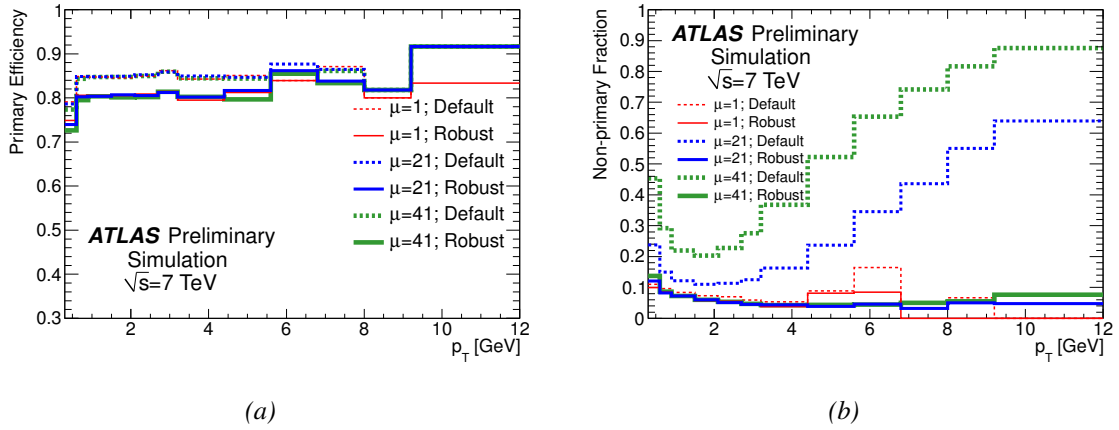


Figure 4.1: (a) Primary particle track reconstruction efficiency as a function of the track p_T . (b) Fraction of non primary tracks as a function of the track p_T . To monitor the pile-up dependence of the track reconstruction, three samples with different pile-up conditions have been used: in red a sample with no pile-up ($\mu = 1$), in blue a sample with medium pile-up ($\mu = 21$) and in green a sample with high pile-up ($\mu = 41$) [103].

The identification of primary vertices (PV) exploits an iterative χ^2 algorithm. The crossing points of reconstructed tracks with the beam axis are taken as seeds. A compatibility weight is then associated to each track to assess the probability that it belongs to a certain vertex, where any considered vertex must have at least two tracks associated to it.

The vertex reconstruction efficiency is at the 80% level in minimum bias events, as can be seen in Fig. 4.2a. With increasing μ a degradation in the efficiency is also observed: for $\mu = 41$ the average reconstruction efficiency is of 50%. When considering only vertices with at least two tracks in the acceptance region of the inner detector and applying the pile-up robust selection, the interaction reconstruction efficiency can exceed 90%.

The probability of having fake vertices increases with pile-up from a percent at $\mu = 1$ to 7% at $\mu = 41$, as shown in Fig. 4.2b. A vertex is defined as fake when the leading contributions to it come from fake tracks. The robust requirements ensure that the fake vertex contribution remains below the percent level even when a high number of interactions per bunch crossing are recorded without decreasing sensibly the reconstruction efficiency.

4.2 Electrons

Electrons provide a clear signature and have a very good performance in terms of reconstruction and identification efficiencies and low systematical uncertainties related to the determination of their energy

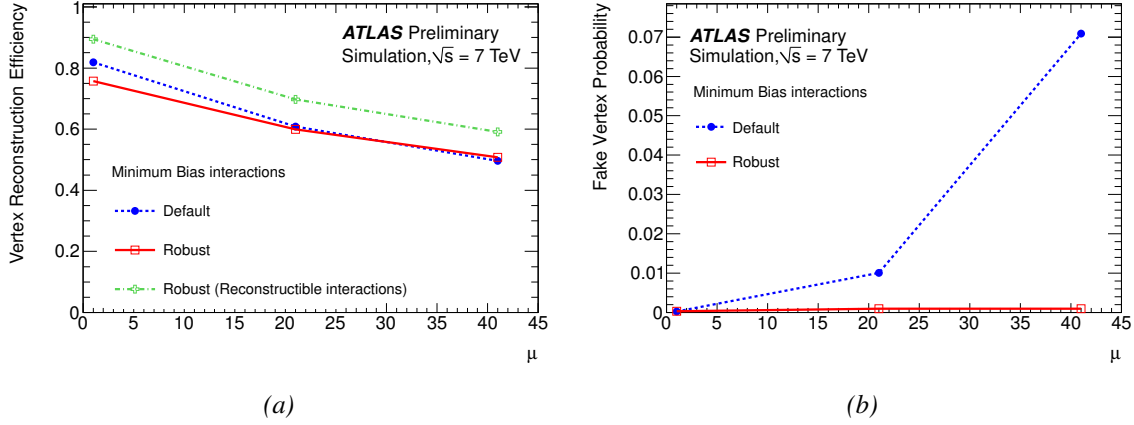


Figure 4.2: (a) Dependency of the vertex reconstruction efficiency on the pile-up in minimum bias Monte Carlo events. Reconstructible interactions, green dashed line, are defined as the vertices with at least two primary tracks in $|\eta| < 2.5$ and with $p_T > 0.4$ GeV. (b) Probability of reconstructing a fake vertex as a function of μ [103].

scale and resolution.

The electron triggers are based on the energy deposition in the calorimeters by electromagnetic showers; this energy has to exceed pre-defined thresholds in order for the event to be selected. The details on the performance of the electron triggers can be found in Ref. [104].

In the following, electron reconstruction and identification is discussed in Section 4.2.1, and the results of the determination of the electron energy scale and its resolution, based on tag-and-probe methods, are reported in Section 4.2.2. These studies make use of $J/\psi \rightarrow ee$, $Z \rightarrow ee$ and $W \rightarrow e\nu$ datasets recorded by the ATLAS experiment at $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV in 2011 and 2012.

4.2.1 Reconstruction and Identification

The reconstruction of electrons in the central detector region, $|\eta| < 2.5$, consists of three steps [105]. First electromagnetic clusters are defined by selecting cells with energy above 2.5 GeV and by grouping them in 3×5 arrays of $\Delta\eta \times \Delta\phi = 0.25 \times 0.25$ calorimeter cells. The second step is the track-cluster matching. Tracks with $p_T > 0.5$ GeV are selected and are extrapolated to the middle electromagnetic calorimeter layer to define the track coordinates; these are compared to the barycentre position of the cluster: if their distance is less than 0.05 in η and less than 0.1 in ϕ a successful match is found and the electron is defined as reconstructed. In the case of multiple matches the one with the minimum ΔR is chosen. For the 8 TeV dataset, additional track-matching criteria have also been taken into account to properly reconstruct electrons that lost significant amount of energy in the dead material in front of the calorimeter due to bremsstrahlung [106]. Finally the size of the clusters is optimised to account for the energy deposited in all layers of the calorimeter. The cluster windows are hence enlarged to 3×7 cells in the barrel and 5×5 in the endcaps.

The electron candidate energy is the sum of the measured cluster energy and the estimated energy lost before the calorimeter, not included into the cluster (lateral leakage) and deposited in the hadronic calorimeter (longitudinal leakage).

Three sets of identification criteria, loose, medium and tight, are defined based on sequential cuts on the candidate's properties. For the 8 TeV dataset, identification selections based on a multivariate analysis are also available but will not be further discussed since they are not used in the analyses presented in this thesis (details can be found in Ref. [106]).

An electron is defined as *loose* when it passes requirements on shower shape variables, hadronic leakage, quality of the track and of the track-cluster match. A *medium* electron must satisfy more stringent selections on the variables used for loose electrons and in addition selections on the hits in the pixel detector and on the transverse impact parameter are added. The *tight* identification has tighter selections with respect to medium and additional requirements on track quality, on the ratio of the cluster energy to track momentum and a veto on photon conversion vertices. The loose, medium and tight requirements have a rejection factor of order 2500, 25000 and 50000, respectively, against reconstructed hadronic jets with $p_T > 20$ GeV.

Calorimeter or track based isolation requirements can be additionally applied to select clean electron candidates.

To quantify the performance of the electron reconstruction and identification, the total electron efficiency, ε_e , is defined as

$$\varepsilon_e = \varepsilon_{cluster} \cdot \varepsilon_{reco} \cdot \varepsilon_{id} \cdot \varepsilon_{trig} \cdot \varepsilon_{other}. \quad (4.1)$$

ε_e is the product of the clustering, reconstruction, identification and trigger efficiencies, which are analysis independent quantities, and of an analysis specific term, ε_{other} , that takes into account the efficiency of the additional selections applied to the electron, e.g. isolation requirements.

For electrons with transverse energy above 20 GeV the efficiency to identify the cluster is higher than 99%. The efficiency measurements are divided in E_T and η bins.

The combined reconstruction and identification efficiency for the 7 TeV dataset is shown in Fig. 4.3a as a function of the transverse energy of the electron for the loose, medium and tight identification requirements and in Fig. 4.3b the efficiency uncertainties are shown, again as a function of E_T . The reconstruction efficiency for an electron with $E_T > 30$ GeV is of 96% in the barrel and 90% in the endcaps region. The identification efficiencies vary from low to high E_T between 90% and 98% for the loose, between 80% and 90% for the medium and between 65% and 80% for the tight selections.

The results obtained with the 8 TeV dataset are shown in Figs. 4.3c and 4.3d. Here also the data to MC efficiency ratios are displayed and show that the scale factors to be applied to the MC, for it to correctly describe data, are very near to 1 with larger deviations at low E_T or high η . Taking the average over η , the reconstruction efficiency is of 97% for electrons with $E_T = 15$ GeV and reaches 99% for 50 GeV electrons. The identification efficiency depends strongly on the energy of the electron, the loose identification selection gives in average an efficiency of 96%, the tight one has an average efficiency of 78%.

4.2.2 Energy Scale and Resolution

To determine the absolute electron energy scale the Z resonance line shape is used [107], while the electron energy resolution and the uncertainties on it are derived by studying the Z resonance width.

The energy scale and resolution are determined only as a function of η since the residual non uniformity in ϕ is of 0.75% and the stability over time is at the 0.05% level. The difference in response between data and MC is a measure of the energy miscalibration. The corrections are extracted as factors α_i representing the deviations from optimal calibration in the i^{th} η bin as

$$E_{data} = E_{MC}(1 + \alpha_i). \quad (4.2)$$

The measured energy corrections, summarised in Fig. 4.4a as a function of η , are at the percent level with larger deviations (2-4%) in the calorimeter transition regions and at high η ; the uncertainty on the α_i varies between 0.5 per mil in the central region to 0.4% in the calorimeter transition regions.

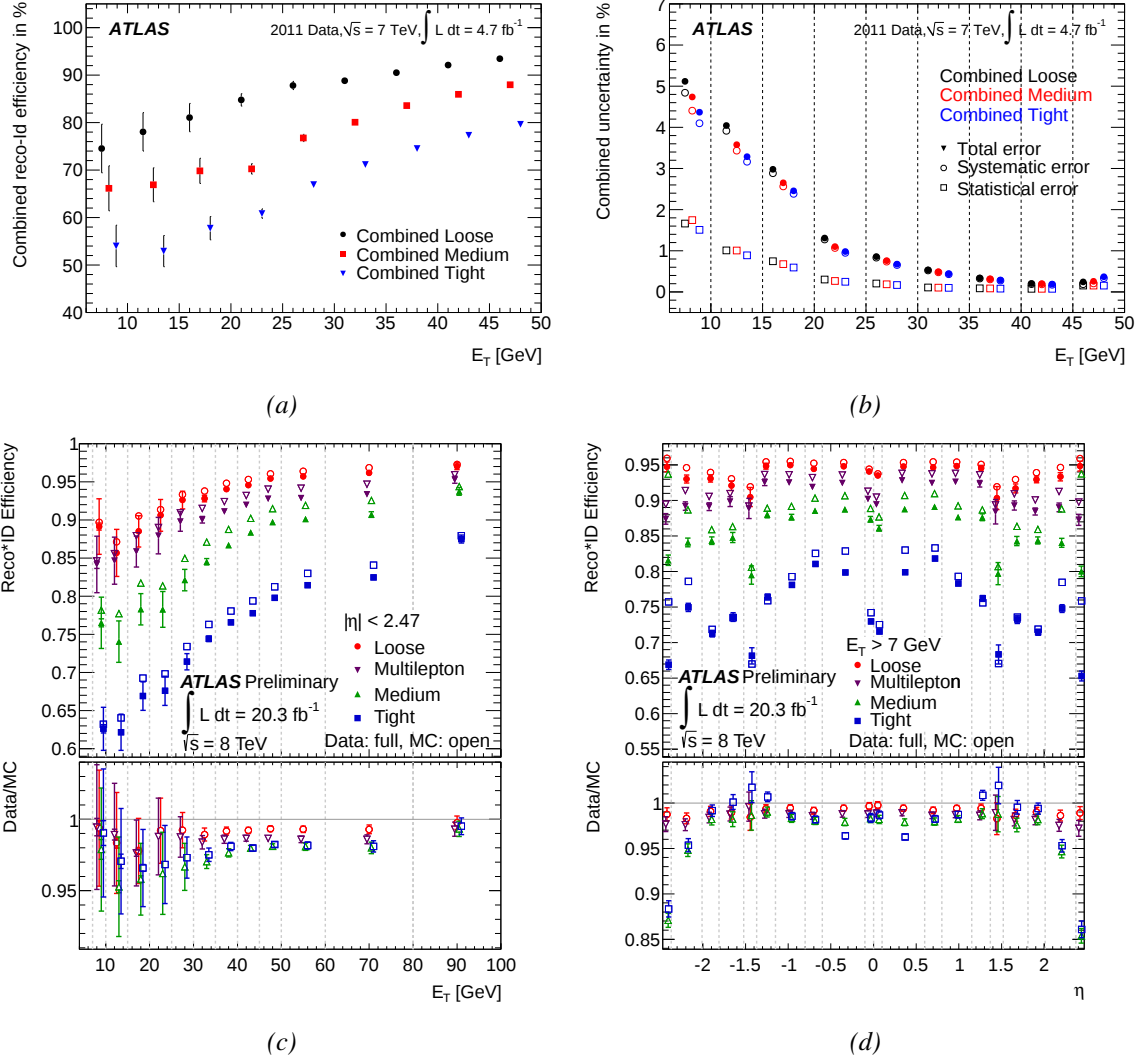


Figure 4.3: (a) Combined reconstruction and identification efficiency in data for the loose, medium and tight electron identification requirements as a function of E_T for the 7 TeV dataset, the error bars represent the total uncertainty; (b) breakdown of the uncertainty in statistical and systematic component as a function of E_T for the 7 TeV dataset [105]. Combined reconstruction and identification efficiency in data and MC for the loose, medium, tight and multilepton electron identification requirements as a function (c) of E_T and (d) of η for the 8 TeV dataset, the error bars represent the total uncertainty and data to MC efficiency ratios are also shown [106].

The parameterization of the energy resolution is defined as

$$\frac{\sigma_E}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c, \quad (4.3)$$

where a is the sampling term, assumed to be known from test beam studies to be 10%, b is the noise term and c is the constant term.

Assuming that the simulation reproduces well the resolution curve up to a Gaussian constant term, the resolution in data, $(\sigma_E/E)_{data}$, can be written as the resolution in MC to be summed in quadrature

with a constant Gaussian correction c :

$$\left(\frac{\sigma_E}{E}\right)_{data} = \left(\frac{\sigma_E}{E}\right)_{MC} \oplus c. \quad (4.4)$$

The resolution corrections are shown as a function of η in Fig. 4.4b. They are at the 0.8% level in the central calorimeter region and at 1% in the endcaps with an uncertainty of ± 0.3 to $\pm 0.5\%$. Figure 4.4c shows the dielectron invariant mass distributions after all calibrations have been applied to data and after the MC has been corrected to match the measured energy resolution. Some deviations are still observed at low mass but they are within the calibration uncertainties. Finally in Fig. 4.4d the electron energy resolution is shown as a function of E_T for electrons at $|\eta| = 0.2$. It varies from 3% for 20 GeV electrons to almost 1% for high p_T electrons. The resolution uncertainty is minimal at 40 GeV where it amounts to $\pm 5\%$ and increases with the electron energy to $\pm 25\%$ for 200 GeV electrons.

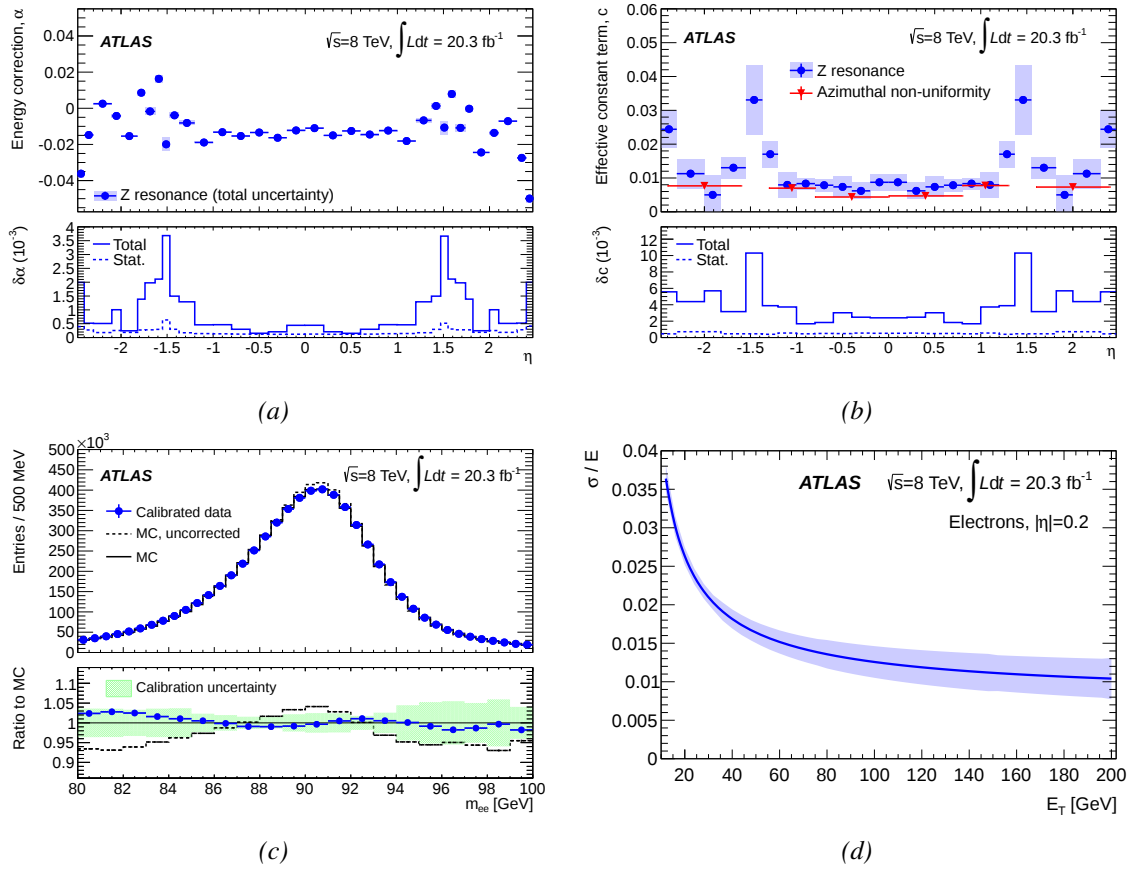


Figure 4.4: (a) Energy correction α_i as a function of η ; in the bottom panel the uncertainty on the correction is shown. (b) Constant term c of the energy resolution as a function of η ; in the bottom panel the uncertainty on the measured constant term is shown. (c) Invariant mass distributions of the selected electron pair from $Z \rightarrow ee$ in data and in MC, with or without energy corrections applied; in the bottom panel the ratios of the data and of the base MC over the corrected MC are shown with the uncertainty band corresponding to the total calibration uncertainties. (d) Resolution curve with the total uncertainty band as a function of the electron energy at $|\eta| = 0.2$ [107].

4.3 Muons

As electrons, muons have a clear signature, a good reconstruction and identification efficiency, and low uncertainties associated to the determination of their energy scale and resolution. Again, tag-and-probe methods have been employed to determine the reconstruction efficiencies in $Z \rightarrow \mu\mu$, $J/\psi \rightarrow \mu\mu$ and $\Upsilon \rightarrow \mu\mu$ samples [108]. These same samples have been exploited to define the momentum and mass scale and resolution. The ratio of the reconstruction efficiencies in data and in MC is the scaling factor that has to be applied to MC in order to reproduce the data behaviour and the detector conditions. Scale factors are provided as maps with a fine η and ϕ binning.

Detailed information about the operation and performance of the muon triggers, used to select events with high momentum muons with $|\eta| < 2.4$, can be found in Ref. [109].

In the following sections, first the identification and determination of the muon reconstruction efficiencies, then the results of the studies of the momentum and mass scale and resolution are presented.

4.3.1 Reconstruction and Identification

Muons are identified and reconstructed by using the information gathered by the muon spectrometer, up to $|\eta| = 2.7$. The measurements of the inner detector, up to $|\eta| = 2.5$, are also used to improve the muon momentum reconstruction performance. The muon tracks in the spectrometer are reconstructed by identifying track segments in each layer of the chambers, that are then combined to form a full track. Muons are classified in different types based on their reconstruction.

- *Stand-Alone* muons (SA) are reconstructed using only the hits in the muon spectrometer, used mainly in the region $2.5 < |\eta| < 2.7$ not covered by the inner detector.
- *Combined* muons (CB) are reconstructed by matching a track reconstructed in the ID and in the MS. They are the muon class with the highest purity and the recommended ones for physics analyses.
- *Segment-tagged* muons (ST) are muons where a track reconstructed in the ID is matched to a track segment in the MDT or CSC chambers. They are used to recover the acceptance that may be lost by the CB muons.
- *Calorimeter-tagged* muons (CaloTag) identified by a track in the ID matched to an energy deposit in the calorimeter compatible with a minimum ionizing particle, can be used to recover the acceptance at $|\eta| < 0.1$ where no muon chambers are present.

The ID tracks used to reconstruct a muon have to pass the following quality selections: ≥ 1 pixel hit; ≥ 5 SCT hits; ≤ 2 holes in the silicon detectors; if $0.1 < |\eta| < 1.9$, ≥ 9 TRT hits.

Two different reconstruction algorithms have been used to reconstruct muons during LHC Run 1. Their performances are analogous, therefore only the results for the first Chain algorithm are reported.

The muon reconstruction efficiency is shown in Fig. 4.5a as a function of η for different muon types. The selection used for the analyses is CB+ST muons which reaches a 99% efficiency in the complete range where the muon chambers are present. The ratio plot represents the data to MC scaling factors which deviate from 1 at the 1% level, with some exceptions in the transition regions where it is known that the simulation does not reproduce the data correctly. The reconstruction efficiency for CB+ST muons as a function of the muon p_T is shown in Fig. 4.5b. The minimum p_T needed for a muon to reach the muon chambers and to be reconstructed is 3 GeV, therefore at low p_T a steep increase in efficiency is observed as the muon p_T reaches 6-8 GeV and then stabilises. For $p_T > 20$ GeV the efficiency is

independent of the momentum of the muons within $\pm 0.5\%$ deviations. The CaloTag muons, used for $|\eta| < 0.1$, reach 97% efficiency for $p_T > 30$ GeV. The CB+ST reconstruction efficiency is also stable with pile-up at the 99% level; a loss in efficiency of 1% is observed for $\langle \mu \rangle \geq 35$.

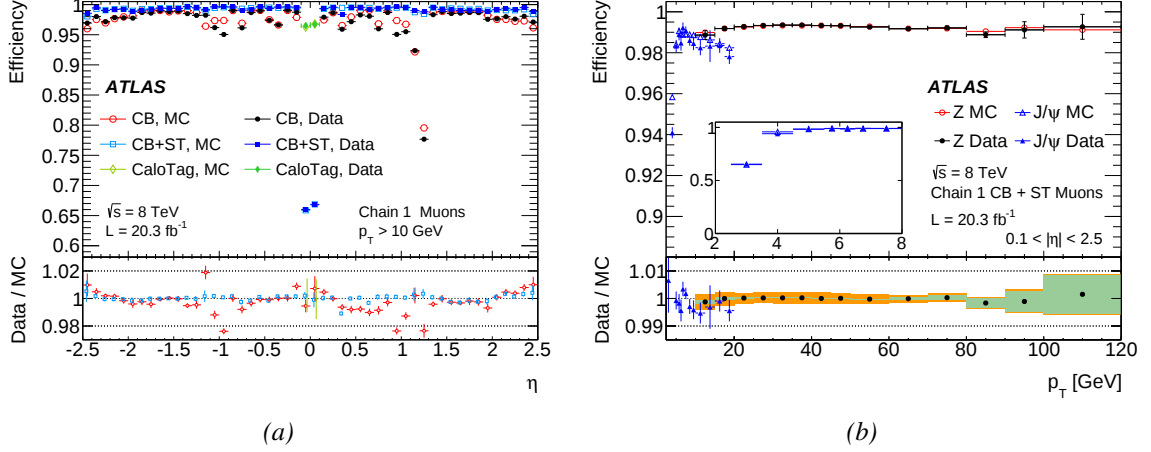


Figure 4.5: (a) Muon reconstruction efficiency as a function of η in $Z \rightarrow \mu\mu$ events. The efficiencies are shown for data and MC, and for different muon types or combination of them, the data to MC ratio represents the data to MC scale factors. (b) Efficiency for CB+ST muons as a function of the muon p_T . The error bars represent the statistical uncertainty for $Z \rightarrow \mu\mu$ events and the statistical and fit uncertainty for $J/\psi \rightarrow \mu\mu$ events; in the data to MC efficiency ratio plot the green band represents the statistical uncertainty, the yellow one the statistical and systematic uncertainties. The “Chain 1” is one of the muon reconstruction algorithms that are used by the ATLAS collaboration [108].

4.3.2 Energy Scale and Resolution

The muon transverse momenta in MC samples need to be corrected in order to match the scale and the resolution measured with the high statistics data samples. Muon momentum smearing and scale correction factors are extracted as a function of η and ϕ of the muons and depending on the detector in which the momentum has been measured, ID or MS. A linear combination of the corrections is used to set the final correction parameters for CB muons.

The momentum resolution can be parameterized as

$$\frac{\sigma_{p_T}}{p_T} = \frac{r_0}{p_T} \oplus r_1 \oplus r_2 \cdot p_T, \quad (4.5)$$

where r_0 corrects for the fluctuations in the energy loss, r_1 takes into account local non uniformity of the magnetic field and multiple scattering, and r_2 represents the intrinsic resolution due to the spatial resolution of the hits and to the residual misalignments.

The scale correction for ID tracks is smaller than 0.1% with uncertainties of ± 0.2 per mil in the central region and ± 2 per mil in the high η range. For MS tracks the scale correction is of the order of 0.1%, with larger corrections of the order of $\pm(0.3 - 0.4)\%$ for specific η ranges. If the p_T reconstructed in the MS is small an additional correction of -30 MeV is needed. The p_T resolution smearing corrections are below 10% for ID tracks and below 15% for MS tracks.

To extract the momentum resolution, a fit of the mass of the studied resonances is performed. Assuming that the momentum resolution of the two muons is similar, the mass and momentum resolutions are related as

$$\frac{\sigma_{m_{\mu\mu}}}{m_{\mu\mu}} = \frac{1}{\sqrt{2}} \frac{\sigma_p}{p}. \quad (4.6)$$

After applying the correction factors to the MC, the agreement in the mass scale between data and MC is within the scale systematic uncertainties that range between ± 0.35 per mil (barrel) and ± 2 per mil (high η). Figure 4.6a shows the data-to-MC ratio for the dimuon invariant mass as a function of the mean muon p_T , $\langle p_T \rangle$, defined as

$$\langle p_T \rangle = \frac{1}{2}(p_{T, \mu_1} + p_{T, \mu_2}) \quad (4.7)$$

for the $J/\psi \rightarrow \mu\mu$ and $\Upsilon \rightarrow \mu\mu$ samples, and as p_T^* for the $Z \rightarrow \mu\mu$ sample, where p_T^* is defined as

$$p_T^* = m_Z \sqrt{\frac{\sin \theta_1 \sin \theta_2}{2(1 - \cos \alpha_{12})}}, \quad (4.8)$$

with $\theta_{1,2}$ polar angles of the selected muons and α_{12} opening angle of the two muons.

The muon mass resolution is dominated by the resolution of the ID up to $|\eta| = 1.5$ and then the MS part becomes more and more important. The uncorrected MC has a 5-10% better resolution than measured in data. After applying the p_T corrections, the data-MC agreement is within uncertainties. Figure 4.6b shows the muon resolution in three $|\eta|$ ranges for the three chosen resonances as a function of $\langle p_T \rangle$. In the central η region the resolution is of 1.2% for 10 GeV muons and reaches 2% for a $p_T = 100$ GeV, while for $|\eta| > 1$ the resolution ranges between 2% and 3%. This translate into a momentum resolution between 1.7%, at low p_T and small η , and 4%, at high p_T and large η .

4.4 Jets

At hadron colliders, jets are key ingredients for the selection of events, for the measurement of known processes and for the study of new phenomena. Jets are reconstructed starting from energy clusters measured in the calorimeters. Since low p_T jets have a strong pile-up dependence, different pile-up suppression strategies have been developed in 2011 and 2012. Jets are calibrated with the help of Monte Carlo simulation and *in situ* techniques using dijet, Z+jets and γ +jets events.

In the following sections, first the anti- k_t reconstruction algorithm is presented together with the definition of the topoclusters, of the matching between tracks and clusters and of the jet vertex fraction (JVF) in Section 4.4.1; then the determination of the jet energy scale (JES) and resolution (JER) are presented in Section 4.4.2. Finally the methods and the performance of the heavy flavour jet tagging are described in Section 4.4.3.

4.4.1 Reconstruction

The main jet clustering algorithm used in the ATLAS experiment, and in the performed analyses, is the anti- k_t [110] algorithm. Other algorithms, such as the Cambridge/Aachen algorithm [111, 112], are also used by some analyses in the collaboration but are not discussed here.

The anti- k_t algorithm is an iterative routine that groups together particles or clusters based on their energy and on their distance. The relevant formulas are those of the system of equations 4.9, with power $p = -1$ of the transverse momenta q_t . The same equations are used to define k_t jets, exploited in the jet area methods for the pile-up suppression in jets, when $p = 1$, and Cambridge/Aachen jets for the choice $p = 0$. The distances in the transverse momentum space d_{ij} , between the objects i and j , and d_{iB} ,

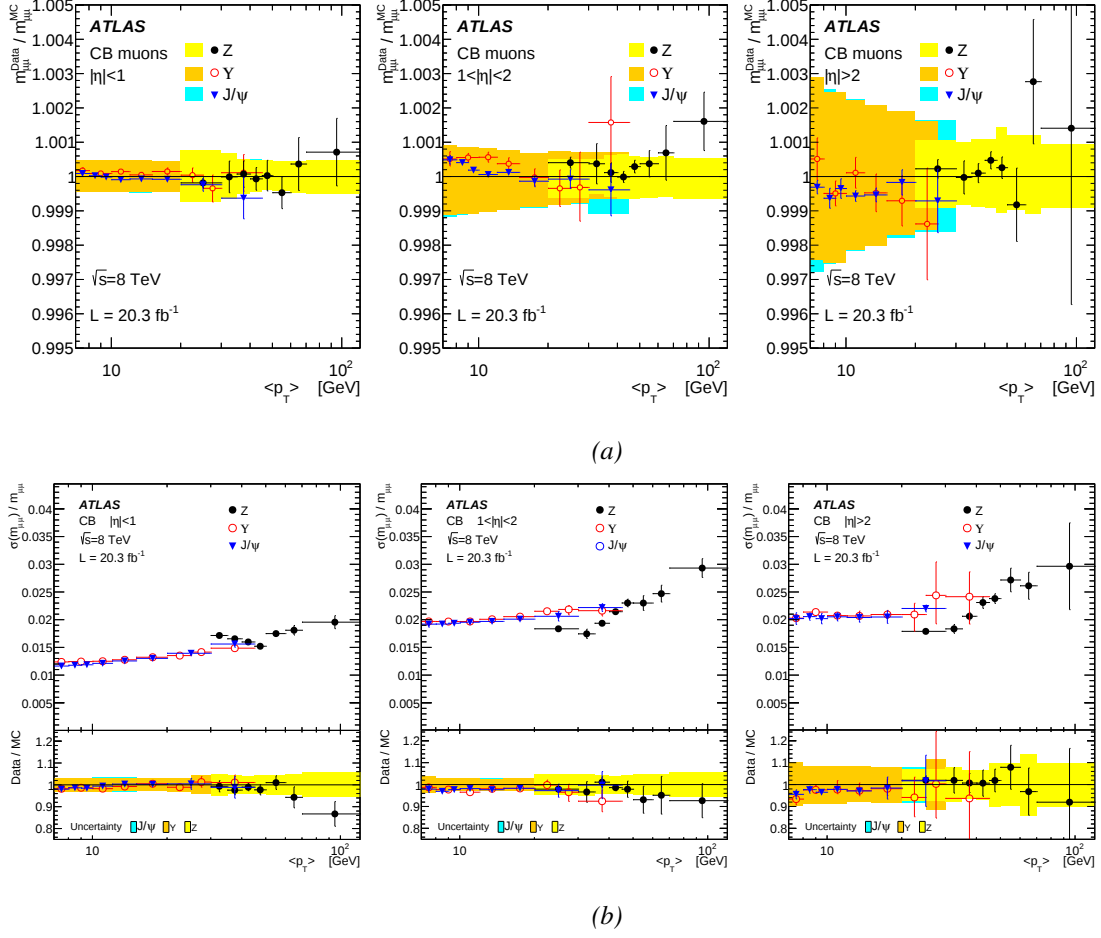


Figure 4.6: (a) Ratio of the mean dimuon mass in data and MC. (b) Relative dimuon invariant mass resolution, $\delta m/m$, as a function of the average p_T in three η ranges, the error bars represent the total uncertainty and the band represents the uncertainty on MC due to the p_T corrections; $\langle p_T \rangle = \frac{1}{2}(p_{T, \mu_1} + p_{T, \mu_2})$ for $J/\psi \rightarrow \mu\mu$ and $\Upsilon \rightarrow \mu\mu$, and $\langle p_T \rangle = p_T^*$ for $Z \rightarrow \mu\mu$ [108].

between the object i and the beam, are defined; $q_{t,i(j)}$ are the transverse momenta of the objects $i(j)$, Δ_{ij} is the distance between the two objects and y is the rapidity, defined in equation 4.10, which in the limit of massless particles, as assumed for the jet constituents, equals the pseudorapidity η ; finally R is the radius parameter used for the jet finding. The radius used for the analyses performed for this thesis is $R = 0.4$ and in the following only its performances are presented.

$$\begin{cases} d_{ij} = \min(q_{t,i}^{2p}, q_{t,j}^{2p}) \frac{\Delta_{ij}^2}{R^2} \\ d_{iB} = q_{t,i}^{2p} \\ \Delta_{ij}^2 = (y_i - y_j)^2 + (\phi_i - \phi_j)^2 \end{cases} \quad (4.9)$$

$$y = \frac{1}{2} \ln \left(\frac{E + q_z}{E - q_z} \right) \quad (4.10)$$

To reconstruct a jet, the distances d_{ij} and d_{iB} are computed. As long as a d_{ij} exists which is smaller than d_{iB} , the objects i and j are clustered together in a new object α ; when one of the d_{iB} values is the

smallest distance, the object i is removed from the list of possible objects and is labelled as “jet”. The clustered objects can be calorimeter clusters, giving origin to calorimeter jets, tracks, giving track jets, or simulated particles, used for the truth jets.

The anti- k_t algorithm is infrared and collinear safe, the jet boundaries are regular as opposed to e.g. Cambridge/Aachen jets, see Fig. 4.7, since only hard particles can modify the jet shape. This gives a certain pile-up robustness to the algorithm: soft particles tend to cluster with hard ones, without modifying much either the shape or the momentum of the final jet, before clustering among themselves. A jet will be perfectly conical if it has no neighbouring jets in a radius $2R$; if the distance between two hard objects α and β is $R < \Delta_{\alpha\beta} < 2R$ the jet with harder momentum k_t will be conical, the other partly conical.

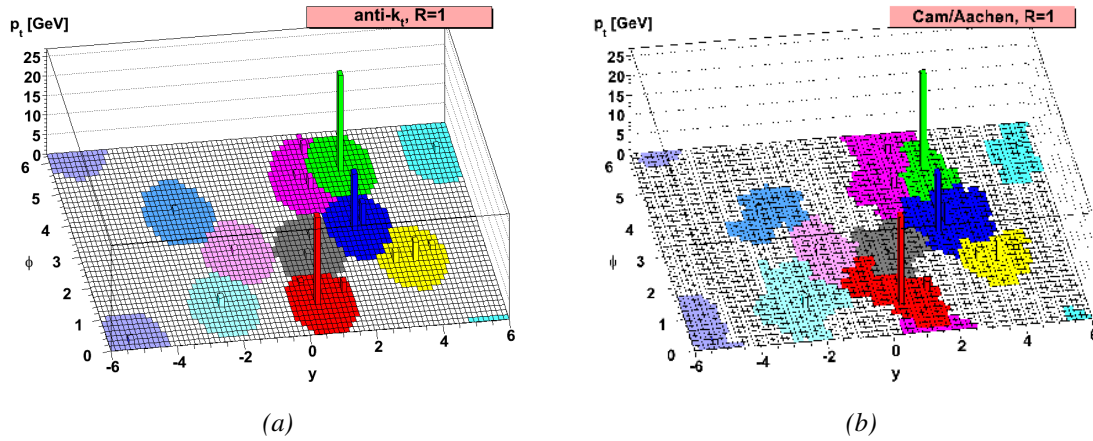


Figure 4.7: (a) Active areas of anti- k_t jets reclustered with radius $R = 1$. (b) Active areas of Cambridge/Aachen jets reclustered with radius $R = 1$ [110].

Another good property of the anti- k_t jets is that their mean area is very close to πR^2 and it has little dependency on the jet p_T . This is shown in Fig. 4.8 where the ratio of the jet area over πR^2 is plotted for different reconstruction algorithms. This flatness is a consequence of the anti- k_t jet shapes being not affected by soft radiation.

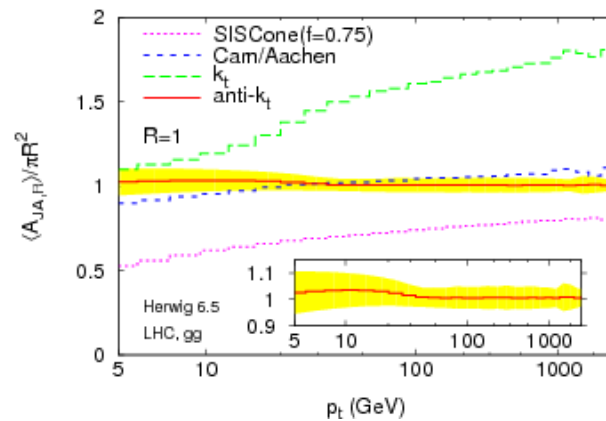


Figure 4.8: Behaviour of the average jet area with respect to the circular area πR^2 as a function of the p_T of the jet for four different clustering algorithms [110].

Within the ATLAS collaboration, jets are reconstructed starting from calorimeter energy deposits

grouped into topoclusters. The topocluster seed cell is a cell where the energy deposited exceeds four times the noise RMS. The noise RMS, σ_{noise} , corresponds to the electronic and the pile-up noise RMS summed in quadrature:

$$\sigma_{\text{noise}} = \sqrt{(\sigma_{\text{noise}}^{\text{electronic}})^2 + (\sigma_{\text{noise}}^{\text{pile-up}})^2}. \quad (4.11)$$

The cluster is then formed by adding to the seed cell all the adjacent cells with a signal to noise ratio greater than 2 and the first layer of neighbouring cells that do not satisfy any of the previous requirements. The topocluster can be either calibrated at the electromagnetic scale (EM) or local cluster weights (LCW), that calibrate the jets at the hadronic scale, can be applied.

When calorimeter jets are formed, they can be associated to tracks measured in the inner detector in order to better identify their origin. Two methods can be exploited, a simple ΔR matching or a method based on ghost association [113]. This last method has a better performance and it is therefore used as baseline.

The track-cluster association is also necessary to define the jet vertex fraction (JVF), a property that can be used to suppress pile-up jets since it gives an estimate of the energy of the jet that comes from the hard scattering [114]. The JVF is defined as

$$\text{JVF}(\text{jet}_i, \text{PV}_j) = \frac{\sum_k p_T(\text{track}_k^{\text{jet}_i}, \text{PV}_j)}{\sum_n \sum_l p_T(\text{track}_l^{\text{jet}_i}, \text{PV}_n)}. \quad (4.12)$$

Chosen a primary vertex PV_j , the JVF of the jet_{*i*} with respect to this vertex is the ratio of the sum of the p_T of the tracks associated to the jet originating from the vertex PV_j over the p_T sum of all the tracks associated to the jet regardless of the vertex.

The JVF ranges between 0 and 1 and jets with no associated tracks are assigned $\text{JVF} = -1$. A jet with:

- $\text{JVF} = 0$ has all tracks originating from pile-up vertices
- $\text{JVF} = 1$ has all associated tracks coming from the hard scatter vertex candidate
- $0 < \text{JVF} < 1$ has some tracks coming from pile-up vertices and some from the hard scatter vertex candidate

The requirement of a minimum JVF for the selected jets guarantees a better stability of the number of selected jets as the pile-up in the event increases. A JVF selection is particularly effective in rejecting low p_T jets arising from pile-up, while it has almost no impact on the high- p_T jets where the fake rate is negligible.

4.4.2 Energy Scale and Resolution

To have fully calibrated jets a series of corrections are applied in subsequent steps [115]. First the calorimeter clusters are calibrated at the EM scale. To have EM topo jets the jet finding algorithm is run directly; to have LCW jets local weights are first applied to the clusters and then the jet finding algorithm is run on these newly calibrated clusters.

When the jets are defined, a first MC based correction is applied to correct for the energy offset introduced by pile-up. For the 2011 dataset the corrections are dependent on N_{pv} and $\langle \mu \rangle$; for the 2012 dataset the jet area correction method is used instead [113, 116, 114], which has the advantages of being independent of the jet algorithm used, of being based on calorimetric information and, hence, of not

relying on the correct association of tracks and vertices to the topocluster. The jet area correction is extracted by first computing the transverse momentum density of the event, ρ , which is a measure of the pile-up contribution in the event and it is used to estimate the pile-up inside the jet area A^{jet} . The jet p_T is then corrected as $p_T^{\text{jetcorr}} = p_T^{\text{jet}} - \rho \times A^{\text{jet}}$. If p_T^{jetcorr} is negative, $p_T^{\text{jetcorr}} = 0$ is set.

The direction of the pile-up corrected jets is then adjusted to point to the primary vertex.

An inclusive jet MC sample is used to extract the energy response, $\mathfrak{R}^{\text{EM(LCW)}}(\eta)$, which is the ratio of the jet energy at the EM (LCW) scale to the energy of the truth-matched jet defined as

$$\mathfrak{R}^{\text{EM(LCW)}}(\eta) = \frac{E_{\text{jet}}^{\text{EM(LCW)}}}{E_{\text{jet}}^{\text{truth}}}. \quad (4.13)$$

The response is the inverse of the correction to be applied to the jet, it is extracted for different jet energies and has a dependency on the jet η .

Finally, a residual *in situ* jet correction is extracted. It consists of an η -intercalibration, extracted from a di-jet sample, that corrects the jet response for the η dependency, and of the *in situ* JES correction extracted by exploiting γ +jets, Z +jets and multi-jet samples where the boson (or a system of low p_T jets) is used as the reference object against which the jet to be calibrated recoils. In this way jets with $20 \text{ GeV} < p_T < 2 \text{ TeV}$ can be calibrated. This last correction is obtained by comparing the ratio of the p_T of the jets measured in data over the p_T of a reference object (e.g. γ or Z boson), to the p_T of the jet measured in MC again over the p_T of a reference object, see equation 4.14.

$$c = \frac{\langle p_T^{\text{jet}} / p_T^{\text{ref}} \rangle_{\text{data}}}{\langle p_T^{\text{jet}} / p_T^{\text{ref}} \rangle_{\text{MC}}} \quad (4.14)$$

The analysis of the 2011 dataset presented in Chapter 7 is based on jets calibrated at the EM scale plus the jet energy corrections (EM+JES jets), while the analysis of the 2012 dataset makes use of LCW jets with their jet energy scale calibration applied (LCW+JES jets).

The difference of response in data and MC is shown against the jet p_T for the 2011 dataset in Fig. 4.9a for anti- k_t $R = 0.4$ jets calibrated at the EM+JES scale. For a jet p_T below 100 GeV a -2% offset in the response of the data is observed, which decreases to -1% for $p_T^{\text{jet}} > 200 \text{ GeV}$. The uncertainty on the JES correction is of $\pm 2.5\%$ for low p_T jets and gets below $\pm 1\%$ for jets $50 < p_T < 500 \text{ GeV}$; at higher p_T the uncertainty increases again at the $\pm 1.5\%$ level mainly due to the increased statistical uncertainty. The response ratio for the 8 TeV dataset versus the jet p_T is shown in Fig. 4.9b for anti- k_t $R = 0.4$ jets calibrated at the LCW+JES scale. Here the deviation from one stays, in most of the p_T range, below 1%; the uncertainties on the corrections vary between $\pm 2\%$ at low p_T to less than $\pm 1\%$ for central p_T values.

The final relative JES uncertainty is shown in Fig. 4.10 for the 7 TeV dataset for anti- k_t $R = 0.4$ EM+JES jets, versus the p_T of the jet for $\eta = 0.5$ (a) and versus η for jets with $p_T = 25 \text{ GeV}$ (b). The uncertainty is larger at high η and at low jet p_T reaching $\pm 6\%$ for jets with $p_T \approx 25 \text{ GeV}$ and $|\eta| \approx 4$. Jets with $p_T > 1 \text{ TeV}$ suffer from a much higher JES uncertainty, which, due to the very low data-event population of this region of the parameter space, was extracted from test beam measurements. For central jets with $p_T > 25 \text{ GeV}$ the uncertainty does not exceed $\pm 2\%$ and central jets with $55 \leq p_T < 500$ are affected by an uncertainty smaller than $\pm 1\%$.

The relative JES uncertainty for the 8 TeV dataset is very similar to what was obtained with the 2011 dataset.

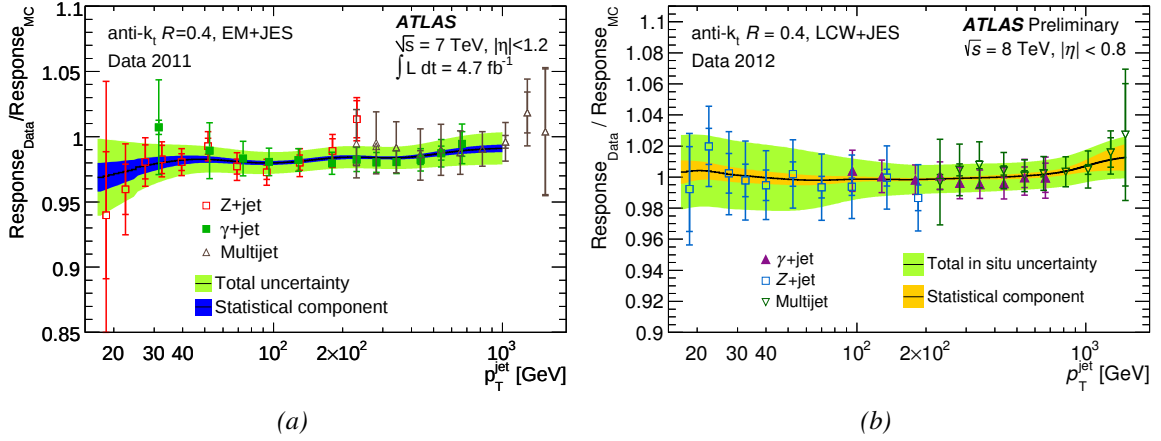


Figure 4.9: Ratio of the jet response in data and in MC as a function of the jet p_T (a) for anti- k_t $R = 0.4$ jets calibrated at the EM+JES scale for the 7 TeV dataset [115], and (b) for anti- k_t $R = 0.4$ jets calibrated at the LCW+JES scale for the 8 TeV dataset [117]. The results of all the three *in situ* methods are shown, the error bars represent the total uncertainty. The green band shows the total uncertainty on the calibrations, obtained as combination of the three methods, the blue and yellow ones only the statistical component.

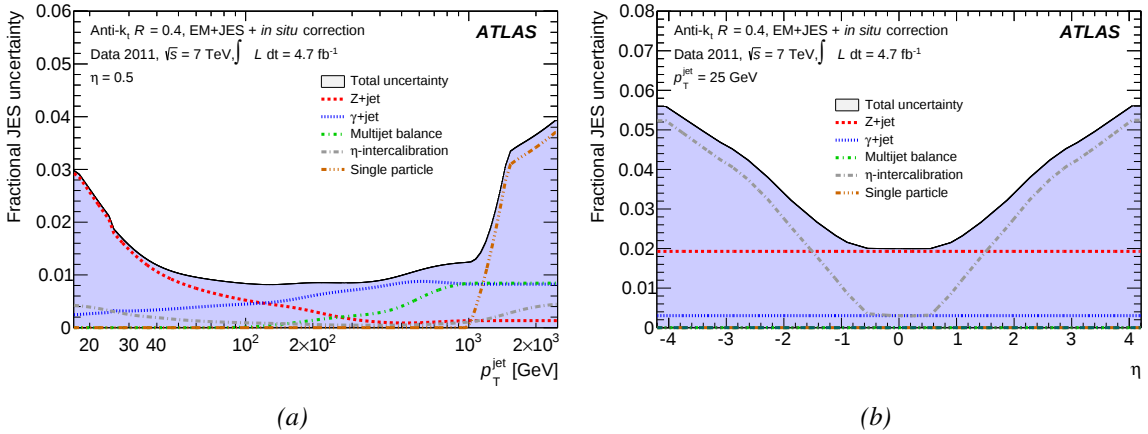


Figure 4.10: Final relative JES uncertainties for the 2011 7 TeV dataset for anti- k_t $R = 0.4$ EM+JES jets (a) as a function of p_T for jets with $\eta = 0.5$, and (b) as a function of η for jets with $p_T = 25$ GeV [115].

The jet energy resolution is determined by studying the momentum balance in events containing high- p_T jets [118]. Two *in situ* methods have been developed, the dijet balance method and the bisector method, and are both used in order to have two independent resolution measurements that can validate the MC. The jet resolution depends on the presence of additional hadronic activity in the event and on the underlying event. It can be parameterized as

$$\frac{\sigma_{p_T}}{p_T} = \frac{N}{p_T} \oplus \frac{S}{\sqrt{p_T}} \oplus C, \quad (4.15)$$

that is the sum in quadrature of a p_T independent term, N , relevant for $p_T^{\text{jet}} < 30$ GeV, which is due to electronic and detector noise and pile-up, a term due to statistical fluctuations, S , dominant for intermediate jet p_T and a constant term, C , that dominates at high p_T .

Figure 4.11 shows that the agreement between the two methods to extract the jet resolution is very

good and that the data-MC offset is at the $\pm 10\%$ level in the 7 TeV dataset. Low- p_T jets have a 20% energy resolution that decrease to 10% and less for jets with $p_T > 200$ GeV. The uncertainties on the resolution range from $\pm 10\%$ for central high- p_T jets to $\pm 20\%$ for low- p_T forward jets. Similar results are obtained for the 2012 8 TeV dataset.

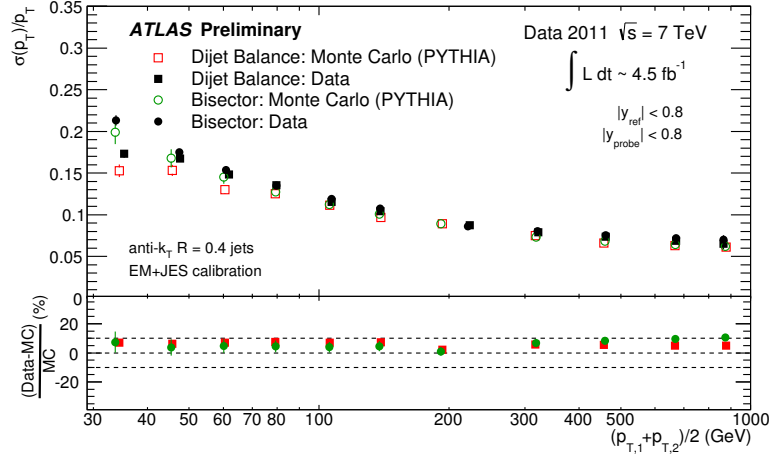


Figure 4.11: Jet energy resolution as a function of the mean p_T of the selected jets for anti- k_t $R = 0.4$ jets calibrated at the EM+JES scale [119].

4.4.3 Heavy Flavour Tagging

The high performance in the identification of jets originating from the hadronisation of a b -quark, b -jets, is important for many physics processes under study at the ATLAS experiment. In the analyses presented in this thesis, the selection of events with b -jets is used to identify regions with a pure signal sample and to reject vector boson events produced in association with jets.

To identify jets coming from a b -quark the long lifetime of b -hadrons is exploited. A b -hadron with a lifetime between 1.5 and 1.6 ps with $p_T = 50$ GeV travels 3 – 5 mm before decaying, generating a secondary vertex that can be separated from the primary vertex of the hard scattering.

The b -tagging algorithms developed within the ATLAS collaboration exploit either the properties of the tracks impact parameter or the presence of a secondary vertex. Both methods rely on the measurement of the tracks in the inner detector and therefore the jets originating from a b -hadron can be identified only for $|\eta| < 2.5$.

The impact parameter of a track is a signed quantity defined as the minimum distance between the track itself and the primary vertex of the event; the angle between the line identified by the distance vertex-track and the jet direction is used to define the sign: positive if the angle is smaller than $\pi/2$, negative otherwise. The identification of secondary vertices starts from combining the jet tracks in pairs and identifying the vertices that are significantly separated from the PV. All vertices that are compatible with light meson decays or with material interactions are rejected. Then all tracks that belong to a vertex are combined together to form a global vertex. By means of a χ^2 -fitting procedure the tracks that are less compatible with the vertex are removed until a good quality of the fit is reached.

The baseline b -tagging algorithms are summarised here.

- *JetProb* is an impact-parameter-based algorithm. The discriminating variables used are the signed

transverse impact parameter significance d_0/σ_{d_0} and a resolution function that measures the probability that the selected track comes from the primary vertex [120].

- *SV0* is a secondary-vertex-based algorithm. It reconstructs secondary vertices from the tracks associated to the jet and sets a requirement on the signed decay length significance, L/σ_L as well as on the p_T of the tracks and on the longitudinal and transverse impact parameters of the tracks and their significance [121].
- *IP3D* is an impact-parameter-based algorithm. Two dimensional histograms of the transverse and longitudinal impact parameter significance are compared to smoothed distribution of the b - and light-jet hypotheses using a likelihood ratio algorithm [122].
- *SV1* is a secondary-vertex-based algorithm. It uses a likelihood ratio technique to combine the information of the invariant mass of the tracks associated to a vertex, of the ratio of the energy of the tracks associated to the vertex over the energy of all the tracks associated to the jet and the number of vertices with two associated tracks [122].
- *JetFitter* discriminates between light- and b -jets by taking advantage of the topology of the weak b - and c -hadron decays in the jets and extracts the flight trajectory of the b -hadron. The final discrimination is achieved by combining the discriminating variables used also by SV1 and the flight length significance of the vertex with a likelihood ratio method [122].

The b -tagging algorithms chosen for the analyses increase the b -/light-jets discrimination power of the baseline algorithms by combining them with neural network techniques. These are:

- *JetFitterCombNN* is a neural network algorithm that combines the discrimination power of the IP3D and JetFitter algorithms [122], used for the analysis of the 2011 $\sqrt{s} = 7$ TeV dataset.
- *MV1* is a neural network algorithm that combines the discrimination power of the IP3D, SV1 and JetFitterCombNN weights [123], used for the analysis of the 2012 $\sqrt{s} = 8$ TeV dataset.

The good performance of a b -tagging algorithm is measured not only by the efficiency in tagging jets originating from a b -hadron, but also by the level of rejection of jets originating from c -hadrons, c -jets, and from hadrons that do not contain neither b nor c quarks, that give origin to the so called light jets. The efficiency in MC is measured by the ratio of the tagged jets to the jets that are matched to a b -quark at the truth level. The efficiency in data is measured with multiple methods, such as the p_T^{rel} and the system8 method, for details see Ref. [123]. Efficiency points are defined to extract data to MC scale factors (SF) to correct the difference in response observed in the simulation with respect to the measured data, see equation 4.16. Scale factors are extracted, binned in jet p_T and η , for b -jets, c -jets and light jets.

$$SF_x = \frac{\epsilon_x^{data}}{\epsilon_x^{MC}}, \quad x = b, c, light \quad (4.16)$$

The selection for a given efficiency working point (WP) is determined by finding the cut on the b -tagging weights that in a $t\bar{t}$ sample gives an inclusive efficiency equal to that of the chosen WP, in other words the 60% WP is the selection for which 60% of the b -jets from the $t\bar{t}$ decay are correctly tagged. The light and c -jet rejection as a function of the b -tagging efficiency can be seen in Fig. 4.12 for the 7 TeV dataset.

The b -tagging algorithm used for the analysis of the 7 TeV dataset is JetFitterCombNN at the 60%

efficiency point. It can be observed that the light jet rejection is of about 300, while the c -jet rejection is 8. The b -tag efficiency as a function of the jet p_T is reported in Fig. 4.13a for the JetFitterCombNN algorithm at the 60% efficiency point for the p_T^{rel} method; at low jet p_T the tagging efficiency increases rapidly and stabilises at $p_T = 80$ GeV. The data to MC scale factors versus the jet p_T are shown in Fig. 4.13b for the p_T^{rel} and system8 methods and their combination. The combined scale factors vary between 0.85 and 0.95 depending on the p_T bin. Higher efficiency WP have SF that are closer to unity.

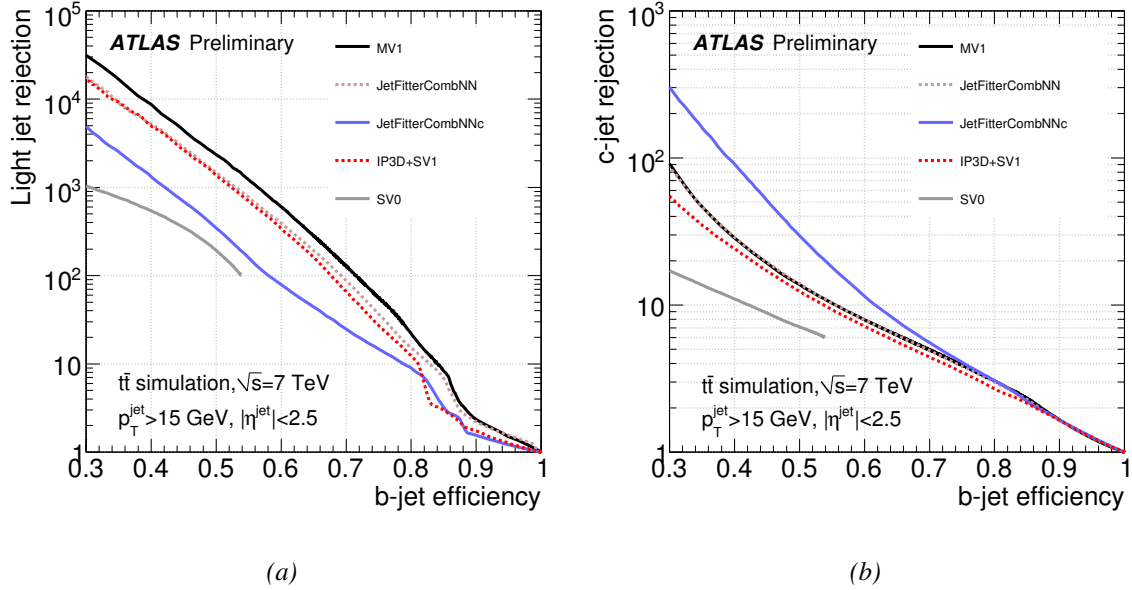


Figure 4.12: (a) Light-jet and (b) c -jet rejection as a function of the b -tag efficiency for different b -tagging algorithms used in the 7 TeV ATLAS dataset [123].

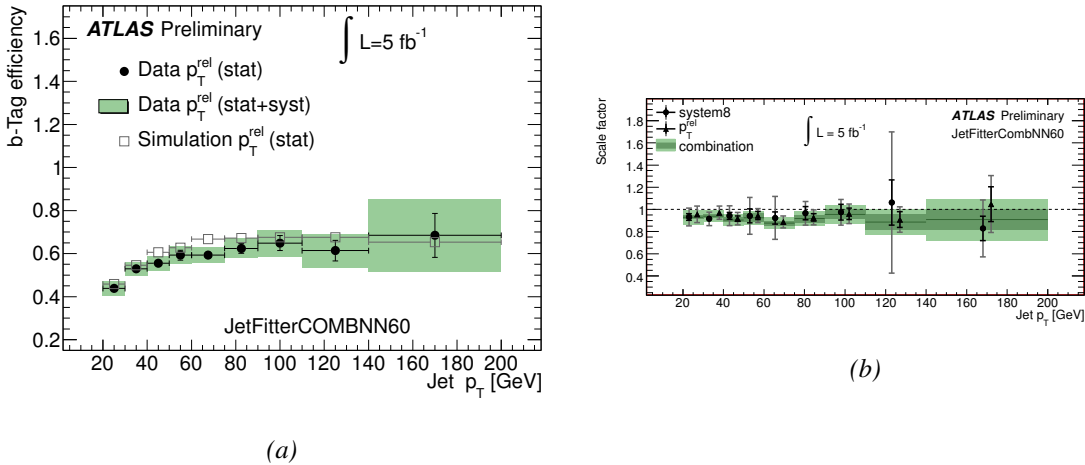


Figure 4.13: (a) b -tag efficiency as a function of the jet p_T in a $t\bar{t}$ sample extracted with the p_T^{rel} method for the JetFitterCombNN b -tagging algorithm at the 60% efficiency point. (b) Data-to-MC scale factors as a function of the jet p_T for the p_T^{rel} and system8 methods and their combination. The error bars show the statistical plus systematical uncertainty on the SF, the dark band represents the statistical component of the uncertainty for the combined SF, the light one the total statistical plus systematical uncertainty [123].

The b -tagging algorithm chosen for the analysis of the 8 TeV dataset is the MV1 tagger at the 70% WP. For this tagger a 70% b -tag efficiency gives a light jet rejection of 200. The efficiency of tagging b -jets, c -jets or light jets (mistag rate) as a function of the jet p_T is shown in Fig. 4.14a. It can be seen that for a jet p_T above 150 – 200 GeV the b - and c -tagging efficiency drops while the mistag rate increases. This is due both to the difficulty to identify a secondary vertex for very boosted objects and to the higher probability that a high energy b -hadron decays after the first pixel layer without leaving any hit in the pixel b -layer to be used for the secondary vertex reconstruction. The data-to-MC scale factors for the $t\bar{t}$ kinematic selection method is shown as a function of the jet p_T in Fig. 4.14b. The SF are in general closer to unity and have smaller uncertainty with respect to those used for the 7 TeV dataset.

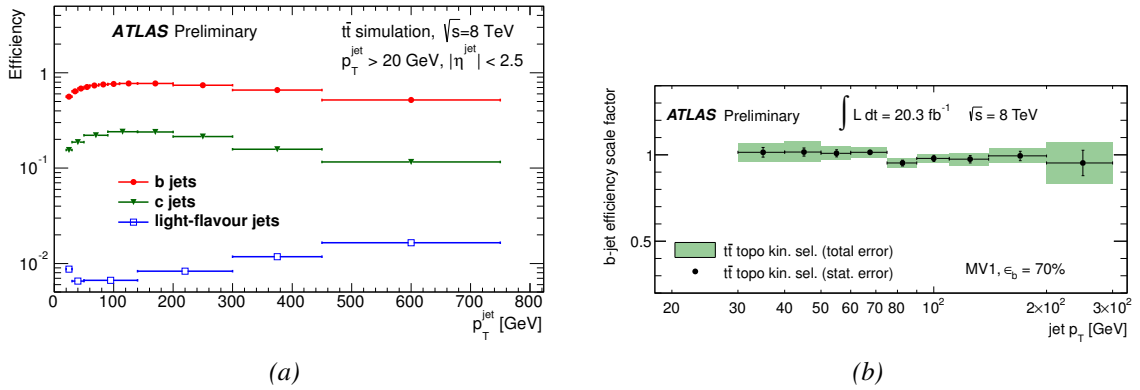


Figure 4.14: (a) Tagging efficiency of b -, c - and light jets with the MV1 tagger as a function of the jet p_T for a 8TeV $t\bar{t}$ simulated sample [124]. (b) Data-to-MC scale factors as a function of the jet p_T for a $t\bar{t}$ kinematic selection for the 8 TeV dataset using the MV1 tagger at the 70% efficiency point [125].

4.5 Missing Transverse Momentum

The missing transverse momentum, $\mathbf{E}_T^{\text{miss}}$, is often used as a discriminating variable in the search for supersymmetric particles. The energy momentum conservation in the transverse plane to the beam is used to define it as

$$\mathbf{E}_T^{\text{miss}} = - \sum_{\text{detected objects}} \mathbf{p}_T^{\text{obj}}. \quad (4.17)$$

If the measurement of the particles in the detector gives an imbalance in the transverse plane, it means that one or more weakly interacting particles escaped without being measured. Genuine sources of E_T^{miss} are, for example, the neutrinos in the leptonic decay of the W boson, $W \rightarrow \ell\nu$, or the neutralino from SUSY decays, $\tilde{\chi}_1^0$, while fake sources are the mismeasurement of the objects due e.g. to their crossing dead material of the detector or being out of its acceptance. The performance of the measurement of the missing transverse momentum has a strong dependence on the level of in-time and out-of-time pile-up of the event and it is studied in $Z \rightarrow \ell\ell$, $W \rightarrow \ell\nu$ and minimum bias events and validated in more complex processes such as the semi-leptonic $t\bar{t}$ decay.

In the next paragraphs the performance of the E_T^{miss} reconstruction in the 7 and 8 TeV ATLAS datasets is discussed together with possible strategies that could help in the suppression of the fake E_T^{miss} component coming from the underlying event.

4.5.1 Reconstruction

The missing energy along the $x(y)$ axis is defined as the sum of the missing energy measured in the calorimeters and the one measured in the muon spectrometer:

$$E_{x(y)}^{\text{miss}} = E_{x(y)}^{\text{miss, calo}} + E_{x(y)}^{\text{miss, } \mu}. \quad (4.18)$$

To recover the contribution from low- p_T particles, tracks not associated to energy deposits in the calorimeter are also added to the E_T^{miss} computation as well as muons reconstructed in the inner detector for those regions not covered by the muon spectrometer.

The magnitude of $\mathbf{E}_T^{\text{miss}}$, E_T^{miss} , is defined as

$$E_T^{\text{miss}} = \sqrt{(E_x^{\text{miss}})^2 + (E_y^{\text{miss}})^2}, \quad (4.19)$$

and its direction ϕ as

$$\phi^{\text{miss}} = \arctan\left(\frac{E_y^{\text{miss}}}{E_x^{\text{miss}}}\right). \quad (4.20)$$

The $E_x^{\text{miss}}(E_y^{\text{miss}})$ calorimeter term [126] is defined as

$$E_{x(y)}^{\text{miss, calo}} = E_{x(y)}^{\text{miss, e}} + E_{x(y)}^{\text{miss, } \gamma} + E_{x(y)}^{\text{miss, } \tau} + E_{x(y)}^{\text{miss, jets}} + E_{x(y)}^{\text{miss, softjets}} + (E_{x(y)}^{\text{miss, calo, } \mu}) + E_{x(y)}^{\text{miss, CellOut}}. \quad (4.21)$$

It is the sum of the missing momentum contributions, measured in the calorimeter, of electrons, photons, hadronically decaying taus, jets, softjets, muons and of cells not associated to any other objects (CellOut).

The jet component includes the contributions of all cells being part of calibrated anti- k_t $R = 0.4$ LCW+JES jets with $p_T > 20$ GeV; reconstructed anti- k_t $R = 0.4$ jets with $10 < p_T < 20$ GeV are LCW calibrated only and are added to the softjets term.

The CellOut term includes the contributions from topoclusters not associated to any other object and are calibrated at the LCW scale. To build this term tracks with $p_T > 400$ MeV are extrapolated to the second EM calorimeter level, if they are not associated to any object nor topocluster they are added to the CellOut term, if they are associated to a topocluster that is not part of any object, the contribution of the track is added and the one of the cluster subtracted from the CellOut term, finally all the topoclusters that are not associated to any track nor to any object (neutral component) are kept into the CellOut term. For the 2012 8 TeV dataset the softjets and CellOut terms are summed together in a single Soft-term.

The calorimeter muon term is the contribution from the energy loss of the muons in the calorimeter. It is added only for non isolated muons for which the calorimeter contribution cannot always be decoupled from the one coming from the jet, and only if there is a mismatch between the combined measurement and the standalone measurement of the muon spectrometer.

The muon term is computed as the negative sum of the momentum of the muons as measured in the muon spectrometer:

$$E_{x(y)}^{\text{miss, } \mu} = - \sum_{\text{muons}} p_{x(y)}^{\mu}. \quad (4.22)$$

For $|\eta| < 2.5$ combined muons are used, while for $2.5 \leq |\eta| < 2.7$, where no inner detector information is available, only the measurement from the muon spectrometer is used. Extrapolated tracks from the inner detector are used to recover the contributions from the muons in the crack regions of the muon

spectrometer.

The total transverse energy $\sum E_T$, which is the sum of the energy contribution of all hard and soft objects, is also an important quantity used to study the performance of the E_T^{miss} measurement and to parameterize it.

Since the E_T^{miss} , and especially its soft component, is very sensitive to the level of pile-up in the event, different procedures to suppress it have been developed following two strategies, one based on the track information, the Soft-term Vertex Fraction (STVF) method, the other based on the jet area method.

The STVF is calculated similarly to the jet vertex fraction, see equation 4.12, by summing over the tracks associated to the Soft-term instead of the one matched to the jet. The obtained value is used to multiply the Soft-term component of the E_T^{miss} , getting thus the STVF corrected E_T^{miss} .

To apply the correction based on the jet area, see Section 4.4.2, the topoclusters assigned to the Soft-term are reclustered with the k_t algorithm down to $p_T = 0$ with radius $R = 0.6$ or $R = 0.4$. Additionally the jet area corrected k_t jets may be rejected if their JVF is smaller than 0.25. The pile-up jet area corrected Soft-term is finally computed by adding the k_t contributions that satisfied the requirements. Three slightly different choices are defined:

- Extrapolated Jet Area (EJA): ρ is computed only for $|\eta| < 1.8$ and is parameterized to cover the higher η region. No JVF selections applied.
- Extrapolated Jet Area Filtered (EJAF): as above but with the JVF requirement applied.
- Jet Area Filtered - JAF: ρ is computed for the complete η region, $|\eta| < 5$.

The E_T^{miss} and $\sum E_T$ distributions for the 8 TeV dataset are presented in Figs. 4.15a and 4.15b for a $Z \rightarrow \mu\mu$ selection, where the MC has been normalised to the cross section and recorded luminosity and the $\langle\mu\rangle$ distribution in the MC has been corrected for the one measured in data. The E_T^{miss} distribution is well parameterized by the MC samples, the data-MC agreement in the $\sum E_T$ distribution, on the other hand, is bad. A big part of the discrepancy is due to the poor MC description of the activity in the forward region $3.2 < |\eta| < 4.9$. The behaviour of the distributions for the 7 TeV dataset is analogous.

In Figures 4.15c and 4.15d the E_T^{miss} distribution for the baseline and STVF pile-up suppressed Soft-term is shown. It can be seen that the data-MC agreement gets worse when the STVF selections are applied. This is the case also when pile-up suppression with Jet Area methods is employed.

4.5.2 Performance

Two main processes are used to study the E_T^{miss} performance: $Z \rightarrow \ell\ell$ and $W \rightarrow \ell\nu$ [128]. The first gives a very clean signature where no true missing momentum is expected, so that the measured E_T^{miss} comes from the mismeasurement of the objects due to non perfect reconstruction or detector response. The latter has genuine E_T^{miss} , but still a clear signature.

The E_T^{miss} scale can be checked in $Z \rightarrow \ell\ell$ events by taking the mean value of the projection of the E_T^{miss} on the Z boson boost axis in the transverse plane, $\mathbf{A}_Z$, defined as

$$\mathbf{A}_Z = \frac{\mathbf{p}_T^{\ell^+} + \mathbf{p}_T^{\ell^-}}{|\mathbf{p}_T^{\ell^+} + \mathbf{p}_T^{\ell^-}|}. \quad (4.23)$$

$\mathbf{A}_Z$ is sensitive to the balance between the leptons and the hadronic recoil; when the balance is good $\langle \mathbf{E}_T^{\text{miss}} \cdot \mathbf{A}_Z \rangle = 0$ is expected.

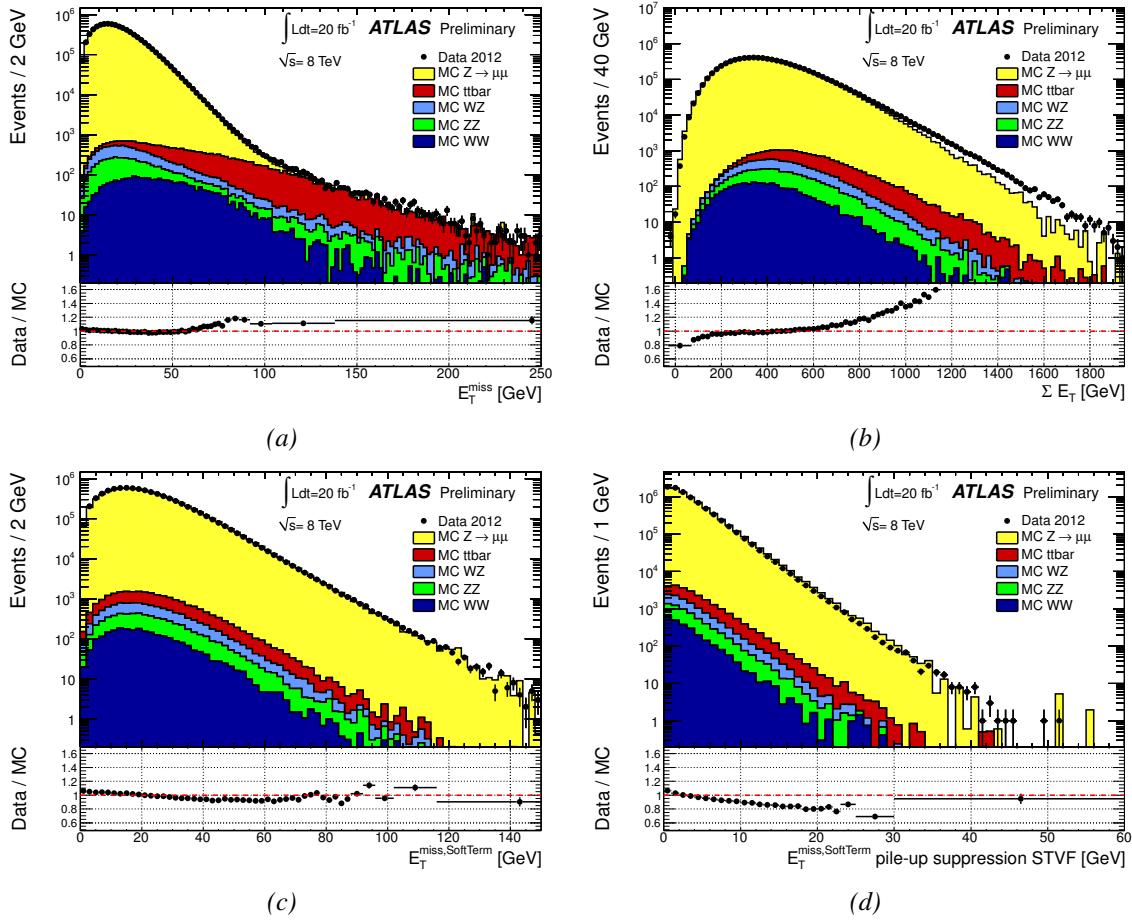


Figure 4.15: Distribution of the total missing transverse momentum (a) and of the scalar sum of the energy measured in each event (b) for the 8 TeV 2012 ATLAS dataset. Distribution of the E_T^{miss} soft component with no pile-up suppression (c) and with STVF pile-up suppression applied (d) [127]. The MC simulation has been normalised to the cross section and the measured luminosity in data corresponding to an integrated luminosity of 20 fb^{-1} .

In $W \rightarrow \ell\nu$ events, and in general for processes with true E_T^{miss} , the linearity is used instead. It is defined as

$$\text{Linearity} = \left\langle \frac{E_T^{\text{miss}} - E_T^{\text{miss, True}}}{E_T^{\text{miss, True}}} \right\rangle \quad (4.24)$$

and if the E_T^{miss} is reconstructed with the correct scale it is expected to be zero.

The scale performance in $Z \rightarrow ee$ and in $W \rightarrow \ell\nu$ events for the 7 TeV dataset is shown in Fig. 4.16. For low $p_T^Z \langle \mathbf{E}_T^{\text{miss}} \cdot \mathbf{A}_Z \rangle$ is not zero, this is caused either by an overestimation of the p_T of the lepton system, or by an underestimation of the p_T of the hadronic recoil. Given the similar results in the muon channel, it is believed that the bias comes from the underestimation of the hadronic recoil.

For $W \rightarrow \ell\nu$ events a bias due to the finite E_T^{miss} resolution, reaching almost the 15% level, is observed at low $E_T^{\text{miss, True}}$ values. Events with $E_T^{\text{miss, True}} > 40$ have a linearity that is better than 3(5)% for the $W \rightarrow \mu\nu$ ($W \rightarrow e\nu$) sample [128].

The selected scale performance plots for the 8 TeV dataset are presented in Fig. 4.17. From (a) it can be seen that the hadronic recoil in $Z \rightarrow \mu\mu$ events, but analogously in $Z \rightarrow ee$, is again underestimated and that the pile-up suppression methods, especially the STVF method, worsen the situation

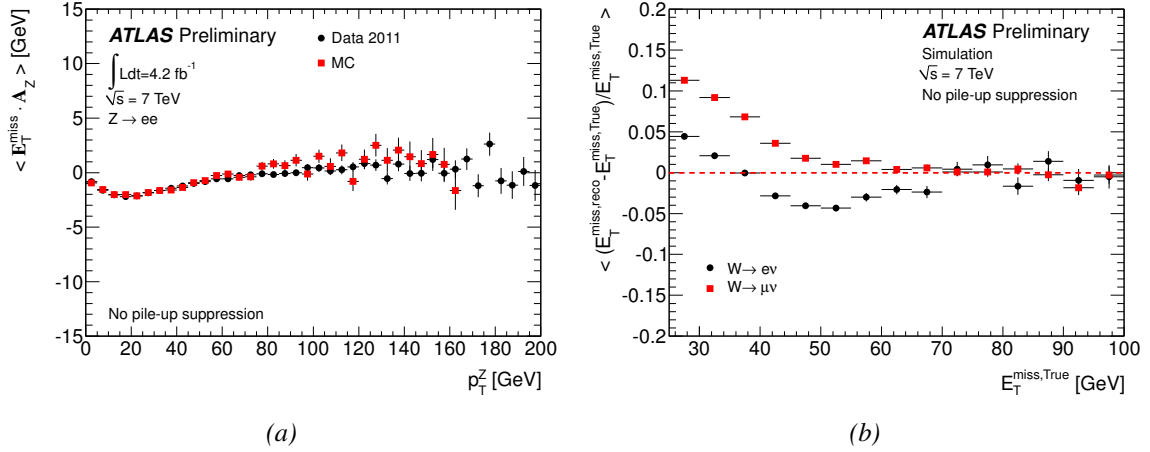


Figure 4.16: (a) Distribution of the $\langle E_T^{\text{miss}} \cdot A_Z \rangle$ as a function of the Z boson p_T in $Z \rightarrow ee$ events at 7 TeV. (b) Distribution of the mean linearity versus $E_T^{\text{miss, True}}$ for $W \rightarrow \ell \nu$ events at 7 TeV [128].

by subtracting from the Soft-term not only the pile-up contribution but also part of the hadronic recoil itself. The linearity is shown for $W \rightarrow e \nu$ events in (b). Apart from deviations in the low $E_T^{\text{miss, True}}$ due to the finite resolution the bias stays within $\pm 5\%$; this is as well the case for $W \rightarrow \mu \nu$ and other tested processes [127].

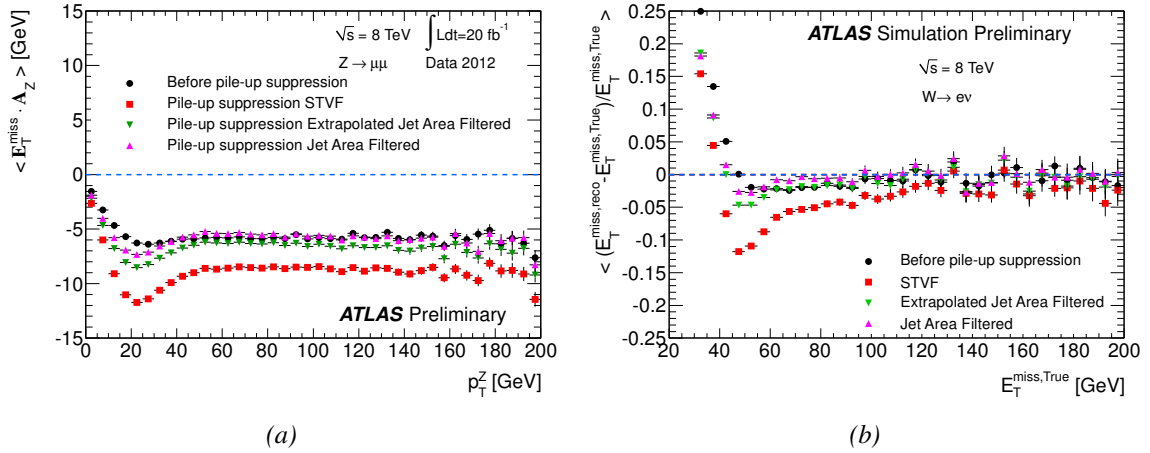


Figure 4.17: (a) Distribution of the $\langle E_T^{\text{miss}} \cdot A_Z \rangle$ as a function of the Z boson p_T in $Z \rightarrow \mu\mu$ events in the 8 TeV dataset corresponding to an integrated luminosity of 20 fb^{-1} of data for different choices of pile-up suppression method for the Soft-term. (b) Distribution of the linearity versus $E_T^{\text{miss, True}}$ for $W \rightarrow e \nu$ events at 8 TeV for different choices of pile-up suppression method for the Soft-term [127].

The E_T^{miss} resolution is studied by comparing the difference in the measured and in the truth missing momentum on the x and on the y axes; this results in a residual distribution that can be fitted, usually in $\sum E_T$, N_{pv} or $\langle \mu \rangle$ bins, with a Gaussian function whose width represents the average resolution of that class of events. For the dileptonic decay of the Z no true E_T^{miss} is expected, therefore, especially for events with no jets, the resolution can be extracted directly from the width of E_x^{miss} and E_y^{miss} and that can be done also in data where there is no knowledge of the $E_T^{\text{miss, True}}$. It is expected for the E_T^{miss} resolution to have an almost stochastic behaviour as a function of the total transverse energy of the event, so that

the resolution can be parameterized as $\sigma_{Reso} = k \cdot \sqrt{\Sigma E_T}$.

The value of k obtained for the 2011 7 TeV dataset is $k = 0.7 \sqrt{\text{GeV}}$ and it is consistent within different processes and for $Z \rightarrow \ell\ell$ data and MC. This can be seen in Fig. 4.18a where the E_x^{miss} and E_y^{miss} resolution is drawn as a function of the total transverse energy of the event.

The resolution curves obtained for the 8 TeV dataset are shown in Fig. 4.18b. The resolution is quite consistent among different physics processes over the full ΣE_T range. For Z events a good data-MC agreement is observed and an improved resolution is obtained when the STVF pile-up suppression is applied. For semi-leptonically decaying $t\bar{t}$ and for SUSY events, where the contribution from the Soft-term to the total E_T^{miss} is small, no significant resolution improvement is seen for the E_T^{miss} variations computed with pile-up suppression methods.

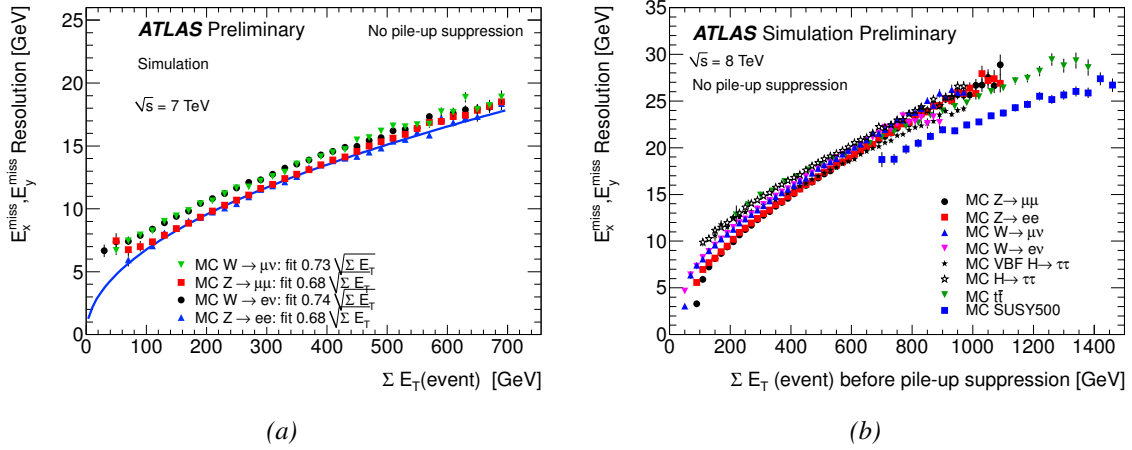


Figure 4.18: Fig. (a) distribution of the $E_x^{\text{miss}}, E_y^{\text{miss}}$ resolution as a function of the ΣE_T for the $Z \rightarrow \ell\ell$ and $W \rightarrow \ell\nu$ selections at 7 TeV [128]. Fig. (b) distribution of the $E_x^{\text{miss}}, E_y^{\text{miss}}$ resolution as a function of the ΣE_T for the $Z \rightarrow \ell\ell$, $W \rightarrow \ell\nu$, $t\bar{t}$, Higgs and SUSY selections studied at 8 TeV [127].

The systematic uncertainties on the E_T^{miss} scale and resolution are extracted by combining the contributions from each of its terms. The uncertainties on the reconstruction and identifications of the hard terms are propagated to the E_T^{miss} and the only component that has to be taken care of separately is the soft one. Since the relative weight of the Soft-term on the total E_T^{miss} differs depending on the physics process, the impact of its systematic uncertainties on the total E_T^{miss} uncertainties varies.

Two methods have been developed to estimate the Soft-term scale and resolution uncertainties in $Z \rightarrow \ell\ell$ events [128]. The first one is based on the data-to-MC ratio of the average hadronic recoil $\langle \mathbf{E}_T^{\text{miss}} \cdot \mathbf{A}_Z \rangle$ as a function of ΣE_T in events with no reconstructed jets, used to evaluate the scale, and on the ratio of the resolutions in data and MC, used to determine the uncertainty on the Soft-term resolution. In the 2011 dataset, the uncertainty on the soft scale has been found to be $\pm 5\%$, the one on its resolution $\pm 2\%$. The second method uses the balance between the soft and the hard E_T^{miss} components to define a kind of true soft E_T^{miss} term, the $p_{x(y)}^{\text{hard}}$ defined as

$$p_{x(y)}^{\text{hard}} = -\left(E_{x(y)}^{\text{miss}} - E_{x(y)}^{\text{miss, softjets}} - E_{x(y)}^{\text{miss, CellOut}}\right) + E_{x(y)}^{\text{miss, True}}. \quad (4.25)$$

The p_T^{hard} variable can then be defined as the sum in quadrature of the p_x^{hard} and p_y^{hard} components:

$$p_T^{\text{hard}} = \sqrt{(p_x^{\text{hard}})^2 + (p_y^{\text{hard}})^2}. \quad (4.26)$$

This method can be applied only to MC, since the knowledge of the true E_T^{miss} is required, and only $Z \rightarrow \ell\ell$ events can be used to check the results in data by exploiting the hypothesis that $E_T^{\text{miss, True}} = 0$.

The $E_T^{\text{miss, Soft}}$ is decomposed along and perpendicular to the p_T^{hard} axis. The average longitudinal component gives a measure of the $E_T^{\text{miss, Soft}}$ scale as a function of p_T^{hard} , while the resolution is evaluated by fitting with Gauss functions the longitudinal and perpendicular $E_T^{\text{miss, Soft}}$ components in p_T^{hard} bins. Considering the 7 TeV dataset, the consistency in the scale between data and MC is within ± 1 GeV, while for the resolution a $\pm 2\%$ conservative uncertainty is assigned.

The uncertainties measured in the 8 TeV dataset are of $\pm 3.6\%$ on the soft scale and $\pm 2.3\%$ on the soft resolution, when using the standard E_T^{miss} definition, and increase to almost 8% and 5%, respectively for the scale and the resolution, when suppressing the pile-up contribution with the STVF method.

In the next chapter some studies on a possible parameterization of the Soft-term resolution are presented. These are intended as a possibility to get smaller systematical uncertainties and, in general, a better understanding of the E_T^{miss} soft component.

E_T^{miss} Soft-Term Resolution Parameterization

The performance of the Soft component of the missing transverse momentum, especially its contribution to the total E_T^{miss} resolution, is still not deeply understood. Increasing the knowledge of the properties of this term would allow to have a stronger handle on the systematic uncertainties associated to it, which affect especially Standard Model precision measurements. Moreover, if its resolution would be known with more precision, it would be possible to have a better definition of the E_T^{miss} significance variables to be used e.g. in SUSY analyses to discriminate the signal from the SM background.

In this chapter studies on the E_T^{miss} Soft-term are presented. They are intended to gain a better understanding of the Soft-term contribution to the E_T^{miss} resolution as a function of the event topology under study, and to develop a strategy to parameterize it. First, the Run 1 results describing the E_T^{miss} Soft-term behaviour with and without pile-up suppression applied are presented in Section 5.1, then the resolution studies, which are part of the work done for this PhD thesis, are presented in Section 5.2. In this section, the choice of the samples, the procedure followed to extract a possible parameterization of the E_T^{miss} Soft-term resolution and the results of the study are discussed.

The results of the presented study are an important first step towards a possible correct treatment of the Soft-term resolution within the E_T^{miss} performance studies. Though, in order to evaluate the impact of the improved description of the E_T^{miss} resolution, the parameterization found for the Soft-term has to be propagated to the calculation of the systematic uncertainties. The universality of the parameterization has also to be further probed by extracting it for different physics processes which may contain objects not yet studied, such as τ leptons and photons, and by comparing it with the results of this work.

Interesting studies could also be done to check more extensively processes with real E_T^{miss} in data, such as the leptonic decay of the W boson. In this case, by selecting events with no jets and by constraining the lepton and the E_T^{miss} to form a W boson candidate a sort of truth E_T^{miss} could be defined and used to further probe the results. Finally, the improvement in the E_T^{miss} significance variables should be tested for those physics processes where a very large E_T^{miss} is expected, e.g. in many R-parity conserving SUSY scenarios.

5.1 The E_T^{miss} Soft-Term

The definition of the Soft-term of the missing transverse momentum, $E_T^{\text{miss, Soft}}$, has been presented in Section 4.5. This term is particularly affected by the level of pile-up present in the event.

The pile-up dependency can be observed clearly from Fig. 5.1 where the average transverse sum of the soft contributions, $\sum E_T^{\text{Soft}}$, and $E_T^{\text{miss, Soft}}$ are shown as a function of N_{PV} for the baseline and the different pile-up suppression definitions for a $Z \rightarrow \mu\mu$ selection in the ATLAS 8 TeV dataset. The pile-up suppression methods are rejecting most of the energy coming from the soft underlying event and the methods based on the jet area correction give a flat and stable distribution as N_{PV} increases. From Fig. 5.1b it can be observed that the STVF method tends to overcorrect the pile-up contribution.

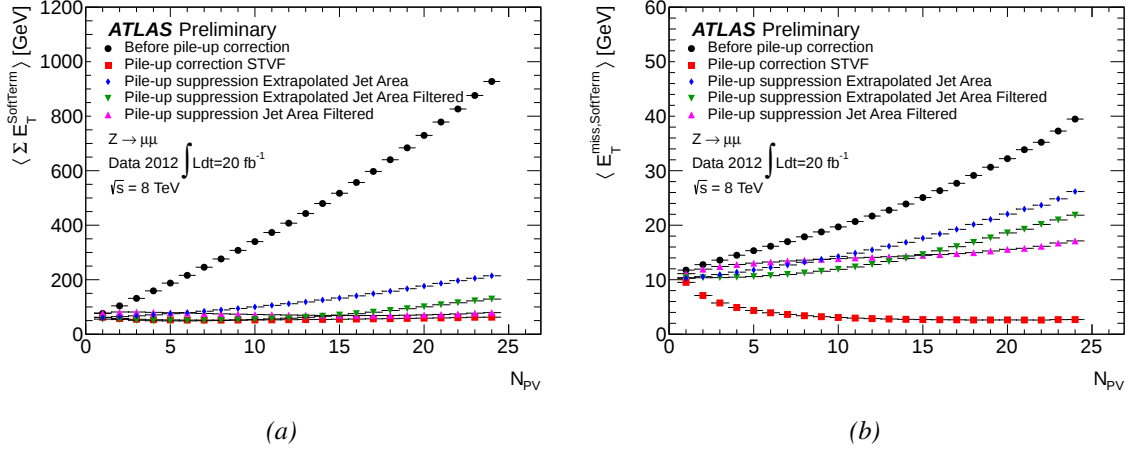


Figure 5.1: Average $\sum E_T^{\text{SoftTerm}}$ (a) and $E_T^{\text{miss, SoftTerm}}$ (b) as a function of the number of primary vertices, N_{PV} , for a $Z \rightarrow \mu\mu$ event sample using the 8 TeV 2012 ATLAS dataset corresponding to an integrated luminosity of 20 fb^{-1} . The results are shown for the baseline E_T^{miss} and for the E_T^{miss} recomputed after applying different pile-up suppression selections [129].

The pile-up dependence can also be seen in the distributions of the total E_T^{miss} resolution and average missing transverse energy, $\langle E_T^{\text{miss}} \rangle$, as a function of the number of reconstructed primary vertices, as in Fig. 5.2. Also here the pile-up suppression methods have a positive effect in making the resolution and the $\langle E_T^{\text{miss}} \rangle$ curves independent of pile-up even if the effect is less strong than on the $E_T^{\text{miss, Soft}}$ term alone.

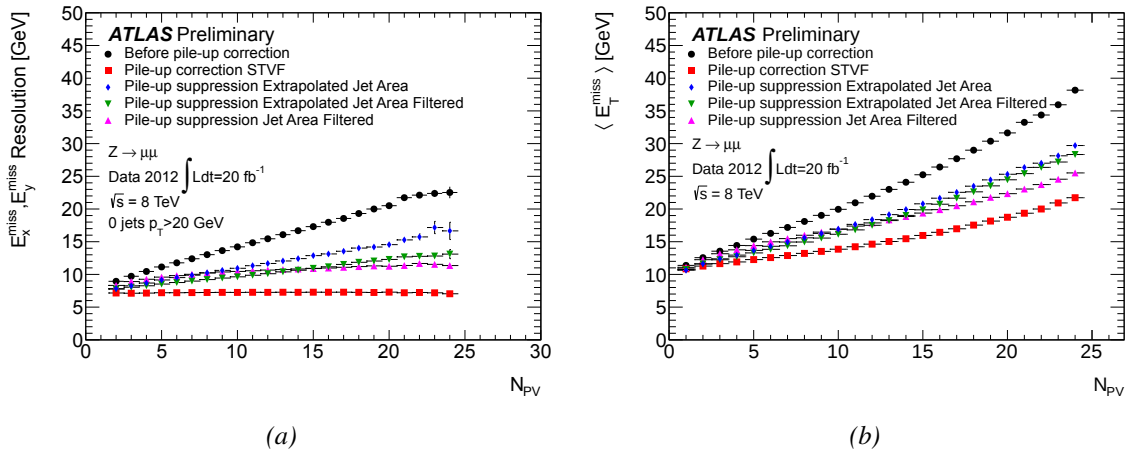


Figure 5.2: (a) $E_x^{\text{miss}}, E_y^{\text{miss}}$ resolution, and (b) average measured E_T^{miss} as a function of the number of primary vertices, N_{PV} for a $Z \rightarrow \mu\mu$ event sample using the 8 TeV 2012 ATLAS dataset corresponding to an integrated luminosity of 20 fb^{-1} . The results are shown for the baseline E_T^{miss} and for the E_T^{miss} recomputed after applying different pile-up suppression selections [129].

Figure 5.3 collects additional figures that show the behaviour of the $E_T^{\text{miss, Soft}}$ term without pile-up suppression applied or after the recalculation when track-based or jet-area-based pile-up suppression methods are used. The selected sample contains $Z \rightarrow \mu\mu$ events with no jets of $p_T > 20$ GeV and corresponds to an integrated luminosity of 20 fb^{-1} recorded at 8 TeV. The MC has been normalised to data by accounting for the process cross section and the recorded luminosity [129]. The data-MC ratio shows that the agreement gets worse for the distributions with pile-up suppression methods applied, especially in the tails. This discrepancy comes from a non-correct modelling of the low p_T tracks and their association to the clusters in PYTHIA8. From these figures it is possible to appreciate the effect of the pile-up suppression methods in decreasing the amount of $E_T^{\text{miss, Soft}}$, as already observed for $\langle E_T^{\text{miss, Soft}} \rangle$. The resulting $E_T^{\text{miss, Soft}}$ spectrum is shifted to lower values especially for the STVF method.

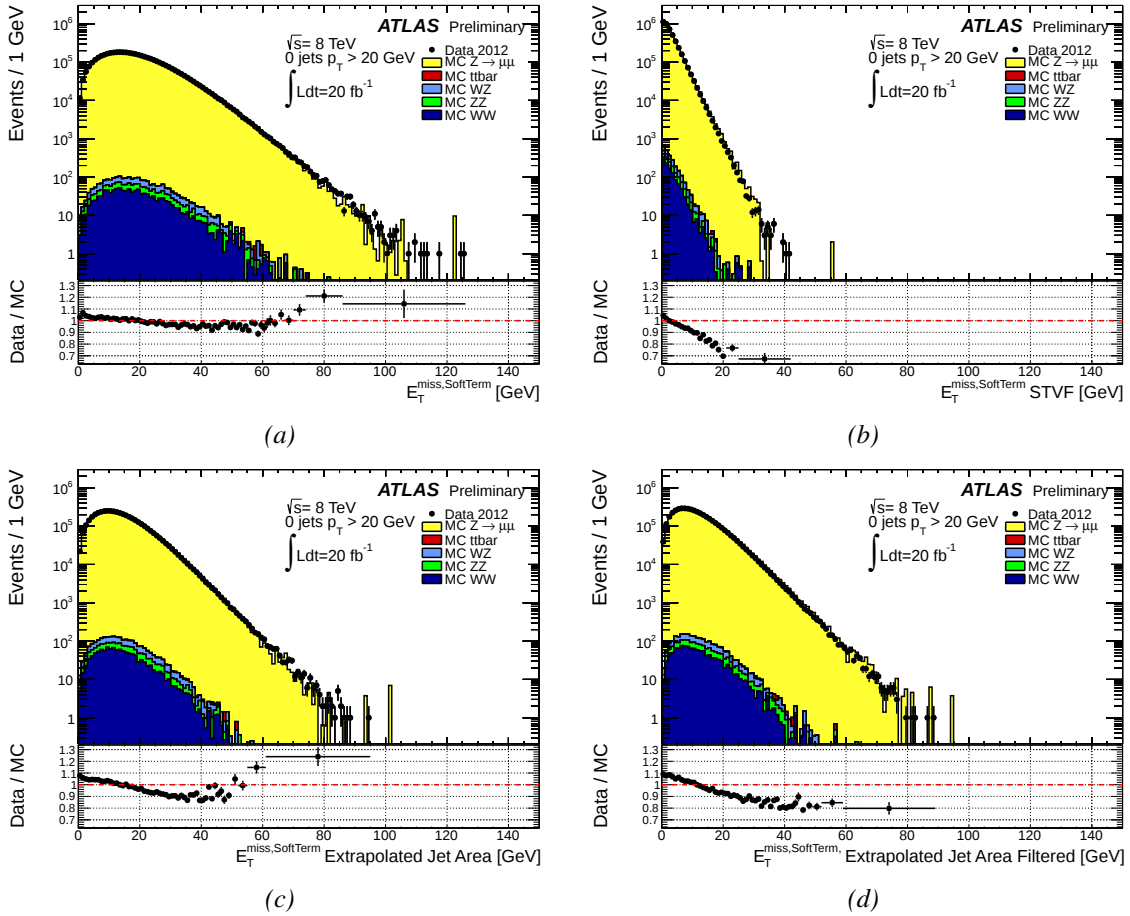


Figure 5.3: Distribution of the $E_T^{\text{miss, SoftTerm}}$ component in Data and MC $Z \rightarrow \mu\mu$ events with no jets of $p_T > 20$ GeV with no pile-up suppression applied (a), with the STVF pile-up suppression method (b) with the Extrapolated Jet Area pile-up suppression method (c) and with the Extrapolated Jet Area pile-up suppression method (d). MC is normalised to the cross section times recorded luminosity. The analysed data corresponds to an integrated luminosity of 20 fb^{-1} , that is the complete 8 TeV dataset recorded by the ATLAS experiment. The ratio plot shows the data to MC ratio where the error bars represent the statistical uncertainty on the data points [129].

The average value of the projection of E_T^{miss} on the Z boson boost axis versus p_T^Z is shown in Fig. 5.4 for a $Z \rightarrow ee$ selection with no jets of $p_T > 20$ GeV (a) and for an inclusive selection (b). From the first distribution it can be seen how, for all the E_T^{miss} definitions, the hadronic recoil is underestimated and

that if the pile-up contribution is suppressed this has a bad effect on the E_T^{miss} scale. From the second it can be observed that the E_T^{miss} scale and linearity are at least partly recovered at higher values of p_T^Z where $E_T^{\text{miss, Soft}}$ is not anymore the dominant term. Also in this figure it can be noted that the STVF pile-up suppression method is rejecting a good part of the hadronic recoil and therefore, by overcorrecting the $E_T^{\text{miss, Soft}}$ term, it creates problems in the overall E_T^{miss} scale.

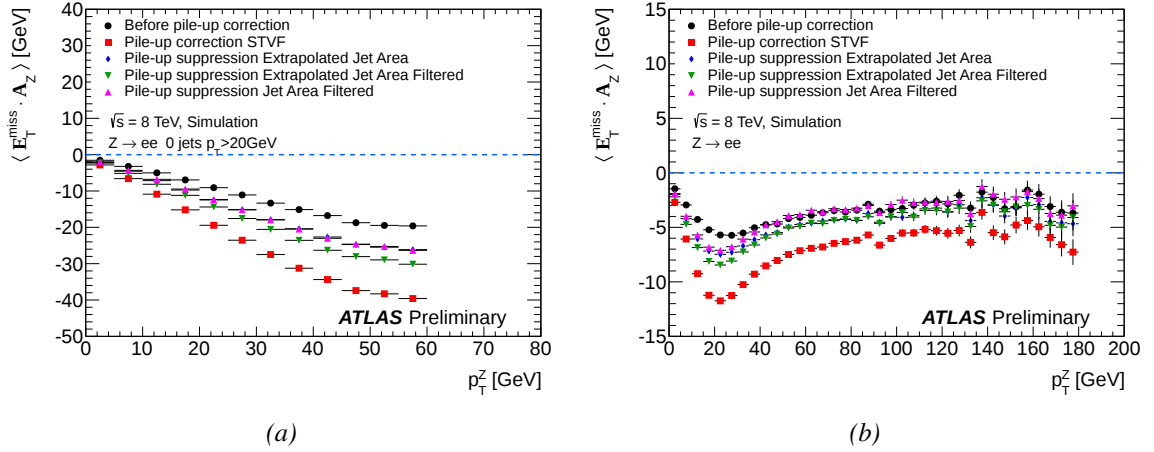


Figure 5.4: E_T^{miss} projection on the Z boost axis A_Z as a function of p_T^Z for a $Z \rightarrow ee$ selection using the 8 TeV 2012 ATLAS dataset corresponding to an integrated luminosity of 20 fb^{-1} for a selection with no jets with $p_T > 20 \text{ GeV}$ (a) and for an inclusive selection (b). The results for the baseline E_T^{miss} and for the E_T^{miss} recomputed after applying different pile-up suppression selections are plotted [129].

Another possibility explored to suppress the pile-up dependency of the $E_T^{\text{miss, Soft}}$ is to use a track-based Soft-term (TST) instead of the classical cluster-based Soft-term (CST). Using only the tracks associated to the hard scatter vertex to build the TST, the effect of the pile-up is almost completely suppressed. In this way, however, only the charged fraction of the soft component is considered and the average projection of the E_T^{miss} on the p_T^{hard} direction as a function of p_T^{hard} shows a large soft-hard imbalance in the events.

During Run 1 there have been great efforts intended to find solutions for a more stable and pile-up robust $E_T^{\text{miss, Soft}}$ term. Some problems have been solved but better solutions still have to be found for the new run, since a higher centre-of-mass collision-energy and higher pile-up contributions are expected. It is important, therefore, to try to gain a better understanding of the Soft-term properties.

5.2 Studies of the Soft-Term Resolution

One aspect that needed investigation is the Soft-term resolution, how it behaves for different processes and different amount of hadronic activity in the event, how and if it can be parameterized and which are the variables it depends on.

The analysis focused on the calorimeter-based Soft-term with no pile-up suppression corrections applied. To study its resolution the $Z \rightarrow \mu\mu$ MC sample was chosen as reference because of the cleanliness of its signal and because in events with no jets the major contribution to the measured E_T^{miss} comes from the $E_T^{\text{miss, Soft}}$. Other MC samples were also used to cross-check the results, $Z \rightarrow ee$, $W \rightarrow \ell\nu$ and $t\bar{t}$, as well as a $Z \rightarrow \mu\mu$ selection in data. The considered dataset was collected at a centre-of-mass collision energy of 8 TeV with the ATLAS detector during 2012.

5.2.1 Samples and Selections

The selected MC samples were all generated with PowHeg at NLO [85, 86] matched to PYTHIA8 for the parton showering [77] and CT10 as PDF set [61]. For the $Z \rightarrow \ell\ell$ and $W \rightarrow \ell\nu$ samples the ATLAS AU2 [73] tune was used, for the $t\bar{t}$ sample the Perugia 2011 C tune [71] was used, instead.

The data considered for the analysis was recorded with the detector fully working and nominal magnetic fields. The events must satisfy data quality selections and both recorded and simulated events are cleaned to reject beam background, such as out-of-time pile-up events, and cosmic background that could be a source of fake E_T^{miss} .

The events are selected based on an OR of single lepton triggers, summarised in Table 5.1, and, for each event, it is checked that the selected lepton(s) are matched to the trigger that fired. To select events in the efficiency plateau of the triggers a minimum p_T threshold of 25 GeV is required and additionally, since the EF_e24vhi_medium1 and EF_mu24i_tight triggers require lepton isolation, the selected leptons must satisfy $p_{T\text{cone20}}/p_T(e) < 0.1$ and $p_{T\text{cone20}}/p_T(\mu) < 0.12$ for electrons and muons respectively. The $p_{T\text{cone20}}$ is an isolation variable that measures the energy deposited in the ID in a cone of $\Delta R = 0.2$ around the selected lepton track, with its own contribution subtracted.

	Trigger	Offline Selection
electron	EF_e24vhi_medium1 OR EF_e60_medium1	$p_T(e) > 25 \text{ GeV}$, $p_{T\text{cone20}}/p_T(e) < 0.1$
muon	EF_mu24i_tight OR EF_mu36_tight	$p_T(\mu) > 25 \text{ GeV}$, $p_{T\text{cone20}}/p_T(\mu) < 0.12$

Table 5.1: Single electron and muon triggers used for the E_T^{miss} Soft-term studies. The offline selections to be applied to select only events in the trigger efficiency plateau and to satisfy the isolation criteria applied at trigger level are also reported.

Electrons are selected with the medium identification requirements, $p_T > 10 \text{ GeV}$ and $|\eta| < 2.47$ and their energy is corrected based on the energy scale and resolution measurements. Electrons falling in the calorimeter crack, $1.37 < |\eta| < 1.56$, are rejected. Muons are required to be combined muons, have $p_T > 10 \text{ GeV}$ and $|\eta| < 2.4$. Both signal electrons and muons are required to be isolated. η -intercalibration, JES and jet area pile-up corrections are applied to the jets, that are required to have $p_T > 20 \text{ GeV}$ and $|\eta| < 4.5$.

The overlap removal between electrons and jets have been taken care of by rejecting the objects which have been assigned a E_T^{miss} weight equal to zero, $w_{\text{et}} = 0$, during reconstruction, i.e. all the objects that were not used to compute the final E_T^{miss} value.

For the simulated samples also truth-level leptons and jets are considered. They can be taken directly as the particle-level objects from the MC generator, e.g. the muons, or by reclustering the truth particles from the generator and the showering with the same algorithms used for the detected objects, e.g. the truth jets are defined by reclustering with the anti- k_t algorithm truth level particles. The truth objects can be matched, with a simple ΔR algorithm, to the reconstructed objects. The radii chosen for the matching are $\Delta R < 0.3$ for jets and electrons and $\Delta R < 0.1$ for muons; in case of multiple matches, the one with the minimum ΔR is chosen.

The true missing transverse momentum, $E_T^{\text{miss, Truth}}$, is defined as the sum of the transverse momenta of the neutrinos or, more in general, of all the particles that interact only via the weak force.

The requirements specific to the $Z \rightarrow \ell\ell$ and $W \rightarrow \ell\nu$ selections are presented in the following paragraphs.

$Z \rightarrow \ell\ell$

For an event to be identified as a $Z \rightarrow \ell\ell$ decay, two same-flavour leptons with opposite charge (OS) and $p_T > 25$ GeV have to be selected. Since no veto on additional leptons is placed, the Z boson lepton pair is chosen as the one with invariant mass

$$m_{\ell\ell} = \sqrt{(E^{\ell_1} + E^{\ell_2})^2 - \|\mathbf{p}^{\ell_1} + \mathbf{p}^{\ell_2}\|^2} \quad (5.1)$$

nearest to the Z mass value quoted in the PDG [12], $m_Z = (91.1876 \pm 0.0021)$ GeV. The mass of this selected pair must be within a 25 GeV range of m_Z , i.e. satisfy $66 < m_{\ell\ell} < 116$ GeV, for the event to be considered in the analysis.

$W \rightarrow \ell\nu$

For the $W \rightarrow \ell\nu$ selection a single electron or muon with $p_T > 25$ GeV is required and if any additional lepton with $p_T > 10$ GeV is found the event is rejected. A minimum amount of $E_T^{\text{miss}}, E_T^{\text{miss}} > 25$ GeV, has to be measured and the transverse mass between the lepton and the E_T^{miss} , $m_T(\ell, E_T^{\text{miss}})$, defined as

$$m_T(\ell, E_T^{\text{miss}}) = \sqrt{2 \left[p_T^\ell E_T^{\text{miss}} - \mathbf{p}_T^\ell \cdot \mathbf{p}_T^{\text{miss}} \right]} = \sqrt{2 \left[p_T^\ell E_T^{\text{miss}} \left(1 - \cos \Delta\phi(\mathbf{p}_T^\ell, \mathbf{p}_T^{\text{miss}}) \right) \right]}, \quad (5.2)$$

has to exceed 50 GeV.

For the $t\bar{t}$ sample the $W \rightarrow \ell\nu$ requirements have been applied selecting, thus, its semileptonic decay, and only electrons and muons are considered as leptons.

5.2.2 Procedure

So far it was assumed that the resolution of the E_T^{miss} Soft-term would be proportional to $\sqrt{\sum E_T^{\text{Soft}}}$, which is a naive assumption based on the knowledge of how the resolution of the objects measured in the calorimeters usually behaves. This has to be checked and, if needed, a better description and parameterization of the Soft-term resolution has to be found.

The E_T^{miss} resolution of the selected events can be measured by fitting with a Gauss function a residual distribution, $(\delta E_T^{\text{miss}})_{x(y)}$, usually binned in the total transverse energy of the event, $\sum E_T$. This gives the total E_T^{miss} resolution of a class of events. To extract the resolution contribution of the Soft-term alone, a new definition for the residuals, $(\delta p_T^{\text{soft}})_{x(y)}$, had to be set where the contributions from the hard objects could be subtracted. To extract the Soft resolution, the natural choice was to perform the Gauss fits binned in the total Soft transverse energy, $\sum E_T^{\text{Soft}}$. The meaning of the δp_T^{soft} variable can be better understood from the sketch of a Z + jets event presented in Fig. 5.5.

The three following residual definitions, calculated event-per-event, have been, hence, considered in the analysis: one used to extract the total resolution, the other two to try to extract a sensible resolution of the $E_T^{\text{miss, Soft}}$ component.

- $(\delta E_T^{\text{miss}})_{x(y)} = (E_T^{\text{miss}})_{x(y)} - (E_T^{\text{miss, Truth}})_{x(y)}$
when fitted gives a measure of the total resolution of a class of events. The effects of the resolution smearing of all the selected objects are convoluted together.
- $(\delta p_T^{\text{soft}})_{x(y)}^{\text{recoObj}} = (E_T^{\text{miss, Soft}})_{x(y)} - \left[(E_T^{\text{miss, Truth}})_{x(y)} - (E_T^{\text{miss, } \ell})_{x(y)} - (E_T^{\text{miss, Jet}})_{x(y)} \right], \ell = e, \mu$
only the dominant terms of the selected events have been taken into account. This definition

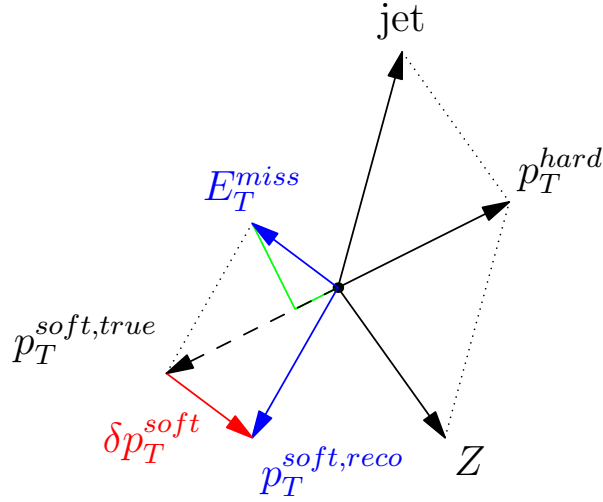


Figure 5.5: $Z + \text{jets}$ event: schematic overview of the objects contributing to the E_T^{miss} calculation [130].

should minimise the effect on the resolution coming from the smearing of the hard objects and, when fitted, gives a measure of the resolution of the Soft-term. In the following, the results obtained starting from this definition are labelled as extracted with the reco-subtraction method.

- $(\delta p_T^{\text{soft}})^{\text{truthObj}}_{x(y)} = (E_T^{\text{miss, Soft}})_{x(y)} - \left[(E_T^{\text{miss, Truth}})_{x(y)} - (E_T^{\text{miss, TruthMatch } \ell})_{x(y)} - (E_T^{\text{miss, TruthMatch Jet}})_{x(y)} \right]$
as above but derived using the truth objects matched to the reconstructed ones; the definition of $(E_T^{\text{miss, TruthMatch } k})_{x(y)}$ for a general object k is

$$(E_T^{\text{miss, TruthMatch } k})_{x(y)} = - \sum_{k=1}^n (p_T^k)_{x(y)}, \quad (5.3)$$

where n is the number of objects of type k in the event. With this definition the resolution from the hard objects is factorised out as much as possible. In the following, the results obtained starting from this definition are labelled as extracted with the truth-subtraction method.

These definitions rely upon the knowledge of the true E_T^{miss} of the event. They can, thus, be applied only to MC samples and to a $Z \rightarrow \ell\ell$ selection in data where it can be assumed that no real missing transverse momentum is present in the events.

As introduced before, to determine the resolution of a class of events Gaussian fits are performed on the residual distributions binned in $\sum E_T$. Two examples of these fits for selected $Z \rightarrow \mu\mu$ candidate events with no contribution from the jet term, i.e. the total jet transverse energy ($\sum E_T^{\text{jet}}$) is zero, and residuals defined as $(\delta E_T^{\text{miss}})_x$ are shown in Fig. 5.6 for the bins $300 < \sum E_T < 305$ GeV (a) and $1000 < \sum E_T < 1500$ GeV (b).

The choice of the binning was to have a minimum bin width of 5 GeV and a minimum amount of 1000 events per bin. The residual distribution is first fitted with a Gauss function in the range $-80 < (\delta E_T^{\text{miss}})_{x(y)} < 80$ GeV, then it is iteratively fitted in the range $\langle \mu_{\text{Gauss}} \rangle \pm 1.6 \cdot \sigma_{\text{Gauss}}$, where $\langle \mu_{\text{Gauss}} \rangle$ is the mean of the previously fitted Gauss function and σ_{Gauss} its standard deviation. The distribution is refitted until a stable result is achieved or more than 10 tries have been done. The decision to refit only the bulk of the distribution is supported by the observation that possible non-Gaussian tails can be present and that the important information to retain in this context is the width of the residuals distribution and not

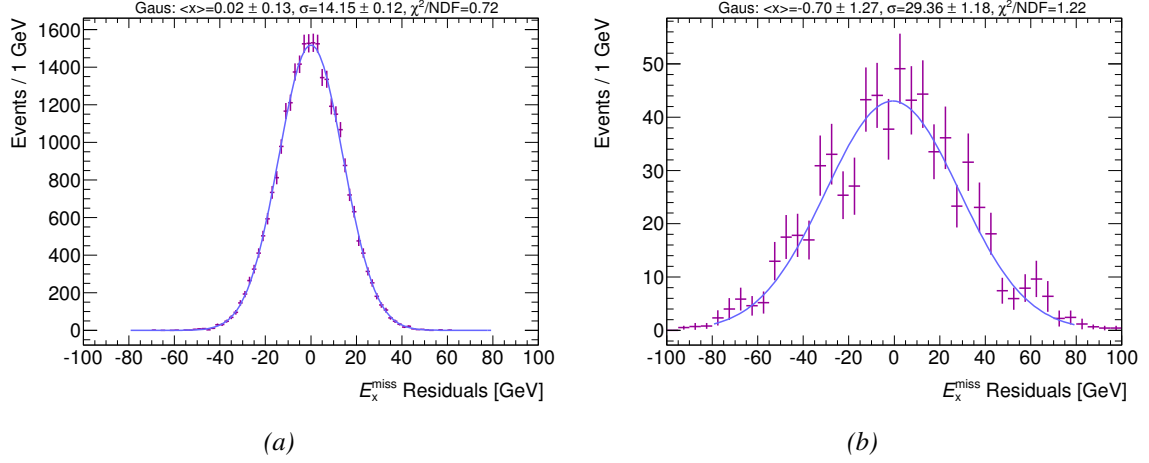


Figure 5.6: Examples of $(\delta E_T^{\text{miss}})_x$ Gaussian fits for a $Z \rightarrow \mu\mu$ selection with no contributions from the jet term. The $\sum E_T$ bins shown are $300 < \sum E_T < 305$ GeV (a) and $1000 < \sum E_T < 1500$ GeV (b).

the contribution coming from the tails.

The two-dimensional distribution of the $(\delta E_T^{\text{miss}})_x$ versus the total $\sum E_T$ for a $Z \rightarrow \mu\mu$ sample with no jet activity is shown in Fig. 5.7a. The resolution curve as a function of $\sum E_T$, obtained by fitting the $\sum E_T$ slices of the distribution of Fig. 5.7a, is shown in Fig. 5.7b. Here the uncertainty bars represent the uncertainty on the width of the Gauss fit function. It can be observed that the resolution of the events worsens steadily as the $\sum E_T$ increases. The resolution curve of the selected events, integrated over the full $\sum E_T$ range, is shown in Fig. 5.7c for the case where the resolutions of the selected objects are added in quadrature and it is assumed that the $E_T^{\text{miss, Soft}}$ resolution behaves as $\sqrt{\sum E_T^{\text{Soft}}}$. This has to be compared to the curve of Fig. 5.7d where the resolution curve is obtained as the convolution of the results of Fig. 5.7b: for each $\sum E_T$ bin the number of events of that bin is multiplied by its measured resolution. This way of obtaining the total E_T^{miss} resolution distribution is identified as convolution method in the following. The second distribution is narrower as the previous one and the peak position is shifted to lower values by about 4 GeV. This is the first hint that the naive assumption on the resolution of the Soft-term tends to overestimate the resolution measured in the events.

The two-dimensional distributions representing the $(\delta p_T^{\text{soft}})^{\text{recoObj}}$ and $(\delta p_T^{\text{soft}})^{\text{truthObj}}$ versus $\sum E_T^{\text{Soft}}$ are shown in Figs. 5.8a and 5.8c, respectively, still for a $Z \rightarrow \mu\mu$ selection in MC with no jet activity. Since in these events the only hard objects are the muons, that have a much smaller resolution in comparison to the one of the hadronic objects, the differences between the two-distributions are minimal, while larger differences are expected for selections with jets. This can be observed also in Figs. 5.8b and 5.8d where the measured events $E_T^{\text{miss, Soft}}$ resolution is plotted as a function of the $\sum E_T^{\text{Soft}}$ and the two curves result to be almost identical.

To be able to assign to each event its most plausible Soft-term resolution, it was decided to fit the $E_T^{\text{miss, Soft}}$ resolution curve with a function with a constant, a square root and a linear term in $\sum E_T^{\text{Soft}}$ added together as

$$\text{Reso}(E_T^{\text{miss, Soft}}) = a + b \cdot \sqrt{\sum E_T^{\text{Soft}}} + c \cdot \sum E_T^{\text{Soft}}, \quad (5.4)$$

where the parameter b, associated to the $\sqrt{\sum E_T^{\text{Soft}}}$ term, has been constrained to be always positive.

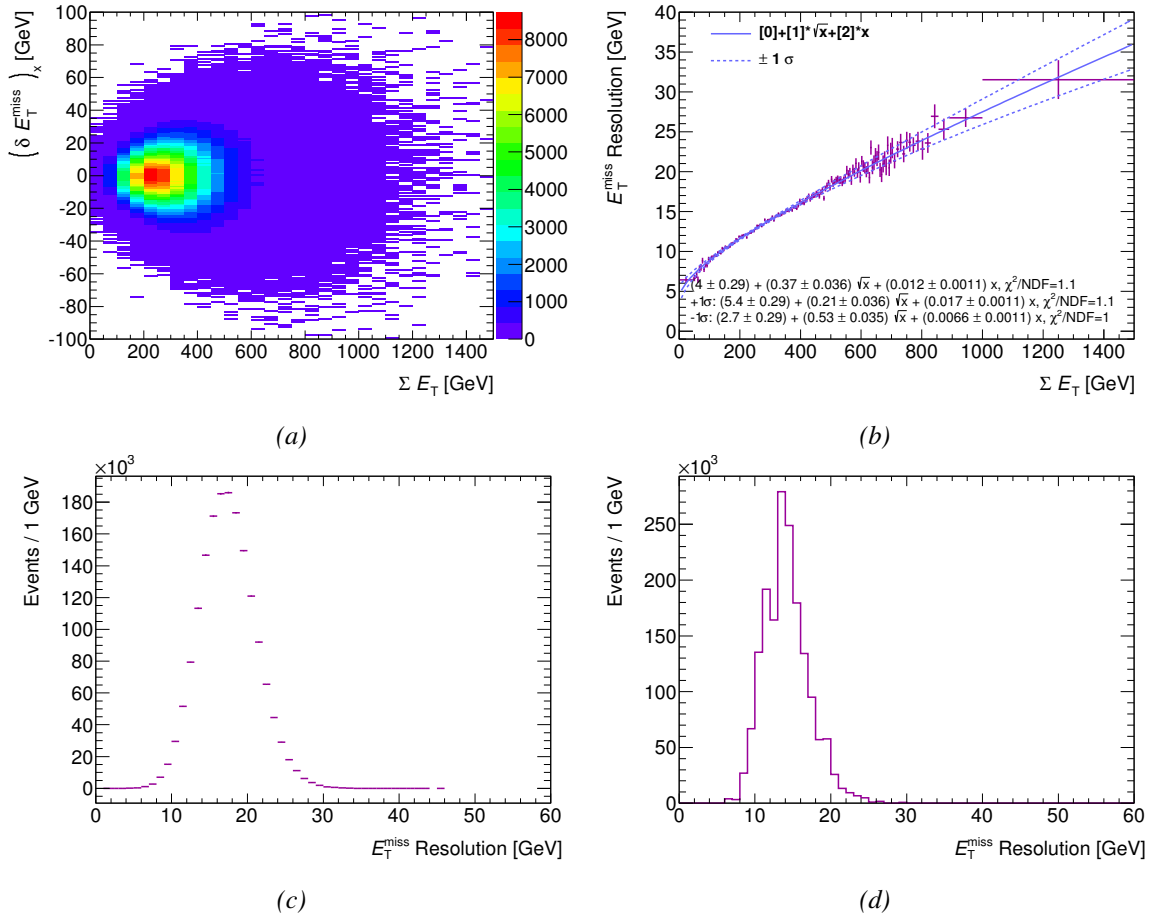


Figure 5.7: (a) Two-dimensional distribution of the $(\delta E_T^{\text{miss}})_x$ versus the total ΣE_T of the events. (b) Measured resolution curve as a function of the event ΣE_T , the uncertainty bars represent the uncertainty on the width of the Gauss fit function. (c) E_T^{miss} resolution curve obtained by summing in quadrature the resolution of all the objects selected for the E_T^{miss} reconstruction, the assumption for the resolution of the Soft-term is $\sqrt{\Sigma E_T^{\text{Soft}}}$. (d) Measured resolution distribution, obtained as the convolution of the results of (b). A $Z \rightarrow \mu\mu$ sample with the $Z \rightarrow \ell\ell$ selections applied and the requirement of no jet activity has been used to generate these distributions.

The $\pm 1\sigma$ bands have been drawn by repeating the same fit on the histograms built by adding or subtracting to the central resolution histogram the uncertainties on the resolution as obtained from the Gauss residual fits. The fit of the resolution curves is performed with a χ^2 minimisation technique and the quantity χ^2 over the number of degree of freedom of the fit (NDF) was taken as a measure of the goodness of the fit.

The measured resolution curves of Figs. 5.8b and 5.8d have, in both cases, a very good compatibility with the fit function. The values of the fit parameters and the fit goodness for the $Z \rightarrow \mu\mu$, $Z \rightarrow ee$ and $W \rightarrow \mu\nu$ selections are summarised in Table 5.2 for events with no jet activity. The parameters obtained by fitting the reco-subtracted residuals and the truth-subtracted residuals versus ΣE_T^{Soft} are compatible within their uncertainty at the $\pm 1\sigma$ level for all the processes investigated. This is not anymore true when fits for events with jets are performed because of their larger resolution. The $Z \rightarrow ee$ and $W \rightarrow \mu\nu$ fit values lie within the $\pm 1\sigma$ bands of the $Z \rightarrow \mu\mu$ fits, showing that the obtained results are compatible independently of the physics process under study.

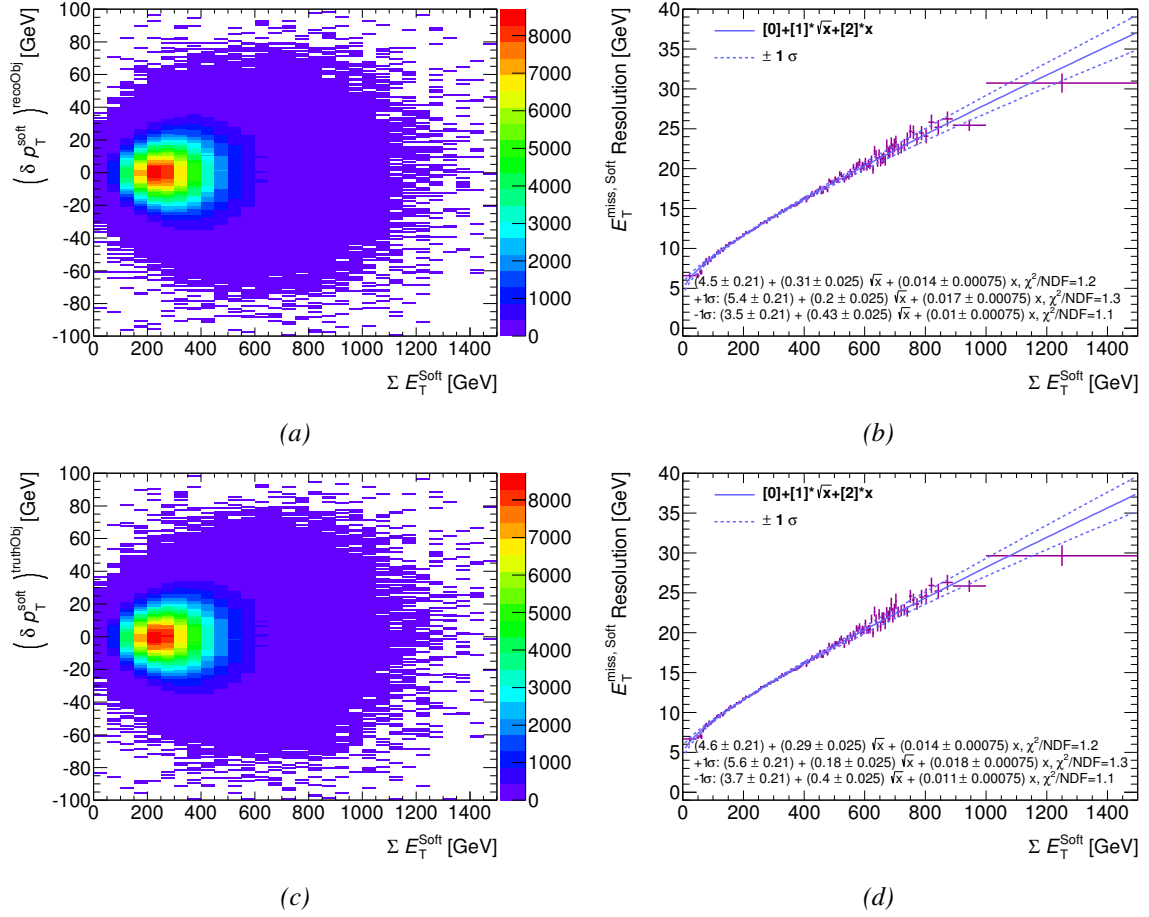


Figure 5.8: (a) Two-dimensional distribution of $(\delta p_T^{\text{soft}})^{\text{recoObj}}$ versus ΣE_T^{Soft} . (b) $E_T^{\text{miss, Soft}}$ resolution curve as a function of ΣE_T^{Soft} , fits of $(\delta p_T^{\text{soft}})^{\text{recoObj}}$. (c) Two-dimensional distribution of $(\delta p_T^{\text{soft}})^{\text{truthObj}}$ versus ΣE_T^{Soft} . (d) $E_T^{\text{miss, Soft}}$ resolution curve as a function of ΣE_T^{Soft} , fits of $(\delta p_T^{\text{soft}})^{\text{truthObj}}$. A $Z \rightarrow \mu\mu$ sample with the $Z \rightarrow \ell\ell$ selections applied and the requirement of no jet activity has been used to generate these distributions.

These results show that the choice done to extract the $E_T^{\text{miss, Soft}}$ resolution seems to be reasonable. What has to be faced and solved is, however, the dependence of the resolution on the jet and, more generally, on the hadronic activity of the events. If the Soft-term resolution computed for events with no jets is applied to events where some jets have been selected, the total event resolution is observed to be smaller than the one measured directly by performing the $(\delta E_T^{\text{miss}})$ fits.

To take the jet activity into account and to have a sensible parameterization for the $E_T^{\text{miss, Soft}}$ resolution as the hadronic activity increases, three binning options were tested:

- n_{jets} bins: 0, 1, ≥ 2
- ΣE_T^{Jet} bins: [0,10), [10,40), [40,80), [80,150), ≥ 150 GeV
- p_T^{hard} bins: [0,10), [10,20), [20,30), [30,50), ≥ 50 GeV

The first option has the problem of a non-smooth variation between the different bins. Moreover, the last bin has so few events in the $Z \rightarrow \ell\ell$ and $W \rightarrow \ell\nu$ samples that the fits are no more stable and that

Fit of $(\delta p_T^{\text{soft}})^{\text{recoObj}}$				
Fit	a	b	c	χ^2/NDF
$Z \rightarrow \mu\mu$ Central	4.45 ± 0.21	0.314 ± 0.025	0.0137 ± 0.0007	1.19
$Z \rightarrow \mu\mu + 1\sigma$	5.39 ± 0.21	0.202 ± 0.025	0.0173 ± 0.0007	1.31
$Z \rightarrow \mu\mu - 1\sigma$	3.51 ± 0.21	0.425 ± 0.025	0.0100 ± 0.0007	1.11
$Z \rightarrow ee$ Central	4.23 ± 0.22	0.319 ± 0.028	0.0142 ± 0.0008	1.04
$W \rightarrow \mu\nu$ Central	5.03 ± 0.17	0.223 ± 0.021	0.0152 ± 0.0006	1.50

Fit of $(\delta p_T^{\text{soft}})^{\text{truthObj}}$				
Fit	a	b	c	χ^2/NDF
$Z \rightarrow \mu\mu$ Central	4.62 ± 0.21	0.289 ± 0.025	0.0144 ± 0.0007	1.18
$Z \rightarrow \mu\mu + 1\sigma$	5.56 ± 0.21	0.177 ± 0.025	0.0182 ± 0.0007	1.31
$Z \rightarrow \mu\mu - 1\sigma$	3.67 ± 0.21	0.401 ± 0.025	0.0107 ± 0.0007	1.10
$Z \rightarrow ee$ Central	3.95 ± 0.23	0.376 ± 0.028	0.0127 ± 0.0008	1.20
$W \rightarrow \mu\nu$ Central	5.00 ± 0.16	0.222 ± 0.020	0.0153 ± 0.0006	1.59

Table 5.2: Values of the $E_T^{\text{miss, Soft}}$ resolution fit parameters and the goodness of the fits for $\sum E_T^{\text{Jet}} < 10$ GeV for $Z \rightarrow \mu\mu$, $Z \rightarrow ee$ and $W \rightarrow \mu\nu$. For $Z \rightarrow \mu\mu$, also the fits for the $\pm 1\sigma$ bands are reported, which corresponds to the fits of the distributions obtained by considering the nominal value varied up or down by one sigma deviation its uncertainty.

a too coarse $\sum E_T^{\text{Soft}}$ binning has to be chosen to extract the resolutions. This becomes a problem when the computed $E_T^{\text{miss, Soft}}$ resolution has to be used in samples, such as $t\bar{t}$, where a higher number of jets is always present. In the light of these disadvantages the n_{jets} binning choice will not be further discussed. The second and the third options give better results. The main disadvantage of the $\sum E_T^{\text{Jet}}$ binning is that different processes have different $\sum E_T^{\text{Jet}}$ distributions making it very difficult, when not impossible, to use a unique binning, this is the case e.g. for $Z \rightarrow \mu\mu$ and $t\bar{t}$. The p_T^{hard} distribution, instead, is much more similar among different physics processes, making it easier to define a unique binning that could be used to compare the results obtained with different test samples. The two-dimensional distributions of the $\sum E_T^{\text{Jet}}$ versus p_T^{hard} and the simple distributions of the number of events as a function of the two variables for a $Z \rightarrow \mu\mu$ and a semileptonic $t\bar{t}$ inclusive MC selection are shown in Fig. 5.9.

An additional advantage of using the p_T^{hard} variable is that the E_T^{miss} uncertainties are usually computed as a function of this variable. Its big drawback, however, is that it can be defined only for MC samples or for processes where no real E_T^{miss} is expected. If a parameterization depending on this variable is extracted, a solution has to be found for how to translate it in such a way that it could be used also in data events.

In the following section the results of the study are presented mainly for the $\sum E_T^{\text{Jet}}$ binning choice and only some remarks for the p_T^{hard} option are discussed.

5.2.3 Results and Closure-Test

The results of the $E_T^{\text{miss, Soft}}$ resolution fits are summarised in Table 5.3 for the reco-subtraction method fits (Fit of $(\delta p_T^{\text{soft}})^{\text{recoObj}}$) and in Table 5.4 for the truth-subtraction method fits (Fit of $(\delta p_T^{\text{soft}})^{\text{truthObj}}$) in bins of $\sum E_T^{\text{Jet}}$. The baseline sample used to define the resolution parameterization is $Z \rightarrow \mu\mu$. The fit parameters obtained with this sample are compared with those obtained in $Z \rightarrow ee$, $W \rightarrow \mu\nu$ and $t\bar{t}$ MC samples and with what is obtained for a $Z \rightarrow \mu\mu$ selection in the 8 TeV period B ATLAS dataset. The

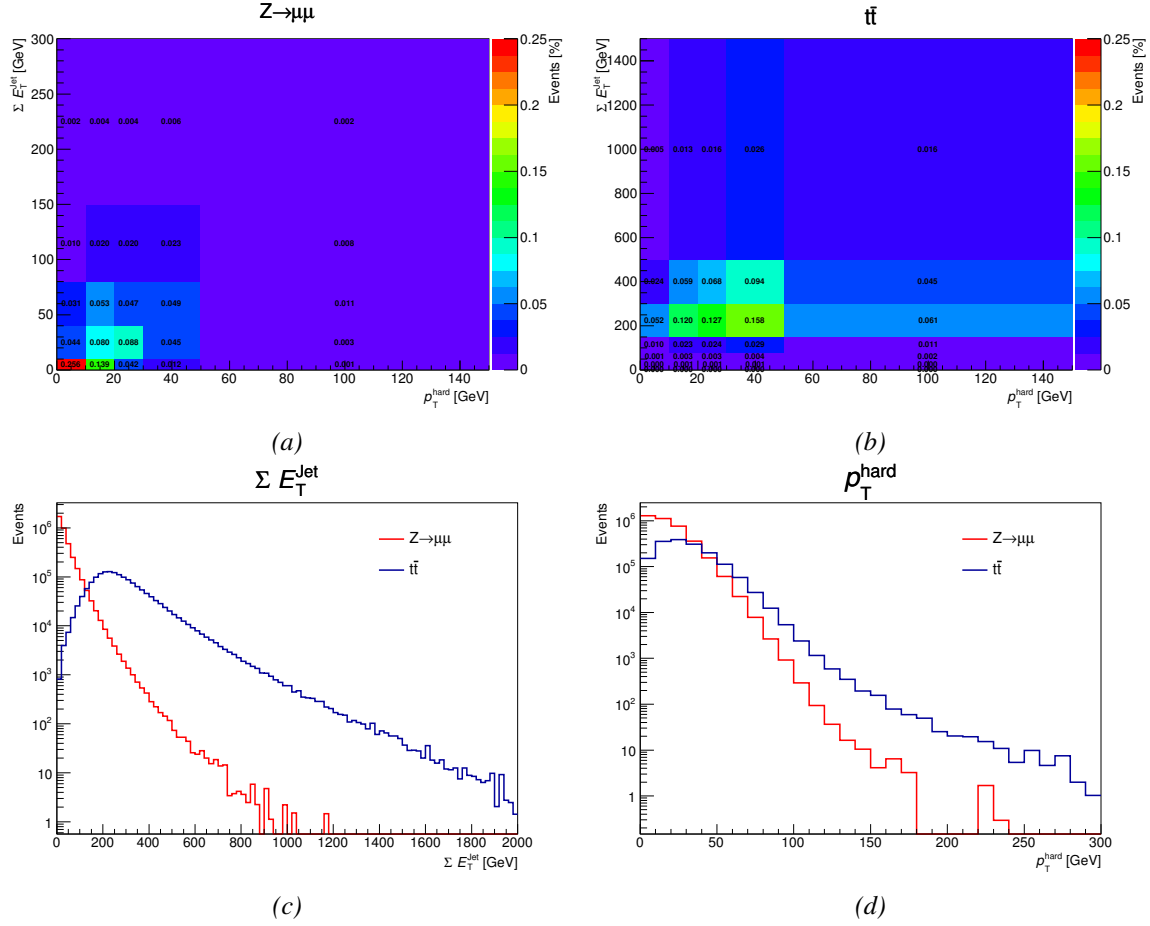


Figure 5.9: (a) ΣE_T^{Jet} versus p_T^{hard} for a $Z \rightarrow \mu\mu$ inclusive selection in MC. (b) ΣE_T^{Jet} versus p_T^{hard} for a semileptonic $t\bar{t}$ inclusive selection in MC. (c) distribution of the ΣE_T^{Jet} for a $Z \rightarrow \mu\mu$ and a semileptonic $t\bar{t}$ inclusive MC selection. (d) distribution of the p_T^{hard} for a $Z \rightarrow \mu\mu$ and a semileptonic $t\bar{t}$ inclusive MC selection.

resolution curves for the latter sample can be extracted only with the reco-subtraction method and by assuming that the $E_T^{\text{miss, Truth}}$ is zero. It can be observed that, in general, the quality of the fits is good and that the results of the $Z \rightarrow \ell\ell$ and $W \rightarrow \mu\nu$ fits are compatible among each other within the $\pm 1\sigma$ band of the $Z \rightarrow \mu\mu$ resolution functions, with some larger deviation only in the highest ΣE_T^{Jet} bin. For the $t\bar{t}$ sample a different ΣE_T^{Jet} binning was chosen because of the different shape and range of this distribution with respect to the one of $Z \rightarrow \mu\mu$. The chosen ΣE_T^{Jet} bins are $[0,80)$, $[80,150)$, $[150,300)$, $[300,500)$ and $\Sigma E_T^{\text{Jet}} \geq 500$ GeV.

The parameterizations obtained with the truth-subtraction method are more stable, have in general a better χ^2/NDF and have an even higher compatibility between samples with respect to those obtained with the reco-subtraction method.

For the $t\bar{t}$ sample the first ΣE_T^{Jet} bin is not really representative, because only events with a very low jet activity are selected, and gives a very different fit result with respect to the other bins. The resolution fits in the others $t\bar{t}$ ΣE_T^{Jet} bins are reasonably compatible with the $Z \rightarrow \mu\mu$ fits in its higher ΣE_T^{Jet} bins. The $E_T^{\text{miss, Soft}}$ resolution curves as a function of ΣE_T^{Soft} for the $Z \rightarrow \mu\mu$ sample and a bin-by-bin comparison with the $W \rightarrow \mu\nu$ fits for the truth-subtraction method are shown in Fig. 5.10. The central fit function and the $\pm 1\sigma$ variations are drawn for each ΣE_T^{Jet} bin. From the first figure it can be observed

that the change in the resolution curves depending on the $\sum E_T^{\text{Jet}}$ of the events is quite smooth. From the others, the compatibility between the $Z \rightarrow \mu\mu$ and $W \rightarrow \mu\nu$ fits can be seen. The resolution curves for all the $\sum E_T^{\text{Jet}}$ bins for the $W \rightarrow \mu\nu$ and $t\bar{t}$ samples (truth-subtraction method) and the $Z \rightarrow \mu\mu$ selection in data (reco-subtraction method) are shown in Fig. 5.11. For the data selection the resolution curve of the first $\sum E_T^{\text{Jet}}$ bin is also compared with the $Z \rightarrow \mu\mu$ resolution curve obtained in MC showing their agreement.

To check the goodness of the $E_T^{\text{miss, Soft}}$ resolution parameterization found, a closure test was performed. Four resolution curves for the total E_T^{miss} resolution have been compared to show the improvement in the description of the $E_T^{\text{miss, Soft}}$ resolution with the extracted parameterizations with respect to the $\sqrt{\sum E_T^{\text{Soft}}}$ choice, and the compatibility with the measured resolution in the selected events. The results found for the total resolution of the $Z \rightarrow \mu\mu$ sample in the chosen $\sum E_T^{\text{Jet}}$ bins are shown in Fig. 5.12, and the four compared resolution curves are

- green line: the measured E_T^{miss} resolution of the events, obtained with the convolution method,
- blue line: the total E_T^{miss} resolution computed as the sum in quadrature of the resolution of the selected hard objects and of the Soft-term with the choice $\text{Reso}(\text{Soft}) = \sqrt{\sum E_T^{\text{Soft}}}$,
- magenta line: the total E_T^{miss} resolution computed as the sum in quadrature of the resolution of the selected hard objects and of the Soft-term, extracted from the parameterization, in $\sum E_T^{\text{Jet}}$ bins, obtained with the reco-subtraction method,
- orange line: the total E_T^{miss} resolution computed as the sum in quadrature of the resolution of the selected hard objects and of the Soft-term, extracted from the parameterization, in $\sum E_T^{\text{Jet}}$ bins, obtained with the truth-subtraction method.

The ratio between the resolution curves obtained by setting the Soft-term resolution to the values extracted from the Soft-term resolution fits, either with the reco-subtraction (magenta) or with the truth-subtraction (orange) method, and the measured resolution is also shown. The statistical relative uncertainty of the measured resolution curve is also drawn as green hatched band.

In the first bins the agreement between the convolution curve and the distribution obtained by using the parameterized $E_T^{\text{miss, Soft}}$ resolution extracted with the truth-subtraction method is quite good. For the higher $\sum E_T^{\text{Jet}}$ bins a less good agreement is observed; this is, however, also partly due to the impossibility to define a fine enough binning to use for the convolution, whose curve is not anymore smooth. In general, the best description of the total resolution is achieved with the truth-subtraction method, which was also the one giving better compatibility among different physics processes.

The two-dimensional distribution shown in Fig. 5.12f supports further the chosen parameterization: it displays the correlation between the value of the total resolution obtained with the convolution method and the value obtained by summing in quadrature the resolutions of the hard objects and the $E_T^{\text{miss, Soft}}$ resolution from the truth-subtraction parameterization in the $40 \leq \sum E_T^{\text{Jet}} < 80$ GeV bin.

Additional comparisons for other event categorisation choices and for the $W \rightarrow \mu\nu$ sample are shown in Appendix A.

The other possible binning choice to extract the $E_T^{\text{miss, Soft}}$ resolution parameterization is to use the p_T^{hard} variable. This choice makes a larger use of the truth information as the previous one, but, as already mentioned, it is interesting to check the results that can be obtained by the use of this variable,

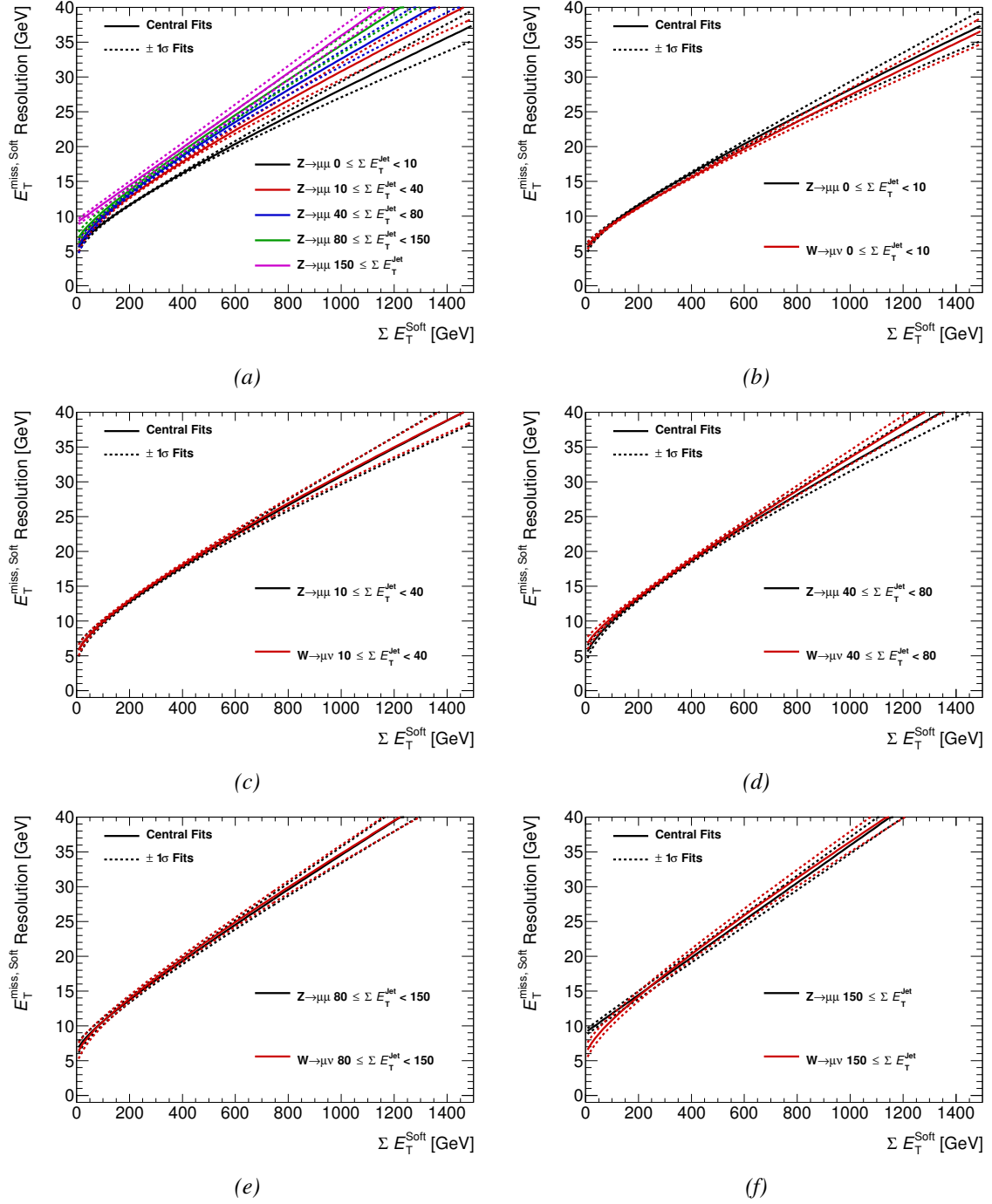


Figure 5.10: $E_T^{\text{miss, Soft}}$ resolution as a function of ΣE_T^{Soft} obtained with the truth-subtraction method (a) for the $Z \rightarrow \mu\mu$ MC sample and the different ΣE_T^{Jet} bins, and for the comparison of the $Z \rightarrow \mu\mu$ and $W \rightarrow \mu\nu$ fits in the ΣE_T^{Jet} bins (b) [0,10), (c) [10,40), (d) [40,80), (e) [80,150) and (f) ≥ 150 GeV. In the figures the solid line represents the central fit curve, while the hatched lines represent the result of the fit if the underlying distribution is varied up or down by one sigma deviation of its uncertainty.

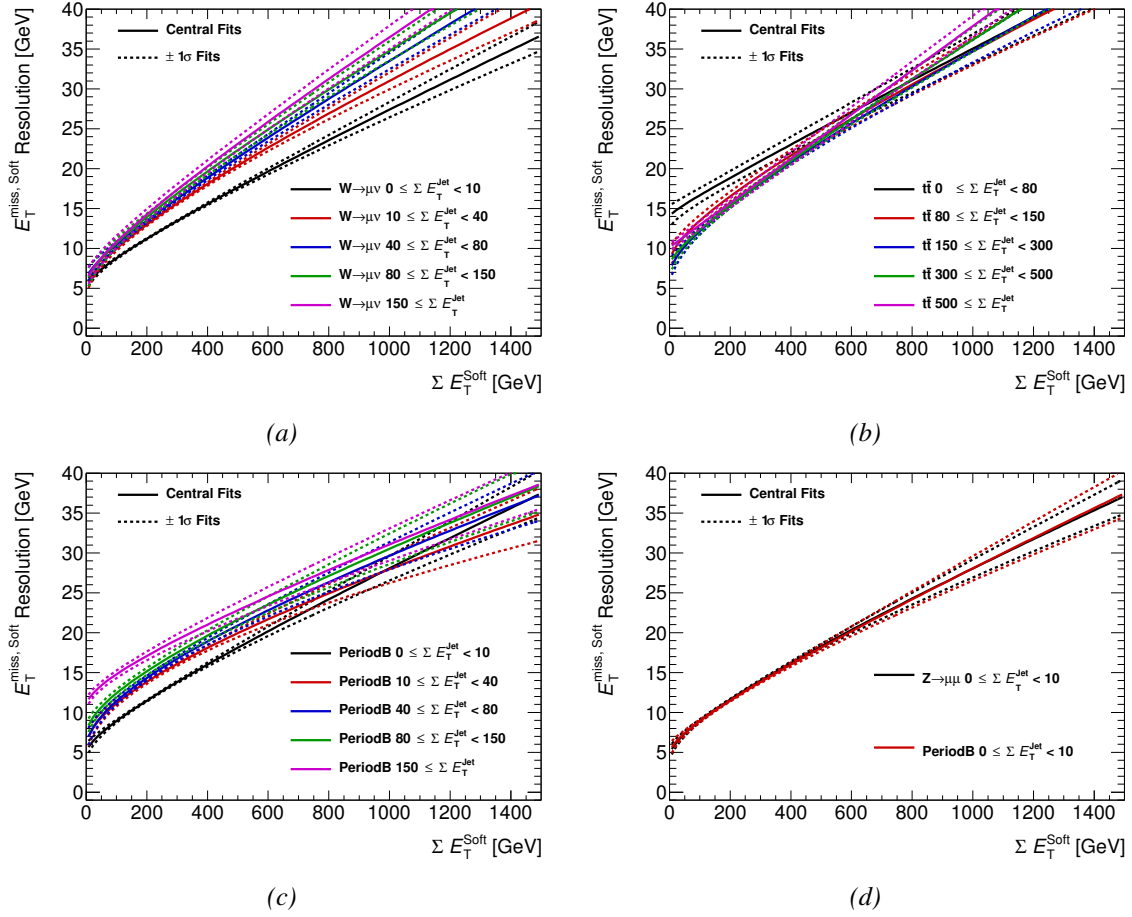


Figure 5.11: $E_T^{\text{miss, Soft}}$ resolution curves as a function of ΣE_T^{Soft} obtained with the truth-subtraction method in ΣE_T^{jet} bins for a $W \rightarrow \mu\nu$ sample (a) and for a $t\bar{t}$ sample (b). $E_T^{\text{miss, Soft}}$ resolution curves as a function of ΣE_T^{Soft} obtained with the reco-subtraction method in ΣE_T^{jet} bins for a $Z \rightarrow \mu\mu$ selection in data period B at 8 TeV (c) and comparison with the results obtained with the $Z \rightarrow \mu\mu$ MC sample in the first ΣE_T^{jet} bin (d). In the figures the solid line represents the central fit curve, while the hatched lines represent the result of the fit if the underlying distribution is varied up or down by one sigma deviation of its uncertainty.

since the E_T^{miss} systematic uncertainties are computed along this axis.

For this choice, only the fit results that exploit the residuals computed with the truth matched objects, truth-subtraction method, are shown. The $E_T^{\text{miss, Soft}}$ resolution as a function of the ΣE_T^{Soft} in the $30 < p_T^{\text{hard}} < 50$ GeV bin is shown in Fig. 5.13a for the distribution obtained with the reco-subtraction method and in Fig. 5.13b with the truth-subtraction method. It can be clearly observed that it is not possible to fit the first distribution with the chosen resolution fit function. On the other hand, the second plot shows an almost linear increase of the resolution with ΣE_T^{Soft} that can still be fitted.

The parameters obtained from the fits are summarised in Table 5.5 for the $Z \rightarrow \mu\mu$, $Z \rightarrow ee$, $W \rightarrow \mu\nu$ and $t\bar{t}$ samples for the five chosen p_T^{hard} bins. The compatibility of the results obtained with the $Z \rightarrow \ell\ell$ and $W \rightarrow \mu\nu$ samples is extremely good, while the curves obtained with the $t\bar{t}$ sample are quite different. This can be noted also by looking at Figs. 5.13c and 5.13d where the resolution parameterizations as a function of the ΣE_T^{Soft} and for the different p_T^{hard} bins are displayed for the $Z \rightarrow \mu\mu$ and $t\bar{t}$ samples, respectively.

The resolution curves are also changing less smoothly from a p_T^{hard} bin to the next with respect to what

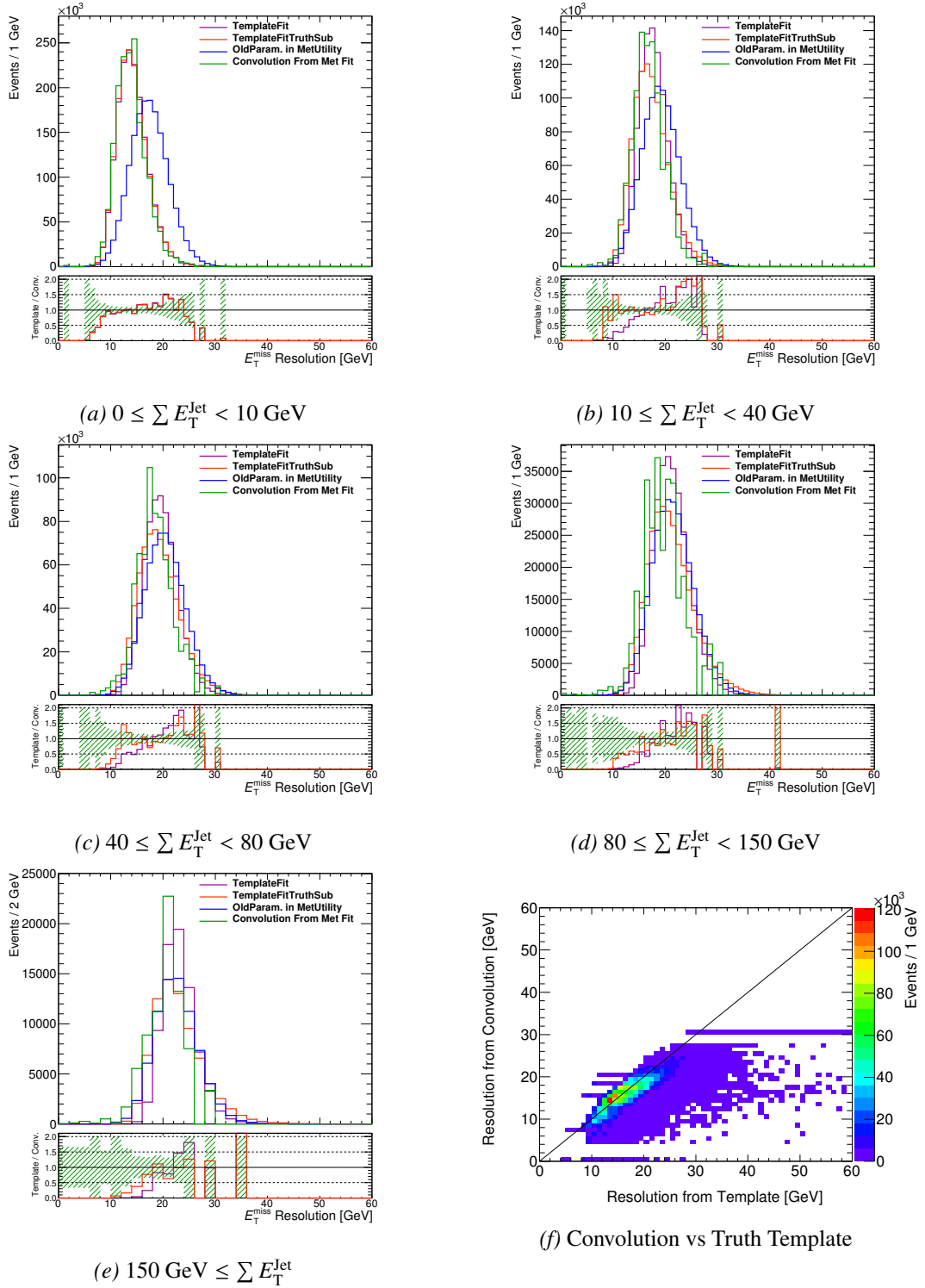


Figure 5.12: Distributions of the total E_T^{miss} resolution for the $Z \rightarrow \mu\mu$ sample in the chosen $\sum E_T^{\text{JEt}}$ bins: $0 \leq \sum E_T^{\text{JEt}} < 10 \text{ GeV}$ in (a), $10 \leq \sum E_T^{\text{JEt}} < 40 \text{ GeV}$ in (b), $40 \leq \sum E_T^{\text{JEt}} < 80 \text{ GeV}$ in (c), $80 \leq \sum E_T^{\text{JEt}} < 150 \text{ GeV}$ in (d), $150 \text{ GeV} \leq \sum E_T^{\text{JEt}}$ in (e). The magenta, the orange and the blue lines are the sum in quadrature of the resolutions of the selected hard objects and the $E_T^{\text{miss, Soft}}$ resolution as extracted with the reco- and truth-subtraction methods, or as $\sigma_{E_T^{\text{miss, Soft}}} = \sqrt{\sum E_T^{\text{Soft}}}$; the green line is the measured total resolution obtained with the convolution method. The ratio between the results based on the templates and the ones from the convolution method is also shown. The green hatched band in the ratio plot represents the relative uncertainty of the resolution curve obtained with the convolution method. (f) Two-dimensional distribution of the total E_T^{miss} resolution obtained by the convolution method versus the distribution obtained by summing in quadrature the resolutions of the hard objects and the $E_T^{\text{miss, Soft}}$ resolution from the truth subtraction parameterization for the $40 \leq \sum E_T^{\text{JEt}} < 80 \text{ GeV}$ bin.

is observed for the $\sum E_T^{\text{Jet}}$ binning choice.

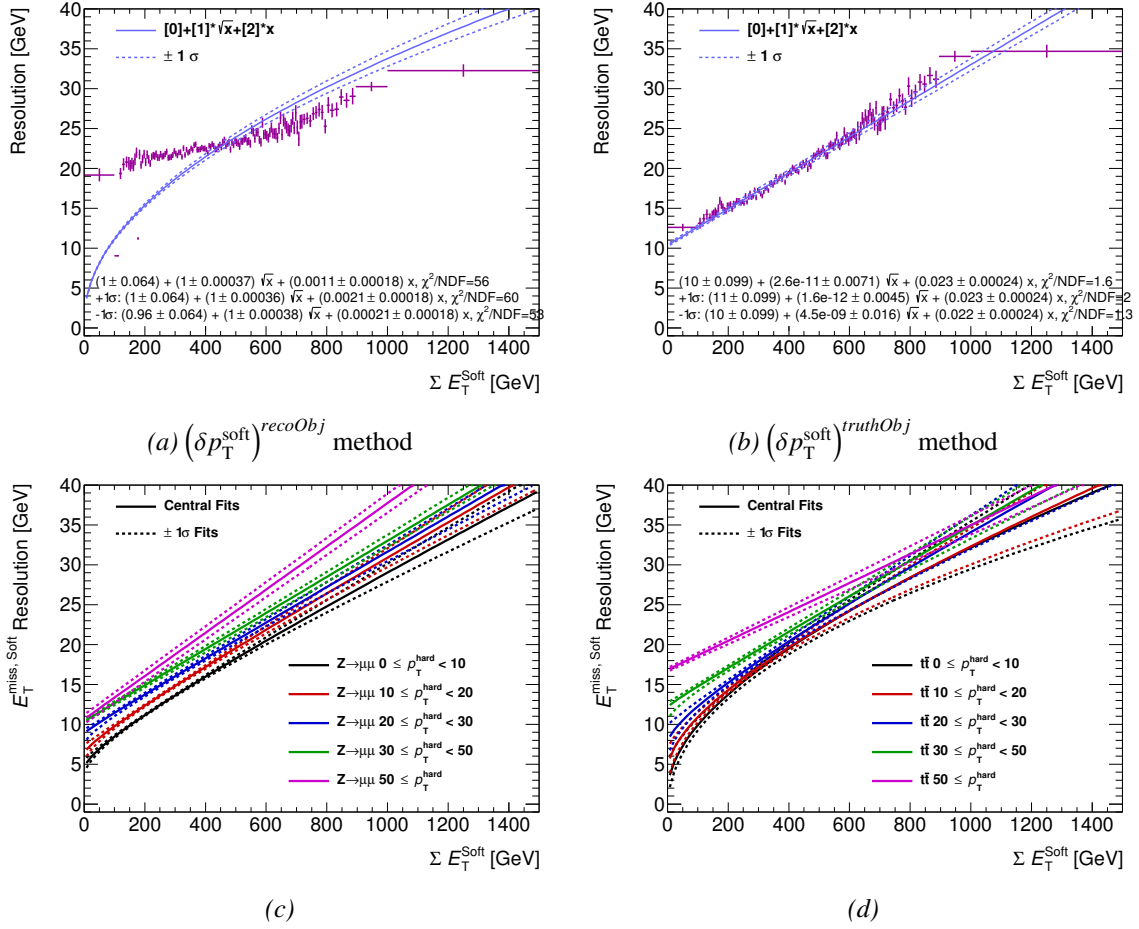


Figure 5.13: Resolution of the $E_T^{\text{miss, Soft}}$ as a function of ΣE_T^{Soft} measured starting from the residual distributions $(\delta p_T^{\text{soft}})^{\text{recoObj}}$ (a) and $(\delta p_T^{\text{soft}})^{\text{truthObj}}$ (b) for the $30 < p_T^{\text{hard}} < 50$ GeV bin., $E_T^{\text{miss, Soft}}$ resolution curves, binned in p_T^{hard} , as a function of ΣE_T^{Soft} obtained for the $(\delta p_T^{\text{soft}})^{\text{truthObj}}$ choice for the $Z \rightarrow \mu\mu$ (c) and $t\bar{t}$ (d) samples. In the figures the solid line represents the central fit curve, while the hatched lines represent the result of the fit if the underlying distribution is varied up or down by one sigma deviation of its uncertainty.

5.2.4 Conclusions

The performed studies show that it is possible to develop a method to determine a better parameterization for the $E_T^{\text{miss, Soft}}$ resolution. It is not possible, however, to define a unique resolution function, independent of the hadronic activity of the selected events, to be used to extract sensible $E_T^{\text{miss, Soft}}$ resolution values for each event. It is already known that the $E_T^{\text{miss, Soft}}$ term strongly depends on the pile-up and it has been found that the best choice for a stable $E_T^{\text{miss, Soft}}$ resolution parameterization is to categorise the events in $\sum E_T^{\text{Jet}}$ bins.

Two different Soft-term residual definitions have been tested, one based on the subtraction of the measured objects, the other based on the subtraction of the true objects that have a match with the measured ones. It was found that the truth-subtraction method yields better results. In particular it gives a better compatibility among different physics processes and between the curve that represents the total meas-

ured E_T^{miss} resolution, and the one obtained by summing in quadrature the resolution of the hard objects and the resolution of the $E_T^{\text{miss, Soft}}$ as extracted from the parameterized Soft-term resolution curve. The reason for this is mainly based on the fact that, proceeding in this way, the resolution smearing that comes from the hard objects is subtracted before the $E_T^{\text{miss, Soft}}$ resolution is extracted and, therefore, does not influence its value.

The definitions used to extract the parameterization rely on information extracted from truth objects. The results could, hence, be checked in data only for a $Z \rightarrow \ell\ell$ selection where it can be assumed that the true missing transverse momentum is zero.

The $E_T^{\text{miss, Soft}}$ resolution parameterization was also extracted by categorising the events in p_T^{hard} bins. In this case larger differences have been observed between $t\bar{t}$ and $Z \rightarrow \ell\ell$ or $W \rightarrow \ell\nu$ samples. Moreover, it is not possible to apply to data a parameterization based on this variable, because of its definition.

The results obtained are very promising and represent an important first step for a more correct description of the E_T^{miss} resolution. To make a collaboration-wide use of these results, though, the parameterization has to be validated with additional physics processes, to further probe its universality, and its impact on the systematic uncertainties needs to be studied.

Fit of $(\delta p_T^{\text{soft}})^{\text{recoObj}}$					
Sample	Fit	a	b	c	χ^2/NDF
$\sum E_T^{\text{Jet}} < 10 \text{ GeV}$					
$Z \rightarrow \mu\mu$	Central	4.45 ± 0.21	0.314 ± 0.025	0.0137 ± 0.0007	1.19
	$+1\sigma$	5.39 ± 0.21	0.202 ± 0.025	0.0174 ± 0.0007	1.30
	-1σ	3.51 ± 0.21	0.425 ± 0.025	0.0100 ± 0.0007	1.11
$Z \rightarrow \mu\mu$ PeriodB	Central	4.88 ± 0.23	0.251 ± 0.030	0.0152 ± 0.0009	1.15
$Z \rightarrow ee$	Central	4.10 ± 0.22	0.336 ± 0.028	0.0136 ± 0.0008	1.24
$W \rightarrow \mu\nu$	Central	5.12 ± 0.17	0.210 ± 0.021	0.0156 ± 0.0006	1.51
$10 \leq \sum E_T^{\text{Jet}} < 40 \text{ GeV}$					
$Z \rightarrow \mu\mu$	Central	5.36 ± 0.36	0.508 ± 0.040	0.0066 ± 0.0011	1.28
	$+1\sigma$	6.72 ± 0.36	0.368 ± 0.040	0.0109 ± 0.0011	1.35
	-1σ	4.01 ± 0.36	0.649 ± 0.040	0.0024 ± 0.0011	1.25
$Z \rightarrow \mu\mu$ PeriodB	Central	5.56 ± 0.42	0.487 ± 0.048	0.0070 ± 0.0014	1.61
$Z \rightarrow ee$	Central	4.99 ± 0.42	0.543 ± 0.047	0.0056 ± 0.0013	1.17
$W \rightarrow \mu\nu$	Central	6.69 ± 0.33	0.370 ± 0.036	0.0093 ± 0.0010	1.14
$40 \leq \sum E_T^{\text{Jet}} < 80 \text{ GeV} (\text{t}\bar{\text{t}}: \sum E_T^{\text{Jet}} < 80 \text{ GeV})$					
$Z \rightarrow \mu\mu$	Central	4.19 ± 0.45	0.671 ± 0.047	0.0037 ± 0.0012	1.35
	$+1\sigma$	5.49 ± 0.45	0.550 ± 0.047	0.0072 ± 0.0012	1.42
	-1σ	2.90 ± 0.45	0.793 ± 0.046	0.0001 ± 0.0012	1.34
$Z \rightarrow \mu\mu$ PeriodB	Central	5.53 ± 0.52	0.507 ± 0.058	0.0081 ± 0.0016	1.35
$Z \rightarrow ee$	Central	4.32 ± 0.56	0.621 ± 0.059	0.0049 ± 0.0015	1.02
$W \rightarrow \mu\nu$	Central	5.53 ± 0.42	0.552 ± 0.044	0.0060 ± 0.0011	1.10
$\text{t}\bar{\text{t}}$	Central	15.34 ± 0.50	0.000 ± 0.125	0.0201 ± 0.0014	1.55
$80 \leq \sum E_T^{\text{Jet}} < 150 \text{ GeV}$					
$Z \rightarrow \mu\mu$	Central	6.45 ± 0.69	0.510 ± 0.070	0.0077 ± 0.0017	0.92
	$+1\sigma$	7.60 ± 0.70	0.425 ± 0.070	0.0103 ± 0.0017	1.00
	-1σ	5.30 ± 0.69	0.594 ± 0.070	0.0052 ± 0.0017	0.89
$Z \rightarrow \mu\mu$ PeriodB	Central	7.13 ± 0.74	0.428 ± 0.081	0.0098 ± 0.0022	1.25
$Z \rightarrow ee$	Central	4.85 ± 0.66	0.643 ± 0.069	0.0040 ± 0.0018	0.85
$W \rightarrow \mu\nu$	Central	5.80 ± 0.73	0.585 ± 0.0728	0.0067 ± 0.0018	1.47
$\text{t}\bar{\text{t}}$	Central	10.30 ± 1.24	0.334 ± 0.133	0.0134 ± 0.0036	1.27
$150 \text{ GeV} \leq \sum E_T^{\text{Jet}} (\text{t}\bar{\text{t}}: 150 \leq \sum E_T^{\text{Jet}} < 300 \text{ GeV})$					
$Z \rightarrow \mu\mu$	Central	10.22 ± 1.43	0.314 ± 0.137	0.0010 ± 0.0033	2.06
	$+1\sigma$	11.27 ± 1.43	0.264 ± 0.137	0.0116 ± 0.0033	2.24
	-1σ	9.17 ± 1.43	0.364 ± 0.137	0.0083 ± 0.0033	1.91
$Z \rightarrow \mu\mu$ PeriodB	Central	10.78 ± 1.21	0.289 ± 0.131	0.0111 ± 0.0036	1.17
$Z \rightarrow ee$	Central	8.18 ± 1.84	0.485 ± 0.181	0.0054 ± 0.0046	1.29
$W \rightarrow \mu\nu$	Central	7.21 ± 1.61	0.650 ± 0.156	0.0042 ± 0.0039	1.11
$\text{t}\bar{\text{t}}$	Central	16.29 ± 0.04	0.000 ± 0.001	0.0139 ± 0.0001	13.74
$300 \leq \sum E_T^{\text{Jet}} < 500 \text{ GeV}$					
$\text{t}\bar{\text{t}}$	Central	9.68 ± 0.79	0.502 ± 0.081	0.0075 ± 0.0021	1.12
$500 \text{ GeV} \leq \sum E_T^{\text{Jet}}$					
$\text{t}\bar{\text{t}}$	Central	15.42 ± 1.52	0.125 ± 0.153	0.0163 ± 0.0041	1.18

Table 5.3: Results of the $E_T^{\text{miss, Soft}}$ resolution fits for the reco-subtraction method in $\sum E_T^{\text{Jet}}$ steps. The fit parameters and their uncertainties are reported for the selected $\sum E_T^{\text{Jet}}$ binning for the processes $Z \rightarrow \mu\mu$, a $Z \rightarrow \mu\mu$ selection in the 8 TeV period B dataset, $Z \rightarrow ee$, $W \rightarrow \mu\nu$ and $\text{t}\bar{\text{t}}$. For the $\text{t}\bar{\text{t}}$ sample a different binning was chosen to better cover its $\sum E_T^{\text{Jet}}$ distribution.

Fit of $(\delta p_T^{\text{soft}})^{\text{truthObj}}$					
Sample	Fit	a	b	c	χ^2/NDF
$\sum E_T^{\text{Jet}} < 10 \text{ GeV}$					
$Z \rightarrow \mu\mu$	Central	4.62 ± 0.21	0.289 ± 0.025	0.0144 ± 0.0007	1.18
	$+1\sigma$	5.56 ± 0.21	0.177 ± 0.025	0.0182 ± 0.0007	1.31
	-1σ	3.67 ± 0.21	0.401 ± 0.025	0.0107 ± 0.0007	1.10
$Z \rightarrow ee$	Central	3.92 ± 0.23	0.383 ± 0.029	0.0124 ± 0.0009	1.24
$W \rightarrow \mu\nu$	Central	5.08 ± 0.17	0.214 ± 0.020	0.0156 ± 0.0006	1.57
$10 \leq \sum E_T^{\text{Jet}} < 40 \text{ GeV}$					
$Z \rightarrow \mu\mu$	Central	4.76 ± 0.34	0.35 ± 0.038	0.0149 ± 0.0010	1.50
	$+1\sigma$	6.03 ± 0.33	0.218 ± 0.037	0.0191 ± 0.0010	1.59
	-1σ	3.49 ± 0.34	0.488 ± 0.038	0.0107 ± 0.0010	1.46
$Z \rightarrow ee$	Central	3.93 ± 0.42	0.468 ± 0.046	0.0122 ± 0.0013	1.17
$W \rightarrow \mu\nu$	Central	4.61 ± 0.29	0.395 ± 0.033	0.0139 ± 0.0009	1.05
$40 \leq \sum E_T^{\text{Jet}} < 80 \text{ GeV} (\text{t}\bar{\text{t}}: \sum E_T^{\text{Jet}} < 80 \text{ GeV})$					
$Z \rightarrow \mu\mu$	Central	4.40 ± 0.41	0.400 ± 0.044	0.0156 ± 0.0012	1.34
	$+1\sigma$	5.62 ± 0.42	0.279 ± 0.044	0.0192 ± 0.0012	1.48
	-1σ	3.17 ± 0.41	0.520 ± 0.044	0.0119 ± 0.0012	1.26
$Z \rightarrow ee$	Central	4.58 ± 0.54	0.384 ± 0.058	0.0165 ± 0.0015	1.33
$W \rightarrow \mu\nu$	Central	6.00 ± 0.39	0.252 ± 0.042	0.0195 ± 0.0011	1.38
$\text{t}\bar{\text{t}}$	Central	14.01 ± 2.67	0.080 ± 0.507	0.0185 ± 0.0081	1.26
$80 \leq \sum E_T^{\text{Jet}} < 150 \text{ GeV}$					
$Z \rightarrow \mu\mu$	Central	6.12 ± 0.62	0.245 ± 0.064	0.0207 ± 0.0017	1.00
	$+1\sigma$	7.11 ± 0.62	0.165 ± 0.065	0.0234 ± 0.0017	1.10
	-1σ	5.12 ± 0.61	0.325 ± 0.064	0.0180 ± 0.0016	0.95
$Z \rightarrow ee$	Central	5.16 ± 0.84	0.342 ± 0.087	0.0184 ± 0.0022	1.64
$W \rightarrow \mu\nu$	Central	5.31 ± 0.85	0.348 ± 0.085	0.0184 ± 0.0021	1.02
$\text{t}\bar{\text{t}}$	Central	8.11 ± 1.17	0.394 ± 0.127	0.0141 ± 0.0035	1.34
$150 \text{ GeV} \leq \sum E_T^{\text{Jet}} (\text{t}\bar{\text{t}}: 150 \leq \sum E_T^{\text{Jet}} < 300 \text{ GeV})$					
$Z \rightarrow \mu\mu$	Central	9.06 ± 0.25	0.000 ± 0.093	0.0269 ± 0.0006	1.40
	$+1\sigma$	9.45 ± 0.25	0.000 ± 0.053	0.0277 ± 0.0006	1.52
	-1σ	8.67 ± 0.25	0.000 ± 0.683	0.0261 ± 0.0006	1.31
$Z \rightarrow ee$	Central	7.53 ± 2.75	0.174 ± 0.253	0.0219 ± 0.0068	1.62
$W \rightarrow \mu\nu$	Central	5.52 ± 2.09	0.323 ± 0.199	0.0207 ± 0.0049	1.28
$\text{t}\bar{\text{t}}$	Central	6.68 ± 0.46	0.391 ± 0.050	0.0157 ± 0.0014	1.07
$300 \leq \sum E_T^{\text{Jet}} < 500 \text{ GeV}$					
$\text{t}\bar{\text{t}}$	Central	7.79 ± 0.65	0.249 ± 0.069	0.0205 ± 0.0018	1.29
$500 \text{ GeV} \leq \sum E_T^{\text{Jet}}$					
$\text{t}\bar{\text{t}}$	Central	10.15 ± 0.21	0.000 ± 0.060	0.0277 ± 0.0006	1.35

Table 5.4: Results of the $E_T^{\text{miss, Soft}}$ resolution fits for the truth-subtraction method in $\sum E_T^{\text{Jet}}$ steps. The fit parameters and their uncertainties are reported for the selected $\sum E_T^{\text{Jet}}$ binning for the processes $Z \rightarrow \mu\mu$, $Z \rightarrow ee$, $W \rightarrow \mu\nu$ and $\text{t}\bar{\text{t}}$ samples. A different binning was chosen for the $\text{t}\bar{\text{t}}$ sample to better cover its $\sum E_T^{\text{Jet}}$ distribution.

Fit of $(\delta p_T^{\text{soft}})^{\text{truthObj}}$					
Sample	Fit	a	b	c	χ^2/NDF
$p_T^{\text{hard}} < 10 \text{ GeV}$					
$Z \rightarrow \mu\mu$	Central	4.38 ± 0.21	0.235 ± 0.026	0.0172 ± 0.0008	1.31
	$+1\sigma$	5.27 ± 0.21	0.131 ± 0.026	0.0207 ± 0.0008	1.48
	-1σ	3.50 ± 0.21	0.339 ± 0.026	0.0136 ± 0.0008	1.17
$Z \rightarrow ee$	Central	4.01 ± 0.24	0.298 ± 0.030	0.0160 ± 0.0009	1.11
$W \rightarrow \mu\nu$	Central	5.06 ± 0.17	0.117 ± 0.022	0.0199 ± 0.0007	1.55
$t\bar{t}$	Central	1.42 ± 0.93	0.790 ± 0.104	0.0058 ± 0.0029	1.27
$10 \leq p_T^{\text{hard}} < 20 \text{ GeV}$					
$Z \rightarrow \mu\mu$	Central	6.26 ± 0.29	0.148 ± 0.033	0.0199 ± 0.0009	1.03
	$+1\sigma$	7.39 ± 0.27	0.023 ± 0.031	0.0240 ± 0.0009	1.12
	-1σ	5.14 ± 0.29	0.273 ± 0.033	0.0159 ± 0.0009	0.98
$Z \rightarrow ee$	Central	5.08 ± 0.34	0.304 ± 0.039	0.0158 ± 0.0011	1.40
$W \rightarrow \mu\nu$	Central	7.34 ± 0.25	0.041 ± 0.029	0.0225 ± 0.0008	1.25
$t\bar{t}$	Central	4.06 ± 0.69	0.586 ± 0.076	0.0097 ± 0.0021	2.09
$20 \leq p_T^{\text{hard}} < 30 \text{ GeV}$					
$Z \rightarrow \mu\mu$	Central	8.85 ± 0.45	0.041 ± 0.048	0.0215 ± 0.0013	1.14
	$+1\sigma$	9.34 ± 0.07	0.000 ± 0.010	0.0231 ± 0.0002	1.32
	-1σ	7.45 ± 0.42	0.183 ± 0.046	0.0172 ± 0.0012	1.04
$Z \rightarrow ee$	Central	8.70 ± 0.53	0.075 ± 0.057	0.0207 ± 0.0015	1.23
$W \rightarrow \mu\nu$	Central	9.62 ± 0.06	0.000 ± 0.027	0.0220 ± 0.0002	1.12
$t\bar{t}$	Central	7.49 ± 0.71	0.308 ± 0.078	0.0168 ± 0.0021	1.33
$30 \leq p_T^{\text{hard}} < 50 \text{ GeV}$					
$Z \rightarrow \mu\mu$	Central	10.38 ± 0.10	0.000 ± 0.007	0.0226 ± 0.0002	1.61
	$+1\sigma$	10.55 ± 0.10	0.000 ± 0.004	0.0232 ± 0.0002	2.03
	-1σ	10.21 ± 0.10	0.000 ± 0.016	0.0220 ± 0.0002	1.34
$Z \rightarrow ee$	Central	10.47 ± 0.13	0.000 ± 0.012	0.0231 ± 0.0003	1.25
$W \rightarrow \mu\nu$	Central	10.39 ± 0.09	0.000 ± 0.006	0.0230 ± 0.0002	2.25
$t\bar{t}$	Central	12.14 ± 0.73	0.048 ± 0.076	0.0213 ± 0.0020	1.20
$50 \text{ GeV} \leq p_T^{\text{hard}}$					
$Z \rightarrow \mu\mu$	Central	10.64 ± 0.27	0.000 ± 0.016	0.0271 ± 0.0006	1.60
	$+1\sigma$	11.22 ± 0.27	0.000 ± 0.015	0.0277 ± 0.0006	1.68
	-1σ	10.06 ± 0.27	0.000 ± 0.016	0.0265 ± 0.0006	1.54
$Z \rightarrow ee$	Central	10.46 ± 0.39	0.000 ± 0.023	0.0279 ± 0.0008	1.56
$W \rightarrow \mu\nu$	Central	11.21 ± 0.27	0.000 ± 0.015	0.0262 ± 0.0006	2.41
$t\bar{t}$	Central	16.84 ± 0.20	0.000 ± 0.009	0.0181 ± 0.0005	1.74

Table 5.5: Results of the $E_T^{\text{miss, Soft}}$ resolution fits of $(\delta p_T^{\text{soft}})^{\text{truthObj}}$ in p_T^{hard} steps. The fit parameters and their uncertainties are reported for the selected p_T^{hard} binning for the processes $Z \rightarrow \mu\mu$, $Z \rightarrow ee$, $W \rightarrow \mu\nu$ and $t\bar{t}$.

Searches for Supersymmetry

In this chapter the motivations and the common aspects of the performed analyses are presented.

First an overview of the results of the SUSY searches with the ATLAS experiment obtained with the datasets recorded at $\sqrt{s} = 7$ TeV and $\sqrt{s} = 8$ TeV is given in Section 6.1. In particular, motivations for the choice of a stop search in the light mass range with the $\sqrt{s} = 7$ TeV dataset, presented in full details in Chapter 7, and for the one performed with the $\sqrt{s} = 8$ TeV dataset, that covers mainly the high stop masses and is presented in Chapter 8, are given.

Then the benchmark signal models used to optimise the analyses and to set model dependent limits are presented in Section 6.2. The description of the analysis strategy follows in Section 6.3. Here the procedure used to define signal and background enhanced regions is explained. Moreover, common variables used for basic selections are introduced together with the list of cleaning cuts, which have the primary scope of rejecting events affected by large non-collision backgrounds or detector malfunctioning.

The relevant systematic uncertainties, both experimental and theoretical, are described in Section 6.4.

Finally, an overview of the theory and tools used for the statistical interpretation of the analysis results is given in Section 6.5.

6.1 SUSY Searches at the ATLAS Experiment

The SUSY searches programme of the ATLAS experiment covers a broad spectrum of models, production mechanisms, and final states. The production cross sections of gluino, squark and slepton pairs and of some electroweak processes are shown in Fig. 6.1 for a centre-of-mass energy of (a) 7 and (b) 8 TeV. They have been computed with Prospino at NLO [131, 132, 133, 134, 135].

The searches can be divided in four main categories: the inclusive strong production of squarks and gluinos, the direct production of third generation squarks, the production of SUSY particles via electroweak interactions, and the searches focusing on models with R-parity violation or long lived particles.

In this section, after a brief introduction of the search categories, the results of the ATLAS experiment SUSY analyses with the Run 1 dataset are presented.

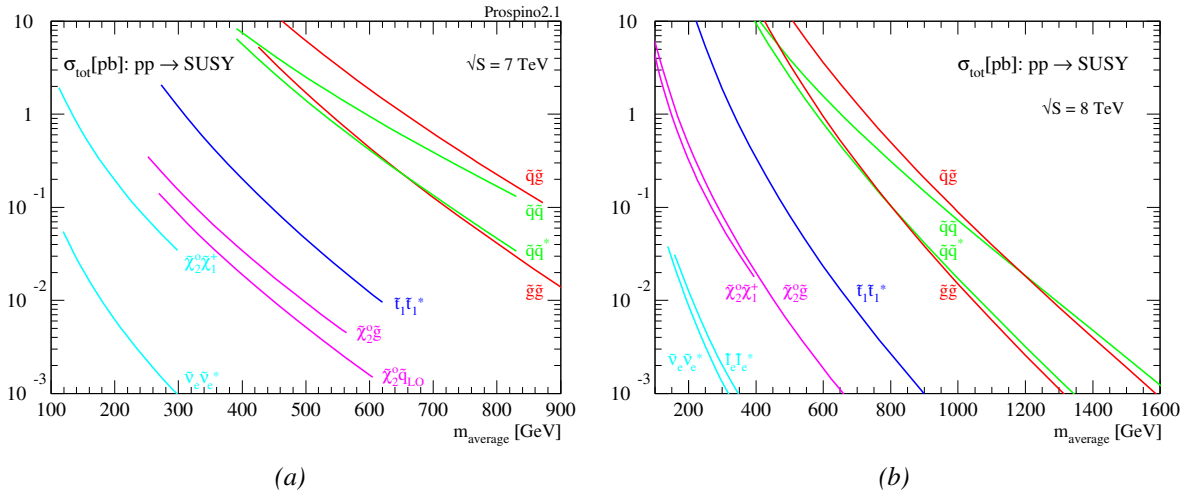


Figure 6.1: Production cross sections of SUSY particles at a centre-of-mass energy of (a) 7 and (b) 8 TeV computed with Prospino with a NLO precision [136].

6.1.1 Inclusive Strong Production Searches

The inclusive searches for the strong production of squarks and gluinos assuming R -parity conservation were the first SUSY analyses performed at the ATLAS experiment. The production cross sections of the squarks of the first two generations and of the gluinos are the highest of all SUSY processes. Moreover, when the mass spectra are not compressed, a very clear signature is expected for the final states, that have many jets, large missing transverse momentum and may contain leptons with large transverse momentum.

The searches are often interpreted in mSUGRA models and limits are set on the m_0 and $m_{1/2}$ parameters at a fixed $\tan\beta$ value. Alternatively simplified models are used, where different SUSY decay chains are tested. These range from the so-called one step decay chains, such as the production of a squark pairs decaying in quark and LSP, generally the lightest neutralino, and giving final states with very few energetic objects, to very long decay chains, where high-multiplicity events are expected. Among the simplified models considered there is also the gluino mediated production of third generation squarks, which gives final states with a very large b -jet multiplicity, otherwise uncommon in any SM process. Other scenarios considered to optimise the analyses are GMSB and General Gauge Mediation (GGM) models where different next to lightest supersymmetric particles (NLSPs) are considered.

6.1.2 Third Generation Direct Production Searches

The searches for the direct production of third generation squarks (stop and sbottom) are interesting because they are designed to probe natural SUSY. For a fixed mass of the SUSY particle under study, the production cross section of stops and sbottoms is typically one order of magnitude smaller than the one of strong gluino and first and second generation squark production. The lower cross section is not the only challenge of these searches: in most scenarios the sought final states have topologies similar to those of $t\bar{t}$ events or to electroweak processes produced in association with heavy flavour jets.

The analyses are optimised on simplified models where the stop or sbottom can decay only through few (typically one) simple decay chains. The constraints on the masses of third generation SUSY particles coming from previous experiments are also taken into consideration when the signal models are built. pMSSM signal models have also been used for results interpretation, where all naturalness

constraints and the mass of the discovered Higgs boson are built in and less simplified decay branching ratios are achieved.

6.1.3 Electroweak Production Searches

The electroweak production cross section of SUSY particles is even smaller than that of third generation squarks. The searches that fall in this category are the direct pair production of sleptons of all generations, charginos, and neutralinos, where the R-parity conservation is assumed and the LSP is the lightest neutralino. In general a high lepton multiplicity and large missing momentum are looked for in events where the hadronic activity is low. Decay chains involving the Higgs boson are also considered.

6.1.4 R-Parity Violation and Long Lived Particles Searches

The searches that do not have R-parity conserving signals as benchmark models can be subdivided in three categories: searches for SUSY particles in R-parity violating models, where the LSP is a slepton or a sneutrino and including searches for final states where the lepton flavour is violated; searches for long lived particles that do not decay, such as R-hadrons; and searches for long lived particles that still decay within the detector giving e.g. signatures of displaced vertices, disappearing tracks or photons not pointing to the interaction vertex.

6.1.5 ATLAS Experiment SUSY Searches: from the First Searches to the Final Run 1 Results

With the dataset recorded at $\sqrt{s} = 7$ TeV in 2010, which corresponds to an integrated luminosity of 35 pb^{-1} , inclusive 0, 1 and 2 lepton final state searches were performed, and since no significant excesses over the expectations were found, limits were placed on mSUGRA-based models and on phenomenological simplified models [137, 138, 139, 140, 141]. Besides the inclusive searches in R-parity conserving models, the data were analysed to test R-parity violating models and to search for long lived and stable massive particles [142, 143, 144, 145].

In 2011 about 5 fb^{-1} of data were collected by the ATLAS experiment at $\sqrt{s} = 7$ TeV. The size of this dataset and the improved knowledge of the performance of the experiment made it possible to extend the search programme to more complicated final states and lower production cross sections.

A summary of the models investigated and of the exclusion limits set on the masses of the relevant particles with the ATLAS 2010 and partial 2011 7 TeV datasets is shown in Fig. 6.2. It can be observed that already with 1 fb^{-1} of data squark and gluino masses up to the TeV scale could be excluded. This was the status, when it became possible to start searching for the direct production of third generation squarks.

At that point the only - very weak - limits available on the top and bottom squark masses were those of the Tevatron experiments [147, 148, 149, 150], and new analysis teams started to work on direct sbottom production searches in the decay channel $\tilde{b}_1 \rightarrow b\tilde{\chi}_1^0$, and on direct stop production decaying either as $\tilde{t}_1 \rightarrow t\tilde{\chi}_1^0$ or as $\tilde{t}_1 \rightarrow b\tilde{\chi}_1^\pm \rightarrow bW^{(*)}\tilde{\chi}_1^0$.

The searches for direct stop production in the low mass range, where the decay $\tilde{t}_1 \rightarrow b\tilde{\chi}_1^\pm \rightarrow bW^{(*)}\tilde{\chi}_1^0$ is allowed, were of particular interest because they would have given a very “natural” mass for the top squark, but also challenging due to the softness of the stop decay products in comparison to those of the SM background processes. The limits based on this scenario from the CDF experiment at the Tevatron are shown in Fig. 6.3 in the $(\tilde{t}, \tilde{\chi}_1^0)$ mass plane for a chargino with a mass of 105.8 GeV and of 125.8 GeV. The limits relevant for the decay $\tilde{\chi}_1^\pm \rightarrow W^{(*)}\tilde{\chi}_1^0$, studied by the analyses of the ATLAS

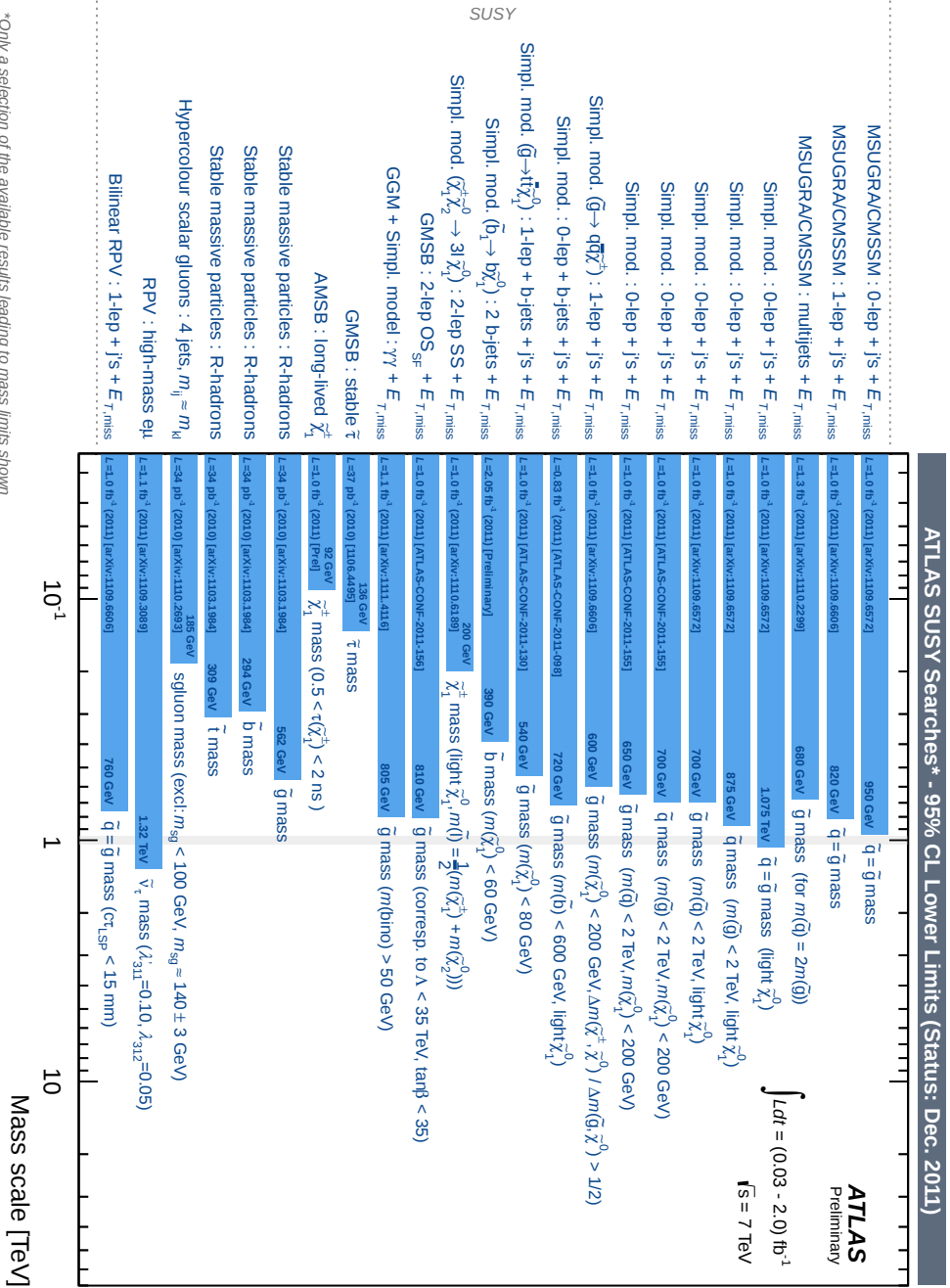


Figure 6.2: Summary of the models where limits on the SUSY particles masses have been set with the ATLAS 2010 and partial 2011 7 TeV datasets. This plot represents the status of the publications as of December 2011 [146].

collaboration, are those of the $BR^2(\tilde{\chi}_1^\pm \rightarrow \tilde{\chi}_1^0 \ell \nu) = 0.11$ line. The other contours represent the limits achieved if an higher branching ratio in dilepton final states would be realised.

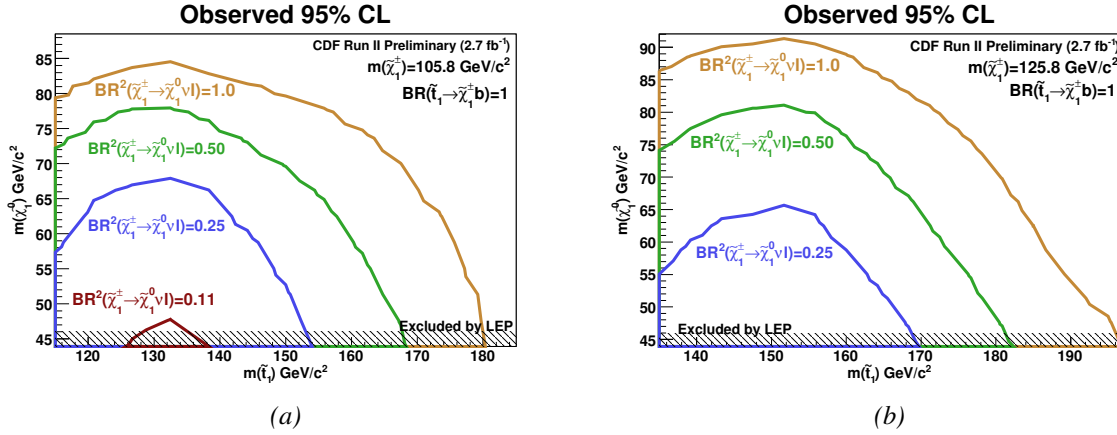


Figure 6.3: Exclusion limits of the CDF experiment for $\tilde{t}_1 \rightarrow b\tilde{\chi}_1^\pm$. Observed 95% CL in the $(\tilde{\chi}_1^0, \tilde{t}_1)$ mass plane, for various dilepton branching ratios, at chargino masses of 105.8 GeV (a) and 125.8 GeV (b). It is assumed that electrons, muons and taus all equally contribute to the dilepton final state [148].

After having investigated the low stop mass range with the dataset recorded at $\sqrt{s} = 7$ TeV, it was possible to extend the sensitivity of the searches to very high stop masses with the dataset recorded at a pp centre-of-mass energy of 8 TeV. There the decay $\tilde{t} \rightarrow t\tilde{\chi}_1^0$ is kinematically allowed and the naturalness hypotheses can be further probed.

The summary of the main models investigated by the ATLAS SUSY searches and the limits set on the relevant SUSY particles can be seen in Fig. 6.4 as of the end of the summer 2014. Most of the searches have been updated to the full 8 TeV dataset and limits above or very near the TeV scale have been set on gluinos and squarks of the first two generations, while slightly less stringent limits have been observed for the third generation particles. The loosest limits are those set by the direct electroweak production analyses on the masses of charginos and neutralinos.

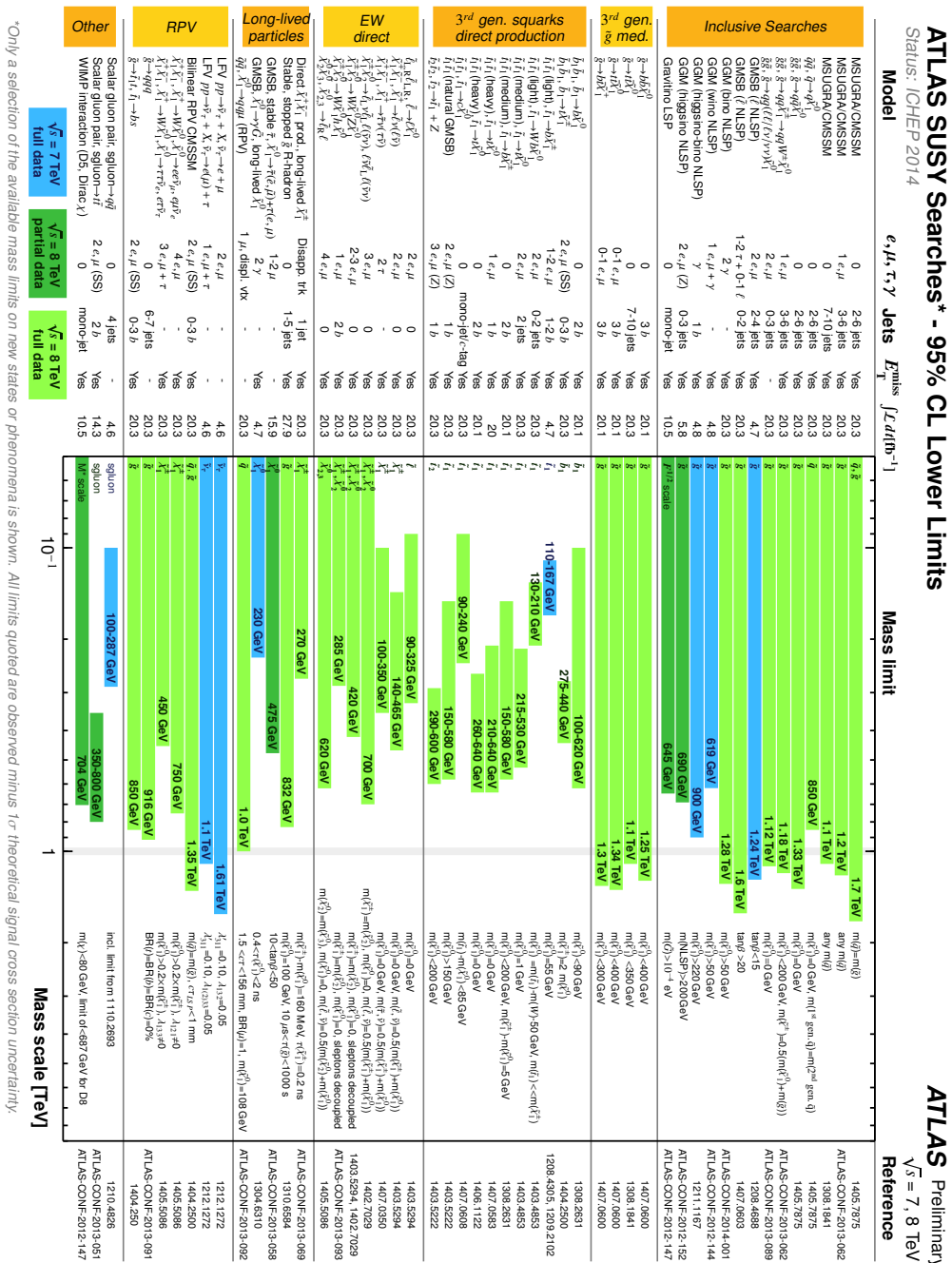
6.2 Signal Models

In this section the benchmark signal models used for the analyses of Chapters 7 and 8 are presented. These are simplified models of direct stop production and decay, where all the SUSY particles not involved in the decays are decoupled to a high scale that cannot be probed by the experiment.

The Feynman diagrams of the stop direct pair production and decay in the $\tilde{t} \rightarrow t\tilde{\chi}_1^0$ and $\tilde{t} \rightarrow b\tilde{\chi}_1^\pm$, with $\tilde{\chi}_1^\pm \rightarrow W^{(*)}\tilde{\chi}_1^0$, channels are shown in Fig. 6.5, where the top quarks and the W bosons further decay with the BRs measured in the SM. Since a mixture of these decays is probably realised in nature, limits that depend on the decay BR in these two main modes should be extracted. This can be achieved by properly combining a signal where all stops decay as $\tilde{t} \rightarrow t\tilde{\chi}_1^0$, one where both pair-produced stops decay as $\tilde{t} \rightarrow b\tilde{\chi}_1^\pm \rightarrow bW^{(*)}\tilde{\chi}_1^0$ and one where, of the two produced stops, one decays following the first mode, the second the other mode. These are the three signal models presented in the following paragraphs.

Since the mass of the SUSY particles is not known, grids of signal samples are simulated, which follow a given model or particle mass hierarchy. Each model has two main free parameters used also to define the reach of the analysis. For the direct stop pair production searches the results of the analyses are usually displayed on the $(\tilde{t}, \tilde{\chi}_1^0)$ mass plane. For the samples involving a chargino, a relation between

Figure 6.4: Summary of the main models where limits on the SUSY particles masses have been set with the ATLAS 2010 and 2011 $\sqrt{s} = 7$ TeV, and 2012 $\sqrt{s} = 8$ TeV datasets. This plot represents the status of the publications as of ICHEP 2014 [146].



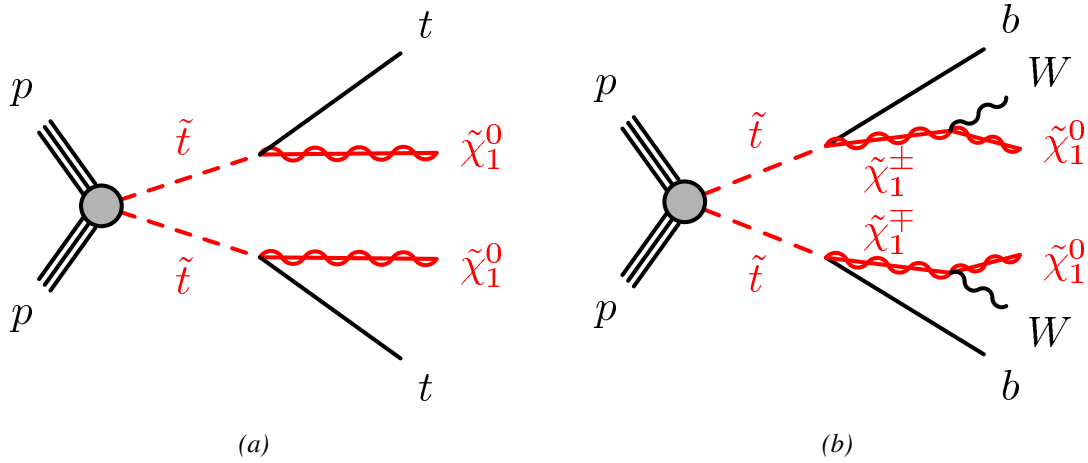


Figure 6.5: Feynman diagrams of the direct pair production of top squarks decaying as $\tilde{t} \rightarrow t\tilde{\chi}_1^0$ (a) and as $\tilde{t} \rightarrow b\tilde{\chi}_1^\pm \rightarrow bW^{(*)}\tilde{\chi}_1^0$ (b).

the mass of the chargino and either the mass of the lightest neutralino or of the stop is assumed to decrease the number of free parameters.

6.2.1 Stop to Top Neutralino, BR=100%

The signal grid with the lightest stop, $\tilde{t}_1$, decaying with a 100% branching ratio in top neutralino, $\tilde{t}_1 \rightarrow t\tilde{\chi}_1^0$, has been simulated with HERWIG++, matched to PYTHIA, and the polarisation of the decay products is properly propagated. Since the baseline signal grid has a $\tilde{t}_1$ which is $\tilde{t}_R$ -like, a grid with $\tilde{t}_1 \sim \tilde{t}_L$ was also simulated with HERWIG++ to assess the impact of the different stop polarisations on the results of the searches.

6.2.2 Stop to b Chargino, BR=100%

For the case of the stop decaying, with 100% BR, in $b\tilde{\chi}_1^\pm$, with $\tilde{\chi}_1^\pm \rightarrow W^{(*)}\tilde{\chi}_1^0$, there are three free mass parameters, of which one is constrained. The signal grids used to set exclusion limits are:

- Fixed chargino mass $m(\tilde{\chi}_1^\pm) = 106$ GeV, just above the LEP limit [151]
- Fixed stop mass $m(\tilde{t}_1) = 180$ GeV, the limits are then set in the neutralino-chargino plane
- Gaugino universality grid, $m(\tilde{\chi}_1^\pm) = 2 \cdot m(\tilde{\chi}_1^0)$

Other signal grid exist for a stop decaying in the $b\tilde{\chi}_1^\pm$ channel, which are not used for the interpretations presented in this thesis. These are e.g. models where the mass difference between chargino and neutralino is fixed to 5 or 20 GeV, and models with fixed mass difference between stop and chargino.

The hypothesis of the chargino having double the mass of the neutralino fits in a scenario of gaugino universality ($M_2 = 2 * M_1$ at the unification scale) where the lightest neutralino is bino-like and the light chargino is wino-like.

The chargino decays to an on-shell W boson if $m(\tilde{\chi}_1^\pm) > m(\tilde{\chi}_1^0) + 81$ GeV, otherwise to an off-shell W. The polarisation of the stop decay products is properly calculated for the samples with an on-shell W, while the information is lost for the other samples. The kinematics of the final state particles is, in the

case of a three-body decay, not affected by the loss of polarisation information.

The samples simulated at a centre-of-mass energy of 7 TeV were generated with HERWIG++ (grid $m(\tilde{\chi}_1^\pm) = 2 * m(\tilde{\chi}_1^0)$ and $m(\tilde{t}_1) = 180$ GeV) and PYTHIA (grid $m(\tilde{\chi}_1^\pm) = 106$ GeV), the ones simulated at $\sqrt{s} = 8$ TeV were generated with MadGraph interfaced to PYTHIA for the showering and the underlying event.

6.2.3 Mixed Grid

The mixed grid contains events where of the two pair produced stop, one decays as $\tilde{t}_1 \rightarrow t\tilde{\chi}_1^0$, the second as $\tilde{t}_1 \rightarrow b\tilde{\chi}_1^\pm \rightarrow bW^{(*)}\tilde{\chi}_1^0$ in the gaugino universality hypothesis $m(\tilde{\chi}_1^\pm) = 2 \cdot m(\tilde{\chi}_1^0)$. This grid is needed to create, together with the 100% BR grids $\tilde{t}_1 \rightarrow t\tilde{\chi}_1^0$ and $\tilde{t}_1 \rightarrow b\tilde{\chi}_1^\pm$, realistic models based on the merging of the possible decays with the proper ratio. In these samples, generated with MadGraph interfaced to PYTHIA, a stop maximal mixing is assumed.

6.3 Analysis Strategy

The steps needed to design a robust analysis are presented in this section. Considering the signal model and the final state of interest, regions of the parameter space where the signal contribution is enhanced have to be defined, see Section 6.3.1. Then, kinematical regions characterised by low signal contamination and high purity in one specific SM background process are defined to validate the MC predictions on the shape of kinematical distribution and determine their normalisation, see Section 6.3.2. A list of important variables used to reject the backgrounds of the searches and to help in the signal-background discrimination is given in Section 6.3.3. Finally in Section 6.3.4 the variables used to veto spurious events recorded while parts of the detector were not fully functional or events due to cosmics or beam halo processes are presented.

6.3.1 Definition of the Signal Regions

To define a signal enhanced region, or simply signal region (SR), it is necessary to well understand the properties of the searched signal. A limited number of benchmark signal points is chosen and the kinematic and topological variables that should show different behaviours for the SUSY signal and for the Standard Model background are selected. The ones that show the best signal-to-background separation power are chosen and selections are applied to retain only the events that have signal-like topologies. To determine the best selections that define one or a set of SRs, an estimator of the significance of the signal with respect to the expected background has to be defined. The final SRs are those which maximise the chosen significance estimator.

The simplest estimator is the signal over background ratio, $\frac{N_{sig}}{N_{bkg}}$. It gives the signal purity of the selected sample and, even if in most cases it is not the quantity used to pick the best region, it is always taken into consideration to assess the composition of the chosen SR.

The searches are often optimised for the discovery significance S_d , a simple estimator defined as

$$S_d = \frac{N_{sig}}{\sqrt{\sigma_{bkg,stat}^2 + \sigma_{bkg,syst}^2}} \stackrel{\text{Large } N_{bkg}}{\simeq} \frac{N_{sig}}{\sqrt{N_{bkg} + \sigma_{bkg,syst}^2}}. \quad (6.1)$$

Here $\sigma_{bkg,stat}$ is the background statistical uncertainty that, if the number of background events in the region is sufficiently large, in general larger than 10, can be approximated with the Gaussian error on

the event counts $\sqrt{N_{bkg}}$, and $\sigma_{bkg,syst}$ is the systematic component of the background uncertainty. Since the denominator represents the background total uncertainty, S_d is a measure of how many signal events are needed to overcome a one sigma variation of the background. Following the high energy physics conventions, to have the possibility of an observation of a signal this ratio should be of the order of or larger than three, for a discovery larger than five.

The exclusion significance S_e has a similar definition as the discovery significance. In this case, however, also the statistical uncertainty of the signal, $\sigma_{sig,stat}$, is taken into consideration:

$$S_e = \frac{N_{sig}}{\sqrt{\sigma_{sig,stat}^2 + \sigma_{bkg,stat}^2 + \sigma_{bkg,syst}^2}} \stackrel{\text{Large } N_{sig}, N_{bkg}}{\approx} \frac{N_{sig}}{\sqrt{N_{sig} + N_{bkg} + \sigma_{bkg,syst}^2}}. \quad (6.2)$$

This quantity gives an approximate feeling for the reach of a search when a signal model is introduced. This has to be done when no excess over the expected background is observed, and limits are set on the relevant models. The selections that give the best exclusion significance are in general looser than those that give the best discovery significance.

Finally, if it is of interest to have a more accurate value for the discovery significance, yet it is not possible to use the complete statistical treatment of the signal and background uncertainties, the Asimov formula

$$S_A = \sqrt{2 \cdot \left\{ (N_{sig} + N_{bkg}) \cdot \ln \left[\frac{(N_{sig} + N_{bkg})(N_{bkg} + \sigma_{bkg}^2)}{N_{bkg}^2 + (N_{sig} + N_{bkg})\sigma_{bkg}^2} \right] - \frac{N_{bkg}^2}{\sigma_{bkg}^2} \cdot \ln \left[1 + \frac{N_{sig}\sigma_{bkg}^2}{N_{bkg}(N_{bkg} + \sigma_{bkg}^2)} \right] \right\}} \quad (6.3)$$

can be used [152], where σ_{bkg} is the systematic component of the background uncertainty.

6.3.2 Background Estimates

To improve the sensitivity of an analysis and to be able to define properly a SR, a good knowledge of the background processes contributing to that region has to be gained. The background processes to a searched signal can be divided in two categories: the reducible and the irreducible backgrounds. The processes that do not have the same topology as the signal, and that contribute to the SRs through combinatorial effects or because some objects were mismeasured or fell out of detector acceptance, belong to the first class. To the second one belong all those processes that have a similar signature to that of the signal, i.e. having the same minimum amount of physical objects and similar topological properties.

Even though Monte Carlo simulations help greatly in understanding many processes, a better control over the backgrounds is needed to be able to reduce the impact of systematic uncertainties on the analyses. Moreover, in the searches for new physics, corners of parameter space are investigated for which the Standard Model MC samples were not designed and, hence, their reliability has to be tested.

The main background processes are studied and their contribution to the SR is estimated via data-driven or semi-data-driven techniques. In the first case background templates are extracted purely from data, in the second case the MC simulation is corrected for the events observed in data in a dedicated region, but the shape of the MC distributions is trusted to be true.

In the following paragraphs the concept of control and validation regions as well as the main methods used to estimate the fake backgrounds are introduced.

Control and Validation Regions

To study the properties of a background process a region of the parameter space has to be defined with a high process purity, a low signal contamination and a similar topology to that of the signal region. Such a region is called Control Region (CR). There the shape of the MC is validated against data and the background normalisation is extracted and the prediction extrapolated to the SR. The design of a CR has to satisfy certain criteria. First, it should contain a sufficiently large number of events so that the statistical uncertainty introduced from this choice does not become the dominating uncertainty. On the other side, the selections applied to define it should resemble, as much as possible, those of the SR to allow for a good cancellation of the systematic uncertainties. Finally, the contamination from the searched signal and from other backgrounds has to be kept as low as possible.

Considering a semi-data-driven estimate, the background MC is normalised in the CR to the observed data and then extrapolated to the signal region where the expected events N_{bkg}^{SR} are given by

$$N_{bkg}^{SR} = \frac{N_{bkg, MC}^{SR}}{N_{bkg, MC}^{CR}} (N_{data}^{CR} - N_{bkg-others, MC}^{CR}) = TF_{CR \rightarrow SR} (N_{data}^{CR} - N_{bkg-others, MC}^{CR}), \quad (6.4)$$

where $N_{bkg, MC}^{SR(CR)}$ is the number of events of the background under study in the SR (CR) in MC, $(N_{data}^{CR} - N_{bkg-others, MC}^{CR})$ is the number of data events in the CR corrected for the contamination from other background processes, which is taken from MC, and $TF_{CR \rightarrow SR}$ is the so called *transfer factor* from the control to the signal region.

The best CR for a given SR is the one that minimises the uncertainty contribution to the latter by having the right balance between a low statistical uncertainty and a good cancellation of the systematic uncertainties. It is also important that only few variables are used for the $CR \rightarrow SR$ extrapolation.

The ratio

$$NF_{bkg_i}^{CR_j} = \frac{N_{data}^{CR_j} - N_{bkg-others, MC}^{CR_j}}{N_{bkg_i, MC}^{CR_j}} \quad (6.5)$$

is the *normalisation factor* of the background i extracted from the control region j , which is used in combination with the TF to understand how well the MC describes the data in the regions of interest. Since with a semi-data-driven estimate the shape of the background distributions is taken from MC, it is necessary to check that all variables used to extrapolate from the CR to the SR are well described by MC and particularly that no significant slopes in the data to MC ratios are present.

Especially when the extrapolation needed from the CR to the SR is large, additional intermediate regions may be defined where the background normalisation, extracted in the CR, is again checked against data. These regions are called Validation Regions (VR). Often they have a lower purity or a lower number of events and therefore could not be chosen as CRs.

Certain background process, e.g. the W boson production in association with heavy flavour jets, are very difficult to isolate and the definition of a pure CR for them is almost impossible. In such cases the normalisation factors of n backgrounds can be extracted simultaneously from n CRs, where their contributions are mixed, by solving a simple system of n equations with n unknown normalisation weights.

Fake Backgrounds

The contribution of the fake backgrounds to the SRs is usually very small. Though, since the MC describes them badly, they have to be estimated with data-driven techniques. As mentioned before, fake events can pass the signal selections because the original process has a very high cross section and due to some detector failures, the misidentification of some objects or them falling outside of the detector acceptance, can mimic the signal signature.

The typical fake background for a SUSY search with no or one lepton and large missing transverse energy in the final state are multi-jet events, including all-hadronic $t\bar{t}$ decays. The two most common methods used to estimate the fakes, the matrix method and the jet smearing method, are briefly introduced below, they are usually affected by a large systematic uncertainty which is, however, not critical for the final result because of the very low fake contribution to the SRs.

- Matrix Method

It is used for the searches with one or more leptons in the final state [153]. In this case a jet is misidentified as a lepton, typically an electron, or a lepton from the semi-leptonic decay of a b - or c -hadron is selected. To define the background control sample, the lepton identification criteria are relaxed. Real and fake efficiency factors are extracted, which measure the probability of a real(fake) loose lepton to pass the tight identification criteria. Then the number of events with a fake lepton that pass the signal selections can be estimated by combining the efficiency information together with the information on how many events in the control sample satisfy also the tight selections and how many fail this requirement.

- Jet Smearing Method

It is used for searches in all-hadronic final states [154]. Clean seed events with a low E_T^{miss} significance ($E_T^{\text{miss}} / \sqrt{\sum E_T}$) and the same jet multiplicity required by the analysis in the SRs are selected in data. The momentum of the jets of the seed events is then smeared by sampling a response function

$$R = \frac{p_T(j_{\text{reco}})}{p_T(j_{\text{true}})} \quad (6.6)$$

extracted from a sample of simulated events, where b -tagged and non b -tagged jets have different response functions, validated and corrected with recorded data. The smearing procedure is repeated 10000 times per seed event, so that random configurations, with different jet fluctuations, can be realised. This sample of pseudo-events is then normalised to data in a multi-jet dominated region, and the contribution to the signal regions can be then computed.

6.3.3 Definition of Variables

In this section, a list of the most important and common variables for the background rejection and signal selection is presented. These are calculated from basic kinematic quantities of the selected objects and are:

- The scalar sum of the jet momenta in the transverse plane

$$H_T = \sum_{i=1}^{n_{\text{jets}}} (p_T^{\text{jet}})_i, \quad (6.7)$$

where the sum runs over a selected set or reconstructed objects, in this case jets.

This variable, depending on the analysis, can be computed with all selected jets, or only with a subset. Since H_T is usually well described by MC simulation, it can also be used to define a missing momentum significance variable: $E_T^{\text{miss}} / \sqrt{H_T}$.

- The effective mass

$$m_{\text{eff}} = E_T^{\text{miss}} + \sum_{i=0}^{n_{\text{jets}}} (p_T^{\text{jet}})_i + \sum_{j=0}^{n_{\ell}} (p_T^{\ell})_j \quad (6.8)$$

is a similar variable to the $\sum E_T$. However, only the contributions from the objects selected in the analysis are summed together so that the MC description of this variable is in general good. The ratio $E_T^{\text{miss}}/m_{\text{eff}}$ can be used to reject events that have a higher probability of coming from mismeasured processes, which have usually a low ratio value, while signal events have higher $E_T^{\text{miss}}/m_{\text{eff}}$.

- The invariant mass of n selected objects defined as

$$m_{\text{inv}} = \sqrt{\left(\sum_{i \leq n} E_i\right)^2 - \left\|\sum_{i \leq n} \mathbf{p}_i\right\|^2} \quad (6.9)$$

is often used to select events containing the decay products of a heavy particle. Common examples are the invariant mass of a lepton-pair from the Z boson decay, and the mass of three jets selected as coming from a top decay.

- The transverse mass is usually computed between an object k and the E_T^{miss} , for which no information in the η plane is available. It is defined as

$$m_T(k, E_T^{\text{miss}}) = \sqrt{2 \left[p_T^k E_T^{\text{miss}} - \mathbf{p}_T^k \cdot \mathbf{p}_T^{\text{miss}} \right]} = \sqrt{2 \left[p_T^k E_T^{\text{miss}} (1 - \cos \Delta\phi(\mathbf{p}_T^k, \mathbf{p}_T^{\text{miss}})) \right]}, \quad (6.10)$$

and its most common variants are the $m_T(\ell, E_T^{\text{miss}})$, between a selected lepton and the E_T^{miss} , and the $m_T(b, E_T^{\text{miss}})$, between a selected b -jet and the E_T^{miss} .

- The minimal azimuthal distance between n jets and the missing transverse momentum

$$\min_{i \leq n_{\text{jets}}} \left| \Delta\phi(\text{jet}^i, p_T^{\text{miss}}) \right|, \quad (6.11)$$

is a variable used to reject the multi-jet fake background where the E_T^{miss} is aligned to a jet that was mismeasured. This variable can be computed either considering all selected jets, or only the most energetic ones.

6.3.4 Cleaning Selections

To eliminate spurious events in data, cleaning selections have to be applied. This is done before requiring that the events satisfy any analysis specific selections. The cleaning requirements can be divided in three main categories: general data cleaning, detector failures cleaning, and object specific cleaning. The overlap removal, albeit not being a cleaning selection as the others, is also presented at the end of this section.

Data Cleaning and Detector Failures

These selections aim at rejecting data events recorded with non optimal detector conditions, or that may have been recorded only partially due to subdetectors failures.

- Good Run List

It is applied only to data, the event must be in the Good Run List (GRL) otherwise it is rejected. The GRL contains the information on which of the runs and luminosity blocks were recorded under optimal detector conditions. The events recorded as one or more subdetectors had a failure and that do not satisfy basic data quality criteria cannot be used for physics analyses.

- Trigger

Events to be analysed are selected based on the firing of a trigger, which is usually required both in data and in MC. Single or double lepton triggers are used to select events with energetic leptons in the final state. For analyses looking to all-hadronic final states E_T^{miss} or jets triggers are required. An event is flagged if one of its objects exceeds the trigger threshold. The triggers are not fully efficient at the threshold value, but show a turn-on curve which often differs in data and simulation. Additional requirements on the objects are added at a later stage so that the selected events are on the trigger efficiency plateau. If the MC and the data trigger efficiency differs, trigger efficiency corrections have to be applied to MC.

- Vertex Quality

The primary vertex of the event, i.e. the vertex with the highest sum of the momentum of the associated tracks, must have at least 5 tracks associated to it. This selection is applied to both data and MC.

- LAr and Tile Flags

This flags are used to veto data events recorded while the LAr calorimeter had noise bursts, and while the Tile calorimeter had failures or was reset and therefore only part of the event could be correctly recorded.

Objects cleaning

These selections are particularly important to reject events where a mismeasurement of the selected objects leads to a high fake missing transverse momentum.

- Jets due to calorimeter noise or non-collision backgrounds

This selection is intended to reject events where jets are reconstructed from energy deposits in the calorimeters mainly due either to calorimeter noise or to non-collision backgrounds. If a jet with $p_T > 20$ GeV does not satisfy specific requirements on timing variables, on the fraction of the energy deposited in the EM and in the hadronic calorimeters, and in problematic calorimeter cells, on the fraction of the total jet energy coming from charged particles, and on the negative energy measured in the cells belonging to the jet, the event is flagged as “bad jet” event and vetoed. Some of the requirements are η dependent, because of the different coverage of the ID and calorimeters.

- LAr hole veto

This selection is used to reject events with jets falling into LAr dead cells located at $-0.1 < \eta < 1.5$ and $-0.9 < \phi < -0.5$. These cells were repaired for the $\sqrt{s} = 8$ TeV data taking period.

- Tile negative energy veto

Events are vetoed if the Soft E_T^{miss} component exceeds 50% of the total missing momentum corrected for the cosine of the azimuthal angle between the Soft and the total E_T^{miss} direction.

- Fake E_T^{miss} due to bad Tile modules

The events with fake E_T^{miss} due to non working cells in the Tile and endcap hadronic calorimeter are vetoed if, before the overlap removal, a jet has $p_T > 80$ GeV, is near to the E_T^{miss} in the azimuthal plane, $\Delta\phi(\text{jet}, E_T^{\text{miss}}) < 0.2$, and has more than 5% of its energy recorded in bad cells.

- Jet charged fraction

This selection helps in rejecting cosmics, beam background, and detector noise where no tracks are expected. The leading central jets must have a charged fraction above 2% or above 5% if they have and electromagnetic fraction exceeding 90%.

- Jet timing

The average time stamp of the reconstructed and selected jets must match the timing of the bunch crossing within 5 ns, otherwise the event is rejected.

- Misidentified muons

An event is rejected if it contains a muon, labelled as “bad muon”, with a large significance of the charge to momentum fraction, $\frac{\sigma(q/p)}{|q/p|} > 0.2$. This can arise when the shower of a very energetic jet is not completely contained by the calorimeter and “punches through” to the muon spectrometer.

- Cosmic muons

Events with a muon compatible with cosmic background are rejected. A muon is tagged as cosmic if its longitudinal and transverse impact parameters are not compatible with the primary interaction point, $|d_0| > 0.2$ mm or $|z_0| > 1.0$ mm.

Overlap removal

The overlap removal is a procedure intended to resolve the double counting that may arise from the overlaps between reconstructed jets and leptons. If overlapping objects are found only one of them has to be kept. The variable used to check the overlaps is ΔR , defined in equation 3.2. The steps of the overlap removal are:

- Jet-Electron Overlap Removal

If a jet with $\Delta R(\text{jet}, e) < 0.2$ is found the jet is removed and the electron is kept. In the analysis of the dataset recorded at $\sqrt{s} = 8$ TeV it is also checked if the jet has a b -tagging weight exceeding the b -jet identification threshold. In this case the jet is kept and the electron removed. This allows to retain the jets originating from the decay of a b -hadron that may also contain a lepton.

- Electron-Jet Overlap Removal

If an electron is found within $\Delta R(e, \text{jet}) < 0.4$ from a selected jet, the electron is rejected, while the jet is kept.

- Muon-Jet Overlap Removal

If a muon has $\Delta R(\mu, \text{jet}) < 0.4$ from a selected jet, the muon is rejected, while the jet is kept.

6.4 Systematic Uncertainties

The knowledge of the impact of the uncertainties on the event yields in the SRs is necessary to be able to statistically interpret the analysis results. The uncertainties have to be assigned in the SRs to the background and signal components. For the backgrounds that are estimated with the aid of a CR, the uncertainty is computed separately in control and signal regions and the correlations between them are taken into account. This allows for a reduction of the uncertainties due to the cancellation of similar effects in the two regions.

The uncertainties affecting the estimates of the background and of the signal processes are of statistical and of systematic nature. The statistical component includes both the Poissonian uncertainty on the event counts in the considered regions and the uncertainty on the limited MC sample size.

The systematic uncertainties can be divided in two classes the detector and the theory related ones. The uncertainties relevant to the performed analyses are presented in the following.

6.4.1 Detector-Related Uncertainties

The detector-related systematic uncertainties are extracted from the reconstruction and performance studies of the physics objects. The methods used to extract the calibration and the energy scale of the objects have been presented in Chapter 4, where also the sizes of the uncertainties are reported.

The most relevant uncertainties for the performed analyses are:

- Luminosity

The measurement of the luminosity delivered to the experiment and that can be used for physics analyses comes with an uncertainty. This uncertainty has to be propagated to the MC samples used for the background and signal estimates since they need to be normalised to the amount of analysed data.

- Pile-up

The MC samples are simulated with a fixed pile-up distribution, that, in most of the cases, does not match the distribution observed in data. A pile-up reweighting of the MC samples is therefore performed and an uncertainty on the final yields is assigned by varying the value of the average interactions per bunch crossing 10% up and down.

- Jet Energy Scale (JES)

After correcting the jets in MC events to match the energy scale measured in data, the JES uncertainty is assigned by scaling the energy of the jets in the simulation up and down by a one sigma variation of the mean jet energy scale, where the values are given in η and p_T bins. It is an asymmetric uncertainty, which has also to be propagated to the E_T^{miss} calculation. The variation can be done considering the total uncertainty or by varying separately the single components that contribute to the jet energy scale uncertainty, e.g. the uncertainty on the flavour composition of the jet or on the effective number of partons considered.

- Jet Energy Resolution (JER)

The jet energy resolution in data differs from what is observed in the MC samples. The difference in the measured resolutions is used as a symmetric uncertainty to be assigned to simulated jets. This is done by smearing the p_T of the simulated jets according to a Gaussian distribution with mean one and a p_T and η dependent width. Also in this case, the changes have to be propagated to the E_T^{miss} reconstruction.

- B-tagging uncertainties

b -tagging scaling factors are calculated to account for the different response to b -tagging algorithms in data and MC. These are extracted together with a $\pm 1\sigma$ variation of the fit results separately for the b , c , and light components. The effect of these variation on the MC estimates has to be checked.

- Lepton identification and resolution

As for the jets, scale factors with the related scale and resolution uncertainties, corresponding to their $\pm 1\sigma$ variation, are provided for electrons and muons. In analyses with many jets in the final state, the contribution to the total uncertainty coming from the leptons SF variations is generally negligible.

- E_T^{miss} Soft Component

The uncertainty on the soft component of the missing transverse momentum has an asymmetric scale uncertainty and a resolution component. The first one comes from the variation of the energy scale of the calorimeter clusters not assigned to any physics object, while the methods used to extract the resolution uncertainty are described in Section 4.5.2.

6.4.2 Theory Uncertainties

The theory uncertainties represent our ignorance about the theoretical description of a process or its implementation in a MC generator. They are process dependent and may be not uniquely or well defined. In many cases they are evaluated with a simplified version of the analysis that makes use of truth level objects. Here, a list of possible uncertainties is presented, which may be taken into account for the background and signal processes considered in an analysis.

- Cross section

The cross section of most production processes is known at least at the NLO+NLL QCD precision. For complex SM processes, such as the associated production of a $t\bar{t}$ pair with a vector boson or the W boson production in association with heavy flavour jets, the cross section uncertainty may become the dominant one. It is in general non negligible also for SUSY signal processes. However, a cross section uncertainty is not applied to the processes that are estimated partially or completely with data in dedicated CRs.

- Initial and Final State Radiation (ISR/FSR)

To assess the impact of the initial and final state radiation on the event yields, samples are simulated where the initial or final radiation activity is augmented or decreased, either separately or simultaneously for ISR and FSR. The yield difference obtained by the comparison of these samples is taken as ISR/FSR uncertainty.

- MC Generator

Significantly different yields may be found when estimating a process with the aid of different MC generators. This may happen because, depending on the choices of the simulation parameters, the kinematic distributions of the relevant variables show discrepancies. As long as the differences do not make one of the samples incompatible with the data in the CR or in control distributions, the symmetrized difference between the baseline and an alternative generator is taken as uncertainty. The comparison is done among MC generators that simulate events with the same precision order.

- Parton Shower

Since the parton shower models are phenomenological models with many parameters that have to be tuned with data, an uncertainty is estimated for the choice of a given parton shower model. Samples produced with the same MC generator but matched to different parton shower programs are compared and the relative difference on the events yield in the selected region is taken as uncertainty.

- PDF Set

The PDFs have intrinsic uncertainties. Usually the impact of the uncertainty on the PDFs on the physics analyses is evaluated by comparing the results obtained by using different PDF sets with respect to the baseline choice.

- Renormalisation and Factorisation Scale

As introduced in Section 2.3 the renormalisation and factorisation scales are not physical quantities. The impact of the choice of these scales on the event yield of a given process is conventionally checked by varying them separately for a factor 2 and $1/2$.

6.5 Statistical Interpretation of the Results

The last step of an analysis consists in the statistical interpretation of the results in the designed signal regions. The goal of a search is to find a signal that would cause an increase in the observed events with respect to what expected from the known background processes. The signal sensitive regions of an analysis can be either one-bin regions, in the so called cut-and-count analyses, or make use of the shape of a discriminating variable, in the multi-bins or shape-aware analyses. In the following, only the definitions for the one-bin approach are discussed, which is the relevant one for the analyses presented in the next chapters.

In order to assess if the observed events are compatible with the expected background, the background hypothesis, or null hypothesis $\mathcal{H}_0$, has to be tested against the background+signal hypothesis, $\mathcal{H}_{s+b}$, where the $\mathcal{H}_0$ probability curve is centred on the number of expected background events, n_b , while $\mathcal{H}_{s+b}$ is centred on n_{b+s} , sum of the expected background and signal events. The agreement between the observed data and the background expectation is quantified by the p -value. Given the hypothesis $\mathcal{H}_x$, the p -value under this hypothesis is a measure of the probability of observing data which is at least as incompatible with $\mathcal{H}_x$ as the observed one [152].

The p -value can be translated in the significance S , which represents the number of standard deviations from the mean of a Gaussian distributed variable needed to have an upper-tail probability equal to p . In experimental particle physics a discovery is claimed when a significance $S = 5$ over the background only hypothesis is reached, which corresponds to a p -value $p = 2.87 \cdot 10^{-7}$. The significance needed to exclude a particular signal is fixed at $S = 1.64$ or to a p -value of $p = 0.05$, which is often reported as the 95% confidence level (CL) quantile of the probability distribution, with $CL = 1 - p$.

The test statistic generally chosen by the ATLAS collaboration is the log-likelihood ratio with a frequentist statistical approach [152]. The likelihood function is defined as the product of the Poissonian probabilities of the considered bins as

$$L(\mu, \theta | n) = \prod_{j=1}^N \frac{(\mu s_j(\theta_s) + b_j(\theta_b))^{n_j}}{n_j!} e^{-(\mu s_j(\theta_s) + b_j(\theta_b))}, \quad (6.12)$$

where μ is the strength of the signal process, with $\mu = 0$ corresponding to no signal presence and

$\mu = 1$ to the nominal signal hypothesis, and θ is a vector of parameters, the *nuisance* parameters, that describe the shape of the probability density functions of the background and signal distributions. This basic likelihood function can be multiplied by auxiliary terms, representing subsidiary measurements, that help to constrain the nuisance parameters. The final likelihood function used in an analysis assumes then the form

$$L(\mu, \mu_b, \theta | n, \theta_0) = P_{\text{SR}}(n | \mu, \mu_b, \theta) \times \prod_{i=1}^{n_{\text{CR}}} P_{\text{CR}_i}(n | \mu, \mu_b, \theta) \times C_{\text{syst}}(\theta_0 | \theta), \quad (6.13)$$

with P_{SR} and P_{CR_i} Poisson probability density functions of the data in the signal and background control regions. Here the parameter μ_b has been introduced to define the floating normalisation of the background processes, which is determined in the CRs. The term C_{syst} contains the knowledge about the systematical uncertainties coming from the subsidiary measurements. The value of the nuisance parameters θ can float to best accomodate the data according to a Gaussian probability distribution centred on θ_0 , the measured central uncertainty value.

The log-likelihood ratio test statistic, depending on the signal strength μ , can now be written as

$$t_\mu = -2 \ln \frac{L(\mu, \hat{\theta})}{L(\hat{\mu}, \hat{\theta})}. \quad (6.14)$$

In this equation $\hat{\mu}$ and $\hat{\theta}$ are the values of μ and θ that maximise the likelihood, while $\hat{\theta}$ is the value of θ that maximises the likelihood for the chosen μ .

The p -value, given the test statistic t_μ , is given by integrating the t_μ probability density function between the observed t_μ value and infinity

$$p_\mu = \int_{t_\mu, \text{obs}}^{\infty} f(t_\mu | \mu) dt_\mu. \quad (6.15)$$

The discovery p -value can be computed by setting $\mu = 0$, while the exclusion p -value of a given signal model is found by setting the signal to its nominal value, corresponding to $\mu = 1$.

A powerful property of the likelihood function is that orthogonal channels can be easily combined by just multiplying the Poissonian terms of the new regions considered with the original one-channel likelihood. This is important since, by combining different signal channels, the statistical power and sensitivity of an analysis to specific models can be substantially improved.

6.5.1 The CLs Method

The concept of CL_s was introduced in order to have a protection against the possibility to exclude or discover signals to which an analysis is not sensitive [155]. The CL_s is defined as the ratio of the confidence levels of the background plus signal hypothesis to the background only hypothesis

$$\text{CL}_s = \frac{\text{CL}_{s+b}}{\text{CL}_b}. \quad (6.16)$$

The confidence level of the background plus signal hypothesis CL_{s+b} is defined as the probability, under this hypothesis, to obtain a lower value of the test statistic t_μ with respect to the observed value:

$$\text{CL}_{s+b} = P_{s+b}(t_\mu \leq t_{\mu, \text{obs}}) = \int_{-\infty}^{t_{\mu, \text{obs}}} \frac{dP_{s+b}}{dt_\mu} dt_\mu = 1 - p_{\mu, s+b}, \quad (6.17)$$

while the confidence level of the background only hypothesis is defined as

$$\text{CL}_b = P_b(t_\mu \leq t_{\mu, \text{obs}}). \quad (6.18)$$

A small CL_{s+b} is an indication of a bad compatibility of the data with the background plus signal hypothesis, which would then favour the background only hypothesis, while a CL_b close to 1 means a poor compatibility with the background hypothesis.

A signal is considered excluded at a certain confidence level CL when

$$1 - \text{CL}_s \leq CL. \quad (6.19)$$

The limits obtained with the CL_s method are conservative, but allow to treat correctly situations with very low background rates where it is not always possible to disentangle clearly the background from the background+signal hypotheses.

6.5.2 The Statistical Framework: HistFitter

The statistical framework used to extract the final results of the analyses is the HistFitter package [156], which uses the HistFactory [157] and RooStats [158] softwares based on RooFit [159] and ROOT [160, 161]. With this framework it is possible to build models that contain the description of complex analyses in terms of control, validation and signal regions, where the uncertainties on the background and signal samples, as well as their correlations, are treated coherently.

After the signal model has been built, different types of fits can be performed:

- **Background Fit**

In this fit configuration only the background samples are taken into consideration and their normalisation is fixed in the CRs, where no signal contamination is assumed. The background components are compared to the data in the VRs and SRs. This fit configuration is useful to have signal model independent results as well as to compare the expected and observed events in each region, giving also the compatibility of the observed data with the background expectation in the signal regions.

- **Exclusion Fit**

This is a model dependent fit performed simultaneously in the control and signal regions, when no significant excess in the SRs has been observed by performing the background only fit. The signal contamination in the CRs is taken into account and correctly subtracted when deriving the background normalisation factors. Limit contours in two-dimensional parameter spaces can be defined by running the fit on the points of a signal grid.

- **Discovery and Model Independent Fit**

This fit can be only performed in the one-bin mode since no assumptions on the signal model are done. For this same reason no signal contamination in the background control regions is considered. The fit is performed on the CRs and SRs simultaneously fixing the signal strength parameter $\mu = 0$ to test the background hypothesis (discovery fit), and to $\mu = 1$ to have the results for the model independent upper limits on the number of signal events in the SRs.

The results of the exclusion fit can be displayed as exclusion contours in multi-dimensional planes. The expected and observed 95% CL exclusion contours are shown together with a 1σ uncertainty band. All the background and signal uncertainties, with the exception of the theoretical uncertainties on the

signal, are properly summed to obtain the expected limit uncertainty band. The impact of the signal theoretical uncertainties on the exclusion contour are represented by the uncertainty band on the observed limit.

The validation regions are used to test the robustness of the background estimates. The pull distribution, with the pull χ defined as

$$\chi = \frac{n_{obs} - n_{exp}}{\sigma_{tot}} = \frac{n_{obs} - n_{exp}}{\sqrt{\sigma_{exp}^2 + \sigma_{stat,exp}^2}}, \quad (6.20)$$

can be used as estimator to check the compatibility of the background estimates with the observed data events in these regions. In the formula σ_{tot} is the total uncertainty on the expected background, which is the sum in quadrature of the systematic uncertainty and of the Poissonian statistical uncertainty on the expected number of background events.

Searches for the top squark at $\sqrt{s} = 7$ TeV

In this chapter a search for the direct production of the top squark with the 7 TeV ATLAS dataset is presented. This is one of the first direct stop production searches performed at the ATLAS experiment and focuses on the light stop mass range where $m(\tilde{t}_1) \lesssim m(t)$. In this region of the parameter space the stop is allowed to decay as $\tilde{t} \rightarrow b\tilde{\chi}_1^\pm \rightarrow bW^{(*)}\tilde{\chi}_1^0$, with the W boson decaying with the SM branching ratios, and it being on- or off-shell depending on the mass difference between the chargino and the neutralino. The Feynman diagram that represents the stop pair production and decay in this benchmark channel is shown in Fig. 7.1a for the semi-leptonic final state.

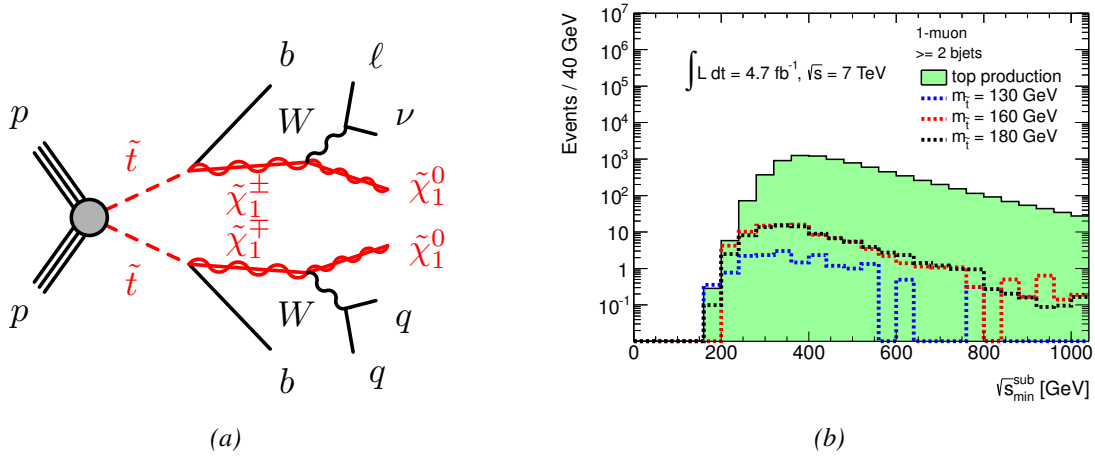


Figure 7.1: Feynman diagram of the pair production of top squarks decaying as $\tilde{t} \rightarrow b\tilde{\chi}_1^\pm \rightarrow bW^{(*)}\tilde{\chi}_1^0$ for semi-leptonic final states (a); distribution of the $\sqrt{s_{\min}^{\text{sub}}}$ variable for a one muon selection for the $t\bar{t}$ background and three signal points with mass $m(\tilde{t}) = 130, 160, 180$ GeV, $m(\tilde{\chi}_1^0) = 60$ GeV and $m(\tilde{\chi}_1^\pm) = 2 \cdot m(\tilde{\chi}_1^0)$.

This search is particularly complex not only due to the process being very similar to the decay of a pair-produced $t\bar{t}$, but also because the $\tilde{t}$ decay products are, in general, softer than those of the top quark decay. The discrimination between signal and background processes cannot, hence, be achieved by applying tight selections e.g. on the missing transverse momentum or on the p_T of jets and leptons. It was found that a very good signal separation could be realised with the $\sqrt{s_{\min}^{\text{sub}}}$ variable [162], which is introduced in Section 7.2. The distribution of this variable for a one muon and four jets selection is shown in Fig. 7.1b for the $t\bar{t}$ background and for three signal samples. The peak is located at about

$2 \times m(t)$ for the $t\bar{t}$ background and at a lower value for the signal processes.

The search has been performed in final states with jets, b -jets and one or two leptons. The one and two leptons channels have been combined to increase the sensitivity of the search and the final results were published in Ref. [163].

In the following, the results of the search in final states with one lepton and at least four jets, of which two b -tagged, are presented in detail, while only the necessary information to understand the final results is given for the search in two leptons final states. The analysed dataset and the MC samples used for the analysis are introduced in Section 7.1. The design of the signal region is presented in Section 7.2, after having introduced the baseline object and event selections, the $\sqrt{s}_{\min}^{(\text{sub})}$ variable, and the reconstruction of the semi-leptonic $t\bar{t}$ decay.

The $t\bar{t}$ pair-production is the main background of this search, hence the reconstruction of the $t\bar{t}$ decay is of particular importance also for the background estimation. The definition of the control regions for the main backgrounds to the analysis, $t\bar{t}$ and the associated production of a W boson with heavy flavour jets, and how they have been estimated is presented in Section 7.3, together with a small paragraph on the estimate of the fake lepton background. The experimental and theoretical uncertainties are presented in Section 7.4, and the final results of the analysis are discussed in Section 7.5. Here also the results of the two leptons analysis are presented, in order to give the complete and final picture of the search.

The results published in Ref. [163] were obtained within the research done for my PhD thesis. In particular, my personal contributions are in the definition of the $t\bar{t}$ decay reconstruction method, the method to fit the reconstructed top hadronic mass used to define the signal, $t\bar{t}$ and W + jets enriched regions, the design of the $t\bar{t}$ and W + jets control regions and the estimate of this backgrounds, together with the estimate of the theoretical and experimental uncertainties related to them.

7.1 Data and Monte Carlo Samples

The analysed data correspond to an integrated luminosity of $\mathcal{L}_{\text{int}} = 4.7 \pm 0.2 \text{ fb}^{-1}$, recorded by the ATLAS experiment at a centre-of-mass energy of $\sqrt{s} = 7$ TeV in 2011 and selected as good data for the analyses by the GRL of the ATLAS collaboration SUSY group.

The background and signal MC samples used in the analysis are summarised in the next paragraph. The GEANT4 detector simulation was used for the simulated background samples, while AFII was used for the signal samples. The complete list of the used samples can be found in Appendix B.

7.1.1 Background Samples

Monte Carlo simulated samples have been used for the background estimates either directly, for the minor backgrounds, or as a support for the semi- or fully-data-driven estimates of the major backgrounds.

- Top production

The baseline $t\bar{t}$ and single top MC samples were simulated with MC@NLO [84], which includes the full NLO corrections to the matrix element of the hard process, interfaced to HERWIG [78], for the parton shower, and JIMMY [75], for the underlying event. The CT10 [61] PDF set at NLO was used and the mass of the top quark was fixed to 172.5 GeV. For the normalisation of the $t\bar{t}$ sample, the NLO+NLL $t\bar{t}$ production cross section was used.

The t -channel single top baseline sample was generated with ACER MC [82]. ALPGEN [81] was

used to simulate samples of associated production of $t\bar{t}$ with a $b\bar{b}$ pair, as well as for the $t\bar{t}$ production in association with jets (0-3), used to assess the systematic uncertainties of the $t\bar{t}$ estimate. For the computation of the systematic uncertainties of the top background also PowHeg [85] and ACER MC samples were used.

- W and Z production

The samples for the associated production of W and Z bosons with light or heavy flavour jets were simulated with ALPGEN matched to JIMMY for the underlying event, and the CTEQ6 [62] PDF set at LO was used. Since ALPGEN does not consider the mass of the heavy quarks, the overlaps between boson+jets and boson+heavy-jets samples have to be correctly resolved. The samples are generated at LO and k -factors are applied to get to the NNLO accuracy of the cross section value. Additional scaling factors of 1.63 ± 0.76 and 1.11 ± 0.35 are applied, respectively, to the $W + cc/W + bb$ and $W + c$ samples, which were extracted from the measurement of Ref. [164].

- $t\bar{t}$ +X production

The generation of the samples for the associated production of $t\bar{t}$ with one or more vector bosons was done with MadGraph [83] interfaced to PYTHIA [76], and to normalise the MC yields the cross section at LO was used. To extract the systematic uncertainty on this estimate samples generated with ALPGEN+HERWIG and ACER MC were used.

- Diboson production

The baseline WW , WZ and ZZ samples were generated with HERWIG, and samples generated with ALPGEN interfaced to HERWIG were used to estimate the systematic uncertainties. The MC event yields were then normalised to the NLO production cross section.

7.1.2 Signal Samples

The signal models considered for this search are

- Gaugino universality grid, $m(\tilde{\chi}_1^\pm) = 2 \cdot m(\tilde{\chi}_1^0)$, the limits are set in the $(\tilde{t}, \tilde{\chi}_1^0)$ mass plane
- Fixed stop mass $m(\tilde{t}_1) = 180$ GeV, the limits are set in the $(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0)$ mass plane
- Fixed chargino mass $m(\tilde{\chi}_1^\pm) = 106$ GeV, the limits are set in the $(\tilde{t}, \tilde{\chi}_1^0)$ mass plane

where the stop decays with a 100% BR in $b\tilde{\chi}_1^\pm$, the chargino decays as $\tilde{\chi}_1^\pm \rightarrow W^{(*)}\tilde{\chi}_1^0$ and the W decays with the SM branching ratios in leptons or quarks.

The first two grids were generated with HERWIG++ [79] with the MRST2007 LO PDF set [165], the last was generated with PYTHIA with a two lepton generator filter. The signal yields are normalised using the cross section computed at NLO by Prospino plus the contributions from the resummation of soft collinear gluon emissions at the next-to-leading-logarithmic precision [166, 167, 168].

7.2 Analysis Strategy

In this section the baseline and cleaning selections applied to the data and MC events are first discussed together with the requirements on the selected physics objects. Some data-MC comparisons at an early stage of the selections are shown in Paragraph 7.2.3 for the most important distributions for the analysis. The method used for the reconstruction of the $t\bar{t}$ semi-leptonic decay is explained in Paragraph 7.2.4 and

the $\sqrt{s}_{\min}^{(\text{sub})}$ variable is described in Paragraph 7.2.5. Finally in Paragraph 7.2.6 the choice of the final signal region is presented.

7.2.1 Trigger Selection

To select events in data the single lepton triggers with the lowest p_T -threshold were chosen. These triggers are also required not to be scaled down in rate by data-taking bandwidth considerations. They needed, therefore, to have tighter p_T -threshold or identification and isolation requirements as the data taking conditions changed and higher instantaneous luminosity were achieved. The triggers were applied also to MC events, together with efficiency scale factors to correct for the differences in data and simulation. The triggers used for each data period are summarised in Table 7.1.

Period	Electron trigger	Muon trigger
B to I	e20_medium	mu18
J	e20_medium	mu18_medium
K	e22_medium	mu18_medium
L, M	e22vh_medium1 e45_medium1	mu18_medium

Table 7.1: Single lepton triggers used for the analysis.

7.2.2 Object Selection

In this paragraph the requirements on the objects selected in the analysis are reported. These are electrons, muons, jets, b -tagging selections, and missing transverse momentum. The definitions of the identification requirements of the physics objects have been introduced in Chapter 4 and are, hence, not repeated here.

After the baseline objects have been selected, the jet-lepton overlap removal procedure is applied following the steps presented in Paragraph 6.3.4.

- Electrons

The baseline electrons are selected with the medium identification requirements as cluster seeded electrons. Quality checks are applied to ensure that all the energy of the shower was properly recorded and that no problematic calorimeter cells could have significantly altered the measurement of the electron shower.

The selected electrons must have $p_T > 20 \text{ GeV}$ and $|\eta| < 2.47$. In addition the signal electrons must satisfy the tight identification criteria and be isolated. The isolation requirement is $p_{T\text{cone20}}/p_T < 0.1$, which means that the sum of the p_T of the tracks in a cone of $\Delta R = 0.2$ around the electron track must add up to less than 10% of the electron p_T .

- Muons

The baseline muons have $p_T > 10 \text{ GeV}$ and $|\eta| < 2.4$. Since combined muons are considered in the analysis, a minimum of pixel and SCT hits and holes are required as well as a minimum number of points in the TRT for the covered region. A muon is labelled as coming from cosmic decays if its transverse and longitudinal impact parameters do not satisfy $|d_0| < 0.2 \text{ mm}$ and $|z_0| < 1.0 \text{ mm}$. The signal muons are additionally required to be isolated and satisfy $p_{T\text{cone20}}/p_T < 0.18$.

- Jets

The selected jets are anti- k_t , $R=0.4$ jets reconstructed from topoclusters at the electromagnetic

scale to which JES and vertex-origin corrections have been applied. The baseline calibrated jets are required to have $p_T > 20$ GeV and $|\eta| < 2.5$. To ensure robustness against pile-up, a requirement on the jet vertex fraction, $JVF > 0.75$, was applied.

- b -tagging

A selected jet is labelled as coming from a b -hadron decay if the b -tagging weight, computed with the JETCOMBNN algorithm, exceeded 1.8. This corresponds to the 60% efficiency working point, the tightest point for which calibrations and efficiency scale factors were available.

- E_T^{miss}

In the E_T^{miss} calculation the contributions from the jets at the electromagnetic scale corrected for the JES with $p_T > 20$ GeV, the selected electrons and muons, and the isolated calorimeter clusters are summed together. The chosen E_T^{miss} variable does not treat tau contributions separately from those of the jets.

7.2.3 Preselections and Event Cleaning

The set of cleaning and baseline requirements applied to the events to select a first sample containing events with the right objects is presented in the following. The basic cleaning selections have been already introduced in Paragraph 6.3.4 and a more detailed description can, hence, be found there.

- GRL

It is applied only to data to select only the events recorded with optimal detector conditions.

- Trigger

The trigger requirement is applied both to data and MC samples.

- Primary vertex

The primary vertex must have at least five tracks associated with it.

- Cosmic muons veto

If a selected baseline muon is tagged as cosmic candidate the event is vetoed.

- Bad muons veto

If a selected baseline muon is tagged as “bad muon” candidate the event is vetoed.

- Bad jets veto

If a selected baseline jet is labelled as “very loose bad” jet the event is vetoed.

- Smart LAr hole veto

If any jet falls in the LAr hole region and may give a large fake E_T^{miss} contribution, the event is rejected.

- One signal lepton

The event must contain one single signal lepton with $p_T > 25(20)$ GeV for the electron(muon) channel which is matched to the trigger decision. The higher threshold on the lepton p_T is needed to be sure of selecting only the events recorded in the trigger efficiency plateau. If any additional baseline electron(muon) with $p_T > 20(10)$ GeV has been selected, the event is vetoed.

- $n_{\text{jets}} \geq 4$

The event must contain at least four signal jets with $p_T > 20$ GeV and $|\eta| < 2.5$.

- $\underline{n_{b\text{-jets}} \geq 2}$
At least two of the jets of the event must be b -tagged. The chosen WP is the 60% efficiency point.
- $\underline{n_{light\text{-jets}} \geq 2}$
At least two of the jets of the event must be light jets.
- $\underline{E_T^{\text{miss}} > 40 \text{ GeV}}$
- $\underline{m_T(\ell, E_T^{\text{miss}}) > 30 \text{ GeV}}$

The requirements on the jets as well as on the missing transverse momentum are needed to select enough objects that can be used for the reconstruction of the semi-leptonic decay of the $t\bar{t}$ pair, described in the next paragraph. The requirement on the transverse mass between the lepton and the E_T^{miss} helps in rejecting multi-jets events faking the signal signature.

Weights are assigned to the surviving events in MC for the differences observed with data. The applied weights are lepton identification and trigger efficiency factors, b -tagging scaling factors and the pile-up weights. These last weights are obtained when the $\langle\mu\rangle$ distributions in MC is reweighted to match the one measured in data.

Data-MC comparisons for the baseline variables used in the analysis at an early stage of the selections are shown in Figs. 7.2, and 7.3. The distributions are displayed separately for the electron, on the left, and for the muon channel, on the right.

The number of b -tagged jets with only the cleaning, the single lepton, and the E_T^{miss} selections applied, and the total number of jets after the additional requirements on the jets are shown in Fig. 7.2. The data-MC agreement is very good in the first two distributions, while it can be observed that the MC seems to not describe perfectly the data for events with a very high jet multiplicity. The first two plots show that the two b -jets requirement is very effective in rejecting the W +jets background and gives a better signal to background ratio, than what observed in the one b -jet bin. The main background then becomes the $t\bar{t}$ production as can be seen from the n_{jets} distributions.

The distributions of the p_T of the leading lepton, of the leading jet and of the E_T^{miss} in the events are shown in Fig. 7.3. The data-MC agreement is good and no trends in the data-MC ratios are observed, giving confidence that the shape of the variables is well described by the MC simulated samples.

7.2.4 $t\bar{t}$ Decay Reconstruction

Since $t\bar{t}$ is the main background to this search a method to reconstruct its semi-leptonic decay has been developed. The reconstructed mass of the hadronically-decaying top is a powerful variable to separate the signal from the $t\bar{t}$ background as well as to define a $t\bar{t}$ enriched region for its estimation. The steps in the identification of the objects belonging to the $t\bar{t}$ decay and its reconstructions are explained below.

- It is first assumed that the E_T^{miss} and the selected lepton come from the leptonic decay of a W boson, where the E_T^{miss} represents the transverse component of the momentum of the neutrino. The longitudinal component of the neutrino momentum, p_z^ν , can be extracted by imposing that the invariant mass between the lepton and the neutrino is equal to the PDG value of the W mass [12]. The resulting quadratic equation can have either zero or two solutions. In the latter case both solutions are considered, in the former the p_z^ν is set to the value that gives a null discriminant for the given equation. The invariant mass of the lepton and neutrino is saved as $m(W_{lep})$.

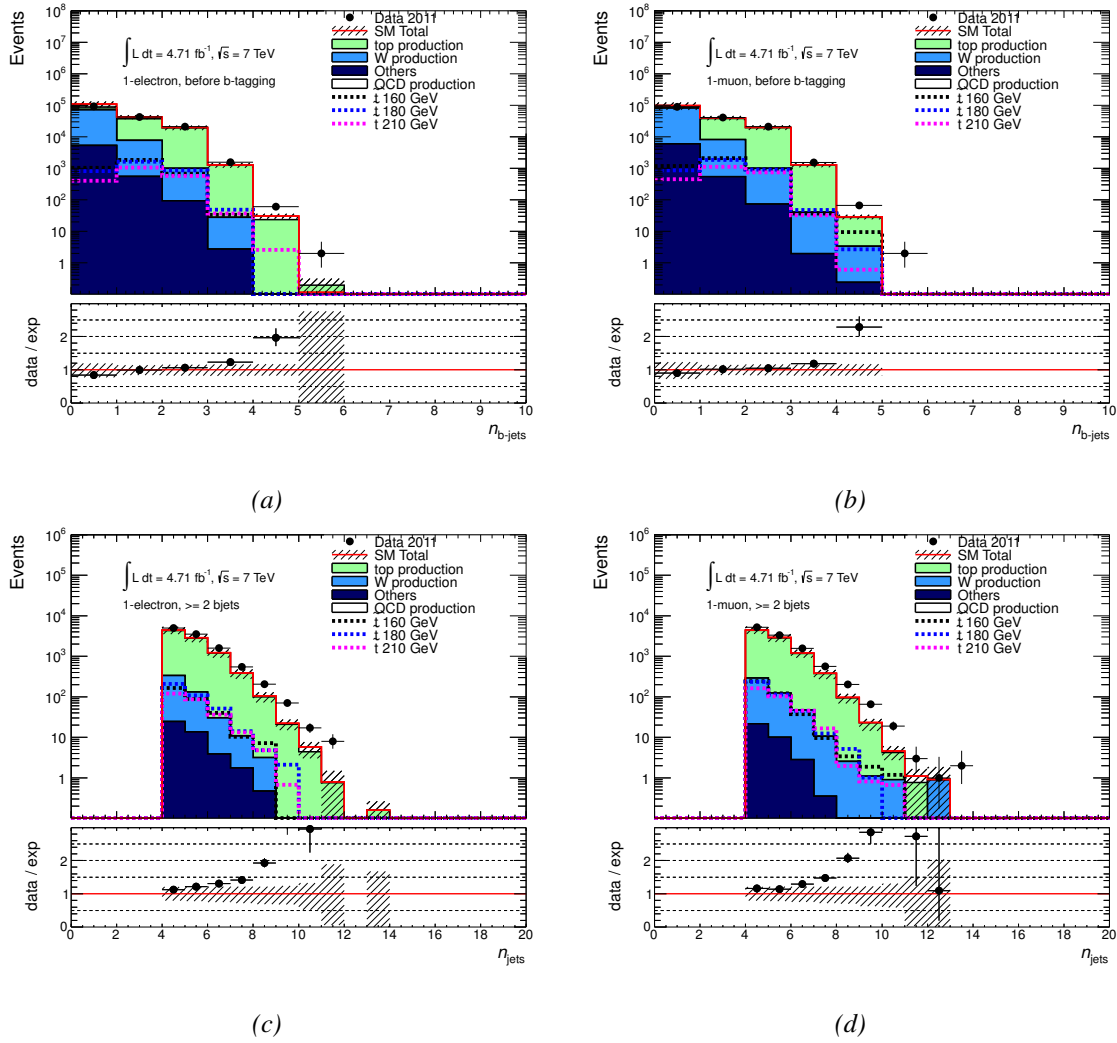


Figure 7.2: Number of b -tagged jets for the 1-electron (a) and the 1-muon (b) channel after applying only the cleaning selections plus the single lepton and E_T^{miss} selections. Here the b -tagging scale factors are not applied. Number of jets after the cleaning selections, single lepton, E_T^{miss} , and jets selections in the electron (c) and muon (d) channels. The hatched band represents the total uncertainty on the background expectation. The background contributions are stacked, while the signal contributions are superimposed. The signal models chosen have a neutralino with mass $m(\tilde{\chi}_1^0) = 60 \text{ GeV}$ and $m(\tilde{\chi}_1^\pm) = 2 \cdot m(\tilde{\chi}_1^0)$.

- All possible combinations of two light jets are tested and their mass is saved as $m(W_{\text{had}})$.
- All possible combinations of a b -jet and a W_{had} are checked and their mass is saved as $m(t_{\text{had}})$.
- All extracted p_z^ν are used in combinations with the selected b -jets and the lepton to define the top leptonic mass, $m(t_{\text{lep}})$.
- Assuming that the masses are distributed with a Gaussian probability density function, with mean value $m(X)_{\text{true}}$, $X = W_{\text{lep}}, W_{\text{had}}, t_{\text{lep}}, t_{\text{had}}$, and true width Γ_{true} found by matching the reconstructed objects used in the $t\bar{t}$ reconstruction with the parton level particles, a probability for each mass is assigned as

$$P(m(X)) = 1 - \text{Erf} \left(\frac{|m(X) - m(X)_{\text{true}}|}{\sqrt{2}\Gamma_{\text{true}}} \right), \quad (7.1)$$

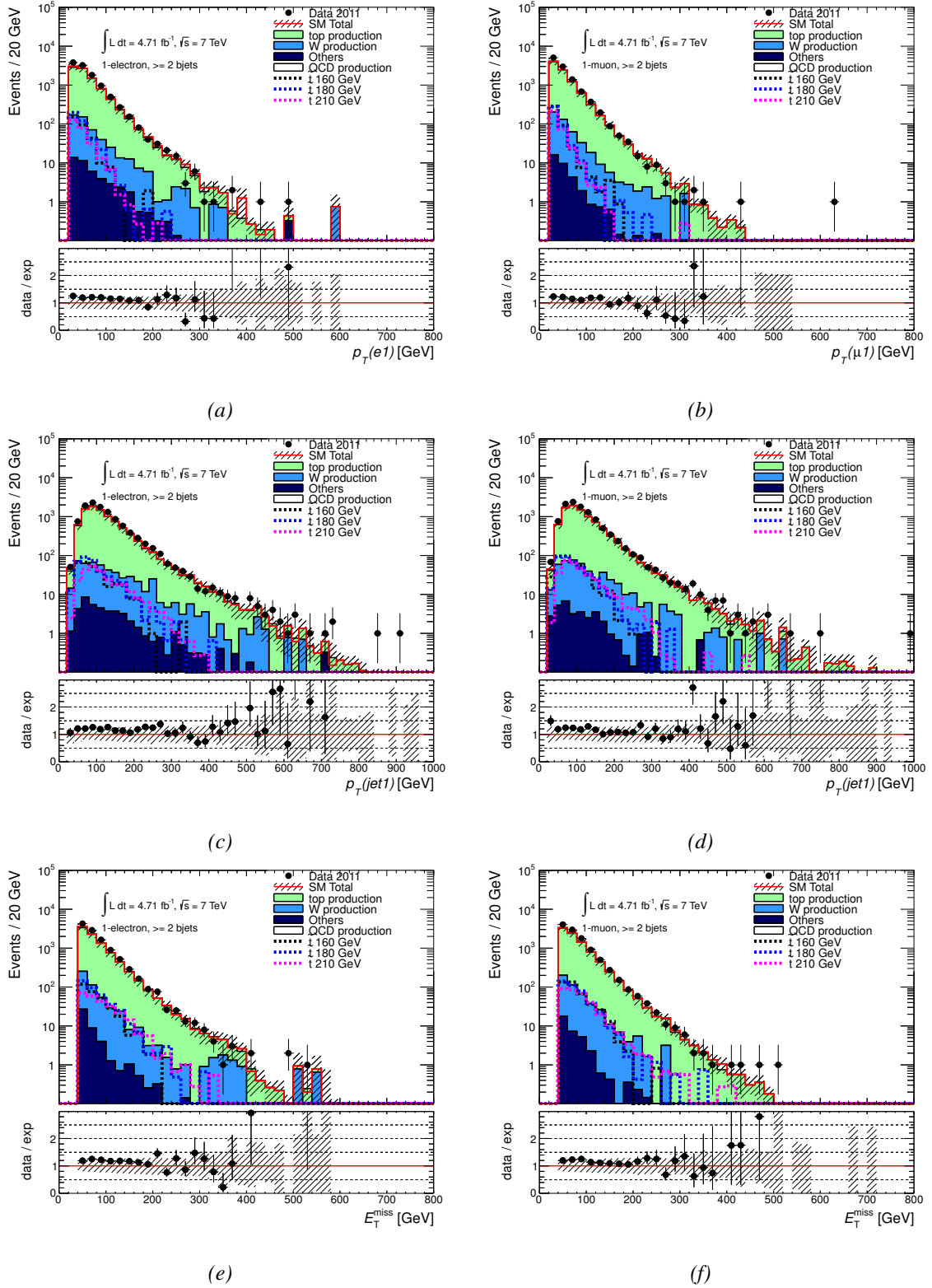


Figure 7.3: Distributions of the leading lepton p_T for the electron (a) and muon (b) channels, of the leading jet p_T for the electron (c) and muon (d) channels, and of the E_T^{miss} for the electron (e) and muon (f) channels. The cleaning selections, single lepton, E_T^{miss} , and jets selections have been applied. The hatched band represents the total uncertainty on the background expectation. The background contributions are stacked, while the signal contributions are superimposed. The signal models chosen have a neutralino with mass $m(\tilde{\chi}_1^0) = 60$ GeV and $m(\tilde{\chi}_1^\pm) = 2 \cdot m(\tilde{\chi}_1^0)$.

where Erf is the Gauss error function.

- Among all jets and p_z^ν combinations, the one with highest total probability

$$P_{\text{tot}} = P(m(W_{\text{had}})) \cdot P(m(t_{\text{had}})) \cdot P(m(W_{\text{lep}})) \cdot P(m(t_{\text{lep}})) \quad (7.2)$$

is chosen as the combination giving the correct $t\bar{t}$ decay objects.

The signal is expected to peak at a lower value of $m(t_{\text{had}})$ with respect to the $t\bar{t}$ background because of the presence of the massive neutralinos in the decay chain. The $t\bar{t}$ enriched region, used for its estimate, can be defined as the region around the $t\bar{t}$ $m(t_{\text{had}})$ peak, while the events in the signal region must have a $m(t_{\text{had}})$ value below the top mass peak.

To properly define these regions, a Gaussian fit of the $m(t_{\text{had}})$ distribution was performed following these steps:

- A first fit is performed in the range 100–300 GeV, obtaining a value for the mean value μ_{raw} and for the sigma σ_{raw} of the distribution.
- The Gaussian fit is then repeated in the range $[\mu_{\text{raw}} - \sigma_{\text{raw}}, \mu_{\text{raw}} + \sigma_{\text{raw}}]$, to obtain new values $\hat{\mu}$, $\hat{\sigma}$.

A top dominated region $t\bar{t}\text{CR1}$ can then be defined by selecting the events that satisfy

$$\hat{\mu} - 0.5\hat{\sigma} < m(t_{\text{had}}) < \hat{\mu} + 0.5\hat{\sigma}, \quad (7.3)$$

while the events fulfilling the requirement

$$m(t_{\text{had}}) < \hat{\mu} - 0.5\hat{\sigma}, \quad (7.4)$$

are considered as possible candidates for the signal region selection.

The mean values and width of the fits performed on the $m(t_{\text{had}})$ distributions in the electron and muon channels for the nominal $t\bar{t}$ MC sample, for the distributions obtained by varying the jet energy scale, and for the data are summarised in Table 7.2. The mean and width fit values obtained in data and MC are compatible within uncertainties.

Channel	Nominal MC		JES Up		JES Down		Data	
	$\hat{\mu}$	$\hat{\sigma}$	$\hat{\mu}$	$\hat{\sigma}$	$\hat{\mu}$	$\hat{\sigma}$	$\hat{\mu}$	$\hat{\sigma}$
Electron	168.4 ± 0.1	18.0 ± 0.2	171.5	18.2	163.3	19.1	168.6 ± 0.4	17.9 ± 0.8
Muon	168.2 ± 0.1	18.6 ± 0.2	171.2	19.4	163.4	19.1	168.5 ± 0.5	18.9 ± 0.8

Table 7.2: Comparison of the mean value and width, in GeV, of the fit of the m_t^{had} distribution in data and MC. The values obtained by fitting the distributions when the JES is scaled up or down are also reported.

7.2.5 $\sqrt{s}_{\text{min}}^{(\text{sub})}$ Variable

The other main discriminating variable of the analysis is the $\sqrt{s}_{\text{min}}^{(\text{sub})}$ variable, defined as

$$\sqrt{s}_{\text{min}}^{(\text{sub})} = \left\{ \left(\sqrt{m_{(\text{sub})}^2 + p_{\text{T}(\text{sub})}^2} + \sqrt{(m_{\text{miss}})^2 + (E_{\text{T}}^{\text{miss}})^2} \right)^2 - (\mathbf{p}_{\text{T}(\text{sub})} + \mathbf{p}_{\text{T}}^{\text{miss}})^2 \right\}^{\frac{1}{2}}, \quad (7.5)$$

where $m_{(\text{sub})}$ is the visible mass of the subsystem under study, $p_{T(\text{sub})}$ is the visible transverse momentum of the subsystem, m^{miss} is the mass of the particles that cross the detector without interacting with it, and p_T^{miss} and E_T^{miss} are defined as usual as the missing momentum and energy measured in the detector. This variable represents the minimum value that the Mandelstam invariant mass variable $\sqrt{s}$ can assume, which is compatible with the energy measured in the event under study.

Given an event with n_{vis} visible reconstructed objects, of which n_{sub} belong to the subsystem of interest and the rest are up-stream objects that come from initial state radiation or, in general, from the underlying event, and n_{inv} particles that fly out of the detector without interacting with it, and all belonging to the subsystem, the energy and the momentum of the n_{sub} objects can be defined. A scheme of this can be seen in Fig. 7.4. The advantage of dividing the event in an up-stream and in a subsystem part is that the $\sqrt{s}_{\text{min}}^{(\text{sub})}$ variable defined only with the contribution from the subsystem particles is not sensitive to the underlying event and to ISR.

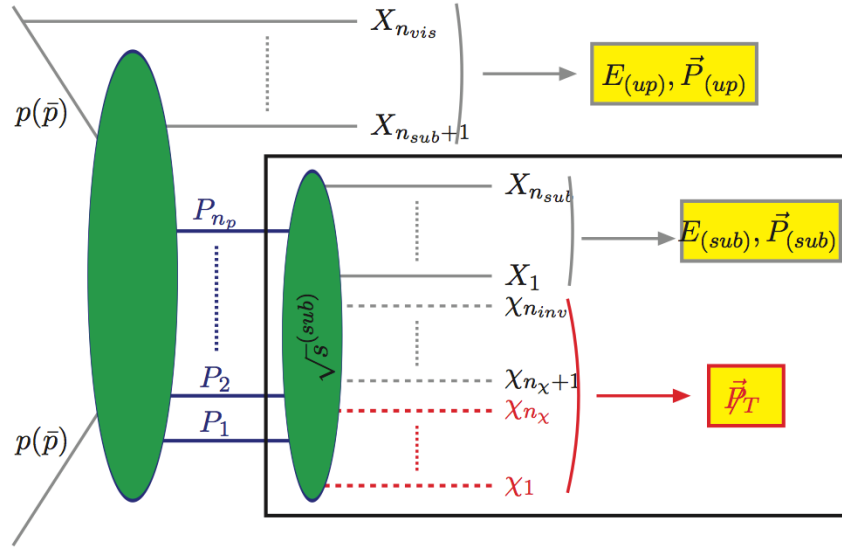


Figure 7.4: Event with a well defined subsystem, delineated by the black rectangle, with total invariant mass $\sqrt{s}^{(\text{sub})}$. The system contains n_{sub} visible particles X_i , $i = 1, 2, \dots, n_{\text{sub}}$, belonging to the subsystem, while the remaining $n_{\text{vis}} - n_{\text{sub}}$ visible particles $X_{n_{\text{sub}}+1}, \dots, X_{n_{\text{vis}}}$ are the up-stream particles. The subsystem results from the production and decays of a certain number of parent particles P_j , $j = 1, 2, \dots, n_p$, which may have some invisible decay products. All invisible particles $\chi_1, \dots, \chi_{n_{\text{inv}}}$ are assumed to originate from within the subsystem [162].

For the scope of this analysis the subsystem is composed by the E_T^{miss} , the selected lepton, and the jets that have been chosen in the $t\bar{t}$ reconstruction. The mass of the invisible particles is set to zero, so that the reconstructed system is again what we would expect from $t\bar{t}$, with a peak at around $2 \cdot m(t)$. Since the invisible decay products of the pair-produced stops are not only massless neutrinos, but also neutralinos with a non-negligible mass, the signal $\sqrt{s}_{\text{min}}^{(\text{sub})}$ distribution peaks at lower values than the one of the $t\bar{t}$ background. The signal region must be, therefore, identified by selecting events that lie below an upper threshold on the $\sqrt{s}_{\text{min}}^{(\text{sub})}$ variable.

The data-MC comparisons for the $\sqrt{s}_{\text{min}}^{(\text{sub})}$, W_{had} mass, and t_{had} mass distributions are shown in Fig. 7.5, where the cleaning, single lepton, E_T^{miss} , and jets requirements have been applied. The data-MC agreement is good for all variables and in both electron and muon channel. As for the baseline variables, the shape of this reconstructed variables is well described by the simulated samples, giving confidence that a semi-data-driven estimate of the backgrounds which exploits them, will give robust results.

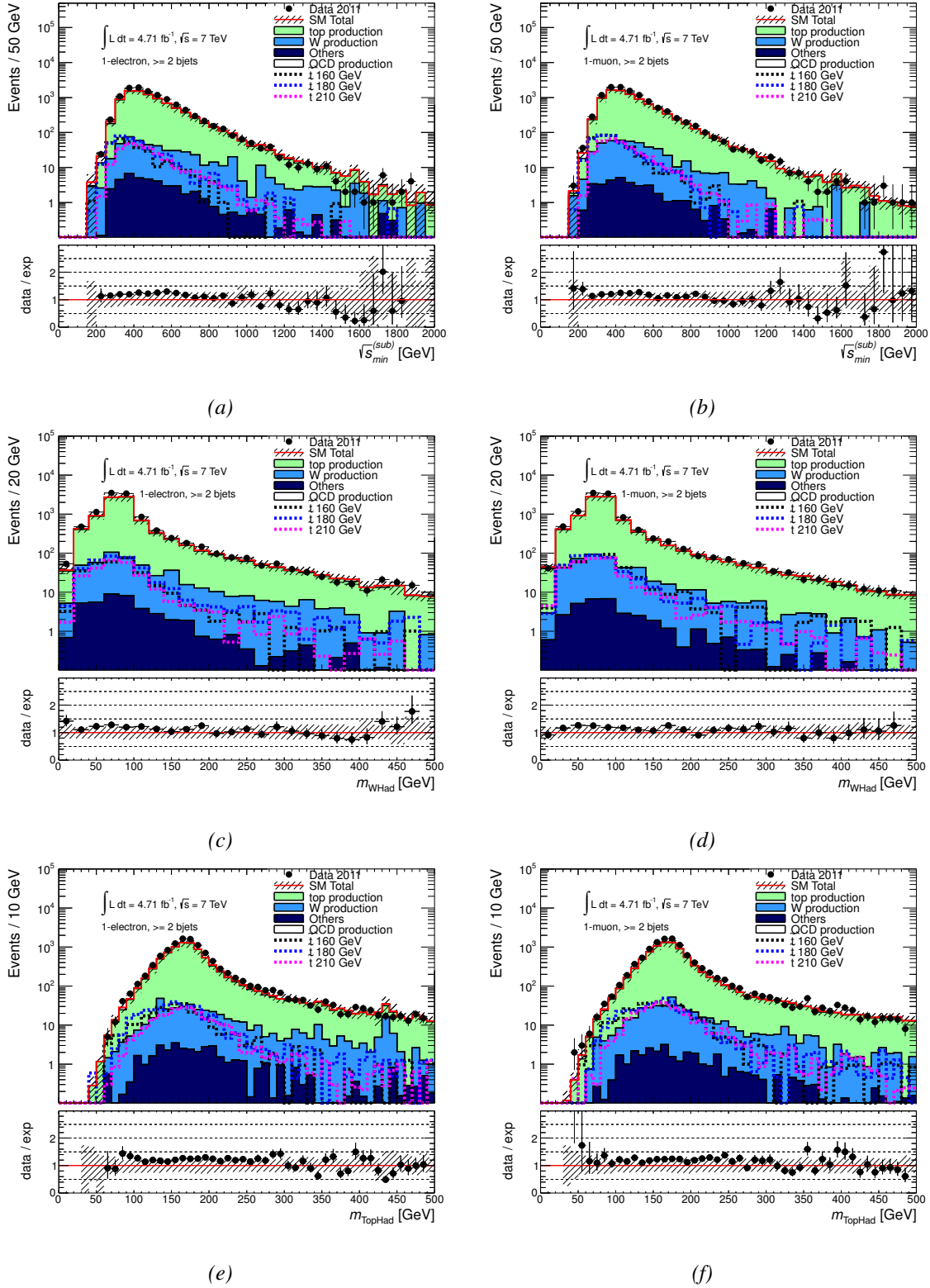


Figure 7.5: Distributions of the $\sqrt{s_{\min}^{(\text{sub})}}$ variable for the electron (a) and muon (b) channels, of the reconstructed W^{had} mass for the electron (c) and muon (d) channels, and of the reconstructed t^{had} mass for the electron (e) and muon (f) channels. The cleaning selections, single lepton, $E_{\text{T}}^{\text{miss}}$, and jets selections have been applied. The hatched band represents the total uncertainty on the background expectation. The background contributions are stacked, while the signal contributions are superimposed. The signal models chosen have a neutralino with mass $m(\tilde{\chi}_1^0) = 60 \text{ GeV}$ and $m(\tilde{\chi}_1^\pm) = 2 \cdot m(\tilde{\chi}_1^0)$.

7.2.6 Signal Region Definition

The definition of the signal region for the analysis is based on the optimisation of the selection on the $\sqrt{s}_{\min}^{(\text{sub})}$ variable. The significance estimator used for this scope is S_d as defined in Section 6.3.1.

All backgrounds, except for the fake lepton contribution, have been taken into account and three selections have been tested, with increasing flat uncertainty on the background as the selection becomes tighter. The flat-uncertainty assumption is a simplification used only in the optimisation procedure. The tested selections with their uncertainty values are:

- $\sqrt{s}_{\min}^{(\text{sub})} < 225 \text{ GeV}$, $\sigma_{\text{bkg, syst}} = 40\% N_{\text{bkg}}$
- $\sqrt{s}_{\min}^{(\text{sub})} < 235 \text{ GeV}$, $\sigma_{\text{bkg, syst}} = 35\% N_{\text{bkg}}$
- $\sqrt{s}_{\min}^{(\text{sub})} < 250 \text{ GeV}$, $\sigma_{\text{bkg, syst}} = 30\% N_{\text{bkg}}$

The highest significance values are obtained in the region where $m(\tilde{t}) \simeq m(t)$, and the best selection is found to be $\sqrt{s}_{\min}^{(\text{sub})} < 250 \text{ GeV}$.

The complete list of the selections for the search in one lepton final states is reported in Table 7.3. The selections are subdivided in baseline selections, channel specific selections, and signal region selections.

	Selection	Cut Value / Comment
Baseline	GRL	Applied only to data
	Trigger	Single electron or single muon
	Primary Vertex	≥ 5 tracks associated
	Cosmic Muons	Veto event if it has a cosmic candidate
	Bad Muons	Veto event if it has a bad muon candidate
	Bad Jets	Veto event if it has a “very loose bad” jet candidate
	Smart LAr Veto	Veto event if signal jet in LAr hole
Channel	One signal lepton	$p_T(e) > 25 \text{ GeV}$, $p_T(\mu) > 20 \text{ GeV}$
	Jets	≥ 4 , $p_T > 20 \text{ GeV}$ and $ \eta < 2.5$
	b -jets	≥ 2 , efficiency WP 60%
	light-jets	≥ 2
	E_T^{miss}	$> 40 \text{ GeV}$
	$m_T(\ell, E_T^{\text{miss}})$	$> 30 \text{ GeV}$
SR	m_t^{had}	$< \hat{\mu} - 0.5 \times \hat{\sigma}$
	$\sqrt{s}_{\min}^{(\text{sub})}$	$< 250 \text{ GeV}$

Table 7.3: Summary of the event selections for the one lepton final states analysis.

A summary of the expected event yield in the electron and muon channel for the main backgrounds at different stages of the selections is summarised in Table 7.4. All the yields, except for the fake lepton contribution, are taken from MC without applying any correction. The yields of three signal points are also added to the table, together with the observed events in data.

7.3 Background Estimation

In this section, the definition of the background enriched regions and the estimates of the main backgrounds are discussed. A semi-data-driven technique was used to estimate the contribution from $t\bar{t}$

1-electron	Top	W	Fake lepton	Others	Total	Data	Stop mass [GeV]		
							130	180	210
4 jets	43208	66985	119631	19180	249003	215632	2721	2333	1324
$E_T^{\text{miss}} > 40$ GeV	28703	37134	16369	4852	87059	78852	1810	1679	1033
2 b -jets	7985	464	268	367	9083	10961	311	391	261
SR	8	5	4	1	18	18	12	9	1

1-muon	Top	W	Fake lepton	Others	Total	Data	Stop mass [GeV]		
							130	180	210
4 jets	41881	71082	36967	11597	161527	169507	3136	2639	1523
$E_T^{\text{miss}} > 40$ GeV	28918	41857	4262	5201	80238	76471	2127	1841	1167
2 b -jets	8122	442	169	372	9105	10913	421	410	331
SR	10	4	3	2	19	32	23	13	1

Table 7.4: Event yields for the 1-lepton selection; the SM backgrounds, data and three signal points are compared. The first selection requires four jets and one lepton in the event. The category “others” contains the contributions from Z, single top and dibosons. The signal points have $m_{\tilde{\chi}_1^0} = 60$ GeV.

and W + jets, see Section 7.3.2, while a completely data-driven method was used for the fake lepton background, see Section 7.3.1.

7.3.1 Fake Background

The fake background was estimated with the matrix method introduced in Section 6.3.2. The events belonging to this category arise from leptonic decays of b - or c -hadrons, where the heavy jet was not reconstructed and an isolated lepton could be selected or where the lepton was emitted off-axis with respect to the jet.

The loose sample was defined by selecting events with a single baseline lepton with $p_T > 25(20)$ GeV for electrons(muons). The efficiency to reconstruct prompt electrons ranges between 0.82 and 0.95, with higher efficiency at high p_T , and the one of prompt muons is of order 0.98. Both the statistical and systematic uncertainties on these efficiency are at the percent level. The efficiency to reconstruct non-prompt leptons is computed in a multi-jet dominated region enriched of heavy-flavour-jets events; the contributions from other SM backgrounds in this region are subtracted using MC. In the electron channel pseudorapidity-dependent efficiencies between 0.16 and 0.45 are found. In the muon channel the η dependence is negligible and the fake efficiencies range between 0.28 and 0.33, with lower fake efficiency at high p_T . The statistical uncertainty on the fake efficiency is at the percent level, while the systematic uncertainty is of order 10%. The contribution from fake lepton processes to the SR is, as expected, subdominant with respect to the other backgrounds. The total final uncertainty on the fake lepton estimate is of 30%.

7.3.2 $t\bar{t}$ and W + jets Backgrounds

The $t\bar{t}$ and the W + jets backgrounds are both estimated by normalising the MC to data in dedicated control regions. The reconstructed top hadronic mass can be used to define these regions. The number W + jets background events is at least one order of magnitude smaller than that of the $t\bar{t}$ events in almost all the parameter space. Observing Figs. 7.5e and 7.5f it can be seen that the best purity of W +jets events

can be achieved in the high tail of the m_t^{had} distribution. Nevertheless, since the selections requires at least four jets, this is only order of 10% of the $t\bar{t}$ events and additional selections have to be applied to try to increase the W + jets purity. In most of the W + jets events the two jets tagged as coming from a b -quark arise from the splitting of a gluon in a $b\bar{b}$ pair. These two b -jets are, hence, close in angle and have a small invariant mass m_{bb} . In $t\bar{t}$ events m_{bb} is generally larger since the b -jets come from the decay of the two top quarks and have a larger angular separation. The m_{bb} distributions are shown in Fig. 7.6 for events with $m_t^{\text{had}} > 250$ GeV in the electron (a) and muon channel (b), and in the signal region, again for the electron (c) and muon channel (d). The clustering of the W + jets events at low m_{bb} values can be appreciated for both selections.

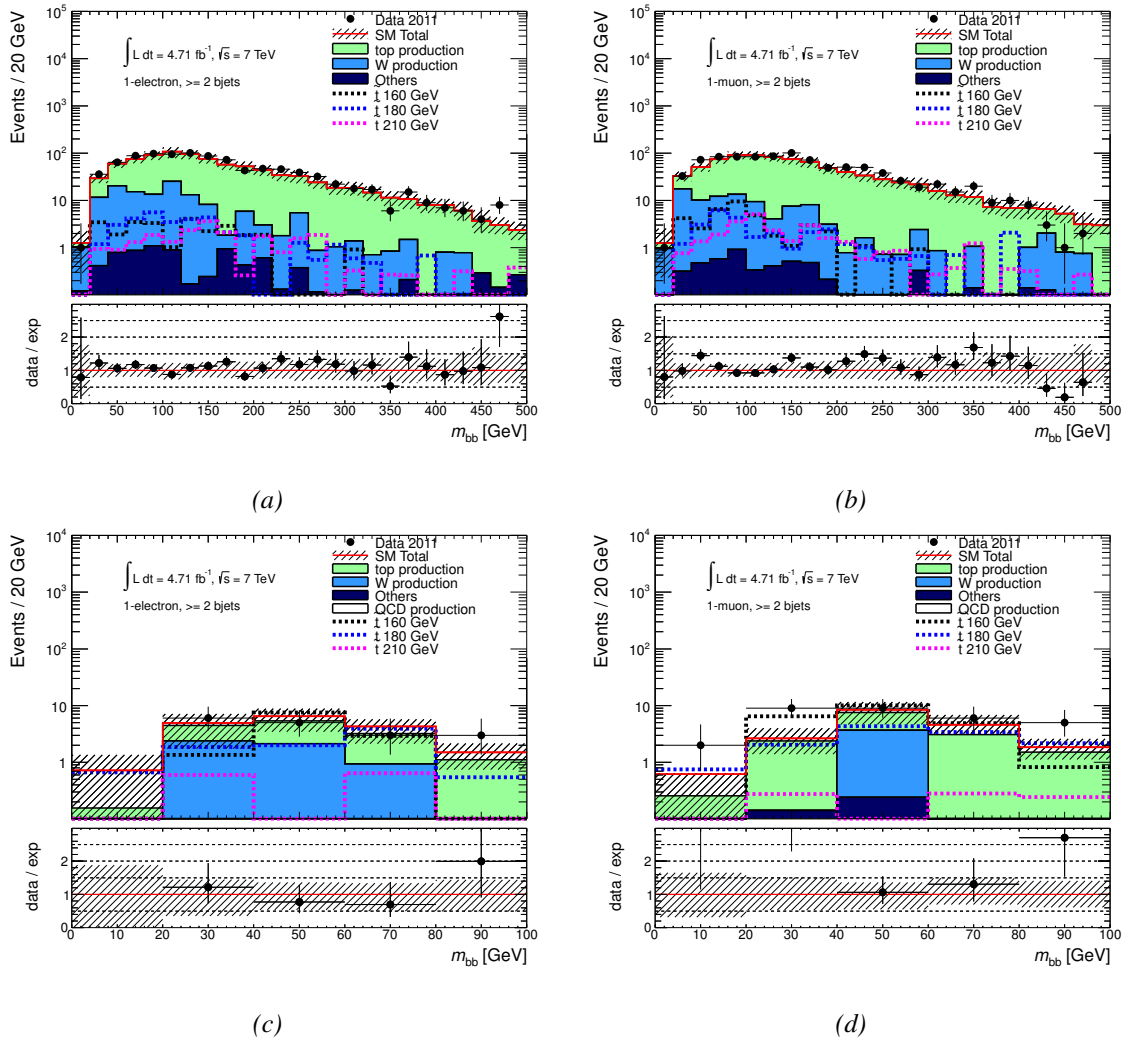


Figure 7.6: Invariant mass of the $b\bar{b}$ system for events with $m_t^{\text{had}} > 250$ GeV for the electron (a) and muon channel (b) and in the signal region for the electron (c) and muon channel (d). The hatched band represents the total uncertainty on the background expectation. The background contributions are stacked, while the signal contributions are superimposed. The signal models chosen have a neutralino with mass $m(\tilde{\chi}_1^0) = 60$ GeV and $m(\tilde{\chi}_1^\pm) = 2 \cdot m(\tilde{\chi}_1^0)$.

A region enriched in W + jets events could then be defined by exploiting the m_{bb} variable. This region, called WCR, has a W + jets purity of 35%, a contribution from $t\bar{t}$ events of 60% and of 5% from other backgrounds. On top of the channel specific selections, events are classified as belonging to WCR if:

- $m_t^{\text{had}} > 250 \text{ GeV}$
- $m_{bb} < 50 \text{ GeV}$

A $t\bar{t}$ dominated region was already defined as $t\bar{t}\text{CR1}$, by selecting the events that fulfil the channel specific requirements and have a top hadronic mass in the range $\hat{\mu} - 0.5 \times \hat{\sigma} < m_t^{\text{had}} < \hat{\mu} + 0.5 \times \hat{\sigma}$. In the $t\bar{t}\text{CR1}$ the $t\bar{t}$ purity is above 90% and the relative statistical uncertainty of the data sample is small given the large number of events populating this region. A second $t\bar{t}$ dominated region, $t\bar{t}\text{CR2}$, is defined by requiring:

- $\hat{\mu} - 0.5 \times \hat{\sigma} < m_t^{\text{had}} < \hat{\mu} + 0.5 \times \hat{\sigma}$
- $\sqrt{s_{\text{min}}}^{(\text{sub})} < 320 \text{ GeV}$

The sample size of this region is smaller with respect to the one of $t\bar{t}\text{CR1}$, but it has the advantage of selecting events with a topology very similar to that of the SR events and gives the possibility of better constraining the $t\bar{t}$ related systematic uncertainties. Nevertheless, the $\sqrt{s_{\text{min}}}^{(\text{sub})}$ selection is looser than the one chosen for the SR in order to keep enough events and have a low signal contamination. The signal and control regions defined so far are summarised in the scheme of Fig. 7.7. The cut values for m_t^{had} that define the $t\bar{t}\text{CR}$ and the SR are the rounded value obtained for the fit of the m_t^{had} distribution for the nominal $t\bar{t}$ MC sample.

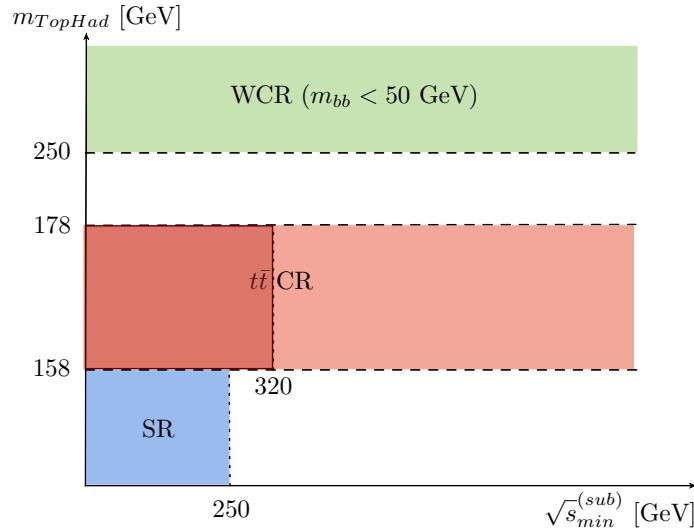


Figure 7.7: Summary scheme of the signal and control regions of the one lepton analysis. The $t\bar{t}$ has a looser CR with no $\sqrt{s_{\text{min}}}^{(\text{sub})}$ cut applied $t\bar{t}\text{CR1}$, and a tighter one with the requirement $\sqrt{s_{\text{min}}}^{(\text{sub})} < 320 \text{ GeV}$, $t\bar{t}\text{CR2}$ in darker red. The cut values for m_{TopHad} are the rounded value obtained for the nominal $t\bar{t}$ MC sample.

The two dimensional distributions of the top hadronic mass versus the $\sqrt{s_{\text{min}}}^{(\text{sub})}$ variable are shown in Fig. 7.8 for the $t\bar{t}$ (a), $Wb\bar{b}$ (c) samples and for a Stop sample with $m(\tilde{t}, \tilde{\chi}_1^\pm, \tilde{\chi}_1^0) = (160, 120, 60) \text{ GeV}$ (d). The m_t^{had} distribution for the $t\bar{t}$ sample for the nominal selection, JES up, and JES down variations is shown in Fig. 7.8b. From the two dimensional distributions it can be observed that the correlation between the $\sqrt{s_{\text{min}}}^{(\text{sub})}$ and m_t^{had} variables is different in the different samples. The signal density is higher at low values of both variables, for the W + jets the variables are highly correlated, while for the $t\bar{t}$ background the correlation is very low. Given the observed shift in the m_t^{had} distribution for the JES

variations, a $t\bar{t}$ enriched region is defined for each systematic variation. This was shown to help in controlling and suppressing the systematic contributions to the $t\bar{t}$ background estimate in the SR.

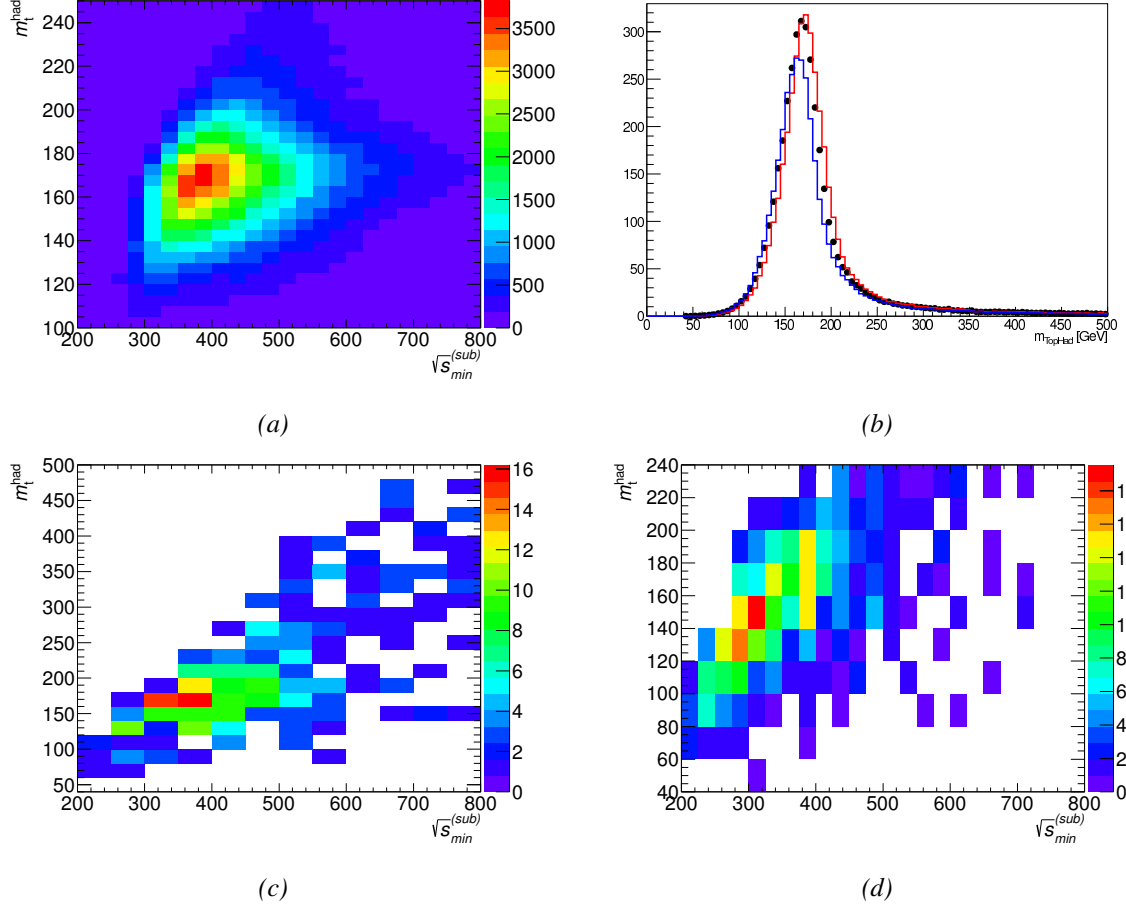


Figure 7.8: Two dimensional distributions of m_t^{had} versus $\sqrt{s}_{\min}^{(\text{sub})}$ for the $t\bar{t}$ (a), Wbb (c) and Stop $m(\tilde{t}, \tilde{\chi}_1^+, \tilde{\chi}_1^0) = (160, 120, 60)$ GeV (d) samples. (b) m_t^{had} distribution for the $t\bar{t}$ sample for the nominal selection, black points, JES up, red histogram, and JES down variations, blue histogram. The selected events satisfied the cleaning, single lepton, E_T^{miss} , and jets requirements. The normalisation is arbitrary.

Simultaneous Normalisation of the Backgrounds

Since the purity of the WCR could not be increased above 35%, the W and $t\bar{t}$ normalisation factors had to be extracted simultaneously by combining the informations that can be extracted from the events selected in the WCR and in the $t\bar{t}$ CR1. The top and W backgrounds normalisation factors w_t and w_W , respectively, can be defined as in Equation 6.5. These equation can be written for both regions and backgrounds and rearranged as

$$\begin{cases} w_t \cdot N_{tt} = D_t - w_W \cdot N_{Wt} - O_t \\ w_W \cdot N_{WW} = D_W - w_t \cdot N_{tW} - O_W \end{cases} \quad (7.6)$$

where $N_{tt}(N_{Wt})$ and $N_{tW}(N_{WW})$ are the number of normalised MC $t\bar{t}(W + \text{jets})$ events in $t\bar{t}$ CR1 and WCR, respectively, D_t and D_W are the number of observed data events in $t\bar{t}$ CR1 and WCR, and O_t and

O_W are the normalised contributions from the minor backgrounds in the two regions, taken directly from MC.

The system can be solved and the extracted normalisation factors are

$$w_t = \frac{D_t \cdot N_{WW} - D_W \cdot N_{Wt} + O_W \cdot N_{Wt} - O_t \cdot N_{WW}}{N_{tt} \cdot N_{WW} - N_{tW} \cdot N_{Wt}}, \quad (7.7)$$

$$w_W = \frac{D_W \cdot N_{tt} - D_t \cdot N_{tW} + O_t \cdot N_{tW} - O_W \cdot N_{tt}}{N_{WW} \cdot N_{tt} - N_{Wt} \cdot N_{tW}}. \quad (7.8)$$

The composition of the $t\bar{t}$ CR1 and of the WCR, together with the number of the data observed events in the regions, is summarised in Table 7.5 separately for the electron and muon channel and for their sum. The uncertainty quoted for the 1-electron and 1-muon results is the sum in quadrature of the statistic and systematic uncertainties on each background, for the 1-lepton results the two component have been kept separate, except for the fake lepton estimate where the error is combined. The values of the normalisation weights are also given in the table. The top normalisation factor is found to be $w_t = 1.25 \pm 0.05$, while for the $W + \text{jets}$ a value of $w_W = 0.7 \pm 0.1$ was extracted.

Process	1-electron		1-muon		1-lepton	
	$t\bar{t}$ CR1	WCR	$t\bar{t}$ CR1	WCR	$t\bar{t}$ CR1	WCR
$t\bar{t}$	2250	33	2300	30	$4550 \pm 14 \pm 790$	$63 \pm 2 \pm 10$
Single top	55	2.8	52	3.8	$107 \pm 4 \pm 15$	$6.6 \pm 1.1 \pm 0.9$
W	52	21	71	26	$123 \pm 11 \pm 21$	$46 \pm 6.2 \pm 9.1$
Z	2.5	1	3.3	0.5	$5.8 \pm 1.1 \pm 3.2$	$1.4 \pm 0.4 \pm 0.3$
Dibosons	1	0.1	1.3	0.3	$2.3 \pm 0.3 \pm 0.4$	$0.4 \pm 0.1 \pm 0.1$
Fake lepton	49	3.5	33	1.1	82 ± 40	4.6 ± 2.2
Total	2410 ± 480	61 ± 10	2460 ± 490	62 ± 10	$4870 \pm 18 \pm 830$	$122 \pm 7 \pm 20$
Data	3014	66	3038	59	6052	125

$$w_W = 0.7 \pm 0.1, w_t = 1.25 \pm 0.05$$

Table 7.5: Data and MC event yields in the $t\bar{t}$ CR1 and WCR control regions. The last two column correspond to the total 1-lepton channel prediction. For the electron and muon predictions, the uncertainty represents the combined statistical and systematic uncertainty, while for the lepton sum, the uncertainties are split into statistical and systematic uncertainties respectively. For the fake lepton background the combined statistic and systematic uncertainty is given.

Finally, an additional normalisation factor ω for the $t\bar{t}$ background is extracted in the $t\bar{t}$ CR2 region, after having normalised the $t\bar{t}$ and $W + \text{jets}$ MC yields with the extracted w_t and w_W , so that ω in the $t\bar{t}$ CR2 is defined as

$$\omega = \frac{D - w_W N_W - O}{w_t N_t}. \quad (7.9)$$

The composition of the $t\bar{t}$ CR2 is summarised in Table 7.6 for the electron and muon channels and their combination. The $t\bar{t}$ and $W + \text{jets}$ contributions have been normalised with the w_t and w_W factors, and ω is found to be $\omega = 0.95 \pm 0.07$, where the uncertainty is only due to the data counts in the $t\bar{t}$ CR2 giving a complete compatibility between the results of the two $t\bar{t}$ control regions. The $t\bar{t}$ background in the SR is then estimated to be the MC yield multiplied by $w_t \cdot \omega$.

The signal contamination in the three control regions has been checked giving contributions of less

Process	1-electron	1-muon	1-lepton
$t\bar{t}$	71	87	$158 \pm 3 \pm 52$
Single top	2.9	3.2	$6.1 \pm 0.8 \pm 2.4$
W	3.9	4.3	$8.2 \pm 2.3 \pm 1.4$
Z	< 0.1	0.1	$0.2 \pm 0.1 \pm 0.1$
Dibosons	0.05	0.1	$0.15 \pm 0.1 \pm 0.1$
Fake lepton	1.6	1.9	3.5 ± 2.2
Total	79.5 ± 9	97 ± 10	$176 \pm 4 \pm 56$
Data	75	94	169

$$\omega = 0.95 \pm 0.07$$

Table 7.6: Data and MC event yields in the $t\bar{t}$ CR2 control region. The last column corresponds to the total 1-lepton channel prediction. The W and $t\bar{t}$ predictions correspond to the MC prediction multiplied by the w_W and w_t factors. For the electron and muon predictions, the uncertainty represents the combined statistical and systematic uncertainty, while for the lepton sum, the uncertainties are split into statistical and systematic uncertainties respectively. For the fake lepton background the combined statistic and systematic uncertainty is given.

than 3% in the $t\bar{t}$ CR1, of up to 13% in the $t\bar{t}$ CR2, and of less than 6% for all signal models in the WCR. The relative signal contamination for the points of the gaugino universality grid is shown in Fig. 7.9 for the $t\bar{t}$ CR1 (a), $t\bar{t}$ CR2 (b), and WCR (c).

The distributions for the main variables in the 1-lepton WCR selection are shown in Fig. 7.10. In these distributions the w_t and w_W normalisation factors have been applied to the $t\bar{t}$ and W + jets backgrounds. The variables shown are the E_T^{miss} (a), the number of selected jets (b), the leading electron (c) and muon (d) p_T , the reconstructed top hadronic mass (e), and the $\sqrt{s}_{\text{min}}^{(\text{sub})}$ variable (f). In all the distributions a good data-MC agreement is observed together with no significant slope in any of the data-MC ratios.

The distributions for the 1-lepton $t\bar{t}$ CR1 selection are shown in Fig. 7.11. Here the variables shown are the E_T^{miss} (a), the number of selected jets (b), the leading electron (c) and muon (d) p_T , the invariant mass of the two selected b -jets (e), and the $\sqrt{s}_{\text{min}}^{(\text{sub})}$ variable (f). Also in these figures the w_t and w_W normalisation factors have been applied. In all the distributions an excellent data-MC agreement is observed, only the distributions of the number of selected jets shows that the baseline $t\bar{t}$ MC underestimates the contributions of events with an high jet multiplicity.

Finally a selection of distributions for the 1-lepton $t\bar{t}$ CR2 selection is shown in Fig. 7.12. Here the electron and the muon channels are shown separately, the w_t and w_W normalisation factors have been applied but not the ω one. The variables shown are the E_T^{miss} for the electron (a) and the muon channel (b), the electron (c) and the muon (d) p_T , and the leading jet p_T in the electron (e) and muon (f) channel. The data-MC agreement is observed to be good also in this less populated top control region.

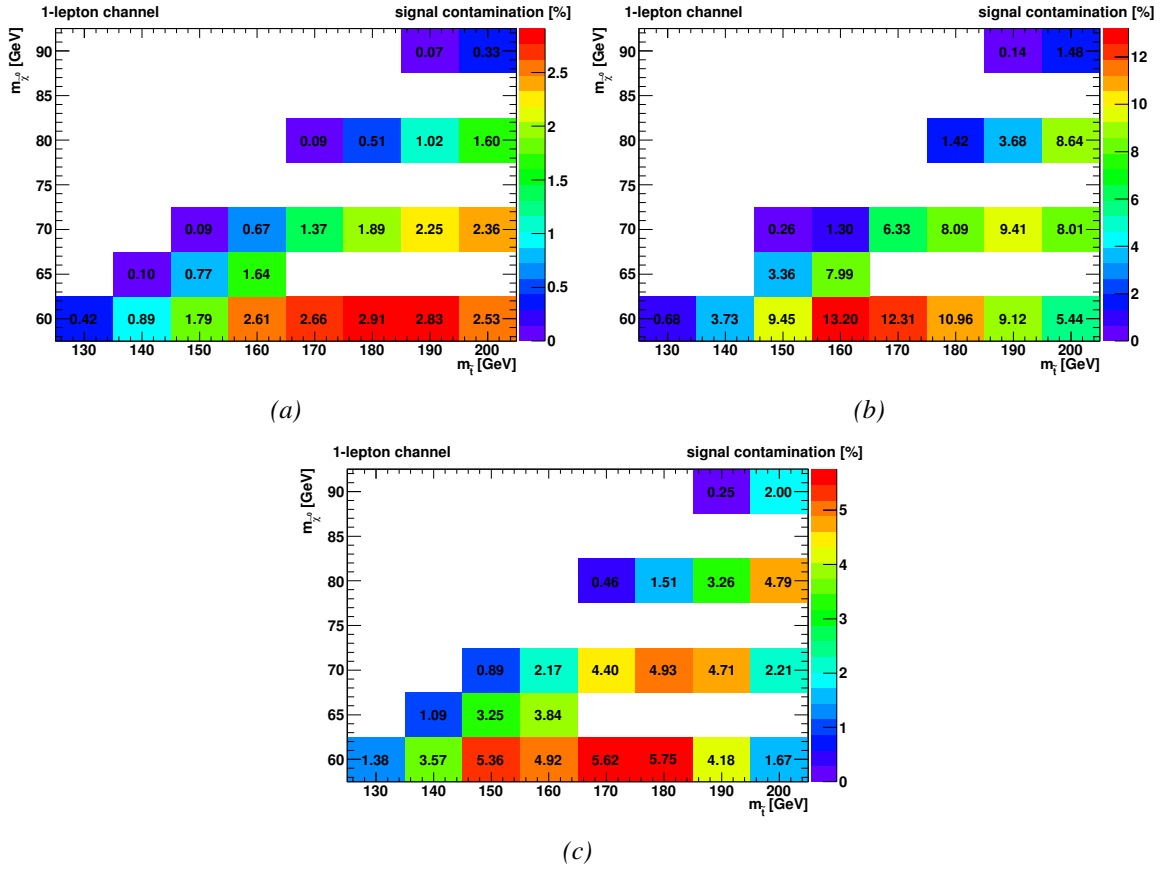


Figure 7.9: Signal contamination in the $t\bar{t}\text{CR1}$ (a), $t\bar{t}\text{CR2}$ (b) and WCR (c) regions. The chosen signal grid is the gaugino universality grid where the relation $m(\tilde{\chi}_1^\pm) = 2 \cdot m(\tilde{\chi}_1^0)$ is assumed.

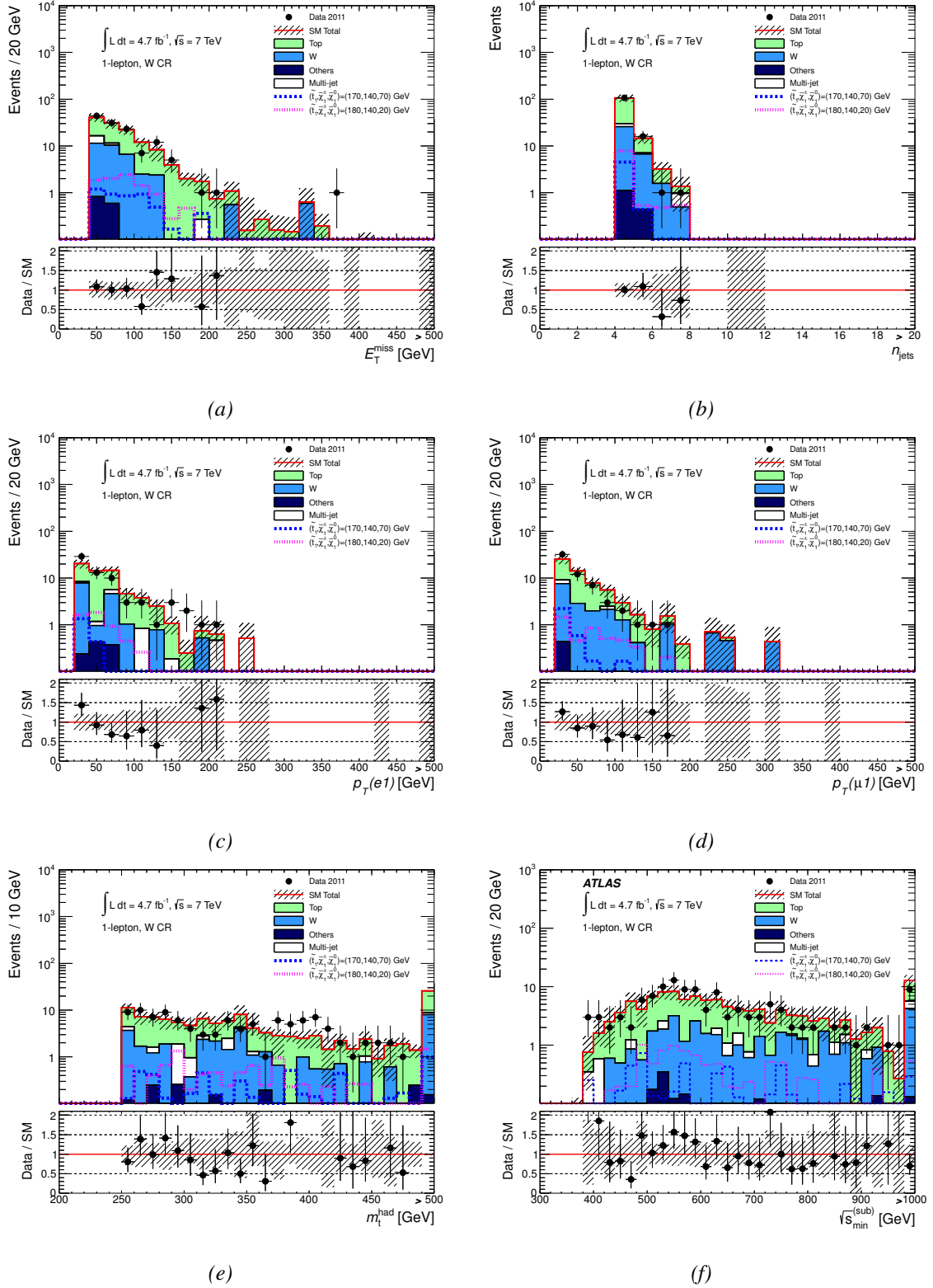


Figure 7.10: Distributions in the WCR: (a) E_T^{miss} , (b) n_{jets} , (c) leading electron p_T , (d) leading muon p_T , (e) m_t^{had} and (f) $\sqrt{s}_{\text{min}}^{(\text{sub})}$ [163]. The electron and the muon channel distributions have been summed to give the 1-lepton distributions. The scale factors w_t and w_W are applied in these distributions. The hatched band represents the total uncertainty on the background expectation. The background contributions are stacked, while the signal contributions are superimposed. The signal models chosen have a neutralino with mass $m(\tilde{\chi}_1^0) = 60$ GeV and $m(\tilde{\chi}_1^\pm) = 2 \cdot m(\tilde{\chi}_1^0)$.

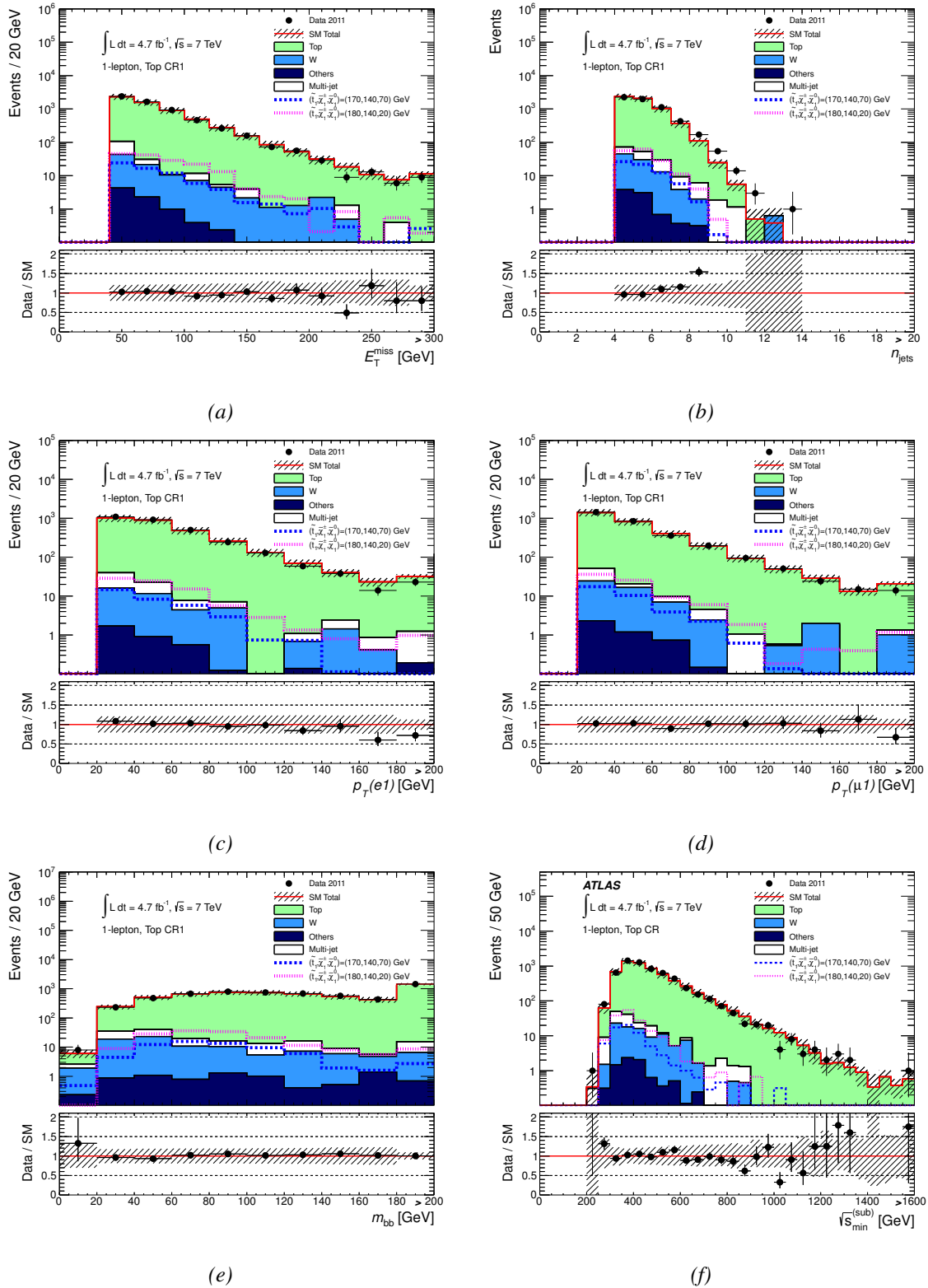


Figure 7.11: Distributions in the $t\bar{t}$ CR1: (a) E_T^{miss} , (b) n_{jets} , (c) leading electron p_T , (d) leading muon p_T , (e) m_t^{had} and (f) $\sqrt{s_{\text{min}}^{\text{(sub)}}}$ [163]. The electron and the muon channel distributions have been summed to give the 1-lepton distributions. The scale factors w_t and w_W are applied in these distributions. The hatched band represents the total uncertainty on the background expectation. The background contributions are stacked, while the signal contributions are superimposed. The signal models chosen have a neutralino with mass $m(\tilde{\chi}_1^0) = 60$ GeV and $m(\tilde{\chi}_1^\pm) = 2 \cdot m(\tilde{\chi}_1^0)$.

7 Searches for the top squark at $\sqrt{s} = 7$ TeV

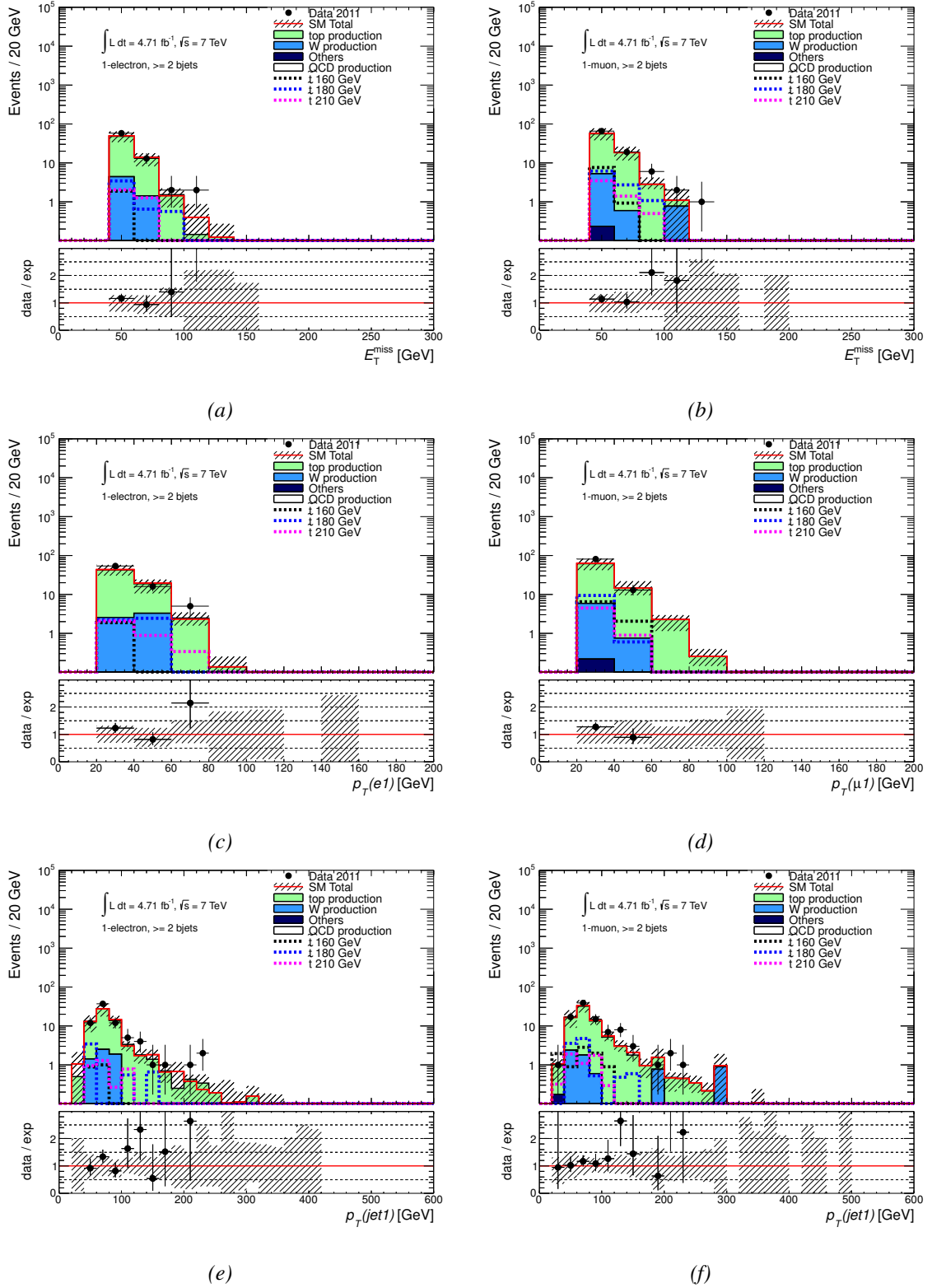


Figure 7.12: Distribution of the E_T^{miss} for the electron (a) and the muon channel (b), the electron (c) and the muon (d) p_T , and the leading jet p_T in the electron (e) and muon (f) channel in the $t\bar{t}\text{CR2}$. The scale factor ω is not applied in these distributions. The hatched band represents the total uncertainty on the background expectation. The background contributions are stacked, while the signal contributions are superimposed. The signal models chosen have a neutralino with mass $m(\tilde{\chi}_1^0) = 60$ GeV and $m(\tilde{\chi}_1^\pm) = 2 \cdot m(\tilde{\chi}_1^0)$.

7.4 Systematic Uncertainties

In the next paragraphs the systematic uncertainties considered in the analysis and their impact on the background estimate are discussed. The detector related uncertainties are discussed first, followed by the theory uncertainties on the background and signal processes.

The statistical and systematic uncertainties are summarised in Table 7.7 for each background and for its total sum in the SR, where the contribution from the uncertainty on the fake estimation method is not added. The statistical uncertainty in the control regions has an impact of 11% on the SR yield, while the uncertainty due to the limited MC statistic contributes to less than 5% of the total uncertainty.

Process	CR stat	MC stat	Detector Unc.							Theory Unc.	
			JES	JER	b -tag	lep ID	E_T^{miss}	SoftTerm	PU	$t\bar{t}$	W
$t\bar{t}$	11%	5%	$+2\%$ -15%	10%	0.4%	1%	9%	3%	3%	12.5%	1.5%
single top	-	25%	40%	24%	25%	2%	12%	3%	3%	26%	-
W	13%	20%	$+13\%$ -18%	7%	0.5%	1%	25%	3%	3%	8%	15%
Z	-	60%	40%	24%	25%	2%	12%	3%	3%	-	-
dibosons	-	35%	30%	40%	30%	3%	30%	3%	3%	-	-
fake lepton	30%										
total	11%	4.6%	$+5\%$ -15%	10%	0.4%	1.5%	9%	3%	3%	7.2%	4.5%

Table 7.7: Relative detector and theory systematic and statistical uncertainties associated to the background processes contributing to the signal region. For the “total” the relative uncertainty on the total standard model background has been calculated by rerunning the full analysis with each specific final state object reconstruction uncertainty. The uncertainty associated to the fake lepton estimate is not included in the “total”.

7.4.1 Detector-Related Uncertainties

The detector-related uncertainties considered and their impact on the final results are summarised below. The description of their meaning and of how they are extracted can be found in Chapter 4 and in Section 6.4.1.

- Luminosity 3.9% uncertainty on the total integrated luminosity used to normalise the MC samples.
- Pile-up uncertainty contributes to 3% of the total uncertainty.
- JES it is one of the main contributions on the total uncertainty ($+5\%$
 -15%). It is particularly large for the backgrounds estimated only with simulated samples (up to 40%).
- JER it has an impact of 10% on the SR yield. As for the JES, it is particularly large for the backgrounds estimated directly from MC.
- b -tag has a negligible impact on the total uncertainty, contributing for less than 1%.
- Lepton Identification is also a negligible uncertainty, having a final impact of 1.5%.
- E_T^{miss} SoftTerm it is, together with JES and JER, one of the larger contributions (9%) to the final total uncertainty.

7.4.2 Theory Uncertainties

The considered theory uncertainties are listed below for the main background processes. The signal theoretical uncertainties are also discussed.

$t\bar{t}$ production

- ISR/FSR: the impact of an augmented or diminished initial or final state radiation activity is evaluated by comparing the yields obtained with dedicated ACER MC samples.
- MC generator: the baseline MC@NLO sample is compared with a sample simulated with PowHeg interfaced to HERWIG for the parton shower. The difference in yield between the two samples is taken as MC generator uncertainty.
- Parton shower: two PowHeg samples are compared, which are interfaced to HERWIG or to PYTHIA for the parton shower. The difference in yield between the two is taken as parton shower uncertainty.

The uncertainty on the $t\bar{t}$ cross section, $\sigma_{t\bar{t}} = (166.8^{+11.45}_{-15.78})$ pb, is not added as a contribution to the total $t\bar{t}$ theoretical uncertainty since the final normalisation of the $t\bar{t}$ sample is extracted by comparing the MC to the data in a CR.

Single top production

The cross sections used to normalise the single top samples are

- $\sigma(t - \text{channel}) = (64.57^{+3.32}_{-2.32})$ pb
- $\sigma(s - \text{channel}) = (4.63^{+0.29}_{-0.27})$ pb
- $\sigma(Wt) = (15.34^{+1.34}_{-1.36})$ pb

The dominant contribution to this analysis comes from the Wt production and a systematic uncertainty of 8% is, hence, assigned as single top production cross section uncertainty.

Since the single top contributions to all regions considered is of the order of 10% of the $t\bar{t}$ background, the same theoretical uncertainty found for the top production is assigned to the single top contribution.

$W + \text{jets}$ production

- Factorisation and renormalisation scale: having the ALPGEN samples as baseline, this uncertainty can be calculated by changing the relative cross section for the emission of additional partons, which corresponds to the variation of the scale of α_s in the matching process [169].
- MC generator: a comparison with a NLO PowHeg sample was performed. Since the final yields were compatible within statistical uncertainty, no additional contribution from this has been added.

The total cross section used to normalise the ALPGEN MC yields and its related uncertainty is $\sigma(W) = (31.4 \pm 1.2)$ pb.

Signal production

As introduced in Paragraph 7.1.2 the cross section used to normalise the signal contribution are calculated at NLO+NLL.

The uncertainty on the production cross section is extracted by defining a 68% C.L. envelope of cross section predictions with two different PDF sets, MSTW2008 and CTEQ6. Moreover the factorisation and the renormalisation scales are varied following the usual prescriptions. The nominal cross section is taken as the central point of the envelope and its uncertainty is half the width of the envelope [170].

The values of the cross sections for the considered stop mass range can be read from Fig. 7.13. The NLO+NLL nominal values for the two PDF sets considered and the size of the uncertainties associated to them are shown in the figure. The nominal cross section value and its total uncertainty is given by the green lines.

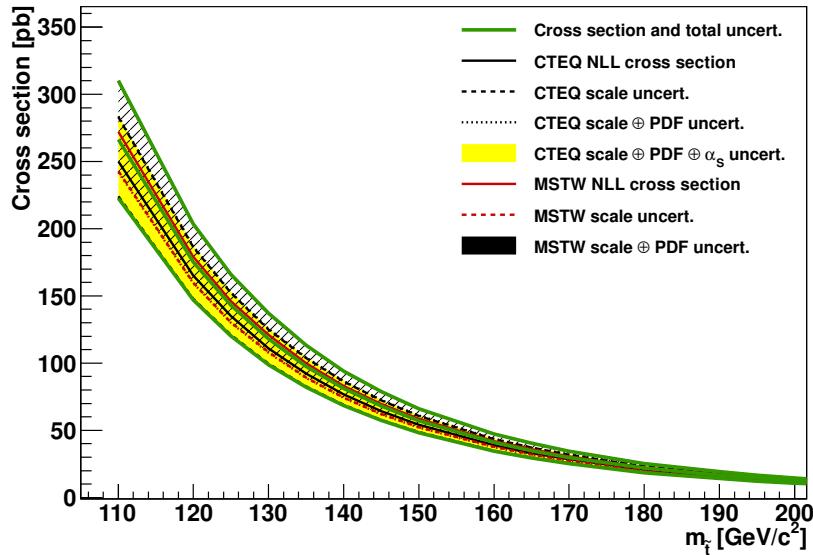


Figure 7.13: NLO+NLL stop production cross sections as a function of the stop mass. The black lines correspond to the cross section values predicted using the CTEQ PDF set, which summed in quadrature give the yellow band. The red lines correspond to the MSTW predictions, which summed in quadrature give the dashed black region. The green solid lines correspond to the final cross section used with the corresponding uncertainty [170].

7.5 Results

The final results of the search are presented in this section. First the yields and distributions in the one lepton signal region are discussed, then the signal regions, the strategy and the results of the two leptons final states analysis are presented. Finally the combined final results and their statistical interpretation as model independent limits on the stop production cross section and model dependent limits on the selected signal models are discussed.

7.5.1 One-Lepton Results

The final background yields in the signal region, together with the observed number of events in data are reported in Table 7.8. The results in the one electron and one muon channel are given together with the those for their combination as one lepton results, presented with their statistical and systematic uncertainties. The uncertainties associated to the sum of the SM backgrounds have been computed by summing in quadrature the uncertainty contributions listed in Table 7.7 and the fake lepton uncertainty. The $t\bar{t}$ and the W + jets background yields are obtained by normalising the MC yields with the normalisation factors w_t , ω , and w_W extracted in the $t\bar{t}$ CR1, $t\bar{t}$ CR2, and WCR regions, respectively. In brackets the pure MC yields are given for a comparison.

The number of expected and observed events in the electron channel is perfectly compatible, while a small, non-significant, excess is observed in the muon channel, which is though not statistically significant. The combined one lepton results show, hence, a small excess of observed over expected events corresponding to a p -value for the background only hypothesis of $p = 0.1135$.

Process	SR yields		
	1-electron	1-muon	1-lepton
$t\bar{t}$	9.5 (8.0)	12.2 (9.9)	$21.7 \pm 2.6 \pm 5.2$ (17.9)
Single top	1.1	1.3	$2.4 \pm 0.1 \pm 0.3$
W	4.2 (5.3)	2.4 (4.1)	$6.6 \pm 1.5 \pm 2.2$ (9.4)
Z	< 0.2	0.3	$0.5 \pm 0.3 \pm 0.3$
Sibosons	0.1	0.2	$0.3 \pm 0.1 \pm 0.1$
Sake lepton	3.5	3.4	6.9 ± 2.0
Total	18.5 (18.2)	19.7 (19.2)	$38.4 \pm 3.3 \pm 7.3$ (37.4)
Data	18	32	50

Table 7.8: Expected and observed event yield in the one lepton signal region. The 1-lepton yields are given with the statistical and systematic uncertainties, except for the fake lepton background where the total uncertainty is reported. For the $t\bar{t}$ and W + jets backgrounds, estimated by normalising the background in dedicated control regions, the pure MC prediction is also reported in brackets.

The distribution of the reconstructed hadronic top mass, m_t^{had} , with all the one lepton channel selections applied, but those of the signal region, is shown in Fig. 7.14a, and in Fig. 7.14b the $\sqrt{s}_{\text{min}}^{(\text{sub})}$ distribution is shown for the events that satisfied all the selections except for the cut on $\sqrt{s}_{\text{min}}^{(\text{sub})}$ itself. The $t\bar{t}$ and W + jets normalisation factors have been applied and it can be observed that the data-MC agreement is remarkable over the full range of the distributions, and that the small observed excess in the signal region comes from events with $225 < \sqrt{s}_{\text{min}}^{(\text{sub})} < 250$ GeV.

The distributions of few important kinematic variables with all SR selections applied are shown in Fig. 7.15. The variables chosen are the E_T^{miss} in the electron (a) and muon (b) channel, the electron (c) and the muon (d) p_T , and the leading jet p_T in the electron (e) and muon (f) channel. In these figures the $t\bar{t}$ and W + jets normalisation factors have been applied. The small excess in the muon channel is equally distributed in all bins of the chosen distributions, while the electron channel distributions show a good data-MC agreement.

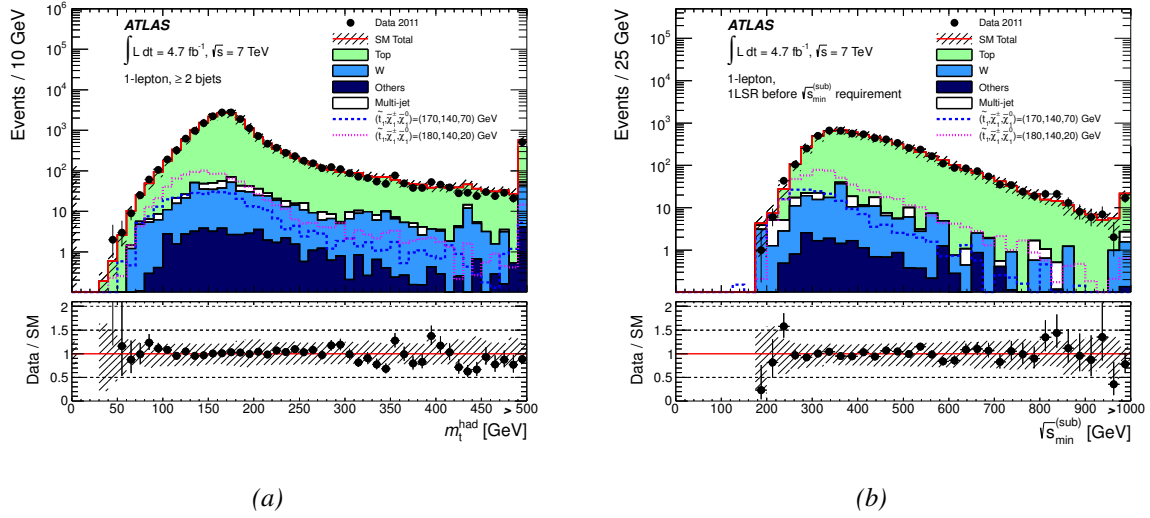


Figure 7.14: Distribution of the reconstructed hadronic top mass with all the one lepton channel selections applied (a) and $\sqrt{s_{\min}^{(\text{sub})}}$ distribution for events that satisfied all the selections except for the cut on $\sqrt{s_{\min}^{(\text{sub})}}$ itself (b). The hatched band represents the total uncertainty on the background expectation. The background contributions are stacked, while the signal contributions are superimposed [163].

7.5.2 Two-Lepton Analysis

The search for direct stop production and decay as $\tilde{t} \rightarrow b\tilde{\chi}_1^\pm \rightarrow bW^{(*)}\tilde{\chi}_1^0$ in two-lepton final states has a similar structure as the search in one lepton final states. The baseline and cleaning selections are the same as in the one lepton analysis, see Table 7.3, then two signal leptons with opposite electric charge (OS) are required with transverse momentum of

- $e^\pm e^\mp$: $p_T > 25, 20$ GeV,
- $\mu^\pm \mu^\mp$: $p_T > 20, 10$ GeV,
- $e^\pm \mu^\mp$: if electron is leading $p_T(e) > 25, p_T(\mu) > 10$ GeV, otherwise $p_T(e) > 20, p_T(\mu) > 20$ GeV.

At least two jets with $p_T > 20$ GeV and $|\eta| < 2.5$ have to be selected and at least one of the two leading jets must be tagged as b -jet. A minimum E_T^{miss} of 40 GeV and a minimum invariant mass of the two lepton of 30 GeV are also required.

The variables that better discriminate between signal and background, in this case $t\bar{t}$ and Z + jets production, are the invariant mass of the two selected leptons, $m_{\ell\ell}$, and the $\sqrt{s_{\min}^{(\text{sub})}}$ variable.

The $t\bar{t}$ and the Z + jets backgrounds are estimated with a semi-data-driven method analogous to that used in the one lepton analysis, while the fake leptons background (multi-jet and W + jets events) is estimated with a data-driven matrix method. The Z control region, ZCR, where the Z + jets background is normalised to data, is defined by the requirements of $81 < m_{\ell\ell} < 101$ GeV and $\sqrt{s_{\min}^{(\text{sub})}} < 225$ GeV, while the $t\bar{t}$ control region ($t\bar{t}$ CR2L) events are required to have $m_{\ell\ell} > 101$ GeV and $\sqrt{s_{\min}^{(\text{sub})}} < 325$ GeV. Two signal regions are defined for $30 < m_{\ell\ell} < 81$ GeV. In the first one, SR1, events are selected that satisfy $\sqrt{s_{\min}^{(\text{sub})}} < 225$ GeV, in the second one, SR2, the signal selections are $\sqrt{s_{\min}^{(\text{sub})}} < 235$ GeV and $m_{j\ell\ell} < 140$ GeV, where $m_{j\ell\ell}$ is the invariant mass of the two selected leptons and of the two leading jets.

The two lepton channel baseline selections together with those of the ZCR, $t\bar{t}$ CR2L, SR1 and SR2 are summarised in Table 7.9.

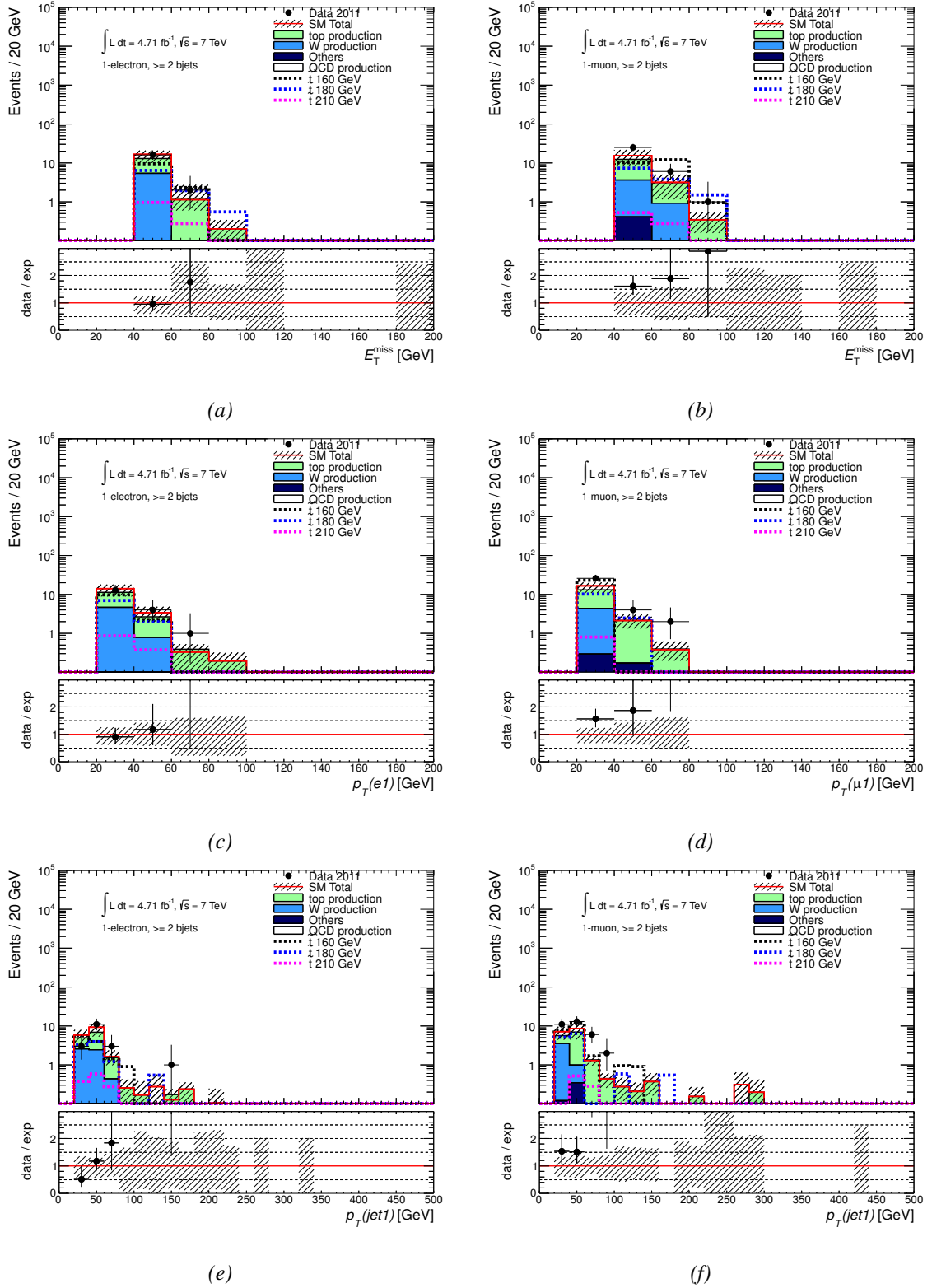


Figure 7.15: One lepton SR distributions: E_T^{miss} in the electron (a) and muon (b) channel, electron (c) and muon (d) p_T , and leading jet p_T in the electron (e) and muon (f) channel. In these figures the $t\bar{t}$ and W + jets normalisation factors have been applied. The hatched band represents the total uncertainty on the background expectation. The background contributions are stacked, while the signal contributions are superimposed. The signal models chosen have a neutralino with mass $m(\tilde{\chi}_1^0) = 60$ GeV and $m(\tilde{\chi}_1^+) = 2 \cdot m(\tilde{\chi}_1^0)$.

	Selection	Cut Value / Comment
Channel	Two OS signal leptons Jets b -jets E_T^{miss} $m_{\ell\ell}$	leading lepton: $p_T(e) > 25$ GeV, $p_T(\mu) > 20$ GeV ≥ 2 , $p_T > 20$ GeV and $ \eta < 2.5$ ≥ 1 among the two leading, efficiency WP 60% > 40 GeV > 30 GeV
ZCR	$m_{\ell\ell}$ leptons $\sqrt{s}_{\text{min}}^{(\text{sub})}$	$81 < m_{\ell\ell} < 101$ GeV only same flavour < 225 GeV
$t\bar{t}$ CR2L	$m_{\ell\ell}$ $\sqrt{s}_{\text{min}}^{(\text{sub})}$	> 101 GeV < 325 GeV
SR1	$m_{\ell\ell}$ $\sqrt{s}_{\text{min}}^{(\text{sub})}$	$30 < m_{\ell\ell} < 81$ GeV < 225 GeV
SR2	$m_{\ell\ell}$ $\sqrt{s}_{\text{min}}^{(\text{sub})}$ $m_{jj\ell\ell}$	$30 < m_{\ell\ell} < 81$ GeV < 235 GeV < 140 GeV

Table 7.9: Summary of the event selections for the two leptons final states analysis.

The $t\bar{t}$ and Z + jets normalisation factors extracted from the control regions are $f_t = 1.15 \pm 0.21$ and $f_Z = 0.76 \pm 0.48$, respectively, and the signal contamination is below 10% in the $t\bar{t}$ CR2L, and below 25% in the ZCR. The total relative uncertainty in the signal regions is lower than in the one lepton channel. The main systematic contributions come from the JES and JER (5-10%) and from the top theory uncertainties (order of 10%). The total statistical uncertainty has a 7% weight in SR1 and 10% in SR2.

The distributions of the three discriminating variables of the two leptons analysis are shown in Fig. 7.16. The $m_{\ell\ell}$ distribution (a) is obtained by applying all two leptons channel requirements but not those specific to the SRs. The $\sqrt{s}_{\text{min}}^{(\text{sub})}$ (b) and the $m_{jj\ell\ell}$ (c) distributions are shown for all the events that satisfy the $m_{\ell\ell}$ SR requirement, $30 < m_{\ell\ell} < 81$ GeV. The normalisation factors for the Z and $t\bar{t}$ backgrounds extracted from the ZCR and $t\bar{t}$ CR2L regions have been applied to produce these figures. All the distributions show a good data-MC agreement and no data excess is observed in any bin.

7.5.3 Combined Results and Interpretation

The expected and observed event yields in the one lepton signal region, 1LSR, and in the two lepton signal regions, 2LSR1 and 2LSR2, are summarised in Table 7.10, together with the expected yields for two signal points, $m(\tilde{t}, \tilde{\chi}_1^\pm, \tilde{\chi}_1^0) = (170, 140, 70)$ GeV and $m(\tilde{t}, \tilde{\chi}_1^\pm, \tilde{\chi}_1^0) = (180, 140, 20)$ GeV. No significant excess above the expected SM background was observed in any signal region and model independent limits on the visible cross section could be set.

The visible cross section is defined as

$$\sigma_{\text{vis}} = \sigma \times A \times \epsilon, \quad (7.10)$$

where σ is the total cross section for a non-SM signal process, A is the acceptance of the selections calculated at particle level, and ϵ represents the detector reconstruction, identification and trigger effi-

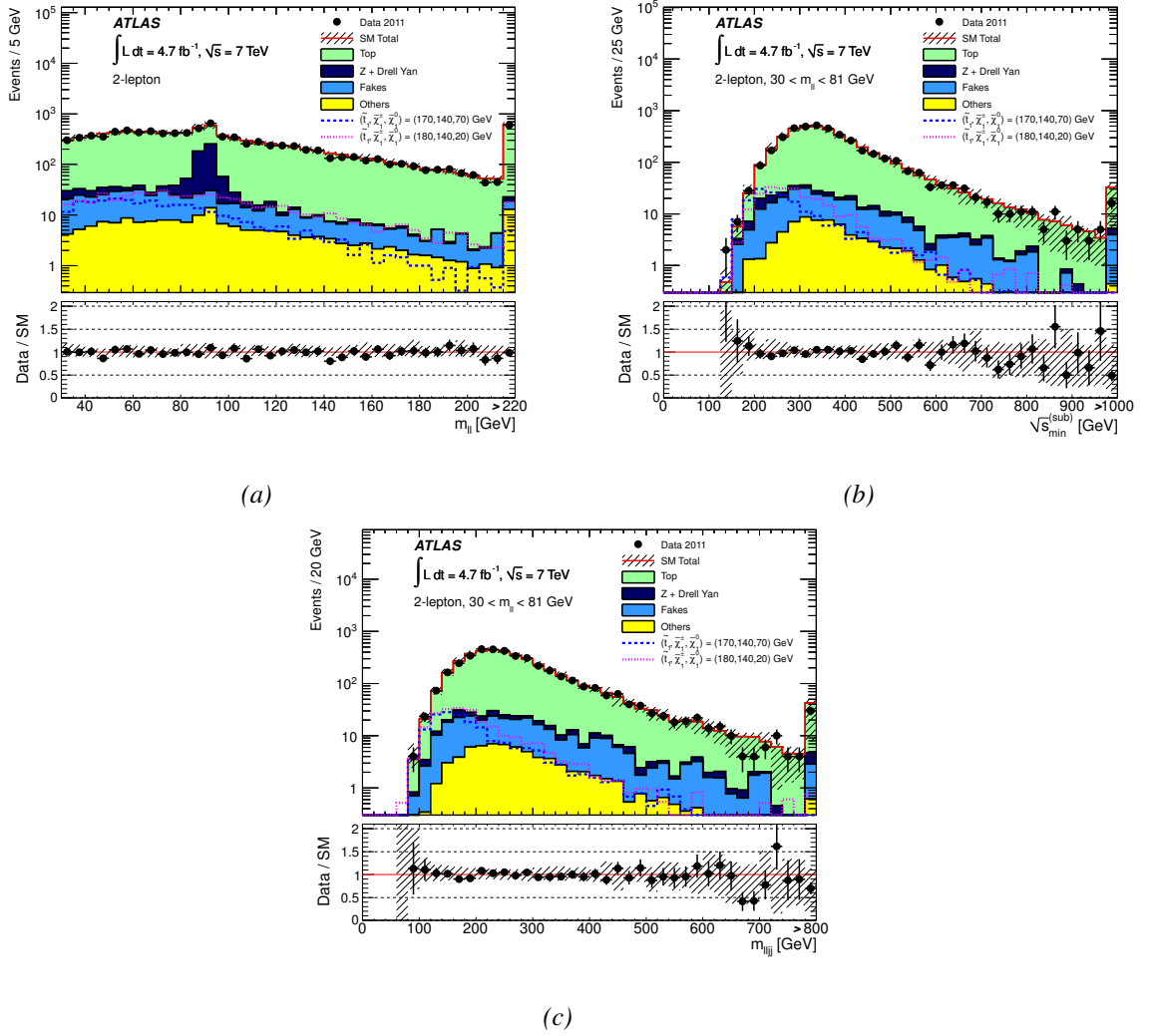


Figure 7.16: $m_{\ell\ell}$ distribution (a) for the two leptons channel selection. $\sqrt{s}_{\min}^{(\text{sub})}$ (b) and $m_{jj\ell\ell}$ (c) distributions for all the events that satisfy the $m_{\ell\ell}$ SR requirement, $30 < m_{\ell\ell} < 81$ GeV. The normalisation factors for the Z and $t\bar{t}$ backgrounds have been applied. The hatched band represents the total uncertainty on the background expectation. The background contributions are stacked, while the signal contributions are superimposed [163].

ciency.

Since in all SRs the number of observed data events is higher than the expected event yield, the 95% CL limit on the observed σ_{vis} is always larger than that on the expected σ_{vis} .

The obtained results have been then used to set model dependent 95% CL limits in the chosen production and decay signal scenarios introduced in Paragraph 7.1.2. For each point of the signal grid, the combination of signal regions that gives the best p -value to exclude the given signal point has been chosen. The possible combinations of regions are either 1LSR+2LSR1 or 1LSR+2LSR2. Since the selections for the two channels are orthogonal, the combination of the signal regions can be achieved by multiplying the likelihood function of the one and of the two lepton channels.

The 95% CL exclusion limit curves for the studied signal mass range and scenarios are shown in Fig. 7.17. The dashed blue line represents the central expected limit with the yellow area being the associated one sigma uncertainty variation band; the observed limit curve is drawn with a full red line,

Process	1LSR	2LSR1	2LSR2
Top	$24 \pm 3 \pm 5$	$89 \pm 6 \pm 10$	$36 \pm 2 \pm 5$
W +jets	$6 \pm 1 \pm 2$	—	—
Z +jets	$0.5 \pm 0.3 \pm 0.3$	$11 \pm 4 \pm 3$	$3 \pm 1 \pm 1$
Fake leptons	$7 \pm 1 \pm 2$	$12 \pm 5 \pm 11$	$6 \pm 4 \pm 4$
Others	$0.3 \pm 0.1 \pm 0.1$	$2.7 \pm 0.9 \pm 0.7$	$0.9 \pm 0.2 \pm 0.5$
Total SM	$38 \pm 3 \pm 7$	$115 \pm 8 \pm 15$	$46 \pm 4 \pm 7$
Data	50	123	47
$m_{\tilde{t}_1} = 170 \text{ GeV}, m_{\tilde{\chi}_1^0} = 70 \text{ GeV}$	$26 \pm 2 \pm 6$	$57 \pm 3 \pm 6$	$36 \pm 2 \pm 4$
$m_{\tilde{t}_1} = 180 \text{ GeV}, m_{\tilde{\chi}_1^0} = 20 \text{ GeV}$	$20 \pm 2 \pm 4$	$41 \pm 3 \pm 5$	$27 \pm 2 \pm 3$
95% CL upper limits			
σ_{vis} (expected) [fb]	4.2	9.3	4.6
σ_{vis} (observed) [fb]	6.1	11	5.2

Table 7.10: Expected and observed event yields in the one and two lepton signal regions, quoted together with their statistical and systematic uncertainties. The Top yield is the sum of the $t\bar{t}$ and single top contributions, while the W +jets contributions in the two leptons signal regions are included in the fake leptons contribution. The expected event yield for two signal scenarios with a $m(\tilde{\chi}_1^\pm) = 140 \text{ GeV}$ is also given, together with the observed and expected upper limits at 95% confidence level on the visible cross section [163].

with the $\pm 1\sigma$ uncertainty band on the signal cross section shown as red dotted line. The limits set on the gaugino-universality signal grid (a), allow to exclude stop masses between 120 and 167 GeV for a neutralino mass of 55 GeV. For a fixed stop mass of $m(\tilde{t}) = 180 \text{ GeV}$, the limits have been set in the $(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0)$ mass plane (b) giving an excluded area around the signal point with $m(\tilde{\chi}_1^\pm) = 140 \text{ GeV}$ and $m(\tilde{\chi}_1^0) = 70 \text{ GeV}$; the area excluded by the LEP SUSY analyses is also drawn in grey [151]. Finally, the excluded area for the signal grid with fixed chargino mass $m(\tilde{\chi}_1^\pm) = 106 \text{ GeV}$ can be seen in Fig. 7.17c. Here, for a neutralino mass $m(\tilde{\chi}_1^0) = 55 \text{ GeV}$ stop masses between 123 and 167 GeV could be excluded, and for $m(\tilde{\chi}_1^0) = 70 \text{ GeV}$ the excluded stop masses are in the range $125 < m(\tilde{t}) < 155 \text{ GeV}$. In this figure the area excluded by the Tevatron measurement is shown in green [148] and the blue line shows the area excluded by the ATLAS search published in Ref. [171].

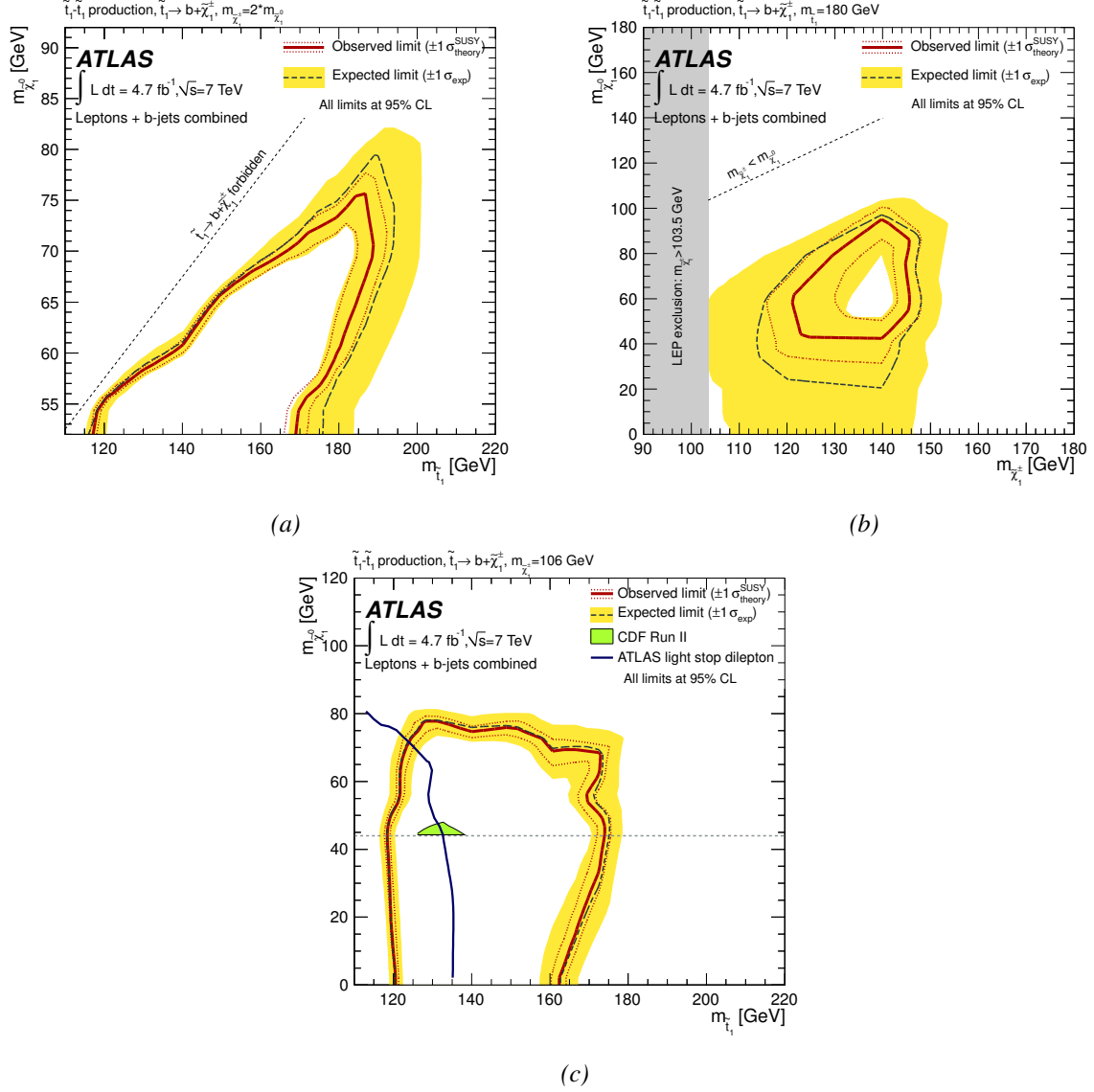


Figure 7.17: 95% CL exclusion limits in the chosen signal scenarios for the combination of the analyses in one and two lepton final states. (a) 95% CL exclusion limits in the $(\tilde{t}, \tilde{\chi}_1^0)$ mass plane for a signal model with $m(\tilde{\chi}_1^+) = 2 \cdot m(\tilde{\chi}_1^0)$; (b) 95% CL exclusion limits in the $(\tilde{\chi}_1^+, \tilde{\chi}_1^0)$ mass plane for a signal model with $m(\tilde{t}) = 180$ GeV, where the grey area was excluded by LEP [151]; (c) 95% CL exclusion limits in the $(\tilde{t}, \tilde{\chi}_1^0)$ mass plane for a signal model with $m(\tilde{\chi}_1^+) = 106$ GeV, where the area excluded by the Tevatron measurement is shown in green [148] and the blue line shows the area excluded by the ATLAS search published in Ref. [171]. The dashed lines represent the expected limit, the solid lines the observed one. The yellow area represents the $\pm 1\sigma$ uncertainty variation on the expected exclusion, the dotted lines the $\pm 1\sigma$ variation of the results when the signal cross section is varied within its 68% CL theoretical uncertainty [163].

7.6 Direct Stop Searches at the ATLAS Experiment at $\sqrt{s} = 7$ TeV

The direct stop production search programme of the ATLAS collaboration with the 7 TeV dataset included searches in the low stop mass range, where the only allowed decay of the top squark is $\tilde{t} \rightarrow b\tilde{\chi}_1^\pm \rightarrow bW^{(*)}\tilde{\chi}_1^0$, as well as searches for a top squark with larger mass than that of the top quark, which can decay as $\tilde{t} \rightarrow t\tilde{\chi}_1^0$.

The sensitivity of the direct stop searches performed by the ATLAS collaboration greatly exceeded that of the searches done previously by the Tevatron and the LEP experiments. The ATLAS direct stop searches were optimised for all-hadronic, one lepton, and two leptons final states. None of them observed a significant excess over the expected SM background and therefore 95% CL exclusion limits were set in the two dimensional $(\tilde{t}, \tilde{\chi}_1^0)$ mass plane. These are summarised in Fig. 7.18, where the coloured areas correspond to the parameter space excluded by the different searches.

The excluded areas for the signal models considered are:

- $\tilde{t} \rightarrow b\tilde{\chi}_1^\pm \rightarrow bW^{(*)}\tilde{\chi}_1^0$: in green for a chargino mass of 106 GeV [163, 171], and in blue for signals with $m(\tilde{\chi}_1^\pm) = 2 \cdot m(\tilde{\chi}_1^0)$ [163]. Stop masses between 110 and 160 GeV could be excluded for a neutralino with mass of 55 GeV.
- $\tilde{t} \rightarrow t\tilde{\chi}_1^0$: in orange for the search in all-hadronic final states [172], in yellow for the search in one lepton final states [173], and in red for the search in two lepton final states [174]. Stop masses between 230 and 490 GeV could be excluded for an almost massless neutralino.

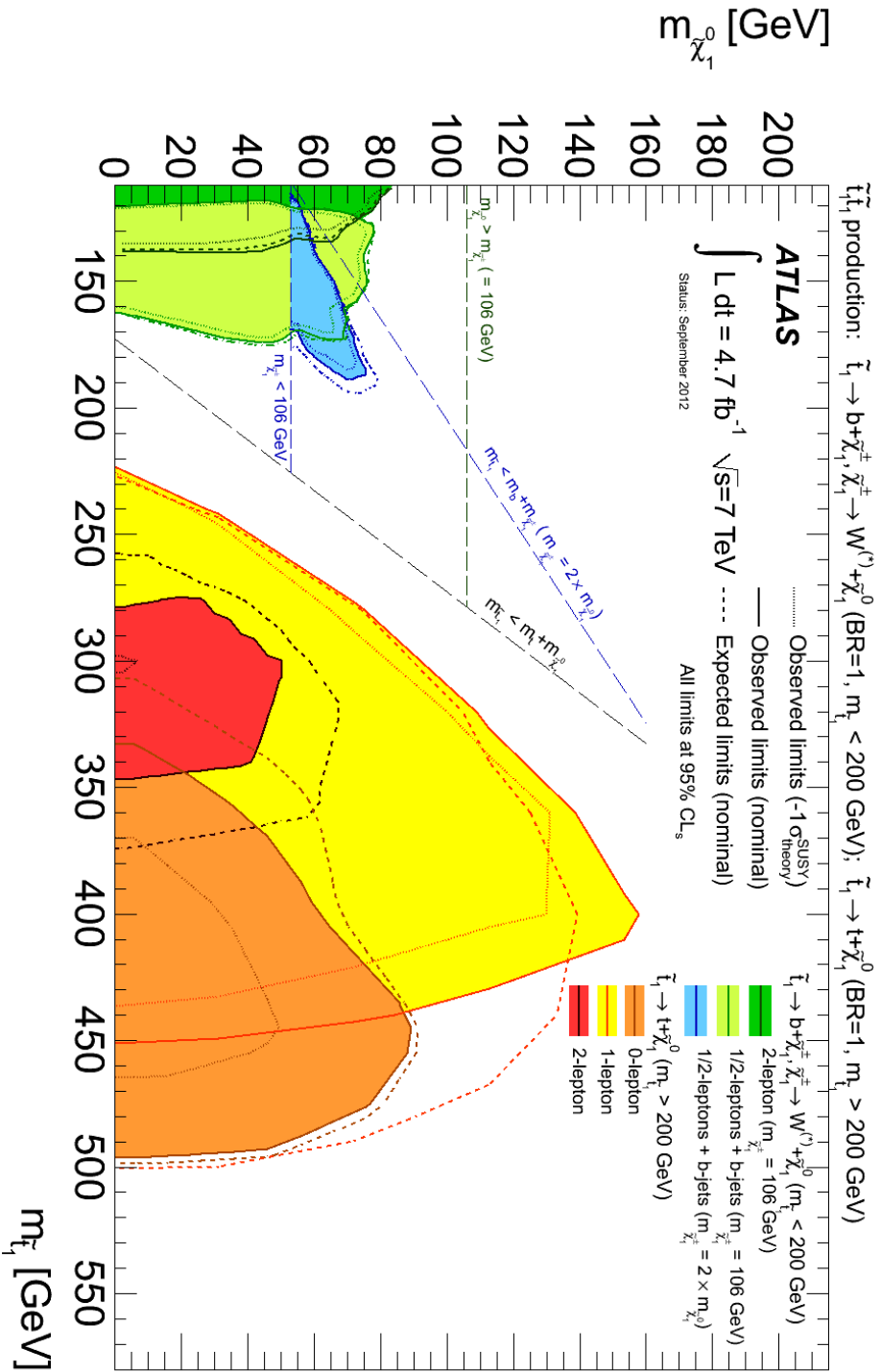


Figure 7.18: Summary of the 95% CL exclusion contours for the direct stop pair production searches with the 7 TeV ATLAS dataset [175]. The signal models considered are: $\tilde{t} \rightarrow b\tilde{\chi}_1^\pm \rightarrow bW^{(*)}\tilde{\chi}_1^0$ in green for a chargino mass of 106 GeV [163, 171], and in blue for signals with $m(\tilde{\chi}_1^\pm) = 2 \cdot m(\tilde{\chi}_1^0)$ [163]; $\tilde{t} \rightarrow t\tilde{\chi}_1^0$ in orange for the search in all-hadronic final states [172], in yellow for the search in one lepton final states [173], and in red for the search in two lepton final states [174].

Searches for the top squark at $\sqrt{s} = 8$ TeV

In this chapter a second search for the direct stop pair production is presented. The dataset recorded at $\sqrt{s} = 8$ TeV by the ATLAS experiment was analysed to search for the light top squark in all-hadronic final states in a regime where $m(\tilde{t}) > m(t) + m(\tilde{\chi}_1^0)$, and the stop is allowed to decay as $\tilde{t} \rightarrow t\tilde{\chi}_1^0$. The results of this search have been published in Ref. [176]. Preliminary results, obtained by repeating an analysis done on the 7 TeV dataset [172] only with minor optimisation and modifications, were released as conference note short after the 2012 data taking period was concluded [177].

The baseline scenario for this analysis is the stop pair production and decay as $\tilde{t} \rightarrow t\tilde{\chi}_1^0$ with a 100% branching ratio, see Feynman diagram of Fig. 8.1a. In nature, it is more likely that a mixture of decays is realised, hence the search sensitivity was improved and optimised for scenarios in which one of the pair produced stops decays in $t\tilde{\chi}_1^0$ and the other in $b\tilde{\chi}_1^\pm$. As a consequence also the sensitivity to models where the stop decays with 100% BR as $\tilde{t} \rightarrow b\tilde{\chi}_1^\pm$, see Feynman diagram of Fig. 8.1b, improved. Combining these signal models, limit contours that depend on the decay branching ratios in the two channels can be extracted.

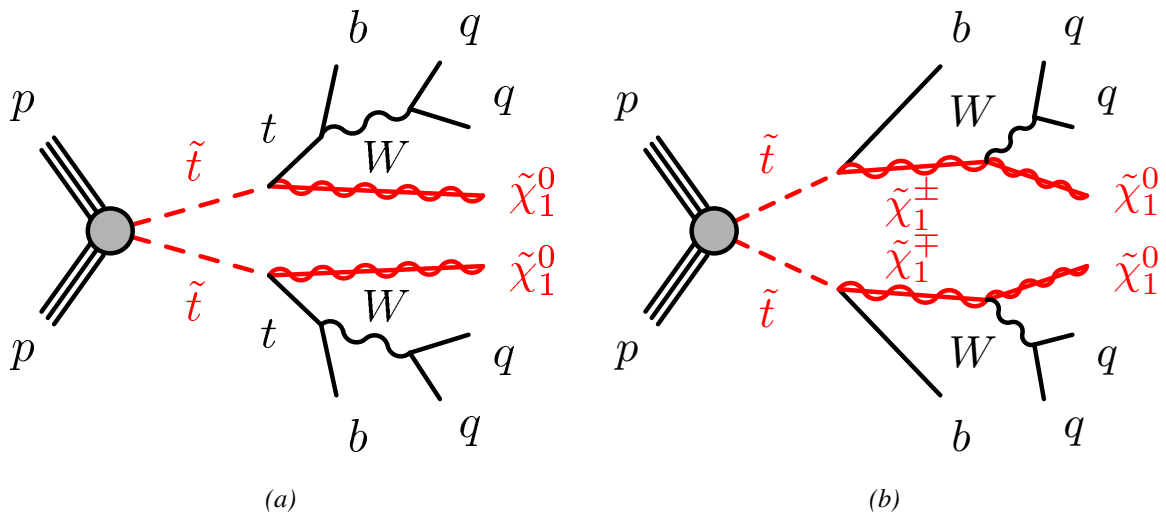


Figure 8.1: Feynman diagrams of the direct stop pair production and decay in all-hadronic final states in the $\tilde{t} \rightarrow t\tilde{\chi}_1^0$ (a) and $\tilde{t} \rightarrow b\tilde{\chi}_1^\pm$ (b) channels.

The search for the top squark in all-hadronic final states is especially powerful for the regions of the parameter space where the mass difference between the stop and the neutralino, or between the stop and the chargino and then between the chargino and the neutralino, is large, while for small mass splittings the analysis has a poor sensitivity due to the lack of objects that can be used to select the events at trigger level. The main backgrounds to this search are the semi-leptonic decay of pair produced top, where the lepton has not been identified or is a tau that decays into hadrons, the associated production of jets and heavy flavour jets with a Z boson, decaying as $Z \rightarrow \nu\nu + \text{jets}$, and the associated production of $t\bar{t}$ with a Z boson, with the $t\bar{t}$ decaying hadronically and the Z decaying into neutrinos. This last process is the only irreducible background having a signature almost indistinguishable from that of the signal process. Events arising from multi-jet QCD production or from $t\bar{t}$ full-hadronic decays give a negligible contribution to the signal selection, since they can be selected only if the physics objects belonging to the event are mismeasured and large missing transverse momentum is, hence, found.

The chapter is structured as follows. The analysed dataset and the used background and signal MC samples are summarised in Section 8.1. The strategy of the analysis is presented in Section 8.2 with the choice of the trigger, the list of the baseline and cleaning selections, the description of the $t\bar{t}$ decay reconstruction method, and the definition of the signal regions. The estimation of the $t\bar{t}$, $W + \text{jets}$, $Z + \text{jets}$, and fake backgrounds is presented in Section 8.3, while the description of the experimental and theoretical systematic uncertainties follows in Section 8.4. Finally the final results of the analysis together with the fit strategy are presented in Section 8.5.

The results published in Ref. [176] were obtained within the research done for my PhD thesis. In particular, my personal contributions are in the definition and optimisation of the $t\bar{t}$ decay reconstruction method, the definition of the signal regions that target the bulk of the $\tilde{t} \rightarrow t\tilde{\chi}_1^0$ and mixed grids (SRA), and the estimate of the $t\bar{t}$ background with the definition of control and validation regions for the SRA and SRC sets of signal enriched regions, together with the study of the impact on the results of different methods to reweight the $t\bar{t}$ sample, which otherwise showed a non satisfying description of some kinematic variables.

8.1 Data and Monte Carlo Samples

The complete 2012 ATLAS dataset, corresponding to $20.1 \pm 0.6 \text{ fb}^{-1}$ of integrated luminosity, recorded at a centre-of-mass energy of 8 TeV was analysed for this search. Only the data listed in the ATLAS physics good run list were used for the analysis. These data were recorded with optimal detector conditions and must satisfy basic data-quality criteria.

In the following paragraphs, the Monte Carlo simulated samples used in the analysis for the background and signal processes are listed. These include the baseline samples and the samples used to estimate the impact of the theoretical systematic uncertainties on the signal and background yields. Both the background and signal baseline samples are mainly produced with the AFII detector simulation, but the samples where only decays with τ leptons are selected use the GEANT4 detector simulation. Some of the samples exploited to determine the systematic uncertainties are particle level samples where no detector simulation has been applied.

8.1.1 Background Samples

The MC samples for the background processes have been used either to estimate directly the contribution of a given process in the signal regions, e.g. dibosons, $t\bar{t} + V$ production, single top production, or used

as a support for semi or fully data-driven background estimates, as for the semi-leptonic $t\bar{t}$ background, the Z + jets and the multi-jets backgrounds. A complete list of the samples used in the analysis can be found in Appendix C.

- Top production

The baseline top pair-production MC sample, filtered to contain only events with at least a lepton in the decay chain (e, μ, τ), was generated with PowHeg [85] interfaced to PYTHIA6 [76] with the Perugia 2011 tune [71] for the model of the underlying event.

The samples produced to estimate the $t\bar{t}$ systematic uncertainties are PowHeg samples at particle level with varied renormalisation and factorisation scales, a sample generated with PowHeg interfaced to JIMMY [75], ACER MC [82] samples with varied initial and final state radiation activity, and a sample generated with MC@NLO [84].

The single top baseline samples for the Wt and s -channel were also generated with PowHeg interfaced to PYTHIA, while the t -channel sample was produced with the ACER MC generator. For the systematic variations samples generated with MC@NLO, ACER MC, PowHeg interfaced to JIMMY were produced.

- W and Z production

The baseline W + jets and Z + jets samples were generated with SHERPA [80] with the b and c quarks correctly treated as massive particles. Z + jets ALPGEN samples were used to determine the Z background uncertainty, while for the W + jets background SHERPA samples with scale variations and different numbers of final state partons considered in the matrix element were produced.

- $t\bar{t} + V/VV$ production

The samples of the associated production of $t\bar{t}$ with one or more vector bosons were generated with MadGraph [83] interfaced to PYTHIA for the parton showering and the underlying event. The samples with variation of the generator parameters used to assess the impact of the systematic on the $t\bar{t} + V$ yields were also generated with MadGraph. A set of ALPGEN [81] samples was also available for comparisons.

- Diboson production

The dibosons samples were generated with SHERPA, with a massive treatment of the b and c quarks.

- Multi-jet production

The QCD multi-jet samples were generated with PYTHIA, while MC@NLO was used to generate a sample of $t\bar{t}$ production and decay in all-hadronic final states.

8.1.2 Signal Samples

The signal scenarios considered for this analysis are:

- $\tilde{t} \rightarrow t\tilde{\chi}_1^0$, BR=100%, signal grid generated with HERWIG++ [79]
- $\tilde{t} \rightarrow b\tilde{\chi}_1^\pm$, BR=100%, signal grid generated with MadGraph interfaced to PYTHIA6
- $\tilde{t}\tilde{t}^* \rightarrow t\tilde{\chi}_1^0 b\tilde{\chi}_1^\pm$, mixed grid (see Paragraph 6.2.3), signal grid generated with MadGraph interfaced to PYTHIA6

The Feynman diagrams of the considered stop decays are shown in Fig. 8.2 for the hadronic decay of the W boson. The $\tilde{t} \rightarrow t\tilde{\chi}_1^0$ decay is shown in (a), the $\tilde{t} \rightarrow b\tilde{\chi}_1^\pm$ decay in (b).

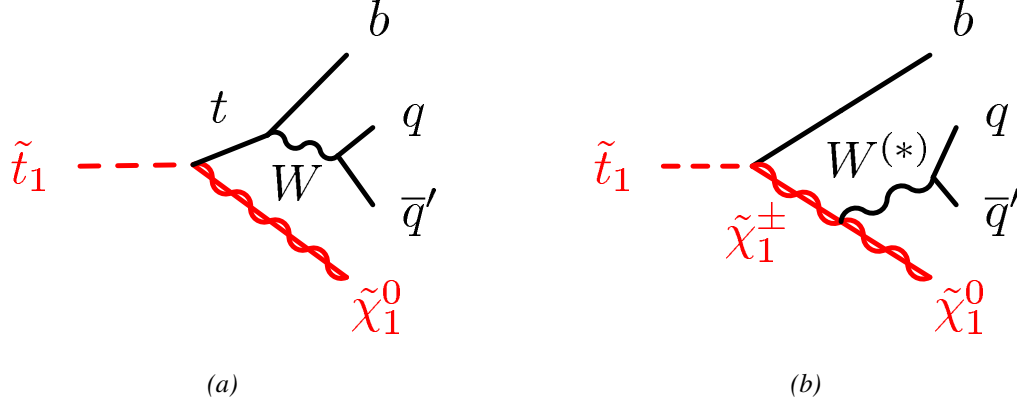


Figure 8.2: Feynman diagrams of the $\tilde{t}_1$ decay modes considered for hadronic final states: (a) $\tilde{t}_1 \rightarrow t\tilde{\chi}_1^0$ and (b) $\tilde{t}_1 \rightarrow b\tilde{\chi}_1^\pm \rightarrow bW^{(*)}\tilde{\chi}_1^0$ [176].

8.2 Analysis Strategy

In this section the strategy of the analysis is explained. First the choice of the trigger is introduced in Paragraph 8.2.1, then the definition of the selected objects and of the baseline and cleaning selections are listed, respectively, in Paragraphs 8.2.2 and 8.2.3. The methods that can be used to reconstruct the hadronic decay of a $t\bar{t}$ pair are explained in Paragraph 8.2.4. Finally the optimisation of the selections to define the signal regions is described in Paragraph 8.2.5. Here a particular attention is given to the optimisation procedure adopted to define the SRA set of signal regions, while for the other two sets, SRB and SRC, only the final choice of selections is presented.

8.2.1 Trigger Selection

The final state under study contains only jets and missing transverse momentum. The trigger chosen to select the events that may belong to a stop signal decaying into hadrons is a E_T^{miss} trigger, `EF_xe80_tclcw_loose`, with an online threshold on the E_T^{miss} of 80 GeV. This trigger was not turned on at the beginning of the data taking in 2012; instead a modified version of it was enabled, `EF_xe80T_tclcw_loose`, which started recording the events after the first three bunch crossing of every new fill. The overall loss in recorded luminosity is of the order of 0.2 fb^{-1} of data, i.e. about 1% of the total recorded luminosity recorded in 2012. The selected triggers and the periods in which they were active are summarised in Table 8.1. These triggers are fully efficient for an offline E_T^{miss} selection of 150 GeV, when two jets of $p_T > 80 \text{ GeV}$ are also selected.

2012 Period	E_T^{miss} Trigger
Period A-Run 203680	<code>EF_xe80T_tclcw_loose</code>
Run 203719-Period L	<code>EF_xe80_tclcw_loose</code>

Table 8.1: Triggers used to select the signal events in the 8 TeV dataset.

The regions used to estimate the $t\bar{t}$, W + jets and Z + jets backgrounds are defined by selecting one or two signal leptons. The events that may belong to these regions are, hence, selected with the aid of the first unprescaled lepton triggers, which are summarised in Table 8.2. For the electron case, the e24vhi_medium1 trigger sets requirements on the energy leakage of the electromagnetic shower in the hadronic calorimeter and places selections on the isolation of the selected lepton. The second trigger, e60_medium1, is then used to recover the loss of acceptance for high p_T electrons, which may deposit a fraction of their energy in the hadronic calorimeter. Similarly for the muons the lowest p_T trigger requires the muon to be isolated, while the second one selects also muons that are energetic but not necessarily isolated.

Channel	Single Lepton Triggers
Electron	e24vhi_medium1 -OR- e60_medium1
Muon	mu24i_tight -OR- mu36_tight

Table 8.2: Lepton triggers used to select the events of the background enriched regions.

8.2.2 Object Selection

The properties of the objects selected for the analysis are summarised in this subsection. The selected electrons, muons and jets are checked against overlaps with the overlap removal procedure explained in Paragraph 6.3.4. If an electron overlaps with a b -tagged jet within a radius of $\Delta R = 0.2$ the electron is rejected and the jet is kept, as it is likely to come from a leptonic decay of a b - or c -hadron.

- Electrons

The baseline electrons are selected with the loose identification requirements as cluster seeded electrons.

The selected electrons must have $p_T > 10$ GeV and $|\eta| < 2.47$. In addition the so-called signal electrons must satisfy the tight identification criteria and be isolated at tracking and calorimeter level, and specifically they have to satisfy $p_{T\text{cone30}}/p_T < 0.16$ and $E_{T\text{cone30}}/p_T < 0.18$.

- Muons

The baseline muons have to pass loose selection requirements, have $p_T > 10$ GeV and $|\eta| < 2.4$. For this analysis combined and segment tagged muons are considered. A muon is labelled as coming from cosmic decays if its transverse and longitudinal impact parameters do not satisfy $|d_0| < 0.2$ mm and $|z_0| < 1.0$ mm. The so-called signal muons are additionally required to be isolated at tracker and calorimeter level, i.e. to satisfy $p_{T\text{cone30}}/p_T < 0.12$ and $E_{T\text{cone30}}/p_T < 0.18$.

- Jets

The selected jets are anti- k_t $R=0.4$ jets reconstructed from topoclusters and calibrated with local hadronic calibration weights. The jet energy scale correction was applied to the reconstructed jets together with a correction of the energy deposited by pile-up jets based on the event average density. The direction of the jet is then adjusted to point to the identified primary vertex. The baseline calibrated jets are required to have $p_T > 20$ GeV and $|\eta| < 2.8$. The jets selected for the analysis must additionally satisfy jet cleaning criteria, not be identified as coming from calorimeter noise or non-collision background, and have a calibrated $p_T > 35$ GeV. No additional pile-up rejection cut is applied to select jets.

- b -tagging

A selected jet is labelled as coming from a b -hadron decay if the b -tagging weight, computed with the MV1 algorithm, is above the 70% efficiency working point of the algorithm. A jet can be selected as b -jet if its p_T is above 20 GeV and it has $|\eta| < 2.5$.

- E_T^{miss}

In the E_T^{miss} calculation the contributions considered are those of the jets that, after the local hadronic scale calibration and the correction for the JES, have $p_T > 20 \text{ GeV}$ and $|\eta| < 4.5$, the selected electrons and muons, and the calorimeter clusters not associated to any other object. The chosen E_T^{miss} variable does not treat tau contributions separately from those of the jets.

8.2.3 Preselections and Event Cleaning

Here the cleaning selections and basic requirements that each event has to satisfy in order to be considered for the signal selection are listed. A more detailed description of the cleaning selection can be found in Paragraph 6.3.4.

- GRL

It is applied only to the data, events must have been recorded under optimal detector conditions.

- Trigger

The event must pass the E_T^{miss} trigger selection.

- Tile Trip Veto

It vetoes data events recorded as the tile cells were not fully functional due to transient trips in their voltage supply.

- Primary Vertex

The primary vertex of the event is required to have at least 5 tracks.

- Bad Jet Veto

The event must not contain any jet with $p_T > 20 \text{ GeV}$ identified as coming from calorimeter noise or non-collision background.

- Jet charged fraction

The leading 2 jets with $p_T > 100 \text{ GeV}$ and $|\eta| < 2$ must satisfy the charged fraction requirements for the event to be kept, see Paragraph 6.3.4.

- Fake E_T^{miss} due to bad Tile modules

If the event has a high probability of having large E_T^{miss} due to non working tile cells the event is vetoed.

- LAr and Tile Flags Veto

It is applied only to data, and rejects events where noise burst or trips were registered in the LAr or Tile calorimeters.

- Tile negative energy veto

Events are vetoed if the Soft E_T^{miss} component exceeds 50% of the total missing momentum corrected for the cosine of the azimuthal angle between the Soft and the total E_T^{miss} direction.

- Hot tile veto

It is a veto applied only to data to correct for a noisy Tile cell ($-0.2 < \eta < -0.1$ and $2.65 < \phi < 2.75$), which was not masked in reconstruction during a period where 0.27 fb^{-1} of data were recorded.

- Jet Timing

Veto events with reconstructed jets that have a time stamp indicating that they belong to the previous or following bunch-crossing.

- Cosmic Muons Veto

The event must not contain any selected muons with $|d_0| > 0.2 \text{ mm}$ or $|z_0| > 1.0 \text{ mm}$.

- Bad Muons Veto

The event is vetoed if it contains any selected “bad muon”, see Paragraph 6.3.4.

- Lepton veto

Events are rejected if a baseline electron or muon with $p_T > 10 \text{ GeV}$ is selected.

- $E_T^{\text{miss}} > 150 \text{ GeV}$

Threshold to select events in the trigger efficiency plateau.

- $n_{\text{jets}} \geq 4$

At least four jets with $p_T > 35 \text{ GeV}$ are required for all the defined signal region selections.

- $n_{b\text{-jets}} \geq 2$

The event must contain at least two b -tagged jets, with $p_T > 35 \text{ GeV}$ and $|\eta| < 2.5$, the chosen WP is at the 70% efficiency of the MV1 b -tagging algorithm.

- $\min \left| \Delta\phi(\text{jet}^{0-2}, E_T^{\text{miss}}) \right| > \pi/5$

This selection, applied to the three leading jets, rejects most of the multi-jets background, where the E_T^{miss} comes from the mismeasurement of the energy deposited by the selected jets.

- $E_T^{\text{miss,track}} > 30 \text{ GeV}$

A minimum missing transverse momentum reconstructed solely from the tracks measured in the inner detector is required. This selection is used to reject events with fake calorimetric E_T^{miss} , e.g. multi-jet QCD production.

- $\left| \Delta\phi(E_T^{\text{miss}}, E_T^{\text{miss,track}}) \right| < \pi/3$

The E_T^{miss} calculated with calorimeter informations and the $E_T^{\text{miss,track}}$ built only with the track information recorded in the inner detector must be aligned for the event to be selected. This selection is also designed to reject the multi-jet background that have large fake calorimetric E_T^{miss} .

- $m_T^{b, \text{min}} > 175 \text{ GeV}$

The transverse mass between the nearest b -jet to the p_T^{miss} direction and the p_T^{miss} must exceed the top mass. This selection rejects most of the semi-leptonic $t\bar{t}$ background because this variables present an endpoint at the top mass for the decay $t \rightarrow bW \rightarrow b\ell\nu$, where the lepton is either misidentified or falls out of acceptance of the detector.

The events selected for the $t\bar{t}$, $W + \text{jets}$, and $Z + \text{jets}$ background enriched regions contain exactly one or two signal leptons and are not necessarily required to pass all the selections listed after the lepton veto, more details on the requirements for the control regions are given in Section 8.3.

In the same way as for the analysis presented in the previous chapter, weights are assigned to the surviving events in MC for the differences observed with data. These are lepton identification and trigger efficiency factors, b -tagging scaling factors and pile-up weights, which are obtained by reweighting the $\langle\mu\rangle$ distributions in MC to match the one measured in data.

The cleaning and baseline selections for the zero lepton regions are also summarised in Table 8.3.

	Selection	Cut Value / Comment
Baseline	GRL	Data only: Event is in GRL
	Trigger	E_T^{miss}
	Tile trip veto	Data only: veto tile corrupted events
	Primary vertex	Primary vertex has ≥ 5 tracks
	Bad jet veto	Veto event if it has a “bad jet” candidate
	f_{ch} veto	Jet charged fraction veto
	Calorimeter cleaning	LAr and Tile flags
	Tile negative energy	Veto event
	Hot tile veto	Applied only to data
	Jet Timing	All baseline jets compatible with bunch crossing time
	Cosmic Muon veto	Veto event if it contains a cosmic muon candidate
	Bad Muon veto	Veto event if it contains a bad muon candidate
Channel	Lepton veto	Veto event if baseline lepton $p_T > 10 \text{ GeV}$ is found
	E_T^{miss}	$E_T^{\text{miss}} > 150 \text{ GeV}$
	n_{jets}	≥ 4
	$n_{b\text{-jets}}$	≥ 2
	$\min \left \Delta\phi \left(\text{jet}^{0-2}, E_T^{\text{miss}} \right) \right $	$> \pi/5$
	$E_T^{\text{miss,track}}$	$> 30 \text{ GeV}$
	$\left \Delta\phi \left(E_T^{\text{miss}}, E_T^{\text{miss,track}} \right) \right $	$< \pi/3$
	$m_T^{b, \text{min}}$	$> 175 \text{ GeV}$

Table 8.3: Summary of the cleaning selections and of the baseline requirements to be satisfied by the selected events.

8.2.4 $t\bar{t}$ Decay Reconstruction

The reconstruction of the $t\bar{t}$ hadronic decay, and therefore the identification of the physical objects belonging to it, can be used for the discrimination of the signal-like events from the background-like ones. In the case of the baseline signal model, where the stop decays with 100% as $\tilde{t} \rightarrow t\tilde{\chi}_1^0$, two hadronically decaying top quarks can be reconstructed and the missing transverse momentum arises exclusively from the two neutralinos. The only SM background where two hadronic tops can be reconstructed is the associated production of $t\bar{t}$ with a Z boson. The main background contributions come, though, from the semi-leptonic decay of a $t\bar{t}$ pair and from the associated production of a Z boson with jets, where the Z decays in two neutrinos. In the latter no real hadronic decaying top exist, while in the former only one top decays hadronically and the lepton from the decay of the second top is either out of detector

acceptance or is a τ lepton that decays into hadrons.

A selection on the mass of the two reconstructed tops can then be used to reject most of the $Z + \text{jets}$ background and of the $W + \text{jets}$ background, together with a good fraction of the remaining semi-leptonic $t\bar{t}$ background after the $m_T^{b, \min}$ selection.

Two different approaches to reconstruct the $t\bar{t}$ decay can be followed depending on the number of selected jets in the final state. If six or more jets are selected the two tops can be identified by grouping the jets in two top candidates by exploiting the jet separation in ΔR . If four or five jets are selected, the anti- k_t $R = 0.4$ jets can be reclustered into jets with larger radius, $\Delta R = 0.8$ or $\Delta R = 1.2$, that can be identified as top candidates by requiring that the mass of the reclustered jet sits in a defined range. The first method is described in detail in the following, while further details about the second scenario can be found in Ref. [176].

To reconstruct two hadronic top candidates at least six jets have to be selected in the event, which can be labeled as belonging to a top candidate based on their vicinity in ΔR . Two variants of this method, called $\Delta R_{\min}$ method, can be tested. The simplest version does not consider if the selected jets are b -tagged or not, the second variant selects the two b -jets with the highest b -tag weights and uses explicitly this information in the reconstruction. The steps of the simple $\Delta R_{\min}$ $t\bar{t}$ decay reconstruction are:

- W_{had}^1 candidate
The two jets with the smallest $\Delta R(jj)$ are selected to form the first W hadronic candidate and removed from the list of available jets.
- t_{had}^1 candidate
The jet nearest to the W_{had}^1 candidate is selected to form the first top hadronic candidate and again it is removed from the list of the jets in the event. The mass of the first top candidate is indicated as m_{jjj}^0 .
- W_{had}^2 candidate
The two nearest jets among the ones not yet assigned to the t_{had}^1 candidate are selected as second W candidate.
- t_{had}^2 candidate
Finally the ΔR distance between the W_{had}^2 candidate and the remaining jets is computed and the nearest one is chosen to form the second top hadronic candidate. The mass of the second top candidate is indicated as m_{jjj}^1 .

If the b -tagged jets are explicitly considered, the assignment of the jets to the final objects is done slightly differently:

- b -jet selection
If more than two b -jets are found in the event, the two with the highest b -tag weight are considered as b -jets, while the others are added to the light-jets container.
- $W_{\text{had,b}}^1$ candidate
Among all light jets, the two nearest in ΔR are chosen as first W candidate.
- $t_{\text{had,b}}^1$ candidate
The distance between the W candidate and the two selected b -jets is calculated, and the nearest

b -jet is selected to complete the first top hadronic candidate. The mass of the first top candidate is indicated as m_{bjj}^0 .

- $W_{\text{had,b}}^2$ candidate

The two nearest light jets in ΔR not already selected for the $W_{\text{had,b}}^1$ candidate, are chosen to form the second W candidate.

- $t_{\text{had,b}}^2$ candidate

The b -jet not selected for the first top candidate is assigned to the $W_{\text{had,b}}^2$ to form the second top candidate. The mass of the second top candidate is indicated as m_{bjj}^1 .

The $t\bar{t}$ decay reconstruction based on the $\Delta R_{\min}$ method does not apply any constraint on the mass of the reconstructed objects. This has the disadvantage of having broader mass distributions, but, on the other hand, does not bias the shape of the background distributions and provides good signal discrimination. A χ^2 -based minimisation method, where mass constraints were applied, was tested giving narrower signal peaks, but also shifting all background processes towards the top mass peak. This feature leads to a worse discrimination power between signal and background than what was observed for the $\Delta R_{\min}$ method. The basic $\Delta R_{\min}$ method was used to reconstruct the $t\bar{t}$ decay in the 7 TeV ATLAS analysis in this channel, which is not part of this thesis, and to obtain the first preliminary results with the 8 TeV dataset [172, 177]. The reconstruction which uses the b -jets information was instead used for the published analysis of the 8 TeV data [176].

The mass distributions of the first (a) and second (b) hadronic top candidate are shown in Fig. 8.3. The shape of the distributions of the two variants of the $\Delta R_{\min}$ $t\bar{t}$ decay reconstruction methods is compared for the $t\bar{t}$ sample and for a signal sample of the $\tilde{t} \rightarrow t\tilde{\chi}_1^0$ grid with $m(\tilde{t}) = 600$ GeV and $m(\tilde{\chi}_1^0) = 1$ GeV. It can be observed that around the top mass peak region the signal to background ratio is higher for the b -jet aware method, which was finally chosen as the baseline method to reconstruct the $t\bar{t}$ decay.

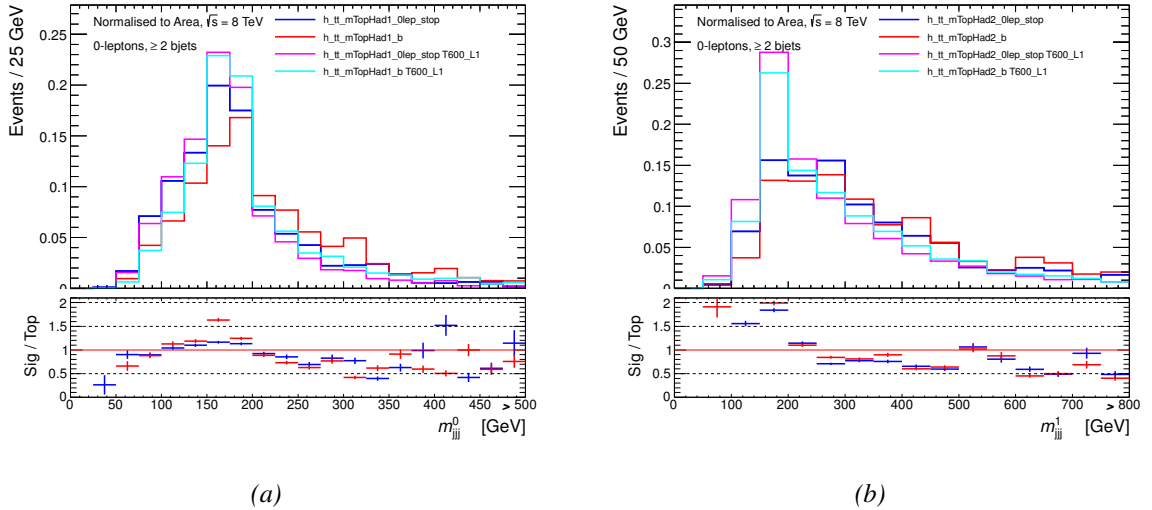


Figure 8.3: Comparison of the two $\Delta R_{\min}$ top reconstruction algorithms for a six jets inclusive selection. The result of the reconstruction is shown for the $t\bar{t}$ background and for the signal point $m(\tilde{t}) = 600$, $m(\tilde{\chi}_1^0) = 1$ GeV, the distributions are normalised to unit area. The baseline reconstruction is shown in blue for the $t\bar{t}$ and in pink for the signal; the reconstruction with b -jets is shown in red for the top background and in light-blue for signal. The ratio between signal and top is also shown in blue for the basic reconstruction and in red for the b -jets aware one.

8.2.5 Definition of the Signal Regions

Three sets of signal regions, SRA, SRB, and SRC, were defined for this search, targeting different signal scenarios or regions of the parameter space.

The events belonging to the SRA set of regions are required to have at least six reconstructed jets, which are the minimum amount of jets the signal has if all its decay products are measured, as individual objects, in the detector. This set of regions is optimised to cover the bulk of the $\tilde{t} \rightarrow t\tilde{\chi}_1^0$ signal models.

The SRB regions target the boosted scenarios, especially for the $\tilde{t} \rightarrow t\tilde{\chi}_1^0$ models, where some decay products merge into the same reconstructed physics objects and only four or five anti- k_t $R = 0.4$ jets are reconstructed. In these regions the discrimination power is based on the mass and momentum of “fat-jets” that are anti- k_t $R = 0.4$ jets reclustered into $R = 0.8$ and $R = 1.2$ jets.

Finally, the SRC set was designed to recover the sensitivity to the decays of the stop in $b\tilde{\chi}_1^\pm$. It is based on an exclusive five jets selection and no explicit reconstruction of the $t\bar{t}$ decay is performed.

The SRB and SRC sets are designed to have no overlap to the SRA set so that they can be easily statistically combined to improve the sensitivity of the search. The signal regions have been optimised for a signal discovery using the S_d estimator introduced in Paragraph 6.3.1 as baseline estimator. For the optimisation of the signal selections a simplified assumption for the systematic uncertainty of the background was made: a flat systematic uncertainty was assigned to the background contribution in the range of 20% to 40%, depending on the background yield.

In the following paragraphs the selections that define each set of signal regions are reported. The procedure and variables used to define the SRA set of regions are described in detail, while for the other sets only the final region definition is given, together with an explanation of the region specific variables.

SRA

The decision of which region, of the SRA set, was optimal for each signal hypothesis has been done with the help of the S_d estimator and of the Asimov formula, see Equation 6.3. When the best set of regions was chosen their performance for the model dependent exclusion was also tested in order to select the regions with the best balance between discovery and exclusion power.

As introduced before, the SRA baseline selections require the events to have at least six selected anti- k_t $R = 0.4$ signal jets with $p_T > 35$ GeV and the two leading with $p_T > 80$ GeV. The discriminating variables used in the optimisation process are E_T^{miss} , $m_T^{b,\text{min}}$, $\min[m_T(\text{jet}^i, p_T^{\text{miss}})]$, m_{bjj}^0 , m_{bjj}^1 , m_{jjj}^0 , and m_{jjj}^1 . A scan of possible selection criteria on these variables was run and all different combinations of selections were tested. It was required that a fixed minimum number of MC events survived the final selection, to be sure that the best region was not chosen based on a statistical fluctuation. For the optimisation of the signal selections, all the background components were taken from MC simulated samples and no contribution from fake multi-jet events was considered.

The distributions of some important variables are shown in Fig. 8.4 for the $t\bar{t}$ and $Z + \text{jets}$ (blue) backgrounds and for three signal points of the $\tilde{t} \rightarrow t\tilde{\chi}_1^0$ grid, two with a large mass splitting between stop and neutralino, $(m(\tilde{t}), m(\tilde{\chi}_1^0)) = (600, 1)$ GeV and $(m(\tilde{t}), m(\tilde{\chi}_1^0)) = (700, 1)$ GeV, and one with a mass splitting that leaves only about 25 GeV free energy for the stop decay products, $(m(\tilde{t}), m(\tilde{\chi}_1^0)) = (300, 100)$ GeV. The signal to background ratio is drawn separately for the $t\bar{t}$ and $Z + \text{jets}$ backgrounds and the signal point is $(m(\tilde{t}), m(\tilde{\chi}_1^0)) = (600, 1)$ GeV.

The $m_T^{b,\text{min}}$ distribution for events with six jets of which at least two b -tagged and $E_T^{\text{miss}} > 130$ GeV is shown in Fig. 8.4a. It can be observed that the $t\bar{t}$ distribution steeply falls at 160-180 GeV, while the distributions for the Z background and for the signal points with large mass splitting are much broader and

most events exceed the top mass end point. On the other hand the signal point with small mass splitting has an even softer spectrum than that of the $t\bar{t}$ background and almost all events have $m_T^{b,\min} < 175 \text{ GeV}$. For this signal point, no good sensitivity can be achieved because, even though at very low $m_T^{b,\min}$ values a good ratio of signal over $t\bar{t}$ events is observed. This is because of the large contribution of fake multi-jet events for $m_T^{b,\min} < 50 \text{ GeV}$. The example of this point with small mass splitting shows that the analysis cannot approach easily the diagonal $m(\tilde{t}) = m(t) + m(\tilde{\chi}_1^0)$.

The $|\Delta\phi(b, b)|$ distribution is shown in Fig. 8.4b, where the same selections as in the previous figure have been applied. The distribution is almost flat for the signal points with large mass splitting, for the $t\bar{t}$ sample and for the third signal point the two b -jets are preferentially back-to-back, while for the $Z + \text{jets}$ background the two b -jet are close together and in general flying almost in the same direction. This happens because in most of the selected Z events the two b -jets are originated from a radiated gluon that splits into a $b\bar{b}$ pair. No selection has been applied to this variable because, as can be seen from Fig. 8.4c, when the requirement $m_T^{b,\min} > 175 \text{ GeV}$ is applied the signal distributions are also shifted to lower values of $|\Delta\phi(b, b)|$ and the gain in background rejection, that comes from rejecting events with a small $b\bar{b}$ angular separation, would not be enough to justify a large loss of signal events.

The E_T^{miss} distribution obtained after the six jets and $m_T^{b,\min} > 175 \text{ GeV}$ requirements is shown in Fig. 8.4d, and the very good discriminating power of this variable for signals with large mass splitting can be clearly seen.

The distributions of m_{bjj}^0 and m_{bjj}^1 , after the six jets, $E_T^{\text{miss}} > 130 \text{ GeV}$ and $m_T^{b,\min} > 175 \text{ GeV}$ requirements, are shown in Fig. 8.4 (e) and (f). It can be observed that a tight selection on the first candidate rejects a large number of $Z + \text{jets}$ events and that a selection on the second candidate is effective in rejecting not only additional $Z + \text{jets}$ events but also semi-leptonic $t\bar{t}$ events.

The best selections obtained with the optimisation procedure are summarised in Table 8.4. The τ veto rejects mainly $t\bar{t}$ events where a top decays hadronically and the other in a b -jet, a τ lepton and a τ neutrino, with the τ decaying to hadrons. A tau candidate is a jet, which is not tagged as coming from a b -hadron if $|\eta(j)| < 2.5$, that has less than four tracks associated to it, and has a distance with the E_T^{miss} direction $|\Delta\phi(\text{jet}, E_T^{\text{miss}})| < 0.2$. If such a candidate is found and the tau veto is applied the event is rejected. The $\min[m_T(\text{jet}^i, p_T^{\text{miss}})]$ variable is used to check which is the minimum distance between any jet i and the E_T^{miss} . This variable helps in rejecting part of the $W + \text{jets}$ and $t\bar{t}$ backgrounds that were not rejected by the $m_T^{b,\min}$ selection.

The optimal cut for the $m_T^{b,\min}$ selection is found to be always 175 GeV, as it was found for the previous analyses. The four signal regions can be divided in two subgroups. SRA1 and SRA2 target signals with a small stop mass and generally not very large mass splittings. A very tight selection is applied on the mass of the first and second hadronic top candidates while relatively little missing transverse momentum is required. SRA3 and SRA4 have a looser requirement on the mass of the second reconstructed hadronic top, in order to not loose signal acceptance for signal models with very low cross section, but much tighter selections on the required E_T^{miss} . In these regions the selection $\min[m_T(\text{jet}^i, p_T^{\text{miss}})] > 50 \text{ GeV}$ is also applied.

The yields obtained directly from the MC samples in the four signal regions of the SRA set are summarised in Table 8.5 for the backgrounds, the data, and three signal points of the $\tilde{t} \rightarrow t\tilde{\chi}_1^0$ grid.

The distributions of the main discriminating variables for all the backgrounds and three signal points, $(\tilde{t}, \tilde{\chi}_1^0) = (400, 1) \text{ GeV}$, $(\tilde{t}, \tilde{\chi}_1^0) = (600, 1) \text{ GeV}$ and $(\tilde{t}, \tilde{\chi}_1^0) = (700, 1) \text{ GeV}$, are shown in Figs. 8.5 and 8.6. They are normalised according to the process cross section to an integrated luminosity of 20.1 fb^{-1} . The distributions of Fig. 8.5 are drawn at an early stage of the selections: the E_T^{miss} (a) and $m_T^{b,\min}$ (b) distributions are drawn after the preselection and the six jets requirements; then the E_T^{miss} (c),

	SRA1	SRA2	SRA3	SRA4
anti- k_t $R = 0.4$ jets	$\geq 6, p_T > 80, 80, 35, 35, 35, 35$ GeV			
m_{bjj}^0	< 225 GeV		[50,250] GeV	
m_{bjj}^1	< 250 GeV		[50,400] GeV	
$\min [m_T(\text{jet}^i, p_T^{\text{miss}})]$	–		> 50 GeV	
τ veto	yes			
E_T^{miss}	> 150 GeV	> 250 GeV	> 300 GeV	> 350 GeV

Table 8.4: Selection criteria for the SRA set of signal regions [176].

Sample	SRA1	SRA2	SRA3	SRA4
Z	1.52 ± 0.30	0.68 ± 0.15	1.33 ± 0.28	0.72 ± 0.15
W	0.95 ± 0.24	0.46 ± 0.17	0.21 ± 0.10	0.06 ± 0.05
$t\bar{t}$	10.42 ± 0.76	1.88 ± 0.33	1.15 ± 0.25	0.54 ± 0.16
Single top	1.01 ± 0.17	0.31 ± 0.09	0.45 ± 0.12	0.31 ± 0.10
$t\bar{t}+V$	1.81 ± 0.09	0.85 ± 0.06	0.82 ± 0.06	0.50 ± 0.05
Dibosons	0.00	0.00	0.32 ± 0.32	0.32 ± 0.32
Tot. MC	15.95 ± 0.91	4.17 ± 0.42	4.22 ± 0.49	2.13 ± 0.25
Data	11	4	5	4
$m(\tilde{t}) = 400$ GeV, $m(\tilde{\chi}_1^0) = 1$ GeV	39.92 ± 2.03	22.22 ± 1.51	13.39 ± 1.17	3.95 ± 0.65
$m(\tilde{t}) = 600$ GeV, $m(\tilde{\chi}_1^0) = 1$ GeV	8.06 ± 0.15	6.92 ± 0.14	8.66 ± 0.16	6.83 ± 0.14
$m(\tilde{t}) = 700$ GeV, $m(\tilde{\chi}_1^0) = 1$ GeV	3.01 ± 0.19	2.82 ± 0.18	3.78 ± 0.21	3.30 ± 0.20

Table 8.5: MC yields for the SRA selections normalised to an integrated luminosity of 20.1 fb^{-1}

$\min[m_T(\text{jet}^i, p_T^{\text{miss}})]$ (d), m_{bjj}^0 (e) and m_{bjj}^1 (f) distributions are shown after the preselection, six jets and $m_T^{b, \min}$ requirements.

Figure 8.6 contains the distributions of selected discriminating variables at an advanced stage of the selection: the E_T^{miss} (a), $\min[m_T(\text{jet}^i, p_T^{\text{miss}})]$ (b), and m_{bjj}^1 (c) distributions are drawn for the events that satisfy all the basic requirements and the $50 < m_{bjj}^0 < 250$ GeV selection; then the E_T^{miss} distribution for the SRA1 (d) and SRA3 (e) selections, except for the final E_T^{miss} requirement, are presented.

It can be observed that the signals $(\tilde{t}, \tilde{\chi}_1^0) = (400, 1)$ GeV and $(\tilde{t}, \tilde{\chi}_1^0) = (600, 1)$ GeV would give significantly more events than those expected from the background, while the signal $(\tilde{t}, \tilde{\chi}_1^0) = (700, 1)$ GeV is difficult to discover and exclude because of its very low cross section, and, therefore, event yield, even though the signal events would have a much harder E_T^{miss} spectrum than that of all the other background processes.

Data-MC comparisons are presented in Figs. 8.7, 8.8 and 8.9 for events that satisfied the preselection, six jets and two b -jets, E_T^{miss} and $m_T^{b, \min}$ requirements.

The number of jets (a) and of b -tagged jets (b), the E_T^{miss} (c), $E_T^{\text{miss}}/m_{\text{eff}}$ (d), $E_T^{\text{miss, track}}$ (e), and $|\Delta\phi(E_T^{\text{miss}}, E_T^{\text{miss, track}})|$ (f) distributions are shown in Fig. 8.7. The data-MC agreement is observed to be good and no significant trends are observed in the data-MC ratios.

The p_T of the four leading jets and of the two b -jets with the higher b -tag weight are shown in Fig. 8.8. Also here the data-MC agreement is good and no trends are observed.

Finally the $m_T^{b, \min}$ (a), $\min[m_T(\text{jet}^i, p_T^{\text{miss}})]$ (b), H_T (c), $|\Delta\phi(b, b)|$ (d), m_{bjj}^0 (e), and m_{bjj}^1 (f) distributions are shown in Fig. 8.9 and an overall good data-MC agreement is again observed.

SRB

The selections of the SRB set of regions are summarised in Table 8.6. In this region, optimised to select boosted signal events, the discrimination is obtained by exploiting the properties of “fat” reclustered jets. Four or five anti- k_t $R = 0.4$ jets are required, that are then reclustered into anti- k_t $R = 1.2$ and $R = 0.8$ jets. At least two “fat jets” are required in each event so that the mass asymmetry variable, $\mathcal{A}_{m_t}$, can be defined as

$$\mathcal{A}_{m_t} = \frac{|m_{\text{jet}, R=1.2}^0 - m_{\text{jet}, R=1.2}^1|}{m_{\text{jet}, R=1.2}^0 + m_{\text{jet}, R=1.2}^1}, \quad (8.1)$$

where $m_{\text{jet}, R=1.2}^0 (m_{\text{jet}, R=1.2}^1)$ is the mass of the anti- k_t $R = 1.2$ with highest(second highest) transverse momentum. The two anti- k_t $R = 1.2$ jets are treated as top candidates and two event categories can be defined, one for events with $\mathcal{A}_{m_t} < 0.5$ where the two top candidates are balanced and well reconstructed, and one for events with $\mathcal{A}_{m_t} > 0.5$ where the two fat jets tend to overlap and they are not well balanced in mass. The background composition for the two groups of events is different and, hence, the two regions, SRB1 and SRB2, were optimised separately. Though, after the final selections have been set, SRB1 and SRB2 are combined into a single region, SRB, that is used to evaluate the sensitivity to boosted signal models.

	SRB1	SRB2
anti- k_t $R = 0.4$ jets	4 or 5, $p_T > 80, 80, 35, 35, (35) \text{ GeV}$	5, $p_T > 100, 100, 35, 35, 35 \text{ GeV}$
$\mathcal{A}_{m_t}$	< 0.5	> 0.5
$p_{T, \text{jet}, R=1.2}^0$	–	$> 350 \text{ GeV}$
$m_{\text{jet}, R=1.2}^0$	$> 80 \text{ GeV}$	$[140, 500] \text{ GeV}$
$m_{\text{jet}, R=1.2}^1$	$[60, 200] \text{ GeV}$	–
$m_{\text{jet}, R=0.8}^0$	$> 50 \text{ GeV}$	$[70, 300] \text{ GeV}$
$m_T^{\min}$	$> 175 \text{ GeV}$	$> 125 \text{ GeV}$
$m_T(\text{jet}^3, p_T^{\text{miss}})$	$> 280 \text{ GeV}$ for 4-jet case	–
$E_T^{\text{miss}} / \sqrt{H_T}$	–	$> 17 \sqrt{\text{GeV}}$
E_T^{miss}	$> 325 \text{ GeV}$	$> 400 \text{ GeV}$

Table 8.6: Selection criteria for SRB with four or five anti- k_t $R = 0.4$ jets, reclustered into anti- k_t $R = 1.2$ and $R = 0.8$ jets [176].

SRC

The SRC set of regions was optimised to gain and improve the sensitivity of the search to scenarios where the signal has no top decay, because the stop decays through the $b\bar{\chi}_1^\pm$ channel. In this case the discrimination power can be achieved by exploiting the different properties of the b -jets in signal and

background. Here two variants of the $m_T(b, E_T^{\text{miss}})$ variable are used: $m_T^{b, \text{min}}$, the same as in the other set of regions, and $m_T^{b, \text{max}}$, the transverse mass between the farther b -jet to the p_T^{miss} and the p_T^{miss} itself. The selection on these two variables are tight, while the requirements on the E_T^{miss} are quite loose. These regions are orthogonal to the SRA set and can be combined with them to increase the sensitivity to signal models where a considerable fraction of the stop decays is in the $b\tilde{\chi}_1^\pm$ channel and to compressed scenarios where a jet of the stop decay could not be selected due to its low momentum. The final selections of the SRC regions are summarised in Table 8.7.

	SRC1	SRC2	SRC3
anti- k_t $R = 0.4$ jets	5, $p_T > 80, 80, 35, 35, 35$ GeV		
$ \Delta\phi(b, b) $	$> 0.2\pi$		
$m_T^{b, \text{min}}$	> 185 GeV	> 200 GeV	> 200 GeV
$m_T^{b, \text{max}}$	> 205 GeV	> 290 GeV	> 325 GeV
τ veto	yes		
E_T^{miss}	> 160 GeV	> 160 GeV	> 215 GeV

Table 8.7: Selection criteria for SRC with five anti- k_t $R = 0.4$ jets [176].

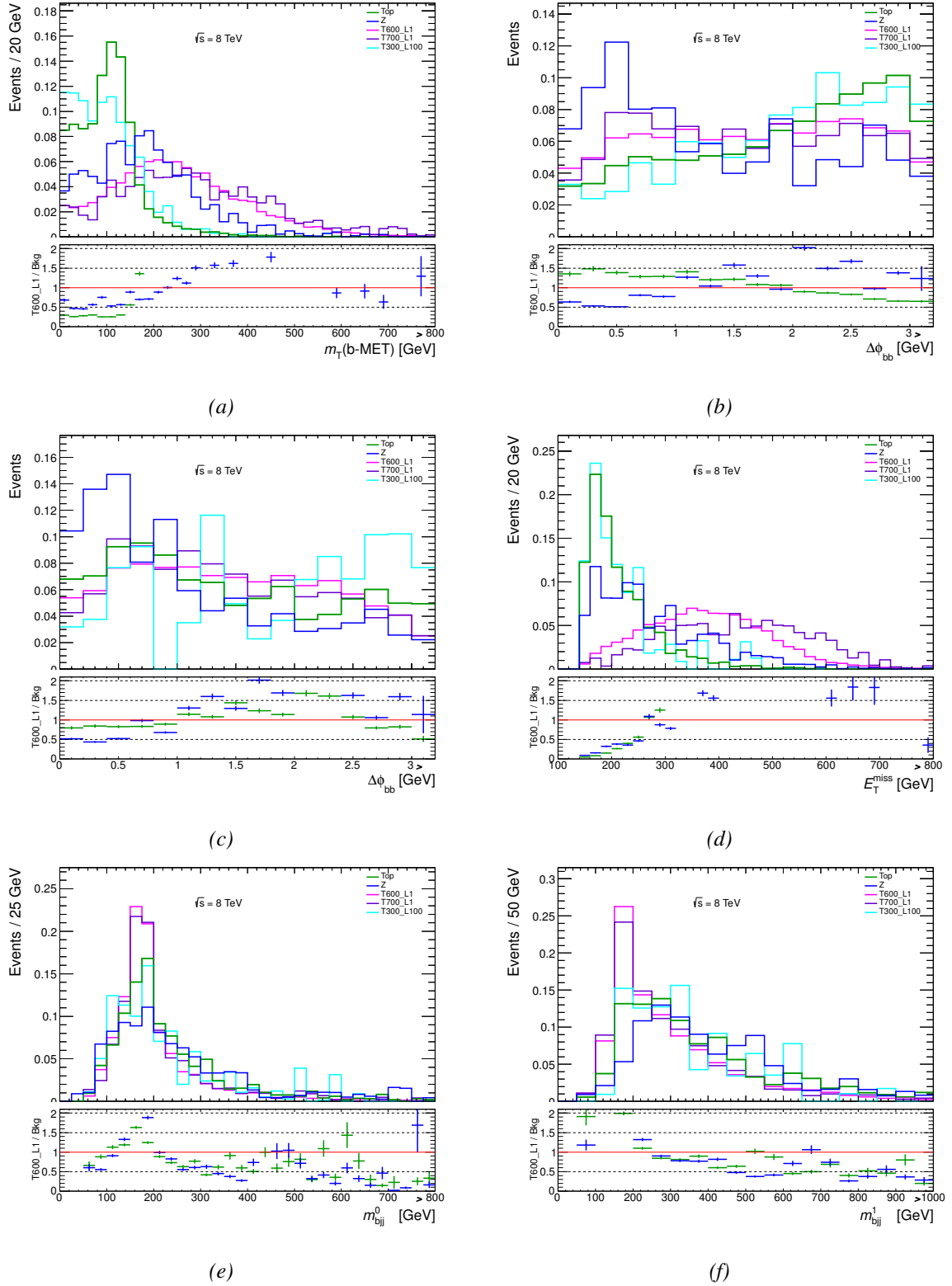


Figure 8.4: Distributions of the $m_T^{b, \min}$ (a) and $|\Delta\phi(b, b)|$ (b) variables after the six jets and $E_T^{\text{miss}} > 130$ GeV requirements, and of the $|\Delta\phi(b, b)|$ (c), E_T^{miss} (d), m_{bjj}^0 (e) and m_{bjj}^1 (f) variables after the six jets, $E_T^{\text{miss}} > 130$ GeV, and $m_T^{b, \min} > 175$ GeV requirements for the $t\bar{t}$ (green) and Z + jets (blue) backgrounds and for three signal points of the $\tilde{t} \rightarrow t\tilde{\chi}_1^0$ grid, $(m(\tilde{t}), m(\tilde{\chi}_1^0)) = (600, 1)$ GeV (pink) and $(m(\tilde{t}), m(\tilde{\chi}_1^0)) = (700, 1)$ GeV (violet), and $(m(\tilde{t}), m(\tilde{\chi}_1^0)) = (300, 100)$ GeV (light blue). The distributions are all normalised to unit area. The signal to background ratio is drawn separately for the $t\bar{t}$ and Z + jets backgrounds and the signal point chosen is $(m(\tilde{t}), m(\tilde{\chi}_1^0)) = (600, 1)$ GeV.

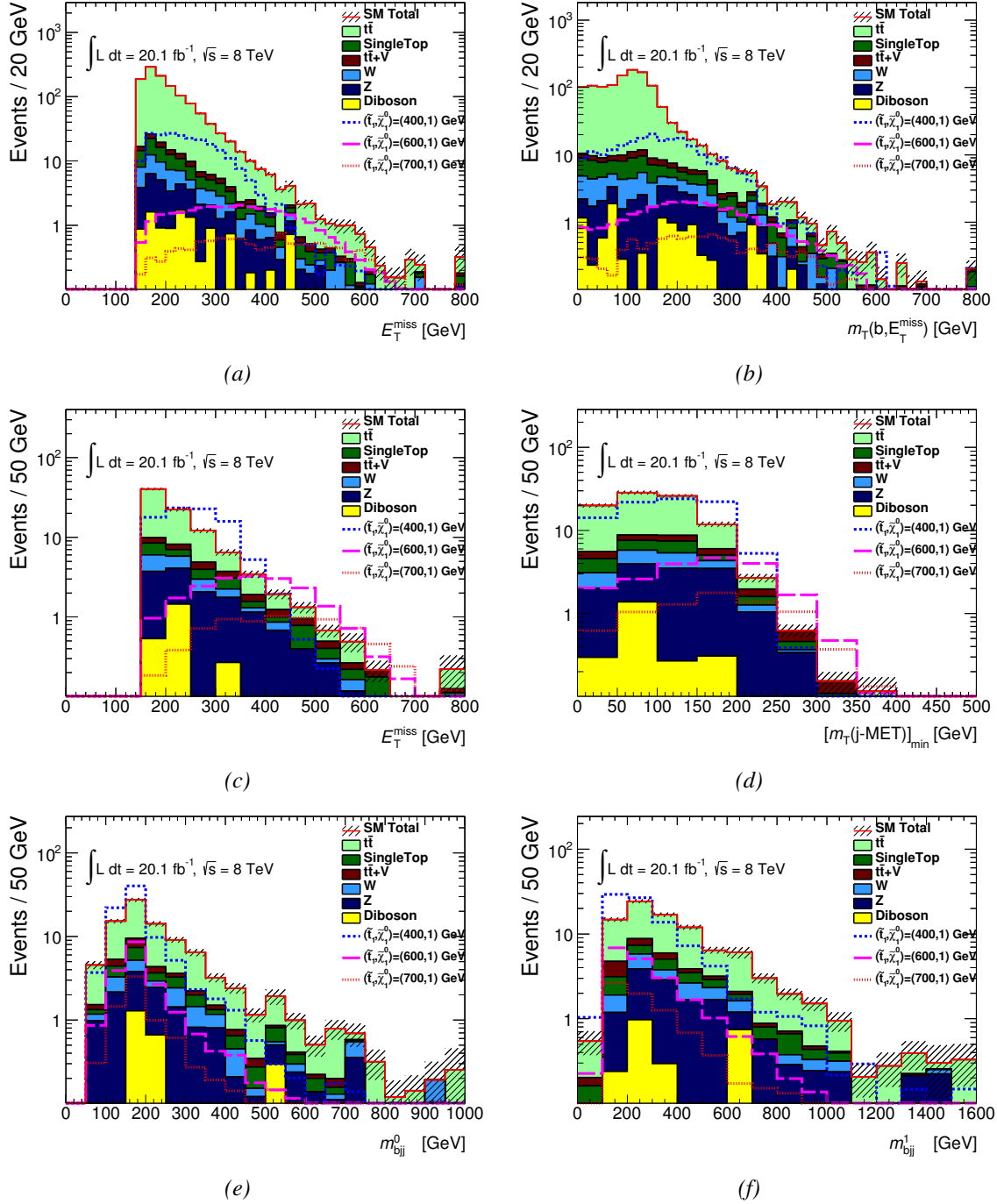


Figure 8.5: Distributions of selected discriminating variables at different stages of the selection: E_T^{miss} (a) and $m_T^{b, \min}$ (b) after the preselection, and the six jets requirements; E_T^{miss} (c), $\min [m_T(\text{jet}^i, p_T^{\text{miss}})]$ (d), $m_{b_{jj}}^0$ (e) and $m_{b_{jj}}^1$ (f) after preselection, six jets and $m_T^{b, \min}$ requirements. The background MC distributions are the coloured stacked histograms, while the signals distributions are overlaid. In each distribution three signal points are drawn: $(\tilde{t}, \tilde{\chi}_1^0) = (400, 1)$ GeV, $(\tilde{t}, \tilde{\chi}_1^0) = (600, 1)$ GeV and $(\tilde{t}, \tilde{\chi}_1^0) = (700, 1)$ GeV.

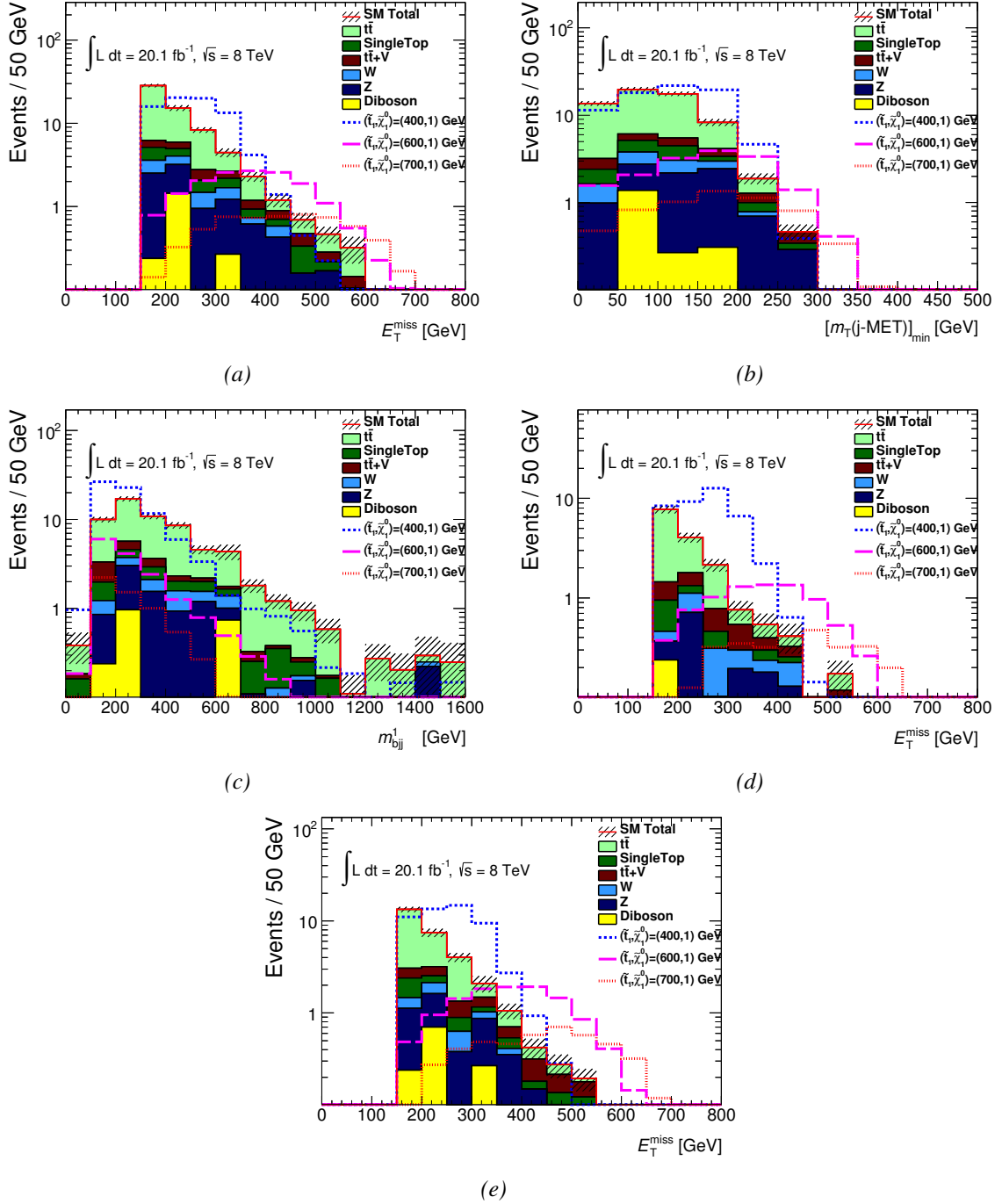


Figure 8.6: Distributions of selected discriminating variables at an advanced stage of the selection: E_T^{miss} (a), $\min[m_T(\text{jet}^i, p_T^{\text{miss}})]$ (b), and m_{bjj}^1 (c) for the events that satisfy all the basic requirements and $50 < m_{bjj}^0 < 250$ GeV; E_T^{miss} for the SRA1 (d), SRA3 (e) selections, except for the final E_T^{miss} selection. The background MC distributions are the coloured stacked histograms, while the signals distributions are overlaid. In each distribution three signal points are drawn: $(\tilde{t}, \tilde{\chi}_1^0) = (400, 1)$ GeV, $(\tilde{t}, \tilde{\chi}_1^0) = (600, 1)$ GeV and $(\tilde{t}, \tilde{\chi}_1^0) = (700, 1)$ GeV.

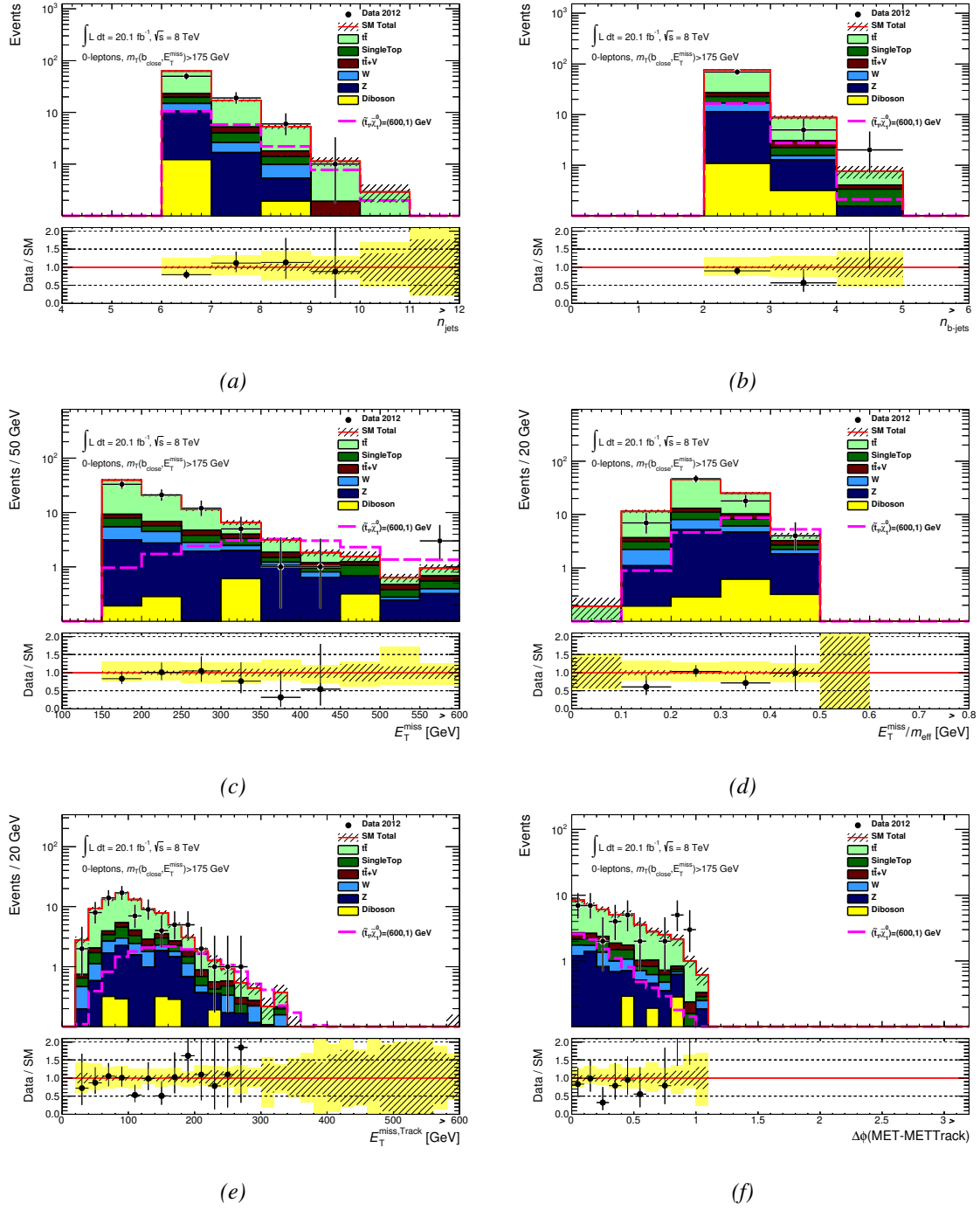


Figure 8.7: Data Monte-Carlo comparison after preselection, jets, b-jets and $m_T^{b,\min}$ selections of SRA. The shown distributions are the number of (a) jets and (b) b -tagged jets, (c) E_T^{miss} , (d) $E_T^{\text{miss}}/m_{\text{eff}}$, (e) $E_T^{\text{miss,track}}$, and (f) $|\Delta\phi(E_T^{\text{miss}}, E_T^{\text{miss,track}})|$. The data are represented by the black points and the MC is the coloured stacked histogram normalised to an integrated luminosity of 20.1 fb^{-1} . The hatched band in the “Data/SM” ratio represents the MC statistical uncertainty while the yellow band is the sum in quadrature of MC statistical uncertainty and detector systematics. The $t\bar{t}$ sample was reweighted following the procedure detailed in Paragraph 8.3.1, and the $t\bar{t}$ and Z + jets backgrounds were normalised with the normalisation factor extracted from the CR fit, see Table 8.15. The last bin contains also the overflow.

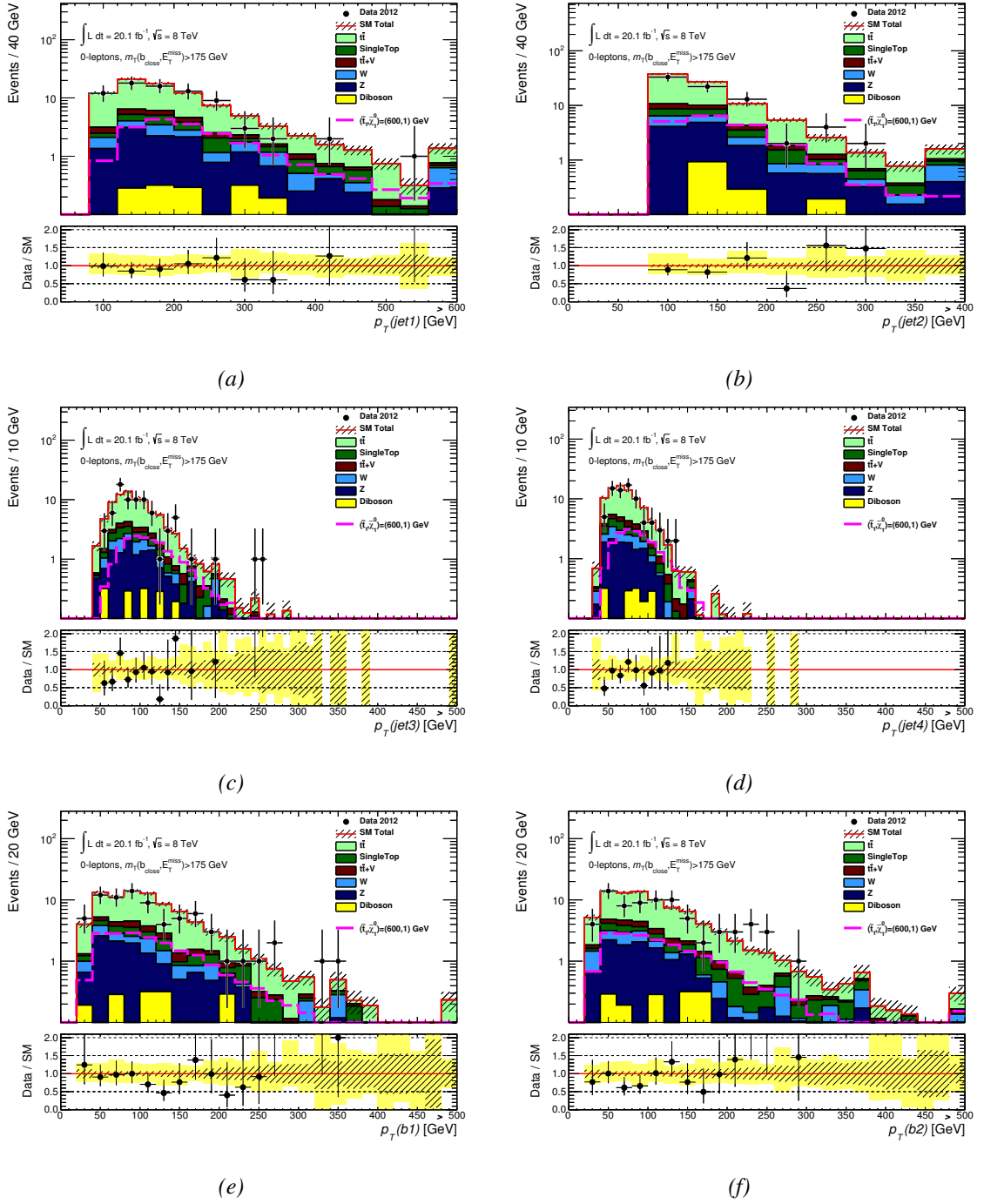


Figure 8.8: Data Monte-Carlo comparison after preselection, jets, b-jets and $m_T^{b,\min}$ selections of SRA. The shown distributions, from top to bottom, left to right, are the p_T of jets 1 to 4 and first two b-tagged jets. The data are represented by the black points and the MC is the coloured stacked histogram normalised to an integrated luminosity of 20.1 fb^{-1} . The hatched band in the “Data/SM” ratio represents the MC statistical uncertainty while the yellow band is the sum in quadrature of MC statistical uncertainty and detector systematics. The $t\bar{t}$ sample was reweighted following the procedure detailed in Paragraph 8.3.1, and the $t\bar{t}$ and Z + jets backgrounds were normalised with the normalisation factor extracted from the CR fit, see Table 8.15. The last bin contains also the overflow.

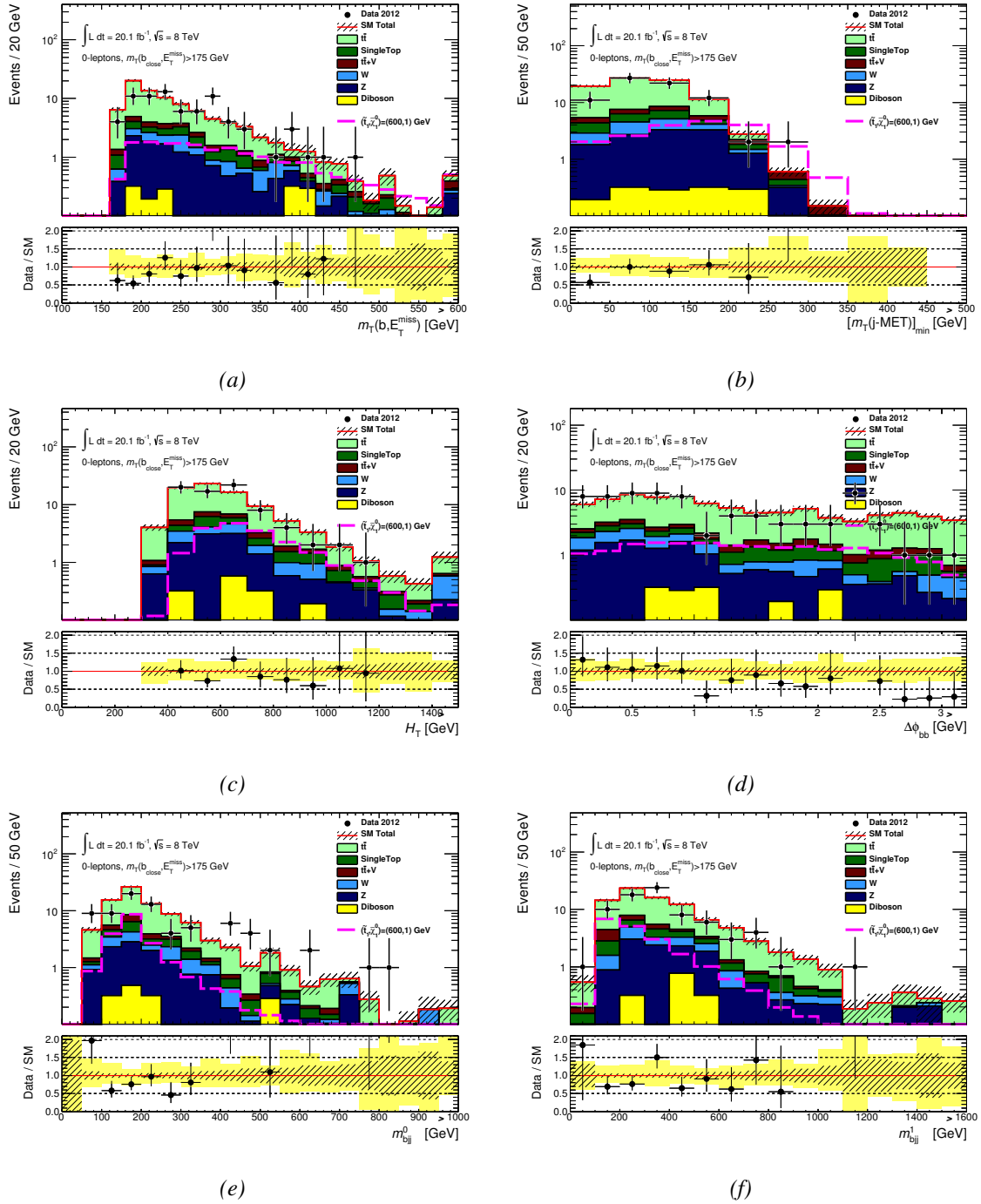


Figure 8.9: Data Monte-Carlo comparison after preselection, jets, b-jets and $m_T^{b, \min}$ selections of SRA. The shown distributions are (a) $m_T^{b, \min}$, (b) $\min[m_T(\text{jet}^i, p_T^{\text{miss}})]$, (c) H_T , (d) $|\Delta\phi(b, b)|$, and the two reconstructed hadronic top masses (e) m_{bj}^0 and (f) m_{bj}^1 . The data are represented by the black points and the MC is the coloured stacked histogram normalised to an integrated luminosity of 20.1 fb^{-1} . The hatched band in the “Data/SM” ratio represents the MC statistical uncertainty while the yellow band is the sum in quadrature of MC statistical uncertainty and detector systematics. The $t\bar{t}$ sample was reweighted following the procedure detailed in Paragraph 8.3.1, and the $t\bar{t}$ and $Z + \text{jets}$ backgrounds were normalised with the normalisation factor extracted from the CR fit, see Table 8.15. The last bin contains also the overflow.

8.3 Background Estimation

The definition of the background enriched regions and the description of the methods used to estimate the main backgrounds are presented in this section. The $t\bar{t}$ and W + jets backgrounds are estimated with standard semi data-driven techniques, the Z + jets background is estimated with a semi data-driven technique where an extrapolation is done on the fraction of selected b -jets, and the fake background is estimated with a data-driven jet smearing technique.

The $t\bar{t}$ background is discussed in Paragraph 8.3.1. Emphasis is given to the definition of the control and validation regions for the SRA and SRC set of signal regions and for the studies of the reweighting of the $t\bar{t}$ sample.

In Paragraph 8.3.2 the definition of the control region for the W + jets background in SRB is discussed, and in Paragraph 8.3.3 the method used for the Z + jets background estimation is explained. Finally the estimate of the multi-jet background is briefly discussed in Paragraph 8.3.4.

8.3.1 Semileptonic $t\bar{t}$ Background

The $t\bar{t}$ background gives the largest SM contribution in SR for the most SRA and SRC regions. It is, hence, important to design $t\bar{t}$ enriched regions where the MC can be corrected for the observation in data and that have the right balance between a large yield, to keep the statistical uncertainty as low as possible, and selections similar to the one in the signal regions to avoid large extrapolations, hence large systematic uncertainties.

The $t\bar{t}$ enriched regions are based on a one-lepton (electron or muon) selection, and the normalisation obtained there is then checked in zero lepton regions in order to prove that the use of a one-lepton control region did not bias the estimate for the lepton-veto regions.

As discussed in details later in this section, a trend in the data-MC ratio is observed for the jet and H_T distributions in the one lepton $t\bar{t}$ control regions. These variables are not directly used in the selection and no significant impact of this mismodelling is expected on the analysis results. To prove this, different reweighting strategies are tested and their effect on the estimate of the $t\bar{t}$ events in the SRs is studied. The final decision is to reweight the $t\bar{t}$ MC sample based on the ATLAS $t\bar{t}$ cross section measurement of Ref. [178] extended to the full 7 TeV ATLAS dataset as done also by the parallel stop search in one lepton final states [179]. These studies are summarised in the next paragraph after the selections for the control regions are defined.

$t\bar{t}$ Control Regions

The choice of the $t\bar{t}$ control regions for the SRA and SRC signal region sets is done based on the minimisation of the impact of the detector systematic and statistical uncertainties on the estimate of the $t\bar{t}$ contribution. The $t\bar{t}$ gives a negligible contribution in SRB, nonetheless it is necessary to define a $t\bar{t}$ CR to correctly estimate the $t\bar{t}$ background in the W + jets control region, which has a large contamination from $t\bar{t}$ events. The $t\bar{t}$ and W + jets normalisation factors for SRB are then extracted through a combined fit of the two control regions.

More details are given for the regions used to estimate the semi-leptonic $t\bar{t}$ contribution in the SRA and SRC sets of signal regions, as this is part of the work done for this thesis.

The $t\bar{t}$ control regions are defined for events containing exactly one isolated signal lepton with $p_T > 35$ GeV, that is then treated as if it was a light-jet for the QCD rejection cut and for the $t\bar{t}$ decay reconstruction.

The jet multiplicity of each CR, where the lepton is counted as one of the jets, is the same as in its cor-

responding set of SRs and also in the CRs two b -tagged jets are required. Only events with $m_T(\ell, E_T^{\text{miss}})$ in the range 40 to 120 GeV are considered. The lower bound is intended to reject multi-jet fake events, and the upper bound is needed both to select the W decay Jacobian peak, where a high $t\bar{t}$ purity can be achieved, and to select a region of the parameter space which is mutually exclusive to the signal regions of the stop search in one lepton final states [179].

The control region corresponding to the SRA set of signal regions, CRA, selects events with $E_T^{\text{miss}} > 150$ GeV, where at least one of the reconstructed top-quarks has a mass below 600 GeV, in order to reject events which have been clearly wrongly reconstructed, and with $m_T^{b, \text{min}} > 125$ GeV. A single CR was defined for all signal regions because this turns out to be the region with the best balance between statistical uncertainty and cancellation of systematic-uncertainty effects between control and signal regions. A tighter E_T^{miss} selection could have been used for the tight SRs but it was found that the selected sample would be too small and affected by high statistical uncertainties. Moreover, it is better to apply a tight selection on the $m_T^{b, \text{min}}$ variable than on the E_T^{miss} because the $m_T^{b, \text{min}}$ requirement changes sensibly the topology of the selected events.

For the control region corresponding to the SRB, CRB, on top of the common selections, the requirements to be satisfied are to select two reclustered $R = 1.2$ jets, corresponding to the top candidates, and to have $E_T^{\text{miss}} > 150$ GeV.

The requirements for the control region used to estimate the $t\bar{t}$ contribution in the SRC set, CRC, are $|\Delta\phi(b, b)| > 0.2\pi$, $E_T^{\text{miss}} > 100$ GeV, $m_T^{b, \text{min}} > 150$, and $m_T^{b, \text{max}} > 125$. Since the selections on the transverse mass variables change the topological properties of the events, also for this region it is more important to have tight requirements on the $m_T(b, E_T^{\text{miss}})$ variables than on the missing transverse momentum.

The selections of the three $t\bar{t}$ control regions are summarised in Table 8.8. It can be observed that the selections to reject multi-jet events are looser than for the signal region selections, and that no requirement on the E_T^{miss} measured in the inner detector is applied.

Selection	CRA	CRB	CRC
Trigger	single electron or muon trigger		
Lepton Selection	1 lepton $p_T(\ell) > 35\text{GeV}$, treated as a jet		
n_{jets} , included lepton	≥ 6	4 or 5	5
Jet p_T [GeV]	$> 80, 80, 35, 35, 35, 35$	$> 80, 80, 35, 35$	$> 80, 80, 35, 35, 35$
QCD Rejection	$\min \Delta\phi(\text{jet}^{0-2}, E_T^{\text{miss}}) > 0.1\pi$ (anti- k_t $R = 0.4$)		
$n_{b\text{-jets}}$	≥ 2		
$m_T(\ell, E_T^{\text{miss}})$ [GeV]	$40 < m_T(\ell, E_T^{\text{miss}}) < 120$		
Top Reconstruction [GeV]	m_{bjj}^0 OR $m_{bjj}^1 < 600$	≥ 2 $R = 1.2$ jets	-
$ \Delta\phi(b, b) $	-	-	$> 0.2\pi$
E_T^{miss} [GeV]	> 150	> 150	> 100
$m_T^{b, \text{min}}$ [GeV]	> 125	-	> 150
$m_T^{b, \text{max}}$ [GeV]	-	-	> 125

Table 8.8: Summary of the selection for the $t\bar{t}$ 1-lepton control regions.

It was observed that, for a loose one lepton selection, the H_T distribution as well as some of the jet p_T distributions showed a significant trend in the data-MC ratio. The data-MC comparison for events with one selected signal lepton, five real jets of which two b -tagged, $E_T^{\text{miss}} > 100$ GeV, that passed

also the QCD cleaning selection $\min|\Delta\phi(\text{jet}^{0-2}, E_T^{\text{miss}})| > 0.1\pi$, is shown for the H_T distribution in Fig. 8.10. The distribution shown in (b) is the same as in (a) but with broader bins to decrease the statistical uncertainty of the events in each bin. The linear fit of the “Data/SM” ratio, $f(H_T) = a + b \cdot H_T$, results in a slope $b = (-4.64 \pm 0.8) \cdot 10^{-4}$ which is not compatible with a constant value. Even though no extrapolation is done between the control and the signal regions neither on the H_T variable nor on the p_T of the selected jets, it was decided to check the effect of a reweighting of the $t\bar{t}$ sample, done to reabsorb the observed trend, on the final results.

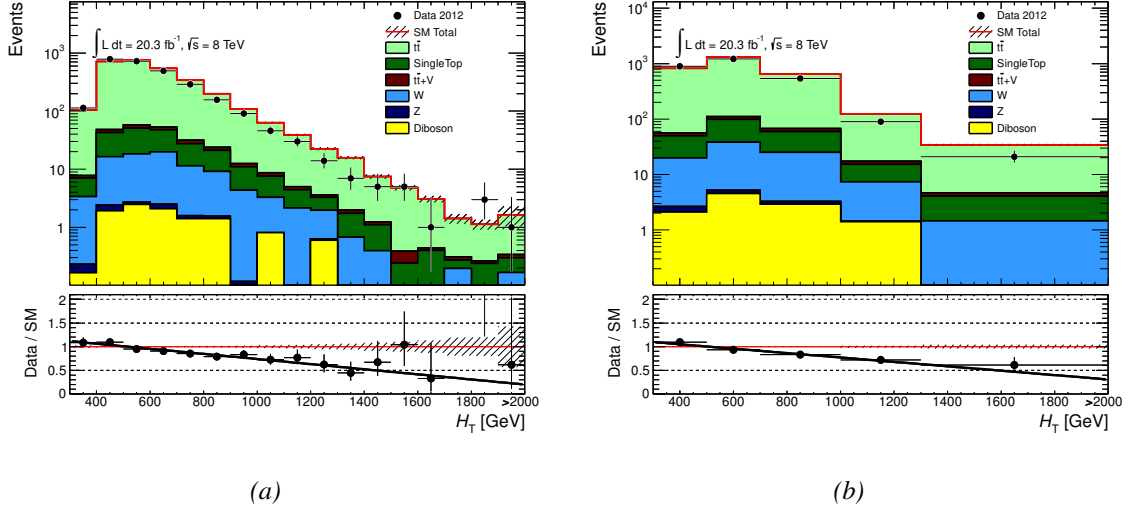


Figure 8.10: Data-Monte Carlo comparison for the H_T variable (a) with normal binning and (b) with the binning chosen to extract the weights to be applied to the $t\bar{t}$ events. The data are represented by the black points and the MC is the coloured stacked histogram normalised to an integrated luminosity of 20.3 fb^{-1} . The hatched band represents the MC statistical uncertainty. The last bin contains also all events with $H_T > 2 \text{ TeV}$.

$t\bar{t}$ Sample Reweighting

Three different reweighting possibilities were tested. One based on the fit of the slope in the data-MC ratio in the H_T distribution of Fig. 8.10, one based on the minimisation of the χ^2 distribution representing the compatibility of the data and MC histograms for selected variables by mean of a scan of weights to be assigned to the $t\bar{t}$ events, and one based on the assignment of weights to the $t\bar{t}$ events based on the $t\bar{t}$ cross section measurement of Ref. [178]. In both the second and third case the weights are defined as a function of the p_T of the truth $t\bar{t}$ system.

The effects of the reweighting are analogous for all the approaches and it was decided to use the one based on the $t\bar{t}$ ATLAS differential cross section measurement. The weights applied to the simulated $t\bar{t}$ events are the mean of the weights extracted in the one electron and one muon channels, and can be read from the last column of Table 8.9.

The effects of the reweighting on the H_T , leading and sub-leading jet p_T distributions can be seen in Fig. 8.11 for a selection corresponding to the $t\bar{t}$ CRA with no requirement on $m_T^{b,\text{min}}$ applied. In these figures only the MC statistical uncertainty is shown with the grey hatched bands. The trend observed in the data-MC ratio distributions with the nominal $t\bar{t}$ MC sample, (a) H_T , (c) $p_T(\text{jet1})$, (e) $p_T(\text{jet2})$, almost completely disappears after the weights have been applied, (b) H_T , (d) $p_T(\text{jet1})$, (f) $p_T(\text{jet2})$. The χ^2/ndf of the H_T and of the sub-leading jet p_T distributions also slightly improve after applying the weights based on the true p_T of the $t\bar{t}$ system.

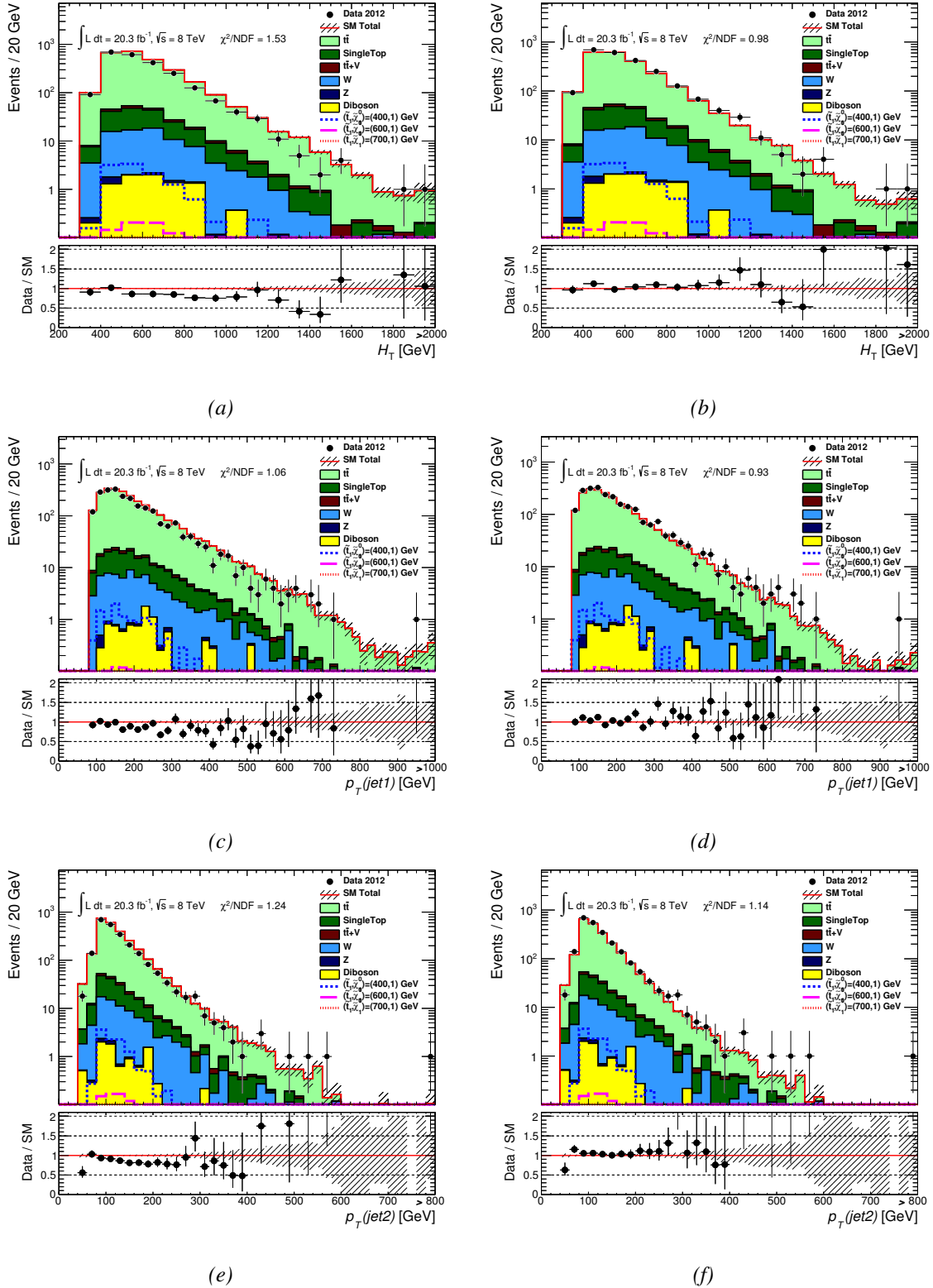


Figure 8.11: Distributions of the (a) H_T , (c) $p_T(\text{jet1})$, (e) $p_T(\text{jet2})$ variables for the nominal $t\bar{t}$ sample and of the (b) H_T , (d) $p_T(\text{jet1})$, (f) $p_T(\text{jet2})$ distributions for the reweighted $t\bar{t}$ MC sample. The events are selected based on the $t\bar{t}$ CRA requirements with no cut on $m_T^{b,\min}$ applied. The background SM samples are stacked and normalised to an integrated luminosity of 20.3 fb⁻¹ and the hatched band represent the MC statistical uncertainty.

$t\bar{t} p_T$ bin [GeV]	weight 1-electron	weight 1-muon	weight average
0-40	0.988	1.006	0.997
40-170	0.912	0.967	0.939
170-340	0.710	0.758	0.734
>340	0.556	0.584	0.570

Table 8.9: Event weights extracted from the Top differential cross section measurement to be applied to the $t\bar{t}$ events depending on the truth p_T of the system for 1 electron, 1 muon events and for the mean of the two weights.

The event yields in CRA and in CRC are summarised in Table 8.11 for the nominal and reweighted $t\bar{t}$ MC sample. The number of observed data events is also shown and the $t\bar{t}$ normalisation factor can be extracted both for the nominal and for the reweighted sample. The normalisation factor for CRA changes from $NF_{t\bar{t}}^A = 1.00 \pm 0.08$ for the nominal sample to $NF_{t\bar{t}}^{A,RW} = 1.23 \pm 0.10$ for the reweighted sample. The normalisation factors extracted in CRC are $NF_{t\bar{t}}^C = 0.96 \pm 0.07$ for the nominal sample and $NF_{t\bar{t}}^{C,RW} = 1.06 \pm 0.08$ for the reweighted sample.

The effect of the reweighting on the expected number of $t\bar{t}$ events in the SRA and SRC regions is summarised in Table 8.10. The MC yields for the nominal and the reweighted $t\bar{t}$ samples normalised with the factor extracted in the control regions are compatible within statistical uncertainty. This shows the robustness of the designed control regions, which, having a similar topology to the signal regions, properly correct the normalisation of the MC simulation even though the shape of some distributions (not used for the extrapolation) is not perfectly described by the MC simulation.

SR		$t\bar{t}$ nominal	$t\bar{t}$ with cross section weight
SRA1	MC	10.42 ± 0.76	8.64 ± 0.63
	MC· $NF_{t\bar{t}}$	10.42	10.68
SRA2	MC	1.88 ± 0.33	1.47 ± 0.26
	MC· $NF_{t\bar{t}}$	1.88	1.81
SRA3	MC	1.15 ± 0.25	0.85 ± 0.19
	MC· $NF_{t\bar{t}}$	1.15	1.04
SRA4	MC	0.54 ± 0.16	0.40 ± 0.12
	MC· $NF_{t\bar{t}}$	0.54	0.49
SRC1	MC	57.35 ± 1.77	49.50 ± 1.54
	MC· $NF_{t\bar{t}}$	55.06	52.47
SRC2	MC	27.37 ± 1.23	23.23 ± 1.05
	MC· $NF_{t\bar{t}}$	26.27	24.62
SRC3	MC	14.00 ± 0.88	11.59 ± 0.73
	MC· $NF_{t\bar{t}}$	13.44	12.28

Table 8.10: $t\bar{t}$ yields in each of the SRA and SRC signal regions for the nominal and the reweighted samples. The MC yields are normalised to an integrated luminosity of 20.1 fb^{-1} . The pure MC yields are given together with the yields obtained normalising the MC to data in the control regions.

The yields in the $t\bar{t}$ CRA and CRC are summarised in Table 8.11. The MC yields have been normalised to an integrated luminosity of 20.3 fb^{-1} and summed over electron and muon channels. Both the nominal and reweighted $t\bar{t}$ yields are reported. The purity of the control regions is almost 80% and the other main contributions come from $W + \text{jets}$ and Single Top events which contribute for 18% in CRA

and 21% in CRC. The signal contamination in these control regions is maximal for the signal point $m(\tilde{t}) = 400$ GeV, $m(\tilde{\chi}_1^0) = 1$ GeV but always below one percent.

The normalisation factors extracted from the final control regions with the $t\bar{t}$ sample reweighting applied are, as reported above, $NF_{t\bar{t}}^A = 1.23 \pm 0.10$ and $NF_{t\bar{t}}^C = 1.06 \pm 0.08$.

Contribution	CRA	CRC
Observed	247	313
Top	196.67 ± 3.26	248.90 ± 3.67
Top Reweighted	160.65 ± 2.80	226.04 ± 3.46
Single Top	24.55 ± 0.97	40.53 ± 1.28
W	20.02 ± 1.13	28.41 ± 1.54
Dibosons	1.38 ± 0.51	2.48 ± 0.80
$t\bar{t} + V$	3.62 ± 0.13	2.24 ± 0.11
Z	0.31 ± 0.15	0.17 ± 0.08
TotMC	249.09 ± 3.75	322.74 ± 4.26
TotMC with Top Reweighted	213.07 ± 3.35	299.89 ± 4.08

Table 8.11: Event Yield in the Top control regions CRA and CRC selection normalised to a luminosity of 20.3 fb^{-1} and summed over electrons and muons. For Top both the nominal and the reweighted MC yields are given.

The data-MC comparisons of the key variables of the $t\bar{t}$ CRA and CRC are shown in Figs. 8.12 and 8.13, respectively.

The distributions shown for the CRA, Fig. 8.12, are the E_T^{miss} (a), $m_{b\bar{b}}^0$ (b), $m_T^{b,\text{min}}$ (c), $m_{b\bar{b}}^1$ (d), $n_{b\text{-jets}}$ (e), and H_T (f). In the $n_{b\text{-jets}}$ distributions the needed normalisation factor of about 1.2 for the $t\bar{t}$ background is clearly visible. The data-MC agreement is in general good and well within the uncertainties. From the last two figures the very low signal contamination can be appreciated, being the blue line the histogram for the signal point $m(\tilde{t}) = 400$ GeV, $m(\tilde{\chi}_1^0) = 1$ GeV.

The chosen distributions for the CRC, Fig. 8.13, are the E_T^{miss} (a), $m_T^{b,\text{max}}$ (b), $m_T^{b,\text{min}}$ (c), $|\Delta\phi(b, b)|$ (d), leading jet p_T (e), and H_T (f). All the region selections have been applied, except in the $|\Delta\phi(b, b)|$ figure where the selection on $|\Delta\phi(b, b)|$ itself was dropped. A very good data-MC agreement and no significant trends in the data/MC ratios are observed for all distributions.

Given that the shape of the distributions of the variables used to extrapolate the $t\bar{t}$ estimate from the control to the signal regions are well described by MC simulation, the semi-leptonic $t\bar{t}$ background estimation is regarded to be robust. To this statement contributes also the knowledge that, albeit a reweighting of the $t\bar{t}$ sample has been applied, the estimate in the signal regions remains compatible with the results obtained directly with the nominal $t\bar{t}$ MC sample.

The $t\bar{t}$ normalisation factor extracted from the combined fit of CRB and of the $W + \text{jets}$ CR, see Subsection 8.3.2, is $NF_{t\bar{t}}^B = 1.00^{+0.10}_{-0.05}$ and the yields in this region are reported in the final CR table, Table 8.16. Data-MC comparisons of selected distributions are shown in Fig. 8.14 for the E_T^{miss} (a), $m_{\text{jet}, R=1.2}^0$ (b), $m_T^{b,\text{min}}$ (c), $E_T^{\text{miss}} / \sqrt{H_T}$ (d) variables. All distributions show a good data-MC agreement and no significative trends in the ratio of the data to the expected SM are observed.

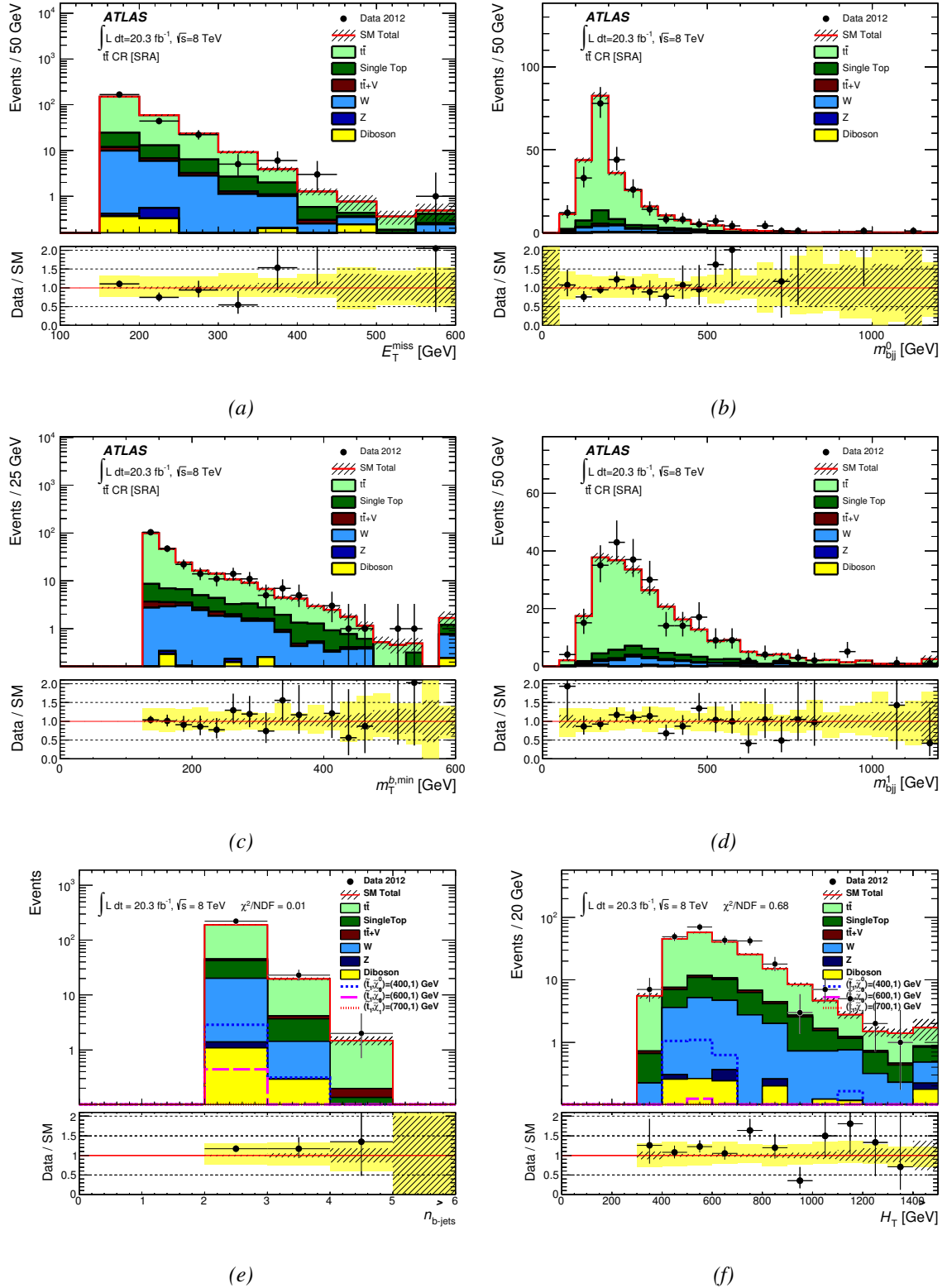


Figure 8.12: Data-MC comparisons in the $t\bar{t}$ CR region of the E_T^{miss} (a), $m_{b\bar{b}}^0$ (b), $m_T^{b,\text{min}}$ (c), $m_{b\bar{b}}^1$ (d), $n_{b\text{-jets}}$ (e), and H_T (f) distributions. All the region selection have been applied, except in the $|\Delta\phi(b, b)|$ figure where the selection on $|\Delta\phi(b, b)|$ itself was dropped. The background samples are stacked and normalised to an integrated luminosity of 20.3 fb^{-1} . The $t\bar{t}$ and Z + jets normalisation factors extracted from the global fit, see Table 8.15, are applied in the figures (a) to (d), but not in the last two. The last bin includes all overflows, the hatched uncertainty band represents the SM statistical uncertainty and the yellow band drawn in the “Data/SM” ratios represents the sum in quadrature of statistical and detector-related systematic uncertainties [176].

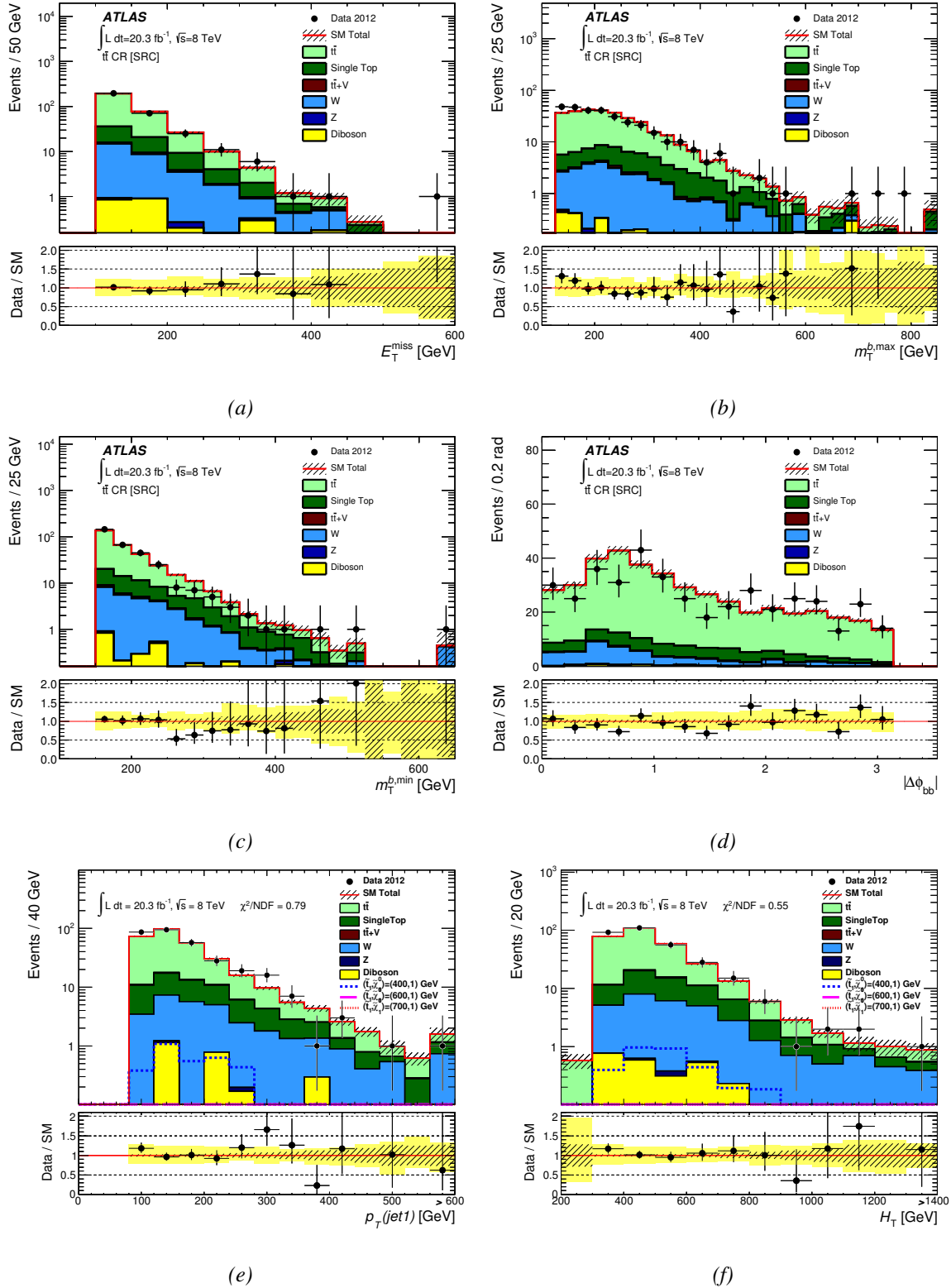


Figure 8.13: Data-MC comparisons in the $t\bar{t}$ CRC region of the E_T^{miss} (a), $m_T^{b,\text{max}}$ (b), $m_T^{b,\text{min}}$ (c), $|\Delta\phi(b,b)|$ (d), leading jet p_T (e), and H_T (f) distributions. All the region selection have been applied. The background samples are stacked and normalised to an integrated luminosity of 20.3 fb⁻¹. The $t\bar{t}$ and Z + jets normalisation factors extracted from the global fit, see Table 8.15, are applied in the figures (a) to (d), but not in the last two. The last bin includes all overflows, the hatched uncertainty band represents the SM statistical uncertainty and the yellow band drawn in the “Data/SM” ratios represents the sum in quadrature of statistical and detector-related systematic uncertainties [176].

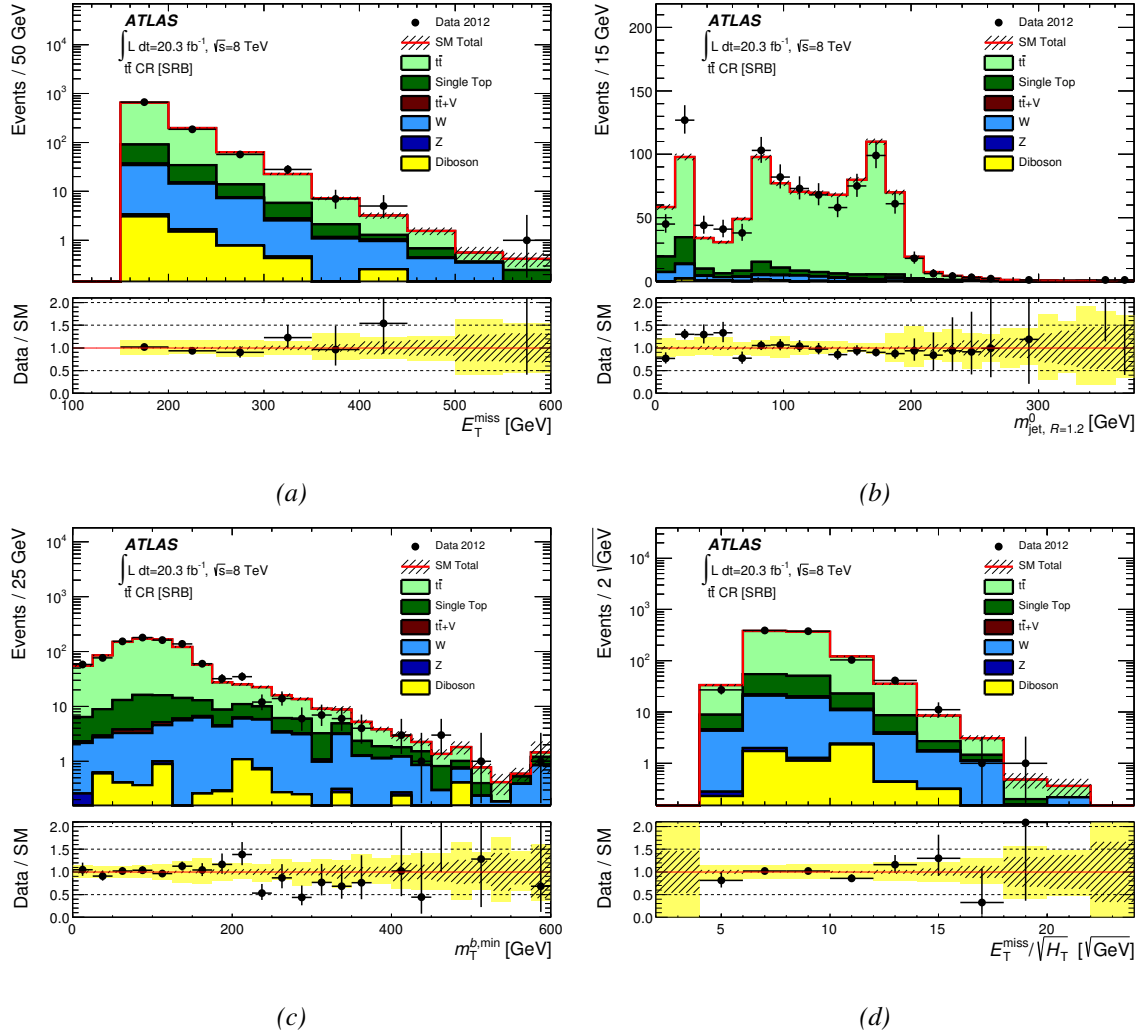


Figure 8.14: Data-MC comparisons in the $t\bar{t}$ CRB region of the E_T^{miss} (a), $m_{\text{jet}, R=1.2}^0$ (b), $m_T^{b, \text{min}}$ (c), $E_T^{\text{miss}} / \sqrt{H_T}$ (d) distributions. All the region selection have been applied. The background samples are stacked and normalised to an integrated luminosity of 20.3 fb^{-1} . The $t\bar{t}$, W + jets, and Z + jets normalisation factors extracted from the global fit, see Table 8.15, are applied in the figures. The last bin includes all overflows, the hatched uncertainty band represents the SM statistical uncertainty and the yellow band drawn in the “Data/SM” ratios represents the sum in quadrature of statistical and detector-related systematic uncertainties [176].

$t\bar{t}$ Validation Regions

The $t\bar{t}$ control regions have been chosen as one-lepton regions because the $t\bar{t}$ contribution in the signal regions arises from the semi-leptonic decay of the $t\bar{t}$ system. It is, though, not sure that the observed behaviour in a leptonic region is the same as in a region where a lepton veto is applied. Moreover, between one third and an half of the selected $t\bar{t}$ events in the signal region come from the decay of one top quark in a b -jet, a τ lepton and a ν_τ , with the τ lepton decaying into hadrons, and these events are not directly considered in the control regions introduced above.

For these reasons a set of $t\bar{t}$ validation regions was designed to check if the normalisation extracted in the $t\bar{t}$ control region was universal and if the MC described well the shape of the distributions also in

these regions, which are more similar to the final signal regions. These regions were not used directly as control regions because of the small number of events populating them, and of the signal contamination which is larger than in the one-lepton CRs and can be as high as 30%.

The selections applied to define the validation regions are summarised in Table 8.12. For completeness the validation region selections for the SRB set are also given but no further details are discussed, nor distributions shown.

For both the regions A and C two $t\bar{t}$ validation regions were defined; one with all the signal region selections applied but in a region of $m_T^{b,\min}$ delimited from the cut on this variable in the CR from below and by the the signal region selection from above, VRA1 and VRC1; the other where events containing a tau candidate are selected, VRA2 and VRC2. For the VRA2 it was possible to apply all the common signal region selections, except for the requirements on the reconstructed top masses, and just revert the tau veto; this was not possible for VRC2, though, because of a too large signal contamination which could reach the 50% level.

Selection	TopVRA-Mt (VRA1)	VRA-Tau (VRA2)	VRB (VRB)	VRC-Mt (VRC1)	VRC-Tau (VRC2)
n_{jets}	≥ 6		4 or 5	5	
jets p_{T} (GeV)	Leading two jets with $p_{\text{T}} > 80.$, $80.$, remaining jets $p_{\text{T}} >, 35.$				
$n_{b\text{-jets}}$	≥ 2				
$ \Delta\phi(b, b) $	-		-	$> 0.2 \pi$	
τ lepton	Veto	Anti Veto	-	Veto	Anti Veto
$m_{\text{T}}^{b, \text{min}}$ (GeV)	[125., 175.]	$> 175.$	-	[150., 185.]	
$m_{\text{T}}^{b, \text{max}}$ (GeV)	-		-	> 125	
$E_{\text{T}}^{\text{miss}}$ (GeV)	$> 150.$				

Table 8.12: Top VR selections for signal region A, B and C.

The background and data yields for the VRA, VRB and VRC regions are presented in Table 8.17 as a results of the analysis combined fit. The numbers are normalised to an integrated luminosity of 20.1 fb^{-1} and the $t\bar{t}$ and $Z + \text{jets}$ normalisation factors extracted from the control regions are also applied. The observed data are compatible with the estimated background in all the regions. A difference of about 1.2 standard deviations is observed in VRA1, while in all the other regions the deviation does not exceed one sigma. The $t\bar{t}$ purity of these regions varies between the almost 70% of VRA2 and the 90% of VRA1.

Data-MC comparisons in the validation regions are shown in Figs. 8.15 to 8.18.

The chosen distributions for VRA1 are presented in Fig. 8.15 and are E_T^{miss} (a), H_T (b), leading (c) and sub-leading (d) jet p_T , m_{bjj}^0 (e), and m_{bjj}^1 (f). No significative trends can be observed in the ratios, but the small overshoot of the MC is visible at low values of E_T^{miss} , and low p_T of the jets.

For VRA2, Fig. 8.16, the selected distributions are E_T^{miss} (a), H_T (b), leading jet p_T (c), $m_T^{b,\min}$ (d), m_{bjj}^0 (e), and m_{bjj}^1 (f). Here the data-MC agreement is in general good in all chosen distributions and no significative trends are visible in the ratios.

The distributions of VRC1 are shown in Fig. 8.17 for the E_T^{miss} (a), H_T (b), leading jet p_T (c), and $m_T^{b,\max}$ (d) variables. Also here the data-MC agreement is good in all distributions.

Finally, the data-MC comparisons in VRC2 are shown in Fig. 8.18 for the E_T^{miss} (a), H_T (b), leading jet p_T (c), and $m_T^{b,\max}$ (d) variables. Despite the very low number of events selected in this region the agreement between data and expected SM background is very good.

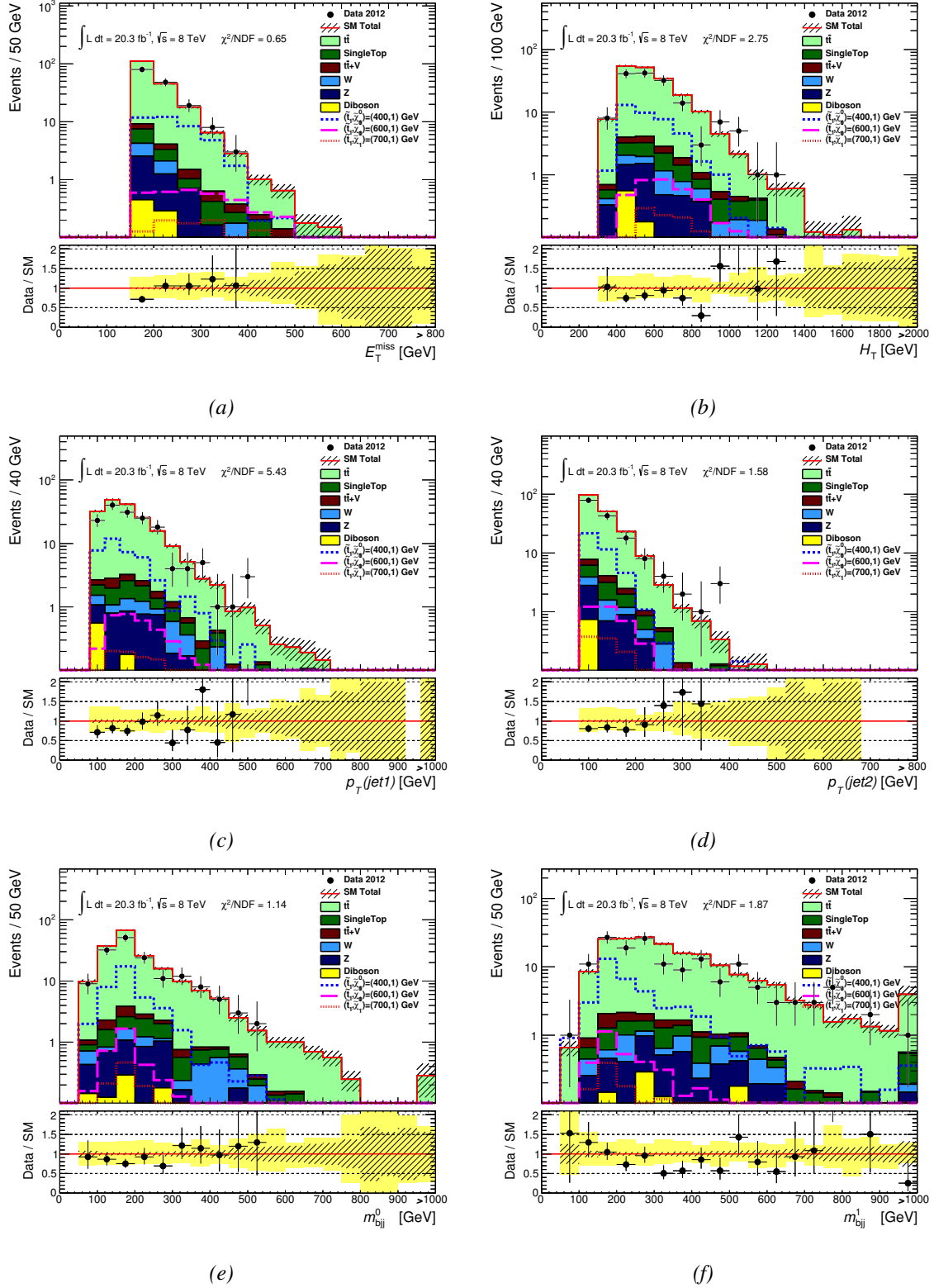


Figure 8.15: Data-Monte Carlo comparisons in VRA1 for the E_T^{miss} (a), H_T (b), leading (c) and subleading (d) jet p_T , $m_{b_{jj}}^0$ (e), and $m_{b_{jj}}^1$ (f) distributions. The data are represented by the black points and the MC is the coloured stacked histogram normalised to an integrated luminosity of 20.1 fb^{-1} and the $t\bar{t}$ and Z + jets normalisation factors have been applied, see Table 8.15. The hatched band represents the MC statistical uncertainty while the yellow band is the sum of MC statistical uncertainty and detector systematics. The last bin contains also the overflow.

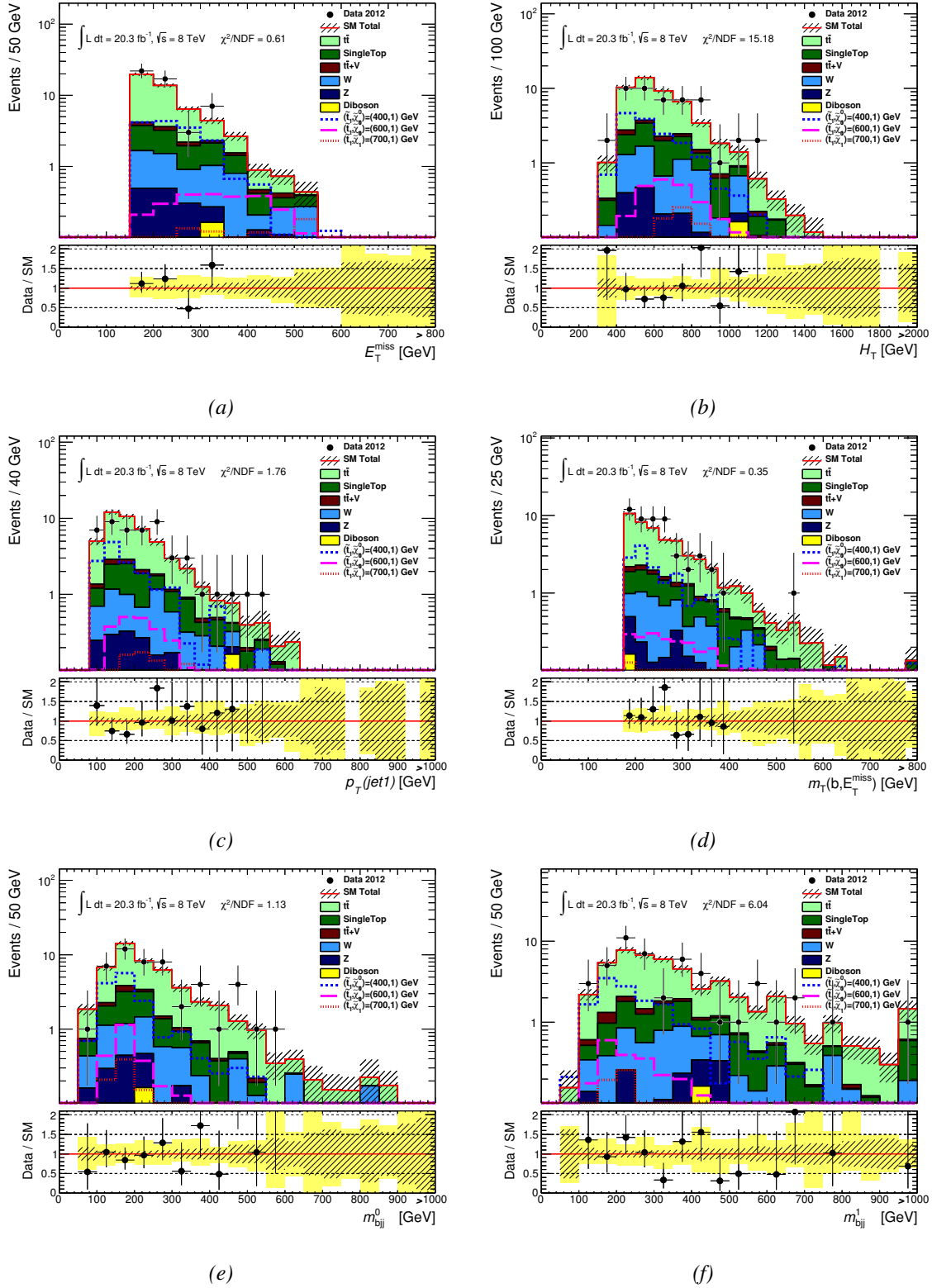


Figure 8.16: Data-Monte Carlo comparisons in VRA2 for the E_T^{miss} (a), H_T (b), leading jet p_T (c), $m_T^{\text{b}, \text{min}}$ (d), $m_{b_{jj}}^0$ (e), and $m_{b_{jj}}^1$ (f) distributions. The data are represented by the black points and the MC is the coloured stacked histogram normalised to an integrated luminosity of 20.1 fb^{-1} and the $t\bar{t}$ and Z + jets normalisation factors have been applied, see Table 8.15. The hatched band represents the MC statistical uncertainty while the yellow band is the sum of MC statistical uncertainty and detector systematics. The last bin contains also the overflow.

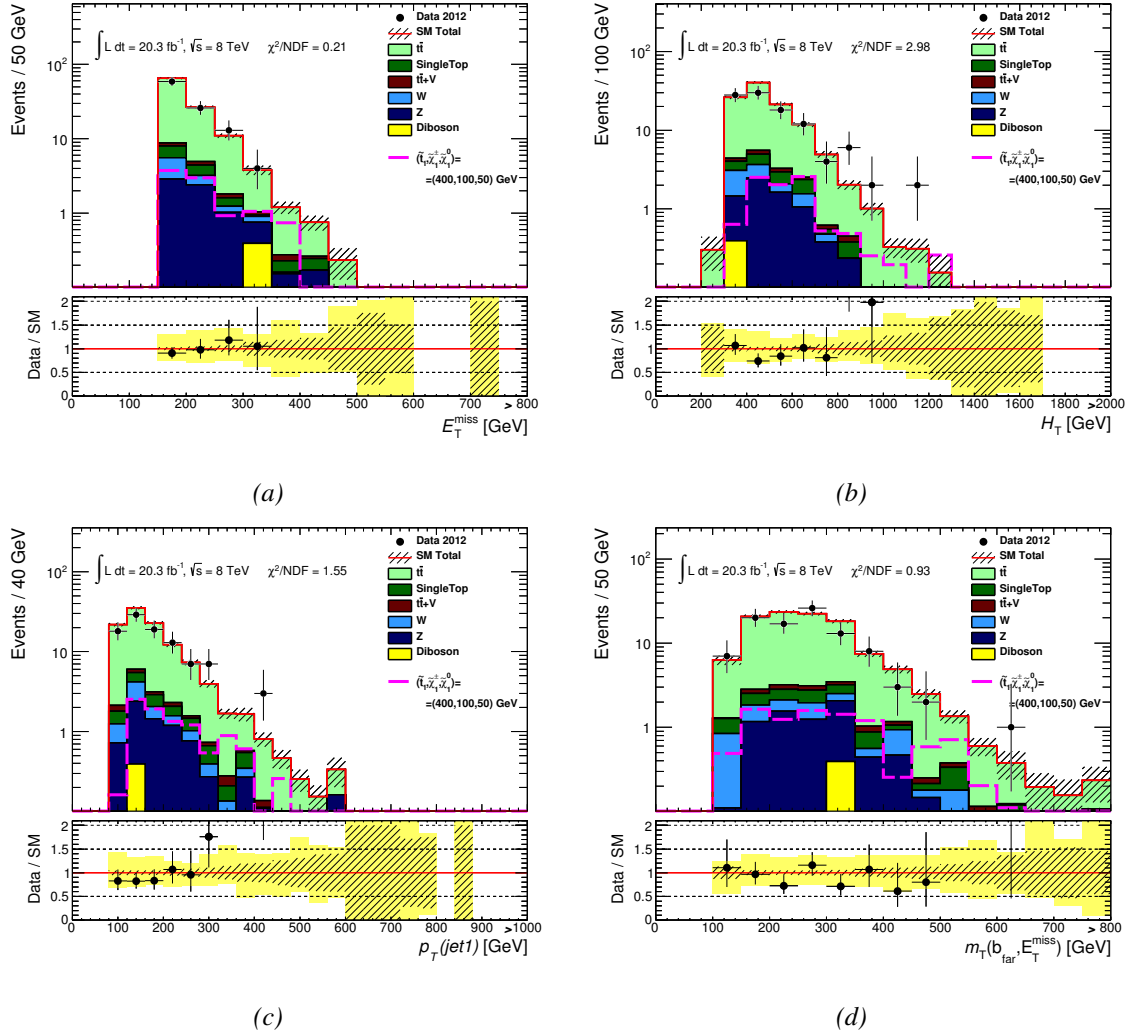


Figure 8.17: Data-Monte Carlo comparisons in VRC1 for the E_T^{miss} (a), H_T (b), leading jet p_T (c), and $m_T^{b,\text{max}}$ (d) distributions. The data are represented by the black points and the MC is the coloured stacked histogram normalised to an integrated luminosity of 20.1 fb^{-1} and the $t\bar{t}$ and Z + jets normalisation factors have been applied, see Table 8.15. The hatched band represents the MC statistical uncertainty while the yellow band is the sum of MC statistical uncertainty and detector systematics. The last bin contains also the overflow.

8.3.2 W + jets Background

Since the W + jets contribution in the regions of the SRA and SRC sets is always below 15% of the total background, no dedicated W + jets CRs were designed and its contribution in the SRs was estimated directly from simulated samples. A W control region was, instead, defined to estimate the W + jets background in SRB, since it contributes for more than 20% of the total SM expectation. This is a one lepton region where the events are selected based on similar requirements as those of the $t\bar{t}$ control region with the differences of asking only for at least one b -tagged jet, needed to increase the W + jets purity in the region, and of selecting only events with a top mass asymmetry below 0.5. It is also required that the mass of the first jet with recluster parameter 1.2 is below 40 GeV. The selection is summarised in Table 8.13. The W purity reached in this region is of about 50%, and almost all remaining events are

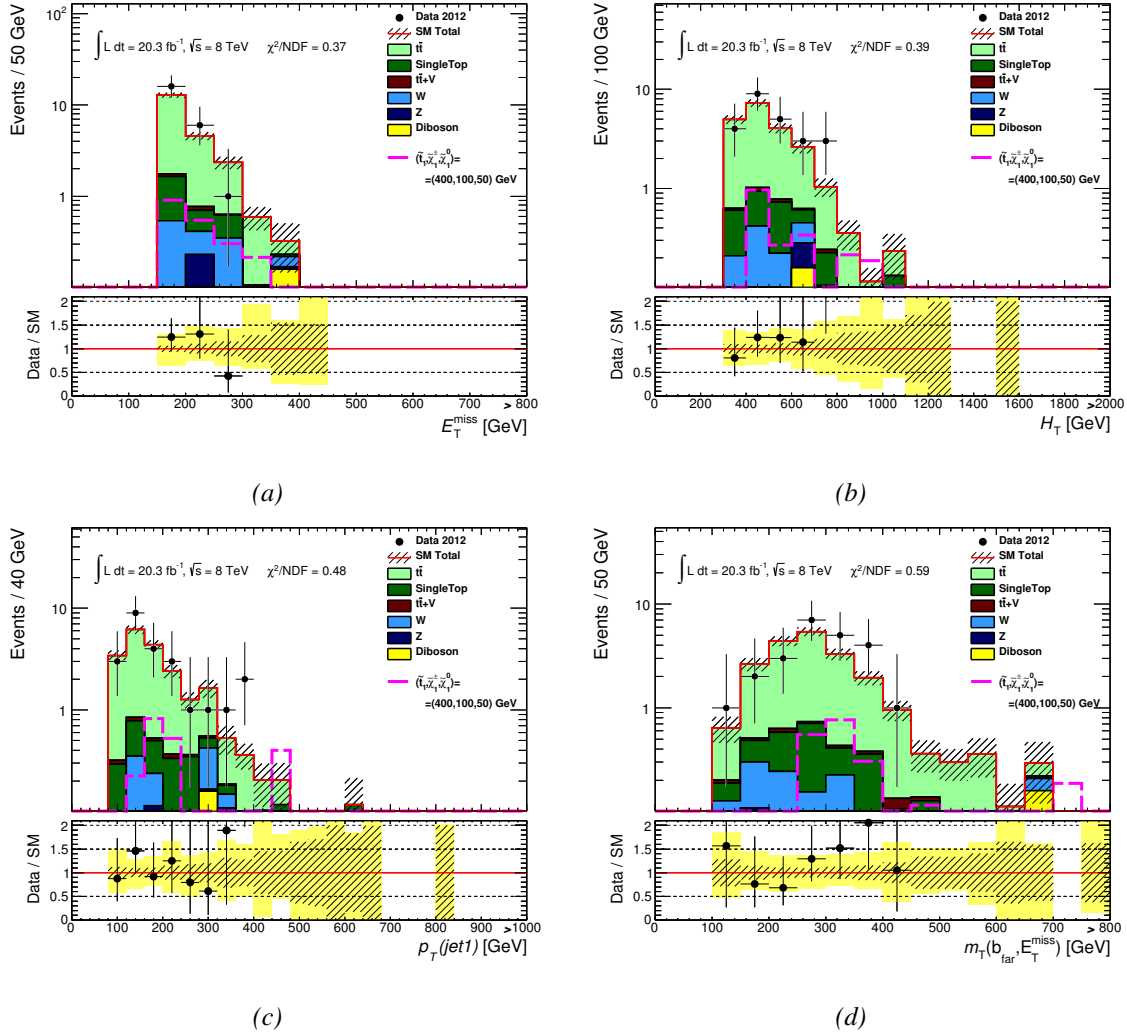


Figure 8.18: Data-Monte Carlo comparisons in VRC2 for the E_T^{miss} (a), H_T (b), leading jet p_T (c), and $m_T^{b,\text{max}}$ (d) distributions. The data are represented by the black points and the MC is the coloured stacked histogram normalised to an integrated luminosity of 20.1 fb^{-1} and the $t\bar{t}$ and Z + jets normalisation factors have been applied, see Table 8.15. The hatched band represents the MC statistical uncertainty while the yellow band is the sum of MC statistical uncertainty and detector systematics. The last bin contains also the overflow.

coming from semi-leptonic $t\bar{t}$ decays. To extract the W + jets normalisation a combined fit of the $t\bar{t}$ CRB and of the W CR is, hence, performed and the normalisation factor $NF_{W+\text{jets}}^B = 1.0 \pm 0.4$ is found. The yields in the W control region are presented in Table 8.16.

The data-MC comparisons for the W + jets control region for SRB are shown in Fig. 8.19. All the region selections have been applied. The chosen distributions are those of the E_T^{miss} (a), and $E_T^{\text{miss}} / \sqrt{H_T}$ (b) variables.

Even though a trend is observed in the E_T^{miss} distribution, the data are compatible with the expectation within the statistical plus detector systematic uncertainties. It was checked that the effects of changing the normalisation of the W + jets background, or of applying a reweighting to the W + jets simulated samples were negligible on the final results in signal region and on the sensitivity power of SRB. Also the application of larger systematic uncertainties on the W + jets contribution does not change signific-

Selection	Requirement
Trigger	single electron or muon trigger
Lepton Selection	Exactly 1 lepton $p_T(\ell) > 35\text{GeV}$, treated as a jet
n_{jets} (anti- k_t $R = 0.4$), included lepton	4 or 5
Jet p_T [GeV] (anti- k_t $R = 0.4$)	$> 80, 80, 35, 35$
QCD Rejection	$\min \Delta\phi(\text{jet}^{0-2}, E_T^{\text{miss}}) > 0.1\pi$ (anti- k_t $R = 0.4$)
$n_{b\text{-jets}}$	1
$m_T(\ell, E_T^{\text{miss}})$ [GeV]	$40 < m_T(\ell, E_T^{\text{miss}}) < 120$
Top Reconstruction [GeV]	≥ 2 $R = 1.2$ jets
E_T^{miss} [GeV]	> 150
$\mathcal{A}_{m_t}$	< 0.5
$m_{\text{jet}, R=1.2}^0$ [GeV]	< 40

Table 8.13: Summary of the selection for the W +jets control region. Event cleaning requirements are also applied.

antly the SRB sensitivity since the region is dominated by statistical uncertainties.

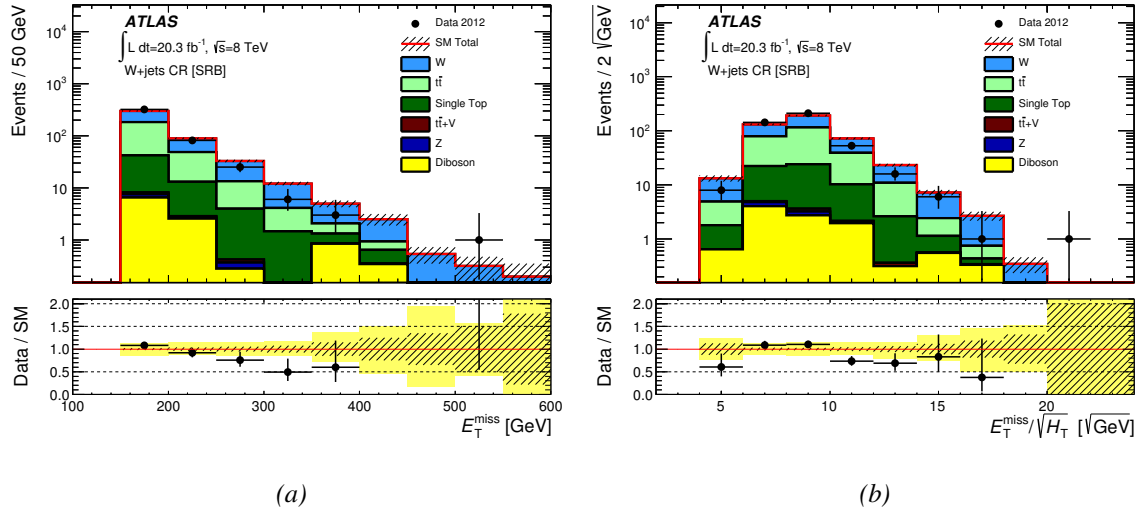


Figure 8.19: Data-MC comparisons in the W +jets CRB of E_T^{miss} (e), and $E_T^{\text{miss}} / \sqrt{H_T}$ (f) distributions. All the region selection have been applied. The background samples are stacked and normalised to an integrated luminosity of 20.3 fb^{-1} . The $t\bar{t}$, W + jets, and Z + jets normalisation factors extracted from the global fit, see Table 8.15, are applied in the figures. The last bin includes all overflows, the hatched uncertainty band represents the SM statistical uncertainty and the yellow band drawn in the “Data/SM” ratios represents the sum in quadrature of statistical and detector-related systematic uncertainties [176].

8.3.3 Z +jets Background

The $Z \rightarrow \nu\nu$ +jets background, that becomes the largest SM contribution in the tight signal regions, is estimated with the help of a $Z \rightarrow \ell\ell$ +jets selection, where the leptons are either electrons or muons. A very pure $Z \rightarrow \ell\ell$ selection can be defined in a two lepton region, but it has the disadvantage that the branching ratio of the Z boson in neutrinos is almost three times larger than the combined BR in electrons and muons. In particular the large E_T^{miss} requirement, which represents the boost of the Z

boson, the large number of jets in the signal regions and the requirement of selecting at least two b -jets reject a large fraction of the Z + jets events decreasing the statistical power of a possible CR. It was observed that the E_T^{miss} is independent of the b -jet content of the events and, since in most of the Z + jets events the b -tagged jets arise from the splitting of a gluon in a $b\bar{b}$ pair, it was possible to define regions with no requirements on the heavy flavour jets and to estimate separately the fraction of events with at least two selected b -jets.

Three regions were defined to estimate the Z + jets background, CRZ4, CRZ5, and CRZ6, based on the number of selected jets. The CR events are required to pass the requirements of two electrons or muons with opposite electric charge and $p_T(\ell 1) > 25$ GeV, $p_T(\ell 2) > 10$ GeV. The invariant mass of the two selected signal leptons must be within five GeV of the PDG value of the Z boson mass [12] and the missing transverse momentum is required to be smaller than 50 GeV to reject the $t\bar{t}$ contribution. Since the goal is to estimate the $Z \rightarrow \nu\nu$ contribution in signal regions, the selected charged leptons are “transformed” to neutrinos by removing them from the visible objects and adding their four-vectors to the E_T^{miss} calculation. In this way a new E_T^{miss} variable is defined $(E_T^{\text{miss}})'$ that is required to be larger than 70 GeV. The Z control region requirements are summarised in Table 8.14.

Selection	CRZ4	CRZ5	CRZ6
Trigger	single electron or muon trigger		
Leptons	e^+e^- or $\mu^+\mu^-$, $p_T > 25, 10$ GeV		
$m_{\ell\ell}$	$86 < M(\ell\ell) < 96$ GeV		
E_T^{miss}	$E_T^{\text{miss}} < 50$ GeV		
$(E_T^{\text{miss}})'$	$(E_T^{\text{miss}})' > 70$ GeV		
n_{jets}	= 4	= 5	= 6

Table 8.14: Summary of the selection for the Z + jets control regions.

Since the b -jets come mainly from gluon splitting, the fraction of events with two tagged b -jets, the $b\bar{b}$ -fraction, increases linearly with the number of selected jets. This observation was validated in a $Z \rightarrow \ell\ell$ sample by fitting the $b\bar{b}$ -fraction with first grade polynomial functions for different jets-multiplicity bin ranges, and for different E_T^{miss} selections, both at particle level and for detector-reconstructed events. The estimator used to evaluate the goodness of the fits is the χ^2 over the number of degrees of freedom of the fit. It was found that a linear function always described well the $b\bar{b}$ -fraction distribution. Moreover the fits performed for a $Z \rightarrow \ell\ell$ simulated sample and for a $Z \rightarrow \ell\ell$ selection in data, where the contributions from the other backgrounds were subtracted, are compatible within uncertainties.

The results used in the analysis are obtained by fitting the $b\bar{b}$ -fraction distribution with a linear function in the jet multiplicity bins between two and six for a $Z \rightarrow \ell\ell$ simulated sample and for a $Z \rightarrow \ell\ell$ data sample, where the contributions from the other backgrounds were subtracted. Thanks to the $b\bar{b}$ -fraction fit the uncertainty associated to the Z + jets estimate can be decreased significantly. The systematic uncertainty related to the fit procedure is estimated to be 17%, and the statistical component of the uncertainty comes from the untagged sample, which has a much larger population than the sample where two b -tagged jets are required. In the six jets bin, e.g. the statistical uncertainty of the two b -tags sample is of almost 30%, while the one of the untagged sample is of 10%.

Data-MC comparisons of the $(E_T^{\text{miss}})'$ distributions for the CRZ selections are shown in Fig. 8.20 in (a) for an inclusive four jets selection, in (c) for a five jets exclusive selection and in (d) for a six jets inclusive selection. The data and MC are normalised to a unitary area and it can be observed that the MC describes well the shape of the distribution.

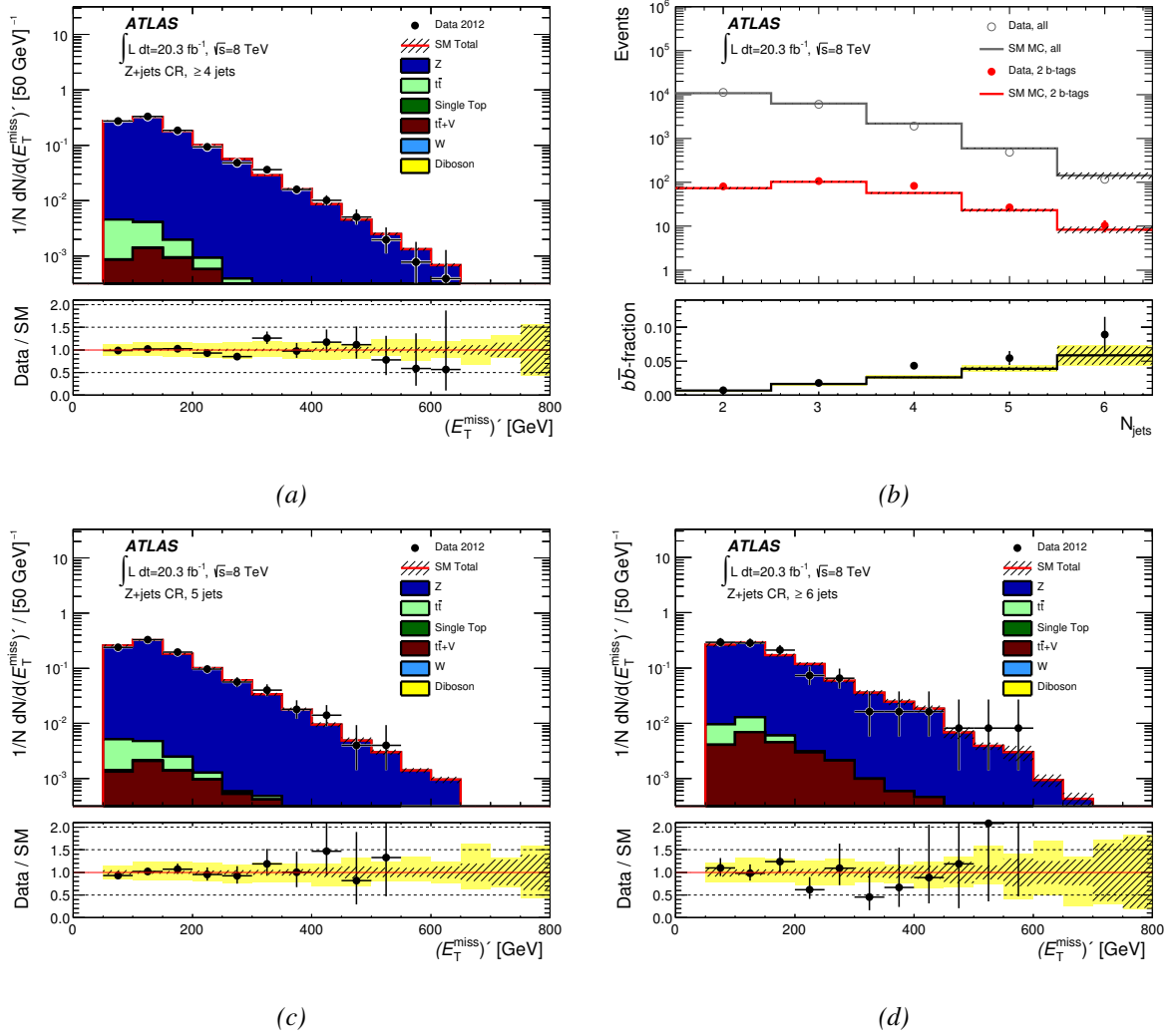


Figure 8.20: The (E_T^{miss}) distribution in the Z + jets control region for events with ≥ 4 jets (a), with exactly five jets (c) and with ≥ 6 jets (d) normalized to unit area. The stacked histograms represent the SM expectations. The last bin includes all overflows. The hatched band represents the statistical uncertainty and the yellow band represents the sum in quadrature of statistical and detector-related systematic uncertainties. (b) number of events in data and simulation as a function of jet multiplicity. The open (solid) points show all events (events with two or more b -tagged jets) in data, while the grey (red) line indicates the SM expectation for all events (events with two or more b -tagged jets). The $b\bar{b}$ -fraction in data (simulation) is shown in the bottom panel, as indicated by the points (line). The hatched areas indicate MC statistical uncertainties and the yellow band includes the b -tagging systematic uncertainty. The last bin includes all overflows [176].

The number of events per jet multiplicity bin in data (points) and MC (lines) is shown in Fig. 8.20(b) in grey for all selected events, and in red for the events with two selected b -tagged jets. The $b\bar{b}$ -fraction is also shown for data (points) and MC (line).

8.3.4 Fake Background

The contribution from multi-jet QCD production and $t\bar{t}$ full-hadronic decays to the signal regions is negligible. Such events could pass the signal region selections because of large fake missing transverse momentum coming from misreconstructed jets. This background is estimated with a jet-smearing

technique, which has been introduced in Paragraph 6.3.2. The pseudo events are normalised in zero lepton regions with the same jet and b -jet multiplicity as the signal region sets, $E_T^{\text{miss}} > 150$ GeV, no requirement on the $|\Delta\phi(E_T^{\text{miss}}, E_T^{\text{miss,track}})|$ and with the selection $|\Delta\phi(\text{jet}, p_T^{\text{miss}})| < 0.1$. The shape of the obtained template is then validated with data in multi-jet enriched regions defined as the control regions but with a looser selection on $|\Delta\phi(\text{jet}, p_T^{\text{miss}})|$, $|\Delta\phi(\text{jet}, p_T^{\text{miss}})| < 0.2\pi$, which is the reversed selection with respect to what applied in the signal regions. The data-template agreement in these regions is observed to be good, nevertheless a conservative uncertainty of 100% is assigned to this estimate, which has no negative effects on the sensitivity of the analysis.

8.4 Systematic Uncertainties

In this section the background and signal systematic uncertainties are discussed. First the relevant detector-related systematic uncertainties are listed together with their relative impact on the results. The sample variations considered to assess the theory uncertainties are presented afterwards for the SM background components and for the signal. The correlations among the uncertainty sources are extracted from the global fit of the control, validation and signal regions. In general the detector-related and experimental uncertainties are correlated among regions and among samples, both signal and background, while the theory uncertainties are correlated between signal and control regions but uncorrelated between different processes.

8.4.1 Experimental and Detector-Related Uncertainties

In this paragraph the detector-related and experimental uncertainties relevant to the analysis are presented. A description of how these uncertainties are extracted is given in Paragraph 6.4.1.

- Luminosity: 2.8% uncertainty on the total integrated luminosity used to normalise the MC samples.
- Pile-up: the uncertainty due to pile-up modelling gives a negligible contribution to the final results (1-2%).
- JES: the impact of the jet energy scale uncertainty on the results is greatly mitigated by the use of control regions to estimate all significant backgrounds. Overall it contributes 5-9% in SRA, 6% in SRB, and 8-11% in SRC. The largest contributions come from the uncertainty components related to the flavour composition of the jets and to the effective number of partons considered.
- JER: the uncertainty on the jet energy resolution is one of the largest contributions from the experimental uncertainties to the final results; it ranges between 6 and 15% in the SRA set, is 16% in SRB and is between 3 and 6% in the SRC set of regions.
- b -tag: the uncertainty on b -tagging is small and it contributes for less than 5% in all regions.
- E_T^{miss} SoftTerm: due to the tight selections on the E_T^{miss} and on the rejection of the events with fake E_T^{miss} , the impact on the final results of the uncertainties related to the E_T^{miss} Soft Term is negligible.
- Z fit method: an uncertainty of 17%, coming from the uncertainty on the fit of the $b\bar{b}$ -fraction, is associated to the results of the Z + jets estimate.

- Jet smearing method: a conservative uncertainty of 100% is assigned to the multi-jet yields in the signal regions. This does not affect negatively the final result of the analysis since the multi-jet contribution to the signal regions is negligible.
- Uncertainties related to the $|\Delta\phi(E_T^{\text{miss}}, E_T^{\text{miss,track}})|$ and τ veto selections: the data-MC agreement in regions enriched with tau leptons and for the $E_T^{\text{miss,track}}$ distributions is found to be good and previous studies showed a negligible impact, therefore no additional uncertainties have been applied.

8.4.2 Theory Uncertainties

The methods used to determine the impact of the theory uncertainties on the SM and signal processes, and which uncertainties are generally considered were introduced in Paragraph 6.4.2. Here for each of the considered background component the evaluated theory uncertainties are listed.

Most of the theory uncertainties have been evaluated at particle level. In some cases the uncertainties had to be extrapolated from regions with looser selections than those applied in the signal regions because otherwise too few events could survive the final selections introducing a large statistical component to the systematic uncertainty estimate.

$t\bar{t}$ production

The uncertainties on the $t\bar{t}$ background are evaluated based on the impact they have in the combined fit of the control and signal regions. The uncertainties considered are:

- Factorisation and renormalisation scale: PowHeg samples with the renormalisation and factorisation scales set to 2 or 0.5 times the nominal values were used to study the impact of this uncertainty.
- ISR/FSR: the impact of an augmented or diminished initial or final state radiation activity is evaluated by comparing the yields obtained with dedicated ACER MC samples.
- MC generator: the baseline PowHeg sample is compared with a sample simulated with MC@NLO interfaced to JIMMY for the parton shower. Since the MC@NLO sample does not describe well the selected data, this uncertainty component was not considered.
- Parton shower: two PowHeg samples are compared, which are interfaced to HERWIG or PYTHIA for the parton shower. The relative difference of the two transfer factors is taken as parton shower uncertainty.
- PDF: this uncertainty is evaluated by varying the baseline PDF set, CT10, within its uncertainty and by comparing the results with those obtained if other PDF sets are used, e.g. HERA PDFs.

The $t\bar{t}$ theory uncertainties give one of the largest contribution to the total uncertainty in all signal regions. The impact of these uncertainties on the $t\bar{t}$ yield is of 11% for SRA1, 18% for SRA2, more than 40% for SRA3 and SRA4, 30% for SRB, and 7-8% for the SRC set.

$t\bar{t} + W/Z$ production

The theory uncertainties on the $t\bar{t} + V$ production are all computed with the help of dedicated varied MadGraph samples. Since no control regions are defined for the associated production of $t\bar{t}$ with a vector boson, the impact of the variations was computed directly in the signal regions. The considered variations are:

- Factorisation and renormalisation scale: the two scales are varied independently a factor two up and down with respect to the nominal choice.
- ISR/FSR: samples with more or less radiation activity varied separately have been used to check the impact of this component.
- Matching scale: the matching scale between the matrix element and the parton shower is varied up and down of 5 GeV from the nominal value of 20 GeV.
- Finite number of partons: The yields obtained from samples with two additional partons included in the matrix element were compared with samples containing not more than one additional parton in the matrix element calculation.
- Cross section: an uncertainty on the $t\bar{t} + V$ production cross section of 22% was assigned [180, 181].

The final theory uncertainty of the $t\bar{t} + V$ contribution in the signal regions is completely dominated by the cross section uncertainty and ranges between 22 and 26%.

Single top production

The main single top production contribution to the signal regions comes from the associated production of a top quark with a W boson. Since no control regions are defined for the associated production of Single Top, the impact of the variations was computed directly in the signal regions. The uncertainties considered are:

- MC generator: comparison between the PowHeg baseline sample and a MC@NLO sample.
- Parton shower: the baseline PowHeg sample interface to PYTHIA is compared to a sample interfaced to JIMMY.
- Interference with $t\bar{t}$: the combined yields of the $t\bar{t}$ and Wt PowHeg samples are compared to the results obtained with and ACER MC $WWbb$ sample.
- ISR/FSR: ACER MC samples with more or less initial and final state radiation activity are compared.
- PDF: the PDF uncertainty was calculated as for the $t\bar{t}$ sample.
- Cross section: a 6.8% uncertainty on the single top production cross section in the Wt -channel is assigned [182].

The impact of the single top theory uncertainties on its signal region yields is between 16 and 33% in SRA, of about 20% in SRB, and between 33 and 37% in SRC.

Z + jets production

The theoretical uncertainties on the Z component were calculated based on their impact in the combined fit of control and signal regions, as done for the $t\bar{t}$ background. The uncertainties have been estimated at parton level with looser selections than those of the analysis because of the small size of the simulated samples. The uncertainty values were validated by checking that the obtained results are invariant if they are computed in a region with even looser selections. The component considered are:

- MC generator: the baseline SHERPA samples are compared with ALPGEN samples at parton level.
- Finite number of partons: ALPGEN samples with four or five additional partons at matrix element are compared.
- PDF: this uncertainty was computed as for the $t\bar{t}$ background.

The impact of the Z + jets theory uncertainty on the signal regions is very low, being between 7 and 10% in SRA, about 8.5% in SRB, and between 7 and 9% in SRC.

W + jets production

The uncertainties considered for the W + jets background, calculated directly in the signal regions for the SRA and SRC sets and via the combined fit of signal and control regions for SRB, are:

- Factorisation, renormalisation and matching scale: the baseline SHERPA samples are compared with SHERPA samples with varied factorisation, renormalisation and matching scales.
- Finite number of partons: samples with four or five additional partons at matrix element are compared.
- PDF: this uncertainty was computed as for the $t\bar{t}$ background.
- Cross section: a 38% uncertainty is assigned for the associated production of a W boson with b-jets [183].

The cross section uncertainty is the dominant theoretical uncertainty component on the W + jets background in all signal regions. For the SRB region an additional 20% uncertainty is added to take into consideration the different flavour composition of control and signal regions.

Diboson production

The uncertainty on the diboson production is set to 50% and has an impact of less than 1% on the total uncertainty of all signal regions.

Signal production

The uncertainty on the production cross section of the signal samples is based on the variation of the factorisation and renormalisation scales, on the variation of the chosen value for α_s , and on the uncertainty on the chosen PDF set. The direct stop production cross section curve and its uncertainty is shown in Fig. 8.21 as a function of the top squark mass for a centre-of-mass energy of 8 TeV.

In order to assign an uncertainty on the signal acceptance, a comparison between signal samples produced with different MC generators was also performed. Since the signal yields in the SRs obtained with the different generators are compatible within a one sigma statistical variation, no additional contribution from the generator choice is added to the total signal theory systematic uncertainty.

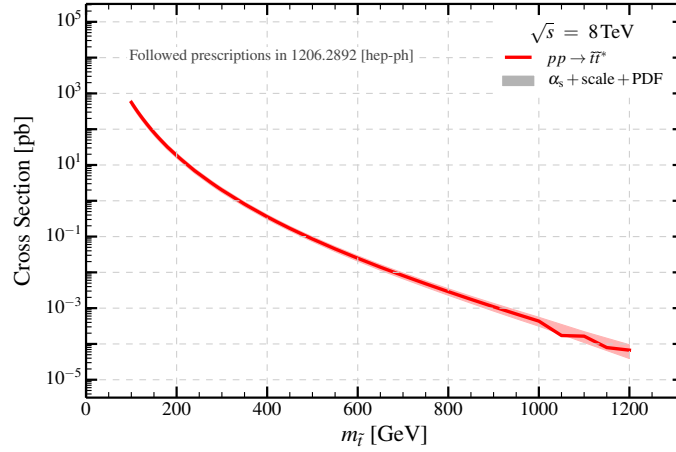


Figure 8.21: Direct stop production cross section curve (red line) and its uncertainty (shaded area) as a function of the top squark mass at $\sqrt{s} = 8$ TeV.

8.5 Results

A global likelihood fit is performed to determine the background normalisation factors and test the statistical power of the analysis. The likelihood function to be maximised is of the form of Equation 6.13. All the signal and control regions considered are treated as one-bin regions, i.e. a global normalisation factor is extracted in each CR, which is not dependent on the shape of any distribution, and the SM expectation in each signal region is compared to the data again without considering the shape of any distribution. For all sets of signal regions the constraints extracted by the corresponding $t\bar{t}$, Z + jets, and multi-jet control regions are exploited, and for the SRB the constraint from the W + jets control region are also added. The fit nuisance parameters can be set to be:

- completely correlated among regions and samples: this is the case e.g. of detector-related uncertainties.
- correlated among regions, uncorrelated among samples: this is the case e.g. of the theoretical uncertainties on the background components.
- fully uncorrelated: for example the MC statistical uncertainty is sample and region dependent. A nuisance parameter is assigned to each sample in each region.

The final correlations among nuisance parameters and the background normalisation factors are determined by maximising the likelihood function in the Background Fit configuration, see Paragraph 6.5.2. The normalisation factors of the background components to be estimated in the CRs are left free to float, as well as the nuisance parameters related to the uncertainties, to find the values which maximise the

Background Source	SRA	SRB	SRC
$t\bar{t}$	1.24 ± 0.13	$1.00^{+0.10}_{-0.05}$	1.07 ± 0.11
$W + \text{jets}$	–	1.0 ± 0.4	–
$Z + \text{jets}$	$0.94^{+0.16}_{-0.15}$	1.07 ± 0.07	1.07 ± 0.07

Table 8.15: Normalisation factors of the $t\bar{t}$, $W + \text{jets}$, and $Z + \text{jets}$ backgrounds extracted from the background fits of the SRA, SRB and SRC channels [176].

likelihood. The background components that are estimated directly from MC are treated as fixed parameters in the fit. The fit is done separately for each channel, i.e. for each set of signal regions, and the channels A and B, and A and C are later statistically combined for the discovery and exclusion fits.

The background normalisations and their uncertainties for the $t\bar{t}$, $Z + \text{jets}$, and $W + \text{jets}$ SM processes are summarised in Table 8.15. The normalisation factors of the SRB and SRC channels are correlated because the region are not mutually exclusive. This does not create any problem since it was never foreseen to combine SRB with SRC. A correlation matrix for the SRA channel can be found in Appendix C, Fig. C.1. For the SRA channel a large correlation between the multi-jet and the $t\bar{t}$ normalisation factors is observed due to the $t\bar{t}$ contributing for 20% of the total in the multi-jet CR.

The number of observed events, expected events from MC samples, and fitted background events in the control regions is shown in Table 8.16 for all three search channels SRA, SRB, and SRC. The contributions coming from the single top, $t\bar{t} + V$, and diboson production are summed together. The value of the uncertainties quoted represents the total statistical and systematic uncertainty of that background component.

The results obtained with the background fit are validated by checking the compatibility of the observed data with the expected SM events in the validation regions defined in Paragraph 8.3.1. These regions are dominated by $t\bar{t}$ events and the total fitted background is found to be compatible with the observed events within uncertainties. The results for all the five validation regions are reported in Table 8.17.

The fit results are used to determine the final contribution of each background to the signal regions. The summary of the observed and expected events in each signal region is given in Table 8.18. It can be observed that whereas in the looser signal regions the dominant background is semi-leptonic decaying $t\bar{t}$, in the tighter regions the contributions from $Z + \text{jets}$ and from $t\bar{t} + V$ events become larger and even dominant over $t\bar{t}$. In all selected regions no significant excess over the SM background expectation is observed and 95% confidence level model independent limits on the observed and expected visible cross section (σ_{vis}), see explanation in Paragraph 7.5.3, and on the number of events from new physics processes could be set.

The data-MC comparisons of the $E_{\text{T}}^{\text{miss}}$ and $m_{\text{T}}^{b, \text{min}}$ distributions in the signal regions are shown in Fig. 8.22 for SRA, Fig. 8.23 for SRB, and Fig. 8.24 for SRC.

For the SRA set, Fig. 8.22, the $E_{\text{T}}^{\text{miss}}$ distribution for SRA1 and SRA2 is shown in (a) and for SRA3 and SRA4 in (b); the $m_{\text{T}}^{b, \text{min}}$ distribution for SRA1 is drawn in (c), for SRA2 in (d), for SRA3 in (e), and for SRA4 in (f).

Two high $E_{\text{T}}^{\text{miss}}$ events are observed in the SRA3 and SRA4 regions. These events have also large $m_{\text{T}}^{b, \text{min}}$ and are discussed in more details in the next paragraph.

For the SRB set, Fig. 8.23, the $E_{\text{T}}^{\text{miss}}$ distribution is shown in (a) and the $m_{\text{T}}^{b, \text{min}}$ distribution in (b).

CRs for SRA			CRs for SRB			CRs for SRC			
$t\bar{t}$	Z + jets	Multijets	$t\bar{t}$	W + jets	Z + jets	Multijets	$t\bar{t}$	Z + jets	Multijets
Observed events									
247	101	592	950	440	499	2082	313	499	1017
Fitted background events									
Total SM	247 ± 16	101 ± 10	593 ± 27	440 ± 40	499 ± 22	2082 ± 48	313 ± 18	499 ± 22	1018 ± 34
$t\bar{t}$	197 ± 21	12.6 ± 3.0	109 ± 23	800 ± 50	46 ± 7	140 ± 14	239 ± 24	49 ± 12	115 ± 23
Z + jets	0.28 ± 0.19	73 ± 11	2.5 ± 0.6	0.59 ± 0.16	423 ± 25	11.7 ± 1.6	0.18 ± 0.07	420 ± 26	6.7 ± 0.9
W + jets	20 ± 9	–	4.5 ± 2.2	54 ± 20	–	18 ± 7	28 ± 12	–	9 ± 4
Multijets	–	–	460 ± 40	–	–	1890 ± 50	–	–	870 ± 40
Others	29 ± 4	15 ± 4	11.8 ± 1.6	93 ± 13	30 ± 10	22.7 ± 3.0	45 ± 7	30 ± 7	12.6 ± 1.6
Expected events (before fit)									
$t\bar{t}$	159	10.2	88	800	46	140	224	46	108
Z + jets	0.31	78	2.7	0.55	394	10.9	0.17	394	6.3
W + jets	20	–	4.5	52	–	17	28	–	9
Multijets	–	–	460	–	–	2090	–	–	870
Others	29	15	11.7	93	30	22.7	45	30	12.6

Table 8.16: Event yields in the control regions, before (pure MC estimate) and after the profile likelihood fit (constraints from the data observed in the CR applied). The uncertainties quoted include statistical and systematic contributions. The contributions from single-top, $t\bar{t}$ + W/Z, and diboson production are included in “Others” [176].

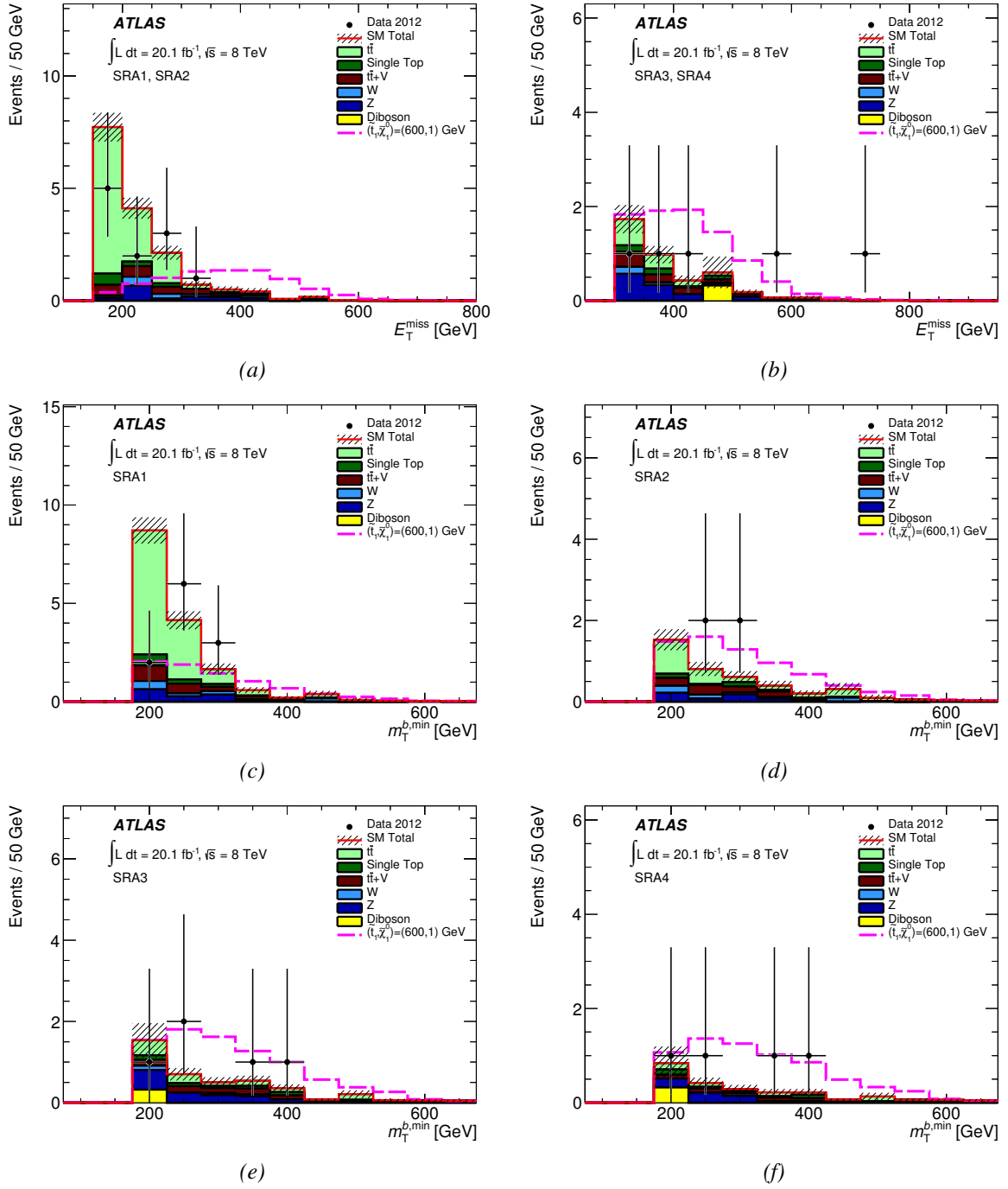


Figure 8.22: Data-MC distributions in SRA: E_T^{miss} in SRA1 and SRA2 (a), and in SRA3 and SRA4 (b); $m_T^{b,\text{min}}$ in SRA1 (c), in SRA2 (d), in SRA3 (e), and in SRA4 (f). The SM background expectation is normalised to an integrated luminosity of 20.1 fb^{-1} , the $t\bar{t}$, Z + jets, and W + jets components have been normalised with the factors extracted from the background fit, and the hatched band represent the SM statistical uncertainty. The background histograms are stacked while the signal point, $m(\tilde{t}) = 600 \text{ GeV}$, $m(\tilde{\chi}_1^0) = 1 \text{ GeV}$ of the grid $\tilde{t} \rightarrow t\tilde{\chi}_1^0$, is overlaid [176].

	VRA1	VRA2	VRB	VRC1	VRC2
Observed events					
	158	51	69	103	24
Fitted background events					
Total SM	189 ± 26	50 ± 6	70 ± 19	110 ± 12	21.1 ± 2.9
$t\bar{t}$	170 ± 27	34 ± 7	60 ± 19	93 ± 12	17.3 ± 2.8
$Z + \text{jets}$	4.0 ± 1.1	1.5 ± 0.4	1.5 ± 0.5	6.9 ± 1.5	0.24 ± 0.20
$W + \text{jets}$	2.8 ± 1.2	4.8 ± 2.2	2.1 ± 1.4	3.9 ± 1.8	1.1 ± 0.5
Others	11.8 ± 3.1	9.1 ± 2.2	7.2 ± 2.5	6.7 ± 2.0	2.4 ± 0.7

Table 8.17: Observed data in validation regions compared to the background estimates extracted from the likelihood fit. The uncertainties quoted include statistical and systematic contributions. The contributions from single-top, $t\bar{t} + W/Z$, and diboson production are included in “Others” [176].

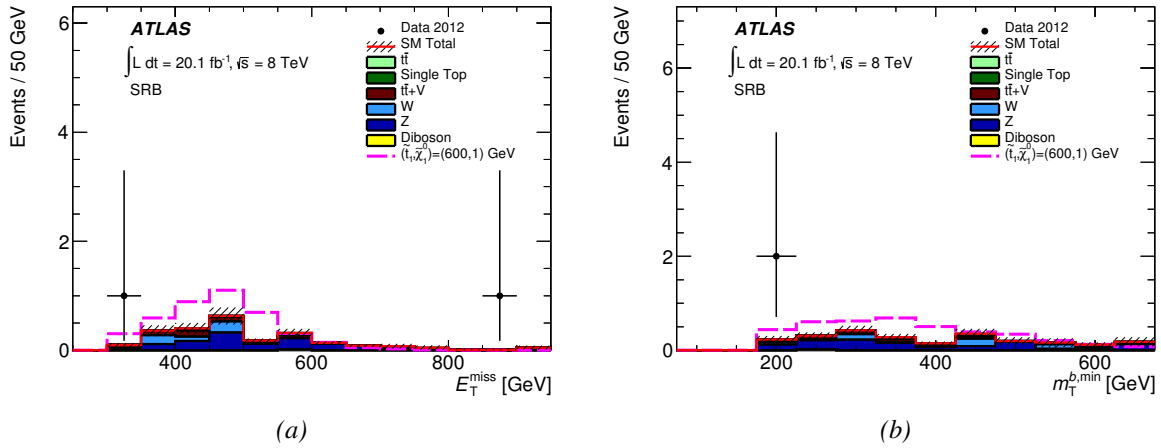


Figure 8.23: Data-MC distributions in SRB: E_T^{miss} (a) and $m_T^{b,\text{min}}$ (b). The SM background expectation is normalised to an integrated luminosity of 20.1 fb^{-1} , the $t\bar{t}$, $Z + \text{jets}$, and $W + \text{jets}$ components have been normalised with the factors extracted from the background fit, and the hatched band represent the SM statistical uncertainty. The background histograms are stacked while the signal point, $m(\tilde{t}) = 600 \text{ GeV}$, $m(\tilde{\chi}_1^0) = 1 \text{ GeV}$ of the grid $\tilde{t} \rightarrow \tilde{t}\tilde{\chi}_1^0$, is overlaid [176].

For the SRC set, Fig. 8.24, the E_T^{miss} distribution for SRC1 is shown in (a), for SRC2 in (b), and for SRC3 in (c); the $m_T^{b,\text{min}}$ distribution for SRC1 is drawn in (d), for SRC2 in (e), and for SRC3 in (f).

An event with E_T^{miss} of almost 900 GeV is observed both in SRB and in SRC. The properties of this event are also discussed in the next paragraph.

8.5.1 Events with Large E_T^{miss}

Three events with very large missing transverse momentum were found in the signal regions. Two belonging to SRA3 and SRA4, and one selected both in SRB and in SRC.

The probability to observe such high E_T^{miss} events was evaluated by computing the p -value corres-

	SR A1	SR A2	SR A3	SR A4	SR B	SR C1	SR C2	SR C3
Observed events	11	4	5	4	2	59	30	15
Total SM	15.8 ± 1.9	4.1 ± 0.8	4.1 ± 0.9	2.4 ± 0.7	2.4 ± 0.7	68 ± 7	34 ± 5	20.3 ± 3.0
$\bar{t}\bar{t}$	10.6 ± 1.9	1.8 ± 0.5	1.1 ± 0.6	0.49 ± 0.34	$0.10^{+0.14}_{-0.10}$	32 ± 4	12.9 ± 2.0	6.7 ± 1.2
$t\bar{t} + W/Z$	1.8 ± 0.6	0.85 ± 0.29	0.82 ± 0.29	0.50 ± 0.17	0.47 ± 0.17	3.2 ± 0.8	1.9 ± 0.5	1.3 ± 0.4
$Z + \text{jets}$	1.4 ± 0.5	0.63 ± 0.22	1.2 ± 0.4	0.68 ± 0.27	1.23 ± 0.31	15.7 ± 3.5	9.0 ± 1.9	6.1 ± 1.3
$W + \text{jets}$	1.0 ± 0.5	0.46 ± 0.21	0.21 ± 0.19	$0.06^{+0.10}_{-0.06}$	0.49 ± 0.33	8 ± 4	4.8 ± 2.2	2.8 ± 1.2
Single top	1.0 ± 0.4	0.30 ± 0.17	0.44 ± 0.14	0.31 ± 0.16	0.08 ± 0.06	7.2 ± 2.9	4.5 ± 1.8	2.9 ± 1.4
Diboson	< 0.4	< 0.13	0.32 ± 0.17	0.32 ± 0.18	0.02 ± 0.01	1.1 ± 0.8	$0.6^{+0.7}_{-0.6}$	$0.6^{+0.7}_{-0.6}$
Multijets	< 0.001	< 0.001	< 0.001	< 0.001	< 0.001	0.24 ± 0.24	0.06 ± 0.06	0.01 ± 0.01
$\sigma_{\text{vis}} (\text{obs}) [\text{fb}]$	0.33	0.29	0.33	0.32	0.21	0.78	0.62	0.40
$\sigma_{\text{vis}} (\text{exp}) [\text{fb}]$	$0.48^{+0.21}_{-0.14}$	$0.29^{+0.13}_{-0.09}$	$0.29^{+0.14}_{-0.09}$	$0.25^{+0.13}_{-0.07}$	$0.24^{+0.13}_{-0.06}$	$1.03^{+0.42}_{-0.29}$	$0.73^{+0.31}_{-0.21}$	$0.55^{+0.24}_{-0.15}$
N_{vis}^{95}	6.6	5.7	6.7	6.5	4.2	15.7	12.4	8.0
N_{vis}^{95}	$9.7^{+4.3}_{-3.0}$	$5.8^{+2.6}_{-1.8}$	$5.9^{+2.8}_{-1.9}$	$5.0^{+2.6}_{-1.4}$	$4.7^{+2.6}_{-1.2}$	$20.7^{+8.4}_{-5.8}$	$14.7^{+6.2}_{-4.2}$	$11.0^{+4.9}_{-3.1}$

Table 8.18: Observed and estimated event yields in each signal region of the SR A, SR B, and SR C sets. The statistical, detector-related, and theoretical systematic uncertainties are included as well as their correlations to give the final overall uncertainty. For each signal region, the 95% CL upper limits on the expected (observed) visible cross sections $\sigma_{\text{vis}} (\text{exp})$ ($\sigma_{\text{vis}} (\text{obs})$) and the expected (observed) event yields N_{exp}^{95} (N_{obs}^{95}) are summarised [176].

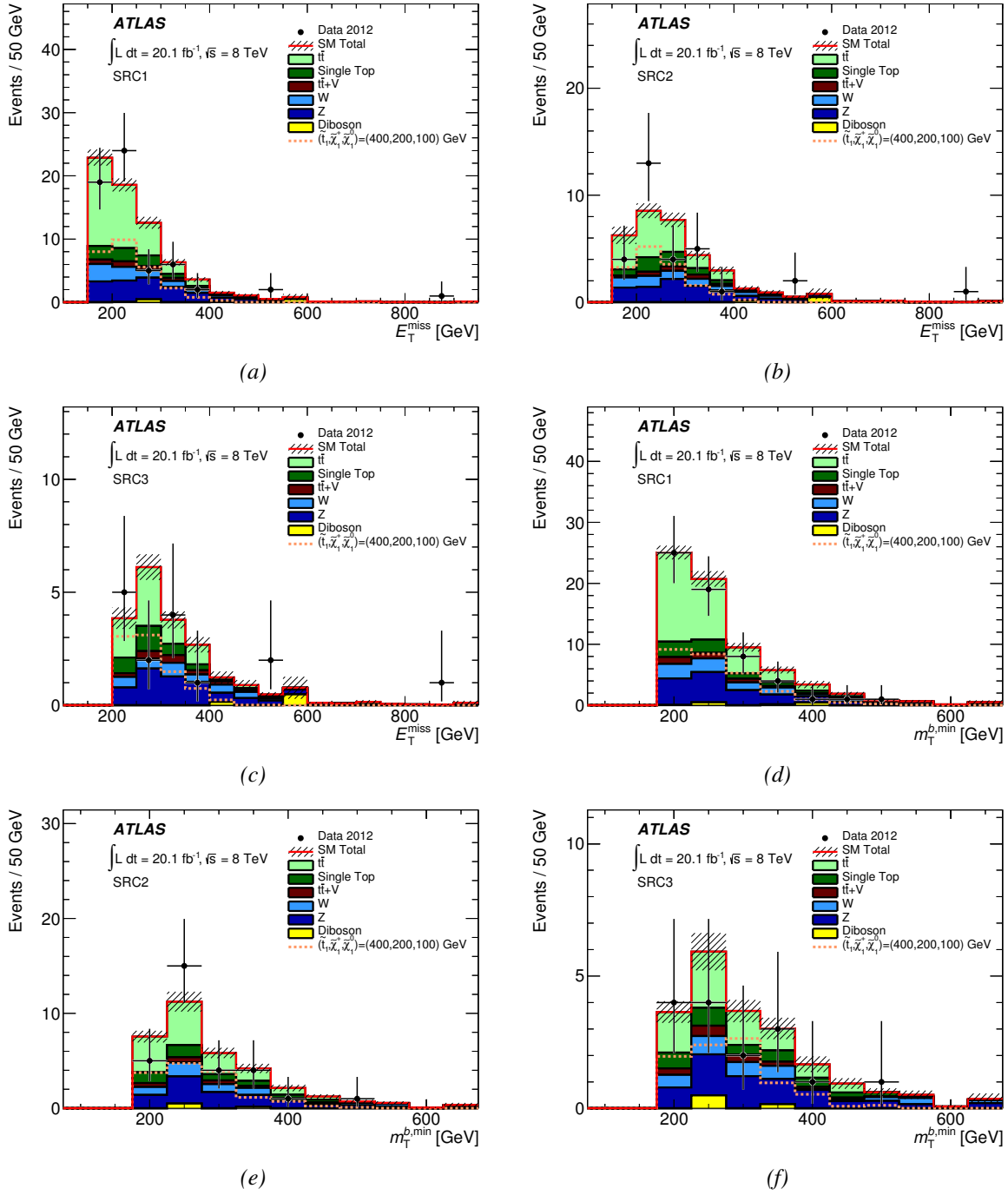


Figure 8.24: Data-MC distributions in SRC: E_T^{miss} in SRC1 (a), in SRC2 (b), and in SRC3 (c); $m_T^{b,\text{min}}$ in SRC1 (d), in SRC2 (e), and in SRC3 (f). The SM background expectation is normalised to an integrated luminosity of 20.1 fb^{-1} , the $t\bar{t}$, Z + jets, and W + jets components have been normalised with the factors extracted from the background fit, and the hatched band represent the SM statistical uncertainty. The background histograms are stacked while the signal point, $m(\tilde{t}) = 400 \text{ GeV}$, $m(\tilde{\chi}_1^\pm) = 200 \text{ GeV}$, $m(\tilde{\chi}_1^0) = 100 \text{ GeV}$ of the mixed grid, is overlaid [176].

ponding to an observation of at least two events with $E_T^{\text{miss}} > 500 \text{ GeV}$, and of at least one event with $E_T^{\text{miss}} > 600, 700, 800, 900 \text{ GeV}$ in SRA, SRB and SRC. A Poissonian distribution centred on the number of expected SM events in the chosen region is used as probability density function and it is compared with the observation of one or two data events. The same procedure is repeated for a distribution centred on the background expectation plus one sigma variation of the background uncertainties. The probability of observing two or more events with $E_T^{\text{miss}} > 500 \text{ GeV}$ in SRA is less than 5%, around 20% for the $n_{bkg} + 1\sigma$ hypothesis, and the probability to observe one or more events with $E_T^{\text{miss}} > 700 \text{ GeV}$ is less than 2%, 3.5% for the $n_{bkg} + 1\sigma$ hypothesis. On the other side the probability of observing one or more events with $E_T^{\text{miss}} > 900 \text{ GeV}$ in SRB(SRC) is around 5%(10%) for the nominal hypothesis, and almost 9%(more than 40%) for the $n_{bkg} + 1\sigma$ hypothesis.

The kinematic and topological properties of the three high E_T^{miss} events are:

- Event 99327014 in Run 214176 appearing in SRA3 and SRA4

This event has seven jets, two of which b -tagged, $E_T^{\text{miss}} = 746 \text{ GeV}$, $m_T^{b,\text{min}} = 407 \text{ GeV}$, and two top candidates with $m_{bjj}^0 = 244 \text{ GeV}$ and $m_{bjj}^1 = 197 \text{ GeV}$, or, with the simple ΔR_{min} top reconstruction, $m_{jjj}^0 = 180 \text{ GeV}$ and $m_{jjj}^1 = 183 \text{ GeV}$. The leading jet has $p_T = 422 \text{ GeV}$ and is not contained in either top candidate. The event display for this event is shown in Fig. 8.25.

- Event 53426101 in run 213819 appearing in SRA3 and SRA4

This event has six jets, two of which b -tagged, $E_T^{\text{miss}} = 585 \text{ GeV}$, $m_T^{b,\text{min}} = 374 \text{ GeV}$, and two top candidates with $m_{bjj}^0 = 107 \text{ GeV}$ and $m_{bjj}^1 = 304 \text{ GeV}$, the same values found for m_{jjj}^0 and m_{jjj}^1 with the simple ΔR_{min} top reconstruction. The leading jet has $p_T = 250 \text{ GeV}$. The event display for this event is shown in Fig. 8.26.

- Event 13555486 in run 215571 appearing in SRB and SRC

This event has five jets, two of which b -tagged, $E_T^{\text{miss}} = 896 \text{ GeV}$, $m_T^{b,\text{min}} = 212 \text{ GeV}$, $E_T^{\text{miss}} / \sqrt{H_T} = 23 \sqrt{\text{GeV}}$, and two reclustered top candidates with $m_{\text{jet}, R=1.2}^0 = 167 \text{ GeV}$ and $m_{\text{jet}, R=1.2}^1 = 170 \text{ GeV}$. The event display for this event is shown in Fig. 8.27.

8.5.2 Interpretation

Since no significant excess over the SM background expectation was observed in any region, the results were interpreted in the signal scenarios introduced in Section 8.1.2 and 95% C.L. exclusion limits were set on the $(\tilde{t}, \tilde{\chi}_1^0)$ mass plane.

The SRB and SRC sets are designed to be orthogonal to the SRA set, to enhance the sensitivity from the bulk of the $(\tilde{t}, \tilde{\chi}_1^0)$ mass plane respectively to boosted scenarios, where the mass difference between the particles involved in the decay chain is large, and to more compressed scenarios or to high decay branching ratios of the stop to $b\tilde{\chi}_1^\pm$.

Considering first the $\tilde{t} \rightarrow t\tilde{\chi}_1^0$, BR=100%, signal grid and a given $(m(\tilde{t}), m(\tilde{\chi}_1^0))$ point, the statistical combination of signal regions with the highest expected sensitivity to that model, i.e. the one with the lowest exclusion p -value (or analogously the lowest CL_s) in that point, is chosen. This means that, for each signal region, the background yield is set to the number of expected SM events and the CL_s is computed by assuming that the observed events equal the SM background expectation. To find the most sensitive combined signal region, the exclusion p -value is computed for each combination of the four SRA regions with the three SRC regions, giving twelve possibilities, and for the four SRA regions with the SRB, giving additional four possibilities.

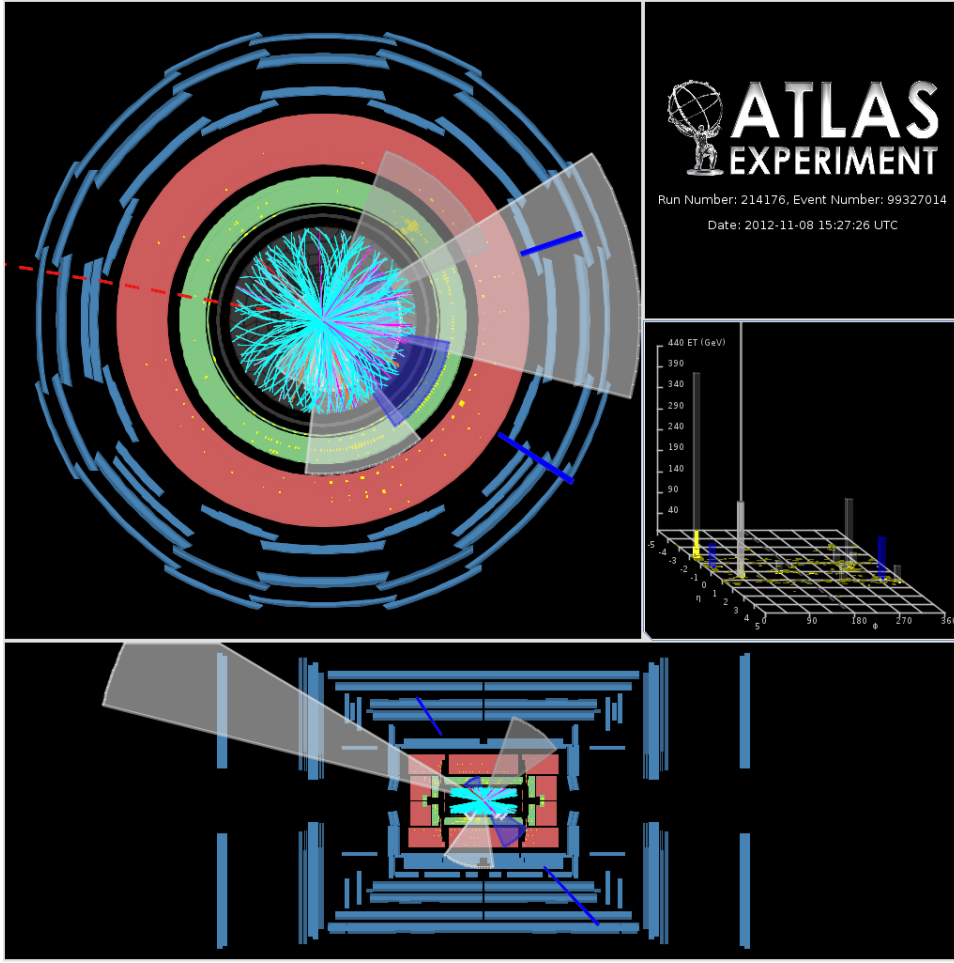


Figure 8.25: Event display of the event 99327014 in run 214176 appearing in SRA3 and SRA4. It has seven jets, two of which b -tagged, $E_T^{\text{miss}} = 746$ GeV, $m_{\text{T}}^{b, \text{min}} = 407$ GeV, and two top candidates with $m_{bjj}^0 = 244$ GeV and $m_{bjj}^1 = 197$ GeV. The leading jet has $p_{\text{T}} = 422$ GeV and is not contained in either top candidate. The E_T^{miss} is indicated by a red dashed line, jets are indicated by white cones, and b -tagged jets are indicated by blue cones. The colour spectrum (blue to red) for the inner detector tracks indicates the relative p_{T} (low to high) [176].

The best SR combination for each $\tilde{t} \rightarrow t\tilde{\chi}_1^0$ model is reported in Fig. 8.28. As expected in the low mass range and for compressed scenarios the best combination is given by one of the loosest SRA selections combined with the loosest SRC selection. For an almost massless neutralino and a stop mass above 300 GeV, the best combination is between a SRA region, with tighter selections as the stop mass increases, and SRB.

The 95% C.L. exclusion contours in the $\tilde{t} \rightarrow t\tilde{\chi}_1^0$ grid, with BR=100%, are shown in Fig. 8.29 for the best SRA (a) and for the best combination SRA+SRB or SRA+SRC (b).

By combining the SR sets, the expected exclusion contour could be extended towards the diagonal by 10 to 20 GeV, and towards higher stop masses by 40 GeV, where the benchmark point $m(\tilde{t}) = 700$ GeV, $m(\tilde{\chi}_1^0) = 1$ GeV could be reached.

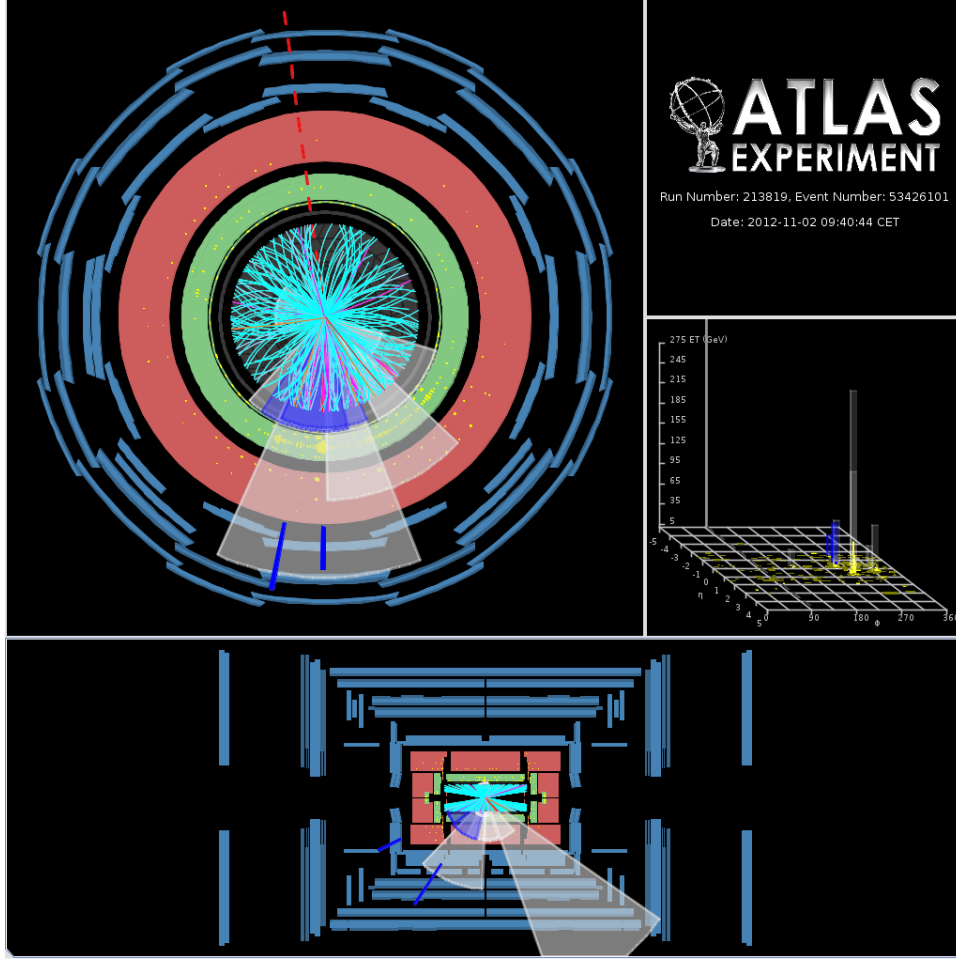


Figure 8.26: Event display of the event 53426101 in run 213819 appearing in SRA3 and SRA4. It has six jets, two of which b -tagged, $E_{\text{T}}^{\text{miss}} = 585 \text{ GeV}$, $m_{\text{T}}^{b, \text{min}} = 374 \text{ GeV}$, and two top candidates with $m_{bjj}^0 = 107 \text{ GeV}$ and $m_{bjj}^1 = 304 \text{ GeV}$. The leading jet has $p_{\text{T}} = 250 \text{ GeV}$. The $E_{\text{T}}^{\text{miss}}$ is indicated by a red dashed line, jets are indicated by white cones, and b -tagged jets are indicated by blue cones. The colour spectrum (blue to red) for the inner detector tracks indicates the relative p_{T} (low to high) [176].

8.5.3 Branching Ratio Limits

To set limits which depend on the branching ratio of the possible $\tilde{t}$ decays, the first step is to identify the decays to be considered. It was assumed that the only possible decay channels for the light stop are $\tilde{t} \rightarrow t\tilde{\chi}_1^0$ and $\tilde{t} \rightarrow b\tilde{\chi}_1^\pm$, where the mass of the chargino is set to be twice the mass of the neutralino. The decay cross section of the stop pairs can then be calculated as:

$$\sigma(\tilde{t}\tilde{t}^* \rightarrow t\tilde{\chi}_1^0 t\tilde{\chi}_1^0) = \left(\text{BR}(t\tilde{\chi}_1^0)\right)^2 \sigma(\tilde{t}\tilde{t}^*) \quad (8.2)$$

$$\sigma(\tilde{t}\tilde{t}^* \rightarrow b\tilde{\chi}_1^+ b\tilde{\chi}_1^-) = \left(1 - \text{BR}(t\tilde{\chi}_1^0)\right)^2 \sigma(\tilde{t}\tilde{t}^*) \quad (8.3)$$

$$\sigma(\tilde{t}\tilde{t}^* \rightarrow t\tilde{\chi}_1^0 b\tilde{\chi}_1^+) = 2\text{BR}(t\tilde{\chi}_1^0) \left(1 - \text{BR}(t\tilde{\chi}_1^0)\right) \sigma(\tilde{t}\tilde{t}^*), \quad (8.4)$$

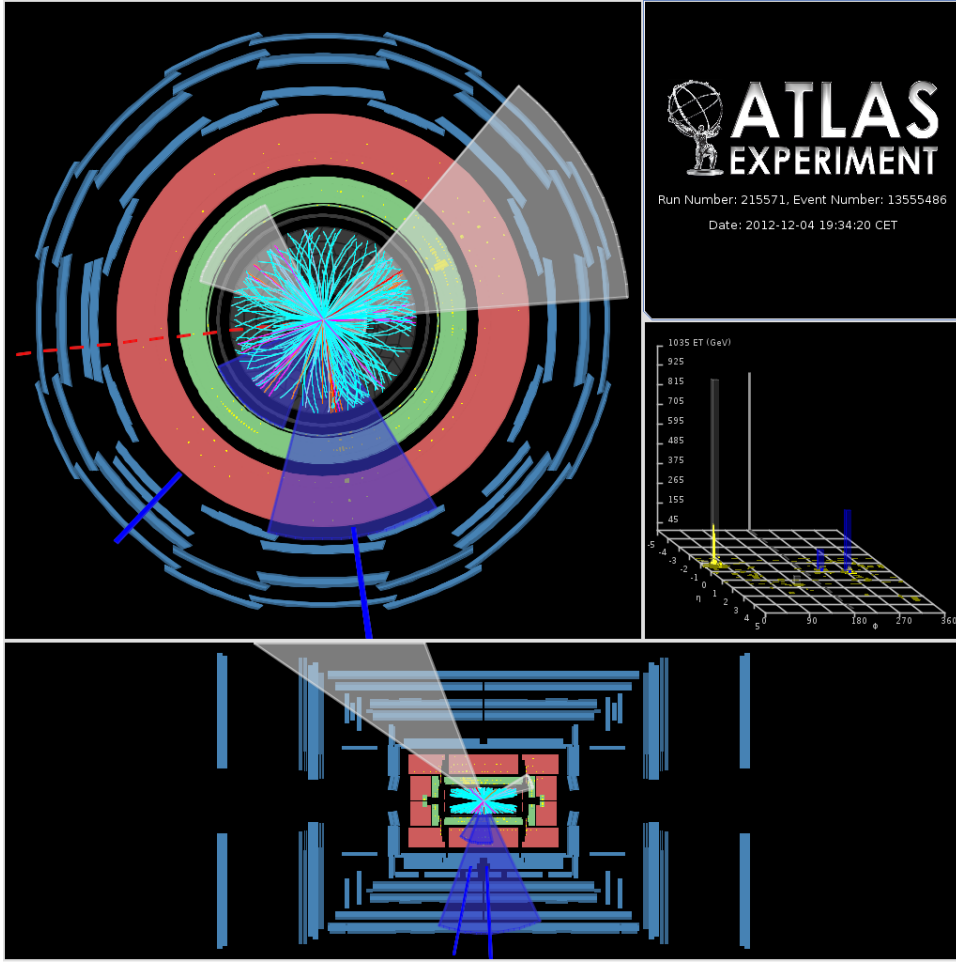


Figure 8.27: Event display of the event 13555486 in run 215571 appearing in SRB and SRC. It has five jets, two of which b -tagged, $E_T^{\text{miss}} = 896$ GeV, $m_T^{b, \min} = 212$ GeV, $E_T^{\text{miss}} / \sqrt{H_T} = 23 \sqrt{\text{GeV}}$, and two reclustered top candidates with $m_{\text{jet}, R=1.2}^0 = 167$ GeV and $m_{\text{jet}, R=1.2}^1 = 170$ GeV. The leading jet has $p_T = 995$ GeV. The E_T^{miss} is indicated by a red dashed line, jets are indicated by white cones, and b -tagged jets are indicated by blue cones. The colour spectrum (blue to red) for the inner detector tracks indicates the relative p_T (low to high) [176].

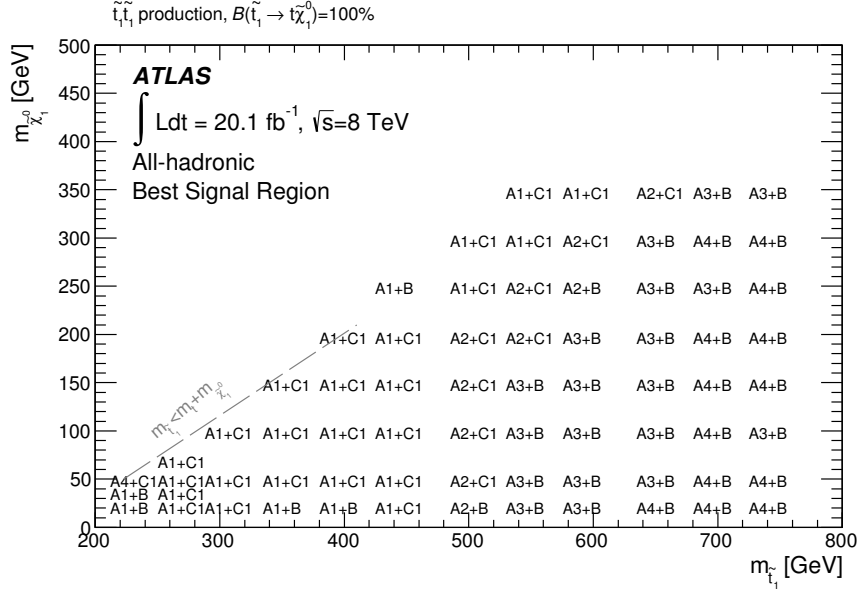
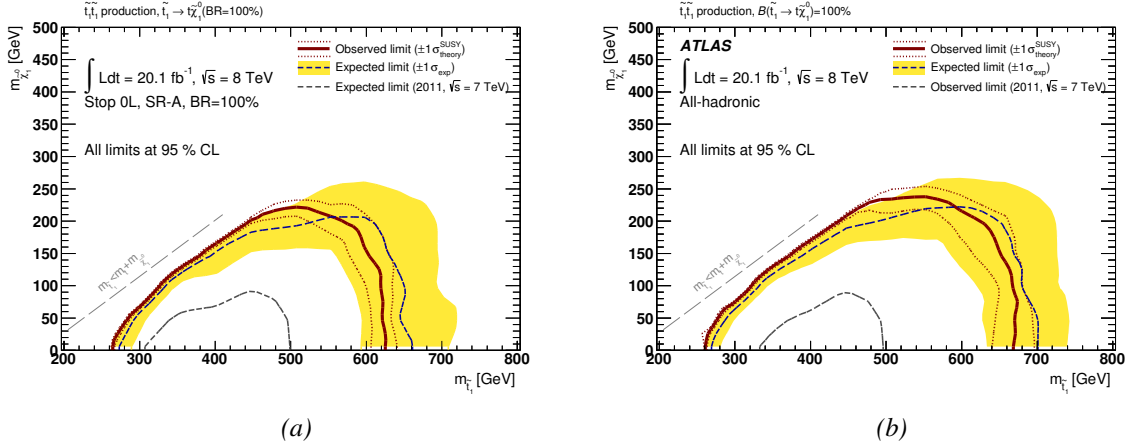
where $\text{BR}(t\tilde{\chi}^0)$ is the branching ratio of the decay $\tilde{t} \rightarrow t\tilde{\chi}_1^0$, and $(1 - \text{BR}(t\tilde{\chi}^0)) = \text{BR}(b\tilde{\chi}_1^\pm)$ is the branching ratio of the decay $\tilde{t} \rightarrow b\tilde{\chi}_1^\pm$.

Given a branching ratio of the stop in $t\tilde{\chi}_1^0$, $\text{BR}(t\tilde{\chi}^0) = \delta$, and a signal point $(m(\tilde{t}), m(\tilde{\chi}_1^0)) = s$, the signal event yield, $N(s, \delta)$, in this scenario can be calculated as

$$N(p, \delta) = \delta^2 \times N(s, \text{BR}(t\tilde{\chi}^0) = 1) + 2\delta(1 - \delta) \times N(s, \tilde{t}\tilde{t}^* \rightarrow t\tilde{\chi}_1^0 b\tilde{\chi}_1^\pm) + (1 - \delta) \times N(s, \text{BR}(b\tilde{\chi}_1^\pm) = 1), \quad (8.5)$$

with $N(s, \text{BR}(t\tilde{\chi}^0) = 1)$ event yield for the signal point in the $\tilde{t} \rightarrow t\tilde{\chi}_1^0$, $\text{BR}=1$, grid, $N(s, \tilde{t}\tilde{t}^* \rightarrow t\tilde{\chi}_1^0 b\tilde{\chi}_1^\pm)$ event yield for the chosen signal point in the mixed grid and $N(s, \text{BR}(b\tilde{\chi}_1^\pm) = 1)$ event yield in the $\tilde{t} \rightarrow b\tilde{\chi}_1^\pm$ grid.

Five branching ratios of the decay $\tilde{t} \rightarrow t\tilde{\chi}_1^0$ have been chosen in 25% steps, ranging from 0 to 100%. The signal regions have been statistically combined following the same procedure as for the $\tilde{t} \rightarrow t\tilde{\chi}_1^0$,


 Figure 8.28: Best SR combination for each point of the $\tilde{t} \rightarrow t\tilde{\chi}_1^0$ BR=100% signal grid [176].

 Figure 8.29: Exclusion contours at 95% C.L. for the $\tilde{t} \rightarrow t\tilde{\chi}_1^0$, BR=100%, scenario for the best SRA (a) and for the best combination SRA+SRB or SRA+SRC (b). The expected exclusion is represented by the blue dashed line and the yellow area is the $\pm 1\sigma$ uncertainty band around the expected exclusion contour. The uncertainty band includes the contribution from the SM theory uncertainty and from the statistical and detector-related uncertainty for background and signal. The red solid line is the observed exclusion contour at 95% C.L.; the dotted red lines represent the $\pm 1\sigma$ variation of the observed limit when the signal cross section is varied up or down within its uncertainty. The grey dashed line is the observed exclusion limit obtained by the search for direct stop production in hadronic final states performed with the ATLAS $\sqrt{s} = 7$ TeV dataset [172]. [176]

BR=100%, scenario, to find the combination with the best CL_s for each $(m(\tilde{t}), m(\tilde{\chi}_1^0))$ point. For low branching ratios in $t\tilde{\chi}_1^0$ and for compressed scenarios the best combinations are those of the loose SRA regions with the SRC regions. For high $t\tilde{\chi}_1^0$ branching ratios and for scenarios with large mass splittings, that allow the decay products to be boosted, the combinations with the best sensitivity are those between the tight SRA regions and SRB.

The 95% C.L. exclusion contour for the 50% decay branching ratio of the stop in $t\tilde{\chi}_1^0$ is shown in

Fig. 8.30a, where the uncertainty bands have the same meaning as in Fig. 8.29 and the grey area represents the parameter space excluded by the LEP searches for the light chargino [151]. The 95% C.L. limit contours for the five chosen branching ratios are summarised in Fig. 8.30b, where the solid lines represent the observed exclusion limits and the dotted lines the expected ones.

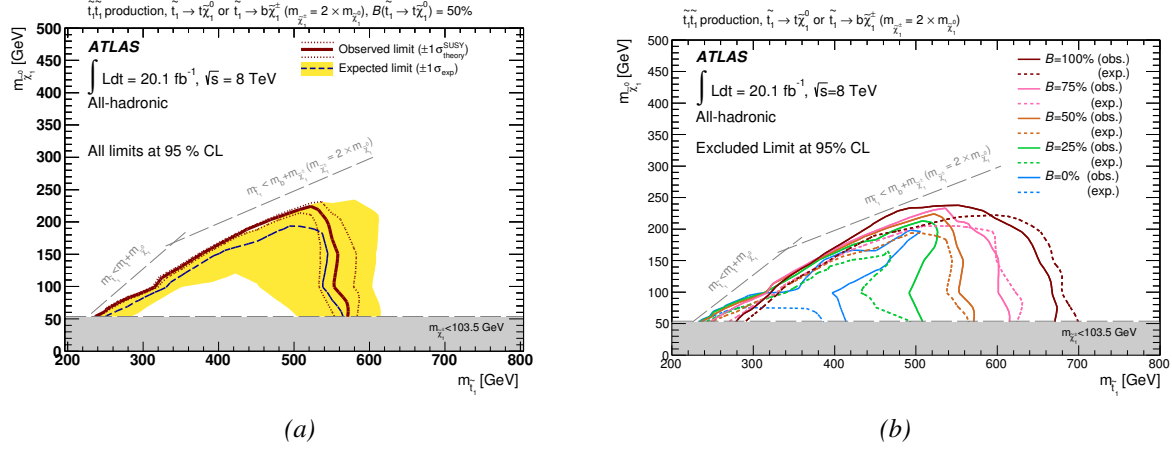


Figure 8.30: (a) Exclusion contour at 95% C.L. for the 50% decay branching ratio of the stop in $t\tilde{\chi}_1^0$. The expected exclusion is represented by the blue dashed line and the yellow area is the $\pm 1\sigma$ uncertainty band around the expected exclusion contour. The uncertainty band includes the contribution from the SM theory uncertainty and from the statistical and detector-related uncertainty for background and signal. The red solid line is the observed exclusion contour at 95% C.L.; the dotted red lines represent the $\pm 1\sigma$ variation of the observed limit when the signal cross section is varied up or down within its uncertainty. (b) Observed (solid lines) and expected (dotted lines) 95% C.L. exclusion contours for varying branching ratio of the stop in $t\tilde{\chi}_1^0$ from 0% to 100%. The grey area represents the parameter space excluded by the LEP searches for the light chargino [151]. [176]

The stop mass ranges excluded for a low neutralino mass are summarised in Table 8.19 for the studied branching ratios. Stop masses between 270 and 645 GeV could be excluded for a scenario where the stop decays always in $t\tilde{\chi}_1^0$ for neutralino masses below 30 GeV, while for a scenario where the pair produced stops decay with a 100% branching ratio in $b\tilde{\chi}_1^\pm$ the excluded stop masses are in the 245–400 GeV range for a neutralino with mass below 60 GeV.

$BR(\tilde{t}_1 \rightarrow t\tilde{\chi}_1^0)$	$m_{\tilde{t}_1}$	$m_{\tilde{\chi}_1^0}$
0%	245–400 GeV	< 60 GeV
25%	245–485 GeV	< 60 GeV
50%	250–550 GeV	< 60 GeV
75%	265–595 GeV	< 60 GeV
100%	270–645 GeV	< 30 GeV

Table 8.19: Excluded top squark masses for the chosen decay branching ratios of the stop in $t\tilde{\chi}_1^0$, under the assumption $m_{\tilde{\chi}_1^\pm} = 2m_{\tilde{\chi}_1^0}$. The excluded mass ranges correspond to the observed limit minus one standard deviation of the uncertainty on the signal cross section [176].

8.6 Direct Stop Searches at the ATLAS Experiment at $\sqrt{s} = 8$ TeV

The programme of the direct stop production searches pursued by the ATLAS collaboration is very wide: different stop decay channels are considered as well as final states with zero, one or two leptons. No direct stop production searches could observe a significant excess over the expected Standard Model background and the summary of the 95% C.L. exclusion contours is drawn in Figs. 8.31 and 8.32 in the $(\tilde{t}, \tilde{\chi}_1^0)$ mass plane, where the results of the searches with the 7 and 8 TeV ATLAS datasets, corresponding respectively to an integrated luminosity of 4.7 and 20 fb⁻¹ of data, are reported. The solid lines represent the observed exclusion contours, while the dashed lines the expected ones.

Three stop decay scenarios, all under the hypothesis of a 100% decay branching ratio, are considered in Fig. 8.31:

- $\tilde{t} \rightarrow t\tilde{\chi}_1^0$: searches in zero, one and two lepton final states were interpreted in this scenario. The dark orange area was excluded by the 7 TeV ATLAS searches [172, 173, 174]. The parameter space excluded by the ATLAS 8 TeV searches is given by the light orange area, excluded by the search in all-hadronic final states presented in this chapter [176], the yellow area, excluded by the search in one lepton final states [179], and the red area, excluded by the search in two lepton final states [184]. For an almost massless neutralino stop masses between 200 and about 670 GeV are excluded.
- $\tilde{t} \rightarrow Wb\tilde{\chi}_1^0$: searches in one and two lepton final states were interpreted in this scenario, where the $\tilde{t}-\tilde{\chi}_1^0$ mass difference is smaller than the top mass but larger than the sum of the W boson and b quark masses. This scenario was not considered by the searches performed with the ATLAS 7 TeV dataset. The area excluded by the one lepton search is drawn in magenta [179], the one excluded by the two lepton search in violet [184].
- $\tilde{t} \rightarrow ff'b\tilde{\chi}_1^0$ and $\tilde{t} \rightarrow c\tilde{\chi}_1^0$: searches in zero and one lepton final states were interpreted in this scenario, where the $\tilde{t}-\tilde{\chi}_1^0$ mass difference is smaller than the sum of the W boson and b quark masses. This scenario was considered only by searches that analysed the ATLAS 8 TeV dataset. The search in all-hadronic final states excluded the light lilla area, for the first model, and the pink area when considering the $\tilde{t} \rightarrow c\tilde{\chi}_1^0$ model [185]. The dark lilla area was excluded by the one lepton search considering the $\tilde{t} \rightarrow ff'b\tilde{\chi}_1^0$ model [179].

Similar direct stop production searches were performed also by the CMS collaboration with the 8 TeV dataset [186, 187, 188, 189]. These searches have a similar sensitivity to the scenarios presented above as the searches designed by the ATLAS collaboration.

Only the stop decay scenario $\tilde{t} \rightarrow b\tilde{\chi}_1^\pm \rightarrow bW^{(*)}\tilde{\chi}_1^0$, BR=100%, is considered, instead, in Fig. 8.31, with the following $\tilde{t}$, $\tilde{\chi}_1^\pm$, and $\tilde{\chi}_1^0$ mass hierarchies:

- $m(\tilde{\chi}_1^\pm) = m(\tilde{\chi}_1^0) + 5(20)$ GeV, top-left box: zero and one lepton searches, performed with the ATLAS 8 TeV dataset, were interpreted in this scenario [179, 190]. The area of the parameter space excluded if the mass difference between chargino and neutralino is of only 5 GeV is shown in light green, in darker green if the mass difference is of 20 GeV. The LEP limit on the chargino mass ($m(\tilde{\chi}_1^\pm) > 103.5$ GeV) [151] is also shown as the grey area. For a neutralino of about 100 GeV stop masses between 140 and 600 GeV could be excluded.

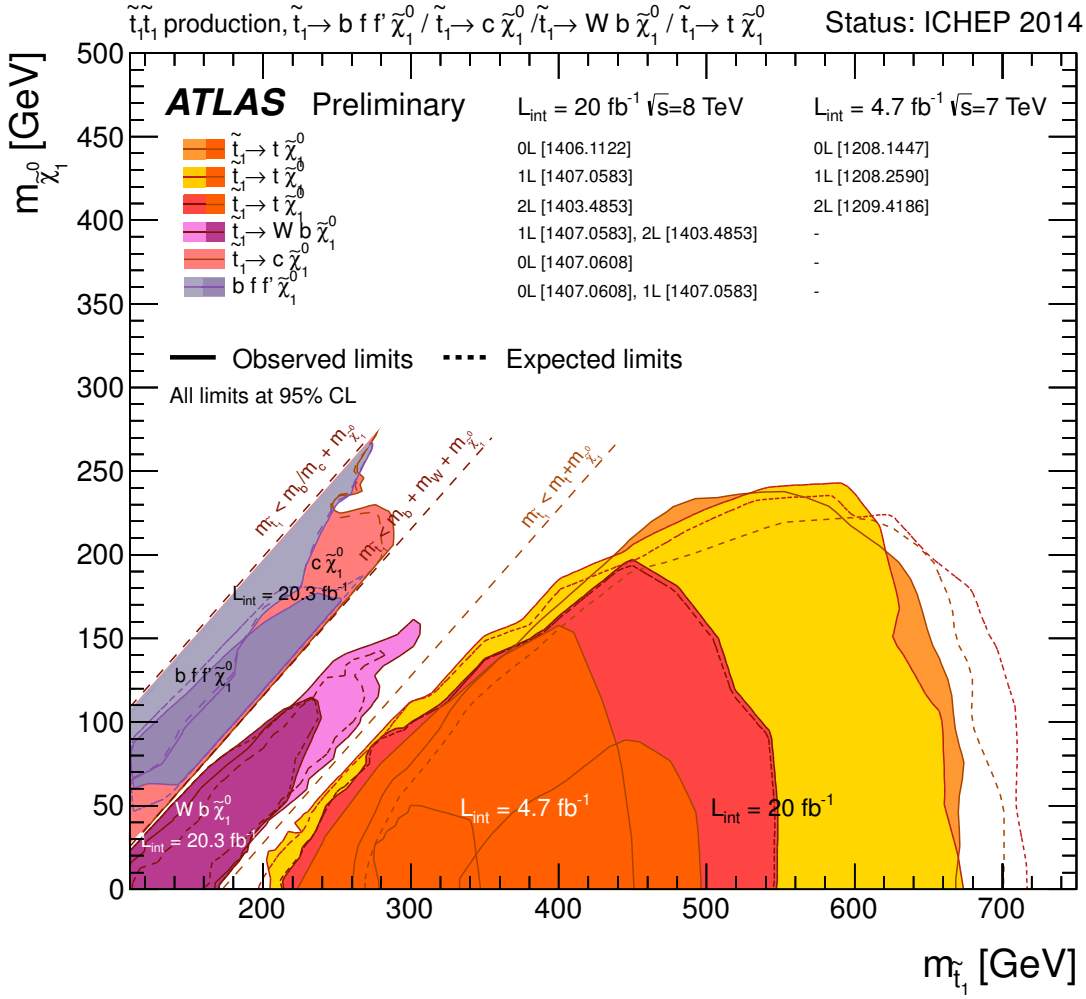


Figure 8.31: Summary of the 95% C.L. exclusion limits of the direct stop pair production searches with the ATLAS 7 and 8 TeV datasets, corresponding to an integrated luminosity of 4.7 and 20 fb^{-1} , respectively. The solid lines represent the observed exclusion limits, while the dashed lines represent the expected limits. The three decay modes considered are $\tilde{t} \rightarrow t\tilde{\chi}_1^0$ [172, 173, 174, 176, 179, 184], three body decay $\tilde{t} \rightarrow Wb\tilde{\chi}_1^0$ [179, 184], and four body decay $\tilde{t} \rightarrow ff'b\tilde{\chi}_1^0$ or $\tilde{t} \rightarrow c\tilde{\chi}_1^0$ decay [179, 185] [175].

- fixed chargino mass $m(\tilde{\chi}_1^\pm) = 106, 150 \text{ GeV}$, top-right box: zero, one and two lepton searches performed with the 7 and 8 TeV ATLAS datasets were interpreted in the $m(\tilde{\chi}_1^\pm) = 106 \text{ GeV}$ scenario. The emerald green area was excluded by the $\sqrt{s} = 7 \text{ TeV}$ one and two lepton searches [163, 171], while the dark green area was excluded by one and two lepton searches performed with the 8 TeV dataset [179, 184]. The lighter green area was excluded by the zero and one lepton $\sqrt{s} = 8 \text{ TeV}$ searches under the hypothesis $m(\tilde{\chi}_1^\pm) = 150 \text{ GeV}$ [179, 190].
- $m(\tilde{\chi}_1^\pm) = 2 \cdot m(\tilde{\chi}_1^0)$, bottom-left box: this is the gaugino universality scenario in which one and two lepton searches, performed both at $\sqrt{s} = 7 \text{ TeV}$ and at $\sqrt{s} = 8 \text{ TeV}$, were interpreted. The area excluded by the 7 TeV analysis, presented in the previous chapter, is shown in dark blue [163], while the area excluded by the 8 TeV searches is drawn in light blue [179, 184]. Also here the area excluded by the LEP searches is drawn in grey.

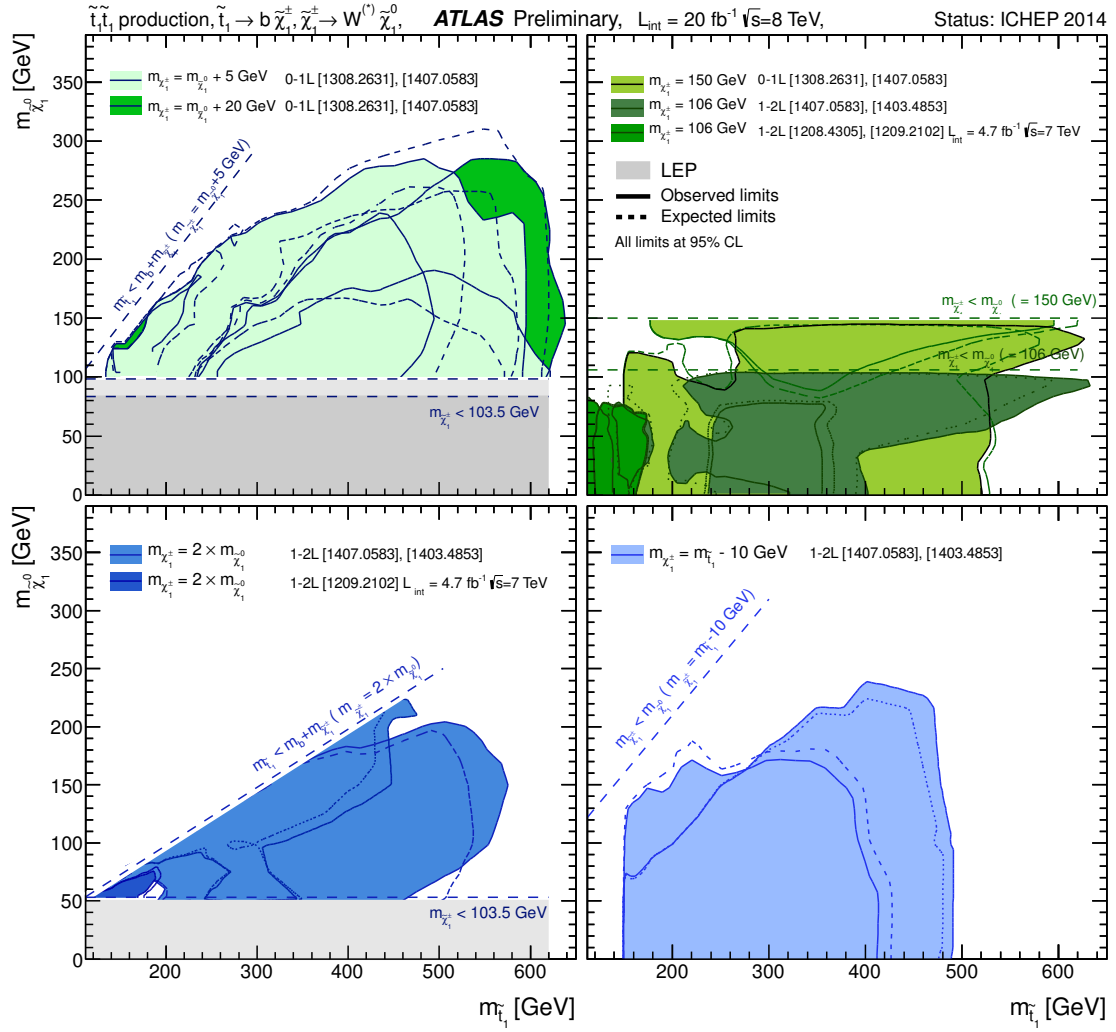


Figure 8.32: Summary of the 95% C.L. exclusion limits of the direct stop pair production searches with the ATLAS 7 and 8 TeV datasets, corresponding to an integrated luminosity of 4.7 and 20 fb^{-1} , respectively. The solid lines represent the observed exclusion limits, while the dashed lines represent the expected limits. The decay mode considered is $\tilde{t} \rightarrow b \tilde{\chi}_1^\pm$. The hypothesis on the $\tilde{t}$, $\tilde{\chi}_1^\pm$, and $\tilde{\chi}_1^0$ mass hierarchies are: $m(\tilde{\chi}_1^\pm) = m(\tilde{\chi}_1^0) + 5(20) \text{ GeV}$ (top-left) [179, 190], fixed chargino mass $m(\tilde{\chi}_1^\pm) = 106, 150 \text{ GeV}$ (top-right) [163, 171, 179, 184, 190], $m(\tilde{\chi}_1^\pm) = 2 \cdot m(\tilde{\chi}_1^0)$ (bottom-left) [163, 179, 184], $m(\tilde{\chi}_1^\pm) = m(\tilde{t}) - 10 \text{ GeV}$ (bottom-right) [179, 184] [175].

- $m(\tilde{\chi}_1^\pm) = m(\tilde{t}) - 10 \text{ GeV}$, bottom-right box: one and two lepton 8 TeV searches were interpreted in this scenario [179, 184]. For a neutralino with mass of 50 GeV stop masses between 150 and 490 GeV could be excluded.

Summary and Outlook

The LHC, after its start at the end of 2009, had a very successful period of operation until the end of 2012. An integrated luminosity corresponding to almost 5 fb^{-1} of data was recorded at a proton–proton centre-of-mass collision energy of 7 TeV in 2010 and 2011, and more than 20 fb^{-1} of data were recorded at $\sqrt{s} = 8 \text{ TeV}$ in 2012. One of the major successes was the discovery of a Higgs boson with mass of about 125 GeV by the ATLAS and CMS collaborations, which is compatible with the one predicted by the Standard Model.

The Higgs boson was the last missing particle predicted by the SM which, despite of its successes, does not have a candidate for the Dark Matter of the universe and has no way of solving the Higgs boson mass hierarchy problem. An elegant solution to the latter can be provided by Supersymmetry, a theory that extends the Standard Model by introducing a new symmetry between bosons and fermions, which gives also a good candidate for Dark Matter, the Lightest Supersymmetric Particle, if the R -parity is conserved.

Within the ATLAS collaboration, a wide programme of searches for supersymmetric particles was pursued. With the first data recorded at $\sqrt{s} = 7 \text{ TeV}$, inclusive searches for the partners of the quarks of the first and second generations and of the gluons were performed. These processes have a relative large production cross section and were the first the experiment was sensitive to. Since no significant excess above the SM background expectation was observed in any analysis, tight limits on the masses of squarks and gluinos were set, which in some cases exceeded the 1 TeV threshold.

However, to solve the hierarchy problem with a low fine tuning of the theory it is important that the partners of the third generation SM quarks, stop and sbottom, are found below or at about 1 TeV, while the other SUSY partners of quarks and leptons may be at a higher scale.

One of the key features of SUSY events in models where the R -parity is conserved is the missing transverse momentum arising from the LSPs, which leave the experiment undetected. Within this thesis, a study was performed to gain a better understanding of the $E_{\text{T}}^{\text{miss}}$ performance. The resolution of the Soft component of the missing transverse momentum was investigated, especially in $Z \rightarrow \ell\ell$ events, and a parameterization to describe it was extracted, which depends on the total energy of the Soft objects and on the amount of hadronic activity of the event. The use of this parameterization could lead, after a thorough validation, to the decrease of the systematic uncertainties that affect the $E_{\text{T}}^{\text{miss}}$ measurement and to the possibility of defining powerful $E_{\text{T}}^{\text{miss}}$ significance variables to be used, e.g. in SUSY searches.

Two searches for the direct production of stop-pairs are presented, which are based on the selection of events with jets, of which some are identified as coming from a b -quark, one or no leptons (electrons and

muons) and missing transverse momentum. In the SUSY scenarios considered, R -parity is conserved and the LSP is assumed to be the lightest neutralino, $\tilde{\chi}_1^0$, a stable massive particle that interacts only via the electroweak force. Two stop decay channels were investigated, one where the stop decays in top and neutralino, $\tilde{t} \rightarrow t\tilde{\chi}_1^0$, open only if the mass difference between the neutralino and the stop is larger than the mass of the top-quark, and one where the stop decays in a b -quark and a chargino, which in return decays in a on- or off-shell W boson and a neutralino, $\tilde{t} \rightarrow b\tilde{\chi}_1^\pm \rightarrow bW^{(*)}\tilde{\chi}_1^0$, a channel open also for a stop with mass below the top-quark mass.

The first search was performed with the 2011 data collected at $\sqrt{s} = 7$ TeV, which corresponds to an integrated luminosity of 4.7 fb^{-1} . The signal is a stop which is lighter or in the same mass range as the top-quark and the decay channel considered is $\tilde{t} \rightarrow b\tilde{\chi}_1^\pm$, with a 100% decay branching ratio. The signal selection is based on events that contain jets, b -jets, one electron or muon, and missing transverse momentum. The discrimination between signal and background is achieved by reconstructing the $t\bar{t}$ decay and exploiting the differences in the top mass distribution and in the shape of the $\sqrt{s}_{\text{min}}^{(\text{sub})}$ variable. No significant excess was observed and 95% C.L. exclusion limits were placed. These were obtained by combining statistically the results of this search with the one obtained by a similar search in two lepton final states. In a scenario where the chargino is two times heavier than the neutralino, stop masses between 120 and 167 GeV were excluded for a neutralino with a mass of 55 GeV. If the mass of the chargino is fixed to 106 GeV, which is just above the LEP limit, stop masses between 123 and 167 GeV were excluded for a neutralino with a mass of 55 GeV.

A search for direct stop pair production and decay in final states with no leptons, jets, b -jets, and large missing transverse momentum was, instead, performed with the full dataset recorded at $\sqrt{s} = 8$ TeV, corresponding to an integrated luminosity of 20.1 fb^{-1} . Here the signal discrimination is achieved by using transverse mass variables and by reconstructing the all-hadronic decay of a $t\bar{t}$ pair. Also for this search no significant excess over the SM expectation was observed and 95% C.L. exclusion limits were set. The main model considered is that of a stop decaying directly in a top-quark and a neutralino, with a decay branching ratio of 100%. In this case stop masses between 270 and 645 GeV were excluded at 95% C.L. for a neutralino with mass below 30 GeV. Exclusion limits at 95% C.L. on the stop mass were also set for a signal that could decay with different branching ratios as $\tilde{t} \rightarrow t\tilde{\chi}_1^0$ or $\tilde{t} \rightarrow b\tilde{\chi}_1^\pm$, in models where the mass of the chargino is two times that of the neutralino. For a 50% branching ratio of the $\tilde{t} \rightarrow t\tilde{\chi}_1^0$ decay, stop masses between 250 and 550 GeV were excluded for a neutralino with mass below 60 GeV. For a scenario where the stop always decays as $\tilde{t} \rightarrow b\tilde{\chi}_1^\pm$, the excluded stop masses are in the range 245-400 GeV for a neutralino with mass below 60 GeV.

The results of the SUSY searches performed by the ATLAS collaboration, and particularly of the ones presented in this thesis, strongly constrain natural Supersymmetry models. However, it should be considered that the searches are interpreted in simplified models. These cannot cover all the decay chains that may appear in nature and some phenomenological models with light supersymmetric particles have not been excluded, yet.

After the shutdown of 2013 and 2014, the LHC will resume operation in late spring 2015 and the pp center-of-mass collision energy will be increased to 13 TeV. At this higher energy the production cross sections of SUSY processes increase significantly and it is expected that already with an integrated luminosity of 5 fb^{-1} it will be possible to exceed the present results. This gives the possibility of observing soon a supersymmetric signal not visible before.

Appendix

Closure-Test of the $E_T^{\text{miss, Soft}}$ Resolution Parameterization

In this appendix, additional figures drawn to compare the measured E_T^{miss} resolution to the resolution obtained by parameterizing the Soft-term resolution contribution are shown. The studies are extensively described in Chapter 5, and in Fig. 5.12 the closure-test for a $Z \rightarrow \mu\mu$ sample, divided in $\sum E_T^{\text{Jet}}$ bins, is shown.

Here the comparisons between the resolution curves are presented for a $Z \rightarrow \mu\mu$ sample in bins based on the jet multiplicity of the events, and for a $W \rightarrow \mu\nu$ sample in $\sum E_T^{\text{Jet}}$ and jet multiplicity bins.

In each figure four E_T^{miss} resolution curves are compared, which represent

- green line: the measured E_T^{miss} resolution of the events, obtained with the convolution method.
- blue line: the total E_T^{miss} resolution computed as the sum in quadrature of the resolution of the selected hard objects and of the Soft-term with the choice $\text{Reso}(\text{Soft}) = \sqrt{\sum E_T^{\text{Soft}}}$.
- magenta line: the total E_T^{miss} resolution computed as the sum in quadrature of the resolution of the selected hard objects and of the Soft-term, extracted from the parameterization, in $\sum E_T^{\text{Jet}}$ bins, obtained with the reco-subtraction method in a $Z \rightarrow \mu\mu$ simulated sample. The values of the fit parameters are summarised in Table 5.3.
- orange line: the total E_T^{miss} resolution computed as the sum in quadrature of the resolution of the selected hard objects and of the Soft-term, extracted from the parameterization, in $\sum E_T^{\text{Jet}}$ bins, obtained with the truth-subtraction method in a $Z \rightarrow \mu\mu$ simulated sample. The values of the fit parameters are summarised in Table 5.4.

The ratio between the resolution curves obtained by setting the Soft-term resolution to the values extracted from the Soft-term resolution fits, either with the reco-subtraction (magenta) or with the truth-subtraction (orange) method, and the measured resolution is also shown. The statistical relative uncertainty of the measured resolution curve is also drawn as green hashed band.

A.1 $Z \rightarrow \mu\mu$ Sample

The comparisons of the resolution curves for the $Z \rightarrow \mu\mu$ sample for a binning based on the jet multiplicity of the selected events are shown in Fig. A.1. The bins chosen are for a zero jets (a) exclusive and (b) inclusive selection, for a one jet (c) exclusive and (d) inclusive selection, and for a two jets (e) exclusive and (f) inclusive selection. For the zero and one jet selections the agreement between the measured resolution and the resolution computed as sum in quadrature of the resolution of the hard objects and of the Soft-term as extracted from the truth-subtraction method is good. For a two jet selection the agreement is slightly worse, partly due to the low yield of $Z \rightarrow \mu\mu$ events produced with at least two additional jets.

A.2 $W \rightarrow \mu\nu$ Sample

The comparisons of the resolution curves for the $W \rightarrow \mu\nu$ sample for a binning based on the $\sum E_T^{\text{Jet}}$ and on the jet multiplicity of the selected events are shown in Figs. A.2 and A.3, respectively.

In Fig. A.2 the bins chosen are (a) $0 \leq \sum E_T^{\text{Jet}} < 10$ GeV, (b) $10 \leq \sum E_T^{\text{Jet}} < 40$ GeV, (c) $40 \leq \sum E_T^{\text{Jet}} < 80$ GeV, (d) $80 \leq \sum E_T^{\text{Jet}} < 150$ GeV, and (e) $\sum E_T^{\text{Jet}} > 150$ GeV selection. In the first two bins the measured resolution is observed to be better than what found by using the Soft-term resolution extracted from the fits. The shift between the two curves is, however, of the order of 1 GeV, while, by setting the resolution of the Soft-term to $\sqrt{\sum E_T^{\text{Soft}}}$, the differences between the measured resolution curve and the curve obtained by summing in quadrature of the resolution of the selected hard objects and of the Soft-term for each selected event are of about four GeV. For the three highest $\sum E_T^{\text{Jet}}$ bins, the agreement between the measured resolution curve and the curves obtained with the Soft-term resolution templates is good.

In Fig. A.3 the bins chosen are for a zero jets (a) exclusive and (b) inclusive selection, for a one jet (c) exclusive and (d) inclusive selection, and for a two jets (e) exclusive and (f) inclusive selection. The agreement between the measured resolution curve and the curve obtained by setting the Soft-term resolution to the value extracted from the truth-subtraction fit is overall good, and the one for the inclusive selection n_{jets} is especially good.

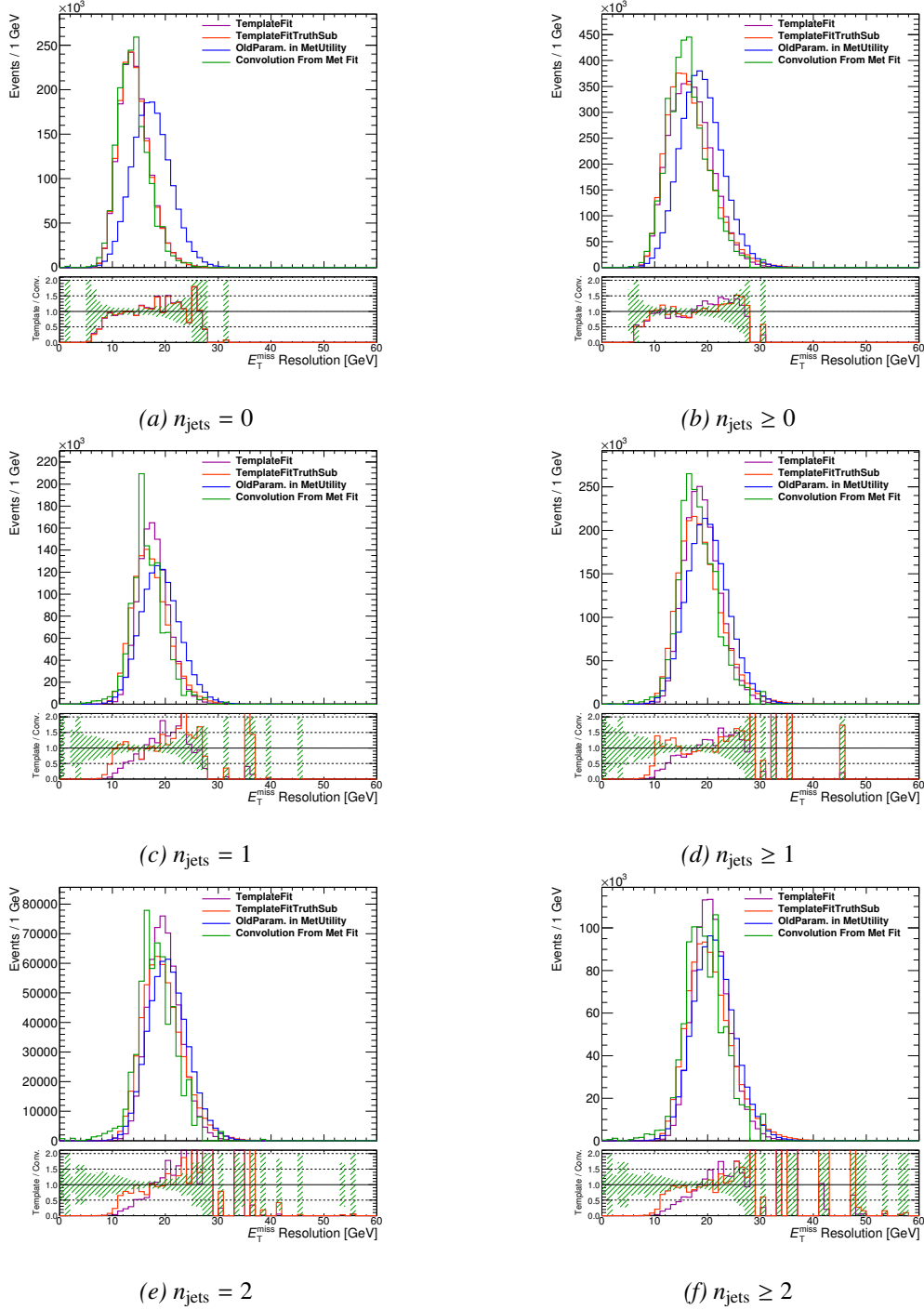


Figure A.1: Distributions of the total E_T^{miss} resolution for the $Z \rightarrow \mu\mu$ sample in the chosen n_{jets} bins: zero jets exclusive (a) and inclusive (b) selection, one jet exclusive (c) and inclusive (d) selection, two jets exclusive (e) and inclusive (f) selection. The magenta, the orange and the blue lines are the sum in quadrature of the resolutions of the selected hard objects and the $E_T^{\text{miss, Soft}}$ resolution as extracted with the reco- and truth-subtraction methods, or as $\sigma_{E_T^{\text{miss, Soft}}} = \sqrt{\sum E_T^{\text{Soft}}}$; the green line is the measured total resolution obtained with the convolution method. The ratio between the results based on the templates and the ones from the convolution method is also shown. The green hatched band in the ratio plot represents the relative uncertainty of the resolution curve obtained with the convolution method.

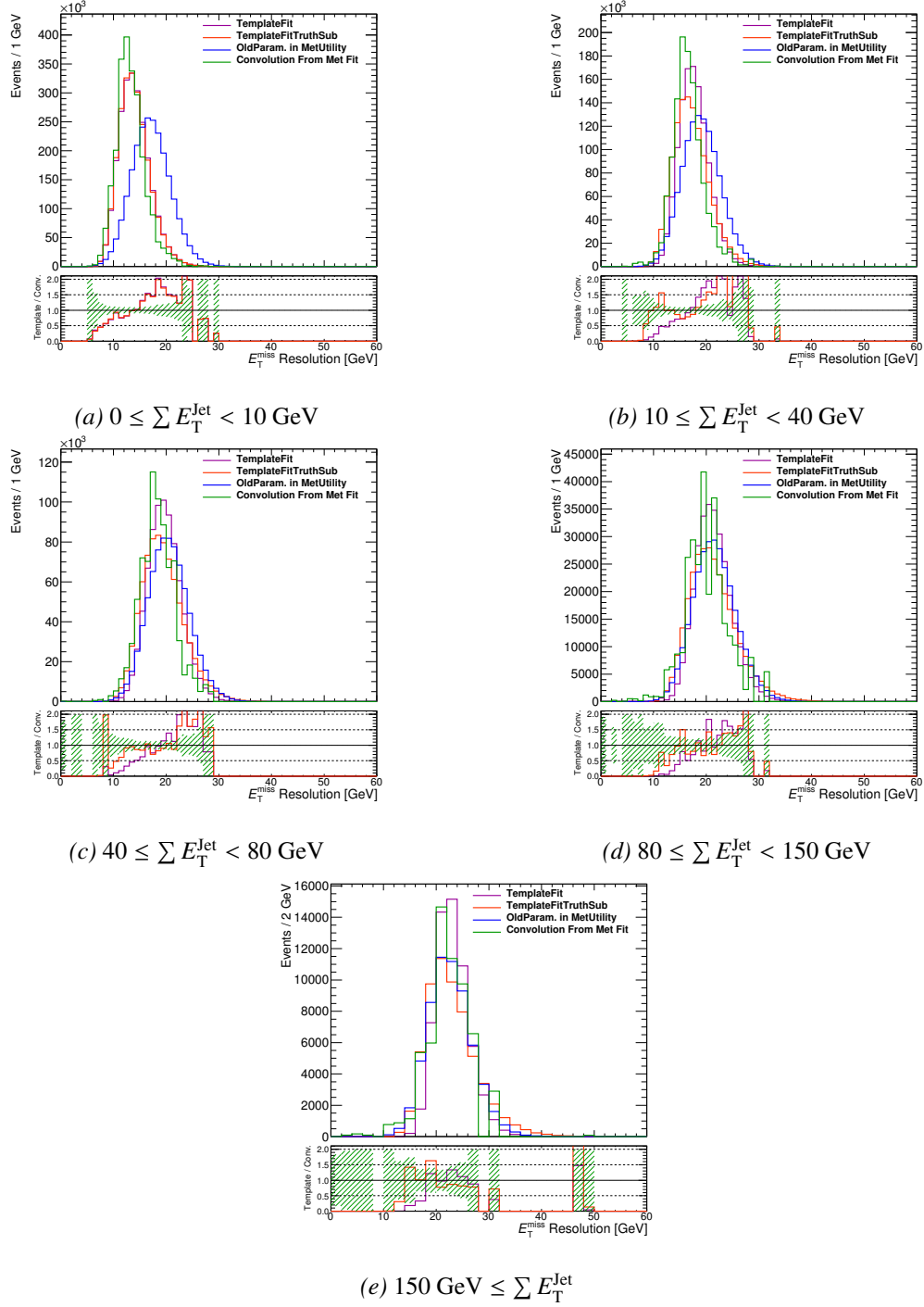


Figure A.2: Distributions of the total E_T^{miss} resolution for the $W \rightarrow \mu\nu$ sample in the chosen $\sum E_T^{\text{J}et}$ bins: $0 \leq \sum E_T^{\text{J}et} < 10 \text{ GeV}$ in (a), $10 \leq \sum E_T^{\text{J}et} < 40 \text{ GeV}$ in (b), $40 \leq \sum E_T^{\text{J}et} < 80 \text{ GeV}$ in (c), $80 \leq \sum E_T^{\text{J}et} < 150 \text{ GeV}$ in (d), $150 \text{ GeV} \leq \sum E_T^{\text{J}et}$ in (e). The magenta, the orange and the blue lines are the sum in quadrature of the resolutions of the selected hard objects and the $E_T^{\text{miss, Soft}}$ resolution as extracted with the reco- and truth-subtraction methods, or as $\sigma_{E_T^{\text{miss, Soft}}} = \sqrt{\sum E_T^{\text{Soft}}}$; the green line is the measured total resolution obtained with the convolution method. The ratio between the results based on the templates and the ones from the convolution method is also shown. The green hatched band in the ratio plot represents the relative uncertainty of the resolution curve obtained with the convolution method.

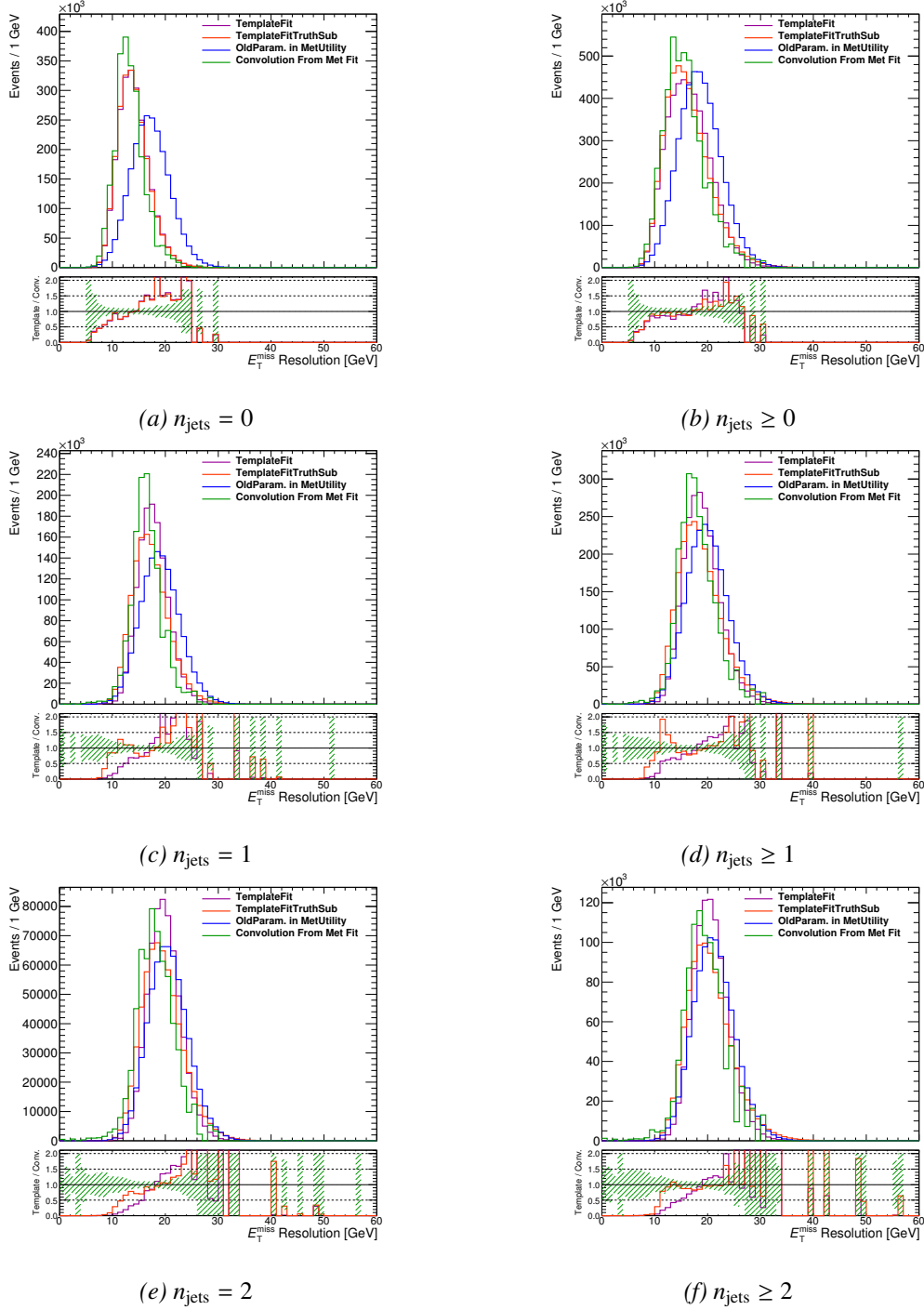


Figure A.3: Distributions of the total E_T^{miss} resolution for the $W \rightarrow \mu\nu$ sample in the chosen n_{jets} bins: zero jets exclusive (a) and inclusive (b) selection, one jet exclusive (c) and inclusive (d) selection, two jets exclusive (e) and inclusive (f) selection. The magenta, the orange and the blue lines are the sum in quadrature of the resolutions of the selected hard objects and the $E_T^{\text{miss, Soft}}$ resolution as extracted with the reco- and truth-subtraction methods, or as $\sigma_{E_T^{\text{miss, Soft}}} = \sqrt{\sum E_T^{\text{Soft}}}$; the green line is the measured total resolution obtained with the convolution method. The ratio between the results based on the templates and the ones from the convolution method is also shown. The green hatched band in the ratio plot represents the relative uncertainty of the resolution curve obtained with the convolution method.

Stop 7 TeV Analysis Samples

The samples used for the analysis presented in Chapter 7 are summarised in Tables B.1 and B.2 for the background and for the signal processes, respectively.

Process	dataset ID	generator	$\mathcal{L}$ [fb ⁻¹]
$t\bar{t}$	105200	MC@NLO	164
Single Top	108340-108345	MC@NLO	43
Wt	108346	MC@NLO	57
W($\ell\nu$) + jets	107680-107685, 107690-107695, 107700-107705	Alpgen+Herwig	0.4 – 8
W(bb/cc) + jets	107280-107287	Alpgen+Herwig	8
W(c) + jets	117293-117297	Alpgen+Herwig	8
Z($\ell\ell$)+jets	107650-107655, 107660-107665, 107670-107675	Alpgen+Herwig	8 – 53
Z($\ell\ell$) + $b\bar{b}$ jets	109300-109303, 109305-109308, 109310-109312	Alpgen+Herwig	50
Z($\ell\ell$) + $c\bar{c}$ jets	126414-126421	Alpgen+Herwig	40
WW,WZ,ZZ	105985-105987	Herwig	150
W/Z γ	106001-106003, 108288-108290, 108323-108325	MadGraph	3–5
$t\bar{t}$ + V/VV	119353-119356, 119583	MadGraph	800–80000
$t\bar{t}$ + γ	117401	Whizard+Jimmy	600
$t\bar{t}$ (varied ISR/FSR)	117255-117260	AcerMC	100
$t\bar{t}$	105860-105861	Powheg	20
W(bb)	126322-126327	Powheg	80
QCD	105009-105017	Pythia	1×10^{-4}
QCD $b\bar{b}$	105757-105759	Pythia	0.7

Table B.1: List of Standard Model Monte Carlo samples used in the analysis. The final column lists the equivalent luminosity for each sample.

Grid	Main parameters	Samples (Dataset range)	Filter	Generator
$m(\tilde{\chi}_1^\pm) = 2 \cdot m(\tilde{\chi}_1^0)$	$m_{\tilde{t}_1}, m_{\tilde{\chi}_1^0}$	76 (139175-139229 / 144747-144765)	1-lepton	HERWIG++
$m(\tilde{t}) = 180$ GeV	$m_{\tilde{\chi}_1^\pm}, m_{\tilde{\chi}_1^0}$	25 (144766-144790)	1-lepton	HERWIG++
$m(\tilde{\chi}_1^\pm) = 106$ GeV	$m_{\tilde{t}_1}, m_{\tilde{\chi}_1^0}$	70 (144025-144052 + extension)	2-lepton	PYTHIA

Table B.2: Summary of signal samples considered in the analysis.

Stop 8 TeV Additional Material

The baseline SM Monte Carlo samples used in the analysis presented in Chapter 8 are listed in Table C.1.

The correlation matrix obtained for the global fit of the control regions used to estimate the background contributions in the SRA set of signal regions is shown in Fig. C.1. The nuisance parameters

- α_{BJes} , $\alpha_{\text{EffectiveNP}_1}$, $\alpha_{\text{EffectiveNP}_2}$, $\alpha_{\text{FlavourCompUncert}}$, and $\alpha_{\text{PileupRhoTopology}}$ are related to the jet energy scale uncertainty;
- α_{JER} is related to the jet energy resolution uncertainty;
- α_{PILEUP} is related to the pile-up uncertainty;
- α_{RESOST} and α_{SCALEST} are related to the $E_{\text{T}}^{\text{miss}}$ Soft-term resolution and scale uncertainties;
- α_{bJET} , α_{cJET} , and α_{bMISS} are related to the b -tagging uncertainties respectively for the b -jets, c -jets, and light jets;
- $\alpha_{\text{theoSysDiboson}}$, $\alpha_{\text{theoSysTtbarV}}$, and α_{theoSysW} are related to the theoretical systematic uncertainties associated respectively to the diboson, $t\bar{t} + V$, and $W + \text{jets}$ production;
- $\gamma_{\text{stat_CRTop_cuts_bin_0}}$, and $\gamma_{\text{stat_CRZ_cuts_bin_0}}$ are related to the statistical uncertainty of the data respectively in the $t\bar{t}$ and $Z + \text{jets}$ control regions.

Finally, $\mu_{\text{Multijets}}$, μ_{Zjets} , and $\mu_{\text{t\bar{t}}}$ are the normalisation parameters of the multi-jet, $Z + \text{jets}$, and $t\bar{t}$ backgrounds, determined in the respective control region.

In general the correlations among the fit parameters are low. A large correlation is observed between the normalisation parameters of the multi-jet and $t\bar{t}$ backgrounds, because of a 20% contamination of $t\bar{t}$ events in the multi-jet control region, and between the nuisance parameter representing the theoretical uncertainties related to $W + \text{jets}$ and the $t\bar{t}$ normalisation factor.

Process	DS ID	Generator	Simulation	Equiv. lumi.
$t\bar{t}$ (lepton filter)	117050	PowHeg+PYTHIA6	AFII	580 fb^{-1}
$t\bar{t}$ (all hadronic)	105204	MC@NLO+HERWIG	GEANT4	11 fb^{-1}
QCD multijets	147911 – 147917	PYTHIA8	GEANT4	$1.6 \times 10^{-4} - 3.4 \times 10^6 \text{ fb}^{-1}$
W + jets (b -filter, p_T bins)	several	SHERPA	AFII, GEANT4	$107\text{-}890 \text{ fb}^{-1}$
W + jets (c -filter, p_T bins)	several	SHERPA	AFII, GEANT4	$19\text{-}360 \text{ fb}^{-1}$
W + jets (b, c -veto, p_T bins)	several	SHERPA	AFII, GEANT4	$1.5\text{-}670 \text{ fb}^{-1}$
Z + jets (b -filter, p_T bins)	several	SHERPA	AFII, GEANT4	$130\text{-}5700 \text{ fb}^{-1}$
Z + jets (c -filter, p_T bins)	several	SHERPA	AFII, GEANT4	$10\text{-}1700 \text{ fb}^{-1}$
Z + jets (b, c -veto, p_T bins)	several	SHERPA	AFII, GEANT4	$1.3\text{-}7000 \text{ fb}^{-1}$
single top (s chan)	110119	PowHeg+PYTHIA6	AFII	330 fb^{-1}
single top (t chan)	110101	ACER MC	AFII	320 fb^{-1}
single top (t chan)	110140	PowHeg+PYTHIA6	AFII	900 fb^{-1}
$t\bar{t}$ + Z boson	119353, 174830-1	MadGraph+PYTHIA	GEANT4	$3.3\text{-}8.2 \text{ ab}^{-1}$
$t\bar{t}$ + W boson	113955, 174832-3	MadGraph+PYTHIA	GEANT4	$3.4\text{-}4.4 \text{ ab}^{-1}$
Diboson (massive b, c)	several	SHERPA	GEANT4	$110\text{-}1700 \text{ fb}^{-1}$

Table C.1.: Baseline Standard Model MC samples used in this analysis.

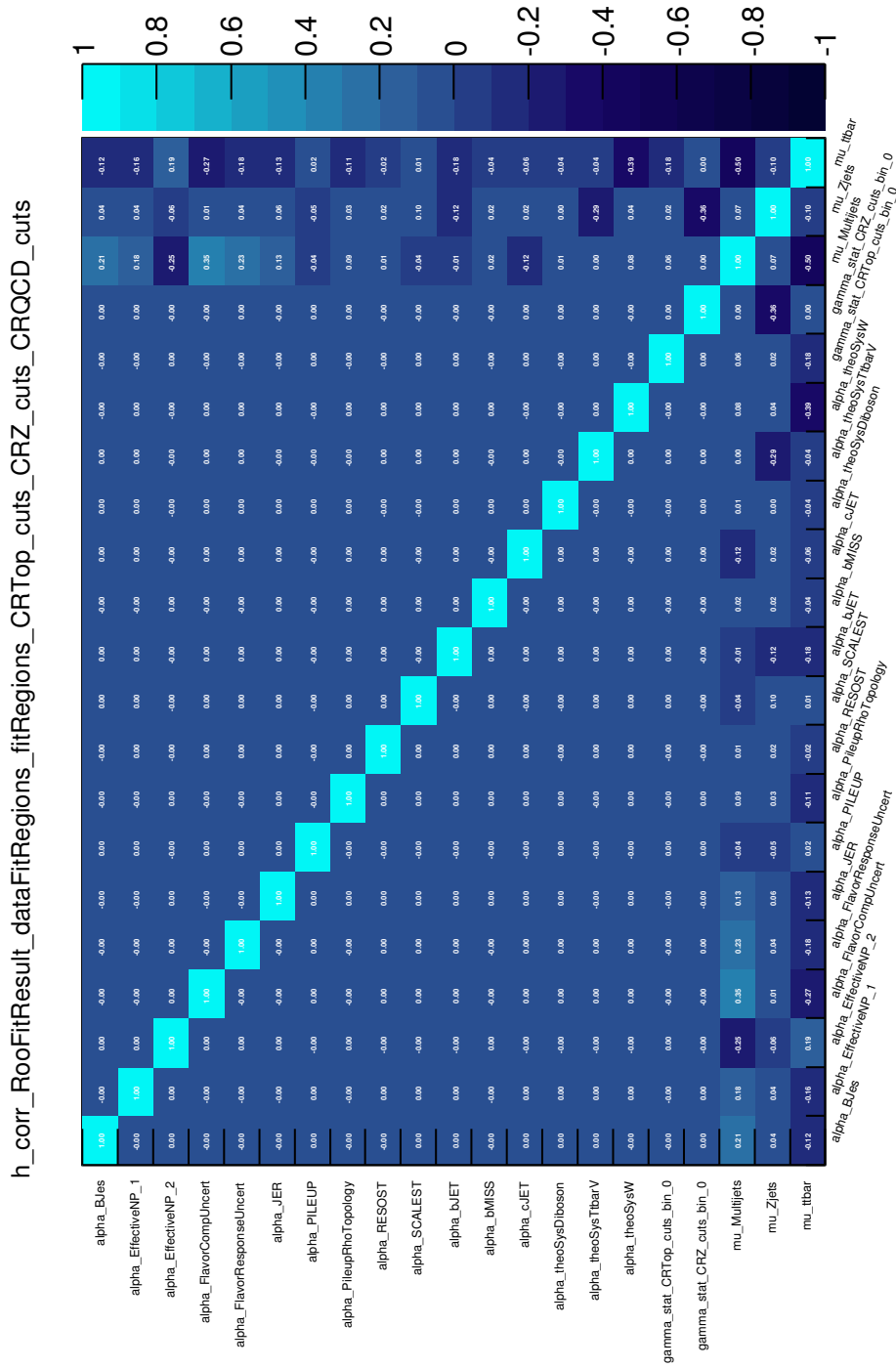


Figure C.1: Correlation matrix of the background fit of the CRAZ, CRAZ and CRAQCD for the estimate of the SM contribution and uncertainty in SRA.

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