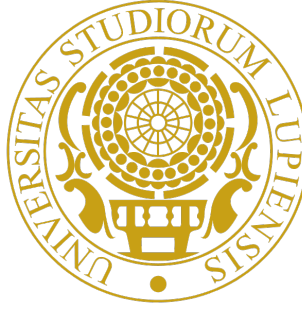




UNIVERSITÀ DEL SALENTO

DIPARTIMENTO DI MATEMATICA E FISICA
“ENNIO DE GIORGI”

DOTTORATO DI RICERCA IN FISICA E NANOSCIENZE
XXXVI CICLO

PH.D. THESIS

**Search for direct production of charginos
and sleptons in LHC Run 2 pp collision data
collected by the ATLAS experiment, and discovery
prospects for top-squark pair production
at High-Luminosity LHC with the ATLAS detector**

Supervisors:

Prof. Edoardo Gorini

Dr. Margherita Primavera

Candidate:

Dr. Matteo Greco



Contents

Contents	I
Introduction	1
1 The Standard Model of Elementary Particles and the Supersymmetry	5
1.1 The Standard Model of Elementary Particles	6
1.1.1 The symmetry of the Standard Model	7
1.1.2 The Higgs Mechanism	9
1.1.3 The limits of the Standard Model	12
1.2 Supersymmetry	14
1.2.1 The R-parity	17
1.2.2 Soft SUSY breaking	18
1.2.2.1 Neutralinos and charginos	19
1.2.2.2 Squarks and sleptons	19
1.2.3 The phenomenological MSSM	19
1.3 SUSY searches at LHC	20
1.3.1 Searches in the strong sector	23
1.3.2 Searches in the electroweak sector	24
2 The Large Hadron Collider and the ATLAS experiment	27
2.1 The Large Hadron Collider	28
2.1.1 Luminosity	30
2.2 The ATLAS experiment	33
2.2.1 The magnetic system	35
2.2.2 The inner detector	36
2.2.3 Calorimetry	38
2.2.3.1 The Electromagnetic Calorimeter	39
2.2.3.2 The Hadronic Calorimeter	39
2.2.3.3 The Forward Calorimeter	40

2.2.4	The muon spectrometer	40
2.2.4.1	The Monitored Drift Tubes (MDTs)	41
2.2.4.2	The Cathode-Strip Chambers (CSCs)	42
2.2.4.3	The Resistive Plate Chambers (RPCs)	42
2.2.4.4	The Thin Gap Chambers (TGCs)	44
2.2.5	Forward detectors	44
2.2.6	The trigger and the data acquisition systems	45
2.2.6.1	L1 trigger	45
2.2.6.2	The HLT	46
2.2.6.3	The DAQ system	47
2.3	The Run 3 of LHC and the HL-LHC	47
2.3.1	The New Small Wheels	47
2.3.1.1	The MicroMegas detectors	48
2.3.1.2	Study of the correlation between the MM readout boards construction parameters and their performance	51
2.3.1.3	Misalignment study of the NSWs using the ‘as-built’ parameters	53
2.3.2	The High-Luminosity LHC	59
3	Object reconstruction in ATLAS	61
3.1	Track and vertex reconstruction	62
3.1.1	Track reconstruction	62
3.1.2	Vertex reconstruction	63
3.2	Electrons and photons	64
3.2.1	Topo-cluster reconstruction	64
3.2.2	Track reconstruction, track-cluster matching, and photon conversion reconstruction	65
3.2.2.1	Track matching for electrons	65
3.2.2.2	Photon conversion	66
3.2.3	Supercluster reconstruction	66
3.2.3.1	Creation of electron and photon candidates	67
3.2.4	Electron and photon identification	68
3.2.4.1	Electron identification	68
3.2.4.2	Photon identification	68
3.2.5	Electron and photon isolation	70
3.3	Muons	72
3.3.1	Muon reconstruction	72
3.3.2	Muon identification	73
3.3.3	Muon isolation	75
3.4	Jets	76
3.4.1	Jet reconstruction	77
3.4.2	Jet energy scale calibration	77
3.4.3	Pile-up jets discrimination	78
3.4.4	b-tagging	81

3.5	Missing Transverse Energy	83
3.5.1	E_T^{miss} significance	85
4	Search for sleptons and charginos in moderately compressed regions	87
4.1	General strategy for SUSY searches	88
4.1.1	Selection of signal-like events: signal regions definition	89
4.1.2	Background estimation: control and validation regions definition	89
4.1.3	The likelihood fit	91
4.2	Data samples	94
4.3	Monte Carlo samples	95
4.3.1	Signal samples	96
4.3.2	Background samples	97
4.4	Trigger selection	99
4.5	Physics object selection	100
4.5.1	Overlap removal	102
4.6	Event preliminary selection	102
4.6.1	Kinematic variables	104
4.6.2	Signal significance Z_n	105
4.7	Fake and non-prompt lepton estimate	106
4.8	Systematic uncertainties	108
4.8.1	Experimental uncertainties	108
4.8.2	Theoretical uncertainties	108
4.8.3	Fake and non-prompt lepton systematics	109
5	Description and results of the slepton search	111
5.1	Status of the ATLAS searches for sleptons	112
5.2	Signal Region definition	113
5.3	Flavour symmetric background estimation	116
5.3.1	The efficiency correction method	116
5.3.1.1	The κ factor	118
5.3.1.2	The α factor	119
5.3.1.3	Validation of the FS background estimation	120
5.4	Systematic uncertainties	125
5.5	Results and interpretation	126
6	Description and results of the chargino search	133
6.1	Status of the ATLAS searches for charginos	134
6.2	Machine learning-based analyses	135
6.2.1	Machine learning technique for the chargino search	136
6.3	Signal region definition	137
6.4	Background estimation	141
6.4.1	Control regions for diboson and top backgrounds	141
6.4.2	Validation regions for diboson and top backgrounds	143

6.5	Systematic uncertainties for the chargino search	147
6.6	Results and interpretation	148
7	Prospects for a search for direct pair production of top-squarks at HL-LHC	153
7.1	Motivation and analysis description	154
7.2	Event simulation	155
7.3	Physics object selection	157
7.4	Event selection	159
7.4.1	4-body selection	159
7.4.2	3-body selection	163
7.5	Systematic uncertainties	167
7.6	Results	169
7.6.1	4-body expected sensitivity	169
7.6.2	3-body expected sensitivity	170
7.6.3	Combined limits	170
	Conclusions	173
A	RECAST validation for the reinterpretation of ATLAS SUSY analyses in the pMSSM framework	177
A.1	The RECAST preservation	181
A.2	The RECAST validation	184
	Bibliography	187
	Acknowledgements	213

Introduction

The behaviour and interactions of the elementary particles are described by the Standard Model (SM) of fundamental interactions, confirmed over the years by many experimental results. The discovery of the Higgs boson in 2012, at the CERN Large Hadron Collider (LHC) [1] by the combined effort of the ATLAS and CMS experiments, was the latest and most important validation of the model.

However, there are still some open problems in particle physics which didn't find a solution within the SM framework: the hierarchy problem, the matter-antimatter asymmetry in our universe, the existence of dark matter. These limitations suggest the necessity to have a new theory, or at least an extension of the existing SM, in order to reach an exhaustive view of particle physics. There are several theories which extend the SM going beyond, thus called Beyond the Standard Model (BSM) theories. Among them, Supersymmetry (SUSY) is promising, and it foresees the existence of a new symmetry which transforms a boson state in a fermionic one and vice versa, thus supposing the existence in nature of fermionic (bosonic) supersymmetric partners for the bosons (fermions) predicted in the SM, whose spin differs by $1/2$ unit from their SM partners. SUSY provides an elegant solution to the hierarchy problem through loop cancellations. Moreover, in SUSY models that conserve the R-parity quantum number SUSY particles (sparticles) can be produced only in pairs, and at the end of each SUSY decay chain the lightest supersymmetric particle (LSP) is stable and weakly interacting, thus potentially providing a viable candidate for dark matter. Finally, this theory would allow the unification of the strong, electromagnetic and weak interactions. The simplest SUSY formulation is the Minimal Supersymmetric Standard Model (MSSM). Many searches of Supersymmetry were performed during the years by the ATLAS [2] and CMS [3] collaborations, analyzing data from proton-proton (pp) collisions at LHC, without observing any evidence of sparticles and setting exclusion limits for their existence. In this PhD thesis two searches for supersymmetric particles are presented, based on simplified, R-parity conserving models.

The first search targets the direct production of pairs of sleptons, supersymmetric partners of the SM leptons, and pairs of charginos, the mass eigenstates obtained by the combination of the supersymmetric partners of the charged gauge and Higgs bosons, in pp collisions at

$\sqrt{s} = 13$ TeV, and uses data collected by the ATLAS experiment during Run 2 of LHC (2015-2018), corresponding to an integrated luminosity of 139 fb^{-1} . In these simplified models each slepton decays in the relative lepton (its SM partner) and a neutralino, whilst each chargino decays in an on-shell W -boson (decaying in turn leptonically) and a neutralino, with branching ratios of 100%. The analysis is focused on the challenging regions ‘moderately compressed’, where the mass difference between the slepton or chargino and the neutralino is of the order of the W -boson mass, and the signature consists of two opposite-sign charged leptons and missing transverse energy. The results, presented in several international conferences, are reported in the paper *Search for direct pair production of sleptons and charginos decaying to two leptons and neutralinos with mass splittings near the W -boson mass in $\sqrt{s} = 13$ TeV pp collisions with the ATLAS detector* [4], published in June 2023 on *Journal of High Energy Physics* by the ATLAS Collaboration.

My main contributions in this analysis include the study of the data modelling by the Monte Carlo simulations, the validation of the machine learning techniques used in the search for chargino, the signal regions optimization and, most of all, the definition and optimization of the control and validation regions for the SM background estimation. Moreover, I took care of the analysis preservation efforts, fundamental step for each ATLAS SUSY analysis in order to ensure that the analysis software can be preserved and possibly reused for future reinterpretation of the analysis results in different models, like the Phenomenological MSSM (pMSSM).

The second ‘search’ investigates the ATLAS sensitivity to the stop (top-squark) pair direct production in the High-Luminosity phase of LHC (HL-LHC) [5]. In this study simplified models of the stop pair production and decay are considered, where each stop decays with a 100% branching ratio in a final state with two leptons, a b -jet and a neutralino. In particular, depending on the mass difference between the stop and the neutralino, a 2-body, 3-body or 4-body decay can happen. After optimizing the strategy already developed in a previous published ATLAS search [6], which used the data collected during Run 2 at LHC, two selections were defined, targeting the 3-body and 4-body decays, but finally applying the 3-body selection also to the 2-body decay. The results are reported in the Public Note ATL-PHYS-PUB-2024-001 *Prospects for a search for direct pair production of top squarks at the high-luminosity LHC with the ATLAS detector* [7], published in January 2024 by the ATLAS Collaboration.

My main contributions in this analysis include the 4-body signal regions optimization and, most of all, the setup of the likelihood fit for the two selections and for their combination, in order to extract the expected exclusion limits at 95% Confidence Level and the potential discovery sensitivities at HL-LHC.

This thesis is structured as follows. In Chapter 1 the Standard Model of the elementary particles is briefly reviewed along with the Supersymmetry and its searches at LHC. In Chapter 2 LHC and the ATLAS detector are described, as well as the work on the New Small Wheel (NSW) in which I was involved. In Chapter 3 the procedures used in ATLAS to reconstruct the objects of interest for the described analyses and the features of these

objects are discussed. In Chapter 4 the general strategy adopted in the SUSY searches and the searches for slepton and chargino pair production are introduced, focusing on the aspects in common between the two, including also the description of the fake non-prompt lepton background estimation and the main sources of systematic uncertainties. The detailed selections, the background estimations and the final results of the two searches are described in Chapter 5 for the slepton case and in Chapter 6 for the chargino case. In Chapter 7 the description of the analysis investigating the prospects for a search for direct pair production of top-squarks at the high-luminosity LHC with the ATLAS detector is reported. Finally, in Appendix A my contribution to the analysis preservation efforts for the reinterpretation of the ATLAS SUSY analyses in the context of the pMSSM is described.

CHAPTER

1

The Standard Model of Elementary Particles and the Supersymmetry

Description of the Standard Model of the elementary particles and their interactions and introduction to the Minimal Supersymmetric Standard Model and supersymmetric searches at LHC.

The most significant and important achievement of particle physics during the XX century has been the formulation of the *Standard Model* (SM) [8–14], an orderly and rigorous representation of the primary constituents of matter, the elementary particles, whose properties and interactions are perfectly described by an elegant and complex mathematical formalism. Several experiments, conducted by physicists from all over the world and throughout the years, have always produced results in a striking agreement with the theory. Nevertheless, the SM turns to be insufficient to explain some physical issues that still remain unsolved, like the *hierarchy problem* [15] and the nature of *dark matter* [16]. This leads to think at the existence of new physics, which goes *Beyond the Standard Model* (BSM) and overcomes its limitations. Among the several BSM theories, one of special interest, which will be the main topic of this thesis, is the *Supersymmetry* (SUSY) [17].

In this first chapter, after having introduced the Standard Model of elementary particles, Supersymmetry and one of its simplest formulation, the *Minimal Supersymmetric Standard Model* (MSSM), will be described, showing how they can respond to the issues that are still

unresolved in particle physics. In particular, the last part of this chapter will be devoted to describe the processes which are the main subjects of this thesis.

1.1 The Standard Model of Elementary Particles

In the Standard Model the matter is described as formed by *leptons* and *quarks*, which are fermions of spin- $1/2$, and these particles interact through the *interaction mediators*, which are bosons, with integer spin. The SM physical-mathematical formalism relies on the *Quantum Field Theory* (QFT), where the particles are *quantum fields* described by operators defined in every points of the space-time, and the excitations of the fields are associated with particle states [18].

The leptons are the *electron*, e , the *muon*, μ , the *tauon*, τ , and their relative *neutrinos*, ν_e , ν_μ , ν_τ , and they are classified into three generations, each consisting of the lepton and its neutrino, of increasing mass and with the same electric charge, Q , spin, S , weak isospin, T , and weak hypercharge, Y ¹. Leptons are classified according to their electric charge (unitary or null) and their leptonic quantum number, and organized in doublet or singlet of the weak isospin group $SU(2)_L$, according to their *left-handed*, L , or *right-handed*, R , helicity².

Similarly to the leptons, the quarks, characterized by six *flavours*, which are *up*, *down*, *charm*, *strange*, *top* and *bottom* (or *beauty*) and indicated as, u , d , c , s , t and b respectively, are arranged into three generations. Their properties are described by the quantum numbers associated to the electric charge, which can be $1/3$ and $-2/3$, to the baryonic number, equal to $1/3$, and, unlike leptons, to the *color charge*, conventionally assigned into three different variants: *red*, r , *blue*, b , and *green*, g . The color charge is described in the context of the color gauge symmetry group $SU(3)_C$. As long as colored particles have never been observed, quarks are described as confined inside the color neutral states called *hadrons*. According to their left-handed or right-handed helicity, the quarks can also be described as *doublets* or *singlets* of the $SU(2)_L$ group, respectively.

Fermions are arranged in the SM in the following way:

$$\text{I generation:} \quad \begin{pmatrix} \nu_e \\ e \end{pmatrix}_L \quad e_R \quad \begin{pmatrix} u \\ d' \end{pmatrix}_L \quad u_R \quad d'_R \quad (1.1)$$

$$\text{II generation:} \quad \begin{pmatrix} \nu_\mu \\ \mu \end{pmatrix}_L \quad \mu_R \quad \begin{pmatrix} c \\ s' \end{pmatrix}_L \quad c_R \quad s'_R \quad (1.2)$$

$$\text{III generation:} \quad \begin{pmatrix} \nu_\tau \\ \tau \end{pmatrix}_L \quad \tau_R \quad \begin{pmatrix} t \\ b' \end{pmatrix}_L \quad t_R \quad b'_R \quad (1.3)$$

SM neutrinos are assumed to be massless and no right-handed neutrino states (or left-handed anti-neutrino states) are allowed to exist. For the quark sector, d' , s' and b' are the weak

¹The *weak hypercharge*, Y , is defined by the electric charge, Q , and by the third component of the weak isospin, T_3 , by the relationship: $Q = T_3 + \frac{1}{2}Y$.

²The left-handed, ψ_L , and right-handed, ψ_R , fermionic fields are defined by the chiral operator γ_5 in the following way: $\psi_L = \frac{1}{2}(1 - \gamma_5)\psi$ and $\psi_R = \frac{1}{2}(1 + \gamma_5)\psi$, where ψ is the Dirac's spinor associated to the fermion.

interaction eigenstates obtained as linear combination of the flavour physical eigenstates d , s and b , by the usage of the *Cabibbo-Kobayashi-Maskawa*, CKM, matrix [19, 20]. In Table 1.1 Q , T_3 and Y values are summarized for each of the lepton and quark generations, and for their left-handed or right-handed components.

	Left-handed helicity	Q	T_3	Y	Right-handed helicity	Q	T_3	Y
Leptons	ν_e, ν_μ, ν_τ	0	$+1/2$	-1	-	-	-	-
	e_L^-, μ_L^-, τ_L^-	-1	$-1/2$	-1	e_R^-, μ_R^-, τ_R^-	-1	0	-2
Quarks	u_L, c_L, t_L	$+2/3$	$+1/2$	$+1/3$	u_R, c_R, t_R	$+2/3$	0	$+4/3$
	d_L', s_L', b_L'	$-1/3$	$-1/2$	$+1/3$	d_R', s_R', b_R'	$-1/3$	0	$-2/3$

Table 1.1: Electric charge, Q , in unit of the elementary charge, $|e|$, third component of the weak isospin, T_3 , and hypercharge, Y , for the left-handed and right-handed components of leptons and quarks.

Each quark and each lepton has an antiparticle, obtained by the application of the charge conjugation operator, C , reversing its electric charge and all the internal quantum numbers (baryon and lepton numbers, strangeness, etc.).

The interactions between the elementary particles³ are explained through the exchange of mediator bosons of spin-1: the *photon*, γ , for the electromagnetic interaction, electrically neutral and massless; $W^\pm$ and Z^0 for the weak interaction, heavy, with weak charge and, in case of $W^\pm$, also electric charge; and 8 *gluons*, $g_{i=1,\dots,8}$, for the strong interaction, massless, electrically neutral and with color charge.

In addition, the *Higgs boson* completes the particle scenario. It is a neutral, scalar boson associated to the spontaneous symmetry breaking mechanism theorized by P. Higgs [21], F. Englert and R. Brout [22]. The Higgs boson, which was discovered in 2012 thanks to the combined efforts of the ATLAS [23] and CMS [24] collaborations, is needed to justify the mass of the particles in the Standard Model.

The main properties of all the Standard Model particles described so far are summarized in Table 1.2.

1.1.1 The symmetry of the Standard Model

Overall, the group of symmetry, or *gauge invariance*⁴, of the SM is:

$$SU(3)_C \otimes SU(2)_L \otimes U(1)_Y. \quad (1.4)$$

Symmetries under local (gauge) transformations are fundamental in order to explain the existence of the interactions among the particles through their mediators, actually called *gauge*

³Gravity is excluded from this model, because too weak for having a significant role at subatomic level.

⁴Generally, these symmetries are invariances of the lagrangian that describes the system under groups of local (gauge) transformations of the physical fields.

	Generation	Particle	Q	S	B	L	Mass [GeV]
Leptons	I	e	-1	$1/2$	0	1	$\sim 0.511 \times 10^{-3}$
		ν_e	0	$1/2$	0	1	~ 0
	II	μ	-1	$1/2$	0	1	$\sim 105 \times 10^{-3}$
		ν_μ	0	$1/2$	0	1	~ 0
	III	τ	-1	$1/2$	0	1	1.77686 ± 0.00012
		ν_τ	0	$1/2$	0	1	~ 0
Quarks	I	u	$+2/3$	$1/2$	$1/3$	0	$2.16^{+0.49}_{-0.26} \times 10^{-3}$
		d	$-1/3$	$1/2$	$1/3$	0	$4.67^{+0.48}_{-0.17} \times 10^{-3}$
	II	c	$+2/3$	$1/2$	$1/3$	0	1.27 ± 0.02
		s	$-1/3$	$1/2$	$1/3$	0	$93.4^{+8.6}_{-3.4} \times 10^{-3}$
	III	t	$+2/3$	$1/2$	$1/3$	0	172.69 ± 0.30
		b	$-1/3$	$1/2$	$1/3$	0	$4.18^{+0.03}_{-0.02}$
Bosons		γ	0	1	0	0	$< 1 \times 10^{-27}$
		$W^\pm$	± 1	1	0	0	80.377 ± 0.012
		Z^0	0	1	0	0	91.1876 ± 0.0021
		$g_{i=1,\dots,8}$	0	1	0	0	0
Higgs		h	0	0	0	0	125.25 ± 0.17

Table 1.2: Summary of the properties of the SM particles: the electric charge, Q , in unit of the elementary charge, $|e|$, the spin, S , the baryon, B , and lepton, L , quantum numbers are reported. The Natural Units system is adopted to express kinematic quantities, implying $\hbar = c = 1$ [25].

bosons. To date, all the results of the experiments that have been conducted are consistent with the SM description. By using a more rigorous *group theory* formalism, the symmetries of the SM are the following:

- **$U(1)_Y$:** invariance under the group $U(1)$ associated to the hypercharge quantum number Y , introduced by S. Glashow, A. Salam and J. Ward in order to unify the weak and electromagnetic interactions in the *electroweak* one. The gauge boson required from this invariance of the theory under $U(1)_Y$ transformations is indicated as B^μ , and the associated particle has spin-1. The $U(1)_Y$ group is an *abelian*⁵ group.
- **$SU(2)_L$:** symmetry under the group $SU(2)$ associated to the weak isospin quantum number. The subscript ‘L’ is referred to the fact that this symmetry involves only

⁵In case of an *abelian* symmetry group it is possible to change the order of the group transformations without changing the result.

left-handed fermions, that are, in fact, organized in *weak isospin doublets*, while the right-handed fermions remain excluded by the symmetry and are organized in *weak isospin singlets*, as described in Table 1.1 and in formulas 1.1, 1.2 and 1.3. This is a *non-abelian* gauge invariance, and the gauge bosons associated to it are W_i^μ , with $i = 1, 2, 3$; three as the number of generators of $SU(2)_L$.

- **SU(3)_C**: symmetry under the group $SU(3)$ associated to the color charge quantum number. This group is non-abelian and in this case the gauge bosons are G_a^μ , with $a = 1, \dots, 8$, as many as the number of generators of $SU(3)_C$. These bosons are the gluons and the theory of the strong interactions is the *Quantum Chromodynamics* (QCD) [26].

The three symmetries just described don't involve all the SM particles: for example, the leptons don't have any color charge, therefore they are not subjected to the color $SU(3)_C$ symmetry. Furthermore, the gauge bosons of the electroweak symmetry $SU(2)_L \otimes U(1)_Y$ don't coincide with the physical observed bosons, because of the spontaneous symmetry breaking and the Higgs mechanism, described in the next section [27].

All properties explained above are mathematically described by a unique lagrangian, which describes all the interactions between fermions and bosons. A compact form of the SM lagrangian is:

$$\mathcal{L}_{SM} = -\frac{1}{4}F_{\mu\nu}^a F^{a\mu\nu} + (i\bar{\psi}\not{D}\psi + h.c.) + (\psi_i y_{ij} \psi_j \phi + h.c.) + |D_\mu \phi|^2 - V(\phi). \quad (1.5)$$

The first term is a scalar product between tensors, called *field strenghts*, and it represents the kinetic term of a generic gauge field. The second term describes how the mediator bosons interact with fermions, generically indicated as ψ , where $\not{D} = \gamma^\mu D_\mu$ is the *covariant derivative*, containing the description of all the electromagnetic, weak and strong interactions. The third and the forth terms are the interaction between fermions and bosons respectively with the Brout-Englert-Higgs (BEH) field, ϕ , which will be better described in the following section. In particular, the y_{ij} coefficients are the so called *Yukawa terms* which are the coupling parameters between fermions and the Higgs field ϕ , directly correlated to the mass of the particle in exam. The last term is the potential associated to the BEH field [28].

1.1.2 The Higgs Mechanism

Until '60 the electromagnetic and weak interactions were considered as two separated fundamental interactions. Then S. Glashow, A. Salam and S. Weinberg formulated a model where the two forces are unified into the electroweak interaction, described by the gauge invariance group $SU(2)_L \otimes U(1)_Y$. This model foresees that the weak interaction is mediated by massless gauge bosons which, after a mechanism of symmetry breaking, acquire mass. However, in order to avoid to obtain a non-renormalizable theory, and thus unphysical, this breaking needs to be spontaneous⁶ [30]. The mechanism that describes this *Spontaneous Symmetry*

⁶The *spontaneous symmetry breaking* (SSB) is the phenomenon for which a stable state of a system (for example the ground state or a thermal equilibrium state) is not symmetric under a symmetry of the

Breaking (SSB) was developed by P. Higgs, F. Englert and R. Brout, and it's known as the *Higgs mechanism*. It consists in considering in the SM massless particles, an additional scalar field, called *Brout-Englert-Higgs field*, with a non-vanishing vacuum expectation value. The interaction of this field with the particles produces the SSB and provides masses to these particles.

The lagrangian that describes the electroweak symmetry $SU(2)_L \otimes U(1)_Y$ can be written as

$$\begin{aligned} \mathcal{L}_{SU(2)_L \otimes U(1)_Y} = & i(\bar{\nu}_f \quad \bar{f})_L \gamma^\mu \left[\partial_\mu + ig \frac{\tau_i}{2} \cdot W_\mu^i + ig' \frac{Y}{2} B_\mu \right] \begin{pmatrix} \nu_f \\ f \end{pmatrix}_L + \\ & + i\bar{f}_R \gamma^\mu \left(\partial_\mu + ig' \frac{Y}{2} B_\mu \right) f_R - \frac{1}{4} B_{\mu\nu} B^{\mu\nu} - \frac{1}{4} W_{\mu\nu}^i W^{\mu\nu i}, \end{aligned} \quad (1.6)$$

where f represents a generic fermion with $T_3 = -1/2$, g and g' are the coupling constants of the weak isospin and hypercharge groups respectively, τ_i are the Pauli's matrices⁷ and

$$\begin{aligned} B_{\mu\nu} &= \partial_\mu B_\nu - \partial_\nu B_\mu, \\ W_{\mu\nu}^i &= \partial_\mu W_\nu^i - \partial_\nu W_\mu^i - g\epsilon_{ijk} W_\mu^j W_\nu^k. \end{aligned} \quad (1.7)$$

Introducing in the Lagrangian a weak isospin doublet characterized by having $Y = 1$, known as *Higgs doublet*, through the four real scalar fields ϕ_i , with $i = 1, 2, 3, 4$:

$$\Phi = \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} \quad \text{with} \quad \begin{cases} \phi^+ = (\phi_1 + i\phi_2)/\sqrt{2} \\ \phi^0 = (\phi_3 + i\phi_4)/\sqrt{2} \end{cases} \quad (1.8)$$

we get, for this doublet:

$$\begin{aligned} \mathcal{L}_\Phi &= \left| \left(\partial_\mu + ig \frac{\tau_i}{2} \cdot W_\mu^i + ig' \frac{Y}{2} B_\mu \right) \Phi \right|^2 - V(\Phi) = \\ &= \left| \left(\partial_\mu + ig \frac{\tau_i}{2} \cdot W_\mu^i + ig' \frac{Y}{2} B_\mu \right) \Phi \right|^2 - \mu^2 \Phi^\dagger \Phi - \lambda (\Phi^\dagger \Phi)^2, \end{aligned} \quad (1.9)$$

where $V(\Phi)$ represents the potential associated to the scalar field, and μ and λ are two real constants. By considering the case $\mu^2 < 0$ and $\lambda > 0$, a minimum value of the potential $V(\Phi)$ can be reached, with value:

$$\Phi^\dagger \Phi = \frac{1}{2}(\phi_1^2 + \phi_2^2 + \phi_3^2 + \phi_4^2) = -\frac{\mu^2}{2\lambda}, \quad (1.10)$$

Hamiltonian, Lagrangian or action which describe the system itself [29].

⁷The *Pauli's matrices*, τ_i , with $i = 1, 2, 3$, are defined as $\tau_i = \frac{\sigma_i}{2}$, where σ_i are:

$$\sigma_1 = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}, \quad \sigma_2 = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}, \quad \sigma_3 = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}.$$

These matrices satisfy the relation $\sigma_1^2 = \sigma_2^2 = \sigma_3^2 = I$, with I identity matrix, and they have $\det \sigma_i = -1$ and $\text{tr} \sigma_i = 0$. They also satisfy the commutation relationships $[\sigma_i, \sigma_j] = 2i\epsilon_{ijk}\sigma_k$, with ϵ_{ijk} the *Levi-Civita tensor*, and the anticommutation relationships $\{\sigma_i, \sigma_j\} = 2\delta_{ij}I$, with δ_{ij} the *Kronecker delta*.

defining a geometric locus of the points which is invariant under transformation of $SU(2)_L$. Choosing

$$\Phi_0 = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v \end{pmatrix} \quad \text{with} \quad v = \sqrt{-\frac{\mu^2}{\lambda}}, \quad (1.11)$$

as vacuum expectation value of Φ , where v represents the value that minimizes the potential, such a choice breaks both the $SU(2)_L$ and $U(1)_Y$ symmetries, being characterized by $T = 1/2$, $T_3 = -1/2$ and $Y = 1$. However, it allows for a new $U(1)$ gauge symmetry, with generator the electric charge operator Q , i.e. the electromagnetic gauge symmetry $U(1)_{em}$. Therefore, the Higgs mechanism consists in breaking the symmetry $SU(2)_L \otimes U(1)_Y$ providing mass to three of the relative gauge bosons and leaving massless the one associated to $U(1)_{em}$, that is the photon. The field Φ can be written as:

$$\Phi = U \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + h \end{pmatrix}, \quad (1.12)$$

where U represents a generic gauge transformation of $SU(2)_L$ and h a real fluctuation of the field Φ with respect to the vacuum expectation value. Under the choice of a proper gauge transformation, the Higgs doublet can be reduced to the real scalar field h , the *Higgs field*, whose mass is:

$$m_h = \sqrt{-2\mu^2} = \sqrt{2\lambda v^2}. \quad (1.13)$$

From the interaction terms of this field with the gauge bosons, the physical bosons $W^\pm$, Z and γ are obtained through the following relationships:

$$W_\mu^\pm = \frac{W_\mu^1 \mp iW_\mu^2}{\sqrt{2}}, \quad \begin{pmatrix} Z_\mu \\ A_\mu \end{pmatrix} = \begin{pmatrix} \cos \theta_W & -\sin \theta_W \\ \sin \theta_W & \cos \theta_W \end{pmatrix} \begin{pmatrix} W_\mu^3 \\ B_\mu \end{pmatrix}, \quad (1.14)$$

where θ_W , known as *Weinberg angle*, is given by:

$$\tan \theta_W = \frac{g'}{g}. \quad (1.15)$$

Following the equations 1.14, the masses of the physical gauge vector bosons for the electroweak interactions are:

$$m_{W^\pm} = \frac{1}{2}vg, \quad m_{Z^0} = \frac{1}{2}v\sqrt{g^2 + g'^2}, \quad m_\gamma = 0. \quad (1.16)$$

Therefore, the physical $W^\pm$ bosons are obtained as a linear combination of the interaction bosons W^1 e W^2 , whereas the Z^0 and γ bosons from the combination of the bosons W^3 (indicated also as W^0) and B^0 . An ATLAS recently published measurement of the W -boson mass [31], compared with other experimental results, is reported in Figure 1.1.

The mechanism described above can be applied to the fermion mass generation. Also in this case, an interaction term called *Yukawa term* is introduced in the lagrangian:

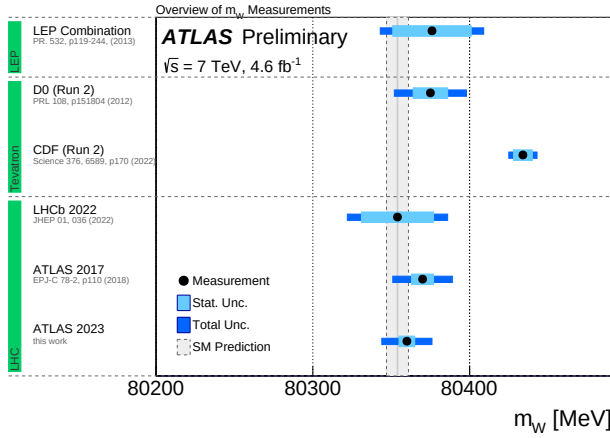


Figure 1.1: The measured value of m_W [31] is compared to SM prediction from the global electroweak fit [32], and to the combined values of m_W measured at LEP [33], Tevatron [34, 35] and the LHC [36, 37].

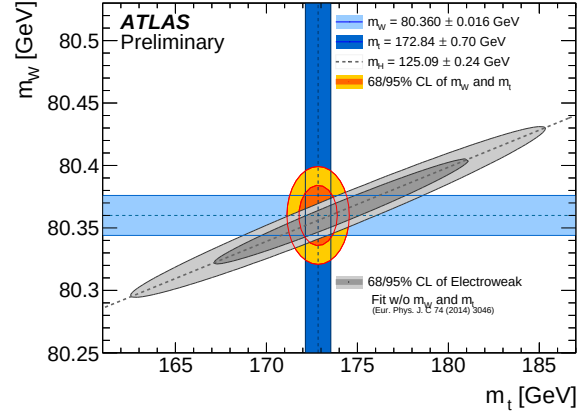


Figure 1.2: The 68% and 95% confidence-level contours of the m_W and m_t indirect determinations from the global electroweak fit are compared to the 68% and 95% confidence-level contours of the ATLAS measurements of the top-quark and W -boson masses [31].

$$\mathcal{L}_{Yukawa} = -G_f \left[(\bar{\nu}_f \quad \bar{f})_L \begin{pmatrix} \phi^+ \\ \phi^0 \end{pmatrix} f_R + \bar{f}_R (\phi^- \quad \bar{\phi}^0) \begin{pmatrix} \nu_f \\ f \end{pmatrix}_L \right], \quad (1.17)$$

with G_f the fermionic coupling constant. By properly substituting Φ , the mass of the generic fermion is:

$$m_f = \frac{G_f}{\sqrt{2}} v. \quad (1.18)$$

In case of the quarks, the Yukawa term to be provided is more general, because it's needed to generate the mass for the upper member of the weak doublet, but also for the lower one by taking into account the CKM matrix. The interaction term for quarks is:

$$\mathcal{L}_{Yukawa} = -G_d^{ij} (\bar{u}_i \bar{d}'_i)_L \Phi d_{jR} - G_u^{ij} (\bar{u}_i \bar{d}'_i)_L (-i\tau_2) \Phi^* u_{jR} + h.c. \quad \text{con } i, j = 1, 2, 3, \quad (1.19)$$

where u_i represents one of the quarks (u, c, t), d'_i one of the quarks (d', s', b') and G_d^{ij} , G_u^{ij} the coupling constants between the Higgs field and the quarks d_i and u_i respectively. The agreement [31] between the ATLAS measurements of the top-quark and W -boson masses with the values obtained from the electroweak global fit of the SM is shown in Figure 1.2.

1.1.3 The limits of the Standard Model

As already mentioned in the introduction to this chapter, despite the large number of experimental verifications, the Standard Model can't explain some, still open, issues in particle physics. Among the most relevant there are:

- the *matter-antimatter asymmetry*: according to the cosmological model of *Big Bang*, the Universe originally contained with the same amount of matter and antimatter, while today, moving from the smallest forms of life to the largest cosmological objects, we observe that everything is composed almost entirely of matter;
- the *existence of dark matter*: experimental evidences in astrophysics and cosmology suggest that the ordinary baryonic matter represents only the 5% of our universe, and the existence of a type of matter detectable only by its gravitational effects ('dark'), which explains another 27% of the total universe. The remaining 68% is imputable to dark energy⁸. Searches for new particles that can be possible dark matter candidates are fundamental and, in several scenarios, general arguments suggest that they have mass lower than 1 TeV⁹. If this kind of particles exist, they are expected to not interact electromagnetically or strongly with the ordinary matter;
- the *unification of the fundamental interactions*: as already specified, the gravitational interaction is not included in the SM formulation, while it would be desirable to have a theory which unifies all the existing interactions¹⁰ [38].

Taking into account all these problems, the SM can therefore be thought as an effective theory, i.e. a low-energy limit of a more complete and general theory. A maximum energetic scale, Λ , can be defined so that the SM is still valid below that value. This energetic threshold, Λ , can be the Planck scale ($M_P \sim 10^{19}$ GeV), for which the gravitational effects start to be not negligible, or the GUT¹¹ energy scale ($\Lambda_{GUT} \sim 10^{16}$ GeV), relative to the unification of the fundamental interactions, electromagnetic, weak and strong. Both these two solutions encounters the so called *hierarchy problem*, that is the presence of a *cutoff*, several order of magnitude larger than the electroweak scale (~ 100 GeV). This produces a strong sensitivity of the Higgs mass m_h to the presence of new physics, with the consequence of huge quantum radiative corrections from virtual effects of each particle and from other couplings that are involved directly or indirectly with the Higgs field. For example, the one-loop correction of Figure 1.3, which contains a Dirac fermion f with mass m_f , contributes to the Higgs mass. If

⁸Until '90, it was known that the Universe is expanding, but it was common belief that such expansion had to slow down due to gravity. In 1998 the Hubble Space Telescope (HBT) observed that the Universe expansion is not slowing down, but, on the contrary, is accelerating. There is still no an explanation to this unexpected behaviour, but theorists have hypothesized that this could be due to a 'dark force', therefore to a *dark energy*, which pushes the galaxies far away from each other.

⁹In particle physics the mass is usually expressed in eV/c^2 , the momentum in eV/c and the energy in eV . Nevertheless, for simplifying the notation, the eV is often used, with its multiples, independently for mass, momentum or energy. In this thesis it was decided to follow this convention.

¹⁰A very promising theory is the *string theory*, whose theoretical-mathematical formulation is able to conciliate the quantum mechanics and the general relativity and to unify the gravity with all the other interactions.

¹¹The *Great Unification Theory* (GUT) foresees that the fundamental interactions (electromagnetic, weak and strong) are described by an unique gauge group. This implies the presence of an unique interaction constant, independently from the type of coupling.

the Higgs field is coupled with the fermion according to the interaction lagrangian

$$\mathcal{L}_{hff} = -\frac{G_f}{\sqrt{2}} h \bar{f} f, \quad (1.20)$$

and it is supposed that the fermion is enough massive to neglect the four-momentum of h , then this diagram leads to the correction:

$$\delta m_h^2 = -\frac{G_f^2}{8\pi^2} \left[\Lambda^2 - 6m_f^2 \ln \left(\frac{\Lambda}{m_f} \right) + 2m_f^2 \right] + \mathcal{O}(1/\Lambda^2) \propto \Lambda^2. \quad (1.21)$$

This implies that corrections to m_h^2 of the order of $(10^{19})^2$ or $(10^{16})^2$ GeV² appears, in front of an Higgs mass of about 126 GeV. Therefore, the existence of a counter-term, with a precision of $\mathcal{O}(10^{-30})$, that allows to remove the quadratic divergences just described, is needed in order to have a m_h value which agrees with the experimental results (such procedure is known as *fine-tuning*) [39].

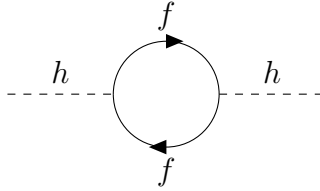


Figure 1.3: One-loop quantum correction to the squared mass parameter of the Higgs boson m_h^2 , due to a Dirac fermion f .

1.2 Supersymmetry

Among the BSM theories, one of the most interesting is the *Supersymmetry* (SUSY), which could solve several SM still open issues. This theory hypothesizes the presence of a new symmetry Q which transforms a boson state in a fermionic one and vice versa, and the two states differ of $1/2$ in spin:

$$Q|\text{Boson}\rangle = |\text{Fermion}\rangle, \quad Q|\text{Fermion}\rangle = |\text{Boson}\rangle. \quad (1.22)$$

The simplest formulation of SUSY, which contains the lowest number of theory parameters, is the *Minimal Supersymmetric Standard Model* (MSSM), where each of the SM particles has a *superpartner* with spin-0 for each chiral component of fermions and with spin- $1/2$ for each gauge boson. According to this, to quarks and leptons are associated spin-0 superpartners, simply called *squarks* $\tilde{q}$ and *sleptons* $\tilde{\ell}$, or generically *sfermions*, where the ‘s’ reminds the ‘scalar’ property, and the symbols are simply obtained putting a tilde over the SM partner symbols. It must be specified that, even if fermions have two different helicity components, their left-handed and right-handed superpartners, being scalars, don’t have any helicity, but

their left/right property simply reminds the one of the original SM fermion [40].

After the introduction of the new set of particles, the problem of the quadratic divergence δm_h^2 can be re-analyzed. When supposing, for each of the quarks and leptons, the existence of two scalar particles s of mass m_s , these particles are coupled to the Higgs field by the following trilinear and quadrilinear terms:

$$\mathcal{L}_{hss} = -v\lambda_s s\bar{s}, \quad \mathcal{L}_{hhss} = -\lambda_s h^2 s\bar{s}, \quad (1.23)$$

where v is the vacuum expectation value of h and λ_s is the coupling constant of the scalar particle with h . The following diagrams will contribute to the correction δm_h^2 :

$$\delta m_h^2 = \text{---}h\text{---} \bigcirc_f \text{---}h\text{---} + \text{---}h\text{---} \bigcirc_s \text{---}h\text{---} + \text{---}h\text{---} \bigcirc_s \text{---}h\text{---}, \quad (1.24)$$

and, taking into account the multiplicity of the scalar field with respect to the fermionic one, the correction will be:

$$\begin{aligned} \delta m_h^2 = & -\frac{G_f^2}{8\pi^2} \left[\Lambda^2 - 6m_f^2 \ln \left(\frac{\Lambda}{m_f} \right) + 2m_f^2 \right] + 2 \left\{ \frac{\lambda_s}{16\pi^2} \left[\Lambda^2 - 2m_s^2 \ln \left(\frac{\Lambda}{m_s} \right) \right] + \right. \\ & \left. -\frac{\lambda_s^2 v^2}{16\pi^2} \left[-1 + 2 \ln \left(\frac{\Lambda}{m_s} \right) \right] \right\} + \mathcal{O}(1/\Lambda^2). \end{aligned} \quad (1.25)$$

The scalar field contributes with a quadratic divergence, however, since $\sqrt{2}m_f = G_f v$, if $G_f^2 = -\lambda_s$ is assumed, the divergence disappears after simplifying with the quadratic divergence due to the Higgs coupling with the fermion f , and the equation 1.25 can be simplified as:

$$\delta m_h^2 = \frac{G_f^2}{4\pi^2} \left[(m_f^2 - m_s^2) \ln \left(\frac{\Lambda}{m_s} \right) + 3m_f^3 \ln \left(\frac{m_s}{m_f} \right) \right] + \mathcal{O}(1/\Lambda^2), \quad (1.26)$$

where only a logarithmic divergence is present, which can be dropped down under the assumption that supersymmetry is an exact symmetry, that is if $m_s = m_f$. Nevertheless, since no supersymmetric partner has been discovered yet, SUSY needs to be broken and the new particles need to have masses of the TeV order [39].

As shown in Figure 1.4 the introduction of SUSY, and in particular of the MSSM, would solve the problem of the interaction unification. In fact, unlike the SM case (a), in MSSM (b) the coupling constants of the three fundamental interactions (strong, electromagnetic and weak) meet at a unique point at an energy scale close to the Planck's value.

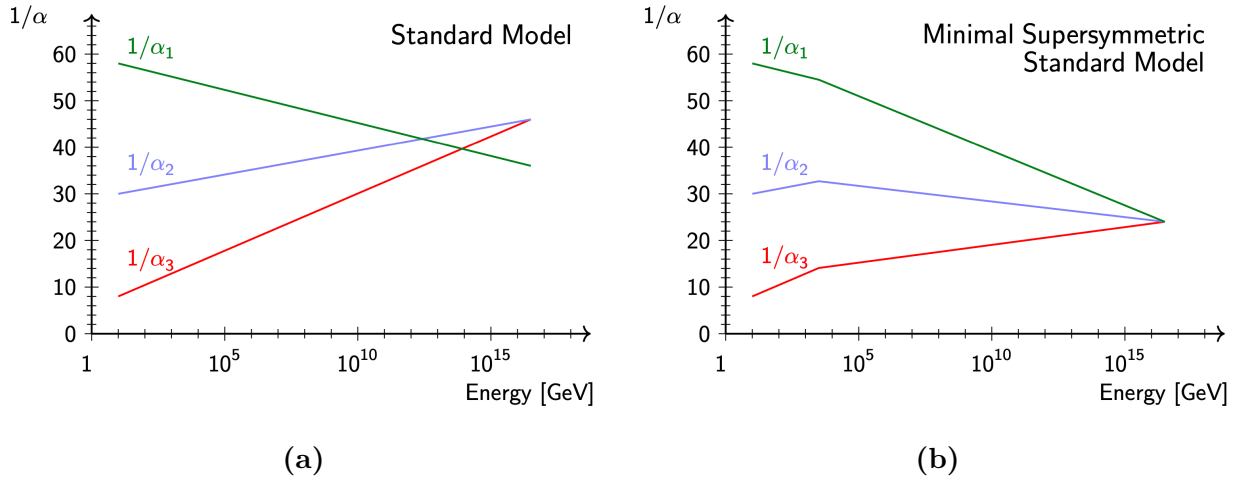


Figure 1.4: Trend of the inverse of the coupling constants of the three fundamental interactions (gravity is excluded) as function of the energy, in the SM (a) and in the MSSM (b). α_1 , α_2 and α_3 are the coupling constants of the electromagnetic, weak and strong interactions respectively. In MSSM the unification of the three interactions, after extrapolating the coupling constants at the energy scale of 10^{15} GeV, is allowed.

Extending the SM to the MSSM implies also the extension of the Higgs sector. In order to avoid the presence of (gauge) anomalies, a supersymmetric chiral fermionic partner of the Higgs boson needs to be an isospin doublet with weak hypercharge $Y = 1$ or $Y = -1$. Each of the hypercharge components produces an anomaly, unless the existence of two supermultiplets of Higgs is assumed, one with hypercharge $Y = 1$ and the other with hypercharge $Y = -1$. As consequence of this, the SM has to be modified, by introducing two $SU(2)_L$ doublets of complex scalar fields H_u and H_d which, in terms of their components, are:

$$H_u = \begin{pmatrix} H_u^+ \\ H_u^0 \end{pmatrix}, \quad H_d = \begin{pmatrix} H_d^0 \\ H_d^- \end{pmatrix}. \quad (1.27)$$

The neutral scalar that corresponds to the known Higgs boson of the SM is a linear combination of H_u^0 and H_d^0 . The supersymmetric partners, with spin-1/2, are generally known as *higgsinos* and indicated as $\tilde{H}_u$ and $\tilde{H}_d$,

$$\tilde{H}_u = \begin{pmatrix} \tilde{H}_u^+ \\ \tilde{H}_u^0 \end{pmatrix}, \quad \tilde{H}_d = \begin{pmatrix} \tilde{H}_d^0 \\ \tilde{H}_d^- \end{pmatrix}. \quad (1.28)$$

The supermultiplet structures within the MSSM are summarized in Table 1.3. For simplicity, only the first generation of fermions and sfermions is shown.

The vector bosons of the SM need to be arranged in gauge supermultiplets. Their fermionic superpartners are generically called *gauginos*. In particular, the spin-1/2 superpartners of gluons are *gluinos*, while for the electroweak gauge bosons, W^+ , W^0 , W^- and B^0 , the spin-1/2 superpartners associated are called *winos*, $\tilde{W}^+$, $\tilde{W}^0$, $\tilde{W}^-$, and *binos*, $\tilde{B}^0$. Likewise it happens

Names		Spin-0	Spin-1/2	$(SU(3)_C, SU(2)_L, U(1)_Y)$
squarks, quarks ($\times 3$ generations)	Q	$(\tilde{u}_L \ \tilde{d}_L)$	$(u_L \ d_L)$	$(\mathbf{3}, \mathbf{2}, 1/6)$
	$\bar{u}$	$\tilde{u}_R^*$	$u_R^\dagger$	$(\bar{\mathbf{3}}, \mathbf{1}, -2/3)$
	$\bar{d}$	$\tilde{d}_R^*$	$d_R^\dagger$	$(\bar{\mathbf{3}}, \mathbf{1}, 1/3)$
sleptons, leptons ($\times 3$ generations)	L	$(\tilde{\nu} \ \tilde{e}_L)$	$(\nu \ e_L)$	$(\mathbf{1}, \mathbf{2}, -1/2)$
	$\bar{e}$	$\tilde{e}_R^*$	$e_R^\dagger$	$(\mathbf{1}, \mathbf{1}, 1)$
Higgs, higgsinos	H_u	$(H_u^+ \ H_u^0)$	$(\tilde{H}_u^+ \ \tilde{H}_u^0)$	$(\mathbf{1}, \mathbf{2}, +1/2)$
	H_d	$(H_d^0 \ H_d^-)$	$(\tilde{H}_d^0 \ \tilde{H}_d^-)$	$(\mathbf{1}, \mathbf{2}, -1/2)$

Table 1.3: Chiral supermultiplets in the Minimal Supersymmetric Standard Model. The spin-0 fields are complex scalars, and the spin-1/2 fields are left-handed two-component Weyl fermions [40]. For simplicity, only the first generation of fermions and sfermions is shown.

for the SM sector, in the supersymmetric one a spontaneous symmetry breaking happens, by obtaining the physical bosons $\tilde{Z}^0$, *zino*, and $\tilde{\gamma}$, *photino*, through a mixing of the interaction eigenstates $\tilde{W}^0$ and $\tilde{B}^0$. The gauge supermultiplets within the MSSM are summarized in Table 1.4 [40].

Names	Spin-1/2	Spin-1	$SU(3)_C, SU(2)_L, U(1)_Y$
gluino, gluon	$\tilde{g}$	g	$(\mathbf{8}, \mathbf{1}, 0)$
winos, W -bosons	$\tilde{W}^\pm \ \tilde{W}^0$	$W^\pm \ W^0$	$(\mathbf{1}, \mathbf{3}, 0)$
bino, B -boson	$\tilde{B}^0$	B^0	$(\mathbf{1}, \mathbf{1}, 0)$

Table 1.4: Gauge supermultiplets in the Minimal Supersymmetric Standard Model [40].

1.2.1 The R-parity

Due to the renormalizability and gauge invariance, the SM lagrangian preserves the baryonic, B , and leptonic, L , quantum numbers, without assuming it explicitly. When the most general gauge-invariant and renormalizable superpotential is built, in the MSSM the B and L quantum numbers can be violated and new decay channels never observed before are allowed. To avoid this problem, a new symmetry is requested, called *R-parity*, and the associate quantum number is defined as:

$$R = (-1)^{3(B-L)+2S}, \quad (1.29)$$

where S is the spin. This number is different for the SM particles and their SUSY partners:

$$R = \begin{cases} +1 & \text{for SM particles} \\ -1 & \text{for MSSM particles} \end{cases} \quad (1.30)$$

and R-parity is conserved as long as the difference $B - L$ is conserved, even if the baryonic and leptonic numbers are separately violated. Assuming the R-parity conservation simplifies the experimental signatures that can be investigated [41]. In fact, if we suppose a SUSY production starting from only SM particles, SUSY particles can be produced only in pair in order to preserve R-parity and, at the end of each SUSY decay chain, the *Lightest Supersymmetric Particle* (LSP) is always present, since it cannot further decay either in any SUSY or SM particles. In particular, under these assumptions, the LSP, being electrically neutral, stable and very weakly interacting, could represent a good candidate of non-baryonic dark matter. Other SUSY models, different from MSSM, do not require R-parity conservation. In this thesis only R-parity conserving scenarios will be investigated.

1.2.2 Soft SUSY breaking

SUSY and MSSM assume particles and their superpartners to be mass degenerate. Since experimental results didn't show any evidence of sparticles, some additional terms are needed to be added in the MSSM lagrangian, leading to supersymmetry breaking but preserving, at the same time, the gauge invariance and the cancellation of the divergent terms in the radiative corrections:

$$L_{MSSM} = L_{SUSY} + L_{Breaking}. \quad (1.31)$$

The explicit term of symmetry breaking is called *soft-breaking* [39]. Without going into the details of this lagrangian, the breaking term contains some non-SUSY-invariant pieces (e.g. interactions which introduce asymmetries among fermions and bosons), but the phenomenology and the relationships between the coupling constants are preserved, in order to ensure the radiative corrections to the Higgs boson mass. In absence of extra constraints applied to the lagrangian ('unconstrained' MSSM), the theory has 105 new parameters, in addition to the 19 of the SM.

For which concerns the electroweak symmetry breaking, since in the MSSM there are two Higgs doublets, of the initial 8 degrees of freedom 3 are absorbed and give rise to the vector bosons Z^0 and $W^\pm$, whereas the other 5 flow into 5 Higgs bosons H^+ , H^- , H^0 , A and h^0 . In particular, by considering the one, two and three-loops corrections to $m_{h^0}^2$ to which all the other Higgs bosons contribute, and by assuming that all the sparticles that contribute to the corrections have masses below 1 TeV, the following limit is reached:

$$m_{h^0} \leq 135 \text{ GeV}. \quad (1.32)$$

This value is comparable with the experimental one of the Higgs boson mass (about 125 GeV) measured at LHC in 2012 [40].

1.2.2.1 Neutralinos and charginos

Similarly to the mechanism that brings to the creation of the mass eigenstates for the electroweak interaction bosons, also higgsinos and gauginos can mix together in order to create new mass eigenstates:

- from the combination of the neutral higgsinos, $\tilde{H}_u^0$ and $\tilde{H}_d^0$, and the neutral gauginos, $\tilde{B}$ and $\tilde{W}^0$, four neutral mass eigenstates are generated, called *neutralinos* and indicated as $\tilde{\chi}_i^0$ ($i = 1, 2, 3, 4$), with the convention $m(\tilde{\chi}_1^0) < m(\tilde{\chi}_2^0) < m(\tilde{\chi}_3^0) < m(\tilde{\chi}_4^0)$;
- from the combination of the charged higgsinos, $\tilde{H}_u^+$ and $\tilde{H}_d^-$, and winos, $\tilde{W}^+$ and $\tilde{W}^-$, four charged mass eigenstates are generated, called *charginos* and indicated as $\tilde{\chi}_i^\pm$ ($i = 1, 2$), with the convention $m(\tilde{\chi}_1^\pm) < m(\tilde{\chi}_2^\pm)$.

In many SUSY models the neutralino $\tilde{\chi}_1^0$ is interpreted as the LSP. It weakly interacts with the ordinary matter and can be only observed as missing energy in the balance of the event [40].

1.2.2.2 Squarks and sleptons

The mixing can happen for any scalars with the same electric charge, R-parity and color charge quantum numbers. Therefore, the mass eigenstates of squarks and sleptons in the MSSM can be obtained by diagonalizing three 6×6 squared-mass matrices for up-type squarks ($\tilde{u}_L, \tilde{c}_L, \tilde{t}_L, \tilde{u}_R, \tilde{c}_R, \tilde{t}_R$), down-type squarks ($\tilde{d}_L, \tilde{s}_L, \tilde{b}_L, \tilde{d}_R, \tilde{s}_R, \tilde{b}_R$) and charged sleptons ($\tilde{e}_L, \tilde{\mu}_L, \tilde{\tau}_L, \tilde{e}_R, \tilde{\mu}_R, \tilde{\tau}_R$) and one 3×3 matrix for sneutrinos ($\tilde{\nu}_e, \tilde{\nu}_\mu, \tilde{\nu}_\tau$). It can be demonstrated that most of the mixing angles are very small and the Yukawa terms negligible for the I and II generations of squarks and charged sleptons. For the III generation, instead, the mixing terms are non-negligible. In particular, for the top-squark the mixing is very strong:

$$\begin{pmatrix} \tilde{t}_1 \\ \tilde{t}_2 \end{pmatrix} = \begin{pmatrix} \cos \theta_t & -\sin \theta_t \\ \sin \theta_t & \cos \theta_t \end{pmatrix} \begin{pmatrix} \tilde{t}_L \\ \tilde{t}_R \end{pmatrix}, \quad \text{with } \theta \in [0, \pi], \quad (1.33)$$

and the mass splitting $m(\tilde{t}_2) - m(\tilde{t}_1)$ is high, making $m(\tilde{t}_1)$ much lighter than the other squarks [40].

1.2.3 The phenomenological MSSM

The large number of parameters makes the MSSM analyses very challenging. A phenomenologically more viable model can be obtained making some assumptions on these parameters:

- all the soft-SUSY-breaking parameters are real, then no new CP-violation sources are introduced, except for the one from the CKM matrix;
- the matrices which describe the sfermion masses and the trilinear couplings are diagonal, thus implying the absence of *Flavour Changing Neutral Currents* (FCNCs) at tree level;

- the soft-SUSY-breaking masses and trilinear couplings of the I and II generations are the same at low energy (to cope with the severe constraints from $K_0 - \bar{K}_0$ mixing).

These three assumptions lead to a significant reduction in the number of the parameters, which become 19 and are:

- $\tan \beta$: the ratio of the vacuum expectation values of the two Higgs doublet fields;
- M_A : the pseudoscalar Higgs boson mass;
- μ : the bilinear higgsino mass parameter;
- M_1, M_2, M_3 : the bino, wino and gluino mass parameters;
- the mass parameters for the first, second and third generation of sfermions;
- A_t, A_b, A_τ : the III generation trilinear couplings.

This model is called *constrained MSSM* [39]. Being more easier to be investigated phenomenologically, it's also known as *phenomenological MSSM* or *pMSSM*. In Appendix A are reported some details about the pMSSM studies that the ATLAS collaboration is performing.

1.3 SUSY searches at LHC

Experimentally, one of the best place for searching SUSY is a hadron collider like LHC, where sparticles can be produced from the partonic collisions in electroweak interactions:

$$q\bar{q} \rightarrow \tilde{\chi}_i^+ \tilde{\chi}_j^-, \tilde{\chi}_i^0 \tilde{\chi}_j^0, \quad u\bar{d} \rightarrow \tilde{\chi}_i^+ \tilde{\chi}_j^0, \quad d\bar{u} \rightarrow \tilde{\chi}_i^- \tilde{\chi}_j^0, \quad (1.34)$$

$$q\bar{q} \rightarrow \tilde{\ell}_i^+ \tilde{\ell}_j^-, \tilde{\nu}_\ell \tilde{\nu}_\ell^*, \quad u\bar{d} \rightarrow \tilde{\ell}_L^+ \tilde{\nu}_\ell, \quad d\bar{u} \rightarrow \tilde{\ell}_L^- \tilde{\nu}_\ell^*, \quad (1.35)$$

as shown in Figure 1.5, or in pure QCD processes:

$$gg \rightarrow \tilde{g}\tilde{g}, \tilde{q}_i\tilde{q}_j^*, \quad gq \rightarrow \tilde{g}\tilde{q}_i, \quad q\bar{q} \rightarrow \tilde{g}\tilde{g}, \tilde{q}_i\tilde{q}_j^*, \quad qq \rightarrow \tilde{q}_i\tilde{q}_j^*, \quad (1.36)$$

shown in Figures 1.6 and 1.7. SUSY coloured particles (squarks and gluinos) production is largely favoured at LHC with respect to the electroweak one, as shown in Figure 1.8, where the production cross sections for different SUSY processes are reported.

For any of these processes, if R-parity conservation is assumed, two LSPs are foreseen in the final state. Therefore, the searches target signatures with missing transverse energy, in addition to leptons and hadronic jets¹² [40].

Due to the large number of MSSM parameters, that make SUSY analyses very complex and challenging, in LHC SUSY searches a simplified approach is commonly adopted, which consists

¹²An *hadronic jet* is a group of particles created by the hadronization of a single quark or gluon.

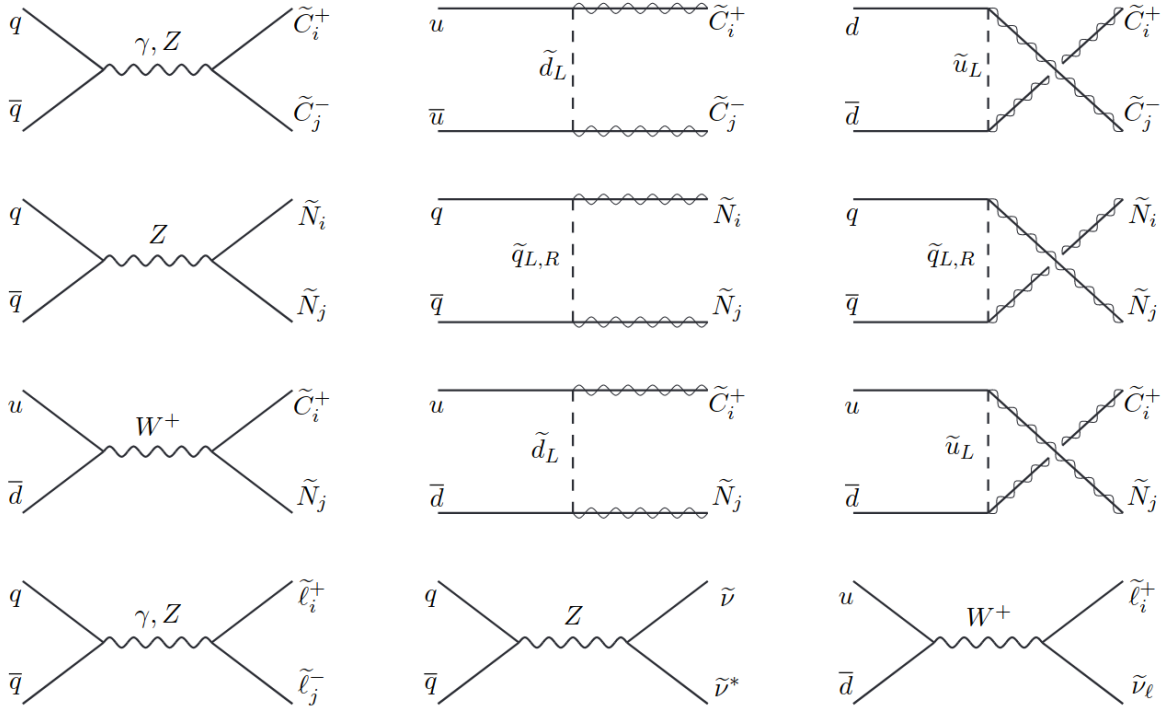


Figure 1.5: Feynman diagrams for electroweak production of sparticles at hadron colliders from quark-antiquark annihilation. Charginos and neutralinos are indicated as $\tilde{C}_i^\pm$ and $\tilde{N}_i$ respectively. In the t-channel diagrams, charginos and neutralinos can couple with massless quarks only because of their gaugino content, and this is indicated, in figure, with a solid line and a wavy line superimposed [40].

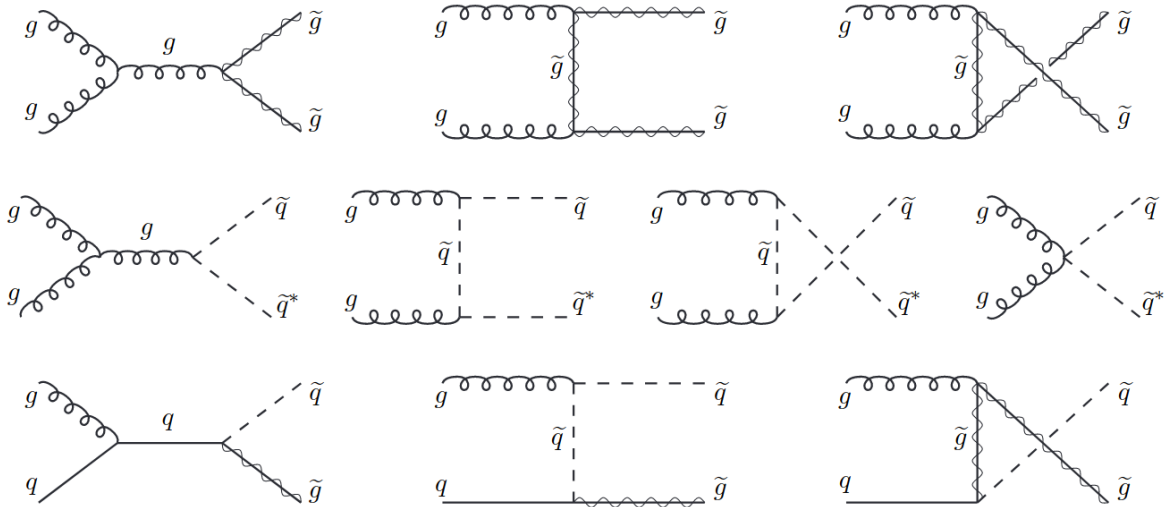


Figure 1.6: Feynman diagrams for gluino and squark production at hadron colliders from gluon-gluon and gluon-quark fusion [40].

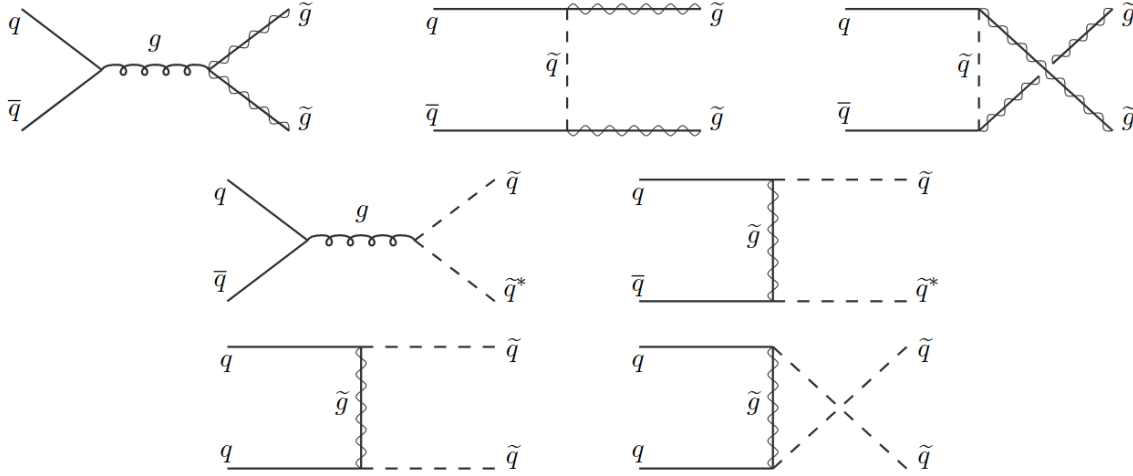


Figure 1.7: Feynman diagrams for gluino and squark production at hadron colliders from strong quark-antiquark annihilation and quark-quark scattering [40].

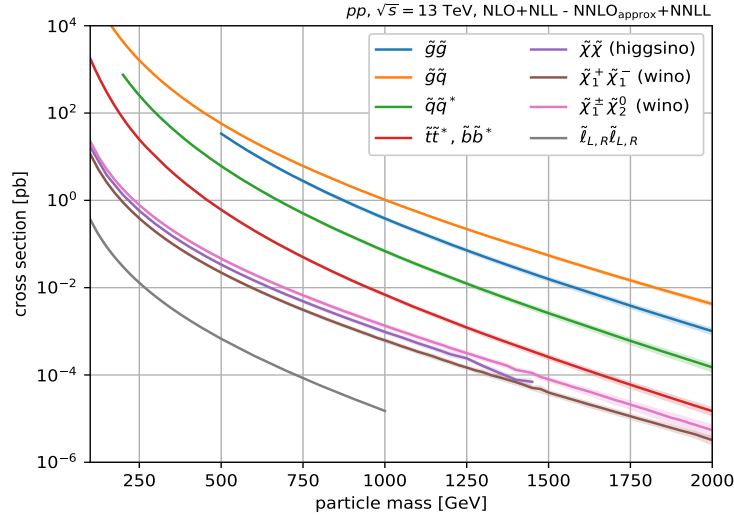


Figure 1.8: Production cross section of supersymmetric particles as function of their mass at proton-proton collisions with a center of mass energy of $\sqrt{s} = 13$ TeV [42].

in considering the so called *simplified SUSY models* [43]. Such models can be described by a smaller number of parameters directly related to collider physics observables, like particle masses and their decay widths, branching ratios and production cross sections [44]. The advantage of using simplified models consists in their flexibility, which allows to focus a generic analysis on a specific model and then to reinterpret the obtained results in another model sharing a similar topology. A simplified model is obtained from a more generic SUSY model which is progressively minimized by ignoring the masses of the sparticles not involved in the

model of interest, keeping them to unphysical values at the TeV scale. A generic analysis can be optimized for a specific model and the results can be afterwards reinterpreted for other models, which share a similar topology with the previous, allowing a large flexibility and efficiency in scanning a specific mass phase space.

1.3.1 Searches in the strong sector

As shown in Figure 1.8, the SUSY strong searches are favoured at LHC with respect to the electroweak ones. In particular, since the $\tilde{t}_1$ is the lightest squark, it is expected to be observed at lower energies. Depending on the mass difference between the $\tilde{t}_1$ and the $\tilde{\chi}_1^0$, the $\tilde{t}_1$ can decay in different modes, as shown in Figure 1.9: (a) if $\Delta m(\tilde{t}_1, \tilde{\chi}_1^0) = m(\tilde{t}_1) - m(\tilde{\chi}_1^0) > m(t)$, the top-squark decays into an on-shell top-quark and the lightest neutralino, $\tilde{t}_1 \rightarrow t\tilde{\chi}_1^0$ (*2-body* decay), (b) if $m(W) + m(b) < \Delta m(\tilde{t}_1, \tilde{\chi}_1^0) < m(t)$, the top-squark decays through an off-shell top-quark, which decays in an on-shell W -boson, $\tilde{t}_1 \rightarrow bW\tilde{\chi}_1^0$ (*3-body* decay), and (c) if $\Delta m(\tilde{t}_1, \tilde{\chi}_1^0) < m(W) + m(b)$, the W -boson from the virtual top-quark is off-shell (W^*), and the decay is $\tilde{t}_1 \rightarrow b\ell\nu\tilde{\chi}_1^0$, where ℓ and ν are two fermions, which are a lepton and a neutrino in the case of a leptonic decay of the W -boson (*4-body* decay). These decay modes were investigated by the ATLAS and CMS collaborations and so far evidences of top-squarks have not been observed. In Figure 1.10 is reported in (a) a plot which collects all the most recent results [6, 45–54] by the ATLAS collaboration for the search of $\tilde{t}_1$, and in (b) the analogous from CMS searches [55–59]. Exclusion limits at 95% of Confidence Level (CL) in the $(m(\tilde{t}_1), m(\tilde{\chi}_1^0))$ mass plane are reported in different colours, as set by all the listed corresponding analyses. More in general, analyses from the ATLAS and CMS collaborations have excluded the existence of squarks and gluinos, produced in strong interactions, up to the TeV energies. LHC during its *high-luminosity* (HL-LHC) phase, given the expected large increase in statistics, can still offer a good opportunity to find strong interacting SUSY particles. A prospect for future searches of $\tilde{t}_1$ at HL-LHC will be presented in the last chapter of this thesis.

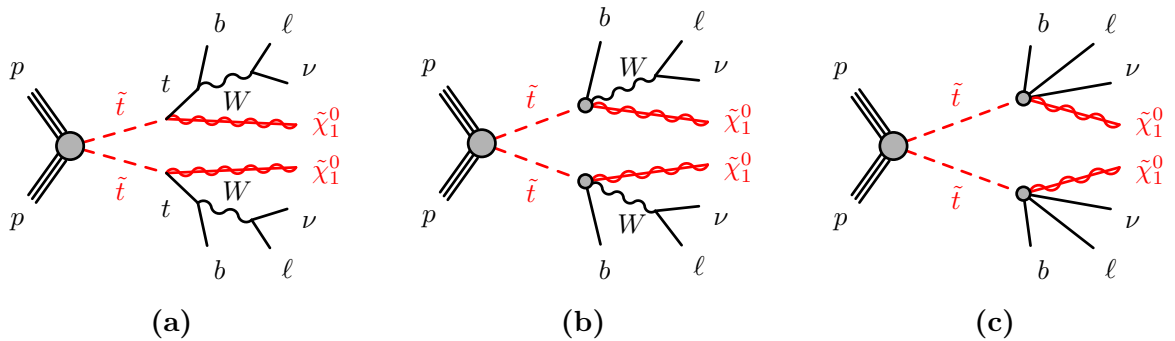


Figure 1.9: (a) the 2-body $\tilde{t}_1$ decay into an on-shell top-quark and the lightest neutralino ($\tilde{t}_1 \rightarrow t\tilde{\chi}_1^0$), (b) the 3-body $\tilde{t}_1$ decay mode into an on-shell W -boson, a b -quark and the lightest neutralino ($\tilde{t}_1 \rightarrow bW\tilde{\chi}_1^0$), (c) the 4-body $\tilde{t}_1$ decay mode ($\tilde{t}_1 \rightarrow b\ell\nu\tilde{\chi}_1^0$) where ℓ and ν are an anti-lepton (lepton) with its neutrino (anti-neutrino). In all the diagrams particles and anti-particles are indicated with the same symbols [6].

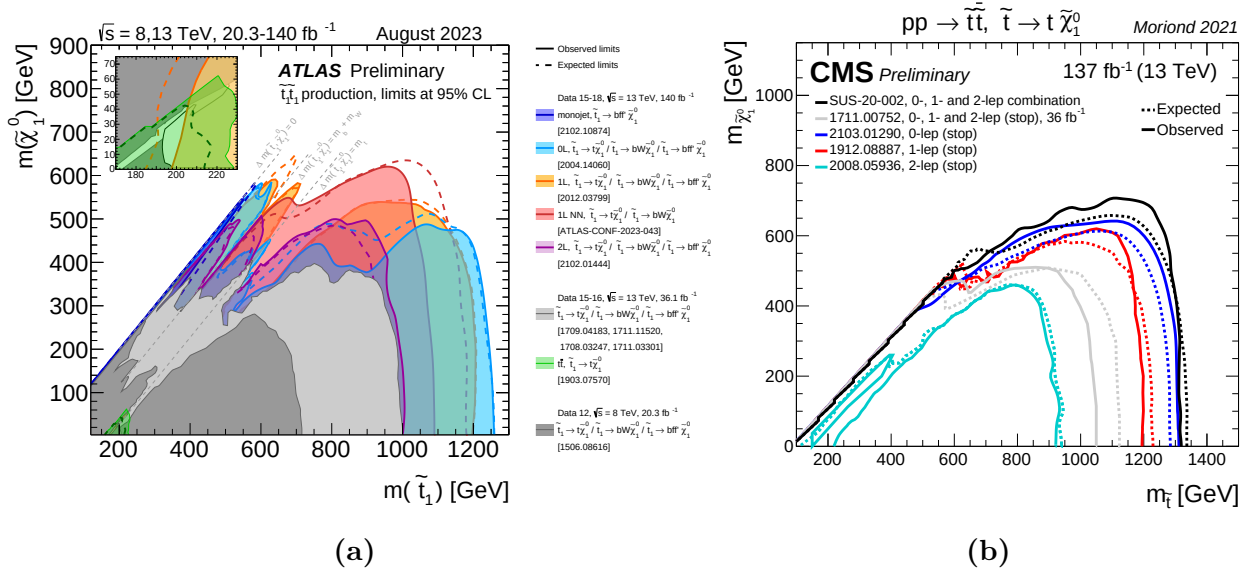


Figure 1.10: In (a) the summary plot from the ATLAS searches for top-squark (stop) pair production in proton-proton collision data taken at $\sqrt{s} = 8$ TeV and $\sqrt{s} = 13$ TeV. Exclusion limits at 95% CL are shown in the $(m(\tilde{t}_1), m(\tilde{\chi}_1^0))$ mass plane. The dashed and solid lines show the expected and observed limits, respectively, including all uncertainties except the theoretical signal cross section uncertainty (PDF and scale). Three decay modes are considered separately with 100% BR: $\tilde{t}_1 \rightarrow t\tilde{\chi}_1^0$ (where the $\tilde{t}_1$ is mostly right, $\tilde{t}_R$), $\tilde{t}_1 \rightarrow bW\tilde{\chi}_1^0$ (3-body decay for $m(\tilde{t}_1) < m(t) + m(\tilde{\chi}_1^0)$), and $\tilde{t}_1 \rightarrow bff'\tilde{\chi}_1^0$ (4-body decay) [60]. In (b) the summary plot from the CMS searches for top-squark pair production, where the top-squark decays to a on- or off-shell top-quark and the LSP, in final states with two bottom-quarks, two W -bosons, and two LSPs [61].

1.3.2 Searches in the electroweak sector

Although the SUSY strong production cross sections are larger at LHC than the electroweak ones, if the masses of squarks and gluinos are larger than 3-4 TeV, the electroweak production of sleptons and charginos would dominate at LHC (Figure 1.8).

In 2020 the ATLAS collaboration published the results of the search [62] for the pair production of charginos and sleptons which decay in final states with two charged leptons (only electrons or muons were considered), using the data collected by the ATLAS detector during Run 2 (2015-2018) of LHC, corresponding to an integrated luminosity of 139 fb⁻¹ in proton-proton collisions at $\sqrt{s} = 13$ TeV. The analysis focused on three different processes reported in Figure 1.11: the direct production of $\tilde{\chi}_1^+\tilde{\chi}_1^-$ where each chargino can decay in (a) the LSP and a real W -boson or (b) a neutrino/lepton and a slepton/sneutrino (which decays in turn in the correspondent lepton, by producing a LSP) and (c) the direct production of sleptons, $\tilde{\ell}\tilde{\ell}$, which decay in the correspondent leptons, without flavour changing, and the LSPs.

In Figure 1.12 are reported the exclusion limits at 95% CL set by the published analysis for these three processes. In general, charginos and sleptons were excluded for a large portion of

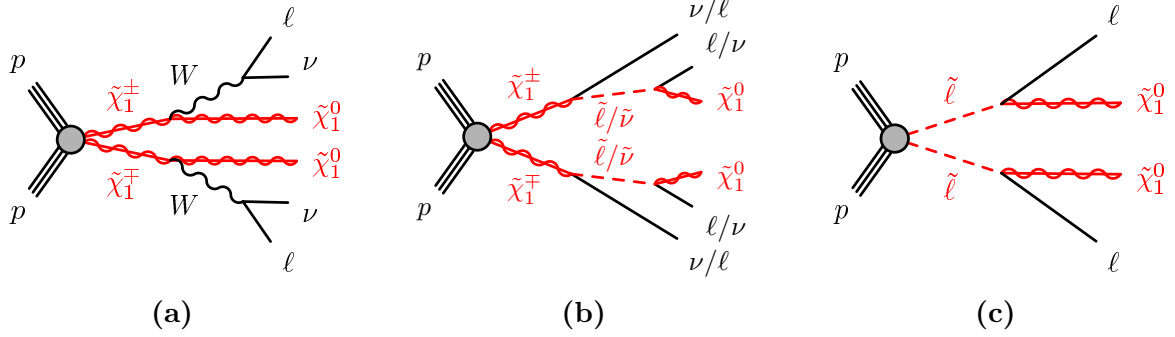


Figure 1.11: Diagrams of the three different models considered in Ref. [62], with two leptons and missing transverse energy in the final state: (a) $\tilde{\chi}_1^+\tilde{\chi}_1^-$ production via W -mediated decays, (b) $\tilde{\chi}_1^+\tilde{\chi}_1^-$ production via slepton/sneutrino decay and (c) sleptons pair production. In the model (b) all the three flavours are included $\tilde{e}, \tilde{\mu}, \tilde{\tau}$, while only $\tilde{e}$ and $\tilde{\mu}$ in the direct production of sleptons (c). In the final state ℓ is referred to and electron or a muon, which can be produced either directly or from the leptonic decay of τ with additional neutrinos [62].

the mass-plane by several ATLAS and CMS analyses. Nevertheless, the so called *compressed regions* of the phase-space, which are those regions where the mass difference, known as *mass splitting*, between the searched particle and the LSP is less or of the order of the W -boson mass, are still largely not covered:

$$\Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0) = m(\tilde{\chi}_1^\pm) - m(\tilde{\chi}_1^0) < m(W), \quad (1.37)$$

$$\Delta m(\tilde{\ell}, \tilde{\chi}_1^0) = m(\tilde{\ell}) - m(\tilde{\chi}_1^0) < m(W). \quad (1.38)$$

These regions, characterized by soft leptons in the final state, are experimentally challenging due to their topologies very similar to those of some Standard Model processes. Close to the W -boson mass, such regions are called *moderately compressed*, i.e. $\Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0) \sim m(W)$ and $\Delta m(\tilde{\ell}, \tilde{\chi}_1^0) \sim m(W)$, and they were investigated by an analysis [4] published in 2023 by the ATLAS collaboration. In particular, this analysis focuses on two channels: the direct slepton production, Figure 1.11c, and the chargino pair production via W -boson mediated decay, Figure 1.11a, and adopts special strategies in order to improve the sensitivity in such regions of the mass planes. A complete description of it will be presented, being the main topic of this thesis, and its results extend the exclusion limits imposed by previous searches of sleptons and charginos at LHC from the ATLAS and CMS collaborations [63–69].

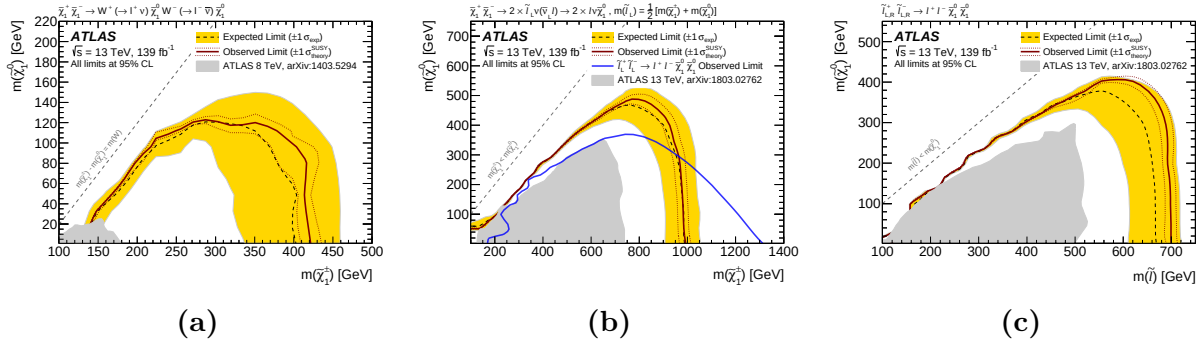


Figure 1.12: Expected and observed exclusion limits for the production of chargino pairs which decay via either (a) W -bosons or (b) via sleptons/sneutrinos, and (c) for the production of slepton pairs from Ref. [62].

CHAPTER

2

The Large Hadron Collider and the ATLAS experiment

Introduction to the Large Hadron Collider at CERN (Geneva), and description of the ATLAS detector. Overview of the LHC and experiment upgrades.

The main purpose of CERN (*Conseil Européen pour la Recherche Nucléaire*) [70] has always been to provide to physicists the necessary means for doing fundamental research, by building large accelerators, capable of reaching high energies and with increasingly cutting-edge technologies. To date, CERN manages the largest and most powerful accelerator in the world, the *Large Hadron Collider* (LHC) [1], projected for accelerating two proton beams in opposite directions, along a circular orbit, up to center of mass energies of 14 TeV. In order to fully exploit its power, several experiments are located along the collider, and the four biggest and most important are: ATLAS, *A Toroidal LHC ApparatuS* [2], CMS, *Compact Muon Solenoid* [3], LHCb, *Large Hadron Collider beauty* [71], and ALICE, *A Large Ion Collider Experiment* [72].

After introducing the LHC and its main functionalities, this chapter will be devoted in the first part to the description of the ATLAS experiment. Afterwards, in Section 2.3.1 the New Small Wheel (NSW) detectors, which are part of the ATLAS Phase-I upgrade program, will be described, along with my contributions to the NSW studies: in Section 2.3.1.2, the correlation between the construction parameters of the MicroMegas detectors installed on these detectors and their performance and, in Section 2.3.1.3, the misalignment study of the

NSWs, reporting its impact on the muon reconstruction performance. The chapter will end, in Section 2.3.2, with a description of the LHC High-Luminosity upgrade program, expected to start in 2029.

2.1 The Large Hadron Collider

At LHC two proton beams interact at an energy in the center of mass that reached 13.6 TeV so far. LHC replaced the previous collider, the *Lepton Electron-Positron* (LEP) machine [73] in the same tunnel, and it started to run on 10th September 2008. A few days after its switch on, it suffered a serious accident which compromised its operation and delayed its physics program. In November 2009, LHC was turned back on, starting the *Run 1* data taking, and collecting events from proton-proton (*pp*) collisions at an energy in the center of mass of 7 and 8 TeV until the end of 2012, corresponding to 4.7 and 20.3 fb⁻¹ of integrated luminosity respectively. After two years of technical stop, called LS1 (*Long Shutdown 1*), deputed to upgrades and maintenance of both the accelerating machines and the experiments, the LHC *Run 2* started in 2015, by producing collisions up to an energy of 13 TeV in the center of mass and corresponding to 158 fb⁻¹ of collected data, about 139 fb⁻¹ of which good for physics analyses. In 2018, at the end of Run 2, there was another technical stop, LS2 (*Long Shutdown 2*), aimed to general improvements. The LHC Run 3 started in July 2022, reaching the record energy of 13.6 TeV, and it's foreseen to run until the end of 2025, to collect an integrated luminosity of about 300 fb⁻¹.



Figure 2.1: LHC timeline for the next decade and beyond showing the collision energy (upper line) and luminosity (lower line). After LS3, the machine will work in the high-luminosity configuration [74].

In the period 2026-2028 LHC will evolve to *High-Luminosity LHC* (HL-LHC), which will reach an instantaneous luminosity¹³ of $5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$ [74], more than two times the one obtained at LHC. In Figure 2.1 is reported the most recent timeline of the LHC past, present and future programs.

The LHC machine is located in a circular tunnel about 100 meters underground between the french and swiss borders, as shown in Figure 2.2, and 27 kilometers long. Protons run in opposite directions and collide into four interaction points where the four main experiments (ATLAS, CMS, LHCb and ALICE) are positioned. LHC consists of a tube where the two particle beams are accelerated into two *beam pipes*, kept under ultra high vacuum conditions overall the circular trajectory. The tube consists of 8 straight sections and 8 arches, where 1232 dipolar magnets 15 m long and 392 quadripolar magnets 5-7 m long produce strong magnetic fields which respectively lead and focus the two beams. The magnets are superconductive, and kept at a temperature of -271.3°C (close to the absolute zero) by a large liquid helium distribution system.

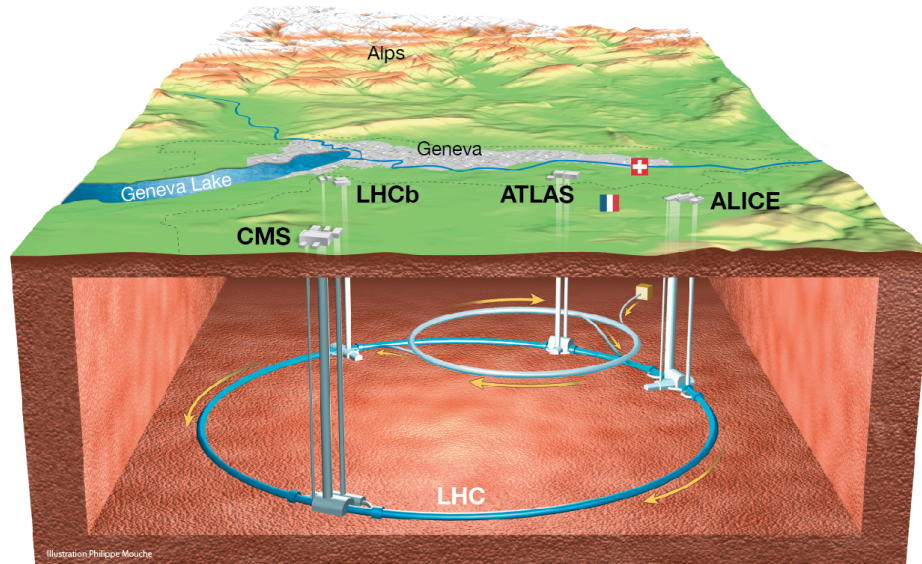
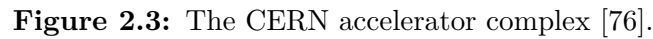


Figure 2.2: Pictorial representation of the structure of LHC at CERN. The colliding circular machine is located at about 100 meters underground between the swiss and french borders. It is 27 km long and the two beams collide in four interaction points, where the four main experiments (ATLAS, CMS, LHCb and ALICE) are placed [75].

LHC is the last ‘element’ of the CERN’s accelerating complex: the protons are accelerated gradually by several machines, increasing their energy at each step, as illustrated in Figure 2.3.

¹³The *instantaneous luminosity* represents the number of interactions per second and per unit of area. It will be described in the following of this chapter.



2.1.1 Luminosity

$$\frac{dN}{dt} = \mathcal{L} \cdot \sigma_p, \quad (2.1)$$

where $\mathcal{L}$ represents the amount of interactions per second per unit of area that a particle accelerator is able to produce, known as *instantaneous luminosity*, and expressed in $\text{cm}^{-2}\text{s}^{-1}$ [77]. By integrating over the time the equation 2.1, it's possible to determine the number of

expected events, N_{exp} , produced during a generic time interval for a process with σ_p :

$$N_{exp} = \sigma_p \times \int \mathcal{L}(t) dt, \quad (2.2)$$

which is known as *integrated luminosity*¹⁴. In LHC particles are organized in *bunches*. Let's consider two bunches containing a number of particles n_1 and n_2 respectively, which collide frontally with a collision frequency of f_{coll} . If we assume that they have the same transverse profile, that the profile is gaussian and independent from the position along the bunch, and that the distribution of particles does not vary during the *bunch crossing* (BC) [78], the instantaneous luminosity is defined as:

$$\mathcal{L} = f_{coll} \frac{n_1 n_2}{4\pi\sigma_x\sigma_y}, \quad (2.3)$$

where σ_x and σ_y are the standard deviations associated to the transverse dimensions of the beams at the interaction point. LHC has been designed in order to reach an instantaneous luminosity of $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$, with 25 ns of time difference between two bunch crossings. So far, it reached, during Run 2, a peak instantaneous luminosity of about $2 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ [79], more than double of the nominal value expected. In Figure 2.4 are reported the distributions of the peak instantaneous luminosity per day delivered to ATLAS in pp collisions with stable beam conditions at $\sqrt{s} = 13 \text{ TeV}$ for each fill of LHC over the four years of Run 2.

In Figure 2.5a is shown the cumulative luminosity per each year from 2011 to 2018, delivered to ATLAS in pp collisions during stable beam conditions and for $\sqrt{s} = 7, 8$ and 13 TeV . In Figure 2.5b is reported the cumulative luminosity delivered to ATLAS (green), recorded by ATLAS (yellow) and classified of 'good quality' (blue), in pp collisions during stable beam conditions at $\sqrt{s} = 13 \text{ TeV}$, during Run 2.

For each pp collision at LHC several interactions take place. These interactions contaminate the hard scatter processes typically triggering the event and complicate the event reconstruction and identification. These additional interactions are referred to *pile-up* (PU). The mean number of PU interactions per bunch crossing is indicated as $\langle\mu\rangle$ and computed as:

$$\langle\mu\rangle = L_{\text{bunch}} \times \frac{\sigma_{\text{inel}}}{f_r}, \quad (2.4)$$

where L_{bunch} is the bunch instantaneous luminosity, σ_{inel} is the total inelastic cross section, which is about 80 mb for 13 TeV collisions, and f_r is the revolution frequency of LHC. In Figure 2.6 is reported the luminosity-weighted distribution of $\langle\mu\rangle$ per bunch crossing for each year and for the entire LHC Run 2, in pp collision data at $\sqrt{s} = 13 \text{ TeV}$. The mean value of pile-up interactions per bunch crossing during Run 2 was about 34. This number is expected to increase up to 140-200 per bunch crossing at High-Luminosity LHC.

¹⁴The unit of the integrated luminosity is cm^{-2} but it is more commonly expressed in inverse barn (b^{-1}), where $1 \text{ b} = 10^{-24} \text{ cm}^2$.

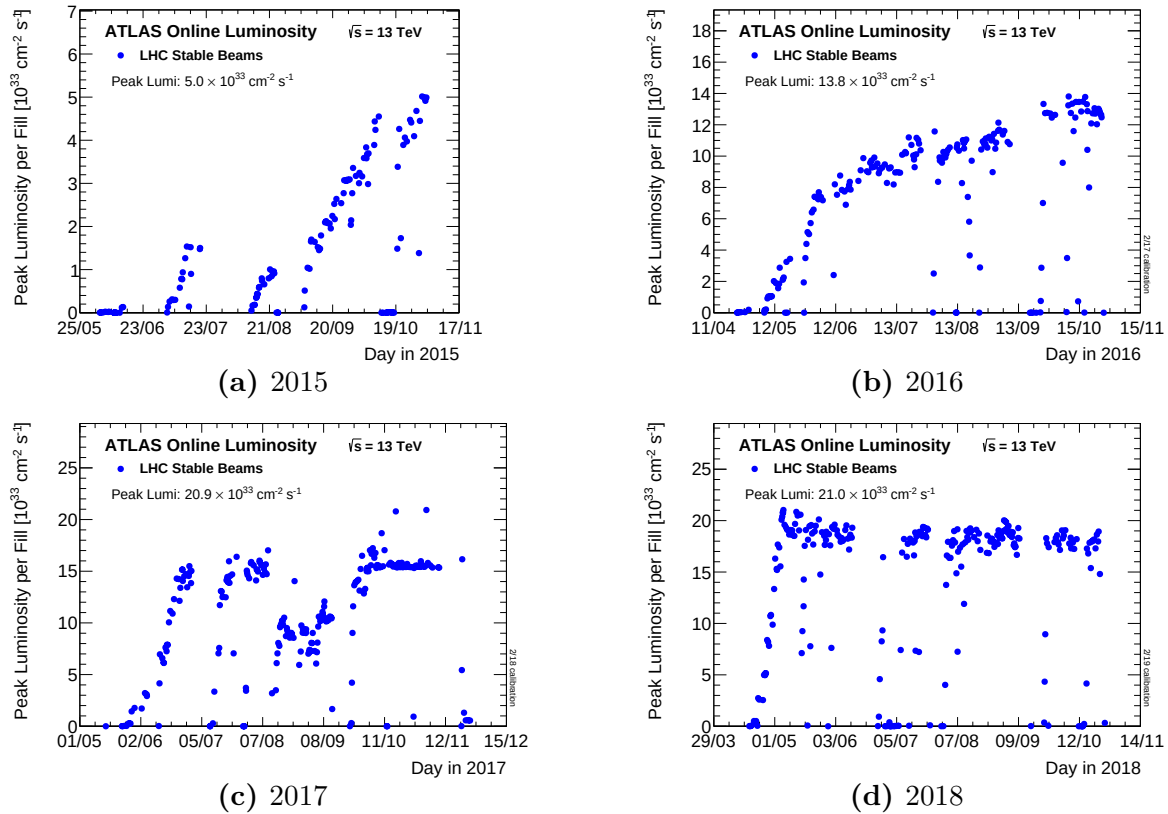


Figure 2.4: Distributions of the peak instantaneous luminosity per day delivered to ATLAS in pp collisions with stable beam conditions at $\sqrt{s} = 13$ TeV for each fill of LHC over the four years of Run 2: (a) 2015, (b) 2016, (c) 2017 and (d) 2018 [80].

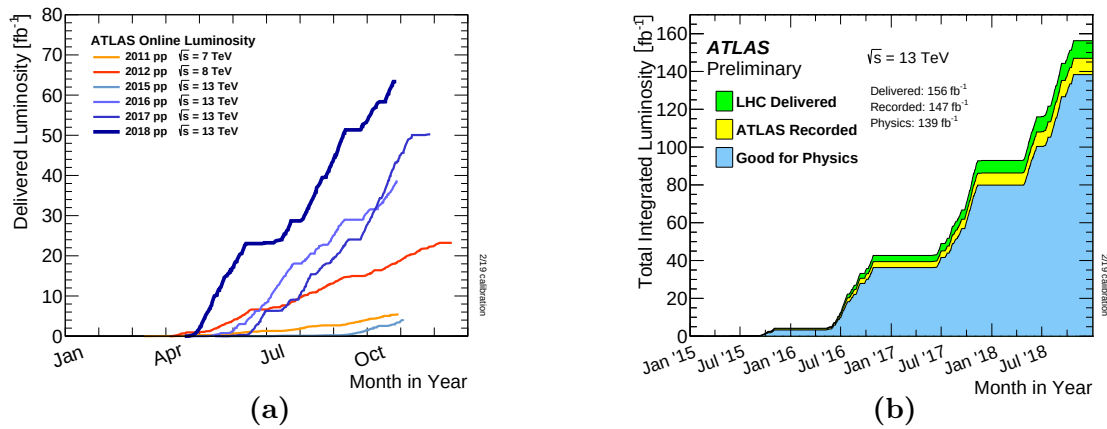


Figure 2.5: In (a) the cumulative luminosity for each year from 2011 to 2018, delivered to ATLAS in pp collisions during stable beam conditions and for $\sqrt{s} = 7, 8$ and 13 TeV. In (b) the cumulative luminosity delivered to ATLAS (green), recorded by ATLAS (yellow) and classified as 'good for physics' (blue), in pp collisions during stable beam conditions at $\sqrt{s} = 13$ TeV, during Run 2 [80].

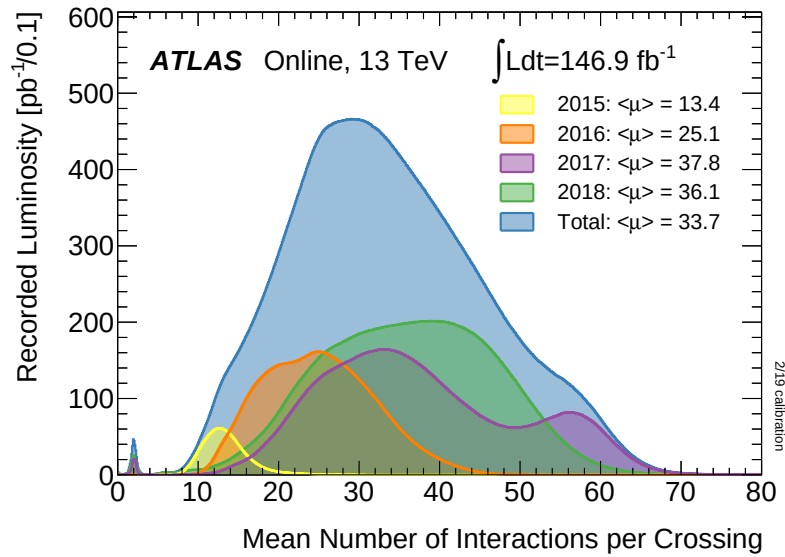


Figure 2.6: Luminosity-weighted distribution of the mean number of interactions per bunch crossing for each year and for the entire LHC Run 2, in pp collision data at $\sqrt{s} = 13$ TeV [80].

2.2 The ATLAS experiment

ATLAS, acronym of *A Toroidal LHC ApparatuS*, is the largest collider experiment ever built: about 25 m in diameter, about 46 m long and with 7000 tonnes of weight. It is installed at *Point 1* along the LHC ring. Together with its competitor, the CMS experiment, ATLAS is a *general-purpose* experiment since it is able to detect all the particles which are produced in the event, and therefore to study all processes accessible to the collider, which implies the possibility of investigating many possible new physics scenarios.

The ATLAS structure is illustrated in Figure 2.7: it is the typical one of a high energy collider experiment, made with coaxial cylindrical shells of different detectors, depending on the different types of particles that need to be identified. The detector is symmetric with respect to the interaction point (*forward-backward symmetry*) [2]. In the ATLAS reference system the origin coincides with the interaction point and the z axis with the beam direction. The x axis assumes positive values moving from the interaction point to the center of LHC, while the y axis has positive values moving from the origin to the earth surface. In the (x, y) plane, called *transverse plane*, the azimuthal angle ϕ of a given point in the plane is measured with respect to the positive x axis, while its radial coordinate r is the radial distance of the point from the interaction point. The polar angle ϑ is defined as the angle in the (z, y) plane starting from the z axis positive direction, nevertheless, another variable, the *pseudorapidity* η ¹⁵, is often

¹⁵The use of this variable is preferable to the use of ϑ since it's expected that the particle production is uniform in η and differences in pseudorapidity are invariant under Lorentz boosts along the z axis. With good approximation the pseudorapidity is here approximable to the rapidity, defined as $y = \frac{1}{2} \ln \frac{E+p_z}{E-p_z}$ which is, unlike the polar angle, a Lorentz-invariant quantity.

used:

$$\eta = -\ln \tan \left(\frac{\vartheta}{2} \right) \quad (2.5)$$

Three different zones inside ATLAS are identified in terms of η : the *barrel* (central) region, characterized by $|\eta| < 1$, and two lateral regions called *end-caps*, with $|\eta| > 1$ (acceptance in $|\eta| > 1$ is limited by the presence of the beam pipe). A complex magnetic system provides the fields which bend the charged particles, allowing for the measurement of their momenta directly from the bending. The system consists of a superconductive solenoid, which envelops the inner detector with a 2 T magnetic field, and external superconductive air toroids which envelops the entire muon spectrometer. Starting from the center of the experiment, close to the beams interaction point, there is the inner detector, which reconstructs the primary and secondary interaction vertices and the trajectories of the charged particles, and measures their momenta. Immediately afterwards, the calorimetric system measures the energy of electrons, photons and hadrons and, in the outermost part, the muon chambers identify the muons, reconstruct their trajectories and measure their momenta.

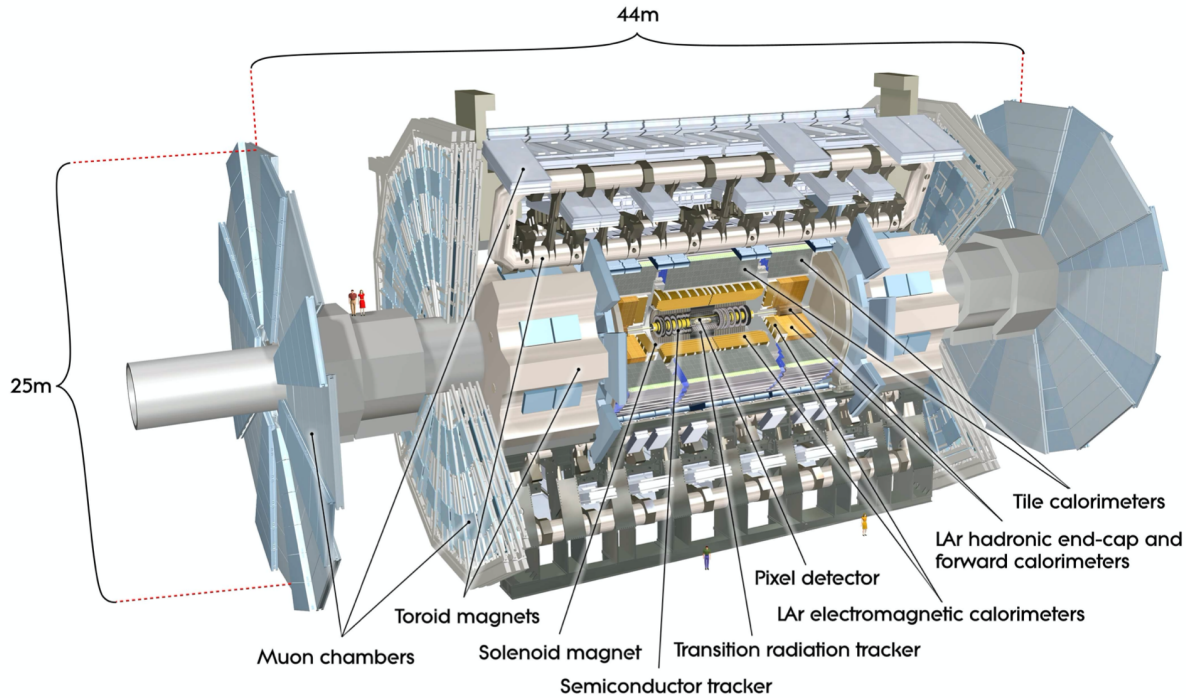


Figure 2.7: Cut-away view of the ATLAS detector. The dimension of the detector are about 25 m in diameter and about 46 m in length. The overall weight of the detector is approximately 7000 tonnes [2].

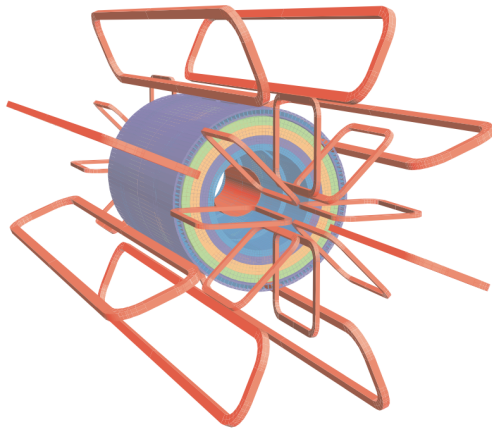


Figure 2.8: Central solenoid and coils of the toroidal magnet in the barrel, interspersed by the ones of the end-cap toroidal magnets [2].



Figure 2.9: Picture of the solenoid after the completion of the wire envelope [2].

2.2.1 The magnetic system

The ATLAS magnetic system is composed by four big superconductive magnets and, in its entirety, it is 36 m long and 22 m in diameter, with a total stored energy of 1.6 GJ. The system includes a solenoid, a central toroid and two lateral toroids, as shown in Figure 2.8. The characteristics of these magnets are described in the following.

- The **central solenoid** [2] is a huge superconductive coil wrapped around the inner tracker and with its axis aligned on the beam axis, designed to generate a 2 T uniform magnetic field along the z direction. The coil is realised with a high-strength Al-stabilised NbTi (niobium-titanium) conductor and cooled down to the temperature of 4.5 K (-268°C) by an helium liquid flux. The solenoid is 5.8 m long and with inner and outer diameters of 2.46 m and 2.56 m respectively. A picture of the solenoid is shown in Figure 2.9.
- The **central toroid** [2], in the barrel region, curves the muon trajectories in the (r, z) plane. It is located outside the calorimeters and contains the barrel part of the muon spectrometer. The toroid consists of 8 coils made with semiconductor wire (Al-stabilized Ni/Ti/Cu), each enveloped and kept inside a cryostat. This magnetic system is, for its dimensions and stored energy, the biggest ever built: 25.3 m long and with inner and outer diameters of 9.4 m and 20.1 m respectively, a weight of 380 tonnes and a stored energy of 1080 MJ. At working regime these coils are crossed by a nominal current of about 20.5 kA which generate a maximum magnetic field of 4 T. In Figure 2.10 a picture of the barrel toroid, after its installation in the ATLAS cavern, is shown.
- The **end-cap toroids** [2] curve the muon trajectories in the (r, z) plane. Each end-cap toroid is formed by eight coils radially and symmetrically assembled around the beam

direction, all inside (unlike the barrel) an unique cryostat. Each coil is 5 m long, with a 1.6-10 m radial extension, and an overall weight of 239 tonnes. They generate a non-uniform magnetic field, with a maximum reachable value of 4 T. In Figure 2.11 a picture of one of the two end-cap toroids, before to be assembled inside the detector, is shown.

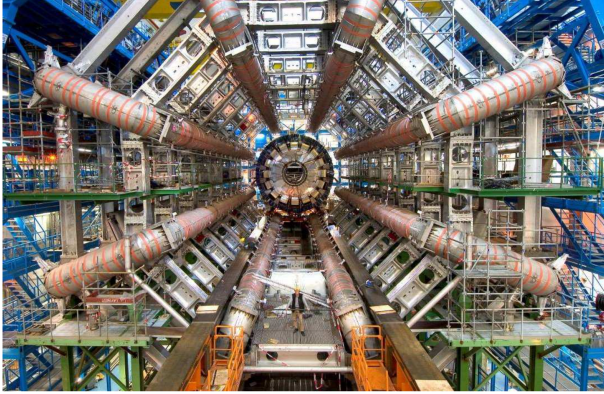


Figure 2.10: Central toroid assembled in the ATLAS cavern [2].

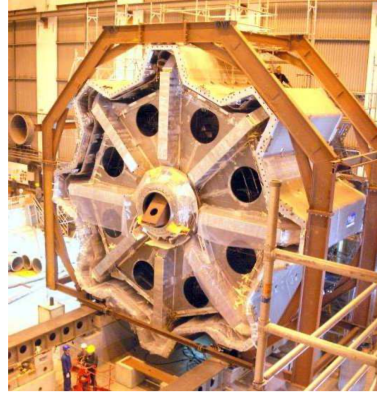


Figure 2.11: End-cap toroid inside its cryostat [2].

2.2.2 The inner detector

The *inner detector* (ID) [81] is located in the region closest to the interaction point. It is designed to reconstruct primary and secondary interaction vertices and the tracks of charged particles in order to measure their transverse momentum (p_T) in the region $|\eta| < 2.5$. Due to the high particle flux, a high granularity of the detector is needed, in order to reach the spatial and momentum resolutions requested by the experiment [82]. The ID consists of three components, which are from inside to outside: the *pixel detector* [83, 84], the *semiconductor tracker* (SCT) [85] and the *transition radiation tracker* (TRT) [86]. These components, shown in Figure 2.12, are described in the following.

- The **pixel detector** is the innermost part of the ID and it is made of four layers with silicon pixels arranged in concentric layers in the barrel zone and of two end-caps, each consisting of three disks perpendicular to the beam axis. The dimensions of the 80 million of pixels installed on this detector are $50\ \mu\text{m} \times 400\ \mu\text{m}$, except for the innermost part of the ID, called *Insertable B-Layer* (IBL) [87], which were installed during LS1 and whose 13 million of pixels have size of $50\ \mu\text{m} \times 250\ \mu\text{m}$ [88]. In terms of the spatial resolution, IBL is able to reach $9\ \mu\text{m}$ in the transverse plane and about $60\ \mu\text{m}$ along the z axis, while in the remaining layers the spatial resolution is $10\ \mu\text{m}$ in the transverse plane and $115\ \mu\text{m}$ along the z axis in the barrel and along the radial direction in the end-caps.
- The **Semiconductor Tracker (SCT)** consists in double-sided silicon strips detectors, organized in four cylindrical concentric layers, with a radial coverage of 299-560 mm

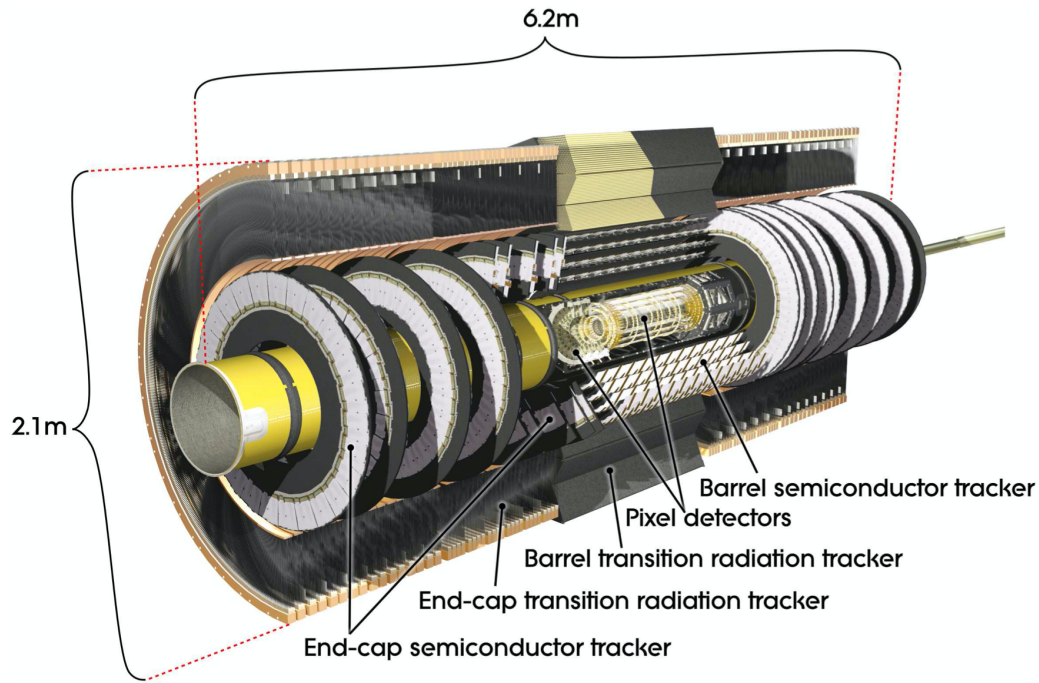


Figure 2.12: ATLAS inner detector structure [2].

around the beam direction, and nine coaxial disks for each end-cap region [88]. The nominal resolution of these modules is $17\text{ }\mu\text{m}$ in the transverse plane and $580\text{ }\mu\text{m}$ along the z axis in the barrel and along the radial direction in the end-caps.

- The **Transition Radiation Tracker (TRT)** occupies the region which radially extends from 563 mm to 1066 mm , and it consists of about 300000 proportional drift tubes which are placed parallel to the beam axis in the barrel region ($|\eta| < 1$) and radially in the end-caps [88]. Each tube (*straw*) is filled with a gas mixture of 70% Xe, 27% CO₂ and 3% O₂, has a diameter of 4 mm , and an anodic tungsten wire with a diameter of $30\text{ }\mu\text{m}$ at the center. The TRT has an accuracy of $130\text{ }\mu\text{m}$ per wire on (r, ϕ) measurements [89] and is able to perform electron/hadron identification by exploiting the *transition radiation*¹⁶. X-ray photons are detected from the gas mixture, finally allowing a significant discriminating power between electrons and charged pions in the energy range of 1-100 GeV [86].

¹⁶When a relativistic charged particle crosses the border between two means with different electromagnetic properties, an electromagnetic radiation, in the X-ray spectrum, is emitted. Since electrons have a low mass, they reach the relativistic condition needed for the emission of transition radiation at lower energies with respect to hadrons.

2.2.3 Calorimetry

The calorimetric system of ATLAS, illustrated in Figure 2.13, is devoted to the particle energy measurement. The system has a ϕ -symmetry and full coverage around the beam axis, while covers in pseudorapidity a region up to $|\eta| \sim 4.9$. It consists of several components, which are realized with different technologies and readout granularity. The system is located immediately after the inner detector, and the calorimeters closest to the beam line are enclosed in three different cryostats. Closest to the ID, the *electromagnetic calorimeter*, a high granularity sampling calorimeter made of lead and liquid argon (LAr Calo), is located. It is divided in barrel ($|\eta| < 1.475$) and two end-caps ($1.375 < |\eta| < 3.2$), each one inserted in a dedicated cryostat. A *pre-sampler* is installed between the inner cold wall of the cryostat and the calorimeters, which is necessary in order to correct fluctuations in the energy loss upstream of the calorimeter. The pre-sampler covers a pseudorapidity region of $|\eta| < 1.52$ in the barrel and $1.5 < |\eta| < 1.8$ in the end-caps. After the electromagnetic calorimeter the *hadronic calorimeter* (TileCal) is divided in barrel ($|\eta| < 0.8$) and two end-caps ($0.8 < |\eta| < 1.7$). The outermost part of the calorimetric system is realized with copper-liquid argon modules, to measure the electromagnetic showers, and tungsten-liquid argon, for the hadronic showers, in the forward regions $3.1 < |\eta| < 4.9$ [90]. A more detailed description of the calorimeter sub-components is given in the following.

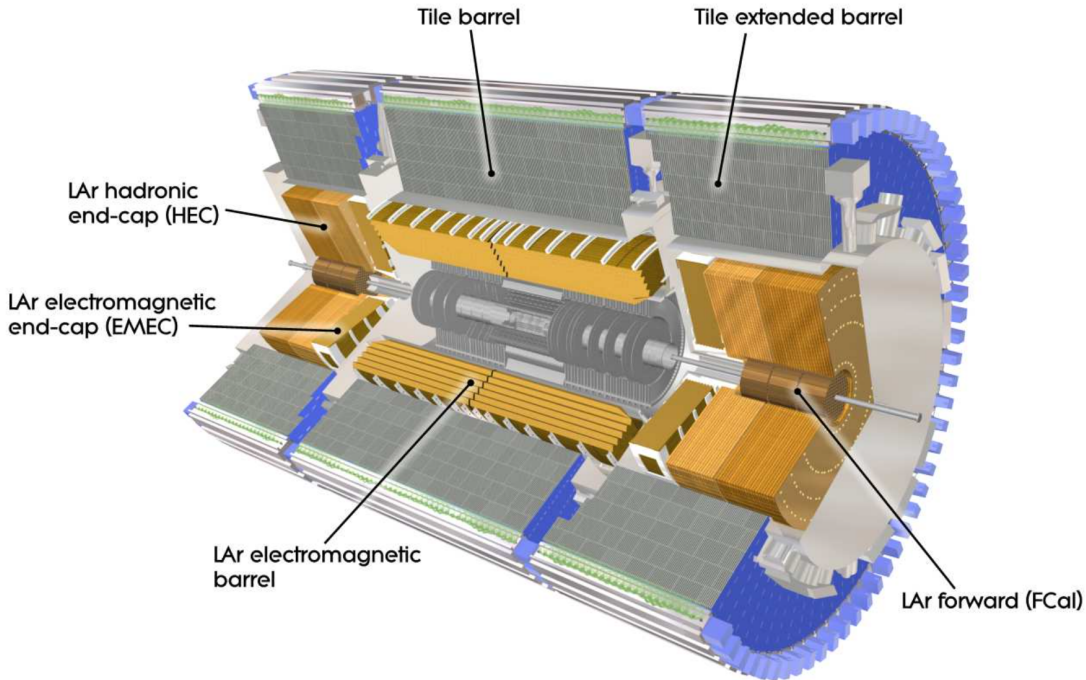


Figure 2.13: General view of the ATLAS calorimeter system [2].

2.2.3.1 The Electromagnetic Calorimeter

The electromagnetic calorimeter (LAr Calo) [91] is a sampling calorimeter¹⁷, made by alternate layers of lead, as absorber, and liquid argon, as active medium. The layers have a peculiar accordion shape with kapton electrodes for the readout, whose dimension and shape is schematically shown in Figure 2.14. Such a configuration ensures a full azimuthal coverage. In the $|\eta| < 2.5$ region the calorimeter is subdivided into three longitudinal layers with different (η, ϕ) granularity:

- the first layer is highly segmented in order to ensure a good $\gamma - \pi^0$ separation and to measure the photon direction;
- the second layer collects most of the shower energy, with a lower granularity than the previous one;
- the third layer, with a coarser segmentation with respect to the previous layers, is used to correct for the energy loss in the last part of the calorimeter.

The overall depth of the calorimeter is slightly larger than 24 radiation lengths. The energy resolution [92] is:

$$\frac{\sigma(E)}{E} = \frac{10\%}{\sqrt{E(\text{GeV})}} \oplus 0.7\%. \quad (2.6)$$

2.2.3.2 The Hadronic Calorimeter

TileCal [94] consists of steel layers alternated with scintillating tiles of 3 mm width, as shown in Figure 2.15. The scintillating tiles are read from two sides by optical *wavelength shifting* (WLS) fibers, in order to optimize the light transmission towards two separated photomultipliers. The steel/scintillator ratio of 4.7 to 1 ensures a high sampling with reduced dimensions. The calorimeter is about 11 interaction lengths deep at $|\eta| \sim 0$, and radially segmented in three layers. The end-cap part ($1.5 < |\eta| < 3.2$) of the hadronic calorimeter (HEC) uses LAr with copper absorber, and it is located directly after the electromagnetic end-cap calorimeter, inside the same cryostat. The nominal energy resolution of TileCal and HEC is:

$$\frac{\sigma(E)}{E} = \frac{50\%}{\sqrt{E(\text{GeV})}} \oplus 3\%. \quad (2.7)$$

¹⁷A *sampling calorimeter* is characterized by alternate layers of passive (absorbers) and active media. In the passive medium the electromagnetic/hadronic shower is generated after the passage of a primary particle, while in the active medium the deposited energy is measured. Vice versa an *homogeneous calorimeter* is characterized by an unique medium which works both as passive and active medium.

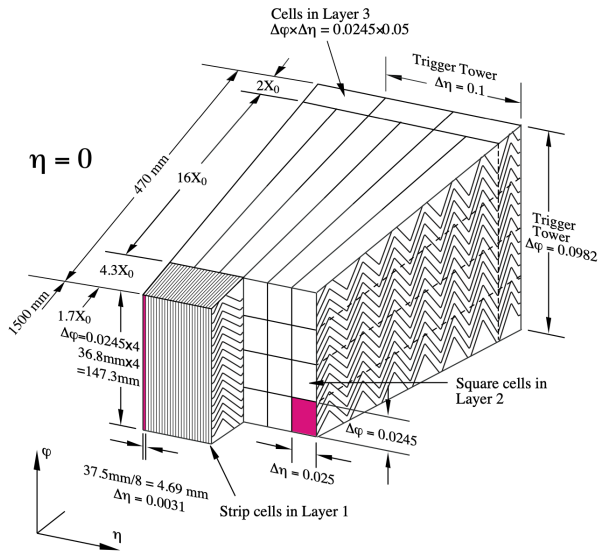


Figure 2.14: Schematic view and dimensions of the ATLAS electromagnetic calorimeter [2].

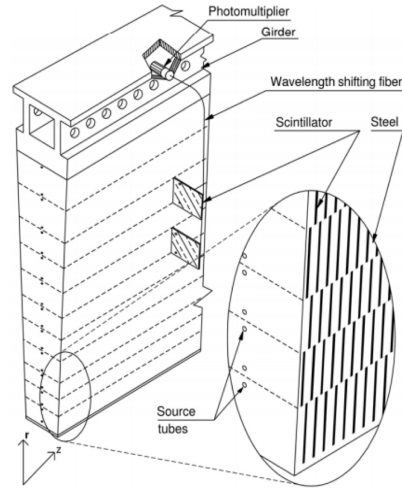


Figure 2.15: Schematic view of the mechanical assembling and the optical readout of the ATLAS TileCal. Several components are shown: the tiles, the fibers and the photomultipliers [93].

2.2.3.3 The Forward Calorimeter

In the high pseudorapidity regions ($3.1 < |\eta| < 4.9$), the *forward calorimeter* (FCal) is located. Since the particle flux in this region is very high, FCal is made by very thin and dense layers of the active medium (LAr). The calorimeter is subdivided into three different sectors: one electromagnetic-like, by using copper as absorber, and two hadronic-like, by using tungsten as absorber [2]. The nominal energy resolution of FCal is:

$$\frac{\sigma(E)}{E} = \frac{100\%}{\sqrt{E(\text{GeV})}} \oplus 10\%. \quad (2.8)$$

2.2.4 The muon spectrometer

The *muon spectrometer* [95] is the outermost part of ATLAS. It provides a trigger when muons cross it in the $|\eta| < 2.4$ region, tracks them and measures their momentum in a range of $|\eta| < 2.7$ from the track deflection in the magnetic field generated by three air-core toroidal magnets. The spectrometer was designed with the aim of reaching a transverse momentum resolution of 10% in reconstructing 1 TeV muons in standalone mode (further details in section 3.3.1). The spectrometer, illustrated in Figure 2.16, was built by exploiting four different detector technologies, chosen accordingly to their placement on the detector (barrel or end-cap) and the requested functionality (trigger or tracking). As shown in Figure 2.17a, in the barrel ($|\eta| < 1$) the spectrometer is extended over three different cylindrical surfaces, with axis coincident to the beam direction, at radial distances of 5, 7.5 and 10 m respectively and

the chambers are organized in 16 sectors (8 big and 8 small). In the end-caps the chambers are organized in three wheels perpendicular to the beam axis, which are located at distances from the interaction point of 7.4, 14, and 21.5 m respectively, as shown in Figure 2.17b [2].

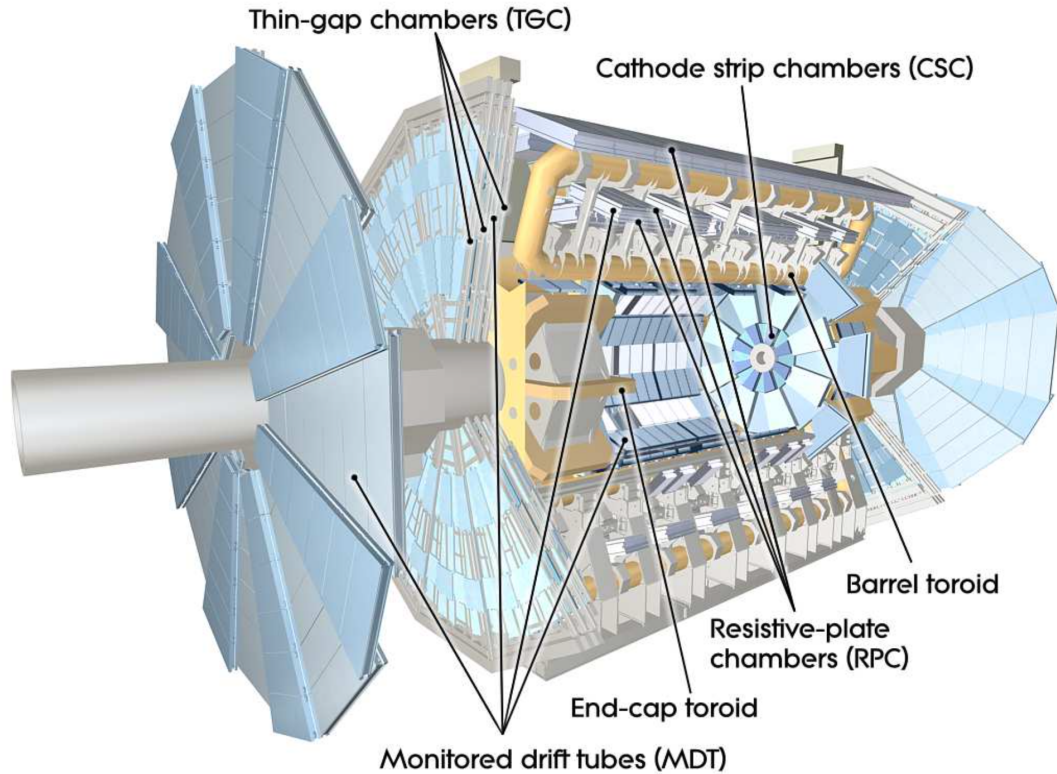


Figure 2.16: Cut-away view of the ATLAS muon spectrometer [2].

2.2.4.1 The Monitored Drift Tubes (MDTs)

Muon tracks are reconstructed with high precision by using the *Monitored Drift Tube* (MDT). MDT chambers are made by layers of aluminium drift tubes, with a diameter of about 30 mm, as shown in Figure 2.18a. Each tube operates with an Ar-CO₂ (93:7) gas mixture at a pressure of 3 bar, in order to increase the ionization inside the gas, thus reaching a spatial resolution per single tube of 80 μm and of 50 μm for the whole chamber. The chambers are arranged in three stations: each station has 2 multi-layers of 3 (4 in the innermost station) layers of tubes, which are directed along the force lines of the toroidal magnetic field (along ϕ). The chambers are rectangularly-shaped in the barrel and trapezoidally-shaped in the end-caps. In the spectrometer 1200 MDT chambers are located, 400000 tubes of 1-6 m length [97] in total. Sophisticated alignment systems allow to exactly know the wire position inside the tubes and the relative position of the chambers, in order to satisfy the stringent request on momentum resolution for 1 TeV muons.

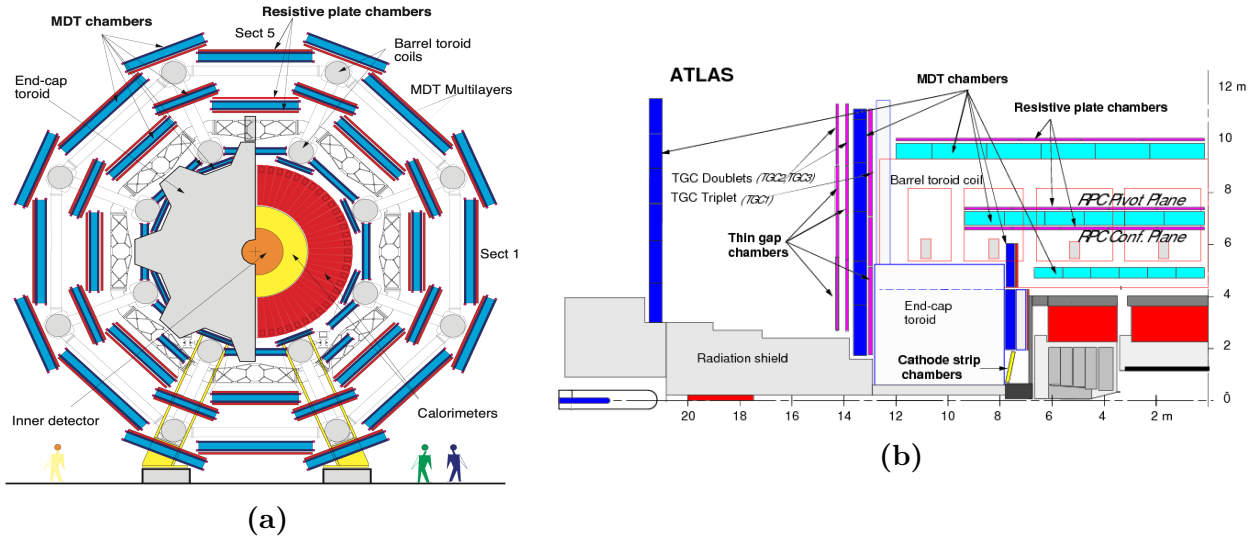


Figure 2.17: (a) Transverse (x, y) view of the muon spectrometer and (b) longitudinal (r, z) view [96].

2.2.4.2 The Cathode-Strip Chambers (CSCs)

In the end-cap regions, with high pseudorapidity ($2.0 < |\eta| < 2.7$), due to the high track multiplicity, the *Cathode-Strip Chambers* (CSCs) are used for the muon tracking, since they are more granular than the MDTs. The ATLAS CSCs are multiwire proportional chambers [98] with segmented cathodic strips, as illustrated in Figure 2.18b. They are arranged in two disks with eight chambers each, eight small and eight large. Each chamber contains four CSC planes, resulting in four independent measurements of the r and ϕ coordinates. The operating gas mixture is Ar:CO₂ (80:20). The CSCs have high spatial resolution and can sustain very intense particle fluxes, with a good track separation, short electron drift time and a good time resolution. At low rate of events the r spatial resolution is about 60 μm with 4 layers of chambers [99].

2.2.4.3 The Resistive Plate Chambers (RPCs)

The trigger in the barrel muon spectrometer makes use of the *Resistive Plate Chambers* (RPCs), covering a range of $|\eta| < 1.0$. The RPC chambers used by ATLAS are gaseous detectors formed by two gas gaps, each one realized with planar resistive electrodes, made of a mixture of phenolic resins (bakelite), filled in the middle with a gas mixture of C₂H₂F₄ (94.7%) - C₄H₁₀ (5%) - SF₆ (0.3%). The bakelite planes are 2 mm thick and spaced to each other of 2 mm. A voltage of about 10 kV is applied to the gap, in order to generate a very intense and uniform electric field. The external surfaces of the electrodes are coated by thin layers of graphite painting, to allow for the high voltage to be uniformly distributed along the plate. When ionizing particles cross the gap, the strong electric field between the two plates allows the generation of the avalanche process, with the following drift towards the anode. The generated signal is read out via capacitive couplings to metallic strips, mounted

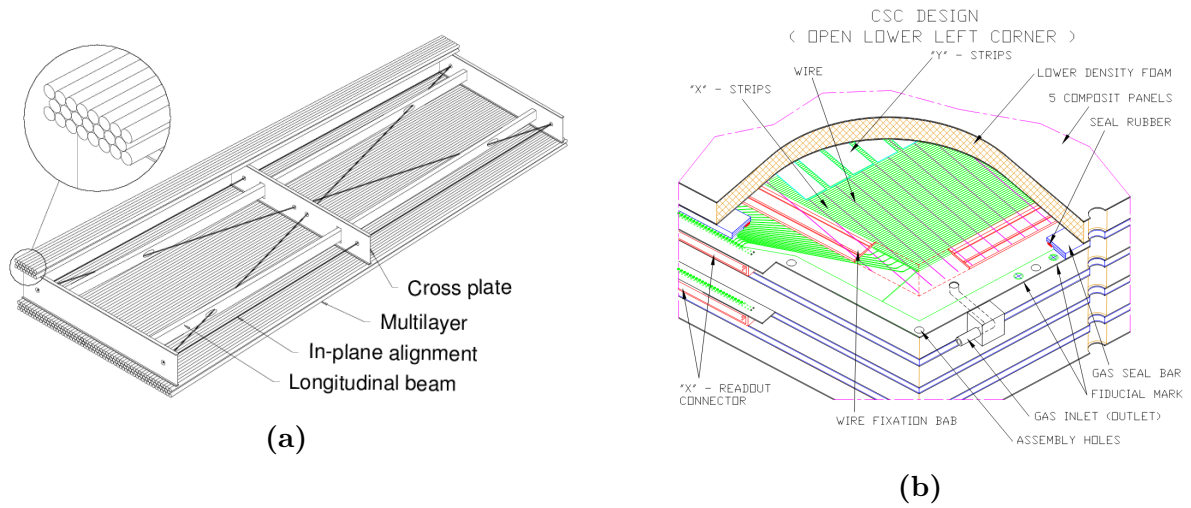


Figure 2.18: Schematic illustration of the two tracking technologies used in the ATLAS muon spectrometer: (a) the MDT [97] and (b) the CSC [2].

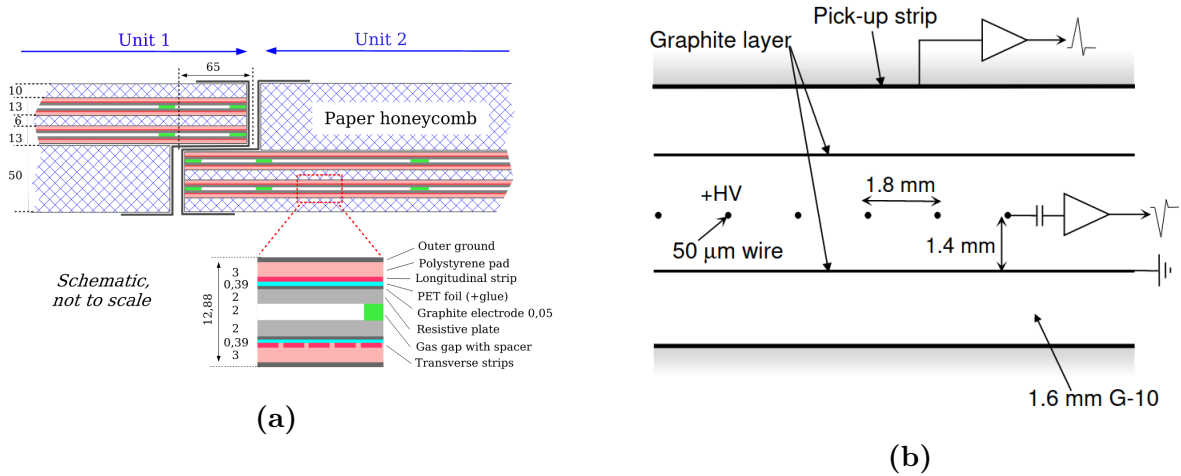


Figure 2.19: Schematic illustration of the two trigger technologies used in the ATLAS muon spectrometer: (a) the RPC [2] and (b) the TGC [2].

on the outer sides of the resistive plates and located over two orthogonal readout panels. The RPCs also provide the ϕ coordinate measurements to the track reconstructing procedure, complementing the η measurement performed by the MDTs, since they can only measure the hit position on the z axis. Although the spatial resolution is ~ 1 cm both in ϕ and in η , the RPC time resolution is instead very good (few ns) [100]. In Figure 2.19a a section view of a RPC, where two units are joint to form a chamber, is shown. The sandwich structure (hashed) is made of paper honeycomb. The ϕ -strips are in the plane of the figure and the η -strips are perpendicular to it. Dimensions are given in mm.

2.2.4.4 The Thin Gap Chambers (TGCs)

Similarly to the muon tracking, also for the muon trigger a more performing detector is needed in the end-cap regions, where the flux of particles is very large. The *Thin Gap Chambers* (TGCs) are exploited here, since their granularity, higher than the RPCs, make them more suitable to operate in such high radiation environment. As shown in Figure 2.19b, a TGC is composed by a plane of parallel tungsten gold-plated wires sandwiched between two grounded cathodic electrodes, 1.4 mm far from the anodic wires. The wire pitch is 1.8 mm and a 3.1 kV positive high voltage is applied. The gas mixture inside the gap is 45% n-Pentan and 55% CO₂, which has the peculiarity of having a very high electron drift velocity. The gas mixture together with the very intense HV (3 kV) and the small gap dimension ensure very fast signals, with a typical rise time of 5 ns, which makes these detectors particularly suited for triggering muons at LHC [101] and for measuring the second, azimuthal coordinate in order to complete the information from the precision tracking detectors. The TGCs are arranged in two coaxial circular disks for each side in the muon spectrometer, one covering a pseudorapidity region of $1.05 < |\eta| < 1.92$ (end-caps), and the other in the range $1.92 < |\eta| < 2.24$ (forward). The spatial resolution is 2-6 mm in the radial direction and 3-7 mm in the ϕ direction.

2.2.5 Forward detectors

The very forward regions are occupied by other detectors, mainly devoted to the luminosity measurements, the detection of particles coming from heavy ions collisions, and the beam monitoring. They are described in the following.

- The **LUMinosity measurement using Cerenkov Integrating Detector (LUCID)** [102] is the detector deputed to monitor the relative luminosity, and it consists of two identical modules, symmetrically located at a distance of ± 17 m from the interaction point. The detector consists of twenty aluminium tubes filled with C₄F₁₀ at a constant pressure of 1.2-1.4 bar. At the end of these tubes there are PMTs which collect the Cherenkov light produced by the passage of the particles [2]. Two different techniques can be employed by the LUCID system to measure luminosity: hit/event counting, which counts the hits produced by one or several particles being inside the detector acceptance, after applying a threshold in amplitude to discriminate the electric signal, and particle flow, which registers the amplitude of the electric signal, proportional to the passage of one or more particles, if no threshold is applied. Independently of the technique, LUCID is able to estimate the number of particles exiting the forward region due to inelastic pp scattering and to provide both a measurement of the integrated luminosity and the online monitoring of the instantaneous luminosity and of the beam conditions.
- The **Absolute Luminosity For ATLAS (ALFA)** [103] detector is devoted to the measurement of the absolute luminosity via elastic scattering at small angle. Nevertheless, since the scattering angle (3 μ rad) needs to be lower than the overall divergence of the proton beam, dedicated beam conditions must be set up in order to perform

the measurement. The ALFA detector, consisting of scintillating fiber trackers located inside Roman pots, is located ± 240 m far from the interaction point [2].

- The **Zero-Degree Calorimeter (ZDC)** is devoted to the detection of neutrons with $|\eta| > 8.3$ in heavy-ion collisions. It consists of two sampling calorimeters, located ± 140 m from the interaction point [2], each one composed of 4 modules: one electromagnetic (about $29 X_0$) and three hadronic (each about 1.14 interaction lengths). Tungsten plates are the absorber material and quartz rods the active medium for both calorimeters. In addition to neutron detection, the ZDC system is used to reduce the background of beam-gas and beam-halo interactions by requiring a tight coincidence from the two detectors at the opposite sides of the interaction point.

Furthermore, other three detectors are exploited to protect the entire apparatus when several proton bunches hit the collimators in front of the detectors. In this situation, in fact, the huge instantaneous rate might cause severely detector damages. Therefore, this set of detectors is designed to identify this kind of events and trigger an abort in time. These are diamond detectors: the *Diamond Beam Monitor* (DBM) [104] (also used for luminosity measurements), the *Beam Condition Monitor* (BCM) [105] and the *Beam Loss Monitor* (BLM) [106], symmetrically located at 0.93 m, 1.84 m and 3.45 m from the interaction point, respectively.

2.2.6 The trigger and the data acquisition systems

Given the high collision rate at LHC, the trigger and the data acquisition (TDAQ) systems [107] need to be designed in order to provide a sustainable final rate of interesting physics events. The trigger system is structured in two levels: the *Level 1* (L1), purely hardware, and the *High-Level Trigger* (HLT), completely software. A block diagram of the trigger and data acquisition systems is shown in Figure 2.20.

2.2.6.1 L1 trigger

The ATLAS L1 trigger performs the initial selection of the events coming from LHC, by reducing the event rate from 40 MHz to 100 kHz. This selection uses the information coming from the calorimeters and the muon spectrometer. The calorimeter trigger (L1Calo) aims to select high- E_T objects such as electrons, photons, jets and τ -leptons decaying into hadrons, as well as high- E_T^{miss} and high total transverse energy events. The muon trigger (L1 muon) selects high- p_T muons, identified from their signals generated in the RPC and TGC detectors of the muon spectrometer. Since the time interval between two subsequent LHC bunch crossings is 25 ns, while the calorimeters and the muon spectrometer take more time to elaborate an event, the signals coming from the detectors can be related to different bunch crossings, then L1 needs to be able to assign events to the corresponding BC, keeping the latency (i.e. the time interval between the pp collision and the trigger decision) under $2.5 \mu\text{s}$ [2]. Results from the L1 muon and calorimeter triggers are processed by the *Central Trigger Processor* (CPT), which implements a trigger menu containing trigger items which combine different trigger

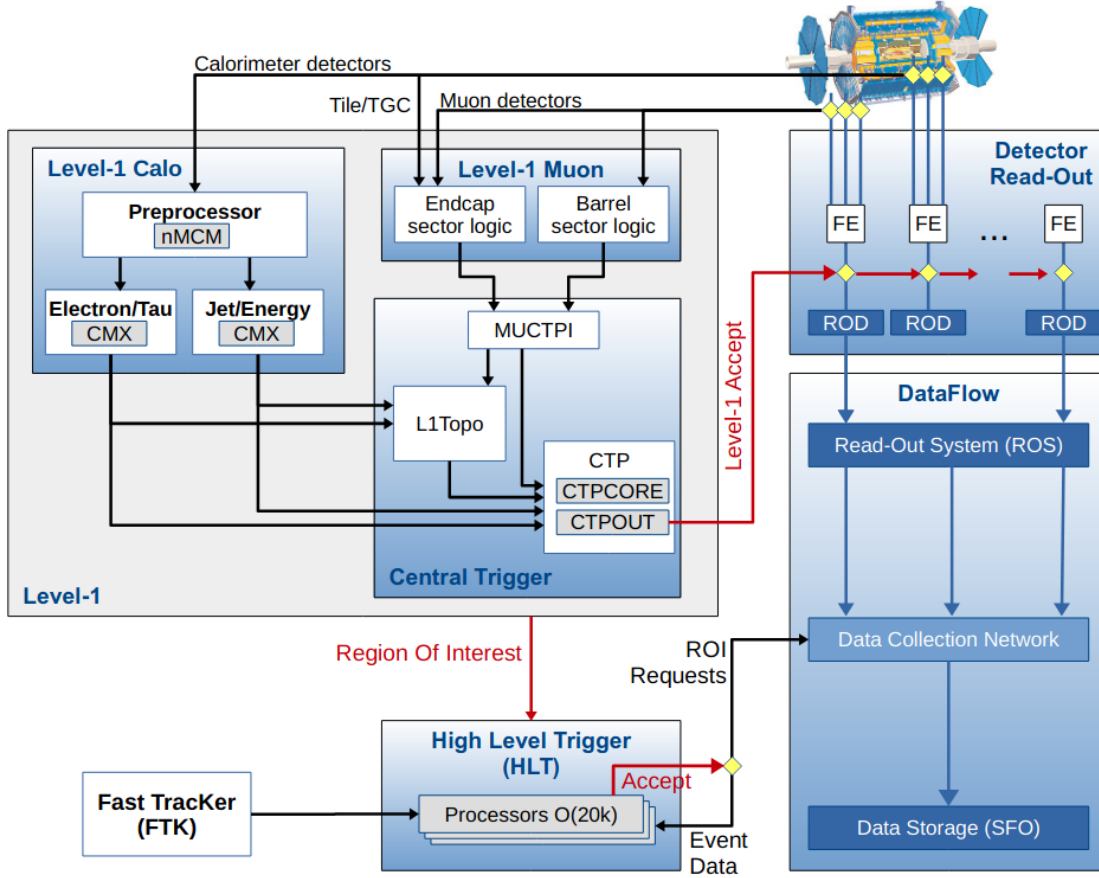


Figure 2.20: Schematic layout of the ATLAS trigger and data acquisition system in Run 2 [108].

selections. In each event, L1 defines one or more *Regions-of-Interests* (RoI), defined by their η and ϕ coordinates in the detector, where interesting features were identified, and they are taken as seeds for the subsequent HLT processing. After the L1 trigger acceptance, surviving events are buffered in the *ReadOut System* (ROS) and processed by the HLT.

2.2.6.2 The HLT

Events surviving the L1 trigger requirements are buffered in the *ReadOut-System* (ROS) and processed by the High-Level trigger. The latter allows to further reduce the L1 event rate from 100 kHz to about 1 kHz. At this stage events reconstructed from the precision measurements in the muon spectrometer and the tracking information in the inner detector are reprocessed by using the additional information coming from the finer granularity of the calorimetric clusters. The HLT algorithms are applied either considering the full detector or inside the RoIs defined at the L1 stage, and the accepted events are sent to the *Tier-0* storage facility for final offline reconstructions.

2.2.6.3 The DAQ system

The DAQ system is the component which manages the storage and transmission of information among the steps so far described. It first receives and buffers data collected by the L1 trigger, and afterwards it transmits, via point-to-point *Readout Links* (ROL), the information to the HLT. The events built at this latter stage are then moved by the DAQ to a permanent event storage. The DAQ also provides the configuration, control and monitor of the ATLAS detector during data-taking [2].

2.3 The Run 3 of LHC and the HL-LHC

The ATLAS setup described so far reflects the general composition of the detector as it was until the Run 2 operations (2015-2018). During the Long technical Shutdown LS2 (2018-2022), several upgrades have been made for the Run 3, known as *Phase-I upgrade*, and others are expected to be made for the HL-LHC, called *Phase-II upgrade*. The latter one is mainly aimed to improve the performance of the detector in prevision of the large increase of luminosity expected in the High-Luminosity phase. The upgrades involve the muon spectrometer, the calorimeters, the inner detector and the TDAQ [109, 110].

2.3.1 The New Small Wheels

Part of the ATLAS Phase-I upgrade consisted in the substitution of the two inner end-cap stations of the muon spectrometer, called *Small Wheels* (SWs), with two new stations, named *New Small Wheels* (NSWs) [111], exploiting new detector technologies that can sustain the new harsh operating condition of Run 3 and HL-LHC. During Run 3 a peak instantaneous luminosity of $2\text{--}3 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ and 55-80 mean interactions per bunch crossing are expected, while $5 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ and up to 140 pile-up events are expected at HL-LHC. The performance of the SWs would have been limited in the conditions expected for Run 3, with a significantly higher flux of particles in their covered η region, by not being equipped with trigger chambers, with strong implications for mis-measurement of transverse momentum of forward muons. Therefore they had to be replaced by the NSWs, which need to operate in this high-radiation environment for other 5-10 years, thus, for safety reason, they have been designed to sustain an instantaneous luminosity of $7 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$, a pile-up rate of 200 events per bunch crossing and an integrated luminosity of 3000 fb^{-1} .

Each of the MDT tubes which were installed on the Small Wheels could operate at a maximum hit rate of 300 kHz, before to suffer a hit inefficiency of 35%, thus they had to be replaced with new detectors. The new technologies must ensure a position resolution of the reconstructed track segments of $50 \mu\text{m}$ in the bending plane, resulting in resolution per plane, for a 4-layer multi-plane detector, better than $100 \mu\text{m}$. The segment finding efficiency has to be better than 97% for muons with $p_T > 10 \text{ GeV}$ and efficiencies and resolutions should not degrade at very high momenta or for a high background flux. A further request is to measure the second coordinate with a resolution of 1–2 mm to facilitate the match between the MS and the ID tracks for the combined muon reconstruction.

Concerning the trigger, in order to reduce the muon Level-1 trigger rate to about 20 kHz, expected for an instantaneous luminosity of $3 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ for muons with $p_T > 20 \text{ GeV}$, the New Small Wheel triggering detectors should satisfy some requirements: the track segment reconstruction must have an angular resolution of 1 mrad or better; the granularity has to be better than 0.04×0.04 in the (η, ϕ) plane, in order to match the one of the current muon trigger system; the online track segment reconstruction efficiency should be better than 95% in the full η coverage of the NSW trigger ($1.3 < |\eta| < 2.5$) [111].

In order to fulfill all these requirements the technologies that have been adopted in the NSWs are: the *MicroMegas Chambers* (MMs), primarily deputed for the muon precision tracking, and the *Small Strips Thin Gap Chambers* (sTGCs), mainly devoted to the L1 trigger. Nevertheless, the two technologies can be adopted for both trigger and tracking tasks.

The structure of the two NSWs is shown in Figure 2.21a. It is characterized by 16 sectors, also called *double wedges* (DWs), 8 of which have bigger dimensions, *Large sectors*, and 8 smaller, *Small sectors*. Each sector has 8 layers of sTGC detectors and as many of MM detectors, organized in two *multiplets*, separated by a 40 mm spacer and formed by a sTGC and a MM *quadruplet*¹⁸, installed, as illustrated in Figure 2.21b, in the order sTGC-MM, for the quadruplet facing the interaction point (IP), and MM-sTGC for the opposite one (HO). To date the two NSWs have been installed in ATLAS (NSW ‘side A’ and NSW ‘side C’), and are working in Run 3 of LHC. The commissioning of the NSWs, which involved the muon community on several aspects of the detector, was performed before and after the detector installation inside the cavern. During my PhD, besides the analyses that will be presented in the next chapters of this thesis, I worked on the NSW commissioning performing several studies on the MM detectors. In the following the MM detectors will be described in details, and two different studies I did will be reported: a study of the correlation between some of the construction parameters of the MM readout boards and the performance of the detectors, and a study on the misalignment of the NSWs, showing how the construction defects of the MM *Printed Circuit Boards* (PCBs) can affect the muon track reconstruction.

2.3.1.1 The MicroMegas detectors

A MicroMegas (abbreviation of ‘Micro Mesh gaseous detector’) detector, schematically illustrated in Figure 2.22, consists of a planar cathodic plane, a few millimetres gas gap acting as conversion and drift region, and a thin metallic mesh typically at 100-150 μm distance from the readout electrode, which defines the amplification region. The metallic mesh is positioned on the top of about 120 μm high insulating spacers, called pillars, directly placed over the readout boards. The anodic electrode is made with copper resistive strips on a kapton layer, of about 300 μm width and 400 μm far one of each other (strip pitch). The drift cathode, 5 mm apart from the mesh, is held at a negative High Voltage (HV), typically at 300 V, with respect to the mesh, which is grounded. The anode is held at a positive HV, typically around 500-600 V. The electric field in the drift region is a few hundreds of V cm^{-1} , whereas in the

¹⁸A *multiplet* is a group of eight parallel layers of detectors. A *quadruplet* is a group of four parallel layer of the same detector type.

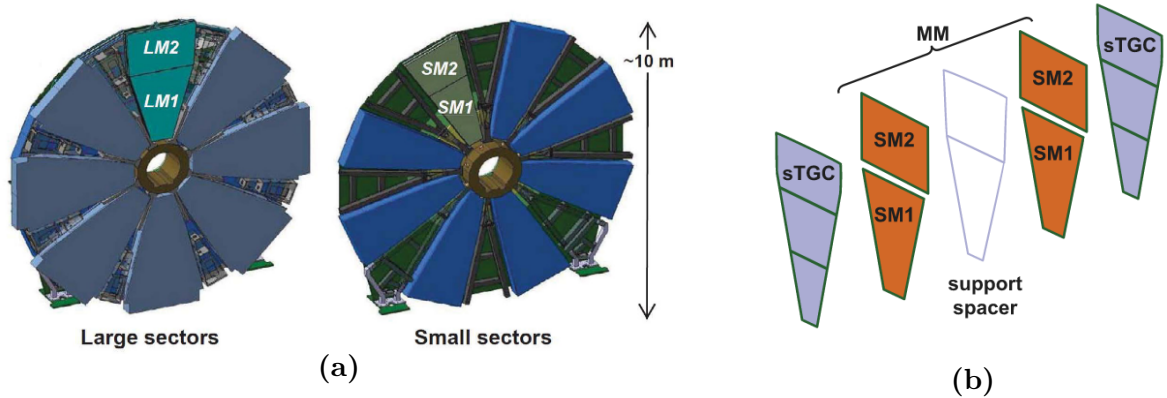


Figure 2.21: Overall view of the New Small Wheel. (a) views of the wheel, highlighting the large sectors LM1 and LM2 and the small ones SM1 and SM2. (b) exploded view of the wheel, for a small sector, with two sTGC chambers and two MM quadruplets [112]

amplification region it is $40\text{-}50\text{ kV cm}^{-1}$. In order to prevent sparking, which can damage both the detector and the readout electronics or alter the chemical structure of the materials used to build the chamber, thus increasing the spark rate and the time needed to deplete the charge, the readout strips are protected by a thin additional layer of insulator, on top of which a layer of resistive strips is deposited, matching the pattern of the readout strips. As shown in Figure 2.22, when a charged particle crosses the drift region, it ionizes the gas, thus producing electrons which drift towards the mesh, transparent to more than 95% of the electrons, since in the amplification region the electric field is 50-100 times stronger than in the drift region. When the electrons arrive in the amplification region, the avalanche multiplication occurs in a few nanoseconds, resulting in a fast signal pulse on the readout strips, where the output signal is formed. The charge produced by the avalanche process is read through capacitive couplings between the resistive and copper strips, preventing these ones to be directly exposed to the gas and to the sparks. The small amplification gap provides a fast evacuation of the positive ions (about 100 ns), which is one of the reason MM detectors are very suited to operate in very high particle fluxes environment, like the one of Run 3 and HL-LHC [111]. The standard baseline gas mixture for the MM chambers is 93% Ar and 7% CO₂ at 3 mbar, however the final mixture used for the MM detectors installed on the NSWs is 93% Ar, 5% CO₂ and 2% iC₄H₁₀. The isobutane was added to reduce the effects of the sparks inside the detector and to guarantee a better HV stability.

As already described, the MM detectors are arranged, in the NSW, into quadruplets of 4 layers each, as shown in Figure 2.23a. Each MM layer has 8 MM PCBs, formed by 1024 readout strips covered by the resistive strips, and powered by two HV sectors (each sector covers 512 strips) and read out by two readout boards called MMFE8, standing for 8-channels *MicroMegas Front-End*. Each MMFE8 has eight 64-channel *Application Specific Integrated Circuits* (ASICs) called VMMS, which provide the address, amplitude, and time of all MM hits that are read out in response to a Level-1 trigger, and the *Address in Real Time* (ART) data

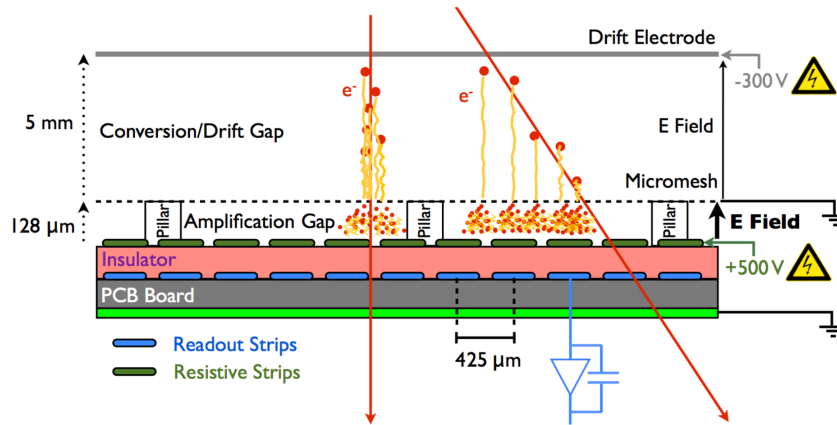


Figure 2.22: Schematic view of a MM detector and working principle of the signal formation when a particle crosses the detector [112].

that is used to form the Level-1 trigger [111]. Each quadruplet can be large (L) or small (S) if they belong to a large or small sector, and they are also divided into two modules: *LM1/SM1* containing five MM-PCBs for each layers, and *LM2/SM2* containing three MM-PCBs, as illustrated in Figure 2.23b. PCBs can also be classified in terms of the orientation of their readout strips: if they are aligned with the η direction they are called *Eta PCBs*, while if they are rotated by a stereo angle, of $\pm 1.5^\circ$, they are called *Stereo PCBs*.

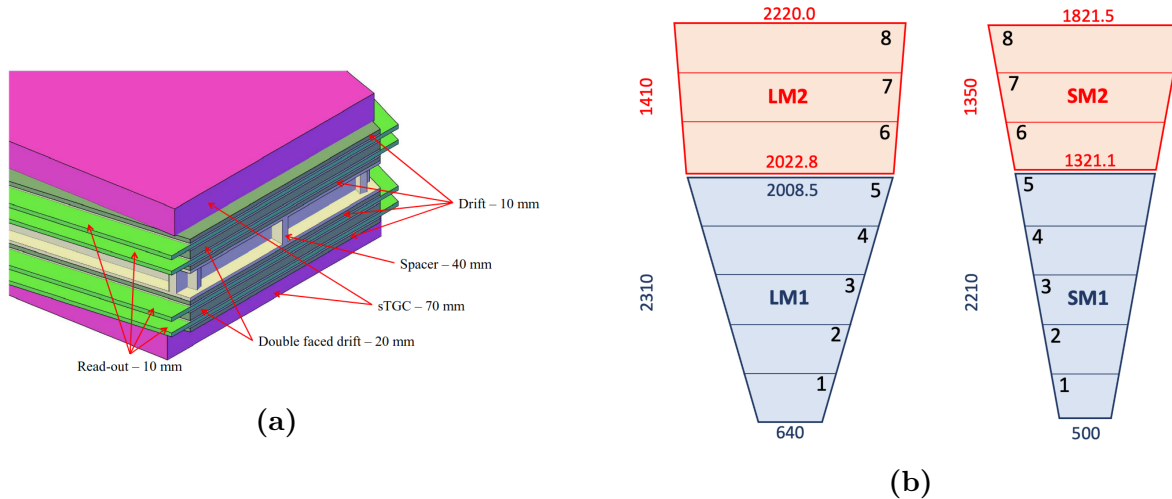


Figure 2.23: In (a) schematic view of a NSW multiplet, underlying how the MM layers are installed [111]. In (b) schematic view of the large/small MM sectors in terms of dimensions (mm).

2.3.1.2 Study of the correlation between the MM readout boards construction parameters and their performance

Several systematic studies have been performed on the two NSWs to monitor their operational conditions. Some of them have been conducted by checking the correlation between the working high voltage (HV) and some construction parameters (as the mean pillar height, the mean resistivity and the resistance of the resistive strips) of each MicroMegas PCB.

The measurements used for the HV study have been taken from the validation runs performed at the BB5 facility at CERN before applying the passivation¹⁹ procedure, and, although the presently used MM mixture is Ar:CO₂:iC₄H₁₀, they were performed on a Ar:CO₂ mixture which, being less stable than the one containing isobutane, could enhance the presence of problems. In Figure 2.24a the distribution, normalized to the total number of sectors, of the working HV for one type of MM-PCBs (called type 1), by distinguishing in PCBs placed either on large or small sectors, is reported. It shows that large sectors had a considerable fraction of HV sectors far away from the nominal value, while the small sectors were closer to the nominal value of 570 V. By considering instead either eta or stereo PCB types, as shown in Figure 2.24b, no large differences were evident, and they performed in a similar way. The same behaviour was observed for all other PCB types.

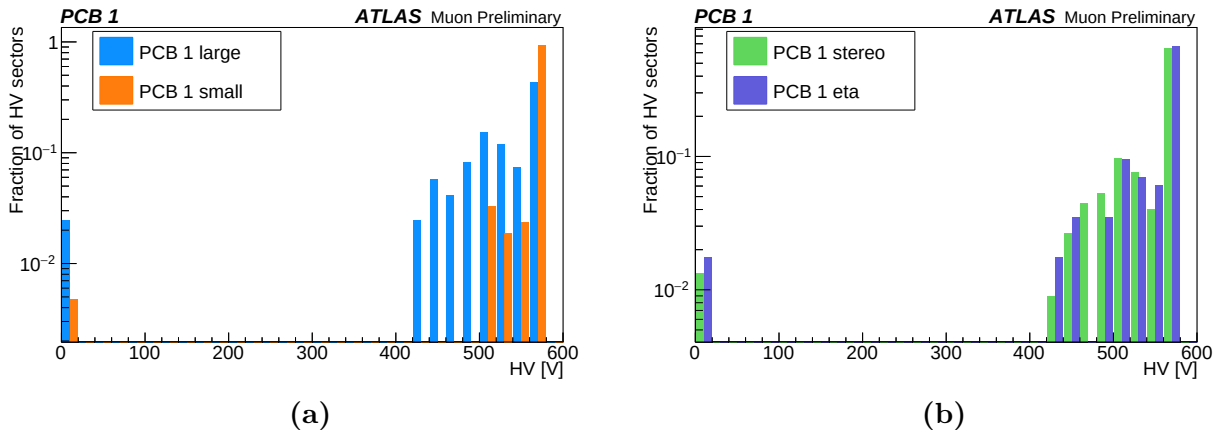


Figure 2.24: Distribution (normalized to the total number of sectors) of the working HV for (a) large/small and (b) eta/stereo MM PCBs of type 1 [113].

The height of the pillars which hold the amplification mesh was another important parameter to be studied, since differences in the pillar height could impact on the uniformity of the high electric field in the amplification gap, and consequently on the signal. Several are the factors that could influence the pillar height itself, e.g. the applied HV, which could compromise on

¹⁹Some boards showed a high HV instability. This problem was understood to be strictly correlated to low resistance values of the anodic strips. The passivation procedure solves this issue, deactivating the regions where the resistance is under 0.8 MΩ [113].

the construction integrity of the pillars and then lead to structural differences among them. As shown in Figure 2.25a this seemed to be not the case, and no correlation between the HV and the mean pillar height was observed. Another aspect that could be considered was that the MM board production was assigned to two different industries, Eltos (Italy) and Elvia (France), which could be source of differences at the pillar level. In Figure 2.25b is reported the mean pillar height distribution, in percentage of the total HV sectors, by distinguishing the two different supply companies. It clearly appears that there was a difference of few microns in the two sets of pillars: those produced by Eltos are higher (about $2\mu\text{m}$ in average) than the other ones produced by Elvia.

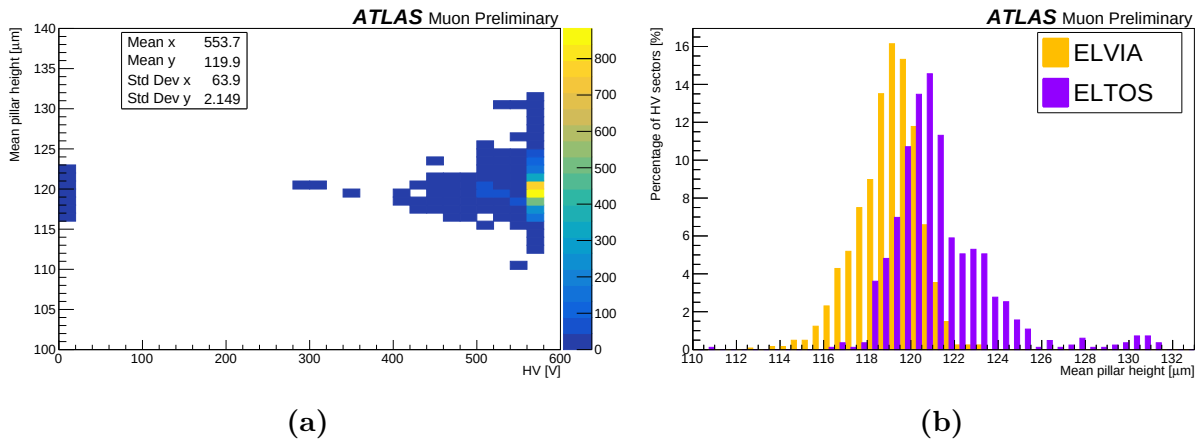


Figure 2.25: Distributions of (a) the mean pillar height vs. the working HV and (b) the mean pillar height for Elvia and Eltos productions [113].

Some differences could also appear in the same PCBs between pillars in different zones of the board. By distinguishing the mean pillar height measured on the left side of the board and the one evaluated on the right side, the difference between them, called left/right asymmetry, should be ideally zero, but it was expected to be different from zero because of possible structural or construction differences in the board itself. In Figure 2.26 is shown the absolute value of the left/right asymmetry as function of the HV, and it appears that there was an asymmetry significantly different from zero without any correlation with the applied HV.

Another parameter to be considered was the mean resistivity of the MM resistive strips. Measurements of this resistivity taken during the QA/QC phase were used. As shown in Figure 2.27a, for eta boards there was a difference among PCBs placed on different modules, in fact those placed on LM1 or SM1 modules had a tighter mean resistivity distribution, peaked around $0.8\text{ M}\Omega/\text{sq}$, than the ones on LM2 or SM2 modules, which had instead a long tail. Furthermore, as shown in Figure 2.27b, there was a correlation between the applied working HV and the mean resistivity: the resistivity tended to be higher, close to 570 V (the nominal HV value), and almost all sections reached the highest nominal voltage for a resistivity higher than $\sim 1.2\text{ M}\Omega/\text{sq}$ [113].

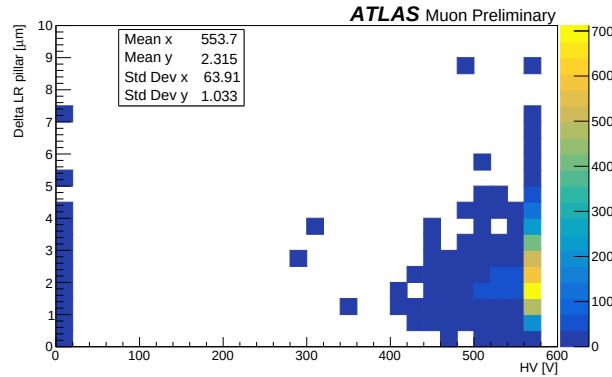


Figure 2.26: Absolute value of the left/right asymmetry vs. the working HV [113].

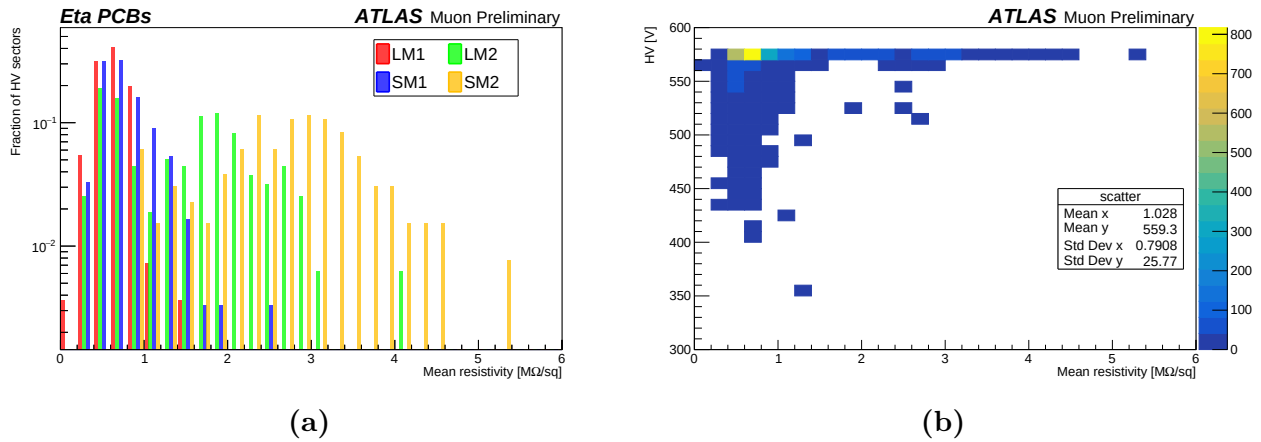


Figure 2.27: In (a) mean resistivity distribution for each MM module type, selecting only eta PCBs. In (b) working HV vs. mean resistivity [113].

2.3.1.3 Misalignment study of the NSWs using the ‘as-built’ parameters

In ATLAS the identification of muons uses track reconstruction in both the inner detector (ID) and in the muon spectrometer (MS) independently or combining them. In the MS the reconstruction uses the chamber hit informations to build *track segments*, which represent the reconstructed muon track in a specific station. Then track candidates are built from segments, typically starting from the outer and middle stations and extrapolating back through the magnetic field to the segments reconstructed in the inner stations. Each time a reasonable match is found, the segment is added to the track candidate. The final track-fitting procedure takes into account all relevant effects (e.g. multiple scattering, magnetic field layout, relative chamber misalignments, etc.). A similar approach is followed in the reconstruction of muons tracks in the ID [114]. The misalignment of the MS detectors with respect to the ATLAS coordinate system needs to be taken into account and appropriately corrected. Sophisticated optical alignment systems are used in ATLAS in order to know accurately the positions of the detectors, but this cannot prevent the effect of internal misalignments or deformations of

the detectors, which need to be investigated. In particular, in order to guarantee the nominal detector performance, the recent installation of the NSWs must be validated also in terms of their internal defects, which cause discrepancies with respect to the ideal geometry and positions thus spoiling the muon reconstruction. Two main types of internal misalignments can happen:

- those related to the position and geometry of the detectors with respect to the ATLAS reference system, like translations and rotations (called *A-lines* and *B-lines*);
- those related to construction defects, like deformations and expansions (called *as-built* parameters).

The study described in the following aimed to explore the second type, i.e. the effect of the as-built parameters on the muon reconstruction, investigating those mainly affecting it. In particular, among the different types of reconstructed tracks (more details are in section 3.3), for the following analysis only two types of tracks were considered: the *combined muon* tracks, which are those tracks that combine the information got from the muon spectrometer with that one obtained from the ID, and the *MSOE* tracks, which are the muon tracks reconstructed in the muon spectrometer and extrapolated to the beam spot by considering the energy loss in the calorimeters. Reconstruction was performed on simulated events, by considering events with two muons produced with opposite direction in the end-cap regions and with a trasverse momentum (p_T^{truth}) in the range $500 \leq p_T^{truth} \leq 1500$ GeV. The reason of using so energetic muons was to have straight tracks for the misalignment study.

The as-built parameters, for both the MM and sTGC detectors installed on the NSWs, were measured and stored in appropriate databases in the ATLAS database system. When applying the corrections to the reconstruction one wouldn't expect huge changes in the performance with respect to use the nominal geometry. E.g. in Figure 2.28a is shown the difference in the reconstructed cluster x -coordinate for the MM eta layers, with and without the correction for the real as-built parameters. The 1-sigma gaussian fit of this distribution show an expected mean value of this difference at zero and a standard deviation of the order of 160 μm . Figure 2.28b shows the same data in a 2D histogram of the x -coordinate with and without the correction for the real as-built parameters and, as expected, data are distributed along the bisector of this figure.

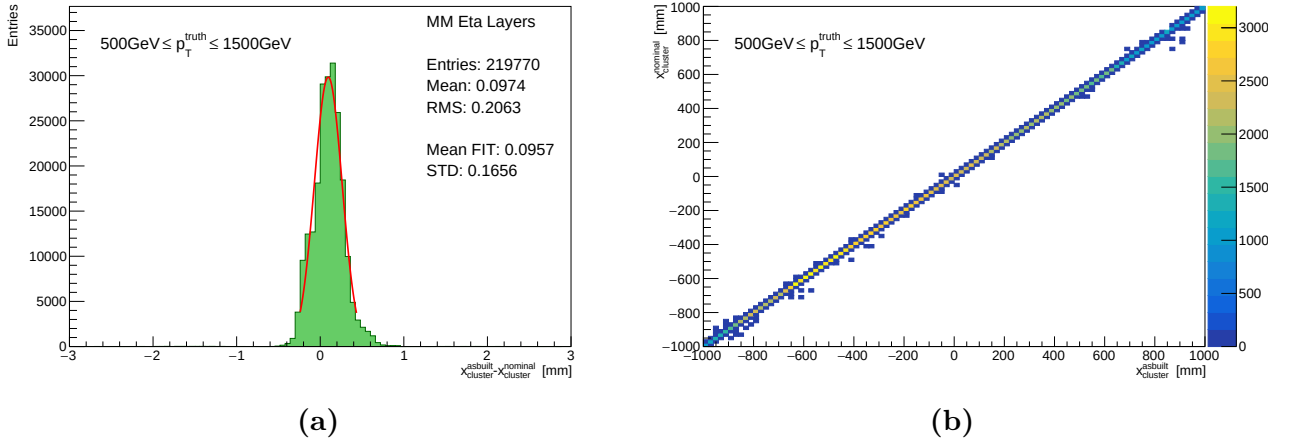


Figure 2.28: Simulated muon reconstruction by considering events with two muons produced with opposite direction in the end-cap regions and with $500 \leq p_T^{truth} \leq 1500$ GeV, with and without the application of the corrections for the as-built parameters. In (a) is reported the distribution of the difference in the reconstructed cluster x -coordinate applying or not the as-built parameters corrections, with a 1-sigma gaussian fit superimposed, for MM eta board. In (b) is reported the 2D histogram of the reconstructed cluster x -coordinate with and without the application of the corrections for the as-built parameters. As expected, data are distributed over the bisector.

In order to estimate the impact of the as-built parameters correction on the reconstruction performance, we could study the relative q/p :

$$\frac{(q/p)^{reco} - (q/p)^{truth}}{(q/p)^{truth}}, \quad (2.9)$$

where q and p are the charge and the momentum of the muon respectively, $(q/p)^{truth}$ is the Monte Carlo truth value of q/p for the simulated muons, while $(q/p)^{reco}$ is the reconstructed value. From the distribution of the relative q/p a single gaussian fit can be performed, and its standard deviation can be defined as the resolution. In Figure 2.29a the standard deviation obtained from a single gaussian fit of the relative q/p distribution is shown as function of the $|\eta|$ of the truth-muons, while in Figure 2.29b is shown as function of the p_T of the truth-muons. The plots were obtained both for combined muons and MSOE tracks (in blue and red respectively) and by applying or not the real as-built geometry (empty-circles or full-triangles respectively). Both plots show that, as expected, the resolution for MSOE tracks is generally worse than the combined one, since in the latter case also the ID informations are exploited, and the application of the as-built geometry correction does not change too much the reconstruction performance. Small deviations can be seen only at high value of $|\eta^{truth}|$ and p_T^{truth} .

There are several types of internal deformations that MM could have. Focusing only on the MM PCBs, the main types of deformations are pictorially schematized in Figure 2.30. These deformations could appear both along the x and the y axes. If the PCB is elongated along

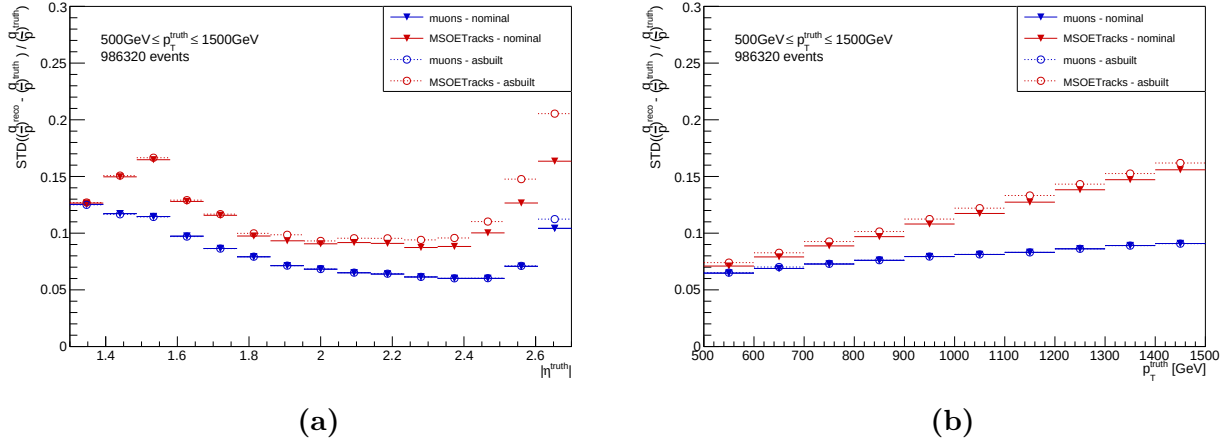


Figure 2.29: Standard deviation of the relative q/p distribution from a single gaussian fit vs (a) $|\eta^{truth}|$ and (b) p_T^{truth} . Red points represent MSOE tracks while blue points combined muons. Full-triangles/empty-circles are values obtained from a simulated reconstruction with/without the nominal geometry.

either the x or y axis with respect to the ideal shape, we call it elongation along x , egX , or y , egY . If this elongation is not uniform along the x or y direction, there is a gradient of the elongation along (c) x , $degX$, or (d) y , $degY$. Finally, the board can also be bent along the (e) x and (f) y axis, indicating these deformations as $sagX$ and $sagY$ respectively. In order to understand which is the impact of these deformations over the reconstruction, six different reconstructions of simulated muons were launched, by keeping the ideal geometry of all the parameters except the one to be studied. In Table 2.1 are summarized how the six as-built parameters were changed in the reconstruction: for egX , egY , $degX$ and $degY$ the applied value was changed differently for each pair of sectors, in steps of 1‰ from 0 to 7‰, positively for side A DWs and negatively for side C DWs; similarly for $sagX$ and $sagY$ the value was changed in steps of 0.5 mm from 0 to 3.5 mm, positively for side A and negatively for side C. These values were not changed for sectors 1 and 2, in order to keep them as reference of the nominal geometry.

After applying the modified parameters to the reconstruction, it was studied how each of them impacted on the resolution. In Figure 2.31 are reported, for the side A sectors, the standard deviations of the relative q/p distribution from a single gaussian fit for the three reconstructions where the $degX$, egY and $sagY$ parameters were changed. For each of them it can be seen how changing the parameters does not affect the reconstruction resolution of the combined muons, and the same was seen changing the remaining parameters ($degY$, egX and $sagX$). The same cannot be said for the resolution of MSOE tracks; in fact, while for the $degX$ variations the resolution was not affected, and the same was seen for $degY$, egX , and $sagX$, this is not true anymore for egY and $sagY$ variations: the resolution slightly became worse when we changed the elongation along the y axis, going above the 10‰ when egY was higher than 3‰, while the resolution became dramatically worse when the bending along y was

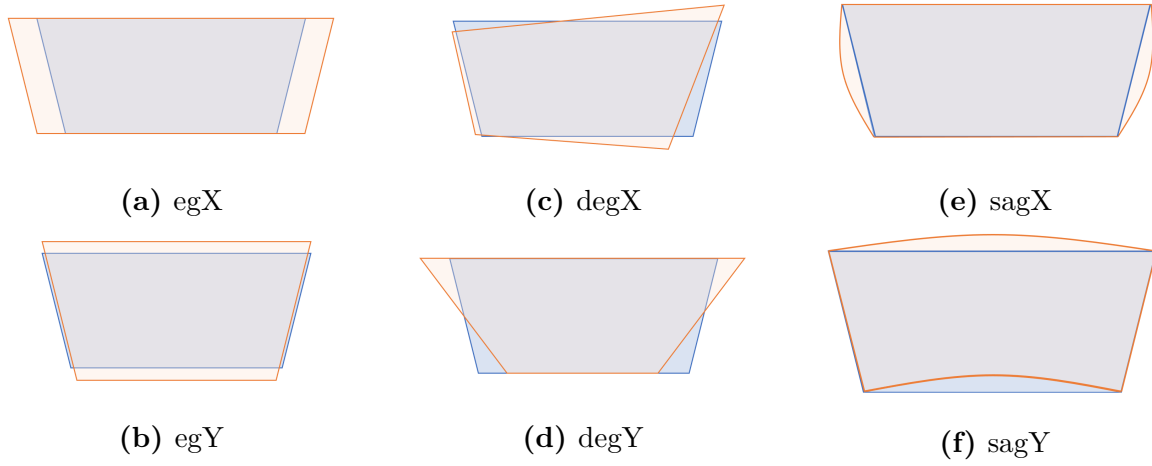


Figure 2.30: Schematic representation of the main types of internal deformations that a MM-PCB could have. The blue trapezoid represents the ideal shape of a PCB, while the orange one the deformed PCB. Deformations could be along either the x or y axes and they are: (a) and (b) the elongation of the board along the x and y directions respectively, (c) and (d) the gradient of the elongations, and (e) and (f) the bending of the boards along the x and y axes respectively.

Sector	egX [‰]		egY [‰]		degX [‰]		degY [‰]		sagX [mm]		sagY [mm]	
	A	C	A	C	A	C	A	C	A	C	A	C
1-2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
3-4	1.0	-1.0	1.0	-1.0	1.0	-1.0	1.0	-1.0	0.5	-0.5	0.5	-0.5
5-6	2.0	-2.0	2.0	-2.0	2.0	-2.0	2.0	-2.0	1.0	-1.0	1.0	-1.0
7-8	3.0	-3.0	3.0	-3.0	3.0	-3.0	3.0	-3.0	1.5	-1.5	1.5	-1.5
9-10	4.0	-4.0	4.0	-4.0	4.0	-4.0	4.0	-4.0	2.0	-2.0	2.0	-2.0
11-12	5.0	-5.0	5.0	-5.0	5.0	-5.0	5.0	-5.0	2.5	-2.5	2.5	-2.5
13-14	6.0	-6.0	6.0	-6.0	6.0	-6.0	6.0	-6.0	3.0	-3.0	3.0	-3.0
15-16	7.0	-7.0	7.0	-7.0	7.0	-7.0	7.0	-7.0	3.5	-3.5	3.5	-3.5

Table 2.1: Summary of the six different reconstructions done by changing only one of the six as-built parameters and keeping the other to the nominal value. The value for egX, egY, degX and degY was changed for each sector in steps of 1‰ from 0 to 7‰, positively for side A DWs and negatively for side C DWs. The value for sagX and sagY was changed in steps of 0.5 mm from 0 to 3.5 mm, positively for side A and negatively for side C. For sectors 1 and 2 no modification was applied in order to keep them as reference of the nominal geometry.

changed. In Figure 2.32 are reported, for these two latter cases, the standard deviations of the relative q/p distribution from a single gaussian fit vs $|\eta|$ of the truth-muon for the MSOE tracks and by dividing into the different variations (therefore the different sectors) applied accordingly to Table 2.1. For both egY (a) and sagY (b) variations, the resolution is affected,

and more strongly moving to high values of $|\eta^{truth}|$.

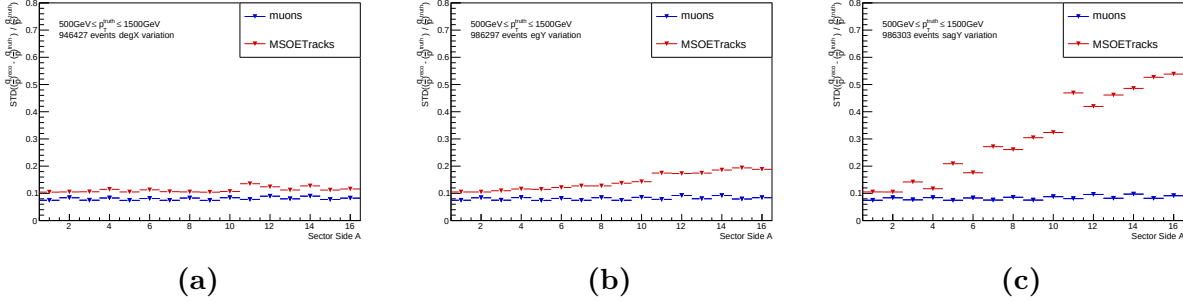


Figure 2.31: Standard deviation, for the side A sectors, of the relative q/p distribution from a single gaussian fit for three different reconstructions changing the (a) degX, (b) egY and (c) sagY parameters, according to Table 2.1. In blue are reported results for combined muon tracks, while in red for MSOE tracks.

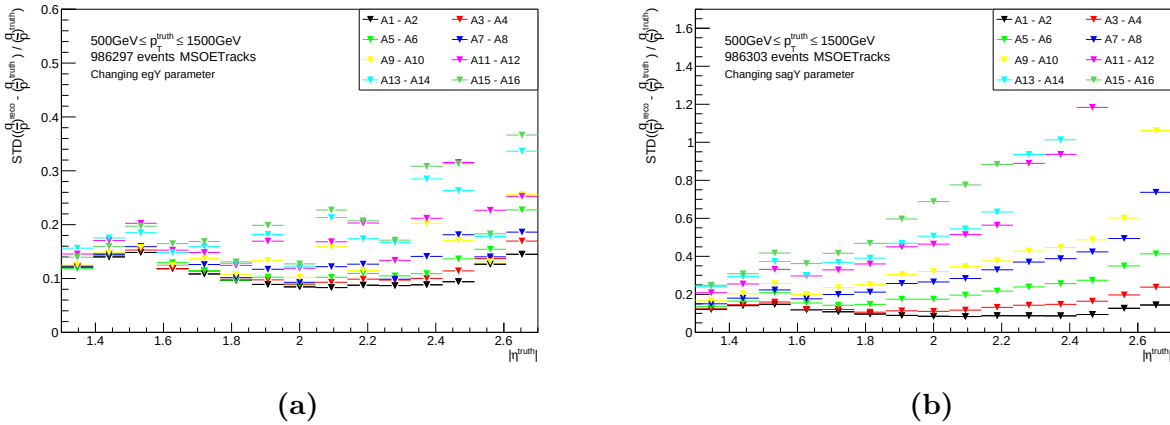


Figure 2.32: Standard deviation of the relative q/p distribution from a single gaussian fit vs $|\eta^{truth}|$, obtained by changing in the reconstruction the (a) egY and (b) sagY parameters for all side A sectors as written in Table 2.1.

From this study it can be understood that the parameters which mainly affect the reconstruction are those related to the y axis, and in particular the elongation and the bending. Therefore one needs to take care mostly of these two parameters in the muon reconstruction, trying to correctly estimate the uncertainty that they introduce in the reconstruction.

2.3.2 The High-Luminosity LHC

The most ambitious upgrade of LHC consists in its *high-luminosity* phase, expected to start in 2029, as shown in the timeline of Figure 2.1. The High-Luminosity LHC [5] project (or High-Lumi LHC or simply HL-LHC) was born in order to accomplish the original aim of reaching the 14 TeV of the accelerator energy and to hugely increase the statistics, reaching an instantaneous luminosity of $5\text{--}7 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$, thus allowing the study of very rare processes. Since the high-lumi phase will start in 2026, the detector Phase-II upgrades are presently ongoing.

There are several upgrades to the machine expected for the high-luminosity phase, with the purpose to improve the instantaneous luminosity of the collider and to reach the goal of collecting 250 fb^{-1} per year of integrated luminosity, and a total of 3000 fb^{-1} after 12 years of operation [5]. In order to increase the luminosity, new powerful focusing magnets need to be used. The current 8 T LHC quadrupole magnets will be replaced with 12 T quadrupoles which will allow to increase the number of collisions from about 30 to 140 each time two bunches will meet in the centre of ATLAS and CMS detectors. One challenge of the high-luminosity LHC will be trying to keep the luminosity as constant as possible during the most part of the physics fill, by improving the focusing systems of the beam. Furthermore, the present injection chain of LHC will be changed, and the major improvement will be the replacement of *Linac2* with *Linac4*. Several other improvements are foreseen for HL-LHC: innovative superconductive transmission lines, able to carry very high intensity currents, sixteen crab cavities installed next to ATLAS and CMS to obtain a better overlap of the colliding bunches, new collimators and, last but not least, new building facilities around the CERN area.

Together with the accelerator high-luminosity improvements, the ATLAS experiment will be extensively upgraded, in order to sustain the improved running conditions due to the higher luminosity and the expected increased pile-up of additional interactions per bunch crossing, reaching $\mu = 200$. The main upgrades to the detectors are described in the following.

- The current ATLAS ID was designed in order to cope ten years of operations exposed to a peak luminosity of $10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ with a pile-up of 23 interactions per bunch crossing, thus, since it cannot sustain the larger radiation exposure at HL-LHC, it will be replaced by the *Inner Tracker* (ITk) [115, 116]. This is a cylindrical detector composed by four double-sided silicon strip detectors and five layers of silicon pixel sensors in the barrel region, and six pixel disks and seven strip disks in the forward regions. This new configuration will extend the η coverage of the present detector from $|\eta| < 2.5$ to $|\eta| < 4.0$. The improvement that the new detector will bring is a more accurate charged particles tracking, since a higher mean number of precision hits is expected, and a better vertex reconstruction, pile-up jet rejection and jet flavour tagging [117]. With respect to the previous tracker, ITk uses half of the material, reducing in this way the energy loss and multiple scattering effects.
- The upgrades of the calorimeters [118, 119] will mainly consist in replacing their readout electronics with a more suitable one for the conditions of HL-LHC. Both the LAr

and TileCal readout electronics powering system will be replaced due to their limited radiation tolerance and incompatibility with the new trigger system. The new front-end electronics will allow the analog to digital conversion at 40 MHz, and the serialization of data and their transmission over high-speed optical links. Directly in front of the end-cap and forward calorimeters, a new detector, called *High Granularity Timing Detector* (HGTD), will be located. This detector is designed to reduce the noise coming from the large amount of pile-up expected at HL-LHC, providing a time resolution of about 30 ps and covering a region of $2.4 < |\eta| < 4.0$.

- The muon spectrometer will be subjected to a further upgrade for HL-LHC, following the Phase-I upgrade with the installation of the NSWs. In the Phase-II upgrade, the front-end readout and trigger electronics will be replaced for most of the RPCs, TGCs and MDTs in order to be compatible with the higher trigger rates and longer latencies foreseen for the new upgraded *L0 trigger* (which will replace the current L1 trigger). Furthermore, in order to increase the acceptance of the trigger, additional RPC chambers will be installed and some of the inner barrel MDT chambers will be replaced with new ones, equipped with tubes with smaller diameter (*small-diameter MDT*). In the transition region between barrel and end-cap new TGC triplets will be installed, by replacing the present doublets, to further suppress the fake trigger rate from random coincidences [120].
- In order to cope with the increase in luminosity and pile-up, the trigger and data acquisition system will be improved. The trigger will take advantage of the increased granularity of the upgraded calorimeters, will improve the efficiency of the muon-based triggers and will also perform a hardware-based tracking, by taking advantage of the extended coverage of ITk. In order to perform the HL-LHC physics program, the trigger rates are expected to be a factor 10 higher than those of Run 3 [121]. The L0 trigger will accept inputs from the calorimeters and the muon spectrometer operating at rate of 500 kHz and 6 μ s of latency. An upgraded L1 trigger will follow the L0 trigger, reducing the rate to 200 kHz, and it will be followed by an upgraded High Level trigger selection software coping for the upgraded detector condition and improved computing technologies.

The HL-LHC environment, together with the detector upgrades, will allow for a large physics program in the ATLAS experiment, particularly in the Higgs sector, and in the new physics searches. The high-luminosity condition will favor: more precise measurements of the Higgs boson properties, such as masses, widths, couplings with the other particles and self-coupling; precision measurements in the electroweak sector, like vector boson scattering, triboson couplings and rare processes; beyond Standard Model searches, like Supersymmetry, long-lived particles and new resonances; flavour physics studies, like rare decays of b and t quarks and constraint measurements of the CKM matrix.

CHAPTER

3

Object reconstruction in ATLAS

Description of the methods applied in ATLAS to reconstruct and identify the physics objects in the events.

For each bunch-crossing a large amount of particles are originated and can cross several subdetector systems in ATLAS producing there electric signals, indicative of their passage. These particles can come not necessarily from a hard pp collision, but can be due to underlying event²⁰ or extra (pile-up) interactions. Distinctive signatures characterize the different types of particles in an event, and their reconstruction and identification represent the fundamental first step of any physics analysis. This step, known as *object reconstruction* and performed by complex algorithms in order to identify and classify the originating particles, to determine their properties and to get, finally, the full event reconstruction, is the underlying infrastructure of each ATLAS physics analysis. In this chapter, the description of the general procedure adopted by the ATLAS collaboration for the reconstruction of events is documented, focusing on those ‘objects’ which are involved in the analyses described in this thesis: electrons, muons, jets and missing transverse energy.

²⁰The *underlying event* is defined as the aspects of the hadronic interaction which cannot be attributed to the hard scatter process, but rather to the accompanying interactions of the proton remnants.

3.1 Track and vertex reconstruction

The high instantaneous luminosity at LHC results in a large track occupancy in each event. Particle tracking is one of the first task to be performed in the event reconstruction, and a correct track reconstruction is a key element for the precise determination of the *primary vertices*, defined as the points where proton-proton interactions occurred. Because of the environment very dense of particles, tracks and vertices reconstruction is very challenging, and the procedure adopted by ATLAS is described in the following.

3.1.1 Track reconstruction

As soon as they are produced, particles firstly encounter the inner detector (ID), which allows for the reconstruction of the charged particles trajectories in a region of pseudorapidity $|\eta| < 2.5$. Tracking in the ID is performed in three steps [122], specified below.

- **Track finding.** When a charged particle crosses the ID, its passage is followed by the formation of hits in the pixel and SCT detectors. These hits are grouped in clusters built by a dedicated procedure, called *Connected Component Analysis* (CCA) [123], which groups pixels and strips, with measured signals over a certain threshold, and which share edges or corners. To these clusters are associated three-dimensional space-points, which represent the points where the charged particle has passed inside the ID. A set of three space-points composes a *track seed*. Among the measured track seeds, in order to find those which can be real track candidates, some requirements on the transverse momentum p_T , and on the impact parameter of the seeds are set. The number of good track candidates over the total number of seeds represents the purity, which can be further improved by considering a fourth point in the track seed. Once the good candidates have been selected, a combinatorial Kalman filter [124] is applied in order to build the track candidates from the seeds, by incorporating additional space-points, belonging to the remaining pixel and SCT layers, which are compatible with the raw trajectory reconstructed up to this point.
- **Ambiguity solving.** In general, multiple tracks are produced from a given seed, creating ambiguities that need to be solved. In order to understand which track candidates must be dropped, a quality parameter, called *track score*, is defined, as based on the χ^2 of the fitted space-points and on the logarithm of the charged particle transverse momentum, $\log(p_T)$. Good track candidates are requested to have a good χ^2 and a high $\log(p_T)$ value, since bad candidates mostly appear at low momentum. After calculating the track score, an artificial neural network (ANN) is used in order to solve the ambiguities of seeds assigned to multiple track candidates [125].
- **Track fitting.** After having solved the ambiguities, the track fit is performed, which takes into account the multiple scattering and the energy losses in the various detector elements crossed by the track and determines the final track parameters. Surviving ambiguities, like the ones related to clusters of hits which can be associated to more

than one particle, are solved via a second set of neural networks, which use separate trainings for one, two and three particle clusters, while a third group of neural networks is exploited for estimating the uncertainties on the position measurements [122]. Starting from the estimated position of the track candidate, an extension of it inside the TRT is attempted, by using again a Kalman filter for identifying the extension candidates. The TRT hits are then added to the track candidate and the same fit procedure is performed again [126].

3.1.2 Vertex reconstruction

The correct assignment of a generic charged particle track to the corresponding vertex is fundamental in order to reconstruct the full kinematic properties of the hard scatter interaction. The procedure for the primary vertex reconstruction is described in the following.

- **Track finding.** The primary vertex reconstruction uses a subset of all the reconstructed tracks, selected with tight requirements over several parameters, like the transverse momentum and the impact parameter, in order to reduce contamination from fake tracks or from tracks coming from secondary vertices.
- **Primary vertex reconstruction.** After the track selection is done, a seed position of the first vertex is defined, choosing its (x, y) position as the center of the beam spot, and its z -coordinate as the mode of the z -coordinates of tracks at their respective points of closest approach to the reconstructed center of the beam spot. Then an iterative fit is performed, by using tracks and the vertex seed, in order to estimate the best vertex position: after each iteration, the less compatible tracks are down-weighted, and the vertex position estimate repeated with the new weights. Once the vertex position is computed, the tracks incompatible with it are removed from the fit and they are allowed to be used in the determination of another vertex. Vertices are required to have at least two associated tracks. This procedure is then repeated with the remaining tracks of the event until all of the tracks are associated to a vertex in the event or no additional vertex can be found in the remaining set of tracks.
- **Beam spot constraint.** During the fitting procedure of the primary vertex the information of the reconstructed position and width of the beam spot can be used as an additional constraint: tracks which are outside the beam spot can be removed [127].

For which concerns secondary vertices, their reconstruction is particularly important for the identification of b -hadrons, which will be dealt in section 3.4.4. The general procedure for identifying a secondary vertex consists first in finding all the vertices coming from two tracks, and afterwards, in this group, via proper discriminating algorithms, in selecting only those of interest, which are converted into multi-track vertices, by merging those which are close in space [128].

3.2 Electrons and photons

Electrons and positrons, from now on referred just as *electrons*, are reconstructed by using both the information of the calorimeter and of the ID, since, being charged particles, they produce a signal in the tracking detectors. Photons, being neutral, are reconstructed only by using the calorimetry information. Even if not used for the analyses considered in this thesis, photons will be briefly described, together with electrons, since their reconstruction procedures are similar.

The reconstruction of these objects starts from the clusters in the calorimeter, groups of neighboring calorimeter cells, where electrons or photons deposit their energy. The cluster reconstruction was previously performed in ATLAS via a sliding-window algorithm²¹ [130, 131], but it was improved using dynamic, variable-size clusters, called *superclusters*. The advantage of this alternative approach is the possibility to change the size of the cluster according to the necessity, in order to recover energy from bremsstrahlung photons or from electrons from photon conversion ($\gamma \rightarrow e^+e^-$). According to this new definition, an electron is identified as a supercluster in the calorimeter which matches with a reconstructed track. For which concerns the photon, instead, it can be classified either as *converted photon*, if there is a supercluster in the calorimeter which matches a conversion vertex (or vertices), or as *unconverted photon*, if the supercluster does not match an electron track or a conversion vertex. At low $|\eta|$ about the 20% of the photons converts in the ID, while at $|\eta| \approx 2.3$ almost the 65% [132]. The procedure followed in the electron and photon reconstruction, in the region $|\eta| < 2.5$, is described in the sections below.

3.2.1 Topo-cluster reconstruction

The first step consists in the selection of those tracks and clusters that will be used in the reconstruction. The clusters originated by energy deposits measured in topologically connected cells of both the electromagnetic and the hadronic calorimeters are called *topological clusters*, or *topo-clusters*. To each cell of the calorimeter can be assigned a significance, $\varsigma_{\text{cell}}^{\text{EM}}$, which is computed as:

$$\varsigma_{\text{cell}}^{\text{EM}} = \left| \frac{E_{\text{cell}}^{\text{EM}}}{\sigma_{\text{noise, cell}}^{\text{EM}}} \right|, \quad (3.1)$$

where $|E_{\text{cell}}^{\text{EM}}|$ is the energy deposited in the cell at the EM scale²² and $\sigma_{\text{noise, cell}}^{\text{EM}}$ is the expected cell noise, which includes the known electronic noise and an estimate of the pile-up noise corresponding to the average instantaneous luminosity expected for Run 2. The reconstruction starts from those cells with $\varsigma_{\text{cell}}^{\text{EM}} > 4$ in order to form *proto-clusters*, after applying an appropriate noise threshold and excluding cells from the presampler and the L1. Afterwards, to the

²¹The *sliding-window* algorithm is based on summing cells within a fixed-size rectangular window. The position of the window is adjusted so that the transverse energy contained in the window is a local maximum [129].

²²The EM scale is the basic signal scale accounting correctly for the energy deposited in the calorimeter by electromagnetic showers [132].

proto-cluster are included also the neighbouring cells with $\zeta_{\text{cell}}^{\text{EM}} > 2$, and each neighbouring cell passing this threshold becomes a seed cell in the next iteration, thus enlarging the proto-cluster. If two proto-clusters contain the same cell, satisfying the 2σ noise threshold, then they are merged in a single proto-cluster. Once all the neighbouring cells passing the 2σ threshold are collected, than a last set of neighbouring cells, independently on their energy, are added to the proto-cluster. In a proto-cluster a local maximum is defined as a cell where the energy $|E_{\text{cell}}^{\text{EM}}| > 500 \text{ MeV}$. If there are more than one local maximum, and such maxima have at least four neighbours and none of them have a signal larger than that of the local maxima themselves, then the proto-cluster can be divided in different clusters [133].

Electron and photon reconstruction can start from these topo-clusters, only using the information from the EM calorimeter, except in the transition region $1.37 < |\eta| < 1.63$, where the non-negligible amount of energy released by electrons and photons in the presampler and the scintillator between the calorimeter cryostats is also added. The fraction of energy which derives from the EM calorimeter is indicated as f_{EM} and only clusters with an EM energy greater than 400 MeV are considered from now on in the reconstruction [132].

3.2.2 Track reconstruction, track-cluster matching, and photon conversion reconstruction

In ATLAS the track reconstruction of electrons and photons starts from EM clusters which satisfy some loose shower shape requirements regarding hadronic leakage and $|\eta|$ energy distribution. These sets of clusters are used to create *Regions of Interest* (ROIs), in which a *standard track pattern* recognition [134] is initially performed. If the pattern recognition fails for a silicon track seed within the ROI, then another modified pattern reconstruction algorithm is used, based on a Kalman filter [124]. This algorithm allows up to 30% of energy loss in each material intersection. Then, track candidates are fitted using the pion or electron hypothesis with the global χ^2 fitter [135], allowing for additional energy loss in case the standard track fit fails. If a track has no associated hits in the silicon detector, it is discarded from the procedure in order to reject photon conversions, while tracks with at least four silicon hits loosely matched to EM clusters are refitted with a *Gaussian Sum Filter* (GSF) fitter [136], which is a non-linear generalization of the Kalman filter, suitable for an improved track parameter estimation [133].

3.2.2.1 Track matching for electrons

The refitted tracks can be matched to the EM topo-clusters previously described by using tight requirements in η and ϕ :

$$|\Delta\eta| < 0.05 \quad \text{and} \quad -0.10 < q \cdot (\phi_{\text{track}} - \phi_{\text{clus}}) < 0.05, \quad (3.2)$$

where q is referred to the reconstructed charge of the track. The asymmetric requirement is because tracks sometimes miss some energy from radiated photons that clusters measure. If more than one track is matching to the same cluster, they are ranked according to the following criteria:

- tracks with hits in the pixel detectors are better ranked than those with hits in the SCT;
- tracks with a smaller angular distance ΔR ²³ and matching to the cluster in the second layer of the calorimeter are better ranked. In order to compute ΔR the extrapolation of the tracks to the calorimeter is done in two ways: using the track momentum information rescaled to the cluster energy and without applying the rescaling. If the differences in ΔR computed with both the extrapolations are small, the track with more pixel hits is better ranked.

According to these criteria, the highest-ranked track is used to define the reconstructed electron properties [132].

3.2.2.2 Photon conversion

For photon candidates, it is expected to observe a cluster in the calorimeter without any associated track, in case of no photon conversion, or with two tracks, in case of the photon conversion in an electron-positron pair. Both tracks with silicon hits (Si-tracks) and tracks reconstructed only in the TRT (TRT-tracks) are used for the conversion reconstruction. Two-track conversion vertices can derive from two tracks coming from oppositely charged particles which match to a vertex consistent with a massless particle (*two-tracks vertices*), or from a single track which doesn't have any hit in the innermost sensitive layers (*single-track vertices*). In both cases, in order to increase the conversion photon reconstruction purity, the tracks used for matching the conversion vertex need to be identified as electrons. The conversion vertices are then matched to the EM topo-clusters. If there are multiple conversion vertices matching the same EM topo-cluster, those with the smallest conversion radius²⁴ and coming from tracks with hits in the silicon detector are preferred [133].

3.2.3 Supercluster reconstruction

After having identified all the electron and photon topo-clusters, superclusters can be built. In both cases the procedure consists in identifying, among the topo-clusters, those which can be electron/photon seed supercluster candidates and the ones close to the seed, called *satellite* topo-clusters. The procedure for building a supercluster is described below.

- From an initial list of EM topo-clusters, sorted by descending E_T , each element, starting from the most energetic one, is tested as seed for the supercluster. The requirement for being considered as a seed supercluster is, for electrons, $E_T > 1$ GeV and a matching to a track with at least four hits in the silicon detector. For photons only $E_T > 1.5$ GeV is requested.

²³Given two points of coordinates (η_1, ϕ_1) and (η_2, ϕ_2) , the *angular distance* ΔR is defined as $\Delta R = \sqrt{(\eta_1 - \eta_2)^2 + (\phi_1 - \phi_2)^2}$.

²⁴The *conversion radius* is the distance covered by the photon between its production and conversion points.

- If a cluster has been recognized as a supercluster seed, the algorithm continues by searching the satellite clusters. For both electrons and photons, a cluster is considered a satellite if it falls within a window of $\Delta\eta \times \Delta\phi = 0.075 \times 0.125$ around the seed barycentre, as pictorially illustrated in Figure 3.1, since these cases tend to represent secondary EM showers originating from the same initial electron or photon. Furthermore, electrons are also considered satellites if they fall in a wider window ($\Delta\eta \times \Delta\phi = 0.075 \times 0.300$) around the seed barycentre and its best-matched track is also the best-matched track for the seed. For photons with conversion vertices made up of tracks with hits in the silicon detector, a cluster is added as a satellite one if its best-matched (electron) track belongs to the conversion vertex matched to the seed cluster.
- Finally, an algorithm assigns, to the seed and its satellites forming the supercluster, the relative calorimeter cells. Only cells from the pre-sampler and from the first three layers of the LAr calorimeter are considered, except in the transition region $1.4 < |\eta| < 1.6$.

The supercluster sensitivity to pile-up noise is limited by considering topo-clusters with a maximal width in η of 0.075, in the barrel, and 0.125, in the end-caps [132].

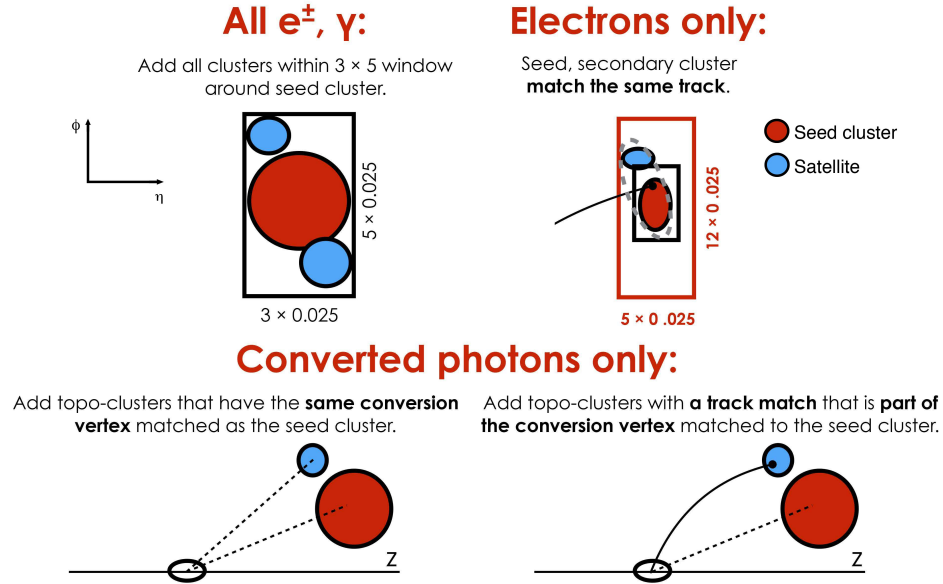


Figure 3.1: Diagram of the superclustering algorithm for electrons and photons. Seed clusters are shown in red, satellite clusters in blue [132].

3.2.3.1 Creation of electron and photon candidates

Once the electron and photon superclusters are built, an initial energy calibration and position correction is applied to them. Similarly as done for the track matching with the EM topo-clusters, tracks and conversion vertices are matched to the electron and photon superclusters respectively. Since the electron and photon supercluster building procedures are independent,

it can happen that the same supercluster is classified as candidate for both the categories. In these cases both an electron and a photon object are created and such cases are labelled as ambiguous, allowing the final classification of the objects to be determined taking into account the specific requirements of each analysis. After the track/conversion vertex matching, the energy calibration [137] is repeated. Finally, the last step consists in creating shower shape and other discriminating variables that are used for the electron and photon identification. These variables are summarized in Table 3.1 [132].

3.2.4 Electron and photon identification

The candidates for electrons and photons so far described must pass further selection criteria, aimed to improve the purity of the finally identified electron and photon objects.

3.2.4.1 Electron identification

A set of quantities measured in the inner detector and in the calorimeter are suitable to discriminate prompt isolated electrons from electrons produced in heavy-flavour hadron decays, from photon conversions and from energy deposit of hadronic jets. These variables can be grouped into properties of the primary electron track, the lateral and longitudinal development of the electromagnetic shower, and the spatial compatibility of the primary electron track with the reconstructed cluster.

Starting from these variables, a Likelihood-based (LH) discriminant is built, in terms of the distributions of the reconstructed electrons to originate from signal or background. Signal *probability density functions* were derived from either $Z \rightarrow ee$ (if $E_T > 15$ GeV) or $J/\psi \rightarrow ee$ (if $E_T < 15$ GeV) data events (collected in 2015-2016), after applying the *tag-and-probe* [138] method. The electron identification has typically three different levels, or *working points* (WPs): *Loose*, *Medium* and *Tight*, according to an increasingly stringent selection and therefore with a higher background rejection. These three working points are built using the same set of variables to define the LH discriminant, but the different selections applied are such that the electrons classified as *Tight* are a subset of the ones selected as *Medium*, in turn being a subset of the *Loose* ones.

The average identification efficiencies for *Loose*, *Medium* and *Tight* selections are 93%, 88% and 80% respectively, and gradually increase as the E_T increases. The background rejection in *Medium* and *Tight* electrons selections is a factor of 2.0 and 3.5 respectively, in the range $20 < E_T < 50$ GeV. This particular trend of the efficiencies is well illustrated in Figure 3.2, where in (a) is reported their behaviour in terms of E_T , showing how the efficiency generally increases with E_T for all the selections, except for very low E_T , where there is a rise in the trend due to some unknown mismodelling in the variables used in the LH discriminant [132].

3.2.4.2 Photon identification

Similarly to electrons, photon identification is done using different selection criteria by exploiting the discriminating calorimetric variables of Table 3.1. These variables are particularly important in rejecting photons from π^0 decay, which, being highly collimated, look like single

Category	Description	Name	Usage
Hadronic leakage	Ratio of E_T in the first layer of the hadronic calorimeter to E_T of the EM cluster (used over the ranges $ \eta < 0.8$ and $ \eta > 1.37$)	R_{had_1}	e/γ
	Ratio of E_T in the hadronic calorimeter to E_T of the EM cluster (used over the range $0.8 < \eta < 1.37$)	R_{had}	e/γ
EM third layer	Ratio of the energy in the third layer to the total energy in the EM calorimeter	f_3	e
EM second layer	Ratio of the sum of the energies of the cells contained in a $3 \times 7 \eta \times \phi$ rectangle (measured in cell units) to the sum of the cell energies in a 7×7 rectangle, both centred around the most energetic cell	R_η	e/γ
	Lateral shower width, $\sqrt{(\sum E_i \eta_i^2)/(\sum E_i) - ((\sum E_i \eta_i)/(\sum E_i))^2}$, where E_i is the energy and η_i is the pseudorapidity of cell i and the sum is calculated within a window of 3×5 cells	w_{η_2}	e/γ
	Ratio of the sum of the energies of the cells contained in a $3 \times 3 \eta \times \phi$ rectangle (measured in cell units) to the sum of the cell energies in a 3×7 rectangle, both centred around the most energetic cell	R_ϕ	e/γ
EM first layer	Total lateral shower width, $\sqrt{(\sum E_i (i - i_{\text{max}})^2)/(\sum E_i)}$, where i runs over all cells in a window of $\Delta\eta \approx 0.0625$ and i_{max} is the index of the highest-energy cell	$w_{s \text{ tot}}$	e/γ
	Lateral shower width, $\sqrt{(\sum E_i (i - i_{\text{max}})^2)/(\sum E_i)}$, where i runs over all cells in a window of 3 cells around the highest-energy cell	$w_{s 3}$	γ
	Energy fraction outside core of three central cells, within seven cells	f_{side}	γ
	Difference between the energy of the cell associated with the second maximum, and the energy reconstructed in the cell with the smallest value found between the first and second maxima	ΔE_s	γ
	Ratio of the energy difference between the maximum energy deposit and the energy deposit in a secondary maximum in the cluster to the sum of these energies	E_{ratio}	e/γ
Track conditions	Ratio of the energy measured in the first layer of the electromagnetic calorimeter to the total energy of the EM cluster	f_1	e/γ
	Number of hits in the innermost pixel layer	$n_{\text{innermost}}$	e
	Number of hits in the pixel detector	n_{Pixel}	e
	Total number of hits in the pixel and SCT detectors	n_{Si}	e
	Transverse impact parameter relative to the beam-line	d_0	e
	Significance of transverse impact parameter defined as the ratio of d_0 to its uncertainty	$ d_0/\sigma(d_0) $	e
	Momentum lost by the track between the perigee and the last measurement point divided by the momentum at perigee	$\Delta p/p$	e
	Likelihood probability based on transition radiation in the TRT	eProbabilityHT	e
	$\Delta\eta$ between the cluster position in the first layer of the EM calorimeter and the extrapolated track	$\Delta\eta_1$	e
	$\Delta\phi$ between the cluster position in the second layer of the EM calorimeter and the momentum-rescaled track, extrapolated from the perigee, times the charge q	$\Delta\phi_{\text{res}}$	e
Track-cluster matching	Ratio of the cluster energy to the measured track momentum	E/p	e

Table 3.1: List of the discriminating variables used for electron and photon identification. The ‘Usage’ column indicates if the variable is used for the identification of electrons, photons, or both [132].

photons. Also in this case, three different working points are considered, with increasingly tighter selections from Loose and Medium (used in the trigger) to Tight (for the primary identification selection). Because the reconstruction of photons in the ATLAS trigger does not

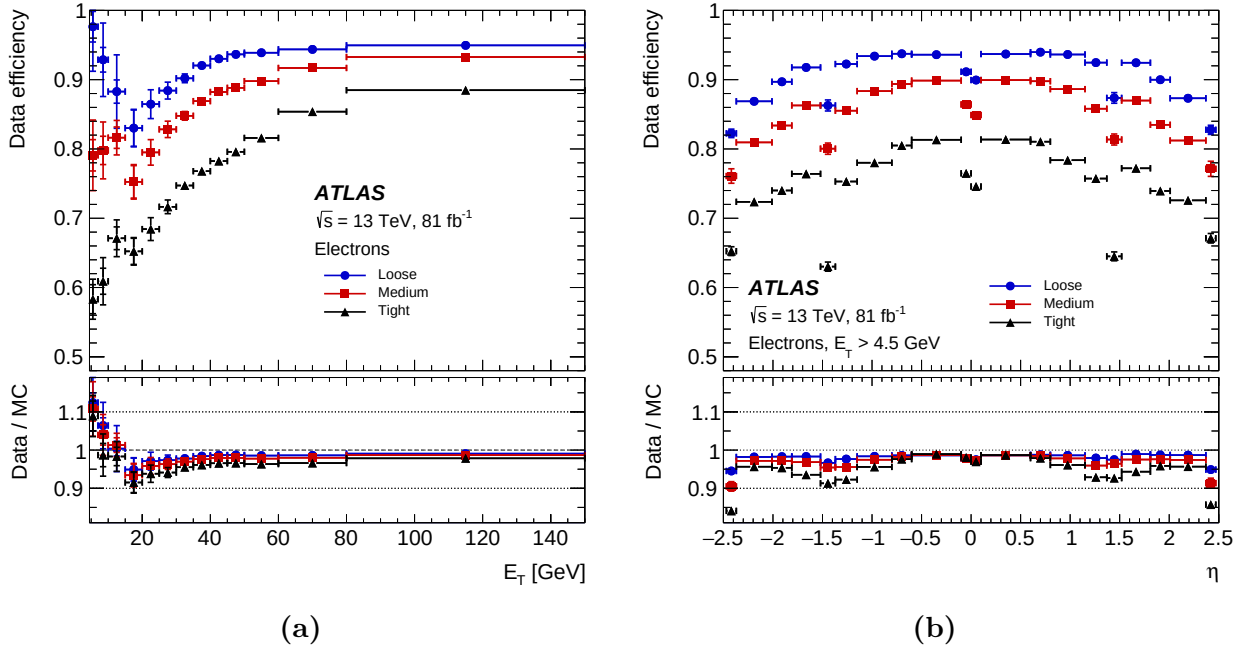


Figure 3.2: The electron identification efficiency as function of (a) E_T and (b) η , for $Z \rightarrow ee$ events in data, for the Loose, Medium and Tight working points [132]. For both plots, the bottom panel shows the data-to-simulation (MC) ratios.

differentiate between converted and unconverted photons, the Loose and Medium identification criteria are the same for the two types of photons, while the Tight identification is performed separately for converted and unconverted photons.

In order to study the Tight photon identification efficiency, three different measurements are performed using different data samples: inclusive photon production, photon radiation from $Z \rightarrow \ell\ell\gamma$, and electrons from $Z \rightarrow ee$, with a method transforming the electron shower shapes to resemble the photon shower shapes. The resulting efficiencies are larger than 80% for $E_T > 30$ GeV photons, reaching values of about 92% and 98% for unconverted and converted photons respectively, at $E_T \sim 70$ GeV and above, as shown in Figure 3.3 [132].

3.2.5 Electron and photon isolation

In addition to the quality requirements discussed above, many analyses require electrons to fulfill isolation requirements, in order to enhance the discrimination between signal and background. The isolation can be quantified from the tracks of nearby charged particles or from energy deposits in the calorimeters. The two classes of isolation requirements are described below.

- **Calorimetric isolation.** The calorimetric isolation variable, E_T^{coneXX} , is obtained by summing the transverse energy of those topo-clusters whose barycentre falls within a cone centered around the barycentre of the electron/photon cluster, and by subtracting

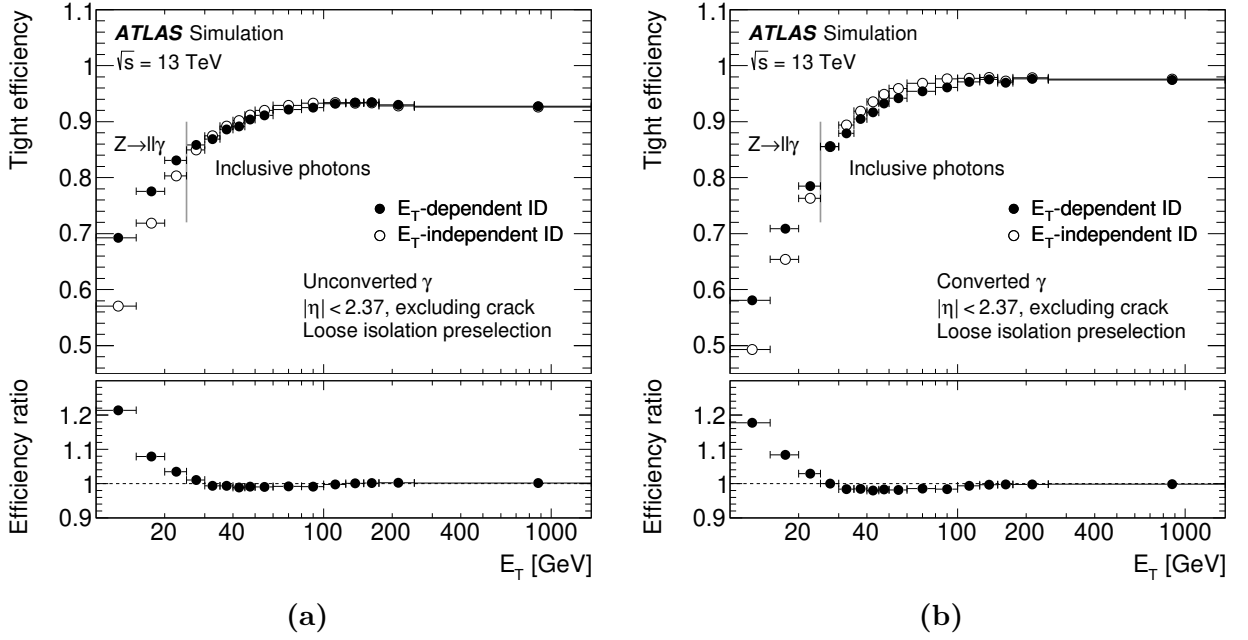


Figure 3.3: Tight photon identification efficiency as function of the photon E_T for (a) unconverted and (b) converted photons. Signal events derive from samples of $Z \rightarrow \ell\ell\gamma$, for photons with $E_T < 25$ GeV, and inclusive-photon production, for photons with $E_T > 25$ GeV. Two different selections are compared, based on dependence of E_T and a Loose isolation requirement is applied at preselection. The lower plot in each figures shows the ratio between the efficiencies in the two selections [132].

the energy of the EM particle (the core) and some terms related to pile-up events which overlap inside the cluster. The ‘XX’ is referred to the size of the employed cone, $\Delta R = XX/100$. A cone size $\Delta R = 0.2$ is used for the electron working points whereas cone sizes $\Delta R = 0.2$ and 0.4 are used for photon working points [132].

- **Track isolation.** Similarly, the track isolation variable, p_T^{coneXX} , is computed by summing the transverse momentum of those selected tracks which fall in a cone centered around the electron track or photon cluster direction. For electrons, especially if produced by the decay of heavy particles, the track can be surrounded by other tracks, therefore the isolation variable is defined by a variable size (ΔR) cone, therefore indicated as $p_T^{\text{varconeXX}}$, with respect to the momentum of the track:

$$\Delta R = \min \left(\frac{10}{p_T [\text{GeV}]}, \Delta R_{\text{max}} \right), \quad (3.3)$$

where ΔR_{max} is the maximum size of the cone (typically 0.2) [132].

The final implementation of the isolation criteria depends on the specific analysis. For electrons the three different isolation working points defined in ATLAS are reported in Table 3.2. They are chosen in two different ways, either targeting a fixed value of efficiency (*Gradient*) or with

fixed selections on the calorimeter and/or track isolation variables (*HighPtCaloOnly*, *Loose*, *Tight*).

Similarly, for photon isolation three different working points using fixed selections are defined (*Loose*, *Tight* and *TightCaloOnly*), and they are explicitly reported in Table 3.3 [132].

Working point	Calorimeter isolation	Track isolation
Gradient	$\varepsilon = 0.1143 \times p_T + 92.14\%$ (with E_T^{cone20})	$\varepsilon = 0.1143 \times p_T + 92.14\%$ (with $p_T^{\text{varcone20}}$)
HighPtCaloOnly	$E_T^{\text{cone20}} < \max(0.015 \times p_T, 3.5 \text{ GeV})$	-
Loose	$E_T^{\text{cone20}}/p_T < 0.20$	$p_T^{\text{varcone20}}/p_T < 0.15$
Tight	$E_T^{\text{cone20}}/p_T < 0.06$	$p_T^{\text{varcone20}}/p_T < 0.06$

Table 3.2: Definition of the electron isolation working points and isolation efficiency ε [132].

Working point	Calorimeter isolation	Track isolation
Loose	$E_T^{\text{cone20}} < 0.065 \times E_T$	$p_T^{\text{cone20}}/E_T < 0.05$
Tight	$E_T^{\text{cone20}} < 0.022 \times E_T + 2.45 \text{ GeV}$	$p_T^{\text{cone20}}/E_T < 0.05$
TightCaloOnly	$E_T^{\text{cone20}} < 0.022 \times E_T + 2.45 \text{ GeV}$	-

Table 3.3: Definition of the photon isolation working points [132].

3.3 Muons

Muons are reconstructed using several information coming mainly from the muon spectrometer and the inner detector, but the information coming from calorimeters is also included. In the following paragraphs all steps of the muon reconstruction will be described.

3.3.1 Muon reconstruction

The first step of the muon reconstruction consists in building short straight-line local track segments from the pattern of hits in an individual MS station. Muon track candidates are then built by combining hits from segments in different layers, and a combinatorial search of the best candidates is performed starting from the middle layer segment as seed. The search for segments is then extended to the outer and inner layers. The selection of segments consists in applying several criteria based on the fit quality and the hit multiplicity, while the matching between segments is made using their relative position and angles. The hits associated with each track candidate are fitted using a global χ^2 fit, which has to satisfy some requirements in order to accept the track. Those hits associated to large χ^2 contribution are removed from the track and the fit procedure is repeated. A hit recovery process is then

performed, by looking for additional hits which are compatible with the candidate trajectory and, if they are found, the track candidate is refit.

After the reconstruction in the MS, according to the type of information that is used, different classes of muon tracks are defined in ATLAS, as described below.

- **Combined (CB) muons.** Tracks from the ID and from the MS can be matched and combined via a global fit, which uses the hits from both ID and MS subdetectors. Muons are reconstructed by using an *outside-in* strategy, thus reconstructing first the track in the MS and then extrapolating it to the ID track. Nevertheless, an *inside-out* strategy is also used as a complementary approach.
- **Segment-tagged (ST) muons.** If an ID track extrapolated to the MS matches at least one reconstructed MS segment, in the MDT or in the CSC chambers, it is classified as *segmented-tagged* (ST) muon. These tracks are used to recover muons crossing only one layer of the MS, either because of their low momentum or of the reduced acceptance of the crossed MS region.
- **Calorimeter-tagged (CT) muons.** Similarly to what done for the ST muons, if an ID track matches an energy deposit in the calorimeter consistent with a minimum-ionizing particle (MIP), this is classified as *calorimeter-tagged* (CT) muon. This muon category is characterized by the lowest hit purity, but it allows to recover the acceptance in the not instrumented regions of the MS. The identification criteria for CT muons are optimized for $|\eta| < 0.1$ and $15 < p_T < 100$ GeV tracks.
- **Extrapolated (ME) or standalone (SA) muons.** If a MS track cannot be matched with any ID information, it can be extrapolated to the beam line, and thus included in a new class of tracks called *muon spectrometer extrapolated* (ME) or *standalone* (SA) muons. The extrapolation takes also into account the estimated energy loss and multiple scattering in the calorimeters. The muons considered have to cross at least two layers of the MS chambers (three in the forward regions) and they allow to extend the acceptance region in the range $2.5 < |\eta| < 2.7$, not covered by the ID [139].

3.3.2 Muon identification

After the reconstruction, the candidate muons are classified on the basis of quality criteria taking into account the specific requirements of the analyses. As done for electrons and photons, different identification categories (or working points) are defined also for muons, with different selections exploiting variables which are, in case of CB tracks:

- q/p significance, defined as the absolute value of the difference between the ratio of the charge and momentum of the muons measured in the ID and MS divided by the sum in quadrature of the corresponding uncertainties;
- ρ' , defined as the absolute value of the difference between the transverse momentum measurements in the ID and MS divided by the p_T of the combined track;

- the normalised χ^2 of the combined track fit.

Four muon identification selections have been defined to adapt to different physical analysis requirements. These selections are *Loose*, *Medium*, *Tight* and *High- p_T* [139]. In general, the Loose working point is mainly suited for Higgs-searches in four muons final states [140], the Medium for several analyses, the Tight for analyses limited by background of non-prompt muons. The High- p_T selection is instead optimised for searches for high-mass Z' and W' resonances [141, 142]. A detailed description of the four working points follows.

- **Medium.** This is the default working point for muons in ATLAS and uses only CB and SA tracks, with at least three hits in at least two MDT layers, except for those in the $|\eta| < 0.1$ region, where it is allowed one MDT layer but no more than one MDT hole layer²⁵. In case of CB muons, a loose selection on the compatibility between the ID and MS momentum measurements is applied, in order to suppress the contamination of muons coming from in-flight charged hadron decays. The requested significance is $q/p < 7$.
- **Loose.** The Loose selection is the same of the Medium one, but less stringent, by using all the muon track types, and it is designed to maximize the reconstruction efficiency while providing a good quality of the muon tracks. All the CB and SA tracks which satisfy the Medium requirement are considered in the Loose selection, and CT and ST muons are also allowed in the $|\eta| < 0.1$ range. In the region $|\eta| < 2.5$, about 97.5% of the Loose muons are CB, approximately 1.5% are CT, and the remaining 1% are reconstructed as ST muons.
- **Tight.** This selection considers only CB muons which have hits in at least two MS stations and which have passed the Medium selection criteria. Furthermore, the normalised χ^2 of the combined track fit has to be less than 8, in order to reject those tracks coming from hadron decays in flight. Moreover, to ensure a stronger rejection of the background for muons with momenta lower than 20 GeV, where the misidentification probability is higher, selection requests are also applied on the ρ' and q/p variables as functions of the p_T .
- **High- p_T .** Muons with high- p_T are characterized by almost straight trajectories. The *High- p_T* selection aims to maximize the momentum resolution for tracks with p_T higher than 100 GeV, by considering only CB muons which have passed the Medium requirements and with at least three hits in three stations of the muon spectrometer. Furthermore those regions where the alignment of the MS is not optimal are excluded [139].

In Table 3.4 are reported the reconstruction efficiencies of the four working points, for signal and background muons, obtained in a simulation of $t\bar{t}$ events, separating low ($4 < p_T < 20$ GeV) and high ($20 < p_T < 100$ GeV) transverse muon momenta [139].

²⁵For *hole layer* or *hole station* is meant a layer supposed to be hit, because it is in the middle of a track fit, but it isn't.

Selection	$4 < p_T[\text{GeV}] < 20$		$20 < p_T[\text{GeV}] < 100$	
	$\varepsilon_\mu^{MC} [\%]$	$\varepsilon_{had}^{MC} [\%]$	$\varepsilon_\mu^{MC} [\%]$	$\varepsilon_{had}^{MC} [\%]$
Loose	96.7	0.53	98.1	0.76
Medium	95.5	0.38	96.1	0.17
Tight	89.9	0.19	91.8	0.11
High- p_T	78.1	0.26	80.4	0.13

Table 3.4: Efficiency for prompt muons from W -boson decays (ε_μ^{MC}) and hadrons decaying in-flight and misidentified as prompt muons (ε_{had}^{MC}), computed using a $t\bar{t}$ MC sample [139].

The muon reconstruction efficiencies for the Loose, Medium and Tight identification working points, as function of the muon pseudorapidity for muons with $p_T > 15$ GeV, are reported in Figure 3.4 in $Z \rightarrow \mu\mu$ events, based on the full pp collision data collected during Run 2 of LHC.

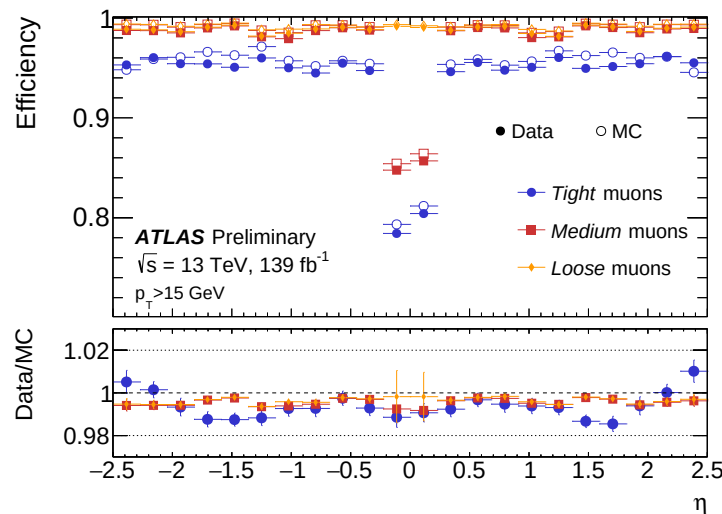


Figure 3.4: Muon reconstruction efficiencies for the Loose, Medium and Tight identification working points as function of the muon pseudorapidity for muons with $p_T > 15$ GeV, in $Z \rightarrow \mu\mu$ events. Comparison is between collision data (full circles) and MC simulations (empty circles). In the panel below is reported the ratio between efficiencies in data and in MC, whose errors are the quadratic sum of statistical and systematic uncertainties [143].

3.3.3 Muon isolation

As discussed for the electrons, many analyses require muons to fulfill isolation requirements and, based on the processes which originate these particles, the isolation features can be different. Muons originating from the decay of Z , W or H bosons, are often isolated, whilst

those produced from semileptonic decays are generally embedded inside jets. The study of the detector activity around a muon candidate is thus needed for improving the background rejection in physics analyses. Similarly to electrons, the isolation can be quantified analyzing the calorimetry activity and the track features.

- **Calorimetry isolation.** For the calorimetry information, the key-variable is the $E_T^{\text{topocone20}}$, which is defined as the sum of the transverse energy of the topo-clusters in a cone of size $\Delta R = 0.2$ around the muon, after having properly subtracted the energy contribution of the muon itself and the pile-up effects.
- **Track isolation.** The key-variable defined for the track isolation criteria is $p_T^{\text{varcone30}}$, which is the scalar sum of the transverse momenta of the tracks with $p_T > 1$ GeV inside a cone of size $\Delta R = \min(10 \text{ GeV}/p_T^\mu, 0.3)$ around the muon transverse momentum p_T^μ , excluding the muon track itself. The size of the cone is p_T -dependent.

The variables so far described, divided by the transverse momentum of the muon, define seven isolation working points, with different selections and efficiencies, according to the main physics analysis requests. These isolation working points are listed in Table 3.5 [139], with the corresponding discriminating variables used and the criteria applied.

Isolation WP	Discriminating variable(s)	Definition
LooseTrackOnly	$p_T^{\text{varcone30}}/p_T^\mu$	$\varepsilon = 99\%$ in η and p_T
Loose	$p_T^{\text{varcone30}}/p_T^\mu, E_T^{\text{topocone20}}/p_T^\mu$	$\varepsilon = 99\%$ in η and p_T
Tight	$p_T^{\text{varcone30}}/p_T^\mu, E_T^{\text{topocone20}}/p_T^\mu$	$\varepsilon = 96\%$ in η and p_T
Gradient	$p_T^{\text{varcone30}}/p_T^\mu, E_T^{\text{topocone20}}/p_T^\mu$	$\varepsilon \geq 90$ (99)% at 25(60) GeV
GradientLoose	$p_T^{\text{varcone30}}/p_T^\mu, E_T^{\text{topocone20}}/p_T^\mu$	$\varepsilon \geq 95$ (99)% at 25(60) GeV
FixedCutTightTrackOnly	$p_T^{\text{varcone30}}/p_T^\mu$	$p_T^{\text{varcone30}}/p_T^\mu < 0.06$
FixedCutLoose	$p_T^{\text{varcone30}}/p_T^\mu, E_T^{\text{topocone20}}/p_T^\mu$	$p_T^{\text{varcone30}}/p_T^\mu < 0.15,$ $E_T^{\text{topocone20}}/p_T^\mu < 0.30$

Table 3.5: Definition of the seven isolation working points in terms of the discriminating variables used (second column) and the selection criteria used (third column) [139].

3.4 Jets

The hadronization of the colored particles emerging from the interaction point produces *jets* of colorless particles, which are among the main objects produced during the hard collision in LHC. They are reconstructed from multiple tracks in the inner detector and energy deposits in the hadronic calorimeter.

3.4.1 Jet reconstruction

Following a similar procedure to the one discussed in the electron and photon case, but after applying different thresholds, topo-clusters are reconstructed in the calorimeter. For each cluster the relevant variables needed for the jet definition and the subsequent reconstruction are the sum of the energies of the cells in a cluster and the cluster direction with respect to the interaction point. The standard ATLAS jet definition algorithm, whose task is to merge the clusters in jets, is the anti- k_t algorithm [144]. It associates the clusters within a conic area of radius R , whose standard value adopted by ATLAS is 0.4.

Topo-cluster information is matched together with the ID tracks by the *particle-flow* algorithm [145], which improves the reconstruction of the hadronic jets and the additional soft hadronic processes (fundamental estimation in the computation of the missing transverse energy, as explained in section 3.5), by building the candidates for the final reconstruction. The algorithm firstly performs a cell-based *energy subtraction* procedure, which consists in removing overlaps between the momentum and the energy measurements made by the ID and the calorimeter respectively. Afterwards, it combines both the unmodified topo-clusters and the corrected ones with tracks, providing a list of candidates. Briefly, the algorithm starts from finding the matching between selected tracks and topo-clusters, and from them it evaluates the expected energy deposited by the particle, computed by the topo-cluster position and the track momentum, by taking into account that more than one topo-clusters can be associated to a single particle. To each track/topo-cluster pair, the algorithm assigns a probability that the particle energy is related to more topo-clusters, and it decides if any additional topo-cluster needs to be added to the track/topo-cluster system, in order to reconstruct the full energy of the hadronic shower. A cell by cell energy subtraction is performed and if the remaining energy is consistent with the energy fluctuations in the shower for a single particle, this residual energy is removed [145].

3.4.2 Jet energy scale calibration

The *Jet Energy Scale* (JES) calibration aims to determine, from the jet energy measured in the detector, the energy at particle-level. The different steps followed in ATLAS for the JES calibration are schematically reported in Figure 3.5, and consist in correcting the measured four-momentum of the jets, by scaling their mass, energy and transverse momentum [146]. Following the scheme in figure, the *EM-scale jets* represents the stage described in the previous paragraph, where the jets reconstructed by the topo-clusters were calibrated at the Electromagnetic (EM) scale. The first applied correction is the *Origin correction*, which consists in re-calculating the jets four-momentum adding the constraint that the jet direction points towards the primary vertex instead of the center of the detector, while keeping the jet energy constant. This correction improves the jet η resolution: from 0.06 to 0.045 for $p_T = 20$ GeV jets, and from 0.03 to 0.006 for $p_T > 200$ GeV. Afterwards the *pile-up correction* follows, which removes the excess of energy due to in-time and out-of-time pile-up²⁶. It

²⁶The pile-up events can be distinguished in *in-time* and *out-of-time*. The first are related to additional pp interactions in the bunch-crossing, while the second are events coming from the previous or the following

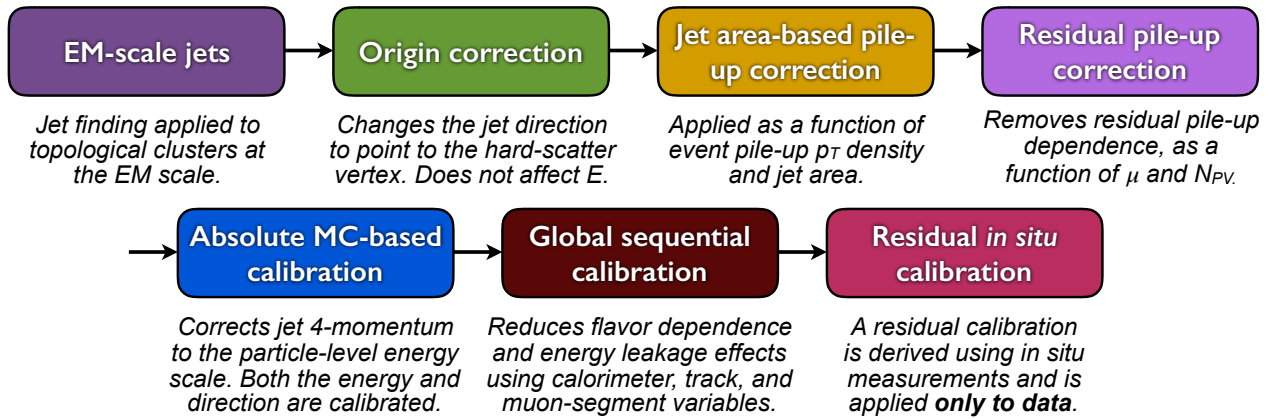


Figure 3.5: Calibration steps for jets. Other than the origin correction, each stage of the calibration is applied to the four-momentum of the jet [146].

consists in a first *area-based* method [147], for which the pile-up contribution is calculated from the density distribution of p_T around the jet, according to its area, and afterwards subtracted, and in a second *residual* correction, derived from MC simulations. The next step is the *absolute MC-based* energy scale and η calibration, for which the reconstructed jet four-momentum is corrected to the particle-level energy scale, as derived using truth jets in dijet MC events, by taking into account biases in the η jet reconstruction. These biases are mainly due to the transition regions between different calorimeter technologies and granularity, which generally provokes a lower energy response due to absorption and undetected particles in these regions. The energy reconstruction and related uncertainties are further improved via a *Global sequential* calibration, by considering other calorimeter, MS and track-based variables. Finally, in order to take into account all the differences in the jet response between data and MC, due to imperfections in the simulation modelling of the detector behaviour, a *residual in situ* calibration is performed. These differences in data and MC are quantified by balancing the p_T of the jets against other better-measured objects, used as reference, e.g. Z -bosons and calibrated jets. In general, four calibrations are performed: an η -intercalibration, which corrects the response of forward jets, and three *in-situ* calibrations which correct the response of central jets [146].

3.4.3 Pile-up jets discrimination

As already described, pile-up contribution can be taken into account and subtracted on average in the jet energy estimate, using an area based method. This assumes an uniform distribution of the pile-up events in the calorimeter, however local fluctuations in the pile-up distribution can lead to additional jets. This additional jets are classified in: *QCD pile-up jets*, where particles close to the jet system are mainly originated by a single QCD process in a single pile-up interaction, and *stochastic pile-up jets*, combining particles from different

bunch-crossing, but falling in the triggered event of the present bunch-crossing.

interactions [148].

The stochastic pile-up jets can be quantified by the *Jet Vertex Fraction* (JVT) variable, which is defined as the scalar sum of the transverse momenta of the tracks associated with a jet and originated in the hard collision vertex, divided by the sum of all the associated tracks momenta:

$$\text{JVT} = \frac{\sum_k p_T^{\text{trk}_k}(PV_0)}{\sum_\ell p_T^{\text{trk}_\ell}(PV_0) + p_T^{PU}}, \quad \text{with } p_T^{PU} = \sum_{n \geq 1} \sum_\ell p_T^{\text{trk}_\ell}(PV_n), \quad (3.4)$$

where PV_0 is the primary vertex of the hard collision, while PV_n , with $n \geq 1$ are the primary vertices for the pile-up interactions in the same bunch-crossing, and p_T^{PU} represents the scalar sum of the transverse momenta of the associated tracks that originate from any of the pile-up interactions. This variable, which assumes values between 0 and 1, is particularly useful in discriminating pile-up jets when imposing a lower selection on its value [149]. Directly connected with the JVF is the *corrJVF*, which is similar to the JVF but takes into account the linear increase of the average p_T^{PU} with the the total number of pile-up tracks in the event n_{trk}^{PU} :

$$\text{corrJVT} = \frac{\sum_k p_T^{\text{trk}_k}(PV_0)}{\sum_\ell p_T^{\text{trk}_\ell}(PV_0) + \frac{p_T^{PU}}{k n_{\text{trk}}^{PU}}}, \quad (3.5)$$

where $k = 0.01$. Another commonly used variable is the R_{pT} , which is defined as the scalar sum of the transverse momenta of the tracks associated with jet and originated from the hard scatter vertex divided by the full calibrated jet transverse momentum, which includes pile-up subtraction:

$$R_{pT} = \frac{\sum_k p_T^{\text{trk}_k}(PV_0)}{p_T^{\text{jet}}} \quad (3.6)$$

In Figure 3.6 are reported: (a) the distribution of the corrJVF for pile-up jets and for hard scatter jets in simulated dijet events, for transverse momentum tracks of $20 < p_T < 30$ GeV; (b) the R_{pT} distribution for both pile-up and hard scatter jets. The variable corrJVF assumes the value -1 for jets not associated to any track, and about the 1% of the hard scatter jets has corrJVF = 0, meaning that there was no matching with hard scatter tracks. The variable R_{pT} is peaked at 0 and rapidly falls down for pile-up jets, while for hard scatter jets the distribution mean value and width are larger.

A new and more effective multivariate discriminant is built from corrJVF and R_{pT} , called *Jet Vertex Tagger* (JVT), defined as a two-dimensional likelihood, based on the k -nearest neighbour (kNN) algorithm [150]. It represents the probability of a jet to be signal-like, as the ratio between the number of hard scatter jets and the total number of jets, for each point in the two-dimensional plane corrJVF- R_{pT} . In Figure 3.7a is reported the distribution of JVT discriminant for pile-up and hard scatter jets [149].

In the pseudorapidity range $|\eta| > 2.5$ the identification of pile-up, or more generically forward, jets is more critical and crucial, due to the lack of track and vertex information. Moreover, the

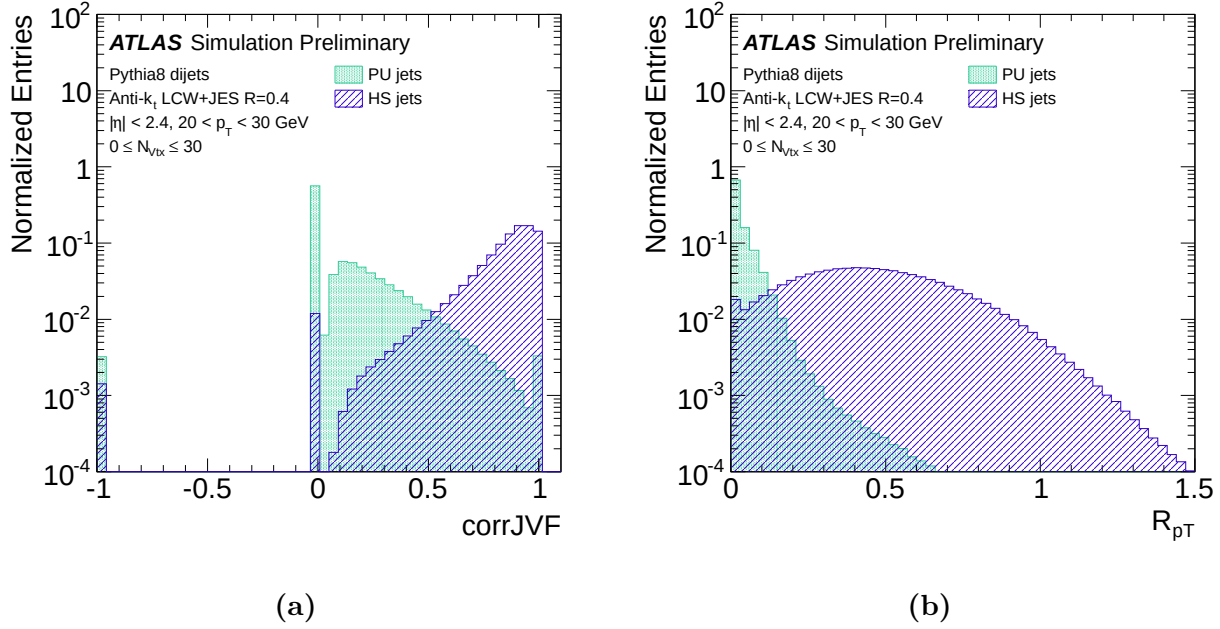


Figure 3.6: Distributions of (a) corrJVF and (b) R_{pT} for pile-up and hard scatter jets with $20 < p_T < 30$ GeV in simulated dijet events [149].

set of variables corrJVF and R_{pT} are effective in suppressing stochastic pile-up jets, but they do not address QCD pile-up jets which are the dominant contribution in the forward region. A more comprehensive approach considers the total transverse momentum of tracks and jets associated with each reconstructed vertex independently: since the momentum conservation implies that the total transverse momentum associated within each pile-up interaction should be conserved, any imbalance would be due to a forward jet from one of the interactions. In order to discriminate forward jets, another algorithm has been implemented, called *forward Jet Vertex Tagging* (fJVT), which uses the maximum value of the JVT, JVT_{max} , in order to reject central hard scatter jets, and the minimum value of the ΔR_{pT} difference, defined as the difference between the leading and median values of R_{pT} for a central jet, in order to ensure that the selected pile-up jets are QCD type. For each pile-up vertex i the missing transverse momentum $\langle p_{T,i}^{\text{miss}} \rangle$ is calculated as the weighted vector sum of the jet and track transverse momenta. This quantity is used to build the fJVT discriminant defined as the normalized projection of the missing transverse momentum on the forward jet's transverse momentum p_T^{fj} :

$$\text{fJVT}_i = \frac{\langle p_{T,i}^{\text{miss}} \rangle \cdot p_T^{fj}}{|p_T^{fj}|^2}, \quad (3.7)$$

The forward jet is therefore tagged as pile-up if its fJVT value, defined as:

$$\text{fJVT} = \max_i(\text{fJVT}_i), \quad (3.8)$$

is above a defined threshold. In Figure 3.7b is shown the fJVT distribution for pile-up and

hard scatter jets, showing how the discriminant tends to have higher value for QCD pile-up jets, while the hard scatter jet distribution steeply falls down [148].

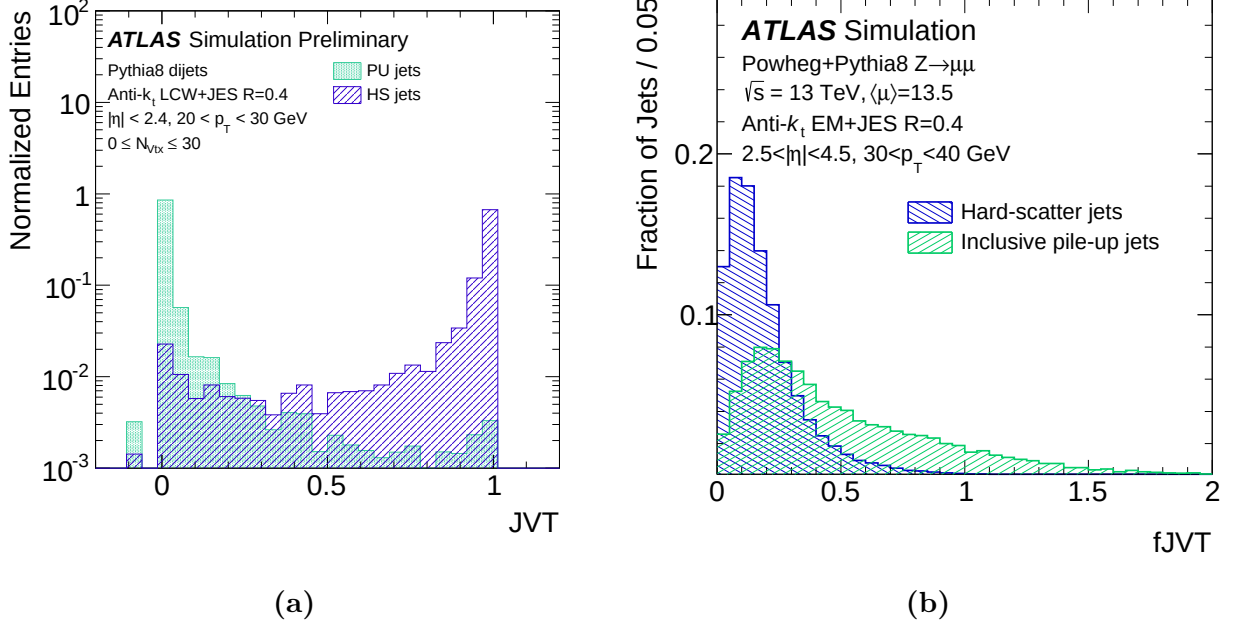


Figure 3.7: (a) Distribution of JVT for pile-up and hard scatter jets with $20 < p_T < 30$ GeV in simulated dijet events [149]. (b) Distribution of fJVT for pile-up and hard scatter jets with $30 < p_T < 40$ GeV in simulated Z+jets events [148].

3.4.4 b-tagging

Among all jets, the identification of those originated from b -hadrons (b -jets), is particularly important for many of the physics processes measured by ATLAS. The b -quark identification was crucial in the observation of Higgs decaying in b -quarks and of the Higgs production with t -quark, and in several Standard Model precision measurements, as well. The ATLAS collaboration uses a set of algorithms for the b -jet identification, known as b -tagging algorithms, which exploit the long lifetime, high mass and high decay multiplicity of b -hadrons as well as the characteristic of the b -quark fragmentation. Due to the relatively long lifetime of b -hadrons, they can flight a significant path inside the detector before decaying, by leading to at least one displaced vertex from the point where the hard scatter took place. The general strategy adopted by ATLAS is to divide the b -tagging procedure in two steps, firstly exploiting low-level algorithms, reconstructing b -quark characteristic features, and afterwards combining the raw results in high-level algorithms in order to maximize the b -tagging performance. Starting from the low-level algorithms, they are classified as follows.

- **Algorithms based on impact parameter.** Two algorithms, IP2D and IP3D [151], are based on the impact parameter information. The IP2D builds a discriminating

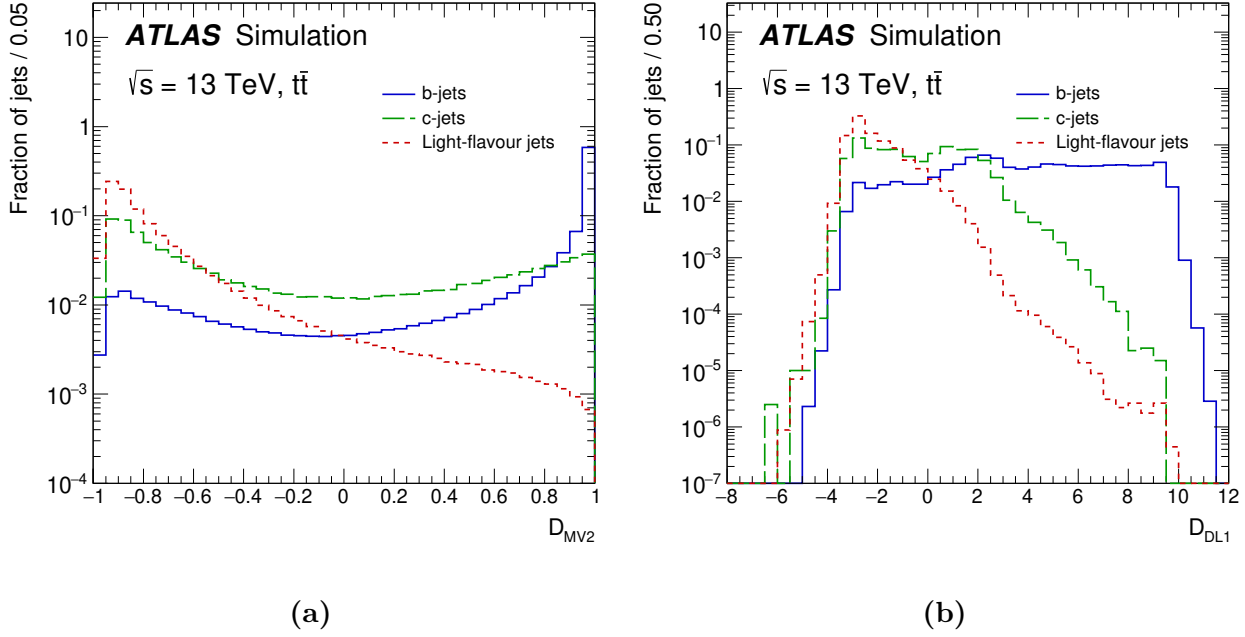


Figure 3.8: Distribution of the output discriminant of the (a) MV2 and (b) DL1 b-tagging algorithms for b-jets, c-jets and light-flavour jets in $t\bar{t}$ simulated events [154].

variable starting from the signed transverse impact parameter significance of tracks, while IP3D assesses the correlation between the track signed transverse and longitudinal impact parameter significance. Directly from this information, different log-likelihood discriminants for identifying b -jets, c -jets and light-flavour jets are computed and passed as input to the high-level algorithms.

- **Secondary vertex finding algorithm.** Another algorithm, called SV1 [152], uses the secondary vertex information. It basically builds a single displaced secondary vertex inside a jet: the algorithm runs iteratively on each pair of tracks in order to find the best fit for the secondary vertex, based on a χ^2 test, rejecting those vertex fit with the largest χ^2 value and accepting those with a vertex invariant mass less than 6 GeV (in order to reject decay of long-lived particles or resonances).
- **Topological multivertex finding algorithms.** The last low-level algorithm is the JETFITTER [153], which exploits the topological structure inside the jets coming from the weak b and c -hadron decays in order to fully reconstruct the b -hadron decay chain. A Kalman filter is applied to extract a common line connecting the primary and the b and c vertices, corresponding approximatively to the b -hadron flight path, and the respective positions of these vertices.

From the low-level algorithms the b -tagging is improved via the two different high-level algorithms, MV2 and DL1 [151]. The MV2 algorithm is based on a Boosted Decision Tree (BDT), by using as input the output of the previous three low-level algorithms. The algorithm

is trained using $t\bar{t}$ +jets events, considering b -jets as signal and c -jets, together with light-flavour jets, as background. The kinematic properties of the jets, p_T and $|\eta|$, are included as training variables. The DL1 algorithm, instead, is based on a deep feed-forward neural network (NN) which produces a multidimensional output corresponding to the probability for a jet to be b -, c - or light-flavour jet. The algorithm uses the same inputs as the MV2 algorithm, plus some additional c -tagging variables, related to properties of secondary and tertiary vertices. The final DL1 b -tagging discriminant is defined as,

$$D_{DL1} = \ln \left(\frac{p_b}{f_c p_c + (1 - f_c) p_{\text{light}}} \right), \quad (3.9)$$

where p_b , p_c and p_{light} are the b -jet, c -jet and light-flavour jet probabilities respectively, while f_c represents the effective c -jet fraction in the background training sample. In Figure 3.8 are reported the distributions of the discriminant outputs for both (a) MV2 and (b) DL1 algorithms for b -jets, c -jets and light-flavour jets, in $t\bar{t}$ simulated events. Performance of the two algorithms are evaluated by using simulated $t\bar{t}$ events and by defining b -jet tagging single-cut operation working points (OPs), which are selection requirements on the b -tagging discriminant distributions ensuring a specific value of b -jet efficiency, ε_b , as shown in Table 3.6. The b -jet tagging efficiencies for MV2 and DL1 algorithms are measured, reaching a precision between 1-8% depending on the jet transverse momentum [154], using 80.5 fb^{-1} of proton-proton collision data at $\sqrt{s} = 13 \text{ TeV}$ at LHC, collected by ATLAS during the period 2015-2017.

ε_b	MV2				DL1			
	Selection	Rejection			Selection	Rejection		
		c -jet	τ -jet	Light-flavour jet		c -jet	τ -jet	Light-flavour jet
60%	> 0.94	23	140	1200	> 2.74	27	220	1300
70%	> 0.83	8.9	36	300	> 2.02	9.4	43	390
77%	> 0.64	4.9	15	110	> 1.45	4.9	14	130
85%	> 0.11	2.7	6.1	25	> 0.46	2.6	3.9	29

Table 3.6: Discriminant selections and c -jet, τ -jet and light-flavour jet rejections related to different b -jet tagging efficiency single-cut operating points for the MV2 and the DL1 b -tagging algorithms, evaluated in simulated $t\bar{t}$ events [154].

3.5 Missing Transverse Energy

During a proton-proton interaction at LHC, undetectable particles, like neutrinos, can be produced, resulting in a missing momentum (and therefore missing energy) in the kinetic balance of the event final state. The measurement of the missing transverse energy, E_T^{miss} , is particularly important in ATLAS, since a value incompatible with zero may indicate

not only the production of SM neutrinos, but also the presence of other undetectable new particles, suggested by BSM models (e.g. SUSY LSP). In each event the E_T^{miss} reconstruction is performed after all other objects, by using them as input. It involves all the detector subsystems and requires a precise description of the hard interaction [155].

The missing transverse momentum, $\mathbf{p}_T^{\text{miss}}$, is constructed from the momentum measurements of various contributions. By indicating with $p_{x(y)}$ the components on the transverse plane of the transverse momentum vector $\mathbf{p}_T$ of these contributions, the missing energy components $E_{x(y)}^{\text{miss}}$ can be derived as,

$$E_{x(y)}^{\text{miss}} = - \sum_{i \in \{\text{hard objects}\}} p_{x(y)}^i - \sum_{j \in \{\text{soft objects}\}} p_{x(y)}^j, \quad (3.10)$$

where *hard objects* represent all the fully reconstructed and calibrated physics objects (electrons, photons, muons and jets) while the *soft objects* are those tracks that pass the basic quality requirements and are associated to the primary vertex, but not to any physics object [4]. From $E_{x(y)}^{\text{miss}}$ the following variables are derived:

$$\mathbf{E}_T^{\text{miss}} = (E_x, E_y), \quad (3.11)$$

$$E_T^{\text{miss}} = |\mathbf{E}_T^{\text{miss}}| = \sqrt{(E_x^{\text{miss}})^2 + (E_y^{\text{miss}})^2}, \quad (3.12)$$

$$\phi^{\text{miss}} = \tan^{-1} \left(\frac{E_y^{\text{miss}}}{E_x^{\text{miss}}} \right). \quad (3.13)$$

The absolute value of the vector $\mathbf{E}_T^{\text{miss}}$ gives the magnitude of the missing transverse momentum and its direction is expressed in terms of its azimuth angle ϕ^{miss} [155].

The hard objects which enter in the E_T^{miss} need to be reconstructed from mutually exclusive detector signals. In the E_T^{miss} reconstruction sequence the followed order is: electrons, photons, τ -lepton hadronically decaying, and finally jets. Also muons enter in the E_T^{miss} reconstruction, but, as already seen, they are reconstructed mainly by the ID and the MS, with corrections based on the energy they deposited in the calorimeter, which can lead to overlapping signals with other particles reconstructed in the calorimeter that need to be taken into account.

Regarding the soft term, its reconstruction is performed with two methods, based on track or calorimetric information. The computation using calorimetric topo-clusters (Calorimeter Soft Term) not associated with reconstructed hard objects is generally less performing than the one using tracks, mainly due to the strong dependence on pile-up. The method which uses the reconstructed tracks associated with the hard scatter vertex (Track Soft Term) is largely unaffected by pile-up effects, but it does not include contributions from any soft neutral particle.

Figure 3.9 shows results of the E_T^{miss} reconstruction performance both in data and MC simulations. The figure reports the (a) E_T^{miss} , (b) E_x^{miss} and (c) E_y^{miss} distributions for an inclusive sample of $Z \rightarrow \mu\mu$ events, by comparing the distributions of these observables in data recorded by the ATLAS experiment during 2015 and in Monte Carlo [155].

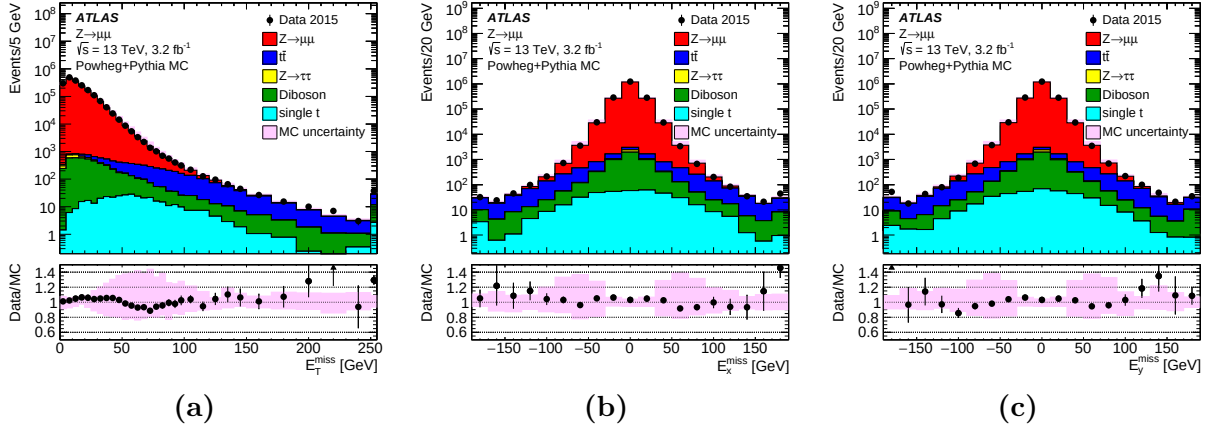


Figure 3.9: Distributions of (a) E_T^{miss} , (b) E_x^{miss} and (c) E_y^{miss} for an inclusive sample of $Z \rightarrow \mu\mu$ in data compared to MC simulations including all relevant backgrounds. The ratios between data and MC simulations are shown below the distributions, with the shaded areas showing the total uncertainty for MC simulations [155].

3.5.1 E_T^{miss} significance

When studying events in collider experiment like ATLAS, fake E_T^{miss} , i.e. not due to real invisible particles, can arise from particles which escape the acceptance of the detector or incorrectly reconstructed or failed to be reconstructed. In order to assess how significant is the E_T^{miss} measurement, the E_T^{miss} significance, $\mathcal{S}$, is introduced, which estimates how much E_T^{miss} is consistent with momentum resolution and particle identification efficiencies. High $\mathcal{S}$ means that the observed E_T^{miss} cannot be explained with resolution effects, but with undetectable particles.

More in details, on an event-by-event basis, the E_T^{miss} significance is determined from the log-likelihood ratio that the reconstructed E_T^{miss} is consistent with the null hypothesis of having zero real total transverse momentum of the invisible particle, $\mathbf{p}_T^{\text{inv}}$, against the hypothesis that is not. By considering the log-likelihood function $\mathcal{L}(\mathbf{E}_T^{\text{miss}} | \mathbf{p}_T^{\text{inv}})$ for a given measured E_T^{miss} , the significance $\mathcal{S}$ is,

$$\mathcal{S}^2 = 2 \ln \left(\frac{\max_{\mathbf{p}_T^{\text{inv}} \neq 0} \mathcal{L}(\mathbf{E}_T^{\text{miss}} | \mathbf{p}_T^{\text{inv}})}{\max_{\mathbf{p}_T^{\text{inv}} = 0} \mathcal{L}(\mathbf{E}_T^{\text{miss}} | \mathbf{p}_T^{\text{inv}})} \right), \quad (3.14)$$

where the numerator of the likelihood ratio is the maximum of the likelihood function in the hypothesis $\mathbf{p}_T^{\text{inv}} \neq 0$, while the denominator in the hypothesis of $\mathbf{p}_T^{\text{inv}} = 0$ [156]. The likelihood function depends on the multiplicities, types and kinematics of the objects measured in each event.

CHAPTER

4

Search for sleptons and charginos in moderately compressed regions

Introduction to the analysis strategy developed for the search of the electroweak production of slepton and chargino pairs, the latter decaying via W -boson, in final state with two opposite-sign charged leptons and missing transverse energy. The search uses collision data collected during Run 2 of LHC by the ATLAS experiment, and targets phase space regions where the mass difference between the slepton/chargino and the lightest neutralino is of the order of the W -boson mass.

As introduced in Chapter 1, the SUSY strong production is favoured at LHC with respect to the SUSY production through electroweak interactions, as shown in Figure 1.8, where cross sections are reported depending on the produced particle mass. Nevertheless, since no evidence of the existence of squarks and gluinos was observed so far below the TeV scale, the weak-scale supersymmetry started to gain more and more interest among the ATLAS BSM searches. In particular, the analysis described in this thesis targets the electroweak direct production of chargino and slepton pairs in the R-parity conserving SUSY models described in section 1.3.2, using the data collected by the ATLAS detector during Run 2 of LHC. The analysis will focus on the processes (a) and (c) reported in Figure 1.11: (a) the direct production of chargino pairs, $\tilde{\chi}_1^+ \tilde{\chi}_1^-$, where each chargino decays to the LSP (the neutralino, $\tilde{\chi}_1^0$) via the emission of a W -boson which decays leptonically; (b) the direct production of slepton pairs, $\tilde{\ell}^+ \tilde{\ell}^-$, decaying to the LSP via the emission of the corresponding charged lepton, ℓ , and in a neutralino. Results on these channels were already published

by the ATLAS collaboration in 2020, in Ref. [62], exploiting the full Run 2 data set and by optimizing the search in the phase-space regions with a large mass difference (from now on also called mass-splitting) between the chargino/slepton and the LSP. The analysis presented here mainly differs from the previous one in the aim to extend the sensitivity of the search in the experimentally challenging region of the mass-planes $(m(\tilde{\chi}_1^\pm), m(\tilde{\chi}_1^0))$ and $(m(\tilde{\ell}), m(\tilde{\chi}_1^0))$, where the mass-splittings $m(\tilde{\chi}_1^\pm) - m(\tilde{\chi}_1^0)$ and $m(\tilde{\ell}) - m(\tilde{\chi}_1^0)$ are of the order of the W -boson mass, known as *moderately compressed* regions. The results of this analysis were published in 2023 by the ATLAS collaboration in the paper *Search for direct pair production of sleptons and charginos decaying to two leptons and neutralinos with mass splittings near the W -boson mass in $\sqrt{s} = 13$ TeV pp collisions with the ATLAS detector* [4]. It will be dealt in detail in this and the following two chapters.

In this chapter the common elements of the searches for the processes (a) and (b) will be described: the general methodologies and common tools in the SUSY analyses; the data, signal and background samples used; the definition and selection criteria of the physical objects of interest; the description of the fake non-prompt lepton background estimation and the main sources of systematic uncertainties. For both channels, a signature with: two *opposite-sign charged* leptons (OS, electrons and/or muons); missing transverse energy, E_T^{miss} , due to the presence of the LSPs, and, in the chargino pair production case, of the neutrinos coming from the leptonic decays of the W -bosons; low hadronic activity, is considered. The two leptons have the *same flavour* (SF) in case of the slepton production, while they can also have *different flavour* (DF) in the chargino search. The gain in sensitivity is reached defining two different strategies for the two channels. For sleptons the analysis consists in searching for an excess of SF events over the SM background, estimated via a dedicated data-driven technique, described in detail in Chapter 5. For chargino, instead, a dedicated machine learning technique, based on boosted decision trees, was exploited, described in Chapter 6.

4.1 General strategy for SUSY searches

When talking about searches for Supersymmetry, it is needed to make a distinction between two different approaches, *inclusive* and *exclusive*. The inclusive analyses consist in searching for any deviation from the Standard Model expectation in decay channels characterized by a specific signature, aiming to estimate the mass scale of the sparticles produced. Exclusive searches, instead, consist in adopting specific production and decay models of the investigated sparticles and in estimating the physical parameters which characterize them [157]. In both cases, the general strategy is developed in consecutive steps, focused on: selecting signal-like events, estimating the SM backgrounds and interpreting the final results, obtained after applying a dedicated fit procedure.

4.1.1 Selection of signal-like events: signal regions definition

A generic SUSY analysis starts from Monte Carlo simulations modelling the behaviour of the SUSY signal models under study and the main Standard Model backgrounds which manifest a signature similar to the searched signal. Through preliminary selections (or ‘cuts’) mainly on relevant variables which characterize the physics objects or the topology of the signal events, discriminating them from the background, a first selection (named *preselection*) is defined. The preselection step is then applied to data samples. It is necessary for both doing a first skimming of the events and for checking, by comparing the distributions of the relevant variables in the survived events in data and Monte Carlo, if any data-MC mis-modelling arises. In the latter case, mis-modelling needs to be corrected before going on with the analysis. Afterwards, looking only at the Monte Carlo samples and using variables with high signal-background discriminating power, tighter selections are applied to the events in order to define some kinematic regions, called *Signal Regions* (SRs), where the presence of the SUSY signal is enhanced, and an excess of signal events over the background ones is expected. Such regions should be defined and optimized in MC by requiring the highest possible purity of signal and the lowest possible background contamination. The reason for using only MC at this stage of the analysis is to avoid any bias due to previous results or theoretical expectations. This is the so-called *Hidden Signal Box Blind Analysis* [158], consisting in defining signal regions where the significance of the analyzed SUSY model is maximized, but the amount of data in these regions is kept hidden until a proper strategy for the background estimation is fully developed.

4.1.2 Background estimation: control and validation regions definition

The backgrounds which enters in a generic analysis can be distinguished in two main categories:

- the *irreducible background*, whose final state is the same as the signal one. If the expected contribution of an irreducible background process is low in the SRs, its estimate obtained from Monte Carlo is considered sufficiently accurate;
- the *reducible background* is characterized by a different final state from the signal one, but, due to errors in the reconstruction, in the identification, etc., the two signatures look similar. An example is an event in which one of the two leptons in the final state is an energy deposit in the calorimeter due to a hadronic jet or coming from a particle decay in a jet (*fake lepton*), but it was wrongly reconstructed and classified as an isolated lepton (*prompt*). This event is classified as coming from *fake non-prompt* (FNP) lepton background.

In both cases, if the amount of background inside the SRs is not negligible, the Monte Carlo simulations are not completely reliable and other dedicated procedures need to be applied to get a more accurate estimates. The reducible background is generally estimated by using techniques based on data (*data-driven*), while the estimation of the irreducible backgrounds inside the SRs is based on a technique based both on data and simulations, called *semi*

data-driven technique. In applying it, the main background yields in the SRs can be derived by defining suitable kinematic regions, called *Control Regions* (CRs), designed to have a high purity in the background to be estimated, and to be free of signal contamination. Through a fit procedure, described afterwards, *normalization data-MC factors* (also called *scale factors*) are obtained in the CRs for the backgrounds of interest, and then applied in the SRs in order to correct their MC estimates. The results of these extrapolations are verified in *Validation Regions* (VRs), typically defined in between of CRs and SRs [159]. As schematically illustrated in Figure 4.1, CRs and VRs need to be chosen as close as possible to the SRs in order to have a similar kinematics, but they also must not overlap each other and with the SRs (*orthogonality*).

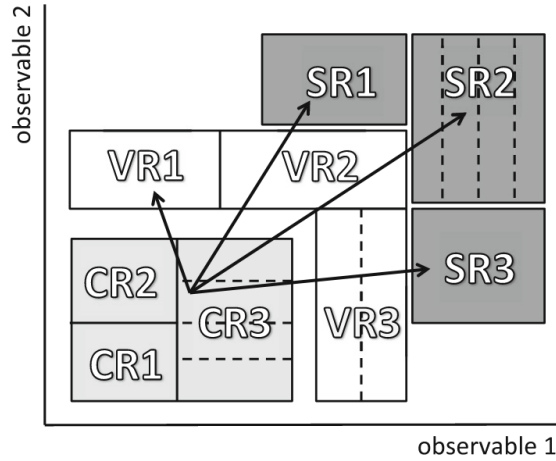


Figure 4.1: A schematic view of an analysis strategy with multiple control, validation and signal regions. All regions can have more than one bin (indicated by the dashed lines). The extrapolation from the CRs to the SRs is verified in the VRs [159].

The tool used in the present analysis in order to perform the background estimation and the statistical interpretation of the results, described in the next paragraph, is HISTFITTER [159], a software codified in Python and C++ languages. HISTFITTER is based on ROOT [160, 161], on the packages ROOSTATS [162] and ROOFIT [163] and on HISTFACTORY [164], a tool to build parametrized *probability density functions* in the ROOFIT/ROOSTATS framework, based on ROOT histograms. HISTFITTER allows to perform a complete statistical analysis, by starting from a pre-formatted input data sample and from a user configuration file, putting all the elements in a coherent programmable framework. HISTFITTER can extrapolate and validate models using control, validation and signal regions, by handling several data models and histograms and performing statistical tests. It provides various statistical methods to calculate the significance of a signal hypothesis and for determining the quality of likelihood fits [159].

4.1.3 The likelihood fit

Data can be described by the probability density functions built for each of the defined SRs, CRs and VRs. Once the MC models of the dominant backgrounds have been normalized to data in the CRs, the normalization parameters can be extrapolated to the VRs and, if a good agreement between the normalized MC and the data is observed in the VRs after the extrapolations, they can be extended to the SRs. Only at this point the observed data inside the SRs can be ‘revealed’ and interpreted, generally referring at this phase as ‘unblinding’ or ‘opening the box’ procedure.

In details, the total background contribution which enters in the SRs and VRs is estimated performing the so called *background-only fit*, which uses only CRs without making assumptions on any signal models. It consists in using only background samples and in normalizing the main processes to the observed data in the CRs. Considering a background p , once the relative normalization factor μ_p has been derived from the fit to data in the CRs, the estimate of the number of events relative to that background inside a specific CR can be obtained via:

$$N_p(CR) = \mu_p \times MC_p(CR), \quad (4.1)$$

where $MC_p(CR)$ is the expected yield of the p background obtained from MC simulations in the CR. Similarly, the estimated number of background events inside a SR can be written as:

$$N_p(SR) = \mu_p \times MC_p(SR) \equiv N_p(CR) \times \left[\frac{MC_p(SR)}{MC_p(CR)} \right], \quad (4.2)$$

where $MC_p(SR)$ is the expected yield of the p background obtained from MC simulations in the SR, and the ratio in square brackets is defined as the *transfer factor* (TF, or *normalization factor*, or *scale factor*). Therefore, using this approach, the estimated number of background events in the SR can be computed via the TF and the number of background events obtained from the fit in the CR.

In statistical terms, the counting of events in the SRs and CRs defined in the analysis can be described by a general likelihood function, obtained as the product of the poisson distributions inside each SR and each CR, indicated as P_{SR} and P_{CR} respectively, plus an additional term containing distributions relative to the systematic uncertainties, C_{syst} , as constraint to the likelihood. In particular, the effect of the systematic uncertainties is described by the *nuisance parameters* θ_i (where i is referred to the i -th uncertainty) which indicate, in units of standard deviation, the contribution of the specific uncertainty. The likelihood function, for a specific signal model, is defined as:

$$\begin{aligned} L(\mathbf{n}, \boldsymbol{\theta}^0 | \mu_{sig}, \boldsymbol{\mu}_p, \boldsymbol{\theta}) &= P_{SR} \times P_{CR} \times C_{syst} = \\ &= \prod_{i \in SR} P(n_i | \lambda_i(\mu_{sig}, \boldsymbol{\mu}_p, \boldsymbol{\theta})) \times \prod_{i \in CR} P(n_i | \lambda_i(\mu_{sig}, \boldsymbol{\mu}_p, \boldsymbol{\theta})) \times C_{syst}(\boldsymbol{\theta}^0, \boldsymbol{\theta}), \end{aligned} \quad (4.3)$$

where P represents the Poisson distribution of n_i observed events in the bin i of the SR(CR), whose expectation value λ_i depends on the prediction of the signal and the various p backgrounds, the systematic uncertainties, indicated via $\boldsymbol{\theta}$, the normalization factors of the several backgrounds $\boldsymbol{\mu}_p$, and the signal μ_{sig} , also known as *signal strength* (from now on simply indicated as μ). If $\mu = 0$, the signal component is turned off and the hypothesis of only background is considered, whilst, if $\mu = 1$, the signal expectation is exactly equal to the nominal value of the model considered. The systematic term, C_{syst} , is expressed as a probability density function, generally gaussian, describing the effect of the systematic uncertainties, in terms of the nuisance parameters and their nominal values $\boldsymbol{\theta}^0$. The maximization of the likelihood provides the best parameters which describe the observed data.

HISTFITTER is able to perform hypothesis tests of different signal models, by exploiting, as statistical test, the *profile likelihood ratio*:

$$\lambda(\mu) = \frac{L(\mu, \hat{\boldsymbol{\theta}}_\mu)}{L(\hat{\mu}, \hat{\boldsymbol{\theta}})}, \quad (4.4)$$

where $\hat{\mu}$ and $\hat{\boldsymbol{\theta}}$ are the parameters which maximize the likelihood, and $\hat{\boldsymbol{\theta}}_\mu$ is the nuisance parameter which maximizes the likelihood function in the specific case of μ . The likelihood ratio $\lambda(\mu)$ can vary between 0 and 1, approaching 1 when it is found an agreement between the experimental data and the tested hypothesis μ . In order to perform hypothesis tests of data, it is convenient to use a logarithmic expression, by introducing the *profile log-likelihood ratio*, defined as:

$$q_\mu = -2 \ln(\lambda(\mu)), \quad 0 \leq \hat{\mu} \leq \mu. \quad (4.5)$$

In particular, it is required that $\hat{\mu} \geq 0$ in order to be sure that the signal rate is non-negative, and that $\hat{\mu} \leq \mu$ to guarantee a one-sided confidence interval and to avoid upwards fluctuation in data ($\hat{\mu} > \mu$). A statistical test, using q_μ , can be performed in order to exclude a specific signal model or to introduce an upper limit on the visible cross section²⁷. The *CLs method* [165] is used, which follows a frequentist approach, using the *frequentist probability value*, also called *p-value*, which is an index of the goodness of an hypothesis, built from a distribution f of the statistic test q_μ , taking into account the systematic uncertainty: $f(q_\mu|\mu, \boldsymbol{\theta})$.

Indicating as the null-hypothesis $\mathcal{H}_0$ that one of having both signal and background ($\mu = 1$), whereas with $\mathcal{H}_1$ the one of only background ($\mu = 0$), the p -values p_{b+s} and p_b , corresponding respectively to the two hypotheses, can be defined as:

$$p_{s+b} = \int_{Q_1}^{+\infty} f(q_\mu|\mu = 1, \boldsymbol{\theta}) dq_\mu \equiv CL_{s+b}, \quad (4.6)$$

$$p_b = \int_{-\infty}^{Q_1} f(q_\mu|\mu = 0, \boldsymbol{\theta}) dq_\mu \equiv 1 - CL_b, \quad (4.7)$$

²⁷The visible cross section is defined as the product between the acceptance, the reconstruction efficiency and the production cross section.

where Q_1 is the observed value of the statistic test q_μ in the signal strength hypothesis of $\mu = 1$, $f(q_\mu|\mu = 1, \boldsymbol{\theta})$ and $f(q_\mu|\mu = 0, \boldsymbol{\theta})$ are the distributions of q_μ in the $\mathcal{H}_0$ and $\mathcal{H}_1$ hypotheses respectively, and CL_{s+b} and CL_b are the confidence level values obtained from the two hypotheses respectively. Similarly, the confidence of a signal-only hypothesis can be assessed by defining the CL_s value:

$$CL_s = \frac{CL_{s+b}}{CL_b} = \frac{p_{s+b}}{1 - p_b}. \quad (4.8)$$

The $\mathcal{H}_0$ hypothesis can be excluded with a 95% Confidence Level (CL) for those models which show a CL_s value lower than 0.05. The obtained results represent the observed values for the specific signal+background hypothesis, therefore, in order to characterize the sensitivity of the experiment, it's necessary to assess the CL_s expectation. To do it, it can be assumed as the integration extreme Q_1 in equations 4.6 and 4.7 the median value of q_μ , in the pure background hypothesis $\mu = 0$. In addition to the expected value is also needed to apply error bands at $\pm 1\sigma$ and $\pm 2\sigma$, corresponding to the 68% and 95% respectively of the $f(q_\mu|\mu = 0, \boldsymbol{\theta})$ distribution. The fit excluding the $\mathcal{H}_0$ hypothesis is called *model-dependent fit*, or *exclusion fit*, since it consists in treating specific signal models, and, if no excess of events is observed in any of the SRs, it imposes exclusion limits on the signal model considered. This type of fit considers both CRs and SRs simultaneously, since they are statistically independent of each other, including the signal model in all the defined regions (also in CRs). The signal strength μ is directly extracted from the fit.

Regardless of the BSM signal model considered, one can evaluate an upper-limit on the number of background events expected in each SR. To do it, HISTFITTER can perform a *model-independent fit* (also called *discovery fit*), which consists in assessing the significance of an excess of events observed in the SRs, without any assumption of the signal, called *dummy signal*, but assuming to have CRs with no signal contaminations. This fit uses the CRs and one SR at a time, where each SR is built as a single bin²⁸, similarly as done for a background-only fit but using the number of observed events in the SRs as input. The fit provides the observed upper limit for the number of signal events in a specific signal region with a 95% CL (S_{obs}^{95}), and the corresponding expected value (S_{exp}^{95}), relative to an expected CL_s lower than 0.05. By normalizing the signal upper limits to the integrated luminosity of the dataset considered, an upper-limit on the visible cross section can be derived.

To claim for the discovery of a new signal, a criterion to reject the background-only hypothesis ($\mu = 0$) is to consider the special case of the log-likelihood ratio:

$$q_0 = -2 \ln(\lambda(0)), \quad \hat{\mu} \geq 0, \quad (4.9)$$

where $\lambda(0)$ is the likelihood ratio in the condition of $\mu = 0$. The disagreement between data

²⁸Since no assumptions are made on the signal model considered, having a signal region with several bins would mean to assume hypotheses on how the signal is distributed over the different bins.

and the background-only hypothesis can be assessed evaluating the relative p -value:

$$p_0 = \int_{Q_0}^{+\infty} f(q_0|\mu = 0, \boldsymbol{\theta}_0) dq_0, \quad (4.10)$$

where Q_0 is the observed value of the statistic test q_0 in the signal strength hypothesis of $\mu = 0$, and $f(q_0|\mu = 0, \boldsymbol{\theta}_0)$ the probability density function of q_0 in this assumption. Usually, the p -value is converted in the equivalent significance Z , which represents the number of standard deviations for which a gaussian variable can fluctuate in order to obtain the same p -value. The physics community agreed to consider $Z = 5$ (corresponding to $p_0 = 2.87 \times 10^{-7}$) as the value for which the background-only hypothesis can be rejected, and the signal discovery can be declared, while $Z = 3$ (corresponding to $p_0 = 0.0135$) as the value suggesting an evidence of the presence of the signal. In Table 4.1 are summarized the main properties of the three types of fit that HISTFITTER can perform [159, 166].

Fit setup	<i>Background-only fit</i>	<i>Model-dependent fit</i>	<i>Model-independent fit</i>
Samples used	backgrounds	backgrounds +signal	backgrounds +dummy signal
Fit regions	CR(s)	CR(s)+SR(s)	CR(s)+SR

Table 4.1: Summary of the fit strategies supported in HISTFITTER [166].

4.2 Data samples

The analysis uses data from pp collisions at an energy in the centre of mass of $\sqrt{s} = 13$ TeV, collected by the ATLAS detector during Run 2 of LHC, from 2015 to 2018, corresponding to an integrated luminosity of 139 fb^{-1} . The total uncertainty of the integrated luminosity is 1.7% [79], as measured by the LUCID-2 detector. Each collision happens every 25 ns, with an average pile-up ranging from 14 in 2015 to 38 in 2017-2018. Data firstly passed some *data-quality* [167] requirements, in order to ensure that all the parts of the detector were operational during the data-taking. These data are tagged as *good for physics*, and the relative *luminosity blocks*²⁹ are included in a list of good runs, called *Good Run List* (GRL). Moreover, events in the GRL must pass other requirements, based on some prescriptions provided by the ATLAS Data Preparation Group, known as *cleaning cuts*. Such criteria are described in the following:

- events which have raised error flags in the calorimeters, both electromagnetic and hadronic, and in the SCT are rejected;

²⁹A *luminosity block* (LB) is a data-taking period characterized by constant experimental and detector conditions, typically of two minutes.

- all incomplete or broken events are removed from the final selections, like events with noise bursts and integrity errors in the LAr and Tile calorimeters;
- the considered events must have a primary vertex;
- all the reconstructed muons not coming from the pp interaction are removed. Such bad muons have e.g. hits in the muon spectrometer due to very energetic jets which are not fully contained in the calorimeter and arrive to the spectrometer, or jets tracks in the inner detector badly matched to muon segments in the spectrometer. Furthermore, cosmic muons are a source of uncorrelated events with the hard collision, and are thus removed;
- some background processes, not directly associated with the hard collision, can release some energy in the calorimeter, wrongly reconstructed as jet. These events are removed imposing a threshold on the jet transverse momentum of $p_T > 20$ GeV [4].

4.3 Monte Carlo samples

The SUSY signal models and the Standard Model background processes are simulated via Monte Carlo (MC) generators which reproduce their expected kinematic properties. The simulation procedure starts from the *event generation* step, which consists in reproducing, from theoretical assumptions, the pp collision and the particles produced. The simulation software is based on detailed computations, describing all the phases of the hadronic interaction. First of all, since protons are not elementary particles, the interaction is simulated between partons (quarks and gluons), whose momentum distribution inside the proton is described by specific *Parton Distribution Functions* (PDFs). From these functions, the interaction cross section of two partons for a specific final state can be derived, by taking into account the possibility of emission of extra quarks or gluons in the initial or final states, thus named *Initial State Radiation* (ISR) and *Final State Radiation* (FSR) respectively. Based on the perturbative-QCD theory, the cross section can be computed with different degrees of approximation, in terms of different orders of the QCD-coupling constant α_s : the lowest-order is called *Leading Order* (LO), while the *Next⁽ⁿ⁾ to Leading Order* (N⁽ⁿ⁾LO), where $n \geq 1$ is the order of α_s , includes higher-order corrections. If the order of the correction is in terms of $\log \alpha_s$, it is defined the *Next⁽ⁿ⁾ to Leading Logarithm* (N⁽ⁿ⁾LL) approximation. In addition to the hard scatter process, the contribution of the underlying events is also simulated. Finally, the hadronization processes of the quarks and gluons produced in the final states, and their consecutive QCD decays, are simulated through non-perturbative QCD computations.

The next step consists in reproducing the *detector response* to the particles arising from the interaction. The ATLAS detector response is modelled by GEANT4 [168], by exploiting a full description of the detector (FULLSIM) [169] for the background processes, while a less detailed, but faster in terms of computation time, representation of the detector (ATLASFAST-II) [169] is used for the signal processes, relying on the parametrization of the calorimeter response and on GEANT4 for the other detector components. Concerning the analysis here described,

the effect of the pile-up is modelled by overlaying simulated inelastic pp events generated with PYTHIA 8.186 [170] and EVTGEN [171], using the NNPDF2.3LO set of parton distribution functions [172] and the A3 set of tuned parameters [173] to the hard scatter events. Afterwards, the MC samples are reweighted according to the observed data, so that the distribution of the average number of interactions per bunch-crossing reproduces that one in the data. The final steps of the simulation are the *digitization*, which basically models all the read-out processes of the detector, and the final *reconstruction*. The same trigger, reconstruction and identification algorithms used on the data are applied to the simulated events. Moreover, in order to take into account all the differences between data and simulation in the jet and lepton reconstruction efficiencies, in the energy scales and resolutions, and in the lepton trigger efficiency [174, 175] and jet b -tagging efficiency [176], correction factors are applied to the simulated event samples [4].

4.3.1 Signal samples

Starting from the signal modelling, the MC generators simulate signal events at leading-order (LO) matrix element with the addition of up to two extra partons. The generators used are MADGRAPH v2.6.1, for the slepton model, and MADGRAPH v2.6.2, for the chargino model via W -boson decay, interfaced with PYTHIA 8.244 [177] and PYTHIA 8.212 [177] respectively. The A14 set of tuned parameters [178] is included for the modelling of the SUSY decay chain, the parton showers, the hadronization and the underlying events. In particular, chargino signal samples in the $\Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0) < 100$ GeV region, have been generated with MADSPIN [179], to take into account spin correlation effects arising in the decay of the off-shell W -bosons.

Parton distribution functions are the NNPDF2.3LO set [172] and the CKKW-L prescription [180] is considered for the matching between the jet and the parton, using a matching scale of one quarter of the mass of the superpartner produced, for the slepton model, and of 15 GeV, for the chargino model. Concerning the signal cross sections, they are computed at NLO, considering the additional soft gluon emission terms at NLL accuracy [181–187]. The nominal cross sections and their uncertainties are taken from an envelope of cross section predictions using different parton distribution sets and factorization and renormalization scales, as described in Ref. [188]. E.g. the cross section for the chargino pair production in the case of $m(\tilde{\chi}_1^\pm) = 150$ GeV is 2.61 ± 0.14 pb, while for the slepton case, for mass of $m(\tilde{\ell}) = 150$ GeV, is 63.3 ± 3.3 fb for each generation of left-handed sleptons and 23.3 ± 1.4 fb for each generation of right-handed sleptons [4].

In Figure 4.2 the simplified SUSY signal models considered for the two channels are summarised. For the slepton channel, 98 signal models have been generated, where each slepton decays in $\tilde{\ell} \rightarrow \ell \tilde{\chi}_1^0$ with a BR of 100% (only $\tilde{e}$ and $\tilde{\mu}$ are considered) and conserving the lepton flavour. The superpartners of the left-handed and right-handed charged leptons, $\tilde{e}_L$, $\tilde{e}_R$, $\tilde{\mu}_L$ and $\tilde{\mu}_R$ are supposed to be mass degenerate. For the chargino channel, instead, 88 signal points have

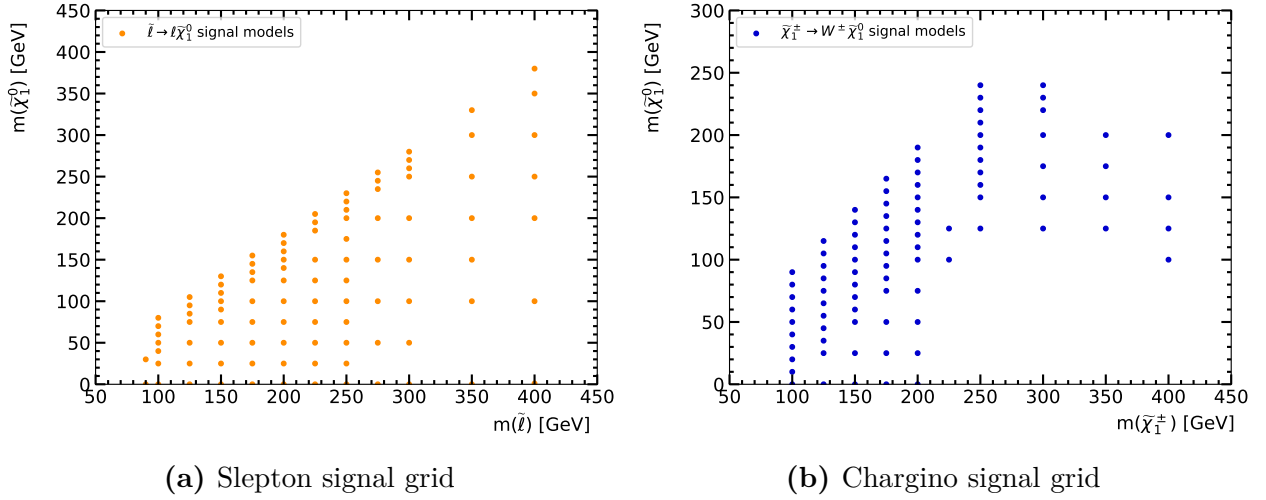


Figure 4.2: Summary of the signal models considered for the two channels: in (a) are reported, in the $(m(\tilde{\ell}), m(\tilde{\chi}_1^0))$ plane, the 98 signal points generated for the slepton search, while in (b) the 88 points for the chargino search in the $(m(\tilde{\chi}_1^\pm), m(\tilde{\chi}_1^0))$ plane.

been produced, where each $\tilde{\chi}_1^\pm$ is assumed to be pure wino³⁰ and decays via the emission of a W -boson, which can decay in turn leptonically in electron or muon plus neutrino(s) either directly or through the emission of a leptonically decaying τ -lepton.

4.3.2 Background samples

Several Standard Model background processes are considered in the analysis, because their signature resembles the one of the searched processes, i.e. two opposite-sign charged leptons and missing transverse energy. The dominant among these processes are listed below.

- **Top-quark production.** The most relevant background processes in the analysis consist in the top-quark production, mainly in pair top anti-top, $t\bar{t}$, or singularly in Wt . In both cases the top-quark decays via $t \rightarrow Wb$. Such processes consist therefore in two W -bosons. If both the W -bosons decay leptonically ($W \rightarrow \ell\nu$ with a $\text{BR} \sim 30\%$), the final signature consists in two opposite-sign charged leptons, missing transverse energy (deputed to the neutrinos from the leptonic W -boson decays) and b -jets. Therefore, the ability of tagging b -jets is a powerful weapon in order to identify such top processes against the signal events. Other minor processes with top-quarks are the $t\bar{t}$ production associated with one, $t\bar{t} + V$, or two, $t\bar{t} + VV$, gauge bosons, with $V = Z, W$, or with a Higgs boson, $t\bar{t} + H$, a top-quark in association with a Z -boson, tZ , or more than two top-quarks, $t\bar{t}t$ and $t\bar{t}t\bar{t}$.

³⁰As described in section 1.2.2, since charginos and neutralinos are obtained from a combination of the higgsinos and gauginos, depending on the relative contributions of these particles, the notations ‘pure wino’, ‘pure bino’, ‘pure higgsino’, ‘wino-like’, ‘bino-like’, ‘higgsino-like’, can be found.

- **Diboson VV and triboson VVV production.** Due to the similarity of SM processes with two or three gauge bosons ($V = W$ or Z) to the signal ones, it is very challenging to reject this background, particularly WW , whose signature is almost identical to the targeted signal signature. Also the cases of two Z -bosons (ZZ), where one Z decays in $\ell^+\ell^-$ and the other one decays in $\nu\nu$, or the production of WWZ where the two W -bosons decay leptonically and the Z decays in a neutrino pair are very difficult to be discriminated.
- **Z/γ^* production with jets.** Another important background is due to events with a leptonically decaying Z/γ^* accompanied by hadronic jets. Such a SM process is relevant in the case of same flavour events and particularly in the compressed regions of the phase space. The missing transverse energy in Z/γ^* events is expected to be low, but the presence of the jets can unbalance the kinematic of the process, thus increasing the missing momentum and leading to a signal-like signature.

Table 4.2 gives a detailed summary of all SM background samples used in this analysis and the relative simulation features, listing the generators, the parton density functions sets in the generators and in the parton showering, the sets of underlying-event and hadronisation parameter values (tune) for the parton shower, and the order of the cross section computation in α_s . In the public notes [189–192] are reported further informations about the simulations of $t\bar{t}$, single-top (Wt), multiboson and boson-plus-jet processes made by ATLAS [4]. A summary of the Standard Model total production cross section measurements, made by the ATLAS experiment, is reported in Figure 4.3.

Physics process	Generator	Parton shower	Normalization	Tune	PDF (generator)	PDF (PS)
$t\bar{t}$	POWHEG Box v2 [193–196]	PYTHIA 8.230 [177]	NNLO+NNLL [197–203]	A14 [178]	NNPDF3.0NLO [204]	NNPDF2.3LO [172]
Single-top (Wt)	POWHEG Box v2 [194–196, 205]	PYTHIA 8.230	NLO+NNLL [206, 207]	A14	NNPDF3.0NLO	NNPDF2.3LO
Diboson VV	SHERPA 2.2.1, 2.2.2 [208]	SHERPA 2.2.1, 2.2.2 [209, 210]	NLO [211–214]	Default [191]	NNPDF3.0NNLO [204]	NNPDF3.0NNLO
Triboson VVV	SHERPA 2.2.2	SHERPA 2.2.2	NLO	Default	NNPDF3.0NNLO	NNPDF3.0NNLO
$t\bar{t}+V$	MADGRAPH5_AMC@NLO 2.3.3 [215]	PYTHIA 8.210 [177]	NLO [215]	A14	NNPDF3.0NLO	NNPDF2.3LO
$t\bar{t}+H$	POWHEG Box v2 [193–196, 216]	PYTHIA 8.230	NLO	A14	NNPDF3.0NLO	NNPDF2.3LO
$t\bar{t}+WW$	MADGRAPH5_AMC@NLO 2.2.2	PYTHIA 8.186 [170]	NLO [215]	A14	NNPDF2.3LO	NNPDF2.3LO
$t\bar{t}+WZ$	MADGRAPH5_AMC@NLO 2.3.3	PYTHIA 8.212 [177]	NLO [215]	A14	NNPDF2.3LO	NNPDF2.3LO
$tZ, t\bar{t}t\bar{t}, t\bar{t}t$	MADGRAPH5_AMC@NLO 2.3.3	PYTHIA 8.230	NLO [215]	A14	NNPDF3.0NLO	NNPDF2.3LO
$Z/\gamma^* (\rightarrow \ell\ell) + \text{jets}$	SHERPA 2.2.1 [208]	SHERPA 2.2.1 [210]	NNLO [217]	Default	NNPDF3.0NNLO	NNPDF3.0NNLO
$H \rightarrow \tau\tau$	POWHEG Box v2 [194–196, 218, 219]	PYTHIA 8.2 [177]	NNLO [220–223]	AZNLO [224]	NNPDF3.0NLO	PDF4LHC15NNLO [225]

Table 4.2: SM background Monte Carlo samples used in this analysis. The matrix element and parton showers (PS) generators, the order of α_s for the event normalization, the tune of the underlying-event and the generator parton density functions sets are reported. For diboson, triboson and $t\bar{t}+V$ samples, V represents a W or Z -boson. Diboson samples also include Higgs boson contributions. ‘Default’ is referred to the default tune of the SHERPA generator [4].

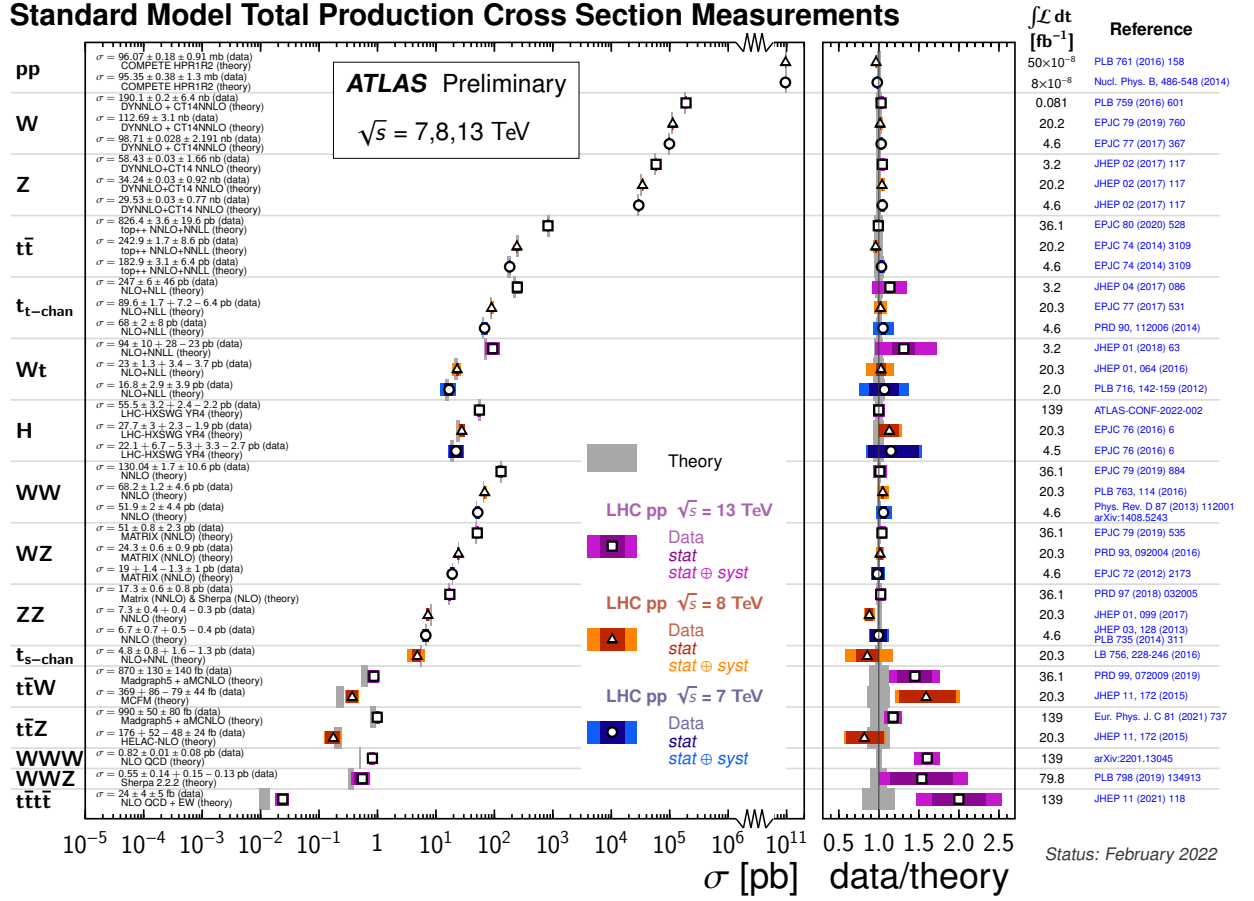


Figure 4.3: Total production cross section measurements of several Standard Model processes, corrected in terms of branching ratios and compared with the theoretical predictions [226].

4.4 Trigger selection

The events considered in the analysis were triggered by various single-electron [227] and single-muon [228] triggers, which include the lowest unprescaled trigger items for the different data taking periods. The trigger thresholds are in the range of 20-120 GeV for data collected in 2015, 24-300 GeV for data collected in 2016 and 26-300 GeV for data collected in 2017 and 2018. Higher p_T requirements are applied to the leptons in the offline selection, in order to efficiently select events triggered with the considered items [4]. Dilepton triggers were also initially considered, but their efficiency on signal was considerably lower than the single lepton one for lower mass-splittings, especially in the case of the chargino analysis. Finally, the gain in efficiency from the combination of the two trigger strategies (single or dilepton triggers) was found to be negligible.

In Table 4.3 is reported the list of the single-lepton triggers used in the analysis for the different data-taking periods. The naming convention contains information about the selections made

by the triggers. The **eXX** (**muXX**) suffix indicates a threshold in the transverse momentum of the electron (muon) at $p_T > \text{XX GeV}$. For muon triggers, the **0eta105** tag indicates that the muons considered have $0 < |\eta| < 1.05$. For single-electron triggers, the **lhtight**, **lhmedium**, **lhloose** tags indicate three different identification working points, which use a multivariate likelihood (LH) discriminant, while the **nod0** suffix indicates that the impact parameter information to the beam-line, d_0 , and its significance, $|d_0|/\sigma_{d_0}$, are not included. The **ivarloose**, **ivarmedium** and **iloose** tags are relative to isolation requirements. The **etcut** is relative to triggers which use only information about the E_T . For all the muon triggers, the tracks considered are combined muons, except for those using only the muon standalone tracks, indicated with the suffix **msonly**. The triggers in the first line also report information about the L1 step: for electron, the suffix **L1EM20VH** means that it is required at least an EM cluster, with an energy threshold of $E_T > 20 \text{ GeV}$, where the threshold is η -dependent (V) and an hadronic veto (H) is applied, while for muons, the **L1MU15** tag indicates that at least a muon is required with $p_T > 15 \text{ GeV}$ [227, 228].

Data period	Single-electron	Single-muon
2015	HLT_e24_lhmedium_L1EM20VH HLT_e60_lhmedium HLT_e120_lhloose	HLT_mu20_iloose_L1MU15 HLT_mu60_0eta105_msonly HLT_mu50
2016	HLT_e24_lhtight_nod0_ivarloose HLT_e26_lhtight_nod0_ivarloose HLT_e60_lhmedium_nod0 HLT_e140_lhloose_nod0 HLT_e300_etcut	HLT_mu26_ivarmedium HLT_mu50
2017-2018	HLT_e26_lhtight_nod0_ivarloose HLT_e60_lhmedium_nod0 HLT_e140_lhloose_nod0 HLT_e300_etcutP	HLT_mu26_ivarmedium HLT_mu50 HLT_mu60_0eta105_msonly

Table 4.3: Summary of the HLT single-electron and single-muon items used in the slepton and chargino searches.

4.5 Physics object selection

Following on the topics discussed in Chapter 3, in a generic physics analysis the objects of interest (electrons, muons, jets and missing transverse momentum) need to be categorized via several criteria defining their quality. The considered events must have at least one hard scatter interaction vertex with at least two associated tracks whose transverse momentum is required to be greater than 500 MeV. If multiple vertices are found in the event, the identification of the primary one is made by selecting the vertex with the highest scalar sum

of the squared transverse momenta of the associated tracks. Leptons are classified in two categories, *baseline* and *signal*, defined in such a way that the objects categorized as signal are selected with tighter criteria with respect to the baseline ones, and represent a subset of them. Baseline leptons are used for computing the missing transverse energy, to solve ambiguities between the analysis objects and in the FNP lepton background estimation. Signal leptons are used in the final event selection.

The electron reconstruction is performed by the EGAMMA algorithm, using three-dimensional clusters of energy deposits in the electromagnetic calorimeter that are matched to an ID track. A *LooseAndBLayerLLH* particle identification requirement (PID) is applied for baseline electrons, which is a *Loose* likelihood-based criterion [132], plus additional conditions on the number of hits recorded in the innermost layer of the pixel detector, and on the electron transverse momentum ($p_T > 9 \text{ GeV}$) and $|\eta| (< 2.47)$. A further request is applied in terms of the longitudinal impact parameter relative to the reconstructed primary vertex, z_0 , by requiring that tracks associated to baseline electrons are within $|z_0 \sin \theta| < 0.5 \text{ mm}$ of the primary vertex. Signal electrons must satisfy the more stringent *Tight* identification requirement [132] by requesting that the impact parameter of the associated track, d_0 , relative to the primary vertex, and its uncertainty, σ_{d_0} , satisfy the condition $|d_0|/\sigma_{d_0} < 5$.

Baseline muons candidates are reconstructed considering the matching between MS and ID tracks in the pseudorapidity range $|\eta| < 2.6$. Such candidates need to have a transverse momentum greater than 9 GeV and to be within $|z_0 \sin \theta| < 0.5 \text{ mm}$ of the primary vertex. The *Medium* [175] identification requirement is applied, based on the number of hits in ID and MS subsystems and on the significance of the charge-to-momentum ratio q/p . For which concerns signal muons the associated tracks must satisfy the condition $|d_0|/\sigma_{d_0} < 3$.

Signal electrons and muons also satisfy an isolation criterion in order to suppress FNP contribution. By considering a variable-size cone around the lepton, the scalar sum of the transverse momenta of the tracks inside this cone, except the lepton track itself, must be less than the 15% of the lepton p_T . As already introduced in sections 3.2.5 and 3.3.3, track isolation criteria are applied requiring as cone size for electrons (muons) the minimum between $\Delta R = 10 \text{ GeV}/p_T$ and $\Delta R = 0.2$ (0.3). Furthermore, the sum of the transverse energy ($E_T = E/\cosh(\eta)$ from Ref. [174]) of the calorimeter energy clusters in a cone of $\Delta R = 0.2$ around the lepton, excluding the lepton itself, must be for electrons less than 20% of the electron p_T , while for muons less than 30% of the muon p_T .

For which concerns the jet reconstruction, as already described in Chapter 3, the ParticleFlow algorithm is exploited, calibrated at the EM scale, and the anti- k_t algorithm for the jet clustering [144], with the FastJet package [229], is used by fixing the radius parameter to 0.4. The reconstruction is afterwards corrected by including the jet energy scale and the jet energy reconstruction calibrations, derived from 13 TeV data and simulation [146]. Jet candidates must satisfy $p_T > 20 \text{ GeV}$ and $|\eta| < 2.4$. Furthermore, for jets with $p_T < 60 \text{ GeV}$, many of the tracks associated with each jet are required to be originated compatibly with the primary vertex, imposing $JVT > 0.5$ [149], by reducing in this way the pile-up jet fraction to 1%, with a 90% efficiency for pure hard scatter jets. Other final jet requirements [230, 231] are applied to remove events due to detector noise and non-collision background. This ensures that the hard scatter jets are selected with an efficiency greater than 99.5% for $p_T > 20 \text{ GeV}$ and than

99.9% for $p_T > 100$ GeV.

Jets are tagged as coming from b -hadrons by the DL1r algorithm [154] if they lie within $|\eta| < 2.4$, with a b -tagging efficiency of 85% in simulated $t\bar{t}$ events. This ensures rejection factors for the main backgrounds, which are c -jets, τ -jets and jets from light quarks and gluons, of 2, 4 and 31, respectively.

As already introduced in section 3.5, the missing transverse momentum $\mathbf{p}_T^{\text{miss}}$ is defined as the negative sum of all the physics objects (electrons, photons, muons and jets) identified and a soft term associated to those reconstructed tracks passing the baseline requirements but not identified as any object. More useful variables are the missing transverse momentum module, denoted as the missing transverse energy E_T^{miss} , and the missing transverse energy significance, this latter defined in the following way,

$$E_T^{\text{miss}} \text{ significance} = \frac{|\mathbf{p}_T^{\text{miss}}|}{\sqrt{\sigma_L^2(1 - \rho_{LT}^2)}}, \quad (4.11)$$

with σ_L the longitudinal component of the total transverse momentum resolution relative to all the objects in the event and ρ_{LT} the correlation between the parallel and perpendicular components of the transverse momentum resolution for each object [4].

In Table 4.4 the selection criteria applied to define the physical objects used in the analysis are summarized.

4.5.1 Overlap removal

Once the physics objects are defined it is necessary to be sure that each of them is considered in only one category, since it can happen that an object can pass different object definitions criteria, being identified as multiple objects and therefore double counted in the event. The procedure to remove these ambiguities is called *Overlap Removal* (OR), and consists in introducing a set of additional prescriptions. It follows three consecutive steps:

- jet candidates within $\Delta R' = \sqrt{\Delta y^2 + \Delta \phi^2} = 0.2$ of an electron candidate or jets with less than three tracks that lie within $\Delta R' = 0.4$ of a muon candidate are removed, since they are mostly originated from electron showers which deposited energy in the calorimeter or due to muon bremsstrahlung effects;
- electrons or muons within $\Delta R' = \min(0.4, 0.04 + 10 \text{ GeV}/p_T)$ of the surviving jets are discarded, in order to reject leptons coming from the decay of b or c -hadrons;
- if an electron shares an ID track with a muon, the electron is discarded unless the muon is tagged as a minimum-ionizing particle in the calorimeter, in which case the muon is discarded [4].

4.6 Event preliminary selection

Once defined the requirements on the objects used in the analysis, the preliminary selection of the events, based on the peculiar features that signal-like events are expected to exhibit, is

Physics Object	Definition	
Electrons	Baseline	Acceptance $p_T > 9 \text{ GeV}, \eta < 2.47$
		PID quality LooseAndBLayerLLH
		Impact parameter $ z_0 \sin \theta < 0.5 \text{ mm}$
	Signal	Acceptance $p_T > 9 \text{ GeV}, \eta < 2.47$ PID quality TightLLH Isolation FCLoose Impact parameter $ d_0/\sigma_{d_0} < 5$
Muons	Baseline	Acceptance $p_T > 9 \text{ GeV}, \eta < 2.6$
		PID quality Medium
		Impact parameter $ z_0 \sin \theta < 0.5 \text{ mm}$
	Signal	Acceptance $p_T > 9 \text{ GeV}, \eta < 2.6$ PID quality Medium Isolation FCLoose Impact parameter $ d_0/\sigma_{d_0} < 3$
Jets	Signal jets	JVT Tight
		Acceptance $p_T > 20 \text{ GeV}, \eta < 2.4$
	Signal b -jets	b -tagging algorithm DL1r
		Efficiency 85% Acceptance $p_T > 20 \text{ GeV}, \eta < 2.4$

Table 4.4: Summary of the criteria applied to electron, muon and jet candidates in order to define the physical objects used in the slepton and chargino searches.

described here. For both the considered models the same preselection criteria are applied. Events are requested to have exactly two oppositely charged (OS) signal leptons (described in section 4.5), ℓ_1 and ℓ_2 , where ℓ_1 (called *leading lepton*) is the lepton with the highest transverse momentum, $p_T^{\ell_1}$, and ℓ_2 (called *sub-leading lepton*) is the one with the lowest transverse momentum, $p_T^{\ell_2}$. The two leptons must satisfy the requests: $p_T^{\ell_1} > 27 \text{ GeV}$, $p_T^{\ell_2} > 9 \text{ GeV}$ and their invariant mass $m_{\ell\ell} > 11 \text{ GeV}$, in order to remove the background coming from Drell-Yan [232] and low-mass resonances (J/ψ , ϕ' , Υ , ...). According to the flavour of the two signal leptons, events are separated into two classes, same flavour (SF) events, if the two leptons are either both electrons ($e^\pm e^\mp$) or muons ($\mu^\pm \mu^\mp$), and different flavour (DF) events, if the leptons are an electron and a muon ($e^\pm \mu^\mp$). In particular, in order to reduce the VZ (with $V = W, Z$) and Z + jets backgrounds, SF events are also required to have a dilepton invariant mass far away from the Z peak, by imposing $|m_{\ell\ell} - m_Z| > 15 \text{ GeV}$, with $m_Z = 91 \text{ GeV}$. A selection criterion has been imposed on the E_T^{miss} significance, by requiring E_T^{miss} significance > 3 , and a condition has been applied to the number of jets, n_{jet-20} in the events, by imposing $n_{jet-20} < 2$ [4], due to the low hadronic activity expected in both the signal models. A summary of the preselection requests applied in the analysis is reported in

Table 4.5.

Variable	Request
$N_{\text{OS leptons}}$	$= 2$
$p_T^{\ell_1}$	$> 27 \text{ GeV}$
$p_T^{\ell_2}$	$> 9 \text{ GeV}$
$m_{\ell\ell}$	$> 11 \text{ GeV}$
n_{jet-20}	< 2
E_T^{miss} significance	> 3
$ m_{\ell\ell} - m_Z $	$> 15 \text{ GeV (for SF only)}$

Table 4.5: Preselection requirements on SF and DF events.

4.6.1 Kinematic variables

The final event selection has been performed using some kinematic variables which have been found particularly sensitive to the searched SUSY signals. These variables are described in the following.

- The stransverse mass [233, 234] m_{T2} is a widely used variable in SUSY searches. It is a generalization of the transverse mass³¹ m_T in the case of symmetric event topologies with two identical particles both decaying into a visible and an invisible product. In this case the individual transverse momenta of the invisible particles can no longer be directly approximated by the measured missing transverse momentum, because the information about their individual contributions to the missing transverse momentum is lost. The stransverse mass is defined as:

$$m_{T2}(\mathbf{p}_{T,1}, \mathbf{p}_{T,2}, \mathbf{p}_T^{\text{miss}}) = \min_{\mathbf{q}_{T,1} + \mathbf{q}_{T,2} = \mathbf{p}_T^{\text{miss}}} \{ \max[m_T(\mathbf{p}_{T,1}, \mathbf{q}_{T,1}), m_T(\mathbf{p}_{T,2}, \mathbf{q}_{T,2})] \}, \quad (4.12)$$

where $\mathbf{p}_{T,1}$ and $\mathbf{p}_{T,2}$ are the transverse momenta of the two visible particles, while $\mathbf{q}_{T,1}$ and $\mathbf{q}_{T,2}$ are the ones associated to the invisible particles, with the condition $\mathbf{q}_{T,1} + \mathbf{q}_{T,2} = \mathbf{p}_T^{\text{miss}}$. The minimization is performed over all the possible decompositions of $\mathbf{p}_T^{\text{miss}}$. Since the mass of the invisible particle is unknown a priori, it enters as a free parameter in the definition of the stransverse mass, then it has been chosen to be 100 GeV for the slepton case, and 0 GeV for the chargino case, thus defying the m_{T2}^{100} and m_{T2}^0 variables respectively. One peculiarity of these two variables is the fact that they have different kinematic endpoints for SUSY processes and SM backgrounds, thus providing a powerful discrimination between background events and some of the signals considered herein.

³¹The transverse mass m_T is defined as $m_T^2 = m_1^2 + m_2^2 + 2(E_{T,1}E_{T,2} + \mathbf{p}_{T,1} \cdot \mathbf{p}_{T,2})$, where m_1, m_2 are the masses and $\mathbf{p}_{T,1}, \mathbf{p}_{T,2}$ the transverse momenta of the two particles.

- The angular variable $\cos \theta^*$, where θ^* is the polar angle between the produced sparticle and the incoming quark in one of the protons in the collision. This variable is sensitive to the spin of the sparticle [235], and the cross section behaves differently according to the spin of the sparticle: for sleptons, being scalar sparticles, the cross section is proportional to $\sin^2 \theta^*$. Since θ^* is not directly accessible at LHC, the $\cos \theta_{\ell\ell}^*$ variable is built starting from the difference in pseudorapidity of the two leptons, $\Delta\eta_{\ell\ell}$:

$$\cos \theta_{\ell\ell}^* = \tanh \left(\frac{\Delta\eta_{\ell\ell}}{2} \right), \quad (4.13)$$

In the slepton model, it is sensitive to the slepton production angle. The leptons inherit some knowledge of the rapidity of their slepton parents, and the two variables $\cos \theta_{\ell\ell}^*$ and $\cos \theta^*$ are strictly correlated.

- Other useful variables are the azimuthal angular separations between the two leptons, $\Delta\phi_{\ell,\ell}$, between $\mathbf{p}_T^{\text{miss}}$ and the leading lepton, $\Delta\phi_{p_T^{\text{miss}},\ell_1}$, and between $\mathbf{p}_T^{\text{miss}}$ and the sub-leading lepton, $\Delta\phi_{p_T^{\text{miss}},\ell_2}$. The distributions of these variables are strongly affected by the presence of jets in the event. For example, in the case of the slepton pair production, in the absence of jets, the two sleptons are expected to be produced back-to-back³² in the azimuthal plane, and the produced leptons to be well separated in the azimuthal plane. The most energetic $\tilde{\chi}_1^0$ and the sub-leading lepton are expected to come from the same slepton, therefore the $\mathbf{p}_T^{\text{miss}}$ vector is expected to be well separated from the $p_T^{\ell_1}$ direction.
- Another important variable is $p_{T,\text{boost}}^{\ell\ell}$, i.e. the magnitude of the vector $\mathbf{p}_{T,\text{boost}}^{\ell\ell}$, defined as the vector sum of the transverse momentum of the two leptons and the $\mathbf{p}_T^{\text{miss}}$. It can be interpreted as the magnitude of the vector sum of all the transverse hadronic activity in the event. In both of the analyzed SUSY scenarios, in absence of jets, $p_{T,\text{boost}}^{\ell\ell}$ is expected to be low due to the p_T balance of the system. The azimuthal separation between $\mathbf{p}_T^{\text{miss}}$ and $p_{T,\text{boost}}^{\ell\ell}$ is indicated as $\Delta\phi_{\text{boost}}$ [4].

4.6.2 Signal significance Z_n

In order to assess the effectiveness of the discriminating variables and of the defined selections, the significance Z_n of the signal has been exploited in the analysis. Among the several definitions of the significance, the one used during the optimization procedure of these searches has been [236]:

$$Z_n = \sqrt{2 \left[n \log \left(\frac{n(b + \sigma^2)}{b^2 + n\sigma^2} \right) - \frac{b^2}{\sigma^2} \log \left(1 + \frac{\sigma^2(n - b)}{b(b + \sigma^2)} \right) \right]}, \quad (4.14)$$

where: b is the number of background events and σ the related uncertainty; n is the number of observed events, given by the sum of the background and signal (s) events, $n = s + b$.

³²Two particles in the *back-to-back* configuration have an angular separation between their directions of 180° .

4.7 Fake and non-prompt lepton estimate

The reducible background from *fake non-prompt* (FNP) leptons is estimated via a data-driven method, known as *matrix method* (MM) [237], which uses the signal and baseline leptons as defined in Table 4.4. Let's indicate with L the leptons which pass the loose baseline requirement, named *inclusive loose* leptons, with T those passing the tight signal selection, and with l those leptons passing the loose requirement but not the tight one, therefore called *exclusive loose* leptons. Such categorization is schematically reported in Figure 4.4.

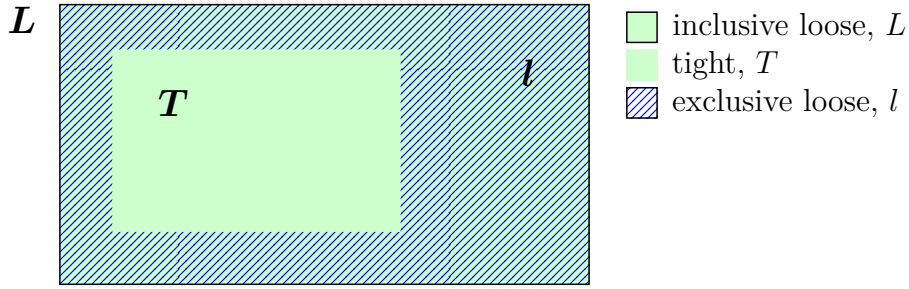


Figure 4.4: Schematic view of the lepton categorization made in the Matrix Method. L stands for inclusive loose leptons, T for tight leptons and l for exclusive loose leptons.

All the observed events containing two inclusive loose leptons are counted and classified into four different categories: N_{TT} , if both the leptons pass the tight requirement, N_{Tl} and N_{lT} , if a lepton passes the tight and the other the exclusive loose requirements, and N_{ll} , if both the leptons are exclusive loose, where the first letter in the subscript indicates the lepton with the highest p_T . Furthermore, the following two probabilities are defined:

- *real efficiency*, r , which is the probability that a real lepton which passed the inclusive loose selection, also passed the tight requirement;
- *fake rate*, f , which is the probability that a fake non-prompt lepton, passing the loose criteria, also passed the tight selection.

Since events with two leptons are considered, the probabilities to be taken into account are four: r_1 , r_2 , f_1 and f_2 , where the subscripts, 1 and 2, indicate the hardest and second hardest lepton in p_T , respectively. These probabilities take into account that: the two leptons can be of opposite flavour ($e\mu$ or μe), and electrons and muons have different probabilities in general; they are dependent on p_T and η of the two leptons. From the knowledge of these probabilities and of the number of events N_{TT} , N_{Tl} , N_{lT} and N_{ll} , the estimated number of events with two real (N_{LL}^{RR}), one real and one FNP (N_{LL}^{RF} and N_{LL}^{FR}) and two FNP (N_{LL}^{FF}) leptons, can be

computed by inverting the following equation:

$$\begin{pmatrix} N_{TT} \\ N_{Tl} \\ N_{lT} \\ N_{ll} \end{pmatrix} = \begin{pmatrix} r_1 r_2 & r_1 f_2 & f_1 r_2 & f_1 f_2 \\ r_1(1-r_2) & r_1(1-f_2) & f_1(1-r_2) & f_1(1-f_2) \\ (1-r_1)r_2 & (1-r_1)f_2 & (1-f_1)r_2 & (1-f_1)f_2 \\ (1-r_1)(1-r_2) & (1-r_1)(1-f_2) & (1-f_1)(1-r_2) & (1-f_1)(1-f_2) \end{pmatrix} \begin{pmatrix} N_{LL}^{RR} \\ N_{LL}^{RF} \\ N_{LL}^{FR} \\ N_{LL}^{FF} \end{pmatrix}, \quad (4.15)$$

thus obtaining:

$$N_{LL}^{RR} = (1-f_1)(1-f_2)N_{TT} - [f_2(1-f_1)]N_{Tl} - [f_1(1-f_2)]N_{lT} + f_1 f_2 N_{ll}, \quad (4.16)$$

$$N_{LL}^{RF} = -(1-f_1)(1-r_2)N_{TT} + [r_2(1-f_1)]N_{Tl} + [f_1(1-r_2)]N_{lT} + f_1 r_2 N_{ll}, \quad (4.17)$$

$$N_{LL}^{FR} = -(1-f_2)(1-r_1)N_{TT} + [f_2(1-r_1)]N_{Tl} + [r_1(1-f_2)]N_{lT} + f_2 r_1 N_{ll}, \quad (4.18)$$

$$N_{LL}^{FF} = (1-r_1)(1-r_2)N_{TT} - [r_2(1-r_1)]N_{Tl} - [r_1(1-r_2)]N_{lT} + r_1 r_2 N_{ll}. \quad (4.19)$$

where these numbers are the expected numbers of events with two (equation 4.16), one (equations 4.17 and 4.18) and zero (equation 4.19) prompt real leptons in a sample of two inclusive loose leptons (thus the LL subscript). In order to predict the expected numbers of events for a sample of two signal (tight) leptons, it's sufficient to multiply equations 4.16 - 4.19 by the appropriate probabilities:

$$N_{TT}^{RR} = r_1 r_2 N_{LL}^{RR} \quad (4.20)$$

$$N_{TT}^{RF} = r_1 f_2 N_{LL}^{RF} \quad (4.21)$$

$$N_{TT}^{FR} = f_1 r_2 N_{LL}^{FR} \quad (4.22)$$

$$N_{TT}^{FF} = f_1 f_2 N_{LL}^{FF}, \quad (4.23)$$

The expected number of FNP leptons in the signal selection is obtained by summing the numbers obtained by the equations 4.21 - 4.23. The real efficiencies, r_1 and r_2 are measured as functions of the lepton p_T and η in MC simulations and using control samples with high purity of real leptons. Similarly the fake rates f_1 and f_2 for FNP leptons are measured with data containing leptons from heavy-flavour hadron decays and from photon conversion, and with MC simulations in suitable control regions dominated by leptons coming from the decay of light-flavour quarks. The relative contributions, in terms of weights, of each of these processes, are extracted from MC simulations and applied to the final FNP probabilities. Once computed, the four probabilities r_1 , r_2 , f_1 and f_2 can be used in the MM to solve the equations above. In order to avoid double counting between the FNP leptons estimated via the described MM from the data and the FNP leptons in the MC simulated samples of events, all the MC simulated events in the analysis with one or more FNP leptons are removed [4].

4.8 Systematic uncertainties

Several sources of experimental and theoretical systematic uncertainties affect the estimation of the SM background and the SUSY signal, and they are taken into account by the likelihood fit. In addition to the sources described below, further search-specific systematic uncertainties for the two channels are described in section 5.4 for the sleptons search and section 6.5 for the chargino search.

4.8.1 Experimental uncertainties

Experimental uncertainties affecting the analysis are described below.

- An important source of experimental systematics comes from the JES and JER uncertainties. They are computed as functions of the jet transverse momentum and pseudorapidity, taking into account the pile-up and the flavour composition of the selected jet sample. By using a combination of data and MC events, such uncertainties are derived including measurements of the transverse momentum balance between a jet and a reference object in samples of dijet, $Z + \text{jets}$ and $\gamma + \text{jets}$ events [146, 238, 239].
- The modelling of $\mathbf{p}_T^{\text{miss}}$ brings an additional uncertainty coming from the soft-term resolution and scale [155].
- Other experimental uncertainties come from the scale factors used to account for differences between the data and the simulation in the identification of b -jets, in the lepton reconstruction and trigger efficiencies.
- Experimental uncertainties which have been found negligible in the analysis are related to the lepton energy scale and resolution [4].

4.8.2 Theoretical uncertainties

Several theoretical uncertainties derive from the modelling of the SM backgrounds which are considered in the analysis, mainly diboson, $t\bar{t}$, single-top (Wt) and $Z + \text{jets}$ backgrounds for the chargino search, and WZ/ZZ diboson and $Z + \text{jets}$ in the slepton search, based on the data-driven procedure used in this case for the background estimation. The theoretical uncertainties are listed in the following.

- The diboson simulated samples are mainly affected by uncertainties in the SHERPA generator, and they are assessed by varying the QCD renormalization and factorization scales and the PDF sets [204]. In order to take into account those uncertainties coming from missing higher order terms in the modelling [240], the QCD factorization and renormalization scales in the matrix elements underwent six variations, by factors of 0.5 and 2, with respect to the nominal values used in the MC generator, avoiding variations in the opposite directions. Other uncertainties related to the resummation and the

matching scales between the matrix element generator and the parton shower are also accounted for.

- The $t\bar{t}$ background estimate is mainly affected by uncertainties associated to the modelling of the parton shower, the initial and final state radiation (ISR/FSR) and the different approaches used for the matching between matrix element and parton shower. In order to estimate those related to the parton shower, a comparison between samples generated with POWHEG BOX interfaced to either PYTHIA 8.186 or HERWIG 7.04 [241, 242] was performed. For which concerns the ISR/FSR uncertainties, they are assessed by using samples from generators with the relevant parameters varied, and comparing them with the ones obtained in the nominal parameter configuration [243]. The last source of uncertainties, associated with the generator chosen, is estimated by comparing the nominal samples with another set obtained with AMC@NLO interfaced to PYTHIA 8.186 [243]
- For single-top production, the main source of theoretical uncertainty comes from the interference between Wt and $t\bar{t}$ samples. The diagram removal method (DR) is used for the nominal sample, and compared with an alternative sample produced using the diagram subtraction method (DS). The comparison is used for estimating the uncertainty [244, 245].
- Finally, the estimation of the Z +jets background is affected by QCD factorization and renormalization scale uncertainties. Also uncertainties coming from the resummation and the matching scales between the parton shower and the matrix element generator [4] are considered.

4.8.3 Fake and non-prompt lepton systematics

The uncertainty on the FNP lepton background, estimated via the MM described in section 4.7, includes several components. The real lepton efficiencies and the electron light-flavour fake rate (standing for fake electrons coming from light-flavour quark decays and computed via MC simulation) are mainly affected by experimental uncertainties on the applied scale factors in order to take into account the differences between data and MC simulations in the lepton trigger, identification, reconstruction and isolation efficiencies. For the heavy-flavour fake rate, which is estimated from a control region, the amount of uncertainty coming from this component, when subtracting the prompt-lepton contamination from the control region, is assessed by varying this contamination and evaluating the changes in the FNP background estimation. The uncertainties coming from the expected composition of FNP leptons is afterwards applied to the signal regions defined in the analysis, along with the statistical uncertainties of the real efficiencies and the fake rates which have been used in the described calculation [4].

CHAPTER

5

Description and results of the slepton search

Description of the search for slepton pair production in pp collisions, where each slepton decays in a lepton (electron or muon) and the lightest neutralino, in moderately compressed regions of the phase space. Discussion and interpretation of the results.

This chapter is devoted to the description of the search for the direct production of slepton pairs $\tilde{\ell}\tilde{\ell}$ in pp collisions at LHC. Only $\tilde{e}$ and $\tilde{\mu}$ are considered (the search for $\tilde{\tau}$ is described in Ref. [246]), and no flavour changing is assumed in the supersymmetric chain, therefore each slepton decays in the relative SM lepton and in the lightest neutralino, as shown in Figure 5.1a. The final state is characterised by the presence of two opposite-sign charged leptons (electrons or muons) with the same-flavour and missing transverse energy, due to the presence of the LSPs, which escape detection. The presence of jets is not expected, except for those due to the initial state radiation (ISR).

As already discussed in the previous chapter, so far the most recent exclusion limit for this process was published by the ATLAS collaboration in Ref. [62], based on Run 2 data, and it is shown in Figure 5.1b and in Figure 5.2a together with the results of other analyses targeting the slepton search. The above mentioned analysis was originally optimized for the observation of the direct production of $\tilde{\chi}_1^+ \tilde{\chi}_1^-$ pairs (via W -boson decay), by focusing on the phase space region with mass-splitting larger than the W -boson mass, $\Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0) = m(\tilde{\chi}_1^\pm) - m(\tilde{\chi}_1^0) > m_W$, and it was re-interpreted in the context of the slepton model. No sensitivity was shown in the *compressed region*, highlighted with the blue arrow in Figure 5.1b, where the mass-splitting is

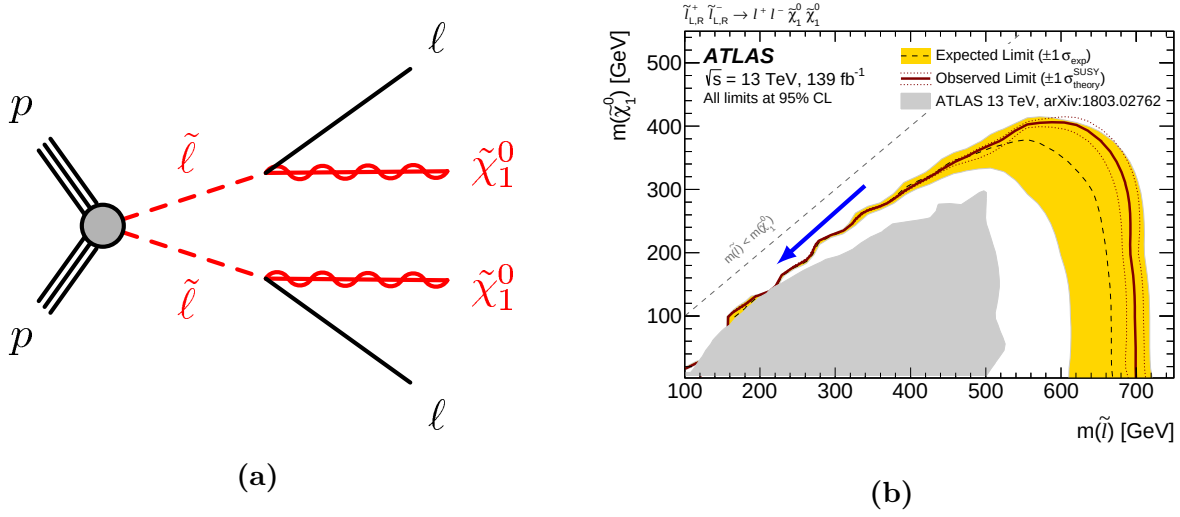


Figure 5.1: (a) Diagram of the slepton pair production model analyzed in this chapter, whose final state is characterized by the presence of two leptons and two neutralinos $\tilde{\chi}_1^0$. (b) Expected and observed exclusion limits for this channel, published in Ref. [62]. The blue arrow indicates the compressed region in the $(m(\tilde{\ell}), m(\tilde{\chi}_1^0))$ mass plane.

lower than the W -boson mass, $\Delta m(\tilde{\ell}, \tilde{\chi}_1^0) = m(\tilde{\ell}) - m(\tilde{\chi}_1^0) < m_W$. The analysis described here was specifically optimized for getting sensitivity in the *moderately compressed region* of the $(m(\tilde{\ell}), m(\tilde{\chi}_1^0))$ plane, with $\Delta m(\tilde{\ell}, \tilde{\chi}_1^0) \sim m_W$. The optimization consists in using a data-driven method for estimating the main background, that is due to those SM processes which mimic exactly the signal signature of two SFOS leptons and E_T^{miss} .

In this chapter, the developed analysis strategy is reported in detail, describing: the criteria chosen to define the signal regions where the slepton signal is expected to arise; the data-driven procedure for estimating the main background; the final results and their interpretation, after looking at the data inside the SRs.

5.1 Status of the ATLAS searches for sleptons

The ATLAS collaboration performed several analyses targeting the discovery of sleptons production in pp collisions. Each of these analyses was developed and optimized to investigate specific portions of the $(m(\tilde{\ell}), m(\tilde{\chi}_1^0))$ phase space, and with specific hypotheses on the kinematics of the produced particles, in such a way that they are mostly independent. Results are combined, and the current status of the exclusion limits is updated from time to time. In Figure 5.2a is reported the overall exclusion limit status in the search for slepton pairs, by 2020, thus before including the results of this analysis, but at the end of this chapter this plot will be proposed again after including them.

The interest on the slepton search in such experimentally challenging regions is strengthened

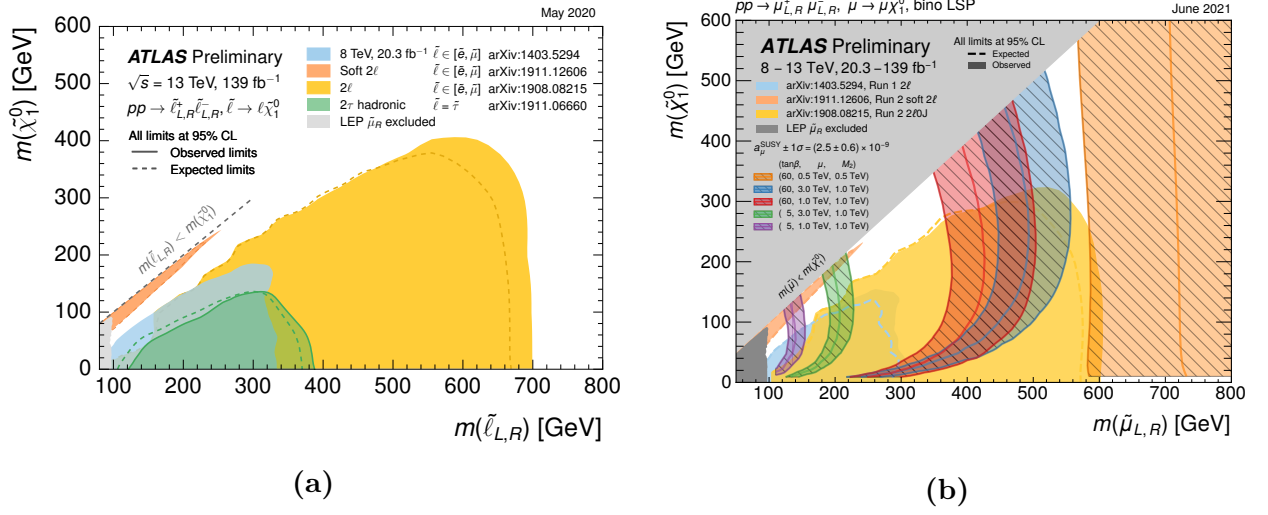


Figure 5.2: Exclusion limits at 95% CL based on 13 TeV data in the (a) $(m(\tilde{\ell}), m(\tilde{\chi}_1^0))$ and (b) $(m(\tilde{\mu}), m(\tilde{\chi}_1^0))$ mass planes for different analyses probing the direct production of (a) sleptons decaying to leptons and neutralinos and of (b) smuons, decaying in muons and neutralinos. For the smuon plot, the hatched bands represents some regions, corresponding to the pMSSM parameters specified in the legend, which are compatible with the observed $(g - 2)_\mu$ anomaly measured by the Fermilab and BNL experiments [247]) [252].

by the fact that light smuons, $\tilde{\mu}$, can explain the $(g - 2)_\mu$ anomaly³³ [248, 249], via the addition of loop corrections involving such exotic particles. In particular those regions of the $(m(\tilde{\mu}), m(\tilde{\chi}_1^0))$ mass plane where $m(\tilde{\mu}) - m(\tilde{\chi}_1^0) \lesssim m_W$ are favoured to explain the $(g - 2)_\mu$ anomaly for small values of $\tan\beta$ [250], defined in the MSSM as the ratio between the vacuum expectation values of the two complex Higgs doublets. Previous LEP and LHC searches [251] already excluded portions of the mass plane, and this search extends the results beyond the previous limits. In Figure 5.2b is reported the status of the ATLAS searches for the discovery of smuons by 2021.

5.2 Signal Region definition

The slepton search was optimized by using some benchmark signal points³⁴, with particular attention to those points still not excluded from the previously published limits. The first

³³The magnetic dipole momentum of a charged particle is proportional to the g-factor, g , which is predicted to be 2 in relativistic quantum mechanics. In quantum field theory, with radiative corrections taken into account, the g-factor is expected to be larger than 2, and the amount of deviation is known as anomalous magnetic momentum, $a = (g - 2)/2$. In case of the muon anomalous magnetic momentum, $a_\mu = (g - 2)_\mu/2$, there is a discrepancy of about 5σ between its SM predicted value and the one recently measured by the Fermilab Muon $g - 2$ experiment [247]. This discrepancy could be explained by the presence of additional radiative corrections due to new particles like, in case of supersymmetry, the smuons.

³⁴The benchmark signal points used are $\Delta m(\tilde{\ell}, \tilde{\chi}_1^0) = (100, 70), (100, 50), (150, 100), (150, 120)$ GeV.

step consisted in the application of the preselection criteria described in Table 4.5, which acted as a preliminary filter of the events requiring, as already mentioned, only events with two OS leptons (electrons or muons), with some requirements on their transverse momenta ($p_T^{\ell_1} > 27$ GeV and $p_T^{\ell_2} > 9$ GeV), on the dilepton mass ($m_{\ell\ell} > 11$ GeV, $|m_{\ell\ell} - m_Z| > 15$ GeV), and on the number of jets. The targeted final state in the slepton production has only same-flavour leptons (SFOS), missing transverse energy and low hadronic activity, except for the initial-state radiation (ISR) or pile-up. In Figure 5.3 an ATLAS event display of a $\tilde{e}\tilde{e}$ event candidate is shown, characterized by two electrons (identified as the two energy clusters in the EM calorimeter matching with two tracks in the inner detector), missing transverse energy and no hadronic activity.

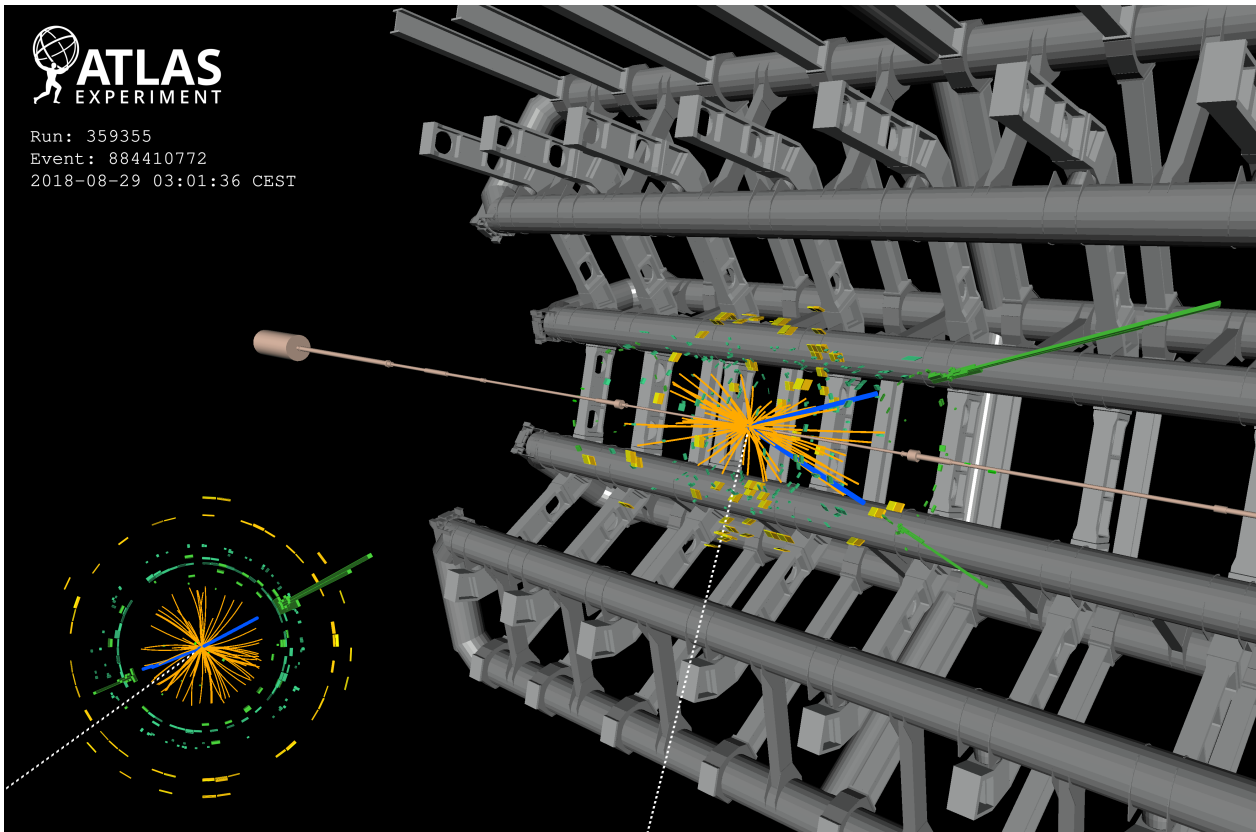


Figure 5.3: ATLAS event display of a candidate $\tilde{e}\tilde{e}$ pair production event, decaying into electrons and $\tilde{\chi}_1^0\tilde{\chi}_1^0$, recorded during $\sqrt{s} = 13$ TeV pp collisions at LHC in the year 2018. The event is shown along with a portion of the ATLAS detector on the right, and in the transverse, (x, y) , plane on the left. Tracks of charged particles reconstructed in the inner detector are shown in orange. The matching between these tracks and the energy clusters in the EM calorimeter (green) allows the reconstruction of electrons (blue). The E_T^{miss} is indicated via the dashed white line. The measured transverse momenta of the two electrons are 159 GeV and 55 GeV, while the E_T^{miss} has magnitude 101 GeV. From these values the measured ‘transverse mass’ (m_{T2}^{100}) is 104 GeV (auxiliary material of Ref. [4]).

After the preselection, only events with no b -jets were selected (by requiring $n_{b\text{-tagged jets}} = 0$), in order to reduce the contamination from $t\bar{t}$ and single-top backgrounds. Furthermore, a distinction was made in terms of the non- b -tagged jets multiplicity, leading to two different SRs: SR-0J with no hadronic jets ($n_{\text{non-}b\text{-tagged jets}} = 0$) and SR-1J with one hadronic jet ($n_{\text{non-}b\text{-tagged jets}} = 1$). Further requests were applied, by exploiting the kinematic variables defined in section 4.6.1. These criteria have been optimized by using the $N-1$ plots technique, which consists in finding the best requirement on a variable after applying the optimal criterion on all the other selected variables, except the one under study. The procedure is iterated until no further optimization is possible. The best selection was finally assessed by looking at the kinematic distributions of the main discriminating variable and by maximizing the significance of the signal, defined in equation 4.14.

In particular, for both the SRs the E_T^{miss} significance > 7 request was applied, in order to reduce the $Z + \text{jets}$ background. The requirements on the leading lepton transverse momentum ($p_T^{\ell_1} > 140$ GeV for the SR-0J and $p_T^{\ell_1} > 100$ GeV for the SR-1J) were driven by the E_T^{miss} significance > 7 request, because of the correlation between the E_T^{miss} significance and the $p_T^{\ell_1}$ variables. The $p_T^{\ell_2}$ is instead not affected by any correlation with E_T^{miss} significance. Moreover, only for the SR-1J, the $m_{\ell\ell}$ request was increased up to 60 GeV, to ensure the orthogonality with an ATLAS Run 2 analysis [253], which investigated the same compressed region, but requiring $m_{\ell\ell} < 60$ GeV, aiming to a future combination. In the 0J case selections on $p_{T,\text{boost}}^{\ell\ell}$ and $\Delta\phi_{p_T^{\text{miss}},\ell_1}$ were applied in order to balance the transverse momentum in the event, which are no longer useful for the 1J event category since the presence of the jet implies that the E_T^{miss} significance and the leptons p_T are not balanced anymore.

Finally, the most sensitive variable for the signal from background discrimination was found to be the transverse mass m_{T2} , since SM background and signal have different endpoints in this variable, as schematically illustrated in Figure 5.4a. In the definition of the transverse mass, the mass of the invisible particle is a free parameter. If its mass is exactly the one of the real invisible particle, m_{inv} , the m_{T2} distribution has a kinematic endpoint in correspondence of the mass of the mother particle (the slepton), as shown in Figure 5.4b.

On the contrary, if the hypothesis on the mass of the invisible particle is different from the real invisible particle mass, then the kinematic endpoint is at $\sim m_{\text{inv}} + \Delta m$, with Δm the difference between the mother particle and the invisible particle masses, as shown in Figure 5.4c. This feature of the m_{T2} variable gives different sensitivity to different slepton masses and different mass-splittings. The hypothesis for the invisible particle mass at 100 GeV gave in this analysis the best sensitivity, therefore the m_{T2}^{100} variable was used. Two different sets of SRs were defined in terms of this variable and according to different fit configurations: a set of *exclusive* SRs, ‘binned’ in m_{T2}^{100} , to be used for a model-dependent fit, and a set of *inclusive* SRs, for the model-independent results. The binning in m_{T2}^{100} was chosen to maximize the search sensitivity and retain a sufficient number of events in each bin, and the ‘inclusive’ SRs were defined for various lower bounds on m_{T2}^{100} to enhance sensitivity to new physics with various mass scales [4]. The selection criteria used for the ‘binned’ and ‘inclusive’ SRs definitions are summarized in Table 5.1.

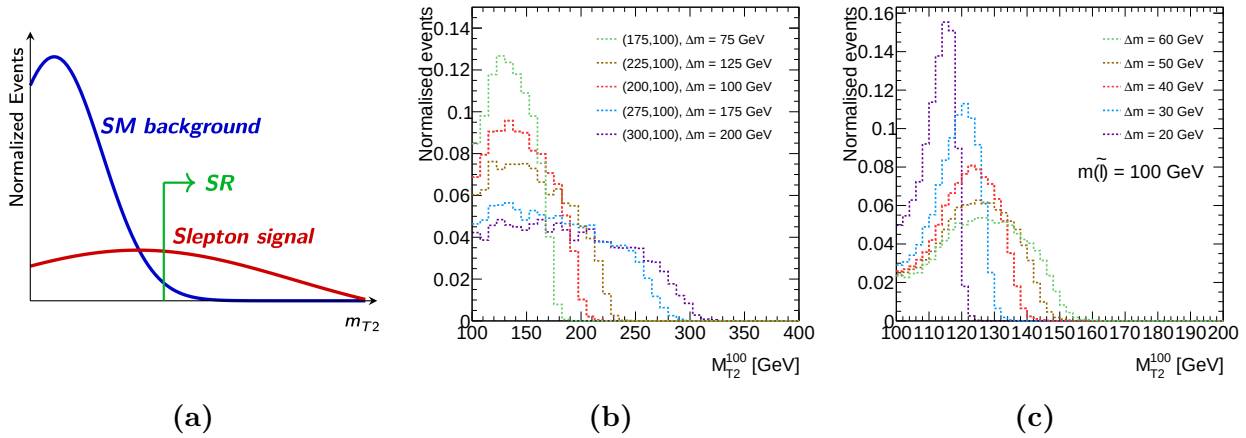


Figure 5.4: (a) Schematic plot of the m_{T2} variable for the SM background and the slepton signal, showing how they generally have different kinematic endpoints for this variable. (b) Comparison between M_{T2}^{100} distributions of signal points with the same invisible particle mass, but with different slepton masses, showing different endpoints as function of the slepton mass. (c) Comparison between M_{T2}^{100} distributions of the signal points with the same slepton mass but with different mass-splittings, showing different endpoints as function of the mass-splitting. M_{T2}^{100} (referred as m_{T2}^{100} in the text) indicates the m_{T2} variable assuming the mass of the invisible particle to be 100 GeV.

5.3 Flavour symmetric background estimation

The slepton pair production is a *flavour asymmetric* process, because it is characterized by events with two OS leptons with the same-flavour (100%), while the most relevant irreducible SM backgrounds ($t\bar{t}$, single-top, WW , $Z(\rightarrow \tau\tau) + \text{jets}$) are *flavour symmetric* (FS) processes, since in the final state they can have both same-flavour and different-flavour lepton pairs with the same probability (50%). It is possible to exploit this peculiarity in order to estimate the amount of *flavour symmetric background* (FSB) which enters the SRs. A dedicated data-driven technique was applied, consisting in estimating the SF background events due to the FSB in the SRs from the DF data passing the SR criteria of Table 5.1. From a practical point of view, the estimation is not straightforward, since differences between electrons and muons, in terms of identification, isolation, reconstruction and trigger efficiencies, must be accounted for. The applied technique is called *efficiency correction method* and it is described in the following section³⁵.

5.3.1 The efficiency correction method

After subtracting the FNP lepton contribution, the number of data events with DF leptons which passed the SRs requirements (N_{DF}) can be used to estimate the FSB contribution in the SF channel. The efficiency correction method foresees an event reweighting, on an event-

³⁵A second method, called *transfer factor*, has also been exploited during the analysis in order to validate the results of the efficiency correction method. The transfer factor approach is not discussed in this thesis.

Signal region (SR)	SR-0J	SR-1J
$n_{b\text{-tagged jets}}$	= 0	
E_T^{miss} significance	>7	
$n_{\text{non-}b\text{-tagged jets}}$	= 0	= 1
$p_T^{\ell_1}$ [GeV]	> 140	> 100
$p_T^{\ell_2}$ [GeV]	> 20	> 50
$m_{\ell\ell}$ [GeV]	> 11	> 60
$p_{T,\text{boost}}^{\ell\ell}$ [GeV]	< 5	-
$ \cos\theta_{\ell\ell}^* $	< 0.2	< 0.1
$\Delta\phi_{\ell,\ell}$	> 2.2	> 2.8
$\Delta\phi_{p_T^{\text{miss}},\ell_1}$	> 2.2	-
Binned SRs		
m_{T2}^{100} [GeV]	$\in[100,105)$	
	$\in[105,110)$	
	$\in[110,115)$	
	$\in[115,120)$	
	$\in[120,125)$	
	$\in[125,130)$	
	$\in[130,140)$	
	$\in[140,\infty)$	
Inclusive SRs		
m_{T2}^{100} [GeV]	$\in[100,\infty)$	
	$\in[110,\infty)$	
	$\in[120,\infty)$	
	$\in[130,\infty)$	
	$\in[140,\infty)$	

Table 5.1: The definitions of the binned and inclusive signal regions for the slepton model in terms of the relevant kinematic variables described in the text. The ‘0J’ and ‘1J’ labels refer to the multiplicity of non- b -tagged jets [4].

by-event basis, according to the differences between electrons and muons mentioned before, by introducing two factors, named κ and α . Once the number of DF events is computed, it is possible to measure the expected numbers of dielectron ee events (N_{ee}^{exp}) and dimuon $\mu\mu$ events ($N_{\mu\mu}^{\text{exp}}$) from:

$$N_{ee}^{\text{exp}} = \frac{1}{2} \frac{\alpha}{\kappa} N_{DF}, \quad N_{\mu\mu}^{\text{exp}} = \frac{1}{2} \kappa \alpha N_{DF}, \quad (5.1)$$

and the expected total number of SF events is given by:

$$N_{SF}^{\text{exp}} = N_{ee}^{\text{exp}} + N_{\mu\mu}^{\text{exp}} = \frac{1}{2} \left(\frac{1}{\kappa} + \kappa \right) \alpha N_{DF}. \quad (5.2)$$

The $1/2$ factor takes into account the fact that the DF rate is a factor two larger than the dielectron plus dimuon rate. The differences in muon and electron acceptance, identification efficiency and reconstruction efficiency are taken into account by κ , defined as:

$$\kappa = \sqrt{\frac{N_{\mu^+\mu^-}}{N_{e^+e^-}}}, \quad (5.3)$$

with $N_{\mu^+\mu^-}$ and $N_{e^+e^-}$ being the numbers of dimuon and dielectron events respectively. The trigger efficiency differences are instead considered by the α factor, defined as:

$$\alpha = \frac{\sqrt{\varepsilon_{\mu\mu}^{\text{trig}} \varepsilon_{ee}^{\text{trig}}}}{\varepsilon_{e\mu}^{\text{trig}}}, \quad (5.4)$$

with $\varepsilon_{\mu\mu}^{\text{trig}}$, $\varepsilon_{ee}^{\text{trig}}$ and $\varepsilon_{e\mu}^{\text{trig}}$ the efficiencies for triggering dimuon, dielectron and electron-muon events with the triggers described in section 4.4, given by:

$$\varepsilon_{\mu\mu,ee,e\mu}^{\text{trig}} = \left(\frac{N^{E_T^{\text{miss}} \text{ \& singlelep triggers}}}{N^{E_T^{\text{miss}} \text{ trigger}}} \right)_{\mu\mu,ee,e\mu}, \quad (5.5)$$

where the denominator represents the number of $\mu\mu$, ee , $e\mu$ events which passed the E_T^{miss} trigger (which is orthogonal to the single-lepton trigger used in the analysis) and the numerator is the number of events which passed both the E_T^{miss} and single-lepton triggers.

The κ and α factors have been computed both inclusively and in different pseudorapidity regions, by extracting their values from properly defined control regions.

5.3.1.1 The κ factor

The control region to extract the κ factor, named CR^{eff} , was defined by relaxing the requirements on the transverse momentum of the leading lepton and on E_T^{miss} significance and inverting the selection in $|\cos\theta_{\ell\ell}^*|$, to be orthogonal with the SRs and therefore completely independent from them. A tighter selection, with respect to the preselection, was performed to ensure a higher purity of the backgrounds expected in the SRs. The selection criteria of CR^{eff} are reported in Table 5.2.

The agreement between data and MC simulation was verified inside the control region, and thus the κ values directly extracted. The results are reported in Table 5.3, showing, for both data and MC, an inclusive κ value and the values for different η regions: *central*, if at least one of the lepton entered in the barrel region ($|\eta| < 1.05$), *bar-bar*, if both the leptons were in the barrel region, *end-end*, if both the leptons were in the end-cap region ($|\eta| > 1.05$), and *bar-end*, if one lepton was in the barrel and the other in the end-cap. As expected, κ tends to be lower in the barrel cases, because of lack of coverage for muons in the region $|\eta| < 0.1$.

The differences arising for the κ factor in the different pseudorapidity regions were due to the inclusion of events with low transverse momentum of the leading lepton. The factor was

Variable	Request		MC (FS)	Data
n_{jet-20}	< 2	κ	1.1576 ± 0.0014	1.1942 ± 0.0043
$N_{OS \text{ leptons}}$	$= 2$	$\kappa^{central}$	0.8509 ± 0.0042	0.852 ± 0.013
$p_T^{\ell_1}$	$> 30 \text{ GeV}$	$\kappa^{bar-bar}$	1.0352 ± 0.0029	1.0655 ± 0.0089
$p_T^{\ell_2}$	$> 9 \text{ GeV}$	$\kappa^{end-end}$	1.38526 ± 0.0042	1.440 ± 0.010
E_T^{miss}	> 6	$\kappa^{bar-end}$	1.1947 ± 0.0020	1.2198 ± 0.0061
significance	> 0.2			
$ \cos \theta_{\ell\ell}^* $				

Table 5.2: Selection criteria for CR^{eff} used to estimate κ .

Table 5.3: Values of the κ factor calculated inclusively and in different η regions of the detector for MC (FS) and data. Only statistical uncertainties are considered.

found to be uniform for high values of $p_T^{\ell_1}$, indeed, independently from the η region considered. To account for this behaviour, the κ factor was fitted to the function:

$$\kappa(p_T^{\ell_1}) = b + \frac{a}{p_T^{\ell_1}}, \quad (5.6)$$

where the parameter a affects κ at low $p_T^{\ell_1}$ values, whilst b represents the asymptotic behaviour for high values of the leading lepton transverse momentum. The high threshold in $p_T^{\ell_1}$ requested in the two SRs ensures to be in the asymptotic regime, where no dependencies on $p_T^{\ell_1}$ are shown. In Figure 5.5 the κ factor is shown as function of the trasverse momentum of the leading lepton, $p_T^{\ell_1}$, for data (points) and MC (colored lines) in the different η regions of Table 5.3.

5.3.1.2 The α factor

The α factor was computed from the global efficiencies of the trigger selections applied in the analysis, by using a control sample selected with the criteria reported in Table 5.4. The requirements $E_T^{miss} > 230 \text{ GeV}$ and $p_T^{\ell_1} > 30 \text{ GeV}$ ensured to be on the efficiency plateau of the E_T^{miss} trigger. The global trigger efficiencies and the values for the α factor, measured both inclusively and in different η regions (the same considered for the κ factor), are reported in Table 5.5 as obtained in data and in MC. The trigger efficiencies as functions of the leading-lepton p_T are shown in Figure 5.6a for data and in Figure 5.6b for MC. It can be observed in these figures that for $p_T^{\ell_1} > 30 \text{ GeV}$ the trigger efficiency plateau is reached.

In Figure 5.7a the MC/data ratio of the efficiencies is shown for the three different channels considered, showing a good agreement within statistical uncertainties in the whole $p_T^{\ell_1}$ range. In Figure 5.7b the α values are reported for both data and MC, showing an agreement which stays around the 1%, within the statistical uncertainties.

Variable	Request
n_{jet-20}	< 2
$N_{OS\ SF\ leptons}$	$= 2$
$p_T^{\ell_1}$	$> 30\ \text{GeV}$
$p_T^{\ell_2}$	$> 20\ \text{GeV}$
E_T^{miss}	$> 230\ \text{GeV}$
$m_{\ell\ell}$	$> 11\ \text{GeV}$
$ m_{\ell\ell} - m_Z $	$> 15\ \text{GeV}$

Table 5.4: Selection criteria for the control sample used to estimate the trigger efficiencies $\varepsilon_{ee}^{\text{trig}}$, $\varepsilon_{\mu\mu}^{\text{trig}}$ and $\varepsilon_{e\mu}^{\text{trig}}$.

	MC	Data
$\varepsilon_{ee}^{\text{trig}}$	0.9915 ± 0.0019	0.9945 ± 0.0039
$\varepsilon_{\mu\mu}^{\text{trig}}$	0.9791 ± 0.0027	0.9803 ± 0.0080
$\varepsilon_{e\mu}^{\text{trig}}$	0.9879 ± 0.0012	0.9865 ± 0.0045
α	0.9973 ± 0.0021	$1.0008^{+0.0062}_{-0.0093}$
$\alpha^{\text{bar-bar}}$	0.9968 ± 0.0035	$1.006^{+0.007}_{-0.016}$
$\alpha^{\text{end-end}}$	0.9902 ± 0.0048	$1.010^{+0.018}_{-0.037}$
$\alpha^{\text{bar-end}}$	0.9996 ± 0.0031	$0.992^{+0.010}_{-0.018}$

Table 5.5: The first three lines report the global trigger efficiencies $\varepsilon_{ee}^{\text{trig}}$, $\varepsilon_{\mu\mu}^{\text{trig}}$ and $\varepsilon_{e\mu}^{\text{trig}}$ calculated in MC and in data. The other lines report the values, for MC and data, of the α factors computed both inclusively and in different η regions.

5.3.1.3 Validation of the FS background estimation

In order to validate the efficiency correction method, two validation regions, VR-0J and VR-1J, were defined, with the same selection of the SR-0J and SR-1J respectively, but inverting the $|\cos \theta_{\ell\ell}^*|$ requirement, so that the orthogonality condition was ensured. These regions were chosen close to the SRs. The selection criteria are reported in Table 5.6.

Although the validation regions are a subset of the control sample used to extract the κ factor, they use different events, since in these VRs the FSB contribution is evaluated from DF events in data using equation 5.2. In Figure 5.8 the data-MC distributions are reported for VR-0J and VR-1J for each of the m_{T2}^{100} bins composing the binned SRs, showing a good agreement between the data and the total estimated SM background [4].

Once the κ and α factors were extracted and validated, they were applied to the DF data observed in the SRs in order to estimate the amount of SF events related to the FS background. A total of 71 DF events were observed in data, 40 of which with both leptons in the barrel region, 21 with both leptons in the end-caps and 10 with one lepton in the barrel and the other one in the end-cap. By applying, on an event-by-event basis, the κ and α factors to the DF data surviving the SR selections, via equations 5.1 and 5.2, the estimated amount of ee , $\mu\mu$ and total SF, for both SR-0J and SR-1J, are reported in first, second and third columns respectively of Table 5.7. Subdominant irreducible SM background contributions arising from Drell-Yan, $t\bar{t} + \text{boson}(s)$, tZ , $t\bar{t}t\bar{t}$, $t\bar{t}t$, Higgs boson, and VVV processes, referred to as ‘Other backgrounds’ (or ‘Others’), are estimated from simulation using the samples described in section 4.3.2 [4]. The reducible background from FNP leptons is estimated from data using the matrix method (MM) as described in section 4.7.

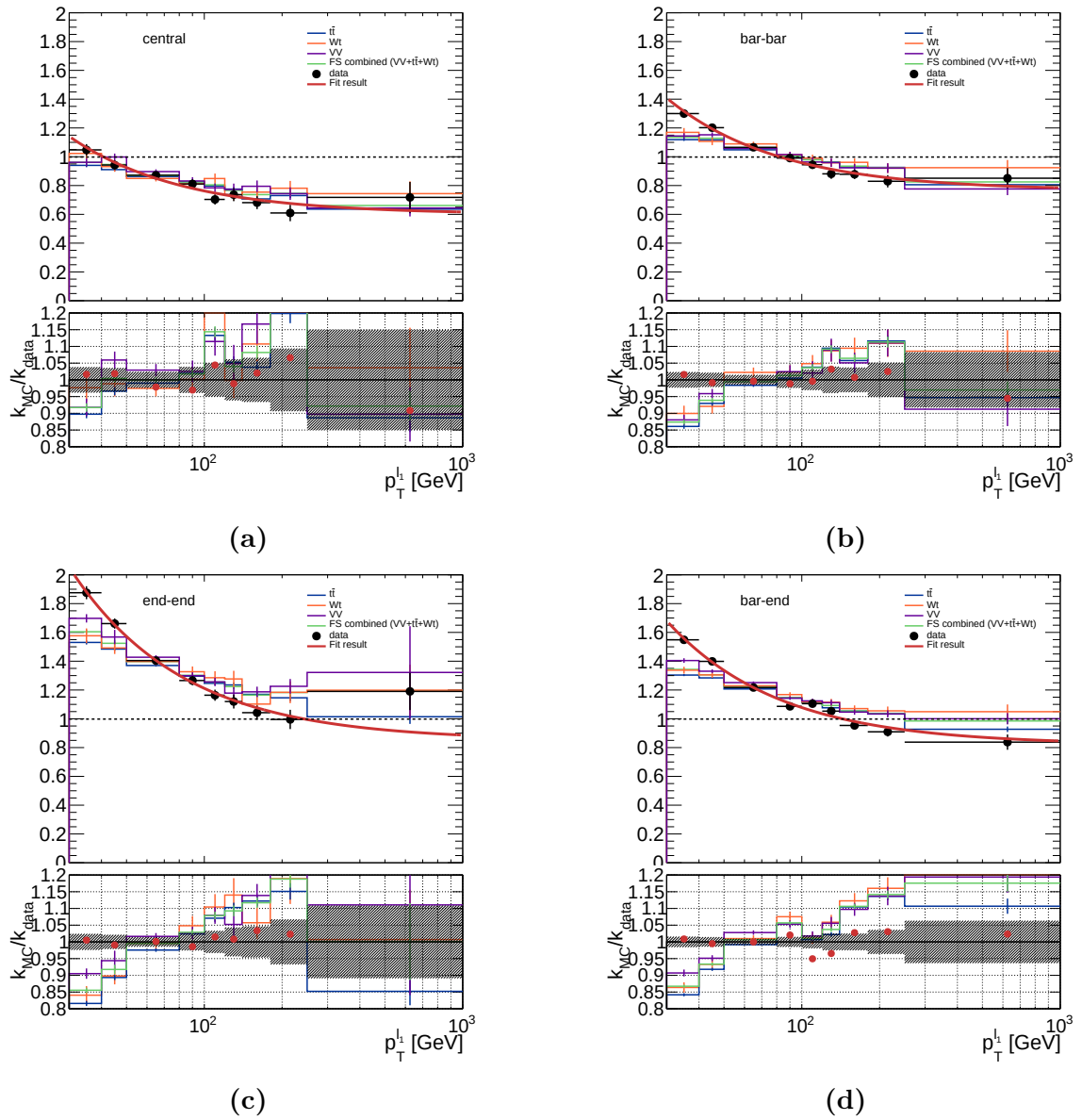


Figure 5.5: κ factor as function of the transverse momentum of the leading lepton, $p_T^{\ell_1}$, for data (points) and MC (colored lines) in the different η regions of Table 5.3. The MC κ factor is shown for different FS backgrounds: $t\bar{t}$ (blue), single-top (orange), VV (purple). The fit with the function 5.6 is performed only for the data, and the red line represents the fitted function. The bottom plot in each canvas is the data/MC ratio. Only statistical uncertainties are considered.

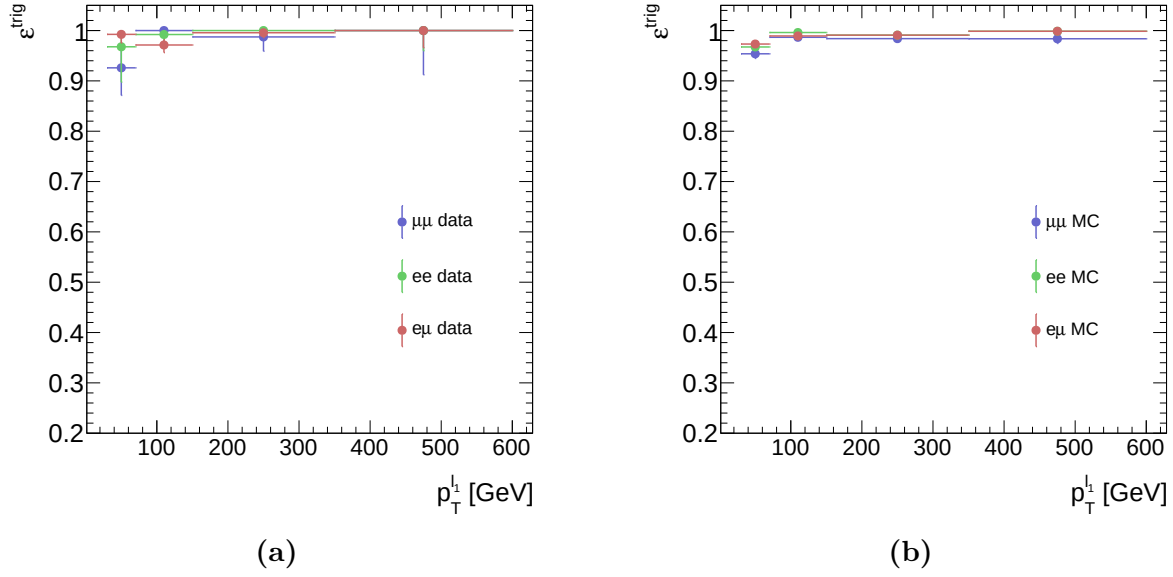


Figure 5.6: Trigger efficiencies for data (a) and MC (b) as function of $p_T^{\ell_1}$, in three different channels: $\mu\mu$ (blue), ee (green), and $e\mu$ (red). The MC included the $t\bar{t}$, single-top, $Z(\rightarrow \tau\tau) + \text{jets}$, VV and VVV backgrounds. Only statistical uncertainties are shown.

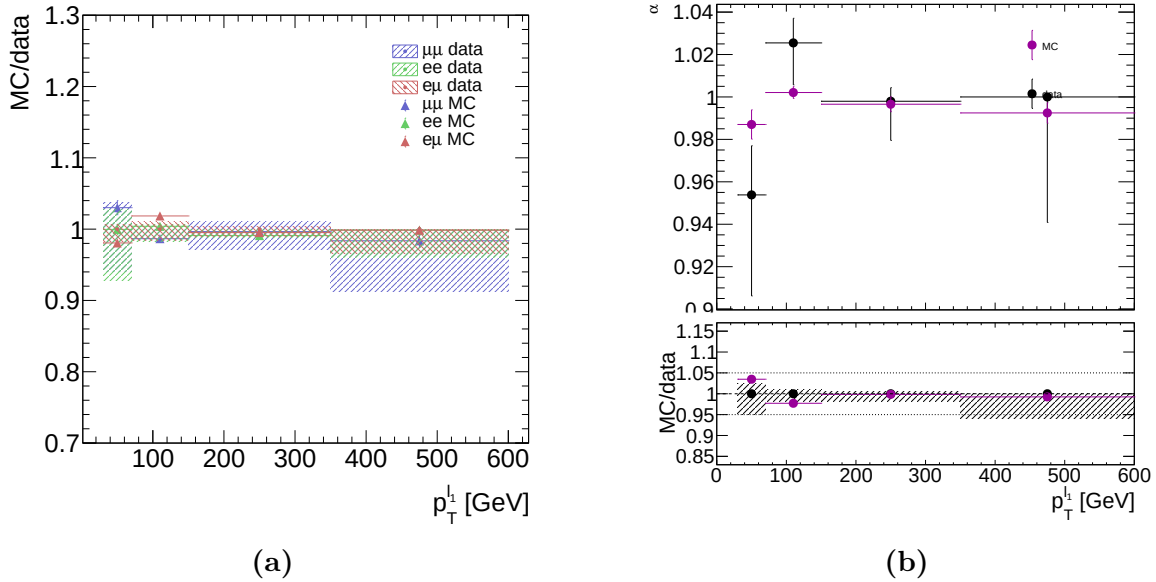


Figure 5.7: (a) MC trigger efficiencies normalized to data as functions of $p_T^{\ell_1}$, in three different channels: $\mu\mu$ (blue), ee (green), and $e\mu$ (red). (b) The α factor, calculated for data (black) and MC (purple) as functions of $p_T^{\ell_1}$. The bottom plot shows the MC/data ratio. The MC includes the $t\bar{t}$, single-top, $Z(\rightarrow \tau\tau) + \text{jets}$, VV and VVV backgrounds. Only statistical uncertainties are shown.

Validation region (VR)	VR-0J	VR-1J
$n_{b\text{-tagged jets}}$	$= 0$	
E_T^{miss} significance	> 7	
$n_{\text{non-}b\text{-tagged jets}}$	$= 0$	$= 1$
$p_T^{\ell_1}$ [GeV]	> 140	> 100
$p_T^{\ell_2}$ [GeV]	> 20	> 50
$m_{\ell_1\ell_2}$ [GeV]	> 11	> 60
$p_{T,\text{boost}}^{\ell\ell}$ [GeV]	< 5	-
$ \cos\theta_{\ell\ell}^* $	> 0.2	> 0.1
$\Delta\phi_{\ell,\ell}$	> 2.2	> 2.8
$\Delta\phi_{p_T^{\text{miss}},\ell_1}$	> 2.2	-

Table 5.6: The definitions of the validation regions for validating the FSB estimation method. Relevant kinematic variables are defined in the text. The ‘0J’ and ‘1J’ labels refer to the multiplicity of non- b -tagged jets.

SR	ee events	$\mu\mu$ events	Total
SR-0J	34.6 ± 4.9	30.2 ± 4.4	64.8 ± 9.3
SR-1J	37.1 ± 5.0	31.8 ± 4.46	68.9 ± 9.4

Table 5.7: Yields of the flavour symmetric background, separated in dielectron, dimuon and total events, for both the SR-0J and SR-1J. The background is estimated via the DF data events surviving the SRs selection and applying the factors κ and α on an event-by-event basis. Only statistical uncertainties are shown [4].

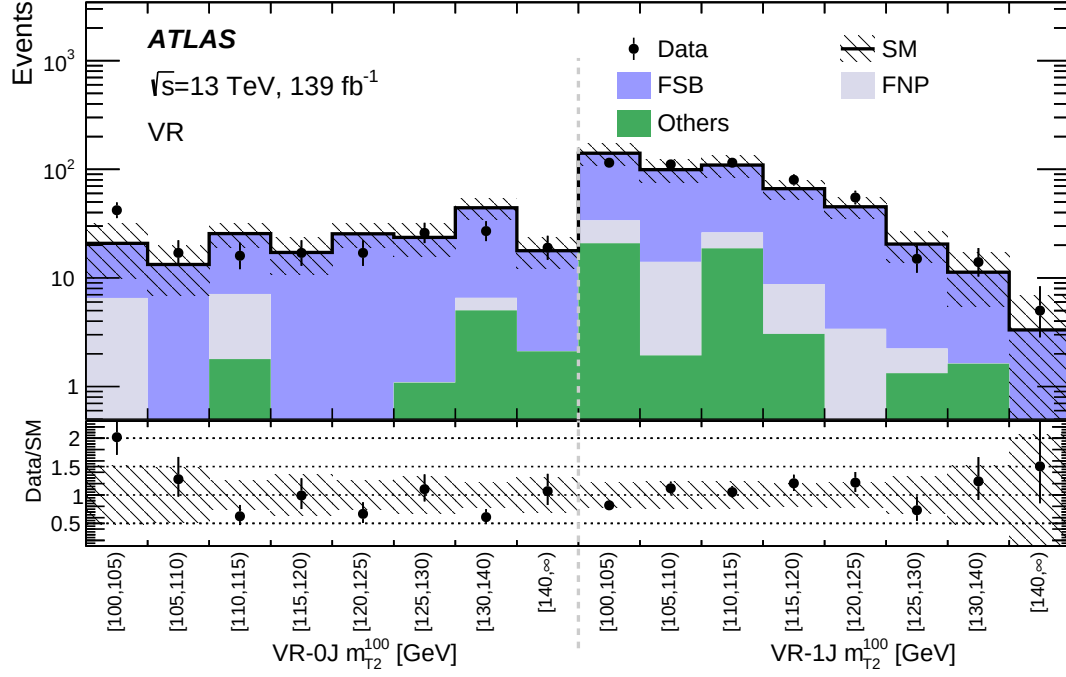


Figure 5.8: In the upper panel the distribution of the m_{T2}^{100} variable in the two binned VR-0J and VR-1J for both data and estimated SM backgrounds. The contribution of the FSB is estimated via the efficiency correction method, while the FNP lepton background is estimated via the matrix-method. The ‘Others’ category includes the non-dominant background sources, e.g. $t\bar{t}+V$, Higgs boson and Drell-Yan events. The total uncertainty on the SM background simulation is represented by the shaded band. The lower panel reports the ratio between data and the total SM background estimation [4].

5.4 Systematic uncertainties

In addition to the ones described in section 4.8, other uncertainties, directly related to the data-driven method for the FS background estimation, need to be taken into account for the slepton search. The statistical uncertainty of the DF sample is included.

In the computation of the α factor the source of systematic uncertainty directly comes from the differences between the data and the MC in the measurement of the global trigger efficiencies. Such source of uncertainty was propagated along with the statistical uncertainty, assuming that there are no correlations among dielectron, dimuon and electron-muon events. In the computation of the κ factor the main systematic uncertainty is related to the different η regions considered for the measurement.

Moreover, if the FS background estimation was evaluated by reweighting in terms of the sub-leading lepton transverse momentum, instead of the leading lepton one, it would have produced differences lower than 1% in the estimation of the FS background, therefore an additional uncertainty was included to take into account this effect. Finally, other systematic source of uncertainty came from the fit function chosen for the κ factor estimation. In Table 5.8 is reported a list of the several sources of systematic uncertainties, and their percentage impact on the background yields in the largest inclusive SR ($m_{T2}^{100} \in [100, \infty)$ GeV), for both ‘0J’ and ‘1J’ channel, after performing the likelihood fit [4].

Region m_{T2}^{100} [GeV]	SR-0J $\in [100, \infty)$	SR-1J $\in [100, \infty)$
Total background expectation	76	78
MC and FSB statistical uncertainties	14%	13%
FSB estimate	9%	9%
FNP leptons	5%	4%
$Z/\gamma^*(\rightarrow \ell\ell)$ +jets theoretical uncertainties	< 1%	3%
E_T^{miss} modelling	2.3%	< 1%
Jet energy scale	< 1%	< 1%
Jet energy resolution	< 1%	1%
b -tagging	< 1%	< 1%
Lepton modelling	1%	< 1%
Total systematic uncertainty	17%	17%

Table 5.8: Summary of the dominant systematic uncertainties in the background estimation in the inclusive SRs requiring $m_{T2}^{100} \in [100, \infty)$ GeV for the ‘0J’ and ‘1J’ selections in the slepton search. The individual uncertainties can be correlated, and do not necessarily sum in quadrature to the total background uncertainty. The percentages represent the size of the uncertainty relative to the total background expectation [4].

5.5 Results and interpretation

After the ‘unblinding’ of the analysis, the data inside the SRs were revealed, and the statistical interpretation of the results was performed with the HISTFITTER framework, described in section 4.1, through the likelihood fit.

In Figure 5.9 the data-MC comparison between the expected background, predicted via the method previously described, and the observed data in each of the binned SRs defined in Table 5.1 is reported. In most of the bins there is a good data-MC agreement except in some bins, where the disagreement was carefully investigated. Such discrepancies are described below.

- **SR-0J:** In two m_{T2}^{100} bins, [115,120) and [125,130) GeV, the expected background exceeds the observed data with a local significance of about 2σ . The same behaviour is observed in these bins when using pure MC simulations to estimate the background, instead of the data-driven method. Therefore the disagreement most likely arises from statistical fluctuations in data.

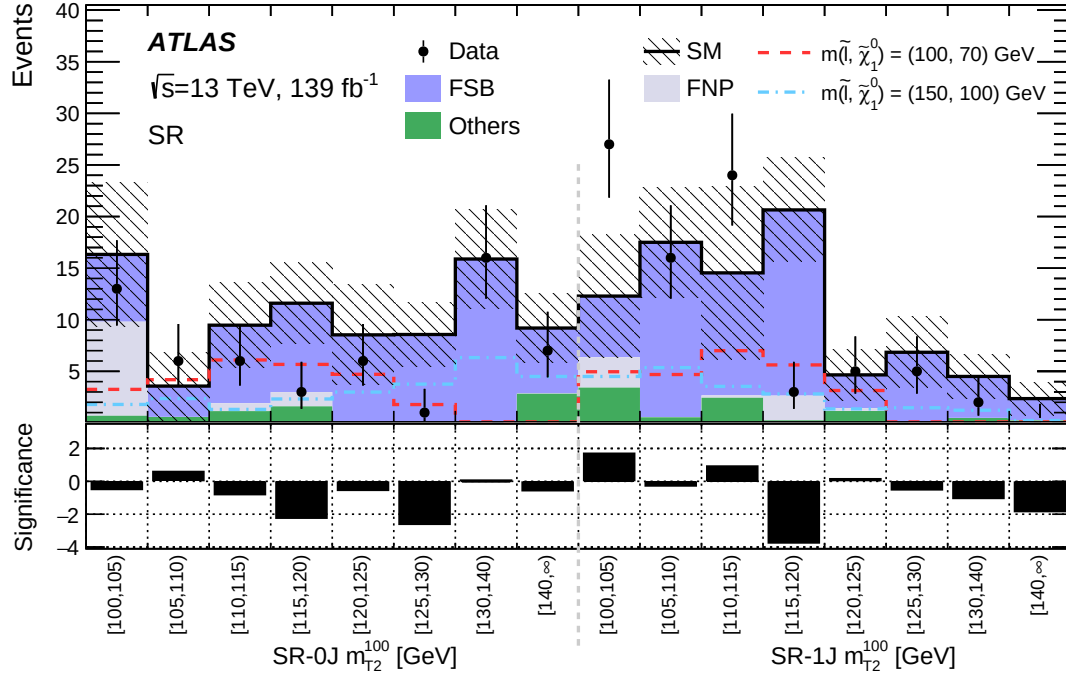


Figure 5.9: Data events in each of the m_{T2}^{100} bins defined in Table 5.1, for SR-0J and SR-1J, along with the expected SM background estimated with the efficiency correction method. The ‘Others’ category includes the non-dominant background sources, e.g. $t\bar{t}+V$, Higgs boson and Drell-Yan events. The total uncertainty on the SM background simulation is represented by the shaded band. The distribution of two benchmark signal points with mass splittings $\Delta m(\tilde{l}, \tilde{\chi}_1^0) = m(\tilde{l}) - m(\tilde{\chi}_1^0)$ of 30 GeV and 50 GeV are also shown. In the lower panel is reported the significance [4, 254].

- **SR-1J:** An excess of data over the background expectation of about 1.5σ is observed instead in two m_{T2}^{100} bins, $[100, 105)$ and $[110, 115)$ GeV, while there is an excess of the expected background over the data of about 3.5σ in the bin $[115, 120)$ GeV. It was observed that such discrepancies also appear when comparing pure MC simulations with the DF data in the SRs, and that an opposite fluctuation arises if comparing simulations with the SF data, whose combined effect further enhances the disagreement. The effect is therefore mainly related to statistical fluctuation in the distribution of the DF data used for the FSB estimation.

In order to assess if these results can suggest the presence of BSM phenomena in data, independently from the signal model considered, a model-independent hypothesis test was performed, deriving the upper limits at 95% confidence level (CL) on the visible signal cross section σ^{obs} , by using the CLs method, described in section 4.1.3. The inclusive SRs, defined in Table 5.1, were considered one by one in the likelihood fit procedure, obtaining from it the observed ($S_{\text{obs}}^{0.95}$) and expected ($S_{\text{exp}}^{0.95}$) limits at 95% CL on the number of events from processes beyond the SM in that inclusive SR. In Table 5.9 are reported the observed and predicted numbers of background events in the inclusive SRs, together with the model-independent upper limits on the visible cross section, the observed and expected limits at 95% CL on the number of potential beyond-the-SM events, and the p_0 values. The latter represent the probability of having only SM background whose yields fluctuate with respect to the observed events and it is capped at $p_0 = 0.50$.

In Figure 5.10 the exclusion limits at 95% CL on the masses of the sleptons and neutralino, considering the case of mass-degenerate $\tilde{e}_{L,R}/\tilde{\mu}_{L,R}$, are shown. The results bridge the gap between the previous searches of the ATLAS collaboration and surpass the limits imposed by LEP: the existence of sleptons up to 150 GeV can be excluded at 95% CL in case of a 50 GeV mass-splitting between the slepton and the LSP.

In Figure 5.11 are reported the exclusion limits at 95% CL for single slepton species $\tilde{e}_{L,R}$ and $\tilde{\mu}_{L,R}$, for which the same selection (including in the likelihood fit both dielectron and dimuon events) of the general case was applied. In the case of smuons, in particular, parts of the excluded $(m(\tilde{\mu}), m(\tilde{\chi}_1^0))$ mass plane are compatible with the $(g-2)_\mu$ anomaly for small $\tan\beta$ [251] values [4].

These results have been included in the ATLAS summary plots, and in Figure 5.12b is reported the status of the exclusion limits by August 2023. In (a) the current exclusion limits from the searches of sleptons are reported in the $(m(\tilde{\ell}), m(\tilde{\chi}_1^0))$ mass plane. The result of the current analysis, which slightly improves the current exclusion status of a little portion in the compressed region, is reported in red. In (b) the summary plot in the case of $\tilde{\mu}$ is reported, and the contribution of the present result appears as the excluded region in red.

Signal region [GeV]	Observed	Expected	σ^{obs} [fb]	$S_{\text{obs}}^{0.95}$	$S_{\text{exp}}^{0.95}$	p_0
SR-0J $m_{T2}^{100} \in [100, \infty)$	58	76 ± 13	0.13	18.3	26_{-7}^{+10}	0.50
SR-0J $m_{T2}^{100} \in [110, \infty)$	39	58 ± 11	0.09	13.2	21_{-6}^{+8}	0.50
SR-0J $m_{T2}^{100} \in [120, \infty)$	30	40 ± 8	0.10	13.5	18_{-5}^{+7}	0.50
SR-0J $m_{T2}^{100} \in [130, \infty)$	23	24 ± 6	0.10	14.2	15_{-4}^{+6}	0.50
SR-0J $m_{T2}^{100} \in [140, \infty)$	7	9.2 ± 3.4	0.05	7.5	$8.6_{-2.5}^{+4}$	0.50
SR-1J $m_{T2}^{100} \in [100, \infty)$	82	78 ± 13	0.24	33.5	31_{-8}^{+11}	0.41
SR-1J $m_{T2}^{100} \in [110, \infty)$	39	50 ± 17	0.17	24.0	28_{-7}^{+9}	0.50
SR-1J $m_{T2}^{100} \in [120, \infty)$	12	16 ± 5	0.07	9.5	12_{-3}^{+5}	0.50
SR-1J $m_{T2}^{100} \in [130, \infty)$	2	6.9 ± 2.8	0.03	3.9	$6.1_{-1.9}^{+3.0}$	0.50
SR-1J $m_{T2}^{100} \in [140, \infty)$	0	2.4 ± 1.6	0.02	2.4	$3.4_{-1.2}^{+2.2}$	0.50

Table 5.9: In the left part of the table are reported the observed event yields and the expected background yields for the inclusive SRs defined in Table 5.1. In the right part the model-independent upper limits at 95% CL on the observed ($S_{\text{obs}}^{0.95}$) and expected ($S_{\text{exp}}^{0.95}$) number of BSM events and on the effective BSM cross section σ^{obs} (defined as $\langle A\epsilon\sigma \rangle_{\text{obs}}^{0.95}$) are reported. Such results are obtained via the fit procedure described in section 4.1.3. The $\pm 1\sigma$ variations on $S_{\text{exp}}^{0.95}$ are provided. In the last column the p_0 -values are reported considering the SM background-only hypothesis, and they are capped to 0.50 in those regions where the data yields is smaller than expected [4].

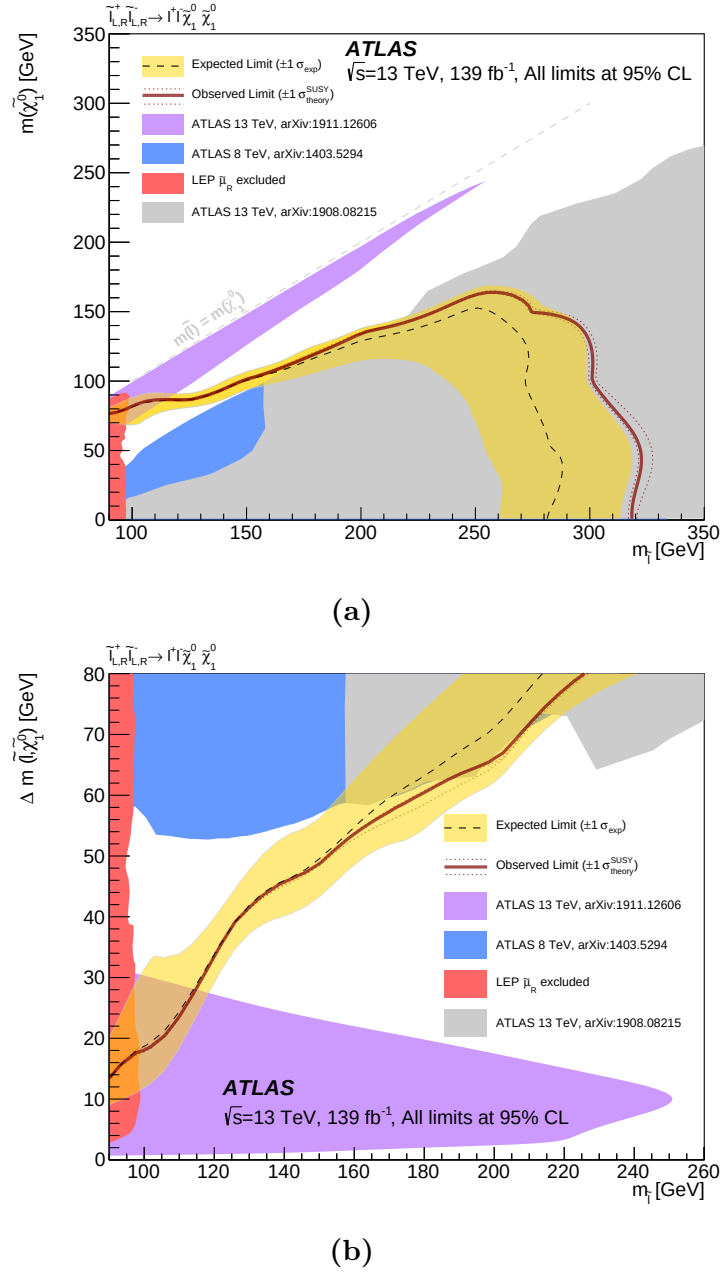


Figure 5.10: Observed and expected exclusion limits on SUSY simplified models for slepton-pair production in the (a) $(m(\tilde{\ell}), m(\tilde{\chi}_1^0))$ and (b) $(m(\tilde{\ell}), \Delta m(\tilde{\ell}, \tilde{\chi}_1^0))$ planes. Only $\tilde{e}$ and $\tilde{\mu}$ are considered. The results of the current analysis are shown: the observed (solid thick red line) and the expected (thin dashed line) contours. The yellow shaded band around the expected exclusion contour represents its $\pm 1\sigma$ variations, including all the sources of uncertainties except for the theoretical associated to the signal cross section. The dotted lines around the observed limit shows how it would change if the nominal signal cross section is scaled up and down by theoretical uncertainty. All limits are computed at 95% CL. The observed limits obtained at LEP [255] for $\tilde{\mu}_R$ and by the ATLAS experiment in previous searches [62, 63, 256] are also shown [4].

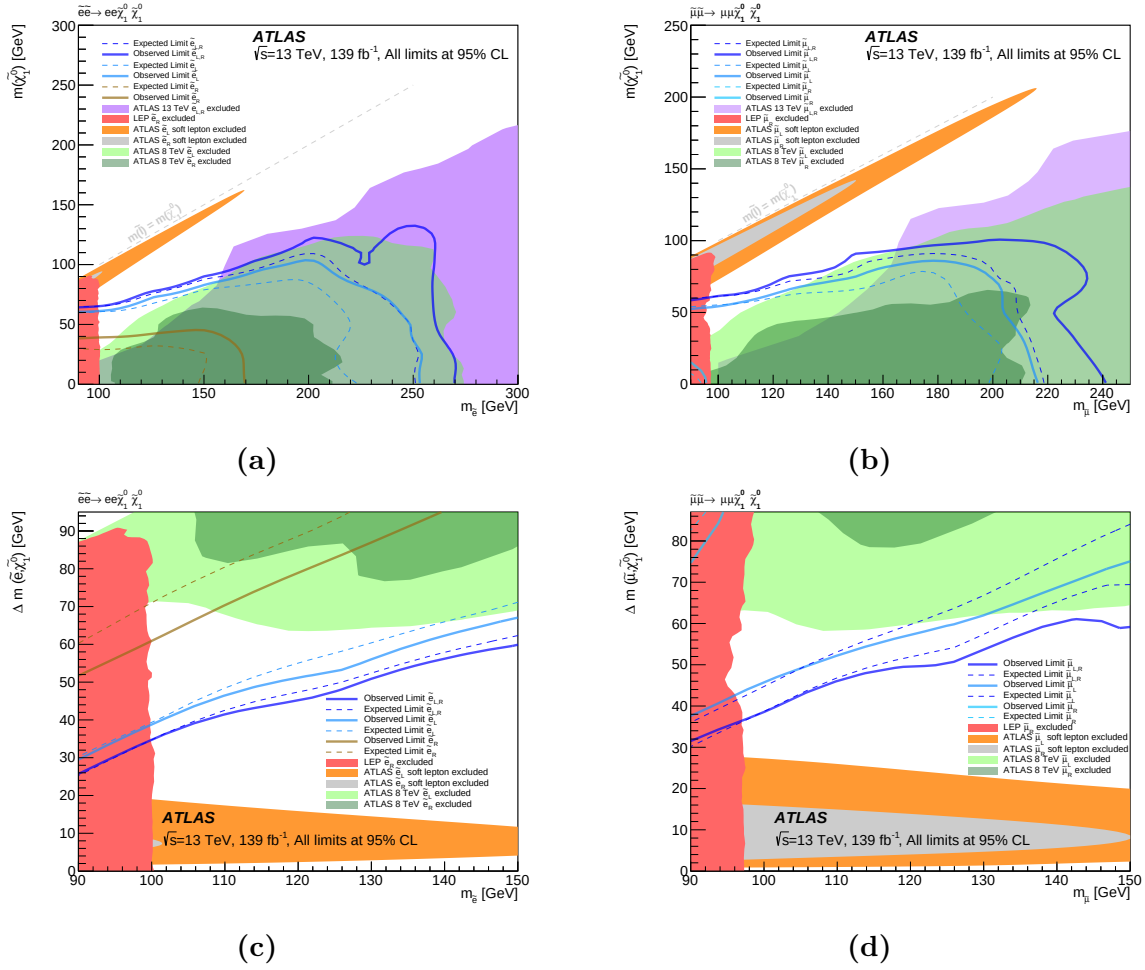


Figure 5.11: Observed and expected exclusion limits on SUSY simplified models for direct selectron production in the (a) $(m(\tilde{e}), m(\tilde{\chi}_1^0))$ and (c) $(m(\tilde{e}), \Delta m(\tilde{e}, \tilde{\chi}_1^0))$ planes, and for direct smuon production in the (b) $(m(\tilde{\mu}), m(\tilde{\chi}_1^0))$ and (d) $(m(\tilde{\mu}), \Delta m(\tilde{\mu}, \tilde{\chi}_1^0))$ planes. For selectrons, in (a) and (c) are reported the observed (solid thick lines) and expected (dashed lines) exclusion contours at 95% CL for combined $\tilde{e}_{L,R}$ and for $\tilde{e}_L$ and $\tilde{e}_R$. For smuons, in (b) and (d) are reported the observed (solid thick lines) and expected (dashed lines) exclusion contours at 95% CL for combined $\tilde{\mu}_{L,R}$ and for $\tilde{\mu}_L$, whilst no sensitivity is observed to $\tilde{\mu}_R$. In the plots are also shown the observed limits obtained at LEP [255] and by the ATLAS experiment in previous searches [62, 63, 256] in the shaded areas [4].

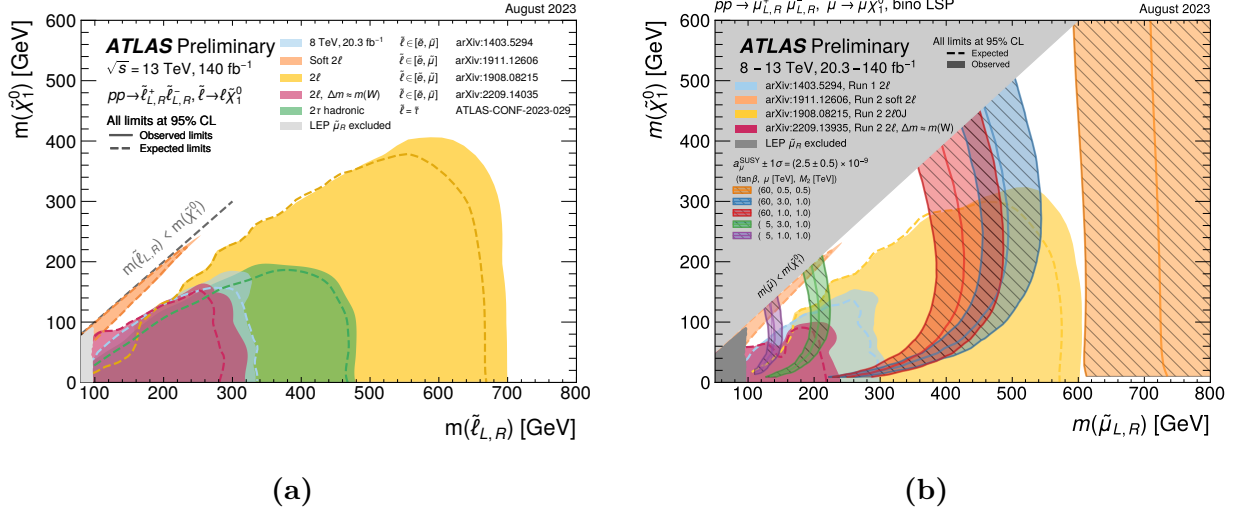


Figure 5.12: Exclusion limits at 95% CL based on 13 TeV data in the (a) $(m(\tilde{\ell}), m(\tilde{\chi}_1^0))$ and (b) $(m(\tilde{\mu}), m(\tilde{\chi}_1^0))$ mass planes for different analyses probing the direct production of (a) sleptons decaying to leptons and neutralinos and of (b) smuons, decaying in muons and neutralinos. For the smuon plot, the hatched bands represent regions which are compatible with the observed $(g - 2)_\mu$ anomaly (measured by the Fermilab and BNL experiments [247]) at $\pm 1\sigma$ level corresponding to the pMSSM parameters specified in the legend [60].

CHAPTER

6

Description and results of the chargino search

Description of the search for charginos pair production in pp collisions, where each chargino decays in a W -boson and the lightest neutralino, and the W -boson decays leptonically, in moderately compressed regions of the phase space. Discussion and interpretation of the results.

This chapter is devoted to the description of the search for the direct production of chargino pairs $\tilde{\chi}_1^+ \tilde{\chi}_1^-$, in pp collisions at LHC. In this search each chargino decays in a W -boson and the LSP, and the W -boson decays leptonically ($W \rightarrow \ell \nu_\ell$), as shown in Figure 6.1a. Only electrons or muons are considered, either directly produced in the W -boson decay or through the emission of a leptonically decaying τ -lepton. The final state is characterised by the presence of two opposite-sign charged leptons (electrons or muons), which can be both SF or DF (unlike the slepton case), and missing transverse energy E_T^{miss} , due to the presence of the LSPs and the neutrinos coming from the W -boson decays. The presence of jets is not expected, except for those due to the initial state radiation.

The most recent exclusion limits set by the ATLAS collaboration on this model are reported in Ref. [62]. The analysis presented here, like the slepton search, was optimized for getting sensitivity in the moderately compressed region, where the previous analysis didn't show sensitivity, in which the mass splitting is $\Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0) = m(\tilde{\chi}_1^\pm) - m(\tilde{\chi}_1^0) \sim m_W$. In Figure 6.1b the exclusion limit set by the analysis of Ref. [62] for the process under study is reported, and the portion of the compressed region in the $(m(\tilde{\chi}_1^\pm), m(\tilde{\chi}_1^0))$ phase space, where

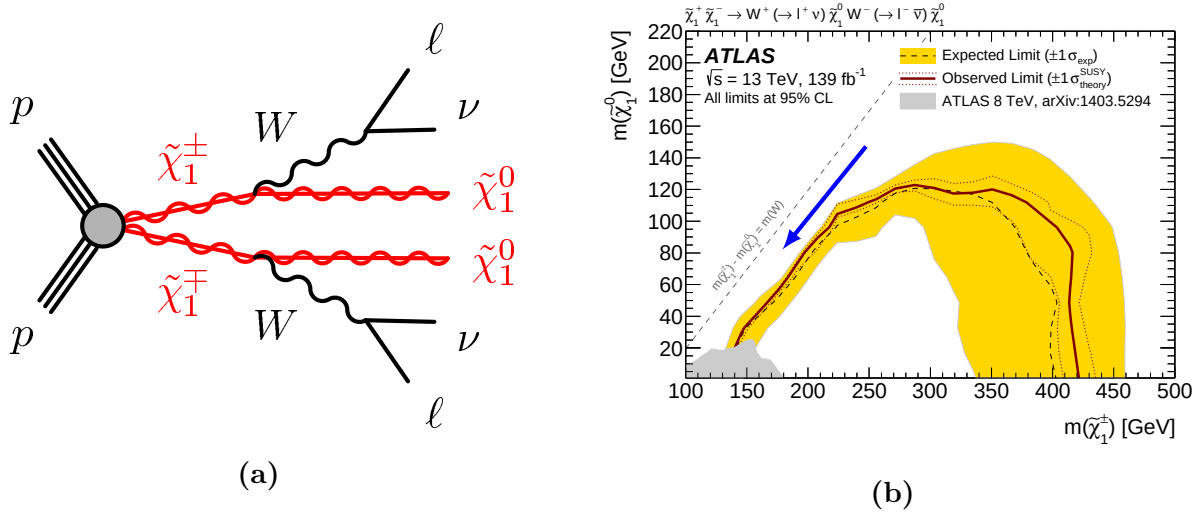


Figure 6.1: (a) Diagram of the chargino pair production model analyzed in this chapter, whose final state is characterized by the presence of two leptons. (b) Expected and observed exclusion limits for this channel [62]. The blue arrow indicates the compressed region in the $(m(\tilde{\chi}_1^\pm), m(\tilde{\chi}_1^0))$ plane.

$\Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0) = m(\tilde{\chi}_1^\pm) - m(\tilde{\chi}_1^0) < m_W$, is highlighted with the blue arrow.

In this chapter, the developed analysis strategy [257] is presented in detail, describing: the criteria chosen to define the signal regions; the approach adopted for estimating the main SM background; the final results and their interpretation, after looking at the data inside the SRs. Unlike the slepton analysis, the method used for discriminating the signal from the background and improving the search sensitivity is based on machine learning techniques.

6.1 Status of the ATLAS searches for charginos

In Figure 6.2 is reported the 2021 (before this analysis started) summary plot of the results of several searches targeting the production of: a chargino decaying via a W -boson and a second neutralino, $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$, decaying either via a Z -boson (orange contours) or via a Higgs boson (blue contours); chargino pairs $\tilde{\chi}_1^+ \tilde{\chi}_1^-$ decaying via W -bosons (green contours). Concerning the latter process, the plot shows that there were several portions of the $(m(\tilde{\chi}_1^\pm), m(\tilde{\chi}_1^0))$ mass plane, in particular in the compressed region, not covered by any analysis at that time. At the end of this chapter this plot will be proposed again after including the results of this analysis.

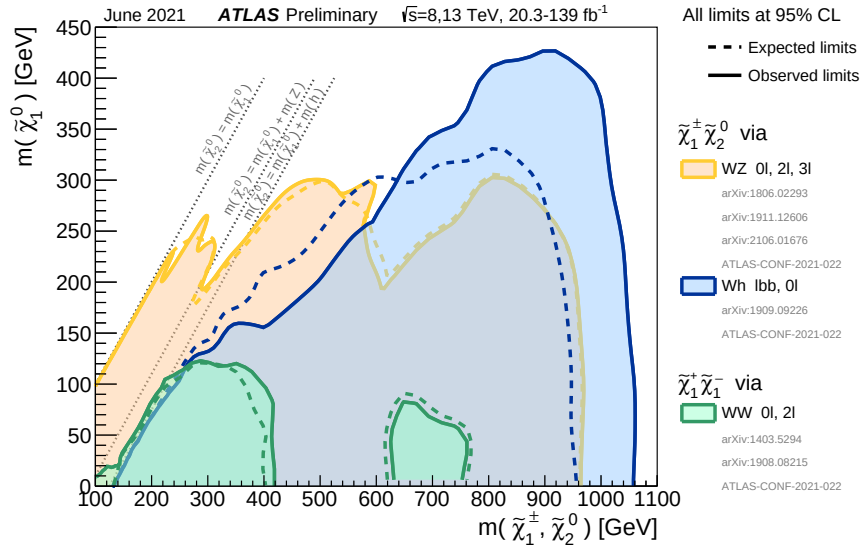


Figure 6.2: Status by June 2021 of the exclusion limits at 95% CL on $\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp$ and $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ production with SM-boson mediated decays as functions of $\tilde{\chi}_1^\pm$, $\tilde{\chi}_2^0$ and $\tilde{\chi}_1^0$ masses. The production cross section is assumed for pure wino $\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp$ and $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ pairs. Each exclusion contour represents a union of the excluded regions of one or more analyses [252].

6.2 Machine learning-based analyses

In high-energy physics analyses, it is common to deal with processes that are expected to be very rare and difficult to separate from a dominant background, thus implying the need to apply more and more sophisticated techniques of signal from background discrimination. For this reason, the development of *multivariate analyses* (MVAs) is increasingly widespread, and particularly the implementation of machine learning methods, handling with large amount of data. Such methodologies consist in building signal-background discriminating algorithms, based on discriminating variables provided as input, which are firstly trained over a *training* sample of data, and afterwards validated with a *test* sample completely independent from the training dataset. The input variables are generally kinematic variables (momenta, angles, missing energy, etc.) and properties of the physics objects considered (lepton or jet multiplicity), and they are combined together in order to define new variables, called *classifier*, which improve the signal-background discriminating power, with respect to the single input variables.

Among the several classifiers that are used in SUSY and generally in physics analyses, there are the *decision trees*, which consist in tree-like structures based on binary selection criteria which improve the signal efficiency and the background rejection: each variable is given as input to the decision tree, and a selection criterion is applied to that variable, forming a *decision node*. For each event the procedure follows the decision chain up to the final one, the *leaf node*, which corresponds to the classification as signal or background for that specific event. A schematic representation of a decision tree is shown in Figure 6.3. A simple decision

tree can be not sufficient for an effective discrimination, especially if its performance is just slightly better than a random classification. An extension of the decision tree is given by the *boosting* procedure, which consists in enhancing the performance of a decision tree classifier by considering, instead of a single tree, several trees which thus form a *forest*. Such trees are derived from the same training dataset (reweighting the events) and combined in an unique classifier, called *Boosted Decision Tree* (BDT), which represents a weighted mean of the individual decision trees. The boosting stabilizes the response of the decision tree and noticeably improves the classification performance [150]. Several boosting procedures can be applied to the individual trees, such as the *Gradient* algorithm, which consists in serially connecting the single trees in such a way that the next one minimizes the errors of the previous one, producing at the end a strong classifier.

6.2.1 Machine learning technique for the chargino search

For the chargino search, the machine learning approach implemented to improve the signal-background discrimination was the *Gradient Boosted Decision Tree*, incorporated in the *LightGBM framework* [258], which is characterized by a high computing speed and a high performance level over a large amount of data.

Before applying the discriminating algorithm, signal and MC simulations were required to pass the preselection criteria of Table 4.5, with the additional request of no hadronic jets in the event³⁶ (neither non-*b*-tagged nor *b*-tagged). Events were then separated in two classes according to the lepton flavours: different (DF) or same flavour (SF). Each of these classes was randomly splitted in the training and the test datasets, in such a way that they both contained half of the total MC sample. Then, for each of the two categories, the BDT classifier was trained over the training set and validated by using the test set (statistically independent from the training set), in order to measure and optimize the classifier's performance and to derive the final results. In order to overcome the limitation to use only half of the statistics to train the classifier, and to keep the whole dataset for the final analysis fit, a second BDT classifier was introduced, trained over the original test set and tested over the original training set. In this way the entire MC statistics was used for the fit, whilst always testing over a statistically independent data sample. The training was performed by adding together some benchmark signal points of the grid, characterized by a mass-splitting between the chargino and neutralino of 90 and 100 GeV, since they were found to provide the best sensitivity. Trainings with lower mass-splitting showed a very limited sensitivity and they were no longer considered, especially the signals with 80 GeV mass-splitting, which are very similar to the *WW* background.

A *multiclass* classification was performed, resulting in a better sensitivity for the analysis. The classifier was trained in order to separate the events in four classes: signal, diboson (*WW*, *WZ* and *ZZ*) background, top (*t $\bar{t}$* and *Wt*) background and all the other backgrounds (*Z*/ γ + jets, *VVV* and other minor backgrounds). For each class, a score representing the probability of the event to belong to that specific category is assigned. These scores are:

³⁶The reason to apply this request is that it was found to improve the sensitivity of the analysis.

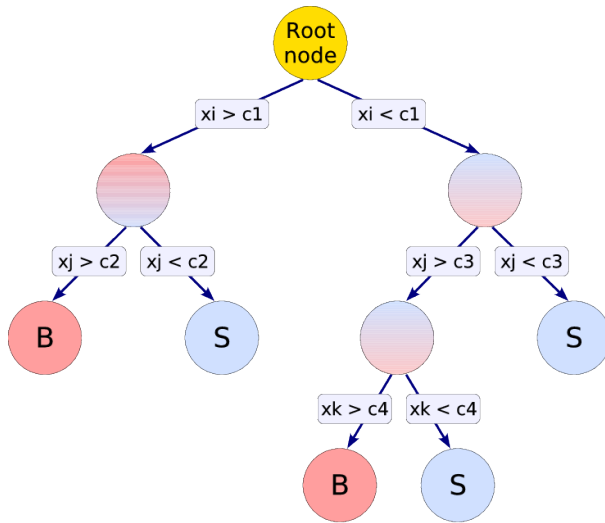


Figure 6.3: Diagram of a decision tree, where different selections for different variables (x_i , x_j , x_k) are made in order to maximize the discrimination between background, ‘B’, and signal, ‘S’. Figure taken from Ref. [150].

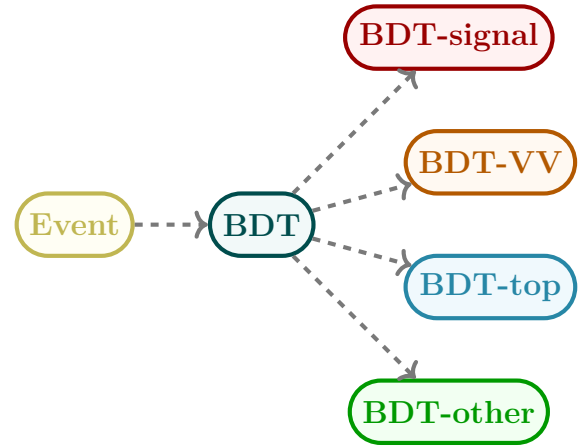


Figure 6.4: Multiclass classification scheme of the classifier. The BDT is trained to separate four classes of events: signal (BDT-signal), diboson background (BDT-VV), top background (BDT-top), namely $t\bar{t}$ and Wt , and all other backgrounds (BDT-other), i.e. Z/γ +jets, VVV and other minor backgrounds.

BDT-signal, BDT-VV, BDT-top and BDT-other, for signal, diboson, top and other classes respectively. They sum to one, and are schematically depicted in Figure 6.4.

The training used the set of kinematic variables: $p_T^{\ell_1}$, $p_T^{\ell_2}$, E_T^{miss} , m_{T2}^0 , $m_{\ell\ell}$, $\Delta\phi_{\text{boost}}$, $\Delta\phi_{p_T^{\text{miss}}, \ell_1}$, $\Delta\phi_{p_T^{\text{miss}}, \ell_2}$, $\cos\theta_{\ell\ell}^*$ and E_T^{miss} significance. This final list was decided after a suitable optimization procedure. Starting from a larger set of variables, via an iterative approach, each variable was removed one-by-one from the set and the training performance was assessed. Only those variables whose removal provoked a loss in performance were retained [4].

6.3 Signal region definition

Different and same flavour events passing the preselection requirements of Table 4.5 and the requests $n_{b\text{-tagged jets}} = 0$, to reject $t\bar{t}$ and Wt backgrounds, and $n_{\text{non-}b\text{-tagged jets}} = 0$, to improve the analysis sensitivity, were considered as candidates to enter in the signal regions. Moreover, the requirements E_T^{miss} significance > 8 , since high E_T^{miss} significance is expected for signal-like events, and m_{T2}^0 greater than 50 GeV, to ensure good data/MC modelling, were imposed. Then two sets of SRs, reported in Table 6.1, were defined according to the DF or SF classification: SRs-DF and SRs-SF.

SRs were defined by selecting events with high values of the BDT-signal variable. As it can be observed in Figure 6.5, which reports the BDT-signal distribution after applying the requirements listed above for both the DF and SF channels, the background contribution

decreases as the BDT-signal increases, while the signal contribution is relatively constant throughout the bins. The signal significance, defined in equation 4.14 and computed after applying the requests on the minimum numbers of signal s and background b events reported in Figure 6.5, increases as well. In particular, for the DF channel only events with BDT-signal greater than 0.81 were accepted in the SRs-DF, and events with BDT-signal greater than 0.77 in the SRs-SF.

Since for the SF channel a considerable amount of Z/γ + jets events was passing the selection on the BDT-signal, only for SF events an additional requirement on the BDT-other was introduced in order to reduce the contribution of this background.

Similarly to the slepton search, two classes of signal regions were considered: ‘binned’ SRs, where the BDT-signal binning was optimized in order to maximize the search significance for the model-dependent fit requiring less than approximately 30 events of predicted background in each bin, and ‘inclusive’, overlapping, SRs, where the BDT-signal ranges were chosen to maximize the significance for the model-independent fit [4]. In Table 6.2 are reported the simulated event yields for each bin of the binned SRs defined in Table 6.1. Each bin is characterized by less than 30 total SM events, and the yields of four benchmark signal points, $m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0) = (125, 25)$, $(125, 35)$, $(150, 50)$ and $(100, 10)$ GeV, are reported, along with the relative significance (in brackets).

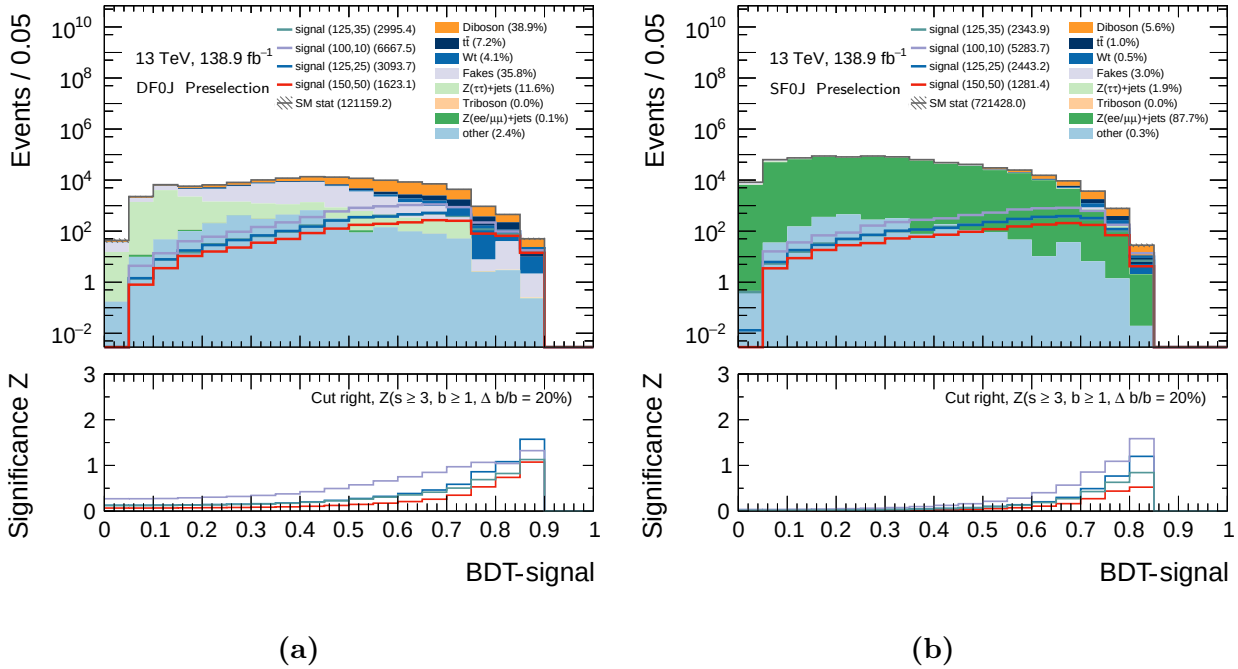


Figure 6.5: Distributions of the BDT-signal for the backgrounds and the signal samples, in (a) the DF and (b) the SF channels after applying the preselection requirements of Table 4.5. The lower panel shows the signal significance, defined in equation 4.14 and computed requiring the minimum numbers of signal s and background b events reported in the panel and with the assumption of a flat 20% uncertainty on b .

Signal region (SR)	SR-DF	SR-SF
$n_{b\text{-tagged jets}}$		$= 0$
$n_{\text{non-}b\text{-tagged jets}}$		$= 0$
E_T^{miss} significance		> 8
m_{T2}^0 [GeV]		> 50
BDT-other		< 0.01
Binned SRs		
BDT-signal	$\in (0.81, 0.8125]$	$\in (0.77, 0.775]$
	$\in (0.8125, 0.815]$	$\in (0.775, 0.78]$
	$\in (0.815, 0.8175]$	$\in (0.78, 0.785]$
	$\in (0.8175, 0.82]$	$\in (0.785, 0.79]$
	$\in (0.82, 0.8225]$	$\in (0.79, 0.795]$
	$\in (0.8225, 0.825]$	$\in (0.795, 0.80]$
	$\in (0.825, 0.8275]$	$\in (0.80, 0.81]$
	$\in (0.8275, 0.83]$	$\in (0.81, 1]$
	$\in (0.83, 0.8325]$	
	$\in (0.8325, 0.835]$	
	$\in (0.835, 0.8375]$	
	$\in (0.8375, 0.84]$	
	$\in (0.84, 0.845]$	
	$\in (0.845, 0.85]$	
	$\in (0.85, 0.86]$	
	$\in (0.86, 1]$	
Inclusive SRs		
BDT-signal	$\in (0.81, 1]$ for DF and $\in (0.77, 1]$ for SF	
	$\in (0.81, 1]$	
	$\in (0.82, 1]$	
	$\in (0.83, 1]$	
	$\in (0.84, 1]$	
	$\in (0.85, 1]$	
		$\in (0.77, 1]$
		$\in (0.78, 1]$
		$\in (0.79, 1]$
		$\in (0.80, 1]$

Table 6.1: The definitions of the binned and inclusive signal regions for the chargino model in terms of the relevant variables described in the text. The signal regions are separated for the DF and SF channels, except for the first inclusive SR (subsequently indicated with $\text{SR}_{\text{SF BDT-signal} \in (0.77, 1]}^{\text{DF BDT-signal} \in (0.81, 1]}$), which contains DF events with $\text{BDT-signal} \in (0.81, 1]$ and SF events with $\text{BDT-signal} \in (0.77, 1]$ [4].

Sample	SR-DF BDT-signal $\in$ (0.81, 0.8125]	SR-DF BDT-signal $\in$ (0.8125, 0.815]	SR-DF BDT-signal $\in$ (0.815, 0.8175]	SR-DF BDT-signal $\in$ (0.8175, 82]
Simulated VV	12.1 ± 1.2	14.8 ± 1.3	12.6 ± 1.2	10.2 ± 2.0
Simulated $t\bar{t}$	7.1 ± 0.5	7.0 ± 0.5	7.2 ± 0.5	7.1 ± 0.5
Simulated Wt	4.8 ± 0.8	6.7 ± 1.0	2.3 ± 0.6	6.2 ± 0.9
Other backgrounds	0.0 ± 0.0	0.0 ± 0.0	0.1 ± 0.0	0.2 ± 0.1
FNIP leptons	2.1 ± 3.1	3.8 ± 3.4	0.0 ± 2.2	1.7 ± 3.1
Total SM background	26.1 ± 3.5	32.3 ± 3.8	22.1 ± 2.6	25.3 ± 3.9
$m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0) = (125, 25)$ GeV	4.5 ± 0.9 (0.6)	3.7 ± 0.8 (0.4)	5.8 ± 1.1 (0.8)	6.5 ± 1.1 (0.9)
$m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0) = (125, 35)$ GeV	4.9 ± 1.0 (0.6)	4.9 ± 1.0 (0.5)	3.8 ± 0.9 (0.6)	3.6 ± 0.9 (0.5)
$m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0) = (150, 50)$ GeV	3.2 ± 0.8 (0.4)	3.7 ± 0.8 (0.4)	4.4 ± 0.9 (0.6)	4.0 ± 0.9 (0.5)
$m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0) = (100, 10)$ GeV	5.3 ± 1.5 (0.7)	5.4 ± 1.6 (0.6)	6.0 ± 1.6 (0.9)	5.1 ± 1.5 (0.7)

Sample	SR-DF BDT-signal $\in$ (0.82, 0.8225]	SR-DF BDT-signal $\in$ (0.8225, 0.825]	SR-DF BDT-signal $\in$ (0.825, 0.8275]	SR-DF BDT-signal $\in$ (0.8275, 0.83]
Simulated VV	13.4 ± 1.2	9.9 ± 1.1	12.1 ± 1.2	11.4 ± 1.1
Simulated $t\bar{t}$	6.6 ± 0.5	5.1 ± 0.4	5.8 ± 0.5	6.2 ± 0.5
Simulated Wt	4.1 ± 0.7	3.6 ± 0.7	4.3 ± 0.8	3.6 ± 0.7
Other backgrounds	0.0 ± 0.1	0.1 ± 0.0	0.1 ± 0.0	1.7 ± 1.7
FNIP leptons	11.6 ± 5.6	1.0 ± 2.5	1.0 ± 3.0	0.0 ± 1.5
Total SM background	35.8 ± 5.8	19.7 ± 2.9	23.3 ± 3.3	22.8 ± 2.7
$m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0) = (125, 25)$ GeV	3.4 ± 0.8 (0.4)	5.8 ± 1.1 (0.9)	6.2 ± 1.1 (0.9)	7.5 ± 1.2 (1.1)
$m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0) = (125, 35)$ GeV	4.6 ± 1.0 (0.5)	4.3 ± 1.0 (0.7)	4.9 ± 0.9 (0.7)	3.4 ± 0.8 (0.5)
$m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0) = (150, 50)$ GeV	3.8 ± 0.8 (0.4)	4.3 ± 0.9 (0.7)	3.7 ± 0.8 (0.5)	4.0 ± 0.8 (0.6)
$m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0) = (100, 10)$ GeV	7.0 ± 1.7 (0.7)	4.6 ± 1.4 (0.7)	5.1 ± 1.6 (0.7)	4.2 ± 1.4 (0.6)

Sample	SR-DF BDT-signal $\in$ (0.83, 0.8325]	SR-DF BDT-signal $\in$ (0.8325, 0.835]	SR-DF BDT-signal $\in$ (0.835, 0.8375]	SR-DF BDT-signal $\in$ (0.8375, 0.84]
Simulated VV	13.5 ± 1.2	11.3 ± 1.1	10.4 ± 1.2	10.1 ± 1.0
Simulated $t\bar{t}$	4.5 ± 0.4	4.3 ± 0.4	3.7 ± 0.4	3.4 ± 0.4
Simulated Wt	3.6 ± 0.7	2.3 ± 0.6	3.2 ± 0.6	2.1 ± 0.5
Other backgrounds	0.1 ± 0.1	0.2 ± 0.1	0.0 ± 0.0	0.0 ± 0.0
FNIP leptons	2.1 ± 2.5	1.9 ± 3.0	3.4 ± 2.8	5.1 ± 4.2
Total SM background	23.8 ± 2.9	20.1 ± 3.3	20.7 ± 3.1	20.7 ± 4.3
$m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0) = (125, 25)$ GeV	5.1 ± 1.0 (0.7)	5.8 ± 1.1 (0.9)	5.2 ± 1.0 (0.8)	4.9 ± 1.0 (0.8)
$m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0) = (125, 35)$ GeV	4.5 ± 1.0 (0.6)	3.5 ± 0.8 (0.6)	3.8 ± 0.8 (0.6)	2.4 ± 0.7 (0.4)
$m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0) = (150, 50)$ GeV	2.2 ± 0.7 (0.3)	4.7 ± 0.9 (0.7)	2.4 ± 0.6 (0.4)	3.2 ± 0.8 (0.5)
$m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0) = (100, 10)$ GeV	6.0 ± 1.6 (0.8)	5.0 ± 1.4 (0.8)	3.0 ± 1.1 (0.5)	6.2 ± 1.6 (0.9)

Sample	SR-DF BDT-signal $\in$ (0.84, 0.845]	SR-DF BDT-signal $\in$ (0.845, 0.85]	SR-DF BDT-signal $\in$ (0.85, 0.86]	SR-DF BDT-signal $\in$ (0.86, 1]
Simulated VV	12.9 ± 1.3	13.0 ± 1.2	16.4 ± 1.4	13.9 ± 1.2
Simulated $t\bar{t}$	6.5 ± 0.5	4.7 ± 0.4	6.2 ± 0.5	3.8 ± 0.4
Simulated Wt	4.3 ± 0.7	2.4 ± 0.6	5.0 ± 0.8	2.8 ± 0.6
Other backgrounds	0.1 ± 0.1	0.0 ± 0.0	0.1 ± 0.1	0.1 ± 0.1
FNIP leptons	0.3 ± 2.6	4.5 ± 3.6	1.9 ± 3.0	0.0 ± 2.9
Total SM background	24.2 ± 3.0	24.6 ± 3.9	29.6 ± 3.4	20.6 ± 3.2
$m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0) = (125, 25)$ GeV	8.3 ± 1.2 (1.1)	6.1 ± 1.1 (0.8)	10.8 ± 1.4 (1.2)	10.7 ± 1.5 (1.6)
$m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0) = (125, 35)$ GeV	5.2 ± 1.0 (0.7)	3.4 ± 0.8 (0.5)	7.8 ± 1.2 (0.9)	7.2 ± 1.2 (1.1)
$m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0) = (150, 50)$ GeV	4.9 ± 0.9 (0.7)	4.3 ± 0.9 (0.6)	7.0 ± 1.1 (0.8)	7.2 ± 1.1 (1.1)
$m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0) = (100, 10)$ GeV	9.6 ± 2.1 (1.3)	2.6 ± 1.0 (0.4)	11.0 ± 2.3 (1.3)	6.8 ± 1.8 (1.0)

Sample	SR-SF BDT-signal $\in$ (0.77, 0.775]	SR-SF BDT-signal $\in$ (0.775, 0.78]	SR-SF BDT-signal $\in$ (0.78, 0.785]	SR-SF BDT-signal $\in$ (0.785, 0.79]
Simulated VV	15.1 ± 1.3	13.6 ± 1.2	13.1 ± 1.1	10.3 ± 1.0
Simulated $t\bar{t}$	5.4 ± 0.5	4.3 ± 0.4	2.5 ± 0.3	2.9 ± 0.3
Simulated Wt	3.1 ± 0.6	3.0 ± 0.6	4.0 ± 0.8	1.8 ± 0.5
Other backgrounds	1.6 ± 1.6	0.7 ± 0.5	3.8 ± 1.9	1.2 ± 1.6
FNIP leptons	0.0 ± 2.0	0.0 ± 4.7	0.0 ± 1.4	0.0 ± 0.5
Total SM background	25.2 ± 3.0	21.6 ± 4.9	23.3 ± 2.8	16.2 ± 2.1
$m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0) = (125, 25)$ GeV	4.6 ± 0.9 (0.6)	6.3 ± 1.2 (0.9)	3.8 ± 0.8 (0.5)	4.7 ± 1.0 (0.9)
$m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0) = (125, 35)$ GeV	3.9 ± 0.9 (0.5)	3.1 ± 0.8 (0.5)	3.4 ± 0.8 (0.5)	2.8 ± 0.7 (0.5)
$m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0) = (150, 50)$ GeV	4.6 ± 0.9 (0.6)	3.0 ± 0.8 (0.5)	3.1 ± 0.8 (0.5)	2.6 ± 0.7 (0.5)
$m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0) = (100, 10)$ GeV	5.3 ± 1.5 (0.7)	4.4 ± 1.5 (0.7)	2.7 ± 1.0 (0.4)	5.7 ± 1.6 (1.0)

Sample	SR-SF BDT-signal $\in$ (0.79, 0.795]	SR-SF BDT-signal $\in$ (0.795, 0.80]	SR-SF BDT-signal $\in$ (0.80, 0.81]	SR-SF BDT-signal $\in$ (0.81, 1]
Simulated VV	5.9 ± 0.9	7.1 ± 0.9	7.8 ± 0.9	5.3 ± 0.7
Simulated $t\bar{t}$	2.5 ± 0.3	1.8 ± 0.3	2.0 ± 0.3	1.0 ± 0.2
Simulated Wt	1.6 ± 0.5	2.0 ± 0.5	0.9 ± 0.4	0.9 ± 0.4
Other backgrounds	2.8 ± 2.9	1.4 ± 1.1	1.1 ± 1.7	2.7 ± 1.8
FNIP leptons	1.0 ± 2.0	0.0 ± 0.5	0.0 ± 0.6	0.0 ± 0.5
Total SM background	13.7 ± 3.6	12.2 ± 1.6	11.9 ± 2.1	9.9 ± 2.0
$m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0) = (125, 25)$ GeV	4.8 ± 1.0 (1.0)	3.4 ± 0.8 (0.8)	6.1 ± 1.1 (1.3)	1.8 ± 0.6 (0.5)
$m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0) = (125, 35)$ GeV	2.5 ± 0.7 (0.5)	3.1 ± 0.8 (0.7)	4.0 ± 0.9 (0.9)	1.3 ± 0.6 (0.3)
$m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0) = (150, 50)$ GeV	2.2 ± 0.6 (0.5)	1.5 ± 0.5 (0.3)	2.1 ± 0.6 (0.5)	0.8 ± 0.3 (0.2)
$m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0) = (100, 10)$ GeV	5.2 ± 1.5 (1.0)	2.9 ± 1.1 (0.7)	5.6 ± 1.6 (1.2)	4.6 ± 1.5 (1.1)

Table 6.2: The MC expected yields in the signal regions bins, with the significance values in brackets after the signal yields. The category ‘Other backgrounds’ includes the non-dominant background sources, e.g. $t\bar{t}+V$, Higgs boson and Drell–Yan events. The uncertainties quoted are statistical only.

6.4 Background estimation

The chargino search used a semi data-driven technique (introduced in section 4.1) to estimate the dominant backgrounds, which are in this case $t\bar{t}$, single-top (Wt) and diboson (VV) events, in the SRs. These contributions were evaluated by defining dedicated control regions (CRs), characterized by high purity in the specific background under study, which were used to normalize the MC simulation yields to data. This was done via the simultaneous likelihood fit, described in section 4.1.3, by extracting normalization factors which were applied to the simulated events of the main backgrounds in the SRs. For each of the dominant backgrounds, the relative control region was enriched in the background of interest, it was defined orthogonal to the SRs (in general this is realized by inverting some of the SRs selection criteria) and with a low signal contamination. Validation regions (VRs) kinematically close to the SRs, but orthogonal to the SRs and the CRs, were defined in order to validate the background estimation performed in the CRs and, therefore, its extrapolation to the SRs [4].

CRs and VRs for diboson and top ($t\bar{t}$ and single-top) were selected orthogonal to the SRs and with low signal contamination by reversing the BDT-signal requirement of the SRs or selecting events with $n_{b\text{-tagged jets}} = 1$. Two control regions, CR-VV and CR-top, were defined for the normalization of the diboson and top background respectively, and six validation regions, VR-VV-DF, VR-VV-SF, VR-top0J-DF, VR-top0J-SF, VR-top-DF and VR-top-SF, were used to verify that the SM predictions and data agree within uncertainties in regions with a phase space close to the SRs, after performing the likelihood fit. In Figure 6.6 a simplified scheme of all the CRs, VRs and SRs defined in the analysis is reported in terms of the BDT-signal and the number of b -jets, showing how all these regions are kinematically independent (orthogonal).

6.4.1 Control regions for diboson and top backgrounds

The definition of the control regions included, in addition to the preselection, the same requirements applied in the SRs on the E_T^{miss} significance, m_{T2}^{100} and number of non- b -tagged jets, in order to ensure a similar kinematic, and both CR-VV and CR-top were each divided in DF and SF, in order to be consistent with what done for the SRs.

For the diboson background, in CR-VV-DF and in CR-VV-SF the BDT-signal interval was chosen to be $(0.2, 0.65]$, while BDT-VV was requested to be > 0.2 and BDT-top < 0.1 , in order to improve the diboson purity. For the top background, CR-top-SF and CR-top-DF were defined in terms of the BDT-signal in intervals different from the ones of the SRs, and requested to have exactly one b -tagged jet in the event, in order to guarantee low signal contamination, to ensure the orthogonality with the SRs and to improve the purity of top. This also allowed no additional requests to be applied to BDT-VV and BDT-top. As done in the SRs, in all CRs the requirement $\text{BDT-other} < 0.01$ was imposed to the SF events to reduce the $Z/\gamma + \text{jets}$ contamination. The CR selections are summarized in Table 6.3, whose definition was optimized by maximizing the purity of the background of interest while minimizing the signal contamination: for the diboson CRs, the diboson purity is around

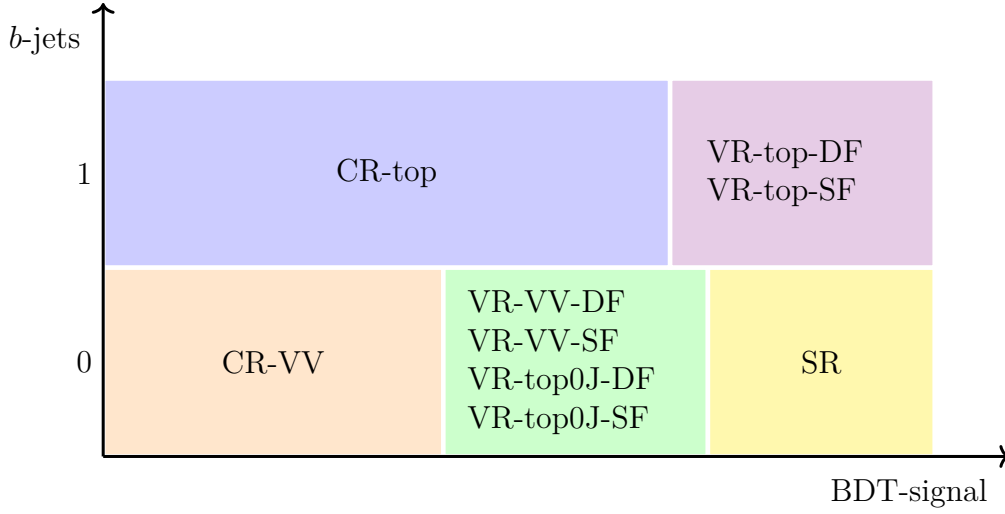


Figure 6.6: A simplified scheme showing the strategy applied in defining control and validation regions in the analysis. Different requirements on the BDT-signal variable and the number of b -jets were used to ensure the orthogonality. The validation regions were close in phase space to the signal regions.

Control region (CR)	CR-VV-DF	CR-VV-SF	CR-top-DF	CR-top-SF
E_T^{miss} significance		> 8		
m_{T2}^0 [GeV]		> 50		
$n_{\text{non-}b\text{-tagged jets}}$		$= 0$		
$n_{b\text{-tagged jets}}$	$= 0$	$= 0$	$= 1$	$= 1$
BDT-other	-	< 0.01	-	< 0.01
BDT-signal	$\in (0.2, 0.65]$	$\in (0.2, 0.65]$	$\in (0.5, 0.7]$	$\in (0.7, 0.75]$
BDT-VV	> 0.2	> 0.2	-	-
BDT-top	< 0.1	< 0.1	-	-

Table 6.3: Definition of the control regions for extracting the normalization factors of the dominant SM background in the chargino search. The requirements were applied on top of the preselection in Table 4.5. The ‘DF’ or ‘SF’ labels refer to control regions with different flavour or same flavour lepton pairs, respectively [4].

70-82%, while having a low signal contamination, around 1-7%, instead for the top CRs, the top purity is around 97-99%, while the signal contamination is generally lower than 0.5%.

A background-only fit was performed using the CRs described above, from which the two normalization factors μ_{VV} and μ_{top} were extracted for correcting the MC yields of the diboson and top backgrounds respectively. These normalization factors are $\mu_{VV} = 1.38 \pm 0.08$ and $\mu_{\text{top}} = 1.09 \pm 0.03$ respectively, whose errors take into account all the uncertainties described in section 4.8. In Table 6.4 the background composition inside CR-VV and CR-top is described, as obtained from the fit and from ‘pure’ MC simulations. After the fit, a good agreement in

the data-MC comparison for several kinematic distributions was found in both CRs, as shown in Figure 6.7.

Region	CR-VV	CR-top
Observed events	634	4468
Fitted backgrounds	634 ± 25	4468 ± 7
Fitted VV	520 ± 27	68 ± 12
Fitted $t\bar{t}$	69 ± 7	3243 ± 100
Fitted single top	40 ± 6	1129 ± 90
Other backgrounds	$4.8^{+5.1}_{-4.8}$	29 ± 5
FNP leptons	$0.02^{+1.4}_{-0.02}$	$0.06^{+12}_{-0.06}$
Simulated VV	376	49
Simulated $t\bar{t}$	63	2974
Simulated single top	37	1036

Table 6.4: Observed event yields and expected background yields as obtained from the likelihood fit in the CRs for the chargino search. In the bottom part of the table the expected yields from the ‘pure’ MC simulation (i.e. before the likelihood fit) is also shown for the main backgrounds. The FNP lepton background is estimated via the matrix method described in section 4.7. The category ‘Other backgrounds’ includes the non-dominant background sources, e.g. $t\bar{t}+V$, Higgs boson and Drell–Yan events. Both statistical and systematic contributions are included in the uncertainties [4].

6.4.2 Validation regions for diboson and top backgrounds

The reliability of the likelihood fit results was probed in the six validation regions previously introduced. The definition of the VRs included, in addition to the preselection, the same requirements applied in the SRs on the E_T^{miss} significance, m_{T2}^{100} and number of non- b -tagged jets. Moreover:

- VR-VV-DF and VR-VV-SF: for the diboson background, two validation regions, one targeting the DF and the other the SF channel, were defined requiring $\text{BDT-signal} \in (0.65, 0.81]$ for the DF case and $\text{BDT-signal} \in (0.65, 0.77]$ for the SF case, therefore between the SR and CR-VV. As done for the CRs, BDT-VV was requested to be > 0.2 and $\text{BDT-top} < 0.1$.
- VR-top-DF and VR-top-SF: for the top background the validation regions were defined in BDT-signal ranges $(0.7, 1]$, for DF, and $(0.75, 1]$, for SF, to be kinematically close to the SRs. As done for the CRs, it was requested to have exactly one b -tagged jet in the event,
- VR-top0J-DF and VR-top0J-SF: two additional VRs were defined for the top background, vetoing b -tagged jets in the event in order to validate the extrapolation of the

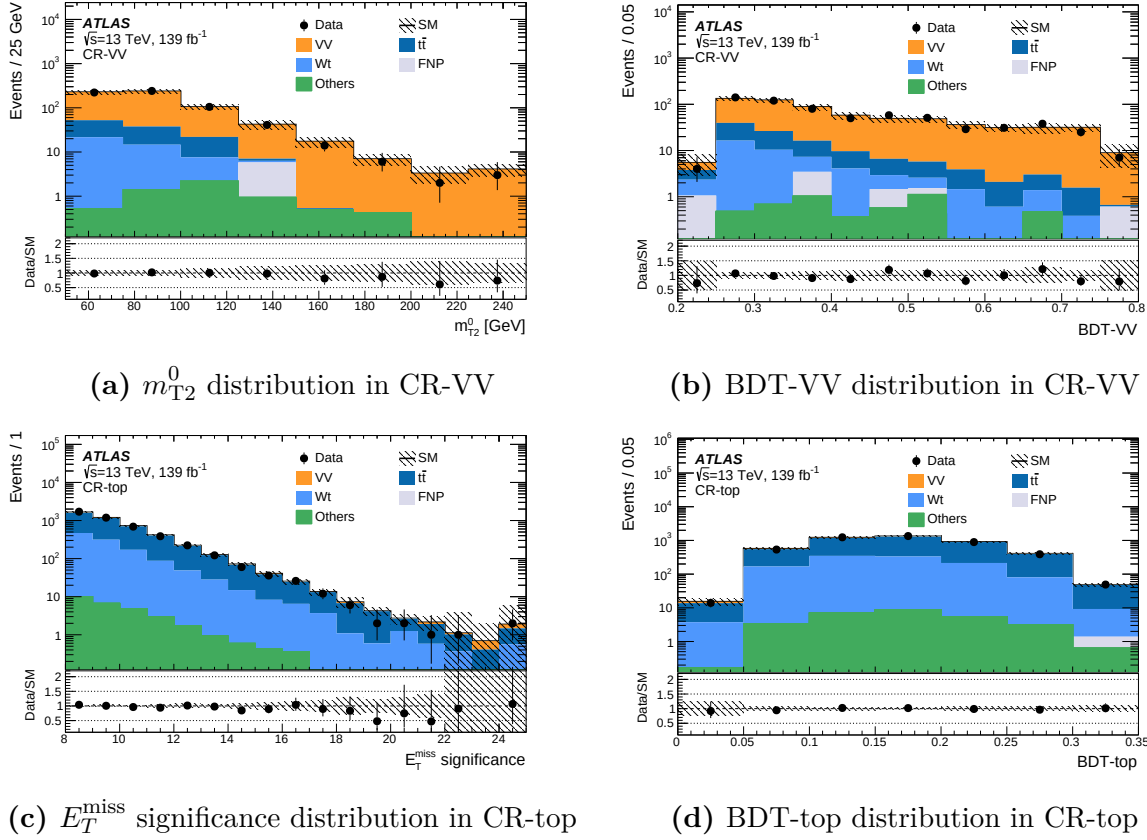


Figure 6.7: Distributions of (a) m_{T2}^0 , (b) BDT-VV in CR-VV, (c) E_T^{miss} significance and (d) BDT-top in CR-top for data and the estimated SM backgrounds. The $t\bar{t}$, single-top-quark and VV backgrounds were normalized by using the scale factors obtained from the fit. The FNP lepton background was estimated via the matrix method described in section 4.7. The ‘Others’ category includes the non-dominant background sources, e.g. $t\bar{t}+V$, Higgs boson and Drell–Yan events. The total uncertainty on the SM background simulation is represented by the shaded band and the final bin in each histogram includes the overflow. In the lower panel the ratio between data and the estimated SM background is shown [4].

normalization factor obtained from CR-top, characterized by $n_{b\text{-tagged jets}} = 1$, to the signal regions, where, instead, $n_{b\text{-tagged jets}} = 0$. Moreover they were used to verify the top estimation strategy, since in these regions the $t\bar{t}$ to Wt ratio was similar to the one observed in SRs.

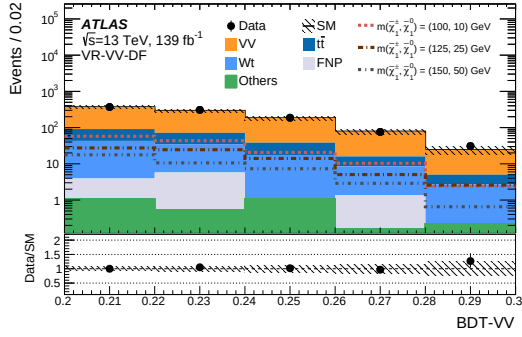
In Table 6.6 the background composition inside the VRs is described, as obtained from the fit and from ‘pure’ MC simulations. Predicted and observed yields agree in all regions within one standard deviation, except in VR-top0J-DF, where a disagreement of 1.8σ is observed. Also in the validation regions a generally good agreement within uncertainties was found in the data-MC comparison for several kinematic variables, as shown in Figure 6.8.

Validation region (VR)	VR-VV-DF	VR-VV-SF	VR-top-DF	VR-top-SF	VR-top0J-DF	VR-top0J-SF
E_T^{miss} significance				> 8		
m_{T2}^0 [GeV]				> 50		
$n_{\text{non-}b\text{-tagged jets}}$				$= 0$		
$n_{b\text{-tagged jets}}$	$= 0$	$= 0$	$= 1$	$= 1$	$= 0$	$= 0$
BDT-other	-	< 0.01	-	< 0.01	-	< 0.01
BDT-signal	$\in (0.65, 0.81]$	$\in (0.65, 0.77]$	$\in (0.7, 1]$	$\in (0.75, 1]$	$\in (0.5, 0.81]$	$\in (0.5, 0.77]$
BDT-VV	> 0.2	> 0.2	-	-	< 0.15	< 0.15
BDT-top	< 0.1	< 0.1	-	-	-	-

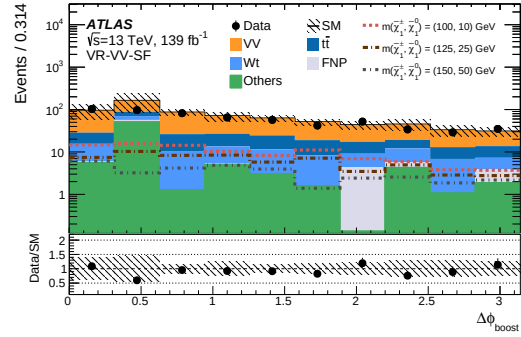
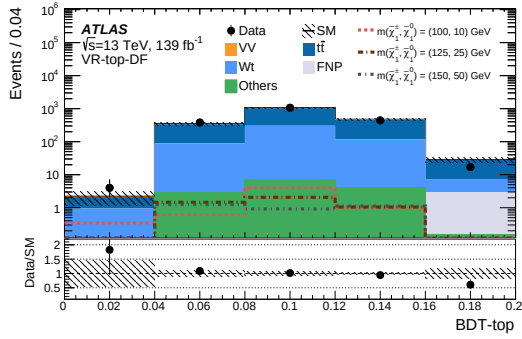
Table 6.5: Definition of the validation regions for verifying the normalization factors of the dominant SM background in the chargino search. The requirements were applied on top of the preselection in Table 4.5. The ‘DF’ or ‘SF’ labels refer to signal regions with different lepton flavour or same lepton flavour pair, respectively [4].

Regions	VR-VV-DF	VR-VV-SF	VR-top-DF	VR-top-SF	VR-top0J-DF	VR-top0J-SF
Observed events	972	596	1910	95	810	17
Fitted backgrounds	940 ± 60	670 ± 90	1900 ± 90	101 ± 10	880 ± 40	18 ± 4
Fitted VV	730 ± 50	400 ± 50	32 ± 13	2.2 ± 2.1	427 ± 30	8.1 ± 2.6
Fitted $t\bar{t}$	116 ± 12	111 ± 11	1350 ± 50	67 ± 7	260 ± 21	5.8 ± 1.8
Fitted single-top	94 ± 19	75 ± 11	500 ± 60	27 ± 7	168 ± 18	4 ± 1
Other backgrounds	3.1 ± 1.5	70 ± 70	13.6 ± 2.5	0.8 ± 0.4	5.2 ± 1.9	0.05 ± 0.05
FNP leptons	$0.02^{+2.3}_{-0.02}$	7 ± 4	$0.03^{+5}_{-0.03}$	4.2 ± 1.3	21 ± 8	$0.05^{+0.15}_{-0.05}$
Simulated VV	527	291	23	1.6	309	5.9
Simulated $t\bar{t}$	106	102	1240	61	239	5.3
Simulated single-top	87	69	460	25	154	3.2

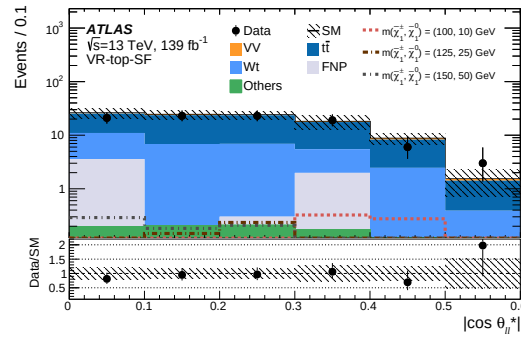
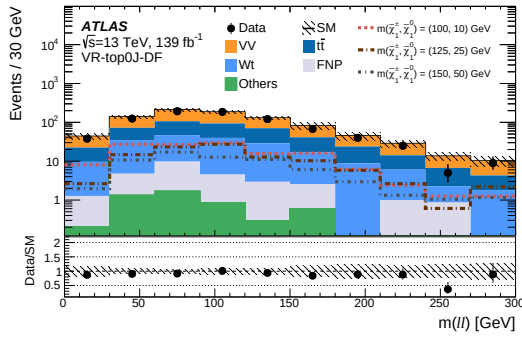
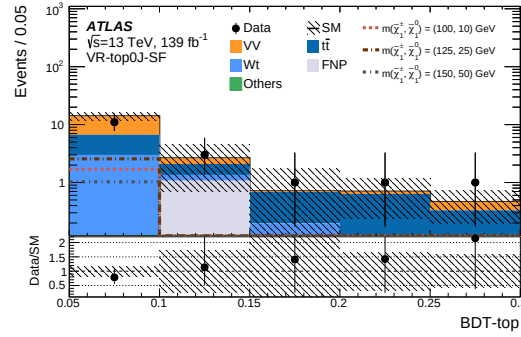
Table 6.6: Observed event yields and expected background yields as obtained from the likelihood fit in the VRs for the chargino search. In the bottom part of the table the expected yields from the ‘pure’ MC simulation (i.e. before the likelihood fit) is also shown for the main backgrounds. The FNP lepton background is estimated via the matrix method described in section 4.7. The category ‘Other backgrounds’ includes the non-dominant background sources, e.g. $t\bar{t}+V$, Higgs boson and Drell–Yan events. Both statistical and systematic contributions are included in the uncertainties [4].



(a) BDT-VV distribution in VR-VV-DF

(b) $\Delta\phi_{\text{boost}}$ distribution in VR-VV-SF

(c) BDT-top distribution in VR-top-DF

(d) $|\cos\theta_{\ell\ell}^*|$ distribution in VR-top-SF(e) $m_{\ell\ell}$ distribution in VR-top0J-DF

(f) BDT-top distribution in VR-top0J-SF

Figure 6.8: Distributions of (a) BDT-VV in VR-VV-DF, (b) $\Delta\phi_{\text{boost}}$ in VR-VV-SF, (c) BDT-top in VR-top-DF, (d) $|\cos\theta_{\ell\ell}^*|$ in VR-top-SF, (e) $m_{\ell\ell}$ in VR-top0J-DF and (f) BDT-top in VR-top0J-SF for data and the estimated SM backgrounds. The $t\bar{t}$, single-top-quark and VV backgrounds were normalized by using the scale factors obtained from the fit. The FNP lepton background was estimated via the matrix method described in section 4.7. The ‘Others’ category includes the non-dominant background sources, e.g. $t\bar{t}+V$, Higgs boson and Drell–Yan events. The total uncertainty on the SM background simulation is represented by the shaded band and the final bin in each histogram includes the overflow. The distribution of three benchmark signal points, $m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0) = (100, 10)$, $(125, 25)$ and $(150, 50)$ GeV, is superimposed. In the lower panel the ratio between data and the estimated SM background is shown [4].

6.5 Systematic uncertainties for the chargino search

In addition to the ones described in section 4.8, other uncertainties, directly related to the semi data-driven procedure for estimating the diboson and top backgrounds, need to be taken into account for the chargino search. The major sources of uncertainty in the chargino came from the diboson theoretical uncertainty, the normalization of the dominant backgrounds, and the uncertainty associated with the jet energy scale and resolution and with the E_T^{miss} soft-term scale and resolution. Statistical uncertainties on the simulated MC samples were also considered. In particular, in the cases where the normalization was performed through the CRs (diboson and top), the systematic uncertainties only affected the extrapolation to the signal regions.

In Table 6.7 a summary of the systematic uncertainties for the chargino search, after performing the fit, is given in terms of percentage of background yields entering in the inclusive region $\text{SR}_{\text{-SF BDT-signal} \in (0.77, 1]}^{\text{-DF BDT-signal} \in (0.81, 1]}$, which is a combination of all the binned signal regions defined in Table 6.1.

Region	$\text{SR}_{\text{-SF BDT-signal} \in (0.77, 1]}^{\text{-DF BDT-signal} \in (0.81, 1]}$
Total background expectation	630
E_T^{miss} modelling	9.1%
Diboson theoretical uncertainties	5.8%
Jet energy scale	5.2%
VV normalization	3.6%
Jet energy resolution	1.7%
MC statistical uncertainties	1.7%
Lepton modelling	1.2%
Top theoretical uncertainties	1%
$t\bar{t}$ normalization	1%
FNP leptons	0.8%
b -tagging	0.7%
$Z/\gamma^*(\rightarrow \ell\ell)$ +jets theoretical uncertainties	0.04%
Total systematic uncertainty	12%

Table 6.7: Summary of the systematic uncertainties in background estimation in the inclusive region $\text{SR}_{\text{-SF BDT-signal} \in (0.77, 1]}^{\text{-DF BDT-signal} \in (0.81, 1]}$ in the chargino search. The individual uncertainties can be correlated, and do not necessarily sum in quadrature to the total background uncertainty. The percentages represent the size of the uncertainty relative to the total background expectation [4].

6.6 Results and interpretation

After the ‘unblinding’ of the analysis, the data inside the SRs were revealed, and the statistical interpretation of the results was performed with the HISTFITTER framework, described in section 4.1, through the likelihood fit.

In Figure 6.9 the data-MC comparison between the observed data and the predicted number of background events obtained after the background-only fit in each of the binned SRs defined in Table 6.1 is reported. A good agreement with the SM expectations can be observed in all the SRs considered.

A model-independent likelihood fit was performed in order to derive upper limits at 95% CL on the visible signal cross section σ^{obs} . The inclusive SRs defined in Table 6.1 were considered one by one in the likelihood fit procedure, thus obtaining the observed ($S_{\text{obs}}^{0.95}$) and expected ($S_{\text{exp}}^{0.95}$) limits at 95% CL in the number of potential BSM events, and the p_0 -values, capped

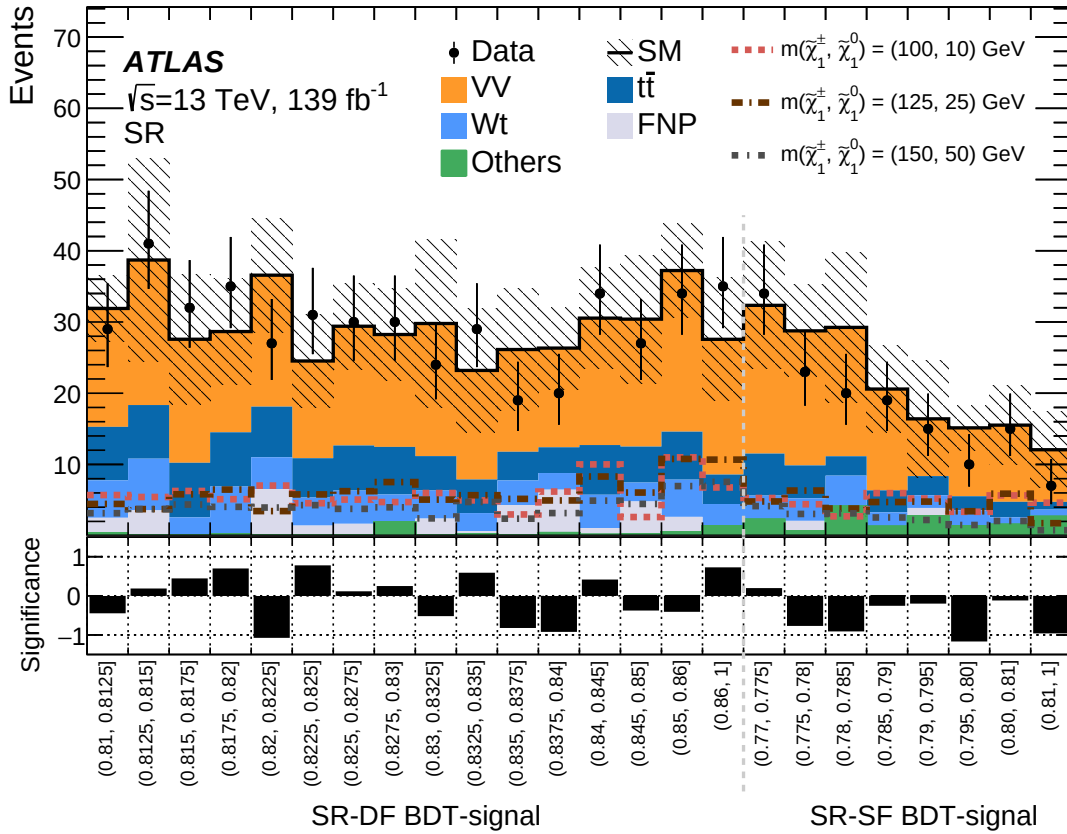


Figure 6.9: Observed number of events in the SRs defined in Table 6.1 along with the expected SM background estimated after the background-only fit in CRs. The ‘Others’ category includes the non-dominant background sources, e.g. $t\bar{t}+V$, Higgs boson and Drell-Yan events. The total uncertainty on the SM background simulation is represented by the shaded band. The distribution of three benchmark signal points, $m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0) = (100, 10)$, $(125, 25)$ and $(150, 50)$ GeV, are overlaid for comparison. In the lower panel is reported the significance [4, 254].

Signal region	Observed	Expected	σ^{obs} [fb]	$S_{\text{obs}}^{0.95}$	$S_{\text{exp}}^{0.95}$	p_0
SR ^{-DF} BDT-signal $\in(0.81,1]$ SR ^{-SF} BDT-signal $\in(0.77,1]$	620	630 ± 70	1.20	166.2	$175.1^{+44.9}_{-49.2}$	0.50
SR-DF BDT-signal $\in(0.81,1]$	477	470 ± 50	0.80	111.0	$108.9^{+43.1}_{-31.1}$	0.47
SR-DF BDT-signal $\in(0.82,1]$	340	350 ± 40	0.55	76.0	$81.5^{+32.7}_{-22.9}$	0.50
SR-DF BDT-signal $\in(0.83,1]$	222	231 ± 26	0.38	52.3	$57.8^{+22.9}_{-16.1}$	0.50
SR-DF BDT-signal $\in(0.84,1]$	130	126 ± 15	0.29	40.0	$37.5^{+15.0}_{-10.5}$	0.41
SR-DF BDT-signal $\in(0.85,1]$	69	65 ± 10	0.22	30.9	$28.0^{+12.0}_{-8.3}$	0.38
SR-SF BDT-signal $\in(0.77,1]$	143	167 ± 32	0.47	65.5	$80.6^{+19.4}_{-23.0}$	0.50
SR-SF BDT-signal $\in(0.78,1]$	86	108 ± 23	0.31	42.8	$53.9^{+18.9}_{-13.6}$	0.50
SR-SF BDT-signal $\in(0.79,1]$	47	58 ± 15	0.21	28.9	$34.1^{+10.8}_{-7.8}$	0.50
SR-SF BDT-signal $\in(0.80,1]$	22	28 ± 8	0.10	14.3	$16.8^{+5.9}_{-4.5}$	0.50

Table 6.8: In the left part of the table are reported the observed event yields and the predicted background yields for the inclusive SRs defined in Table 6.1. In the right part the model-independent upper limits at 95% CL on the observed ($S_{\text{obs}}^{0.95}$) and expected ($S_{\text{exp}}^{0.95}$) number of BSM events and on the effective BSM cross section σ^{obs} (defined as $\langle A\epsilon\sigma \rangle_{\text{obs}}^{0.95}$) are reported. Such results are obtained via the fit procedure described in section 4.1.3. The $\pm 1\sigma$ variations on $S_{\text{exp}}^{0.95}$ are provided. In the last column the p_0 -values are reported considering the SM background-only hypothesis, and they are capped to 0.50 in those regions where the data yields is smaller than expected [4].

at $p_0 = 0.50$. These results are reported in Table 6.8, along with the observed data and the expected number of background events in the inclusive SRs. In none of them a significant deviation of the data from the expectations is observed.

Through a simultaneous likelihood fit which includes both SRs and CRs, exclusion limits at 95% CL were set on the masses of the chargino and the LSP. These limits are reported in Figure 6.10 both in the (a) $(m(\tilde{\chi}_1^\pm), m(\tilde{\chi}_1^0))$ and (b) $(m(\tilde{\chi}_1^0), \Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0))$ mass planes. Chargino masses up to 140 GeV are excluded at 95% CL in case of a mass-splitting between the chargino and neutralino as low as about 100 GeV.

These results improve the previous exclusion limit of a portion in the compressed region, and were included in the ATLAS summary plot, which is shown in Figure 6.11 and summarise the status of the searches for chargino pairs $\tilde{\chi}_1^+ \tilde{\chi}_1^-$ decaying via W -bosons in March 2023.

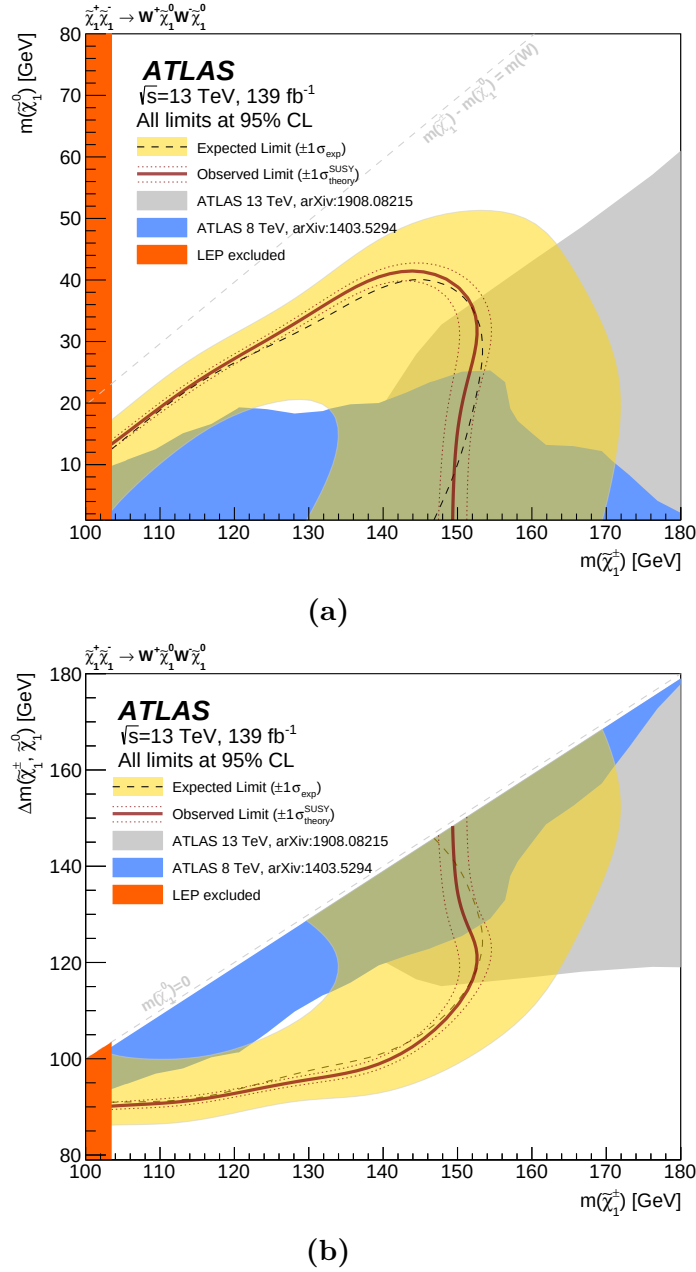


Figure 6.10: Observed and expected exclusion limits on SUSY simplified models for chargino-pair production with W -boson-mediated decays in the (a) $(m(\tilde{\chi}_1^\pm), m(\tilde{\chi}_1^0))$ and (b) $(m(\tilde{\chi}_1^\pm), \Delta m(\tilde{\chi}_1^\pm, \tilde{\chi}_1^0))$ planes. The results of the current analysis are shown: the observed (solid thick red line) and the expected (thin dashed line) contours. The yellow shaded band around the expected exclusion contour represents its $\pm 1\sigma$ variations, including all the sources of uncertainties except for the theoretical ones in the signal cross section. The dotted lines around the observed limit shows how it would change if the nominal signal cross section is scaled up and down by theoretical uncertainty. All limits are computed at 95% CL. The observed limits obtained at LEP [259] and by the ATLAS experiment in previous searches [62, 63] are also shown. In the case of the search performed on ATLAS Run 1 data at $\sqrt{s} = 8$ TeV [63] no sensitivity was expected for the exclusion in the mass plane [4].

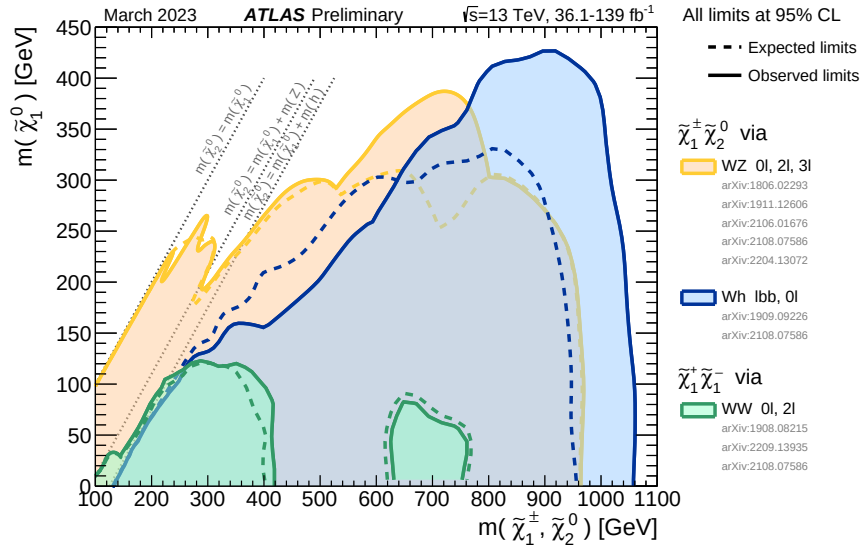


Figure 6.11: Status by March 2023 of the exclusion limits at 95% CL on $\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp$ and $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ production with SM-boson mediated decays as functions of $\tilde{\chi}_1^\pm$, $\tilde{\chi}_2^0$ and $\tilde{\chi}_1^0$ masses. The production cross section is for pure wino $\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp$ and $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$. Each individual exclusion contour represents a union of the excluded regions of one or more analyses [60].

CHAPTER

7

Prospects for a search for direct pair production of top-squarks at HL-LHC

Prospects for a future search for direct pair production of top-squarks (stop) in events with two opposite-sign charged leptons (electrons or muons), jets and missing transverse momentum in pp collisions at the High-Luminosity LHC.

As already discussed in section 1.3.1, the searches for supersymmetric particles produced in strong interactions are favoured at LHC due to their larger production cross section, but so far no evidence of squarks and gluinos was observed, and they were excluded up to the TeV scale masses. In particular, the searches for $\tilde{t}_1$ investigated a large region of the $(m(\tilde{t}_1), m(\tilde{\chi}_1^0))$ mass plane, extending more and more the observed exclusion limits, as shown in Figure 1.10. The chance of discovering such particles will increase during the LHC's High-Luminosity phase, described in section 2.3.2, due to the expected increase of cross section with the center of mass energy ($\sqrt{s} = 14$ TeV) and of the instantaneous luminosity (nominally $5 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$, with a possible maximum value of $7.5 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$). The ATLAS and CMS experiments are expected to collect in this phase an integrated luminosity of about 3000 fb^{-1} .

In this chapter a study of the discovery prospects at HL-LHC of the direct production of stop pairs, $\tilde{t}_1\tilde{t}_1$, in events with final states with two opposite-sign charged leptons, missing transverse energy and jets, is described. This study consisted in optimizing the strategy already developed in a previous published ATLAS search [6], which used the data collected during Run 2 at LHC, targeting the same supersymmetric channels. This chapter will report

the description of: the topic, the motivations, the adopted strategy, the physics objects and simulation tools used, the procedure to optimize the event selection, the sources of systematic uncertainties and, finally, the expected results of this search at HL-LHC and their interpretation. This study was published in 2024 by the ATLAS collaboration in the public note *Prospects for a search for direct pair production of top-squarks at the high-luminosity LHC with the ATLAS detector* [7].

7.1 Motivation and analysis description

Assuming a R-parity conserving SUSY model, depending on the mass-splitting between the $\tilde{t}_1$ and the $\tilde{\chi}_1^0$, $\Delta m(\tilde{t}_1, \tilde{\chi}_1^0) = m(\tilde{t}_1) - m(\tilde{\chi}_1^0)$, the $\tilde{t}_1$ can decay in different channels:

- *2-body decay*: if the mass-splitting is larger than the mass of the t -quark, $\Delta m(\tilde{t}_1, \tilde{\chi}_1^0) > m(t)$, the $\tilde{t}_1$ can decay in a real top-quark and in a LSP, $\tilde{t}_1 \rightarrow t\tilde{\chi}_1^0$ (2-body decay);
- *3-body decay*: if the mass-splitting is smaller than the mass of the t -quark but larger than the sum of the W -boson and b -quark masses, $m(W) + m(b) < \Delta m(\tilde{t}_1, \tilde{\chi}_1^0) < m(t)$, the $\tilde{t}_1$ can decay in a virtual top (which, in turn, decays via a real W -boson and a b -quark), and in a LSP, $\tilde{t}_1 \rightarrow Wb\tilde{\chi}_1^0$ (3-body decay);
- *4-body decay*: if the mass-splitting is smaller than the sum of the W -boson and b -quark masses, $\Delta m(\tilde{t}_1, \tilde{\chi}_1^0) < m(W) + m(b)$, the W -boson deriving from the decay of the virtual top is virtual as well, thus $\tilde{t}_1$ can decay in $\tilde{t}_1 \rightarrow ff'b\tilde{\chi}_1^0$, where f and f' are two fermions coming from the decay of the virtual W -boson (4-body decay).

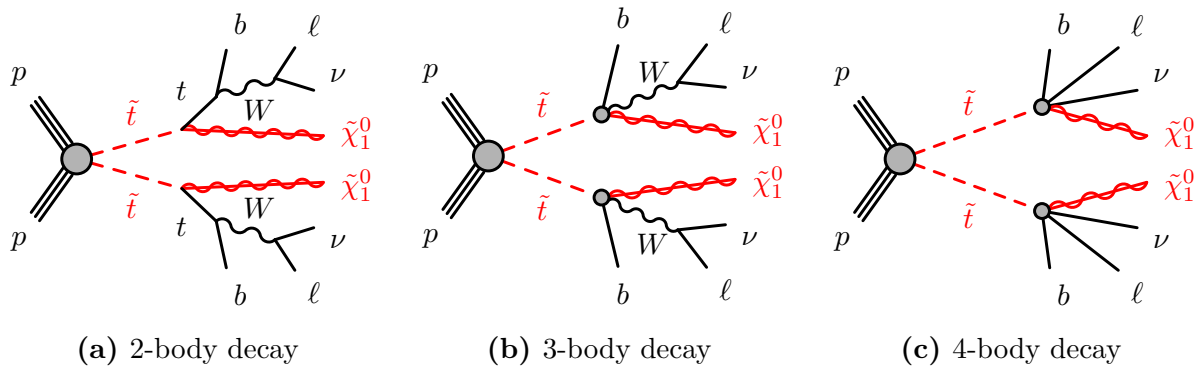


Figure 7.1: Diagrams of the signal models targeted by the search presented in this chapter: (a) the 2-body $\tilde{t}_1$ decay into an on-shell t -quark and the lightest neutralino ($\tilde{t}_1 \rightarrow t\tilde{\chi}_1^0$); (b) the 3-body $\tilde{t}_1$ decay into an on-shell W -boson, a b -quark and the lightest neutralino ($\tilde{t}_1 \rightarrow bW\tilde{\chi}_1^0$); (c) the 4-body $\tilde{t}_1$ decay ($\tilde{t}_1 \rightarrow b\bar{\ell}\nu\tilde{\chi}_1^0$) where $\bar{\ell}$ and ν are an anti-lepton (lepton) with its neutrino (anti-neutrino). For all diagrams the distinction between particle and anti-particle is omitted [6].

For all the three decay modes, if both the two W -bosons produced in the $\tilde{t}_1$ pair production, either real or virtual, decay leptonically, the final state contains two leptons, two b -tagged

jets and missing transverse energy (from the LSPs and the neutrinos), and the diagrams of the three processes described above are shown in Figure 7.1.

The previously published ATLAS search [6] performed a dedicated selection for each of the decay modes in Figure 7.1, obtaining the exclusion limits reported in Figure 7.2, which excluded $\tilde{t}_1$ with masses up to 1 TeV for a massless $\tilde{\chi}_1^0$.

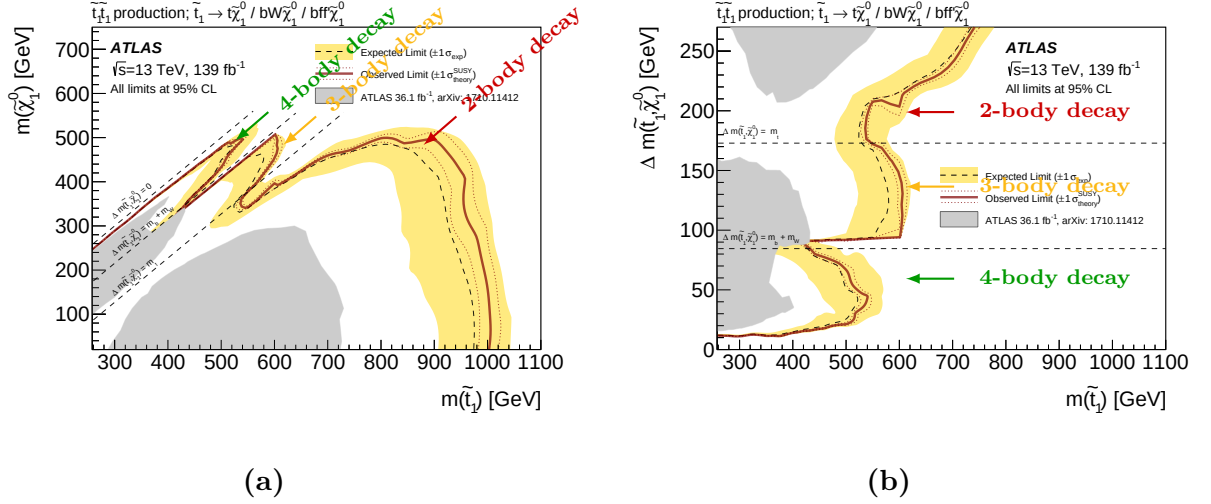


Figure 7.2: Exclusion limits at 95% Confidence Level (CL) for a simplified model assuming $\tilde{t}_1$ pair production, where each stop decays in $\tilde{t}_1 \rightarrow t^{(*)} \tilde{\chi}_1^0$ with a 100% BR, in the (a) $(m(\tilde{t}_1), m(\tilde{\chi}_1^0))$ and (b) $(m(\tilde{t}_1), \Delta m(\tilde{t}_1, \tilde{\chi}_1^0))$ mass planes. The dashed lines and the shaded yellow bands are the expected limits and their $\pm 1\sigma$ errors respectively. The thick solid red lines represent the observed limits relative to the central value of the signal cross section. For both expected and observed limits, the effect in the signal cross section of theoretical uncertainties is not accounted for. Instead, the red dotted lines represent the observed limits when varying the signal cross section by $\pm 1\sigma$ theoretical uncertainty [6]. In the two plots the three different decay mode regions are highlighted.

Starting from the selection strategy exploited in this analysis, the aim of the current study is to define a possible analysis to be performed on data collected by ATLAS in the HL-LHC condition. In particular, this analysis is focused on the region $\Delta m(\tilde{t}_1, \tilde{\chi}_1^0) < m(t)$, where the $\tilde{t}_1$ can decay through either a 3-body or 4-body mode. However, since the analysis showed a good sensitivity, the results were also extended to the 2-body decay region ($\Delta m(\tilde{t}_1, \tilde{\chi}_1^0) > m(t)$).

7.2 Event simulation

The study is based on MC simulations which try to mimic the expected conditions at HL-LHC. The simulated samples for both the supersymmetric signal and the SM backgrounds were produced in the Run 2 layout at 13 TeV and scaled to the 14 TeV cross sections and to the 3000 fb $^{-1}$ of integrated luminosity, expected at HL-LHC, then without taking into account the larger pileup and the upgraded detector conditions. Accordingly, the expected changes in the

distributions of the kinematic observables, due to the increased center of mass energy, were not taken into account either, since preliminary studies showed that they only marginally affect the signal significance Z_n [236].

The SM background samples were simulated with the generators listed in Table 7.1, successively processed in the ATLAS detector full simulation (FULLSIM) with the Run 2 layout. The main background contributions come from VV , VVV , $t\bar{t}$ and single-top. For each sample, the cross sections were extrapolated to 14 TeV by increasing the cross sections at 13 TeV of the appropriate percentages: 10% for VV , 20% for $t\bar{t} + Z$, 9% for $V + \text{jets}$ and 18% for $t\bar{t}$, single-top and all the other backgrounds [260, 261]. For which concerns the background due to fake and non-prompt (FNP) leptons, which is not negligible for the 4-body selection due to the low p_T requirements in the lepton selection, it was estimated with the ‘fake factor’ [262–265] method, as described in Ref. [6].

This procedure consists in defining two independent lepton categories, one labelled as ‘Id’, referring to leptons passing the signal criteria, and the other as ‘anti-Id’, containing leptons failing the isolation requirement either for electrons or muons. Their ratio is the ‘fake factor’ and it is computed separately for electrons and muons as a function of their transverse momentum and pseudorapidity, in proper control samples enriched of $Z + \text{jets}$ events. The FNP estimates of each region defined in the analysis are obtained by applying the fake factors to the events entering in that specific region, but replacing at least one of the signal leptons with an anti-Id lepton. Nevertheless, in the HL-LHC condition the FNP rejection power could increase thanks to an improved performance of the isolation algorithms and a higher granularity of the upgraded detectors.

For which concerns the signal points, simplified $\tilde{t}_1$ models were considered and generated with aMC@NLO 2.6.2 [215] using the matrix element calculation at the lowest level (LO) and with up to two additional partons. The generation was interfaced both with PYTHIA 8.212 and MADSPIN [177, 179], for the parton showering, hadronization and b and c hadron decays modellings. The parton distribution function set applied in the generation was the NNPDF2.3LO set [172], with the A14 [178] tune of the underlying-event and shower parameters. In particular the matching between the matrix element and the parton shower (ME-PS) was performed with the CKKW-L prescription [180], considering a matching scale of one quarter of the mass of the top-squark. Signal samples were processed with the SIMPLEANALYSIS [266] software, which used a set of smearing functions (applied at generator level) to emulate the effect of the improved ATLAS detector [267, 268].

The signal cross sections were computed at NNLO in the strong coupling constant α_s , taking into account effects of soft gluon emission at next-to-next-to-leading-logarithm accuracy (NNLO+NNLL) [269–276]. These cross sections depend on the mass of the stop. For example, for a stop mass of 500 GeV the stop pair production cross section is 610 fb, while for a stop mass of 1000 GeV it is 6.8 fb. The signal cross sections were extrapolated to 14 TeV using the ratio of NNLO calculations, available at 13 TeV and 14 TeV. For example, such ratio is 1.28 for a stop mass of 500 GeV and 1.40 for a stop mass of 1000 GeV [7]. In Figure 7.3 the signal models considered for the processes under study are reported: (a) 226 points for the 4-body process and (b) 68 and 153 points for the 3-body and 2-body processes respectively.

Physics process	Generator	Parton shower	Normalisation	PDF (generator)	PDF (PS)
SUSY Signals	MADGRAPH5_aMC@NLO [215]	PYTHIA 8.212 [177, 179]	NNLO+NNLL [269–276]	NNPDF2.3LO [172]	NNPDF2.3LO
$t\bar{t}$	POWHEG-Box v2 [194–196]	PYTHIA 8.230	NNLO+NNLL [203]	NNPDF3.0NLO [204]	NNPDF2.3LO
$t\bar{t} + V$ ($V = W, Z$)	MADGRAPH5_aMC@NLO	PYTHIA 8.210	NLO [215, 277]	NNPDF3.0NLO	NNPDF2.3LO
Single top	POWHEG-Box v2 [194–196, 278, 279]	PYTHIA 8.230	NNLO+NNLL [206, 207, 280, 281]	NNPDF3.0NLO	NNPDF2.3LO
$Z/\gamma^* (\rightarrow \ell\ell) + \text{jets}$	SHERPA 2.2.1 [282, 283]	SHERPA 2.2.1	NNLO [284]	NNPDF3.0NNLO [204]	NNPDF3.0NNLO
Diboson VV ($V = W, Z$)	SHERPA 2.2.1 or 2.2.2 [282]	SHERPA 2.2.1 or 2.2.2	NLO [191]	NNPDF3.0NNLO	NNPDF3.0NNLO
Triboson VVV ($V = W, Z$)	SHERPA 2.2.2	SHERPA 2.2.2	NLO [191, 282]	NNPDF3.0NNLO	NNPDF3.0NNLO
$t\bar{t}H$	POWHEG-Box v2 [195, 196, 216]	PYTHIA 8.230	NLO [215, 277]	NNPDF3.0NLO	NNPDF2.3LO
$t\bar{t}WW$	MADGRAPH5_aMC@NLO	PYTHIA 8.186 [177]	NLO [215]	NNPDF2.3LO	NNPDF2.3LO
$t\bar{t}WZ$	MADGRAPH5_aMC@NLO	PYTHIA 8.212	NLO [215]	NNPDF3.0NLO	NNPDF2.3LO
$tZ, t\bar{t}t, t\bar{t}t$	MADGRAPH5_aMC@NLO	PYTHIA 8.230	NLO [215]	NNPDF3.0NLO	NNPDF2.3LO

Table 7.1: Summary of the generators used for signal and background processes. The matrix element (ME) and parton shower (PS) generators, the cross section order in α_s used to normalise the event yield, and the PDF sets used in ME and PS are reported [7].

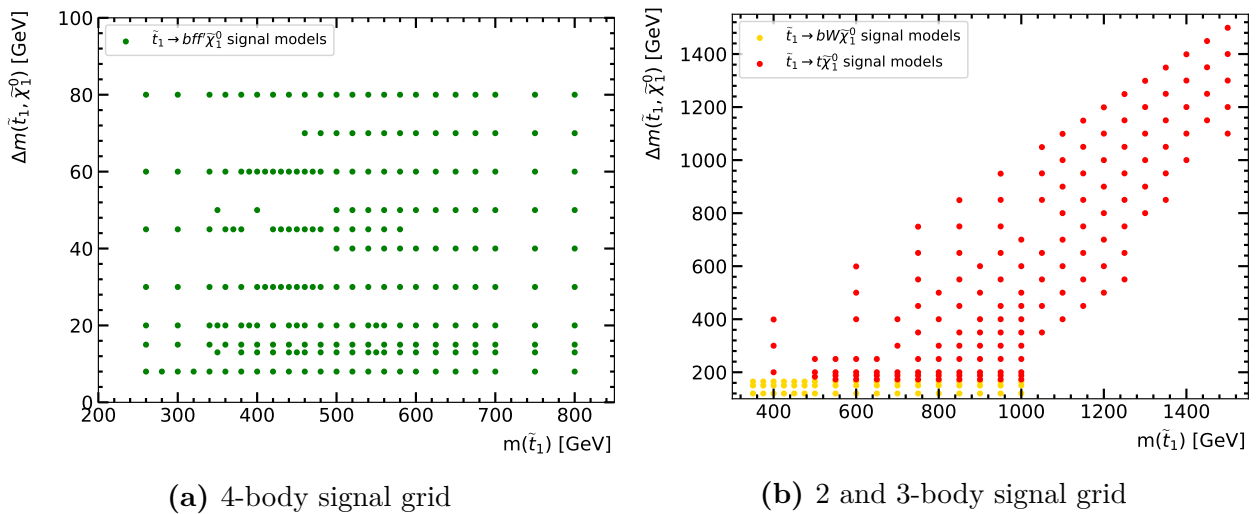


Figure 7.3: Summary of the signal models in the $(m(\tilde{t}_1), \Delta m(\tilde{t}_1, \tilde{\chi}_1^0))$ plane considered for the three processes studied in the search: (a) 226 points in the 4-body region and (b) 68 and 153 points in the 3-body and 2-body regions respectively.

7.3 Physics object selection

The physics objects of interest for the analysis are electrons, muons, jets and missing transverse energy. Their definitions, for the 4-body and 3-body selections, are similar to those used in Ref. [6] and to those defined in section 4.5 for the slepton and chargino analysis. In Table 7.2 are summarized all the requirements for the physical objects used, and, since most of them were already described in Table 4.4, only their differences are highlighted in this section.

Baseline electrons are required to have $E_T > 4.5$ GeV and $|\eta| < 2.47$ along with the *Loose* PID quality working point and impact parameter conditions described in section 4.5. Signal electrons require a *Medium* identification working-point and the *Gradient* isolation criteria, reported in Table 3.2, plus the $|d_0/\sigma_{d_0}| < 5$ condition.

Baseline muons are required to have an associated track with a transverse momentum $p_T > 4$ GeV, and $|\eta| < 2.7$, for the 4-body selection, and $|\eta| < 2.4$, for the 3-body selection.

The same PID quality, isolation and impact parameter requirements as those of Table 4.4 are applied here for baseline and signal muons.

Concerning jets, they are required to have a $p_T > 20 \text{ GeV}$ and $|\eta| < 2.8$, plus the same *Tight* request on the JVT used for the chargino and slepton analysis. Jets identified as coming from b -hadrons are reconstructed via the MV2c10 boosted decision tree algorithm [154], for $|\eta| < 2.5$, by using as input quantities like the impact parameters of the tracks associated with the jet and the well-reconstructed secondary vertices. The algorithm is implemented with a working point providing a 77% of b -tagging efficiency in $t\bar{t}$ events. Rejection factors for c -jets, τ -jets and jets from light quarks or gluons are 4.9, 1.5 and 110 respectively [7].

Physics Object	Definition		
Electrons	Baseline	Acceptance PID quality Impact parameter	$E_T > 4.5 \text{ GeV}$, $ \eta < 2.47$ LooseAndBLayerLLH $ z_0 \sin \theta < 0.5 \text{ mm}$
	Signal	Acceptance PID quality Isolation Impact parameter	$E_T > 4.5 \text{ GeV}$, $ \eta < 2.47$ MediumLH Gradient $ d_0/\sigma_{d_0} < 5$
Muons	Baseline	Acceptance PID quality Impact parameter	$p_T > 4 \text{ GeV}$, $ \eta < 2.7$ (if 4-body) or $ \eta < 2.4$ (if 3-body) Medium $ z_0 \sin \theta < 0.5 \text{ mm}$
	Signal	Acceptance PID quality Isolation Impact parameter	$p_T > 4 \text{ GeV}$, $ \eta < 2.7$ (if 4-body) or $ \eta < 2.4$ (if 3-body) Medium FCLoose $ d_0/\sigma_{d_0} < 3$
Jets	Signal jets	JVT Acceptance	Tight $p_T > 20 \text{ GeV}$, $ \eta < 2.8$
	Signal b -jets	b -tagging algorithm Efficiency Acceptance	MV2c10 77% $p_T > 20 \text{ GeV}$, $ \eta < 2.8$

Table 7.2: Summary of the criteria applied to electrons, muons and jets candidates in order to define the physical objects used in the stop at HL-LHC search.

7.4 Event selection

The selections of the 4-body and 3-body decay modes were optimized in order to have the highest signal purity and lowest background contamination, thus maximising the signal significance Z . Events with exactly two signal leptons, both electrons, both muons or one electron and one muon, were requested. In particular, for the 4-body selection a soft lepton threshold was imposed, since this process is characterized by the presence of leptons with low transverse momentum. The leading and the sub-leading leptons were requested to have a transverse momentum $p_T > 5$ GeV, while for the 3-body selection a higher p_T threshold was imposed: $p_T^{\ell_1} > 25$ GeV and $p_T^{\ell_2} > 20$ GeV. Several kinematic variables were used in the event selection, some of them already mentioned in the already described analyses, like the E_T^{miss} significance and the multiplicity of jets and b -jets, others specifically introduced for this analysis. The two selections are described in sections 7.4.1 and 7.4.2, and they derive from the original criteria adopted in the Run 2 paper [6], optimized in order to get the largest sensitivity in the HL-LHC conditions.

7.4.1 4-body selection

As shown in Figure 7.1c, the stop 4-body decay can happen in regions of the phase space where $m(b) < \Delta m(\tilde{t}_1, \tilde{\chi}_1^0) < m(b) + m(W)$, where the $\tilde{t}_1$ decays in an off-shell t -quark, which in turn decays in an off-shell W -boson and a b -quark. Two signal regions were defined, targeting different mass-splitting configurations: a SR optimized for small values of $\Delta m(\tilde{t}_1, \tilde{\chi}_1^0)$, $\text{SR}_{\text{Small } \Delta m}^{4\text{-body}}$, and a SR optimized for larger values of $\Delta m(\tilde{t}_1, \tilde{\chi}_1^0)$, $\text{SR}_{\text{Large } \Delta m}^{4\text{-body}}$. The definition of these regions is reported in Table 7.3.

Since the $\text{SR}_{\text{Small } \Delta m}^{4\text{-body}}$ targets small values of mass-splitting, the lower and the upper p_T thresholds were chosen at 5 GeV and 10 GeV, for the sub-leading lepton, and at 5 GeV and 25 GeV, for the leading lepton. The Run 2 analysis requested a transverse momentum lower threshold of 4.5 GeV for electrons and 4 GeV for muons, but they were here increased to 5 GeV in order to reduce the contribution of the FNP background and to improve the sensitivity. The $\text{SR}_{\text{Large } \Delta m}^{4\text{-body}}$ targets higher values of mass-splitting, requiring an upper threshold of 100 GeV and 20 GeV for leading and sub-leading lepton transverse momenta respectively, and a lower threshold of 10 GeV for both. In particular, the requirement on the sub-leading lepton transverse momentum ensured the orthogonality between the two SRs, and with the 3-body selection, which instead, as reported in section 7.4.2, required the sub-leading lepton transverse momentum larger than 20 GeV.

The E_T^{miss} trigger was used in the event selection and events with energetic ISR jets were considered, since in the recoil against the two $\tilde{t}_1$ the E_T^{miss} from neutrinos and neutralinos is enhanced above the threshold of the E_T^{miss} trigger. Therefore, assuming the leading jet j_1 to be an ISR jet, its transverse momentum was required to be greater than 150 GeV.

Furthermore, $m_{\ell\ell}$ was imposed to be larger than 10 GeV in order to remove leptons coming from low mass and Drell-Yan resonances. Further selections were applied in terms of the

$p_{T, \text{boost}}^{\ell\ell}$, $R_{2\ell}$ and $R_{2\ell 4j}$, these two latter defined as:

$$R_{2\ell} = \frac{E_T^{\text{miss}}}{p_T^{\ell_1} + p_T^{\ell_2}}, \quad R_{2\ell 4j} = \frac{E_T^{\text{miss}}}{E_T^{\text{miss}} + p_T^{\ell_1} + p_T^{\ell_2} + \sum_{i=1}^4 p_T^{j_i}}, \quad (7.1)$$

where j_i are the four most energetic jets. A further requirement was applied in order to improve the isolation of the sub-leading lepton, by exploiting the following isolation variable:

$$\min \Delta R_{\ell_2, j_i} = \min_{j_i \in [\text{jets}]} \Delta R(\ell_2, j_i), \quad (7.2)$$

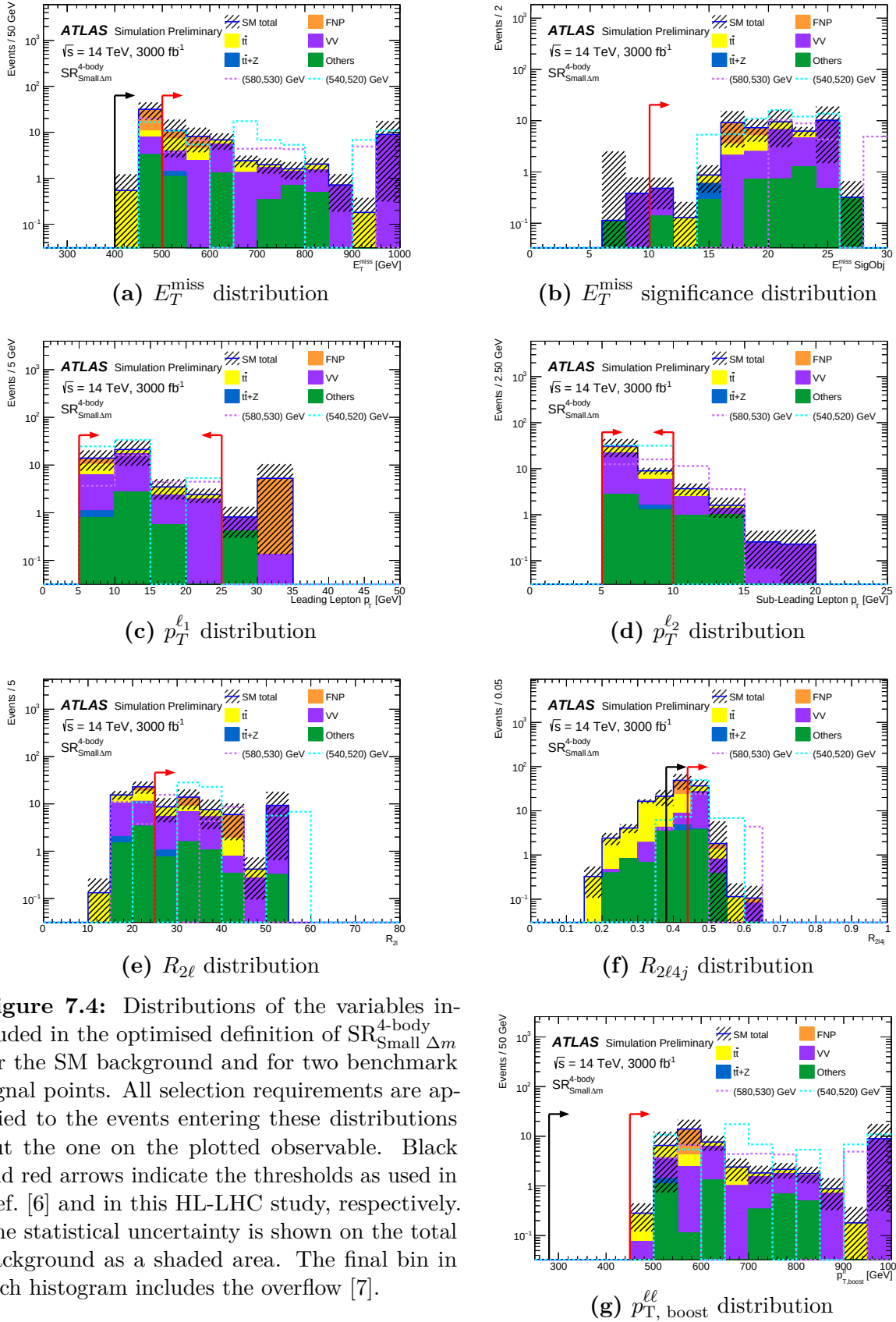
where ‘[jets]’ contains all the jets in the event. This criterion reduced the FNP lepton probability.

	SR _{Small Δm} ^{4-body}	SR _{Large Δm} ^{4-body}
$p_T^{\ell_1}$ [GeV]	[5, 25]	[10, 100]
$p_T^{\ell_2}$ [GeV]	[5, 10]	[10, 20]
$m_{\ell\ell}$ [GeV]	> 10	
$p_T^{j_1}$ [GeV]	> 150	
$\min \Delta R_{\ell_2, j_i}$	> 1	
E_T^{miss} significance	> 10	> 18
$p_{T, \text{boost}}^{\ell\ell}$ [GeV]	> 450	
E_T^{miss} [GeV]	> 500	
$R_{2\ell}$	> 25	> 13
$R_{2\ell 4j}$	> 0.45	> 0.44

Table 7.3: Selection criteria of the two 4-body signal regions [7].

In Figures 7.4 and 7.5 are reported the distribution of these variables for SR_{Small Δm} ^{4-body} and SR_{Large Δm} ^{4-body} respectively, for all backgrounds affecting the analysis and for some benchmark signal points: one with $\Delta m(\tilde{t}_1, \tilde{\chi}_1^0) = 20$ GeV targeting SR_{Small Δm} ^{4-body}, another one with $\Delta m(\tilde{t}_1, \tilde{\chi}_1^0) = 80$ GeV targeting SR_{Large Δm} ^{4-body} and a third point with $\Delta m(\tilde{t}_1, \tilde{\chi}_1^0) = 50$ GeV, targeting both SRs. The black and red arrows in the plots are related to the selections made in Ref. [6] and in the current optimization aimed to HL-LHC respectively.

In Table 7.4 the expected yields for signal and background in SR_{Small Δm} ^{4-body} and SR_{Large Δm} ^{4-body} are reported. ‘Others’ include the minor background contributions, which are the single-top, $Z + \text{jets}$, VVV , $t\bar{t}t$, $t\bar{t}t\bar{t}$, $t\bar{t} + V$, $t\bar{t} + VV$, $t\bar{t}H$ and tZ processes [7].



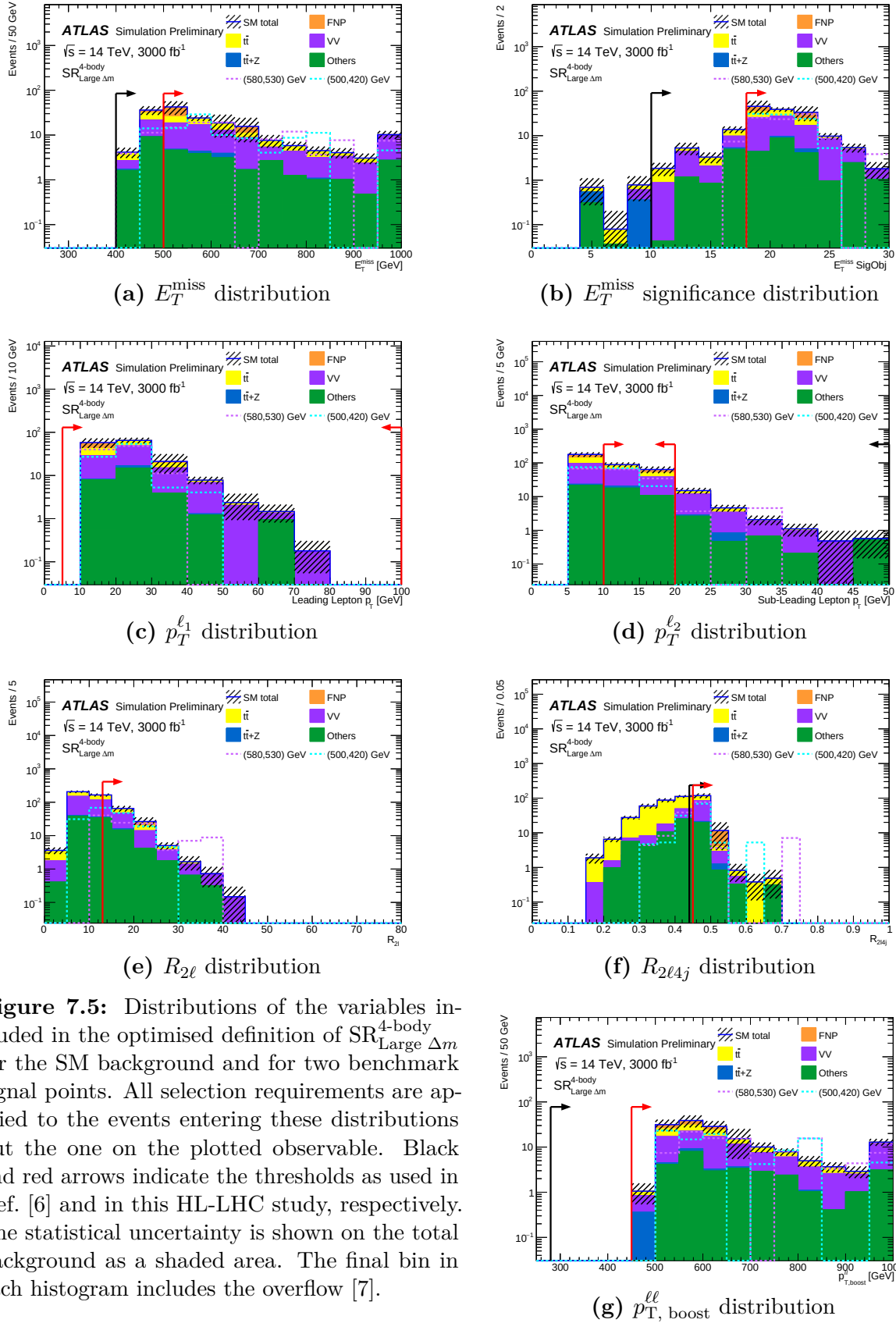


Figure 7.5: Distributions of the variables included in the optimised definition of $\text{SR}^{4\text{-body}}_{\text{Large } \Delta m}$ for the SM background and for two benchmark signal points. All selection requirements are applied to the events entering these distributions but the one on the plotted observable. Black and red arrows indicate the thresholds as used in Ref. [6] and in this HL-LHC study, respectively. The statistical uncertainty is shown on the total background as a shaded area. The final bin in each histogram includes the overflow [7].

Expected Background	$\text{SR}_{\text{Small } \Delta m}^{4\text{-body}}$	$\text{SR}_{\text{Large } \Delta m}^{4\text{-body}}$
MC SM events	40 ± 13	126 ± 25
MC $t\bar{t}$ events	8.0 ± 2.8	25 ± 5
MC VV events	23 ± 10	62 ± 18
MC $t\bar{t} + Z$ events	$0.24^{+0.51}_{-0.24}$	1.45 ± 0.29
MC Others events	3.9 ± 1.3	21 ± 5
FNP events	4.4 ± 1.4	16 ± 9
$m(\tilde{t}_1, \tilde{\chi}_1^0) = (540, 520)$ GeV events	63.7	–
$m(\tilde{t}_1, \tilde{\chi}_1^0) = (500, 420)$ GeV events	9.9	90.2
$m(\tilde{t}_1, \tilde{\chi}_1^0) = (580, 530)$ GeV events	28.5	92.0

Table 7.4: Expected yields for SM background and signal in $\text{SR}_{\text{Small } \Delta m}^{4\text{-body}}$ and $\text{SR}_{\text{Large } \Delta m}^{4\text{-body}}$ for an integrated luminosity of 3000 fb^{-1} . The uncertainties include both the statistical and systematic contributions [7].

7.4.2 3-body selection

As shown in Figure 7.1b, the stop 3-body decay can happen in regions of the phase space where $m(W) + m(b) < \Delta m(\tilde{t}_1, \tilde{\chi}_1^0) < m(t)$, where the $\tilde{t}_1$ decays in an off-shell t -quark, which in turn decays in an on-shell W -boson and in a b -quark. Two signal regions were defined using, besides the usual kinematic variables, a set of new quantities called ‘Super-Razor’ variables [285], built in a reference frame where the two leptons have equal, but opposite, longitudinal transverse momentum p_z . In particular, the Super-Razor variables of interest for the final selection are R_{p_T} , $1/\gamma_{R+1}$, $\Delta\phi_\beta^R$ and M_Δ^R , defined as follows.

- R_{p_T} :

$$R_{p_T} = \frac{|\vec{P}_T|}{|\vec{P}_T| + \sqrt{\hat{s}_R/4}}, \quad (7.3)$$

where $\vec{P}_T$ is the vector sum of the transverse momenta of the visible particles and the missing transverse momentum, while $\sqrt{\hat{s}_R}$ is an estimate of the system’s energy in the Razor frame.

- The *Lorentz factor* γ_{R+1} is related to the boost from the Razor frame to the approximated frames of the two decays of the parent particles. $1/\gamma_{R+1}$ is called ‘visible shape’ and measures how the leptons are distributed. Its value tends to zero for back-to-back visible particles or when they have different momenta, instead it approaches one when the two leptons are collinear and have the same or similar momenta.
- $\Delta\phi_\beta^R$ is the azimuthal angle between the Razor boost from the laboratory and the Razor frame and the sum of the visible momenta evaluated in the Razor frame. Such variable is a good discriminator for models with small mass-splittings.

- M_{Δ}^R :

$$M_{\Delta}^R = \frac{\sqrt{\hat{s}_R}}{\gamma_{R+1}}, \quad (7.4)$$

is particularly useful in discriminating signal from $t\bar{t}$ and diboson backgrounds, for which it has different kinematic end-points, proportional to the mass-splitting between the parent and the invisible particles.

In the 3-body decay the presence of b -jets is highly dependent on the difference $\Delta m(\tilde{t}_1, \tilde{\chi}_1^0)$, because for low mass-splitting the b -jets have a low momentum and their reconstruction efficiency is lower. Two signal regions were defined in order to target different mass-splitting regions: $\text{SR}_W^{3\text{-body}}$, targeting $\Delta m(\tilde{t}_1, \tilde{\chi}_1^0) \sim m(W)$ and $\text{SR}_t^{3\text{-body}}$, targeting $\Delta m(\tilde{t}_1, \tilde{\chi}_1^0) \sim m(t)$. A b -jet veto was required in $\text{SR}_W^{3\text{-body}}$ and at least one b -jet in $\text{SR}_t^{3\text{-body}}$, thus ensuring the orthogonality of the two signal regions. Moreover, the two SRs were furtherly separated in same-flavour and different-flavour: $\text{SR-SF}_W^{3\text{-body}}$, $\text{SR-DF}_W^{3\text{-body}}$, $\text{SR-SF}_t^{3\text{-body}}$ and $\text{SR-DF}_t^{3\text{-body}}$, whose definitions are reported in Table 7.5.

The same criteria were applied for the leading and sub-leading lepton transverse momenta for both selections. Also in this case the request $m_{\ell\ell}$ larger than 20 GeV was applied in order to remove Drell-Yan and low-mass resonances, and, only for SF events, $|m_{\ell\ell} - m_Z| > 20$ GeV was required, in order to reduce the Z -boson background.

	$\text{SR}_W^{3\text{-body}}$		$\text{SR}_t^{3\text{-body}}$	
Leptons flavour	DF	SF	DF	SF
$p_T^{\ell_1}$ [GeV]	> 25		> 25	
$p_T^{\ell_2}$ [GeV]	> 20		> 20	
$m_{\ell\ell}$ [GeV]	> 20		> 20	
$ m_{\ell\ell} - m_Z $ [GeV]	–	> 20	–	> 20
$n_{b\text{-tagged-jets}}$	$= 0$		≥ 1	
$\Delta\phi_{\beta}^R$ [rad]	> 2.3		> 2.3	
E_T^{miss} significance	> 15		> 14	
$1/\gamma_{R+1}$	> 0.76		> 0.76	
R_{p_T}	> 0.78		> 0.75	
M_{Δ}^R [GeV]	> 110		> 132	

Table 7.5: Selection criteria of the two 3-body signal regions [7].

In Figure 7.6 and 7.7 the distributions of the relevant variables for the optimisation at HL-LHC of $\text{SR}_W^{3\text{-body}}$ and $\text{SR}_t^{3\text{-body}}$, respectively, are reported for all the backgrounds affecting the analysis and four benchmark signal models, chosen with mass-splitting $\Delta m(\tilde{t}_1, \tilde{\chi}_1^0)$ between 90 GeV and 165 GeV. The black and red arrows in the plots are related to the selections made in Ref. [6] and in the current optimization aimed to HL-LHC respectively.

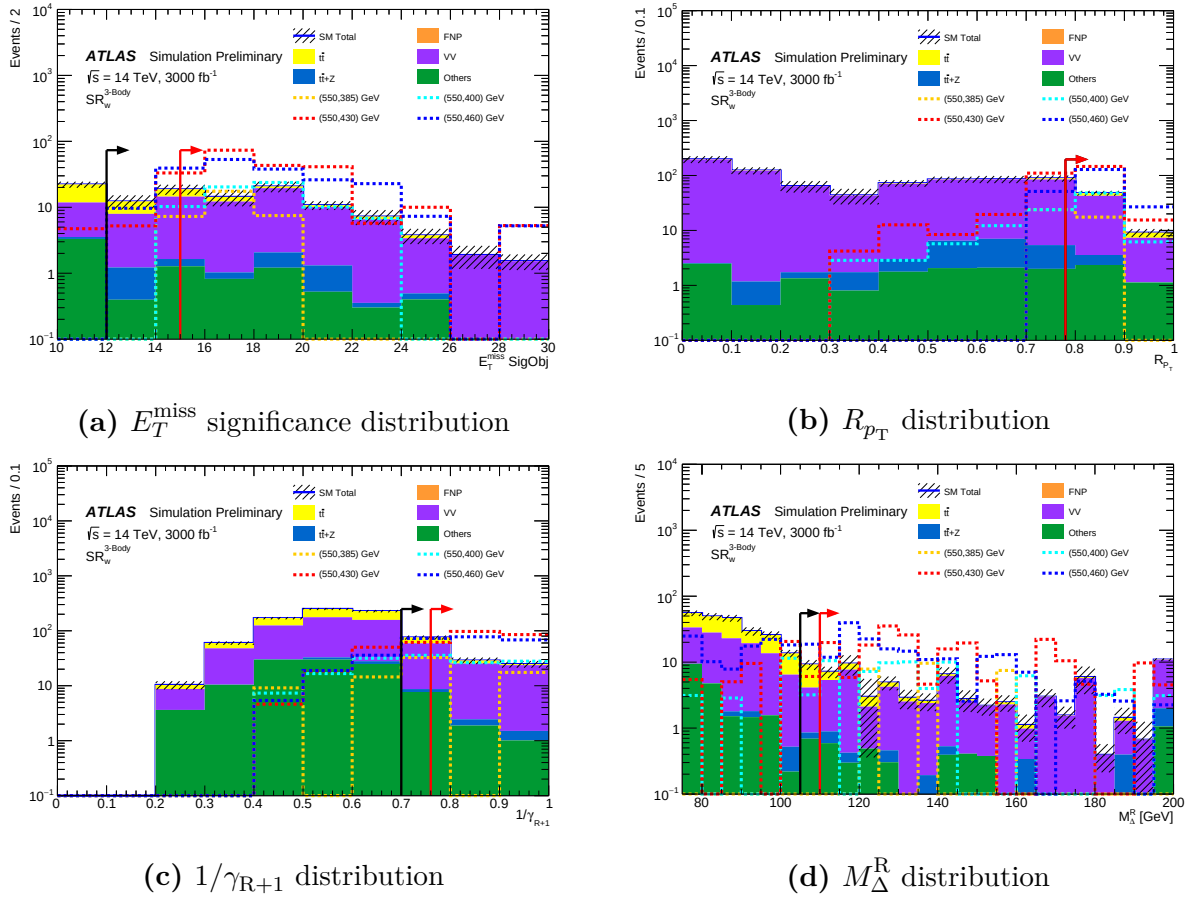


Figure 7.6: Distributions of the variables included in the optimised definition of $\text{SR}_W^{3\text{-body}}$ for the SM background and four benchmark signal points. All selection requirements are applied to the events entering these distributions but the one on the plotted observable. Black and red arrows indicate the thresholds as used in Ref. [6] and in this HL-LHC prospect study, respectively. The statistical uncertainty is shown on the total background as a shaded area. The final bin in each histogram includes the overflow [7].

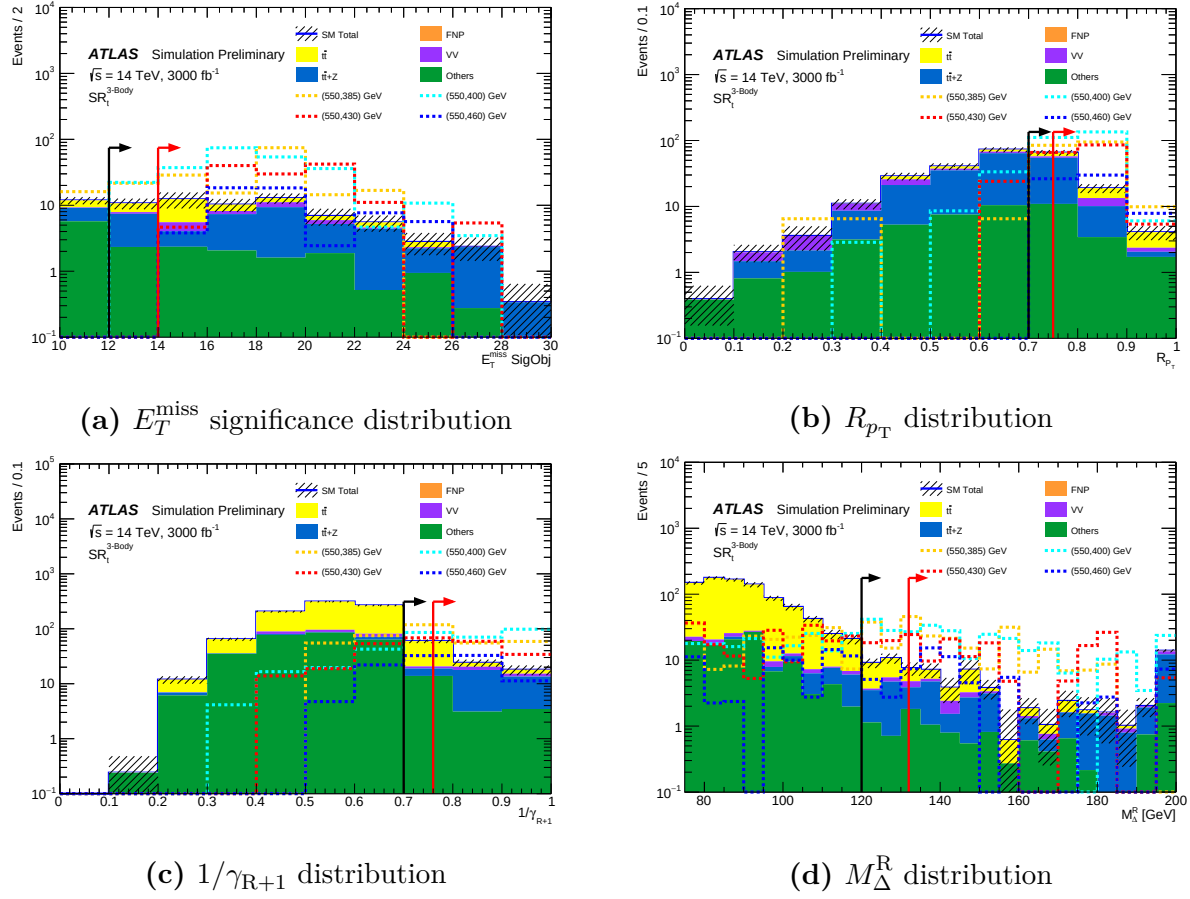


Figure 7.7: Distributions of the variables included in the optimised definition of $\text{SR}_t^{3\text{-body}}$ for the SM background and four benchmark signal points. All selection requirements are applied to the events entering these distributions but the one on the plotted observable. Black and red arrows indicate the thresholds as used in Ref. [6] and in this HL-LHC prospect study, respectively. The statistical uncertainty is shown on the total background as a shaded area. The final bin in each histogram includes the overflow [7].

Expected Background	SR-DF _W ^{3-body}	SR-SF _W ^{3-body}	SR-DF _t ^{3-body}	SR-SF _t ^{3-body}
MC SM events	29 ± 9	39 ± 13	35 ± 9	20 ± 9
MC ttbar events	5.0 ± 2.8	1.4 ^{+4.9} _{-1.4}	10 ± 4	2.4 ± 1.8
MC VV events	19 ± 7	32 ± 12	2.3 ± 1.7	2.4 ± 1.1
MC tt+Z events	0.6 ^{+0.9} _{-0.6}	1.4 ± 0.6	16 ± 4	11 ± 7
MC Others events	4.3 ± 1.2	4.2 ± 0.9	6.8 ± 1.4	3.5 ± 1.4
$m(\tilde{t}_1, \tilde{\chi}_1^0) = (550, 385)$ GeV events	24.9	-	91.4	58.6
$m(\tilde{t}_1, \tilde{\chi}_1^0) = (550, 400)$ GeV events	47.2	20.7	123.7	97.0
$m(\tilde{t}_1, \tilde{\chi}_1^0) = (550, 430)$ GeV events	109.3	92.5	89.0	44.2
$m(\tilde{t}_1, \tilde{\chi}_1^0) = (550, 460)$ GeV events	106.4	70.8	36.0	20.4

Table 7.6: Expected yields for SM background and signal in $\text{SR}_W^{3\text{-body}}$ and $\text{SR}_t^{3\text{-body}}$, separated in DF and SF events, for an integrated luminosity of 3000 fb^{-1} . The uncertainties include both the statistical and systematic contributions. The FNP background contribution is negligible [7].

In Table 7.6 the expected yields for signal and background in $\text{SR}_W^{3\text{-body}}$ and $\text{SR}_t^{3\text{-body}}$ are reported. ‘Others’ include the minor background contributions, which are single-top, Z + jets, VVV , $t\bar{t}t$, $t\bar{t}t\bar{t}$, $t\bar{t} + V$, $t\bar{t} + VV$, $t\bar{t}H$ and tZ processes [7].

7.5 Systematic uncertainties

All sources of detector related systematic uncertainties on the SM background were accounted for in the analysis. Such uncertainties come from: electron and muon efficiency, momentum or energy scale and resolution [132, 139], trigger efficiency [227, 228, 286], jet energy scale and resolution [146, 238, 239] and flavour tagging, the last one related to the modelling of the b -tagging efficiencies for b -jets, c -jets and jets from light-flavour hadron decays [287, 288]. Energy and momentum scale uncertainties of electrons, muons and jets are propagated through E_T^{miss} computation, and additional sources on E_T^{miss} are related to the ‘soft term’ entering in the definition of the missing transverse momentum [155].

Theoretical uncertainties on the description of the parton-level final states include all the uncertainties on the proton parton distribution function, cross section and strong coupling constant α_s , and were estimated varying the renormalisation and factorisation scales and the amount of initial and final state radiation. The parton showering and hadronisation processes, representing how the partons are converted into the hadronic final states, were assessed by comparing the different showering and hadronisation modelling from PYTHIA And HERWIG. This estimation method was used for the main SM backgrounds, while for the remaining minor backgrounds and for the signal samples a conservative approach was applied estimating the theoretical systematic uncertainties in a range from 10% to 24% depending on $\Delta m(\tilde{t}_1, \tilde{\chi}_1^0)$. The expected improved condition at HL-LHC were taken into account using a set of prescrip-

tions defined by the CMS and ATLAS collaborations [289]. The theoretical uncertainties are expected to be reduced by half. Flavour tagging uncertainties are also expected to be reduced by half due to the tracking and vertex performance improvements. Instead, all the remaining uncertainties are expected to be similar to those of the Run 2 analysis [6].

The systematic uncertainties deriving from the data-driven FNP background estimate are also expected, related to potential differences in the FNP composition (heavy flavour, light flavour or photon conversions) between the regions defined in the analysis and those used to assess the fake factor. The statistical error is also considered, by propagating the statistical uncertainty in the ratio used for computing the fake factor.

In Table 7.7 the different sources of systematic uncertainties are reported for each of the signal regions defined in the analysis. The main contribution for all the SRs is due to the statistical uncertainties from the simulated event samples, labelled as ‘MC statistical uncertainty’, even though this is expected to be significantly reduced by increasing the simulation statistics. ‘Other theoretical uncertainties’ collect the theoretical uncertainties on the minor backgrounds (VVV , $t\bar{t}t$, $t\bar{t}t\bar{t}$, $t\bar{t}W$, $t\bar{t}WW$, $t\bar{t}WZ$, $t\bar{t}H$, and tZ). ‘Normalisation’ indicates the uncertainty on the main SM background data-driven scale factors, extracted in the Run 2 analysis from dedicated control regions after performing the profile likelihood fit, and applied to the current analysis [7].

Signal Region	SR-DF _W ^{3-body}	SR-SF _W ^{3-body}	SR-DF _t ^{3-body}	SR-SF _t ^{3-body}	SR ^{4-body} _{Small Δm}	SR ^{4-body} _{Large Δm}
Total SM background uncertainty	14%	13%	13%	19%	14%	7.9%
VV theoretical uncertainties	10%	12%	1.4%	2.5%	8.9%	3.3%
$t\bar{t}$ theoretical uncertainties	2.8%	1.0%	3.7%	1.5%	1.5%	1.4%
$t\bar{t} + Z$ theoretical uncertainties	-	-	1.6%	2.4%	-	-
$t\bar{t} - Wt$ interference	-	-	-	1.0%	1.0	1.0%
Other theoretical uncertainties	-	-	1.2%	2.3%	-	-
MC statistical uncertainty	13%	9.5%	11%	15%	17%	5.3%
Normalisation	15%	17%	7.3%	8.9%	12%	10%
Jet energy scale	5.6%	7.5%	11%	20%	4.1%	4.8%
Jet energy resolution	8.9%	7.3%	11%	34%	3.5%	4.6%
Lepton modelling	3.0%	3.0%	5.3%	7.8%	6.9%	6.0%
E_T^{miss} modelling	1.4%	1.0%	3.1%	5.7%	1.3%	1.0%
Flavour tagging	1.0%	1.0%	1.0%	1.7%	-	1.0%
Pile-up reweighting and JVT	2.6%	2.0%	1.0%	1.0%	3.1%	1.0%
Fake and non-prompt leptons	-	-	-	-	3.5%	6.7%

Table 7.7: List of the sources of systematic uncertainties in the estimation of the SM backgrounds. The values are the relative uncertainties on the total expected background yields in the SRs. Those entries marked as ‘-’ indicate a contribution smaller than 1%. The individual components can be correlated and therefore do not necessarily add up in quadrature to the total systematic uncertainty [7].

7.6 Results

The expected sensitivity to the $\tilde{t}_1$ search in the HL-LHC condition was assessed via the CLs method [165], performing a profile likelihood fit built in the HISTFITTER framework, already introduced in the previous chapters. All the systematic uncertainties, described in section 7.5, were accounted for in the fit, modelled by Gaussian terms in the likelihood function. A profile likelihood ratio fit was performed for each signal point using pseudo-data corresponding to the sum of the expected background and the signal, in order to get the sensitivity. The contours in the $(m(\tilde{t}_1), m(\tilde{\chi}_1^0))$ and $(m(\tilde{t}_1), \Delta m(\tilde{t}_1, \tilde{\chi}_1^0))$ mass planes, corresponding to the 3σ and 5σ discovery potential, along with the excluded regions, in case of no observation of excess events, were obtained at 95% CL using the expected HL-LHC full luminosity at 14 TeV [7].

7.6.1 4-body expected sensitivity

The two signal regions of the 4-body search, $\text{SR}_{\text{Small } \Delta m}^{4\text{-body}}$ and $\text{SR}_{\text{Large } \Delta m}^{4\text{-body}}$, were statistically combined in the fit, obtaining the final sensitivity results. In Figure 7.8 are reported the expected exclusion at 95% CL and the 3σ (green) and 5σ (blue) discovery contours in (a) the $(m(\tilde{t}_1), m(\tilde{\chi}_1^0))$ and (b) the $(m(\tilde{t}_1), \Delta m(\tilde{t}_1, \tilde{\chi}_1^0))$ mass planes, along with the 95% CL observed exclusion limit (red) from Ref. [6]. These results show how the optimized selection for HL-LHC could enhance the 5σ discovery limit up to mass of the $\tilde{t}_1$ of about 380 GeV in case of $\Delta m(\tilde{t}_1, \tilde{\chi}_1^0)$ of about 65 GeV and of about 480 GeV for $\Delta m(\tilde{t}_1, \tilde{\chi}_1^0)$ of about 25 GeV. The expected exclusion limit at 95% CL is extended up to $\tilde{t}_1$ masses of about 690 GeV for a neutralino mass of about 660 GeV [7].

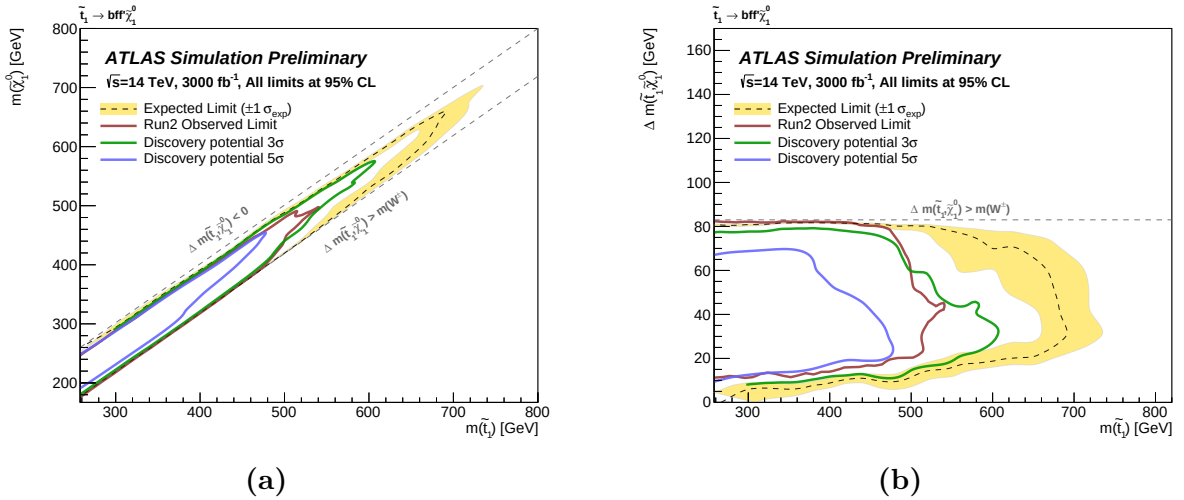


Figure 7.8: Sensitivity contours for the 4-body selection in the (a) $(m(\tilde{t}_1), m(\tilde{\chi}_1^0))$ and (b) $(m(\tilde{t}_1), \Delta m(\tilde{t}_1, \tilde{\chi}_1^0))$ mass planes. The expected 3σ (green) and 5σ (blue) discovery contours and the expected 95% CL exclusion contour at HL-LHC, obtained from combining $\text{SR}_{\text{Small } \Delta m}^{4\text{-body}}$ and $\text{SR}_{\text{Large } \Delta m}^{4\text{-body}}$ in the likelihood fit, are compared with the observed 95% CL Run 2 exclusion contour [7].

7.6.2 3-body expected sensitivity

The four signal regions of the 3-body were statistically combined in the fit, and in this case the selection was applied to both the 3-body and the 2-body decay regions. In Figure 7.9 are reported the expected exclusion limits at 95% CL and the 3σ (green) and 5σ (blue) discovery potential limits for the 3-body selection, in the (a) $(m(\tilde{t}_1), m(\tilde{\chi}_1^0))$ and the (b) $(m(\tilde{t}_1), \Delta m(\tilde{t}_1, \tilde{\chi}_1^0))$ mass planes, along with the 95% CL observed exclusion limit (red) from Ref. [6]. In this case the 5σ discovery potential limit brings the sensitivity to $\tilde{t}_1$ masses up to about 660 GeV for a neutralino mass of about 490 GeV in the 3-body region and up to about 810 GeV for a massless neutralino in the 2-body region, while the expected exclusion limits reaches $\tilde{t}_1$ masses up to 850 GeV for a neutralino mass of about 680 GeV in the 3-body region and up to about 1010 GeV for a massless neutralino in the 2-body decay region [7].

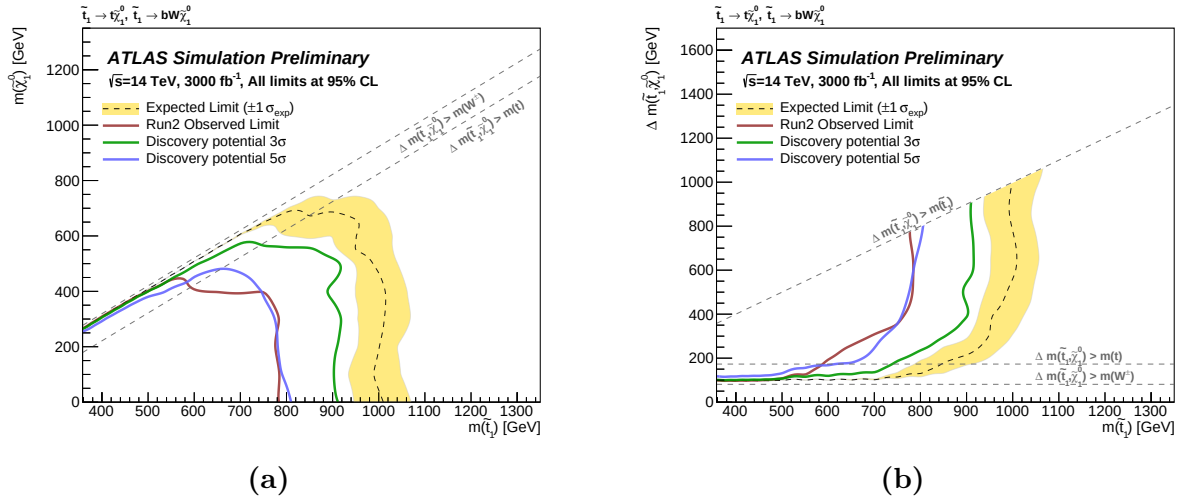


Figure 7.9: Sensitivity contours for the 3-body selection in the (a) $(m(\tilde{t}_1), m(\tilde{\chi}_1^0))$ and (b) $(m(\tilde{t}_1), \Delta m(\tilde{t}_1, \tilde{\chi}_1^0))$ mass planes. The expected 3σ (green) and the 5σ (blue) discovery contours and the expected 95% CL exclusion contour at HL-LHC, obtained from combining $\text{SR}_t^{3\text{-body}}$ and $\text{SR}_W^{3\text{-body}}$ in the likelihood fit, are compared with the observed 95% CL Run 2 exclusion contour [7].

7.6.3 Combined limits

Since all the six signal regions defined for the two searches are orthogonal, they can be statistically combined in the fit. In Figure 7.10 are reported the expected exclusion limits at 95% CL along with the 3σ (green) and 5σ (blue) discovery potential limits reachable at HL-LHC for (a) the $(m(\tilde{t}_1), m(\tilde{\chi}_1^0))$ and (b) the $(m(\tilde{t}_1), \Delta m(\tilde{t}_1, \tilde{\chi}_1^0))$ mass planes, combining the two described 4-body and 3-body selections. The results of the combination show that the discovery potential at 5σ extends up to $\tilde{t}_1$ masses of about 660 GeV for a neutralino mass of about 500 GeV in the 3-body region and of about 820 GeV for a massless neutralino in the 2-body region. The expected exclusion sensitivity extends up to $\tilde{t}_1$ masses of about 730 GeV for a neutralino mass of about 670 GeV in the 4-body region, of about 860 GeV for a

neutralino mass of about 690 GeV in the 3-body region, and of about 1010 GeV for a massless neutralino in the 2-body region.

It's important to emphasize that the presented results are expected to be conservative, because this study doesn't exploit the HL-LHC upgraded detector simulation, and therefore it doesn't consider the advantages coming from the extended detector coverage and the lower trigger thresholds. Furthermore, improvements in the identification performance, in the object reconstruction, in the analysis techniques used and in the reduction of the experimental and theoretical systematic uncertainties could further improve the results presented beyond the anticipated gains from increased luminosity and cross sections here considered [7].

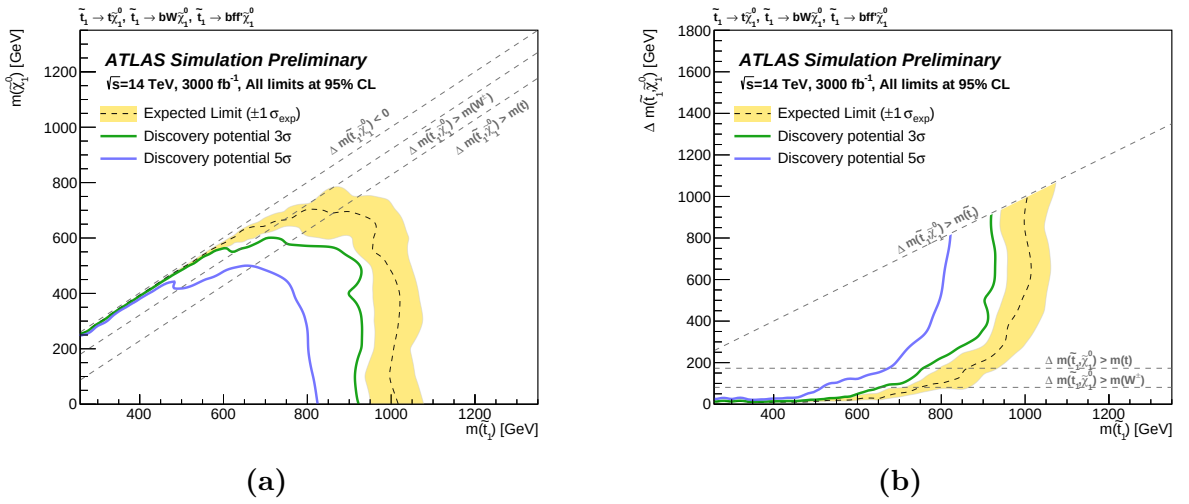


Figure 7.10: Sensitivity contours for the statistical combination of the 4-body and 3-body selections in the (a) $(m(\tilde{t}_1), m(\tilde{\chi}_1^0))$ and (b) $(m(\tilde{t}_1), \Delta m(\tilde{t}_1, \tilde{\chi}_1^0))$ mass planes. The expected 3σ (green) and the 5σ (blue) discovery contours and the expected 95% CL exclusion contour at HL-LHC, obtained from combining $\text{SR}_{\text{Small } \Delta m}^{4\text{-body}}$, $\text{SR}_{\text{Large } \Delta m}^{4\text{-body}}$, $\text{SR}_t^{3\text{-body}}$ and $\text{SR}_W^{3\text{-body}}$ in the likelihood fit, are shown [7].

Conclusions

This PhD thesis is focused on searches for supersymmetric particles, produced in pp collisions at the CERN Large Hadron Collider (LHC), with the ATLAS experiment. The first search targets the direct pair production of: a) sleptons, where each slepton decays to the relative SM lepton and the lightest neutralino; b) charginos, where each chargino decays to a W -boson, decaying in turn leptonically, and the lightest neutralino. In particular, the ‘moderately compressed’ regions, where the mass difference (mass-splitting) between the slepton/chargino and the neutralino is of the order of the W -boson mass, were explored, even because the interest in these regions is increasing by the fact that slepton models with smuon production with mass-splittings up to 150 GeV are favoured to explain the $(g - 2)_\mu$ anomaly of the muon at small values of $\tan\beta$. The search used data collected during Run 2 (2015-2018) of LHC at $\sqrt{s} = 13$ TeV center of mass energy, corresponding to an integrated luminosity of 139 fb^{-1} . The second ‘search’ is, actually, an analysis of the prospects for a search of stop pair production in pp collision at the ATLAS experiment in the high-luminosity LHC (HL-LHC) phase, at $\sqrt{s} = 14$ TeV center of mass energy and assuming an integrated luminosity of 3000 fb^{-1} . The interpretation of the results was based on simplified models for all the investigated processes.

In the first analysis [4], published in June 2023 on Journal of High Energy Physics by the ATLAS Collaboration (*Search for direct pair production of sleptons and charginos decaying to two leptons and neutralinos with mass splittings near the W -boson mass in $\sqrt{s} = 13$ TeV pp collisions with the ATLAS detector*), the signature of interest consisted of two opposite-sign charged leptons and missing transverse energy. A data-driven technique, based on the efficiency correction method, was used to estimate the main Standard Model backgrounds in the slepton search, consisting in same-flavour events originating from flavour-symmetric background like $t\bar{t}$, single-top, WW and $Z(\rightarrow \tau\tau) + \text{jets}$. In the chargino search, a semi data-driven approach, relying on dedicated Control Regions to normalize the Monte Carlo predictions to the observed data through a likelihood fit procedure, was used to estimate the main Standard Model backgrounds, i.e. the top and diboson processes, classified with a Boosted Decision Tree. Particularly the WW component of the diboson background makes this search challenging because of its similarity with the signal model under study. A profile likelihood fit was performed for the two channels a) and b), and the observed data were

found to be consistent with the SM expectations after the fit. Therefore exclusion limits at 95% Confidence Level (CL) were set in the $(m(\tilde{\ell}), m(\tilde{\chi}_1^0))$ and $(m(\tilde{\chi}_1^\pm), m(\tilde{\chi}_1^0))$ mass planes. Furthermore, upper limits on the visible cross section of possible Beyond Standard Model physics were also calculated. Slepton masses up to 150 GeV were excluded in the case of a mass-splitting of 50 GeV between the slepton and the neutralino, thus surpassing the exclusion limits previously set at LEP [255]. Chargino masses up to 140 GeV were excluded at 95% CL in the case of a mass-splitting between the chargino and the neutralino as low as about 100 GeV. These results further extends the exclusion limits set by previous searches at LHC by the ATLAS and CMS collaborations [63–69], investigating the same scenarios with mass differences up to about 150 GeV between the slepton or chargino and neutralino.

Plans for further improving the sensitivity of the two searches, aiming to Run 3 data analysis, can involve, for example, lepton selections with lower thresholds on the transverse momenta, and thus a combination of the di-lepton, single-lepton and E_T^{miss} triggers. The efforts may be focused on targeting even more compressed scenarios, exploiting machine learning approaches.

In the second analysis [7], published in January 2024 in the Public Note ATL-PHYS-PUB-2024-001 by the ATLAS Collaboration (*Prospects for a search for direct pair production of top-squarks at the high-luminosity LHC with the ATLAS detector*), the signature of the final state required two leptons, jets and missing transverse energy. It had the purpose to derive the sensitivity at High-Luminosity LHC of an already published search for direct production of pairs of top-squarks in Run 2 data [6] after a suitable optimization of the selection criteria. The analysis was based on Monte Carlo samples of signals and Standard Model backgrounds simulated in the Run 2 detector layout and normalized to the 14 TeV cross sections and the 3000 fb^{-1} of expected integrated luminosity. The selections of two different stop decay modes were optimized independently: the 4-body selection, targeting the regions of $(m(\tilde{t}_1), m(\tilde{\chi}_1^0))$ mass plane where the difference in mass between the stop and the neutralino, $\Delta m(\tilde{t}_1, \tilde{\chi}_1^0)$, is $m(b) < \Delta m(\tilde{t}_1, \tilde{\chi}_1^0) < m(b) + m(W)$, and the 3-body selection, where $m(b) + m(W) < \Delta m(\tilde{t}_1, \tilde{\chi}_1^0) < m(t)$. The latter selection was also applied in the regions $\Delta m(\tilde{t}_1, \tilde{\chi}_1^0) > m(t)$, where the stop is expected to decay in two bodies ($\tilde{t}_1 \rightarrow t\tilde{\chi}_1^0$). A profile likelihood fit was performed and the discovery sensitivity with a 3σ and a 5σ significance as well as the 95% CL expected exclusion limits were derived. In the 4-body decay region the discovery sensitivity with a 5σ significance extends up to $m(\tilde{t}_1)$ of about 380 GeV for $\Delta m(\tilde{t}_1, \tilde{\chi}_1^0)$ of about 65 GeV and reaches about 480 GeV for $\Delta m(\tilde{t}_1, \tilde{\chi}_1^0)$ of about 25 GeV. The discovery potential at 5σ extends up to stop masses of about 660 GeV for a $\tilde{\chi}_1^0$ mass of about 490 GeV in the 3-body decay region and up to about 810 GeV for a massless $\tilde{\chi}_1^0$ in the 2-body decay region. The 95% CL exclusion limit extends up to $m(\tilde{t}_1)$ of about 690 GeV, for a $\tilde{\chi}_1^0$ mass of about 660 GeV in the 4-body decay region, up to $m(\tilde{t}_1)$ of about 850 GeV for a $\tilde{\chi}_1^0$ mass of about 680 GeV in the 3-body decay region and up to $m(\tilde{t}_1)$ of about 1010 GeV for a massless $\tilde{\chi}_1^0$ in the 2-body decay region, significantly improving the current limits.

The results of this study are supposed to be conservative, since it didn't use the simulation of the upgraded (at HL-LHC) detector layout, thus all benefits from the extended coverage

of the detector and from the lowered trigger thresholds were not considered. Moreover the discovery sensitivity could be further enhanced if considering all the potential improvements in the object reconstruction and identification and in analysis techniques, and the reduction of the systematic uncertainties (both experimental and theoretical), beyond the gains obtained in this study from increased luminosity and cross sections. However it can be certainly considered a suitable starting point for the ATLAS search for stops in the Run 3 data, which has just started.

APPENDIX



RECAST validation for the reinterpretation of ATLAS SUSY analyses in the pMSSM framework

Introduction to the Phenomenological MSSM interpretations and description of the RECAST procedure and its validation, fundamental to preserve the analysis frameworks for future reinterpretations in ATLAS.

So far, several analyses searching for supersymmetry in the context of the MSSM were performed in ATLAS using the data collected during Run 2 of LHC, improving the previous exclusion limits set after Run 1. Since the MSSM is described by more than a hundred parameters, such analyses are generally based on ‘simplified SUSY models’, where (as already specified in section 1.3) the masses of the involved particles are the only free parameters to be taken into account, making easier the interpretation of the search results and the achievement of the exclusion limits. Nevertheless, the results obtained with these simplified assumptions on the considered signal models cannot say too much in terms of the more general MSSM. An intermediate step between the MSSM and the simplified models is given by the *Phenomenological MSSM* or pMSSM, introduced in section 1.2.3, which consists in making some assumptions on the parameters defining the MSSM in order to reduce the number of free parameters from more than a hundred to 19. An explanatory scheme is reported in Figure A.1. This reduced number of parameters is obtained by assuming CP and R-parity conservation, minimum flavour violation, and first and second generations of sfermions to

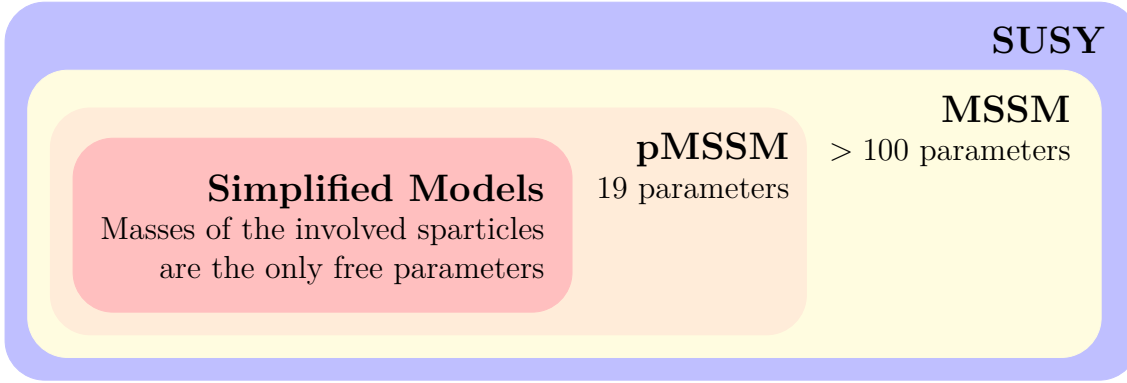


Figure A.1: Scheme of supersymmetric models in terms of their number of parameters. The largest model is labelled as ‘SUSY’, containing all possible supersymmetric theories. Among them there is the MSSM, described by more than a hundred parameters. Under some assumptions (described in section 1.2.3 and in the text above), the number of parameters is reduced to 19 in the pMSSM. The simplest supersymmetric models are the ‘simplified models’, like the ones adopted in the analyses described in this thesis, where the only free parameters are the masses of the sparticles considered in the specific model itself.

be mass-degenerate and with a negligible Yukawa coupling. The parameters, reported in Table A.1, are: ten masses for the sfermions, five relative to the first and second degenerate generations, $M_{\tilde{q}}, M_{\tilde{u}_R}, M_{\tilde{d}_R}, M_{\tilde{\ell}}, M_{\tilde{e}_R}$, and five relative to the third generation, $M_{\tilde{Q}}, M_{\tilde{t}_R}, M_{\tilde{b}_R}, M_{\tilde{L}}, M_{\tilde{\tau}_R}$; three trilinear couplings of the Higgs field to the third generation sfermions, A_t, A_b, A_τ ; the masses of bino, wino and gluino, M_1, M_2, M_3 ; a bilinear mass parameter for the higgsino, μ ; a mass parameter for the pseudoscalar Higgs boson, M_A ; the ratio between the vacuum expectation values of the Higgs fields, $\tan \beta$.

pMSSM parameter	Meaning
$\tan \beta$	Ratio of the Higgs vacuum expectation values
M_A	Pseudoscalar (CP-odd) Higgs boson mass parameter
μ	Bilinear higgsino mass parameter
M_1, M_2, M_3	Bino, wino and gluino mass parameters
A_t, A_b, A_τ	Third generation tri-linear couplings
$M_{\tilde{q}}, M_{\tilde{u}_R}, M_{\tilde{d}_R}, M_{\tilde{\ell}}, M_{\tilde{e}_R}$	First/second generation sfermion mass parameters
$M_{\tilde{Q}}, M_{\tilde{t}_R}, M_{\tilde{b}_R}, M_{\tilde{L}}, M_{\tilde{\tau}_R}$	Third generation sfermion mass parameters

Table A.1: Summary of the 19 pMSSM parameters [290].

The ATLAS Run 2 SUSY searches can be reinterpreted in the context of the pMSSM, in order to extract general limits on the observation of SUSY particles. In particular, ATLAS is working on three different classes of reinterpretations, one focused only on searches for electroweak produced sparticle, another focused on the analyses targeting third generation

squarks, and a third, more general, which includes all searches for sparticles. Each of these reinterpretations follows the same approach, illustrated in the flowchart in Figure A.2. Several pMSSM signal models of sparticle pair production are randomly generated by fixing a certain range for the 19 parameters and a specific sampling rate. These models, before to enter in the analysis workflows, are processed and filtered according to several criteria. The full procedure is described the following.

- First of all, the generated pMSSM models are processed by some programs to compute several quantities: SPHENO 4.0.5 [291, 292] is used to compute the masses and decays of the supersymmetric particles; FEYNHIGGS 2.18 [293–300] calculates some Higgs variables, MICROMEGAS 5.2.1 [301, 302] predicts the relic density of dark-matter (Ωh^2), as well as the interaction cross section of a weakly interacting massive particle (WIMP) and a nucleon and the dark-matter annihilation cross section; SUPERISO 4.0 [303] computes flavour observables.
- Once all these parameters are calculated, some requirements are applied to the models, e.g. those models where the $\tilde{\chi}_1^0$ is not the LSP are not considered. Moreover, a constraint on the Higgs mass is imposed, assuming that it is inside a 10 GeV window around the measured value of 125 GeV. Also the chargino mass must be greater than the limits imposed by LEP and the relic dark-matter density must be lower than the observed limit $\Omega h^2 = 0.12$ [304].
- For all models passing the previous criteria, the relative pair production cross sections are computed by PROSPINO [305]. Other constraints to the models require to reject them if the chargino mass is greater than 1200 GeV, the $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_2^0$ are stable and the cross section for electroweak production of SUSY particles is below a certain limit.
- The survived models can pass to the event simulation step. For each one, signal events are simulated by MADGRAPH and PYTHIA at the leading-order. The detector effects are simulated using SIMPLEANALYSIS [266], which uses functions for modelling the detector response in a faster but rough way with respect to a full simulation made by GEANT4. For each model simulated events are then passed to PYHF [306, 307] which produces an estimate of the expected and observed CL_s . These values are coarse evaluations since neither the statistical nor the systematic uncertainties are considered for the signal.
- If, for a specific model, the expected ‘coarse’ CL_s is lower than 0.001, the model is ‘likely to be excluded’, while if greater than 0.1, the model is ‘likely to be not excluded’. For those models for which $0.001 \leq \text{CL}_s \leq 0.1$, the event samples are reprocessed with a more detailed description of the detector and the results are extracted again but using the original Run 2 analysis setup, which handles statistical and systematic uncertainties. In order to perform this step the used tool is the RECAST, described in Section A.1.
- Finally, whether the decision is taken on the ‘coarse’ CL_s or via the RECAST, if the CL_s is lower than 0.05 the model is excluded, otherwise it is not.

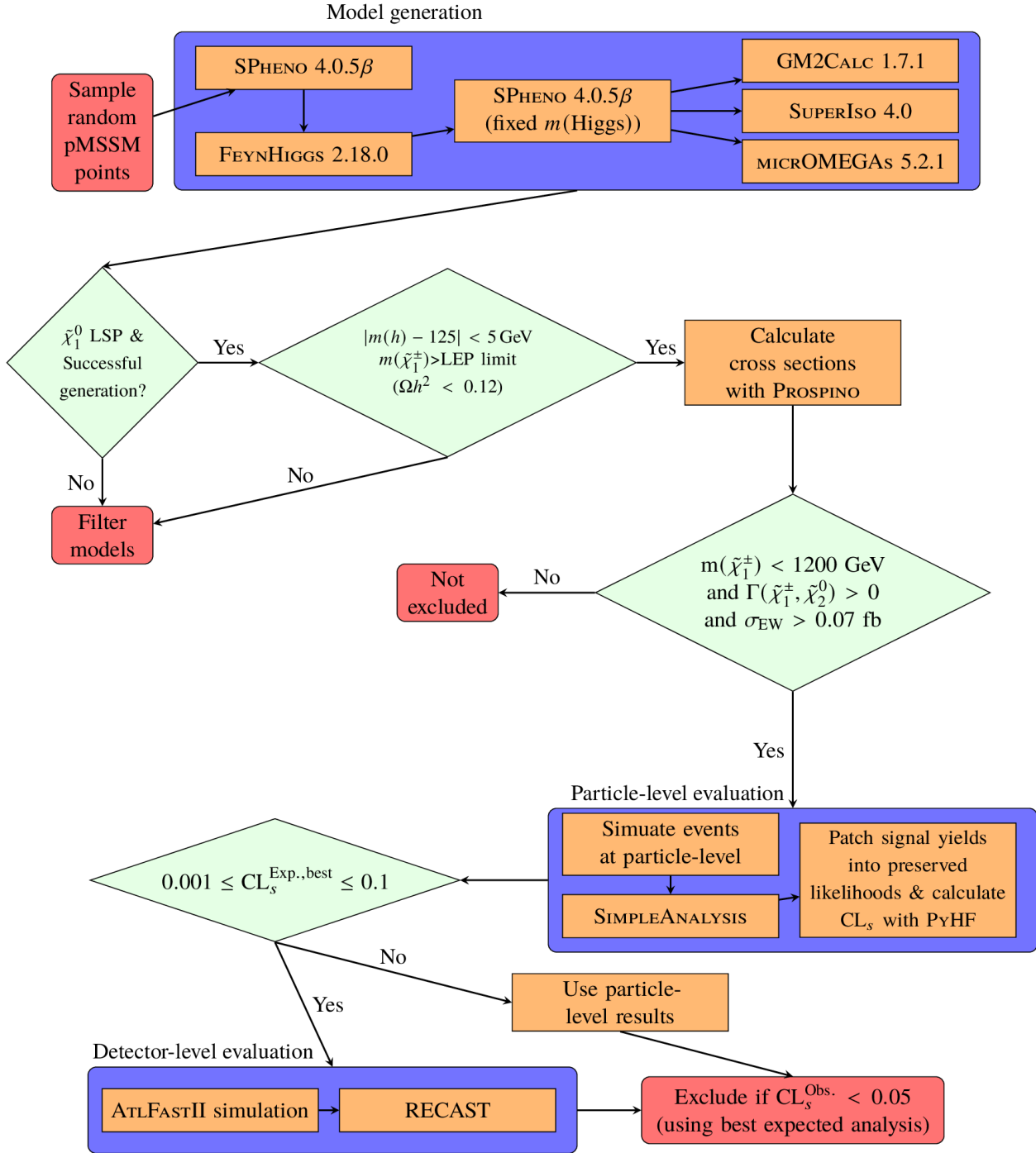


Figure A.2: Flowchart of the pMSSM reinterpretations [290].

This approach is applied to all the three classes mentioned above, and some recent results on the electroweak SUSY production can be found in Ref. [290]. For example, in Figure A.3 are reported the results of the electroweak reinterpretation in the (a) $(m(\tilde{\chi}_1^\pm), m(\tilde{\chi}_1^0))$ and (b) $(m(\tilde{\chi}_2^0), m(\tilde{\chi}_1^0))$ mass planes in terms of the fraction of excluded models by the ATLAS Run 2 electroweak searches, along with the exclusion limits obtained from a combination of the results of three ATLAS Run 2 SUSY electroweak analyses, Ref. [308–310], performed with simplified models. Most of the excluded models are inside this contour, reaching the 100% of the models excluded at low masses for the considered sparticles. A similar study is going on for the ATLAS analyses targeting the pair production of third generation squarks. In particular, in the next paragraphs the RECAST procedure and its validation will be described for the analyses of the SUSY third generation searches, since this was my main contribution to this effort.

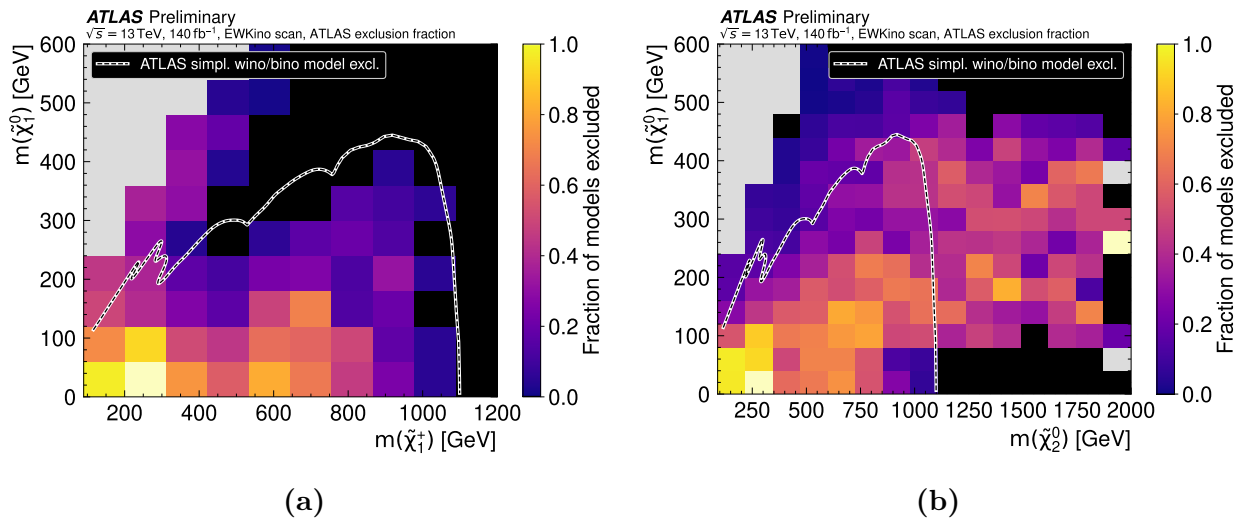


Figure A.3: Fraction of the electroweak pMSSM models excluded by ATLAS Run 2 results: (a) in the $(m(\tilde{\chi}_1^\pm), m(\tilde{\chi}_1^0))$ mass plane, (b) in the $(m(\tilde{\chi}_2^0), m(\tilde{\chi}_1^0))$ mass plane. The overlaid dashed line shows the envelop of the exclusion limits of a wino-bino-like $\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$ simplified model with $\text{BR}(\tilde{\chi}_1^\pm \rightarrow W^\pm \tilde{\chi}_1^0) = 100\%$ and $\text{BR}(\tilde{\chi}_2^0 \rightarrow Z \tilde{\chi}_1^0) = 100\%$ from the analysis of Ref. [308–310]. Bins in grey have no models to be considered [290].

A.1 The RECAST preservation

The ATLAS collaboration performs many physics analyses, which often require a huge amount of time and human resources. In particular, if an analysis is studying a specific physics model in the same phase space already investigated by a previous analysis for another model, it can be useful to save time and efforts to exploit the software tools developed for that analysis, since the Standard Model background estimates shouldn't be affected too much when considering alternative physics models in the same phase space. To this purpose, many of the ATLAS analyses, and in particular those searching for SUSY, are required to store their analysis

infrastructures for future reinterpretations, like the pMSSM one. Such procedure is called RECAST and consists in recreating the analysis, by keeping the same event selection strategy and the same procedure for estimating the Standard Model backgrounds and by automating the processing and the interpretation (in terms of CL_s) of a new signal model.

The easiest way to preserve the software tools used during the analysis is DOCKER [311], an industry-standard technology which allows to capture the software in *Container Images*, portraits of a filesystem collecting all the analysis software tools and their dependencies. The advantage is that the analysis software can be processed directly inside the container, regardless of the operating system used and without the need of install any component, except for the image itself [312]. Such containers are passed to the analysis workflow, which is built in terms of the Yadage workflow system, a tool properly developed for the reinterpretation purposes of the ATLAS experiment. It basically indicates all the inputs to be provided to the analysis, such as signal files or variables, the docker images to be used for each analysis steps, and the actions to be executed inside those containers on the specific inputs. This project is built in GitLab, since it supports a *continuous integration* (CI), which means that the project is frequently tested each time a change is applied, helping in this way to rapidly identify errors and bugs. Limitation of running it is the restricted computing time and the possibility of processing one signal model at the time. This issue is overcome by using the REANA [313] (*REproducible ANalysis*) platform which allows to reproduce Yadage workflows in parallel and with a larger computing power.

In Figure A.4 is reported the RECAST workflow for the chargino and slepton analysis described in this thesis. It basically uses three different packages, deputed to perform different steps in the analysis:

- MELANALYSIS: this package represents the first step of the analysis workflow. It consists in processing the input DAOD³⁷ signal files in order to produce a non final version of the ntuples³⁸ to be used in the analysis.
- LOOPSUSYFRAME : this package is the second step of the analysis and it takes as input the ntuples produced by MELANALYSIS, processing them in order to provide a compressed and more usable version of the analysis ntuples. In particular, in the case of the chargino analysis this package executes the software to obtain and append the BDT discriminator variables in the output ntuples.
- HISTFITTER [159]: the output ntuples produced by LOOPSUSYFRAME are processed in the final step, consisting in executing the HISTFITTER package, for the final results and interpretation in terms of the CL_s values.

³⁷In the analysis model, real data and simulated signal and background samples follow different steps of data processing and filtering in the experiment, and the final format for analysis usage is the DAOD, standing for *Derived Analysis Object Data*. DAODs contains AOD objects but are much smaller than AODs, and they are centrally produced according to the needs of the physics groups.

³⁸A *ntuple* is a ROOT [160, 161] file containing information of each simulated or observed event.

Each step of the workflow takes as input several variables which are provided by the previous step. Three DAOD signal files, relative to a specific signal model, are given as input to the workflow, each one relative to a different ATLAS Monte Carlo campaign: **mc16a**, **mc16d** and **mc16e** relative to modelling the 2015, 2016 and 2017-2018 data of Run 2 respectively. The chain starts from the **MELANALYSIS** step, which is divided into three blocks relative to the three MC campaigns, taking as input the corresponding DAOD file and other characterizing variables like the number of events that needs to be processed. The output file of each stage goes to the **LOOPSUSYFRAME** step, also separated into three different blocks and taking as input a variable which tells if to include or not the BDT variables, depending on if the chargino or the slepton analysis are running. The three output ntuples then reach a ‘merging’ step, which includes them in an unique file to be provided to the final stage, in which **HISTFITTER** performs the likelihood fit and produces the final results in terms of CL_s .

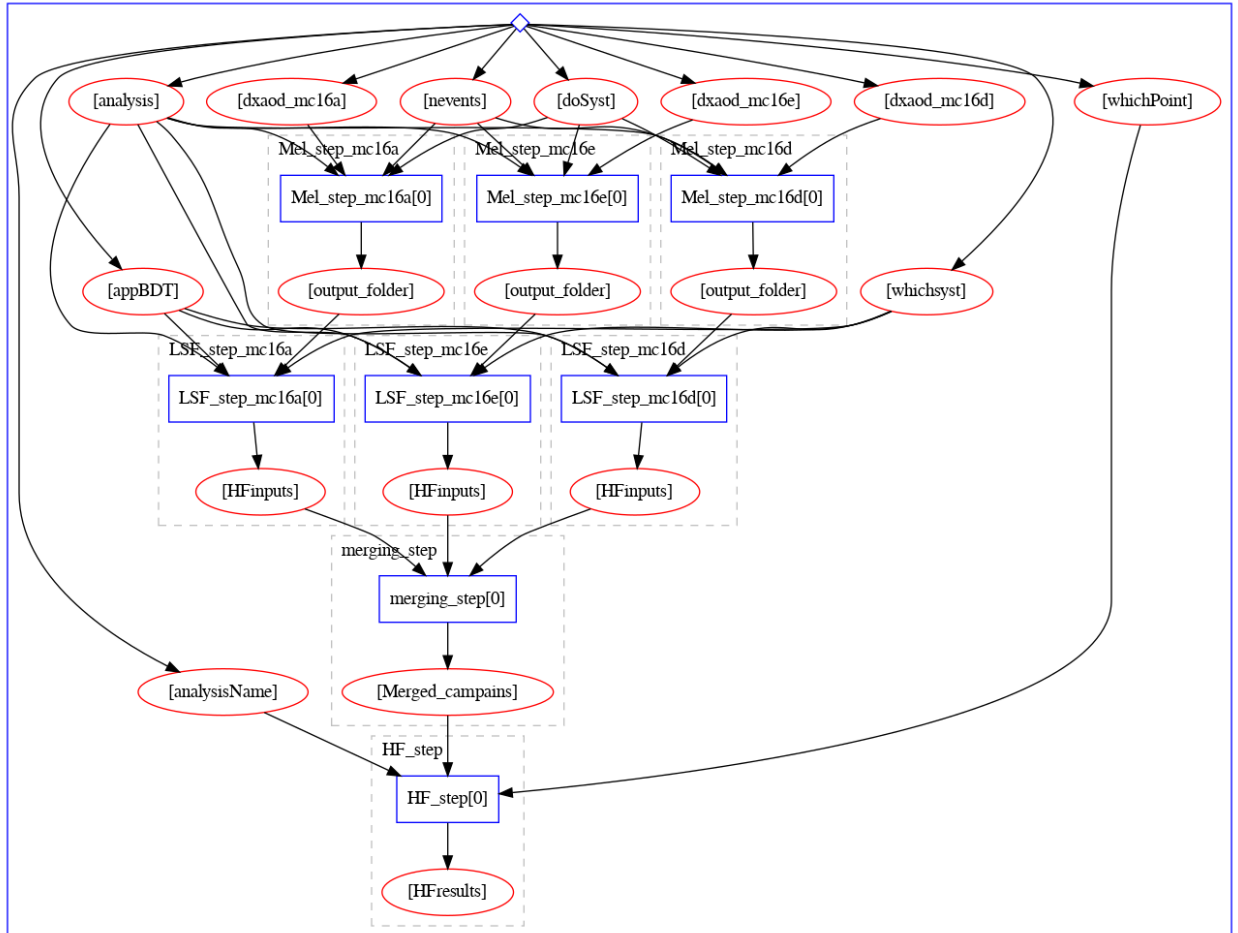


Figure A.4: RECAST workflow of the chargino and slepton analysis [4].

A.2 The RECAST validation

The implementation in RECAST of the already completed analyses for the reinterpretation purpose should be, in principle, straightforward, but in practice RECAST workflows, before being used in the pMSSM efforts, must be validated. This validation consists in re-running the RECAST and reproducing the original results using the original samples, debugging the project, and testing that it is suitable for the pMSSM samples to be used afterwards.

In particular, for the third generation reinterpretation, several Run 2 analyses searching for $\tilde{t}_1$ and $\tilde{t}_2$ [6, 314–317] and $\tilde{b}$ [318–320] were considered. One of them was the search for $\tilde{t}_1$ pair production with two leptons in the final state mentioned in Chapter 7. This analysis used the same analysis software of the chargino and slepton search described in the previous section, and it had four different selections, targeting different decay modes, i.e. 2-body, 3-body, and 4-body decays, or the dark-matter, χ , production via a scalar/pseudoscalar ϕ /a boson. Its RECAST implementation was tested for a handful of signal points trying to reproduce the original results. The tested points were: $(m(\tilde{t}_1), m(\tilde{\chi}_1^0)) = (950, 200)$, $(450, 330)$ and $(480, 400)$ GeV for the 2-body, 3-body and 4-body selections respectively, and $(m(\phi), m(\chi)) = (150, 1)$ GeV for the dark matter selection. In Table A.2 are reported the results of the validation: the first column shows the type of results, which are CL_s values for the three different decay modes, and upper limits in the observation of dark matter; the second column reports the original results for the tested points, the third column the results reproduced using RECAST and the fourth column the results in the REANA cluster. The three different results agree each other, as it must be expected.

The RECAST validation was essential for finding possible issues, before performing the pMSSM reinterpretation. It allowed to be brought to light incoherences in the workflow setup. Only once sure that the workflow is fully well implemented, it can be tested with the new signal models and the results of the analyses reinterpreted in these models.

I performed the validation effort for some of the already mentioned analyses (precisely for the searches [6, 317, 319]). It is still ongoing in ATLAS for other analyses. Once ready, they can be reinterpreted in the pMSSM context, following the same procedure described for the electroweak reinterpretation. A mechanism was developed for automating and parallelizing the process for each signal model generated via the RECAST workflow for any analysis.

Results	Original results	Reproduced locally	Reproduced via REANA
2-body - Tested point: $(m(\tilde{t}_1), m(\tilde{\chi}_1^0)) = (950, 200)$ GeV			
CL_s	0.016114	0.015978	0.015980
CL_b	0.261913	0.261165	0.261149
CL_{s+b}	0.004220	0.004173	0.004173
CL_s^{exp}	0.045885	0.045717	0.045725
$CL_s(-1\sigma)$	0.008608	0.008565	0.008567
$CL_s(+1\sigma)$	0.189595	0.189151	0.189173
3-body - Tested point: $(m(\tilde{t}_1), m(\tilde{\chi}_1^0)) = (450, 330)$ GeV			
CL_s	$5.211\,37 \times 10^{-7}$	$5.581\,78 \times 10^{-7}$	$5.805\,42 \times 10^{-7}$
CL_b	0.19291	0.19234	0.19222
CL_{s+b}	$1.005\,33 \times 10^{-7}$	$1.073\,59 \times 10^{-7}$	$1.115\,92 \times 10^{-7}$
CL_s^{exp}	$1.483\,44 \times 10^{-5}$	$1.582\,98 \times 10^{-5}$	$1.638\,68 \times 10^{-5}$
$CL_s(-1\sigma)$	$3.075\,92 \times 10^{-7}$	$3.327\,99 \times 10^{-7}$	$3.470\,59 \times 10^{-7}$
$CL_s(+1\sigma)$	0.00051	0.00054	0.00056
4-body - Tested point: $(m(\tilde{t}_1), m(\tilde{\chi}_1^0)) = (480, 400)$ GeV			
CL_s	0.085006	0.085551	0.083970
CL_b :	0.424042	0.423978	0.425637
CL_{s+b}	0.036046	0.036272	0.035741
CL_s^{exp}	0.108061	0.108721	0.106330
$CL_s(-1\sigma)$	0.028788	0.029041	0.028127
$CL_s(+1\sigma)$	0.323215	0.324400	0.320091
Dark Matter - Tested point: $(m(\phi), m(\chi)) = (150, 1)$ GeV			
Observed limit	0.537012	0.519988	0.52133
Expected limit (-2σ)	0.308737	0.306514	0.30639
Expected limit (-1σ)	0.421967	0.416758	0.41655
Expected limit	0.603967	0.591487	0.59114
Expected limit $(+1\sigma)$	0.883838	0.849886	0.84921
Expected limit $(+2\sigma)$	1.26343	1.18761	1.18643

Table A.2: Validation of the RECAST implementation of the analysis [6]. Four different workflows were defined in the project, according to the four different selections performed in the analysis: 2-body, 3-body, 4-body decays, DM.

Bibliography

- [1] O. S. Bruning et al., *LHC Design Report Vol.1: The LHC Main Ring*, CERN, Geneva, Switzerland (June 2004), ed. by O. S. Bruning et al., ISSN: 0007-8328, DOI: 10.5170/CERN-2004-003-V-1.
- [2] ATLAS Collaboration, *The ATLAS Experiment at the CERN Large Hadron Collider*, JINST **3.08** (Aug. 2008), S08003, DOI: 10.1088/1748-0221/3/08/S08003.
- [3] CMS Collaboration, *The CMS Experiment at the CERN LHC*, JINST **3.08** (Aug. 2008), S08004, DOI: 10.1088/1748-0221/3/08/S08004.
- [4] ATLAS Collaboration, *Search for direct pair production of sleptons and charginos decaying to two leptons and neutralinos with mass splittings near the W -boson mass in $\sqrt{s} = 13$ TeV pp collisions with the ATLAS detector*, JHEP **06** (2023), p. 031, DOI: 10.1007/JHEP06(2023)031, arXiv: 2209.13935 [hep-ex].
- [5] O. Aberle et al., *High-Luminosity Large Hadron Collider (HL-LHC): Technical design report*, CERN Yellow Rep. Monogr. **10** (Dec. 2020), ed. by I. Béjar Alonso et al., DOI: 10.23731/CYRM-2020-0010.
- [6] ATLAS Collaboration, *Search for new phenomena in events with two opposite-charge leptons, jets and missing transverse momentum in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector*, JHEP **04** (2021), p. 165, DOI: 10.1007/JHEP04(2021)165, arXiv: 2102.01444 [hep-ex].
- [7] ATLAS Collaboration, *Prospects for a search for direct pair production of top squarks at the high-luminosity LHC with the ATLAS detector*, ATL-PHYS-PUB-2024-001, CERN, Geneva, Switzerland, 2024, URL: <https://cds.cern.ch/record/2886538>.
- [8] J. I. Illana and A. Jimenez Cano, *Quantum field theory and the structure of the Standard Model*, PoS **CORFU2021** (2022), p. 314, DOI: 10.22323/1.406.0314, arXiv: 2211.14636 [hep-ph].
- [9] S. L. Glashow, J. Iliopoulos, and L. Maiani, *Weak Interactions with Lepton-Hadron Symmetry*, Phys. Rev. D **2** (7 Oct. 1970), pp. 1285–1292, DOI: 10.1103/PhysRevD.2.1285.

- [10] S. Weinberg, *A Model of Leptons*, Phys. Rev. Lett. **19** (21 Sept. 1967), pp. 1264–1266, DOI: 10.1103/PhysRevLett.19.1264.
- [11] A. Salam and J. C. Ward, *Weak and electromagnetic interactions*, Il Nuovo Cimento (1955-1965) **11.4** (Feb. 1959), pp. 568–577, ISSN: 1827-6121, DOI: 10.1007/BF02726525.
- [12] S. L. Glashow, *Partial-symmetries of weak interactions*, Nuclear Physics **22.4** (1961), pp. 579–588, ISSN: 0029-5582, DOI: 10.1016/0029-5582(61)90469-2.
- [13] G. Altarelli, *The physics of deep inelastic phenomena*, La Rivista del Nuovo Cimento (1971-1977) **4.3** (July 1974), pp. 335–397, ISSN: 1826-9850, DOI: 10.1007/BF02748093.
- [14] H. David Politzer, *Asymptotic freedom: An approach to strong interactions*, Physics Reports **14.4** (1974), pp. 129–180, ISSN: 0370-1573, DOI: 10.1016/0370-1573(74)90014-3.
- [15] E. Gildener, *Gauge-symmetry hierarchies*, Phys. Rev. D **14** (6 Sept. 1976), pp. 1667–1672, DOI: 10.1103/PhysRevD.14.1667.
- [16] G. Bertone, D. Hooper, and J. Silk, *Particle dark matter: evidence, candidates and constraints*, Physics Reports **405.5** (2005), pp. 279–390, ISSN: 0370-1573, DOI: 10.1016/j.physrep.2004.08.031.
- [17] P. Fayet and S. Ferrara, *Supersymmetry*, Physics Reports **32.5** (1977), pp. 249–334, ISSN: 0370-1573, DOI: 10.1016/0370-1573(77)90066-7.
- [18] L. Alvarez-Gaume and M. A. Vazquez-Mozo, *Introductory lectures on quantum field theory*, “3rd CERN-CLAF School of High Energy Physics”, 2006, pp. 1–80, DOI: 10.5170/CERN-2006-015.1, arXiv: hep-th/0510040.
- [19] N. Cabibbo, *Unitary Symmetry and Leptonic Decays*, Phys. Rev. Lett. **10** (12 June 1963), pp. 531–533, DOI: 10.1103/PhysRevLett.10.531.
- [20] M. Kobayashi and T. Maskawa, *CP Violation in the Renormalizable Theory of Weak Interaction*, Prog. Theor. Phys. **49** (1973), pp. 652–657, DOI: 10.1143/PTP.49.652.
- [21] P. W. Higgs, *Broken Symmetries and the Masses of Gauge Bosons*, Phys. Rev. Lett. **13** (1964), ed. by J. C. Taylor, pp. 508–509, DOI: 10.1103/PhysRevLett.13.508.
- [22] F. Englert and R. Brout, *Broken Symmetry and the Mass of Gauge Vector Mesons*, Phys. Rev. Lett. **13** (1964), ed. by J. C. Taylor, pp. 321–323, DOI: 10.1103/PhysRevLett.13.321.
- [23] ATLAS Collaboration, *Observation of a new particle in the search for the Standard Model Higgs boson with the ATLAS detector at the LHC*, Phys. Lett. B **716** (2012), pp. 1–29, DOI: 10.1016/j.physletb.2012.08.020, arXiv: 1207.7214 [hep-ex].
- [24] CMS Collaboration, *Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC*, Phys. Lett. B **716** (2012), pp. 30–61, DOI: 10.1016/j.physletb.2012.08.021, arXiv: 1207.7235 [hep-ex].
- [25] R. L. Workman et al., *Review of Particle Physics*, PTEP **2022** (2022), p. 083C01, DOI: 10.1093/ptep/ptac097.

- [26] G. Kane, *Modern Elementary Particle Physics - The Fundamental Particles and Forces? (updated edition)*, Addison-Wesley Publishing Company, Mar. 1993, pp. 71–72, ISBN: 0-201-62460-5.
- [27] V. A. Bednyakov, N. D. Giokaris, and A. V. Bednyakov, *On Higgs mass generation mechanism in the Standard Model*, Phys. Part. Nucl. **39** (2008), pp. 13–36, DOI: 10.1007/s11496-008-1002-9, arXiv: hep-ph/0703280.
- [28] J. Woithe, G. J. Wiener, and F. F. V. der Veken, *Let's have a coffee with the Standard Model of particle physics!*, Physics Education **52.3** (Mar. 2017), p. 034001, DOI: 10.1088/1361-6552/aa5b25.
- [29] A. Beekman, L. Rademaker, and J. van Wezel, *An introduction to spontaneous symmetry breaking*, SciPost Physics Lecture Notes (Dec. 2019), DOI: 10.21468/scipostphyslectnotes.11.
- [30] T. W. B. Kibble, *History of electroweak symmetry breaking*, J. Phys. Conf. Ser. **626.1** (2015), ed. by H. T. Elze et al., p. 012001, DOI: 10.1088/1742-6596/626/1/012001, arXiv: 1502.06276 [physics.hist-ph].
- [31] ATLAS Collaboration, *Improved W boson Mass Measurement using 7 TeV Proton-Proton Collisions with the ATLAS Detector*, ATLAS-CONF-2023-004, CERN, Geneva, Switzerland, 2023, URL: <https://cds.cern.ch/record/2853290>.
- [32] J. Haller et al., *Status of the global electroweak fit with Gfitter in the light of new precision measurements*, PoS ICHEP2022 (Nov. 2022), p. 897, DOI: 10.22323/1.414.0897, arXiv: 2211.07665 [hep-ph].
- [33] ALEPH, DELPHI, L3 and OPAL Collaborations and LEPEWWG, *Electroweak measurements in electron-positron collisions at W-boson-pair energies at LEP*, Physics Reports **532.4** (2013), Electroweak Measurements in Electron-Positron Collisions at W-Boson-Pair Energies at LEP, pp. 119–244, ISSN: 0370-1573, DOI: 10.1016/j.physrep.2013.07.004.
- [34] CDF Collaboration, *Precise Measurement of the W-Boson Mass with the CDF II Detector*, Phys. Rev. Lett. **108** (15 Apr. 2012), p. 151803, DOI: 10.1103/PhysRevLett.108.151803.
- [35] D0 Collaboration, *Measurement of the W boson mass with the D0 detector*, Phys. Rev. D **89** (1 Jan. 2014), p. 012005, DOI: 10.1103/PhysRevD.89.012005.
- [36] ATLAS Collaboration, *Measurement of the W-boson mass in pp collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector*, The European Physical Journal C **78.2** (Feb. 2018), p. 110, ISSN: 1434-6052, DOI: 10.1140/epjc/s10052-017-5475-4.
- [37] LHCb Collaboration, *Measurement of the W boson mass*, JHEP **2022.1** (Jan. 2022), p. 36, ISSN: 1029-8479, DOI: 10.1007/JHEP01(2022)036.
- [38] E. John, *Outstanding questions: physics beyond the Standard*, Phil. Trans. R. Soc. A **370** (2012), DOI: 10.1098/rsta.2011.0452.

- [39] A. Djouadi, *The anatomy of electroweak symmetry breaking Tome II: The Higgs bosons in the Minimal Supersymmetric Model*, Physics Reports **459**.1-6 (Apr. 2008), pp. 1–241, DOI: 10.1016/j.physrep.2007.10.005.
- [40] S. P. Martin, *A Supersymmetry primer*, Adv. Ser. Direct. High Energy Phys. **18** (1998), ed. by G. L. Kane, pp. 1–98, DOI: 10.1142/9789812839657_0001, arXiv: hep-ph/9709356.
- [41] R. Barbier et al., *R-parity violating supersymmetry*, Phys. Rept. **420** (2005), pp. 1–202, DOI: 10.1016/j.physrep.2005.08.006, arXiv: hep-ph/0406039.
- [42] CERN twiki pages, *LHC SUSY Cross Section Working Group*, URL: https://twiki.cern.ch/twiki/bin/view/LHCPhysics/SUSYCrossSections#Cross_sections_for_various_s_AN1.
- [43] J. Alwall, P. Schuster, and N. Toro, *Simplified Models for a First Characterization of New Physics at the LHC*, Phys. Rev. D **79** (2009), p. 075020, DOI: 10.1103/PhysRevD.79.075020, arXiv: 0810.3921 [hep-ph].
- [44] D. Alves, *Simplified Models for LHC New Physics Searches*, J. Phys. G **39** (2012), ed. by N. Arkani-Hamed et al., p. 105005, DOI: 10.1088/0954-3899/39/10/105005, arXiv: 1105.2838 [hep-ph].
- [45] ATLAS Collaboration, *Search for new phenomena in events with an energetic jet and missing transverse momentum in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector*, Phys. Rev. D **103**.11 (2021), p. 112006, DOI: 10.1103/PhysRevD.103.112006, arXiv: 2102.10874 [hep-ex].
- [46] ATLAS Collaboration, *Search for a scalar partner of the top quark in the all-hadronic $t\bar{t}$ plus missing transverse momentum final state at $\sqrt{s} = 13$ TeV with the ATLAS detector*, Eur. Phys. J. C **80**.8 (2020), p. 737, DOI: 10.1140/epjc/s10052-020-8102-8, arXiv: 2004.14060 [hep-ex].
- [47] ATLAS Collaboration, *Search for new phenomena with top quark pairs in final states with one lepton, jets, and missing transverse momentum in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector*, JHEP **04** (2021), p. 174, DOI: 10.1007/JHEP04(2021)174, arXiv: 2012.03799 [hep-ex].
- [48] ATLAS Collaboration, *Search for new phenomena with top-quark pairs in final states with one lepton, jets and missing transverse momentum using 140 fb^{-1} of data at $\sqrt{s} = 13$ TeV with the ATLAS detector*, ATLAS-CONF-2023-043, CERN, Geneva, Switzerland, 2023, URL: <http://cds.cern.ch/record/2869241>.
- [49] ATLAS Collaboration, *Search for a scalar partner of the top quark in the jets plus missing transverse momentum final state at $\sqrt{s} = 13$ TeV with the ATLAS detector*, JHEP **12** (2017), p. 085, DOI: 10.1007/JHEP12(2017)085, arXiv: 1709.04183 [hep-ex].
- [50] ATLAS Collaboration, *Search for top-squark pair production in final states with one lepton, jets, and missing transverse momentum using 36 fb^{-1} of $\sqrt{s} = 13$ TeV pp collision data with the ATLAS detector*, JHEP **06** (2018), p. 108, DOI: 10.1007/JHEP06(2018)108, arXiv: 1711.11520 [hep-ex].

- [51] ATLAS Collaboration, *Search for direct top squark pair production in final states with two leptons in $\sqrt{s} = 13$ TeV pp collisions with the ATLAS detector*, Eur. Phys. J. C **77.12** (2017), p. 898, DOI: 10.1140/epjc/s10052-017-5445-x, arXiv: 1708.03247 [hep-ex].
- [52] ATLAS Collaboration, *Search for dark matter and other new phenomena in events with an energetic jet and large missing transverse momentum using the ATLAS detector*, JHEP **01** (2018), p. 126, DOI: 10.1007/JHEP01(2018)126, arXiv: 1711.03301 [hep-ex].
- [53] ATLAS Collaboration, *Measurements of top-quark pair spin correlations in the $e\mu$ channel at $\sqrt{s} = 13$ TeV using pp collisions in the ATLAS detector*, Eur. Phys. J. C **80.8** (2020), p. 754, DOI: 10.1140/epjc/s10052-020-8181-6, arXiv: 1903.07570 [hep-ex].
- [54] ATLAS Collaboration, *ATLAS Run 1 searches for direct pair production of third-generation squarks at the Large Hadron Collider*, Eur. Phys. J. C **75.10** (2015), [Erratum: Eur.Phys.J.C 76, 153 (2016)], p. 510, DOI: 10.1140/epjc/s10052-015-3726-9, arXiv: 1506.08616 [hep-ex].
- [55] CMS Collaboration, *Combined searches for the production of supersymmetric top quark partners in proton–proton collisions at $\sqrt{s} = 13$ TeV*, Eur. Phys. J. C **81.11** (2021), p. 970, DOI: 10.1140/epjc/s10052-021-09721-5, arXiv: 2107.10892 [hep-ex].
- [56] CMS Collaboration, *Search for top squarks and dark matter particles in opposite-charge dilepton final states at $\sqrt{s} = 13$ TeV*, Phys. Rev. D **97.3** (2018), p. 032009, DOI: 10.1103/PhysRevD.97.032009, arXiv: 1711.00752 [hep-ex].
- [57] CMS Collaboration, *Search for top squark production in fully-hadronic final states in proton-proton collisions at $\sqrt{s} = 13$ TeV*, Phys. Rev. D **104.5** (2021), p. 052001, DOI: 10.1103/PhysRevD.104.052001, arXiv: 2103.01290 [hep-ex].
- [58] CMS Collaboration, *Search for direct top squark pair production in events with one lepton, jets, and missing transverse momentum at 13 TeV with the CMS experiment*, JHEP **05** (2020), p. 032, DOI: 10.1007/JHEP05(2020)032, arXiv: 1912.08887 [hep-ex].
- [59] CMS Collaboration, *Search for top squark pair production using dilepton final states in pp collision data collected at $\sqrt{s} = 13$ TeV*, Eur. Phys. J. C **81.1** (2021), p. 3, DOI: 10.1140/epjc/s10052-020-08701-5, arXiv: 2008.05936 [hep-ex].
- [60] ATLAS Collaboration, *SUSY Summary Plots August 2023*, ATL-PHYS-PUB-2023-025, CERN, Geneva, Switzerland, 2023, URL: <http://cds.cern.ch/record/2871728>.
- [61] CERN twiki pages, *CMS SUS Physics Results*, URL: https://twiki.cern.ch/twiki/bin/view/CMSPublic/PhysicsResultsSUS#Run_2_Summary_Plots_13_TeV.
- [62] ATLAS Collaboration, *Search for electroweak production of charginos and sleptons decaying into final states with two leptons and missing transverse momentum in $\sqrt{s} = 13$ TeV pp collisions using the ATLAS detector*, Eur. Phys. J. C **80.2** (2020), p. 123, DOI: 10.1140/epjc/s10052-019-7594-6, arXiv: 1908.08215 [hep-ex].

- [63] ATLAS Collaboration, *Search for direct production of charginos, neutralinos and sleptons in final states with two leptons and missing transverse momentum in pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector*, JHEP **05** (2014), p. 071, DOI: 10.1007/JHEP05(2014)071, arXiv: 1403.5294 [hep-ex].
- [64] ATLAS Collaboration, *Search for electroweak production of supersymmetric particles in final states with two or three leptons at $\sqrt{s} = 13$ TeV with the ATLAS detector*, Eur. Phys. J. C **78.12** (2018), p. 995, DOI: 10.1140/epjc/s10052-018-6423-7, arXiv: 1803.02762 [hep-ex].
- [65] CMS Collaboration, *Searches for electroweak production of charginos, neutralinos, and sleptons decaying to leptons and W, Z, and Higgs bosons in pp collisions at 8 TeV*, Eur. Phys. J. C **74.9** (2014), p. 3036, DOI: 10.1140/epjc/s10052-014-3036-7, arXiv: 1405.7570 [hep-ex].
- [66] CMS Collaboration, *Searches for electroweak neutralino and chargino production in channels with Higgs, Z, and W bosons in pp collisions at 8 TeV*, Phys. Rev. D **90.9** (2014), p. 092007, DOI: 10.1103/PhysRevD.90.092007, arXiv: 1409.3168 [hep-ex].
- [67] CMS Collaboration, *Search for electroweak production of charginos and neutralinos in multilepton final states in proton-proton collisions at $\sqrt{s} = 13$ TeV*, JHEP **03** (2018), p. 166, DOI: 10.1007/JHEP03(2018)166, arXiv: 1709.05406 [hep-ex].
- [68] CMS Collaboration, *Combined search for electroweak production of charginos and neutralinos in proton-proton collisions at $\sqrt{s} = 13$ TeV*, JHEP **03** (2018), p. 160, DOI: 10.1007/JHEP03(2018)160, arXiv: 1801.03957 [hep-ex].
- [69] CMS Collaboration, *Searches for pair production of charginos and top squarks in final states with two oppositely charged leptons in proton-proton collisions at $\sqrt{s} = 13$ TeV*, JHEP **11** (2018), p. 079, DOI: 10.1007/JHEP11(2018)079, arXiv: 1807.07799 [hep-ex].
- [70] CERN website, *CERN Accelerating science*, URL: <https://www.home.cern>.
- [71] LHCb Collaboration, *The LHCb Detector at the LHC*, JINST **3** (2008), S08005, DOI: 10.1088/1748-0221/3/08/S08005.
- [72] ALICE Collaboration, *The ALICE experiment at the CERN LHC*, JINST **3** (2008), S08002, DOI: 10.1088/1748-0221/3/08/S08002.
- [73] CERN, *LEP Design Report: Vol.2. The LEP Main Ring*, CERN-LEP-84-01, CERN, Geneva, Switzerland, June 1984, URL: <http://cds.cern.ch/record/102083>.
- [74] CERN website, *The HL-LHC project*, URL: <https://hilumilhc.web.cern.ch/content/hl-lhc-project>.
- [75] P. Mouche, *Overall view of the LHC. Vue d'ensemble du LHC*, General Photo, 2014, URL: <https://cds.cern.ch/record/1708847>.
- [76] E. Lopienska, *The CERN accelerator complex, layout in 2022. Complexe des accélérateurs du CERN en janvier 2022*, General Photo, 2022, URL: <https://cds.cern.ch/record/2800984>.

- [77] W. Herr and B. Muratori, *Concept of luminosity*, CERN, Geneva, Switzerland, 2006, DOI: 10.5170/CERN-2006-002.361.
- [78] M. Tanabashi et al., *Review of Particle Physics*, Phys. Rev. D **98** (3 Aug. 2018), p. 030001, DOI: 10.1103/PhysRevD.98.030001.
- [79] ATLAS Collaboration, *Luminosity determination in pp collisions at $\sqrt{s} = 13$ TeV using the ATLAS detector at the LHC*, ATLAS-CONF-2019-021, CERN, Geneva, Switzerland, June 2019, URL: <https://cds.cern.ch/record/2677054>.
- [80] CERN twiki pages, *Public ATLAS Luminosity Results for Run-2 of the LHC*, URL: <https://twiki.cern.ch/twiki/bin/view/AtlasPublic/LuminosityPublicResultsRun2>.
- [81] ATLAS Collaboration, *ATLAS inner detector: Technical design report. Vol. 2*, CERN-LHCC-97-17, CERN, Geneva, Switzerland, Apr. 1997, URL: <https://cds.cern.ch/record/331064>.
- [82] E. Stanecka, *The ATLAS Inner Detector operation, data quality and tracking performance*, 2013, arXiv: 1303.3630 [physics.ins-det].
- [83] ATLAS Collaboration, *ATLAS pixel detector: Technical design report*, CERN-LHCC-98-13, CERN, Geneva, Switzerland, May 1998, URL: <https://cds.cern.ch/record/381263>.
- [84] ATLAS Collaboration, *ATLAS pixel detector electronics and sensors*, JINST **3**.07 (July 2008), P07007, DOI: 10.1088/1748-0221/3/07/P07007.
- [85] ATLAS Collaboration, *Operation and performance of the ATLAS semiconductor tracker*, JINST **9**.08 (Aug. 2014), P08009, DOI: 10.1088/1748-0221/9/08/P08009.
- [86] ATLAS Collaboration, *Performance of the ATLAS Transition Radiation Tracker in Run 1 of the LHC: tracker properties*, JINST **12**.05 (May 2017), P05002, DOI: 10.1088/1748-0221/12/05/P05002.
- [87] M. Capeans et al., *ATLAS Insertable B-Layer Technical Design Report*, CERN-LHCC-2010-013, ATLAS-TDR-19, CERN, Geneva, Switzerland, Sept. 2010, URL: <https://cds.cern.ch/record/1291633>.
- [88] ATLAS Collaboration, *The ATLAS Inner Detector commissioning and calibration*, Eur. Phys. J. C **70** (2010), pp. 787–821, DOI: 10.1140/epjc/s10052-010-1366-7, arXiv: 1004.5293 [physics.ins-det].
- [89] ATLAS Collaboration, *Reconstruction of primary vertices at the ATLAS experiment in Run 1 proton–proton collisions at the LHC*, Eur. Phys. J. C **77**.5 (2017), p. 332, DOI: 10.1140/epjc/s10052-017-4887-5, arXiv: 1611.10235 [physics.ins-det].
- [90] ATLAS Collaboration, *ATLAS calorimeter performance Technical Design Report*, CERN-LHCC-96-40, CERN, Geneva, Switzerland, Dec. 1996, URL: <https://cds.cern.ch/record/331059>.
- [91] ATLAS Collaboration, *Construction, assembly and tests of the ATLAS electromagnetic end-cap calorimeters*, JINST **3** (2008), P06002, DOI: 10.1088/1748-0221/3/06/P06002.

- [92] A. Menzione and A. Scribano, eds., *Proceedings of the Fourth International Conference on Calorimetry in High Energy Physics: La Bidola, Isola d'Elba, Italy, 19-25 September 1993*, World Scientific Publishing Co. Pte. Ltd., Singapore, 1994.
- [93] A. Henriques, *The ATLAS tile calorimeter*, “4th International Conference on Advancements in Nuclear Instrumentation Measurement Methods and their Applications”, IEEE Nucl.Sci.Symp.Conf.Rec. 2015, p. 7465554, DOI: 10.1109/ANIMMA.2015.7465554.
- [94] ATLAS Collaboration, *ATLAS tile calorimeter: Technical design report*, CERN-LHCC-96-42, CERN, Geneva, Switzerland, Dec. 1996, URL: <https://cds.cern.ch/record/331062>.
- [95] ATLAS Collaboration, *ATLAS muon spectrometer: Technical design report*, CERN-LHCC-97-22, ATLAS-TDR-10, CERN, Geneva, Switzerland, June 1997, URL: <https://cds.cern.ch/record/331068>.
- [96] ATLAS Collaboration, *Commissioning of the ATLAS Muon Spectrometer with Cosmic Rays*, Eur. Phys. J. C **70** (2010), pp. 875–916, DOI: 10.1140/epjc/s10052-010-1415-2, arXiv: 1006.4384 [physics.ins-det].
- [97] F. Bauer et al., *Construction and Test of MDT Chambers for the ATLAS Muon Spectrometer*, Nucl. Instrum. Meth. A **461** (2001), ed. by G. Batignani, F. Cervelli, G. Chiarelli, and A. Scribano, pp. 17–20, DOI: 10.1016/S0168-9002(00)01156-6, arXiv: 1604.02000 [physics.ins-det].
- [98] G. Charpak and F. Sauli, *Multiwire proportional chambers and drift chambers*, Nuclear Instruments and Methods **162.1** (1979), pp. 405–428, ISSN: 0029-554X, DOI: [https://doi.org/10.1016/0029-554X\(79\)90726-2](https://doi.org/10.1016/0029-554X(79)90726-2).
- [99] T. G. Argyropoulos et al., *Cathode strip chambers in ATLAS : Installation, commissioning and in situ performance*, “2008 IEEE Nuclear Science Symposium and Medical Imaging Conference and 16th International Workshop on Room-Temperature Semiconductor X-Ray and Gamma-Ray Detectors” (Dresden, Germany), 2008, pp. 2819–2824, DOI: 10.1109/NSSMIC.2008.4774958.
- [100] G. Cattani on behalf of the RPC group, *The Resistive Plate Chambers of the ATLAS experiment: performance studies*, Journal of Physics: Conference Series **280.1** (Feb. 2011), p. 012001, DOI: 10.1088/1742-6596/280/1/012001.
- [101] E. Etzion et al., *The certification of ATLAS thin gap chambers produced in Israel and China*, “IEEE Symposium Conference Record Nuclear Science 2004.” (Rome, Italy), vol. 1, IEEE, 2004, pp. 236–241, DOI: 10.1109/nssmic.2004.1462188.
- [102] G. Avoni et al., *The new LUCID-2 detector for luminosity measurement and monitoring in ATLAS*, JINST **13.07** (2018), P07017, DOI: 10.1088/1748-0221/13/07/P07017.
- [103] P. Jenni, M. Nordberg, M. Nessi, and K. Jon-And, *ATLAS Forward Detectors for Measurement of Elastic Scattering and Luminosity*, CERN-LHCC-2008-004, ATLAS-TDR-18, CERN, Geneva, Switzerland, 2008, DOI: 10.17181/CERN-LHCC-2008-004.
- [104] M. Červ, *The ATLAS Diamond Beam Monitor*, JINST **9.02** (Feb. 2014), p. C02026, DOI: 10.1088/1748-0221/9/02/C02026.

- [105] V. Cindro et al., *The ATLAS Beam Conditions Monitor*, JINST **3.02** (Feb. 2008), P02004, DOI: 10.1088/1748-0221/3/02/P02004.
- [106] I. Dolenc on behalf of ATLAS BCM and BLM group, *The ATLAS Beam Condition and Beam Loss Monitors*, Astroparticle, Particle, Space Physics, Radiation Interaction, Detectors and Medical Physics Applications (2010), pp. 443–448, DOI: 10.1142/9789814307529_0073.
- [107] ATLAS Collaboration, *ATLAS high-level trigger, data acquisition and controls: Technical design report*, CERN-LHCC-2003-022, ATLAS-TRD-016, CERN, Geneva, Switzerland, July 2003, URL: <https://cds.cern.ch/record/616089?ln=it>.
- [108] A. R. Martínez and on behalf of the ATLAS Collaboration, *The Run-2 ATLAS Trigger System*, Journal of Physics: Conference Series **762.1** (Oct. 2016), p. 012003, DOI: 10.1088/1742-6596/762/1/012003.
- [109] V. Izzo, *ATLAS upgrades*, PoS **LHCP2020** (2021), ed. by B. Mansoulie, G. Marchiori, R. Salern, and T. Bos, p. 094, DOI: 10.22323/1.382.0094.
- [110] A. Ventura, *The Muon Trigger of the ATLAS experiment: performance and improvements for Run 3*, PoS **ICHEP2022** (Nov. 2022), p. 654, DOI: 10.22323/1.414.0654.
- [111] T. Kawamoto et al., *New Small Wheel Technical Design Report*, CERN-LHCC-2013-006, ATLAS-TDR-020, June 2013, URL: <http://cds.cern.ch/record/1552862>.
- [112] T. Alexopoulos et al., *Construction techniques and performances of a full-size prototype Micromegas chamber for the ATLAS muon spectrometer upgrade*, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment **955** (2020), p. 162086, ISSN: 0168-9002, DOI: <https://doi.org/10.1016/j.nima.2019.04.040>.
- [113] M. Greco, *Study of the correlation between the construction parameters of the MM readout boards and performance of the Micromegas detectors*, PoS **LHCP2022** (2023), p. 289, DOI: 10.22323/1.422.0289.
- [114] ATLAS Collaboration, *Muon reconstruction efficiency and momentum resolution of the ATLAS experiment in proton-proton collisions at $\sqrt{s} = 7$ TeV in 2010*, Eur. Phys. J. C **74.9** (2014), p. 3034, DOI: 10.1140/epjc/s10052-014-3034-9, arXiv: 1404.4562 [hep-ex].
- [115] ATLAS Collaboration, *Technical Design Report for the ATLAS Inner Tracker Strip Detector*, CERN-LHCC-2017-005, ATLAS-TDR-025, CERN, Geneva, Switzerland, Apr. 2017, URL: <https://cds.cern.ch/record/2257755>.
- [116] ATLAS Collaboration, *Technical Design Report for the ATLAS Inner Tracker Pixel Detector*, CERN-LHCC-2017-021, ATLAS-TDR-030, CERN, Geneva, Switzerland, 2017, DOI: 10.17181/CERN.FOZZ.ZP3Q, URL: <https://cds.cern.ch/record/2285585>.
- [117] ATLAS Collaboration, *Sensitivity of the ATLAS experiment to long-lived particles with a displaced vertex and E_T^{miss} signature at the HL-LHC*, ATL-PHYS-PUB-2018-033, CERN, Geneva, Switzerland, 2018, URL: <https://cds.cern.ch/record/2647992>.

- [118] ATLAS Collaboration, *ATLAS Liquid Argon Calorimeter Phase-II Upgrade : Technical Design Report*, CERN-LHCC-2017-018, ATLAS-TDR-027, DOI: 10.17181/CERN.6QIO.YGHO, URL: <https://cds.cern.ch/record/2285582>.
- [119] ATLAS Collaboration, *Technical Design Report for the Phase-II Upgrade of the ATLAS Tile Calorimeter*, CERN-LHCC-2017-019, ATLAS-TDR-028, URL: <https://cds.cern.ch/record/2285583>.
- [120] ATLAS Collaboration, *Technical Design Report for the Phase-II Upgrade of the ATLAS Muon Spectrometer*, CERN-LHCC-2017-017, ATLAS-TDR-026, URL: <https://cds.cern.ch/record/2285580>.
- [121] ATLAS Collaboration, *Technical Design Report for the Phase-II Upgrade of the ATLAS TDAQ System*, CERN-LHCC-2017-020, ATLAS-TDR-029, DOI: 10.17181/CERN.2LBB.4IAL, URL: <https://cds.cern.ch/record/2285584>.
- [122] L. G. Gagnon and on behalf of the ATLAS Collaboration, *Development and performance of track reconstruction algorithms at the energy frontier with the ATLAS detector*, Journal of Physics: Conference Series **898.4** (Oct. 2017), p. 042007, DOI: 10.1088/1742-6596/898/4/042007.
- [123] A. Rosenfeld and J. L. Pfaltz, *Sequential Operations in Digital Picture Processing*, J. ACM **13.4** (Oct. 1966), pp. 471–494, ISSN: 0004-5411, DOI: 10.1145/321356.321357.
- [124] R. Frühwirth, *Application of Kalman filtering to track and vertex fitting*, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment **262.2** (1987), pp. 444–450, ISSN: 0168-9002, DOI: [https://doi.org/10.1016/0168-9002\(87\)90887-4](https://doi.org/10.1016/0168-9002(87)90887-4).
- [125] ATLAS Collaboration, *Performance of the ATLAS Track Reconstruction Algorithms in Dense Environments in LHC Run 2*, Eur. Phys. J. C **77.10** (2017), p. 673, DOI: 10.1140/epjc/s10052-017-5225-7, arXiv: 1704.07983 [hep-ex].
- [126] ATLAS Software Documentation, *ATLAS Tracking Software Tutorial. Inside out – Ambiguity solving and TRT extension*, URL: <https://atlassoftwaredocs.web.cern.ch/trackingTutorial/ambitrt/>.
- [127] S. Boutle et al., *Primary vertex reconstruction at the ATLAS experiment*, Journal of Physics: Conference Series **898.4** (Oct. 2017), p. 042056, DOI: 10.1088/1742-6596/898/4/042056.
- [128] ATLAS Collaboration, *Secondary vertex finding for jet flavour identification with the ATLAS detector*, ATL-PHYS-PUB-2017-011, CERN, Geneva, Switzerland, June 2017, URL: <https://cds.cern.ch/record/2270366>.
- [129] W. Lampl et al., *Calorimeter clustering algorithms: Description and performance*, ATL-LARG-PUB-2008-002, ATL-COM-LARG-2008-003, CERN, Geneva, Switzerland, May 2008, URL: <https://cds.cern.ch/record/1099735>.

- [130] ATLAS Collaboration, *Electron reconstruction and identification in the ATLAS experiment using the 2015 and 2016 LHC proton–proton collision data at $\sqrt{s} = 13$ TeV*, The European Physical Journal C **79.8** (Aug. 2019), p. 639, ISSN: 1434-6052, DOI: 10.1140/epjc/s10052-019-7140-6.
- [131] ATLAS Collaboration, *Measurement of the photon identification efficiencies with the ATLAS detector using LHC Run 2 data collected in 2015 and 2016*, The European Physical Journal C **79.3** (Mar. 2019), p. 205, ISSN: 1434-6052, DOI: 10.1140/epjc/s10052-019-6650-6.
- [132] ATLAS Collaboration, *Electron and photon performance measurements with the ATLAS detector using the 2015–2017 LHC proton-proton collision data*, JINST **14.12** (2019), P12006, DOI: 10.1088/1748-0221/14/12/P12006, arXiv: 1908.00005 [hep-ex].
- [133] ATLAS Collaboration, *Electron and photon reconstruction and performance in ATLAS using a dynamical, topological cell clustering-based approach*, ATL-PHYS-PUB-2017-022, CERN, Geneva, Switzerland, Dec. 2017, URL: <https://cds.cern.ch/record/2298955>.
- [134] T. Cornelissen et al., *Concepts, Design and Implementation of the ATLAS New Tracking (NEWT)*, ed. by A. Salzburger, ATL-SOFT-PUB-2007-007, ATL-COM-SOFT-2007-002, CERN, Geneva, Switzerland, Mar. 2007, URL: <https://cds.cern.ch/record/1020106>.
- [135] T. G. Cornelissen et al., *The global χ^2 track fitter in ATLAS*, Journal of Physics: Conference Series **119.3** (July 2008), p. 032013, DOI: 10.1088/1742-6596/119/3/032013.
- [136] ATLAS Collaboration, *Improved electron reconstruction in ATLAS using the Gaussian Sum Filter-based model for bremsstrahlung*, ATLAS-CONF-2012-047, ATLAS-CONF-2012-047, CERN, Geneva, Switzerland, May 2012, URL: <https://cds.cern.ch/record/1449796>.
- [137] ATLAS Collaboration, *Electron and photon energy calibration with the ATLAS detector using 2015–2016 LHC proton-proton collision data*, JINST **14.03** (Mar. 2019), P03017, DOI: 10.1088/1748-0221/14/03/P03017.
- [138] ATLAS Collaboration, *Electron efficiency measurements with the ATLAS detector using 2012 LHC proton–proton collision data*, Eur. Phys. J. C **77.3** (2017), p. 195, DOI: 10.1140/epjc/s10052-017-4756-2, arXiv: 1612.01456 [hep-ex].
- [139] ATLAS Collaboration, *Muon reconstruction performance of the ATLAS detector in proton–proton collision data at $\sqrt{s} = 13$ TeV*, Eur. Phys. J. C **76.5** (2016), p. 292, DOI: 10.1140/epjc/s10052-016-4120-y, arXiv: 1603.05598 [hep-ex].
- [140] ATLAS Collaboration, *Measurements of Higgs boson production and couplings in the four-lepton channel in pp collisions at center-of-mass energies of 7 and 8 TeV with the ATLAS detector*, Phys. Rev. D **91.1** (2015), p. 012006, DOI: 10.1103/PhysRevD.91.012006, arXiv: 1408.5191 [hep-ex].
- [141] ATLAS Collaboration, *Search for high-mass dilepton resonances in pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector*, Phys. Rev. D **90.5** (2014), p. 052005, DOI: 10.1103/PhysRevD.90.052005, arXiv: 1405.4123 [hep-ex].

- [142] ATLAS Collaboration, *Search for new particles in events with one lepton and missing transverse momentum in pp collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector*, JHEP **09** (2014), p. 037, DOI: 10.1007/JHEP09(2014)037, arXiv: 1407.7494 [hep-ex].
- [143] ATLAS Collaboration, *Muon identification and reconstruction efficiencies in full run-2 dataset*, URL: <https://atlas.web.cern.ch/Atlas/GROUPS/PHYSICS/PLOTS/MUON-2019-03/index.html>.
- [144] M. Cacciari, G. P. Salam, and G. Soyez, *The anti- k_t jet clustering algorithm*, JHEP **04** (2008), p. 063, DOI: 10.1088/1126-6708/2008/04/063, arXiv: 0802.1189 [hep-ph].
- [145] ATLAS Collaboration, *Jet reconstruction and performance using particle flow with the ATLAS Detector*, Eur. Phys. J. C **77.7** (2017), p. 466, DOI: 10.1140/epjc/s10052-017-5031-2, arXiv: 1703.10485 [hep-ex].
- [146] ATLAS Collaboration, *Jet energy scale measurements and their systematic uncertainties in proton-proton collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector*, Phys. Rev. D **96.7** (2017), p. 072002, DOI: 10.1103/PhysRevD.96.072002, arXiv: 1703.09665 [hep-ex].
- [147] M. Cacciari and G. P. Salam, *Pileup subtraction using jet areas*, Phys. Lett. B **659** (2008), pp. 119–126, DOI: 10.1016/j.physletb.2007.09.077, arXiv: 0707.1378 [hep-ph].
- [148] ATLAS Collaboration, *Identification and rejection of pile-up jets at high pseudorapidity with the ATLAS detector*, Eur. Phys. J. C **77.9** (2017), [Erratum: Eur.Phys.J.C 77, 712 (2017)], p. 580, DOI: 10.1140/epjc/s10052-017-5081-5, arXiv: 1705.02211 [hep-ex].
- [149] ATLAS Collaboration, *Tagging and suppression of pileup jets*, ATLAS-CONF-2014-018, CERN, Geneva, Switzerland, May 2014, URL: <https://cds.cern.ch/record/1700870>.
- [150] A. Hoecker et al., *TMVA - Toolkit for Multivariate Data Analysis*, 2009, arXiv: physics/0703039 [physics.data-an].
- [151] ATLAS Collaboration, *Optimisation and performance studies of the ATLAS b-tagging algorithms for the 2017-18 LHC run*, ATL-PHYS-PUB-2017-013, CERN, Geneva, Switzerland, July 2017, URL: <https://cds.cern.ch/record/2273281>.
- [152] ATLAS Collaboration, *Secondary vertex finding for jet flavour identification with the ATLAS detector*, ATL-PHYS-PUB-2017-011, CERN, Geneva, Switzerland, June 2017, URL: <https://cds.cern.ch/record/2270366>.
- [153] ATLAS Collaboration, *Topological b-hadron decay reconstruction and identification of b-jets with the JetFitter package in the ATLAS experiment at the LHC*, ATL-PHYS-PUB-2018-025, CERN, Geneva, Switzerland, 2018, URL: <https://cds.cern.ch/record/2645405>.
- [154] ATLAS Collaboration, *ATLAS b-jet identification performance and efficiency measurement with $t\bar{t}$ events in pp collisions at $\sqrt{s} = 13$ TeV*, Eur. Phys. J. C **79.11** (2019), p. 970, DOI: 10.1140/epjc/s10052-019-7450-8, arXiv: 1907.05120 [hep-ex].
- [155] ATLAS Collaboration, *Performance of missing transverse momentum reconstruction with the ATLAS detector using proton-proton collisions at $\sqrt{s} = 13$ TeV*, Eur. Phys. J. C **78.11** (2018), p. 903, DOI: 10.1140/epjc/s10052-018-6288-9, arXiv: 1802.08168 [hep-ex].

- [156] ATLAS Collaboration, *Object-based missing transverse momentum significance in the ATLAS detector*, ATLAS-CONF-2018-038, CERN, Geneva, Switzerland, July 2018, URL: <https://cds.cern.ch/record/2630948>.
- [157] U. D. Sanctis, *Supersymmetry searches with ATLAS detector at LHC*, Il Nuovo Cimento **B** (2006), pp. 761–770, DOI: 10.1393/ncb/i2007-10009-4.
- [158] A. Roodman, *Blind analysis in particle physics*, eConf **C030908** (2003), ed. by L. Lyons, R. P. Mount, and R. Reitmeyer, TUIT001, arXiv: physics/0312102.
- [159] M. Baak et al., *HistFitter software framework for statistical data analysis*, Eur. Phys. J. C **75** (2015), p. 153, DOI: 10.1140/epjc/s10052-015-3327-7, arXiv: 1410.1280 [hep-ex].
- [160] R. Brun and F. Rademakers, *ROOT: An object oriented data analysis framework*, Nucl. Instrum. Meth. A **389** (1997), ed. by M. Werlen and D. Perret-Gallix, pp. 81–86, DOI: 10.1016/S0168-9002(97)00048-X.
- [161] I. Antcheva et al., *ROOT: A C++ framework for petabyte data storage, statistical analysis and visualization*, Comput. Phys. Commun. **182** (2011), pp. 1384–1385, DOI: 10.1016/j.cpc.2011.02.008.
- [162] L. Moneta et al., *The RooStats Project*, PoS **ACAT2010** (2010), ed. by T. Speer et al., p. 057, DOI: 10.22323/1.093.0057, arXiv: 1009.1003 [physics.data-an].
- [163] W. Verkerke and D. Kirkby, *The RooFit toolkit for data modeling*, 2003, arXiv: physics/0306116 [physics.data-an], URL: <https://arxiv.org/abs/physics/0306116>.
- [164] K. Cranmer et al., *HistFactory: A tool for creating statistical models for use with RooFit and RooStats*, CERN-OPEN-2012-016, CERN, Geneva, Switzerland, June 2012, DOI: 10.17181/CERN-OPEN-2012-016, URL: <https://cds.cern.ch/record/1456844>.
- [165] A. L. Read, *Presentation of search results: The CL_s technique*, J. Phys. G **28** (2002), ed. by M. R. Whalley and L. Lyons, pp. 2693–2704, DOI: 10.1088/0954-3899/28/10/313.
- [166] G. Cowan, K. Cranmer, E. Gross, and O. Vitells, *Asymptotic formulae for likelihood-based tests of new physics*, The European Physical Journal C **71.2** (Feb. 2011), p. 1554, ISSN: 1434-6052, DOI: 10.1140/epjc/s10052-011-1554-0.
- [167] ATLAS Collaboration, *ATLAS data quality operations and performance for 2015–2018 data-taking*, JINST **15.04** (2020), P04003, DOI: 10.1088/1748-0221/15/04/P04003, arXiv: 1911.04632 [physics.ins-det].
- [168] GEANT4 Collaboration, S. Agostinelli, et al., *GEANT4 – a simulation toolkit*, Nucl. Instrum. Meth. A **506** (2003), p. 250, DOI: 10.1016/S0168-9002(03)01368-8.
- [169] ATLAS Collaboration, *The ATLAS Simulation Infrastructure*, Eur. Phys. J. C **70** (2010), p. 823, DOI: 10.1140/epjc/s10052-010-1429-9, arXiv: 1005.4568 [physics.ins-det].
- [170] T. Sjöstrand, S. Mrenna, and P. Skands, *A brief introduction to PYTHIA 8.1*, Computer Physics Communications **178.11** (2008), pp. 852–867, ISSN: 0010-4655, DOI: <https://doi.org/10.1016/j.cpc.2008.01.036>.

- [171] D. J. Lange, *The EvtGen particle decay simulation package*, Nucl. Instrum. Meth. A **462** (2001), p. 152, DOI: 10.1016/S0168-9002(01)00089-4.
- [172] R. D. Ball et al., *Parton distributions with LHC data*, Nucl. Phys. B **867** (2013), p. 244, DOI: 10.1016/j.nuclphysb.2012.10.003, arXiv: 1207.1303 [hep-ph].
- [173] ATLAS Collaboration, *The Pythia 8 A3 tune description of ATLAS minimum bias and inelastic measurements incorporating the Donnachie–Landshoff diffractive model*, ATL-PHYS-PUB-2016-017, CERN, Geneva, Switzerland, 2016, URL: <https://cds.cern.ch/record/2206965>.
- [174] ATLAS Collaboration, *Electron and photon performance measurements with the ATLAS detector using the 2015–2017 LHC proton–proton collision data*, JINST **14** (2019), P12006, DOI: 10.1088/1748-0221/14/12/P12006, arXiv: 1908.00005 [hep-ex].
- [175] ATLAS Collaboration, *Muon reconstruction performance of the ATLAS detector in proton–proton collision data at $\sqrt{s} = 13$ TeV*, Eur. Phys. J. C **76** (2016), p. 292, DOI: 10.1140/epjc/s10052-016-4120-y, arXiv: 1603.05598 [hep-ex].
- [176] ATLAS Collaboration, *ATLAS b -jet identification performance and efficiency measurement with $t\bar{t}$ events in pp collisions at $\sqrt{s} = 13$ TeV*, Eur. Phys. J. C **79** (2019), p. 970, DOI: 10.1140/epjc/s10052-019-7450-8, arXiv: 1907.05120 [hep-ex].
- [177] T. Sjöstrand et al., *An introduction to PYTHIA 8.2*, Comput. Phys. Commun. **191** (2015), p. 159, DOI: 10.1016/j.cpc.2015.01.024, arXiv: 1410.3012 [hep-ph].
- [178] ATLAS Collaboration, *ATLAS Pythia 8 tunes to 7 TeV data*, ATL-PHYS-PUB-2014-021, CERN, Geneva, Switzerland, 2014, URL: <https://cds.cern.ch/record/1966419>.
- [179] P. Artoisenet, R. Frederix, O. Mattelaer, and R. Rietkerk, *Automatic spin-entangled decays of heavy resonances in Monte Carlo simulations*, JHEP **03** (2013), p. 015, DOI: 10.1007/JHEP03(2013)015, arXiv: 1212.3460 [hep-ph].
- [180] L. Lönnblad and S. Prestel, *Merging Multi-leg NLO Matrix Elements with Parton Showers*, JHEP **03** (2013), p. 166, DOI: 10.1007/JHEP03(2013)166, arXiv: 1211.7278 [hep-ph].
- [181] J. Debove, B. Fuks, and M. Klasen, *Threshold resummation for gaugino pair production at hadron colliders*, Nucl. Phys. B **842** (2011), p. 51, DOI: 10.1016/j.nuclphysb.2010.08.016, arXiv: 1005.2909 [hep-ph].
- [182] B. Fuks, M. Klasen, D. R. Lamprea, and M. Rothering, *Gaugino production in proton–proton collisions at a center-of-mass energy of 8 TeV*, JHEP **10** (2012), p. 081, DOI: 10.1007/JHEP10(2012)081, arXiv: 1207.2159 [hep-ph].
- [183] B. Fuks, M. Klasen, D. R. Lamprea, and M. Rothering, *Precision predictions for electroweak superpartner production at hadron colliders with RESUMMINO*, Eur. Phys. J. C **73** (2013), p. 2480, DOI: 10.1140/epjc/s10052-013-2480-0, arXiv: 1304.0790 [hep-ph].
- [184] J. Fiaschi and M. Klasen, *Neutralino-chargino pair production at NLO+NLL with resummation-improved parton density functions for LHC Run II*, Phys. Rev. D **98.5** (2018), p. 055014, DOI: 10.1103/PhysRevD.98.055014, arXiv: 1805.11322 [hep-ph].

- [185] G. Bozzi, B. Fuks, and M. Klasen, *Threshold Resummation for Slepton-Pair Production at Hadron Colliders*, Nucl. Phys. B **777** (2007), pp. 157–181, DOI: 10.1016/j.nuclphysb.2007.03.052, arXiv: hep-ph/0701202.
- [186] B. Fuks, M. Klasen, D. R. Lamprea, and M. Rothering, *Revisiting slepton pair production at the Large Hadron Collider*, JHEP **01** (2014), p. 168, DOI: 10.1007/JHEP01(2014)168, arXiv: 1310.2621 [hep-ph].
- [187] J. Fiaschi and M. Klasen, *Slepton pair production at the LHC in NLO+NLL with resummation-improved parton densities*, JHEP **03** (2018), p. 094, DOI: 10.1007/JHEP03(2018)094, arXiv: 1801.10357 [hep-ph].
- [188] C. Borschensky et al., *Squark and gluino production cross sections in pp collisions at $\sqrt{s} = 13, 14, 33$ and 100 TeV*, Eur. Phys. J. C **74** (2014), p. 3174, DOI: 10.1140/epjc/s10052-014-3174-y, arXiv: 1407.5066 [hep-ph].
- [189] ATLAS Collaboration, *Improvements in $t\bar{t}$ modelling using NLO+PS Monte Carlo generators for Run 2*, ATL-PHYS-PUB-2018-009, CERN, Geneva, Switzerland, 2018, URL: <https://cds.cern.ch/record/2630327>.
- [190] ATLAS Collaboration, *Simulation of top-quark production for the ATLAS experiment at $\sqrt{s} = 13$ TeV*, ATL-PHYS-PUB-2016-004, CERN, Geneva, Switzerland, 2016, URL: <https://cds.cern.ch/record/2120417>.
- [191] ATLAS Collaboration, *Multi-Boson Simulation for 13 TeV ATLAS Analyses*, ATL-PHYS-PUB-2017-005, CERN, Geneva, Switzerland, 2017, URL: <https://cds.cern.ch/record/2261933>.
- [192] ATLAS Collaboration, *ATLAS simulation of boson plus jets processes in Run 2*, ATL-PHYS-PUB-2017-006, CERN, Geneva, Switzerland, 2017, URL: <https://cds.cern.ch/record/2261937>.
- [193] S. Frixione, G. Ridolfi, and P. Nason, *A positive-weight next-to-leading-order Monte Carlo for heavy flavour hadroproduction*, JHEP **09** (2007), p. 126, DOI: 10.1088/1126-6708/2007/09/126, arXiv: 0707.3088 [hep-ph].
- [194] P. Nason, *A new method for combining NLO QCD with shower Monte Carlo algorithms*, JHEP **11** (2004), p. 040, DOI: 10.1088/1126-6708/2004/11/040, arXiv: hep-ph/0409146.
- [195] S. Frixione, P. Nason, and C. Oleari, *Matching NLO QCD computations with parton shower simulations: the POWHEG method*, JHEP **11** (2007), p. 070, DOI: 10.1088/1126-6708/2007/11/070, arXiv: 0709.2092 [hep-ph].
- [196] S. Alioli, P. Nason, C. Oleari, and E. Re, *A general framework for implementing NLO calculations in shower Monte Carlo programs: the POWHEG BOX*, JHEP **06** (2010), p. 043, DOI: 10.1007/JHEP06(2010)043, arXiv: 1002.2581 [hep-ph].
- [197] M. Beneke, P. Falgari, S. Klein, and C. Schwinn, *Hadronic top-quark pair production with NNLL threshold resummation*, Nucl. Phys. B **855** (2012), pp. 695–741, DOI: 10.1016/j.nuclphysb.2011.10.021, arXiv: 1109.1536 [hep-ph].

- [198] M. Cacciari et al., *Top-pair production at hadron colliders with next-to-next-to-leading logarithmic soft-gluon resummation*, Phys. Lett. B **710** (2012), pp. 612–622, DOI: 10.1016/j.physletb.2012.03.013, arXiv: 1111.5869 [hep-ph].
- [199] P. Bärnreuther, M. Czakon, and A. Mitov, *Percent-Level-Precision Physics at the Tevatron: Next-to-Next-to-Leading Order QCD Corrections to $q\bar{q} \rightarrow t\bar{t} + X$* , Phys. Rev. Lett. **109** (2012), p. 132001, DOI: 10.1103/PhysRevLett.109.132001, arXiv: 1204.5201 [hep-ph].
- [200] M. Czakon and A. Mitov, *NNLO corrections to top-pair production at hadron colliders: the all-fermionic scattering channels*, JHEP **12** (2012), p. 054, DOI: 10.1007/JHEP12(2012)054, arXiv: 1207.0236 [hep-ph].
- [201] M. Czakon and A. Mitov, *NNLO corrections to top pair production at hadron colliders: the quark-gluon reaction*, JHEP **01** (2013), p. 080, DOI: 10.1007/JHEP01(2013)080, arXiv: 1210.6832 [hep-ph].
- [202] M. Czakon, P. Fiedler, and A. Mitov, *Total Top-Quark Pair-Production Cross Section at Hadron Colliders Through $\mathcal{O}(\alpha_S^4)$* , Phys. Rev. Lett. **110** (2013), p. 252004, DOI: 10.1103/PhysRevLett.110.252004, arXiv: 1303.6254 [hep-ph].
- [203] M. Czakon and A. Mitov, *Top++: A program for the calculation of the top-pair cross-section at hadron colliders*, Comput. Phys. Commun. **185** (2014), p. 2930, DOI: 10.1016/j.cpc.2014.06.021, arXiv: 1112.5675 [hep-ph].
- [204] R. D. Ball et al., *Parton distributions for the LHC run II*, JHEP **04** (2015), p. 040, DOI: 10.1007/JHEP04(2015)040, arXiv: 1410.8849 [hep-ph].
- [205] E. Re, *Single-top Wt -channel production matched with parton showers using the POWHEG method*, Eur. Phys. J. C **71** (2011), p. 1547, DOI: 10.1140/epjc/s10052-011-1547-z, arXiv: 1009.2450 [hep-ph].
- [206] N. Kidonakis, *Two-loop soft anomalous dimensions for single top quark associated production with a W^- or H^-* , Phys. Rev. D **82** (2010), p. 054018, DOI: 10.1103/PhysRevD.82.054018, arXiv: 1005.4451 [hep-ph].
- [207] N. Kidonakis, *Top Quark Production*, “Proceedings, Helmholtz International Summer School on Physics of Heavy Quarks and Hadrons (HQ 2013)” (JINR, Dubna, Russia, July 15–28, 2013), pp. 139–168, DOI: 10.3204/DESY-PROC-2013-03/Kidonakis, arXiv: 1311.0283 [hep-ph].
- [208] E. Bothmann et al., *Event generation with Sherpa 2.2*, SciPost Phys. **7.3** (2019), p. 034, DOI: 10.21468/SciPostPhys.7.3.034, arXiv: 1905.09127 [hep-ph].
- [209] T. Gleisberg and S. Höche, *Comix, a new matrix element generator*, JHEP **12** (2008), p. 039, DOI: 10.1088/1126-6708/2008/12/039, arXiv: 0808.3674 [hep-ph].
- [210] S. Schumann and F. Krauss, *A parton shower algorithm based on Catani–Seymour dipole factorisation*, JHEP **03** (2008), p. 038, DOI: 10.1088/1126-6708/2008/03/038, arXiv: 0709.1027 [hep-ph].

- [211] S. Höche, F. Krauss, M. Schönherr, and F. Siegert, *A critical appraisal of NLO+PS matching methods*, JHEP **09** (2012), p. 049, DOI: 10.1007/JHEP09(2012)049, arXiv: 1111.1220 [hep-ph].
- [212] S. Höche, F. Krauss, M. Schönherr, and F. Siegert, *QCD matrix elements + parton showers. The NLO case*, JHEP **04** (2013), p. 027, DOI: 10.1007/JHEP04(2013)027, arXiv: 1207.5030 [hep-ph].
- [213] S. Catani, F. Krauss, B. R. Webber, and R. Kuhn, *QCD Matrix Elements + Parton Showers*, JHEP **11** (2001), p. 063, DOI: 10.1088/1126-6708/2001/11/063, arXiv: hep-ph/0109231.
- [214] S. Höche, F. Krauss, S. Schumann, and F. Siegert, *QCD matrix elements and truncated showers*, JHEP **05** (2009), p. 053, DOI: 10.1088/1126-6708/2009/05/053, arXiv: 0903.1219 [hep-ph].
- [215] J. Alwall et al., *The automated computation of tree-level and next-to-leading order differential cross sections, and their matching to parton shower simulations*, JHEP **07** (2014), p. 079, DOI: 10.1007/JHEP07(2014)079, arXiv: 1405.0301 [hep-ph].
- [216] H. B. Hartanto, B. Jäger, L. Reina, and D. Wackerroth, *Higgs boson production in association with top quarks in the POWHEG BOX*, Phys. Rev. D **91**.9 (2015), p. 094003, DOI: 10.1103/PhysRevD.91.094003, arXiv: 1501.04498 [hep-ph].
- [217] C. Anastasiou, L. Dixon, K. Melnikov, and F. Petriello, *High-precision QCD at hadron colliders: Electroweak gauge boson rapidity distributions at next-to-next-to leading order*, Phys. Rev. D **69** (2004), p. 094008, DOI: 10.1103/PhysRevD.69.094008, arXiv: hep-ph/0312266.
- [218] K. Hamilton, P. Nason, E. Re, and G. Zanderighi, *NNLOPS simulation of Higgs boson production*, JHEP **10** (2013), p. 222, DOI: 10.1007/JHEP10(2013)222, arXiv: 1309.0017 [hep-ph].
- [219] K. Hamilton, P. Nason, and G. Zanderighi, *Finite quark-mass effects in the NNLOPS POWHEG+MiNLO Higgs generator*, JHEP **05** (2015), p. 140, DOI: 10.1007/JHEP05(2015)140, arXiv: 1501.04637 [hep-ph].
- [220] K. Hamilton, P. Nason, and G. Zanderighi, *MINLO: multi-scale improved NLO*, JHEP **10** (2012), p. 155, DOI: 10.1007/JHEP10(2012)155, arXiv: 1206.3572 [hep-ph].
- [221] J. M. Campbell et al., *NLO Higgs boson production plus one and two jets using the POWHEG BOX, MadGraph4 and MCFM*, JHEP **07** (2012), p. 092, DOI: 10.1007/JHEP07(2012)092, arXiv: 1202.5475 [hep-ph].
- [222] K. Hamilton, P. Nason, C. Oleari, and G. Zanderighi, *Merging H/W/Z + 0 and 1 jet at NLO with no merging scale: a path to parton shower + NNLO matching*, JHEP **05** (2013), p. 082, DOI: 10.1007/JHEP05(2013)082, arXiv: 1212.4504 [hep-ph].

- [223] S. Catani and M. Grazzini, *Next-to-Next-to-Leading-Order Subtraction Formalism in Hadron Collisions and its Application to Higgs-boson Production at the Large Hadron Collider*, Phys. Rev. Lett. **98** (2007), p. 222002, DOI: 10.1103/PhysRevLett.98.222002, arXiv: hep-ph/0703012 [hep-ph].
- [224] ATLAS Collaboration, *Measurement of the Z/γ^* boson transverse momentum distribution in pp collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector*, JHEP **09** (2014), p. 145, DOI: 10.1007/JHEP09(2014)145, arXiv: 1406.3660 [hep-ex].
- [225] J. Butterworth et al., *PDF4LHC recommendations for LHC Run II*, J. Phys. G **43** (2016), p. 023001, DOI: 10.1088/0954-3899/43/2/023001, arXiv: 1510.03865 [hep-ph].
- [226] ATLAS Collaboration, *Standard Model Summary Plots February 2022*, ATL-PHYS-PUB-2022-009, CERN, Geneva, Switzerland, 2022, URL: <https://cds.cern.ch/record/2804061>.
- [227] ATLAS Collaboration, *Performance of electron and photon triggers in ATLAS during LHC Run 2*, Eur. Phys. J. C **80.1** (2020), p. 47, DOI: 10.1140/epjc/s10052-019-7500-2, arXiv: 1909.00761 [hep-ex].
- [228] ATLAS Collaboration, *Performance of the ATLAS muon triggers in Run 2*, JINST **15.09** (2020), P09015, DOI: 10.1088/1748-0221/15/09/p09015, arXiv: 2004.13447 [physics.ins-det].
- [229] M. Cacciari, G. P. Salam, and G. Soyez, *FastJet User Manual*, Eur. Phys. J. C **72** (2012), p. 1896, DOI: 10.1140/epjc/s10052-012-1896-2, arXiv: 1111.6097 [hep-ph].
- [230] ATLAS Collaboration, *Selection of jets produced in 13TeV proton-proton collisions with the ATLAS detector*, ATLAS-CONF-2015-029, CERN, Geneva, Switzerland, July 2015, URL: <https://cds.cern.ch/record/2037702>.
- [231] ATLAS Collaboration, *Performance of pile-up mitigation techniques for jets in pp collisions at $\sqrt{s} = 8$ TeV using the ATLAS detector*, Eur. Phys. J. C **76.11** (2016), p. 581, DOI: 10.1140/epjc/s10052-016-4395-z, arXiv: 1510.03823 [hep-ex].
- [232] S. D. Drell and T.-M. Yan, *Massive Lepton-Pair Production in Hadron-Hadron Collisions at High Energies*, Phys. Rev. Lett. **25** (5 Aug. 1970), pp. 316–320, DOI: 10.1103/PhysRevLett.25.316.
- [233] C. G. Lester and D. J. Summers, *Measuring masses of semi-invisibly decaying particles pair produced at hadron colliders*, Phys. Lett. B **463** (1999), pp. 99–103, DOI: 10.1016/S0370-2693(99)00945-4, arXiv: hep-ph/9906349.
- [234] A. Barr, C. Lester, and P. Stephens, *A variable for measuring masses at hadron colliders when missing energy is expected; m_{T2} : the truth behind the glamour*, J. Phys. G **29** (2003), pp. 2343–2363, DOI: 10.1088/0954-3899/29/10/304, arXiv: hep-ph/0304226.
- [235] A. J. Barr, *Measuring slepton spin at the LHC*, JHEP **02** (2006), p. 042, DOI: 10.1088/1126-6708/2006/02/042, arXiv: hep-ph/0511115.
- [236] ATLAS Collaboration, *Formulae for Estimating Significance*, ATL-PHYS-PUB-2020-025, CERN, Geneva, Switzerland, 2020, URL: <https://cds.cern.ch/record/2736148>.

- [237] ATLAS Collaboration, *Estimation of non-prompt and fake lepton backgrounds in final states with top quarks produced in proton–proton collisions at $\sqrt{s} = 8$ TeV with the ATLAS Detector*, ATLAS-CONF-2014-058, CERN, Geneva, Switzerland, 2014, URL: <https://cds.cern.ch/record/1951336>.
- [238] ATLAS Collaboration, *Jet energy scale and resolution measured in proton–proton collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector*, Eur. Phys. J. C **81** (2020), p. 689, DOI: 10.1140/epjc/s10052-021-09402-3, arXiv: 2007.02645 [hep-ex].
- [239] ATLAS Collaboration, *Determination of jet calibration and energy resolution in proton–proton collisions at $\sqrt{s} = 8$ TeV using the ATLAS detector*, Eur. Phys. J. C **80** (2020), p. 1104, DOI: 10.1140/epjc/s10052-020-08477-8, arXiv: 1910.04482 [hep-ex].
- [240] E. Bothmann, M. Schönherr, and S. Schumann, *Reweighting QCD matrix-element and parton-shower calculations*, Eur. Phys. J. C **76**.11 (2016), p. 590, DOI: 10.1140/epjc/s10052-016-4430-0, arXiv: 1606.08753 [hep-ph].
- [241] M. Bähr et al., *Herwig++ physics and manual*, Eur. Phys. J. C **58** (2008), p. 639, DOI: 10.1140/epjc/s10052-008-0798-9, arXiv: 0803.0883 [hep-ph].
- [242] J. Bellm et al., *Herwig 7.0/Herwig++ 3.0 release note*, Eur. Phys. J. C **76**.4 (2016), p. 196, DOI: 10.1140/epjc/s10052-016-4018-8, arXiv: 1512.01178 [hep-ph].
- [243] ATLAS Collaboration, *Studies on top-quark Monte Carlo modelling with Sherpa and MG5_aMC@NLO*, ATL-PHYS-PUB-2017-007, CERN, Geneva, Switzerland, 2017, URL: <https://cds.cern.ch/record/2261938>.
- [244] S. Frixione et al., *Single-top hadroproduction in association with a W boson*, JHEP **07** (2008), p. 029, DOI: 10.1088/1126-6708/2008/07/029, arXiv: 0805.3067 [hep-ph].
- [245] ATLAS Collaboration, *Studies on top-quark Monte Carlo modelling for Top2016*, ATL-PHYS-PUB-2016-020, CERN, Geneva, Switzerland, 2016, URL: <https://cds.cern.ch/record/2216168>.
- [246] ATLAS Collaboration, *Search for direct stau production in events with two hadronic τ -leptons in $\sqrt{s} = 13$ TeV pp collisions with the ATLAS detector*, Phys. Rev. D **101** (3 Feb. 2020), p. 032009, DOI: 10.1103/PhysRevD.101.032009.
- [247] D. P. Aguillard et al., *Measurement of the Positive Muon Anomalous Magnetic Moment to 0.20 ppm*, Phys. Rev. Lett. **131**.16 (2023), p. 161802, DOI: 10.1103/PhysRevLett.131.161802, arXiv: 2308.06230 [hep-ex].
- [248] G. W. Bennett et al., *Final Report of the Muon E821 Anomalous Magnetic Moment Measurement at BNL*, Phys. Rev. D **73** (2006), p. 072003, DOI: 10.1103/PhysRevD.73.072003, arXiv: hep-ex/0602035.
- [249] B. Abi et al., *Measurement of the Positive Muon Anomalous Magnetic Moment to 0.46 ppm*, Phys. Rev. Lett. **126**.14 (2021), p. 141801, DOI: 10.1103/PhysRevLett.126.141801, arXiv: 2104.03281 [hep-ex].

- [250] S. Heinemeyer, W. Hollik, and G. Weiglein, *Electroweak precision observables in the minimal supersymmetric standard model*, Phys. Rept. **425** (2006), pp. 265–368, DOI: 10.1016/j.physrep.2005.12.002, arXiv: hep-ph/0412214.
- [251] ATLAS Collaboration, *SUSY Summary Plots March 2022*, ATL-PHYS-PUB-2022-013, CERN, Geneva, Switzerland, 2022, URL: <https://cds.cern.ch/record/2805985>.
- [252] ATLAS Collaboration, *SUSY Summary Plots June 2021*, ATL-PHYS-PUB-2021-019, CERN, Geneva, Switzerland, 2021, URL: <https://cds.cern.ch/record/2771785>.
- [253] ATLAS Collaboration, *Search for electroweak production of supersymmetric states in scenarios with compressed mass spectra at $\sqrt{s} = 13$ TeV with the ATLAS detector*, Phys. Rev. D **97**.5 (2018), p. 052010, DOI: 10.1103/PhysRevD.97.052010, arXiv: 1712.08119 [hep-ex].
- [254] R. D. Cousins, J. T. Linnemann, and J. Tucker, *Evaluation of three methods for calculating statistical significance when incorporating a systematic uncertainty into a test of the background-only hypothesis for a Poisson process*, Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment **595**.2 (Oct. 2008), pp. 480–501, ISSN: 0168-9002, DOI: 10.1016/j.nima.2008.07.086.
- [255] LEPSUSYWG, ALEPH, DELPHI, L3 and OPAL Collaborations, *Combined LEP selectron/smuon/stau results, 183-208 GeV*, LEPSUSYWG/04-01.1 (2004), URL: https://lepsusy.web.cern.ch/lepsusy/www/sleptons_summer04/slep_final.html.
- [256] ATLAS Collaboration, *Searches for electroweak production of supersymmetric particles with compressed mass spectra in $\sqrt{s} = 13$ TeV pp collisions with the ATLAS detector*, Phys. Rev. D **101**.5 (2020), p. 052005, DOI: 10.1103/PhysRevD.101.052005, arXiv: 1911.12606 [hep-ex].
- [257] M. Greco, *Search for the direct production of chargino pairs decaying via W boson in 13 TeV pp collisions with the ATLAS detector*, PoS **ICHEP2022** (2022), p. 1070, DOI: 10.22323/1.414.1070, URL: <https://inspirehep.net/literature/2176464>.
- [258] G. Ke et al., *LightGBM: A Highly Efficient Gradient Boosting Decision Tree*, “Advances in Neural Information Processing Systems”, ed. by I. Guyon et al., vol. 30, Curran Associates, Inc., 2017, URL: https://proceedings.neurips.cc/paper_files/paper/2017/file/6449f44a102fde848669bdd9eb6b76fa-Paper.pdf.
- [259] LEPSUSYWG, ALEPH, DELPHI, L3 and OPAL Collaborations, *Combined LEP chargino results, up to 208 GeV for large m_0* , LEPSUSYWG/01-03.1 (2001), URL: https://lepsusy.web.cern.ch/lepsusy/www/inos_moriond01/charginos_pub.html.
- [260] ATLAS Collaboration, *Measurement prospects of Higgs boson pair production in the $b\bar{b}\gamma\gamma$ final state with the ATLAS experiment at the HL-LHC*, ATL-PHYS-PUB-2022-001, CERN, Geneva, Switzerland, URL: <https://cds.cern.ch/record/2799146>.
- [261] ATLAS Collaboration, *Projected sensitivity of Higgs boson pair production combining the $b\bar{b}\gamma\gamma$ and $b\bar{b}\tau^+\tau^-$ final states with the ATLAS detector at the HL-LHC*, ATL-PHYS-PUB-2022-005, CERN, Geneva, Switzerland, URL: <https://cds.cern.ch/record/2802127>.

- [262] ATLAS Collaboration, *Measurement of the WW cross section in $\sqrt{s} = 7$ TeV pp collisions with ATLAS*, Phys. Rev. Lett. **107** (2011), p. 041802, DOI: 10.1103/PhysRevLett.107.041802, arXiv: 1104.5225 [hep-ex].
- [263] ATLAS Collaboration, *Search for anomalous production of prompt same-sign lepton pairs and pair-produced doubly charged Higgs bosons with $\sqrt{s} = 8$ TeV pp collisions using the ATLAS detector*, JHEP **03** (2015), p. 041, DOI: 10.1007/JHEP03(2015)041, arXiv: 1412.0237 [hep-ex].
- [264] CMS Collaboration, *Search for charged Higgs bosons in the $H^\pm \rightarrow \tau^\pm \nu_\tau$ decay channel in proton-proton collisions at $\sqrt{s} = 13$ TeV*, JHEP **07** (2019), p. 142, DOI: 10.1007/JHEP07(2019)142, arXiv: 1903.04560 [hep-ex].
- [265] CMS Collaboration, *Search for a singly produced third-generation scalar leptoquark decaying to a τ lepton and a bottom quark in proton-proton collisions at $\sqrt{s} = 13$ TeV*, JHEP **07** (2018), p. 115, DOI: 10.1007/JHEP07(2018)115, arXiv: 1806.03472 [hep-ex].
- [266] ATLAS Collaboration, *SimpleAnalysis: Truth-level Analysis Framework*, ATL-PHYS-PUB-2022-017, CERN, Geneva, Switzerland, 2022, DOI: 10.17181/CERN.R6S3.0QKV.
- [267] ATLAS Collaboration, *Expected tracking and related performance with the updated ATLAS Inner Tracker layout at the High-Luminosity LHC*, ATL-PHYS-PUB-2021-024, CERN, Geneva, Switzerland, 2021, URL: <https://cds.cern.ch/record/2776651>.
- [268] ATLAS Collaboration, *Expected performance of the ATLAS detector under different High-Luminosity LHC conditions*, ATL-PHYS-PUB-2021-023, CERN, Geneva, Switzerland, 2021, URL: <https://cds.cern.ch/record/2776650>.
- [269] W. Beenakker et al., *NNLL-fast: predictions for coloured supersymmetric particle production at the LHC with threshold and Coulomb resummation*, JHEP **12** (2016), p. 133, DOI: 10.1007/JHEP12(2016)133, arXiv: 1607.07741 [hep-ph].
- [270] W. Beenakker et al., *NNLL resummation for squark and gluino production at the LHC*, JHEP **12** (2014), p. 023, DOI: 10.1007/JHEP12(2014)023, arXiv: 1404.3134 [hep-ph].
- [271] W. Beenakker et al., *Towards NNLL resummation: hard matching coefficients for squark and gluino hadroproduction*, JHEP **10** (2013), p. 120, DOI: 10.1007/JHEP10(2013)120, arXiv: 1304.6354 [hep-ph].
- [272] W. Beenakker et al., *NNLL resummation for squark-antisquark pair production at the LHC*, JHEP **01** (2012), p. 076, DOI: 10.1007/JHEP01(2012)076, arXiv: 1110.2446 [hep-ph].
- [273] W. Beenakker et al., *Soft-gluon resummation for squark and gluino hadroproduction*, JHEP **12** (2009), p. 041, DOI: 10.1088/1126-6708/2009/12/041, arXiv: 0909.4418 [hep-ph].
- [274] A. Kulesza and L. Motyka, *Soft gluon resummation for the production of gluino-gluino and squark-antisquark pairs at the LHC*, Phys. Rev. D **80** (2009), p. 095004, DOI: 10.1103/PhysRevD.80.095004, arXiv: 0905.4749 [hep-ph].

- [275] A. Kulesza and L. Motyka, *Threshold Resummation for Squark-Antisquark and Gluino-Pair Production at the LHC*, Phys. Rev. Lett. **102** (2009), p. 111802, DOI: 10.1103/PhysRevLett.102.111802, arXiv: 0807.2405 [hep-ph].
- [276] W. Beenakker, R. Höpker, M. Spira, and P. Zerwas, *Squark and gluino production at hadron colliders*, Nucl. Phys. B **492** (1997), p. 51, DOI: 10.1016/S0550-3213(97)00084-9, arXiv: hep-ph/9610490.
- [277] ATLAS Collaboration, *Modelling of the $t\bar{t}H$ and $t\bar{t}V$ ($V = W, Z$) processes for $\sqrt{s} = 13$ TeV ATLAS analyses*, ATL-PHYS-PUB-2016-005, CERN, Geneva, Switzerland, 2016, URL: <https://cds.cern.ch/record/2120826>.
- [278] R. Frederix, E. Re, and P. Torrielli, *Single-top t -channel hadroproduction in the four-flavour scheme with POWHEG and aMC@NLO*, JHEP **09** (2012), p. 130, DOI: 10.1007/JHEP09(2012)130, arXiv: 1207.5391 [hep-ph].
- [279] S. Alioli, P. Nason, C. Oleari, and E. Re, *NLO single-top production matched with shower in POWHEG: s - and t -channel contributions*, JHEP **09** (2009), p. 111, DOI: 10.1088/1126-6708/2009/09/111, arXiv: 0907.4076 [hep-ph].
- [280] M. Aliev et al., *HATHOR – HAdronic Top and Heavy quarks crOss section calculator*, Comput. Phys. Commun. **182** (2011), pp. 1034–1046, DOI: 10.1016/j.cpc.2010.12.040, arXiv: 1007.1327 [hep-ph].
- [281] P. Kant et al., *HatHor for single top-quark production: Updated predictions and uncertainty estimates for single top-quark production in hadronic collisions*, Comput. Phys. Commun. **191** (2015), pp. 74–89, DOI: 10.1016/j.cpc.2015.02.001, arXiv: 1406.4403 [hep-ph].
- [282] T. Gleisberg et al., *Event generation with SHERPA 1.1*, JHEP **02** (2009), p. 007, DOI: 10.1088/1126-6708/2009/02/007, arXiv: 0811.4622 [hep-ph].
- [283] ATLAS Collaboration, *Monte Carlo Generators for the Production of a W or Z/γ^* Boson in Association with Jets at ATLAS in Run 2*, ATL-PHYS-PUB-2016-003, CERN, Geneva, Switzerland, 2016, URL: <https://cds.cern.ch/record/2120133>.
- [284] R. Gavin, Y. Li, F. Petriello, and S. Quackenbush, *FEWZ 2.0: A code for hadronic Z production at next-to-next-to-leading order* (2010), p. 2388, arXiv: 1011.3540 [hep-ph].
- [285] M. R. Buckley, J. D. Lykken, C. Rogan, and M. Spiropulu, *Super-razor and searches for sleptons and charginos at the LHC*, Phys. Rev. D **89** (5 Mar. 2014), p. 055020, DOI: 10.1103/PhysRevD.89.055020.
- [286] ATLAS Collaboration, *Performance of the ATLAS Trigger System in 2015*, Eur. Phys. J. C **77.5** (2017), p. 317, DOI: 10.1140/epjc/s10052-017-4852-3, arXiv: 1611.09661 [hep-ex].
- [287] ATLAS Collaboration, *Calibration of b -tagging using dileptonic top pair events in a combinatorial likelihood approach with the ATLAS experiment*, ATLAS-CONF-2014-004, CERN, Geneva, Switzerland, Feb. 2014, URL: <https://cds.cern.ch/record/1664335>.

- [288] ATLAS Collaboration, *Calibration of the performance of b -tagging for c and light-flavour jets in the 2012 ATLAS data*, ATLAS-CONF-2014-046, CERN, Geneva, Switzerland, 2014, URL: <https://cds.cern.ch/record/1741020>.
- [289] ATLAS and CMS Collaborations, *Addendum to the report on the physics at the HL-LHC, and perspectives for the HE-LHC: Collection of notes from ATLAS and CMS*, CERN Yellow Rep. Monogr. **7** (2019), Addendum, DOI: 10.23731/CYRM-2019-007.Addendum, arXiv: 1902.10229 [hep-ex].
- [290] ATLAS Collaboration, *ATLAS Run 2 searches for electroweak production of supersymmetric particles interpreted within the p MSSM*, ATLAS-CONF-2023-055, CERN, Geneva, Switzerland, 2023, URL: <https://cds.cern.ch/record/2870222>.
- [291] W. Porod, *SPheno, a program for calculating supersymmetric spectra, SUSY particle decays and SUSY particle production at e^+e^- colliders*, Comput. Phys. Commun. **153** (2003), pp. 275–315, DOI: 10.1016/S0010-4655(03)00222-4, arXiv: hep-ph/0301101.
- [292] W. Porod and F. Staub, *SPheno 3.1: Extensions including flavour, CP-phases and models beyond the MSSM*, Comput. Phys. Commun. **183** (2012), pp. 2458–2469, DOI: 10.1016/j.cpc.2012.05.021, arXiv: 1104.1573 [hep-ph].
- [293] H. Bahl et al., *Precision calculations in the MSSM Higgs-boson sector with FeynHiggs 2.14*, Comput. Phys. Commun. **249** (2020), p. 107099, DOI: 10.1016/j.cpc.2019.107099, arXiv: 1811.09073 [hep-ph].
- [294] H. Bahl, S. Heinemeyer, W. Hollik, and G. Weiglein, *Reconciling EFT and hybrid calculations of the light MSSM Higgs-boson mass*, Eur. Phys. J. C **78.1** (2018), p. 57, DOI: 10.1140/epjc/s10052-018-5544-3, arXiv: 1706.00346 [hep-ph].
- [295] H. Bahl and W. Hollik, *Precise prediction for the light MSSM Higgs boson mass combining effective field theory and fixed-order calculations*, Eur. Phys. J. C **76.9** (2016), p. 499, DOI: 10.1140/epjc/s10052-016-4354-8, arXiv: 1608.01880 [hep-ph].
- [296] T. Hahn et al., *High-Precision Predictions for the Light CP -Even Higgs Boson Mass of the Minimal Supersymmetric Standard Model*, Phys. Rev. Lett. **112.14** (2014), p. 141801, DOI: 10.1103/PhysRevLett.112.141801, arXiv: 1312.4937 [hep-ph].
- [297] M. Frank et al., *The Higgs Boson Masses and Mixings of the Complex MSSM in the Feynman-Diagrammatic Approach*, JHEP **02** (2007), p. 047, DOI: 10.1088/1126-6708/2007/02/047, arXiv: hep-ph/0611326.
- [298] G. Degrandi et al., *Towards high precision predictions for the MSSM Higgs sector*, Eur. Phys. J. C **28** (2003), pp. 133–143, DOI: 10.1140/epjc/s2003-01152-2, arXiv: hep-ph/0212020.
- [299] S. Heinemeyer, W. Hollik, and G. Weiglein, *The Masses of the neutral CP - even Higgs bosons in the MSSM: Accurate analysis at the two loop level*, Eur. Phys. J. C **9** (1999), pp. 343–366, DOI: 10.1007/s100529900006, arXiv: hep-ph/9812472.

- [300] S. Heinemeyer, W. Hollik, and G. Weiglein, *FeynHiggs: A Program for the calculation of the masses of the neutral CP even Higgs bosons in the MSSM*, Comput. Phys. Commun. **124** (2000), pp. 76–89, DOI: 10.1016/S0010-4655(99)00364-1, arXiv: hep-ph/9812320.
- [301] D. Barducci et al., *Collider limits on new physics within micrOMEGAs_4.3*, Comput. Phys. Commun. **222** (2018), pp. 327–338, DOI: 10.1016/j.cpc.2017.08.028, arXiv: 1606.03834 [hep-ph].
- [302] G. Belanger, A. Mjallal, and A. Pukhov, *Recasting direct detection limits within micrOMEGAs and implication for non-standard Dark Matter scenarios*, Eur. Phys. J. C **81.3** (2021), p. 239, DOI: 10.1140/epjc/s10052-021-09012-z, arXiv: 2003.08621 [hep-ph].
- [303] F. Mahmoudi, *SuperIso v2.3: A Program for calculating flavor physics observables in Supersymmetry*, Comput. Phys. Commun. **180** (2009), pp. 1579–1613, DOI: 10.1016/j.cpc.2009.02.017, arXiv: 0808.3144 [hep-ph].
- [304] N. Aghanim et al., *Planck 2018 results. VI. Cosmological parameters*, Astron. Astrophys. **641** (2020), [Erratum: Astron. Astrophys. 652, C4 (2021)], A6, DOI: 10.1051/0004-6361/201833910, arXiv: 1807.06209 [astro-ph.CO].
- [305] W. Beenakker, R. Hopker, and M. Spira, *PROSPINO: A Program for the production of supersymmetric particles in next-to-leading order QCD*, Nov. 1996, arXiv: hep-ph/9611232, URL: <https://cds.cern.ch/record/314229>.
- [306] L. Heinrich, M. Feickert and G. Stark, *pyhf: v0.6.3*, URL: <https://zenodo.org/records/10045025>.
- [307] L. Heinrich et al., *pyhf: pure-Python implementation of HistFactory statistical models*, Journal of Open Source Software **6.58** (2021), URL: <https://doi.org/10.21105/joss.02823>.
- [308] ATLAS Collaboration, *Search for chargino–neutralino pair production in final states with three leptons and missing transverse momentum in $\sqrt{s} = 13$ TeV pp collisions with the ATLAS detector*, Eur. Phys. J. C **81.12** (2021), p. 1118, DOI: 10.1140/epjc/s10052-021-09749-7, arXiv: 2106.01676 [hep-ex].
- [309] ATLAS Collaboration, *Search for charginos and neutralinos in final states with two boosted hadronically decaying bosons and missing transverse momentum in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector*, Phys. Rev. D **104.11** (2021), p. 112010, DOI: 10.1103/PhysRevD.104.112010, arXiv: 2108.07586 [hep-ex].
- [310] ATLAS Collaboration, *Searches for new phenomena in events with two leptons, jets, and missing transverse momentum in 139 fb^{-1} of $\sqrt{s} = 13$ TeV pp collisions with the ATLAS detector*, Eur. Phys. J. C **83.6** (2023), p. 515, DOI: 10.1140/epjc/s10052-023-11434-w, arXiv: 2204.13072 [hep-ex].
- [311] *Docker*, URL: <https://www.docker.com/>.
- [312] *RECAST for ATLAS*, URL: <https://recast.docs.cern.ch/>.
- [313] *REANA Documentation*, URL: <https://docs.reana.io/>.

- [314] ATLAS Collaboration, *Search for top squarks in events with a Higgs or Z boson using 139 fb^{-1} of pp collision data at $\sqrt{s} = 13\text{ TeV}$ with the ATLAS detector*, Eur. Phys. J. C **80**.11 (2020), p. 1080, DOI: 10.1140/epjc/s10052-020-08469-8, arXiv: 2006.05880 [hep-ex].
- [315] ATLAS Collaboration, *Search for a scalar partner of the top quark in the all-hadronic $t\bar{t}$ plus missing transverse momentum final state at $\sqrt{s} = 13\text{ TeV}$ with the ATLAS detector*, Eur. Phys. J. C **80**.8 (2020), p. 737, DOI: 10.1140/epjc/s10052-020-8102-8, arXiv: 2004.14060 [hep-ex].
- [316] ATLAS Collaboration, *Search for new phenomena with top quark pairs in final states with one lepton, jets, and missing transverse momentum in pp collisions at $\sqrt{s} = 13\text{ TeV}$ with the ATLAS detector*, JHEP **04** (2021), p. 174, DOI: 10.1007/JHEP04(2021)174, arXiv: 2012.03799 [hep-ex].
- [317] ATLAS Collaboration, *Search for new phenomena in pp collisions in final states with tau leptons, b-jets, and missing transverse momentum with the ATLAS detector*, Phys. Rev. D **104**.11 (2021), p. 112005, DOI: 10.1103/PhysRevD.104.112005, arXiv: 2108.07665 [hep-ex].
- [318] ATLAS Collaboration, *Search for new phenomena in final states with b-jets and missing transverse momentum in $\sqrt{s} = 13\text{ TeV}$ pp collisions with the ATLAS detector*, JHEP **05** (2021), p. 093, DOI: 10.1007/JHEP05(2021)093, arXiv: 2101.12527 [hep-ex].
- [319] ATLAS Collaboration, *Search for bottom-squark pair production in pp collision events at $\sqrt{s} = 13\text{ TeV}$ with hadronically decaying τ -leptons, b-jets and missing transverse momentum using the ATLAS detector*, Phys. Rev. D **104**.3 (2021), p. 032014, DOI: 10.1103/PhysRevD.104.032014, arXiv: 2103.08189 [hep-ex].
- [320] ATLAS Collaboration, *Search for bottom-squark pair production with the ATLAS detector in final states containing Higgs bosons, b-jets and missing transverse momentum*, JHEP **12** (2019), p. 060, DOI: 10.1007/JHEP12(2019)060, arXiv: 1908.03122 [hep-ex].

Acknowledgements

The accomplishment of this thesis represents the end of an educational path which, through thick and thin, enriched me in many ways, both professionally and personally. In support of this achievement I cannot ignore the contribution of who has always motivated and encouraged me.

Firstly, I would like to express my gratitude to my supervisors, Prof. Edoardo Gorini, for giving me the opportunity to undertake this experience, and Dr. Margherita Primavera, for her thoughtfulness and interest in guiding me during these years and in realizing this thesis. A sincere thanks to all the people I worked with, starting from the ‘chargino and slepton search’ team, in particular to Sonia, Eric, Daniel and Jordi, for their kindness and willingness, the ‘stop at HL-LHC’ team, especially to Giulio and Suman, and finally to Paolo, who guided me with care during my qualification task in the ATLAS collaboration. A particular mention to Francesco G. and Luigi, always ready to listen and solve all my doubts with clarity and patience.

A warm thanks to my ‘CERN office mate’ Alessandra, for having endured my anxieties and concerns and for her useful advices, and to my ‘Lecce office mate’ Francesco D., for our long discussion sessions and mutual support. Thanks to Antonio and Elisabetta, for our frequent coffee breaks, sharing laughter and thoughts, and to all the other Fiorini’s colleagues, for our long and playful lunch breaks. Thanks to Mariachiara, for our cultural and sophisticated evenings. A huge thanks to all the wonderful friends I met during my stay at CERN, who made this experience amazing and unforgettable.

A heartfelt thanks goes to my family, my sisters Silvia and Sara, my brother Michele and my parents Rita and Aldo, for always supporting me.

Last but not least, I would like to thank all those among family and friends who I did not mention, but who know they are important to me and that part of this result is also due to them.

Grazie!