A University of Sussex PhD thesis

Available online via Sussex Research Online:

http://sro.sussex.ac.uk/

This thesis is protected by copyright which belongs to the author.

This thesis cannot be reproduced or quoted extensively from without first obtaining permission in writing from the Author

The content must not be changed in any way or sold commercially in any format or medium without the formal permission of the Author

When referring to this work, full bibliographic details including the author, title, awarding institution and date of the thesis must be given

Please visit Sussex Research Online for more information and further details
SEARCHES FOR CHARGINO AND NEUTRALINO PRODUCTION IN DECAYS TO THREE-LEPTON FINAL STATES VIA INTERMEDIATE BOSONS USING $\sqrt{s} = 13$ TeV proton-proton collisions with the ATLAS detector

Fabrizio Trovato

A thesis submitted in fulfilment of the requirements for the degree of Doctor of Philosophy

in the

School of Mathematical and Physical Sciences
Department of Physics and Astronomy

Submission date: 17th December 2020
I, Fabrizio Trovato, hereby declare that this thesis has not been and will not be, submitted in whole or in part to another university for the award of any other degree.

Brighton,

17th December 2020

Fabrizio Trovato
Searches for production of charginos and neutralinos as predicted by Supersymmetry in three-lepton final states are presented. The analyses use data collected by the ATLAS detector at 13-TeV proton-proton collisions between 2015-2018 for a total of 139 fb$^{-1}$. The targeted simplified models are those for the production of the lightest chargino and the next-to-lightest neutralino decaying to the lightest neutralino and Standard Model bosons, $WZ$ or $Wh$, subsequently decaying leptonically to yield three leptons in the final states. No significant deviation with respect to the Standard Model predictions is observed, and results are interpreted as exclusion limits on the considered simplified models. Masses of the lightest chargino and the next-to-lightest neutralino up to 640 GeV are excluded at 95% CL for the $WZ$ model, while in the case of $Wh$ model, masses up to 180 GeV are excluded.
A PhD can be full of surprises, as well as laughter, marvellous achievements but also inevitable low moments. Now that I am just about to submit this thesis, my mind can’t help but think of all the people that have made this journey possible.

Firstly, I want to thank my supervisor, Antonella De Santo, for being such an incredible inspiration and support. She has given me time and motivation to grow, as a physicist and as a person, and I could not be more grateful and honoured for the great time spent working together. I hope I made her proud. I would also like to thank my second supervisor, Fabrizio Salvatore, whose knowledge and infinite kindness have made many of my days at Sussex.

I would like to thank Batool Safarzadeh for being always on my side, even when I could not see it, and for helping me going through most of the work in this thesis. And thanks also to Nicola Abraham and Nicky Santoyo, who have supported me at the beginning of my PhD with the most valuable advice and/or some drinks in R1. I would also like to thank Benedict Allbrooke, for patiently mentoring me during my qualification task, and all the other members of the Sussex group: Alex, Iacopo, Kate, Lily, Tom, and Mark, who I am looking forward to working with in the near future. All of you have made me feel at home.

I am also grateful to all the ATLAS SUSY group, and all the people involved in the three-lepton analyses, particularly Peter Tornambé, Jeanette Lorenz, Alberto Cervelli, Tina Potter, Sara Alderweireldt and Jeff Dandoy, for the fruitful physics talks and the incredible support.

I would like to thank all the people in the 4A26 office, who have made my days at Sussex such an enjoyable time: Mario Grandi, Ioannis, Marco, Meirin, Ondra, Fabio, Fab Miano (who let me use his thesis latex template!), Giuseppe and Sam.

My time in Brighton has been incredible, thanks to the many people I’ve met along the way. A huge thank you to Andrea and Pippa, for being such a cheerful presence in my first year. Thank you also to Dani, Chinmay and Ash, for being there during one of the most difficult moments of my journey. And thank you to Paolo, who is always able to cheer me up.
Also, a big thank you to my friends back in Catania: Salvo, Luca, Federico, Angelo, Luigi and Andrea, for always being with me beside the distance. Thank you also to all my friends from my days at the University of Catania (Michele, Miriam, Ruggero, Nicolò, Valeria, Laura, Paola, Giulia, Giulia, Stefano, Silvia, Jessica, Letizia, Nicola, Mimmo, Ferdinanda and many, many more!). Among all, a big thanks to Mario Spina, who I have shared with more than ten years (since laboratory at year 1!) in physics, and thanks to Lucia for being always such a caring friend.

I am grateful to Santo, who has motivated me during the last years of my PhD, and reminds me every day how insignificant distance can be. And a special thanks to Lorena, who has truly believed in me since the very first moments. Such a friendship is rare, I was just lucky to find it.

My family has been the best support during these years. Thank you to my sister Angela, my niece Ylenia and my nephew Giovanni, whose love is an amazing and constant source of motivation.

I can attempt to describe (part of) the Universe, but no words can do justice to the support, sacrifice and immense love I’ve received from my parents. I am grateful to them, they have taught and pushed me to follow my dreams, always. This thesis is for them.

Finally, thank you to Leon, one of the best people I know. He’s supported me with infinite patience, particularly during these last months. Every day, I feel lucky to have him by my side.
The content of this thesis reflects the work I have done over the period of my PhD at the University of Sussex, as member of the ATLAS Collaboration at CERN, Geneva. The ATLAS experiment addresses a vast physics program which comprises both searches for new physics and precision measurements of Standard Model processes and properties of elementary particles. Collaborative tools and resources are available to ATLAS collaborators, which were used to obtain the results presented in this thesis.

I have been involved in the ATLAS SUSY group since the start of my PhD, working on searches for charginos and neutralinos in three-leptons final states. I have contributed to two rounds of analysis, a first one based on the first 36.1 fb$^{-1}$ of data collected by the ATLAS experiment at $\sqrt{s} = 13$ TeV proton-proton collisions, and the analysis of the full Run-2 dataset (139 fb$^{-1}$). These analyses I have performed as a main analyser, alongside other physicists working in the same analysis groups where the presented work was conducted. I made leading contribution to various aspects of the analyses, such as the optimisation of regions sensitive to the targeted SUSY scenarios, the estimation of the main sources of Standard Model background in the analyses and the statistical interpretation of the results.

In order to become author within ATLAS, I have performed a technical task in view of the future upgrades of the ATLAS detector, beneficial for the entire physics program of the collaboration. This is presented in Appendix A.
# CONTENTS

1 Introduction

2 Theoretical framework
   2.1 The Standard Model ........................................ 4
      2.1.1 Fundamental forces and symmetries ................... 7
      2.1.2 The Brout-Englert-Higgs mechanism .................... 12
      2.1.3 Limitations of the SM ................................. 14
   2.2 Supersymmetry ............................................. 17
      2.2.1 The MSSM ............................................. 19
      2.2.2 Phenomenology of the MSSM at colliders ............ 25
   2.3 Electroweak SUSY searches ................................ 29
      2.3.1 State of art of three-lepton searches for \(\tilde{\chi}_1^\pm\tilde{\chi}_2^0\) via WZ/Wh bosons . 31

3 The ATLAS detector at the Large Hadron Collider
   3.1 The Large Hadron Collider .................................. 37
      3.1.1 The acceleration complex ............................. 38
      3.1.2 The LHC parameters ................................. 38
      3.1.3 The LHC detectors .................................. 39
   3.2 The ATLAS detector .......................................... 41
      3.2.1 The ATLAS coordinate system and some key variables . 42
      3.2.2 The magnet system .................................. 43
      3.2.3 The Inner Detector .................................. 44
### 3.2.4 The calorimetry system


### 3.2.5 The Muon Spectrometer


### 3.2.6 The trigger and data acquisition system


## 4 Event generation, reconstruction and object definitions

4.1 Event flow in ATLAS

4.2 Event generation

4.2.1 The generators in ATLAS

4.2.2 Underlying events and pile-up

4.3 ATLAS simulation and digitisation

4.3.1 The ATLAS fast simulation

4.4 Object reconstruction

4.4.1 Track and vertex reconstruction

4.4.2 Electrons

4.4.3 Muons

4.4.4 Jets

4.4.5 $b$-tagged jets

4.4.6 Taus

4.4.7 Missing transverse momentum

4.4.8 Overlap Removal

4.5 Event quality cuts

4.6 Analysis objects

## 5 Analysis strategy for EWK SUSY searches with three-lepton final states

5.1 Data and simulated samples

5.1.1 SUSY signals

5.1.2 Trigger strategy and data quality

5.1.3 Standard Model backgrounds

5.2 Strategy for the event selection

5.2.1 Selection variables

5.3 Background estimation

5.3.1 Data-driven estimation of FNP backgrounds

5.3.2 Normalisation of irreducible background
5.3.3 Validation of the background estimation ........................................ 91
5.4 Systematic uncertainties ........................................................................ 91
  5.4.1 Detector-level uncertainties ............................................................. 92
  5.4.2 Theory uncertainties ....................................................................... 93
5.5 Statistical analysis of results ................................................................. 94
  5.5.1 Hypothesis test ............................................................................... 94

6 Results of $\tilde{\tau}^{\pm} \tilde{\chi}_1^0 \tilde{\chi}_2^0$ searches with three-lepton and $E_T^{miss}$ final states ................................................................. 98
  6.1 Early Run-2 analysis searching for $\tilde{\tau}^{\pm} \tilde{\chi}_1^0 \tilde{\chi}_2^0$ via $Wh$ ................................................................. 98
  6.2 Full Run-2 analysis searching for $\tilde{\tau}^{\pm} \tilde{\chi}_1^0 \tilde{\chi}_2^0$ via $WZ/Wh$ ................................................................. 109
    6.2.1 Event selection .............................................................................. 109
    6.2.2 Standard Model background estimation ........................................ 117
    6.2.3 Systematic uncertainties ............................................................... 124
    6.2.4 Background-only fit results ......................................................... 126
    6.2.5 Results and statistical interpretation ............................................. 128

7 Conclusions and outlook ............................................................................. 138

A Performance of the Hardware-based Tracking for Trigger upgrade for ATLAS 141
  A.1 The LHC and ATLAS upgrades for high-luminosity .......................... 141
  A.2 ATLAS TDAQ architecture for the Phase-II upgrade ..................... 142
  A.3 The Hardware-based Tracking for Trigger for the HL-LHC ............ 144
    A.3.1 Track fitting in HTT ................................................................. 145
    A.3.2 Reduction of storage space needed by track-fitting step .......... 146
    A.3.3 Exploring the low-$p_T$ range ................................................... 153
  A.4 Conclusions ....................................................................................... 158

List of Acronyms ......................................................................................... 160

List of Figures ............................................................................................... 165

List of Tables .................................................................................................. 177

Bibliography .................................................................................................. 181
Introduction

Until the beginning of the 20th century, atoms were considered indivisible particles. More than a century after, the physics of the elementary particles is completely transformed. Atoms are not indivisible but, like everything in Nature, are composed by sub-atomic, more fundamental components. The Standard Model (SM) is the theory that describes the physics of the elementary particles and theirs interactions. Experimental evidence is consistent with the SM predictions, such as the precise measurements in the so-called electroweak sector by the experiments at Large Electron-Positron collider (LEP), and the discovery of the Higgs boson by the ATLAS and CMS experiments at Large Hadron Collider (LHC).

However, despite its incredible experimental successes, the SM is not the ultimate theory of particles. Many of its extensions postulate solutions to some critical limitations of the theory, particularly the effects of high-energy renormalisation on physical observable, such as the mass of the Higgs boson, and the unknown nature of the Dark Matter. Supersymmetry is one of the most established Beyond the Standard Model (BSM) theories, which extends the particle content of the SM by introducing a fermion-boson symmetry. The new particle states should have a mass around 1 TeV scale.

The analyses in this thesis search for supersymmetry produced via electroweak modes with LHC proton-proton collisions at $\sqrt{s} = 13$ TeV, at a scale where possible hints of supersymmetry can appear. The targeted dataset is the one collected by the ATLAS experiment between the years 2015 and 2018, corresponding to 139 fb$^{-1}$. The targeted final states are those with three leptons and missing transverse momentum.
CHAPTER 1. INTRODUCTION

This thesis is structured as follows. In Chapter 2, the SM framework and its shortcomings are briefly presented, then the supersymmetrical extension of the SM is discussed, along with its phenomenology at the LHC and the state of art of searches for electroweak supersymmetry. Chapter 3 presents the experimental apparatus, the LHC and the ATLAS detector. In Chapter 4, the main features of the generation steps of the simulations used in the analyses are briefly described, as well as the algorithms used for the reconstruction of physics objects from hits in the detectors. In Chapter 5 the analysis strategy for the three-lepton searches is discussed, presenting the strategies for the optimisation of the searches, the techniques for the estimation of the SM backgrounds and the statistical interpretation of the results. In Chapter 6, the results of the analyses are then presented. Finally, conclusions are drawn in Chapter 7.

In this thesis, natural units \( \hbar = c = 1 \) are used.
The SM is the theoretical framework that describes the physics of known elementary particles and their interactions. Despite its many successes, the SM presents several limitations, such as the non-natural radiative corrections to the Higgs boson mass at energies up to the Planck mass scale. In order to respond to such limitations, BSM theories aim to provide valid extensions to the SM at high energy.

Supersymmetry is one of the best established BSM extensions. It postulates the existence of a new symmetry, linking fermions to bosons and introducing additional particles, effectively doubling the particle content of SM. Production and detection of these new particles would open a window on a whole new range of phenomena to be tested experimentally.

In Section 2.1, a brief description of the main features of the SM is presented. In Section 2.2, the supersymmetry extension of the SM is described concisely, with particular emphasis on the minimal supersymmetric Standard Model. Finally, Section 2.3 presents an overview of current experimental results from the search for Electroweak (EWK) supersymmetry signals at the LHC, relevant for the studies presented in this thesis.
2.1 The Standard Model

The SM presents a coherent description of elementary particles’ interactions via three of the four known fundamental forces \([1]\). Its particle content is shown in Figure 2.1.

Figure 2.1: Particle content of the SM. The six quarks \((u, d, s, c, b, t)\) are shown in purple, the six leptons \((e, \mu, \tau, \nu_e, \nu_\mu, \nu_\tau)\) displayed in green, while the gauge bosons \((g, \gamma, Z, W)\) and Higgs boson \((H)\) are shown in red and yellow, respectively. Values of masses, electric charge and spin are also given for each particle. \([2]\)

Particles in the SM can be grouped into two different categories. The first one comprises particles with an integer value of the spin, the bosons. These are the spin-1 gauge bosons \((g, \gamma, Z, W)\), associated with the considered fundamental interactions, as well as an additional spin-0 boson, the so-called Higgs boson, associated with the mechanism that ensures that elementary particles in the SM have non-zero masses. The second group of particles in the SM includes the matter particles, which are all spin-1/2 fermions, separated into leptons and quarks.

Chirality is an important quantum number which characterises particles in the SM. It is conceptually defined as a generalisation of helicity, namely the projection of a particle’s spin along the direction of its motion. A particle’s chirality is defined in terms of how its state transforms under a Poincaré rotation of the group SU(2), and is invariant under a boost from one inertial reference frame to another. Depending on their
chirality, particles can be either left-handed or right-handed.

As mentioned, of the four fundamental forces of nature, only three are included in the SM framework: the weak force, responsible, for example, for $\beta$-decays; the electromagnetic force, described by Maxwell’s equations; and the strong force, which is responsible for the nuclear force\(^1\). The four gauge bosons in the SM are associated with these three fundamental forces. The light particle, the photon $\gamma$, is the massless mediator of the electromagnetic force. It interacts with particles which carry an electric charge. The gluons $g$ are the massless carriers of the strong interaction, and thus couple with particles carrying a colour charge, which can assume three values (labelled as red, green, or blue). The $W^\pm$ and the $Z$ bosons are the force carriers associated with the weak interaction, which is short-range, and the $W^\pm$ and the $Z$ bosons have masses as shown in Figure 2.1, namely close to the electroweak scale of $O(100 \text{ GeV})$. The interactions mediated by the $W$ boson, referred to as charged currents, involve only left-handed fermions with electric charge differing by one unit. This is not the case for the interactions mediated by the $Z$ boson, the so-called neutral currents. It is convenient to organise particles interacting via the weak force into doublets, which are the eigenstates of rotation in the SU(2) group. As it will be further discussed in Section 2.1.1, the formalism of the weak interaction is developed by using the algebra of the SU(2) group, whose generators can be written as a function of the Pauli’s matrices $\sigma_1$, the rotation generators in two-dimensional spaces. The weak isospin, the charge of the weak interaction, is defined as the eigenvalue $T_3$ corresponding to the application of $\sigma_3/2$ to SU(2) states. The so-called Higgs mechanism and the Higgs boson will be discussed in more detail in Section 2.1.2.

The physics of fermions is described by the Dirac equation, which predicts the existence of an antiparticle for each fermion in the SM. Antiparticles have electric charge opposite to their corresponding particle, but have the same values of spin and mass.

The charged leptons are fermions which exist in three distinct flavours: the electron $e$, the muon $\mu$, and the tau $\tau$. Each of the three charged leptons is accompanied by an electrically neutral neutrino of the same flavour. Three additive quantum numbers, called lepton numbers ($L_e$, $L_\mu$ and $L_\tau$), one for each flavour, are separately conserved

\(^1\) The fourth fundamental interaction, gravity, is not included in the SM, but it is the subject of Einstein’s general relativity [3], and a viable quantum theory of gravity remains to be developed.
2.1 The Standard Model

in the SM. Each lepton number is +1 for particles in the relevant lepton flavour family, −1 for the corresponding antileptons, and zero otherwise. This implies that no SM process allows net change in the flavour of involved leptons. All the leptons carry weak isospin.

$SU(2)$ doublets of leptons can be constructed in correspondence to the lepton flavour families:

$$\begin{pmatrix} v_e \\ e^- \end{pmatrix}, \begin{pmatrix} v_\mu \\ \mu^- \end{pmatrix}, \text{ and } \begin{pmatrix} v_\tau \\ \tau^- \end{pmatrix}.$$ \hspace{1cm} (2.1)

The main properties of leptons are summarised in Table 2.1.

<table>
<thead>
<tr>
<th>Name</th>
<th>Symbol</th>
<th>Spin</th>
<th>Electric charge/e</th>
<th>Mass [GeV]</th>
<th>$L_e$</th>
<th>$L_\mu$</th>
<th>$L_\tau$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron</td>
<td>$e^-$</td>
<td>1/2</td>
<td>−1</td>
<td>0.0005</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Electron neutrino</td>
<td>$\nu_e$</td>
<td>1/2</td>
<td>0</td>
<td>&lt;1.1 · 10^{-9}</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Muon</td>
<td>$\mu^-$</td>
<td>1/2</td>
<td>−1</td>
<td>0.1134</td>
<td>0</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Muon neutrino</td>
<td>$\nu_\mu$</td>
<td>1/2</td>
<td>0</td>
<td>&lt;1.9 · 10^{-4}</td>
<td>0</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>Tau</td>
<td>$\tau^-$</td>
<td>1/2</td>
<td>−1</td>
<td>1.77</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>Tau neutrino</td>
<td>$\nu_\tau$</td>
<td>1/2</td>
<td>0</td>
<td>&lt;1.82 · 10^{-2}</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 2.1: Summary of the main properties of the SM leptons. [4]

Quarks, with gluons, are the microscopic constituents of atomic nuclei. They carry a colour charge, an electric charge, and weak isospin, and are hence subject to each of the fundamental forces in the SM. In particular, due to the structure of the strong interaction, quarks are not detectable as isolated particles (confinement), but they aggregate into colourless states, known as hadrons (these can be three-quark states, known as baryons, or quark-antiquark states, known as mesons). Similarly to the leptons, quarks are organised into families, or generations, again arranged into $SU(2)$ doublets:

$$\begin{pmatrix} u \\ d \end{pmatrix}, \begin{pmatrix} c \\ s \end{pmatrix}, \text{ and } \begin{pmatrix} t \\ b \end{pmatrix}.$$ \hspace{1cm} (2.2)

The values of the electric charge of the quarks is fractional: the up-type quarks ($up$, charm, top) have a positive charge $+2/3 \, e$, whilst the down-type quarks ($down$, strange, bottom) have charge $−1/3 \, e$, where $e$ is the magnitude of the electron charge. Quarks carry an additive quantum number, the baryon number $B$, which is conserved
in the SM. For all the quarks, the baryonic number is $+1/3$, and $-1/3$ for antiquarks. A summary of the main properties of quarks is shown in Table 2.2.

<table>
<thead>
<tr>
<th>Name</th>
<th>Symbol</th>
<th>Spin</th>
<th>Electric charge/e</th>
<th>Mass [GeV]</th>
<th>Baryon number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Down</td>
<td>$d$</td>
<td>$1/2$</td>
<td>$-1/3$</td>
<td>0.00467</td>
<td>1/3</td>
</tr>
<tr>
<td>Up</td>
<td>$u$</td>
<td>$1/2$</td>
<td>$+2/3$</td>
<td>0.00217</td>
<td>1/3</td>
</tr>
<tr>
<td>Strange</td>
<td>$s$</td>
<td>$1/2$</td>
<td>$-1/3$</td>
<td>0.093</td>
<td>1/3</td>
</tr>
<tr>
<td>Charm</td>
<td>$c$</td>
<td>$1/2$</td>
<td>$+2/3$</td>
<td>1.27</td>
<td>1/3</td>
</tr>
<tr>
<td>Bottom</td>
<td>$b$</td>
<td>$1/2$</td>
<td>$-1/3$</td>
<td>4.18</td>
<td>1/3</td>
</tr>
<tr>
<td>Top</td>
<td>$t$</td>
<td>$1/2$</td>
<td>$+2/3$</td>
<td>172.9</td>
<td>1/3</td>
</tr>
</tbody>
</table>

Table 2.2: Summary of the main properties of the SM quarks. [4]

### 2.1.1 Fundamental forces and symmetries

The formalism of the SM is that of Quantum Field Theory (QFT) [5], which applies quantisation of continuous fields in order to express interactions and particles as quantum field fluctuations above the vacuum state. The quantity that describes the state of a field in a given point of the spacetime is called lagrangian, $\mathcal{L}$, whose expression depends on the space coordinates $\mathbf{q}$, the velocities $\dot{\mathbf{q}}$, and time $t$. The equations of motion, the *Euler-Lagrange equations*, can be derived from $\mathcal{L}$ after applying the principle of least action, and are written as:

$$
\frac{d}{dt} \frac{\partial \mathcal{L}}{\partial \dot{\mathbf{q}}} - \frac{\partial \mathcal{L}}{\partial \mathbf{q}} = 0.
$$

In the formalism of the SM, a very important role is played by *symmetries*. The lagrangian of a system is *symmetric* if its form does not change after a specific transformation of the field. Through the Noether’s theorem [6], each symmetry of the system corresponds to a conserved quantity or *charge*.

#### 2.1.1.1 Quantum Electrodynamics

The electromagnetic force is described by the theory of Quantum Electrodynamics (QED), whose main ideas are briefly presented in this section. The lagrangian of a free
2.1 The Standard Model

A massless fermion, described through a Dirac spinor $\psi$, is

$$\mathcal{L}(x) = i\bar{\psi}(x)\gamma^\mu \partial_\mu \psi(x),$$

(2.4)

where $x$ is the four-vector of the space-time coordinates and the $\gamma^\mu$ are the anti-commuting Dirac matrices. The lagrangian in Equation 2.4 is symmetric under a global phase transformation of the Dirac spinor in the symmetry group $U(1)$:

$$\psi(x) \xrightarrow{U(1)} \psi'(x) = e^{i\theta} \psi(x),$$

(2.5)

where $\theta$ is the generator of the transformation. Normally, if the transformation is local ($\theta = \theta(x)$), the symmetry is broken, due to the presence of partial derivatives of the field $\psi$ in the lagrangian. The gauge principle imposes that the $U(1)$ phase transformation preserve invariance also under a local transformation. In order to achieve this, two quantities are introduced: a spin-1 vector field $A_\mu(x)$, which under $U(1)$ transforms as

$$A_\mu(x) \xrightarrow{U(1)} A'_\mu(x) = A_\mu(x) - \frac{1}{e} \partial_\mu \theta,$$

(2.6)

and a covariant derivative $D_\mu$,

$$D_\mu \psi(x) \equiv \left[ \partial_\mu + i e A_\mu(x) \right] \psi(x),$$

(2.7)

which behaves like a Dirac spinor under transformations of the $U(1)$ group. The quantity $e$ is the strength of the interaction term, or coupling. The core of the local gauge principle is to replace the partial derivative in the lagrangian in Equation 2.4 with the covariant derivative in Equation 2.7, leading to a locally-symmetric lagrangian under phase transformations of the $U(1)$ group:

$$\mathcal{L}(x) = i\bar{\psi}(x)\gamma^\mu D_\mu \psi(x) = i\bar{\psi}(x)\gamma^\mu \partial_\mu \psi(x) - eA_\mu(x)\psi(x).$$

(2.8)

Equation 2.8 shows that the local gauge invariance of the lagrangian of a free fermionic particle can be respected if a coupling term $-eA_\mu(x)\psi(x)$ between the fermion and the vector field $A_\mu$ is introduced. The field $A_\mu$ is interpreted as the field of the photon $\gamma$, while the parameter $e$ is the electric charge. As it will presented in the follow-
ing sections, the use of the local gauge principle can be extended also to the formalism to describe all the other fundamental forces in the SM.

QED gives some of the most successfully tested predictions of the SM. The magnetic moments of the electron and muon are sensitive to QED-loop corrections, which give rise to anomalies with respect to the classical electrodynamics expectations. The measured values of the anomalies of the electron [7] and the muon [8] agree with the theoretical prediction from QED up to twelve significant figures. In the case of the muon, the measured magnetic moment anomaly, \( a_{\mu}^{\text{QED}} = (116584718.92 \pm 0.03) \times 10^{-11} \), is in agreement within the \( 10^{-14} \) order with the value as expected from QED calculations, \( a_{\mu}^{\text{Exp}} = (11659209.1 \pm 5.4 \pm 3.3) \times 10^{-10} \) [4]. Possible deviations from the SM predictions are explainable by considering additional one-loop diagrams, shown in Figure 2.2, involving supersymmetric particles, whose properties will be discussed in Section 2.2.

![Figure 2.2: One-loop supersymmetric contributions to the anomalous magnetic momentum of the muon, involving chargino and sneutrino (left) and neutralino and smuon (right).][9]

### 2.1.1.2 Quantum Chromodynamics

Quantum Chromodynamics (QCD) is the theoretical framework which describes the strong interaction. The symmetry group which regulates the QCD interactions is SU(3), whose local gauge transformation has the form:

\[
U = \exp \left\{ i \frac{\lambda^a}{2} \theta_a \right\},
\]

where \( \frac{\lambda^a}{2} \) are the eight SU(3) generators. Similarly to QED, the structure of QCD is based on the application of the gauge principle to the lagrangian of a free Dirac spinor,
such that coupling terms with new interaction bosons are coherently included. The local invariance under $SU(3)$ introduces eight new vector fields which couple with the fermions, along with a covariant derivative which transforms like the fermion field under $SU(3)$. The new fields are associated with the mediators of the strong interaction, the gluons. The strength of the interaction is represented by the strong coupling $\alpha_s$, in analogy to the QED coupling $e$ appearing in Equation 2.8.

A crucial difference between QCD and QED is given by the non-abelian nature of the $SU(3)$ symmetry group, meaning that the generators do not commute with each other. For this reason, differently from the photons, the gluons can self-interact, leading to additional loop contributions in the Feynman propagators. As a consequence, the value of the strong coupling $\alpha_s$ changes significantly depending on the energy scale at which the interaction is considered. At energies comparable to the hadronisation scale ($\approx 1 \text{ GeV}$), the strong coupling is $\alpha_s \approx 1$, and interacting particles experience the phenomenon of so-called confinement, which causes the aggregation of coloured particles into colourless hadrons. On the other hand, the strong coupling between particles become asymptotically weaker as the energy of the interaction increases, so that coloured particles reach asymptotic freedom and at asymptotically high energies come into existence as isolated states.

### 2.1.1.3 Electroweak unification

As discussed in Section 2.1, one of the main characteristics of the weak force is the dependency of the interaction on the left-handed and right-handed chirality of the particles. For this reason, it is useful to represent the left-handed fermions as $SU(2)$ doublets, and the right-handed particles as $U(1)$ singlets, written as:

$$
\psi_1(x) = \begin{pmatrix} \nu_e \\ e^- \end{pmatrix}, \quad \psi_2(x) = (e^-)_R, \quad \psi_3(x) = (\nu_e)_R,
$$

where $\psi_1(x)$ is a $SU(2)$ doublet with left-handed elements, $\psi_2(x)$ and $\psi_3(x)$ are $U(1)$ singlets. The symbols $e^-$ and $\nu_e$ represent two particle spinors which differ from one unit of electric charge, whose left-handed components can interact via charged currents. For simplicity, the states in 2.10 are written only for the first family of leptons:
the same structure is maintained for the other leptons and the quarks.

In the electroweak unification theory \([10, 11, 12]\), all \(\psi_1, \psi_2\) and \(\psi_3\) can be transformed by a phase rotation in \(U(1)\), but only \(\psi_1\) has the structure to transform under \(SU(2)\). The overall symmetry group of the interaction is given by the product \(SU(2) \otimes U(1)\). With a formalism analogous to the one for QED and QCD, the application of the local-gauge invariance to \(SU(2) \otimes U(1)\) introduces vector fields in the same number as the generators of the symmetry group. In particular, three vector fields \((W^1_\mu(i = 1,2,3))\) are introduced for the \(SU(2)\), and one \((B_\mu)\) for \(U(1)\). In addition, the local gauge invariance introduces the couplings \(g\) and \(g'\) of the fermions to four vector fields, \(W^1_\mu(i = 1,2,3)\) and \(B_\mu\), respectively.

The two vector fields \(W^1_\mu\) and \(W^2_\mu\) combine together to give rise to states associated with the SM \(W^\pm\) bosons:

\[
W_\mu = \frac{W^1_\mu + iW^2_\mu}{\sqrt{2}}, \quad W^+_\mu = \frac{W^1_\mu - iW^2_\mu}{\sqrt{2}}.
\] (2.11)

The vector fields \(W^3_\mu\) and \(B_\mu\) are both electrically neutral and mix with each other via a rotation matrix with rotation angle given by the Weinberg angle \(\theta_W\):

\[
\begin{pmatrix}
W^3_\mu \\
B_\mu
\end{pmatrix} = \begin{pmatrix}
\cos \theta_W & \sin \theta_W \\
-\sin \theta_W & \cos \theta_W
\end{pmatrix} \begin{pmatrix}
Z_\mu \\
A_\mu
\end{pmatrix}.
\] (2.12)

The fields \(Z_\mu\) and \(A_\mu\) correspond to the \(Z\) boson and the photon \(\gamma\) of the SM.

The electroweak unification relation connects the \(SU(2) \otimes U(1)\) couplings \(g\) and \(g'\) to the \(U(1)\) coupling \(e\):

\[
g \sin \theta_W = g' \cos \theta_W = e.
\] (2.13)

Finally, the Gell-mann-Nishijima relation defines the hypercharge \(Y\), from the electric charge \(Q\) and the third component of the weak isospin \(T_3\) \([13, 14]\), as:

\[
Y = 2(Q - T_3).
\] (2.14)
In conclusion, the overall symmetry group of the SM is given by the product of the groups of the electroweak unification theory and QCD:

\[ SU(3)_C \otimes SU(2)_L \otimes U(1)_Y, \]  

(2.15)

where \( C \) indicates the colour charge, \( L \) refers to the left-handed chirality of the particles, and \( Y \) is the hypercharge.

### 2.1.2 The Brout-Englert-Higgs mechanism

Up to this point, all the particles in the SM are assumed to be massless, since a mass term would explicitly violate the local gauge invariance. However, experiments show that most of the particles in the SM possess a non-zero mass, as seen in Tables 2.1 and 2.2. The Brout-Englert-Higgs (BEH) mechanism [15, 16, 17] provides a solution to this issue. The BEH mechanism considers the locally gauge-invariant lagrangian

\[ \mathcal{L}_S = (D_\mu \phi)^\dagger D^\mu \phi - V(\phi), \quad \text{where } V(\phi) = -\mu^2 \phi^\dagger \phi - h(\phi^\dagger \phi)^2, \]  

(2.16)

where \( \mu^2 \) and \( h \) are parameters that define the shape of the potential, and \( D_\mu \) is the \( SU(2)_L \otimes U(1)_Y \) covariant derivative. The \( \phi(x) \) are \( SU(2)_L \) doublets of complex scalars of the form:

\[ \phi(x) = \begin{pmatrix} \phi^+(x) \\ \phi^0(x) \end{pmatrix}. \]  

(2.17)

For \( \mu^2 < 0 \), the potential \( V(\phi) \) assumes the characteristic “mexican-hat” shape, as shown in Figure 2.3. The minimum of the potential corresponds to an infinite set of points lying on the circle at the “bottom” of the potential in the complex plane \( \{\text{Re} \phi, \text{Im} \phi\} \). The system will “choose” to occupy one random point at the minimum of the potential, corresponding to the vacuum expectation value \( V(\phi_0) = -\mu^2 / h \sqrt{2} \equiv \nu / \sqrt{2} \), where \( \phi_0 \) is the complex scalar spinor that minimises the potential. The choice does not explicitly break the symmetry, which remains hidden. The phenomenon is referred to as spontaneous symmetry breaking. As a consequence of the spontaneous symmetry breaking, the system is bound to move around the chosen vacuum expectation value. Excitations around the minimum lead to phase rotations of \( \theta^i(x) \)
along points at the same minimum value $V(\phi_0)$ and excitations $H(x)$ along the curve of the potential. Taking into account the excitations around the chosen minimum, the $SU(2)_L$ spinor of the complex scalar can be written as;

$$\phi(x) = \exp \left\{ \frac{i}{2} \sigma^i \theta^i(x) \right\} \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + H(x) \end{pmatrix} (i = 1, 2, 3), \quad (2.18)$$

where $\theta^i(x)$ is the parameter of the phase $SU(2)_L$ rotation in the complex plane generated by $\sigma_1$ and $H(x)$ corresponds to the excitations along the curve of the potential $V(\phi)$.

By the imposed local gauge invariance, the potential is invariant under any phase rotation under $SU(2)_L$. Therefore, the gauge $\theta^i(x) = 0$ is a valid choice which does not lack generality. The spontaneous symmetry breaking in the BEH mechanism introduces thus only a massive excitation, associated to a newly introduced complex scalar field $H(x)$. This is conventionally referred to as the Higgs boson. By replacing the spinor in Equation 2.18 inside the lagrangian in Equation 2.16, mass terms for the $W$ and $Z$ bosons are introduced, without explicitly breaking the gauge symmetry.

According to the BEH mechanism, the masses of the $W$ and $Z$ bosons are related
by the Weinberg angle $\theta_W$, as follows:

$$M_W = M_Z \cos \theta_W = \frac{v g}{2}. \quad (2.19)$$

The BEH mechanism also introduces a mass term for the $H$ boson. This gives a mass for the $H$ boson proportional to the $\mu$ parameter of the potential in Equation 2.16:

$$M_H = \sqrt{-2\mu^2}. \quad (2.20)$$

The Higgs boson couples directly to all the massive particles of the SM. In particular, for gauge bosons, coupling to the Higgs boson are proportional to their squared masses, while couplings with fermions are linearly proportional to the values of the fermion masses.

The validity of the BEH mechanism was proven when, in 2012, a new scalar particle with mass approximately of 125 GeV was discovered by the ATLAS and CMS experiments at the LHC [19, 20, 21], and subsequently found to be consistent with the SM Higgs boson of the spontaneous symmetry breaking mechanism. The Higgs boson was initially observed in channels for the tree-level decays $H \to ZZ^* \to 4\ell$ and $H \to WW^* \to \ell\nu\ell\nu$, and the loop-decay into photons $H \to \gamma\gamma$. The reconstructed masses from the $H \to ZZ^* \to 4\ell$ and the $H \to \gamma\gamma$ decays in ATLAS and CMS, respectively, as obtained at the time of the first observation, are shown in Figure 2.4a and 2.4b, respectively.

### 2.1.3 Limitations of the SM

Despite its excellent predicting power, the SM presents several limitations, which motivate the search for signals from new BSM phenomena. In the following, some of the main motivations for BSM theories are briefly discussed.

**Hierarchy problem and naturalness**

One compelling motivation to look for BSM physics is the so-called hierarchy problem, which becomes manifest when the theory is extrapolated to high energy scales, up to the Planck mass scale $M_P = \sqrt{\frac{h c}{G}}$ equal to $2.4 \times 10^{18}$ GeV, where $G$ is the gravitational
2.1 THE STANDARD MODEL

Figure 2.4: The reconstructed mass of the Higgs boson, at the time of its first observation in 2012. On the left, the distribution of the four-lepton invariant mass from the $H \rightarrow ZZ^* \rightarrow 4\ell$ decay, as observed by ATLAS. On the right, the analogous distribution from the $H \rightarrow \gamma\gamma$ channel as measured by CMS.\cite{19, 20}

constant. The mass of the Higgs boson receives important high-order corrections from the one-loop couplings to fermion pairs, $f\bar{f}$, as shown in Figure 2.5.

Figure 2.5: Fermionic one-loop correction to the mass of Higgs boson.

These corrections are proportional to the strength $\lambda_f$ of the Higgs-fermion coupling and depend on the high energy cut-off $\Lambda_{UV}$. One can write them as:

$$\Delta M_H^2 = -\frac{|\lambda_f|^2}{8\pi^2} \Lambda_{UV}^2 + ..., \quad (2.21)$$

where the quantity $\Lambda_{UV}$ is the regulator of the theory, interpreted as the energy scale at which new physics might arise and the SM would lose full validity. Such corrections to the Higgs boson mass are not natural, in the sense that, if $\Lambda_{UV}$ approaches $M_P$, the one-loop corrections increase enormously and become around thirty orders of magnitude larger than the measured mass of the Higgs boson.
Dark Matter

Dark matter constitutes approximately one quarter of the Universe [22]. Its origin is still unknown, but several experimental and observational results point clearly to its existence. One of the historical motivations for dark matter comes from the study of the rotation curves of spiral galaxies [23]. As shown in Figure 2.6, the observed data for the rotation curve of the spiral galaxy NGC-3198 can be explained only by assuming matter abundance not just in the core of the galaxy, as expected, but also in the halo.

![Rotation curve of NGC 3198](image)

Figure 2.6: Rotation curves for the spiral galaxy NGC 3198. Observed data show agreement with the model which assumes a uniform distribution of matter across the core of the galaxy and the halo. [23]

Different models are used to characterise the nature of dark matter, and one of the most accredited models describes its constituents as Weakly Interacting Massive Particle (WIMP), yet eluding direct detection at dedicated experiments. Many BSM extensions bring about massive particles consistent with the WIMP assumption of dark matter, and therefore are good candidates to explain the unknown matter density of the universe.

Grand Unified Theories

The SM does not predict a unification of all the three fundamental interactions it describes. That is because of how the interaction couplings evolve depending on the energy scale. The *running* of the coupling constants is predicted by equations in the renormalisation group. As shown in Figure 2.7, in the SM couplings do not meet at any
2.2 Supersymmetry

Supersymmetry (SUSY) is one of the most widely studied BSM theories that extend the particle content of the SM to include new particle states. The theory postulates the existence of supersymmetric partners of the SM particles, with the same quantum numbers except the spin, which differs by 1/2 between SM and SUSY counterparts. This corresponds to considering an operator $\hat{Q}$ which transforms a fermion in a boson and viceversa [25, 26]:

$$\hat{Q} |\text{Fermion}\rangle = |\text{Boson}\rangle \quad \text{and} \quad \hat{Q} |\text{Boson}\rangle = |\text{Fermion}\rangle . \quad (2.22)$$

This has the effect of approximately doubling the particle content of the SM.

As an important consequence of the introduction of these new particles, SUSY can provide a good solution to the hierarchy problem. In the supersymmetric scenario,
in addition to the high-order corrections to the Higgs boson mass mentioned in Section 2.1.3, analogous corrections arise due to the one-loop diagrams involving the new scalar bosons, as shown in Figure 2.8.

![Figure 2.8: Bosonic one-loop correction to the mass of Higgs boson.](image)

This gives rise to contributions of the form:

\[
\Delta M^2_H = \frac{\lambda_S}{16\pi^2} \Lambda_{UV}^2 + ..., \tag{2.23}
\]

where \(\lambda_S\) is the coupling of the Higgs boson to the new scalar particle and \(\Lambda_{UV}\) is the same energy scale cut-off as before. In SUSY, each correction \(\Delta m^2_H\) from a fermionic loop as in Equation 2.21 is hence balanced by a contribution from a bosonic loop involving its supersymmetry partner, as in Equation 2.23. In the two terms, the contributions to \(\Delta m^2_H\) proportional to \(\Lambda_{UV}^2\) have opposite signs and, when added together, give an overall correction proportional to \((\lambda_S - |\lambda_f|^2)\Lambda_{UV}^2\), which cancels if the couplings of the fermion and the boson to the Higgs are such that \(\lambda_S = |\lambda_f|^2\).

In the SUSY formalism, particles are grouped into supermultiplets. Each supermultiplet contains a SM particle and its SUSY counterpart [27], referred to as supersymmetric partner. A chiral supermultiplet contains a chiral state of a spin-1/2 particle, represented by a Weyl spinor, and two real scalar particles. Therefore, both the left-handed and the right-handed states of fermions in the SM are organised into two different chiral supermultiplets in association with two spin-0 particles, their supersymmetric partners. The supersymmetric partners of leptons and quarks are assigned the same name of their SM counterpart with an "s-" (standing for "scalar") as prefix: sleptons and squarks are the supersymmetric counterparts of leptons and quarks.

SM vector bosons are included in gauge multiplets, along with their spin-1/2 Weyl fermions SUSY partners, assumed massless in order not to break the gauge symmetry. The supersymmetric partners of the SM gauge bosons are called gauginos. Specifically,
the supersymmetric partners of the gluon, $W_\mu$ and $B_\mu$ boson fields are called *gluino*, *wino* and *bino*, respectively.

In order to avoid anomalies in the theory and to give mass to the up-type and down-type fermions separately, two chiral supermultiplets for the Higgs boson are introduced, $H_u$ and $H_d$. Therefore, multiple Higgs bosons are postulated in the SUSY extension of the SM, as discussed later in Section 2.2.1.2. The supersymmetric partners of the Higgs bosons are called *higgsinos*. The two vacuum expectation values for the up-type and down-type Higgs supermultiplets, $v_u$ and $v_d$, are connected to the vacuum expectation value $v$ by the relation $v^2 = v_u^2 + v_d^2$. Often, their ratio $v_u/v_d = \tan \beta$ is considered.

### 2.2.1 The MSSM

The Minimal Supersymmetric Standard Model (MSSM) is the minimal extension of the SM to include supersymmetric partners and solve the hierarchy problem [28, 29]. It has 105 free parameters [30]. The MSSM is a grand unified theory. The running of the couplings as calculated in the MSSM is shown in Figure 2.9. Assuming all the contributions coming from particles in the MSSM, unification of couplings is achieved at energy scales of $10^{15} - 10^{16}$ GeV.

Table 2.3 shows the supermultiplets of the MSSM. For simplicity, only one generation for quarks and leptons is shown. Supermultiplets for the $SU(2)_L$ doublet for squarks-quarks and sleptons-leptons are labelled $Q$ and $L$, while those for the right-handed $U(1)$ singlet are referred to as $\bar{u}$, $\bar{d}$ and $\bar{e}$, for the up-quark, the down-quark and the electron, respectively. By convention, sparticles are labelled by the same symbols of their SM counterparts, with a tilde on top (e.g., $\tilde{e}$ for the selectron).

#### 2.2.1.1 Soft supersymmetry breaking

The supersymmetry operator $\hat{Q}$ commutes with the four-momentum operator $\hat{P}_\mu$, and thus the SM particles and their supersymmetric partner have the same masses. Nevertheless, if that were the case, the sparticles would have been already observed. Therefore, SUSY must be a *broken symmetry*, with the consequence that sparticles must
2.2 Supersymmetry

![Graph showing running of couplings in the MSSM](image)

Figure 2.9: Running of the couplings in the MSSM as a function of the energy scale, where $\alpha_1$ corresponds to the electromagnetic force coupling, $\alpha_2$ the strong force coupling and $\alpha_3$ the weak force coupling. \[24\]

<table>
<thead>
<tr>
<th>Names and symbols</th>
<th>spin-0</th>
<th>spin-1/2</th>
<th>spin-1</th>
</tr>
</thead>
<tbody>
<tr>
<td>Squarks, quarks</td>
<td>$Q$</td>
<td>$(\tilde{u}_L, \tilde{d}_L)$</td>
<td>$(u_L, d_L)$</td>
</tr>
<tr>
<td></td>
<td>$\tilde{u}$</td>
<td>$(\tilde{u}_R)$</td>
<td>$(u_R)$</td>
</tr>
<tr>
<td></td>
<td>$\tilde{d}$</td>
<td>$(\tilde{d}_R)$</td>
<td>$(d_R)$</td>
</tr>
<tr>
<td>Sleptons, leptons</td>
<td>$L$</td>
<td>$(\tilde{e}_L, \tilde{\nu}_L)$</td>
<td>$(e_L, \nu_L)$</td>
</tr>
<tr>
<td></td>
<td>$\tilde{e}$</td>
<td>$(\tilde{e}_R)$</td>
<td>$(e_R)$</td>
</tr>
<tr>
<td>Higgs, higgsinos</td>
<td>$H_u$</td>
<td>$(H^+_u, H^0_u)$</td>
<td>$(\tilde{H}^+_u, \tilde{H}^0_u)$</td>
</tr>
<tr>
<td></td>
<td>$H_d$</td>
<td>$(H^0_d, H^-_d)$</td>
<td>$(\tilde{H}^0_d, \tilde{H}^-_d)$</td>
</tr>
<tr>
<td>Gluinos, Gluons</td>
<td>-</td>
<td>$\tilde{g}$</td>
<td>$g$</td>
</tr>
<tr>
<td>Winos, W bosons</td>
<td>-</td>
<td>$\tilde{W}^\pm, \tilde{W}^0$</td>
<td>$W^\pm, W^3$</td>
</tr>
<tr>
<td>Bino, B boson</td>
<td>-</td>
<td>$\tilde{B}$</td>
<td>$B$</td>
</tr>
</tbody>
</table>

Table 2.3: List of the supermultiplets in the MSSM. Chiral and gauge multiplets are shown. In the case of leptons and quarks, only one generation is reported; two additional sets of chiral supermultiplets are to be considered to account for a total of three families of fermions and SUSY counterparts. \[27\]

have higher masses than their SM partners. However, depending on the masses of the sparticles, the coupling constants of the Higgs boson to fermions and scalars change, leading to the possible situation in which the condition $\lambda_S = |\lambda_4|^2$, necessary to solve the hierarchy problem, might not be satisfied. Therefore, if SUSY has to restore the naturalness of the corrections at the mass of the Higgs boson, it has to be softly broken.
The soft term $\mathcal{L}_{\text{soft}}$ for the symmetry breaking is added to the SUSY lagrangian $\mathcal{L}_{\text{SUSY}}$:

$$\mathcal{L} = \mathcal{L}_{\text{SUSY}} + \mathcal{L}_{\text{soft}}. \quad (2.24)$$

The soft term of the lagrangian ensures the breaking of the supersymmetry, but without inadvertently reintroducing terms proportional to $\Lambda_{\text{UV}}^2$ in the loop corrections to the Higgs mass. This condition is satisfied for masses of the sparticle of $O(\text{TeV})$.

The general idea around the soft supersymmetry breaking is that the mechanism that breaks the symmetry occurs in a hidden sector, regulated by independent symmetry groups. The effect of the soft supersymmetry breaking is “communicated” to the visible sector by mediator carriers. Various options are considered for the nature of the mediators, such as gravity [31, 32], the gauge interaction [33] and extra-dimensions [34].

The soft supersymmetry breaking introduces new parameters in the MSSM. A partial inventory of the parameters in the MSSM is shown in Table 2.4, where only the first generation of quarks and leptons have been listed.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_1$</td>
<td>Mass of bino</td>
</tr>
<tr>
<td>$M_2$</td>
<td>Mass of wino</td>
</tr>
<tr>
<td>$M_3$</td>
<td>Mass of gluino</td>
</tr>
<tr>
<td>$m_Q^2$, $m_L^2$, $m_u^2$, $m_d^2$, $m_e^2$</td>
<td>Squared masses of left-handed ($Q$ and $L$) and right-handed ($\tilde{u}$, $\tilde{d}$ and $\tilde{e}$) squarks and sleptons</td>
</tr>
<tr>
<td>$m_{H_u}^2$, $m_{H_d}^2$</td>
<td>Squared masses of the up-type and down-type Higgs chiral supermultiplets, $H_u$ and $H_d$</td>
</tr>
<tr>
<td>$\mu$, $b$</td>
<td>Mass parameter of Higgs and higgsino, $\mu$ and soft bilinear Higgs term, $b$</td>
</tr>
<tr>
<td>$a_u$, $a_d$, $a_e$</td>
<td>Trilinear couplings of the Higgs bosons to up-squark, down-squark and selectron (Figure 2.10)</td>
</tr>
</tbody>
</table>

Table 2.4: The MSSM parameters introduced by the soft SUSY breaking. Only first generation of scalar quarks and leptons are considered in this table.

### 2.2.1.2 The masses in the MSSM mass spectrum

In analogy to the SM, the electroweak symmetry breaking is applied to all the sparticles through a more complex Higgs potential which takes into account the enhanced Higgs
The consequence of the electroweak symmetry breaking is a mix of the masses of the particles to form mass eigenstates.

**Higgs bosons** When taking into account only the massive excitations in the Higgs potential around the vacuum expectation values, five degrees of freedom are left. These mix together to form five mass eigenstates of the Higgs bosons: $h$, $H^0$, $A^0$, $H^+$, and $H^-$. By convention, $h$ is the lightest neutral Higgs boson, consistent with the 125-GeV boson observed by ATLAS and CMS in 2012.

**Charginos and neutralinos** Winos, bino and higgsinos mix together to generate neutral and charged mass eigenstates. The charged higgsinos and winos mix to form two mass eigenstates called *charginos*, while the neutral higgsinos, the neutral wino and the bino mix into four mass eigenstates called *neutralinos*. Charginos and neutralinos are identified by the $\tilde{\chi}_i^\pm$ and $\tilde{\chi}_i^0$ symbols. The mass mixing is regulated by the matrix relations in Equation 2.25 and Equation 2.26, namely:

\[
\begin{pmatrix}
\tilde{\chi}_1^0 \\
\tilde{\chi}_2^0 \\
\tilde{\chi}_3^0 \\
\tilde{\chi}_4^0 
\end{pmatrix} =
\begin{pmatrix}
M_1 & 0 & -c_\beta m_Z s_W & s_\beta m_Z s_W \\
0 & M_2 & c_\beta m_Z c_W & -s_\beta m_Z s_W \\
-c_\beta m_Z s_W & c_\beta m_Z s_W & 0 & -\mu \\
s_\beta m_Z s_W & -s_\beta m_Z c_W & -\mu & 0 
\end{pmatrix}
\begin{pmatrix}
\tilde{B}^0 \\
\tilde{W}^0 \\
\tilde{H}_u^0 \\
\tilde{H}_d^0 
\end{pmatrix},
\tag{2.25}
\]

and

\[
\begin{pmatrix}
\tilde{\chi}_1^\pm \\
\tilde{\chi}_2^\pm 
\end{pmatrix} =
\begin{pmatrix}
M_2 & \sqrt{2} m_W s_\beta \\
\sqrt{2} m_W c_\beta & \mu 
\end{pmatrix}
\begin{pmatrix}
\tilde{W}^\pm \\
\tilde{H}^\pm 
\end{pmatrix},
\tag{2.26}
\]
Here $c_\beta$ and $s_\beta$ are shorthands for the $\cos \beta$ and $\sin \beta$, and similarly $c_\theta$ and $s_\theta$ are short forms for $\cos \theta_W$ and $\sin \theta_W$. Moreover, $m_W$ and $m_Z$ are the masses of the $W$ and $Z$ bosons, respectively. By convention, the indices of neutralinos and charginos are used to label particles in increasing order of their mass. Therefore, $\tilde{\chi}_1^0$ and $\tilde{\chi}_1^\pm$ are the lightest neutralino and chargino, respectively.

**Squarks and sleptons** Mixing occurs also in the case of squarks and sleptons. As seen for charginos and neutralinos, the mass-mixing are regulated by mass matrices whose terms provide corrections at the nominal mass of the sparticles. In the case of squarks and sleptons, the corrections depend on the squared value of the mass of the corresponding SM partner and specific mixing angles, thus becoming important for the heaviest quarks, bottom $b$ and top $t$, and the heaviest lepton, the tau $\tau$, but otherwise negligible. For illustration, the mass matrix for the scalar top quark can be written as:

$$m_t^2 = \begin{pmatrix} m_{Q_3}^2 + m_t^2 + \Delta_{\tilde{u}_L} & \nu (a_t \sin \beta - \mu y_t \cos \beta) \\ \nu (a_t \sin \beta - \mu^* y_t \cos \beta) & m_{\tilde{u}_3}^2 + m_t^2 + \Delta_{\tilde{u}_R} \end{pmatrix},$$

(2.27)

where $m_t^2$ is the squared mass of the top quark, $m_{Q_3}^2$ and $m_{\tilde{u}_3}^2$ are the squared masses of the left-handed and right-handed third generation supermultiplets, $\Delta_{\tilde{u}_L}$ and $\Delta_{\tilde{u}_R}$ are mass corrections coming from quartic interaction with the Higgs bosons for the left-handed and the right-handed supermultiplets, respectively. Moreover, $a_t$ and $y_t$ are the trilinear coupling and the Yukawa coupling of the top-squark to the Higgs bosons, respectively. The off-diagonal elements of the matrix give negative contributions to the mass, reducing the mass of the top-squark. For this reason, the lightest stop $\tilde{t}_1$ is the lightest squark in the MSSM. Similar, although in reduced magnitude, mixing effects occur in the case of the bottom-squark and tau-slepton.

### 2.2.1.3 R-parity

In the SM, processes which break the conservation of the baryonic and leptonic numbers $B$ and $L$ can be only described through non-renormalisable terms. Therefore, the conservation of $B$ and $L$ is assumed for any possible process involving only SM
2.2 Supersymmetry

particles. On the other hand, all the SUSY non-gauge interactions are described by the *superpotential*

\[
W_{\text{MSSM}} = \tilde{u} y_u Q H_u - \tilde{d} y_d Q H_d - \tilde{e} y_e L H_d + \mu H_u H_d, \tag{2.28}
\]

which admits extra renormalisable terms that can break the conservation of \(B\) and \(L\). These terms are added to the superpotential as

\[
W_{\Delta B/\Delta L} = \frac{1}{2} \lambda^{ijk} L_i L_j \tilde{e}_k + \lambda^{ijk'} L_i Q_j \tilde{d}_k + \lambda^{i'} L_i H_u + \frac{1}{2} \lambda^{ijk'} \tilde{u}_i \tilde{d}_j \tilde{d}_k, \tag{2.29}
\]

where \(i, j\) and \(k\) are family indices, \(\lambda^{ijk}\) and \(\lambda^{ijk'}\) are the trilinear couplings of sfermions, and \(\lambda^{i'}\) is the lepton-number-violating Higgs coupling.

At present, strong constraints exist on the possible violation of \(B\) and \(L\), for example from the search for the evidence of proton decay [35]. Therefore, the conservation of \(B\) and \(L\) is introduced in the MSSM by imposing the conservation of a new quantity called *R-parity* [29], defined as:

\[
R = (-1)^{3(B-L)+2s}, \tag{2.30}
\]

where \(s\) is the spin of the particle, and \(B\) and \(L\) are the usual quantum numbers. R-parity takes the value \(R = +1\) for all SM particles and all the Higgs bosons, and \(R = -1\) for all the sparticles in the MSSM.

The conservation of R-parity at any interaction vertex ensures that \(B\)- and \(L\)-violating terms in Equation 2.29 are cancelled.

Some important phenomenological consequences are expected in the case of R-parity conservation:

- In collisions of SM particles, for example protons into protons, sparticles can be produced only in pairs;
- In the MSSM, sparticles can only decay into an odd number of other MSSM sparticles;
- The Lightest Supersymmetric Particle (LSP) is stable.
2.2.2 Phenomenology of the MSSM at colliders

The work described in this thesis focuses on the search for chargino and neutralino production at the LHC. In the following, particular emphasis will therefore be given to the sparticle production modes mediated by electroweak interactions. A more complete description of the production of squarks and gluinos via strong interaction can be seen, for example, in Ref. [27]. In the following sections, R-parity is assumed to be always conserved.

2.2.2.1 Production channels at hadronic colliders

Despite proton-proton collisions favouring the production of squarks and gluinos, with typical processes:

\[
g g \rightarrow \tilde{g}\tilde{g}, \tilde{q}\tilde{q}^*, \quad g q \rightarrow \tilde{g}\tilde{q}, \quad q q \rightarrow \tilde{g}\tilde{g}, \tilde{q}\tilde{q}^* \quad (2.31)
\]

production channels mediated by the electroweak interaction can still arise from hadronic initial states at a lower cross-section. Some electroweak SUSY production modes are shown in Figure 2.11.

In general, the SUSY production cross-sections increase with the centre of mass energy of the collisions and decreases with the masses of the sparticles. The behaviour of the production cross-sections as a function of the masses of the sparticle is shown in Figure 2.12, where initial states are those in proton-proton collisions at \( \sqrt{s} = 13 \) TeV. As it can be seen, for masses of charginos and neutralinos of the order \( \mathcal{O}(100 \text{ GeV}) \) and masses of squarks and gluinos of \( \mathcal{O}(1 \text{ TeV}) \), cross-section for the electroweak production of gauginos and sleptons become dominant with respect to the channels for the production of squarks and gluinos.

2.2.2.2 Sparticle decays

The strength of the coupling constants at the relevant vertex, as well as the mass spectrum of the involved sparticles, determines which are the favoured decay modes of the
2.2 Supersymmetry

Figure 2.11: Channels for the production of gauginos and sleptons with hadronic initial states, with both contributions from s-channels mediated by gauge bosons and t-channels. In these diagrams, \( \tilde{C}_i^\pm = \tilde{\chi}_i^\pm \) (i=1, 2) and \( \tilde{N}_j^0 = \tilde{\chi}_j^0 \) (j=1, 2, 3, 4). [27]

Figure 2.12: Typical cross-sections for the production of sparticles at the LHC as a function of their masses. The assumed centre of mass energy is \( \sqrt{s} = 13 \) TeV.
2.2 Supersymmetry

sparticles. In the specific case of the gauginos, the allowed decay modes are:

\[ \tilde{\chi}^0_i \rightarrow Z \tilde{\chi}^0_j, \ W^\pm \tilde{\chi}^\pm_j, \ h^0 \tilde{\chi}^0_j, \ \ell \bar{\ell}, \ \nu \bar{\nu} \]  
(2.32)

and

\[ \tilde{\chi}^\pm_i \rightarrow W^\pm \tilde{\chi}^0_j, \ Z \tilde{\chi}^\pm_j, \ h^0 \tilde{\chi}^\pm_j, \ \ell \bar{\nu}, \ \nu \bar{\ell}. \]  
(2.33)

If sleptons are lighter than gauginos and higgsinos, the decays into sleptons are dominant, favouring in particular decays into the tau-slepton, the lightest slepton. Otherwise, the decays into SM gauge bosons and the lightest Higgs boson become dominant.

2.2.2.3 Electroweak SUSY simplified models

Together with the parameters of the MSSM shown in Table 2.4, parameters from the Higgs sectors such as \( \tan \beta \) and the Yukawa couplings also characterise the production and decay modes of sparticles at the LHC. From the point of view of the experiments, the large amount of free parameters is a big limitation: it would be very complicated, or in fact virtually impossible, to design a search able to test all the MSSM parameters at the same time. For this reason, a vast range of searches are performed using simplified models of the MSSM [36, 37], which correspond to specific choices of free parameters of the MSSM, in order to restrict consideration to a specific production channel of sparticles and specific decays. In this way, the MSSM parameter-space is highly reduced, leaving just a few parameters to be tested by the experiment.

The simplified models considered in this thesis are the production of the lightest chargino \( \tilde{\chi}_1^\pm \) and the next-to-lightest neutralino \( \tilde{\chi}_2^0 \). The simplified models considered assume decays into the LSP \( \tilde{\chi}_1^0 \) mediated by SM bosons. In the following, the \( \tilde{\chi}_1^\pm \) and \( \tilde{\chi}_2^0 \) are assumed to be mostly winos, while the LSP \( \tilde{\chi}_1^0 \) is assumed bino-like. Various values of \( \tan \beta \) lead to mass degenerate \( \tilde{\chi}_1^\pm \) and \( \tilde{\chi}_2^0 \), according to the mixings in Equation 2.25 and 2.26. Further details on the chosen simplified models are discussed in what follows.
2.2 Supersymmetry

**$\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ decays via $W$ and $Z$ bosons**

The first set of simplified models considered for analysis here assume $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_2^0$ decays via intermediate gauge bosons $W$ and $Z$, with 100% branching ratios for the $\tilde{\chi}_1^+ \rightarrow W^\pm \tilde{\chi}_1^0$ and $\tilde{\chi}_2^0 \rightarrow Z \tilde{\chi}_1^0$ decays, followed by further decays of the $Z$ and $W$ bosons, according to the SM branching ratios. The corresponding diagram is shown in Figure 2.13. The simplified models permit a direct test of the masses $M_1$ and $M_2$ and of the gauge couplings of the gauginos to the gauge bosons. In what follows, this family of simplified models will be referred to as the “$WZ$ models”.

![Diagram](image)

Figure 2.13: Diagram for the production of chargino and neutralino, with decays via $W$ and $Z$ bosons.

**$\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ decays via $W$ and $h$ bosons**

This other set of simplified models model assumes $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_2^0$ decays, still with a 100% branching ratio, via intermediate $W$ boson and the lightest MSSM Higgs boson $h$, assumed to be SM-like with a mass of 125 GeV. The decays $\tilde{\chi}_1^+ \rightarrow W^\pm \tilde{\chi}_1^0$ and $\tilde{\chi}_2^0 \rightarrow h \tilde{\chi}_1^0$ are followed by decays of the $W$ and the $h$ bosons, regulated by the usual SM branching ratios. The corresponding diagram of these models is shown in Figure 2.14. As in the case of decays via $WZ$ bosons, these simplified models allow the exploration of mass parameters of bino $M_1$ and winos $M_2$. Furthermore, the decay via $W$ and $h$ allows a direct test of the Higgs-higgsino-gaugino coupling. In what follows, these simplified models will be referred to as “$Wh$ models”.

![Diagram](image)
Figure 2.14: Diagram for the production of chargino and neutralino, with decays via $W$ bosons and the Higgs boson $h$.

2.3 Electroweak SUSY searches

As mentioned in Section 2.2.2.1, the production of charginos and neutralinos becomes dominant at LHC if the masses of the gauginos and sleptons are of the order $O(100 \text{ GeV})$ and squarks and gluinos are heavier than $1 \text{ TeV}$. This is suggested by several experimental results, as discussed in the following.

Searches for the top-squark $\tilde{t}_1$ have been performed by the ATLAS [38, 39] and CMS [40, 41] collaborations, using proton-proton collision data collected between the years 2009 and 2012 at $\sqrt{s} = 8 \text{ TeV}$ and between the years 2015 and 2018 at $\sqrt{s} = 13 \text{ TeV}$ at the LHC. A summary of the results from the ATLAS collaboration, as of May 2020, is shown in Figure 2.15. These searches consider the $\tilde{t}_1 \rightarrow t\tilde{\chi}^0_1$ decay, and the top-squark masses of up to $1 \text{ TeV}$ (for a massless LSP) are excluded at 95% CL.

Searches for the direct gluino production at proton-proton collisions were performed by the ATLAS [43] and CMS [44] collaborations. A summary of results from the ATLAS collaboration, also as of May 2020, is shown in Figure 2.16, for the total 2009-2018 dataset at $\sqrt{s} = 8 \text{ TeV}$ and $\sqrt{s} = 13 \text{ TeV}$. Limits are obtained assuming simplified models in which $\tilde{g} \rightarrow t\tilde{\chi}^0_1$. The searches exclude values of the mass of the gluino up to $2.2 \text{ TeV}$ for massless LSP.

In summary, the current observed exclusion limits predict heavy $\tilde{t}_1$ and gluinos, with masses greater as large as $1 \text{ TeV}$ or more. Therefore, searches for electroweak production of sparticles are strongly motivated.

Direct searches for sleptons and searches for charginos and neutralinos decaying
via sleptons have been explored by the ATLAS [45] and the CMS [46] collaborations. Current limits (as of May 2020) on the masses of sleptons are set by the searches for direct production of sleptons with data of proton-proton collision at $\sqrt{s} = 13$ TeV by the ATLAS experiment. The corresponding exclusion limits are shown in Figure 2.17. Under the assumed decay of sleptons into two leptons and two $\tilde{\chi}_1^0$, ATLAS excludes slepton masses up to approximately 700 GeV (for a massless LSP). Searches for direct production of tau-sleptons have also been performed [47, 48], providing exclusion limits on the mass of the tau-slepton up to 400 GeV.

In addition, searches for $\tilde{\chi}_1^0\tilde{\chi}_2^0$ decaying via intermediate sleptons have been performed by the ATLAS [49, 50] and the CMS [51, 52] collaborations. A summary of the results from the ATLAS collaboration, as of July 2019, prior to the work performed in this thesis, is shown in Figure 2.18, where results from analyses of data of proton-proton collisions at $\sqrt{s} = 8$ TeV and $\sqrt{s} = 13$ TeV are included. Such limits exclude masses for the $\tilde{\chi}_1^0\tilde{\chi}_2^0$ decaying via sleptons up to 1.1 TeV.
2.3 Electroweak SUSY searches

2.3.1 State of art of three-lepton searches for $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ via WZ/Wh bosons

Limits prior to work presented in this thesis on the masses of the sleptons and on the decay of $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ via sleptons motivate the focus on the searches for $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ via intermediate bosons. As a reminder, decays mediated by SM bosons are expected to become dominant for heavy sleptons. In what follows, results of searches for simplified models for the decays of $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_2^0$ via intermediate SM bosons are discussed, which set the scene to the searches described in this thesis. Emphasis is given to the channel where the SM bosons decay into light leptons (electrons and muons).

Simplified models for $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_2^0$ decaying via intermediate SM bosons had been explored by the ATLAS and CMS collaborations with 8-TeV proton-proton collision [53, 54], and with proton-proton collision data at $\sqrt{s} = 13$ TeV collected during the years 2015 and 2016 [50, 52]. The observed and expected exclusion limits shown in Figure 2.19 are for the Wh models as provided by the ATLAS collaboration with data at
2.3 Electroweak SUSY searches

Figure 2.17: Observed and expected exclusion limits on the masses of sleptons. The dataset corresponds to 139 fb$^{-1}$ data at $\sqrt{s} = 13$ TeV in proton-proton collisions at the LHC, recorded by the ATLAS experiment. Limits are set at the 95% of confidence level.\textsuperscript{45}

In Figure 2.20, the results of the search for $\tilde{\chi}^{\pm}_1\tilde{\chi}^{0}_2$ production via $WZ$ model by the ATLAS collaboration are presented. The analyses targeted proton-proton collision data at $\sqrt{s} = 13$ TeV collected during the years 2015 and 2016\textsuperscript{50}. The observed and exclusion limits are shown as a statistical combination of the three lepton and two lepton channels. The results excluded masses up to approximately $m_{\tilde{\chi}^{0}_2\tilde{\chi}^{\pm}_1} = 575$ GeV.

A similar analysis was performed by the CMS collaboration\textsuperscript{52}. The searches targeted proton-proton collision data collected at $\sqrt{s} = 13$ TeV during the years 2015 and 2016. A summary of the observed and expected exclusion limits as CMS are shown in Figure 2.21. For the $Wh$ models, channels with one lepton plus two photons, two leptons and at least three leptons in the final states were considered. For the $WZ$ model, channels with two leptons and three leptons in the final states were considered. Masses of $\tilde{\chi}^{\pm}_1\tilde{\chi}^{0}_2$ up to 500 GeV and 600 GeV were excluded, for the $Wh$ and $WZ$ models,
Figure 2.18: Observed and expected exclusion limits on the masses of charginos and neutralinos decaying via intermediate sleptons. The proton-proton collision data was recorded by the ATLAS experiment at $\sqrt{s} = 8$ TeV and $\sqrt{s} = 13$ TeV. All the limits but those for the $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ production are obtained by targeting channels with two leptons in the final states. Searches for $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ are presented as a combination of the three light lepton and two lepton channels. Limits are set at the 95% of confidence level. \[42\]

respectively.

Finally, results of searches for $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ decaying via intermediate SM bosons by the ATLAS experiment as of 2019, prior to publication of work presented in this thesis, are presented in Figure 2.22. In the plot, results for the $WZ$ and $Wh$ simplified models for the production of $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ are shown, along with a third model which assumes the production of $\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp$ decaying via two $W$ bosons.

For the $WZ$ models, the early Run-2 exclusion limits were obtained as a combination of results from the two lepton and three lepton channels. For the $Wh$ models, channels with one lepton plus two $b$-jets and one leptons plus two photons had been considered for the overall combined exclusion limits. In both cases, searches showed good sensitivity at high values of the $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ mass, although with clear room for improvement, especially close to the kinematic edges where the intermediate bosons are on-shell.
Figure 2.19: Observed and expected exclusion limits on the masses of $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_2^0$ and $\tilde{\chi}_1^0$ for the $W h$ models. The dataset corresponds to 20.3 fb$^{-1}$ data collected at $\sqrt{s} = 8$ TeV proton-proton collisions by the ATLAS experiment. Exclusion limits are obtained through a combination of channels with three light leptons, one leptonic $\tau$ and two light leptons and two leptonic $\tau$ and a light lepton. Limits are set at the 95% of confidence level. [53]

Figure 2.20: Observed and expected exclusion limits on the masses of $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_2^0$ and $\tilde{\chi}_1^0$ for the $W Z$ model. The dataset corresponds to 36.1 fb$^{-1}$ of proton-proton collision data collected at $\sqrt{s} = 13$ TeV by the ATLAS experiment. Exclusion limits are obtained by combining the three-lepton and two-lepton channels. All limits are set at the 95% of confidence level. [50]
Figure 2.21: Observed and expected exclusion limits on the masses of \( \tilde{\chi}^\pm_1 \) and \( \tilde{\chi}^0_1 \) for the \( Wh \) and the \( WZ \) models. The dataset corresponds to 35.9 fb\(^{-1}\) of proton-proton collision data collected at \( \sqrt{s} = 13 \) TeV by the CMS experiment. Exclusion limits are shown for channels with one lepton plus photons, the two leptons and at least three leptons in the final states, and the two-lepton and three-lepton channels, for the \( Wh \) and the \( WZ \) models, respectively. All limits are set at the 95% of confidence level. [52]

In this context, the three lepton channel can be particularly interesting to explore, since, as will be discussed, it can give access to regions of the parameter space not easily accessible by other channels.
Figure 2.22: Summary of observed and exclusion limits on the masses of $\tilde{\chi}^\pm_1$ and $\tilde{\chi}^0_2$ and $\tilde{\chi}^0_1$ for the $WZ$, $Wh$ and $WW$ models. The datasets correspond to 36.1 fb$^{-1}$ data collected in 13-TeV proton-proton collisions at the LHC by the ATLAS experiment. Limits are obtained by combining the three-lepton and two-lepton channels. Limits are set at the 95% of confidence level. [42]
3 THE ATLAS DETECTOR AT THE LARGE HADRON COLLIDER

This chapter describes the experimental setup of the LHC and the ATLAS detector, which have been used to collect the data used in this thesis.

3.1 The Large Hadron Collider

Over the past few decades, colliders have been used to explore new physics frontiers and perform precision measurements of known SM physics processes, playing a crucial role in the development of experimental particle physics. The LHC [55] is the most powerful circular particle accelerator ever constructed. It collides high-energy protons and, during special runs, heavy ions. It is located at the European Organization for Nuclear Research (CERN), across the French-Swiss border, near Geneva, between 75-140 m underground, on an inclined plane with respect to the ground level.

The LHC is composed of two 26.7-km rings in which particles are accelerated and made to travel along two opposite-direction circular beams. It accelerates approximately 2800 bunches of $10^{11}$ of protons per beam, with the bunches crossing every 25 ns. The accelerator is structured as a succession of arcs and straight segments, along which Radio-frequency (RF) elements are used for the acceleration, cleaning, injection and dumping of the beams. Series of dipoles and quadrupoles are used for the bending and the focusing of the beams. The 1232 cryostat dipoles used at the LHC operate in a superconducting regime, at a temperature of 1.9 K, and reach magnetic fields of 8.33 T.
So far, collisions at the LHC have been collected over two main data-taking periods, referred to as Run 1 (2010-2011, at 7 TeV; 2012, at 8 TeV) and Run 2 (2015-2018, at 13 TeV). They were interrupted by two long shutdown (LS) periods, during which planned upgrades and maintenance works were, or are being performed on the accelerators and the experiments. The first long shutdown (LS1) took place between 2012 and 2015, while the second long shutdown (LS2) is still in progress, with the machine expected to come back in full operation in 2021 for the start of the Run 3 data-taking period.

### 3.1.1 The acceleration complex

Protons used in the LHC are brought to the required energy in a sequence of accelerators, of which the LHC is the last step. In the first stage, the protons obtained from the ionisation of hydrogen atoms are accelerated by LINAC2, a linear RF acceleration system that feeds the protons into the Proton Synchrotron Booster (PSB), where they reach the energy of 1.4 GeV. In the next step, the Proton Synchrotron (PS) accelerates the protons to an energy of 25 GeV, before they are injected into the Super Proton Synchrotron (SPS), a 7-km circular accelerator that brings the protons to an energy of 450 GeV. Finally, protons are injected into the LHC where they reach the final energy of, currently, 6.5 TeV per beam. Schematics of the CERN acceleration complex is shown in Figure 3.1.

### 3.1.2 The LHC parameters

Together with its centre of mass energy, the luminosity $\mathcal{L}$ is one of the parameters that describe the LHC performance. Its value is fixed by the technical characteristics of the collider. It is given by:

$$\mathcal{L} = \frac{N_1 N_2 f}{4\pi \sigma_x \sigma_y}, \quad (3.1)$$

where $N_1$ and $N_2$ are the number of particles in beams 1 and 2, respectively, $f$ is the revolution frequency, and the $\sigma_x$ and $\sigma_y$ are the horizontal and vertical widths of the two beams.
The luminosity $\mathcal{L}$ typically depends on time $t$ and is connected the production rate $R(t)$ of a given process of cross section $\sigma$ [57] as follows:

$$R(t) = \sigma \cdot \mathcal{L}(t).$$

Equation 3.2 serves as a definition of the instantaneous luminosity $\mathcal{L}(t)$. In 2018, the LHC set a record instantaneous luminosity peak of $2 \cdot 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$ [58].

### 3.1.3 The LHC detectors

Four main experiments (plus other smaller ones, not mentioned here) are located along the LHC circumference. ATLAS (A Toroidal LHC ApparatuS) [59] and CMS (Compact Muon Solenoid) [60] are general-purpose experiments whose physics programmes span a vast range of topics, from SM precision measurements to searches for BSM physics.
The LHCb (LHC-beauty) \cite{LHCb} physics programme focuses especially on measuring the properties of the B-mesons and their decays, to investigate CP violation and search for BSM physics in rare decays. ALICE (A Large Ion Collider Experiment) \cite{ALICE} is dedicated to the study of heavy ions collisions, focusing on the study of the quark-gluon plasma state of matter.

Cumulative integrated luminosity measured by the ATLAS experiment is shown in Figure 3.2 for the different years of data taking in Run 1 and Run 2. For the ATLAS experiment, luminosity measurements are obtained by the use of the Cherenkov radiation detector LUCID-2 \cite{LUCID2}. LUCID-2 is composed of two modules, located on the LHC beam pipe, at equal distance from the ATLAS detector. Each module counts sixteen photomultipliers, arranged around the beam pipe and used as event counter detectors. The photomultipliers are provided with a thin quartz window, which serves as medium for the Cherenkov radiation emission. A dedicated algorithm is used to compute the integrated luminosity as a function of the counted events \cite{Luminosity}.

![Cumulative integrated luminosity delivered to the ATLAS experiment during the data taking years in Run 1 and Run 2, as measured by the LUCID2 detector.](image-url)
3.2 The ATLAS detector

The ATLAS detector uses several techniques for the reconstruction and identification of different particles, including through fast detection and readout of signals, for rapid processing of the collision data. The granularity of sub-detectors is adequate for precise determination of event topology and the reconstruction of the key kinematic variables.

The ATLAS detector has a cylindrical symmetric geometry. The detector is 44-m long, with a height of 25 m and near-full $4\pi$ coverage. A schematic view of the detector is shown in Figure 3.3.

![Figure 3.3: A schematic view of the main components of the ATLAS detector.](image)

Each of the sub-detectors is arranged in a coaxial cylindrical geometry around the beam-pipe, in the barrel region, or “closes” the cylinder at the two ends, in the so-called end-cap regions.

Overall, in Run 2 the data recording efficiency of the ATLAS detector was of approximately 94% of the integrated luminosity delivered by the LHC. This is shown in Figure 3.4.


3.2.1 The ATLAS coordinate system and some key variables

The origin of the coordinate system used by the ATLAS experiment coincides with the collision point at the centre of the detector, with the $x$ axis pointing towards the centre of the LHC, the $y$ axis pointing upwards and the $z$ axis parallel to the beam in the anticlockwise direction. The azimuthal angle $\phi$ spans the $[0, 2\pi]$ range around the $z$ axis, while the polar angle $\theta$ is measured from the positive direction of the $z$ axis. The $xy$ plane is referred to as the transverse plane. The transverse momentum is defined as:

$$p_T = \sqrt{p_x^2 + p_y^2},$$ \hspace{1cm} \text{(3.3)}$$

where $p_x$ and $p_y$ are the components of the momentum vector along the $x$ and $y$ axes of the ATLAS reference frame. The longitudinal component of the momentum, along the beam pipe direction, is $p_z$. Rapidity is defined as:

$$y = \frac{1}{2} \ln \left( \frac{E + p_z}{E - p_z} \right).$$ \hspace{1cm} \text{(3.4)}$$

Rapidity differences $\Delta y$ are Lorentz-invariant. For ultra-relativistic particles ($E \gg m$), such as it is usually the case for particles produced in LHC collisions, rapidity is well
approximated by the *pseudo-rapidity*,

\[ \eta = -\ln\left(\tan\frac{\theta}{2}\right), \]  

(3.5)

which for massless particles maintains the Lorentz-invariant properties of the rapidity.

Sometimes the angular distance between reconstructed objects is used, defined as

\[ \Delta R = \sqrt{(\Delta \eta)^2 + (\Delta \phi)^2}. \]  

(3.6)

Fundamental collisions occur within partons which compose the protons, as will be further discussed in Section 4.2. Therefore, the actual total energy at which the collisions occur is unknown. Nevertheless, conservation of momentum can be applied to the transverse momentum components of detected objects. Neglecting any small \( p_T \) component in the initial state, the missing transverse momentum is thus defined as:

\[ \vec{p}_T^\text{miss} = - \sum_{i \in \text{visible}} \vec{p}_T^i, \]  

(3.7)

where the index \( i \) runs over the visible particles reconstructed in the detector. The missing transverse energy \( E_T^\text{miss} \) is the magnitude of the missing momentum vector, i.e. \( E_T^\text{miss} = |\vec{p}_T^\text{miss}| \).

### 3.2.2 The magnet system

The ATLAS magnet system plays a crucial role in the detection of charged particles. It is composed of four superconducting magnets and, like the detector, has a cylindrical geometry. The system is 26-m long and has a diameter of 22 m. A solenoid provides a longitudinal magnetic field of up to 2 T in the inner detector volume. Additionally, a system of toroids spans the region occupied by the muon spectrometer, one in the barrel (\(|\eta| < 1.4\)) and two in the end-cap (1.6 < \(|\eta| < 2.7\)). The barrel and end-cap toroids provide a magnetic field of approximately 0.5 T and 1 T, respectively, while in the transition region (1.4 < \(|\eta| < 1.6\)) the magnetic field is a combination of the fields coming from the barrel and the end-cap toroids. A schematic representation of the ATLAS magnetic system is shown in Figure 3.5.
3.2.3 The Inner Detector

The innermost part of the ATLAS detector is occupied by the Inner Detector (ID), whose function is to reconstruct tracks of charged particles inside the solenoidal magnetic field. The ID is composed by three different parts. Just outside the beam-pipe, three layers of pixel detectors allow the fast reconstruction of vertices and tracks. The pixel detector is followed by the Semiconductor Tracker (SCT), comprising double-layer silicon strips, and finally by the Transition Radiation Tracker (TRT), which uses straw-shaped gas detection technology for the reconstruction of charged particles trajectories, based on the electromagnetic radiation emitted by particles when transitioning between two different media of different dielectric constants. The ATLAS ID provides precise measurements of the $p_T$ of particles, for pseudorapidities covering $|\eta|<2.5$. A sketch of the ATLAS ID is shown in Figure 3.6. More details on the individual ID components are given below.

3.2.3.1 Silicon Pixel Detector

The pixel detector comprises three barrel pixel layers and three pixel disks in the end-cap, for a total of 1456 modules in the barrel and 288 in the end-cap. Each pixel has a size of approximately $50 \times 400 \mu m^2$, providing the necessary granularity to distinguish vertices and track with a resolution of $10 \times 115 \mu m^2$. During LS1, an Insertable B-Layer (IBL) was added at a radius of 3.2 cm from the beam-pipe, providing a fourth pixel layer [68], in order to improve the precision of vertex reconstruction.
3.2 The ATLAS Detector

(a) Schematic view of the inner detector of the ATLAS detector. [59]

(b) Transverse view of the ATLAS inner detector, showing the position of the barrel modules.[67]

Figure 3.6: Digital-graphic representation of the ATLAS tracker detector.
3.2.3.2 Semiconductor Tracker

The ATLAS SCT is made of 60 m$^2$ of semiconductor material, arranged into four double-sided layers of silicon strips in the barrel, comprising 2112 modules, and nine double-sided layers in the end-cap, corresponding to additional 1976 modules. The strips have a width of about 80 $\mu$m, allowing a position reconstruction of charged track with an accuracy of around 17 $\mu$m.

3.2.3.3 Transition Radiation Tracker

The TRT is the outermost component of the ATLAS ID. Unlike the pixel detector and the SCT, the TRT is a gas detector, which uses layers of 4-mm diameter straw tubes, filled with Xe(70%)CO$_2$(27%)O$_2$(3%) gas. The straw tubes are surrounded by polypropylene, so that a particle would emit transition radiation when crossing a straw tube. The emission of transition radiation can in principle be used for the discrimination of electrons from heavier particles such as pions. In the barrel, 50000 straw tubes of 144-cm diameter are arranged along the direction parallel to the beam pipe. In the end-caps, 250000 straw tubes of 39-cm diameter are arranged on a wheel structure. On its own, the TRT measures particle tracks with a resolution of approximately 130 $\mu$m.

3.2.4 The calorimetry system

The calorimeters allow the measurement of the energy of particles crossing the detector. A particle entering the calorimeters interacts with its active material. Two different calorimeters form the calorimetry system of the ATLAS detector: the Electromagnetic Calorimeter (ECal) and the Hadronic Calorimeter (HCal), with coverage up to $|\eta|<4.9$, as shown schematically in Figure 3.7. The ATLAS detector exploits two different technologies to achieve good energy resolution, one based on Liquid Argon (LAr), for the ECal barrel calorimeter and end-cap calorimeters, and a steel sampling Tile Calorimeter (TileCal) for the HCal barrel.
3.2 The ATLAS detector

3.2.4.1 The Electromagnetic Calorimeter

The region just outside the solenoid is occupied by the LAr electromagnetic calorimeter, which comprises a barrel and Electromagnetic End-cap Calorimeter (EMEC) components. It is composed by lead and LAr in a cryostat as passive-absorber material and active material, respectively. The barrel detector is divided into two parts, with a 4-mm gap at $\eta=0$, and covers a range of pseudorapidity up to $|\eta| < 1.475$. The modules in the barrel are split into three different layers, with changing segmentation, according to the the $|\eta|$ area covered, to improve resolution. Components of the calorimetry layers are arranged in towers, defined as regions in $\Delta\eta \times \Delta\phi$. A sketch of the setup of the barrel modules of the ECal is shown in Figure 3.8.

The ECal end-cap is composed by two coaxial wheels, the inner one covering $2.5 < |\eta| < 3.2$ and the outer one spanning the region $1.375 < |\eta| < 2.5$. In terms of thickness, the barrel lead-LAr calorimeter is approximately 53 cm, corresponding to 22 radiation lengths ($X_0$), while the end-cap detectors have a total thickness of approximately 63 cm ($> 24 X_0$). The ECal towers are positioned in an accordion geometry, which ensures maximal coverage of the pseudorapidity-azimuthal plane.

Finally, a pre-sampler calorimeter is used for $|\eta| < 1.8$. It consists of an active LAr
3.2.4.2 The Hadronic Calorimeter

**Tile calorimeter** The barrel part of the hadronic calorimeter is placed outside the electromagnetic calorimeter and covers a region up to $|\eta| < 1.0$. Two detectors extend the hadronic barrel calorimeter to the $0.8 < |\eta| < 1.7$ region. Across all the $\eta$ region, steel is used as passive-absorber material, while scintillating tiles play the role of the active material for the collection of energy deposits. The overall thickness of the calorimeter is 1.97 m, corresponding to 9.7 interaction lengths at $\eta = 0$. TileCal provides good granularity of $0.1 \times 0.1$ in the pseudorapidity-azimuthal plane $\Delta\eta \times \Delta\phi$.

**LAr end-cap calorimeters** The Hadronic End-cap Calorimeter (HEC) is the component at high pseudorapidity of the HCal. It comprises two wheels of LAr in a cryostat,
3.2 The ATLAS Detector

divided into a total of four layers and covering the $1.5 < |\eta| < 3.2$ region, therefore overlapping with the TileCal extended barrel, ensuring coverage by active material in the transition region between the barrel and the end-cap components of the HCal. Copper plates are used as passive-absorber material.

**LAr forward calorimeters** The Forward Calorimeter (FCal) is used to measure in the $3.1 < |\eta| < 4.9$ pseudorapidity region. It comprises three layers, which overall extend to up to 10 interaction lengths. The first layer is supported by copper plate, while the last two are modules are made in tungsten, providing optimised measurements of hadronic interactions. As for the ECal and the other end-cap components of the calorimetry system, LAr is used as active material.

**3.2.5 The Muon Spectrometer**

The Muon Spectrometer (MS) is the outermost component of the ATLAS detector. It occupies the same volume as the magnetic system. The configuration of the toroids guarantees a magnetic field which is mostly orthogonal to the direction of the muon tracks.

A schematic view of the ATLAS muon system is shown in Figure 3.9. The system is structured in chambers used in offline tracking as well as additional chambers dedicated to triggering. Chambers are arranged into three layers in the barrel region, parallel to the beam direction, and three layers in the end-cap, perpendicular to the beam-pipe.

**Precision tracking chambers**

The 1088 Monitored Drift Tubes (MDTs) in the muon spectrometer extend over the $|\eta| < 2.7$ region. They consist of gas-based drift detectors, relying on the ionisation of a pressurised gas $\text{Ar/CO}_2(93\%:7\%)$. Each tube has a diameter of 30 mm. While each of them allows precision spatial measurement with a resolution around $80 \mu m$, the drift time for the ionised electrons to reach the walls of the tube is approximately 700 ns, making the MDTs not useful for fast tracking and trigger.

In the end-cap, the higher counting rates and the consequent radiation damage requires the use of a different kind of chambers to the MDTs. Cathod Strip Cham-
bers (CSCs) are used in the first end-cap layer, providing high spatial resolution for the tracking of muon passing through the forward region, as well as adequate radiation hardness and fast timing response. The CSCs consist of double disks of multiwire proportional chambers, oriented in the radial direction, filled with Ar/CO$_2$ (80\%:20\%). Their spatial resolution of 5 mm is worse than for the MDTs, but they provide a much faster response with a drift time of approximately 20 ns.

**Trigger chambers**

Different muon chambers are specifically dedicated to triggering purposes, for the selection of events of interest containing muons. These muon detectors, which cover the $|\eta| < 2.4$ region, are required to be robust against radiation damage, to have a fast timing response (< 50 ns), although their spatial resolution can be coarser. Additionally, they provide orthogonal coordinate measurements, which can be used together with those provided by the precision tracking chambers.

In the barrel, for $|\eta| < 1.05$ the muon triggering function is assigned to a set of Resistive Plate Chambers (RPCs). These are gas detectors with a principle of opera-
tion similar to that of multiwire chambers, but using electrode plates instead of wires. They are disposed over three different layers, and are used to trigger on muons with $p_T$ between 6-35 GeV.

In the end-cap region, between $1.05 < \abs{\eta} < 2.7$, the Thin Gap Chambers (TGCs) are used. These consist of multiwire chambers similar to the ones used in the RPCs, where the distance between the electrode plates is smaller than that interposed between the wires. With this configuration, the detector works in a quasi-saturated regime, in which the ionisation avalanches started by the incident particle are multiplicatively produced inside the detector. This allows for a faster timing response, and an improved granularity with respect to the RPCs. Furthermore, the TGCs are more resilient against radiation damage in the forward region.

### 3.2.6 The trigger and data acquisition system

The LHC provides collision events at a rate of 40 MHz, impossible to handle in terms of processing time and storage capacities. Therefore, some form of online data reduction is necessary. The trigger system of the ATLAS detector has the function to decrease the event rate to around 1 kHz by rapidly rejecting events that are not interesting for the physics goals of the experiment [69]. The ATLAS trigger system is composed of two levels [70]. The Level-1 (L1) is a hardware-based trigger, while the subsequent level is a software-based trigger, known as the High-Level Trigger (HLT). A sketch of the ATLAS Trigger and Data Acquisition (TDAQ) architecture, is shown in Figure 3.10.

#### 3.2.6.1 The Level-1 trigger

The TDAQ L1 permits a first, fast selection of the events. It implements two hardware-based algorithms, L1Calo and L1Muon, which use information from the calorimeter system and the muon chambers, respectively. The L1 sends information to the Central Trigger Processor (CTP), which manages the handling of data from the the L1 to the HLT.

During the data taking, the data acquisition system records the hits from the ATLAS sub-detectors, starting the L1 algorithms. At an event rate of 40 MHz, there is not
3.2 The ATLAS detector

sufficient time to reconstruct physics objects. Trigger objects are generated from fast, coarse energy clusters in the calorimeters and from hits in the MS. The L1Calo sets energy thresholds in the calorimeters, while the L1Muon applies a selection based on information coming from the RPCs and the TGCs. In the case of L1Calo, calorimeter towers are used to apply energy thresholds, according to the chosen trigger selection in a given $|\eta|$ region. The clusters passing the energy thresholds are used to define so-called Region of Interest (RoI). The RoI are used to identify $\Delta\eta \times \Delta\phi$ L1 seeds, used by the HLT as targeted regions where to reconstruct physics object and apply the software-based trigger selection. Similarly, the L1Muon algorithm selects trigger objects from MS hits, and for which $p_T$ is above the required threshold. Also in this case, RoIs are defined for muon triggers.

The calorimeter towers and muon segments are then passed to so-called L1Topo,
which applies a more precise reconstruction algorithm to extract topological and kinematic variables such as the missing transverse energy. Finally, the CTP takes all the L1 information and decides which events pass the first level of trigger, and which are to be permanently rejected. The events with an L1 pass are moved to the Read-Out Systems (ROS), as input information for the HLT. The event rate at the end of the L1 step is approximately 100 kHz.

### 3.2.6.2 The High-Level Trigger

After passing the L1 triggers, further skimming is applied by the HLT to bring down the event rate to 1 kHz. At this stage, information from the ID becomes available and it is used for trigger decisions. More sophisticated tower-clustering algorithm are used for precision reconstruction of energy deposits in the calorimeters. Information from the MDTs and CSCs are also added to the L1 muon candidates for precision $p_T$ reconstruction.

In the ID, two algorithms are used, the Fast Track Finder (FTF) and the precision tracking. The FTF is performed in the corresponding RoI seed defined by the L1. The precision tracking can be performed either in a corresponding L1 RoI or as full scan of the ID $|\eta|$ coverage. It relies on full reconstruction of the objects, thus including information from the calorimeters. It allows a complete and precise reconstruction of tracks and calorimetry variables such as $E_{\text{miss}}$.

Events selected by the HLT are stored in the Data Storage unit at the Tier-0, the others are permanently rejected. The final event rate at the end of the HLT is 1 kHz.

### 3.2.6.3 Trigger chains, menus and streams

The list of requirements of the L1 and HLT is summarised in the so-called trigger chain. A trigger chain is labelled according to the naming conventions as follows. The naming of a trigger chain starts with "HLT_ " and then continues with the list of the requirements of the HLT trigger, and, if applicable, it ends with the L1 seed to the HLT. For example, the trigger chain labelled $\text{HLT}_{2\text{e}17}_{\text{I}hv\text{loose}\_\text{nod}0\_\text{L12EM15VHI}}$ (one of those used in the analyses presented in this thesis) means that one is considering the HLT requirements labelled as $\text{HLT}_{2\text{e}17}_{\text{I}hv\text{loose}}$, indicating the presence of two electrons.
with $p_T > 17$ GeV, and which are required to be identified as electrons by the likelihood algorithm "lhvloose", as described in Section 4.4.2. The HLT trigger receives an L1 seed $L12EM15VHI$, indicating the presence in the L1 trigger of two electromagnetic RoI with $E_T > 15$ GeV (2EM15), with $E_T$ thresholds varying according to the $\eta$ to account for energy loss effects (V). Finally, isolation of the hadronic core ("H") and the electromagnetic core (I) of the energy deposit is required.

For each signature, different trigger chains are available, which are distinguished by the requirements on the trigger objects. In some cases, triggers may still present too high a rate at the end of the HLT selection, resulting in streams of events which would be too busy and with rates higher than the desired 1 kHz. In such cases, an appropriate prescale is applied, such that only a fraction of randomly selected events passing the trigger selection is kept. None of the triggers used in the analyses described in this thesis have been pre-scaled.

Trigger chains are used to define trigger menus, the lists of trigger selections considered during the data-taking. Within a trigger menu, specific trigger streams can be defined: main physics triggers, used for physics analysis, to which no pre-scale is applied; support triggers, used for monitoring and performance measurements; alternative triggers, which use alternative reconstruction algorithms; backup triggers, which use tighter selection than the primary triggers; and calibration triggers, used for specific detector-calibration tasks. An express stream is used for quick quality checks of the recorded data. Finally, a special debug stream is filled with events for which an HLT decision could not be reached. These are then reprocessed offline and, if successful, will be retained in the main physics stream.

In view of future high-luminosity upgrades of the LHC, upgrades of the TDAQ system of the ATLAS experiment are foreseen. I made contributions to the performance studies of a tracking-based trigger, as part of my qualification as author of the ATLAS collaboration. This task is further detailed in Appendix A,
This chapter introduces the different steps of a typical analysis using ATLAS data, from simulation to reconstruction and definition of relevant physics objects, as used in the analyses described in this thesis.

4.1 Event flow in ATLAS

The ATHENA framework [71] is used to manage all the necessary software for data analysis at ATLAS. ATHENA is based on the framework GAUDI [72], developed originally for the LHCb experiment. It incorporates tools and packages used for the software components of the trigger, the simulation algorithms, and the reconstruction of physics objects.

A schematic representation of the data flow in ATHENA is shown in 4.1. As described in Section 4.2, physics processes are first generated using Monte Carlo (MC) techniques. The outputs from the generation step are provided in the HepMC format [73]. The generated physics processes are passed through a simulation of the detector, as discussed in Section 4.3. Simulated hits from the detector are then digitised and provide so-called Raw Data Objects (RDO). Section 4.4 presents the reconstruction algorithms used to produce reconstructed samples. The outputs are then provided in the so-called Analysis Object Data (AOD) format. At this point, data is ready for physics analysis.
4.2 Event generation

Proton-proton collisions at the LHC are dominated by the strong interaction and, in a “hard collision”, involve the deep inelastic scattering [74, 75] of partons inside the protons. Interacting partons can be either valence quarks, which determine the proton’s quantum numbers such as the electromagnetic charge and the baryon number, or originated from the sea of virtual quarks and gluons inside each of the protons.

The Parton Distribution Functions (PDF) describe the likelihood to find a parton with momentum fraction $x$ of the parent proton momentum and value $Q^2$ of the transferred momentum squared. PDF have been measured indirectly by H1 [76], ZEUS [77] and other experiments through measurements of the deep inelastic scattering processes [78]. For illustration, the typical shape of a proton’s PDF are shown in Figure 4.2. For the calculation of cross-sections at different energy scales, the evolution of the PDF is described by the Dokshitzer-Gribov-Lipatov-Altarelli-Parisi (DGLAP) equations, detailed in Refs [79] and [80].

Figure 4.1: Schematic representation of the data flow in the ATLAS ATHENA framework prior to physics analysis.
Figure 4.2: Proton PDF as measured by the H1 and ZEUS deep inelastic scattering experiments, at a scale of $\mu_F^2 = 10 \text{ GeV}^2$. The $xu_v$ and $xu_d$ represent the PDF of valence up-quarks and down-quarks. PDF for the gluons, $xg$, and the sea-quarks $xS = 2x(\bar{U} + \bar{D})$, are scaled down by a factor of 20. Experimental and modelling uncertainties are included. [78]

The total proton-proton interaction cross-section can be written as:

$$\sigma_{pp} = \sum_{a,b} \int_0^1 dx_a dx_b \int F_a(x_a, \mu_F) F_b(x_b, \mu_F) d\hat{\alpha}_{ab\rightarrow n}(\mu_F, \mu_R),$$  \hspace{1cm} (4.1)

where

- The factorisation scale $\mu_F$ is the regulator needed to cure the infrared divergences of the theory, which arise due to the emission of massless particles from the initial states, while the renormalisation scale $\mu_R$ is the regulator of the ultraviolet divergences of the theory;

- $F_a(x_a, \mu_F)$ and $F_b(x_b, \mu_F)$ are the PDF of the interacting partons, $a$ and $b$. They depend on the fractions of the proton momentum carried by the partons, $x_a$ and $x_b$, respectively, and on $\mu_F$;
• $\hat{\sigma}_{ab-n}(\mu_F, \mu_R)$ is the differential parton-parton cross-section, which depends on the $\mu_F$ and on $\mu_R$.

Parton-parton interactions involving the highest transferred momentum $Q^2$ are referred to as hard scattering processes. Along with the hard scattering processes, other interactions at lower transferred momentum occur as underlying events between the partons not involved in the hard scattering. In addition to scatterings occurring simultaneously to the hard scattering, pile-up events are defined as overlapping proton-proton collisions other than those originating from the hard scattering interaction. They can happen in the same or in a different bunch-crossing, either slightly before or slightly after the main collision. Simulation techniques of underlying events and pile-up events are described in Section 4.2.2.

**Hard scattering**

At LHC, gluons and quarks involved in the hard scattering typically transfer a momentum larger than the hadronisation scale. Therefore, the cross-section of the parton-parton hard scattering is computed using the perturbation theory of the interaction, and it thus depends on matrix elements.

In general, the computation of the cross-sections takes into account the Feynman diagrams of the interaction. For the results shown in this thesis, dedicated PDF sets are provided to include parton momentum distribution, namely the NNPDF set $[81, 82]$. At the Leading Order (LO) calculation, only the tree-level diagrams are included, while possible radiative corrections are included as Next-to-Leading Order (NLO) matrix elements for one additional order of the perturbation, or, if two more orders of the perturbation are considered, Next-to-Next-Leading Order (NNLO). The precision of the calculation is typically at the Next-to-Leading-Logarithm (NLL) and in some cases at the Next-Next-to-Leading-Logarithm (NNLL). The radiative corrections model Initial State Radiation (ISR) and Final State Radiation (FSR) in the parton-parton interaction. The ISR is defined as the emission of gluons by the partons prior to the hard scattering. Similarly, gluons and quarks can be emitted by the final states of the hard scattering as FSR.
Parton-shower and hadronisation

Following the hard scattering, the typical value of the exchanged momentum between particles decreases. At this stage, the perturbation theory is not able to fully describe the physics of the interactions, and specific phenomenological models characterise the phenomena as parton showers, where continuous interactions of the form \( g \rightarrow gg, g \rightarrow q\bar{q}, q \rightarrow qg \) occur in an avalanche starting from the final states of the hard scattering. Different algorithms are used to model parton-showers. These are based on Markov processes or Markov chains. A Markov chain is a stochastic method that can be used to describe the radiation of a gluon or gluon-gluon splitting at a factorisation scale \( \mu_F \) from a given initial state at higher scale \( \mu_F + d\mu_F \). Examples of parton-shower algorithms are the CKKW (Catani-Krauss-Kuhn-Webber) and the MLM (Michelangelo L. Mangano) algorithms \[83, 84\].

When the transferred momentum of interaction is close to the hadronisation scale, the remnant coloured particles start to feel the confinement of the strong interaction. At this energy scale, the phenomena are entirely described by phenomenological models. Instances of common models used in high-energy physics experiments are the cluster hadronisation \[85\] and the Lund model \[86\]. The parameters of the hadronisation models can be tuned to data. Some instances of model tuning are described in Refs. \[87\], \[88\] and \[89\].

4.2.1 The generators in ATLAS

The hard-scattering parton-parton collisions are modelled by the use of MC techniques, which makes use of the random sampling of events of the same process to extract physical properties and kinematics of the interaction products. Different generators are used in the ATLAS physics analysis. This section briefly describes the main features of those used to extract results presented in this thesis.

Pythia \[90\], Sherpa \[91, 92\] and Herwig \[93\] are general-purpose generators used for LO calculation of the matrix elements. The Sherpa generator calculates the cross-sections up to the NLO accuracy, and also includes proper parton-shower modelling. In order to model the hadronisation, Pythia and Herwig use the cluster hadronisation
model, whilst Sherpa uses the Lund model [86].

The MadGraph [94] generator can calculate matrix elements at LO accuracy, and up to the NLO with the aMC@NLO version. With Powheg [95], it is possible to calculate matrix elements either at LO or NLO level of accuracy. MadGraph and Powheg do not include any modelling for parton-shower and hadronisation. Therefore, they are interfaced with Pythia or Herwig for the modelling of the parton showers and the hadronisation.

The EvtGen [96] package is added to Pythia or Herwig to improve the accuracy in the determination of the parton-shower modelling, implementing physics processes which are relevant for the description of the decays of $B$ mesons.

In order to minimise statistical uncertainties for simulation of rare processes, a generation filter is often used to produce only those with specific characteristics, for instance the presence of a given number of leptons with a given threshold for their $p_T$. A filter efficiency is applied to simulated events as a weight, in order to account for the enhanced statistics.

### 4.2.2 Underlying events and pile-up

Generator like Sherpa and Pythia [97] already include underlying events in the simulation of processes, alongside the hard scattering. The methods described in previous sections are then used for the parton shower, hadronisation modelling and data tuning.

Pile-up events are generated independently and then overlaid to the hard scattering prior to reconstruction [98]. Pythia and MadGraph are used to simulate the pile-up events, accounting for the measured profile of the pile-up events in data. This is expressed as the mean number of interactions per bunch crossing $\langle \mu \rangle$. For Run-2 data, simulated samples for the ATLAS experiment were produced using three different pile-up simulations, to reflect the $\langle \mu \rangle$ distributions seen in data in different data-taking years, as shown in Figure 4.3.
4.3 ATLAS simulation and digitisation

The framework Geant4 [99] is used for the detector simulation. Taking generated events as inputs, Geant4 provides detailed simulation of the entire ATLAS detector, implementing a precise description of its full geometry, material distribution and services, as well as accurate simulations of the interaction of particle radiation with the sub-detectors.

The output of Geant4 is in the identical format as that of actual data collected with the ATLAS detector. This is a file containing byte-stream of the particle interactions with the material of the detector. Files are then processed via digitisation, which converts byte-streams into C files, referred to as RDO, which can now be processed offline for event reconstruction.

4.3.1 The ATLAS fast simulation

ATLFastII (AFII) [100] is a fast simulation of the ATLAS detector. Instead of using the full detector simulation, the AFII uses the package FastCaloSim, which simplifies the calorimeter simulation. In FastCaloSim, calorimeter cells are described by cuboids and
shower development are parametrised by just considering only three particles: electrons, photons and pions. The use of the FastCaloSim the simulation time reduces by a factor 10 with respect to the full detector simulation. Detector hits from FastCaloSim are used to reconstruct basic particle kinematics, finding distributions similar to those extracted from full simulated hits. However, some discrepancies have been found, e.g. in the $\eta$ distributions for jets, as better detailed in Ref. [100]. Therefore, the use of AFII is not recommended for all the simulations. Given the clear advantage of using AFII for the simulation of large amounts of events, as required for low cross-section processes, in this thesis, AFII has been used for the simulation of the SUSY signal samples.

4.4 Object reconstruction

Reconstruction algorithms combine detector hits to extract kinematic variables. Dedicated algorithms are used for the reconstruction of leptons, jets and missing transverse energy $E_T^{\text{miss}}$, with sophisticated procedures applied for the reconstruction of collision vertices and to "tag" jets originating from heavy flavour quarks.

4.4.1 Track and vertex reconstruction

Tracking algorithms

The New Tracking (NEWT) [101] algorithm is implemented in the Athena framework for the track reconstruction from detector hits in the ID.

There are two main algorithms used for the track reconstruction. They both use the same pattern-finding and ambiguity solving steps, but they differ by the way tracks are built in all the sub-detectors. In the case of the inside-out algorithm, the track reconstruction starts from the hits in the SCT, then by the use of Kalman filter [102] techniques, the nominal track is extrapolated and matched to hits in the TRT. Similarly, the outside-in algorithm starts the track reconstruction from hits in the TRT and extends the candidate tracks inwards to include hits from the innermost modules of the ID.

In the first step, ID hits are clustered together and combine via pattern-matching into ID track candidates. Possible ambiguities within the track candidate collection
arise from tracks sharing segments or from multiple tracks being very close. Ambiguities are solved by the use of a score-based algorithm, which favours tracks with more hits or hits on both sides of the SCT modules.

The Kalman filter, and the overall track-fitting procedure, is based on the assumption that tracks can be described as a linear dynamic system. Therefore, a linear correlation must exist between the positions of the hits in the ID and the kinematic variables that describe the kinematics and topology of the tracks. In the ATLAS reference frame, five variables are used to unequivocally describe a track:

- **impact parameter**, which measures how close the track extrapolation is to the origin of the reference system. The parameter $d_0$ is the distance measured from the origin of the axes to the closest track point, while $z_0$ is the longitudinal projection of $d_0$ along the $z$-axis;

- **angular variables**: the pseudorapidity $\eta$ and the polar angle $\phi$, defined from the point of the track the closest to the origin of the reference frame, described in Section 3.2.1;

- the curvature $q/p_T$ of a track, associated with a particle of transverse momentum $p_T$ and its electric charge $q$.

In the analyses presented in this thesis, tracks with $p_T > 500$ MeV and $|\eta| < 2.5$ are selected. At least seven hits in the silicon detectors, including SCT and pixels, are required, with no more than one missing layer in the pixel detector and no more than two in the SCT.

**Vertex reconstruction**

Reconstructed tracks are used to identify the vertices of the interactions. Reconstructed ID tracks are interpolated so that a common origin, or vertex, is found. Requirements on the number of tracks and impact parameter can be set to avoid contamination from underlying or pile-up events [103]. All the vertex candidates must have at least two tracks associated with them, and only those with $|d_0| < 2$ mm and $|\Delta z_0 \sin \theta| < 3$ mm are selected.
Among all the vertex candidates, the primary vertex is defined as the main vertex of the collision, and it is associated with the hard scattering process. The primary vertex is identified as the one whose associated tracks give the highest sum of the squared transverse momenta.

**4.4.2 Electrons**

Electrons are associated with energy deposits in the ECal matching a reconstructed track in the ID [104, 105, 106, 107].

During Run 2, electron reconstruction was based on topo-clusters identified from calorimetry towers, with a substantial energy deposit with respect to noise coming from electronic and pile-up events [108]. The topo-clusters cover a region in $\eta$ and $\phi$, variable in size, which serves as RoI for the tracking reconstruction. Tracks are then extrapolated from the second layer of the topo-cluster to the outer hit in the ID. Matched tracks are required to satisfy $|\eta| < 0.05$ and $-0.10 < q \cdot (\phi_{\text{track}} - \phi_{\text{cluster}}) < 0.05$, where $q$ is the charge of the track, and $\phi_{\text{track}}$ and $\phi_{\text{cluster}}$ are the azimuthal angles of track and cluster, respectively. Moreover, in order to include Bremsstrahlung emission, super-clusters are also built, to include secondary clusters within a window of $3 \times 5$ calorimeter towers around the primary topo-cluster. Only super-clusters with energy above 1 GeV and a matching track in the corresponding RoI with at least four hits in the SCT are considered valid electron candidates.

The same reconstruction algorithm is also used for photons, defined as ECal clusters which do not match any ID track. In ambiguous cases, for instance when a track is matched but no hits from the innermost layers of the ID are found, they are kept in both the photon and electron candidate containers. Additional requirements are then applied to solve any ambiguity in the object reconstruction. This step is made in the overlap removal procedure described below.

**Electron identification**

Not all the reconstructed electrons are indeed real electrons. It can happen that matched cluster-track objects are originated from a jet, leptonic decays of hadronic particles in
the ID, or photon-conversion processes. All these alternatives are referred to as Fake or Non-Prompt (FNP) electrons. In what follows, in order to reduce contamination from FNP electrons, dedicated identification criteria are used on reconstructed electrons, as described below.

The identification of electrons is performed using a Likelihood (LH) approach, which combines evolution properties of the electromagnetic showers in both the longitudinal and transverse directions. The final electron LH is the product of all the Probability Density Function (pdf) associated with the relevant shower quantities:

\[ L_{S/B}(x) = \prod_i P_{S/B}(x_i) , \] (4.2)

where \( x_i \) label the shower-development quantities used to calculate the pdf \( P \). The electron LH is computed for both signal real electrons and background FNP electrons, labelled S and B, respectively. The pdfs are built from simulations of \( Z \rightarrow e^+e^- \) for \( E_T > 15 \text{ GeV} \) and \( J/\Psi \rightarrow e^+e^- \) for \( E_T < 15 \text{ GeV} \). The discriminant is defined from the LH in 4.2, as the ratio between the \( L_S(x) \) and the sum \( L_S(x) + L_B(x) \).

Three operating points, or working points, are defined for the electron identification. The Loose, Medium and Tight working points apply a selection on the LH discriminant corresponding to given values of identification efficiencies. Loose corresponds to an average 93% of identification efficiency, Medium to 88% and Tight to 80%. All the working points require at least seven hits in the pixel detector and SCT, with the Medium and Tight requiring one hit in the innermost layer of the pixel detector. An additional working point, called LooseAndBLayer, uses the same discriminant value as the Loose working point, but requiring at least one hit in the IBL. Performances of the LH identification working points are shown in Figure 4.4.

**Electron isolation**

As for the identification, the use of isolation criteria suppresses contamination from FNP electrons in the final electron candidate collection. An electron satisfies the isolation requirement if the amount of energy and tracks around the nominal calorimeter cluster and track used for its identification is less than a given threshold, typically set by dedicated isolation working points.
4.4 Object Reconstruction

Figure 4.4: Performance of the working points for the LH-based identification of electrons. The upper panel shows efficiencies in data for the three working points: the Loose (blue) presents the highest efficiency with respect to the Medium (red) and Tight (tight). The lower panel shows the ratio between data and MC. Only data collected between 2015-2017 is used. Statistical and systematic uncertainties are considered. [108]

Two different variables are used for the isolation of the electrons, defined from calorimeter clusters and tracks separately. The variable $E_{\text{cone20}}$ is defined as the sum of calorimeter deposits in the ECal within a cone of size $\Delta R = 0.2$ around the core of the topo-cluster reconstructing the electron, after subtracting the energy deposit associated with the electron itself, possible energy leakage from the nominal electromagnetic shower and energy deposits given by pile-up. Similarly, a $p_{\text{varcone20}}$ is defined around the electron track as the sum of $p_T$ of tracks within a cone of $\Delta R = 0.2$ around the nominal track of the electron candidate. The vicinity of the electron track to those from other particle depends on $p_T$ of the electron candidate. For this reason, in contrast to the calorimeter clusters, the size $\Delta R$ of the cone used in the track-isolation is not fixed, but varies with the $p_T$ of the electron candidate:

$$\Delta R = \min \left( \frac{p_T}{10 \text{ GeV}}, 0.2 \right). \quad (4.3)$$
Cuts on $E_{\text{T}}^{\text{cone20}}$ and $p_{\text{T}}^{\text{varcone20}}$ define different working points for the electron isolation, as shown in Table 4.1.

<table>
<thead>
<tr>
<th>Name</th>
<th>Calo-isolation $E_{\text{T}}^{\text{cone20}} / p_{\text{T}}$</th>
<th>Track-isolation $p_{\text{T}}^{\text{varcone20}} / p_{\text{T}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>FCLoose</td>
<td>$&lt; 0.20$</td>
<td>$&lt; 0.15$</td>
</tr>
<tr>
<td>FCITight</td>
<td>$&lt; 0.06$</td>
<td>$&lt; 0.06$</td>
</tr>
</tbody>
</table>

Table 4.1: Working points for isolation of electrons used in the analyses described here. [108]

Figure 4.5 shows the efficiencies for the isolation algorithm for different choices of working points, where a fixed $\Delta R = 0.2$ for calorimeter isolation is used, while the radius of the cone for track isolation is set to $\Delta R = 0.2$, a part from the “Track $R_{\text{max}} 0.4$” working point, where a double-size cone is considered.

Figure 4.5: Performance of the working points for isolation of electrons. The upper panel shows efficiencies in data for different working points. The lower panel shows the ratio between data and MC. Only data collected between 2015-2016 is used, and only statistical uncertainties are shown. [106]
4.4.3 Muons

The reconstruction of muons is based on hits from both the MS and the ID [104, 109, 110]. Muon reconstruction algorithms run independently in the two sub-detectors, and only at a later stage the results are combined to fill the collection of muon candidates.

Hits in the middle layers of the MDTs are used to reconstruct segments via a Hough transform [111], in the cylindrical envelope around the beam-pipe. Hits from the RPCs and TGCs are then used to reconstruct the coordinates. The use of a linear $\chi^2$ fit allows the reconstruction of the track from at least two segments, by extrapolating tracks from the hits in the middle layers to the outer and inner modules of the MS.

Muon tracks from hits in the modules of the ID are reconstructed via tracking algorithms, such as the inside-out and outside-in algorithms, described in Section 4.4.1. Candidate muon tracks are then matched to tracks reconstructed in the MS.

According to the outcome of the track-MS matching, four types of muons are defined:

- **Combined muons**: reconstructed by a global fit of hits in the ID and the MS, if candidate tracks are found in both. Most of the objects are reconstructed with an outside-in approach with fits starting from the hits in the MS and extrapolate the track inward to the ID. The collection of combined muons is highly pure in real muons.

- **Segment-tagged muons**: tracks reconstructed in the ID are extrapolated to the MS through a fit. A muon is reconstructed when an extended track matches a segment in the MDTs or CSCs.

- **Calorimeter-tagged muons**: ID tracks are matched to energy deposit in the calorimeter, compatible with a low-ionising particle. The collection of calorimeter-tagged muons recovers those muons passing through non-instrumented sections of the MS, typically used for services cables and connection for the innermost sub-detector.

- **Extrapolated muons**: only tracks in the MS are used. These are extrapolated inwards to the primary vertex, taking into account possible energy loss of the
muons in the calorimeters.

**Muon identification**

Similarly to the electrons, contamination from FNP muons typically arise from leptonic decays of light mesons. For such muons, the ID tracks do not match any MS segment. Therefore, in order to suppress the contamination from FNP muons, muon candidates are required to meet identification criteria. These are based on key muon quantities, such as: the $q/p$ significance, depending on the ratio $q/p$ of the muon and on the sum in quadrature of the uncertainties on $q$ and $p$; the quantity $\rho'$, defined as the difference of the muon $p_T$ extracted from the ID and the MS separately and divided by the combined $p_T$ of the muon; and the $\chi^2$ of the global fit. Four working points are defined for muon identification:

- **Medium** muons are typically combined muons, with at least three hits in at least two layers of MDTs, at least one hit in $|\eta| < 0.1$, and $q/p$ significance <7. In the $2.5 < |\eta| < 2.7$ region, extrapolated muons are considered to cover regions non-instrumented by the ID, requiring hits in at least three MDTs or CSCs layers.

- The **Loose** working point was optimised for searches for the Higgs boson decaying in four leptons. Muons passing the Loose working point are either Medium muons, or segment-tagged and calorimeter-tagged in the region $|\eta| < 0.1$.

- Furthermore, the **Tight** muons include combined muons which pass the Medium identification, but required to have at least four hits in the MS and a $\chi^2 < 8$. Cuts on the $q/p$ significance and $\rho'$ are in place to improve the purity of real muons.

- Finally, the **HighPt** working point was optimised for searches of heavy resonances decaying to muon pairs, such as the $Z'$. It selects combined muons with $p_T$ above 100 GeV, and at least three hits in three MS stations. The use of the HighPt working point improves the muon identification efficiency by 30% for $p_T > 1.5$ TeV with respect to the other working points.

In all the above cases the MC samples $Z \rightarrow \mu^+\mu^-$ and $J/\Psi \rightarrow \mu^+\mu^-$ are used for the calibration of the identification algorithm.
Figure 4.6 shows the efficiencies for the muon identification working points, where the Tag-and-probe method is applied to target $Z \rightarrow \mu^+ \mu^-$ and $J/\Psi \rightarrow \mu^+ \mu^-$. 

![Efficiency plot for muon identification](image)

Figure 4.6: Performance of the working points for the identification of muons. Upper panel shows efficiencies in data and MC for the Medium working point. The lower panel shows ratio between data and MC. Only data collected in 2015 is used for a total of 3.2 fb$^{-1}$. Statistical and systematic uncertainties are considered. [110]

**Muon isolation**

Two algorithms are used for the isolation of the muons, in order to reduce the contamination from FNP muons. Similarly to the electrons, as described in Section 4.4.2, calorimeter-based and track-based isolation algorithms are used.

For the calorimeter-based isolation, calorimeter clusters are matched to the muon track in the ID. The energy $E_{\text{cone}20}^\tau$ is defined as the energy inside a cone of dimension $\Delta R = 0.2$ drawn around the core energy deposit of the muon, and after subtracting the energy deposit of the muon itself. For the track-based isolation, the total transverse momentum $p_{\text{varcone}20}^\tau$ inside a cone drawn around the muon track, whose size varies according to the relation in 4.3. Cuts for two different working points are shown in Table 4.2.

**4.4.4 Jets**

As already seen for electrons in Section 4.4.2, jet reconstruction is based on topological clustering [107, 112, 113]. The construction of the topo-cluster for jets considers high
energy deposits in the HCal and neighbouring cells. If a cell has energy greater than 500 MeV, it is used for a new clustering attempt as the central core of a topo-cluster. The final topo-clusters are then weighted by a Local Cluster Weight (LCW) [114], which calibrates the position of the cluster and applies a weight, accounting for the electromagnetic and hadronic development of the showers. The calibrated topo-clusters are then used as input for the jet algorithm, whose purpose is to identify which energy deposits are likely to originate from the same jet.

The AntiKt4EMTopo algorithm [115] is used as the default jet reconstruction algorithm in the ATLAS experiment. It is based on the distance between topo-clusters using the following metric:

$$d_{ij} = \min \left( \frac{1}{k_{T,i}}, \frac{1}{k_{T,j}} \right) \frac{\Delta R_{ij}}{R^2},$$

where $i$ and $j$ are the indices of the two topo-clusters, $k_{T,i}$ and $k_{T,j}$ are the transverse momenta of the $i$-th and the $j$-th topo-clusters, and $\Delta R_{ij}$ is the $\Delta R$ between the two clusters. In the rapidity-$\phi$ plane, the radius parameter $R$ corresponds to the size of the circle within the cells are clustered. In the analyses described in this thesis, the radius parameter is fixed at $R = 0.4$.

The general behaviour of the AntiKt4EMTopo algorithm is shown in the Figure 4.7. Due to the dependency on the inverse of the momenta of the topo-clusters, clusters with highest momenta are prioritised in the identification of the jets, which usually have conical shapes. For clusters with low momentum, the AntiKt4EMTopo reconstruction would give a conical jet only for isolated topo-clusters. Otherwise, if a low-momentum cluster is close to a higher momentum cluster, possible overlaps between the two are assigned to the high momentum cluster, resulting in a non-conical shape for low momentum jets.

<table>
<thead>
<tr>
<th>Name</th>
<th>calo-isolation $E_t^{\text{cone20}} / p_T$</th>
<th>track-isolation $p_t^{\text{varcone20}} / p_T$</th>
</tr>
</thead>
<tbody>
<tr>
<td>FCLoose</td>
<td>$&lt; 0.3$</td>
<td>$&lt; 0.16$</td>
</tr>
<tr>
<td>FCTight</td>
<td>$&lt; 0.15$</td>
<td>$&lt; 0.04$</td>
</tr>
</tbody>
</table>

Table 4.2: Working points for isolation of electrons used in the analyses described here. [110]
Figure 4.7: Pictorial representation of the general behaviour of the ANTIKt4EMTOPO algorithm, showing all the possible clustering configurations. Instances of clusters with high momentum and conical reconstructed shape are shown as blue and red cones. An example of isolated low-momentum clusters are represented in cyan and pink. Finally, an instance of a low-momentum cluster in proximity of a high-energy deposit is shown in magenta. [115]

Pile-up mitigation

Jets produced in underlying events and pile-up contribute to the transverse momentum distribution of jets in the analysis. The Jet Vertex Tagger (JVT) [116, 117] algorithm is exploited to suppress contribution from the pile-up jets. The JVT algorithm is based on Multi-Variate Analysis (MVA) techniques, whose inputs are a set of variables related to the topology and the kinematic of jets, to identify the jet tracks associated with the primary and secondary vertices. The output of the JVT algorithm is a MVA discriminant, which is used to distinguish between jets from hard scattering and those coming from underlying events and pile-up.

4.4.5  b-tagged jets

The main feature used to distinguish between b-jets and jets from light quarks, or light jets, is the presence of a displaced secondary vertex. In the case of b-jets, a second-
ary vertex is expected due to the decay of the $b$-hadrons, which travel a few hundred $\mu$m before decaying. The ATLAS $b$-tagging algorithms [118, 119, 120] are applied to reconstructed jets and are optimised for central jets with $|\eta| < 2.4$. Track impact parameters, secondary vertex positions and calorimeter deposits are all input variables to the $b$-tagging procedure, based on MVA techniques.

Likelihood-based taggers are used to provide a first level of discrimination. The IP2D and IP3D algorithms use the impact parameters of the jet tracks and pdfs based on distributions obtained from simulation of $b$-jets, $c$-jets and light-jets. The SV1 algorithm is used to identify secondary vertices in jets, scanning over all possible pairs of tracks in a jet and extrapolating them to a common secondary vertex via a $\chi^2$ fit. Finally, the JETFITTER algorithm extracts decay paths from the tracks in a jet using a Kalman filter [102]. The JETFITTER algorithm identifies the common direction of the decay paths, which would correspond to the direction of the parent particle.

In a subsequent step, the discriminants from the low-level likelihood-based taggers IP2D and IP3D, outputs from SV1 and JETFITTER are inputted to a higher-level MVA-based algorithm. The MV2 algorithm is a Boosted Decision Trees (BDT) algorithm trained on simulation of $t\bar{t}$ processes for the "signal" ($b$-jets) and "background" ($c$-jets and light-jets). A specific version of the MV2 algorithm is used in this thesis, namely MV2c10. In this, the background training sample is composed by the 10% of $c$-jets, while the remaining 90% is made of light-jets. As shown in Figure 4.8, the MV2 algorithm shows clear discrimination power between all the different flavour categories considered.

### 4.4.6 Taus

Specific algorithms for the reconstruction of hadronically decaying taus are used in ATLAS, while leptonically decaying taus are reconstructed as electrons or muons according to the procedures described in Section 4.4.2 and Section 4.4.3. Hadronically decaying taus leave energy deposits in the HCal. They are reconstructed from jet collections and identified by dedicated BDT algorithm, trained on signal taus from $Z \rightarrow \tau\tau$ simulated samples and light jet background from $Z+\text{jets}$.

The analyses described in this thesis do not target final states with hadronically
4.4 Object reconstruction

Figure 4.8: The fraction of jets as a function of the discriminant of the MV2, namely $D_{MV2}$. Distribution for the background $c$-jets (green) and light-jets (red) and the signal $b$-jets (blue) are shown. [120]

decaying taus, therefore a full description of their identification is not reported. Details can be found in the Refs. [121], [122] and [123].

4.4.7 Missing transverse momentum

Two different terms contribute to the final value of the transverse missing energy [124]. The hard-term is obtained by summing all the energy contributions originated from the reconstructed objects in the events, such as electrons, muons, photons, jets. In addition, a soft-term is considered to account for energy releases not reconstructed as a physical object, but associated to the hard-scattering process in the primary vertex. Hard-objects entering the $E_{T}^{\text{miss}}$ calculation are required to be reconstructed and calibrated, no further criteria on the identification and isolation are required. In a general form, the $E_{T}^{\text{miss}}$ can be expressed as a algebraical sum of several terms:

$$
E_{T}^{\text{miss}} = - \sum_{\text{electrons}} E_{T}^{e} - \sum_{\text{photons}} E_{T}^{\gamma} - \sum_{\tau} E_{T}^{\tau} - \sum_{\mu} E_{T}^{\mu} - \sum_{\text{jets}} E_{T}^{\text{jet}} - \sum_{\text{unused tracks}} |\vec{p}_{T}|^{\text{track}} - \sum_{\text{unused CaloCells}} E_{T}^{\text{Cells}},
$$

(4.5)
where $E^e_T$, $E^\gamma_T$, $E^\tau_T$ are the transverse momentum extracted from calorimeter energy deposits for each electron, photon and hadronically decaying tau. Similarly, $E^{\text{jet}}_T$ is the transverse energy term calculated for each reconstructed jet. The term $E^\mu_T$ is the total transverse energy of the each muon, calculated as sum of the $p_T$ measured in the MS and the calorimeter muon energy deposit. The last two terms correspond to the scalar sum of the $p_T$ of tracks and the sum of energy deposits in the calorimeter cells, which do not match any physics object.

### 4.4.8 Overlap Removal

Overlap between objects can occur for different reasons. Energy leakage from the ECal to the HCal and semileptonic in-jet decays are among the main causes, together with double-counting of physics objects arising from ambiguity in the object assignment at reconstruction level (e.g. the mentioned ambiguities between electron and photons). Specific overlap removal procedures are applied to reconstructed objects in order to resolve double-counting by looking at the vicinity of two objects. The effect of the overlap removal is to permanently reject physics objects considered too close to other reconstructed objects. The priority order for the discarding of the objects is decided based on the specific requirements of the physics analysis. In this thesis, the following criteria are used for the overlap removal and applied in the following priority order:

- first, if an electron and a muon share an ID track, they are both discarded;
- second, if the $\Delta R$ distance between a jet and an electron is less than 0.2, the jet is discarded;
- if the same situation as above occurs between a muon and a jet with less than three tracks with $p_T > 500$ MeV, the jet is removed from the object collection;
- finally, if an electron or muon is within $\Delta R=0.4$ of a jet candidate, the electron or muon is discarded;
4.5 Event quality cuts

Events in the simulated and data samples must satisfy a list of quality requirements. These assure a good quality of the data entering the physics analysis, suppressing events from non-collision background and vetoing inactive sections of the detector. An event can fail to pass this step for several reasons:

- corrupted hits due to errors in the LAr or Tile calorimeters;
- missing information for the full event reconstruction;
- presence of reconstructed muons coming from high-energy jets crossing the full hadronic calorimeter, or from cavern background;
- energy deposit in the calorimeters due to non-collision background and reconstructed as jets.

4.6 Analysis objects

As discussed in Section 4.4, physics objects are reconstructed from hits in the detector, which in the case of MC simulation are obtained from GeANT4 simulations of the ATLAS detector.

The choice of working points for the identification and isolation algorithms, as well as kinematic requirements of physics objects, have been optimised prior my contribution to the analyses presented in this thesis. As already mentioned in Section 4.4, identification and isolation criteria serve as a first suppression of the FNP background.

There are two levels of object definition, which, as it will be described in the following sections, are used for different purposes: a looser level of selection, referred to as loose or baseline, defines a first collection of objects; while a tighter selection, referred to as tight or signal, further skims the collection of objects passing the baseline definition. The following sections contain details on the baseline and signal selections for leptons and jets.
Baseline objects

Electrons and muons  Baseline electrons and muons are required to have $z_0 \sin \theta < 0.5$ and $p_T > 10$ GeV, respectively. Electrons must be inside the $|\eta| < 2.47$ region, while muons are reconstructed inside the $|\eta| < 2.5$ region. In addition, baseline electrons must pass the LooseAndBLayer working point for identification, while muons must satisfy the Medium working point.

Jets  Baseline jets must pass the ANTIK4EMTOPO algorithm and have $p_T > 20$ GeV. To maximise the efficiency of reconstruction, their calorimeter release must lie in a region with $|\eta| < 4.5$. At this level of selection, no flavour-tagging is applied.

Overlap Removal  Baseline objects must pass the overlap removal procedure discussed earlier. This provides further cleaning from pile-up of underlying events and further suppression of FNP backgrounds.

Signal objects

Electrons and muons  For signal electrons and muons, the main additional requirements regard the lepton isolation. For electrons only, the identification requirements are tightened and signal electrons must pass the Medium working point for the identification. Signal electrons and signal muons must pass the Tight efficiency working point for the isolation, described in Sections 4.4.2 and 4.4.3, respectively. Both signal electrons and signal muons are required to have $p_T > 10$ GeV. In addition, in order to suppress contributions from FNP background, the $d_0$ significance, defined as the ratio of the impact parameter $d_0$ and its uncertainty, is required to be less than 5 for signal electrons and less than 3 for signal muons.

Jets  No additional cut on $p_T$ is applied for signal jets compared to baseline jets. They need to have $|\eta| < 2.8$ and, if their $p_T$ is greater than 120 GeV and they are within $|\eta| < 2.5$, they must pass a JVT algorithm at the Medium working point, as discussed in Section 4.4.4.
**b-tagged jets** Signal jets can be *b*-tagged if they pass the MV2c10 algorithm at the 85%-efficiency working point, as in Section 4.4.5. Furthermore, the candidate *b*-jet must be within $|\eta| < 2.5$. 
This chapter presents the analysis strategy and key selection variables for the Run-2 ATLAS searches presented in this thesis for the production of $\tilde{\chi}_1^\pm$ and $\tilde{\chi}_2^0$ decaying to three-lepton final states via SM intermediate bosons ($W$, $Z$ and $h$). A discussion on the techniques used for the statistical interpretation of the results is also presented.

5.1 Data and simulated samples

5.1.1 SUSY signals

The simplified models targeted by the analyses in this thesis have been already discussed in Section 2.2.2.3. However, as a reminder, the diagrams for the $WZ$ and the $Wh$ models are shown again in Figure 5.1, where now leptonic decays of the SM bosons are shown.

For both the $Wh$ and $WZ$ models, signal samples are examined for different values of the sparticle masses $m_{\tilde{\chi}_1^\pm} / m_{\tilde{\chi}_2^0} = m_{\tilde{\chi}_1^\pm} = m_{\tilde{\chi}_2^0}$. Each SUSY scenario is a so-called mass point in the corresponding signal grid. The MadGraph generator, interfaced with Pythia for the simulation of the parton shower, is used for the MC production of all the signal samples. Moreover, to ensure that sufficiently large samples are produced with three leptons in the final state, dedicated filters are applied to the $WZ$ and $Wh$ points at generation level.
5.1 Data and simulated samples

![Diagram showing the production of a chargino and neutralino decaying to three-lepton final states via (a) WZ and (b) Wh bosons.](image)

Figure 5.1: Diagrams for the production of chargino and neutralino, decaying to three-lepton final states via (a) WZ and (b) Wh bosons. The channel with exactly three light leptons in the final states is considered.

For the Wh benchmark points, only events where any W boson decays to a charged lepton $\ell$ ($\ell = e, \mu, \tau$) plus neutrino $\nu$, and the Higgs boson decays to $W^+W^-$, $ZZ$ or $\tau^+\tau^-$, are selected. Moreover, events are required to have at least three light leptons with truth-level $p_T > 7$ GeV. Similarly, for the WZ signal samples, only leptonic decays of the W and the Z bosons are considered, and events are required to have at least two light leptons with truth-level $p_T > 7$ GeV.

The sparticles mass ranges and corresponding typical cross sections for the considered signal samples considered in this thesis are summarised in Table 5.1.

<table>
<thead>
<tr>
<th>Model</th>
<th>$m_{\tilde{\chi}^\pm_1/\tilde{\chi}^0_2}$ [GeV]</th>
<th>$m_{\tilde{\chi}^0_1}$ [GeV]</th>
<th>Cross section [pb]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wh</td>
<td>[150,425]</td>
<td>[0,100]</td>
<td>3.274-0.065</td>
</tr>
<tr>
<td>WZ</td>
<td>[100,800]</td>
<td>[0,400]</td>
<td>13.895-0.003</td>
</tr>
</tbody>
</table>

Table 5.1: Features of the MC samples for the targeted SUSY models WZ and Wh. In the last column, the ranges of nominal cross sections for the production of $\tilde{\chi}^\pm_1$ and $\tilde{\chi}^0_2$ at given $m_{\tilde{\chi}^\pm_1/\tilde{\chi}^0_2}$.

Signal benchmark points are used as reference signal models in what follows, and are labelled by the simplified model and the chosen values of the $m_{\tilde{\chi}^\pm_1/\tilde{\chi}^0_2}$ and $m_{\tilde{\chi}^0_1}$ parameters. For instance, the label "Wh(175, 0)" indicates the benchmark signal for the Wh model with $m_{\tilde{\chi}^\pm_1/\tilde{\chi}^0_2} = 175$ GeV and $m_{\tilde{\chi}^0_1} = 0$ GeV. A similar naming convention is maintained for the WZ signal samples.
5.1.2 Trigger strategy and data quality

In order to target final states with three leptons, all events are requested to pass trigger chains which require the presence of one or more light leptons. No pre-scale is applied to the chosen trigger chains, and low $p_T$ thresholds are used for the leptons entering the trigger selection.

All analyses described in this thesis use a logical OR of available di-lepton ($ee$, $\mu\mu$ or $e\mu$) trigger chains, listed in Table 5.2. For the early Run-2 analysis discussed in Section 6.1, the single-lepton triggers listed in Table 5.3 were also used.

<table>
<thead>
<tr>
<th>Year</th>
<th>Trigger signature</th>
<th>Trigger chains</th>
</tr>
</thead>
<tbody>
<tr>
<td>2015</td>
<td>$ee$</td>
<td>HLT_2e12_lhloose_L12EM10VH</td>
</tr>
<tr>
<td></td>
<td>$\mu\mu$</td>
<td>HLT_mu12_mu8noL1</td>
</tr>
<tr>
<td></td>
<td>$e\mu$</td>
<td>HLT_e17_lhloose_mu14</td>
</tr>
<tr>
<td>2016</td>
<td>$ee$</td>
<td>HLT_2e17_lhvloose_nod0</td>
</tr>
<tr>
<td></td>
<td>$\mu\mu$</td>
<td>HLT_mu22_mu8noL1</td>
</tr>
<tr>
<td></td>
<td>$e\mu$</td>
<td>HLT_e17_lhloose_nod0_mu14</td>
</tr>
<tr>
<td>2017-2018</td>
<td>$ee$</td>
<td>HLT_2e17_lhvloose_nod0_L12EM15VHI</td>
</tr>
<tr>
<td></td>
<td></td>
<td>HLT_2e24_lhvloose_nod0_L12EM20VH</td>
</tr>
<tr>
<td></td>
<td>$\mu\mu$</td>
<td>HLT_mu22_mu8noL1</td>
</tr>
<tr>
<td></td>
<td>$e\mu$</td>
<td>HLT_e17_lhloose_nod0_mu14</td>
</tr>
</tbody>
</table>

Table 5.2: Di-lepton trigger chains used for all analyses presented in this thesis, listed by year of data taking.

<table>
<thead>
<tr>
<th>Year</th>
<th>Trigger signature</th>
<th>Trigger chains</th>
</tr>
</thead>
<tbody>
<tr>
<td>2015</td>
<td>$e$</td>
<td>HLT_e24_lhmedium_L1EM20VH</td>
</tr>
<tr>
<td></td>
<td></td>
<td>HLT_e60_lhmedium</td>
</tr>
<tr>
<td></td>
<td></td>
<td>HLT_e120_lhloose</td>
</tr>
<tr>
<td></td>
<td>$\mu$</td>
<td>HLT_mu20_i loose_L1MU15</td>
</tr>
<tr>
<td></td>
<td></td>
<td>HLT_mu40</td>
</tr>
<tr>
<td>2016</td>
<td>$e$</td>
<td>HLT_e26_lhtight_nod0_ivarloose</td>
</tr>
<tr>
<td></td>
<td></td>
<td>HLT_e60_lhmedium_nod0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>HLT_e140_lhloose_nod0</td>
</tr>
<tr>
<td></td>
<td>$\mu$</td>
<td>HLT_mu26_ivarmedium</td>
</tr>
<tr>
<td></td>
<td></td>
<td>HLT_mu50</td>
</tr>
</tbody>
</table>

Table 5.3: Single-lepton trigger chains used for the early Run-2 analysis presented in Section 6.1, listed by year of data taking.

The nomenclature of the trigger chains follows the conventions detailed in Sec-
In the case of the di-electron trigger chain for the year 2017-2018, in order to recover inefficiencies of the \texttt{HLT\_2e17\_lhvloose\_nod0\_L12EM15VHI} during some runs of the year 2017, the additional trigger chain \texttt{HLT\_2e24\_lhvloose\_nod0\_L12EM20VH} was used in a logical OR for the \textit{ee} trigger signature, as discussed in Ref. [125].

### 5.1.3 Standard Model backgrounds

Based on the presence, or not, of FNP leptons in the final states, the SM background processes for this analysis are grouped into two distinct categories:

- **Irreducible backgrounds**, with exactly three real light leptons and real $E_T^{\text{miss}}$,

- **Reducible backgrounds**, in which at least one of the final-state leptons is FNP.

Table 5.4 shows a list of the background processes considered in these searches, grouped according to the above categorisation.

<table>
<thead>
<tr>
<th>Type of background</th>
<th>Processes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Irreducible</td>
<td>$VV, VVV, t\bar{t}+V, t\bar{t}+H, VH$</td>
</tr>
<tr>
<td>Reducible</td>
<td>single-top, $t\bar{t}$, $Z$+jets, $Z+\gamma, W+W$</td>
</tr>
</tbody>
</table>

Table 5.4: SM processes which are significant background for the considered analyses, where $V= W, Z$.

Generators discussed in Section 4.2.1 are used for the generation of SM backgrounds. Unless otherwise specified, cross sections are calculated using NLO matrix elements.

**Multi-boson (VV, VVV)** [126] The production of two ($VV$) or three ($VVV$) vector bosons ($V=W, Z$), with $W$ and $Z$ decaying leptonically, constitute the main SM irreducible backgrounds in the searches. The \texttt{SHERPA-2.2.1} and \texttt{SHERPA-2.2.2} generators are used for the production of the MC samples for the di-boson and tri-boson production, respectively.

**Higgs boson processes** [127] This category includes SM processes that involve the production of a Higgs boson, such as single Higgs boson production via gluon-gluon fusion and Vector-Boson Fusion (VBF), the production of Higgs boson alongside a $t\bar{t}$
pair, or Higgs boson production in association with a $W$ or $Z$ boson. All the Higgs boson samples are generated using \textsc{Powheg}, interfaced with \textsc{Pythia} for the simulation of the parton shower development.

$t\bar{t} + V$ The production of $t\bar{t}$ is association with a vector boson ($V = W, Z$) constitutes an important background process that contributes to the irreducible SM backgrounds. These events are generated using \textsc{Pythia} interfaced with the \textsc{EvtGen} package.

**Other top processes ($t\bar{t}$, single-top)** \cite{128} \cite{129} The top quark decays virtually exclusively to a bottom quark and a $W$ boson, which can in turn decay leptonically. Processes with a $t\bar{t}$ pair or single-top production can mimic the three-lepton signature due to the mis-reconstruction as lepton of a $b$-jet or a light jet and in-jet leptonic decays leading to an FNP leptons in the final state. These other top processes are produced with the \textsc{Powheg}, interfaced with \textsc{Pythia} + \textsc{EvtGen} for parton shower simulation.

$Z$ + jets and $Z + \gamma$ \cite{130} Production of a vector boson $Z$ in association with jets or photons is one of the most important reducible SM processes at low $E_T^{\text{miss}}$. Three-lepton final states are possible when an FNP lepton arises from a mis-reconstructed jet or a photon conversion. \textsc{Sherpa} is used for the simulation of $Z$+jets and $Z + \gamma$ processes.

### 5.2 Strategy for the event selection

The event selection strategy for the searches in this thesis is based on a *cut-and-count approach*, where several requirements on specific selection variables are applied to define Signal Region (SR)s, which are enriched in the targeted SUSY signal, while SM contributions in the same region are adequately suppressed.

The definition of the SRs, and thus the choice of the cuts on the relevant selection variables, is based on the optimisation of the *expected significance* $Z_n$, which represents the level of rejection of the SM “background-only” hypothesis in favour of the “background+signal” hypothesis, as will be further discussed in Section 5.5. It is given
where the function \( \text{erf} \) is the Gaussian error function, and \( p \) represents the probability that the observed data is given by a statistical fluctuation of the background, calculated from the expected number of signal events \( s \), background events \( b \), and the total uncertainty on the background \( \sigma_b \). For the optimisation of the SRs in this thesis, a flat \( \sigma_b \) is assumed, equal to 30\% if not stated otherwise. The significance \( Z_n \) is calculated numerically using the analysis tool ROOT \[131\]. Moreover, each selection is chosen such that at least one background event is left in all the SRs, to ensure robustness of results based on sufficient statistics in the final selections.

5.2.1 Selection variables

For the SR definitions applied in these analyses, events are split into categories according to the flavour and sign combinations of leptons, as explained below.

Firstly, events are classified based on whether at least one pair of Same-Flavour Opposite-Sign (SFOS) leptons is present. The SFOS category can be used for the SR optimisation targeting both the \( WZ \) and \( Wh \) models. In what follows, selections applied to SFOS events will be referred to as SFOS SRs. For the considered signals, in events not containing a SFOS pair, it is normally possible to find a pair of Same-Flavour Same-Sign (SFSS) leptons, plus an additional lepton. In the SR selections, this third lepton is required to be of Different-Flavour Opposite-Sign (DFOS) with respect to the leptons in the SFSS pair. In this way, contributions from events containing leptonically-decaying \( Z \) bosons are suppressed. This kind of selection, referred to as the DFOS SRs in the following, is used to target signals from the \( Wh \) models. Contrary to the \( WZ \) model, in the \( Wh \) signals the decays \( h \rightarrow WW^{*} \) and \( h \rightarrow \tau^{+}\tau^{-} \) can yield two DFOS leptons, one of which can be SFSS to that obtained via leptonic decay of the \( W \) boson coming from the \( \tilde{\chi}_{1}^{\pm} \).

Once events have been divided into the SFOS and DFOS categories, other variables, described below, are used to further optimise the SRs.
Lepton $p_T$  The transverse momentum $p_T$ is already defined in Section 3.2.1. The transverse momentum of the $i$-th lepton in each event is labelled as $p_T^{\ell_i}$ ($i = 1, 2, 3$), where by convention leptons are sorted by descending values of their $p_T$. Similarly, ordered $p_T$ values of the light jets are labelled $p_T^{j_n}$ ($n = 1, ..., N$, where $N$ is the total number of jets in the event).

The scalar sums of the transverse momenta of the three leptons ($H_{lep}^T$), or of the jets ($H^T$) are also introduced:

$$H_T = \sum_{n=1}^{N} |\vec{p}_T^{j_n}|$$ (5.2)

and

$$H_{lep}^T = \sum_{i=1}^{3} |\vec{p}_T^{\ell_i}|.$$ (5.3)

$E_T^{miss}$ significance  The $E_T^{miss}$ significance [132] measures the probability that the measured missing transverse momentum is due to the presence of some invisible particles in the events. It is obtained by a likelihood-based test of the hypothesis that the sum of transverse momenta of invisible particle is equal to 0, against the hypothesis of a non-zero value. In fact, low values of the $E_T^{miss}$ significance are expected for those events where none of the involved particles decays into invisible states, whilst higher values are characteristic of events with prompt decays in invisible particles, such as the SUSY signal considered here.

Invariant and transverse masses  In the case of the SFOS selection, the invariant mass of the SFOS lepton pair is given by:

$$m_{\ell\ell} = \sqrt{(E_{\ell_1} + E_{\ell_2})^2 - (\vec{p}_{\ell_1} + \vec{p}_{\ell_2})^2}. \quad (5.4)$$

It a good discriminant for processes in which the SFOS lepton pair originates from a $Z$ boson decay. With three leptons in the events, there can be up to two lepton pairs which satisfy the SFOS requirement. The choice is made here to select as primary SFOS pair that with invariant mass closest to the nominal $Z$ boson mass.

The invariant mass of the three leptons, called $m_{\ell\ell\ell}$, is also used, given by:

$$m_{\ell\ell\ell} = \sqrt{(E_{\ell_1} + E_{\ell_2} + E_{\ell_3})^2 - (\vec{p}_{\ell_1} + \vec{p}_{\ell_2} + \vec{p}_{\ell_3})^2}. \quad (5.5)$$
The $p_T$ of the third lepton not in the primary SFOS pair and the transverse missing momentum can be combined to define a transverse mass $m_T$ as follows:

$$m_T = \sqrt{2p_T^l E_T^{miss} - 2p_T^l \cdot \vec{p}_{miss}^T}.$$  \hfill (5.6)

While often used as an estimator of the mass of the lepton’s parent, in this context $m_T$ provides good signal-to-background discrimination in the definition of the SR bins.

**Angular variables** A set of angular variables are used in the DFOS selection. These are schematically illustrated in Figure 5.2 and defined in the following:

- The $\Delta R$ distance between the DFOS lepton not in the SFSS pair (called $\ell_{DFOS}$) and the lepton in the SFSS pair (called $\ell_{near}$) closest in $\Delta \phi$ to the $\ell_{DFOS}$ itself. This is called $\Delta R_{OS, near}$.

- The $\Delta \phi$ separation between the SFSS leptons, called $\Delta \phi_{SS}$.

- The invariant mass constructed from the $\ell_{DFOS}$ and $\ell_{near}$ lepton pair, called $m_{\ell_{DFOS} + \ell_{near}}$.

![Figure 5.2: A schematic illustration of the angular variables defined for the DFOS selection. See text for more details.](image-url)
5.3 Background estimation

The understanding of the SM background entering contributions in the SRs is crucial when inspecting data in the SRs (a procedure often referred to as unblinding). An insufficient characterisation of the background processes in the SRs could in fact lead to a “fake” excess in data, in case of an underestimation of the backgrounds, or hide an actual SUSY observation, in case of a background overestimation. Depending on the irreducible or reducible nature of the background processes, different techniques are used for their estimation.

5.3.1 Data-driven estimation of FNP backgrounds

When at least a FNP lepton is present in the event, data-driven methods are used for the estimation of those backgrounds in the SRs. In what follows, the methods used in this thesis are discussed.

5.3.1.1 Fake Factor method

The basic idea of the Fake Factor method is that, for a given selection, the total number of events with FNP leptons can be correlated to the number of events with leptons passing a tight and loose object definition. For the methods used in this thesis, the tight and loose selections are identified as the baseline and signal requirements described in Section 4.6.

For illustration, it is useful to consider first the case with just one lepton in the final state, when one can write:

\[
\begin{pmatrix} N_T \\ N_L \end{pmatrix} = \begin{pmatrix} \epsilon_R & \epsilon_F \\ \bar{\epsilon}_R & \bar{\epsilon}_F \end{pmatrix} \begin{pmatrix} N_R \\ N_F \end{pmatrix},
\]

where \(N_T\) (\(N_L\)) is the number of events with one tight (loose) lepton, and \(N_F\) (\(N_R\)) is the number of events with a FNP (real) lepton. The quantities \(\epsilon_R\) and \(\epsilon_F\) express the real-lepton efficiency and the fake-lepton efficiency. These represent the probability that a prompt lepton, or a fake lepton, respectively, passes the tight selection. Similarly,
\[ \bar{\epsilon}_R = 1 - \epsilon_R \text{ and } \bar{\epsilon}_F = 1 - \epsilon_F \] give the probability that a prompt, or a fake lepton, fails to pass the tight selection.

From the relations defined in Equation 5.7, one can write the formula for the estimation of the number of events with an FNP lepton entering the selection:

\[
N_F^T = N_T - N_R^T
\]
\[
= \frac{\epsilon_F}{\bar{\epsilon}_F} (N_L - \bar{\epsilon}_R N_R)
\]
\[
= \frac{\epsilon_F}{\bar{\epsilon}_F} (N_L - N_L^R),
\]

where \(N_F^T = \epsilon_F N_F\) is the number of FNP leptons that pass the tight selection. Similarly, \(N_R^T\) represents the number of real leptons that satisfy the tight requirements. The ratio \(F = \epsilon_F/\bar{\epsilon}_F\) is referred to as Fake Factor (FF).

The simpler matrix relation in Equation 5.7 can be generalised to the more complex case with three leptons in the final state, when one needs to consider an 8×8 matrix, composed of real and fake lepton efficiencies for the eight possible combination of tight and loose leptons. These are \(TTT, LTT, TLT, TTL, LLT, LTL, TLL\) and \(LLL\).

Extending from the one-lepton case, the formula for the estimation of the number of FNP background events with up to three FNP leptons is written as:

\[
N_{FFF}^{TTT} = N_{TTT} - N_{RRR}^{TTT} = F_1 (N_{LTT} - N_{LLT}^{RRR}) + F_2 (N_{TLT} - N_{TLL}^{RRR})
\]
\[
+ F_3 (N_{TTL} - N_{TLL}^{RRR}) - F_1 F_2 (N_{LLT} - N_{LTL}^{RRR})
\]
\[
- F_2 F_3 (N_{TLL} - N_{LLL}^{RRR}) - F_1 F_3 (N_{TLT} - N_{TLL}^{RRR})
\]
\[
+ F_1 F_2 F_3 (N_{LLL} - N_{LLL}^{RRR}),
\]

where \(F_i\) is the fake factor calculated for the \(i\)-th lepton. The other terms are the number of events with different lepton combinations, where the subscripts indicate if leptons are tight (T) or loose (L), and the superscripts indicate the FNP (F) or real (R) choices of leptons. For example, \(N_{FFF}^{TTT}\) is the number of events with three FNP leptons which pass the tight selection, \(N_{RRR}^{TTT}\) is the number of events with three real leptons, the first two of which pass the tight selection and the third passes the loose selection, but not the tight one; and so on for all the other terms. Terms entering the differences in Equation 5.9 are taken from data from which yields of those MC background processes that are not estimated by the method are subtracted.
Extraction of single-lepton fake factors

The tight and loose selection used to derive the formula for the estimation of the FNP leptons are based on the baseline and signal definitions given in Section 4.6. Electrons and muons are defined as tight if they satisfy the signal definition requirements, while they are counted as loose if they pass the baseline selection, but they fail to pass the signal criteria.

The FF are extracted in a dedicated region, defined so it is highly pure in FNP background. The FF can be written as:

\[ F_i = \frac{N_{\text{data}}^T - N_{\text{others}}^T}{N_{\text{data}}^L - N_{\text{others}}^L}, \]  

where \( N_{\text{data}}^T \) and \( N_{\text{others}}^T \) are the number of events in which the \( i \)-th lepton passes the tight selection, for data or for all the MC processes that are not estimated with the same data-driven method. Once the \( F_i \) are calculated, these enter the final FNP estimation through Equation 5.9. The FF are extracted separately for electrons and muons.

5.3.1.2 Matrix Method

The Matrix Method is based on the inversion of the matrix in Equation 5.7, in order to obtain an expression of the number of FNP leptons depending on the number of tight and loose leptons. For the single-lepton case, this results gives the equation:

\[ N_T^F = \frac{\epsilon_F}{\epsilon_R - \epsilon_F} \left( N_T (\epsilon_R - 1) + \epsilon_R N_L \right), \]  

where the \( \epsilon_R \) and \( \epsilon_F \) are again the real-lepton and the fake-lepton efficiencies, respectively.

As before, the Matrix Method can be generalised to higher number of fake leptons. In the case of three leptons in the final state, a 8 × 8 matrix is inverted in order to obtain a three-lepton counterpart of Equation 5.11.

The Matrix Method uses real-lepton and fake-lepton efficiencies for the derivation of the fake contribution. The real-lepton efficiencies can be calculated via a tag-and-probe technique. This selects a tag lepton which is required to pass the tight selection,
and an additional probe lepton. The invariant mass of the two leptons is required to be within $\pm 10$ GeV of the $Z$ boson mass, to ensure that the two selected objects are prompt leptons coming from the $Z \to \ell \ell$ decay. The real-lepton efficiency is then defined as the ratio between the number of probe leptons which pass the tight selection and those passing the loose requirements.

The extraction of the fake-lepton efficiencies follows a procedure which is very similar to the one applied for the calculation of the FFs. First, a fake-enriched Control Region (CR) is defined selecting events with at least one $b$-tagged jet and two same-sign leptons, comprising a muon with $p_T > 40$ GeV and an additional lepton which passes the loose selection. The fake-lepton efficiencies are calculated using loose leptons for reference, taking the ratio of the number of probes passing the tight selection to the number of those passing the loose definition.

### 5.3.2 Normalisation of irreducible background

Approximated values of the cross sections, detector effects and pile-up effects can affect the modelling of the irreducible background. A semi-data-driven technique is used to address a possible mis-modelling. A dedicated control region, referred to as CR, is defined. Its definition must select the targeted irreducible background with high purity, while keeping possible contaminations from the targeted SUSY signals as low as possible. A CR needs to be kinematically close to the relevant SRs, and must be kept orthogonal to the SRs, meaning that no kinematic overlap can occur between the CR and any of the SRs.

Expected yields of the targeted irreducible background are normalised to the observed data, in order to assign a Normalisation Factor (NF) to it. This is achieved by a fit in the CRs, referred to as background-only fit, based on the maximisation of a likelihood, built on the expected Poisson probability distributions of the observed data and expected background. A fit parameter $\mu$ is assigned to the irreducible background. This is fixed by the fit, and corresponds to the NF. The general form and use of likelihoods in this thesis are further discussed in Section 5.5, where other important aspects of the statistical interpretation of results are also detailed.
5.3.3 Validation of the background estimation

Methods and techniques used for the estimation of the main sources of background must be validated. This is done in dedicated Validation Region (VR), whose definition needs to be tailored to relevant backgrounds but also to ensure low contamination from the targeted SUSY signals. Similarly to the CRs, all the VRs are defined to be orthogonal to the SRs, while targeting a similar kinematic phase space. A VR does not need to be dominated by a specific process, but has to include other sources of backgrounds so to mimic the relative contribution of SM processes in the SRs. For illustration, the interplay between the SRs, CRs and VRs is shown schematically in Figure 5.3, where the orthogonality between all the different regions is achieved by applying cuts on just two observables.

![Figure 5.3: Illustration of the interplay between CRs, VRs and SRs. The arrows represent the extrapolation of NFs from the CRs to the VRs and SRs. [133]](image)

5.4 Systematic uncertainties

Systematic uncertainties play an essential role in the interpretation of results and their statistical treatment. Several sources of systematic uncertainties are considered. Firstly, those linked to the calibration of physics objects and the resolution on measured kin-
5.4 Systematic uncertainties

Systematic uncertainties, such as transverse momenta and $E_T^{\text{miss}}$. Such uncertainties are mainly due to detector effects: pile-up and non-linear response from calorimeter towers are examples of possible sources of said systematic uncertainties. Another source of uncertainty is given by the theoretical predictions of SM processes, such as dependencies on the QCD scale or the choice of PDFs, or assumptions on the value of $\alpha_s$.

5.4.1 Detector-level uncertainties

Electrons and muons There are two kinds of uncertainties associated with electrons. The uncertainties on the energy scale originate from possible mis-calibrations of the ECal, while uncertainties on the energy resolution depend on the precision of calorimeter-based measurements of the energy of electrons. Electron energy scale and energy resolution uncertainties are extracted as a function of $p_T$ and $\eta$, using calibration procedures based on the analysis of $Z\rightarrow ee$ and $J/\Psi \rightarrow ee$ decays \[108\].

Similarly to the electrons, detector-level uncertainties on the energy scale and the resolution for muons are estimated through calibrations using of $Z\rightarrow \mu\mu$ and $J/\Psi \rightarrow \mu$ decays. Contribution from the MS and the ID are considered \[134\].

Jets The Jet Energy Scale (JES) systematics are extracted from the calibration of MC samples using measured values of the jet energy as measured in test beams, and including contribution for in-situ calibration of $Z$+jets, $\gamma$+jets, multi-jet processes, pile-up effects and flavour tagging \[135\]. The Jet Energy Resolution (JER) uncertainty is obtained as the correction applied to the MC jet $p_T$ distribution after applying a Gaussian smearing scale factor obtained from data to account for detector response effects \[113\].

In the jet identification, the JVT algorithm is also affected by systematic uncertainties. These are estimated from $Z(\rightarrow \mu\mu)$+jets events, and are given by differences between data and MC, using both SHERPA and POWHEG to account for possible effects due to the parton shower model \[116\].

$E_T^{\text{miss}}$ The uncertainties on the calibration of the objects entering the $E_T^{\text{miss}}$ calculation in Equation 4.5 are propagated as uncertainty on the same $E_T^{\text{miss}}$. In addition, specific systematic uncertainties are extracted for the soft terms in the $E_T^{\text{miss}}$ using data-to-
MC comparisons [124]. In particular, the $Z \rightarrow \mu\mu$ decay is used, which does not have any source of prompt $E_T^{\text{miss}}$. Disagreements between data and MC can arise in the distributions of the longitudinal and transverse projections of the soft term of Equation 4.5 onto the hard terms. These differences are taken as systematic deviations.

**Pile-up** Pile-up reweighing is based on the comparison of the pile-up profile between data and MC. Varying the distribution of the average number of interaction per bunch crossing by ±10% can introduce a systematic in the final pile-up-related event weight. The discrepancy between the nominal weight and the variation is taken as systematic uncertainty.

**b-jet tagging** Techniques for the identification of $b$- and $c$-jets are described in Section 4.4.5. Flavour-tagging algorithms carry systematic uncertainties coming from different sources, such as differences in the ratio of $b$ and $c$ quark between data and simulated events, as well as differences in the $b$-tagging algorithm efficiency between data and $t\bar{t}$ MC simulations [120].

### 5.4.2 Theory uncertainties

Theory systematic uncertainties are estimated to cover inaccuracies in the theoretical prediction of key parameters. Two main sources of theory uncertainties are considered:

**QCD scale** Variations arising from the the assumption on the normalisation scale $\mu_S$ and the factorisation scale $\mu_F$. The uncertainties propagate to the calculation of the matrix elements in the perturbation theory and, therefore, to the final value of the cross-sections. Typically, QCD scale uncertainties are estimated by varying the normalisation and factorisation scales by a factor of two up and down;

$\alpha_s$ Experimental uncertainties on the estimation of $\alpha_s$ are considered, as well as uncertainties associated with the running of the strong coupling, used to calculate $\alpha_s$ at different energy scales;
5.5 Statistical analysis of results

The statistical interpretation of the searches presented in this thesis is obtained using the H HistFitter framework [133, 136], which provides all the packages and tools necessary both to perform the fits in the CRs (for the extraction of the NFs for the irreducible backgrounds) and to test the signal hypothesis and draw exclusion contours for the targeted SUSY models.

The fits are based on likelihoods, and systematic uncertainties are treated as nuisance parameters, labelled \( \theta_j \). This is done by describing each \( j \)-th systematic uncertainty as a Gaussian centred at \( \theta_j^0 = 0 \) and with width corresponding to the systematic variation itself. The fits in the H HistFitter framework are based on the maximum likelihood approach. For instance, the case of the background-only fit, the likelihood is obtained from the Poisson probability distributions of the observed data, given the expected backgrounds, in all the CR bins. A fit parameter \( \mu \) is then assigned to the targeted irreducible background as a NF, and constrained by maximising the likelihood simultaneously in all the CRs.

5.5.1 Hypothesis test

5.5.1.1 Likelihoods and test statistics

A key point of the statistical treatment of search results is to find a way to establish if the observations are compatible with the SM-only predictions or not.

The likelihood \( L \) is again the fundamental ingredient of the procedure, generally interpreted as a measure of the compatibility of the expected number of both back-

PDFs  Experimental uncertainties on the set of PDF used in the estimation of the matrix elements for the cross-section calculations. These are obtained following specific procedures for the considered PDF set and, generally, account for experimental errors on the data used for the extrapolation of the PDF. Theoretical uncertainties on the PDF arise from the running of the \( \alpha_s \), and are estimated by varying the value of the \( \alpha_s \) and taking into account the differences in the calculated values of the PDF.
5.5 Statistical Analysis of Results

ground and chosen signal model with the observed number of events. In its general form, the likelihood can be written as the product of Poisson distributions $P$ in the considered SRs and CRs:

$$L(n, \theta^0|\mu_{\text{sig}}, b, \theta) = P_{\text{SR}} \times P_{\text{CR}} \times \prod_{j \in \text{NP}} G(\theta^0_j - \theta_j) =$$

$$= \prod_{k \in \text{SR}} P(n_k|\lambda_k(\mu_{\text{sig}}, b, \theta)) \times \prod_{i \in \text{CR}} P(n_i|\lambda_i(\mu_{\text{sig}}, b, \theta)) \times \prod_{j \in \text{NP}} G(\theta^0_j - \theta_j),$$

(5.12)

where $P_{\text{SR}} = \prod_{k \in \text{SR}} P(n_k|\lambda_k(\mu_{\text{sig}}, b, \theta))$ and $P_{\text{CR}} = \prod_{i \in \text{CR}} P(n_i|\lambda_i(\mu_{\text{sig}}, b, \theta))$ are products of Poisson distributions in the SRs and CRs, respectively, obtained from the observed data and expectation functions $\lambda_{i,k}$ which give the expected background events $b$ and the expected signal $s$ in all each region. The fit parameter $\mu_{\text{sig}}$, the so-called signal strength, is assigned to the signal yields in all the regions as a scale factor, and is constrained by the fit. The last term in the product in Equation 5.12 is the Gaussian profiling of the systematic uncertainties (altogether labeled with the symbol $\theta$).

The test of a hypothesis is done according to the Neyman-Pearson lemma, which affirms that the most powerful tool to probe a hypothesis is to define a test statistics $t_{\mu_{\text{sig}}}$, written as:

$$t_{\mu_{\text{sig}}} = -2\ln \frac{L(\mu_{\text{sig}}|\hat{\theta})}{L(\hat{\mu}_{\text{sig}}|\hat{\theta})},$$

(5.13)

where the numerator is a likelihood maximised only over the nuisance parameters $\theta$, while at the denominator the likelihood is maximised looking at both the nuisance parameters $\theta$ and the signal strength $\mu_{\text{sig}}$.

In general, the test statistics in Equation 5.13 can be used to build a pdf $f(t_{\mu}|\mu)$ of the $t_{\mu}$ under the assumption $\mu$. The integral of the pdf $f(t_{\mu}|\mu)$ over the interval $[t_{\mu,\text{obs}}, +\infty]$, where $t_{\mu,\text{obs}}$ is the observed value of the test statistics, is called p-value. This is interpreted as the probability to obtain a test statistics greater than $t_{\mu,\text{obs}}$, therefore the probability that the observed data is consistent with hypothesis defined by the choice of $\mu$, as shown in Figure 5.4. For the specific cases in this thesis, the parameter $\mu$ is replaced with the signal strength $\mu_{\text{sig}}$, in order to test both the $\mu_{\text{sig}} = 0$ (SM-only) and the $\mu_{\text{sig}} = 1$ (SM+SUSY) hypotheses.
Figure 5.4: Definition of the p-value as the probability of the data to be consistent with the null hypothesis under which the pdf of the test statistics was built. [137]

The HistFitter framework allows the test of the SM+SUSY by taking direct inputs from the simulation of the SUSY models considered (model-dependent fit) or by assigning a given value to the signal yields (conventionally +1) in the SRs entering the calculation of the test statistics (model-independent fit).

5.5.1.2 Confidence levels

As it can only state if the SM+SUSY hypothesis is rejected or not, the p-value in itself is not adequate to assess consistency between the observations and the SM-only hypothesis. A more appropriate way to test both hypotheses at the same time is by building two pdfs for the test statistics $q$ as in Equation 5.13, one for the SM-only hypothesis $b$ and one for the SM+SUSY hypothesis $b+s$. These are shown in Figure 5.5. For the pdf $f(q|b)$, one can define the probability $p_b$, corresponding to the yellow area in in Figure 5.5, obtained as integral of $f(q|b)$ over the $[-\infty, q_{obs}]$ interval, and interpreted as the probability that the observation is not consistent with the SM-only hypothesis. At the same time, for the pdf $f(q|s+b)$, the probability $p_{b+s}$, the green area in Figure 5.5, is calculated as integral of $f(q|s+b)$ on the $[q_{obs}, +\infty]$ interval, and it is interpreted as the probability that the observations are consistent with the alternative hypothesis.

The probabilities $p_b$ and $p_{b+s}$ are then used to define the Confidence Level (CL), interpreted as the grade of rejection of the SM+SUSY model, in favour of the SM hypo-
5.5 Statistical Analysis of Results

Figure 5.5: Definition of the p-values $p_{b+s}$ and $p_b$, defined under the alternative hypothesis and the null hypothesis pdf, respectively. The test-statistics $q$ corresponds to the likelihood ratio in Equation 5.13. [137]

thesis. It is expressed as:

$$CL_S = \frac{p_{b+s}}{1 - p_b}.$$  \hspace{1cm} (5.14)

For sufficiently small values of the $CL_S$ the alternative SM+SUSY is excluded and the observations are interpreted as a statistical fluctuation of the SM background. In this thesis, the convention is used that the SM+SUSY hypothesis is excluded if its calculated $CL_S$ is less than 0.05.
Results of $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ searches with three-lepton and $E_T^{\text{miss}}$ final states

In this chapter, results from the Run-2 ATLAS searches for $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ with three light leptons and missing transverse momentum in the final states to which I have made major contribution are presented. The considered dataset is the one recorded by the ATLAS experiment in proton-proton collisions at $\sqrt{s} = 13$ TeV between 2015-2018.

Firstly, results from an early Run-2 analysis of the first 36.1 fb$^{-1}$ dataset collected by ATLAS between the year 2015 and 2016 is described concisely in Section 6.1. This initial work targeted the production of $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ decaying via $Wh$, as an early analysis in preparation for those with the full Run-2 dataset. It was included in the publication reported in Ref. [138].

Results for the searches for $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ via $WZ$ and $Wh$ decays to three light leptons plus $E_T^{\text{miss}}$ using the full 139 fb$^{-1}$ Run-2 dataset are described in Section 6.2. These results were published in the ATLAS conference note in Ref. [139], made public for LHCP2020. A paper is in preparation. The results are a significant improvement on previously published results and provide an important contribution to the comprehensive searches for electroweak SUSY signals by the ATLAS collaboration using the full Run-2 dataset.

6.1 Early Run-2 analysis searching for $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ via $Wh$

The early Run-2 analysis, published in Ref. [138], searched for $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ production with decays via $Wh$ using the first 36.1 fb$^{-1}$ collected by ATLAS between 2015-2016. A num-
ber of final states were considered: with the Higgs boson decaying to $b\bar{b}$ and the $W$ decaying hadronically (full hadronic channel) or leptonically ($1\ell + bb$ channel); the one where $H \rightarrow \gamma\gamma$ and $W \rightarrow \ell\nu$ ($1\ell + \gamma\gamma$); and the fully leptonic channels, either with two same-sign leptons ($\ell^+\ell^\pm$) or three leptons ($3\ell$) in the final state.

For this paper, I was the main analyser for the $3\ell$ final state. I developed and optimised the DFOS SRs, and worked on the definition of the CR and VR for the corresponding background estimation, the estimation of the irreducible backgrounds and the statistical interpretation of the results.

### Event selection

For this analysis, a logical OR combination of di-lepton and single-lepton trigger chains was considered. The trigger chains used are those un-prescaled with lowest available $p_T$ thresholds, listed in Table 5.2 and Table 5.3. The trigger strategy and the object definitions were harmonised across the $3\ell$ and the $\ell^+\ell^\pm$ channels, which shared also the same method for the estimation of the FNP background.

All the events entering the analysis were required to have exactly three light leptons with $p_T > 25$ GeV. Events were rejected if they contained any $b$-tagged jet. A cut on $m_{\ell\ell\ell} > 20$ GeV was used to provide rejection of low-mass resonances and FNP backgrounds, allowing the reduction of the total SM background by around the 40%, while selecting approximately the 90% of the target SUSY signal. The criteria listed above were referred to as the preselection.

The SFOS and DFOS flavour-sign categories, as discussed in Section 5.2.1, were used to define the SRs. Contrary to the one described in Section 5.2.1, the early Run-2 $Wh$ analysis considered an alternative way of solving the possible ambiguity when more than one SFOS pair is present in the event. Instead of identifying the SFOS lepton pair as the one whose invariant mass is closest to the nominal $Z$ boson mass, the third lepton not in the SFOS pair was chosen to be the one with the minimum value of transverse mass $m_T^{\text{min}}$.

The SR definitions for this early analysis are listed in Table 6.1 and Table 6.2, for the DFOS and the SFOS selections, respectively.
The DFOS selection used the jet multiplicity to select events with either no light jets (SR3L-DFOS-0J) or at least one light jet (SR3L-DFOS-1Ja,b). The SRs with at least one signal jet are then distinguished according to a binning in $E_T^{\text{miss}}$. Cuts on $m_{\ell\ell_\text{DFOS}+\ell_\text{near}}$ and $\Delta R_{\text{OS},\text{near}}$, $\Delta \phi_{SS}$ are also applied to some or all of the DFOS SRs.

In the case of the SFOS selection, SRs were again defined based on their light-jet multiplicity ($N_{\text{jet}}$), selecting events with either no light jets (SR3L-SFOS-0Ja,b) or at least one light jet (SR3L-SFOS-aJ). The two zero-jet SRs are distinguished based on $E_T^{\text{miss}}$. A cut $m_T^{\text{min}} > 110$ GeV is used for all the three SRs, to suppress contribution from $WW$ background process.

### Background estimation

A CR is defined in order to normalise the expected MC yields for the WW background to the data, and find an NF to rescale contributions in the SRs. This is performed by the background-only fit procedure described in Section 5.3.2.

The CR3L-onZ-highMET region requires events to have a SFOS lepton pair with invariant mass $m_T^{\text{min}}$ in the [81.2,101.2] GeV interval. Events must also satisfy the requirement $E_T^{\text{miss}} > 80$ GeV, and preselection cuts are applied. Full list of cuts used...
for the definition of the CR3L-onZ-highMET CR is shown in Table 6.3. Contamination from the targeted SUSY signal model in the CR3L-onZ-highMET is < 1% for all the considered mass points. A NF of $1.11 \pm 0.13$ is extracted via the background-only fit. The $E_T^{\text{miss}}$ distribution after the background-only fit in the CR is shown in Figure 6.1. For this and all the other distributions in this chapter, the last bin is an overflow bin, which thus includes entries above the shown $x$-axis range.

![Figure 6.1: $E_T^{\text{miss}}$ distribution in the CR3L-onZ-highMET, after background-only fit. All systematic and statistical uncertainties are considered. [138]](image)

A VR was defined of the $WZ$ background estimation, called VR3L-offZ-HighMET, which selects events in the SFOS flavour-sign category with $m_{\text{min}}^\text{SFOS} > 20$ GeV and outside the [81.2,101.2] GeV interval. In addition, events must have $E_T^{\text{miss}} > 80$ GeV and $m_T^{\text{min}} < 110$ GeV. The latter cut ensures full orthogonality to the SRs and a very limited contamination by the targeted SUSY signal, of again the order of 1% or less for all the considered mass points. The definition of the VR3L-offZ-HighMET VR is shown in Table 6.3.

Data is compared to the SM predictions in the VR, after applying the extracted NF to the $WZ$ background. In Figure 6.2 yields of $\ell^\pm \ell^\pm$ and 3$\ell$ validation regions are shown. The yields for VR3L-offZ-HighMET region are shown in last bin. The other two bins show results for two VRs used in the $\ell^\pm \ell^\pm$ analysis, not discussed in this thesis.

The FNP backgrounds are estimated with the data-driven Matrix Method tech-
Table 6.3: List of cuts for the definition of the CR3L-onZ-HighMET CR and the VR3L-offZ-HighMET VR, used for the estimation and the validation of the WZ background in the early Run-2 3\ell Wh search. Region definitions extracted from Ref. [138].

<table>
<thead>
<tr>
<th>Variable</th>
<th>CR3L-onZ-HighMET</th>
<th>VR3L-offZ-HighMET</th>
</tr>
</thead>
<tbody>
<tr>
<td>Flavour/sign</td>
<td>SFOS</td>
<td>SFOS</td>
</tr>
<tr>
<td>$m_{\text{SFOS}}^\text{min}$ [GeV]</td>
<td>$\in [81.2, 101.2]$</td>
<td>$&gt; 20$, $\notin [81.2, 101.2]$</td>
</tr>
<tr>
<td>$E_T^{\text{miss}}$ [GeV]</td>
<td>$&gt; 80$</td>
<td>$&gt; 80$</td>
</tr>
<tr>
<td>$m_T^\text{min}$ [GeV]</td>
<td>-</td>
<td>$&lt; 110$</td>
</tr>
</tbody>
</table>

Figure 6.2: In the upper panel, yields of observed data and expected background in VR3L-offZ-HighMET (last bin), after the background-only fit. In the lower panel, the data on SM predictions ratio for all the regions are reported. Systematic and statistical uncertainties are considered. [138]

Figure 6.3
derives, discussed in Section 5.3.1.2. For completeness, validation of the data-driven estimation of the FNP backgrounds is briefly discussed in what follows, although I have not made major contribution to this part of the early Wh analysis.

A dedicated VR, named VRSS, was defined after selecting events with two same-sign leptons, providing high purity in FNP background. Comparison between data and the expected SM background in VRSS in the ee channel is shown in Figure 6.3, displaying good agreement everywhere.
6.1 Early Run-2 Analysis Searching for $\tau_1^+\tau_2^0$ via $Wh$

Systematic uncertainties

Along with the detector and theory uncertainties, described in Section 5.4.1 and Section 5.4.2, a dedicated set of systematics uncertainties were evaluated for the data-driven method used for the FNP background estimation. These uncertainties are obtained by changing the definitions of the CR used for the extraction of the real-lepton and the fake-lepton efficiencies, as further discussed in Ref. [138].

The breakdown of all the systematics in the SR is shown in Table 6.4 and Table 6.5, for the DFOS and SFOS regions, respectively. As seen in Table 6.4 and Table 6.5, the detector and theoretical systematic uncertainties are dominant in most of the regions. In a few cases, they are comparable to the statistical uncertainties on the MC samples.

Results and statistical interpretation

Results in the SRs for the early Run-2 $Wh$ $3\ell$ analysis are shown in Table 6.6 and Table 6.7. These are compatible with SM expectations within uncertainties.

Distributions of relevant variables are shown in Figure 6.4, for SR3L-DFOS-0J, SR3L-
6.1 Early Run-2 Analysis Searching for $\tilde{\chi}^{\pm}_{1} \tilde{\chi}^{0}_{2}$ via $W h$

## Table 6.4: Uncertainties in units of number of events in the DFOS SRs. Different sources of uncertainties can correlate and the total does not necessarily correspond to the squared sum of all the contributions. The category "experimental" comprises the detector systematic uncertainties and the ones related to the FNP data-driven estimation. Numbers extracted from Ref. [138].

<table>
<thead>
<tr>
<th>Uncertainty of region</th>
<th>SR3L-DFOS-0Ja</th>
<th>SR3L-DFOS-1Ja</th>
<th>SR3L-DFOS-1Jb</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total background expectation</td>
<td>2.05</td>
<td>8</td>
<td>1.7</td>
</tr>
<tr>
<td>Total background uncertainty</td>
<td>±0.98</td>
<td>±4</td>
<td>±0.7</td>
</tr>
<tr>
<td>Systematic, experimental</td>
<td>±0.8</td>
<td>±4</td>
<td>±0.5</td>
</tr>
<tr>
<td>Systematic, theoretical</td>
<td>±0.11</td>
<td>±0.25</td>
<td>±0.16</td>
</tr>
<tr>
<td>Statistical, MC samples</td>
<td>±0.6</td>
<td>±1.2</td>
<td>±0.4</td>
</tr>
<tr>
<td>Statistical, $\mu_{WZ}$</td>
<td>±0.022</td>
<td>±0.12</td>
<td>±0.06</td>
</tr>
</tbody>
</table>

## Table 6.5: Uncertainties in units of number of events in the SFOS SRs. Different sources of uncertainties can correlate and the total does not necessarily correspond to the squared sum of all the contributions. The category "experimental" comprises the detector systematic uncertainties and the ones related to the FNP data-driven estimation. Numbers extracted from Ref. [138].

<table>
<thead>
<tr>
<th>Uncertainty of region</th>
<th>SR3L-SFOS-0Ja</th>
<th>SR3L-SFOS-0Jb</th>
<th>SR3L-SFOS-1J</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total background expectation</td>
<td>3.8</td>
<td>2.37</td>
<td>11.5</td>
</tr>
<tr>
<td>Total background uncertainty</td>
<td>±1.7</td>
<td>±0.96</td>
<td>±2.6</td>
</tr>
<tr>
<td>Systematic, experimental</td>
<td>±1.7</td>
<td>±0.8</td>
<td>±2.0</td>
</tr>
<tr>
<td>Systematic, theoretical</td>
<td>±0.15</td>
<td>±0.22</td>
<td>±1.5</td>
</tr>
<tr>
<td>Statistical, MC samples</td>
<td>±0.6</td>
<td>±0.4</td>
<td>±0.9</td>
</tr>
<tr>
<td>Statistical, $\mu_{WZ}$</td>
<td>±0.3</td>
<td>±0.24</td>
<td>±0.9</td>
</tr>
</tbody>
</table>

DFOS-1Jb and SR3L-SFOS-1J regions. These plots are so-called “N-1 distributions”, in which all the SR selection cuts but the one on the considered variable are applied. The arrows show the position and “direction” of the cut on the given variable, according to the SR definitions in Table 6.1 and Table 6.2.

Observation in the SRs are interpreted to give upper limits on the cross section multiplied by branching ratio, by testing the SM-only hypothesis through the model-independent procedure, described in Section 5.5.1. The observed and expected number of signal events, namely $S_{\text{obs}}^{95}$ and $S_{\text{exp}}^{95}$, and the p-value $p_0$ are shown in Table 6.8.

The results in the SRs can also be used to extract exclusion limits on the masses of the chargino and neutralinos, $m_{\tilde{\chi}^{\pm}_{1} \tilde{\chi}^{0}_{2}}$ and $m_{\tilde{\chi}^{0}_{1}}$. Due to the limited statistics available for this early analysis, the $3\ell^\prime$ channel did not yet reach sufficient sensitivity to exclude...
any signal points. However, results were used to set expected and observed 95% CL upper limits on the cross sections for different assumption on the $m_{\tilde{\chi}_1^{\pm}/\tilde{\chi}_2^0}$, but only considering mass points with $m_{\tilde{\chi}_1^{\pm}/\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0} = 130$ GeV. These upper limits for the $3\ell$ channel are shown in Figure 6.5, together with results from all the other $Wh$ search channels considered in Ref. [138]. From this one can see how the $3\ell$ channel is sensitive to mass points along the kinematic edge $m_{\tilde{\chi}_1^{\pm}/\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0} = 130$ GeV, which is indeed more challenging for other channels.

<table>
<thead>
<tr>
<th>SR channels</th>
<th>SR3L-DFOS-0J</th>
<th>SR3L-DFOS-1Ja</th>
<th>SR3L-DFOS-1Jb</th>
</tr>
</thead>
<tbody>
<tr>
<td>Observed events</td>
<td>0</td>
<td>7</td>
<td>1</td>
</tr>
<tr>
<td>Fitted bkg events</td>
<td>2.1 ± 1.0</td>
<td>8.3 ± 3.8</td>
<td>1.7 ± 0.7</td>
</tr>
<tr>
<td>$WZ$</td>
<td>0.18 ± 0.13</td>
<td>1.01 ± 0.27</td>
<td>0.54 ± 0.16</td>
</tr>
<tr>
<td>$ZZ$</td>
<td>0.0017 ± 0.0012</td>
<td>0.06 ± 0.02</td>
<td>0.03 ± 0.01</td>
</tr>
<tr>
<td>$t\bar{t} + V$</td>
<td>0.0013 ± 0.0013</td>
<td>0.79 ± 0.29</td>
<td>0.43 ± 0.16</td>
</tr>
<tr>
<td>Tribosons</td>
<td>0.52 ± 0.28</td>
<td>0.66 ± 0.22</td>
<td>0.23 ± 0.08</td>
</tr>
<tr>
<td>Higgs SM</td>
<td>0.39 ± 0.15</td>
<td>0.1^{+0.5}_{-0.1}</td>
<td>0.05 ± 0.04</td>
</tr>
<tr>
<td>FNP events</td>
<td>1.0 ± 0.9</td>
<td>5.6 ± 3.8</td>
<td>0.4^{+0.6}_{-0.4}</td>
</tr>
</tbody>
</table>

Table 6.6: Observed data and expected yields from the relevant SM backgrounds for the region SR3L-DFOS-0J, SR3L-DFOS-1Ja and SR3L-DFOS-1Jb. The $W+Z$ NF after the background-only fit is applied. The category “Higgs MC” comprises the SM $t\bar{t}H$ production. All uncertainties are considered and symmetrised around the nominal post-fit yields, negative errors are truncated at the zero event yields. Numbers extracted from Ref. [138].

<table>
<thead>
<tr>
<th>SR channels</th>
<th>SR3L-SFOS-0Ja</th>
<th>SR3L-SFOS-0Jb</th>
<th>SR3L-SFOS-1J</th>
</tr>
</thead>
<tbody>
<tr>
<td>Observed events</td>
<td>0</td>
<td>3</td>
<td>11</td>
</tr>
<tr>
<td>Fitted bkg events</td>
<td>3.8 ± 1.7</td>
<td>2.4 ± 0.96</td>
<td>11.5 ± 2.6</td>
</tr>
<tr>
<td>$WZ$</td>
<td>2.5 ± 1.2</td>
<td>2.0 ± 0.9</td>
<td>7.4 ± 2.3</td>
</tr>
<tr>
<td>$ZZ$</td>
<td>0.10 ± 0.04</td>
<td>0.07 ± 0.02</td>
<td>0.29 ± 0.09</td>
</tr>
<tr>
<td>$t\bar{t} + V$</td>
<td>0.09 ± 0.03</td>
<td>0.02 ± 0.01</td>
<td>1.9 ± 0.5</td>
</tr>
<tr>
<td>Tribosons</td>
<td>0.57 ± 0.29</td>
<td>0.16 ± 0.08</td>
<td>1.4 ± 0.4</td>
</tr>
<tr>
<td>Higgs SM</td>
<td>0.24^{+0.25}_{-0.24}</td>
<td>0.07 ± 0.07</td>
<td>0.07 ± 0.04</td>
</tr>
<tr>
<td>FNP events</td>
<td>0.27^{+0.31}_{-0.27}</td>
<td>0.11^{+0.20}_{-0.11}</td>
<td>0.4^{+0.5}_{-0.4}</td>
</tr>
</tbody>
</table>

Table 6.7: Observed data and expected yields from the relevant SM backgrounds for the region SR3L-SFOS-0Ja, SR3L-SFOS-0Jb and SR3L-SFOS-1J. The $W+Z$ NF after the background-only fit is applied. The category “Higgs MC” comprises the SM $t\bar{t}H$ production. All uncertainties are considered and symmetrised around the nominal post-fit yields, negative errors are truncated at the zero event yields. Numbers extracted from Ref. [138].
6.1 Early Run-2 Analysis searching for $\tilde{\chi}^{\pm}_{1}/\tilde{\chi}^{0}_{2}$ via $Wh$

Figure 6.4: N-1 distributions of observed data and SM expectation for (a) the $E_T^{\text{miss}}$ in the SR3L-DFOS-0J region, (b) the $m_{\text{DFOS}}^{\ell_1+\ell_2}$ near in the SR3L-DFOS-1Jb region and (c) the $m_{\text{min}}^T$ in the SR3L-SFOS-1J region. The lower panel shows the ratio between the observed data and the SM expectation. The SR selections but the cut on the shown variables are applied. Systematic and statistical uncertainties are considered. [138]

The improved analysis using the full Run-2 statistics was developed in order to target the region close to the kinematic edge $m_{\tilde{\chi}^{\pm}_{1}/\tilde{\chi}^{0}_{2}} - m_{\tilde{\chi}^{0}_{1}} = 130$ GeV. The analysis also extends results for decays via $WZ$ bosons. This more extensive and sensitive analysis is the subject of the remainder of this chapter.
Table 6.8: The observed 95% CL upper limits on the visible cross-section $\sigma_{\text{vis}}$ and the observed and expected number of events from BSM signal model $S^{95}_{\text{obs}}$ and $S^{95}_{\text{exp}}$ are shown in the first three columns for each SR. The correspondent discovery $p_0$-value is reported in the last column. Systematic and statistical uncertainties are considered. [138]
Figure 6.5: Observed and expected 95% CL upper limits on the cross-section for the (a) 3$\ell$ channel of searches of $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ via $Wh$ decays and (b) in comparison to all the consider channels: full-hadronic, 1$\ell + bb$, 1$\ell + \gamma\gamma$ and $\ell^\pm \ell^\pm$, 3$\ell$. Different values of $m_{\tilde{\chi}_1^\pm}$ up to 240 GeV are considered, when $m_{\tilde{\chi}_1^\pm} - m_{\tilde{\chi}_2^0} = 130$ GeV. [138]
6.2 Full Run-2 analysis searching for $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ via $WZ/Wh$

In this section, the full Run-2 searches for the production of $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ decaying to three leptons and transverse missing momentum via intermediate $WZ$ and $Wh$ are described. For the $WZ$ model, signals with sparticle mass spectra were considered which allow decays into either on-shell or off-shell intermediate SM bosons. For the $Wh$ models only on-shell scenarios are considered. This analysis has been published as a conference note by the ATLAS collaboration [139] for the LHCP2020 conference. A journal paper is in preparation. In the following, plots extracted from the published conference note report the corresponding reference in the caption, while those without reference are provided as additional material.

My own work for this publication has focused on the on-shell $WZ$ analysis and the $Wh$ analysis, therefore the off-shell analysis is not discussed in this thesis and the reader is referred to Ref. [139] for details on that aspect of the search.

I was one of the main analysers of the on-shell models, particularly working on the optimisation and definition of the DFOS SR for the $Wh$ channel, the data-driven FNP estimation for both on-shell $WZ$ and $Wh$ models, the validation of the $t\bar{t}$ background estimation, the background-only fit and the statistical interpretation of the results for on-shell $WZ$ and $Wh$ models.

6.2.1 Event selection

Events used in the analyses must have exactly three baseline leptons which also pass the signal object definition in Section 4.6, and pass the logical OR of the di-lepton trigger chains listed in Table 5.2.

As before, a set of initial selection criteria, the pre-selection, are applied. These select events with no $b$-tagged jets and $E_T^{\text{miss}} > 50$ GeV. Furthermore, in order to ensure the selection of events in the plateau of the trigger efficiencies, $p_T$ threshold are applied to the two leading leptons. The first lepton must have $p_T > 25$ GeV, while the second lepton must have $p_T > 20$ GeV.
6.2.1.1 Signal region definitions

Like in the early Run-2 Wh analysis, events are divided into the SFOS and DFOS categories, with additional criteria which separate between events with a SFOS pair compatible with originating from a Z boson decay or not. Thus, three different selections are identified:

**SR\textsubscript{Wh DFOS} selection:** analogously to the early Run-2 Wh analysis, this selection vetoes the presence of a SFOS lepton pair and it targets Wh signal models. The DFOS SRs have been re-optimised fully for the full Run-2 analysis presented here;

**SR\textsubscript{Wh SFOS} selection:** events with an SFOS lepton pair, with invariant mass $m_{\ell\ell}$ outside the [75, 105] GeV interval. Two different $m_{\ell\ell}$ ranges are considered. The selection uses events with $m_{\ell\ell} < 75$ GeV, and events with $m_{\ell\ell} > 105$ GeV, independently optimised, both targeting the Wh models;

**SR\textsubscript{WZ} selection:** events with an SFOS lepton pair, with invariant mass $m_{\ell\ell}$ in the [75, 105] GeV interval around the nominal mass of the Z boson. These SRs are optimised to be sensitive to the WZ models.

As I have not worked on the SFOS SRs optimisation, these will not be discussed in the same detail as for the regions for which I have myself developed the optimisation.

**DFOS signal regions**

The optimisation of the DFOS SRs is presented by considering three benchmark points for the Wh model: Wh(150,0), Wh(190,60), and Wh(200,25) (as a reminder, the first number in parentheses indicates the mass $m_{\tilde{\chi}_1^\pm/\tilde{\chi}_2^0}$, while the second one is $m_{\tilde{\chi}_1^0}$).

Following and improving the ideas developed for the early Run-2 analysis targeting Wh models, the definition of the SRs in the DFOS flavour-sign combination uses distances and angular variables to suppress the SM backgrounds. Furthermore, similarly again to what showed for the 36.1 fb\textsuperscript{-1} analysis, the main contribution to the SM background entering the DFOS selection comes from the reducible background $t\bar{t}$. Non-negligible background contributions come from the production of three vector
bosons and from processes with a SM Higgs boson, mainly the production of a Higgs boson in association with a gauge boson $VH (V = W, Z)$.

Distribution of the light-jet multiplicity ($n_{\text{jets}}$) for events passing the preselection criteria and the DFOS requirement is shown in Figure 6.6. The plot clearly shows sensitivity to the $Wh$ model for low light-jet multiplicities, contrary to some dominant SM backgrounds (e.g. $t\bar{t}$) which instead dominate the bins with at least 2 light jets.

Figure 6.6: In the upper panel, the distributions of the number $n_{\text{jets}}$ of light jets for events passing the preselection and the DFOS flavour-sign requirement. The sensitivities $Z_n$ curves are calculated for possible upper cuts on the given variable and assuming a flat 30% total uncertainty on the SM background.

For this analysis, only events with low light-jet multiplicity are considered, identifying two DFOS SRs: a first one selecting events with no light jets ($SR^{Wh}_{\text{DFOS}-1}$); and a second one selecting events with either one or two light jets ($SR^{Wh}_{\text{DFOS}-2}$). Each SR is then optimised looking at additional variables, as discussed in what follows.

As mentioned, the choice of selection variables and the SR optimisation follows and improves the SR definitions for the early Run-2 $Wh$ analysis. One of the improvements is the use of $E_T^{\text{miss}}$ significance instead of $E_T^{\text{miss}}$ for the definition of the DFOS SRs. This choice is motivated by the distributions in Figure 6.7a and Figure 6.7b, obtained after selecting events passing the preselection criteria and the DFOS flavour-sign requirement. The distributions show, for all the shown $Wh$ benchmark points, that the $E_T^{\text{miss}}$ significance provides a better discrimination of the signal against the background with respect to the $E_T^{\text{miss}}$.

As further motivation for the choice of $E_T^{\text{miss}}$ significance, the correlation plots between the $E_T^{\text{miss}}$ significance and $E_T^{\text{miss}}$ are shown in Figure 6.8a and Figure 6.8b, for the $t\bar{t}$
6.2 Full Run-2 Analysis Searching for $\tilde{t}^\pm \tilde{\chi}_2^0$ via $WZ/Wh$

Figure 6.7: In the upper panels, the distributions of the $E_T^{miss}$ and $E_T^{miss}$ significance for events passing the pre-selection criteria and the DFOS flavour-sign selection. All the sensitivities $Z_n$ curves are calculated for possible lower cuts on the given variables and assuming a flat 30% total uncertainty on the SM background.

Figure 6.8: Correlation between $E_T^{miss}$ and the $E_T^{miss}$ significance variables for (a) the $t\bar{t}$ process and (b) the Wh signal point Wh(175, 0).

As before, the $\Delta R_{OS, near}$ distance and the $p_T$ of the third lepton have been explored. Distribution of the $\Delta R_{OS, near}$ distance and the third lepton $p_T$ are shown in Figure 6.9a and Figure 6.9b, respectively, for events passing the preselection and the DFOS flavour-sign requirement. As can be seen, both the variables provide good suppression of the SM backgrounds, particularly the $WZ$ and $t\bar{t}$. 
6.2 Full Run-2 Analysis Searching for $\tilde{\chi}_1^\pm$, $\tilde{\chi}_2^0$ via WZ/Wh

Figure 6.9: In the upper panels, the distributions of the $\Delta R_{\text{OS, near}}$ and the $p_T^{3\ell}$ for events passing the pre-selection criteria and the DFOS flavour-sign selection. All the sensitivities $Z_n$ curves but those in the $\Delta R_{\text{OS, near}}$ distribution are calculated for possible lower cuts on the given variables and assuming a flat 30% total uncertainty on the SM background.

The two DFOS SRs, $\text{SR}_{\text{DFOS}}^{\text{Wh}}-1$ and $\text{SR}_{\text{DFOS}}^{\text{Wh}}-2$, are defined in Table 6.9. The same selection variables are used in both cases, with different cuts, optimised for the specific selections. The N-1 distributions of SM backgrounds and benchmark Wh signal points in the SRs are shown in Figure 6.10. As anticipated, for the $\text{SR}_{\text{DFOS}}^{\text{Wh}}-1$, the $p_T$ of the third lepton and the $E_T^{\text{miss}}$ significance suppress contribution of $t\bar{t}$ and other irreducible background, while $\Delta R_{\text{OS, near}}$ helps reducing background from less dominant sources. For the $\text{SR}_{\text{DFOS}}^{\text{Wh}}-2$, all the chosen selection variables provide good suppression of $t\bar{t}$, WZ and FNP background. After the selections, the background processes with a Higgs boson are dominant in $\text{SR}_{\text{DFOS}}^{\text{Wh}}-1$, while the $t\bar{t}$ process and the FNP backgrounds constitute the main source of background in $\text{SR}_{\text{DFOS}}^{\text{Wh}}-2$.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Selection requirements</th>
<th>$\text{SR}_{\text{DFOS}}^{\text{Wh}}-1$</th>
<th>$\text{SR}_{\text{DFOS}}^{\text{Wh}}-2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$n_{\text{jets}}$</td>
<td>$= 0$</td>
<td>$\in [1, 2]$</td>
<td></td>
</tr>
<tr>
<td>$E_T^{\text{miss}}$ significance</td>
<td>$&gt; 8$</td>
<td>$&gt; 8$</td>
<td></td>
</tr>
<tr>
<td>$p_T^{3\ell} [\text{GeV}]$</td>
<td>$&gt; 15$</td>
<td>$&gt; 20$</td>
<td></td>
</tr>
<tr>
<td>$\Delta R_{\text{OS, near}}$</td>
<td>$&lt; 1.2$</td>
<td>$&lt; 1.0$</td>
<td></td>
</tr>
</tbody>
</table>

Table 6.9: Summary of the selection criteria for SRs targeting events with a DFOS lepton pair, for the Wh selection. Preselection criteria are applied. [139]
Figure 6.10: N-1 distributions for the \( \text{SR}^{h \rightarrow 0} \) (first column) and \( \text{SR}^{h \rightarrow 2} \) (second column) regions. The upper panels show distribution for relevant background processes and chosen benchmark \( Wh \) signal points, the arrows show the position and the verse of the cuts on the \( p_T \) of the third lepton (first row), the \( E_T^{\text{miss}} \) significance (second row) and the \( \Delta R_{\text{OS, near}} \) (third row). The significance \( Z_n \) is calculated assuming a flat 30% total uncertainty on the SM background.
### 6.2 Full Run-2 Analysis Searching for $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ via $WZ/Wh$

**SFOS signal regions**

The invariant mass $m_{\ell\ell}$ is a good discriminator to target either the $WZ$ or the $Wh$ models, since it provides a good way to select events with the presence (or not) of a $Z$ boson in the decay chains. Figure 6.11a and Figure 6.11b show the distributions of $m_{\ell\ell}$ for events passing the preselection criteria and the SFOS flavour-sign requirement. In both plots, the upper panels show distributions of the main SM background processes and reference mass points for the SUSY models. In the lower panels, the significance $Z_n$ is calculated assuming 15% of uncertainty on the background, for a lower or an upper cut on the invariant mass $m_{\ell\ell}$, to show potential sensitivity for two $WZ$ and $Wh$ benchmark points, as indicated.

![Figure 6.11](image)

**(a) Lower cut $Z_n$**

**(b) Upper cut $Z_n$**

Figure 6.11: In the upper panels, the distributions of the $m_{\ell\ell}$ for events passing the preselection criteria and the SFOS requirement. In the lower pad, the sensitivity $Z_n$ is calculated for (a) a lower cut and for (a) an upper cut on the shown variable. Sensitivity is calculated assuming a 10% flat total uncertainties on the SM background.

A cut on the SFOS invariant mass $m_{\ell\ell} > 12$ GeV is applied to suppress the low-mass (e.g. $J/\Psi$, and the $Y$) resonances. A cut on the trilepton invariant mass $m_{\ell\ell\ell}$ is used to suppress the contribution from FNP processes from the total SM background, requesting $|m_{\ell\ell\ell} - m_Z| > 15$ GeV, where $m_Z$ is the nominal $Z$ boson mass.

The presence of any ISR jet is exploited to boost the $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ system, resulting in a boosted kinematics for the physics objects in the final states. In such configuration, scenario with low mass-splitting, close to the kinematic edge $m_{\tilde{\chi}_1^\pm / \tilde{\chi}_2^0 - m_{\tilde{\chi}_1^0} = m_Z$, can be targeted. In both the SR$^{WZ}$ and SR$^{Wh}_{SFOS}$ selections, events are therefore split into three different categories: those with no the light jets ($n_{jets} = 0$); those, referred to as
low-$H_T$, with at least one jet and moderate hadronic activity, selected through $H_T (H_T < 200 \text{ GeV})$; and those with at least one light jet and significant hadronic activity ($H_T > 200 \text{ GeV}$), referred to as high-$H_T$.

The SRs in both the SR$^{WZ}$ and the SR$^{Wh}_{SFOS}$ selections are optimised in all the hadronic activity configurations separately, using a binning in $m_T$ and $E_T^{miss}$. The motivation for the binning in $m_T$ and $E_T^{miss}$ used in the SFOS SRs is provided by the plots in Figure 6.12, where $m_T$ distributions are shown for the SR$^{WZ}$ selection with either $n_{\text{jets}} = 0$, labelled SR$^{WZ}_{0j}$, or in the high-$H_T$ category, labelled SR$^{WZ}_{\text{High-H}_T}$.

![Figure 6.12](image_url)  
(a) $n_{\text{jets}} = 0$  
(b) $n_{\text{jets}} > 0$ and $H_T > 200 \text{ GeV}$

Figure 6.12: In the upper panels, the distributions of the $m_T$ in the SR$^{WZ}$ selection, split into categories of events with (a) $n_{\text{jets}} = 0$, and (b) $n_{\text{jets}} > 0$ and $H_T > 200 \text{ GeV}$. In each lower panel, the sensitivity $Z_n$ curve is calculated by assuming a 15\% of total uncertainty on the SM background and for possible lower cuts on the shown variables.

A total of twenty SR bins are defined for the on-Z selection targeting the $WZ$ model. Their definitions are shown in Table 6.10, accounting for all hadronic activity configurations described above.

As mentioned, similar strategy has been followed for the optimisation of the SR$^{Wh}_{SFOS}$ SRs. Nevertheless, opposite to the SR$^{WZ}$ SRs, the high-$H_T$ category for the SR$^{Wh}_{SFOS}$ selection did not show any significant contribution to the overall sensitivity for the $Wh$ models. Moreover, for events with $m_{\ell\ell} > 105 \text{ GeV}$, only the zero-jet category $n_{\text{jets}} = 0$ contributes significantly to the analysis.

Definitions of the SR$^{Wh}_{SFOS}$ regions are listed in Table 6.11, showing a total of nineteen SR bins targeting the $Wh$ model.
6.2 Full Run-2 Analysis searching for $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ via $WZ/Wh$

### Selection requirements

<table>
<thead>
<tr>
<th>$m_T$ [GeV]</th>
<th>$E_T^{miss}$ [GeV]</th>
<th>$n_\text{jets}$</th>
<th>$E_T^{miss}$ [GeV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>[100,160]</td>
<td>SR$_{WZ}$-1: [50,100]</td>
<td>SR$_{WZ}$-2: [100,150]</td>
<td>SR$_{WZ}$-3: [150,200]</td>
</tr>
<tr>
<td>$n_\text{jets} &gt; 0$, $H_T &lt; 200$ GeV</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$m_T$ [GeV]</td>
<td>$E_T^{miss}$ [GeV]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>[100,160]</td>
<td>SR$_{WZ}$-9: [100,150]</td>
<td>SR$_{WZ}$-10: [150,200]</td>
<td>SR$_{WZ}$-11: [250,300]</td>
</tr>
<tr>
<td>$n_\text{jets} &gt; 0$, $H_T &gt; 200$ GeV, $H_T^{lep} &lt; 350$ GeV</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$m_T$ [GeV]</td>
<td>$E_T^{miss}$ [GeV]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>&gt; 100</td>
<td>SR$_{WZ}$-17: [150,200]</td>
<td>SR$_{WZ}$-18: [200,300]</td>
<td>SR$_{WZ}$-19: [300,400]</td>
</tr>
</tbody>
</table>

Table 6.10: Summary of the selection criteria for SRs targeting events with at least one SFOS lepton pair and $m_\ell\ell \in [75,105]$ GeV, for the SR$_{WZ}$ search regions. Region selections are binned by $m_T$ (rows) and $E_T^{miss}$ for the two sets of regions, where each set has different $n_\text{jets}$ and $H_T$ requirements. Preselection criteria are applied. [139]

<table>
<thead>
<tr>
<th>$m_T$ [GeV]</th>
<th>$E_T^{miss}$ [GeV]</th>
<th>$n_\text{jets} = 0$</th>
<th>$m_\ell\ell \leq 75$ GeV, $n_\text{jets} = 0$</th>
</tr>
</thead>
<tbody>
<tr>
<td>[0,100]</td>
<td>SR$_{Wh}^{SFOS}$-1: [50,100]</td>
<td>SR$_{Wh}^{SFOS}$-2: [100,150]</td>
<td>SR$_{Wh}^{SFOS}$-3 &gt; 150</td>
</tr>
<tr>
<td>[100,160]</td>
<td>SR$_{Wh}^{SFOS}$-4: [50,100]</td>
<td>SR$_{Wh}^{SFOS}$-5: &gt; 100</td>
<td></td>
</tr>
<tr>
<td>&gt; 160</td>
<td>SR$_{Wh}^{SFOS}$-6: [50,100]</td>
<td>SR$_{Wh}^{SFOS}$-7: &gt; 100</td>
<td></td>
</tr>
<tr>
<td>$m_T$ [GeV]</td>
<td>$E_T^{miss}$ [GeV]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>[0,50]</td>
<td>SR$_{Wh}^{SFOS}$-8: [50,100]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>[50,100]</td>
<td>SR$_{Wh}^{SFOS}$-9: [50,100]</td>
<td></td>
<td></td>
</tr>
<tr>
<td>[0,100]</td>
<td>SR$_{Wh}^{SFOS}$-10: [100,150]</td>
<td>SR$_{Wh}^{SFOS}$-11: &gt; 150</td>
<td></td>
</tr>
<tr>
<td>[100,160]</td>
<td>SR$_{Wh}^{SFOS}$-12: [50,100]</td>
<td>SR$_{Wh}^{SFOS}$-13: [100,150]</td>
<td>SR$_{Wh}^{SFOS}$-14: &gt; 150</td>
</tr>
<tr>
<td>&gt; 160</td>
<td>SR$_{Wh}^{SFOS}$-15: [50,150]</td>
<td>SR$_{Wh}^{SFOS}$-16: &gt; 150</td>
<td></td>
</tr>
</tbody>
</table>

Table 6.11: Summary of the selection criteria for SRs targeting events with at least one SFOS lepton pair and $m_\ell\ell \notin [75,105]$ GeV, for the $Wh$ search regions. Region selections binned by $m_T$ (rows) and $E_T^{miss}$ for the three sets of regions, where each set has different $m_\ell\ell$, $n_\text{jets}$, and $H_T$ requirements. Preselection criteria are applied. [139]

### 6.2.2 Standard Model background estimation

As seen for the early Run-2 $Wh$ analysis, also for the full Run-2 analysis background estimation methods are in place for the sources of irreducible and reducible back-
grounds. Table 6.12 summarises the various techniques used in this thesis for the estimation of the different SM background processes entering the SRs.

<table>
<thead>
<tr>
<th>Process</th>
<th>Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>( WZ )</td>
<td>MC, normalised in CR</td>
</tr>
<tr>
<td>FNP (( Z+)jets)</td>
<td>Data-driven Fake Factor</td>
</tr>
<tr>
<td>( t\bar{t} )</td>
<td>MC, validated in VR</td>
</tr>
<tr>
<td>Others</td>
<td>MC</td>
</tr>
</tbody>
</table>

Table 6.12: Summary of the background estimation methods used for the full Run-2 analysis detailed in this thesis. The category "Others" includes the \( WW \), \( ZZ \), \( t\bar{t}+V \) (\( V=W,Z \)), single-top and processes with a Higgs boson.

Additional details on the methods are discussed in the following. For the background estimation, I made major contribution by doing the FNP data-driven estimation, designing the validation of the \( t\bar{t} \) background, and performing all the steps of the background-only fit for the irreducible background estimation.

**FNP estimation**

The Fake Factor method is used for the estimation of the FNP background from \( Z+\)jets process. The method is described in Section 5.3.1.1. A CR, named CRFF\(^{WZ}\), is used for the extraction of the fake factors for electrons and muons, and it is chosen to select events with FNP contribution, against other SM backgrounds, as well as to emulate an FNP source composition similar to the one expected in the SRs.

The definition of the CRFF\(^{WZ}\) is shown in Table 6.13. While the regular preselection criteria are applied to all the other regions used in this analysis, they are not applied to CRFF\(^{WZ}\), since they are optimised for the suppression of FNP background and would limit the available statistics for the extraction of the FFs. Events with an SFOS pair, no \( b \)-tagged jets and with \( E^\text{miss}_T \in [20,50] \) GeV are selected. The SFOS leptons, labelled \( \ell_{Z1} \) and \( \ell_{Z2} \), are used for the reconstruction of the invariant mass \( m_{\ell\ell} \), required to be \( \in [75,105] \) GeV, and are required to pass the signal object definition. Additional cuts on their \( p_T \) are applied to ensure selection in the plateau of the di-lepton trigger efficiencies. The trasverse mass \( m_T \) of the third lepton not in the SFOS pair is required to have \( m_T < 20 \) GeV. This latter lepton is assumed to be the FNP lepton and is used for the extraction of the fake factors.
The fake factors extracted from the CRFF\textsuperscript{WZ} are calculated as a function of the lepton $p_T$. FFs obtained from data after subtraction of prompt backgrounds are of the order of 0.1, except for leptons with $p_T > 50$ GeV. These are then used for the estimation of the FNP background in the regions, according to the procedure described in Section 5.3.1.1.

A set of dedicated systematic uncertainties are calculated for the FNP estimation. In the case of the Fake Factor method, two main sources are considered:

**Statistical uncertainties on the FFs:** these arise from the Poisson uncertainties associated with the counting of leptons that pass the tight or loose selection. The statistical errors on the FFs are treated as a correlated source of systematic uncertainty across all the SRs.

**Closure test:** the same method is used on MC simulation of $Z$+jets background, using FFs calculated purely from MC. The test is expected to produce results similar to prediction of out-of-the-box MC simulation of the same background in all the SRs. Possible discrepancies are associated to a different FNP source composition in the CRFF\textsuperscript{WZ} with respect to the SRs. In that case, discrepancies between the MC-based Fake Factor estimation and the MC-only expectations are taken as source of uncorrelated systematic uncertainty on the FNP background estimation.

The FNP estimation method is validated in a dedicated VR, named VRFF\textsuperscript{WZ}, defined in a kinematic region which does not overlap with any other region used in the analysis, and where the contribution from the FNP background is dominant. Events with a SFOS pair are selected and with $E_T^{\text{miss}} \in [50,100]$ GeV. Additional cuts on $m_T < 20$ GeV and $m_{\ell\ell\ell\ell} \in [105,160]$ GeV are applied to select events with FNP leptons. The exact definition of the VRFF\textsuperscript{WZ} is shown in Table 6.13.

Distributions of the $p_T$ of the third lepton in the FNP-VR are shown in Figure 6.13, for the four flavour channels $eee$, $ee\mu$, $\mu\mu e$ and $\mu\mu\mu$. The plots show good agreement in all the bins between data and the SM backgrounds, including the FNP background estimation.
Validation of the $t\bar{t}$ background estimation

The MC modelling of the $t\bar{t}$ is validated in a dedicated VR, which select events with no SFOS lepton pairs and with either one or two $b$-tagged jets (VR$\text{t}\bar{t}_{WZ}$). By definition, the VR$\text{t}\bar{t}_{WZ}$ is orthogonal to all the DFOS SRs. Another region is also defined for the validation of the $t\bar{t}$ background. The additional VR$\text{t}\bar{t}_{inc}$ selects events in the DFOS selection and $E_T^{\text{miss}}$ significance less than 8, but it does not apply any requirement on the $b$-tagged-jet multiplicity, approaching the zero-$b$-jets selection applied to the SRs. The exact definitions of the VRs for the $t\bar{t}$ background are shown Table 6.13.

Distribution of $\Delta R_{\text{OS, near}}$, $E_T^{\text{miss}}$ and $E_T^{\text{miss}}$ significance for the data and the SM prediction in the VR$\text{t}\bar{t}_{WZ}$ are shown in Figure 6.14 and Figure 6.15. Good agreement between data and SM expectations is observed which validates the MC modelling of the $t\bar{t}$ process.
6.2 Full Run-2 Analysis Searching for $\tilde{t}^\pm \tilde{t}_2^0$ via $WZ/Wh$

<table>
<thead>
<tr>
<th>Variable</th>
<th>$\text{VR}_{t\bar{t}}^{WZ}$</th>
<th>$\text{VR}_{t\bar{t}}^{inc}$</th>
<th>$\text{CRFF}^{WZ}$</th>
<th>$\text{VRFF}^{WZ}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$n_{SFOS}$</td>
<td>$= 0$</td>
<td>$= 0$</td>
<td>$\geq 1$</td>
<td>$\geq 1$</td>
</tr>
<tr>
<td>$n_{b\text{-jets}}$</td>
<td>$\in [1, 2]$</td>
<td>-</td>
<td>=0</td>
<td>=0</td>
</tr>
<tr>
<td>$</td>
<td>m_{\ell\ell} - m_Z</td>
<td>$ [GeV]</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$p_{T,WZ}$, $p_{T,ZZ}$ [GeV]</td>
<td>-</td>
<td>-</td>
<td>$&gt; 25$, $&gt; 20$</td>
<td>-</td>
</tr>
<tr>
<td>$E_{T,\text{miss}}$ [GeV]</td>
<td>$&gt; 50$</td>
<td>$&gt; 50$</td>
<td>$\in [20, 50]$</td>
<td>$\in [50, 100]$</td>
</tr>
<tr>
<td>$E_{T,\text{miss}}$ significance</td>
<td>-</td>
<td>$&lt; 8$</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>$m_T$ [GeV]</td>
<td>-</td>
<td>-</td>
<td>$&lt; 20$</td>
<td>$&lt; 20$</td>
</tr>
<tr>
<td>$m_{T_\ell}$ [GeV]</td>
<td>-</td>
<td>-</td>
<td>$\in [105, 160]$</td>
<td></td>
</tr>
</tbody>
</table>

Table 6.13: Summary of the selection criteria for the CRs and VRs for $t\bar{t}$ and FNP estimation, for the $SR_{WZ}$ and $SR_{SFOS}^{Wh}$ selections. Preselection criteria are applied for $\text{VR}_{t\bar{t}}^{WZ}$, $\text{VR}_{t\bar{t}}^{inc}$ and $\text{VRFF}^{WZ}$ regions. [139]

Figure 6.14: In the upper panels, the distribution of the (a) $E_{T,\text{miss}}$ and (b) $\Delta R_{OS, \text{near}}$ in the $\text{VR}_{t\bar{t}}^{WZ}$. In the lower pad, ratio between data and SM prediction is shown. Systematic and statistical uncertainties are considered. [139]

Figure 6.15: In the upper panels, the distribution of the (a) $p_T$ of the third lepton and (b) $E_{T,\text{miss}}$ significance in the $\text{VR}_{t\bar{t}}^{WZ}$. In the lower pad, ratio between data and SM prediction is shown. Systematic and statistical uncertainties are considered.
In Figure 6.16 distributions are shown for the $V_R t^\pm W^\mp Z$, including $E_T^\text{miss}$, $\Delta R_{OS}$, near and the $b$-tagged jet multiplicity $n_{b-jets}$. Good agreement is again seen in all the distribution, validating the shape and normalisation of the $t \bar{t}$ process.

### WZ background estimation

As in the early Run-2 analysis, the irreducible background $WZ$ is estimated in a dedicated CR, named CRWZ$^\text{WZ}$. The same hadronic binning in $n_{jets}$ and $H_T$ used in the SFOS SR definition are used for the binning of the CRWZ$^\text{WZ}$. In what follows, bins in $n_{jets}$ and $H_T$ for the CRWZ$^\text{WZ}$ are labelled CRWZ$^\text{WZ}_0j$, CRWZ$^\text{WZ}_{\text{Low}H_T}$ and CRWZ$^\text{WZ}_{\text{High}H_T}$. In addition to the preselection criteria, events with a SFOS lepton pair with invariant mass $m_{\ell \ell} \in [75, 105] \text{ GeV}$ are selected. Moreover, cuts on $E_T^\text{miss} \in [50, 100] \text{ GeV}$ and $m_T \in [20, 100] \text{ GeV}$ are applied. The exact definition of CRWZ$^\text{WZ}$ is shown in Table 6.14.
Distributions of the $m_T$ in all the hadronic binning in $n_{\text{jets}}$ and $H_T$ for the CRWZ$^{WZ}$, before the background-only fit, are shown in Figure 6.17. Some disagreement is noticeable in all the hadronic bins, particularly accentuated for the high-$H_T$ region. The shape of the $m_T$ distribution was further validated by data on background comparison for the $W + \gamma$ background, whose $m_T$ distribution shape does not differ by that from $WZ$. I did not make any contribution to this aspect of the analysis, therefore the reader is remanded to Ref. [139] for further details and description of the method.

Figure 6.17: In the upper panels, distributions of $m_T$ in the CRWZ$^{WZ}$, before the background-only fit. Events are selected in all the hadronic binning considered in the optimisation of the SRs: (a) $n_{\text{jets}} > 0$, (b) $n_{\text{jets}} = 0$ and $H_T < 200$ GeV, and (c) $n_{\text{jets}} > 0$ and $H_T > 200$ GeV. In the lower panels, data on background ratio is compared to the error band, including statistical and systematic uncertainties on the SM background.

A dedicated VR, called VRWZ$^{WZ}$, is introduced to test the NF extracted from the CRWZ$^{WZ}$. Contamination in the VRWZ$^{WZ}$ from SUSY signals is of the order 1% or less for all the signal points not already excluded by previous equivalent searches. Also in this case, the VRWZ$^{WZ}$ is split into the same bins in $n_{\text{jets}}$ and $H_T$, as considered for the corresponding CR and the SR. The VRWZ$^{WZ}$ definition is also shown in Table 6.14.
$m_T$ and the $E_T^{\text{miss}}$ are used to keep all the regions in the analysis orthogonal.

\begin{table}[h]
\centering
\begin{tabular}{lcccc}
\hline
\textbf{Variable} & \textbf{CRWZ} & & \textbf{VRWZ} & \\
 & \textbf{$WZ$} & \textbf{0 jets} & \textbf{low-$H_T$} & \textbf{high-$H_T$} & \textbf{$WZ$} & \textbf{0 jets} & \textbf{low-$H_T$} & \textbf{high-$H_T$} \\
\hline
$n_{\text{jets}}$ & $=0$ & $\geq 1$ & $\geq 1$ & $=0$ & $\geq 1$ & $\geq 1$ \\
$n_{\text{SFOs}}$ & & & & & & \\
$m_T$ [GeV] & $\epsilon [20, 100]$ & $\epsilon [20, 100]$ & & & & \\
$m_{\ell\ell}$ [GeV] & $\epsilon [75, 105]$ & $\epsilon [75, 105]$ & & & & \\
$|m_{\ell\ell} - m_Z|$ [GeV] & $> 15$ & $> 15$ & & & & \\
$E_T^{\text{miss}}$ [GeV] & $\epsilon [50, 100]$ & $> 100$ & & & & \\
\hline
\end{tabular}
\caption{Summary of the selection criteria for the CRs and VRs for $W Z$, for the SR$^{WZ}$ and SR$^{Wh}$ selections. Preselection criteria are applied. In rows where only one value is given it applies to all regions. [139]}
\end{table}

6.2.3 Systematic uncertainties

The detector systematic uncertainties considered in the analysis are those discussed in Section 5.4.1. The theory uncertainties on the MC modelling of the SM processes are described in Section 5.4.2. These are calculated for the $W + Z$ background for all the SFOS regions. For the DFOS SRs, theory uncertainties are calculated for the dominant $VVV$ and the $t\bar{t}$ backgrounds. Furthermore, a set of dedicated systematic uncertainties are considered for the data-driven estimation of the FNP background, discussed in Section 6.2.2.

The plots in Figure 6.18 show the relative uncertainties for all the SR designed for the $W Z$ and the $Wh$ models. In the plots, the category “Experimental” includes all the detector systematics, “Modelling” refers to the theory uncertainties on the main SM background processes, “Fake” are the systematic uncertainties related to the FNP data-driven estimation, “Normalisation” are those on the NF extrapolated from the CR in the background-only fit, and “MC stats” are the uncertainties associated to the statistics available in the used MC samples for the SM background.

Experimental systematic uncertainties and statistical from the MC samples are dominant in most of the SR$^{WZ}$ regions, expect for the high-$H_T$ bins, where the “Modelling” uncertainties for the $W Z$ background become dominant. In the case of the low-$m_{\ell\ell}$ and high-$m_{\ell\ell}$ SRs, modelling of the $W + Z$ background is the dominant contribution to the uncertainties in most of the SR bins, while for the DFOS SRs, uncertainties on the FNP
Figure 6.18: Relative uncertainties in the (a) SR$^{Wh}_{SFOS}$ and SR$^{Wh}_{DFOS}$, and (b) the SR$^{WZ}$ regions. All sources of systematics and statistical uncertainties considered in the analysis are reported. [139]
estimation become dominant in the $SR_{DFOS}^{-2}$.

### 6.2.4 Background-only fit results

The background-only fit to data was performed simultaneously in all the bins in $n_{\text{jets}}$ and $H_T$, producing three different NFs. The NFs extracted for the targeted $WZ$ background are $\mu_{W+Z}^{0\text{jets}} = 1.07 \pm 0.02$, $\mu_{W+Z}^{\text{low}-H_T} = 0.94 \pm 0.03$ and $\mu_{W+Z}^{\text{high}-H_T} = 0.85 \pm 0.05$, for the $\text{CR}_{WZ}^{0\text{j}}$, $\text{CR}_{WZ}^{\text{low}H_T}$ and $\text{CR}_{WZ}^{\text{high}H_T}$, respectively.

Observed event yields in data and results from the background-only fit for all the VRs are summarised in Figure 6.19. In the first three bins, yields before the background-only fit in all the bins of the $\text{CR}_{WZ}^{WZ}$, showing the relative differences between data and SM predictions, of the same order as the NFs extracted through the fit. The other bins show results in the VRs after the background-only fit. Good agreement between observed data and expected yields from SM backgrounds is seen in all the VRs within the error band, comprising statistical and systematic uncertainties on the background.

![Figure 6.19: Data on SM predictions comparisons in all the CRs and VRs considered for the background estimation.](image)

Results of the background-only fit are also shown in Figure 6.20 and Figure 6.21, where distributions of the $m_T$ in all the bins in $n_{\text{jets}}$ and $H_T$ for the $\text{CR}_{WZ}^{WZ}$ and the
6.2 Full Run-2 analysis searching for $\tilde{\chi}^\pm_1 \tilde{\nu}_2^0$ via $WZ/Wh$

$VRWZ^{WZ}$ are presented. As desired, excellent agreement between data and SM predictions is seen everywhere in the CRWZ$^{WZ}$, and good agreement is found in all the hadronic categories of the VRWZ$^{WZ}$.

---

**Figure 6.20:** In the upper panels, distributions of $m_T$ in the CRWZ$^{WZ}$ (left-hand column) and the VRWZ$^{WZ}$ (right-hand column), after the background-only fit. Events are selected in all the hadronic binning categories considered in the optimisation of the SRs $n_{jets} = 0$ (first row), and $n_{jets} > 0$ and $H_T < 200$ GeV (second row). In the lower panels, data on background ratio is compared to the error band, including statistical and systematic uncertainties on the SM background.

Finally, the effect of the simultaneous background-only fit in all the bins in $n_{jets}$ and $H_T$ is shown in Figure 6.22. The visible disagreement in the $n_{jets}$ distribution before the background-only fit is fully recovered by applying the NFs, with clear benefit from the extraction of NFs for the different hadronic activity configurations considered.
6.2 Full Run-2 analysis searching for $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ via $WZ/Wh$

Figure 6.21: In the upper panels, distributions of $m_T$ in the CRW$^{WZ}$ (left-hand column) and the VRW$^{WZ}$ (right-hand column), after the background-only fit. Events are selected in the hadronic binning category $n_{\text{jets}} > 0$ and $H_T > 200$ GeV considered in the optimisation of the SRs. In the lower panels, data on background ratio is compared to the error band, including statistical and systematic uncertainties on the SM background. [139]

Figure 6.22: In the upper panels, distributions of $n_{\text{jets}}$ in the CRW$^{WZ}$, (a) before and (b) after the background-only fit. In the lower panels, data on background ratio is compared to the error band, including statistical uncertainties on the SM background.

6.2.5 Results and statistical interpretation

The results in the SRs, after the background-only fit in the CRs, are summarised in Figure 6.23 and Figures 6.24, for the Wh and WZ models, respectively. In the upper panels, yields of observed data and SM predictions are shown, while the lower panels indicate the significance for each bin. No significant deviation with respect to the SM predictions is seen in any SR, although a mild 2σ deviation from the SM prediction is observed for the SR$^{Wh}_{DFOS}$-1 bin.
6.2 Full Run-2 Analysis Searching for $\tilde{\chi}_1^\pm \tilde{\chi}_2^0$ via $WZ/Wh$

Figure 6.23: In the upper panels, the observed data and SM prediction yields in the SR targeting the Wh model. The lower panel show the significance for the data and SM expectation, accounting for the full set of systematic and statistical uncertainties. [139]

Figure 6.24: In the upper panels, the observed data and SM prediction yields in the SR targeting the WZ model. The lower panel show the significance for the data and SM expectation, accounting for the full set of systematic and statistical uncertainties. [139]

Results in the SRs are also presented as breakdown of the yields for all the SM backgrounds and the observed data in all the SRs. These are shown in Tables 6.15 and Table 6.16, for the Wh and WZ SRs, respectively.
<table>
<thead>
<tr>
<th>Regions</th>
<th>$SR_{Wh}^{SFOS}$-1</th>
<th>$SR_{Wh}^{SFOS}$-2</th>
<th>$SR_{Wh}^{SFOS}$-3</th>
<th>$SR_{Wh}^{SFOS}$-4</th>
<th>$SR_{Wh}^{SFOS}$-5</th>
<th>$SR_{Wh}^{SFOS}$-6</th>
<th>$SR_{Wh}^{SFOS}$-7</th>
</tr>
</thead>
<tbody>
<tr>
<td>Observed</td>
<td>152</td>
<td>14</td>
<td>8</td>
<td>47</td>
<td>6</td>
<td>15</td>
<td>19</td>
</tr>
<tr>
<td>Fitted SM</td>
<td>136 $\pm$ 13</td>
<td>13.5 $\pm$ 1.7</td>
<td>4.3 $\pm$ 0.9</td>
<td>50 $\pm$ 5</td>
<td>4.3 $\pm$ 0.7</td>
<td>20.2 $\pm$ 2.1</td>
<td>16.0 $\pm$ 2.1</td>
</tr>
<tr>
<td>$WZ$</td>
<td>107 $\pm$ 12</td>
<td>10.2 $\pm$ 1.7</td>
<td>3.8 $\pm$ 0.8</td>
<td>32 $\pm$ 4</td>
<td>2.7 $\pm$ 0.6</td>
<td>12.3 $\pm$ 1.6</td>
<td>10.8 $\pm$ 1.7</td>
</tr>
<tr>
<td>$t\bar{t}$</td>
<td>10.3 $\pm$ 2.5</td>
<td>1.6 $\pm$ 0.6</td>
<td>0.13 $\pm$ 0.12</td>
<td>7.7 $\pm$ 1.9</td>
<td>0.74 $\pm$ 0.34</td>
<td>3.5 $\pm$ 1.0</td>
<td>2.5 $\pm$ 0.7</td>
</tr>
<tr>
<td>$Z$+jets</td>
<td>2.5 $\pm$ 2.9</td>
<td>0.00 $\pm$ 0.02</td>
<td>0.00 $\pm$ 0.00</td>
<td>2.0 $\pm$ 1.6</td>
<td>0.00 $\pm$ 0.04</td>
<td>0.00 $\pm$ 0.00</td>
<td>0.00 $\pm$ 0.02</td>
</tr>
<tr>
<td>Higgs</td>
<td>5.7 $\pm$ 0.6</td>
<td>0.69 $\pm$ 0.07</td>
<td>0.20 $\pm$ 0.03</td>
<td>3.12 $\pm$ 0.31</td>
<td>0.26 $\pm$ 0.05</td>
<td>1.29 $\pm$ 0.14</td>
<td>0.81 $\pm$ 0.09</td>
</tr>
<tr>
<td>VVV</td>
<td>1.9 $\pm$ 0.5</td>
<td>0.22 $\pm$ 0.07</td>
<td>0.07 $\pm$ 0.02</td>
<td>1.4 $\pm$ 0.4</td>
<td>0.28 $\pm$ 0.09</td>
<td>0.61 $\pm$ 0.18</td>
<td>0.83 $\pm$ 0.04</td>
</tr>
<tr>
<td>Others</td>
<td>8.6 $\pm$ 1.9</td>
<td>0.84 $\pm$ 0.11</td>
<td>0.08 $\pm$ 0.05</td>
<td>4.0 $\pm$ 0.5</td>
<td>0.23 $\pm$ 0.24</td>
<td>2.54 $\pm$ 0.22</td>
<td>1.11 $\pm$ 0.15</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Regions</th>
<th>$SR_{Wh}^{SFOS}$-8</th>
<th>$SR_{Wh}^{SFOS}$-9</th>
<th>$SR_{Wh}^{SFOS}$-10</th>
<th>$SR_{Wh}^{SFOS}$-11</th>
<th>$SR_{Wh}^{SFOS}$-12</th>
<th>$SR_{Wh}^{SFOS}$-13</th>
<th>$SR_{Wh}^{SFOS}$-14</th>
</tr>
</thead>
<tbody>
<tr>
<td>Observed</td>
<td>113</td>
<td>184</td>
<td>28</td>
<td>5</td>
<td>82</td>
<td>16</td>
<td>4</td>
</tr>
<tr>
<td>Fitted SM</td>
<td>108 $\pm$ 13</td>
<td>180 $\pm$ 17</td>
<td>31 $\pm$ 4</td>
<td>6.6 $\pm$ 0.9</td>
<td>90 $\pm$ 11</td>
<td>18.7 $\pm$ 2.6</td>
<td>2.5 $\pm$ 0.7</td>
</tr>
<tr>
<td>$WZ$</td>
<td>54 $\pm$ 6</td>
<td>127 $\pm$ 13</td>
<td>19.3 $\pm$ 2.3</td>
<td>5.3 $\pm$ 0.8</td>
<td>47 $\pm$ 6</td>
<td>6.8 $\pm$ 1.7</td>
<td>1.26 $\pm$ 0.26</td>
</tr>
<tr>
<td>$t\bar{t}$</td>
<td>21 $\pm$ 6</td>
<td>33 $\pm$ 10</td>
<td>8.2 $\pm$ 2.3</td>
<td>0.7 $\pm$ 0.5</td>
<td>28 $\pm$ 8</td>
<td>8.0 $\pm$ 2.2</td>
<td>0.9 $\pm$ 0.5</td>
</tr>
<tr>
<td>$Z$+jets</td>
<td>19 $\pm$ 10</td>
<td>2.3 $\pm$ 1.9</td>
<td>1.0 $\pm$ 1.3</td>
<td>0.10 $\pm$ 0.21</td>
<td>2.1 $\pm$ 3.1</td>
<td>1.2 $\pm$ 0.7</td>
<td>0.00 $\pm$ 0.12</td>
</tr>
<tr>
<td>Higgs</td>
<td>1.91 $\pm$ 0.19</td>
<td>3.63 $\pm$ 0.35</td>
<td>0.67 $\pm$ 0.06</td>
<td>0.15 $\pm$ 0.02</td>
<td>2.98 $\pm$ 0.25</td>
<td>0.61 $\pm$ 0.07</td>
<td>0.07 $\pm$ 0.07</td>
</tr>
<tr>
<td>VVV</td>
<td>0.79 $\pm$ 0.24</td>
<td>1.4 $\pm$ 0.4</td>
<td>0.41 $\pm$ 0.13</td>
<td>0.12 $\pm$ 0.05</td>
<td>1.6 $\pm$ 0.5</td>
<td>0.56 $\pm$ 0.18</td>
<td>0.13 $\pm$ 0.05</td>
</tr>
<tr>
<td>Others</td>
<td>11.1 $\pm$ 2.2</td>
<td>12.2 $\pm$ 2.2</td>
<td>1.8 $\pm$ 0.4</td>
<td>0.22 $\pm$ 0.05</td>
<td>9.0 $\pm$ 1.1</td>
<td>1.6 $\pm$ 0.7</td>
<td>0.10 $\pm$ 0.05</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Regions</th>
<th>$SR_{Wh}^{SFOS}$-15</th>
<th>$SR_{Wh}^{SFOS}$-16</th>
<th>$SR_{Wh}^{SFOS}$-17</th>
<th>$SR_{Wh}^{SFOS}$-18</th>
<th>$SR_{Wh}^{SFOS}$-19</th>
<th>$SR_{Wh}^{DFOS}$-1</th>
<th>$SR_{Wh}^{DFOS}$-2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Observed</td>
<td>51</td>
<td>5</td>
<td>37</td>
<td>7</td>
<td>4</td>
<td>10</td>
<td>10</td>
</tr>
<tr>
<td>Fitted SM</td>
<td>46 $\pm$ 7</td>
<td>9.8 $\pm$ 1.6</td>
<td>43 $\pm$ 7</td>
<td>12.6 $\pm$ 1.7</td>
<td>1.8 $\pm$ 0.4</td>
<td>4.5 $\pm$ 0.8</td>
<td>7.0 $\pm$ 2.3</td>
</tr>
<tr>
<td>$WZ$</td>
<td>18.9 $\pm$ 2.2</td>
<td>3.9 $\pm$ 0.8</td>
<td>35 $\pm$ 6</td>
<td>9.8 $\pm$ 1.6</td>
<td>1.44 $\pm$ 0.32</td>
<td>0.44 $\pm$ 0.14</td>
<td>1.05 $\pm$ 0.20</td>
</tr>
<tr>
<td>$t\bar{t}$</td>
<td>18 $\pm$ 6</td>
<td>3.2 $\pm$ 1.3</td>
<td>1.00 $\pm$ 0.34</td>
<td>0.33 $\pm$ 0.17</td>
<td>0.00 $\pm$ 0.03</td>
<td>1.0 $\pm$ 0.6</td>
<td>1.7 $\pm$ 1.1</td>
</tr>
<tr>
<td>$Z$+jets</td>
<td>0.00 $\pm$ 0.01</td>
<td>0.00 $\pm$ 0.01</td>
<td>0.00 $\pm$ 0.01</td>
<td>0.00 $\pm$ 0.01</td>
<td>0.00 $\pm$ 0.01</td>
<td>0.00 $\pm$ 0.01</td>
<td>2.5 $\pm$ 2.0</td>
</tr>
<tr>
<td>Higgs</td>
<td>2.06 $\pm$ 0.23</td>
<td>0.36 $\pm$ 0.05</td>
<td>1.02 $\pm$ 0.12</td>
<td>0.44 $\pm$ 0.05</td>
<td>0.05 $\pm$ 0.05</td>
<td>1.59 $\pm$ 0.22</td>
<td>0.96 $\pm$ 0.11</td>
</tr>
<tr>
<td>VVV</td>
<td>1.5 $\pm$ 0.4</td>
<td>0.53 $\pm$ 0.17</td>
<td>2.5 $\pm$ 0.7</td>
<td>1.3 $\pm$ 0.4</td>
<td>0.2 $\pm$ 0.1</td>
<td>0.66 $\pm$ 0.15</td>
<td>0.64 $\pm$ 0.16</td>
</tr>
<tr>
<td>Others</td>
<td>5.0 $\pm$ 0.6</td>
<td>1.8 $\pm$ 0.5</td>
<td>3.0 $\pm$ 0.7</td>
<td>0.73 $\pm$ 0.15</td>
<td>0.14 $\pm$ 0.05</td>
<td>0.81 $\pm$ 0.09</td>
<td>0.21 $\pm$ 0.07</td>
</tr>
</tbody>
</table>

Table 6.15: Observed and expected yields after the background-only fit in the SRs for the $SR_{Wh}^{SFOS}$ and $SR_{Wh}^{DFOS}$ selection. The “Others” category contains the single-top, WW, $t\bar{t}$ + V and rare top processes. Statistical and systematic uncertainties are presented. [139]
Table 6.16: Observed and expected yields after the background-only fit in the SRs for the SRWZ selection. The “Others” category contains the single-top, WW, triboson, Higgs and rare top processes. Statistical and systematic uncertainties are presented. [139]
Finally, the distributions of kinematic variables for some of the SR bins are shown below. In Figure 6.25, the $E_T^{\text{miss}}$ and $m_T$ distributions are shown in the $SR_{WZ}^{0j}$ regions, which selects events in the $SR_{WZ}^{0j}$ selection with $N_{\text{jet}} = 0$, along with distributions of the $p_T$ of the third lepton and the $\Delta R_{\text{OS, near}}$ in the $SR_{\text{DFOS}}^{-1}$ and $SR_{\text{DFOS}}^{-2}$, respectively. As already seen in the results above, no significant deviation from the SM background predictions is visible for any of the $m_T$ and $E_T^{\text{miss}}$ bins, while a mild excess is seen in the region $SR_{\text{DFOS}}^{-1}$.

![Figure 6.25](image)

For completeness, the N-1 distributions of all the other selection variables used in the definitions of $SR_{\text{DFOS}}^{-1}$ and $SR_{\text{DFOS}}^{-2}$ are shown in Figure 6.26. The mild excess in the region $SR_{\text{DFOS}}^{-1}$ is again seen in some of the bins, particularly for $\Delta R_{\text{OS, near}} < 0.5$. 

![Figure 6.26](image)
Model-independent upper-limits

The model-independent fit is performed to set upper-limits on the number of observed and expected events. A set of dedicated discovery regions was identified for the purpose. These are defined to be sensitive to possible BSM physics, by not being optimised for any specific SUSY models, as done for the SRs considered in these searches. For this reason, binning in the SRs targeting the WZ and Wh models were relaxed, in order to consider more inclusive regions to use in a model-independent approach. A total of twelve discovery regions are defined in Table 6.17.

Upper-limits after the model-independent fit are shown in Table 6.18, which lists the upper limits on the observed \(N_{\text{obs}}\) and expected \(N_{\text{exp}}\) number of signal events, the CL value calculated under the SM-only hypothesis, and the p-value \(p_0\), calculated
Table 6.17: Summary of the selection criteria for the inclusive SRs in the SR$_{WZ}$, SR$_{SFOS}$ and SR$_{DFOS}$ selections. [139]

under the SM-only hypothesis in each discovery region. In the case of the SR$_{DFOS}$ selection, relaxing the binning in $n_{jets}$ has had the effect to moderate the 2$\sigma$ excess seen for the single bin SR$_{DFOS}$-1 down to 1.48$\sigma$ for the inclusive DFOS bin incSR$_{DFOS}$-12. Similar deviations are seen for the inclusive incSR$_{WZ}$-6 (1.48$\sigma$) and incSR$_{SFOS}$-7 (1.27$\sigma$) regions.

Table 6.18: Results of the model-independent fit in the discovery regions. The number of observed and expected yields, $N_{obs}$ and $N_{exp}$, are after the background-only fit, for the inclusive discovery regions. Upper limits at 95% CL on the visible cross-section ($\sigma_{vis}^{95}$), the number of signal events ($S_{obs}^{95}$), and the expected number of signal events ($S_{exp}^{95}$) are shown. Finally, the CL value calculated for SM-only hypothesis and the corresponding $p$-value ($p(s = 0)$) are listed. [139]
Model-dependent exclusion limits

In the absence of a significant deviation from the SM predictions, results have been interpreted as exclusion limits on the sparticle masses, independently for the $WZ$ and $Wh$ models targeted by the SRs.

The observed and expected exclusion limits for the $WZ$ model are shown in Figure 6.27 and discussed in what follows.

Figure 6.27: Observed (red solid line) and expected (dashed black line) exclusion limits on the masses $m_{\tilde{\chi}_{1}^{\pm}/\tilde{\chi}_{1}^{0}}$ and $m_{\tilde{\chi}_{1}^{0}}$ for the $WZ$ and $Wh$ models with three-lepton and missing transverse momentum in the final states. The yellow band corresponds to $\pm 1\sigma_{\text{exp}}$ systematic uncertainties. The dotted red lines represent the $\pm 1\sigma_{\text{theory}}$ uncertainties on the observed data from signal cross-section uncertainties. All limits are obtained at the 95% CL. On the left plot, the light and dark grey areas are the corresponding observed exclusion from similar analysis using the 8 TeV 20.3 fb$^{-1}$ dataset [53] and the searches for compressed spectra using the 13 TeV 139 fb$^{-1}$ dataset [140], respectively. [139]

In the case of the $WZ$ model, results from the SR$^{WZ}$ are considered for the $m_{\tilde{\chi}_{1}^{\pm}/\tilde{\chi}_{1}^{0}} > m_{Z}$, while limits on mass points with $m_{\tilde{\chi}_{1}^{\pm}/\tilde{\chi}_{1}^{0}} > m_{Z}$ are obtained via a combination of two set of results: those provided by the analysis targeting off-shell $WZ$-mediated decay, to which I did not make any contribution and it is described in [139], and the interpretation of the SR$^{Wh}$SRs for off-shell $WZ$ points. Although being optimised to target the $Wh$ scenario, the SR$^{Wh}$SRs have shown good sensitivity to the off-shell scenario of the $WZ$ model, as shown in the left-hand plot of Figure 6.28.

Finally, in the right-hand plot in Figure 6.28, the observed and expected exclusion limits for the $WZ$ model are shown, only for scenarios where $WZ$ are on-shell, obtained from the results in the SR$^{WZ}$ regions, dedicatedly optimised to be sensitive to
the WZ model. Overall, the results for the on-shell WZ analysis are able to exclude sparticle mass scenario up to \(m_{\tilde{\chi}^\pm_1/\tilde{\chi}^0_2} = 640 \text{ GeV}\) (for a massless LSP), with a clear improvement with respect to previous equivalent analysis using 36.1 fb\(^{-1}\) \(\sqrt{s} = 13\) TeV data [50]. Furthermore, the analysis reaches good sensitivity to models where the mass splitting is close to the kinematic edge \(m_{\tilde{\chi}^\pm_1/\tilde{\chi}^0_2} - m_{\tilde{\chi}^0_1} = m_Z\), improving the exclusion of scenarios with compressed spectra and low-mass sparticles with respect to previous results from the ATLAS collaboration.

The observed and expected exclusion limits on the \(Wh\) model are shown in Figure 6.27. The limits are calculated at 95% CL, using results in the SR\(_{Wh}^{\text{SFOS}}\) and SR\(_{Wh}^{\text{DFOS}}\) regions. The analysis is able to exclude sparticle mass scenarios up to \(m_{\tilde{\chi}^\pm_1/\tilde{\chi}^0_2} = 180 \text{ GeV}\) (for massless LSP), and shows sensitivity to signal models close to the kinematic edge \(m_{\tilde{\chi}^\pm_1/\tilde{\chi}^0_2} - m_{\tilde{\chi}^0_1} = m_h\), as clear improvement of the equivalent early Run-2 analysis, described in Section 6.1. The difference between the observed and the expected limits is due to the mild excess in the SR\(_{Wh}^{\text{DFOS}}\) \(-1\) region, and it is consistent with the 2\(\sigma\) excess seen in this region. In particular, Figure 6.29 shows the expected sensitivity to the \(Wh\) model calculated for just the SR\(_{Wh}^{\text{DFOS}}\) SRs, with reach expected exclusion for sparticle mass scenarios up to \(m_{\tilde{\chi}^\pm_1/\tilde{\chi}^0_2} = 210 \text{ GeV}\) (for massless LSP).
Figure 6.29: Observed (solid dark red line) and expected (dashed black line) limits on the masses of $\tilde{\chi}^+_1 \tilde{\chi}^0_2$ and $\tilde{\chi}^0_1$ for $Wh$ simplified models with three-lepton and missing transverse momentum in the final states. The yellow band corresponds to $\pm \sigma_{\text{exp}}$ systematic uncertainties. The dotted red lines represent the $\pm 1\sigma_{\text{theory}}$ uncertainties on the observed data from signal cross-section uncertainties. All limits are obtained at the 95% CL.
In this thesis, analyses for the searches for \( \tilde{\chi}_1^\pm \tilde{\chi}_2^0 \) production by the ATLAS experiment with \( \sqrt{s} = 13 \) TeV proton-proton collisions at the LHC are presented. The targeted simplified models are those with intermediate SM bosons, \( WZ \) and \( Wh \), decaying to final states with three light leptons and missing transverse momentum in the final states.

An early Run-2 analysis of 36.1 fb\(^{-1}\) data targeted only the \( Wh \) model in three-lepton final states. Although the analysis did not exclude any of the targeted SUSY scenario, it provided a training ground for the full Run-2 analysis, giving first hints of potential sensitivity for low-mass \( \tilde{\chi}_1^\pm \tilde{\chi}_2^0 \) and mass spectrum scenarios close to the kinematic edge \( m_{\tilde{\chi}_1^\pm/\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0} = m_h \). In this search, I made major contribution as the main analyser of the three-lepton channel.

The full Run-2 analysis of 139 fb\(^{-1}\) collision data targeted both the \( Wh \) and \( WZ \) simplified models. I contributed to the analysis as one of the main analysers, with focus on \( Wh \) and on-shell \( WZ \) channels. No significant excess in data with respect to the SM predictions has been observed, although a mild excess of 2\( \sigma \) is seen for one of the \( Wh \) search bins. Results have been then interpreted as exclusion limits on the targeted simplified models. For the \( WZ \) signal scenario, masses for the \( \tilde{\chi}_1^\pm \) and \( \tilde{\chi}_2^0 \) up to \( m_{\tilde{\chi}_1^\pm/\tilde{\chi}_2^0} = 640 \) GeV are excluded at 95% CL for massless \( \tilde{\chi}_1^0 \). This corresponds to an improvement of approximately 300 GeV with respect to previous equivalent analysis of 36.1 fb\(^{-1}\) data. For the \( Wh \) model, limits are set at 95% CL for masses up to \( m_{\tilde{\chi}_1^\pm/\tilde{\chi}_2^0} = 180 \) GeV for a massless \( \tilde{\chi}_1^0 \). The results for the standalone channel with three light leptons in the final states improve by approximately 30 GeV the Run-1 exclusion
CHAPTER 7. CONCLUSIONS AND OUTLOOK

obtained in combination with final states with hadronically decaying taus. Analysis results also show good sensitivity in SUSY scenarios with mass-splitting close to the diagonal $m_{\tilde{\chi}_1^\pm/\tilde{\chi}_2^0} - m_{\tilde{\chi}_1^0} = m_h$.

Despite no significant deviation from the SM has been observed, the searches for $\tilde{\chi}_1^\pm\tilde{\chi}_2^0$ with three-lepton final states provide an unique insight on the targeted SUSY scenarios, considerably improving the current exclusion limits and opening a window on the exploration of the challenging compressed scenarios for the sparticle mass spectrum. It will also provide a key contribution to the global fit of the MSSM [141], and provide inputs to the constraints on Dark Matter.

The summary plot in Figure 7.1 shows the most up-to-date expected and observed exclusion limits on the production of $\tilde{\chi}_1^\pm\tilde{\chi}_2^0$ decaying via intermediate bosons from the ATLAS collaboration, obtained from inputs of different analyses, including those described in this thesis.

![Figure 7.1: Observed and expected exclusion limits at 95% CL for the $\tilde{\chi}_1^\pm\tilde{\chi}_2^0$ searches via intermediate boson decays by the ATLAS experiment.][42]

The searches discussed in this thesis, and many other electroweak SUSY searches, will play a central role in the physics program of the ATLAS experiment during Run 3. In particular, the investigation of the $Wh$ model in the three-lepton channel, which, although providing already compelling results with the full Run-2, can benefit from increased luminosity to target challenging low-mass scenarios, and from exploitation of some advanced MVA-based techniques, both at the event-reconstruction level and
as part of the analysis strategy.

Exploration of electroweak SUSY models will also have an important role in view of the High-Luminosity LHC (HL-LHC) upgrade \cite{142}. Searches with leptons in the final states will benefit from the increased luminosity and improved analysis techniques which will be crucial in the hunt of elusive SUSY and other BSM scenarios. There is also scope to explore electroweak SUSY models also beyond the LHC era. Searches for production of charginos and neutralinos are part of the perspective physics programme of the main accelerator projects planned to start in the next few decades, both for linear $e^+e^-$ collider \cite{143} and circular hadronic colliders at $\sqrt{s} = 28$ TeV \cite{144} and $\sqrt{s} = 100$ TeV \cite{145}.

In conclusion, the results of the searches presented in this thesis provide an essential contribution to understanding the most fundamental symmetry laws of the Universe, by also setting the ground for future and important developments in the hunt for New Physics.
This appendix focuses on performance optimisation studies of a proposed tracking-based trigger upgrade of the ATLAS detector in view of the HL-LHC, to which I made a contribution for my ATLAS authorship Qualification Task (QT).

A.1 The LHC and ATLAS upgrades for high-luminosity

The HL-LHC is the planned long-term upgrade of the LHC, aimed at a dramatic increase of the instantaneous luminosity of the proton-proton collisions, essential preparation for the future physics programme of the LHC experiments [146]. Collisions at higher luminosity are important to open the chance to target rare processes not yet accessible at the luminosity currently planned for Run 3. Among other analyses, the increased luminosity will allow searches for elusive decays of the Higgs boson into leptons, di-Higgs production modes and heavy Higgs bosons. Also the BSM programme of the LHC experiments will benefit from the increased luminosity, as this will permit the exploration of challenging scenarios with low-\(p_T\) objects, particularly those with at least two light leptons and missing transverse energy in the final states. The main upgrades will particularly involve the injection complex, to allow more protons to populate the bunches in the beams. In particular, the HL-LHC is expected to collide protons at an instantaneous luminosity \(\mathcal{L} = 7.5 \cdot 10^{34} \text{ cm}^{-2} \text{ s}^{-1}\), providing collisions at \(\sqrt{s} = 14\) TeV, and start operations in the year 2026 with the so-called Run 4 of data taking. In parallel with the LHC upgrades, The ATLAS detector is expected to go through a series
A.2 ATLAS TDAQ architecture for the Phase-II upgrade

of upgrades, performed in stages [147, 148].

A first stage of upgrades will involve improvements in the electronic components of the TDAQ system and the CTP. In addition, New Small Wheels are expected to be installed in the end-cap regions to provide coincidence measurements to reject events where forward objects fire mistakenly a muon trigger chain.

In view of the HL-LHC, a new full silicon tracking detector, the so-called Inner TracKer (ITk) [149], will replace the current ID. During LS1, the radiation damages occurred during Run 1 were partly recovered by the insertion and commissioning of the IBL. However, further radiation damages by the end of the Run 3 will inevitably require the full replacement of the current ID. The current design of the ITk comprises both silicon strips and pixel detectors arranged in the barrel and end-cap regions. In the barrel region, the $50 \times 50 \mu m^2$ pixels are arranged on an axial geometry around the beam axis, for a total of five layers in the barrel. In the end-cap region, the pixel modules are disposed in rings around the beam axis. Their position ensures a constant number of hits across all the $\eta$ range, providing a coverage of the forward region $|\eta| < 4$. The silicon strip detector of the ITk comprises four double-layers silicon strip detectors in the barrel region and five disks in the end-cap, arranged in a cylindrical geometry around the beam axis. Overall, the strip detectors cover a region up to $|\eta| < 2.7$. The strips in the end-cap layers are distributed in a radial configuration, pointing at the beam axis and organised in rows for each of the five discs.

A.2 ATLAS TDAQ architecture for the Phase-II upgrade

Along with upgrades purely concerning the detector hardware and design, the architecture of the ATLAS TDAQ will be modified, due to the increased pile-up expected at HL-LHC. A schematic view of the proposed TDAQ structure for HL-LHC is visible in Figure A.1.

In one possible architecture, the Phase-II TDAQ structure is composed of three levels of event selection. At a very initial stage, L0 triggers are performed using features extracted from the calorimetry system and the muon chamber. The L0Calo uses hardware information to extract features of electron, photons, tau and jets. The com-
Figure A.1: Proposed structure of the TDAQ system for the ATLAS detector in view of the HL-LHC. Hits from the calorimetry system, the muon chambers and the inner tracker (in blue) are used in the trigger. The Level-0 (L0) of the trigger structure is represented in dark pink, while the Front-End LInk eXchange (FELIX) and the Data Handlers are represented in green. Finally the Dataflow step and the Event Filter are represented in yellow and red, respectively. [148]

Components able to perform such extraction are referred to as the electron Feature EXtractor (eFEX) and the jet Feature EXtractor (jFEX). In addition, L0Calo performs feature extraction for objects at low $p_T$ in the forward region, using the forward Feature EXtractor (fFEX) component. The L0Muon uses hits from the MS from the RPCs and TGCs and comprises Trigger Processors for the MDTs and the New Small Wheel (NSW). It is interfaced to the CTP through the MUon Central Trigger Processor Interface (MUCTPI). The Global Trigger is another component at the L0 of the TDAQ. It uses the granularity of the calorimeter towers to perform almost-offline algorithms on trigger objects reconstructed by L0Calo and L0Muon. The information is finally passed to the CTP that makes a final decision whether an event passes the L0 trigger step. If it
does, the decision is passed to the Trigger, Timing Control system (TTC) that will allow full readout of detector-wide information.

If an event passes the L0 trigger, it is passed through the Readout sub-system with comprises the FELIX and subsequently the Data Handler. The Readout sub-system collects and processes the specific inputs from the ATLAS sub-detector before being transferred to the Dataflow sub-system stream. The Dataflow sub-system is formed by the Event Handler, the Storage Handler and the Event Aggregator, where information from the Readouts is buffered and aggregated to form the event stream.

With the Data Acquisition (DAQ) as described, the event rate at this stage would still be approximately of the order of 1 MHz, too high to be managed by the CERN storage facilities. For this reason, all components of the DAQ are connected to an Event Filter (EF) system. The EF consists of both CPU-based and hardware-based trigger processing that make a further filter decision of the events before storing them permanently in the facilities. The EF uses information from the ITk to reconstruct tracks and vertexes and uses tracking information to make a decision on whether accept or not the events. The use of tracking informations in essential at this step. The main scope of the upgraded architecture of the TDAQ is to lower the event rate so as to meet storage limitations, while maintaining the same physics acceptance as in Run-1.

A.3 The Hardware-based Tracking for Trigger for the HL-LHC

The proposed Hardware-based Tracking for Trigger (HTT) system is composed of Associative Memory (AM) Application Specific Integrated Circuits (ASICs) for pattern recognition and Field Programmable Arrays (FPGAs) for track fitting, managed within a module called Pattern Recognition Mezzanine (PRM). It takes part in the EF step of the Phase-II architecture of the TDAQ. The pattern recognition and the track fitting steps are consecutive and provide information to the EF to decide whether an event can be stored or not. The EF can ask the HTT to perform two different types of tracking, according to the kind of trigger signature that needs to be tested. In one case, the HTT is requested to perform a regional tracking (rHTT) in specific RoIs, designed around those trigger ob-
jects identified by the L0 detectors with available track information, typically electrons, muons or jets. The rHTT is able to reduce the event rate down to 400 kHz. The other possibility is to run a global tracking (gHTT) across all the $\eta$ scan of the ITk. The gHTT generally provides better resolutions and purity than the rHTT, giving the possibility to the EF to make trigger decisions using information regarding lepton isolation, primary vertex reconstruction or $b$-jet-tagging, but with longer processing times.

Generally, the way HTT reconstructs tracks from hits in the ITk is based on pattern recognition. For both the rHTT and the gHTT configurations, hits from consecutive silicon strips and pixel modules of the ITk are initially clustered and aggregated in so-called superstrips. A sequence of superstrips is called a pattern, characterised by coordinates measured by the silicon modules of the ITk arranged in eight layers of the detector. Each pixel layer and each side of the double-sided strip layers count as a layer in the pattern identification. When a hit pattern is identified, this is compared to candidate template patterns, which are pre-created patterns obtained from simulated samples of single-muon events and stored in the FPGAs in collection called pattern banks. This operation is handled by the AM ASICs. After a hit pattern is matched to a template pattern, track parameters are extracted from pattern coordinates via a track fit in the FPGAs in the PRM. At this point, the response of the HTT changes according to the original request from the EF: the rHTT releases the informations back to the EF. If the gHTT is requested, the track fit is extended to the remaining layers of ITk to give best parameter resolutions.

### A.3.1 Track fitting in HTT

After the pattern recognition and matching, the track parameters are extracted from the coordinates of the superstrip hits that form the matched pattern. A linear correlation is assumed between the hit coordinates and track parameters. One can write:

$$p_i = \sum_{j=1}^{N} C_{ij} x_j + q_i,$$  \hspace{1cm} (A.1)

where $N$ indicates the total number of hit coordinates or layers in the pattern recognition, $p_i$ are the track parameters, $x_j$ are the superstrip coordinates and the $(C_{ij}, q_i)$ are fit parameters. As a reminder, the track parameters are those fully describing a track:
curvature, $\eta$, $\phi$, $d_0$ and $z_0$. Generally, the values of the constants depend on the position of the pattern and they are related to which modules of the detector have recorded hits for the pattern recognition. A sequence of tracker modules hit by the pattern matched is called a *sector*, which is identified by specific and unique values of $(C_{ij}, q_i)$. Therefore, track parameters can be extrapolated looking at all the sectors that describe the modules the pattern passes through. Finally, the track with minimum $\chi^2$ is selected as the reconstructed track.

A full coverage of all the sectors in the ITk is key for an accurate extraction of the track parameters. Generally, this is obtained by training all the possible sectors with simulated single-muon events, so that pre-defined fit parameters can be obtained and stored.

The track fit presents some limitation due to the available hardware. In fact, one would require as many sectors as possible to be stored in specific *sector banks* in the FPGAs, so that full coverage and high statistics for the extrapolation of the fit constants can be ensured throughout the track fit procedure. Nevertheless, this is subject to compelling hardware limitations, since the available storage space would hardly permit a large number of sectors to be saved. Approximately, the FPGAs are expected to contain not much more than 3000 sectors for the track-fitting step. In the following, a possible strategy to reduce the needed storage space for sector bank files is described.

### A.3.2 Reduction of storage space needed by track-fitting step

This section presents the core of my qualification task. As a reminder, the size of the sector banks is limited by the hardware storage capacities. Therefore, there is the need to reduce the size of the sector banks, without affecting performance and coverage of the HTT.

All the studies have been performed over ten thousand simulated single-muon events with $p_T$ of at least 4 GeV. The studies described here were performed by analysing the track fit efficiencies, calculated by using fitted tracks with a $\chi^2 < 40$, and residuals of the track parameters, calculated as difference between the fitted track parameters and the true values from simulation. The reconstruction resolution is calculated as Root Mean Square (RMS). When not specified, the nominal average interactions per
bunch crossing for HL-LHC of $<\mu> = 200$ is assumed by injection of simulated jets in the events.

At first, the reduction of the size of the sector banks was attempted by reducing the size of the single-muon training samples. Different numbers of training events were explored. In the following, results for sector banks trained with one million and fifteen millions muons are shown. The RMS on the residuals for the reconstruction of the $\eta$ are shown in Table A.1.

<table>
<thead>
<tr>
<th>Number of training muons</th>
<th>Number of sectors</th>
<th>Efficiency</th>
<th>RMS on $\eta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 million</td>
<td>3392</td>
<td>$99.11 \pm 0.26%$</td>
<td>0.002452</td>
</tr>
<tr>
<td>15 million</td>
<td>5183</td>
<td>$99.31 \pm 0.29%$</td>
<td>0.002340</td>
</tr>
</tbody>
</table>

Table A.1: Sector numbers, efficiency and RMS on $\eta$ comparison between two sector banks trained with one million and fifteen million simulated single-muons events.

Reducing the number of training muons corresponds to a reduction of the number of sectors, as expected. Reducing the number of training muons from fifteen million to one million reduces the number of sectors to be stored in the FPGAs by approximately 35%. Although no substantial difference is seen in terms of efficiency, a reduction of 4-5% of RMS is found. Therefore, the results suggest a clear loss in reconstruction performance, and simply reducing the number of training muons is not a viable strategy to meet the hardware limitations.

An alternative way was tested. Instead of reducing the training size of the sectors, sector banks trained with the highest available amount of muons were used. The production of the sector banks used around $30 \times 10^6$ muons in the training. Contrary to what was done for the results in Table A.1, the full-statistics sector banks were skimmed by applying a requirement on the number of training muons per sector, discarding those which do not fulfil the criterium. Applying a lower cut on the number of training muons presents a few advantages:

- The size of the bank file is reduced by a cut that can be optimised according to the required performances in the RoIs and as a function of training muon kinematic variables:

- The lower cut on the number of training muons will skim just those sectors which were trained with fewer particles.
Different lower cuts have been tested and compared to each other, in two different \( \eta \) intervals and with or without pile-up. Different \( \eta \) intervals were used to test the validity of the strategy at different RoIs. In all the cases, patterns are required to hit eight layers, one from the pixel modules and seven from the strips of the ITk.

In a first stage, sectors were produced in the \([0.1, 0.3]\) \( \eta \) interval. Pile-up is assumed to be the nominal \(<\mu> = 200\) of the HL-LHC. Resolutions for the five reconstructed track parameters are shown in Figure A.2 and Figure A.3, for a test on ten thousand single-muon events with \( p_T \) between 4 and 400 GeV.

Figure A.2: Resolution of \( d_0 \) and \( z_0 \), calculated as RMS. Calculated over ten thousand simulated single-muon events passing through ITk and requiring at least one pixel layer and seven strip layers to be hit by the particles. The targeted region is the \([0.1, 0.3]\) \( \eta \) interval. Pile-up is assumed to be the nominal of the HL-LHC, \(<\mu> = 200\).
Figure A.3: Resolution of curvature, $\eta$ and $\phi$, calculated as RMS. Calculated over ten thousand simulated single-muon events passing through ITk and requiring at least one pixel layer and seven strip layers to be hit by the particles. The targeted region is the $[0.1, 0.3] \eta$ interval. Pile-up is assumed to be the nominal of the HL-LHC, $<\mu> = 200$. 
As seen in Figure A.2 and Figure A.3, no clear difference in resolution is noticed for any of the track parameters, when comparing five different lower cuts on the number of training muons: 0, 40, 80, 120, 160. Efficiencies and number of sectors are shown in Table A.2. A lower cut at 40 on the number of training muons reduces the sample size by 35%, without any tangible effect on resolution and efficiencies.

<table>
<thead>
<tr>
<th># muon cuts</th>
<th>Number of sectors</th>
<th>Efficiency</th>
<th>RMS on $\eta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>5183</td>
<td>99.7 %</td>
<td>0.002340</td>
</tr>
<tr>
<td>40</td>
<td>3702</td>
<td>99.5 %</td>
<td>0.002331</td>
</tr>
<tr>
<td>80</td>
<td>3203</td>
<td>99.3 %</td>
<td>0.002319</td>
</tr>
<tr>
<td>120</td>
<td>2936</td>
<td>98.9 %</td>
<td>0.002307</td>
</tr>
<tr>
<td>160</td>
<td>2696</td>
<td>98.6 %</td>
<td>0.002312</td>
</tr>
</tbody>
</table>

Table A.2: Sector numbers, efficiency and RMS on $\eta$ for the five cuts on the number of training muons considered in the studies. The $\eta$ range considered is between 0.1-0.3 and pile-up from soft-scattering collisions assumed to be the nominal of the HL-LHC, $<\mu> = 200$.

The same performance studies have been performed in the [0.7,0.9] $\eta$ interval. In this case, the method is tested in a different RoI and without any effects due to additional pile-up jets. Results are shown in Figure A.4 and Figure A.5.

Similarly to the results in the [0.1, 0.3] $\eta$ interval, in Figure A.4 and Figure A.5 no drastic change in resolution is noticed for any track parameter. This is also reflected in Table A.3, although results indicate a tighter cut in the [0.7, 0.9] $\eta$ interval might be needed with respect to the first case analysed.

<table>
<thead>
<tr>
<th># muon cuts</th>
<th>Number of sectors</th>
<th>Efficiency</th>
<th>RMS on $\eta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>8185</td>
<td>97.9 %</td>
<td>0.001160</td>
</tr>
<tr>
<td>40</td>
<td>5039</td>
<td>97.7 %</td>
<td>0.001154</td>
</tr>
<tr>
<td>80</td>
<td>3988</td>
<td>97.3 %</td>
<td>0.001144</td>
</tr>
<tr>
<td>120</td>
<td>3337</td>
<td>96.7 %</td>
<td>0.001145</td>
</tr>
<tr>
<td>160</td>
<td>2877</td>
<td>96.0 %</td>
<td>0.001142</td>
</tr>
</tbody>
</table>

Table A.3: Sector numbers, efficiency and RMS on $\eta$ for the five cuts on the number of training muons considered in the studies. The $\eta$ range considered is between 0.7-0.9 and no pile-up from soft-scattering collisions is considered.
Figure A.4: Resolution of $d_0$ and $z_0$, calculated as RMS. Calculated over ten thousand simulated single-muon events passing through ITk and requiring at least one pixel layer and seven strip layers to be hit by the particles. The targeted region is the $[0.7, 0.9]$ $\eta$ interval. No pile-up is considered, $\langle \mu \rangle = 0$. 
A.3 The Hardware-based Tracking for Trigger for the HL-LHC

Figure A.5: Resolution of curvature, $\eta$, $\phi$, calculated as RMS. Calculated over ten thousand simulated single-muon events passing through ITk and requiring at least one pixel layer and seven strip layers to be hit by the particles. The targeted region is the $[0.7, 0.9]$ $\eta$ interval. No pile-up is considered, $<\mu> = 0$. 

Normalized events vs. $p_T - p_T^{\text{true}}$ [GeV]$^2$

Normalized events vs. $\eta - \eta^{\text{true}}$

Normalized events vs. $\phi - \phi^{\text{true}}$
A.3.3 Exploring the low-$p_T$ range

At this point, only muons with $p_T > 4$ GeV have been tested. Performance studies have been performed for low $p_T$ muons, to test the robustness of the sector reduction strategy even at low $p_T$. The studies presented in Section A.3.2 have been repeated for the $0.7 < |\eta| < 0.9$ interval, but for single-muon events with $p_T > 2$ GeV and 1 GeV. No pile-up is considered. As a consequence of lowering the $p_T$ range, more training muons are needed for the production of the sector banks. Sixty and ninety million training muons were used to cover the RoI coverage and statistics for the sector bank production in the two $p_T$ ranges $[2, 400]$ GeV and $[1, 400]$ GeV, respectively. Residual plots for the track parameters are shown in Figure A.6 and Figure A.7, for the $[2, 400]$ GeV $p_T$ range, and Figure A.8 and Figure A.9, for the $[1, 400]$ GeV $p_T$ range.

As Figure A.6-A.9 show, no substantial loss of resolution on the track parameter is observed, for all the considered lower cuts on the training muons and independently on the muon $p_T$ range. As done in Section A.3.2, the impact of the reduction of the number of sectors on the efficiencies was calculated. Results for the two $p_T$ ranges are shown in Table A.4 and Table A.5, respectively.

<table>
<thead>
<tr>
<th># muon cuts</th>
<th>Number of sectors</th>
<th>Efficiency</th>
<th>RMS on $\eta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>15521</td>
<td>98.23 %</td>
<td>0.001079</td>
</tr>
<tr>
<td>40</td>
<td>10119</td>
<td>98.20 %</td>
<td>0.001078</td>
</tr>
<tr>
<td>80</td>
<td>8632</td>
<td>98.15 %</td>
<td>0.001079</td>
</tr>
<tr>
<td>120</td>
<td>7792</td>
<td>98.10 %</td>
<td>0.001080</td>
</tr>
<tr>
<td>160</td>
<td>7213</td>
<td>98.07 %</td>
<td>0.001081</td>
</tr>
</tbody>
</table>

Table A.4: Sector numbers, efficiency and RMS on $\eta$ for the five cuts on the number of training muons considered in the studies. The $\eta$ range considered is between 0.7-0.9 and no pile-up from soft-scattering collisions is considered. Numbers refer to analysis of ten thousand muons with $p_T$ between 2 GeV and 400 GeV.
Table A.5: Sector numbers, efficiency and \text{RMS} on $\eta$ for the five cuts on the number of training muons considered in the studies. The $\eta$ range considered is between 0.7-0.9 and no pile-up from soft-scattering collisions is considered. Numbers refer to analysis on ten thousand muons with $p_T$ between 1 GeV and 400 GeV.

<table>
<thead>
<tr>
<th># muon cuts</th>
<th>Number of sectors</th>
<th>Efficiency</th>
<th>RMS on $\eta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>31601</td>
<td>98.78 %</td>
<td>0.001092</td>
</tr>
<tr>
<td>40</td>
<td>18992</td>
<td>98.75 %</td>
<td>0.001093</td>
</tr>
<tr>
<td>80</td>
<td>15695</td>
<td>98.72 %</td>
<td>0.001092</td>
</tr>
<tr>
<td>120</td>
<td>13877</td>
<td>98.66 %</td>
<td>0.001093</td>
</tr>
<tr>
<td>160</td>
<td>12691</td>
<td>98.61 %</td>
<td>0.001093</td>
</tr>
</tbody>
</table>

Figure A.6: Resolution of $d_0$ and $z_0$, calculated as \text{RMS}. Calculated over ten thousand simulated single-muon events passing through ITk and requiring at least one pixel layer and seven strip layers to be hit by the particles. The muon $p_T$ range is [2, 400] GeV. The targeted region is the [0.7, 0.9] $\eta$ interval. No pile-up is considered, $<\mu> = 0$. 
Figure A.7: Resolution of curvature, $\eta$, $\phi$, calculated as RMS. Calculated over ten thousand simulated single-muon events passing through ITk and requiring at least one pixel layer and seven strip layers to be hit by the particles. The muon $p_T$ range is $[2, 400]$ GeV. The targeted region is the $[0.7, 0.9]$ $\eta$ interval. No pile-up is considered, $<\mu>$ = 0.
Figure A.8: Resolution of $d_0$ and $z_0$, calculated as RMS. Calculated over ten thousand simulated single-muon events passing through ITk and requiring at least one pixel layer and seven strip layers to be hit by the particles. The muon $p_T$ range is [1, 400] GeV. The targeted region is the [0.7, 0.9] $\eta$ interval. No pile-up is considered, $\langle \mu \rangle = 0$. 

A.3 The Hardware-based Tracking for Trigger for the HL-LHC
Figure A.9: Resolution of curvature, $\eta$, $\phi$, calculated as RMS. Calculated over ten thousand simulated single-muon events passing through ITk and requiring at least one pixel layer and seven strip layers to be hit by the particles. The muon $p_T$ range is $[1, 400]$ GeV. The targeted region is the $[0.7, 0.9]$ $\eta$ interval. No pile-up is considered, $\langle \mu \rangle = 0$. 
As seen in Table A.4 and Table A.5, although clear evidence that the strategy can be extended to the low-$p_T$ case and no important loss of efficiency and resolution is noticeable across all the cuts tested. In particular, due to the increased statistics, at a lower $p_T$ threshold, a tighter cut on the number of training muons is needed for a substantial suppression of the number of sectors. This is shown also in Figure A.10, where the distribution of the average number of training muons per sector as a function of the lepton $p_T$ is presented for all three $p_T$ ranges considered in the studies.

![Figure A.10: Profiling of the number of training muons against their $p_T$. The three $p_T$ ranges between 4 GeV-400 GeV, 2 GeV-400 GeV and 1 GeV-400 GeV are shown.](image)

### A.4 Conclusions

In view of the HL-LHC operations of the ATLAS detector, the realisation of the full silicon ITk will open the window to several improvements of the trigger strategy and permit an efficient reconstruction of those events that are in the interest of the physics reach of the whole experiment. The proposed HTT uses information given by the ITk to skim events and improve the acceptance of interesting events. It uses hits in the pixel and strip modules of the ITk to reconstruct track parameters by fit in specific sectors. Sectors are trained with simulated muons and stored in specific files, and provide the fit parameters necessary for the extraction of key track variables. The size of the sector banks affects the performances of the HTT, and its size needs to meet demanding hardware limitations in terms of storage space. For my ATLAS authorship QT, I studied
a possible strategy to suppress the number of sectors, while maintaining performance and HTT efficiency. It was found that a lower cut on the number of training muons for the stored sectors reduces the number of sectors, without substantial loss of performance of the track fitting. The strategy, originally tested for muons with a $p_T$ of at least 4 GeV, has shown potential extension to the low-$p_T$ case, leaving room for further studies on a cut on the number of training muons as a function of the lepton $p_T$.

In conclusion, the overall HTT strategy shows clear benefit to the future ATLAS searches with leptons in the final stage, particularly those which target scenarios with low-$p_T$ objects. Regarding the models and results presented in this thesis, the upgraded ATLAS trigger strategy in view of the HL-LHC will certainly allow the analysis of new challenging, compressed mass-splitting scenarios as well as open a window into the exploration of new phenomena not yet observed.
## List of Acronyms

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>LEP</td>
<td>Large Electron-Positron collider</td>
</tr>
<tr>
<td>EWK</td>
<td>Electroweak</td>
</tr>
<tr>
<td>QED</td>
<td>Quantum Electrodynamics</td>
</tr>
<tr>
<td>QCD</td>
<td>Quantum Chromodynamics</td>
</tr>
<tr>
<td>QFT</td>
<td>Quantum Field Theory</td>
</tr>
<tr>
<td>BEH</td>
<td>Brout-Englert-Higgs</td>
</tr>
<tr>
<td>LSP</td>
<td>Lightest Supersymmetric Particle</td>
</tr>
<tr>
<td>SM</td>
<td>Standard Model</td>
</tr>
<tr>
<td>SUSY</td>
<td>Supersymmetry</td>
</tr>
<tr>
<td>MSSM</td>
<td>Minimal Supersymmetric Standard Model</td>
</tr>
<tr>
<td>BSM</td>
<td>Beyond the Standard Model</td>
</tr>
<tr>
<td>WIMP</td>
<td>Weakly Interacting Massive Particle</td>
</tr>
<tr>
<td>ISR</td>
<td>Initial State Radiation</td>
</tr>
<tr>
<td>FSR</td>
<td>Final State Radiation</td>
</tr>
<tr>
<td>LS</td>
<td>long shutdown</td>
</tr>
</tbody>
</table>
List of Acronyms

LS1  first long shutdown
LS2  second long shutdown
CERN  European Organization for Nuclear Research
LHC  Large Hadron Collider
HL-LHC  High-Luminosity LHC
RF  Radio-frequency
PSB  Proton Synchrotron Booster
PS  Proton Synchrotron
SPS  Super Proton Synchrotron
ID  Inner Detector
IBL  Insertable B-Layer
SCT  Semiconductor Tracker
TRT  Transition Radiation Tracker
ECal  Electromagnetic Calorimeter
EMEC  Electromagnetic End-cap Calorimeter
HCal  Hadronic Calorimeter
HEC  Hadronic End-cap Calorimeter
LAr  Liquid Argon
TileCal  Tile Calorimeter
FCal  Forward Calorimeter
MS  Muon Spectrometer
MDTs  Monitored Drift Tubes
CSCs  Cathod Strip Chambers
<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>RPCs</td>
<td>Resistive Plate Chambers</td>
</tr>
<tr>
<td>TGCs</td>
<td>Thin Gap Chambers</td>
</tr>
<tr>
<td>HLT</td>
<td>High-Level Trigger</td>
</tr>
<tr>
<td>L1</td>
<td>Level-1</td>
</tr>
<tr>
<td>L0</td>
<td>Level-0</td>
</tr>
<tr>
<td>TDAQ</td>
<td>Trigger and Data Acquisition</td>
</tr>
<tr>
<td>CTP</td>
<td>Central Trigger Processor</td>
</tr>
<tr>
<td>ROS</td>
<td>Read-Out Systems</td>
</tr>
<tr>
<td>RoI</td>
<td>Region of Interests</td>
</tr>
<tr>
<td>FTF</td>
<td>Fast Track Finder</td>
</tr>
<tr>
<td>NSW</td>
<td>New Small Wheel</td>
</tr>
<tr>
<td>ITk</td>
<td>Inner Tracker</td>
</tr>
<tr>
<td>RMS</td>
<td>Root Mean Square</td>
</tr>
<tr>
<td>QT</td>
<td>Qualification Task</td>
</tr>
<tr>
<td>eFEX</td>
<td>electron Feature EXtractor</td>
</tr>
<tr>
<td>jFEX</td>
<td>jet Feature EXtractor</td>
</tr>
<tr>
<td>fFEX</td>
<td>forward Feature EXtractor</td>
</tr>
<tr>
<td>MUCTPI</td>
<td>MUon Central Trigger Processor Interface</td>
</tr>
<tr>
<td>TTC</td>
<td>Trigger, Timing Control system</td>
</tr>
<tr>
<td>DAQ</td>
<td>Data Acquisition</td>
</tr>
<tr>
<td>FELIX</td>
<td>Front-End Link eXchange</td>
</tr>
<tr>
<td>EF</td>
<td>Event Filter</td>
</tr>
<tr>
<td>HTT</td>
<td>Hardware-based Tracking for Trigger</td>
</tr>
</tbody>
</table>
AM  Associative Memory

ASICs  Application Specific Integrated Circuits

FPGAs  Field Programmable Arrays

PRM  Pattern Recognition Mezzanine

rHTT  regional tracking

gHTT  global tracking

MC  Monte Carlo

FNP  Fake or Non-Prompt

VBF  Vector-Boson Fusion

SR  Signal Region

CR  Control Region

VR  Validation Region

SFOS  Same-Flavour Opposite-Sign

SFSS  Same-Flavour Same-Sign

DFOS  Different-Flavour Opposite-Sign

NF  Normalisation Factor

FF  Fake Factor

JVT  Jet Vertex Tagger

JES  Jet Energy Scale

JER  Jet Energy Resolution

PDF  Parton Distribution Functions

pdf  Probability Density Function

CL  Confidence Level
<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>LO</td>
<td>Leading Order</td>
</tr>
<tr>
<td>NLO</td>
<td>Next-to-Leading Order</td>
</tr>
<tr>
<td>NNLO</td>
<td>Next-to-Next-Leading Order</td>
</tr>
<tr>
<td>NLL</td>
<td>Next-to-Leading-Logarithm</td>
</tr>
<tr>
<td>NNLL</td>
<td>Next-Next-to-Leading-Logarithm</td>
</tr>
<tr>
<td>RDO</td>
<td>Raw Data Objects</td>
</tr>
<tr>
<td>AOD</td>
<td>Analysis Object Data</td>
</tr>
<tr>
<td>AFII</td>
<td>ATLFastII</td>
</tr>
<tr>
<td>NEWT</td>
<td>New Tracking</td>
</tr>
<tr>
<td>RoI</td>
<td>Region of Interest</td>
</tr>
<tr>
<td>LH</td>
<td>Likelihood</td>
</tr>
<tr>
<td>LCW</td>
<td>Local Cluster Weight</td>
</tr>
<tr>
<td>MVA</td>
<td>Multi-Variate Analysis</td>
</tr>
<tr>
<td>BDT</td>
<td>Boosted Decision Trees</td>
</tr>
</tbody>
</table>
List of Figures

2.1 Particle content of the SM. The six quarks (u, d, s, c, b and t) are shown in purple, the six leptons (e, μ, τ, νe, νμ and ντ) displayed in green, while the gauge bosons (g, γ, Z and W) and Higgs boson (H) are shown in red and yellow, respectively. Values of masses, electric charge and spin are also given for each particle. [2] .......................................................... 4

2.2 One-loop supersymmetric contributions to the anomalous magnetic momentum of the muon, involving chargino and sneutrino (left) and neutralino and smuon (right). [9] ................................................................. 9

2.3 The complex scalar potential $V(\phi)$ in the Brout-Englert-Higgs mechanism, shown in function of the real and imaginary components of the complex scalar field $\phi$. The potential presents a set of vacuum expectation values, lying on the same complex plane. [18] ......................................................... 13

2.4 The reconstructed mass of the Higgs boson, at the time of its first observation in 2012. On the left, the distribution of the four-lepton invariant mass from the $H \to ZZ^* \to 4\ell$ decay, as observed by ATLAS. On the right, the analogous distribution from the $H \to \gamma\gamma$ channel as measured by CMS.[19, 20] . 15

2.5 Fermionic one-loop correction to the mass of Higgs boson. ......................... 15

2.6 Rotation curves for the spiral galaxy NGC 3198. Observed data show agreement with the model which assumes a uniform distribution of matter across the core of the galaxy and the halo. [23] ................................................. 16
List of Figures

2.7 Running of the interaction couplings in the SM as a function of the energy scale, where $\alpha_1$ corresponds to the electromagnetic force coupling, $\alpha_2$ the strong force coupling and $\alpha_3$ the weak force coupling. \([24]\) ........................................ 17

2.8 Bosonic one-loop correction to the mass of Higgs boson. ................................. 18

2.9 Running of the couplings in the MSSM as a function of the energy scale, where $\alpha_1$ corresponds to the electromagnetic force coupling, $\alpha_2$ the strong force coupling and $\alpha_3$ the weak force coupling. \([24]\) ........................................ 20

2.10 Scalar cubic coupling in the MSSM. Interaction couplings $a$ of Higgs bosons to squark and sleptons are part of the MSSM parameters. \([27]\) ................................. 22

2.11 Channels for the production of gauginos and sleptons with hadronic initial states, with both contributions from $s$-channels mediated by gauge bosons and $t$-channels. In these diagrams, $\tilde{C}_i^\pm = \tilde{\chi}_i^\pm$ ($i=1, 2$) and $\tilde{N}_j^0 = \tilde{\chi}_j^0$ ($j=1, 2, 3, 4$). \([27]\) ......................................................... 26

2.12 Typical cross-sections for the production of sparticles at the LHC as a function of their masses. The assumed centre of mass energy is $\sqrt{s} = 13$ TeV. ............................... 26

2.13 Diagram for the production of chargino and neutralino, with decays via $W$ and $Z$ bosons. .......................................................... 28

2.14 Diagram for the production of chargino and neutralino, with decays via $W$ bosons and the Higgs boson $h$. .......................................................... 29

2.15 Observed and expected exclusion limits on the mass of the top-squark. The dataset corresponds to 20.3 fb$^{-1}$ data at $\sqrt{s} = 8$ TeV and 139 fb$^{-1}$ data at $\sqrt{s} = 13$ TeV in proton-proton collisions at the LHC, recorded by the ATLAS experiment. Limits are set at the 95% of confidence level. \([42]\) ........................................ 30

2.16 Observed and expected exclusion limits on the masses of the gluino. The dataset corresponds to 20.3 fb$^{-1}$ data at $\sqrt{s} = 8$ TeV and 139 fb$^{-1}$ data at $\sqrt{s} = 13$ TeV in proton-proton collisions at the LHC, recorded by the ATLAS experiment. Limits are set at the 95% of confidence level. \([42]\) ........................................ 31

2.17 Observed and expected exclusion limits on the masses of sleptons. The dataset corresponds to 139 fb$^{-1}$ data at $\sqrt{s} = 13$ TeV in proton-proton collisions at the LHC, recorded by the ATLAS experiment. Limits are set at the 95% of confidence level. \([45]\) ................................................................. 32
2.18 Observed and expected exclusion limits on the masses of charginos and neutralinos decaying via intermediate sleptons. The proton-proton collision data was recorded by the ATLAS experiment at $\sqrt{s} = 8$ TeV and $\sqrt{s} = 13$ TeV. All the limits but those for the $\tilde{\chi}_1^\pm \tilde{\chi}^0_2$ production are obtained by targeting channels with two leptons in the final states. Searches for $\tilde{\chi}_1^\pm \tilde{\chi}^0_2$ are presented as a combination of the three light lepton and two lepton channels. Limits are set at the 95% of confidence level. [42] .................. 33

2.19 Observed and expected exclusion limits on the masses of $\tilde{\chi}_1^\pm$ and $\tilde{\chi}^0_2$ and $\tilde{\chi}^0_1$ for the $Wh$ models. The dataset corresponds to 20.3 fb$^{-1}$ data collected at $\sqrt{s} = 8$ TeV proton-proton collisions by the ATLAS experiment. Exclusion limits are obtained through a combination of channels with three light leptons, one leptonic $\tau$ and two light leptons and two leptonic $\tau$ and a light lepton. Limits are set at the 95% of confidence level. [53] ............... 34

2.20 Observed and expected exclusion limits on the masses of $\tilde{\chi}_1^\pm$ and $\tilde{\chi}^0_2$ and $\tilde{\chi}^0_1$ for the $WZ$ model. The dataset corresponds to 36.1 fb$^{-1}$ of proton-proton collision data collected at $\sqrt{s} = 13$ TeV by the ATLAS experiment. Exclusion limits are obtained by combining the three-lepton and two-lepton channels. All limits are set at the 95% of confidence level. [50] ............... 34

2.21 Observed and expected exclusion limits on the masses of $\tilde{\chi}_1^\pm$ and $\tilde{\chi}^0_2$ and $\tilde{\chi}^0_1$ for the $Wh$ and the $WZ$ models. The dataset corresponds to 35.9 fb$^{-1}$ of proton-proton collision data collected at $\sqrt{s} = 13$ TeV by the CMS experiment. Exclusion limits are shown for channels with one lepton plus photons, the two leptons and at least three leptons in the final states, and the two-lepton and three-lepton channels, for the $Wh$ and the $WZ$ models, respectively. All limits are set at the 95% of confidence level. [52] .............. 35

2.22 Summary of observed and exclusion limits on the masses of $\tilde{\chi}_1^\pm$ and $\tilde{\chi}^0_2$ and $\tilde{\chi}^0_1$ for the $WZ$, $Wh$ and $WW$ models. The datasets correspond to 36.1 fb$^{-1}$ data collected in 13-TeV proton-proton collisions at the LHC by the ATLAS experiment. Limits are obtained by combining the three-lepton and two-lepton channels. Limits are set at the 95% of confidence level. [42] .......... 36

3.1 A schematic view of the CERN acceleration complex. [56] ................. 39
List of Figures

3.2  Cumulative integrated luminosity delivered to the ATLAS experiment during the data taking years in Run 1 and Run 2, as measured by the LUCID2 detector. [65] ................................................................. 40

3.3  A schematic view of the main components of the ATLAS detector. [59] .... 41

3.4  Delivered and recorded luminosity as measured by the ATLAS experiment during the LHC Run-2. [65] ................................................................. 42

3.5  Schematic view of the magnet system of the ATLAS detector. [66] .... 44

3.6  Digital-graphic representation of the ATLAS tracker detector. ............... 45

3.7  Schematic view of the calorimetry system of the ATLAS detector. [59] .... 47

3.8  Sketch of the setup of the barrel module of the ECal of the ATLAS detector. Each of the modules is split into three different components with increasing granularity. [59] ................................................................. 48

3.9  Schematic view of the muon system of the ATLAS detector. [59] .... 50

3.10 Schematic description of the ATLAS TDAQ system architecture used in Run 2. [70] ................................................................. 52

4.1  Schematic representation of the data flow in the ATLAS ATHENA framework prior to physics analysis. ................................................................. 56

4.2  Proton PDF as measured by the H1 and ZEUS deep inelastic scattering experiments, at a scale of $\mu^2 = 10 \, GeV^2$. The $xu_v$ and $xu_d$ represent the PDF of valence up-quarks and down-quarks. PDF for the gluons, $xg$, and the sea-quarks $xS = 2x(\bar{U} + \bar{D})$, are scaled down by a factor of 20. Experimental and modelling uncertainties are included. [78] ................................................................. 57

4.3  Distribution of the mean number of interactions per bunch crossing, $<\mu>$, for the different years of data-taking in Run 2. [65] ................................................................. 61

4.4  Performance of the working points for the LH-based identification of electrons. The upper panel shows efficiencies in data for the three working points: the Loose (blue) presents the highest efficiency with respect to the Medium (red) and Tight (tight). The lower panel shows the ratio between data and MC. Only data collected between 2015-2017 is used. Statistical and systematic uncertainties are considered. [108] ................................................................. 66
4.5 Performance of the working points for isolation of electrons. The upper panel shows efficiencies in data for different working points. The lower panel shows the ratio between data and MC. Only data collected between 2015-2016 is used, and only statistical uncertainties are shown. [106] 67

4.6 Performance of the working points for the identification of muons. Upper panel shows efficiencies in data and MC for the Medium working point. The lower panel shows ratio between data and MC. Only data collected in 2015 is used for a total of 3.2 fb\(^{-1}\). Statistical and systematic uncertainties are considered. [110] 70

4.7 Pictorial representation of the general behaviour of the \texttt{AntiKt4EMTopo} algorithm, showing all the possible clustering configurations. Instances of clusters with high momentum and conical reconstructed shape are shown as blue and red cones. An example of isolated low-momentum clusters are represented in cyan and pink. Finally, an instance of a low-momentum cluster in proximity of a high-energy deposit is shown in magenta. [115] 72

4.8 The fraction of jets as a function of the discriminant of the MV2, namely \(D_{MV2}\). Distribution for the background \(c\)-jets (green) and light-jets (red) and the signal \(b\)-jets (blue) are shown. [120] 74

5.1 Diagrams for the production of chargino and neutralino, decaying to three-lepton final states via (a) \(WZ\) and (b) \(Wh\) bosons. The channel with exactly three light leptons in the final states is considered. 80

5.2 A schematic illustration of the angular variables defined for the DFOS selection. See text for more details. 86

5.3 Illustration of the interplay between CRs, VRs and SRs. The arrows represent the extrapolation of NFs from the CRs to the VRs and SRs. [133] 91

5.4 Definition of the p-value as the probability of the data to be consistent with the null hypothesis under which the pdf of the test statistics was built. [137] 96

5.5 Definition of the p-values \(p_{b+s}\) and \(p_{b}\), defined under the alternative hypothesis and the null hypothesis pdf, respectively. The test-statistics \(q\) corresponds to the likelihood ratio in Equation 5.13. [137] 97
6.1 $E_T^{\text{miss}}$ distribution in the CR3L-onZ-highMET, after background-only fit. All systematic and statistical uncertainties are considered. [138] .................................. 101

6.2 In the upper panel, yields of observed data and expected background in VR3L-offZ-HighMET (last bin), after the background-only fit. In the lower panel, the data on SM predictions ratio for all the regions are reported. Systematic and statistical uncertainties are considered. [138] .................................. 102

6.3 Distribution of $E_T^{\text{miss}}$ in the VRSS-ee VR, used to demonstrate the goodness of the FNP background estimation for the multileptonic channels examined in the early Run-2 $Wh$ analysis. [138] .......................................................... 103

6.4 N-1 distributions of observed data and SM expectation for (a) the $E_T^{\text{miss}}$ in the SR3L-DFOS-0J region, (b) the $m_{\ell_{\text{DFOS}}+\ell_{\text{near}}}$ in the SR3L-DFOS-1Jb region and (c) the $m_{T}^{\text{min}}$ in the SR3L-SFOS-1J region. The lower panel shows the ratio between the observed data and the SM expectation. The SR selections but the cut on the shown variables are applied. Systematic and statistical uncertainties are considered. [138] .......................................................... 106

6.5 Observed and expected 95% CL upper limits on the cross-section for the (a) $3\ell$ channel of searches of $\tilde{\chi}_1^{\pm} \tilde{\chi}_2^{0}$ via $Wh$ decays and (b) in comparison to all the consider channels: full-hadronic, $1\ell + bb$, $1\ell + \gamma\gamma$ and $\ell^{\pm}\ell^{\pm}$. Different values of $m_{\tilde{\chi}_1^{\pm}/\tilde{\chi}_2^{0}}$ up to 240 GeV are considered, when $m_{\tilde{\chi}_1^{\pm}/\tilde{\chi}_2^{0}} - m_{\tilde{\chi}_1^{0}} = 130$ GeV. [138] .......................................................... 108

6.6 In the upper panel, the distributions of the number $n_{\text{jets}}$ of light jets for events passing the preselection and the DFOS flavour-sign requirement. The sensitivities $Z_n$ curves are calculated for possible upper cuts on the given variable and assuming a flat 30% total uncertainty on the SM background. .......................................................... 111

6.7 In the upper panels, the distributions of the $E_T^{\text{miss}}$ and $E_T^{\text{miss}}$ significance for events passing the pre-selection criteria and the DFOS flavour-sign selection. All the sensitivities $Z_n$ curves are calculated for possible lower cuts on the given variables and assuming a flat 30% total uncertainty on the SM background. .......................................................... 112

6.8 Correlation between $E_T^{\text{miss}}$ and the $E_T^{\text{miss}}$ significance variables for (a) the $t\bar{t}$ process and (b) the $Wh$ signal point $Wh(175, 0)$. .......................................................... 112
6.9 In the upper panels, the distributions of the $\Delta R_{OS, \text{near}}$ and the $p_T^{f3}$ for events passing the pre-selection criteria and the DFOS flavour-sign selection. All the sensitivities $Z_n$ curves but those in the $\Delta R_{OS, \text{near}}$ distribution are calculated for possible lower cuts on the given variables and assuming a flat 30% total uncertainty on the SM background.

6.10 N-1 distributions for the SR$_{DFOS}$Wh-1 (first column) and SR$_{DFOS}$Wh-2 (second column) regions. The upper panels show distribution for relevant background processes and chosen benchmark $Wh$ signal points, the arrows show the position and the verse of the cuts on the $p_T$ of the third lepton (first row), the $E_T^{\text{miss}}$ significance (second row) and the $\Delta R_{OS, \text{near}}$ (third row). The significance $Z_n$ is calculated assuming a flat 30% total uncertainty on the SM background.

6.11 In the upper panels, the distributions of the $m_{\ell\ell}$ for events passing the preselection criteria and the SFOS requirement. In the lower pad, the sensitivity $Z_n$ is calculated for (a) a lower cut and for (a) an upper cut on the shown variable. Sensitivity is calculated assuming a 10% flat total uncertainties on the SM background.

6.12 In the upper panels, the distributions of the $m_T$ in the SR$_{WZ}$ selection, split into categories of events with (a) $n_{jets} = 0$, and (b) $n_{jets} > 0$ and $H_T > 200$ GeV. In each lower panel, the sensitivity $Z_n$ curve is calculated by assuming a 15% of total uncertainty on the SM background and for possible lower cuts on the shown variables.

6.13 In the upper panels, the distribution of the $p_T$ of the third lepton in the VRFF$_{WZ}$, for two flavour channels (c) $\mu\mu e$ and (d) $\mu\mu\mu$. In the lower pad, ratio between data and SM prediction is shown. Systematic and statistical uncertainties are considered.

6.14 In the upper panels, the distribution of the (a) $E_T^{\text{miss}}$ and (b) $\Delta R_{OS, \text{near}}$ in the VRtt$^{WZ}$. In the lower pad, ratio between data and SM prediction is shown. Systematic and statistical uncertainties are considered. [139]
6.15 In the upper panels, the distribution of the (a) $p_T$ of the third lepton and (b) $E_T^{\text{miss}}$ significance in the $\text{VRt}_{\bar{t}}^{WZ}$. In the lower pad, ratio between data and SM prediction is shown. Systematic and statistical uncertainties are considered. .......................................................... 121

6.16 In the upper panels, the distribution of the (a) $E_T^{\text{miss}}$, (b) $\Delta R_{\text{OS, near}}$, (c) $p_T$ of the third lepton and (d) the number $n_{b\text{-jets}}$ of $b$-tagged jets in the $\text{VRt}_{\bar{t}}^{WZ}$. In the lower pad, ratio between data and SM prediction is shown. Systematic and statistical uncertainties are considered. .......................................................... 122

6.17 In the upper panels, distributions of $m_T$ in the $\text{CRWZ}_{\bar{W}Z}$, before the background-only fit. Events are selected in all the hadronic binning considered in the optimisation of the SRs: (a) $n_{\text{jets}} > 0$, (b) $n_{\text{jets}} = 0$ and $H_T < 200 \text{ GeV}$, and (c) $n_{\text{jets}} > 0$ and $H_T > 200 \text{ GeV}$. In the lower panels, data on background ratio is compared to the error band, including statistical and systematic uncertainties on the SM background. .......................................................... 123

6.18 Relative uncertainties in the (a) $\text{SR}_{\text{Wh}}^{\text{Wh, SFOS}}$ and $\text{SR}_{\text{Wh}}^{\text{Wh, DFOS}}$, and (b) the $\text{SR}_{\bar{W}Z}$ regions. All sources of systematics and statistical uncertainties considered in the analysis are reported. [139] .......................................................... 125

6.19 Data on SM predictions comparisons in all the CRs and VRs considered for the background estimation. In the upper panel, the yields of background processes and data in all the regions. In the lower panel, the comparison between data and SM prediction is expressed as relative difference (in red) for the CR, calculated before the background-only fit, and as significance for the VRs (in black), after the background-only fit. Statistical and systematic uncertainties on the SM backgrounds are considered. [139] .......................................................... 126

6.20 In the upper panels, distributions of $m_T$ in the $\text{CRWZ}_{\bar{W}Z}$ (left-hand column) and the $\text{VRWZ}_{\bar{W}Z}$ (right-hand column), after the background-only fit. Events are selected in all the hadronic binning categories considered in the optimisation of the SRs $n_{\text{jets}} = 0$ (first row), and $n_{\text{jets}} > 0$ and $H_T < 200 \text{ GeV}$ (second row). In the lower panels, data on background ratio is compared to the error band, including statistical and systematic uncertainties on the SM background. .......................................................... 127
6.21 In the upper panels, distributions of $m_T$ in the CRWZ$^{WZ}$ (left-hand column) and the VRWZ$^{WZ}$ (right-hand column), after the background-only fit. Events are selected in the hadronic binning category $n_{\text{jets}} > 0$ and $H_T > 200$ GeV considered in the optimisation of the SRs. In the lower panels, data on background ratio is compared to the error band, including statistical and systematic uncertainties on the SM background. [139] ............................................ 128

6.22 In the upper panels, distributions of $n_{\text{jets}}$ in the CRWZ$^{WZ}$, (a) before and (b) after the background-only fit. In the lower panels, data on background ratio is compared to the error band, including statistical uncertainties on the SM background. .......................................................... 128

6.23 In the upper panels, the observed data and SM prediction yields in the SR targeting the $Wh$ model. The lower panel show the significance for the data and SM expectation, accounting for the full set of systematic and statistical uncertainties. [139] .......................................................... 129

6.24 In the upper panels, the observed data and SM prediction yields in the SR targeting the $WZ$ model. The lower panel show the significance for the data and SM expectation, accounting for the full set of systematic and statistical uncertainties. [139] .......................................................... 129

6.25 In the upper panels, data and SM background distributions of (a) $E_T^{\text{miss}}$ and (b) $m_T$ in the $SR_{WZ}^{Wh}$ selection, and (c) $p_T$ of the 3rd lepton and (d) $\Delta R_{\text{OS, near}}$ in the $SR_{DFOS}^{Wh}$-2 and $SR_{DFOS}^{Wh}$-1 regions, respectively. In the lower panels, data on background ratio are compared to the error band, which includes all the statistical and systematic uncertainties on the background. [139] ................. 132

6.26 In the upper panels, data and SM background distributions of (a) the $p_T$ of the 3rd lepton, (b) $\Delta R_{\text{OS, near}}$ and (c)-(d) $E_T^{\text{miss}}$ significance, in the $SR_{DFOS}^{Wh}$-1 (first column) and $SR_{DFOS}^{Wh}$-2 (second column) regions. In the lower panels, data on background ratio are compared to the error band, which includes all the statistical and systematic uncertainties on the background. ............ 133
6.27 Observed (red solid line) and expected (dashed black line) exclusion limits on the masses $m_{\tilde{\chi}_1^\pm/\tilde{\chi}_2^0}$ and $m_{\tilde{\chi}_1^0}$ for the $WZ$ and $Wh$ models with three-lepton and missing transverse momentum in the final states. The yellow band corresponds to $\pm \sigma_{\text{exp}}$ systematic uncertainties. The dotted red lines represent the $\pm 1\sigma_{\text{theory}}$ uncertainties on the observed data from signal cross-section uncertainties. All limits are obtained at the 95% CL. On the left plot, the light and dark grey areas are the corresponding observed exclusion from similar analysis using the 8 TeV 20.3 fb$^{-1}$ dataset [53] and the searches for compressed spectra using the 13 TeV 139 fb$^{-1}$ dataset [140], respectively. [139]

6.28 Observed (solid dark red line) and expected (dashed black line) limits on the masses of $\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$ and $\tilde{\chi}_1^0$ for $WZ$ simplified models with three-lepton and missing transverse momentum in the final states. The yellow band corresponds to $\pm \sigma_{\text{exp}}$ systematic uncertainties. The dotted red lines represent the $\pm 1\sigma_{\text{theory}}$ uncertainties on the observed data from signal cross-section uncertainties. All limits are obtained at the 95% CL.

6.29 Observed (solid dark red line) and expected (dashed black line) limits on the masses of $\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$ and $\tilde{\chi}_1^0$ for $Wh$ simplified models with three-lepton and missing transverse momentum in the final states. The yellow band corresponds to $\pm \sigma_{\text{exp}}$ systematic uncertainties. The dotted red lines represent the $\pm 1\sigma_{\text{theory}}$ uncertainties on the observed data from signal cross-section uncertainties. All limits are obtained at the 95% CL.

7.1 Observed and expected exclusion limits at 95% CL for the $\tilde{\chi}_1^\pm/\tilde{\chi}_2^0$ searches via intermediate boson decays by the ATLAS experiment. [42]

A.1 Proposed structure of the TDAQ system for the ATLAS detector in view of the HL-LHC. Hits from the calorimetry system, the muon chambers and the inner tracker (in blue) are used in the trigger. The L0 of the trigger structure is represented in dark pink, while the FELIX and the Data Handlers are represented in green. Finally the Dataflow step and the Event Filter are represented in yellow and red, respectively. [148]
A.2 Resolution of $d_0$ and $z_0$, calculated as RMS. Calculated over ten thousand simulated single-muon events passing through ITk and requiring at least one pixel layer and seven strip layers to be hit by the particles. The targeted region is the $[0.1, 0.3] \eta$ interval. Pile-up is assumed to be the nominal of the HL-LHC, $<\mu> = 200$. ................................................................. 148

A.3 Resolution of curvature, $\eta$ and $\phi$, calculated as RMS. Calculated over ten thousand simulated single-muon events passing through ITk and requiring at least one pixel layer and seven strip layers to be hit by the particles. The targeted region is the $[0.1, 0.3] \eta$ interval. Pile-up is assumed to be the nominal of the HL-LHC, $<\mu> = 200$. ................................................................. 149

A.4 Resolution of $d_0$ and $z_0$, calculated as RMS. Calculated over ten thousand simulated single-muon events passing through ITk and requiring at least one pixel layer and seven strip layers to be hit by the particles. The targeted region is the $[0.7, 0.9] \eta$ interval. No pile-up is considered, $<\mu> = 0$. ............... 151

A.5 Resolution of curvature, $\eta$, $\phi$, calculated as RMS. Calculated over ten thousand simulated single-muon events passing through ITk and requiring at least one pixel layer and seven strip layers to be hit by the particles. The targeted region is the $[0.7, 0.9] \eta$ interval. No pile-up is considered, $<\mu> = 0$. 152

A.6 Resolution of $d_0$ and $z_0$, calculated as RMS. Calculated over ten thousand simulated single-muon events passing through ITk and requiring at least one pixel layer and seven strip layers to be hit by the particles. The muon $p_T$ range is $[2, 400]$ GeV. The targeted region is the $[0.7, 0.9] \eta$ interval. No pile-up is considered, $<\mu> = 0$. ......................... 154

A.7 Resolution of curvature, $\eta$, $\phi$, calculated as RMS. Calculated over ten thousand simulated single-muon events passing through ITk and requiring at least one pixel layer and seven strip layers to be hit by the particles. The muon $p_T$ range is $[2, 400]$ GeV. The targeted region is the $[0.7, 0.9] \eta$ interval. No pile-up is considered, $<\mu> = 0$. ......................................................... 155
A.8 Resolution of $d_0$ and $z_0$, calculated as RMS. Calculated over ten thousand simulated single-muon events passing through ITk and requiring at least one pixel layer and seven strip layers to be hit by the particles. The muon $p_T$ range is $[1, 400]$ GeV. The targeted region is the $[0.7, 0.9]$ $\eta$ interval. No pile-up is considered, $<\mu> = 0$. .......................... 156

A.9 Resolution of curvature, $\eta$, $\phi$, calculated as RMS. Calculated over ten thousand simulated single-muon events passing through ITk and requiring at least one pixel layer and seven strip layers to be hit by the particles. The muon $p_T$ range is $[1, 400]$ GeV. The targeted region is the $[0.7, 0.9]$ $\eta$ interval. No pile-up is considered, $<\mu> = 0$. .......................... 157

A.10 Profiling of the number of training muons against their $p_T$. The three $p_T$ ranges between 4 GeV-400 GeV, 2 GeV-400 GeV and 1 GeV-400 GeV are shown. .......................... 158
LIST OF TABLES

2.1 Summary of the main properties of the SM leptons. [4] ............................. 6
2.2 Summary of the main properties of the SM quarks. [4] ............................. 7
2.3 List of the supermultiplets in the MSSM. Chiral and gauge multiplets are shown. In the case of leptons and quarks, only one generation is reported; two additional sets of chiral supermultiplets are to be considered to account for a total of three families of fermions and SUSY counterparts. [27] ............ 20
2.4 The MSSM parameters introduced by the soft SUSY breaking. Only first generation of scalar quarks and leptons are considered in this table. ......................... 21

4.1 Working points for isolation of electrons used in the analyses described here. [108] 67
4.2 Working points for isolation of electrons used in the analyses described here. [110] 71

5.1 Features of the MC samples for the targeted SUSY models $WZ$ and $Wh$. In the last column, the ranges of nominal cross sections for the production of $\tilde{\chi}^+_1$ and $\tilde{\chi}^0_2$ at given $m_{\tilde{\chi}^+_1}/m_{\tilde{\chi}^0_2}$. .................................................. 80
5.2 Di-lepton trigger chains used for all analyses presented in this thesis, listed by year of data taking. .................................................... 81
5.3 Single-lepton trigger chains used for the early Run-2 analysis presented in Section 6.1, listed by year of data taking. ................................................. 81
5.4 SM processes which are significant background for the considered analyses, where $V = W, Z$. ......................................................... 82

6.1 Definitions of the $3\ell$ DFOS SRs used in the early Run-2 $Wh$ analysis. [138] . . 100
6.2 Definitions of the 3ℓ SFOS SRs used in the early Run-2 \( Wh \) analysis. [138] 100

6.3 List of cuts for the definition of the CR3L-on\( Z \)-HighMET CR and the VR3L-off\( Z \)-HighMET VR, used for the estimation and the validation of the \( WZ \) background in the early Run-2 3ℓ \( Wh \) search. Region definitions extracted from Ref. [138]. 102

6.4 Uncertainties in units of number of events in the DFOS SRs. Different sources of uncertainties can correlate and the total does not necessarily correspond to the squared sum of all the contributions. The category "experimental" comprises the detector systematic uncertainties and the ones related to the FNP data-driven estimation. Numbers extracted from Ref. [138]. 104

6.5 Uncertainties in units of number of events in the SFOS SRs. Different sources of uncertainties can correlate and the total does not necessarily correspond to the squared sum of all the contributions. The category "experimental" comprises the detector systematic uncertainties and the ones related to the FNP data-driven estimation. Numbers extracted from Ref. [138]. 104

6.6 Observed data and expected yields from the relevant SM backgrounds for the region SR3L-DFOS-0J, SR3L-DFOS-1Ja and SR3L-DFOS-1Jb. The \( W+Z \) NF after the background-only fit is applied. The category “Higgs MC” comprises the SM \( t\bar{t}H \) production. All uncertainties are considered and symmetrised around the nominal post-fit yields, negative errors are truncated at the zero event yields. Numbers extracted from Ref. [138]. 105

6.7 Observed data and expected yields from the relevant SM backgrounds for the region SR3L-SFOS-0Ja, SR3L-SFOS-0Jb and SR3L-SFOS-1J. The \( W+Z \) NF after the background-only fit is applied. The category “Higgs MC” comprises the SM \( t\bar{t}H \) production. All uncertainties are considered and symmetrised around the nominal post-fit yields, negative errors are truncated at the zero event yields. Numbers extracted from Ref. [138]. 105

6.8 The observed 95% CL upper limits on the visible cross-section \( \sigma_{\text{vis}} \) and the observed and expected number of events from BSM signal model \( S_{\text{obs}}^{95} \) and \( S_{\text{exp}}^{95} \) are shown in the first three columns for each SR. The correspondent discovery \( p_0 \)-value is reported in the last column. Systematic and statistical uncertainties are considered. [138] 107
6.9 Summary of the selection criteria for SRs targeting events with a DFOS lepton pair, for the $Wh$ selection. Preselection criteria are applied. [139] 113

6.10 Summary of the selection criteria for SRs targeting events with at least one SFOS lepton pair and $m_{ll} \in [75, 105]$ GeV, for the $SR^{WZ}$ search regions. Region selections are binned by $m_T$ (rows) and $E_T^{miss}$ for the two sets of regions, where each set has different $n_{jets}$, and $H_T$ requirements. Preselection criteria are applied. [139] 117

6.11 Summary of the selection criteria for SRs targeting events with at least one SFOS lepton pair and $m_{ll} \notin [75, 105]$ GeV, for the $Wh$ search regions. Region selections binned by $m_T$ (rows) and $E_T^{miss}$ for the three sets of regions, where each set has different $m_{ll}$, $n_{jets}$, and $H_T$ requirements. Preselection criteria are applied. [139] 117

6.12 Summary of the background estimation methods used for the full Run-2 analysis detailed in this thesis. The category "Others" includes the $WW$, $ZZ$, $t\bar{t}+V$ ($V=W,Z$), single-top and processes with a Higgs boson. 118

6.13 Summary of the selection criteria for the CRs and VRs for $t\bar{t}$ and FNP estimation, for the $SR^{WZ}$ and $SR^{Wh}_{SFOS}$ selections. Preselection criteria are applied for $VR^{t\bar{t}WZ}$, $VR^{t\bar{t}inc}$ and $VR^{FNP}_{WZ}$ regions. [139] 121

6.14 Summary of the selection criteria for the CRs and VRs for $WZ$, for the $SR^{WZ}$ and $SR^{Wh}_{SFOS}$ selections. Preselection criteria are applied. In rows where only one value is given it applies to all regions. [139] 124

6.15 Observed and expected yields after the background-only fit in the SRs for the $SR^{Wh}_{SFOS}$ and $SR^{Wh}_{DFOS}$ selection. The “Others” category contains the single-top, $WW$, $t\bar{t}+V$ and rare top processes. Statistical and systematic uncertainties are presented. [139] 130

6.16 Observed and expected yields after the background-only fit in the SRs for the $SR^{WZ}$ selection. The “Others” category contains the single-top, $WW$, triboson, Higgs and rare top processes. Statistical and systematic uncertainties are presented. [139] 131

6.17 Summary of the selection criteria for the inclusive SRs in the $SR^{WZ}$, $SR^{Wh}_{SFOS}$ and $SR^{Wh}_{DFOS}$ selections. [139] 134
6.18 Results of the model-independent fit in the discovery regions. The number of observed and expected yields, $N_{\text{obs}}$ and $N_{\text{exp}}$, are after the background-only fit, for the inclusive discovery regions. Upper limits at 95% CL on the visible cross-section ($\sigma^{95}_{\text{vis}}$), the number of signal events ($S^{95}_{\text{obs}}$), and the expected number of signal events ($S^{95}_{\text{exp}}$) are shown. Finally, the CL value calculated for SM-only hypothesis and the correspondent $p$-value ($p(s = 0)$) are listed. [139]

A.1 Sector numbers, efficiency and RMS on $\eta$ comparison between two sector banks trained with one million and fifteen million simulated single-muons events.

A.2 Sector numbers, efficiency and RMS on $\eta$ for the five cuts on the number of training muons considered in the studies. The $\eta$ range considered is between 0.1-0.3 and pile-up from soft-scattering collisions assumed to be the nominal of the HL-LHC, $<\mu> = 200$.

A.3 Sector numbers, efficiency and RMS on $\eta$ for the five cuts on the number of training muons considered in the studies. The $\eta$ range considered is between 0.7-0.9 and no pile-up from soft-scattering collisions is considered.

A.4 Sector numbers, efficiency and RMS on $\eta$ for the five cuts on the number of training muons considered in the studies. The $\eta$ range considered is between 0.7-0.9 and no pile-up from soft-scattering collisions is considered. Numbers refer to analysis of ten thousand muons with $p_T$ between 2 GeV and 400 GeV.

A.5 Sector numbers, efficiency and RMS on $\eta$ for the five cuts on the number of training muons considered in the studies. The $\eta$ range considered is between 0.7-0.9 and no pile-up from soft-scattering collisions is considered. Numbers refer to analysis on ten thousand muons with $p_T$ between 1 GeV and 400 GeV.

https://cds.cern.ch/record/2315477. 35 pages.


[38] 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*, arXiv:2004.14060 [hep-ex].


