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

Licentiate thesis

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Abstract

The Large Hadron Collider (LHC) located at the European Organization for Nuclear Research (CERN) is the most powerful particle accelerator in the world in terms of collision energy and luminosity. This thesis presents a search for supersymmetric particles in proton-proton collision data recorded by the ATLAS experiment.

A search for direct production of chargino and slepton pairs in a final state characterised by the presence of two leptons and missing transverse momentum is presented. This analysis is done using \( \mathcal{L} = 20 \text{ fb}^{-1} \) proton-proton collisions at \( \sqrt{s} = 8 \text{ TeV} \) collected in 2012. No significant excess over background is observed. Exclusion limits at 95% confidence level on chargino, neutralino and slepton production are set.

In 2011-12 the LHC was providing collisions every 50 ns. This puts very strong requirements on the energy measurement in presence of energy deposits from different collisions in the same read-out window and in the same calorimeter channel (pile-up). A quality factor computed offline for each collision and for each channel in the ATLAS Tile Calorimeter (TileCal) is studied. It is shown that the quality factor can be used to select channels that need a special treatment to account for large energy deposition from pile-up. Efficient criteria to detect pile-up in TileCal channels are proposed.
Acknowledgments

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Chapter 1

Introduction

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

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

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

Currently, the best description of particle physics phenomena is given by the theory called the Standard Model (SM). The SM has been extensively tested
during the last four decades and has shown great predictive power. However, there are a few observed phenomena that are not explained by the Standard Model as discussed in Chapter 2. Therefore, a new theory is needed. One of the theories tested with ATLAS is Supersymmetry (SUSY) which is also the main subject of this thesis.

1.1 About this thesis

The work presented in this thesis is about data analysis and detector performance studies I performed on data collected with the ATLAS detector. Part I is a theoretical overview which provides the motivation for the LHC and the ATLAS experiment. Chapter 2 is dedicated to a short presentation of the Standard Model along with its shortcomings. Supersymmetry, a proposed theoretical extension of the SM is introduced in Chapter 3.

Experimental facilities are presented in Part II. Chapter 4 presents the LHC and the design of the ATLAS experiment along with its subsystems. Chapter 5 gives a more detailed description of the Tile Calorimeter (TileCal). The question of pile-up collisions and a method for its identification using a quality factor in each calorimeter channel of TileCal is presented in Chapter 6. The quality factor studies are also presented in Papers I - III.

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

This thesis uses the convention of natural units where $c = \hbar = 1$, where $c$ is the speed of light and $\hbar$ is the reduced Planck constant. Consequently, masses, momenta and energies are given in GeV.
1.2 Author’s contribution

The attached papers are:


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

1.2 Author’s contribution

As a PhD student at Stockholm University my first task was to study the quality factor of pulse shapes in the ATLAS Tile Calorimeter. For this purpose I developed the TileCal pulse simulator. I implemented in this model several effects like variations in signal pulse shapes, timing miscalibrations and implemented the double Gaussian model of the calorimeter noise. I showed that the simulator was able to reproduce the quality factor distributions in collisions in absence of out-of-time pile-up. Then I included the effect of out-of-time pile-up. Using the distributions of quality factor with and without out-of-time pile-up obtained with pulse simulator I have proposed a selection criteria to identify out-of-time pile-up. This work fully performed by myself is presented in **Papers I - III. Paper I** presents an early stage of the study. **Paper III** presents the latest results together with the full description of the method. **Paper II** shows the performance of the signal reconstruction in TileCal which were performed by members of the TileCal collaboration. This paper which I presented on behalf of the ATLAS Tile Calorimeter group contains also the quality factor studies I have carried out.

Next, I started to work on the analysis of ATLAS data. The goal of the
work was to search for chargino and slepton direct pair production. I worked on the jet-veto developed by the Stockholm group. I developed the jet-veto definition. I showed that the jet-veto efficiency in data is well reproduced by Monte Carlo simulation, therefore it can by utilised in the analysis. This work is utilised in Paper IV and Paper V (see below).

I also performed an estimation of ZV background using a method we proposed. The ZV background is one of the dominant backgrounds in the analysis. The developed method was used in Paper IV and Paper V.

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

- The analysis described in Paper IV is a public conference result performed on \( \mathcal{L} = 20.7 \text{ fb}^{-1} \) of 2012 data. For this analysis I have studied the jet-veto performance as described in Chapter 8 of this thesis. I also contributed to the ZV-background estimation using a method similar to the one described in Chapter 9.

- A second analysis of ATLAS 2012 data is going to be described in Paper V and published in JHEP. The paper is at an advanced review stage in ATLAS. In this analysis a reprocessed dataset of recalculated total integrated luminosity \( \mathcal{L} = 21.7 \text{ fb}^{-1} \) is used. Jet-veto calculations using the same method as described in Chapter 8 were performed by me in order to check that the same conclusions apply there too. In this paper in preparation I also performed all calculations for the ZV background and developed the method. The ZV-background estimation method was improved by reoptimising control region definitions. This method is described in Chapter 9 which reflects the method as implemented in the upcoming Paper V and thus slightly different from Paper IV.

I contributed to the following papers not attached to this thesis:

**Paper V:** The ATLAS Collaboration, * Searches for direct production of charginos, neutralinos and sleptons in final states with two leptons and missing transverse momentum in pp collisions at \( \sqrt{s} = 8 \text{ TeV} \) with the ATLAS detector*, in preparation to be submitted to JHEP, 2014.

**Paper VI:** C. Clément et al., *Searching for direct gaugino production and direct slepton production with two leptons and missing transverse momentum in 13 fb\(^{-1}\) of pp collisions at \( \sqrt{s} = 8 \text{ TeV} \)*, ATL-PHYS-INT-2013-002, 2013.
1.2 Author’s contribution

Part I

Theoretical Overview
Chapter 2

The Standard Model of Particle Physics

The twentieth century physicists combined quantum mechanics and special relativity to create quantum field theory which became the mathematical language of the Standard Model of particle physics (SM) [2–4]. The SM is the theory describing observed elementary particle phenomena. It has been extensively tested during the last four decades and shows great predictive power [5].

A general description of matter particles in the Standard Model is given in Section 2.1. Section 2.2 gives a short introduction to fundamental interactions in the SM. The Higgs boson is briefly described in Section 2.3. Finally, shortcomings of the Standard Model are discussed in Section 2.4.

2.1 Elementary Matter Particles

In the Standard Model, matter consists of spin 1/2 fermions obeying Fermi-Dirac statistics. They are divided into quarks and leptons. Quarks are sensitive to the strong nuclear interaction in contrast to leptons which do not interact strongly. The fermions are grouped into three generations. There are two quarks, one charged and one neutral lepton (called neutrino) in each generation. The visible and stable matter in our universe is made of the first generation fermions [6]. Quarks and leptons from higher generations rapidly decay into lighter particles. The exception is neutrinos which do not decay,
they oscillate between generations instead [7].

All the fermions have antiparticles differing only by the sign of the electric charge. In case of quarks and neutral leptons the antiparticles are denoted by the same symbol as the partners with a bar added over it. Antiparticles of charged leptons are denoted with a positive electric charge. Table 2.1 lists the fermions along with some of their properties.

<table>
<thead>
<tr>
<th>Type</th>
<th>Name</th>
<th>Symbol</th>
<th>Mass [MeV]</th>
<th>Electric charge [e]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quarks</td>
<td>up</td>
<td>$u$</td>
<td>2.3</td>
<td>+2/3</td>
</tr>
<tr>
<td>(spin=1/2)</td>
<td>down</td>
<td>$d$</td>
<td>4.8</td>
<td>-1/3</td>
</tr>
<tr>
<td></td>
<td>strange</td>
<td>$s$</td>
<td>95</td>
<td>-1/3</td>
</tr>
<tr>
<td></td>
<td>charm</td>
<td>$c$</td>
<td>1275</td>
<td>+2/3</td>
</tr>
<tr>
<td></td>
<td>bottom</td>
<td>$b$</td>
<td>4180</td>
<td>-1/3</td>
</tr>
<tr>
<td></td>
<td>top</td>
<td>$t$</td>
<td>$173.5 \cdot 10^3$</td>
<td>+2/3</td>
</tr>
<tr>
<td>Leptons</td>
<td>electron</td>
<td>$e$</td>
<td>0.511</td>
<td>-1</td>
</tr>
<tr>
<td>(spin=1/2)</td>
<td>muon</td>
<td>$\mu$</td>
<td>105.7</td>
<td>-1</td>
</tr>
<tr>
<td></td>
<td>tau</td>
<td>$\tau$</td>
<td>1777</td>
<td>-1</td>
</tr>
<tr>
<td></td>
<td>electron neutrino</td>
<td>$\nu_e$</td>
<td>&lt; 0.002</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>muon neutrino</td>
<td>$\nu_\mu$</td>
<td>&lt; 0.19</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>tau neutrino</td>
<td>$\nu_\tau$</td>
<td>&lt; 18.2</td>
<td>0</td>
</tr>
</tbody>
</table>

Table 2.1: The Standard Model elementary fermions and their properties. The electric charge is expressed in term of the elementary charge $e$ [8].

### 2.2 Fundamental Interactions

In Nature four fundamental interactions have been observed: strong, electromagnetic, weak and gravitational. The first three are described by the Standard Model. Gravity is described by General Relativity. The list of fundamental interactions and their mediators is presented in Tab. 2.2. The effect of gravity on elementary particles is negligible compared to that of the other interactions and impossible to observe with present particle physics experiments. Effect of gravity becomes comparable to Standard Model interactions at very high energy scale, of the order of $10^{19}$ GeV, well beyond current or planned experiments. The Standard Model describes the fundamental interactions by the exchange of spin 1 bosons obeying Bose-Einstein statistics that are mediating the interactions. Table 2.3 lists the bosons along
with some of their properties.

<table>
<thead>
<tr>
<th>Interaction</th>
<th>Mediator name</th>
<th>Symbol</th>
<th>Relative strength</th>
<th>Flavour conservation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strong</td>
<td>gluon</td>
<td>$g$</td>
<td>10</td>
<td>✓</td>
</tr>
<tr>
<td>Electromagnetic</td>
<td>photon</td>
<td>$\gamma$</td>
<td>$10^{-2}$</td>
<td>✓</td>
</tr>
<tr>
<td>Weak</td>
<td>$W, Z$</td>
<td>$W^\pm, Z^0$</td>
<td>$10^{-13}$</td>
<td>✗</td>
</tr>
<tr>
<td>Gravity</td>
<td>graviton*</td>
<td>$G$</td>
<td>$10^{-42}$</td>
<td>-</td>
</tr>
</tbody>
</table>

*hypothetical

Table 2.2: The fundamental interactions of Nature with their mediators. The strong, electromagnetic and weak interaction are described by the Standard Model [6]. “✓” means the flavour is conserved, “✗” means the flavour is not conserved, “–” means the flavour conservation is not predicted by the SM.

<table>
<thead>
<tr>
<th>Type</th>
<th>Name</th>
<th>Symbol</th>
<th>Mass [MeV]</th>
<th>Electric charge [e]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gauge bosons</td>
<td>photon</td>
<td>$\gamma$</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>(spin=1)</td>
<td></td>
<td>$W^\pm$</td>
<td>$80.4 \cdot 10^3$</td>
<td>±1</td>
</tr>
<tr>
<td></td>
<td>$Z$</td>
<td>$Z^0$</td>
<td>$91.2 \cdot 10^3$</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>gluon</td>
<td>$g$</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Higgs boson</td>
<td>Higgs</td>
<td>$H$</td>
<td>$126 \cdot 10^4$</td>
<td>0</td>
</tr>
<tr>
<td>(spin=0)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 2.3: The Standard Model elementary bosons and their properties. The electric charge is expressed in term of elementary charge $e$ [8].

The strong interaction

The strong force is responsible for holding the quarks together in hadrons (e.g. protons, neutrons) and nucleons in atomic nuclei and is described by the theory of Quantum Chromodynamics (QCD) [9]. It conserves flavour and acts upon particles carrying colour charge, quarks and gluons. The strong interaction is mediated by the gluon. Gluons carry colour charge, therefore they can also interact with each other. There are eight massless, electrically neutral gluons. The quarks can carry one of three colour charges: red, green and blue. Antiparticles carry inverted colour charge, “anticolour”. A free quark has never been observed. They are always found in colourless bound
states called hadrons. Bound states of three quarks are called baryons (e.g. proton, neutron). A quark-antiquark pair bound states are called mesons (e.g. pions). The phenomenon that colour particles cannot be isolated singularly is called colour confinement. A phenomenological explanation is that the strength of the strong force increases with the distance between coloured particles. Approximately at a distance of 1 fm (typical size of a hadron), it is energetically favourable to produce an extra quark-antiquark pair from the vacuum. This process leads to the creation of a spray of hadrons travelling approximately in the same direction as initial quark and is called a hadronic jet.

The electromagnetic interaction

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

The weak interaction

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

$$n \rightarrow p + e^- + \bar{\nu}_e \quad (2.1)$$

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

$$d \rightarrow u + W^- \rightarrow u + e^- + \bar{\nu}_e \quad (2.2)$$

Figure 2.1 illustrates this process. In the Standard Model the weak and electromagnetic interactions are combined together in a more fundamental
2.3 The Higgs Boson

Without any additional ingredient the Standard Model predicts the mediators of electroweak interactions to be massless. This is wrong since the $W^\pm$ and $Z^0$ bosons are observed experimentally with masses of 80.4 GeV and 91.2 GeV respectively. The photon remains massless. Therefore, a mechanism to provide massive gauge bosons is included in the Standard Model. The so called BEH (Brout-Englert-Higgs) mechanism \cite{10,11} allows to solve this problem.

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

On July 4 2012 it was announced that the Higgs boson was discovered by the ATLAS \cite{12} and CMS \cite{13} experiments at the LHC. Its properties are being probed in order to find out if the new particle is the Standard Model Higgs boson or an indication of beyond SM theory. So far it is in very good agreement with a Standard Model Higgs boson \cite{14,15}.
2.4 Shortcomings of the Standard Model

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

Gravitation

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

Origin of neutrino masses

The Standard Model predicts that neutrinos are massless particles since the BEH mechanism does not give them mass unlike other fermions. Nevertheless, various measurements of solar, atmospheric and reactor neutrinos show that neutrinos have small masses and can oscillate between the generations [7]. Neutrino masses could however be incorporated to the Standard Model by adding new free parameters.

Dark matter and dark energy

Astronomical observations of the movements of galaxies and stars inside galaxies as well as cosmological measurements [16] suggest that the visible matter constitutes only approximately 4.9% of the mass in the Universe. Another 26.8% of its mass is believed to be made up of so called dark matter [17]. It has not been detected through strong or electromagnetic interaction. It was
only observed indirectly through gravitational effects, therefore it is called dark. Neutrinos were considered as good candidates [18]. Nevertheless, they are not abundant and not heavy enough to constitute a significant part of the dark matter of the Universe. The Standard Model does not provide a good candidate of dark matter particle. The remaining 68.3% of the mass of the Universe is believed to be made up of so called dark energy [19,20] that is even less understood than dark matter.

Hierarchy problem

The Higgs boson \((m_H)\) mass can be expressed as a sum of so called bare mass and contributions from quantum corrections:

\[
m^2_{H} = (m^2_{H})_0 + \frac{kg^2\Lambda^2}{16\pi^2} \tag{2.3}
\]

where \((m_H)_0\) is the bare mass, \(k\) is a constant and \(g\) is the coupling constant between fermions and the Higgs field. The last term corresponds to loop corrections involving virtual particles such as the top quark presented in Fig. 2.2. The factor \(\Lambda\) corresponds to the energy scale up to which these processes are calculated. This scale is a cut-off scale above which the Standard Model is no longer valid and new physics should be taken into account. If no new physics appears before the Plank Scale then the quantity \(\Lambda\) is set to a value of the order of \(10^{19}\) GeV. The mass of the Higgs boson measured by ATLAS and CMS experiments is \(m_H = 126\) GeV [12,13]. This is 16 orders of magnitude smaller than the quantum loop corrections. Thus there must be some extraordinary cancellation between nominally uncorrected correction terms. This problem is often referred to as the hierarchy problem or fine tuning problem.

![Figure 2.2: A diagram of a one-loop quantum correction to the Higgs mass.](image-url)
Beyond the Standard Model

In order to address the problems discussed above, a theory of physics beyond the Standard Model is needed. Searching for physics beyond the SM is the main goal of the experiments at the Large Hadron Collider (LHC). There are several new theories being tested. One of them is called Supersymmetry (SUSY). In Supersymmetry models the Lightest Supersymmetric Particle (LSP) could be stable and weakly interacting, thus remaining undetected. Due to its predicted properties the LSP can be a good dark matter candidate, so called Weakly Interacting Massive Particle (WIMP). In Chapter 3 we discuss briefly the Supersymmetry which is also the subject of Paper IV.
Chapter 3

Supersymmetry

In the early 1970s a symmetry that relates fermions and bosons was proposed. “Supersymmetry” (SUSY) [21–24] was introduced to resolve some of the Standard Model shortcomings. A supersymmetric transformation turns a bosonic state into a fermionic one and vice versa. In this way every Standard Model particle has a supersymmetric partner called a superpartner. The superpartners have all quantum numbers and couplings equal to their SM counterparts except for the spin. Their spin differs by 1/2. Every SM fermion (with spin 1/2) has a spin 0 superpartner. Similarly, every SM boson (with spin 1) has a superpartner with spin 1/2.

The nomenclature for supersymmetric particles, so called “sparticles”, adds a prefix “s” to the SM fermion names and adds suffix “ino” to the SM boson names. The new particles (sparticles) are denoted by the same symbols as their Standard Model partners, but with a tilde on top. For instance, the superpartners of leptons are called sleptons, \( \tilde{\ell}^{\pm} \) (selectron - \( \tilde{e} \), smuon - \( \tilde{\mu} \), stau - \( \tilde{\tau} \), sneutrino - \( \tilde{\nu} \)). The so-called left- (right-) handed sleptons are the spin zero superpartners of the left- (right-) handed leptons. A subscript \( L \) (\( R \)) is used to denote the SUSY partners of left- (right-) SM particles. Superpartners of quarks are called squarks (sup - \( \tilde{u} \), sdown - \( \tilde{d} \), sbottom - \( \tilde{b} \), stop - \( \tilde{t} \)) and superpartners of gauge bosons are called gauginos. In this thesis we reserve the term gauginos for either neutralinos (\( \tilde{\chi}^0_i \), \( i = 1, 2, 3, 4 \)) or charginos (\( \tilde{\chi}^{\pm}_i \), \( i = 1, 2 \)). They are mass eigenstates formed from the linear superposition of the SUSY partners of the Higgs and electroweak gauge bosons, higgsinos, winos and binos. The superpartner of the gluon is referred to as gluino in this thesis.
If Nature was exactly supersymmetric all the superpartners would have the same mass as their Standard Model partners. This is obviously not true, since no such particles have been observed to date. Therefore Supersymmetry, if it is a theory describing Nature, must be broken. The mass of the superpartners has to be larger than the mass of Standard Model partners, otherwise the superpartners would have been already observed experimentally.

3.1 MSSM and pMSSM

The Minimal Supersymmetric Standard Model (MSSM) [25–28] is the simplest supersymmetric extension of the Standard Model. In this model each SM particle has exactly one superpartner.

Lepton number $L$ and baryon number $B$ are conserved in the Standard Model. This prevents the proton from decaying. This is not necessarily the case in the MSSM. The experimental lower limit on the proton mean life time is $2.1 \cdot 10^{29}$ years [29]. Therefore, in MSSM a new multiplicative quantum number called is $R$-parity introduced to prevent fast proton decay. It is defined as:

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

(3.1)

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

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

Table 3.1 lists the MSSM sparticles and Higgs bosons with some of their properties.

MSSM introduces more than 100 additional free parameters compared to the Standard Model. Such an amount of arbitrariness makes the model unpredictable and impossible to investigate experimentally. Therefore, the so called
3.1 MSSM and pMSSM

<table>
<thead>
<tr>
<th>Type</th>
<th>Symbol</th>
<th>Spin</th>
<th>R-parity</th>
</tr>
</thead>
<tbody>
<tr>
<td>Squarks</td>
<td>$\tilde{u}_L \tilde{u}_R \tilde{d}_L \tilde{d}_R$</td>
<td>0</td>
<td>-1</td>
</tr>
<tr>
<td></td>
<td>$\tilde{s}_L \tilde{s}_R \tilde{c}_L \tilde{c}_R$</td>
<td>0</td>
<td>-1</td>
</tr>
<tr>
<td></td>
<td>$\tilde{t}_1 \tilde{t}_2 \tilde{b}_1 \tilde{b}_2$</td>
<td>0</td>
<td>-1</td>
</tr>
<tr>
<td>Sleptons</td>
<td>$\tilde{e}_L \tilde{e}_R \tilde{\nu}_e$</td>
<td>0</td>
<td>-1</td>
</tr>
<tr>
<td></td>
<td>$\tilde{\mu}_L \tilde{\mu}<em>R \tilde{\nu}</em>\mu$</td>
<td>0</td>
<td>-1</td>
</tr>
<tr>
<td></td>
<td>$\tilde{\tau}_1 \tilde{\tau}<em>2 \tilde{\nu}</em>\tau$</td>
<td>0</td>
<td>-1</td>
</tr>
<tr>
<td>Neutralinos</td>
<td>$\chi^0_1 \chi^0_2 \chi^0_3 \chi^0_4$</td>
<td>1/2</td>
<td>-1</td>
</tr>
<tr>
<td>Charginos</td>
<td>$\chi^\pm_1 \chi^\pm_2$</td>
<td>1/2</td>
<td>-1</td>
</tr>
<tr>
<td>Gluino</td>
<td>$\tilde{g}$</td>
<td>1/2</td>
<td>-1</td>
</tr>
<tr>
<td>Higgs bosons</td>
<td>$h^0 H^0 A^0 h^\pm$</td>
<td>0</td>
<td>+1</td>
</tr>
</tbody>
</table>

Table 3.1: The Minimal Supersymmetric Standard Model predicted sparticles and some of their properties. Indices 1, 2 are used for $\tilde{t}$, $\tilde{b}$ and $\tilde{\tau}$ due to possible mixing between $L$ and $R$ states. The MSSM Higgs bosons are also listed.

The phenomenological Minimal Supersymmetric Standard Model (pMSSM) [30, 31] has been introduced. The pMSSM is a version of $R$-parity conserving MSSM with 19/20 free parameters. The pMSSM with a neutralino as a LSP has 19 parameters. The 20th parameter is the mass of the gravitino, the hypothetical supersymmetric partner of the graviton. In pMSSM the number of free parameters is reduced compared to MSSM by imposing the following guiding principles:

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

Part III of this thesis presents a search for pMSSM signals and more specifically a search for direct production of chargino pairs and slepton pairs in proton-proton collisions recorded by the ATLAS experiment.
3.2 Supersymmetry and Shortcomings of the Standard Model

Several shortcomings of the Standard Model have been discussed in Chapter 2. The SM model is believed to be a low energy approximation of a more fundamental theory. Supersymmetry was developed to extend the Standard Model in an attempt to answer questions left open by the SM.

As explained in Section 3.1, in models with \( R \)-parity conservation the supersymmetric particles are produced in pairs. The absolutely stable LSP with no electric charge nor colour charge, i.e. interacting only weakly and gravitationally, is an excellent WIMP Dark Matter candidate [18,32]. Such a particle, if produced in proton-proton collisions recorded by ATLAS, would leave the detector undetected giving rise to so called missing energy described in more details in Section 4.2.8.

The SM particles and their superpartners have cancelling contributions to the radiative corrections to the Higgs mass given in Eq. 2.3. An unnatural fine tuning is not needed and the hierarchy problem is elegantly solved in presence of supersymmetric particles. Since no supersymmetric particles are experimentally observed, it is concluded that Supersymmetry must be broken resulting in heavier superpartners. If the sparticle masses are not much larger than 1 TeV, Supersymmetry can still solve the hierarchy problem. A fine tuning is still necessary but to a much lesser degree.

Another theoretical motivation for Supersymmetry is the unification of the coupling constants of the electromagnetic, weak and strong interactions. It is believed that these interactions should unify at so called Grand Unified Theory (GUT) scale [28]. In this theory electromagnetic, weak and strong interactions would be different low energy manifestations of the same fundamental force. If coupling constants are expressed as effective values with loop corrections included in the gauge boson propagator they become energy dependent running parameters. In order to unify at the GUT scale the coupling constants have to converge to a common value. The energy dependence of the coupling constants is dependent on the particle content of the model. The evolution of the inverse of the gauge couplings with the energy in the framework of the Standard Model and the Minimal Supersymmetric Standard Model is presented on Fig. 3.1. In the SM the couplings do not converge at the same point. With the particle content of SUSY they tend to converge at the same value around \( 10^{16} \) GeV.
3.3 Supersymmetry Weak Production

The production cross section of the supersymmetric particles depends on the masses and couplings of the SUSY particles. Figure 3.2 shows the cross section for the production of various supersymmetric particles as a function of the particle mass. It can be seen that the coloured sparticles (squarks and sgluinos) produced in strong interactions have significantly larger cross section than colourless sparticles (sleptons, charginos and neutralinos) of equal mass produced in weak interactions. The direct production of weakly interacting slepton pairs or gaugino pairs can be dominating at the LHC over squarks and gluiness if the masses of squarks and gluinos are much higher than masses of sleptons, charginos and neutralinos. It would be true if the masses squarks were above 1.5 TeV and masses of weak gauginos less than around 400 GeV. Squark masses up to $m_{\tilde{q}} = 1.7$ TeV for neutralino mass $m_{\tilde{\chi}_1^0} = 350$ GeV are excluded in process such as $\tilde{q} \rightarrow q\tilde{\chi}_1^0$ [33].

Part III of this thesis is dedicated to a search for direct chargino and direct slepton pair production. Such a search could still be sensitive to Supersymmetry even if squarks and gluiness were very heavy and out of reach.
Figure 3.2: Cross sections for the production of various supersymmetric particles as a function of the particle mass in $\sqrt{s} = 8$ TeV collisions at the LHC calculated at NLO with PROSPINO [34].
Part II

Experimental Overview
Chapter 4

LHC and ATLAS Detector

4.1 The Large Hadron Collider

The Large Hadron Collider (LHC) [35] is located at the European Organization for Nuclear Research (CERN), in the area around the Swiss-French border outside Geneva. The machine is housed in a 27 km long circular tunnel located approximately 100 meters underground, previously used by the Large Electron Positron Collider (LEP). At the LHC, two counter rotating proton beams containing bunches of up to $10^{11}$ protons collide at a centre of mass energy $\sqrt{s} = 8$ TeV (and up to $\sqrt{s} = 14$ TeV in nominal conditions). A design instantaneous luminosity of the LHC is $10^{34}$ cm$^{-2}$s$^{-1}$ or $10$ nb$^{-1}$s$^{-1}$, where 1 barn (b) is $10^{-24}$ cm$^2$. This makes the LHC the most powerful particle accelerator in the world in terms of collision energy and luminosity. The instantaneous luminosity is defined as:

$$L = \frac{f k N_1 N_2}{4\pi \sigma_x \sigma_y}$$

(4.1)

where $f$ is the proton bunch orbit frequency, $k$ is the number of colliding bunches in each beam, $N_i$ is the number of protons per bunch in each beam, $\sigma_x$ and $\sigma_y$ are the horizontal and vertical beam sizes at the collision point. The luminosity increases quadratically with the number of protons per bunch. This relation can be used to increase the luminosity. Nevertheless, besides difficulties to create and maintain a beam with more protons in each bunch, large $N_i$ increases the probability for multiple collisions per bunch crossing referred to as pile-up. Pile-up is described in more details in Section 6.1.

The so called integrated luminosity is a measure related to the number of
proton-proton collisions. Integrated luminosity is defined as:

$$L = \int Ldt$$

and expressed in fb$^{-1}$. The expected number of events of a given process can be calculated as follows:

$$N = L \times \sigma$$

where $N$ is expected number of events of a given process and $\sigma$ is the cross section for the process.

The LHC beams are bent in the beam pipes by 1232 dipole magnets that produce the field of 8.33 T operating at 1.9 K. Nearly 400 quadrupole magnets are used to focus the beam. The beams intersect at four so called interaction points allowing the protons to collide. Nominally the LHC will operate with proton bunches crossing every 25 ns, although in 2012 it operated with 50 ns bunch spacing and with an expected average number of 20.7 proton-proton collisions per bunch crossing.

At the interaction points, four large detectors are placed in order to observe the collisions. There are two general purpose detectors (ATLAS [36], CMS [37]) and two specialised detectors (ALICE [38], LHCb [39]). Figure 4.1 shows a schematic view of the LHC with its main experiments. Below is a brief description of each detector:

- **ATLAS (A Toroidal LHC ApparatuS)** is a general purpose detector, which covers a broad field of experimental studies. The aim is to observe and study the Higgs boson and other phenomena that could involve heavy particles not observable with earlier accelerators.

- **CMS (Compact Muon Solenoid)** is the second general purpose detector. Although CMS has the same physics goals as ATLAS, it involves different technical solutions. CMS is optimised for tracking muons. Its magnet is the largest solenoid ever built, producing a magnetic field with a strength of 4 T. The main reason to build two general purpose detectors was the requirement that any result should be independently confirmed. Additionally, two detectors give the possibility to perform statistical combination and reduce the systematic errors.

- **ALICE (A Large Ion Collider Experiment)** is designed to study the quark-gluon plasma [40], a state of matter in which the quarks and
gluons can be considered as free particles. This state can be observed in heavy ions collisions.

- LHCb (Large Hadron Collider beauty) is designed to study B hadrons, to investigate CP violation in the $b$ quark sector and in D meson decays.

![Overall view of the LHC experiments.](image)

Figure 4.1: Overview of the Large Hadron Collider and its four major underground experiments: ALICE, ATLAS, CMS and LHCb.

Besides these four main experiments, there are also three smaller ones located at the LHC. The TOTEM (TOTal Elastic and diffractive cross section Measurement) [41] experiment is hosted in the CMS cavern. Its purpose is to measure the total proton-proton cross section, elastic scattering and diffractive processes. It will detect particles with small transverse momentum which cannot be seen by the ATLAS nor CMS. The second smaller experiment is called LHCf (Large Hadron Collider forward) [42]. This detector is installed 140 m in front of and behind the ATLAS. Its purpose is to detect neutral pions ($\pi^0$) with large pseudorapidity which escape from the ATLAS undetected. A measurement of $\pi^0$ production cross section might help explain the origin of ultra-high-energy cosmic rays. The MoEDAL (Monopole and Exotics Detector At the LHC) [43] is the third smaller experiment. It shares the cavern with the LHCb. Its goal is to directly search for hypothetical particles such as magnetic monopoles and other highly ionizing stable massive particles.
4.2 The ATLAS Detector

4.2.1 Introduction

ATLAS [36] is a general purpose detector. Its goal is to observe a large number of different production and decay channels. Therefore, it needs to provide a high momentum and energy resolution as well as an excellent particle identification. In this Section an overview of the ATLAS detector and its subdetectors is given.

The detector is 25 meters high and 44 meters long and weights approximately 7000 tons. The ATLAS detector consists of several concentric subdetectors. The goal of each component is to detect different types of particles. Figure 4.2 shows the interaction of particles with different parts of the detector. As shown in Fig. 4.3 ATLAS consists of the following subdetectors:

- **Inner Detector [44]** - measures charge, transverse momentum and direction of charged particles. It consists of Pixel detector, Semiconductor tracker and Transition Radiation Tracker
- **Calorimeters [45, 46]** - identify electrons, photons and hadrons, measure their energy and direction. It consists of LAr Electromagnetic Calorimeters and Tile Calorimeters and LAr Hadronic End-cap and Forward Calorimeters.
- **Muon Spectrometer [47]** - identifies muons and measure their transverse momentum and direction. It consists of Muon chambers.

Those subsystems are briefly described in the rest of this Chapter.
Figure 4.2: Illustration of the interaction of various particles with the different subdetectors in a wedge of the ATLAS experiment. The particles are produced in the proton-proton collision point located in the circle at the bottom of the figure. The concentrical subdetectors from small to large radius are: Inner Detector, Electromagnetic Calorimeter, Hadronic Calorimeter and Muon Spectrometer.
4.2.2 Geometry and Coordinate System

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

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

$$\eta = - \ln \tan \left( \frac{\theta}{2} \right)$$  \hspace{1cm} (4.4)
The distance between two particles or two points in the detector can be defined in pseudorapidity-azimuth space as:

$$\Delta R = \sqrt{\Delta \eta^2 + \Delta \phi^2}$$  \hspace{1cm} (4.5)

where $\Delta \eta$ is the distance in pseudorapidity and $\Delta \phi$ is the distance in azimuth.

The initial momentum of the interacting partons inside the colliding protons in the $z$-direction is unknown while the initial momentum in the $x$- and $y$-direction is zero. The transverse plane is defined as the $xy$-plane perpendicular to the beam axis. Because of the unknown initial momentum in the $z$-direction transverse quantities such as transverse momentum $p_T$, transverse energy $E_T$ and missing transverse energy $E_T^{\text{miss}}$ are used. The $E_T^{\text{miss}}$ ideally represent the momentum of undetected particles such as neutrinos or hypothetical particles that, like neutrinos, only interact weakly. It is measured by combining the projections of the momenta of all reconstructed particles onto the transverse plane. The impossibility to measure momentum of the neutrinos or neutralinos causes a transverse momentum imbalance. The calculation of the missing transverse energy is presented in Section 4.2.8.

### 4.2.3 Inner Detector

The Inner Detector [44] is the detector system closest to the interaction point. Its goal is the precise measurement of tracks of charged particles as they pass through and interact with the material of the detector. This information is used to determine the momentum, direction and charge of particles. It also allows to identify proton-proton collision vertices and secondary vertices due to long-lived particle decays.

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

$$\frac{\sigma_{p_T}}{p_T} = 3.4 \cdot 10^{-4} p_T \oplus 0.015$$  \hspace{1cm} (4.6)

where $p_T$ is given in GeV and $\oplus$ means quadratic sum (it means that the resolution worsens with increasing $p_T$ of particles).

Figure 4.4 shows the layout of Inner detector with its subdetectors. The dimensions of the Inner Detector are 6.2 m in length and 2.1 m in diameter.
It has to cope with very high multiplicity of particles expected in every event. The measurements are performed by three subsystems:

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

- **Semiconductor Tracker** - located immediately outside the Pixel Detector. The detector uses silicon as an active material structured in strips. It consists of 6.4 million read-out channels. The detector has four layers in the barrel region providing coverage up to $|\eta| = 1.4$ and nine disks in each end-cap region with coverage up to $|\eta| = 2.5$.

- **Transition Radiation Tracker** - located outside the Semiconductor Tracker. It is made of thin drift straws that are 4 mm in diameter and are filled with a gas mixture. Each strip has a 30 $\mu m$ gold plated tungsten wire at centre. The barrel part consists of about 50 000 straws parallel to the beam pipe and provide coverage up to $|\eta| = 0.7$. The end cap part consists of 320 000 straws, perpendicular to the beam pipe with coverage up to $|\eta| = 2.0$. In addition to contributing to the momentum and charge measurement the Transition Radiation Tracker can provide particle identification. The walls of the straw tubes contain polyethylene which enhances production of transition radiation photons which can be detected in Xe gas. The transition radiation occurs when a charged ultrarelativistic particle traverse a boundary between two media with different dielectric constants. The number of produced photons is proportional to the Lorentz boost factor $\gamma = \frac{E}{m}$. Therefore, at a given energy, a lighter particle produces more photons than a heavier particle. Electrons produce most of these photons due to their small mass. Thus, it is possible to distinguish electrons from pions.

Figure 4.5 shows the distance of each subdetector of Inner Detector from the z-axis.
4.2 The ATLAS Detector

The main purpose of the ATLAS Calorimeter is to measure the energy, direction and identify photons, electrons and hadrons in an energy range from a few GeV to a few TeV. It is also used to determine missing energy. Thus, it is important that the calorimeter provides a solid angle coverage as close to $4\pi$ as possible, so that no particles goes undetected. The information from the calorimeter is also utilised by the trigger system. The calorimeter is located outside the solenoid magnet which surrounds the Inner Detector. The calorimeter system consists of several specialised calorimeters based on different technologies: the Liquid Argon (LAr) Electromagnetic Calorimeter [45], the Tile Hadronic Calorimeter (TileCal) [46], the LAr Electromagnetic End-cap (EMEC), the LAr Hadronic End-cap (HEC) and the LAr Forward Calorimeter (FCal). LAr is used in barrel electromagnetic calorimeter. It is also used in both electromagnetic and hadronic end-cap calorimeters in forward region due to high radiation environment. The layout of the calorimeter system is illustrated in Fig. 4.6.
The purpose of the electromagnetic calorimeter is to precisely measure the energy of electrons and photons. It exploits the known interactions of electrons and photons with matter. The ultra relativistic electrons \( (E \gg m_e c^2) \) interact mainly by bremsstrahlung. In this process an electron loses part of its energy and a photon is radiated. The cross section \( \sigma_b \) for this process is proportional to the initial energy of electron \( E_e \) and to the square of the atomic number of the medium \( Z \):

\[
\sigma_b \sim Z^2 E_e \tag{4.7}
\]

In a calorimeter a medium is selected to promote the showering and is called absorber. The high energy photons mainly create electron-positron pairs.
The cross section for electron-positron pair production $\sigma_p$ is proportional to the square of the atomic number of the absorber and to the natural logarithm of photon energy $E_\gamma$:

$$\sigma_p \sim Z^2 \ln E_\gamma$$  \hspace{1cm} (4.8)

These processes lead to cascade of photons and electrons called “electromagnetic shower”. The electrons pass through an active material selected so that an electric signal can be extracted. In an electric field the generated ionisation electrons are collected to create a signal that can be amplified in the electronics.

The ATLAS electromagnetic calorimeter is a sampling calorimeter. It means the calorimeter is build of two alternating materials, an absorber and an active material. In practice, the calorimeter consists of lead plates with high atomic number $Z$ as absorbers and LAr as active material. To use of LAr, the calorimeter must be housed in a cryostat. The absorber plates have an accordion geometry arranged in a cylindrical symmetry around the $z$-axis as shown in Fig. 4.7. This shape allows a full $\phi$ coverage without azimuthal
cracks and ensures that approximately all particles pass through the same amount of material. The energy can be determined by measuring the charge created by ionisation in the active material which is itself proportional to the energy of the incident photon or electron. The measured energy is scaled by the sampling fraction to obtain the true energy deposited in absorber and active material. The energy resolution for electrons and photons is given by [48]:

\[ \frac{\sigma_E}{E} = 10\% \frac{1}{\sqrt{E}} \oplus 0.17\% \]  

(4.9)

where \( \oplus \) means quadratic sum. The resolution becomes better with increasing energy of particles, in contrast with the momentum resolution of the Inner Detector.

![Figure 4.7: Structure of the barrel electromagnetic calorimeter with the accordion shape of the lead absorber plates. The three longitudinal layers of the calorimeter are shown [36].](image)

The barrel part of the electromagnetic calorimeter covers \(|\eta| < 1.475\). It offers a fine segmentation of the read-out cells in all layers, especially in first layer where the cells are \(\Delta \eta = 0.0031\) wide. This allows precise measurements
4.2 The ATLAS Detector

of electromagnetic showers shapes. This information allows to differentiate electrons, photons or hadrons from $\pi^0$ and other hadrons. The end-cap part comprises a two wheel structure that covers $1.375 < |\eta| < 2.5$ and $1.375 < |\eta| < 3.2$. The electromagnetic calorimeter fills in the volume from the diameter of 3 m up to a diameter of 4 m.

The main task of the hadron calorimeters is to identify hadronic jets and measure their energy and direction. This is achieved by the Tile calorimeter in the range $|\eta| < 1.7$ and by the LAr hadronic end-cap in the interval $1.5 < |\eta| < 3.2$. Since part of the work presented in this thesis is a study of the Tile Calorimeter, Chapter 5 is dedicated to a more detailed description of this subdetector and hadronic calorimetry.

To extend the angular coverage at large $\eta$ the Forward Calorimeter is installed in the region $3.1 < |\eta| < 4.9$.

4.2.5 Muon Spectrometer

Muons are the only detectable particles capable of traversing the whole ATLAS Calorimeter. Muons with energy higher than about 3 GeV pass through the calorimeters and have long enough lifetime not to decay in the detector. A Muon Spectrometer [47] is thus installed outside the calorimeters. It is the largest subsystem of the ATLAS Detector. Its aim is the identification, precise momentum and direction measurement of muons with $3 < p_T < 1000$ GeV. The Muon Spectrometer is also used by the trigger system.

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

The Muon Spectrometer consists of four subdetectors shown in Fig. 4.8 and described below:

- Monitored Drift Tube (MDT) chambers - used for precision measurements of the muon track position in region of $|\eta| < 2.7$ except for the innermost end-cap layer where the coverage is up to $|\eta| < 2.0$. 
• Cathode Strip Chambers (CSC) - used for precision measurements of the muon track position in region of $2.0 < |\eta| < 2.7$.

• Resistive Plate Chambers (RPC) - provides dedicated muon trigger in the region of $|\eta| < 1.05$.

• Thin Gap Chambers (TGC) - provides dedicated muon trigger in the region of $1.05 < |\eta| < 2.4$

The barrel toroid magnet, which is placed within $|\eta| < 1.4$ and two end-cap toroid magnets, which are situated between 1.6 and 2.7 in $|\eta|$ provide the magnetic field.

Figure 4.8: Cut-away view of the ATLAS Muon Spectrometer [36].

The core elements of the Muon Spectrometer are about 1200 MDT chambers which are used to precisely measure muon tracks. The MDT are positioned in three concentrical layers at radii of 5 m, 7.5 m, and 10 m from the centre of the $z$-axis in barrel section. In the end-cap region the MDT form large
wheels and are located at distances of $z = 7.4$ m, 10.8 m, 14 m and 21 m from the interaction point. Each MDT chamber consists of six to eight drift tube layers with a diameter of 30 mm each.

A high particle flux is expected in the forward region. Therefore, the CSCs are used instead of the MDT, because of higher radiation tolerance and smaller sizes which lower the pile-up. The RPCs have fast response and are used for triggering. In the very forward region the TGCs are used for triggering instead of the RPCs.

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

### 4.2.6 Magnets

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

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

The central solenoid system is located between the Inner Detector and the Calorimeters. It creates a magnetic field parallel to the $z$-axis in the entire volume of the Inner Detector. The location of the magnet has an advantage that its size is relatively small, reducing the cost considerably. The disadvantage is the possibility that particles start showering already in the magnet system instead of the calorimeters. The solenoid generates an axial field of 2 T that bends the path of charged particles in the Inner Detector in $\phi$-direction. To minimise the material in front of the calorimeters the central solenoid magnet system is made out of a single-layer coil of superconducting NbTi 1.2 mm wire and operates at 4.5 K. Such a low temperature is provided by a cryostat which is shared with the LAr calorimeter in order to use
less material. The dimensions of the central solenoid system are 2.5 m in diameter and 5.6 m in length.

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

### 4.2.7 Trigger and Data Acquisition

At nominal LHC operation, bunches of protons cross each other every 25 ns (in 2012 the bunch spacing was 50 ns), this gives a bunch crossing frequency of 40 MHz. This frequency is used for the electronic master clock that synchronises all LHC detectors with the LHC beams. There are in average 20.7 collisions per bunch crossing in 2012. The data size of one collision event once recorded is approximately 1.5 MB. Neither the data acquisition system nor the resources for offline analysis are capable to handle this event data size of frequency of 40 MHz. Moreover only a tiny fraction of the collisions are interesting. Therefore, to select and record only important events a trigger system is used. The aim of the trigger system in ATLAS is to reduce the event rate to \( O(100 \text{ Hz}) \) for recording all interesting events.

The processes of primary interest are characterised by large momentum transfer. This results in high \( p_T \) leptons, jets and missing transverse energy \( E_T^{\text{miss}} \). Therefore, most of the bandwidth is assigned to triggers which rely on these features. The ATLAS trigger is based on three levels, sequentially refining the selection of the events and reducing the event rate. First level trigger, called Level 1 (L1) trigger, is hardware based. Second and third level triggers, called Level 2 (L2) trigger and Event Filter (EF) respectively, are software based and collectively called High Level Trigger (HLT). Figure 4.9 shows a schematic overview of the trigger system.

The Level 1 trigger must decide quickly whether the event is interesting for further analysis. The latency of the L1 is 2.5 \( \mu \)s, in this time the rate has to be reduced to 100 k\( \text{Hz} \). This gives a rejection factor of 400. To be able to
4.2 The ATLAS Detector

Figure 4.9: An overview of the ATLAS trigger system. The three levels of decision, Level 1, Level 2 and Event Filter are shown on the left side with corresponding event rates. The data flows from on-detector pipeline memories to Read-Out Drivers (ROD) in underground counting room. The Event Filter sends the data out for permanent storage [49].

be fast it uses reduced granularity information from calorimeters and muon detectors.

The electronics modules that implement logic of Level 1 calorimeter trigger (L1Calo) run a algorithms on so called trigger towers to look for high \( p_T \) object candidates. Trigger towers are analog sums of the calorimeter signals in \( \Delta \phi \times \Delta \eta = 0.1 \times 0.1 \) regions. A similar logic is implemented in Level 1 Muon trigger (L1Muon). There the curvature of the muon candidates is approximated in order to estimate their \( p_T \). The information about multiplicities of identified particle candidates over different threshold values is sent to the Central Trigger Processor (CTP). There the L1 decision is taken to pass on the event to the next level of trigger and the regions in the detector where interesting objects might be found are defined. The regions are called Region of Interests (RoI).

Waiting for the L1 trigger to take its decisions whether to keep an event or not, the information from subdetectors is stored in pipeline memories inside
the detector. When the event is accepted by the Level 1 trigger the data is sent from the detector front-end electronics to the subdetector specific Read-Out Drivers (ROD) located 100 m away from the ATLAS. The RODs format digitised signals, e.g. ROD of the Tile Calorimeter reconstruct amplitude, time, pedestal and a so called quality factor of the pulses with Optimal Filtering method described in Chapter 5. Then the data is passed to the Read-Out Buffer (ROB) where it is stored awaiting for a Level 2 trigger decision.

The events kept by L1 are further analysed by Level 2 trigger. L2 is implemented entirely in software and runs on O(1000) nodes. Its latency is 40 ms. In this time the rate of selected collisions is reduced to about 1 kHz at the output of L2. This gives a rejection factor of 100. The Level 2 trigger refines the event selections further by using full detector granularity and also includes information from the Inner Detector about particle tracks. This provides higher purity and additional rejection. In order to remain fast it only retrieves and analyses data from the RoIs defined by L1 rather than using the entire detector.

Events that survive L2 go to the Event Filter for further rejection. There the rate is reduced to O(100 Hz). This gives a rejection factor of 10 for EF and 400 000 for the whole trigger system. The latency of the Event Filter is 4 s. EF is a software based trigger running on O(2000) nodes. It has access to the full event information from various subdetectors with full granularity and uses algorithms similar to those in the offline processing contrary to the L2, where time optimised algorithms are used.

The selected events are sorted into several data streams, depending on what trigger they passed at L1. The most important streams used in physics analysis are Egamma (electrons and photons), Muons and JetTauEtmiss. There are also other streams not intended to be used in physics analysis, e.g. express stream used for detector and data quality monitoring or calibration streams providing calibration data. The work presented in Chapter 6 and Papers I - III is performed with data ATLAS data collected in JetTauEtmiss stream. The study shown in Part III of this thesis and Paper IV is performed with ATLAS data collected in Egamma and Muons streams.
4.2 The ATLAS Detector

4.2.8 Particle identification

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

Events considered in the analysis are requested to have at least five charged tracks associated to the primary vertex. In case of multiple primary vertices in an event, the one with the largest \( \sum p_T^2 \) is selected. In each event electrons, muons and jets are identified and missing energy is calculated. Possible overlaps between the identified objects are then removed. Additional analysis specific selections can be applied as described in Part III of this thesis.

Electrons

The mean information for electron identification is the energy deposited in the electromagnetic calorimeter matching with a charged track in the Inner Detector. Both are required to have \( p_T > 10 \) GeV and \(|\eta| < 2.47\). Also, sufficient number of hits in the Inner Detector are imposed. Electrons can be classified as “loose”, “medium” or “tight” depending on the tightness of the requirements on its shower-shape in the calorimeter and track-selection criteria in the Inner Detector. A large set of shape variables are computed and compared to their expected values for electrons. A tighter definition means higher purity but lower efficiency. In the presented analysis the “tight” requirement is imposed. The electrons are required to be isolated from hadronic activity as expected for leptons from \( W \), \( Z \) or gaugino and slepton decay. The sum of \( p_T \) of tracks with \( p_T > 400 \) MeV observed within a cone of \( \Delta R = 0.3 \), excluding the electron candidate itself, is required to be less than 16% of the electron \( p_T \). The track associated to the electron in the Inner Detector has to point to the event primary vertex. The electron candidates are also required to be isolated within the calorimeter.

Muons

Muons are reconstructed by matching a track in the Muon Spectrometer to a track in the Inner Detector. They are required to have \( p_T > 10 \) GeV and \(|\eta| < 2.4\). Sufficient number of hits in Inner Detector are imposed. After removing the overlaps with other objects the signal muons are defined. The similar requirements as for signal electrons are imposed. The signal muons have to
be isolated. Again, the sum of $p_T$ of tracks with $p_T > 400$ MeV observed within a cone of $\Delta R = 0.3$ excluding the muon candidate itself is required to be less than 16% of the muon $p_T$. The associated muon track in the Inner Detector has to point to the event primary vertex. The track associated to the muon in the Inner Detector has to point to the event primary vertex.

Jets

Jets are collections of hadrons travelling in approximately the same direction and arising from hadronisation of a quark or a gluon. The hadrons deposit energies in the electromagnetic and hadronic calorimeter. The charged particles leave also tracks in the Inner Detector. The calorimeter cells with significant energy deposit are grouped together into clusters [50]. Then the clusters are grouped into jets using the anti-$k_T$ algorithm [51, 52] with the distance parameter of 0.4. The energy of the cluster is calibrated to the electromagnetic scale (energy scale of the photons and electrons). Then the energy of the entire jet is calibrated to the jet energy scale based on calibration constants obtained from test beam studies and detailed detector simulations.

Once calibrated, jets are required to have $p_T > 20$ GeV and $|\eta| < 4.5$. The jet selection is tightened and a so called Jet Vertex Fraction and $b$-tagging algorithms can be utilised. Jet Vertex Fraction (JVF) algorithm is used to distinguish between jets associated with the hard scatter interaction from other jets from pileup interactions using vertex and track information. It relies on information from the Inner Detector.

Jets containing B hadrons can be identified using so called $b$-tagging algorithm. The $b$-tagging algorithm exploits the long lifetime of $b$- and $c$-hadrons inside a jet. It also relies on information from the Inner Detector.

The detailed definition of signal jets is described in Section 8.1.

Missing transverse energy ($E_T^{\text{miss}}$)

The missing transverse energy is the negative transverse vector sum of all measured particles. Because of conservation of momentum the missing transverse energy should be zero if all particle momenta are measured perfectly and there are no invisible particles such as neutrinos or neutralinos. The contributions from all particles defined earlier are included. The missing
transverse energy vector is given by the formula:

\[ E_{\text{miss}}^{T} = - \sum p_{e}^{T} - \sum p_{\mu}^{T} - \sum p_{\text{jet}}^{T} - \sum p_{\text{unclustered}}^{T} \] (4.10)

where \( \sum p_{e}^{T}, \sum p_{\mu}^{T} \) and \( \sum p_{\text{jet}}^{T} \) are the vector sums of the transverse momenta of the electron, muon and jet respectively. \( \sum p_{\text{unclustered}}^{T} \) is the sum of the momenta of calorimeter energy deposits that are not associated to any of the above particles. The modulus of the missing transverse energy vector is a commonly used quantity, \( E_{\text{miss}}^{T} = |E_{\text{miss}}^{T}| \).

4.2.9 Systematic Uncertainties

Systematics uncertainties have an impact on the estimates of the backgrounds and signal event yields in the control and signal regions used in the analysis described in Part III of this thesis and in Paper IV. Systematic uncertainties of experimental origin are associated to each of the identified particles and measured quantities. They are as follows:

- “Electrons”: Uncertainty on the electron identification efficiency and energy measurement. Also uncertainty on the number of fake electrons is considered.
- “Muons”: Uncertainty on muon identification efficiency and momentum measurement in the Inner Detector and the Muon Spectrometer. Also uncertainty on the number of fake muons is considered.
- “Jets”: Uncertainty on the jet energy due to jet energy scale calibration and resolution uncertainties.
- “Missing transverse energy (\( E_{\text{T}}^{\text{miss}} \))”: Uncertainties on electrons, muons and jets energies and momenta are propagated to the \( E_{\text{T}}^{\text{miss}} \) according to Eq. 4.10. An additional source of systematic uncertainty arises from the uncertainty on the energy scale of the energy deposits not assigned to any identified particle (unclustered contribution in Eq. 4.10).
- “\( b \)-tagging”: Uncertainties on the \( b \)-jet identification efficiency for \( b \)-jets and \( c \)-jets and on the probability to wrongly \( b \)-tag a light flavour jet are considered.
- “Luminosity”: Uncertainty on the integrated luminosity is \( \pm 3.6\% \). It is derived, following the same methodology as that detailed in Ref. [53], from a preliminary calibration of the luminosity scale derived in 2012.
• “Trigger”: Uncertainty on the electron and muon trigger efficiency.

Additional sources of systematic uncertainties inherent for instance to the exact background calculate procedures are considered and discussed in III of this thesis.
Chapter 5

The Tile Calorimeter

In order to measure energy and direction of hadrons ATLAS has a scintillating Tile Calorimeter (TileCal) [46]. TileCal fills the volume from an inner radius of 2.28 m to an outer radius 4.23 m. The central barrel covers an area up to $|\eta| < 1.0$. The extended barrel part provides a coverage of the region $0.8 < |\eta| < 1.7$. In this Section a description of the Tile Calorimeter is presented. The principles of hadron showers are given and the energy reconstruction in TileCal is discussed.

5.1 Principle of Hadron Showers

The purpose of hadronic calorimeters is to measure the energy and direction of hadrons. When hadron passes through the calorimeter it loses energy by interaction with matter and a so called hadronic shower [54] is generated. Hadronic showers are more complex than electromagnetic ones briefly described in Section 4.2.4 due to a larger variety of nuclear processes. In hadron interactions with matter, the strong force plays a key role.

A charged hadron traversing a dense medium interacts by ionisation. Then, at some point hadron can interact strongly with atomic nuclei of the medium. In this process the dominant cross section corresponds to inelastic scattering. As a result, a number of secondary hadrons are created, typically pions, protons and neutrons. These particles interact themselves with matter giving rise to a particle shower until the energy of the secondary particles is too low and energy loss becomes dominated by ionisation. The hadronic interactions
leave nuclei in excited states, which can undergo fission or radiate to lower energy states. An average of 16% of the energy of the hadrons is used to break up the nuclear binding of iron in TileCal. This energy is not measured and invisible for the detector. Therefore, the mean measured energy is lower than the real energy of the incoming hadron. Some of the particles produced in the hadronic cascade, in particular π⁰- and η-mesons, decay into pairs of photons and create an electromagnetic shower inside the hadronic shower.

The longitudinal size of the hadronic shower depends on the nuclear interaction length $\lambda_{\text{int}}$, similar to the radiation length of the electromagnetic shower. One interaction length is the average distance a hadron travels in a medium before it interacts strongly with a nucleus in the medium. In iron, which is used in TileCal, the interaction length of protons is 18.8 cm. This is approximately ten times larger than the corresponding radiation length. As a result, hadronic showers are wider and go deeper than electromagnetic showers. For this reason the hadronic calorimeter is placed around the electromagnetic calorimeter and has larger radius. The hadronic shower developed in hadronic calorimeter is illustrated in Fig. 4.2.

5.2 Geometry and Read-out

The ATLAS Tile Calorimeter is a hadronic sampling calorimeter. The main task of TileCal is to identify hadronic jets and measure their energy and direction. TileCal also provides information for the Level 1 trigger and participates in the measurement of the missing energy due to non-interacting particles. It uses iron as an absorber and scintillating plastic tiles as an active material. When a charged particle passes through the scintillating tiles, ultraviolet light is emitted and collected at the edges of each tile. The light is then transported via wavelength shifting fibers to Photomultiplier Tubes (PMT) located in a steel girder at the back of each barrel module. The girder provides the volume to house front-end read-out electronics and makes up the return yoke of the solenoid field. The scintillator tiles are grouped together into cells. The alternating layers of scintillating plastic and iron together with wavelength shifting fibers and PMTs are shown in Fig. 5.1.

TileCal is divided along the z-axis into four partitions for power distribution and data acquisition, two long barrels called LBA and LBC and two extended barrels called EBA and EBC. Each partition consists of 64 modules of equal width $\Delta \phi = 0.1$. Long barrel and extended barrel modules are shown in Fig. 5.2 for $z > 0$. TileCal is subdivided into three separate longitudinal
Figure 5.1: An illustration of the mechanical assembly and optical read-out of a single Tile Calorimeter module. A total of 256 such modules make up full TileCal. Source tubes are used to insert $^{137}$Cs radioactive source for calibration [36].

sampling layers, which allow to sample the shower at three different depths. The longitudinal sampling layers denoted A, BC and D have a granularity $\Delta \eta \times \Delta \phi = 0.1 \times 0.1$ in the two innermost layers and $\Delta \eta \times \Delta \phi = 0.2 \times 0.1$ in the outermost one. In units of nuclear interaction length the sampling layers have thickness of $\lambda_{int} = 1.5$, 4.1 and 1.8 respectively at $\eta = 0$. It ensures that hadron showers are well contained inside the calorimeter and stopped before the Muon Spectrometer. In the space between the long and extended barrels so called crack and gap scintillators are inserted. These scintillators provide necessary corrections for energy losses in dead material in the crack regions.
Figure 5.2: Segmentation in depth and $\eta$ of the Tile Calorimeter modules in the central (left) and extended (right) barrels. The central barrel has a coverage up to $|\eta| < 1.0$. The extended barrel covers the region $0.8 < |\eta| < 1.7$ [36].

Most Tile Calorimeter cells are read out by two PMTs, corresponding to two electronic read-out channels. TileCal has 9856 read-out channels in total corresponding to about 5182 cells. The PMT output is a current pulse and is read-out in two gains, low and high. The amplitude of the current pulse is proportional to the energy deposited in the associated cell. The pulse is amplified and shaped by the electronics mounted on the PMT. The shaping increases the pulse width at half-maximum to 50 ns. Then the analogue pulse is digitised with 7 samples at 25 ns intervals with 10-bit analog to digital converter (ADC). Upon a trigger accept by the Level 1 trigger the samples are sent from the front-end pipeline memories to the back-end electronics, Read-Out Drivers (ROD) located 100 m away in an underground counting room away from radiation. There Digital Signal Processors (DSP) calculate the pulse amplitude, phase and quality factor [55].

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

$$\frac{\sigma_E}{E} = \frac{50\%}{\sqrt{E}} \oplus 3\% \quad (5.1)$$

The resolution becomes better with increasing energy of the incoming hadrons. The 50% sampling term is dominated by stochastic fluctuations of energy deposited in the absorbers and fluctuations in amount of visible energy. The
3% term represents contributions independent on particle energy, such as material non-uniformity, radiation damage and other instrumental effects. This term is dominant at high energies.

5.3 Energy Reconstruction

The purpose of energy reconstruction in the Tile Calorimeter is to calculate the energy deposited in a cell from the number of ADC counts measured in each of the two corresponding read-out channels. Seven samples at 25 ns spacing synchronised with the LHC master clock are available for each channel. These samples are referred to as $S_i$, where $1 \leq i \leq 7$ and are in units ADC counts. Depending on the amplitude of the pulse, either high or low gain is used to maximise the dynamic range. The ratio between the low and the high amplification is 64. For pulses with energy below $\sim 12$ GeV high gain is used. For higher energies low gain is used. The energy of the pulse $E$ in MeV is related to the pulse amplitude $A$ in ADC counts by:

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

where $F_{\text{ADC}\rightarrow\text{MeV}}$ is a conversion factor between ADC counts and MeV and $P$ is the pedestal or baseline of the channel that must be subtracted. One ADC count corresponds to approximately 12 MeV and 800 MeV in high and low gain respectively. The exact correspondence is channel-dependent and requires careful calibration combining a radioactive source, a laser system and injection of calibrated amounts of electric charge into the electronics [56]. The energy reconstruction is performed twice: i) in real time by the RODs (referred to as “online”) and ii) after the data has been recorded (referred to as “offline”). There are two main methods to derive the amplitude $A$ of the pulse from the samples: Fit method and Optimal Filtering method (OFL) [57,58].

Fit method

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

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

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

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

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

**Optimal Digital Filtering**

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

\[
A_{OFL} = \sum_{i=1}^{7} a_i \cdot S_i
\]

\[
t_{OFL} = \frac{1}{A_{OFL}} \sum_{i=1}^{7} b_i \cdot S_i
\]

\[
P_{OFL} = \sum_{i=1}^{7} c_i \cdot S_i
\]

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

**Iterative Optimal Filtering method**

The iterative Optimal Filtering method is currently used in offline reconstruction of recorded data. During the 2010 data taking and early 2011 this method was also used online by the RODs. Later at higher luminosity only non-iterative Optimal Filtering was used online in order to mitigate the effect of pile-up.
The coefficients \(a_i, b_i\) and \(c_i\) are functions of the pulse true phase known only approximately a priori. The phase of the pulse in each channel is adjusted to be close to zero prior the data taking. Nevertheless, this setting is accurate to only 3 ns [59]. Iterative OFL takes the time of the maximum sample as an initial value of the phase. In next iterations, the phase is taken to be equal to \(t_{OFL}\) calculated in the previous iteration. The algorithm converges to the actual phase value with an accuracy better than 0.5 ns in absence of pile-up pulses as shown in Fig. 3 in Paper III. At the end of the iteration procedure, so called quality factor \(Q_{OFL}\) is calculated in order to verify the quality of the estimation:

\[
Q_{OFL} = \sqrt{\sum_{i=1}^{7} (S_i - A_{OFL} \cdot g_i - P_{OFL})^2}
\]  

(5.8)

where the \(g_i\) are the values of the normalised pulse shape function computed at the time of the 7 samples \(S_i\). When the deviation between the true shape and pulse shape function used in reconstruction is large, then \(Q_{OFL}\) also takes large value. Therefore, the quality factor can be used to detect problems in the reconstruction procedure as developed in Chapter 6.

**Non-iterative Optimal Filtering method**

In the Non-iterative Optimal Filtering method the phase is taken to be equal to the time of the maximum sample and no further iterations are performed. Due to insufficient processing time in the DSP the OFL reconstruction must be performed without iterations if the trigger rate is above 50 Hz. Therefore, the non-iterative Optimal Filtering method is now used online by the RODs.

In Paper II a comparison of iterative and non-iterative Optimal Filtering phase reconstruction with presence of out-of-time pile-up is presented. This is due to the fact that during the measurement of amplitude the phase is adjusted to be approximately zero which corresponds to in-time pulse of interest. The out-of-time pile up can lead to reconstructed phase values far from the actual one biasing the energy measurement when iterative method is used. By forcing a phase of zero the non-iterative Optimal Filtering method reconstructs better the phase of in-time-pulse in presence of out-of-time pile-up. This method is also more robust against the electronic noise for very low signals. Paper III shows a detailed study of the effect of pile-up on the quality factor and measured energy.
Chapter 6

Out-of-Time Pile-up and Quality Factor

The detailed description of the quality factor study discussed in this Chapter is presented in Paper III. Paper I and Paper II show an early stage of the study.

6.1 Pile-up

6.1.1 In-Time Pile-up

In 2012 the LHC was operating with proton bunches crossing each other every 50 ns (nominally the bunch spacing is designed to be 25 ns) with an expected average number of proton-proton collisions per crossing $\langle \mu \rangle = 20.7$. The parameter $\mu$ is the mean value of the Poisson distribution describing the number of interactions per bunch crossing at a given luminosity. Figure 6.1 presents the distribution of the parameter $\mu$ in 2011 and 2012 ATLAS data. It is shown that the mean number of interaction varies significantly and can be much higher than the average value in runs when the LHC achieved particularly high luminosity. This leads to a high probability for multiple collisions to occur. It is called in-time pile-up. In this scenario, particles produced in different proton-proton interactions inside the same bunch crossing can deposit energy in the same calorimeter channel at the same time. The energy depositions from multiple interactions are integrated introducing a bias in energy measurement of the collision of interest.
6.1 Pile-up

6.1.2 Out-of-Time Pile-up

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

In TileCal the long signal shaping requires a 150 ns read-out window (±75 ns around the signal peak time). This is larger than the bunch spacing time. Hardware and software delays are adjusted in such a way that the maximum amplitude of the in-time pulse is positioned around to the fourth sample, $S_4$. The effect of out-of-time pile-up is the superposition of pulses shifted in time. This results in anomalous pulse shapes differing from the pulse shape function used for energy reconstruction. This in general introduces a bias in the reconstructed energy. Such situation can be detected by large values of the quality factor introduced in Section 5.3. A special treatment of the double pulses can be applied to the reconstruction of such a signal. Figure 6.2 shows an illustration of such a case. It shows a pulse centred on zero from the collision of interest. A second pulse corresponds to the energy deposited 50 ns later in the same channel. The effect of out-of-time pile-up on the quality factor has been studied in Papers I - III and based on these studies a
criteria for pile-up identification has been proposed.

![Illustration of out-of-time pile-up (+50 ns) in the ATLAS Tile Calorimeter with pulse shapes similar to those of the real detector. The lines shown are functional parameterizations of actual pulse shapes, but are not actually used either in the energy reconstruction, nor in the pile-up simulation. The dots represent seven samples $S_i$.](image)

Figure 6.2: Illustration of out-of-time pile-up (+50 ns) in the ATLAS Tile Calorimeter with pulse shapes similar to those of the real detector. The lines shown are functional parameterizations of actual pulse shapes, but are not actually used either in the energy reconstruction, nor in the pile-up simulation. The dots represent seven samples $S_i$.

### 6.2 Pulse Shape Simulator

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

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

Pulse shape

Equation 5.8 shows that the quality factor expresses the difference between the ideal pulse shape function and the real pulse shape observed in the detector. The real pulse shapes are close to the ideal pulse shape [61]. Nevertheless, even small differences between ideal and real pulses are enlarged when signal amplitudes are large resulting in higher quality factors.

The normalised pulse shape function used in Optimal Filtering method is denoted \( g_i \) at the times of the samples \( S_i \). The normalised real pulse shape observed in the detector is denoted \( h_i \). One can write \( h_i = g_i + \delta_i \), where \( \delta_i \) is the deviation between the pulse shape used for reconstruction and the actual pulse shape. Since the TileCal electronics is linear [55], the shape function can be scaled by the pulse amplitude. Therefore, one can write \( S_i = A \cdot h_i + P = A \cdot g_i + A \cdot \delta_i + P \), where \( A \) is the true amplitude and \( P \) is true pedestal of the pulse observed in the detector. Putting it to the Eq. 5.8 the quality factor can be written as:

\[
Q_{F_{OFL}} = \sqrt{\sum_{i=1}^{7} (A \cdot g_i + A \cdot \delta_i + P - A_{OFL} \cdot g_i - P_{OFL})^2} \tag{6.1}
\]

In absence of the electronic noise and with the pedestal perfectly reconstructed, \( A = A_{OFL} \) and \( P = P_{OFL} \), Eq. 6.1 simplifies to:

\[
Q_{F_{OFL}} = A_{OFL} \cdot \sqrt{\sum_{i=1}^{7} (\delta_i)^2} \tag{6.2}
\]

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

\[
Q_{OFL} = Q_{OFL}^0 + A_{OFL} \cdot \sqrt{\sum_{i=1}^{7} (\delta_i)^2} \tag{6.3}
\]

where \( Q_{OFL}^0 \) is the value of quality factor at low amplitude when it is dominated by noise and timing effects.
In order to make the pulse simulator able to reproduce the quality factors observed in data a different pulse shape from the ideal one must be used. This is motivated by the fact that there are small differences between the ideal pulse shape and actual pulse shapes discussed in Ref. [61].

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

\[ h(\alpha t) = g(t) \]  \hspace{1cm} (6.4)

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

Amplitude distribution

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

Channel to channel phase variation

Ideally the peak of the pulses should be perfectly centered in the middle of the read-out window. Nevertheless, the actual peak position in the Tile Calorimeter varies slightly from channel to channel. This effect is included in the pulse simulator by randomly varying the offset of the pulses. The phase is Gaussian distributed with a mean value \( \mu = 0 \) ns and a standard deviation \( \sigma = 3 \) ns, as this is what is observed in the actual TileCal [59]. The distribution of channel to channel phase variation is shown in Fig. 10 in Paper III. Since iterative Optimal Filtering method is used for reconstruction, the effect of phase variation is small.
Incoherent electronic noise

The incoherent electronic noise randomly modifies the measured values of the samples $S_i$. This effect is to first approximation uncorrelated between the samples $S_i$. The effect of the noise is the second most significant contribution to the quality factor, after the pulse shape, but becomes the dominant factor at low amplitudes. The incoherent electronic noise is modelled with a double Gaussian function that was found to describe the noise in the Tile Calorimeter [55]. The noise constants used to smear the $S_i$ samples are adjusted in order to reproduce the quality factor distribution in data. The following noise constants are used: $\sigma_1 = 1.46$ ADC counts, $\sigma_2 = 3.60$ ADC, $R = 0.07$, where $\sigma_1$ and $\sigma_2$ are a standard deviations of Gaussian distributions centred at zero and $R$ is the relative normalisation between them.

Comparison of the quality factor in TileCal data and pulse simulator

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

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

A good agreement apart from a small discrepancies in the high tail of the quality factor distribution in data and from the simulator is achieved as shown in Fig.12 in Paper III. In a range of $0 < QF_{OFL} < 5$ ADC counts, i.e. for most events without out-of-time pile-up, the relative difference is below 1%. The amplitude dependence of the quality factor in data is well reproduced by the simulator in the range $200 < A_{OFL} < 1024$ ADC counts ($2.4 < A_{OFL} < 12.4$ GeV) as shown in Fig. 11 in Paper III. In the range below 200 ADC counts the amplitude dependence shows non-linear behaviour in the pulse simulator. This is the transition between the region with quality...
factor dominated by noise and the region with quality factor dominated by amplitude.

Each TileCal channel has a slightly different pulse shapes and noise characteristics. Therefore, in order to improve the agreement between data and simulator, different pulses and noise constants have to be used for different channel.

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

6.3 Detection of Pile-up

The aim of the work is to predict the effect of out-of-time pile-up on the quality factor using the pulse simulator described in Section 6.2. The out-of-time pulses are unbiased by the trigger, therefore they can have arbitrary small amplitudes. Small out-of-time pulses have a negligible effect on measured energy. There is no need to detect such cases.

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

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

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

Figure 6.3 black solid line shows $Q_{OFL}$ as a function of the in-time pulse
amplitude $A_{in}$. Different values of $A_{out}/A_{in}$ ratios are presented. In this case the in-time pulse is dominant. The lines correspond to the linear fit to mean value of the quality factor. The quality factor increases linearly with the amplitude for a given $A_{out}/A_{in}$ ratio. Also the amplitude dependence gets steeper when the $A_{out}/A_{in}$ gets closer to one. The strongest amplitude dependence occurs when in-time and out-of-time pulses have equal amplitude ($A_{out} = A_{in}$).

Figure 6.3 purple dashed line shows $QF_{OFL}$ as a function of the out-of-time pulse amplitude $A_{out}$. In this case the out-of-time pulse is dominant. It is presented that there is the same effect on quality factor regardless which pulse, in-time or out-of-time is dominant (solid black and dashed purple lines overlap each other of Fig.6.3). But if $A_{out} > A_{in}$ then the iterative Optimal Filtering starts to measure the amplitude of the out-of-time pulse. This is not the desired effect.

Figure 6.3: Quality factor as a function of the amplitude in different pile-up scenarios in TileCal pulse simulator with non-ideal pulse shapes, timing and noise effects emulated. $A_{in}$ ($A_{out}$) is the amplitude of the in-time (out-of-time) pulse. The x-axis shows the amplitude in ADC counts before channel-dependent calibration constants are applied. The calibration factor is approximately 12 MeV per ADC count.
Amplitude of out-of-time pulses

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

On the other hand the out-of-time pulses are not triggered. They are collected by chance since they were close in time to a triggered proton-proton collision. Therefore, the amplitude of the out-of-time pulses must be modelled by a trigger unbiased energy distribution. This is obtained from a so-called ZeroBias stream which triggers on random collisions. This stream selects randomly a small fraction of events in coincidence with a proton bunch crossing. This allows to measure the pulse amplitude distribution in Tile Calorimeter channels without any trigger bias. The distribution of reconstructed amplitude in ZeroBias stream is shown in Fig. 15 in Papers III.

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

Figure 6.4 shows quality factor distributions in absence (black solid line) and presence (dashed purple line) of out-of-time pile-up obtained with the pulse simulator. The results are presented in three reconstructed amplitude $A_{OFL}$ bins. Each distribution is made with 10 millions generated pulses. A clear separation between the two cases is observed.

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

Based on the results presented in Fig. 6.4 and in Paper III criteria to flag TileCal channels with out-of-time pile-up are proposed. For this purpose efficiency and fake rate quantities are defined. The efficiency is a fraction of out-of-time pile-up events correctly selected as pile-up events. The fake rate is a fraction of non out-of-time pile-up events wrongly selected as pile-up events.

As shown in Section 6.2 quality factor is linear dependent on the amplitude. Therefore, three different criteria are defined for three amplitude bins. The amplitude bins presented in Fig. 6.4 correspond to calculated amplitude $A_{OFL}$. Thus, these results can be used directly to propose the cuts on the quality factor.
Figure 6.4: Normalised distributions of quality factor obtained with the TileCal simulator with non-ideal pulse shapes, timing and noise effects emulated. Two cases are shown: no out-of-time pile-up (black solid line) and with out-of-time pile-up (dashed purple line). Amplitude of in-time pulse is taken from JetTauEtmiss. Amplitude of the out-of-time pulse is taken from ZeroBias stream. Only “significant” out-of-time pulses are considered with amplitude above 34 ADC counts (∼400 MeV). Three measured amplitude bins: $34 < A_{OFL} < 84$ ADC (0.4 < $E_{OFL}$ < 1 GeV), $84 < A_{OFL} < 417$ ADC (1 < $E_{OFL}$ < 5 GeV), $417 < A_{OFL} < 1000$ ADC (5 < $E_{OFL}$ < 12 GeV).

Table 6.1 presents the proposed cuts on the quality factor for three calculated amplitude bins. The first column shows the amplitude range in ADC counts in a particular bin. The second column shows the corresponding energy range in GeV. In order to calculate the energy the calibration factor of approximately 12 MeV per ADC count is used. The third column shows proposed cuts on the quality factor to identify pile-up. The fourth column shows a fake rate in per cent. Finally, the last column shows the efficiency in per cent. If necessary, different amplitude bins can be defined based on the information presented in Fig. 6.3.

In the first bin, $Q_{OFL} > 8.8$ ADC counts cut allows to select all pile-up events with fake rate less than 1%. In the second bin all pile-up events can
Table 6.1: Proposed cuts on $Q_F^{OFL}$ for three reconstructed amplitude bins, together with the corresponding fake rates and efficiencies, in different bins of the reconstructed amplitude. A set of 10 millions events was used to calculate fake rates and efficiencies. The quoted errors are statistical.

<table>
<thead>
<tr>
<th>$A_{OFL}$ [ADC]</th>
<th>$E_{OFL}$ [GeV]</th>
<th>$Q_F^{OFL}$ cut [ADC]</th>
<th>Fake rate [%]</th>
<th>Efficiency [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>34 — 84</td>
<td>0.4 — 1</td>
<td>&gt; 8.8</td>
<td>0.973 ±0.004</td>
<td>100 (&gt; 99.9% at 95% CL)</td>
</tr>
<tr>
<td>84 — 417</td>
<td>1 — 5</td>
<td>&gt; 11.6</td>
<td>0.985 ±0.006</td>
<td>100 (&gt; 99.9% at 95% CL)</td>
</tr>
<tr>
<td>417 — 1024</td>
<td>5 — 12</td>
<td>&gt; 22.9</td>
<td>3.75 ±0.03</td>
<td>99.04 ±0.01</td>
</tr>
<tr>
<td>417 — 1024</td>
<td>5 — 12</td>
<td>&gt; 11.7</td>
<td>26.55 ±0.06</td>
<td>100 (&gt; 99.8% at 95% CL)</td>
</tr>
</tbody>
</table>

be selected with fake rate less than 1% by applying $Q_F^{OFL} > 11.6$ ADC counts cut.

In the third bin the separation between pile-up and no pile-up scenarios is slightly worse. It is caused by larger tails in quality factor distribution in non pile-up events as shown in Fig. 6.4 black solid line. This tail is present in the highest bin due to amplitude dependence of quality factor as discussed in Chapter 6.2. Therefore, three different cuts on quality factor in the third bin are proposed. More than 85% pile-up events can be selected with fake rate less than 1% by applying $Q_F^{OFL} > 29.7$ ADC counts cut. Lower $Q_F^{OFL} > 22.9$ ADC counts cut increase the efficiency to more than 99% and fake rate to 3.75%. The lowest $Q_F^{OFL} > 11.7$ ADC counts cut allow to select all pile-up events with fake rate of 26.55%.

6.4 Conclusions

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

Chargino and Slepton Pair Production
Chapter 7

Search for Direct Chargino and Slepton Pair Production

In SUSY scenarios where masses of the coloured sparticles are much larger than colourless sparticles, the direct production of SUSY partners via weak interaction can be dominant at the LHC. This could be true for instance for squark masses above 1.5 TeV and weak gaugino masses around 400 GeV. The pMSSM allows such a mass difference between coloured and colourless sparticles [31, 62]. In Part III of this thesis discuss the search for direct production of weak gauginos and sleptons.

7.1 Chargino and Slepton Production and Decay

In the present work direct gaugino and direct slepton production is investigated. An analysis of ATLAS data is designed to observe a signature with two opposite sign same flavor leptons, significant missing transverse energy ($E_T^{\text{miss}}$) and no hadronic activity from gaugino or slepton decays. Absence of hadrons in the decay products of charginos and sleptons is used to suppress top quark pair ($t\bar{t}$) background events. Therefore, a veto on hadronic jets is introduced in this analysis. The study of jet-veto is presented in detail in Chapter 8. In this work only final states containing electrons or muons are considered, while final states with tau leptons is studied in Ref. [66]. Signal Monte Carlo samples of direct gaugino and direct slepton production are generated using HERWIG++ [63] at Leading Order (LO). The samples are normalised to Next to Leading Order (NLO) cross sections as described
Chapter 7: Search for Direct Chargino and Slepton Pair Production

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

\begin{align}
\tilde{\chi}_1^\pm & \rightarrow \tilde{\ell}^\pm \nu, \ell^\pm \tilde{\nu} \\
\tilde{\chi}_1^\pm & \rightarrow W^\pm \tilde{\chi}_1^0
\end{align}

where $\ell$ is an electron, muon or tau. Decay in Eq. 7.1 occurs if the sleptons are lighter than the $\tilde{\chi}_1^\pm$. Decay in Eq. 7.2 dominates if sleptons are heavier than $\tilde{\chi}_1^\pm$. The final state leptons are crucial to extract the rare gaugino signal over the large Standard Model background. In case of lighter sleptons the gaugino decays into leptonic final states with 100% branching ratio via on-shell slepton, which boosts the sensitivity of the analysis to the gaugino signal. When the sleptons are heavier than $\tilde{\chi}_1^\pm$ it is much more challenging experimentally because of a much lower leptonic branching ratio (set by $Z \rightarrow \ell \ell$ and $W \rightarrow \ell \nu$ decays).

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

\begin{align}
pp & \rightarrow \tilde{\chi}_1^\pm \tilde{\chi}_1^\mp \rightarrow \tilde{\ell} \nu \ell \ell \nu \nu \rightarrow \ell \nu \tilde{\chi}_1^0 \ell \nu \tilde{\chi}_1^0 \\
pp & \rightarrow W \tilde{\chi}_1^0 W \tilde{\chi}_1^0 \rightarrow \ell \nu \tilde{\chi}_1^0 \ell \nu \tilde{\chi}_1^0
\end{align}

The electric charge is dropped for simplicity, but the two final state leptons are always of opposite sign. Additionally, the neutralinos and neutrinos yield missing transverse energy $E_T^{\text{miss}}$. There is no hadronic activity from the final state particles. These processes are illustrated in Fig. 7.1 top left and top right.

SUSY simplified model are used to generate $\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp$ signal samples. In this model only the $pp \rightarrow Z/\gamma^* \rightarrow \tilde{\chi}_1^\pm \tilde{\chi}_1^\mp$ diagrams are considered. All SUSY particles other than $\tilde{\chi}_1^0, \tilde{\chi}_1^\pm$ are $\tilde{\ell}^\pm$ are assumed to be very massive in order to eliminate their contributions. The $\tilde{\chi}_1^\pm$ is assumed to decay via sleptons or neutrinos with a branching ratio of 50% to each. The slepton branching ratios are set equal between all three lepton generations, i.e. electrons, muons...
and taus. The applied selection vetoes hadronic tau decays to ensure orthogonality with a dedicated search for hadronic tau final states [66]. The lowest considered mass splitting between $\tilde{\chi}^{\pm}_1$ and $\tilde{\chi}^0_1$ is 35 GeV, since the presented analysis is not sensitive to smaller mass gaps as discussed further in Section 7.4. Figure 7.2 shows the Next to Leading Order cross section for pure wino $\tilde{\chi}^{\pm}_1\tilde{\chi}^\mp_1$ and $\tilde{\chi}^{\pm}_1\tilde{\chi}^0_2$ production in proton-proton collisions at $\sqrt{s} = 8$ TeV as a function of $\tilde{\chi}^{\pm}_1$ and $\tilde{\chi}^0_2$ mass calculated with PROSPINO [67].

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

Sleptons can be directly pair-produced in a process similar to so called Drell-Yan dilepton production at high energy [68]. In the present work only production of charged sleptons is considered. The direct production of $\tilde{\ell}^\pm\tilde{\ell}^\mp$ is searched for in the following channel:

$$pp \rightarrow \tilde{\ell}^\pm\tilde{\ell}^\mp \rightarrow \ell^\pm\tilde{\chi}^0_1 \ell^\mp\tilde{\chi}^0_1$$  \hspace{1cm} (7.5)$$

Sleptons decay directly to a lepton and a $\tilde{\chi}^0_1$. Therefore, in this channel there are exactly two oppositely charged leptons and missing transverse energy.
Chapter 7: Search for Direct Chargino and Slepton Pair Production

Figure 7.2: Next to Leading Order production cross sections for simplified models $\tilde{\chi}^0_1\tilde{\chi}^0_2$ and $\tilde{\chi}^\pm_1\tilde{\chi}^\mp_1$ calculated with PROSPINO as a function of the common $\tilde{\chi}^\pm_1$ and $\tilde{\chi}^0_2$ mass [67].

$E_T^{\text{miss}}$ due to neutralinos in the final state. There is no hadronic activity from the final state particles. This process is illustrated in Fig. 7.1 bottom.

To simulate $\tilde{\ell}^\pm\tilde{\ell}^\mp$ the pMSSM [69] framework was used. Both left-handed and right-handed sleptons are considered and assumed to have the same mass. Squarks and gluinos are assumed to be very massive so that their contribution is completely eliminated. Therefore, there is only one kinematically allowed slepton decay channel namely $\tilde{\ell} \rightarrow \tilde{\chi}^0_1 \ell$. The presented analysis is not sensitive to small mass gaps between $\tilde{\ell}$ and $\tilde{\chi}^0_1$ due to the challenging experimental signature arising in this situation. Therefore only models with $m_{\tilde{\ell}} > m_{\tilde{\chi}^0_1} + 40$ GeV are considered. Figure 7.3 shows the charged slepton direct production cross section in proton-proton collisions at $\sqrt{s} = 8$ TeV as a function of the slepton mass per slepton flavour.
Analysis procedure

The search for direct chargino and slepton pair production is performed in several steps. First, signal regions sensitive to chargino and slepton events are defined and optimised using Monte Carlo simulations of all background processes as well as SUSY signal processes. The signal regions used in this work are described in Section 7.3. The Standard Model background in the signal regions is then finally estimated using a combination of data control regions and Monte Carlo simulations. The control regions are constructed to be enriched in the SM processes to be calculated.

Estimation of the background originating from production of a $Z$ boson with an associated vector boson $W$ or $Z$ (denoted $ZV$ background) is presented in Chapter 9. The described method is used to perform calculations of $ZV$ background in Paper IV and upcoming Paper V. Calculation of other SM processes is also included in these papers.

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

A large number of Standard Model processes can give rise to a final state with two opposite sign leptons and missing transverse energy similar to that of chargino and slepton pair production. These backgrounds need to be estimated as precisely as possible before a statement on whether the data is compatible with the background only hypothesis or with a background + SUSY signal hypothesis. In case of data compatibility with the background only hypothesis an upper limit is set on the production cross section of SUSY particles. If an excess is observed in the signal region than the statistical significance of the excess is evaluated.

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

The SM background processes are grouped into five categories labelled as follows:

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

7.3 Observables for Signal Selection

In order to search for direct chargino pair and direct slepton pair production processes (Section 7.1) six signal regions are designed labeled SR-$m_{T2,90}$, SR-$m_{T2,120}$, SR-$m_{T2,150}$ collectively called SR-$m_{T2}$ and SR-$WW_a$, SR-$WW_b$, SR-$WW_c$ collectively called SR-$WW$. This labelling is clarified in the Sections below. The SR-$m_{T2}$ regions are sensitive to $\tilde{\chi}_1^+\tilde{\chi}_1^-$ decays with intermediate sleptons (Eq. 7.3), while the SR-$WW$ regions are sensitive to $\tilde{\chi}_1^+\tilde{\chi}_1^-$ decays with intermediate $W$ bosons (Eq. 7.4). The variety of signal regions result from the need for different selections to accommodate a wide range of SUSY masses.

Signal regions presented in this Section are utilised in the refined analysis described in upcoming Paper V. The differences between signal regions introduced in Paper IV and Paper V are also discussed. Several observables exploited to construct the signal regions are defined below.

7.3.1 $m_{T2}$

Before introducing $m_{T2}$ we start with a related but simpler variable, namely the transverse mass $m_T$ [70]. The $m_T$ variable is defined to measure the mass of particles decaying into a visible particle and an undetectable one. This quantity is exploited in measurements of the $W$ boson mass in $W^\pm \rightarrow \ell^\pm \nu$ events. In this case the $W$ boson decays into a visible charged lepton and an undetectable neutrino. Therefore, one cannot directly reconstruct the $W$ mass from the lepton and neutrino momenta. The $m_T$ is defined as follows:

$$m_T^2 = m_\ell^2 + m_\nu^2 + 2(E_\ell T E_\nu T - \mathbf{p}_\ell T \cdot \mathbf{p}_\nu T)$$

(7.6)

This variable has the property:

$$m_T^2 \leq m_W^2$$

(7.7)

It results in a kinematic edge at the value of the $W$ mass in the $m_T$ distribution allowing to measure the $W$ mass.

The $m_{T2}$ [71–73] variable is similar to $m_T$ but applicable to a system with two particles decaying to a visible and an invisible particle. This quantity is
a function of measured lepton momenta and the missing transverse momentum. The $m_{T2}$ distribution calculated in $t\bar{t}$ and $WW$ events with $W$ boson pairs decaying leptonically have a kinematic edge at the $W$ mass. In practice the imperfect particle measurement allows events to exceed this bound. Nevertheless, $t\bar{t}$ and $WW$ events with $m_{T2} > m_W$ above $W$ mass are significantly suppressed.

SUSY signal events can have values of $m_{T2}$ exceeding the $W$ mass. In case of well measured lepton pairs from slepton pair decays $m_{T2}$ follows:

$$m_{T2} \leq m_{T2, \text{max, no recoil}} = \frac{m_{\ell}^2 - m_{\tilde{\chi}_1^0}^2}{m_{\ell}}$$ (7.8)

More generally, the sleptons pair can be produced in association with other particles. In this case the system of sleptons recoils against these particles. Than $m_{T2}$ can take values:

$$m_{T2} \leq m_{T2, \text{recoil}} = \sqrt{\left(\frac{m_{\ell}^2 - m_{\tilde{\chi}_1^0}^2}{m_{\tilde{\chi}_1^\pm}^2}\right)\left(1 - \frac{m_{\tilde{\chi}_1^0}^2}{m_{\ell}^2}\right)}$$ (7.9)

In practice large recoil is required to produce $m_{T2}$ values in this larger range. This events are significantly suppressed by jet veto. In absence of width effects most of the well reconstructed slepton pair production events have $m_{T2}$ in a range between 0 and $m_{T2, \text{max, no recoil}}$.

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

Figure 7.4 illustrates the shape of the $m_{T2}$ variable for $\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp$ and $\tilde{\ell}^\pm \tilde{\ell}^\mp$ pair production for two sets of sparticle masses points. It shows that the kinematic edge depends on the mass splittings between the primary sparticle ($\tilde{\chi}_1^\pm$ or $\tilde{\ell}^\pm$) and the $\tilde{\chi}_1^0$. The $m_{T2}$ distributions falls faster for $\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp$ production than for $\tilde{\ell}^\pm \tilde{\ell}^\mp$ production due to presence of neutrinos.

The $m_{T2}$ variable gives a sensitivity to scenarios having values of $m_{T2, \text{max, no recoil}}$ exceeding the $W$ mass.

### 7.3.2 Jet-veto

The targeted signal processes do not result in jet activity apart from Initial State Radiation (ISR) jets. Therefore, a jet-veto is used to suppress the high-cross section dileptonic $t\bar{t}$ events which also results in a dilepton and $E_T^{\text{miss}}$.
Figure 7.4: The distribution of the $m_{T2}$ variable for $\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp$ (black points) and $\tilde{\ell}^\pm \tilde{\ell}^\mp$ (red squares) pair production. (a) The $\tilde{\chi}_1^\pm$ mass is $m_{\tilde{\chi}_1^\pm} = 250$ GeV and $\tilde{\chi}_1^0$ mass is $m_{\tilde{\chi}_1^0} = 100$ GeV for $\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp$ production and $\tilde{\ell}^\pm$ mass is $m_{\tilde{\ell}^\pm} = 251$ GeV and $\tilde{\chi}_1^0$ is $m_{\tilde{\chi}_1^0} = 90$ GeV for $\tilde{\ell}^\pm \tilde{\ell}^\mp$. (b) The $\tilde{\chi}_1^\pm$ mass is $m_{\tilde{\chi}_1^\pm} = 250$ GeV and $\tilde{\chi}_1^0$ mass is $m_{\tilde{\chi}_1^0} = 100$ GeV for $\tilde{\chi}_1^\pm \tilde{\chi}_1^\mp$ production and $\tilde{\ell}^\pm$ mass is $m_{\tilde{\ell}^\pm} = 251$ GeV and $\tilde{\chi}_1^0$ is $m_{\tilde{\chi}_1^0} = 90$ GeV for $\tilde{\ell}^\pm \tilde{\ell}^\mp$. 

final state. The detailed description and studies of the jet-veto is presented in Chapter 8.

7.3.3 $E_{T,\text{miss,rel}}$

$E_{T,\text{miss,rel}}$ [74] is constructed from the missing transverse energy $E_{T,\text{miss}}$. It is designed to reduce contributions from mismeasured particle momenta to the $E_{T,\text{miss}}$. The variable $E_{T,\text{miss,rel}}$ is defined as:

$$E_{T,\text{miss,rel}} = \begin{cases} E_{T,\text{miss}} & \text{if } \Delta\phi_{\ell,j} \geq \pi/2 \\ E_{T,\text{miss}} \times \sin\Delta\phi_{\ell,j} & \text{if } \Delta\phi_{\ell,j} < \pi/2 \end{cases}$$  \hspace{1cm} (7.10)

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

Chapter 7: Search for Direct Chargino and Slepton Pair Production

7.4 Signal Region Definitions

7.4.1 SR-$m_{T2}$

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

In SR-$m_{T2}$ two oppositely signed (OS) leptons are imposed. The leading one is required to have $p_T^{\ell_1} > 35$ GeV, the subleading one must have $p_T^{\ell_2} > 20$ GeV. The mass of the leptons system is required to be $m_{\ell\ell} > 20$ GeV. In order to suppress $Z/\gamma^* \rightarrow \ell\ell + \text{jet}$ background, events with dilepton mass away from $Z$ mass ($|m_{\ell\ell} - m_Z| > 10$ GeV) are imposed in $e^+e^-$ and $\mu^+\mu^-$ channels. The jet-veto is used to suppress the high-cross section dileptonic $t\bar{t}$ events which also results in a dilepton and $E_T^{\text{miss}}$ final state. The detailed description and studies of the jet-veto is presented in Chapter 8. A $m_{T2}$ cut is used to suppress a large fraction of $WW$ and the remaining $t\bar{t}$ background events. Different $m_{T2}$ cut values serve a good sensitivity to SUSY scenarios with different masses of sleptons and neutralinos. In case of slepton pair production, harder $m_{T2}$ cuts provide better sensitivity to signals with large mass gaps between slepton and neutralino, while softer $m_{T2}$ cuts provide better sensitivity to small mass gaps. Therefore, three signal regions with different $m_{T2}$ cuts ($m_{T2} > 90$ GeV, $m_{T2} > 120$ GeV and $m_{T2} > 150$ GeV) are defined in order to serve good coverage of possible signal scenarios. The selection in SR-$m_{T2}$ described above is used in the refined analysis presented in upcoming Paper V. The following changes are applied with respect to study shown in Paper IV:

- The cut $|m_{\ell\ell} - m_Z| > 10$ GeV is removed in $e\mu$ channel in Paper V.
- In analysis presented in Paper IV, two control regions with cuts $m_{T2} > 90$ and $m_{T2} > 110$ GeV are used. In order to increase the sensitivity to the signal events three signal events with cuts $m_{T2} > 90$, $m_{T2} > 120$ and $m_{T2} > 150$ GeV are defined in Paper V.
- Requirements on the leading lepton $p_T^{\ell_1} > 35$ GeV and subleading one
7.4 Signal Region Definitions

\( p_T^2 > 20 \text{ GeV} \) are added in Paper V.

7.4.2 SR-WW

Signal regions SR-WW are optimised to provide the sensitivity to direct \( \tilde{\chi}_i^\pm \tilde{\chi}_1^- \) production with intermediate \( W \) bosons. Similarly to SR-\( m_{T2} \) the control regions SR-WW require oppositely signed leptons with transverse momenta \( p_T^1 > 35 \text{ GeV} \) and \( p_T^2 > 20 \text{ GeV} \) and \( m_{\ell\ell} > 20 \text{ GeV} \). Also \( |m_{\ell\ell} - m_Z| > 10 \text{ GeV} \) cut in order to suppress \( Z/\gamma^* \rightarrow \ell\ell+\text{jet} \) events and the jet-veto to reject \( t\bar{t} \) background are used.

The SR-WW_a is defined for scenarios where either the chargino mass is small \( (m_{\tilde{\chi}_1^\pm} < 120 \text{ GeV}) \) or the mass gap between chargino and neutralino is small \( (m_{\tilde{\chi}_1^\pm} - m_{\tilde{\chi}_1^0} < 100 \text{ GeV}) \). In this case \( W \) bosons are produced close to the threshold \( (m_W = 80.4 \text{ GeV}) \). In this signal region \( E_T^{\text{miss,rel}} > 80 \text{ GeV} \) is imposed. The mass of the leptons system is required to be \( m_{\ell\ell} < 120 \text{ GeV} \). Events with total transverse momentum of the two leptons \( p_T^{\ell\ell} > 80 \text{ GeV} \) are considered. These cuts are optimal to reject the WW background events.

The cuts used in SR-WW discussed above are used in the refined analysis presented in upcoming Paper V. Compared to work shown in Paper IV, the following changes are applied:

- The cut \( |m_{\ell\ell} - m_Z| > 10 \text{ GeV} \) is included in \( e^+e^- \) and \( \mu^+\mu^- \) channels to suppress \( Z/\gamma^* \rightarrow \ell\ell+\text{jet} \) background in Paper V.

- In analysis presented in Paper IV, cuts \( E_T^{\text{miss,rel}} > 70 \text{ GeV} \) and \( p_T^{\ell\ell} > 70 \text{ GeV} \) are used in SR-WW_a. In Paper V, these cuts are raised to \( E_T^{\text{miss,rel}} > 80 \text{ GeV} \) and \( p_T^{\ell\ell} > 80 \text{ GeV} \).

- In Paper IV, upper cuts \( m_{\ell\ell} < 80 \text{ GeV} \) in SR-WW_b and \( m_{\ell\ell} < 130 \text{ GeV} \) in SR-WW_c are utilised. In Paper V, these cuts are raised to \( m_{\ell\ell} < 120 \text{ GeV} \) and \( m_{\ell\ell} < 170 \text{ GeV} \) respectively.

- In Paper IV, cuts \( p_T^{\ell\ell} < 170 \text{ GeV} \) in SR-WW_b and \( p_T^{\ell\ell} < 190 \text{ GeV} \) in SR-WW_c are imposed. These cuts are dropped in Paper V.

Signal regions SR-WW_b and SR-WW_c are designed to be sensitive to higher chargino masses \( (m_{\tilde{\chi}_1^\pm} > 120 \text{ GeV}) \) and larger mass gap between chargino and neutralino \( (m_{\tilde{\chi}_1^\pm} - m_{\tilde{\chi}_1^0} > 100 \text{ GeV}) \). In this scenario \( W \) boson is boosted. SR-WW_b and SR-WW_c require \( m_{T2} > 90 \text{ GeV} \) and \( m_{T2} > 100 \text{ GeV} \) respectively.
Harder $m_{T2}$ provides better sensitivity to larger chargino masses and larger $W$ boost. Additionally, SR-WW$_b$ requires the mass of the leptons system to be $m_{\ell\ell} < 170$ GeV.

The definitions of the signal regions are summarised in Tab. 7.1.

<table>
<thead>
<tr>
<th>Signal region</th>
<th>SR-WW$_a$</th>
<th>SR-WW$_b$</th>
<th>SR-WW$_c$</th>
<th>SR-$m_{T2,90}$</th>
<th>SR-$m_{T2,120}$</th>
<th>SR-$m_{T2,150}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>OS</td>
<td></td>
<td></td>
<td></td>
<td>$\checkmark$</td>
<td>$&lt; 10$ GeV</td>
<td>$&gt; 35$ GeV</td>
</tr>
<tr>
<td>$p_T^{\ell_1}$</td>
<td>$&gt; 80$ GeV</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$p_T^{\ell_2}$</td>
<td>$&gt; 80$ GeV</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$</td>
<td>m_{\ell\ell} - m_Z</td>
<td>$</td>
<td>$&lt; 170$ GeV</td>
<td></td>
<td></td>
<td>$&gt; 90$ GeV</td>
</tr>
<tr>
<td>signal central jets</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>signal b-jets</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>signal forward jets</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$p_T^{miss,rel}$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$m_{T2}$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 7.1: Definitions of signal regions SR-WW and SR-$m_{T2}$. “✓” means the cut is applied, “—” means the cut is not applied.

### 7.5 Dataset and Trigger

The search for direct production of charginos and sleptons described in Part III as well as in Paper IV is performed with the entire dataset recorded by the ATLAS detector in 2012 at $\sqrt{s} = 8$ TeV. The jet-veto study presented in Chapter 8 is included in Paper IV. There a total integrated luminosity of $\mathcal{L} = 21.4$ fb$^{-1}$ is used. The requirement that all ATLAS sub-detectors are working acceptably well reduces the luminosity by 6.5% to $\mathcal{L} = 20.7$ fb$^{-1}$.

In upcoming Paper V a refined analysis is described. Estimation of ZV background presented in Chapter 9 is included in Paper V. There a reprocessed dataset of recalculated total integrated luminosity $\mathcal{L}' = 21.7$ fb$^{-1}$ is used. The requirement that all ATLAS sub-detectors are working acceptably well reduces the luminosity by 6.5% to $\mathcal{L}' = 20.3$ fb$^{-1}$.

The dataset used in the analysis is collected in Egamma and Muons streams. Events have to pass one of the lepton triggers. Several triggers are used in order to select the collisions in different regions of $p_T$ phase space. Symmetric triggers look for pair of electrons or muons with transverse momentum $p_T > 14$ GeV. The single electron and muon triggers have also a track isolation...
7.6 Discussion

An asymmetric electron trigger requires pair of electrons with \( p_T > (25, 8) \) GeV. An asymmetric muon trigger looks for two muons with \( p_T > (18, 8) \) GeV. Additionally two asymmetric electron-muon triggers are used with \( p_T^e > (14, 8) \) and \( (8, 18) \) GeV. The same triggers are used in both analysis presented in Paper IV and upcoming Paper V.

7.6 Discussion

The predicted composition based on Monte Carlo predictions in signal regions SR-WW\(_b\), SR-WW\(_c\), SR-\(m_{T2,90}\), SR-\(m_{T2,120}\) and SR-\(m_{T2,150}\) are presented in Tab. 7.2 - 7.6 respectively. The MC predictions are normalised using theory cross section and luminosity. It shows that data is well modelled by Monte Carlo in each signal region. The composition of SR-WW\(_a\) was not studied by the author of this thesis and is therefore not listed.

<table>
<thead>
<tr>
<th>Processes</th>
<th>( e^+e^- )</th>
<th>( \mu^+\mu^- )</th>
<th>( e^+\mu^- )</th>
</tr>
</thead>
<tbody>
<tr>
<td>WW</td>
<td>5.61 ±0.58 ±0.68</td>
<td>8.94 ±0.51 ±1.28</td>
<td>8.81 ±0.54 ±1.68</td>
</tr>
<tr>
<td>ZV</td>
<td>5.20 ±0.42 ±0.44</td>
<td>5.92 ±0.39 ±0.76</td>
<td>0.48 ±0.12 ±0.12</td>
</tr>
<tr>
<td>( Z/\gamma^* \rightarrow ee,\mu\mu )</td>
<td>0.00 ±0.00 ±0.00</td>
<td>0.00 ±0.00 ±0.04</td>
<td>0.00 ±0.00 ±0.00</td>
</tr>
<tr>
<td>( Z/\gamma^* \rightarrow \tau\tau )</td>
<td>0.00 ±0.00 ±0.00</td>
<td>0.00 ±0.00 ±0.00</td>
<td>0.00 ±0.00 ±0.00</td>
</tr>
<tr>
<td>Top</td>
<td>0.13 ±0.79 ±0.60</td>
<td>2.08 ±0.81 ±0.99</td>
<td>3.83 ±0.99 ±1.33</td>
</tr>
<tr>
<td>Fakes</td>
<td>0.34 ±0.39 ±0.00</td>
<td>-0.20 ±0.05 ±0.00</td>
<td>0.21 ±0.35 ±0.00</td>
</tr>
<tr>
<td>Higgs</td>
<td>0.11 ±0.04 ±0.01</td>
<td>0.13 ±0.04 ±0.03</td>
<td>0.19 ±0.05 ±0.02</td>
</tr>
<tr>
<td>Total</td>
<td>11.39 ±1.14 ±1.01</td>
<td>16.87 ±1.03 ±1.78</td>
<td>13.52 ±1.19 ±2.07</td>
</tr>
<tr>
<td>Data (work in progress)</td>
<td>9</td>
<td>15</td>
<td>14</td>
</tr>
</tbody>
</table>

Table 7.2: Predicted composition based on Monte Carlo in the signal region SR-WW\(_b\). The first error is the uncertainty from limited Monte Carlo statistics, the second error is systematic uncertainty arising from all sources of systematics. The prediction correspond to 20.3 fb\(^{-1}\) data. The data counts are the result of a preliminary analysis of 20.3 fb\(^{-1}\) by the author of this thesis and are not an officially approved ATLAS result.
Table 7.3: Predicted composition based on Monte Carlo in the signal region SR-WW\(_c\). The first error is the uncertainty from limited Monte Carlo statistics, the second error is systematic uncertainty arising from all sources of systematics. The prediction correspond to 20.3 fb\(^{-1}\) data. The data counts are the result of a preliminary analysis of 20.3 fb\(^{-1}\) by the author of this thesis and are not an officially approved ATLAS result.

<table>
<thead>
<tr>
<th>Processes</th>
<th>e(^+)e(^-)</th>
<th>(\mu^+\mu^-)</th>
<th>e(^\pm)(\mu^\pm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>WW</td>
<td>4.39 (\pm)0.53 (\pm)0.44</td>
<td>4.84 (\pm)0.39 (\pm)0.84</td>
<td>5.20 (\pm)0.43 (\pm)0.80</td>
</tr>
<tr>
<td>ZV</td>
<td>4.28 (\pm)0.38 (\pm)0.43</td>
<td>5.34 (\pm)0.38 (\pm)0.58</td>
<td>0.38 (\pm)0.12 (\pm)0.06</td>
</tr>
<tr>
<td>(Z/\gamma(*)\rightarrow ee,\mu\mu)</td>
<td>0.00 (\pm)0.00 (\pm)0.00</td>
<td>0.00 (\pm)0.00 (\pm)0.00</td>
<td>0.00 (\pm)0.00 (\pm)0.00</td>
</tr>
<tr>
<td>(Z/\gamma(*)\rightarrow \tau\tau)</td>
<td>0.00 (\pm)0.00 (\pm)0.00</td>
<td>0.00 (\pm)0.00 (\pm)0.00</td>
<td>0.00 (\pm)0.00 (\pm)0.00</td>
</tr>
<tr>
<td>Top</td>
<td>0.10 (\pm)0.70 (\pm)0.78</td>
<td>0.49 (\pm)0.49 (\pm)0.72</td>
<td>0.90 (\pm)0.52 (\pm)0.73</td>
</tr>
<tr>
<td>Fakes</td>
<td>-0.12 (\pm)0.21 (\pm)0.00</td>
<td>-0.05 (\pm)0.02 (\pm)0.00</td>
<td>-0.09 (\pm)0.19 (\pm)0.00</td>
</tr>
<tr>
<td>Higgs</td>
<td>0.07 (\pm)0.03 (\pm)0.01</td>
<td>0.08 (\pm)0.03 (\pm)0.01</td>
<td>0.14 (\pm)0.04 (\pm)0.01</td>
</tr>
<tr>
<td>Total</td>
<td>8.73 (\pm)0.98 (\pm)1.00</td>
<td>10.70 (\pm)0.73 (\pm)1.25</td>
<td>6.54 (\pm)0.71 (\pm)1.09</td>
</tr>
<tr>
<td>Data (work in progress)</td>
<td>6 3 8</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 7.4: Predicted composition based on Monte Carlo in the signal region SR-m\(_{T2,90}\). The first error is the uncertainty from limited Monte Carlo statistics, the second error is systematic uncertainty arising from all sources of systematics. The prediction correspond to 20.3 fb\(^{-1}\) data. The data counts are the result of a preliminary analysis of 20.3 fb\(^{-1}\) by the author of this thesis and are not an officially approved ATLAS result.

<table>
<thead>
<tr>
<th>Processes</th>
<th>e(^+)e(^-)</th>
<th>(\mu^+\mu^-)</th>
<th>e(^\pm)(\mu^\pm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>WW</td>
<td>8.17 (\pm)0.70 (\pm)0.96</td>
<td>11.29 (\pm)0.58 (\pm)1.71</td>
<td>11.93 (\pm)0.63 (\pm)1.96</td>
</tr>
<tr>
<td>ZV</td>
<td>6.22 (\pm)0.48 (\pm)0.48</td>
<td>7.00 (\pm)0.44 (\pm)0.97</td>
<td>0.69 (\pm)0.16 (\pm)0.12</td>
</tr>
<tr>
<td>(Z/\gamma(*)\rightarrow ee,\mu\mu)</td>
<td>0.00 (\pm)0.00 (\pm)0.00</td>
<td>0.00 (\pm)0.00 (\pm)0.04</td>
<td>0.00 (\pm)0.00 (\pm)0.00</td>
</tr>
<tr>
<td>(Z/\gamma(*)\rightarrow \tau\tau)</td>
<td>0.00 (\pm)0.00 (\pm)0.00</td>
<td>0.00 (\pm)0.00 (\pm)0.00</td>
<td>0.00 (\pm)0.00 (\pm)0.00</td>
</tr>
<tr>
<td>Top</td>
<td>0.57 (\pm)0.87 (\pm)0.60</td>
<td>2.33 (\pm)0.86 (\pm)1.00</td>
<td>5.00 (\pm)1.17 (\pm)1.36</td>
</tr>
<tr>
<td>Fakes</td>
<td>0.08 (\pm)0.40 (\pm)0.00</td>
<td>-0.22 (\pm)0.05 (\pm)0.00</td>
<td>0.08 (\pm)0.35 (\pm)0.00</td>
</tr>
<tr>
<td>Higgs</td>
<td>0.11 (\pm)0.04 (\pm)0.01</td>
<td>0.13 (\pm)0.04 (\pm)0.03</td>
<td>0.19 (\pm)0.05 (\pm)0.02</td>
</tr>
<tr>
<td>Total</td>
<td>15.14 (\pm)1.28 (\pm)1.23</td>
<td>20.52 (\pm)1.13 (\pm)2.21</td>
<td>17.89 (\pm)1.39 (\pm)2.38</td>
</tr>
<tr>
<td>Data (work in progress)</td>
<td>14 17 18</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
7.6 Discussion

Table 7.5: Predicted composition based on Monte Carlo in the signal region SR-$m_{T2,120}$. The first error is the uncertainty from limited Monte Carlo statistics, the second error is systematic uncertainty arising from all sources of systematics. The prediction correspond to 20.3 fb$^{-1}$ data. The data counts are the result of a preliminary analysis of 20.3 fb$^{-1}$ by the author of this thesis and are not an officially approved ATLAS result.

<table>
<thead>
<tr>
<th>Processes</th>
<th>$e^+e^-$</th>
<th>$\mu^+\mu^-$</th>
<th>$e^+\mu^*$</th>
</tr>
</thead>
<tbody>
<tr>
<td>WW</td>
<td>1.37±0.28±0.35</td>
<td>1.73±0.23±0.29</td>
<td>2.46±0.29±0.23</td>
</tr>
<tr>
<td>ZV</td>
<td>2.22±0.26±0.25</td>
<td>2.83±0.27±0.29</td>
<td>0.13±0.06±0.04</td>
</tr>
<tr>
<td>$Z/\gamma(*)\to ee,\mu\mu$</td>
<td>0.00±0.00±0.00</td>
<td>0.00±0.00±0.00</td>
<td>0.00±0.00±0.00</td>
</tr>
<tr>
<td>$Z/\gamma(*)\to \tau\tau$</td>
<td>0.00±0.00±0.00</td>
<td>0.00±0.00±0.00</td>
<td>0.00±0.00±0.00</td>
</tr>
<tr>
<td>Top</td>
<td>0.33±0.33±0.01</td>
<td>0.00±0.00±0.00</td>
<td>0.00±0.00±0.00</td>
</tr>
<tr>
<td>Fakes</td>
<td>-0.05±0.20±0.00</td>
<td>-0.04±0.02±0.00</td>
<td>-0.16±0.07±0.00</td>
</tr>
<tr>
<td>Higgs</td>
<td>0.04±0.03±0.00</td>
<td>0.08±0.03±0.01</td>
<td>0.11±0.04±0.01</td>
</tr>
<tr>
<td>Total</td>
<td>3.91±0.54±0.44</td>
<td>4.39±0.36±0.41</td>
<td>2.54±0.31±0.23</td>
</tr>
<tr>
<td>Data (work in progress)</td>
<td>4</td>
<td>2</td>
<td>2</td>
</tr>
</tbody>
</table>

Table 7.6: Predicted composition based on Monte Carlo in the signal region SR-$m_{T2,150}$. The first error is the uncertainty from limited Monte Carlo statistics, the second error is systematic uncertainty arising from all sources of systematics. The prediction correspond to 20.3 fb$^{-1}$ data. The data counts are the result of a preliminary analysis of 20.3 fb$^{-1}$ by the author of this thesis and are not an officially approved ATLAS result.

<table>
<thead>
<tr>
<th>Processes</th>
<th>$e^+e^-$</th>
<th>$\mu^+\mu^-$</th>
<th>$e^+\mu^*$</th>
</tr>
</thead>
<tbody>
<tr>
<td>WW</td>
<td>0.36±0.14±0.28</td>
<td>0.53±0.12±0.09</td>
<td>0.37±0.13±0.14</td>
</tr>
<tr>
<td>ZV</td>
<td>0.88±0.12±0.12</td>
<td>1.28±0.18±0.11</td>
<td>0.03±0.02±0.01</td>
</tr>
<tr>
<td>$Z/\gamma(*)\to \tau\tau$</td>
<td>0.00±0.00±0.00</td>
<td>0.00±0.00±0.00</td>
<td>0.00±0.00±0.00</td>
</tr>
<tr>
<td>$Z/\gamma(*)\to ee,\mu\mu$</td>
<td>0.00±0.00±0.00</td>
<td>0.00±0.00±0.00</td>
<td>0.00±0.00±0.00</td>
</tr>
<tr>
<td>Top</td>
<td>0.00±0.00±0.00</td>
<td>0.00±0.00±0.00</td>
<td>0.00±0.00±0.00</td>
</tr>
<tr>
<td>Fakes</td>
<td>0.06±0.18±0.00</td>
<td>-0.01±0.01±0.00</td>
<td>-0.06±0.04±0.00</td>
</tr>
<tr>
<td>Higgs</td>
<td>0.01±0.01±0.00</td>
<td>0.02±0.01±0.00</td>
<td>0.04±0.02±0.00</td>
</tr>
<tr>
<td>Total</td>
<td>1.31±0.26±0.30</td>
<td>1.82±0.22±0.14</td>
<td>0.57±0.14±0.14</td>
</tr>
<tr>
<td>Data (work in progress)</td>
<td>2</td>
<td>1</td>
<td>2</td>
</tr>
</tbody>
</table>
Chapter 8

Jet-Veto

8.1 Motivation

The targeted signal processes (see Chapter 7) do not yield hadronic activity in form of jets, but jets can still arise from Initial State Radiation (ISR). On the other hand the large $t\bar{t}$ background can yield two leptons and two jets coming from $b$-quarks. The $t\bar{t}$ process has a large cross section and results in a dilepton and $E_T^{\text{miss}}$ final state. A jet-veto is therefore important to suppress this high-cross section background.

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

8.2 Signal Jets

In order not to suppress the chargino and slepton signal it is necessary to differentiate between the jets from the primary interaction and those from pile-up. Therefore, so called signal jets are defined. These signal jets are supposed to come from the primary vertex in the collision of interest.

The signal jets are grouped into three mutually exclusive categories:
8.2 Signal Jets

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

The central light jets have $|\eta| < 2.4$ and are not tagged as $b$-jet. They are required to have transverse momentum $p_T > 20$ GeV. Additionally, Jet Vertex Fraction (JVF) cut is utilised on jets with $p_T < 50$ GeV to confirm that they come from the primary collision and not from pile-up. The JVF variable relies on information from the Inner Detector and can be defined only for jets with $|\eta| < 2.5$. For better accuracy near the boundary of the Semiconducting Tracker system it is used in $|\eta| < 2.4$. The central light jet criteria efficiently selects jets coming from primary vertex while few pile-up jets survive.

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

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

<table>
<thead>
<tr>
<th>Cut</th>
<th>Central light jet (L20)</th>
<th>Central $b$-jet (B20)</th>
<th>Forward jet (F30)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p_T$</td>
<td>$&gt; 20$ GeV</td>
<td>$&gt; 20$ GeV</td>
<td>$&gt; 30$ GeV</td>
</tr>
<tr>
<td>$</td>
<td>\eta</td>
<td>$</td>
<td>$&lt; 2.4$</td>
</tr>
<tr>
<td>$b$-tag</td>
<td>$\times$</td>
<td>$\checkmark$</td>
<td>$-$</td>
</tr>
<tr>
<td>JVF</td>
<td>$\checkmark$ if $p_T &lt; 50$ GeV</td>
<td>$-$</td>
<td>$-$</td>
</tr>
</tbody>
</table>

Table 8.1: Signal jet definitions: central light jets (L20), central $b$-jets (B20) and forward jets (F30). $\checkmark$ means the cut is applied, $\times$ means the cut is reversed, $-$ means the cut is not applied.
Jet-veto requires exactly zero signal jets of all defined kinds in the event: 
\[ N_{L20} + N_{B20} + N_{F30} = 0. \]

8.3 Top Background Calculation and Jet-Veto

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

\[ N^{SR}_{Top} = \mathcal{S} \times N^{SR}_{Top, MC} \times C_S \tag{8.1} \]

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

\[ \mathcal{S} = \frac{N^{CR}_{Top, data}}{N^{CR}_{Top, MC}} \tag{8.2} \]

The correction factor \( C_S \) is used to address potential difference in the jet veto efficiency between data and MC since the Eq. 8.2 relies implicitly on the simulation to derive the probability for \( t\bar{t} \) events to survive the jet-veto. It is given by:

\[ C_S = \frac{\mathcal{E}_{jet \ veto}^{data}}{\mathcal{E}_{jet \ veto}^{MC}} \tag{8.3} \]

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

\[ \mathcal{E}_{jet \ veto} = \frac{N^{CR}_{jet \ veto}}{N^{CR}} \tag{8.4} \]

where \( N^{CR}_{jet \ veto} \) is the number of events in CR with no signal jets while \( N^{CR} \) is the total number of all events in CR.

In this Chapter we present the study of \( C_S \) in two control regions. This method is used in Paper IV and upcoming Paper V.

8.4 Control Regions

The jet-veto efficiency is compared between data and Monte Carlo in two control regions: \( b \)-tag control region and \( Z \) control region.
8.4 Control Regions

<table>
<thead>
<tr>
<th>Top control region</th>
<th>OS</th>
<th>Lepton Flavor</th>
<th>$p_T^{l_1}$</th>
<th>$p_T^{l_2}$</th>
<th>$m_{\ell\ell}$</th>
<th>signal central jets</th>
<th>signal $b$-jets</th>
<th>signal forward jets</th>
<th>$m_T^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>OS</td>
<td>Lepton Flavor</td>
<td>$p_T^{l_1}$</td>
<td>$p_T^{l_2}$</td>
<td>$m_{\ell\ell}$</td>
<td>signal central jets</td>
<td>signal $b$-jets</td>
<td>signal forward jets</td>
<td>$m_T^2$</td>
</tr>
<tr>
<td></td>
<td>OS</td>
<td>Lepton Flavor</td>
<td>$p_T^{l_1}$</td>
<td>$p_T^{l_2}$</td>
<td>$m_{\ell\ell}$</td>
<td>signal central jets</td>
<td>signal $b$-jets</td>
<td>signal forward jets</td>
<td>$m_T^2$</td>
</tr>
<tr>
<td></td>
<td>OS</td>
<td>Lepton Flavor</td>
<td>$p_T^{l_1}$</td>
<td>$p_T^{l_2}$</td>
<td>$m_{\ell\ell}$</td>
<td>signal central jets</td>
<td>signal $b$-jets</td>
<td>signal forward jets</td>
<td>$m_T^2$</td>
</tr>
<tr>
<td></td>
<td>OS</td>
<td>Lepton Flavor</td>
<td>$p_T^{l_1}$</td>
<td>$p_T^{l_2}$</td>
<td>$m_{\ell\ell}$</td>
<td>signal central jets</td>
<td>signal $b$-jets</td>
<td>signal forward jets</td>
<td>$m_T^2$</td>
</tr>
<tr>
<td></td>
<td>OS</td>
<td>Lepton Flavor</td>
<td>$p_T^{l_1}$</td>
<td>$p_T^{l_2}$</td>
<td>$m_{\ell\ell}$</td>
<td>signal central jets</td>
<td>signal $b$-jets</td>
<td>signal forward jets</td>
<td>$m_T^2$</td>
</tr>
<tr>
<td></td>
<td>OS</td>
<td>Lepton Flavor</td>
<td>$p_T^{l_1}$</td>
<td>$p_T^{l_2}$</td>
<td>$m_{\ell\ell}$</td>
<td>signal central jets</td>
<td>signal $b$-jets</td>
<td>signal forward jets</td>
<td>$m_T^2$</td>
</tr>
<tr>
<td></td>
<td>OS</td>
<td>Lepton Flavor</td>
<td>$p_T^{l_1}$</td>
<td>$p_T^{l_2}$</td>
<td>$m_{\ell\ell}$</td>
<td>signal central jets</td>
<td>signal $b$-jets</td>
<td>signal forward jets</td>
<td>$m_T^2$</td>
</tr>
<tr>
<td></td>
<td>OS</td>
<td>Lepton Flavor</td>
<td>$p_T^{l_1}$</td>
<td>$p_T^{l_2}$</td>
<td>$m_{\ell\ell}$</td>
<td>signal central jets</td>
<td>signal $b$-jets</td>
<td>signal forward jets</td>
<td>$m_T^2$</td>
</tr>
</tbody>
</table>

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

8.4.1 $b$-tag control region

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

Figure 8.1 shows the composition of the $b$-tag control region as a function of $E_{T}^{\text{miss}, \text{rel}}$ before jet-veto (left panel). To study the jet-veto in the $b$-tag control region only jets with $\Delta R > 1.0$ from $b$-tagged are considered. The composition of the $b$-tag control region as a function of $E_{T}^{\text{miss}, \text{rel}}$ after jet-veto is showed in Fig. 8.1 right panel. A good agreement between data and MC is observed both before and after jet-veto requirement.

<table>
<thead>
<tr>
<th>Cut</th>
<th>$b$-tag control region</th>
<th>$Z$ control region</th>
</tr>
</thead>
<tbody>
<tr>
<td>OS</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>$m_{\ell\ell}$</td>
<td>&gt; 20 GeV</td>
<td>&gt; 20 GeV</td>
</tr>
<tr>
<td>$</td>
<td>m_{4\ell} - m_Z</td>
<td>$</td>
</tr>
<tr>
<td>$b$-jets ($p_T &gt; 25$ GeV)</td>
<td>≥ 1</td>
<td>—</td>
</tr>
<tr>
<td>$E_{T}^{\text{miss}, \text{rel}}$</td>
<td>&gt; 40 GeV</td>
<td>—</td>
</tr>
</tbody>
</table>

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

The Z control region is also used to study the jet-veto. This region is dominated by Z+jets events and contains mostly central light jets. Therefore, the Z control region can be used to cross check whether the probability to pass the L20 part of the jet-veto in MC agrees with this probability in data. Nevertheless, the scale factor used in Eq. 8.1 is obtained using b-tag control region because by far Top is the main background rejected by the jet-veto. The definition of Z control region is given in Tab. 8.3.

8.5 Results

The b-tag control region is used to compute the probability of an event to survive the jet-veto, so called jet-veto efficiency $E_{\text{jet veto}}$ given by Eq. 8.4. This probability is showed for data and Monte Carlo as a function of number of primary vertices in Fig. 8.2 top panels. It is presented as a function of number of primary vertices in order to test how this probability depends on the primary interactions in the event and how it is modelled by MC. It is shown that less than 20% of events in Top dominated b-tag control region survive the jet-veto. We also note that, there is no dependence of the jet-veto efficiency on the primary vertex multiplicity in both data and MC. The correction factor $C_S$ used in Eq. 8.1 is obtained by fitting a constant to the ratio of jet-veto efficiencies in data and MC showed in the lower panel of plots in Fig. 8.2. This yields $C_S = 0.95 \pm 0.04 \pm 0.17$ in ee channel and $C_S = 1.00 \pm 0.03 \pm 0.21$ in $\mu\mu$ channel, where first error is statistical and second one is systematical. Jet energy scale is the large source of the systematic uncertainty.
Figure 8.1: Distribution of $E_T^{\text{miss,rel}}$ in the $ee$ b-tag control region (top-left) and in the $\mu\mu$ b-tag control region (bottom-left). The top and bottom-right plots show the $ee$ and $\mu\mu$ b-tag control regions after requiring the jet-veto: $N_{L20} + N_{B20} + N_{F30} = 0$. The uncertainty band represents statistical uncertainties only. The data points correspond to 20.7 fb$^{-1}$.
The jet-veto efficiency studied in the $Z$ control region is presented in Fig. 8.2 bottom panels. It is shown that the efficiency is mildly decreasing at high primary vertex multiplicities. Nevertheless, this trend is well reproduced by the Monte Carlo simulation. The same fitting procedure is applied as for the $b$-tag control region. The jet-veto efficiency in the $Z$ control region is $1.032 \pm 0.002$ in $ee$ channel and $1.032 \pm 0.001$ in $\mu \mu$ channel, where error is statistical.

In Paper IV the correction factor of $C_S = 1.0 \pm 0.1$ is used in both $e^+e^-$ and $\mu^+\mu^-$ channels.

### 8.6 Conclusions

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

The study described in this Chapter is included in Paper IV and upcoming Paper V.
Table 8.6.1: Event probability to pass jet-veto for different number of primary vertices.

<table>
<thead>
<tr>
<th>No. of primary vertices</th>
<th>Data 2012</th>
<th>Monte Carlo</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.2</td>
<td>0.1</td>
</tr>
<tr>
<td>5</td>
<td>0.4</td>
<td>0.3</td>
</tr>
<tr>
<td>10</td>
<td>0.6</td>
<td>0.5</td>
</tr>
<tr>
<td>15</td>
<td>0.8</td>
<td>0.7</td>
</tr>
<tr>
<td>20</td>
<td>1.0</td>
<td>0.9</td>
</tr>
<tr>
<td>25</td>
<td>1.2</td>
<td>1.1</td>
</tr>
<tr>
<td>30</td>
<td>1.4</td>
<td>1.3</td>
</tr>
<tr>
<td>35</td>
<td>1.6</td>
<td>1.5</td>
</tr>
<tr>
<td>40</td>
<td>1.8</td>
<td>1.7</td>
</tr>
</tbody>
</table>

Figure 8.2: Event probability to survive the jet-veto in the $b$-tag control region as a function of the number of primary vertices in di-electron (a) and di-muon events (b). Event probability to pass the jet veto in the $Z$ control region as a function of the number of primary vertices in di-electron events (c) and di-muon right events (d). The uncertainty band represents statistical uncertainty. The data points correspond to 20.7 fb$^{-1}$. 
Chapter 9

ZV Background Estimation

In this Chapter the data-driven estimation of ZV background is described. The presented method is used in the analysis described in Paper V. In Paper IV a similar technique is used with slightly different control region definitions.

9.1 Motivation

This Chapter is devoted to the Z+jets, ZW, ZZ and Z+two vector bosons backgrounds determination for the opposite sign signal regions with jet-veto and $m_{T2}$ cut: SR-$m_{T2,90}$, SR-$m_{T2,120}$, SR-$m_{T2,150}$, SR-$WW_b$ and SR-$WW_c$ (see Section 7.4). The label ZV is used generically to refer to these processes. As discussed in Chapter 7, ZV is one of the dominant Standard Model backgrounds since it often yields opposite sign lepton pairs and missing transverse energy in the final state. This Chapter presents a data-driven calculation of this background in signal regions listed above. The signal region SR-$WW_a$ is not considered, since it requires a different control region selection (see Section 9.2). The ZV background estimation in SR-$WW_a$ is presented in Paper IV.

9.2 Control Region

In order to calculate the ZV background in the signal regions SR-$m_{T2,90}$, SR-$m_{T2,120}$, SR-$m_{T2,150}$, SR-$WW_b$ and SR-$WW_c$ a common control region
9.2 Control Region

labelled ZVCR is defined. The control region is constructed to be orthogonal to each signal region. Ideally, the control region should have the same selection as the signal region except the single reversed cut. ZVCR utilises $m_{T2} > 90$ GeV and $|m_{ll} - m_Z| < 10$ GeV, all the other selections are the same as the signal regions mentioned earlier. The ZVCR is rich in ZV processes. All the other cuts are the same as in SR-$m_{T2}$. Table 9.1 gives the exact definition of the control region. The selection $m_{T2} > 90$ GeV is the lowest $m_{T2}$ cut used in signal regions. This relatively low cut provides larger data and Monte Carlo statistics lowering the statistical uncertainty. The lower $m_{T2}$ cut also provides smaller generator systematical uncertainty on transfer factor $T_f$ between control and signal region. Generator uncertainty is estimated by comparing different Monte Carlo generators, POWHEG and SHERPA. For this reason the relative difference between the transfer factors obtained using these generators is calculated. The $T_f$ is further discussed in Section 9.3.

<table>
<thead>
<tr>
<th>ZVCR</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>OS</td>
<td>✓</td>
</tr>
<tr>
<td>Lepton Flavor</td>
<td>ee, µµ</td>
</tr>
<tr>
<td>$p_T^{l1}$</td>
<td>&gt; 35 GeV</td>
</tr>
<tr>
<td>$p_T^{l2}$</td>
<td>&gt; 20 GeV</td>
</tr>
<tr>
<td>$m_{ll}$</td>
<td>&gt; 20 GeV</td>
</tr>
<tr>
<td>$</td>
<td>m_{ll} - m_Z</td>
</tr>
<tr>
<td>signal central jets</td>
<td>= 0</td>
</tr>
<tr>
<td>signal b-jets</td>
<td>= 0</td>
</tr>
<tr>
<td>signal forward jets</td>
<td>= 0</td>
</tr>
<tr>
<td>$m_{T2}$</td>
<td>&gt; 90 GeV</td>
</tr>
</tbody>
</table>

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

Figure 9.1 shows the $E_T^{\text{miss},\text{rel}}$ (top panel) and $m_{T2}$ (bottom panel) in data and Monte Carlo in ZVCR. A good agreement is observed between data and MC prediction. It also clearly shows that ZVCR is dominated by ZV background.
Figure 9.1: Distributions of $E_{\text{T}}^{\text{miss, rel}}$ (top) and $m_{T2}$ (bottom) in the dielectron (left) and dimuon channel (right) in the ZVCR. The uncertainty band represents the total statistical and systematic uncertainty on the Monte Carlo prediction. The data points correspond to 20.3 fb$^{-1}$. 
Table 9.2 presents the process composition of ZVCR obtained from Monte Carlo simulation. The total number of Standard Model background events can be compared with data. A good agreement is observed between data and MC. A very high purity of ZV events in ZVCR is observed, 95% in $e\bar{e}$ channel and 97% in $\mu\mu$ channel. It is observed that no $Z+$jets events in the Monte Carlo survive the ZVCR selection. The $Z+$jets processes do not pass the $m_{T2} < 90$ GeV requirement nor even looser selections and can therefore be ignored. The data in the ZVCR is also consistent with zero $Z+$jets events. As expected very few events are observed in the $e\mu$ channel due to the absence of $Z \to \ell\ell$ processes with this final state. The $e\mu$ channel contain mostly events from $WW$ and top processes where two different flavor leptons can be produced.

<table>
<thead>
<tr>
<th>Processes</th>
<th>$e^+e^-$</th>
<th>$\mu^+\mu^-$</th>
<th>$e^\pm\mu^\mp$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z$</td>
<td>41.90 ±1.17 ±4.53</td>
<td>48.62 ±1.15 ±5.68</td>
<td>0.06 ±0.04 ±0.02</td>
</tr>
<tr>
<td>$Z/\gamma(\ast) \to e\bar{e},\mu\bar{\mu}$</td>
<td>0.00 ±0.00 ±0.00</td>
<td>0.00 ±0.00 ±1.14</td>
<td>0.00 ±0.00 ±0.00</td>
</tr>
<tr>
<td>$WW$</td>
<td>1.89 ±0.27 ±0.18</td>
<td>2.34 ±0.24 ±0.40</td>
<td>2.20 ±0.28 ±0.28</td>
</tr>
<tr>
<td>$Z/\gamma(\ast) \to \tau\tau$</td>
<td>0.00 ±0.00 ±0.00</td>
<td>0.00 ±0.00 ±0.00</td>
<td>0.00 ±0.00 ±0.00</td>
</tr>
<tr>
<td>Top</td>
<td>0.55 ±0.79 ±0.34</td>
<td>0.06 ±0.06 ±0.32</td>
<td>0.64 ±0.37 ±0.31</td>
</tr>
<tr>
<td>Fakes</td>
<td>-0.41 ±0.63 ±0.00</td>
<td>-1.08 ±0.15 ±0.00</td>
<td>0.50 ±0.31 ±0.00</td>
</tr>
<tr>
<td>Higgs</td>
<td>0.05 ±0.02 ±0.01</td>
<td>0.03 ±0.01 ±0.05</td>
<td>0.02 ±0.02 ±0.00</td>
</tr>
<tr>
<td>Total</td>
<td>43.97 ±1.57 ±4.55</td>
<td>49.97 ±1.19 ±5.82</td>
<td>3.42 ±0.57 ±0.41</td>
</tr>
<tr>
<td>Data</td>
<td>45</td>
<td>57</td>
<td>3</td>
</tr>
</tbody>
</table>

Table 9.2: Predicted composition of ZVCR based on Monte Carlo and observed data yields. The first error is the uncertainty from limited Monte Carlo statistics, the second error is systematic uncertainty arising from all sources of systematics. The prediction correspond to 20.3 fb$^{-1}$.

9.3 Method

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

$$N_{ZV}^{SR} = (N_{CR}^{data} - N_{non-Z, MC}^{CR}) \times T_f$$

(9.1)

where $N_{ZV}^{SR}$ is the data-driven estimate of the number of $ZV$ events in the signal region, $N_{CR}^{data}$ is the observed number of events in ZVCR. As presented in Tab. 9.2 the ZVCR is contaminated by other Standard Model processes.
such as $WW$ or top. These events are collectively called non-$Z$ background and are labelled as $N_{\text{non}-Z,\ MC}^{\text{CR}}$. They need to be subtracted from the $N_{\text{non}-Z}^{\text{CR}}$ before extrapolation to the signal regions. Equation 9.1 is applied separately for the $ee$ and $\mu\mu$ channels. The $N_{\text{data}}^{\text{CR}}$ is estimated from the Monte Carlo. The $T_{f}$ is called transfer factor and is the ratio of the number of $ZV$ events in the signal region over the number of $ZV$ events in the ZVCR:

$$
T_{f} = \left( \frac{N_{\text{SR}}^{ZV}}{N_{\text{CR}}^{ZV}} \right)^{\text{MC}}
$$

(9.2)

The $T_{f}$ is the main input from the Monte Carlo in this method.

Equation 9.1 may also be rewritten in term of a scale factor $S$: By taking a ratio of two Monte Carlo yields in two regions which are similar the systematic uncertainty can be reduced.

$$
N_{ZV}^{\text{SR}} = N_{ZV,\ MC}^{\text{SR}} \times S
$$

(9.3)

where $S$ is defined as:

$$
S = \frac{N_{ZV,\ data}^{\text{CR}} - N_{\text{non}-Z,\ MC}^{\text{CR}}}{N_{ZV,\ MC}^{\text{CR}}}
$$

(9.4)

The scale factor takes value $S = 1$ if Monte Carlo is in perfect agreement with data. While the $T_{f}$ is really used to derive the $ZV$ background, the $S$ allows to visualise how much the Monte Carlo needs to be scaled to reproduce the data. Thus its values are provided in result Section 9.5. The correction is needed since the differential cross sections for the Standard Model background processes are not measured. Thus the background calculation do not rely on pure MC estimation.

### 9.4 Signal Contamination

To provide an accurate determination of $ZV$ background the ZVCR should be dominated by this processes as demonstrated in Section 9.3. Since the ZVCR has selections similar to the signal regions it might contain some SUSY events. Therefore, the potential signal contamination from direct $\tilde{\chi}^{\pm} \tilde{\chi}^{\mp}$ production or from direct $\tilde{\ell}^{\pm} \tilde{\ell}^{\mp}$ production is checked for different signal scenarios.

Figure 9.2 top panel shows the contamination in ZVCR from $\tilde{\chi}^{\pm}_{1} \tilde{\chi}^{\mp}_{1}$ events in per cent for different masses of the chargino $\tilde{\chi}^{\pm}_{1}$ and the neutralino $\tilde{\chi}^{0}_{1}$. It shows that the highest contamination is 20% which correspond to 2.2 $\sigma$
9.4 Signal Contamination

significance for the point (155, 5) GeV. Nevertheless, the sparticles mass region with high signal contamination was excluded with earlier searches [75]. Outside the previously excluded region the contamination is below 3% which corresponds to 0.3 $\sigma$ significance or less.

The contamination from $\tilde{\ell}^+ \tilde{\ell}^+$ signal in percent for different slepton $\tilde{\ell}^\pm$ and neutralino $\tilde{\chi}^0_1$ masses is presented in Fig. 9.2 bottom panel. It is found to be 15% which correspond to 1.5 $\sigma$ significance at most for the points (105, 25) and (120, 0) GeV. Again, the region of high signal contamination was already excluded with earlier searches. Outside the previously excluded region the contamination is below 4% which correspond to 0.4 $\sigma$ significance or less.
Chapter 9: ZV Background Estimation

Figure 9.2: Top: signal contamination in percent (z-axis) in ZVCR from direct chargino production with intermediate sleptons (Eq. 7.3) with respect to the chargino mass (x-axis) and to the neutralino mass (y-axis) in $e^+e^-$ channel (left) and $\mu^+\mu^-$ (right) channel. Bottom: signal contamination in percent (z-axis) in ZVCR from direct sleptons production (Eq. 7.5) with respect to the slepton mass (x-axis) and to the neutralino mass (y-axis) (bottom) in $e^+e^-$ channel (left) and $\mu^+\mu^-$ (right) channel. The crosses represent the probed signal points for which Monte Carlo samples have been generated. The continuous colour plane is obtained using an interpolation between the probed points. The white region on the top-left of each plot is kinematically forbidden.
9.5 Results

Using the ZVCR and method discussed in Section 9.3 the ZV background for signal regions SR-\(m_{T2,90}\), SR-\(m_{T2,120}\), SR-\(m_{T2,150}\) SR-WW\(_b\) and SR-WW\(_c\) is estimated. After counting the data yields in the control region the data-driven predictions for the ZV background in the signal regions was obtained. The results are presented in Table 9.3. The data-driven calculation is in good agreement with the MC based prediction. The scale factor \(S = 1.025\) for \(e^+e^-\) channel and \(S = 1.145\) for \(\mu^+\mu^-\) channel is applied on Monte Carlo.

<table>
<thead>
<tr>
<th></th>
<th>(e^+e^-)</th>
<th>(\mu^+\mu^-)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Data-driven</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SR-WW(_b)</td>
<td>5.3 ±0.9</td>
<td>6.8 ±1.0</td>
</tr>
<tr>
<td></td>
<td>+0.4</td>
<td>+0.4</td>
</tr>
<tr>
<td></td>
<td>−0.4</td>
<td>−0.4</td>
</tr>
<tr>
<td>SR-WW(_c)</td>
<td>4.4 ±0.8</td>
<td>6.1 ±0.9</td>
</tr>
<tr>
<td></td>
<td>+0.3</td>
<td>+0.9</td>
</tr>
<tr>
<td></td>
<td>−0.3</td>
<td>−0.9</td>
</tr>
<tr>
<td>SR-(m_{T2,90})</td>
<td>6.4 ±1.1</td>
<td>8.0 ±1.2</td>
</tr>
<tr>
<td></td>
<td>+0.4</td>
<td>+0.4</td>
</tr>
<tr>
<td></td>
<td>+0.8</td>
<td>+1.0</td>
</tr>
<tr>
<td>SR-(m_{T2,120})</td>
<td>2.3 ±0.4</td>
<td>3.2 ±0.5</td>
</tr>
<tr>
<td></td>
<td>+0.3</td>
<td>+0.7</td>
</tr>
<tr>
<td></td>
<td>−0.4</td>
<td>−0.7</td>
</tr>
<tr>
<td>SR-(m_{T2,150})</td>
<td>0.9 ±0.2</td>
<td>1.5 ±0.3</td>
</tr>
<tr>
<td></td>
<td>+0.1</td>
<td>+0.2</td>
</tr>
<tr>
<td></td>
<td>−0.2</td>
<td>−0.2</td>
</tr>
<tr>
<td>Monte Carlo</td>
<td></td>
<td></td>
</tr>
<tr>
<td>SR-WW(_b)</td>
<td>5.2 ±0.4</td>
<td>5.9 ±0.4</td>
</tr>
<tr>
<td></td>
<td>±0.4</td>
<td>±0.4</td>
</tr>
<tr>
<td>SR-WW(_c)</td>
<td>4.3 ±0.4</td>
<td>5.3 ±0.4</td>
</tr>
<tr>
<td></td>
<td>±0.4</td>
<td>±0.6</td>
</tr>
<tr>
<td>SR-(m_{T2,90})</td>
<td>6.2 ±0.5</td>
<td>7.0 ±0.4</td>
</tr>
<tr>
<td></td>
<td>±0.5</td>
<td>±1.0</td>
</tr>
<tr>
<td>SR-(m_{T2,120})</td>
<td>2.2 ±0.3</td>
<td>2.8 ±0.3</td>
</tr>
<tr>
<td></td>
<td>±0.2</td>
<td>±0.3</td>
</tr>
<tr>
<td>SR-(m_{T2,150})</td>
<td>0.9 ±0.1</td>
<td>1.3 ±0.2</td>
</tr>
<tr>
<td></td>
<td>±0.1</td>
<td>±0.1</td>
</tr>
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</table>

Table 9.3: Data-driven and Monte Carlo prediction for the ZV background in the signal regions SR-\(m_{T2,90}\), SR-\(m_{T2,120}\), SR-\(m_{T2,150}\), SR-WW\(_b\) and SR-WW\(_c\). The scale factor \(S\) is also given. The first uncertainty is the combination of the uncertainty from limited Monte Carlo statistics and from control region statistics in data. The second error is the result of all other sources of systematic uncertainties except generator uncertainty. For data driven predictions the third uncertainty arises from generator systematics.
Chapter 10

Results and Conclusions

In this Section, the results from Paper IV are presented although Chapter 9 provides the state of the art calculation of the $ZV$ background for the upcoming Paper V. The results contained in the Paper V are not yet public and thus cannot be shown in this thesis. Therefore, the results from Paper IV are shown. Paper IV makes use of the study presented in Chapter 8 on the jet-veto and a simpler version of the $ZV$ background study given in Chapter 9.

10.1 Methodology

In the signal regions of Paper IV no significant excess over background has been observed. Therefore, upper limits at 95% confidence level ($CL$) on chargino and slepton production are derived.

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

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

For a given signal region and for a given SUSY model defined by the chargino ($m_{\tilde{\chi}^{\pm}_1}$), slepton ($m_{\tilde{\ell}^\pm}$) and neutralino ($m_{\tilde{\chi}^0_1}$) masses a number of signal events
10.1 Methodology

$S$ is expected. The probability to observe $N$ events or more under the signal plus background hypothesis is thus given by:

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

(10.1)

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

$$CL = 1 - \alpha = \sum_{k=0}^{N-1} \frac{e^{-(S+B)}(S + B)^k}{k!}$$

(10.2)

where $\alpha$ is fixed and traditionally set to 5\%, i.e. $CL = 95\%$. An upper limit $S_{\max}$ can be obtained from Eq. 10.2, where $S_{\max}$ is the highest value of $S$ for which $\alpha > 5\%$ or $1 - \alpha < 95\%$. If a given SUSY signal model for a given set of masses $m_{\tilde{\chi}^\pm}$, $m_{\tilde{\ell}^\pm}$ and $m_{\tilde{\chi}^0_1}$ has an expected value $S$ larger than $S_{\max}$ then this particular SUSY model is said to be excluded.

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

$$\sigma_{\max} = \frac{S_{\max}}{\varepsilon L}$$

(10.3)

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

In case of a downward fluctuation of the data, where less events are observed than the expected number of background events, SUSY models could be excluded even in case of absence of experimental sensitivity. To avoid this situation the ATLAS experiment uses the $CL_s$ method [76]. In this method the $CL$ from Eq. 10.2 is reduced in case of a downward fluctuation using the $p$-value of background only hypothesis. The limits presented below use this method.

All systematic uncertainties are taken into account in limits calculation. The signal regions are not mutually exclusive, therefore the region with best expected exclusion limit is used at each mass point.
10.2 Interpretation

The results are presented in Fig. 10.1 and Fig. 10.2. In each limit plot, the dashed black line corresponds to the expected limit, while the solid red line represents observed limits. Statistical and systematic uncertainties are included. The yellow band shows the experimental uncertainties on the expected limit. The dashed red lines indicate the impact on the observed limit when the signal cross section is scaled up and down by 1σ of theoretical uncertainties.

Figure 10.1 (a) shows 95% confidence level exclusion region for the direct chargino pair production with intermediate sleptons in the $m_{\tilde{\chi}^\pm_1} - m_{\tilde{\chi}^0_1}$ plane. The results are obtained using signal regions SR-$m_{T2},90$, SR-$m_{T2},120$ and SR-$m_{T2},150$. Chargino masses between $m_{\tilde{\chi}^\pm_1} = 130$ GeV and $m_{\tilde{\chi}^\pm_1} = 460$ GeV are excluded for neutralino mass $m_{\tilde{\chi}^0_1} = 20$ GeV at 95% CL.

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Figure 10.2 shows 95% confidence level exclusion region for the direct pair production of left-handed (a), right handed (b) and combined left- and right-handed (c) sleptons in the $m_{\tilde{\ell}^\pm} - m_{\tilde{\chi}^0_1}$ plane. Left- and right-handed sleptons are assumed to have equal mass. Signal regions SR-$m_{T2},90$, SR-$m_{T2},120$ and SR-$m_{T2},150$ are used to obtain the results. For neutralino mass $(m_{\tilde{\chi}^0_1} = 30$ GeV) a common value for left- and right-handed slepton mass between $m_{\tilde{\ell}^\pm} = 90$ GeV and $m_{\tilde{\ell}^\pm} = 330$ GeV is excluded at 95% CL. The sensitivity decreases when the mass split $m_{\tilde{\ell}^\pm} - m_{\tilde{\chi}^0_1}$ decreases. It is caused by lower $m_{T2}$ kinematic edge becoming similar to Standard Model background processes. For neutralino mass $m_{\tilde{\chi}^0_1} = 100$ GeV slepton mass between $m_{\tilde{\ell}^\pm} = 160$ GeV and $m_{\tilde{\ell}^\pm} = 320$ GeV is excluded.

The presented analysis significantly improves limits compared to previous results obtained with $\mathcal{L} = 4.7$ fb$^{-1}$ of proton-proton collision data at $\sqrt{s} = 7$ TeV recorded by ATLAS [75].
Figure 10.1: 95% CL exclusion limits for direct $\tilde{\chi}^\pm_1 \tilde{\chi}^\mp_1$ pair production with intermediate sleptons in the decay (a) with respect to the chargino mass ($m_{\tilde{\chi}^\pm_1}$) and to the neutralino mass ($m_{\tilde{\chi}^0_1}$). 95% CL upper limits on the ratio of the cross section over expected cross section for direct $\tilde{\chi}^\pm_1 \tilde{\chi}^\mp_1$ pair production with intermediate $W$ bosons (b) as a function chargino mass ($m_{\tilde{\chi}^\pm_1}$) normalised to the simplified model cross section for a massless neutralino ($m_{\tilde{\chi}^0_1} = 0$ GeV).
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10.1 95\% CL exclusion limits for direct $\tilde{\chi}^\pm_1 \tilde{\chi}^\mp_1$ pair production with intermediate sleptons in the decay (a) with respect to the chargino mass ($m_{\tilde{\chi}^\pm_1}$) and to the neutralino mass ($m_{\tilde{\chi}^0_1}$). 95\% CL upper limits on the ratio of the cross section over expected cross section for direct $\tilde{\chi}^\pm_1 \tilde{\chi}^\mp_1$ pair production with intermediate W bosons (b) as a function chargino mass ($m_{\tilde{\chi}^\pm_1}$) normalised to the simplified model cross section for a massless neutralino ($m_{\tilde{\chi}^0_1} = 0$ GeV).

10.2 95\% CL exclusion limits for direct production of left-handed (a), right-handed (b), combination of left- and right-handed (mass degenerate) slepton pairs with respect to the slepton mass ($m_{\tilde{\ell}_\pm}$) and to the neutralino mass ($m_{\tilde{\chi}^0_1}$).
Bibliography


Paper I
Identification of Pile-up
Using the Quality Factor of Pulse Shapes
in the ATLAS Tile Calorimeter

Christophe Clement, Pawel Klimek
(on behalf of the ATLAS Collaboration)

Abstract—The ATLAS experiment records data from the proton-proton collisions produced by the Large Hadron Collider (LHC). The Tile Calorimeter is the hadronic sampling calorimeter of ATLAS in the region $|\eta| < 1.7$. It uses iron absorbers and scintillators as active material. The LHC will provide collisions every 25 ns, putting very strong requirements on the energy measurement in presence of energy deposits from different collisions in the same read out window and physical calorimeter channel (pile-up). In 2011 the LHC is running with filled bunches at 50 ns spacing and at intensities which yield up to about 8 proton-proton collisions per bunch crossing. We present a quality factor that can be computed online for each collision and for each calorimeter channel within the 10 µs latency of the ATLAS first level trigger (L1 trigger), and could allow to identify calorimeter channels presenting pile-up. In presence of a poor quality factor the data from the corresponding channel is read out with additional information to allow for an offline dedicated treatment of the signals to account for pile-up.

I. INTRODUCTION

THE Large Hadron Collider (LHC), currently under operation at CERN, with its unprecedented high energy and luminosity extends the frontier of particle physics. Bunches of up to $10^{11}$ protons collide 40 million times per second at a center of mass energy of 7 TeV and a design luminosity of $10^{34}$ cm$^{-2}$s$^{-1}$. Nominally the LHC will operate with proton bunches crossing every 25 ns, although in 2011 it has operated with 50 ns bunch spacing and with an expected average number of 8 proton-proton collisions per bunch crossing. The high interaction rates, energies, particle multiplicities, radiation doses and need for precision measurements require new standards for the design of particle detectors at LHC.

ATLAS [1] is one of the major experiments designed to exploit the proton-proton data in this stringent environment. ATLAS is a general-purpose experiment, whose goal is to cover a broad range of experimental particle physics phenomena, with the long sought Higgs boson [2] and supersymmetry [3] on top of the wanted list. The ATLAS experiment needs to be sensitive to a large number of possible decay channels and so must provide an excellent particle identification and high resolution measurements of energies, momenta and directions for the outgoing particles in the proton-proton collisions.

The Tile Calorimeter (TileCal) [4] is the hadronic sampling calorimeter of ATLAS in the region $|\eta| < 1.7$. The purpose of TileCal is to identify hadronic jets and measure their energy and direction. TileCal also provides vital information for the first level of trigger (L1-trigger), participates in the measurement of the missing energy due to non-interacting particles and to the identification of electrons and photons. It uses steel as an absorber and scintillating plastic tiles as an active material. Several scintillating tiles are grouped together at the read out level to form calorimeter cells. The wavelength shifting fibers couple the light from the tiles to photomultipliers (PMTs), with most TileCal cells being read out by two PMTs, corresponding to two electronic read out channels. The PMT output is a current pulse with its amplitude proportional to the energy deposited in the associated cell. Electronics mounted on the PMT amplifies and shapes the output current pulse. Pulse shaping increases the width at half-maximum to 50 ns. The analogue pulse is digitized with 7 samples at 25 ns intervals which are read out upon a trigger accept from the L1 trigger (L1A) and used to compute the pulse amplitude, phase and quality factor. 10-bit analogue to digital converters are used for the digitization.

The presence of collisions every 50 ns and the relatively large read-out window ($\pm 75$ ns) lead to a significant fraction of calorimeter cells receiving energy from more than one bunch crossing within the same read out window and within the same physical calorimeter cell (out-of-time pile-up). Out-of-time pile-up degrades the measurement of the energy deposited in a physical cell. A quality factor is computed online for each event and for each calorimeter channel. It allows to identify calorimeter channels presenting out-of-time pile-up. In presence of a high quality factor value all 7 samples are read out to allow for a dedicated treatment of the pile-up signals offline.

A numerical model has been developed to simulate the TileCal pulse shapes and quality factors with and without out-of-time pile-up. The simulated observables are compared with actual proton-proton data in order to validate the model. The model includes electronic noise, time resolution effects and non-ideal pulse shapes. The numerical model allows to predict quality factor distributions thus permitting the optimization of the quality factor online selection criteria, under the constraints of available bandwidth while keeping a reliable out-of-time pile-up detection.
II. ENERGY RECONSTRUCTION AND QUALITY FACTOR DEFINITION

The goal of the energy reconstruction in TileCal is to compute the energy deposited in a TileCal cell from the number of ADC counts measured in each of the two corresponding read out channels. For each channel, 7 samples at 25 ns spacing are available, these samples are referred to as $S_i$ with $i = 1 - 7$ and are in units of ADC counts. In order to maximize the dynamic range, either a low or a high amplification (or gain) is used, depending on the pulse amplitude. The ratio between the low and the high amplification is 64. The high gain is applied to pulses up to about 12 GeV, while the low gain is applied for higher energies. One ADC count corresponds approximately to 12 MeV of deposited energy in high gain and about 800 MeV in low gain. The exact correspondence is cell-dependent and requires careful calibration [5].

The energy reconstruction combines the $S_i$ to first obtain the amplitude in ADC counts and thereafter applies a calibration constant in MeV per ADC count. The $S_i$ are linearly combined to provide the pulse amplitude $A_{opt}$, the phase with respect to the 40 MHz clock $t_{opt}$ and the electronic pedestal $P_{opt}$, as follows:

$$A_{opt} = \sum_{i=1}^{7} a_i \cdot S_i$$  

(1)

$$t_{opt} = \frac{1}{A_{opt}} \sum_{i=1}^{7} b_i \cdot S_i$$  

(2)

$$P_{opt} = \sum_{i=1}^{7} c_i \cdot S_i$$  

(3)

The linear coefficients are optimized, using the autocorrelation matrix, to minimize the effect of the noise on the reconstructed quantities. This method is called Optimal Filtering. Prior knowledge of the normalized pulse shape function $g(t)$ is required to determine the constants $a_i$, $b_i$, $c_i$. The linear coefficients are functions of the true phase of the pulse $\tau$ with respect to the 40 MHz electronic clock. The pulse shape function as well as the linear constants are stored in a dedicated database. Further information on the use of Optimal Filtering for signal reconstruction in TileCal can be found in Ref. [6].

A. Optimal Filtering Offline

The Optimal Filtering used in this paper is the same that is used to reconstruct offline the data of the ATLAS TileCal in proton-proton collisions. The constants $a_i$, $b_i$, $c_i$ are functions of the actual phase $\tau$ of the pulse which is only approximately known a priori. Therefore the Optimal Filtering is applied offline iteratively with an initial assumed value of the phase $\tau$, equal to the time of the maximum of the $S_i$. In later iterations, the phase is taken to be equal to $t_{opt}$ from the previous iteration. In absence of pile-up the iterative algorithm always converges to the true value of the phase with an accuracy better than 0.5 ns (the algorithm is iterated until the difference between the input phase and $t_{opt}$ of Eq. 2, is less than 0.5 ns or the number of iteration reaches 5) [6].

At the end of the iterative procedure, a quality factor $Q_{opt}$ is computed to verify that the resulting $A_{opt}$, $t_{opt}$ and $P_{opt}$ together with the pulse shape $g(t)$ do model the data $S_i$ accurately. In case of deviation between the actual shape and the expected shape, then $Q_{opt}$ takes large values which can be used to detect problems in the reconstruction procedure. The quality factor is defined after convergence as follows:

$$Q_{opt} = \sqrt{\sum_{i=1}^{7} (S_i - A_{opt} \cdot g_i - P_{opt})^2}$$  

(4)

where the $g_i$ are the values of the normalized pulse shape computed at the time of the 7 samples $S_i$.

B. Optimal Filtering Online

The Optimal Filtering is also run online by the TileCal Digital Signal Processors (DSP) which perform the above linear combinations in real time. Above a trigger rate 50 kHz the Optimal Filtering must be performed without iterations due to insufficient processing time in the DSP. It was also found that in the presence of out-of-time pile-up it is better not to perform the iterations. This is due to the fact that the phase $\tau$ needed to compute $a_i$, $b_i$, $c_i$ is known from timing calibration within a few nanoseconds. On the other hand, the presence of out-of-time pile up can lead to $t_{opt}$ values far from nominal and thus bias the energy reconstruction. For this reason only non-iterative optimal filtering is currently applied online.

III. PILE-UP SCENARIOS

The large per bunch crossing luminosity of the LHC leads to a high probability of multiple proton-proton interactions in the same bunch crossing. This leads to in-time energy deposits from multiple collisions in the same TileCal cell from the same bunch crossing from different p-p collisions. We refer to this type of pile-up as “in-time pile-up” and it can be addressed by determining its average effect on the measured calorimeter energies. It is not discussed further in this paper.

The second type of pile-up, or “out-of-time” pile-up arises when bunch crossings are close in time, and that the signal shaping time is larger than the time between consecutive bunches. In the case of TileCal, the long signal shaping time requires a read-out window of ±75 ns around a triggered event, to be compared with a bunch spacing of 50 ns during the 2011 data-taking. The pulse shape is adjusted in such a way that the maximum of the pulse is located close to the fourth sample, $S_4$. The “out-of-time” pile-up results in the superposition of pulses shifted in time resulting in anomalous pulse shapes which can be detected thanks to large values of $Q_{opt}$. In 2011 the LHC bunch spacing was 50 ns and therefore there are two possible pileup scenarios: the pile-up signal results from energy deposited -50 ns from the collision of interest; the pile-up signal results from energy deposited +50 ns from the collision of interest. Due to the TileCal pulse shape these have different effects on the reconstructed signal in the collision of interest. Both scenarios are studied and the expected quality factor distributions are computed in both scenarios. Fig. 1 shows an illustration of an out-of-time pile-up.
pulse at +50 ns, in the case where the in-time and out-of-time pulses have the same amplitude.

IV. PULSE SHAPE SIMULATOR

A. Working Principle

The pulse shape simulator is based on pseudo-random number generators to generate the 7 samples $S_i$ which constitute a digitized pulse. The pulse simulator uses a number of input probability density functions that model the electronic noise, the distribution of random pulse phases, the timing resolution and the distribution of pulse width. All these components are required to reproduce the characteristics of the digitized pulse in data. The most significant parameters of the model are the noise and the variations in pulse widths which are both adjusted such that the predicted $Q_{opt}$ in the simulator agrees with the $Q_{opt}$ distribution measured in data in absence of out-of-time pile-up. Thanks to the iterative procedure, the value of $Q_{opt}$ is found to be rather independent of the timing effects. Later on in Section V the pulse simulator is used to derive the expected $Q_F$ distribution for out-of-time pulses.

B. Input to the Model

The parameters of the model are the following.

1) Pulse shape: As shown in Eq. 4 the quality factor is a measure of the difference between the ideal pulse shape used to derive the optimal filtering coefficients and the actual pulse shapes in the real detector. It is shown on Fig. 2 that the pulse shapes in TileCal are consistent with the ideal pulse shapes. Nevertheless even small pulse shape differences will be enlarged by signal amplitudes.

The normalized ideal pulse shape used in the optimal filtering is denoted $g(t)$, or $g_i(t)$ at the times of the $S_i$ where the pulse is sampled. The function $h(t)$ denotes the normalized real pulse shape in an actual TileCal channel. One can thus write

$$h(t) = g(t) + \delta(t)$$

where $\delta$ quantifies the deviation between the ideal pulse shape and the actual pulse shape in the detector. In this case one can write

$$S_i = A \cdot h_i + P = A \cdot g_i + A \cdot \delta_i + P$$

where $P$ is the actual pedestal and $A$ is the actual amplitude. Thus the quality factor of Eq. 4 can be reexpressed as:

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

In absence of noise the amplitude and pedestal are perfectly reconstructed by the optimal filtering, thus $P_{opt} = P$ and $A_{opt} = A$, which is approximately true at large amplitudes where the electronic noise becomes negligible, the equation above simplifies to

$$Q_{opt} = A \cdot \sum_{i=1}^{7} (\delta_i)^2$$

Therefore at large signal amplitudes the quality factor depends linearly upon the amplitude of the pulse and the slope depends on the difference between the ideal pulse shape and the actual pulse shape in the detector. Fig. 3 shows $Q_{opt}$ as function of the pulse amplitude in collision data, in absence of out-of-time pile-up, for channels with signals larger than 200 ADC counts, the dependence of the quality factor on the energy appears clearly. For comparison, Fig. 4 shows the quality factor in the simulator if we assume that the measured $S_i$ follow the ideal pulse shape. In order to reproduce the quality factor observed in data, the simulator must use a pulse shape that is different from the ideal pulse shape. The pulse shapes in data are modeled by the normalized ideal pulse shapes, with a modified width. Widened or narrowed pulses are obtained by using a new pulse shape given by $g(\alpha t)$, where $g$ is the
ideal pulse shape used earlier and $\alpha$ is a factor close to one. A value of $\alpha$ equals to one gives the ideal pulse shape, while $\alpha < 1$ corresponds to a narrower pulse and $\alpha > 1$ corresponds to a wider pulse. The $\alpha$ factor is taken to follow a Gaussian distribution with a mean value of 1 and a standard deviation $\sigma$ that is adjusted so that the quality factor distribution observed in the simulator matches that of the data.

2) Energy distribution: As the quality factor is dependent on the amplitude, the simulator has to use the same energy distribution as the data. The pulse shape simulator is validated by comparing its result with the data in Section IV-C using TileCal data collected with a jet or missing energy trigger. For this comparison the probability density function of the energy measured in the TileCal cells is extracted from the data and used to generate the amplitude of the pulses in the simulator. In Section V it is shown that the energy distribution in TileCal cells can be extracted without bias due to the trigger, in order to model the amplitude distribution of the out-of-time pulses.

3) Channel to channel phase variation $\phi_{\text{ch}}$: Ideally the peak of the signal pulses should be perfectly centered in the middle of $\pm 75$ ns read-out window. In the actual Tile Calorimeter the position of the pulse peak has been shown to be within 3 ns of the middle of the read-out window [4]. This effect is taken into account in the simulator by randomly offsetting the simulated pulses before reconstruction with a random phase that is Gaussian distributed with a mean of zero and a standard deviation of 3 ns.

4) Time resolution $t_{\text{opt}}$: The precision of the time $t_{\text{opt}}$ determined with the Optimal Filtering is a known function of the pulse amplitude and has been determined in data. The resolution on $t_{\text{opt}}$ propagates to the quality factor through equation 2 and is therefore taken into account in the simulator by randomly shifting the time of the pulse by an amount determined from a Gaussian with mean zero and an energy dependent standard deviation, given by:

$$\sigma_T = \sqrt{p_0^2 + \left(\frac{p_1}{\sqrt{E}}\right)^2 + \left(\frac{p_2}{E}\right)^2}$$  \hspace{1cm} (7)$$

where the parameters $p_0 = 0.82$ ns, $p_1 = 0$ ns · GeV$^{1/2}$ and $p_2 = 2.30$ ns · GeV have been determined on data.

5) Incoherent electronic noise: The incoherent electronic noise modifies the measured values of the samples $S_i$, randomly around the normalized pulse shape, the effect is to first approximation uncorrelated between the samples $S_i$. This is the second most significant contribution to the quality factor, after the pulse shape, but becomes the dominant factor at low amplitudes. The tail of high quality factor values is particularly sensitive to the noise. For this reason the simulator uses the double Gaussian noise model that was found to describe the TileCal noise data [4]. The noise constants used to smear the $S_i$ were adjusted so that the quality factor distribution obtained with the simulator reproduces the quality factor in the data.
C. Comparison of the Quality Factor in Data and TileCal Pulse Simulator

The quality factor distribution is computed in data using an integrated luminosity of 60 nb⁻¹ taken in March 2011 at a period where the LHC was operating with only 2 bunches per beam, separated by at least 2.5 μs, therefore ensuring the absence of out-of-time pile-up. The collisions were selected to pass either a calorimeter trigger or a missing energy trigger. Fig. 3 shows the energy dependence of the quality factor in this data set. Fig. 5 shows the corresponding distribution of quality factor \( Q_{opt} \) as function of \( A_{opt} \) obtained in the pulse simulator, in absence of out-of-time pile-up as for the data of Fig. 3. The resulting quality factor distribution in data and from the simulator is shown in Fig. 6 and shows a fair agreement apart from the high tail of the quality factor distribution. This demonstrates that the pulse shapes can be simulated in such a way that a complex quantity such as the quality factor can be reproduced. The simulator can then be used to predict the quality factor distribution in presence of out-of-time pile-up in order to derive the optimal criteria to detect out-of-time pile-up while keeping the amount of read out data within the bandwidth budget of TileCal.

V. QUALITY FACTOR SIMULATION WITH PILE-UP

A. Amplitude of Out-of-Time Pulses

The average signal amplitude for in-time pulses is related to the trigger criteria used to record the event, since for instance requiring several highly energetic hadronic jets will certainly increase the amount of energy deposited in the calorimeter and hence the likelihood that a calorimeter channel received a large signal.

The out-of-time pulses on the other hand belong to collisions that did not pass the trigger. They are recorded by chance since they were close in time to a collision that passed the trigger. Therefore the energy distribution from pile-up is that from unbiased collisions before the trigger. This energy distribution can be extracted from data by using a specific trigger. ATLAS possesses a so-called a zero bias trigger, which records a small fraction of collisions randomly selected in coincidence with the crossing of two populated proton bunches. This zero bias trigger allows to measure the energy distribution in TileCal channels without the effect of the trigger bias, and is therefore used as a model to extract the probability density function of the amplitude of the out-of-time pulses. This amplitude distribution is extracted from no pile-up ATLAS data from March 2011 at a time where the LHC was operating with only two bunches per beam, separated with at least 2.5 μs, the corresponding distribution is shown in Fig. 7. This amplitude distribution is used as probability density function to generate out-of-time pulses in the pulse simulator and compute the quality factor in presence of pile-up in Section V-B.

B. Quality Factor Distributions in Presence of Out-of-Time Pile-up

The effect of the out-of-time pile-up on the quality factor is first studied in absence of noise, or timing effects and for ideal pulse-shapes. In this simplified model one can study the effect of the relative sizes of the in-time and out-of-time pulses. Fig. 8 shows the dependence of the quality factor \( Q_{opt} \) as a function of the in-time pulse amplitude \( A_{in} \), given on the x-axis and for different values of the ratio between the in-time and out-of-time pulse amplitude \( A_{out} \). It shows two important features, first that for a given ratio of \( A_{out}/A_{in} \), the quality factor increases linearly with the amplitude of the in-time pulse, and second that the dependence on the amplitude \( A_{in} \) gets steeper when the ratio \( A_{out}/A_{in} \) gets closer to one. The worst case scenario occurs for in-time and out-of-time pulses of equal amplitude, in that case the quality factor becomes maximal. The introduction of an out-of-time pile-up pulse is equivalent to introducing a deviation between the ideal pulse shape and the real pulse shape as discussed in Sect. IV-B1. The linear dependence on the amplitude observed here is therefore
consistent with the observation of a linear dependence upon pulse amplitude made in Section IV-B1.

In order to compute a realistic distribution of the quality factor in presence of out-of-time pile-up, the amplitude of the out-of-time pulse is modeled with the full model, and the probability density function obtained using the zero-bias data as described in Sec. IV. Fig. 9 compares the quality factor in absence (black) and in presence of out-of-time pulse (red and purple) obtained for this model and for an in-time pulse of 1000 ADC counts, corresponding to about 12 GeV. Only the out-of-time pulses yielding an effect of more than 1% bias on the reconstructed amplitude have been retained for this figure, which occurs only for approximately 1 in $O(10^3)$ channels per bunch crossing with an expected average number of collisions of $\langle \mu \rangle = 3.3$. It illustrates that for significant out-of-time pile-up pulses the distribution of quality factor is quite different in case of out-of-time compared to no out-of-time pile-up. There is a clear separation between the two cases. As it has been shown that the quality factor is linearly increasing with the amplitude of the pulses, further separation can be achieved by dividing the quality factor given in Fig. 9 and Eq. 4.

VI. CONCLUSIONS

A numerical model of the ATLAS Tile Calorimeter pulses has been developed in the form of a pulse simulator. This model takes into account small variations in signal pulse shapes, timing resolution and small timing miscalibration effects and uses a realistic model of the calorimeter noise. The simulator is shown to be able to reproduce the quality factor distributions in collisions in absence of out-of-time pulse for pulses with amplitudes larger than 200 ADC counts. The model is still in development and will be improved to model the data quality factor for the full range of pulse amplitude. The signal amplitude for TileCal channels is measured in zero bias triggered data and used as a model for pulses from out-of-time pulse collisions. Using this model of the data, the distribution of quality factor in the presence of out-of-time pile-up is calculated. It shows that significant discrimination can be achieved thanks to the quality factor between the presence and the absence of out-of-time pulse in case the amplitude of the out-of-time pulse large enough to affect the amplitude measurement. Using the predicted distributions of quality factor with and without out-of-time pile, the presence of significant out-of-time pile-up can be identified and a specific treatment of the double pulses can be performed.

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Paper II
Signal reconstruction performance with the ATLAS Hadronic Tile Calorimeter

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Abstract. The Tile Calorimeter (TileCal) is the central section of the hadronic calorimeter of ATLAS. It is a key detector for the reconstruction of hadrons, jets, taus and missing transverse energy. TileCal is a sampling calorimeter with steel as absorber and scintillators as active medium. The scintillators are read-out by wavelength shifting fibers coupled to photomultiplier tubes (PMTs). The analogue signals from the PMTs are amplified, shaped and digitized by sampling the signal every 25 ns. The read out system is designed to reconstruct the data in real time fulfilling the tight constraints imposed by the ATLAS first level trigger rate (100 kHz). The signal amplitude for each channel and their phase are measured using Optimal Filtering techniques both at online and offline level. We present the performance of these techniques on the data collected in the proton-proton collisions at center-of-mass energy equal to 7 TeV. We will address the performance for the measurement on high pile-up environment and on various physics and calibration signals.

1. Introduction

ATLAS [1] is a general-purpose experiment, whose goal is to cover a broad range of experimental particle physics phenomena, with the long sought Higgs boson and supersymmetry on top of the wanted list. The Tile Calorimeter [2] is the hadronic calorimeter of ATLAS in the region $|\eta| < 1.7$. The purpose of TileCal is to identify hadronic jets and measure their energy and direction. It also provides vital information for the first level trigger, the measurement of the missing energy due to non-interacting particles and the identification of electrons and photons. It uses steel as absorber and scintillating plastic tiles as active material.

2. Read out architecture

Photomultiplier tubes (PMTs) read out the light from the scintillating tiles using wavelength shifting fibers. The fibers are grouped to segment the calorimeter in cells with a granularity $\Delta\phi \times \Delta\eta \sim 0.1 \times 0.1$ and 3 radial layers. Each cell is read out by two PMTs, corresponding to two independent electronic channels. The PMT output is a current pulse with its amplitude proportional to the energy deposited in the associated cell. Electronics mounted on the PMT amplifies and shapes the output current pulse. Pulse shaping forms the signal width to 50 ns at half-maximum. In order to effectively extend the dynamic range a bigain read out is used with a ratio between the two of 64. The two analogue pulses (high gain and low gain) are digitized by two 10-bit ADCs at 40 MHz. The high gain chain is used until it saturate at about 12 GeV, for higher energies the low gain is used [3]. The analogue pulse is digitized by 10-bit analogue to
digital converters with 7 samples at 25 ns intervals which are read out upon a trigger accept from the first level trigger and sent to the back-end electronics in a counting room 100 m off detector, the Read Out Drivers (ROD). The RODs use Digital Signal Processors (DSP) to compute the pulse amplitude, phase and quality factor.

3. Optimal Filtering algorithm
The goal of the energy reconstruction algorithms is to compute the energy deposited in a TileCal cell from the number of ADC counts measured in each of the two corresponding read out channels. The samples are referred to as $S_i$ with $i = 1 \ldots 7$ and are in units of ADC counts. The energy reconstruction combines the $S_i$ to first obtain the amplitude in ADC counts and thereafter applies a calibration constant in MeV per ADC count. The $S_i$ are linearly combined to provide the pulse amplitude $A$, the phase $t$ with respect to the 40 MHz clock and the electronic pedestal $P$ (figure 1 left panel). The quality factor $QF$ is also computed to verify that the computed amplitude, phase, pedestal and the known pulse shape $g(t)$ are compatible with the observed data points $S_i$. In case of deviation between the actual shape and the expected shape, the quality factor takes large values which can be used to detect problems in the reconstruction procedure. These quantities are calculated as follows [4]:

$$A = \sum_{i=1}^{7} a_i \cdot S_i, \quad t = \frac{1}{A} \sum_{i=1}^{7} b_i \cdot S_i, \quad P = \sum_{i=1}^{7} c_i \cdot S_i, \quad QF = \left( \sum_{i=1}^{7} \left( S_i - (A \cdot g_i - A \cdot t \cdot g_i' - P) \right) \right)^2$$

This method is called Optimal Filtering. Prior knowledge of the normalized pulse shape function is required to determine the constants $a_i$, $b_i$, $c_i$. The pulse shape was precisely measured in test beam and it was verified with data from the full installed TileCal that this function could be used for all channels. The linear coefficients are optimized, using the autocorrelation matrix, to minimize the effect of the noise on the reconstructed quantities. The coefficients are functions of the phase of the pulse with respect to the 40 MHz electronic clock. The pulse shape function and the linear constants are stored in a dedicated database for calibration constants.

Offline reconstruction can be performed with iterations (Iterative Optimal Filtering) and without iterations (Non-Iterative Optimal Filtering). In the iterative method the quantities are calculated with an initial assumed value of the phase, equal to the time of the maximum of the $S_i$. In later iterations, the phase is taken to be equal to $t$ from the previous iteration. In absence of out-of-time pile-up the iterative algorithm always converges to the true value of the phase with an accuracy better than 0.5 ns. The iterative method is slower and more sensitive to out-of-time pile-up. In the non-iterative method the phase used is the best signal phase known, retrieved from the database for each channel. In this case no further iterations are performed.

The Optimal Filtering reconstruction is also performed online by the DSP which perform the above linear combinations in real time. Above a trigger rate of 30 kHz the Optimal Filtering must be performed without iterations due to the processing time in the DSP exceeding the limit allowed by the data acquisition system. The DSP reconstruction is limited by use of fixed point arithmetic and the internal precision available to describe the linear coefficients and calibration factors. Since the division is a time consuming operation in the DSP the phase is computed using a look-up table with the energy reciprocal pre-defined and stored in the DSP memory.

4. Validation
The ROD can be configured to transmit both the reconstructed quantities and the raw data samples $S_i$. Due to the limited bandwidth digital samples are transmitted only for pulses above a programmable threshold (currently $S_{\text{max}} - S_{\text{min}} > 5$ ADC counts). The raw data obtained in this way can be reconstructed using well tested offline algorithms and can be used to validate the reconstruction in DSP.
**Figure 1.** Left: Sketch of a typical Tile Calorimeter pulse shape with the ADC samples (dots) and the illustration of Optimal Filtering reconstructed quantities. Right: Relative difference between the energy reconstructed with DSP ($E_{DSP}$) and offline Iterative Optimal Filtering method ($E_{OFLI}$) as a function of the phase reconstructed by DSP ($t_{DSP}$) in collision data at 7 TeV. There is a bias in the energy reconstructed online with Optimal Filtering method (OF Online) due to phase variation (circles). The bias can be reduced applying a second order correction using the phase of the pulse (squares). The vertical error bars correspond to the RMS of the distributions.

**Figure 2.** Absolute difference between the energy reconstructed with DSP ($E_{DSP}$) and offline Non-Iterative Optimal Filtering method ($E_{OFLNI}$) as a function of the energy reconstructed offline in collision data at 7 TeV in high gain (left) and low gain (right).

In order to validate the DSP results the consistency of online and offline implementations is checked. Figure 1 right panel shows performance of energy reconstruction with DSP in collision data at 7 TeV. In-time and out-of-time collision events populate the plot in order to evaluate the DSP reconstruction performance on a wide time window. Most of the pulses are in the time range $[-5, 5]$ ns. The circle points show the relative difference between the energy reconstructed with DSP and offline with Iterative Optimal Filtering method. The variation in the phase of pulses leads to an underestimation of the amplitude reconstructed online. This bias is parametrized by second order polynomial and reduced thanks to an amplitude correction function of the phase. The square points show the relative difference after the correction. In the time range $[-10, 10]$...
ns the average difference between the offline and online reconstruction, after the correction, is smaller than 1%.

Figure 2 shows the residuals after applying the parabolic correction between the energy reconstructed with DSP and offline with Non-Iterative Optimal Filtering method in high gain (left panel) and low gain (right panel) in collision data at 7 TeV. The performance is slightly energy dependent. The maximum expected difference due to fixed point arithmetic is proportional to the calibration constant ADC to MeV and therefore changes from channel to channel. The worst cases arise in a few PMTs with abnormal high voltage settings. The response needs to be amplified by a large factor to compensate for the gain deficit. In left panel of figure 2 the red dashed lines indicate the maximum expected precision for standard functioning channels of about 1 MeV and contain 99% of the channels while the blue lines indicate the expected precision for the highest calibration constant of about 2 MeV. For comparison the electronic noise RMS level is about 30 MeV. In right panel of figure 2 the blue lines indicate the precision of about 50 MeV. This is fully adequate in the range where signals are larger than approximately 8 GeV.

Figure 3 shows the absolute difference between phase reconstructed in DSP and offline with Non-Iterative Optimal Filtering as a function of offline reconstructed phase (left panel) and
Figure 5. Left: Quality factor as a function of the amplitude in different pile-up scenarios obtained with the TileCal pulse simulation. $A_{in}$ ($A_{out}$) is the amplitude of the in-time (out-of-time) pulse. The x-axis shows the amplitude in ADC counts before cell-dependent calibration constants are applied. The calibration factor is approximately 12 MeV per ADC count. Right: Normalized distributions of quality factor in TileCal simulator with non-ideal pulse shape. Generated amplitude of in-time pulse is 12 GeV. Amplitude of the out-of-time pulse follows the distribution in ZeroBias trigger with a cut on 34 ADC counts [5].

Figure 6. Left: The phase reconstructed offline with Iterative Optimal Filtering method as a function of the energy reconstructed offline in collision data at 7 TeV. Right: The phase reconstructed with DSP (Non-Iterative Optimal Filtering method) as a function of energy reconstructed with DSP in collision data at 7 TeV. A data sample with presence of out-of-time pile-up (bunch spacing 50 ns) is used.

energy (right panel) in collision data at 7 TeV. Since the same non-iterative algorithm is used online and offline the expected difference is due to fixed point arithmetic and the precision of the look up table (LUT) used in the DSP. The LUT effect is enhanced for larger phases but differences between phases reconstructed in DSP and offline are within 1.5 ns in the $[-25, +25]$ ns range.

5. Out-of-time pile-up
Signal pulses coming from different LHC bunch crossing (bunch spacing of 50 ns) can be measured in the readout windows used of ±75 ns. The out-of-time pile-up results in the
superposition of pulses shifted in time resulting in anomalous pulse shapes which can be detected thanks to large values of $QF$ [5]. Figure 4 shows an illustration of an out-of-time pile-up pulse at $+50$ ns, in the case where the in-time and out-of-time pulses have the same amplitude.

Figure 5 left panel shows the dependence of the quality factor $QF$ as a function of the in-time pulse amplitude $A_{in}$ and the out-of-time pulse amplitude $A_{out}$ for different values of the ratio between the in-time and out-of-time pulse amplitude. A Monte Carlo simulation is used for this study. Data samples are generated according to the expected pulse shape. The lines correspond to a linear fit to the mean value of the quality factor. It shows two important features, first that for a given ratio of $A_{out}/A_{in}$, the quality factor increases linearly with the amplitude of the in-time pulse, and second that the dependence on the amplitude $A_{in}$ gets steeper when the ratio $A_{out}/A_{in}$ gets closer to one. The worst case scenario occurs for in-time and out-of-time pulses of equal amplitude, in that case the quality factor becomes maximal. The introduction of an out-of-time pile-up pulse is equivalent to introducing a deviation between the ideal pulse shape and the real pulse shape.

Figure 5 right panel illustrates that for significant out-of-time pile-up pulses the distribution of quality factor is quite different in case of out-of-time compared to no out-of-time pile-up. A Monte Carlo simulation is used for this study. Data samples are generated according to the expected pulse shape with emulation of electronic noise, pulse shape and phase variation. There is a clear separation between the two cases. The effect of an out-of-time pulse at $-50$ ns is nearly equivalent to the effect of an out-of-time pulse at $+50$ ns. Based on these studies possible identify to select pile-up channels can be proposed.

Figure 6 shows the reconstructed phase as a function of energy reconstructed offline with Iterative Optimal Filtering method (left panel) and in DSP with Non-Iterative Optimal Filtering method (right panel) in collision data at 7 TeV. A run with train of bunches crossing every 50 ns was used. The iterative method is able to reconstruct signals generated by a different bunch crossings (peaks at 0 ns and $\pm 50$ ns on left panel of figure 6). The non-iterative algorithm as implemented in the DSP uses a well defined phase of triggered event. The reconstructed phases correspond to in-time pulses (peak at 0 ns only on right panel of figure 6). Therefore, this algorithm is robust against out-of-time pile-up.

6. Conclusions

The TileCal online signal reconstruction performed in the DSP has been validated with the LHC collision data at 7 TeV reconstructed offline. The results are compatible with the expected differences between the fixed point arithmetic used in the DSP and the floating point arithmetic used for the offline reconstruction. Currently LHC operates with 50 ns bunch spacing causing out-of-time pile-up signals. The Non-Iterative Optimal Filtering method is to a certain extent robust against out-of-time signals. It is shown that the quality factor is very sensitive to differences between expected and real pulses in the detector and that the quality factor can be used to flag cells with presence of pile-up.

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Paper III
Identification of Pile-up Using the Quality Factor of Pulse Shapes in the ATLAS Tile Calorimeter

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Abstract

The ATLAS experiment records data from the proton-proton collisions produced by the Large Hadron Collider (LHC). The Tile Calorimeter is the hadronic sampling calorimeter of ATLAS in the region $|\eta| < 1.7$. It uses iron absorbers and scintillators as active material. The LHC will provide collisions every 25 ns, putting very strong requirements on the energy measurement in presence of energy deposits from different collisions in the same read out window and physical calorimeter channel (pile-up). In 2011 the LHC was running with filled bunches at 50 ns spacing and at intensities which yield up to about 8 proton-proton collisions per bunch crossing. We present a quality factor that is computed offline for each collision and for each calorimeter channel, and provide criteria to detect pile-up in TileCal channels. The quality factor can be used to select channels that need a special treatment to account for large energy deposition from pile-up.

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A Bias and Resolution of Optimal Filtering Reconstruction 23
1 Introduction

The Large Hadron Collider (LHC), currently under operation at CERN, with its unprecedented high energy and luminosity extends the frontier of particle physics. Bunches of up to $10^{11}$ protons collide at a centre of mass energy of 7 TeV (and up to 14 TeV in nominal conditions) and a design luminosity of $10^{34}$ cm$^{-2}$s$^{-1}$. Nominally the LHC will operate with proton bunches crossing every 25 ns, although in 2011 it has operated with 50 ns bunch spacing and with an expected average number of 8 proton-proton collisions per bunch crossing. The high interaction rates, energies, particle multiplicities, radiation doses and need for precision measurements require new standards for the design of particle detectors at the LHC. ATLAS [1] is one of the major experiments designed to exploit the proton-proton data in this challenging environment.

ATLAS is a general-purpose experiment, whose goal is to cover a broad range of experimental particle physics phenomena, with the long sought Higgs boson [2] and supersymmetry [3] being especially important. The ATLAS experiment needs to be sensitive to a large number of possible decay channels and so must provide an excellent particle identification and high resolution measurements of energies, momenta and directions for the outgoing particles in the proton-proton collisions.

The Tile Calorimeter (TileCal) [4] is the hadronic sampling calorimeter of ATLAS in the region $|\eta| < 1.7$. The purpose of TileCal is to identify hadronic jets and measure their energy and direction. TileCal also provides vital information for the first level of trigger (L1 trigger) and participates in the measurement of the missing energy due to non-interacting particles. It uses iron as an absorber and scintillating plastic tiles as an active material. Several scintillating tiles are grouped together at the read out level to form calorimeter cells. The wavelength shifting fibers collect the light from the tiles to photomultipliers (PMTs), with most TileCal cells being read out by two PMTs, corresponding to two electronic read out channels. The PMT output is a current pulse whose amplitude is proportional to the energy deposited in the associated cell. Electronics mounted on the PMT amplifies and shapes the output current pulse. Pulse shaping increases the width at half-maximum to 50 ns. The analogue pulse is digitized with 7 samples at 25 ns intervals which are read out upon a trigger accept from the L1 trigger and used to compute the pulse amplitude, phase and quality factor. Ten-bit analogue to digital converters are used for the digitization.

The presence of collisions every 50 ns and the relatively large read-out window ($\pm 75$ ns) lead to a significant fraction of calorimeter cells receiving energy from more than one bunch crossing within the same read out window and within the same physical calorimeter cell (out-of-time pile-up). Out-of-time pile-up degrades the measurement of the energy deposited in a physical cell. A quality factor is computed online for each event and for each calorimeter channel. It allows the identification of calorimeter channels with out-of-time pile-up. In the presence of a high quality factor value a dedicated treatment of the pile-up signals can be applied.

A numerical model has been developed to simulate the TileCal pulse shapes and quality factors with and without out-of-time pile-up. The simulated observables are compared with actual proton-proton data in order to validate the model. The model includes electronic noise, channel-to-channel phase variations and non-ideal pulse shapes. The model is fine tuned to the data to reproduce the quality factor distribution in data without pile-up. The numerical model is then used to predict quality factor distributions in presence of pile-up thus permitting the optimization of the quality factor selection criteria for pile-up detection, under the constraints of available bandwidth while keeping a reliable out-of-time pile-up detection. It is beyond the scope of the presented work to compare quality factor distributions with pile-up between the model and the data but is possible future development of this work.

In Section 2 the Optimal Filtering algorithm used to reconstruct the energy is briefly recalled, and the definition of the quality factor $QF$ is given. The relevant pile-up scenarios are described in section 3. The model used to build the pulse simulator is presented in Section 4 and the impact of various effects...
on the single pulse $QF$ is studied. This Section also contains a comparison of $QF$ distributions in data and in the simulator. The effect of the out-of-time pile-up on the quality factor is presented in Section 5. In Section 6 we present an optimisation of a cut on the quality factor to identify the out-of-time pile-up.

## 2 Energy Reconstruction and Quality Factor Definition

The goal of the energy reconstruction in TileCal is to compute the energy deposited in a TileCal cell from the number of ADC counts measured in each of the two corresponding read out channels. For each channel, 7 samples at 25 ns spacing are available, these samples are referred to as $S_i$ with $i = 1 - 7$ and are in units of ADC counts. In order to maximize the dynamic range, either a low or a high amplification (or gain) is used, depending on the pulse amplitude. The ratio between the low and the high amplification is 64. The high gain is applied to pulses up to about 12 GeV, while the low gain is applied for higher energies. One ADC count corresponds approximately to 12 MeV of deposited energy in high gain and about 800 MeV in low gain. The exact correspondence is channel-dependent and requires careful calibration [5]. For comparison, the most probably energy of the muon signal for projective cosmic muons entering the barrel modules for the D cells at $0.3 < \eta < 0.4$ is 500 MeV [4].

The energy reconstruction combines the $S_i$ to first obtain the amplitude in ADC counts and thereafter applies a calibration constant in MeV per ADC count. The $S_i$ are linearly combined to provide the pulse amplitude $A_{OFL}$, the phase $t_{OFL}$ with respect to the 40 MHz clock and the electronic pedestal $P_{OFL}$, as follows:

$$A_{OFL} = \sum_{i=1}^{7} a_i \cdot S_i$$

$$t_{OFL} = \frac{1}{A_{OFL}} \sum_{i=1}^{7} b_i \cdot S_i$$

$$P_{OFL} = \sum_{i=1}^{7} c_i \cdot S_i$$

The linear coefficients are optimized, using the autocorrelation matrix, to minimize the effect of the noise on the reconstructed quantities. This method is called Optimal Filtering. Prior knowledge of the normalized pulse shape function $g(t)$ is required to determine the constants $a_i, b_i, c_i$. The pulse shape was precisely determined from test beam data and it was verified with data from the fully installed TileCal that this function could be used for all TileCal channels [6].

The linear coefficients are functions of the true phase of the pulse with respect to the 40 MHz electronic clock. The pulse shape function as well as the linear constants are stored in a dedicated database for calibration constants (called COOL). Further information about the use of Optimal Filtering for signal reconstruction in TileCal can be found in Ref. [7].

### 2.1 Optimal Filtering Offline

The Optimal Filtering used in this note is the same as is used to reconstruct offline data of the ATLAS TileCal in proton-proton collisions. The beam data was used to adjust the average phase for each channel to be close to zero. This setting is accurate to 3 ns. During the 2010 data taking and early 2011 the Optimal Filtering was applied iteratively. Later at higher luminosity only non-iterative Optimal Filtering was used. In this work the iterative Optimal Filtering is studied. The constants $a_i, b_i, c_i$ are functions of the actual phase of the pulse which is only approximately known a priori. Therefore the Optimal Filtering is applied offline iteratively with an initial assumed value of the phase, equal to the time of the maximum
of the $S_i$. In later iterations, the phase is taken to be equal to $t_{OFL}$ from the previous iteration. In absence of pile-up the iterative algorithm always converges to the true value of the phase with an accuracy better than 0.5 ns\textsuperscript{1}[7].

At the end of the iterative procedure, a quality factor $QF_{OFL}$ is computed to verify that the resulting $A_{OFL}$, $t_{OFL}$ and $P_{OFL}$ together with the pulse shape $g(t)$ do model the data $S_i$ accurately. In case of deviation between the actual shape and the expected shape, then $QF_{OFL}$ takes large values which can be used to detect problems in the reconstruction procedure. The quality factor is defined after convergence as follows:

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

where the $g_i$ are the values of the normalized pulse shape computed at the time of the 7 samples $S_i$.

Figure 1 shows the relative difference between reconstructed $A_{OFL}$ and true amplitude $A_{True}$ as a function of true amplitude. In this plot $A_{True}$ was varied with step of one ADC count. Figure 2 shows the relative difference between reconstructed $t_{OFL}$ and true time $t_{True}$ as a function of a true time. In this plot $t_{True}$ was varied with step of one nanosecond. In these histograms each bin consists of 1000 entries. Figures 1, 2 and 3 show that amplitude and time reconstructed well by the Optimal Filtering. One can also note that the precision of the reconstructed amplitude and time deteriorate as expected at low amplitudes where the analog noise and sampling accuracy become important. These plots were obtained with full model of the TileCal pulse simulator described in Section 4. Figures presenting bias and resolution of amplitude and time reconstruction with Optimal Filtering are included in Appendix A. Number of iterations to converge as a function of true time of the pulse is shown on Fig. 4. Iterative Optimal Filtering reconstructs the the phase with an initial assumed value equal to the time of the maximum of the $S_i$. Therefore, if the phase is equal to the time of any sample ($0$, $\pm 25$, $\pm 50$, $\pm 75$ ns) only one iteration is needed. If the phase takes values different than the samples, larger number of iterations is performed.

2.2 Optimal Filtering Online

The Optimal Filtering is also run online by the TileCal Digital Signal Processors (DSP) which perform the above linear combinations in real time. Above a trigger rate of 50 kHz the Optimal Filtering must be performed without iterations due to insufficient processing time in the DSP. It was also found that in the presence of out-of-time pile-up it is better not to perform the iterations. This is due to the fact that the phase needed to compute $a_i$, $b_i$, $c_i$ is known from timing calibration within a few nanoseconds. On the other hand, the presence of out-of-time pile up can lead to $t_{OFL}$ values far from nominal and thus bias the energy reconstruction when iterative method is used. The non-iterative Optimal Filtering method reconstructs better the phase of in-time-pulse. The noise width becomes smaller using non-iterative method. Therefore, the reconstruction is more robust against the noise for very low amplitudes. For this reasons only non-iterative Optimal Filtering is currently applied online.

3 Pile-up Scenarios

The large per bunch crossing luminosity of the LHC leads to a high probability that multiple proton-proton interactions may take place in same bunch crossing where the trigger interaction occurred (in-time pile-up). Due to the presence of the in-time pile-up the signal collected in a single TileCal cell integrate

\textsuperscript{1}The algorithm is iterated until the difference between the input phase and $t_{OFL}$ of Eq. 2 is less than 0.5 ns or the number of iteration reaches 5.
Figure 1: Relative difference between reconstructed and true amplitude as a function of true amplitude in TileCal pulse simulator. This is shown for high gain (left) and low gain (right). Amplitude is reconstructed with Optimal Filtering with iterations in absence of out-of-time pile-up. The purple line corresponds to the linear fit to mean value of the relative difference.

Figure 2: Relative difference between reconstructed and true time as a function of true time in TileCal pulse simulator. This is shown for high gain (left) and low gain (right). Time is reconstructed with Optimal Filtering with iterations in absence of out-of-time pile-up. The purple line corresponds to the linear fit to mean value of the relative difference.
Figure 3: Absolute difference between reconstructed and true time as a function of true amplitude in TileCal pulse simulator. This is shown for high gain (left) and low gain (right). Time is reconstructed with Optimal Filtering with iterations in absence of out-of-time pile-up. The purple line corresponds to the linear fit to mean value of the relative difference.

Figure 4: Number of iterations to convergence in iterative Optimal Filtering as a function of true time of the pulse in TileCal pulse simulator with ideal pulse shapes, in absence of emulation of noise and timing effects. This is shown for high gain (left) and low gain (right). Time is reconstructed with Optimal Filtering with iterations in absence of out-of-time pile-up. This result was obtained by reconstruction of the pulse with amplitude of 84 ADC counts (1 GeV).
the contributions from multiple interactions. The effect of the “in-time pile-up” can be evaluated by determining its average effect on the measured TileCal cell energies. It is not discussed further in this paper.

The second type of pile-up, or “out-of-time” pile-up arises because the signal integration time is larger than the distance between two consecutive bunch crossings. In this case collisions from protons belonging to bunch crossings close in time to the one where the trigger occurred also contribute to the signal a TileCal cell. In the case of TileCal, the long signal shaping time requires a read-out window of ±75 ns around a triggered event, to be compared with a bunch spacing of 50 ns during the 2011 and 2012 data-taking. The hardware delays are adjusted in such a way that the maximum amplitude of the in-time pulses is located close to the fourth sample, $S_4$. The “out-of-time” pile-up results in the superposition of pulses shifted in time resulting in anomalous pulse shapes which can be detected thanks to large values of $Q_{OF}$.

Figure 5 shows an illustration of an out-of-time pile-up pulse having the maximum amplitude located at +50 ns, in the case where the in-time and out-of-time pulses have the same amplitude.

\begin{figure}[h]
\centering
\includegraphics[width=0.5\textwidth]{figure5.png}
\caption{Illustration of out-of-time pile-up (+50 ns) in ATLAS Tile Calorimeter with pulse shapes similar to those in the real detector. The pulse shapes shown here are approximate functional parameterizations of actual pulse shapes, but are not actually used either in the energy reconstruction, nor in the pile-up simulation.}
\end{figure}

4 Pulse Shape Simulator

4.1 Working Principle

The pulse shape simulator is based on pseudo-random number generators to generate the 7 samples $S_i$ which constitute a digitized pulse. The pulse simulator uses a number of input distribution functions such as the electronic noise, width of the pulse shapes, random time phases and amplitudes in order to reproduce the characteristics of the digitized pulse in data. The model is adjusted to reproduce the electronic high frequency noise, channel to channel phase variations, pulse shape variations, quality factor, correlation between quality factor and pulse amplitude observed in the data. In Section 5 the pulse simulator is used to derive the expected $Q_{OF}$ distribution for out-of-time pulses.
4.2 Input to the Model

4.2.1 Pulse shape

As shown in Eq. 4 the quality factor is a measure of the difference between the ideal pulse shape used to derive the Optimal Filtering coefficients and the actual pulse shapes in the real detector. It is shown in Fig. 6 that the pulse shapes in TileCal are consistent with the ideal pulse shapes [6]. Nevertheless, even small pulse shape differences will be enlarged by signal amplitudes causing higher quality factor.

![Figure 6: Pulse shape reconstructed with the Optimal Filtering averaged over all good channels and full energy range in high gain in the TileCal from 2010 data. Overlaid in red is the reference high gain pulse shape used for reconstruction. Bottom: Deviation between data and reference pulses in units of standard deviations. \( \sigma \) is the standard deviation of the data [6].](image)

The normalized ideal pulse shape used in the Optimal Filtering is denoted \( g(t) \), or \( g_i \), at the times of the \( S_i \) where the pulse is sampled. The function \( h(t) \) denotes the normalized real pulse shape in an actual TileCal channel. One can thus write \( h(t) = g(t) + \delta(t) \) or \( h_i = g_i + \delta_i \) at the times of the samples \( S_i \), where \( \delta \) quantifies the deviation between the ideal pulse shape and the actual pulse shape in the detector. The TileCal electronics is linear and no deviations from linearity has been observed in data or test beam [4]. Therefore the shape functions describing the pulses can simply be scaled by the pulse amplitude. In this case one can write \( S_i = A \cdot h_i + P = A \cdot g_i + A \cdot \delta_i + P \), where \( P \) is the actual pedestal and \( A \) is the actual
amplitude. Thus the quality factor of Eq. 4 can be reexpressed as:

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

(5)

In the absence of noise and with the pedestal perfectly reconstructed, \(P_{OFL} = P\) and \(A_{OFL} = A\). In this case Eq. 5 reduces to

\[
Q_{OFL} = A_{OFL} \cdot \sqrt{\sum_{i=1}^{7} (\delta_i)^2}
\]

(6)

This limit corresponds to large signals where the electronic noise and pedestal uncertainties are negligible. Therefore at large signal amplitudes one can expect the quality factor to depend linearly upon the amplitude of the pulse and the slope depends on the difference between the ideal pulse shape and the actual pulse shape in the detector. A deviation from a linear dependence between the quality factor and the amplitude could be used to detect deviations from linearity. Figure 7 left panel shows \(Q_{OFL}\) as function of the pulse amplitude in collision data, in absence of out-of-time pile-up. The purple line corresponds to the linear fit to mean value of the quality factor. The dependence of the quality factor on the amplitude appears clearly. In the 2004 test beam analysis a quadratic trend of the \(\chi^2\) of the fit method was observed as function of the amplitude [8]. This observation is also compatible, since there is a square root in the formula of quality factor which gives linear amplitude dependence. For comparison, Fig. 7 right panel shows the quality factor in the simulator if we assume that the measured \(S_i\) follow the ideal pulse shape. In the case of perfect pulse shape only the timing and noise effects contribute to \(Q_{OFL}\) which takes a constant value as a function of the amplitude as shown in the right panel of Fig. 7. Therefore the quality factor can be written as:

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

(7)

where \(Q_{OFL}^0\) is the value of the quality factor at low amplitude when it is dominated by noise and timing effects. The value of \(Q_{OFL}^0\) was determined from data i.e. using the linear fit (the purple line in left the panel of Fig. 7) the value of quality factor at \(A_{OFL} = 0\) ADC was calculated. Figure 8 left panel shows \((Q_{OFL} - Q_{OFL}^0)/A_{OFL}\) in collision data. The purple line corresponds to the linear fit to mean value. The distribution is flat as a function of amplitude with a mean value around zero (purple line). This is consistent with Eq. 7.

In order to reproduce the quality factor observed in data, the simulator must use a pulse shape that is different from the ideal pulse shape. The pulse shapes in data are modeled by the normalized ideal pulse shapes, with a modified width. Widened or narrowed pulses are obtained by using a new pulse shape given by:

\[
h(\alpha t) = g(t)
\]

(8)

where \(g\) is the ideal pulse shape used earlier and \(\alpha\) is a factor close to one. A value of \(\alpha\) equals to one gives the ideal pulse shape, while \(\alpha < 1\) corresponds to a narrower pulse and \(\alpha > 1\) corresponds to a wider pulse. During the early studies the \(\alpha\) factor was taken to follow a Gaussian distribution with a mean value of 1 and a standard deviation of \(\sigma = 0.01\). These values were observed during previous studies of pulse shape in TileCal [6]. Nevertheless, the simulator showed not adequate agreement between data and simulator. Therefore, the factor \(\alpha\) was adjusted to the data so that the quality factor distribution
Figure 7: Left: Quality factor as a function of reconstructed amplitude in 2011 data. The data consists of runs: 177531, 177539, 177540, 177593, 177682 from March 2011 ($\langle \mu \rangle = 3.3$). This data was recorded while the LHC was running with only 2 bunches per beam separated by at least 2.5 $\mu$s. Right: Quality factor as a function of reconstructed amplitude in TileCal pulse simulator with ideal pulse shape, but timing and noise effects emulated. No out-of-time pile-up. One can observe that with ideal pulse shapes the quality factor is not amplitude-dependent. The x-axis shows the amplitude in ADC counts before channel-dependent calibration constants are applied. The calibration factor is approximately 12 MeV per ADC count. The purple line corresponds to the linear fit to mean value of the quality factor.

Figure 8: Left: $(Q_{OFL} - Q_{OFL}^0)/A_{OFL}$ as a function of reconstructed amplitude ($A_{OFL}$) in 2011 data. The data consists of runs: 177531, 177539, 177540, 177593, 177682 from March 2011 ($\langle \mu \rangle = 3.3$). This data was recorded while the LHC was running with only 2 bunches per beam separated by at least 2.5 $\mu$s. Right: $Q_{OFL}/A_{OFL}$ as a function of reconstructed amplitude in TileCal pulse simulator in absence of emulation of noise and timing effects but using stretched pulse shapes according to $g(\alpha t)$. No out-of-time pile-up. The x-axis shows the amplitude in ADC counts before channel-dependent calibration constants are applied. The calibration factor is approximately 12 MeV per ADC count. The purple line corresponds to the linear fit to mean value.
observed in the simulator matches that of the data. It is found that $\alpha$ modeled with a Gaussian with a mean value of 1.01 and a standard deviation of $\sigma = 0.02$ provides a good model of the data. Figure 8 right panel shows $Q_{OFL/A_{OFL}}$ in the simulator with widened pulse shapes. In this particular case no noise or timing effects are emulated so $Q_{OFL}$ can be assumed to be equal to zero. The distribution is flat as a function of amplitude with a mean value around 0 (purple line) and is consistent with the observation in collision data (Fig. 8 left panel).

### 4.2.2 Amplitude distribution

Fig. 9 top left panel shows the effect of amplitude variation with ideal pulse shape, while top right panel shows the effect of amplitude variation with widened pulse shape. The amplitude is modeled with the probability density function obtained using JetTauEtmiss data. It confirms what was showed in Section 4.2.1 that in presence of non-ideal pulse shape there is a strong amplitude dependence on quality factor. As the quality factor is dependent on the amplitude, the simulator has to use the same amplitude distribution as the data. The pulse shape simulator is validated by comparing its result with the data in Section 4.3 using TileCal data collected in JetTauEtmiss stream. For this comparison the probability density function of the amplitude measured in the TileCal cells is extracted from the data and used to generate the amplitude of the pulses in the simulator. In Section 5 it is shown that the amplitude distribution in TileCal cells can be extracted without bias due to the trigger, in order to model the amplitude distribution of the out-of-time pulses.

### 4.2.3 Channel to channel phase variation $\phi_{ch}$

Ideally the peak of the signal pulses should be perfectly centered in the middle of $\pm 75$ ns read-out window. In the actual Tile Calorimeter the position of the pulse peak has been shown to be within 3 ns of the middle of the read-out window [4]. This effect is taken into account in the simulator by randomly offsetting the simulated pulses before reconstruction with a random phase that is Gaussian distributed with a mean of zero and a standard deviation of $\sigma = 3$ ns, as this is what is observed in the actual TileCal [9]. The corresponding distribution of reconstructed phase in pulse simulator is shown in Fig. 10. The effect of channel to channel phase variation on quality factor is showed on bottom left panel of Fig. 9. Since iterative Optimal Filtering method was used for reconstruction, the effect of phase variation is small.

### 4.2.4 Incoherent electronic noise

The incoherent electronic noise modifies the measured values of the samples $S_i$ randomly around the normalized pulse shape. This effect is to first approximation uncorrelated between the samples $S_i$. Figure 9 shows the impact of different effects on quality factor i.e. the quality factor distribution with amplitude variation (top left panel), with amplitude and pulse shape variation (top right), with channel to channel phase offsets (bottom left panel), and finally with a double Gaussian noise model (bottom right). It appears that the effect of the timing is very small while the effect of the noise is the second most significant contribution to the quality factor, after the pulse shape, but becomes the dominant factor at low amplitudes. Since most of the events have low amplitude they form a peak in quality factor distribution. Therefore, the position of the peak of quality factor values is particularly sensitive to the noise. For this reason the simulator uses the double Gaussian noise model that was found to describe the TileCal noise data [4]. During early studies the mean values of the noise constants stored in COOL data base were used in simulator. Nevertheless, the results showed not adequate agreement between data and simulator. Therefore, the noise constants used to smear the $S_i$ were adjusted so that the quality factor distribution obtained with the simulator reproduces the quality factor in the data. The following noise constants are
Figure 9: Top left: Quality factor with smeared amplitude. Top right: Quality factor with smeared amplitude and widened pulse shapes. Bottom left: Quality factor with smeared channel to channel time offsets. Bottom right: Quality factor with double Gaussian electronic noise.

Figure 10: Channel to channel time offset distribution.
used: $\sigma_1 = 1.46$ ADC, $\sigma_2 = 3.60$ ADC counts and the relative normalization of the two Gaussians $R = 0.07$.

### 4.3 Comparison of the Quality Factor in Data and TileCal Pulse Simulator

All the presented results for both collision data and simulator consist of events acquired with high gain with reconstructed amplitude $A_{OFL} > 34$ ADC counts (400 MeV). The reconstructed amplitude requirement ensure that the studied events consist of real energy depositions in the detector. Pedestal events are not considered in this study.

The quality factor distribution is computed in data using an integrated luminosity of $60 \text{ nb}^{-1}$ taken in March 2011 at a period where the LHC was operating with only 2 bunches per beam, separated by at least 2.5 $\mu$s (runs 177531, 177539, 177540, 177593, 177682), therefore ensuring the absence of out-of-time pile-up. The collisions were collected in JetTauEtmiss stream. The quality factor distribution is also computed in simulator using the model described in Section 4.2 and compared with collision data.

To obtain optimal agreement between data and pulse simulator, one would have to use different noise constants in different channels, since all channels in the real detector have slightly different noise and pulse characteristics. The events from different channels would enter to the histograms with different frequencies dependent on $\eta$ and layer. Also, the pulse shapes would have to be widened differently in different channels. The simulator results presented here are obtained with the simplified model introduced earlier, using the averaged noise and pulse shape variation constants adjusted to data.

Figure 11 left panel shows the reconstructed amplitude dependence on quality factor in collision data while right panel shows the corresponding distribution of quality factor obtained in the pulse simulator, in absence of out-of-time pile-up. The amplitude dependence of the quality factor in data is well reproduced by the simulator in the range $200 - 1024$ ADC counts, as attested by the similar fitted slopes in the right panel of Fig. 11. In the range below 200 ADC counts the amplitude dependence shows non-linear behaviour in the pulse simulator. Therefore, the fit was performed in the linear region only. In order to obtain a good agreement in whole amplitude range one would have to apply a treatment described above. The resulting quality factor distribution in data and from the simulator is shown in top panels of Fig. 12, while the bottom panel shows a relative difference between distributions. A good agreement apart from a small discrepancies in the high tail of the quality factor distribution is shown. In a range of $0 < QF_{OFL} < 5$ ADC counts, i.e. for most events w/o out-of-time pile-up the relative difference is below 1%. Figure 13 shows $QF_{OFL}/A_{OFL}$ distribution in data and from the simulator. Also here a fair agreement is observed.

This demonstrates that the pulse shapes can be simulated in such a way that a complex quantity such as the quality factor and its correlation with amplitude can be reproduced. The simulator can then be used to predict the quality factor distribution in presence of out-of-time pile-up in order to derive the optimal criteria to detect out-of-time pile-up while keeping the amount of read out data within the bandwidth budget of TileCal.

### 5 Quality Factor Simulation with Pile-up

#### 5.1 Strategy

The goal of this section is to determine the effect of out-of-time pile-up on the quality factor in the pile-up scenarios presented in Section 3. The out-of-time pulses in a TileCal cell can be of arbitrary small sizes. For a small enough amplitude of the out-of-time pulse compared to the in-time pulse, the effect on the reconstructed energy in the cell will be negligible. When the effect of the out-of-time pulse on the reconstructed energy is negligible there is no need to detect the out-of-time pulse.
On the other hand when the out-of-time pulse is large enough with respect to the in-time pulse, its effect on the reconstructed energy will be large. Therefore, it is important to detect such a situation so that proper action can be taken, for instance by performing a special energy reconstruction or flagging the cell as providing an unreliable energy measurement.

The strategy presented in this note is therefore that small out-of-time pulses are simply ignored. The amplitude for which the out-of-time pulse becomes non-negligible referred here as “significant” pulses, is determined in bins of the amplitude of the in-time pulse amplitude.

While the average energy distribution in cells due to in-time pulse is related to the trigger item which triggered the recording of the event, the out-of-time pulses on the other hand belong to events that did not fire the trigger therefore the energy distribution of the out-of-time pulses correspond to the energy distribution in a ZeroBias trigger randomly distributed in coincidence with the crossing of populated bunch pairs. So the energy distribution for the significant pulses will be taken from the energy observed in ZeroBias events, and passing the energy threshold that makes the pulse giving a significant bias on the energy reconstruction.

5.2 Effect of Pile-up on the Reconstructed Amplitude

In this section we determine what is a “significant” out-of-time pulse by looking at its effect on the reconstructed amplitude. The amplitude of the in-time pulse is referred to as $A_{in}$. For a given value of $A_{in}$ the amplitude the out-of-time pulse referred to as $A_{out}$ is varied. For each value of $A_{in}$ and $A_{out}$ the amplitude is recomputed with the iterative Optimal Filtering and compared to the true in-time pulse amplitude. Figure 14 gives the size of the deviation of reconstructed amplitude $A_{OFL}$ from the true in-time amplitude as function of the amplitude of out-of-time pulse in the case of out-of-time pile-up located 50 ns earlier than in-time pulse and $A_{out} < A_{in}$. The purple line corresponds to the 9th order polynomial fit to mean value of relative difference. This Figure shows for instance that the maximal average effect on the reconstructed amplitude is 11% in all $A_{in}$ bins. The observed shape is invariant if plotted as a function of $A_{out}/A_{in}$ and indicates that the bias increases with $A_{out}$ up to some point. After the extremum is reached

![Figure 11: Left: Quality factor as a function of reconstructed amplitude in 2011 data. The data consists of runs: 177531, 177539, 177540, 177593, 177682 from March 2011 ($\mu = 3.3$). This data was recorded while the LHC was running with only 2 bunches per beam separated by at least 2.5 $\mu$s. Right: Quality factor as a function of reconstructed amplitude in TileCal pulse simulator with non-ideal pulse shapes, timing and noise effects emulated (full model of the pulse simulator). No out-of-time pile-up. There is amplitude dependence of quality factor. The x-axis shows the amplitude in ADC counts before channel-dependent calibration constants are applied. The calibration factor is approximately 12 MeV per ADC count. The purple line corresponds to the linear fit to mean value of the quality factor.](image)
Figure 12: Comparison of quality factor distribution in 2011 data and in TileCal pulse simulator with non-ideal pulse shapes, timing and noise effects emulated (full model of the pulse simulator). The data consists of runs: 177531, 177539, 177540, 177593, 177682 from March 2011 ($\langle \mu \rangle = 3.3$). This data was recorded while the LHC was running with only 2 bunches per beam separated by at least 2.5 $\mu$s. Plot on left side has y axis in linear scale, plot on right side has y axis in logarithmic scale, plot on the bottom shows relative difference between simulator and data.

Figure 13: Comparison of quality factor divided by reconstructed amplitude distribution in 2011 data and in TileCal pulse simulator with non-ideal pulse shapes, timing and noise effects emulated (full model of the pulse simulator). The data consists of runs: 177531, 177539, 177540, 177593, 177682 from March 2011 ($\langle \mu \rangle = 3.3$). This data was recorded while the LHC was running with only 2 bunches per beam separated by at least 2.5 $\mu$s. Plot on left side has y axis in linear scale while plot on right side has y axis in logarithmic scale.
the bias decreases back. It can be understood in terms of pulse shapes (Fig. 5). The reconstructed phase increases with the ratio $A_{out}/A_{in}$. It takes the value $t_{OFL} = 0$ ns for $A_{out} = 0$ ADC counts and $t_{OFL} = 25$ ns (lies in the middle between the pulses) for $A_{in} = A_{out}$. Since in the reconstruction of amplitude with Optimal Filtering method the largest constant $a_{max}$ correspond to the reconstructed phase, one has to look at the purple line presenting the sum of two pulses in the time region $0 – 25$ ns on Fig. 5. The shape of this line shows the similar behaviour to the shapes observed on Fig. 14. In the reconstruction of pedestal first and last constants ($c_1$ and $c_7$) are the largest. Therefore, in case of no out-of-time pile-up the pedestal is determined mainly from the samples with little or no signal. In presence of pile-up out-of-time signal is added to either first of last sample. Therefore, the reconstructed pedestal is overestimated while the amplitude is underestimated. Maximal average effect on reconstructed amplitude of out-of-time pulses of amplitude $A_{out} = 34$ ADC (400 MeV) or below is 11% for $A_{in} = 34$ ADC, 8.8% for $A_{in} = 84$ ADC, 2.2% for $A_{in} = 417$ ADC and 0.9% for $A_{in} = 1000$ ADC. When $A_{out} > A_{in}$ the out of time pulse becomes dominant. In this case, since iterative the Optimal Filtering method is used the out-of-time amplitude is reconstructed.

We conclude that the “significant” out-of-time pulses are those with amplitude above 34 ADC since their maximal average effect on reconstructed amplitude is 11%. Only these pulses are considered in studies described in Section 4.2.1.

Figure 14: Relative difference between reconstructed amplitude and true in-time pulse amplitude as a function of true out-of-time pulse amplitude in TileCal pulse simulator with non-ideal pulse shapes, timing and noise effects emulated (full model of the pulse simulator). Four cases: $A_{in} = 34$ ADC ($A_{in} = 0.4$ GeV), $A_{in} = 84$ ADC ($A_{in} = 1$ GeV), $A_{in} = 417$ ADC ($A_{in} = 5$ GeV), $A_{in} = 1000$ ADC ($A_{in} = 12$ GeV). The purple line corresponds to the 9th order polynomial fit to mean value of relative difference.
5.3 Amplitude of Out-of-Time Pulses

The average signal amplitude for in-time pulses is related to the trigger criteria used to record the event, since for instance requiring several highly energetic hadronic jets will certainly increase the amount of energy deposited in the calorimeter and hence the likelihood that a calorimeter channel received a large signal.

The out-of-time pulses on the other hand belong to collisions that did not pass the trigger. They are recorded by chance since they were close in time to a collision that passed the trigger. Therefore the energy distribution from pile-up is that from unbiased collisions before the trigger. This energy distribution can be extracted from data by using a specific trigger. ATLAS possesses a so-called a ZeroBias trigger, which records a small fraction of collisions randomly selected in coincidence with the crossing of two populated proton bunches. This ZeroBias trigger allows to measure the energy distribution in TileCal channels without the effect of the trigger bias, and is therefore used as a model to extract the probability density function of the amplitude of the out-of-time pulses. This amplitude distribution is extracted from no pile-up ATLAS data from March 2011 at a time where the LHC was operating with only two bunches per beam, separated with at least 2.5 $\mu$s. The corresponding distribution of amplitude before channel-dependent calibration constants are applied is shown in Fig. 15. This amplitude distribution is used as probability density function to generate out-of-time pulses in the pulse simulator and compute the quality factor in presence of pile-up in Section 5.4. Additionally, a lower cut of 34 ADC counts described in Section 5.2 is applied.

![Distribution of reconstructed amplitude in 2011 data ZeroBias stream, in absence of out-of-time pile-up. The data consists of runs: 177531, 177539, 177540, 177593, 177682 from March 2011 ($\langle \mu \rangle = 3.3$). This data was recorded while the LHC was running with only 2 bunches per beam separated by at least 2.5 $\mu$s. The x-axis shows the amplitude in ADC counts before channel-dependent calibration constants are applied. The calibration factor is approximately 12 MeV per ADC count. The electronic noise is approximately 1.5 ADC counts.](image)

Figure 15: Distribution of reconstructed amplitude in 2011 data ZeroBias stream, in absence of out-of-time pile-up. The data consists of runs: 177531, 177539, 177540, 177593, 177682 from March 2011 ($\langle \mu \rangle = 3.3$). This data was recorded while the LHC was running with only 2 bunches per beam separated by at least 2.5 $\mu$s. The x-axis shows the amplitude in ADC counts before channel-dependent calibration constants are applied. The calibration factor is approximately 12 MeV per ADC count. The electronic noise is approximately 1.5 ADC counts.

5.4 Quality Factor Distributions in Presence of Out-of-Time Pile-up

In this Section the effect of the out-of-time pile-up on the quality factor is studied. Using TileCal pulse simulator model one can study the effect of the relative sizes of the in-time and out-of-time pulses. Fig. 16
shows the dependence of the quality factor $Q_{F_{OFL}}$ as a function of the in-time pulse amplitude $A_{in}$ (out-of-time pulse $A_{out}$) given on the x-axis and for different values of the ratio between the in-time and out-of-time pulse amplitude. The lines correspond to the linear fit to mean value of the quality factor. It shows two important features, first that for a given ratio of $A_{out}/A_{in}$, the quality factor increases linearly with the amplitude, and second that the dependence on the amplitude $A_{in}$ gets steeper when the ratio $A_{out}/A_{in}$ gets closer to one. The worst case scenario occurs for in-time and out-of-time pulses of equal amplitude, in that case the quality factor becomes maximal. The introduction of an out-of-time pile-up pulse is equivalent to introducing a deviation between the ideal pulse shape and the real pulse shape. The linear dependence on the amplitude observed here is therefore consistent with the observation of a linear dependence upon pulse amplitude made in Section 4.2.1. In iterative Optimal Filtering method the reconstructed phase $t_{OFL}$ is proportional to the ratio $A_{out}/A_{in}$. It takes the value $t_{OFL} = 0$ ($t_{OFL} = 50$) ns for $A_{out} = 0$ ($A_{in} = 0$) ADC counts and $t_{OFL} = 25$ ns (lies in the middle between the pulses) for $A_{in} = A_{out}$. Therefore, there is the same effect on quality factor regardless which pulse, in-time or out-of-time is dominant (on Fig. 16 black and purple lines are overlapping).

Figure 16: Quality factor as a function of the amplitude in different pile-up scenarios in TileCal pulse simulator with non-ideal pulse shapes, timing and noise effects emulated (full model of the pulse simulator). $A_{in}$ ($A_{out}$) is the amplitude of the in-time (out-of-time) pulse. The x-axis shows the amplitude in ADC counts before channel-dependent calibration constants are applied. The calibration factor is approximately 12 MeV per ADC count.

In order to compute a realistic distribution of the quality factor in presence of out-of-time pile-up, the pulses are generated with the simulator using all effects described earlier in Section 4. The amplitude of the out-of-time pulse is modeled with the probability density function obtained using the ZeroBias data as described in Section 4 and 5.4. The amplitude of in-time pulse is modeled with the probability density function obtained using JetTauEtmiss data. In both cases, in-time and out-of-time pulse, there is lower cut 34 ADC counts (400 MeV) imposed on the actual amplitude. Figure 17 compares the quality factor in the absence (black) and presence of out-of-time pile-up (purple) obtained for this model in three reconstructed amplitude bins. In order to get the distributions presented in this Figure, a large set of 10 million in-time pulses without out-of-time pile-up was generated using pulse simulator. These events correspond to the black line distributions. Then, the same number of events with out-of-time pile-up were generated. These events correspond to the purple line distributions. Figure 17 illustrates
Figure 17: Normalized distributions of quality factor in TileCal simulator with non-ideal pulse shapes, timing and noise effects emulated (full model of the pulse simulator). Two cases: no out-of-time pile-up (black) and with out-of-time pile-up (purple). Amplitude of in-time pulse follows the distribution in JetTauEtmiss stream with cut corresponding to the bin. Amplitude of the out-of-time pulse follows the distribution in ZeroBias stream with a cut on 34 ADC counts (0.4 GeV). Three reconstructed amplitude bins: $34 < A_{OFL} < 84$ ADC ($0.4 < E_{OFL} < 1$ GeV), $84 < A_{OFL} < 417$ ADC ($1 < E_{OFL} < 5$ GeV), $417 < A_{OFL} < 1000$ ADC ($5 < E_{OFL} < 12$ GeV). The JetTauEtmiss and ZeroBias data was recorded while the LHC was running with only 2 bunches per beam separated by at least 2.5 µs and corresponds to the runs: 177531, 177539, 177540, 177593, 177682 from March 2011 ($⟨μ⟩ = 3.3$). Plots on left side have y axis in linear scale while plots on right side have y axis in logarithmic scale.
Figure 18: Normalized distributions of quality factor divided by reconstructed amplitude in TileCal simulator with non-ideal pulse shapes, timing and noise effects emulated (full model of the pulse simulator). Two cases: no out-of-time pile-up (black) and with out-of-time pile-up (purple). Amplitude of in-time pulse follows the distribution in JetTauEtmiss stream with cut corresponding to the bin. Amplitude of the out-of-time pulse follows the distribution in ZeroBias stream with a cut on 34 ADC counts (0.4 GeV). Three reconstructed amplitude bins: $34 < A_{OFL} < 84$ ADC ($0.4 < E_{OFL} < 1$ GeV), $84 < A_{OFL} < 417$ ADC ($1 < E_{OFL} < 5$ GeV), $417 < A_{OFL} < 1000$ ADC ($5 < E_{OFL} < 12$ GeV). The JetTauEtmiss and ZeroBias data was recorded while the LHC was running with only 2 bunches per beam separated by at least 2.5 μs and corresponds to the runs: 177531, 177539, 177540, 177593, 177682 from March 2011 ($\langle \mu \rangle = 3.3$). Plots on left side have y axis in linear scale while plots on right side have y axis in logarithmic scale.
that for significant out-of-time pile-up pulses the distribution of quality factor is quite different in case of out-of-time compared to no out-of-time pile-up. There is a clear separation between the two cases.

As it has been shown that the quality factor is linearly increasing with the amplitude of the pulses, further studies of quality factor divided by amplitude ($QF_{OFL}/A_{OFL}$) were performed. For this purpose exactly the same simulation model was used. Fig. 18 compares $QF_{OFL}/A_{OFL}$ in the absence (black) and presence of out-of-time pile-up (purple) obtained for this model in three reconstructed amplitude bins. In this case, also good separation is observed. Nevertheless, the best separation between the pile-up and non-pile-up scenarios is obtained by using the quality factor, rather than the quality factor divided by the amplitude as can be seen in Fig. 17. Based on these results possible criteria to select pile-up channels is proposed in the next section.

6 Optimization of the Selection to Detect Pile-up

Using the quality factor distributions presented in Fig. 17 one can propose selections to detect out-of-time pile-up based on a cut on quality factor. Since there is a linear dependence of the amplitude of out-of-time pulse on quality factor, three different selection criteria are defined for three different amplitude bins. The amplitude bins presented in Fig. 17 correspond to the reconstructed amplitude $A_{OFL}$. Therefore, these results can be used directly to propose the cuts on the quality factor.

Table 1 shows proposed cuts on the quality factor for three reconstructed amplitude bins. The first column shows reconstructed amplitude range in ADC counts in particular bin, second column shows reconstructed energy in MeV in each bin (the calibration factor is approximately 12 MeV per ADC count), third column shows proposed cuts on quality factor, fourth column shows fake rate in per cent and last column shows the efficiency in per cent. A fake rate is defined as a fraction of non out-of-time pile-up events that were wrongly selected as a pile-up events. The efficiency is defined as a fraction of out-of-time pile-up events correctly selected as pile-up events. If necessary, one can apply different reconstructed amplitude bins based on the information from Fig. 16.

In case of the first bin ($34 < A_{OFL} < 84$ ADC) a cut of $QF_{OFL} > 8.8$ ADC counts allows the selection of all pile-up events with less than 1% of non-pile-up events wrongly selected. The same result can be obtained in second bin ($84 < A_{OFL} < 417$ ADC) with cut of $QF_{OFL} > 11.6$. In case of third bin ($417 < A_{OFL} < 1024$ ADC) the separation becomes slightly worse due to larger tail in distribution of quality factor in non-pile-up events. The tail is present in highest amplitude bin due to quality factor amplitude dependence described in Section 4.2.1. Therefore, three different cuts on quality factor are presented. Cut of $QF_{OFL} > 29.7$ ADC allows to limit fake rate to less than 1% with 85.03% efficiency. Lower cut of $QF_{OFL} > 22.9$ ADC increase efficiency to 99.04% and fake rate to 3.75%. Using cut of $QF_{OFL} > 11.7$ ADC one can select all pile-up events with fake rate of 26.55%. Depending on the constrains of available bandwidth one of the proposed cut can be chosen in this amplitude bin.

<table>
<thead>
<tr>
<th>$A_{OFL}$ [ADC]</th>
<th>$E_{OFL}$ [GeV]</th>
<th>$QF_{OFL}$ cut [ADC]</th>
<th>Fake rate [%]</th>
<th>Efficiency [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>34 — 84</td>
<td>0.4 — 1</td>
<td>8.8</td>
<td>0.973 ± 0.004</td>
<td>100.0 (&gt; 99.9% at 95% CL)</td>
</tr>
<tr>
<td>84 — 417</td>
<td>1 — 5</td>
<td>11.6</td>
<td>0.985 ± 0.006</td>
<td>100.0 (&gt; 99.9% at 95% CL)</td>
</tr>
<tr>
<td>417 — 1024</td>
<td>5 — 12</td>
<td>29.7</td>
<td>0.99 ± 0.01</td>
<td>85.03 ± 0.03</td>
</tr>
<tr>
<td>417 — 1024</td>
<td>5 — 12</td>
<td>22.9</td>
<td>3.75 ± 0.03</td>
<td>99.04 ± 0.01</td>
</tr>
<tr>
<td>417 — 1024</td>
<td>5 — 12</td>
<td>11.7</td>
<td>26.55 ± 0.06</td>
<td>100.0 (&gt; 99.8% at 95% CL)</td>
</tr>
</tbody>
</table>

Table 1: Proposed cuts on $QF_{OFL}$ for three reconstructed amplitude bins, together with the corresponding fake rates and efficiencies, in different bins of the reconstructed amplitude. A set of 10 millions events was used to calculate fake rates and efficiencies. The quoted errors are statistical.
7 Conclusions

A numerical model of the ATLAS Tile Calorimeter pulses has been developed in the form of a pulse simulator. This model takes into account small variations in signal pulse shapes, small timing miscalibration effects and uses double Gaussian model of the calorimeter noise. The simulator is shown to be able to reproduce the quality factor distributions in collisions in absence of out-of-time pile-up. The variation in pulse shapes from cell to cell is a crucial effect that has to be taken into consideration to model the quality factor at high pulse amplitude. The modeling of the electronic noise is crucial to correctly describe the low energy part of the quality factor distribution. The signal amplitude for TileCal channels is measured in ZeroBias triggered data and used as a model for pulses from out-of-time pile-up collisions. Using this model of the data, the distribution of the quality factor in the presence of out-of-time pile-up is calculated. It shows that when amplitude of the out-of-time pile-up is large enough to affect the amplitude measurement, significant discrimination between the presence and the absence of out-of-time pile-up can be achieved thanks to the quality factor. Using the predicted distributions of quality factor with and without out-of-time pile-up, the presence of significant out-of-time pile-up can be identified and a specific treatment of the double pulses can be performed. For this purpose adequate cuts on quality factor in three various reconstructed amplitude bins are proposed. In particular in the lowest energy bins it is possible to achieve 100% efficiency for significant pile-up pulses while keeping a fake rate of 1%. The presented results have been obtained using iterative Optimal Filtering reconstruction method. In the next step the quality factor calculated with non-iterative method needs to be studied. This would allow to implement identification of pile-up using quality factor online in DSP.

References


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Appendices

A Bias and Resolution of Optimal Filtering Reconstruction

Figure 19: The bias in reconstruction of amplitude as a function of true amplitude in TileCal pulse simulator. This is shown for high gain (left) and low gain (right). Amplitude is reconstructed with Optimal Filtering with iterations in absence of out-of-time pile-up.

Figure 20: The resolution of amplitude reconstruction as a function of true amplitude in TileCal pulse simulator. This is shown for high gain (left) and low gain (right). Amplitude is reconstructed with Optimal Filtering with iterations in absence of out-of-time pile-up.
Figure 21: The bias in reconstruction of time as a function of true time in TileCal pulse simulator. This is shown for high gain (left) and low gain (right). Time is reconstructed with Optimal Filtering with iterations in absence of out-of-time pile-up.

Figure 22: The resolution of time reconstruction as a function of true time in TileCal pulse simulator. This is shown for high gain (left) and low gain (right). Time is reconstructed with Optimal Filtering with iterations in absence of out-of-time pile-up.

Figure 23: The bias in reconstruction of time as a function of true amplitude in TileCal pulse simulator. This is shown for high gain (left) and low gain (right). Time is reconstructed with Optimal Filtering with iterations in absence of out-of-time pile-up.
Figure 24: The resolution of time reconstruction as a function of true time in TileCal pulse simulator. This is shown for high gain (left) and low gain (right). Time is reconstructed with Optimal Filtering with iterations in absence of out-of-time pile-up.
Paper IV
Searches for direct slepton-pair and chargino-pair production in final states with two opposite-sign leptons, missing transverse momentum and no jets in 20 fb$^{-1}$ of $pp$ collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector

The ATLAS Collaboration

Abstract

Searches for the electroweak production of pairs of sleptons or charginos decaying into final states with two leptons, missing transverse momentum and no reconstructed jets are performed using 20.3 fb$^{-1}$ of proton-proton collision data at $\sqrt{s} = 8$ TeV recorded with the ATLAS experiment at the Large Hadron Collider. No significant excesses are observed with respect to the prediction from Standard Model processes. Limits are set on the masses of the slepton and of the lightest chargino for different lightest-neutralino mass hypotheses. In scenarios where sleptons decay directly into the lightest neutralino and a charged lepton, common values for left and right-handed slepton masses between 90 GeV and 320 GeV are excluded at 95% confidence level for a massless neutralino. In the scenario of chargino pair production, with wino-like charginos decaying into the lightest neutralino via an intermediate slepton, chargino masses between 130 GeV and 450 GeV are excluded at 95% confidence level for a 20 GeV neutralino. In the scenario of chargino pair production followed by the $\tilde{\chi}_1^{\pm} \to W^{\pm}\tilde{\chi}_1^0$ decay, the excluded cross-section is above the model cross-section by a factor 1.9–2.8 in the $\tilde{\chi}_1^{\pm}$ mass range of 100–190 GeV and then degrades gradually to 4.7 when reaching a $\tilde{\chi}_1^{\pm}$ mass of 250 GeV.

The following has been revised with respect to the version dated May 13, 2013: in Table 7, the expected number of signal events at the SR-$m_{T2,110}$ cut level for the $e^\pm\mu^\mp$ channel for the benchmark model point $(m_{\tilde{\chi}_1^\pm}, m_{\tilde{\chi}_1^0}) = (425, 75)$ GeV has been changed to its correct value of 5.7 (previously 1.1).

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1 Introduction

Weak-scale Supersymmetry (SUSY) \([1–9]\) is an extension to the Standard Model (SM) of particle physics. It postulates for each known boson or fermion the existence of a particle whose spin differs by one-half unit from the SM partner. The introduction of these new particles provides solutions to the hierarchy problem \([10–13]\) and, if R-parity is conserved \([14–18]\), a dark matter candidate in the form of the lightest supersymmetric particle (LSP). R-parity conservation is assumed in this note, hence SUSY particles are always produced in pairs.

If the masses of the gluinos and squarks are large, the direct production of charginos, neutralinos and sleptons may dominate the production of SUSY particles at the Large Hadron Collider (LHC) \([19]\). Such a scenario is possible in the general framework of the phenomenological minimal supersymmetric SM (pMSSM) \([20–22]\). Naturalness suggests that third-generation sparticles, charginos and neutralinos should have masses of a few hundreds of GeV \([23, 24]\). Light sleptons could also play a role in the co-annihilation of neutralinos, leading to a dark matter relic density consistent with cosmological observations \([33, 34]\).

Light sleptons are expected in gauge-mediated \([25–30]\) and anomaly-mediated \([31, 32]\) SUSY breaking scenarios. Such a scenario is possible in the general framework of the phenomenological minimal supersymmetric SM. Light sleptons could also play a role in the co-annihilation of neutralinos, leading to a dark matter relic density consistent with cosmological observations \([33, 34]\).

This note presents searches for electroweak production of sleptons and charginos using 20.3 \(\text{fb}^{-1}\) of \(\sqrt{s} = 8\) TeV \(pp\) collision data collected with the ATLAS detector. Similar searches have previously been performed by the ATLAS experiment using 4.7 \(\text{fb}^{-1}\) of 7 TeV data \([35]\), and by the CMS experiment using 9.2 \(\text{fb}^{-1}\) of 8 TeV data \([36]\). A related ATLAS search was also performed at 8 TeV \([37]\). The combined LEP limits on the selectron, smuon and chargino masses are \(m_{\tilde{e}} > 99.9\) GeV, \(m_{\tilde{\mu}} > 94.6\) GeV and \(m_{\tilde{\chi}^\pm_1} > 103.5\) GeV \([38]\). Note that the LEP selectron limit assumes gaugino mass unification and cannot be directly compared with the results presented in this note.

The searches presented in this note target the following four scenarios that produce final states with two oppositely-charged leptons (electrons or muons) and missing transverse momentum.

Sleptons can be produced directly in a process similar to Drell-Yan production \([39]\). The direct pair production of charged sleptons, \(q\bar{q} \rightarrow \ell^+\ell^-\) is considered, where each slepton decays through \(\tilde{\ell}^\pm \rightarrow \ell^\pm\tilde{\chi}^0_1\). The undetected neutralinos give rise to large missing transverse momentum in the event.

Direct chargino-pair production through weak interactions, \(q\bar{q} \rightarrow \tilde{\chi}^+_1\tilde{\chi}^-_1\), where each chargino decays through \(\tilde{\chi}^\pm \rightarrow (\ell^\pm\nu\text{ or } \ell^\pm\bar{\nu}) \rightarrow \ell^\pm\nu\tilde{\chi}^0_1\) leads to a signature similar to that of the direct slepton pair production, even though two additional neutrinos contribute to the missing transverse momentum. Unlike the direct slepton production, the final state leptons can be either of the same flavour \((e^+e^-\text{ or } \mu^+\mu^-)\) or of different flavours \((e^+\mu^-)\).

If the lightest chargino is the NLSP, the chargino decays as \(\tilde{\chi}^+_1 \rightarrow W^+\tilde{\chi}^0_1\), producing an on- or off-shell \(W\) boson. If both \(W\) bosons decay leptonically, the final state will again contain two opposite-sign leptons and large missing transverse momentum due to the presence of two neutrinos and two neutralinos. Although the leptons can be of either the same or different flavours, this analysis uses only the \(e^+\mu^-\) channel because of the smaller background.

The gauge-mediated SUSY breaking (GMSB) model proposed in Ref. \([40]\) is also considered. The search strategy is the same as for the channel with two on-shell \(W\) bosons, and so only the \(e^+\mu^-\) channel is considered.

2 The ATLAS Detector

The ATLAS experiment \([41]\) is a multi-purpose particle physics detector with a forward-backward symmetric cylindrical geometry and nearly \(4\pi\) coverage in solid angle\(^1\). It contains four superconducting...
magnet systems, which include a thin solenoid surrounding the inner tracking detector (ID), and barrel and end-cap toroids supporting a muon spectrometer. The ID covers the pseudorapidity region $|\eta| < 2.5$ and consists of a silicon pixel detector, a silicon microstrip detector (SCT), and a transition radiation tracker (TRT). In the pseudorapidity region $|\eta| < 3.2$, high-granularity liquid-argon (LAr) electromagnetic (EM) sampling calorimeters are used. An iron-scintillator tile calorimeter provides coverage for hadron detection over $|\eta| < 1.7$. The end-cap and forward regions, spanning $1.5 < |\eta| < 4.9$, are instrumented with LAr calorimeters for both EM and hadronic measurements. The muon spectrometer surrounds the calorimeters and consists of a system of precision tracking chambers ($|\eta| < 2.7$), and detectors for triggering ($|\eta| < 2.4$).

3 Data Samples

The data used in this analysis were collected during the 2012 proton-proton collision run at $\sqrt{s} = 8$ GeV. After applying beam, detector and data-quality requirements, the dataset corresponds to a total integrated luminosity of 20.3 fb$^{-1}$.

Events are triggered using two-lepton triggers. There are two dielectron triggers with the leading and sub-leading lepton $p_T$ thresholds of (14, 14) GeV and (25, 8) GeV, and two dimuon triggers with the $p_T$ thresholds of (14, 14) GeV and (18, 8) GeV. Additionally, two electron-muon triggers with $(p_T^e, p_T^\mu) > (14, 8)$ GeV and (8, 18) GeV are used. The dielectron triggers have efficiencies ranging between 85% and 98%, where the lowest efficiency comes from the asymmetric dielectron trigger in the end-cap region. The dimuon triggers have efficiencies ranging between 52% (77%) and 80% (98%) in the barrel (end-caps), where the lowest efficiency trigger comes from the symmetric dimuon trigger. The asymmetric electron-muon triggers have efficiencies ranging between 65% and 82%. All quoted efficiencies have been measured in data with respect to reconstructed leptons with $p_T$ in excess of the nominal thresholds.

Monte Carlo (MC) simulated event samples are used to develop and validate the analysis procedure and to evaluate the SM backgrounds. The predictions for the most relevant SM processes are normalised to the NNLO cross-sections obtained using $\text{DYNNLO}$ and $\text{MCFM}$ and $\text{POWHEG}$ for $W$ and $Z$ production. Production of $t\bar{t}$ is simulated with $\text{MADGRAPH}$ plus $\text{PYTHIA}$ and $\text{HERWIG}$ is simulated with $\text{GEANT4}$ based detector simulation [43–45]. The effect of multiple proton-proton collisions from the same or different bunch crossings is incorporated into the simulation by overlaying minimum bias events onto hard scatter events using $\text{PYTHIA}$ [46]. Simulated events are weighted to match the distribution of the number of interactions per bunch crossing observed in data.

The dominant SM background processes include $WW \rightarrow \ell\nu\ell\nu$, $t\bar{t}$, single-top, and $ZV$ where $V = W$ or $Z$. Production of top quark pairs is simulated with $\text{MC@NLO}$ [47–49] using a top-quark mass of 172.5 GeV. Additional samples generated with $\text{POWHEG}$ [50] plus $\text{PYTHIA}$ and $\text{ALPGEN}$ [51] plus $\text{HERWIG}$ [52] are used for the evaluation of systematic uncertainties. The $t\bar{t}$ cross-section is normalised to approximate next-to-next-to-leading order (NNLO) calculations [53]. Single top production is modelled with $\text{MC@NLO}$ for $Wt$ and $s$-channel production, and with $\text{AcerMC}$ [54] for $t$-channel production. Samples of $W \rightarrow \ell\nu$ and $Z/\gamma^* \rightarrow \ell\ell$ produced with accompanying jets (including light and heavy flavours) are obtained with a combination of $\text{SHERPA}$ [55] and $\text{ALPGEN}$. The inclusive $W$ and $Z/\gamma^*$ production cross-sections are normalised to the NNLO cross-sections obtained using $\text{DYNNLO}$ [56]. Diboson ($WW$, $WZ$ and $ZZ$) production is simulated with $\text{POWHEG}$, with additional gluon-gluon contributions simulated with $\text{gg2WW}$ [57] and $\text{gg2ZZ}$ [58]. Additional diboson samples are generated with $\text{SHERPA}$ to assess systematic uncertainties. The diboson cross-sections are normalised using next-to-leading order (NLO) QCD predictions obtained with $\text{MC@NLO}$ [59, 60]. Production of $t\bar{t}$ associated with a vector boson is simulated with the leading-order (LO) generator $\text{HADGRAPH}$ [61] and scaled to the NLO cross-section [62–64]. QCD production of $b\bar{b}$ and $c\bar{c}$ is simulated with $\text{PYTHIA}$. Finally, production of the SM Higgs with $m_H = 125$ GeV around the beam pipe. The pseudorapidity $\eta$ is defined in terms of the polar angle $\theta$ by $\eta = -\ln \tan(\theta/2)$.
through gluon fusion, vector-boson fusion and associated Higgs production (WH and ZH) is considered. The associated production modes are generated with PYTHIA, while POWHEG is used for the others.

Fragmentation and hadronisation for the MC@NLO and ALPGEN samples are performed either with HERWIG using JIMMY [65] for the underlying event, or with PYTHIA. PYTHIA is used for the POWHEG and MADGRAPH samples. The CT10 NLO [66] and CTEQ6L1 [67] parton-distribution function sets are used with the NLO and LO event generators, respectively.

Simulated signal samples are generated with HERWIG++ [68]. Signal cross-sections are calculated at NLO using PROSPINO2 [69].

**Direct-slepton scenario** The direct-slepton models are based on the pMSSM and described in Ref. [70]. The masses of all charginos and neutralinos apart from the $\tilde{\chi}^0_1$ are set to 2.5 TeV. The sensitivity of the present search is determined for models with varying slepton and $\tilde{\chi}_1^0$ masses. The mass of the bino-like $\tilde{\chi}_1^0$ is varied by scanning the gaugino mass parameter $M_1$ in the range 0–200 GeV. The common selectron and smuon mass is generated in the range 90–370 GeV with the constraint $m_{\tilde{t}} \geq m_{\tilde{\chi}^0_1} + 30$ GeV. The cross-section for direct slepton pair production (per slepton flavour) in these models decreases from 127 to 0.5 fb for left-handed sleptons, and from 49 to 0.2 fb for right-handed sleptons, as the slepton mass increases from 90 to 370 GeV.

**Chargino-to-slepton scenario** The chargino-to-slepton decays are simulated in simplified models, in the scenario of charginos decaying into the lightest neutralino via an intermediate on-shell charged slepton, in which the masses of $\tilde{\chi}_1^\pm$, $\tilde{\tau}$, $\tilde{\nu}$ and $\tilde{\chi}_1^0$ are the only free parameters. The squarks are assumed to be well beyond the kinematical reach. The $\tilde{\chi}_1^\pm$ are pair-produced via the s-channel exchange of a virtual gauge boson and decay via left-handed sleptons, including $\tilde{\tau}$ and $\tilde{\nu}$, of mass $m_{\tilde{t}} = m_{\tilde{b}} = (m_{\tilde{\chi}^0_1} + m_{\tilde{\chi}_1^\pm})/2$ with equal branching ratios. The cross-section for $\tilde{\chi}_1^+\tilde{\chi}_1^-\tilde{W}^*$ pair production calculated under the assumption that the chargino is 95% wino-like (with a small higgsino component), is as high as 5 pb for a chargino mass of 100 GeV and decreases rapidly at higher masses, reaching 9 fb at 450 GeV.

**Chargino-to-W scenario** Simulated samples for chargino-to-W decays, where the sleptons are mass decoupled, were also produced with simplified models. The mass grid spans the $m_{\tilde{\chi}_1^\pm}$ vs. $m_{\tilde{\chi}_1^0}$ plane in 10-GeV steps on both axes starting from $(m_{\tilde{\chi}_1^\pm}, m_{\tilde{\chi}_1^0}) = (100, 0)$ GeV (close to the LEP limit [38]) and keeping $m_{\tilde{\chi}_1^\pm} - m_{\tilde{\chi}_1^0} > 80$ GeV. The cross-section used for $\tilde{\chi}_1^\pm\tilde{W}^*$ pair production is the same as for the chargino-to-slepton scenario. The branching ratio of $\tilde{\chi}_1^\pm\rightarrow W^*\tilde{\chi}_1^0$ is assumed to be 100%.

**GMSB model** An additional simplified model sample is generated to probe the GMSB model proposed in Ref. [40]. In this model, the LSP is the gravitino $\tilde{G}$, the NLSP is the chargino with $m_{\tilde{\chi}_1^\pm} = 110$ GeV, and in addition there are two other light neutralinos $m_{\tilde{\chi}_1^0} = 113$ GeV and $m_{\tilde{\chi}_2^0} = 130$ GeV. All coloured sparticles are assumed to be very heavy. Although the $\tilde{\chi}_1^\pm\tilde{W}^*$ production cross-section is not large (~1.4 pb), it is augmented by the $\tilde{\chi}_1^\pm\tilde{\chi}_1^0$ (~2.5 pb), $\tilde{\chi}_1^\pm\tilde{\chi}_2^0$ (~1.0 pb) and $\tilde{\chi}_1^0\tilde{\chi}_2^0$ (~0.5 pb). The $\tilde{\chi}_1^0$ decays 100% into $\tilde{\chi}_1^\pm W^*$, and the $\tilde{\chi}_2^0$ decays either into $\tilde{\chi}_1^\pm W^*\tau^*$ or $\tilde{\chi}_1^0 Z^*$. Because of the small mass differences, the decay products of the off-shell $W$ and $Z$ bosons are unlikely to be detected. As a result, all of the four production channels result in the same experimental signature, and their production cross-sections can be added together for the purpose of this search. Each $\tilde{\chi}_1^\pm$ then decays 100% via $\tilde{\chi}_1^\pm \rightarrow W^*\tilde{G}$, and leptonic decays of the two the on-shell $W$ bosons produce the same final-state as in the chargino-to-W scenario above.
4 Event Selection

Events are selected in which at least five charged tracks are associated to the primary vertex. If there are multiple primary vertices in an event, the one with the largest $\sum p_T^2$ of the associated tracks is chosen. In each event, “candidate” electrons, muons, and jets are constructed. After removing potential overlaps between these objects, the criteria to define “signal” electrons, muons, and jets are refined.

Electron candidates are reconstructed by matching clusters in the EM calorimeter with charged tracks in the ID. They are required to have $p_T > 10$ GeV, $|\eta| < 2.47$, and pass the “medium” shower-shape and track-selection criteria defined in Ref. [71].

Muon candidates are reconstructed by matching a muon spectrometer track to an ID track. They are then required to have $p_T > 10$ GeV and $|\eta| < 2.4$. They must be reconstructed with sufficient hits in the pixel, SCT and TRT detectors.

Jet candidates are reconstructed using the anti-$k_T$ jet clustering algorithm [72, 73] with a distance parameter of 0.4. The jet candidates are corrected for the effects of calorimeter non-compensation and inhomogeneities by using $p_T$ and $\eta$-dependent calibration factors based on MC simulation and validated with extensive test-beam and collision-data studies [74]. Only jet candidates with $p_T > 20$ GeV and $|\eta| < 4.5$ are subsequently retained. Events containing jets that are likely to have arisen from detector noise or cosmic rays are removed [74].

Object overlaps are defined in terms of $\Delta R = \sqrt{(\Delta \eta)^2 + (\Delta \phi)^2}$, where $\Delta \eta$ and $\Delta \phi$ are separations in $\eta$ and $\phi$. Objects are systematically removed so that no two lepton candidates are within $\Delta R = 0.1$ of each other (except for two muons for which the threshold is 0.05) and no lepton is within $\Delta R = 0.4$ of a jet.

Signal electrons must pass the “tight” criteria [71] placed on the ratio of calorimetric energy to track momentum, and the number of high-threshold hits in the TRT. They are also required to be isolated within the tracking volume and the calorimeter. The $p_T$ sum of tracks above 400 MeV within a cone of size $\Delta R = 0.3$ around each electron candidate (excluding the electron candidate itself) is required to be less than 16% of the electron $p_T$. The transverse energies of the surrounding topological clusters within $\Delta R = 0.3$ of each electron candidate, corrected for deposition of energy from pile-up events, is required to be less than 18% of the electron transverse energy. The distance of closest approach of an electron candidate to the event primary vertex must be within five standard deviations in the transverse plane. The distance along the beam direction, $z_0$, must satisfy $|z_0| \sin \theta < 0.4$ mm.

Signal muons must also be isolated: the $p_T$ sum of tracks above 1 GeV within a cone of size $\Delta R = 0.3$ around the muon candidate is required to be less than 12% of the muon $p_T$. The closest approach of a muon candidate to the event primary vertex must be within three standard deviations in the transverse plane, and $|z_0| \sin \theta < 1$ mm along the beam direction.

A $b$-tagging algorithm [75], which exploits the long lifetime of $b$- and $c$-hadron decays inside a candidate jet, is used to identify jets containing a $b$-hadron decay. The mean nominal $b$-tagging efficiency, determined from $t\bar{t}$ MC events, is 80%, with a misidentification (mis-tag) rate for light-quark/gluon jets of less than 1%. Scale factors (which depend on $p_T$ and $\eta$) are applied to all MC samples to correct for small differences in the $b$-tagging performance observed between data and simulation.

Signal jets are classified in three exclusive categories: a jet fulfilling any of these categories is considered to be a signal jet. Central $b$-jets satisfy $|\eta| < 2.4$ and are identified as $b$-jets by the $b$-tagging algorithm. Central light-flavour jets also satisfy $|\eta| < 2.4$ but do not satisfy the $b$-jet identification criteria. If a central light-flavour jet has $p_T < 50$ GeV and has charged tracks associated to it, at least one of the tracks must originate from the event primary vertex. This criterion removes jets that originated in pile-up collisions. Finally, forward jets are those with $2.4 < |\eta| < 4.5$ and $p_T > 30$ GeV.

Having selected signal electrons, muons and jets, exactly two signal leptons of opposite charge and no signal jets of any category in the selected events are required. The two signal leptons are required to have triggered the event, and their $p_T$ must be above the efficiency plateau threshold of the corresponding
trigger. The dilepton invariant mass $m_{\ell\ell}$ must be greater than 20 GeV in all flavour combinations. Events with one or more jets will be used in defining the $t\bar{t}$ control regions, described in Section 6.1.

The measurement of the missing transverse momentum two-vector, $p_T^\text{miss}$, and its magnitude, $E_T^\text{miss}$, is based on the transverse momenta of all electron and muon candidates, all jets, and all clusters of calorimeter energy with $|\eta| < 4.9$ not associated to such objects. The quantity $E_T^\text{miss,rel.}$ is defined as:

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

where $\Delta\phi_{\ell,j}$ is the azimuthal angle between the direction of $p_T^\text{miss}$ and that of the nearest electron, muon, central $b$-jet or central light-flavour jet. In a situation where the momentum of one of the jets or leptons is significantly mis-measured, such that it is aligned with the direction of $p_T^\text{miss}$, only the $E_T^\text{miss}$ component perpendicular to that object is considered. This is used to significantly reduce mis-measured $E_T^\text{miss}$ in processes such as $Z/\gamma^* \rightarrow \ell^+\ell^−[76]$.

The “stransverse” mass variable $m_{T2}$ [77,78] is defined as:

$$m_{T2} = \min_{q_T} \left[ \max \left( m_T(p_T^{\ell1},q_T), m_T(p_T^{\ell2},p_T^\text{miss} − q_T) \right) \right],$$

where $p_T^{\ell1}$ and $p_T^{\ell2}$ are the transverse momenta of the two leptons, and $q_T$ is a transverse vector that minimises the larger of the two transverse masses $m_T$. The latter is defined by

$$m_T(p_T,q_T) = \sqrt{2(p_Tq_T − p_T \cdot q_T)}.$$

For $t\bar{t}$ and WW events, in which two on-shell $W$ bosons decayed leptonically and $p_T^\text{miss}$ is the sum of two neutrinos, the $m_{T2}$ distribution has an upper end-point at the $W$ mass. For large mass differences between the sleptons (charginos) and the lightest neutralino, the $m_{T2}$ distribution for signal events extends significantly beyond the distributions of the $t\bar{t}$ and WW events and so the end-point of this function contains information about this mass difference; additional missing momentum due to the LSPs also contributes to the $m_{T2}$ distribution.

## 5 Signal Regions

Five signal regions (SRs) are defined in this analysis. The first two, referred to as SR-$m_{T2,90}$ and SR-$m_{T2,110}$, are designed to provide sensitivity to sleptons either through direct production or in chargino decays. The other three, SR-WWa, SR-WWb and SR-WWc, are designed to provide sensitivity to chargino- and neutralino-pair production followed by on-shell $W$ decays. Table 1 summarises the definitions of the SRs.

### 5.1 SR-$m_{T2}$

In SR-$m_{T2}$, the properties of $m_{T2}$ are exploited to search for $\tilde{\ell}^+\tilde{\ell}^−$ and $\tilde{\chi}^+_1\tilde{\chi}^0_1$ production followed by decay to final states containing exactly two opposite-sign leptons, no signal jets, and missing transverse momentum. Only same-flavour channels ($e^+e^−$ and $\mu^+\mu^−$) are used in the search for direct slepton production, while the chargino-to-slepton decay search also uses $e^\pm\mu^\mp$. Their invariant mass $m_{\ell\ell}$ must be at least 10 GeV from the nominal $Z$ boson mass to reduce the background from $Z$ decays. Results from different channels are statistically combined through a maximum-likelihood fit.

In this signal region, WW, ZV, and $t\bar{t}$ are dominant sources of background. For large mass differences between the sleptons (charginos) and the lightest neutralino, the $m_{T2}$ distribution for signal events extends beyond the distributions for $t\bar{t}$ and diboson backgrounds, since the neutralinos can be significantly more
Table 1: Signal region definitions of events satisfying the selection of Section 4. ‘Z veto’ refers to $|m_{ℓℓ} - m_Z| > 10$ GeV.

<table>
<thead>
<tr>
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<td>$p_T^\ell_2$</td>
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<tr>
<td>$m_{ℓℓ}$</td>
<td>$Z$ veto</td>
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<td>$&gt; 90$ GeV</td>
<td>$&gt; 110$ GeV</td>
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<tr>
<td>$m_{T2}$</td>
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boosted than the neutrinos from the background sources. Two different requirements, $m_{T2} > 90$ GeV and $m_{T2} > 110$ GeV, are defined for SR-$m_{T2,90}$ and SR-$m_{T2,110}$, respectively. The former provides a better sensitivity to cases in which the slepton or chargino mass is close to the LSP mass, and the latter has a better coverage at larger slepton/chargino-LSP mass differences.

Figure 1 shows the distributions of $E_T^{\text{miss,rel}}$ and $m_{T2}$ satisfying the event selection of Section 4, and requiring $E_T^{\text{miss,rel}} > 40$ GeV and the $Z$ veto. Good agreement between data and Monte Carlo is observed for all variables and samples.

5.2 SR-WW

Three signal regions, SR-WWa, SR-WWb and SR-WWc, are designed to provide sensitivities to direct chargino and neutralino production with $\tilde{χ}_1^± → W^± + \tilde{χ}_1^0$ in three different areas of the $m_{\tilde{χ}_1^±}$ vs. $m_{\tilde{χ}_1^0}$ plane. Only the $e^±μ^±$ combinations are used in these signal regions.

Since the signal is assumed to produce a pair of on-shell $W$ bosons, the signal-to-background ratio can be improved by requiring larger lepton $p_T$ without large loss in acceptance. This would not be the case in the slepton scenarios with small slepton-neutralino mass differences or if the $W$ boson is off-shell. The leading lepton is required to have $p_T > 35$ GeV and the other lepton to have $p_T > 20$ GeV.

Figure 2 shows the data to Monte Carlo agreement in the distributions of $m_{T2}$, $E_T^{\text{miss,rel}}$, $m_{T2}$ and $p_{T,ℓℓ}$ (the transverse momentum of the dilepton system) after the selection described in Section 4 and the additional requirements on the the lepton $p_T$. The four variables are used to define the three signal regions.

The first region, SR-WWa, is designed for scenarios in which either the chargino mass is small ($m_{\tilde{χ}_1^±} < 120$ GeV) or the $W$ boson is produced close to the threshold ($m_W < m_{\tilde{χ}_1^±} - m_{\tilde{χ}_1^0} < 100$ GeV). In this signal region, $E_T^{\text{miss,rel}} > 70$ GeV and $p_{T,ℓℓ} > 70$ GeV are required. These thresholds are found to be optimal to reject SM $WW$ production efficiently while retaining SUSY signal events, characterised by larger transverse momentum of the LSPs. The sensitivity is further increased by requiring $m_{ℓℓ} < 80$ GeV, and the opening angle between the two leptons in the transverse plane $\Delta φ_{ℓℓ}$ to be smaller than 1.8 radians.

The second and third regions, SR-WWb and SR-WWc, are sensitive to larger chargino masses ($m_{\tilde{χ}_1^±} > 120$ GeV), and larger boost of the $W$ boson ($m_{\tilde{χ}_1^±} - m_{\tilde{χ}_1^0} > 100$ GeV). These regions rely on the $m_{T2}$ variable, which is required to be greater than 90 GeV and 100 GeV in SR-WWb and SR-WWc, respectively. Also required are $p_{T,ℓℓ} < 170$ GeV and $< 190$ GeV in SR-WWb and SR-WWc, respectively. The differences in the thresholds make SR-WWc more sensitive to larger chargino masses and larger $W$ boost than SR-WWb. For SR-WWb, $m_{ℓℓ} < 130$ GeV is also required. Finally, the same $Δφ_{ℓℓ} < 1.8$ rad cut as SR-WWa is applied to both signal regions.
Figure 1: Distributions of $E_T^{\text{miss,rel}}$ (left) and $m_{T2}$ (right) in the $e^+e^-$ (top), $\mu^+\mu^-$ (middle) and $e^+\mu^\pm$ (bottom) event samples satisfying the event selection of Section 4, as well as $E_T^{\text{miss,rel}} > 40$ GeV, and the $Z$ veto. The expected distributions from the WW, $t\bar{t}$ and $ZV$ processes are corrected with data-driven scale factors obtained in Section 6. The hashed regions represent the total uncertainties on the background estimates. The right-most bin of each plot includes overflow. Illustrative SUSY benchmark models are super-imposed.
6 Standard Model Background Estimation

After requiring two opposite-sign leptons and no jets, the SM background is dominated by events with two leptonically-decaying $W$ bosons coming from $WW$ diboson and top production. Another significant source of background, in the same-flavour channel, is $ZV$ production. The background from $Z + \text{jets}$ was found to be negligible in all signal regions.

6.1 WW, top and ZV background estimation

The background contributions from top and $WW$ are estimated by defining dedicated control regions (CR) for each background. Similarly, $ZV$ is estimated by defining control regions in the same-flavour channel. Each control region is dominated by one of the three processes and is designed to be kinematic-
Table 2: Control region definitions of events satisfying the selection of Section 4. ‘Z veto’ and ‘Z select’ refer to $|m_{\ell \ell} - m_Z| > 10$ GeV and $< 10$ GeV, respectively.

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<td>&gt; 90 GeV</td>
<td>&gt; 110 GeV</td>
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Table 2: Control region definitions of events satisfying the selection of Section 4. ‘Z veto’ and ‘Z select’ refer to $|m_{\ell \ell} - m_Z| > 10$ GeV and $< 10$ GeV, respectively.

The $WW$ control region for SR-$m_{T^2}$ is defined by requiring $E^\text{miss,rel}_T > 40$ GeV and $50 < m_{T^2} < 90$ GeV. The events must also pass the Z veto and contain no jets. Only the $e^\pm \mu^\mp$ sample is used in this CR because the corresponding regions in the $e^+e^-$ and $\mu^+\mu^-$ samples suffer from contamination from $Z/\gamma^* +$ jets background. The $e^+e^-$ and $\mu^+\mu^-$ components are therefore evaluated using the $e^\pm \mu^\mp$ CR, with appropriate ratios of electron and muon efficiencies. The contamination due to non-$WW$ sources in this CR is dominated by the top (13%) and ZV (3%) events, both of which are corrected by the scale factors.
Figure 3: Distributions of (a) $E_{T}^\text{miss,rel}$ and (b) $m_{T2}$ in the WW CR for SR-$m_{T2}$, (c) $E_{T}^\text{miss,rel}$ in the WW CR for SR-WWa, and (d) $m_{T2}$ in the WW CR for SR-WWb/c. No data-driven scale factor is applied to the SM distributions. The hashed regions represent the total uncertainties on the background estimates. The right-most bin of (a) includes overflow. Illustrative SUSY benchmark models are super-imposed.

determined from the respective CRs. The scale factor is 1.12 ± 0.14, where the error includes statistical and systematic uncertainties. Details on the systematic errors are provided in Section 7. The scale factor value is consistent with observations in other similar analyses [79]. For SR-WWa, the CR is defined by inverting the $E_{T}^\text{miss,rel}$ requirement so that $E_{T}^\text{miss,rel} < 70$ GeV, and relaxing the other criteria except for $\Delta \phi_{tl} < 1.8$ rad. For SR-WWb/c, the $m_{T2}$ cut is inverted to $m_{T2} < 90$ GeV and the $p_{T,tl}$ and $m_{tl}$ cuts are removed. The $\Delta \phi_{tl} < 1.8$ rad cut is still applied. The estimated WW background is larger than the MC prediction by factors of 1.16–1.19 depending on the SR, with total relative uncertainties of 6–8%. Contamination from the signal model $\chi_{1\pm}^{\pm} \rightarrow W^{\pm} W^{\mp} \chi_{14}^{0}\chi_{14}^{0}$ with $m_{\chi_{1\pm}} > 100$ GeV in this CR is less than 10%. Figure 3 shows the $E_{T}^\text{miss,rel}$ and $m_{T2}$ distributions in the WW CRs.

The combined contribution from $t\bar{t}$ and single top events in the signal region is evaluated by normalising MC simulation to data in an appropriate control region. For SR-$m_{T2}$, the CR is defined using the $e^{\pm}\mu^{\mp}$ sample, which suffers from less $Z/\gamma^{*}$ + jets background than the $e^{+}e^{-}$ and $\mu^{+}\mu^{-}$ samples, and by requiring at least two signal jets, one of which must be $b$-tagged. The events must also satisfy $E_{T}^\text{miss,rel} > 40$ GeV and the Z veto, but the $m_{T2}$ criteria are not applied. The resulting CR is dominated by
Figure 4: Distributions of (a) $m_{T2}$ in the top CR for SR-\(m_{T2}\), (b) $p_{T,\ell\ell}$ and (c) $E^{\text{miss,rel}}_T$ in the top CR for SR-WWa, (d) $m_{T2}$ in the top CR for SR-WWb. No data-driven scale factor is applied to the SM distributions. The hashed regions represent the total uncertainties on the background estimates. The right-most bin of each plot includes overflow. Illustrative SUSY benchmark models are super-imposed.

top events. The contamination from non-top events is about 2% for the $e^+\mu^-$ channel. The contamination from SUSY signal is negligible for the models considered. The scale factor is $1.05 \pm 0.05$ where the error includes systematic uncertainties. For SR-WW, the CRs are defined by requiring at least one $b$-tagged jet, with all the other criteria unchanged. The contamination from non-top events is 1% or less, and the contamination from SUSY signal is negligible. The scale factors range from 0.98 to 1.07 with total relative uncertainties between 4% and 13%. Figure 4 shows the $m_{T2}$, $p_{T,\ell\ell}$ and $E^{\text{miss,rel}}_T$ distributions in the top CRs.

In the same-flavour channels, the $ZV$ background is significant, and a dedicated CR is designed for its estimation. The CR is defined to be identical to SR-\(m_{T2}\) but with the $Z$ veto reversed. The population of data events inside the CR not produced by $ZV$ processes is estimated using data $e\mu$ events inside the $Z$-window, correcting for the differences between electron and muon reconstruction efficiencies. The estimated $ZV$ background is consistent within statistics with the MC prediction, with scale factors ranging from 0.96 to 1.06 with total relative uncertainties ranging from 15% to 16%. Figure 5 shows the $E^{\text{miss,rel}}_T$
distribution in the ZV CR.  

6.2 Fake lepton background estimation

The term “fake leptons” refers to hadronic jets mistakenly reconstructed as signal leptons or real leptons originating from heavy-flavour decays or photon conversions. The number of fake lepton events is estimated using the “matrix method” [80], which takes advantage of the difference between the candidate and signal leptons defined in Section 4. Recall that the candidate leptons are selected with a looser lepton identification with no isolation requirements. The “real” and “fake” efficiencies are defined as the fraction of real and fake leptons, respectively, that pass the signal-lepton requirements. The real and fake efficiencies are evaluated in simulated events with $E_{T,\text{rel}}^{\text{miss}} > 40$ GeV using the Monte-Carlo truth information, and corrected for differences between data and MC in separate control samples. The correction for the real efficiency $r$ is derived from $Z \to \ell\ell$ events. The control sample for the fake efficiency $f$ for misidentified jets or leptons from hadron decays consists of events with two candidate leptons, one $b$-tagged jet and $E_{T,\text{rel}}^{\text{miss}} < 40$ GeV. One of the two leptons is required to be a muon and to lie within $\Delta R = 0.4$ of the $b$-tagged jet, and the other lepton is used to measure the fake efficiency. For measuring the fake efficiency for conversions, a $Z + \gamma$ control sample is defined by selecting events with two muons consistent with $Z \to \mu\mu$, $E_{T,\text{rel}}^{\text{miss}} < 50$ GeV and at least one candidate electron (which is the conversion candidate) with $m_T < 40$ GeV.

The overall $f$ is the weighted average of these two fake efficiencies, according to the relative proportions of each component present in the SR. The number of fake leptons in each SR is obtained by multiplying the observed number of candidate and signal leptons with a $4 \times 4$ matrix with terms containing the $f$ and $r$ that relates real and fake leptons to their level of identification. The fake-lepton estimates also include uncertainties related to their dependence on $E_{T,\text{rel}}^{\text{miss}}$ and pseudorapidity and as well as uncertainties on the composition of events in each region. The impact of fake-lepton background in the signal regions is very small as shown in Tables 4 and 5.
Table 3: Systematic uncertainties (in %) on the total background estimated in SR-$m_{T2}$ and SR-WW. Because of correlations between the systematic uncertainties and the fitted backgrounds, the total uncertainty can be smaller than the quadratic sum of the individual uncertainties.

<table>
<thead>
<tr>
<th>Source</th>
<th>SR-$m_{T2,90}$</th>
<th>SR-$m_{T2,110}$</th>
<th>SR-WW ($e^+\mu^-$)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$e^+e^-$</td>
<td>$\mu^+\mu^-$</td>
<td>$e^+\mu^-$</td>
</tr>
<tr>
<td>MC statistics</td>
<td>7.7</td>
<td>6.1</td>
<td>7.5</td>
</tr>
<tr>
<td>Jet</td>
<td>9.5</td>
<td>17</td>
<td>12</td>
</tr>
<tr>
<td>Lepton</td>
<td>3.9</td>
<td>0.5</td>
<td>4.8</td>
</tr>
<tr>
<td>Soft term</td>
<td>1.9</td>
<td>3.2</td>
<td>6.0</td>
</tr>
<tr>
<td>$b$-tagging</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
</tr>
<tr>
<td>Fake lepton</td>
<td>1.0</td>
<td>0.7</td>
<td>0.6</td>
</tr>
<tr>
<td>Luminosity</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Theory &amp; modelling</td>
<td>9.7</td>
<td>9.4</td>
<td>11</td>
</tr>
<tr>
<td>Total</td>
<td>14</td>
<td>15</td>
<td>16</td>
</tr>
</tbody>
</table>

6.3 Fitting procedure

For each signal region, a simultaneous likelihood fit [81] to the signal regions and the control regions is performed to normalise the top, WW and ZV (in the case of SR-$m_{T2}$ only) background estimates and to determine or limit a potential signal contribution. The inputs to the fit are:

- For each control region, the observed number of events in the top, WW and ZV and the expected background estimate from simulation.
- The expected background in the signal regions for all processes determined from simulation.
- The fake-lepton background estimate in the signal regions as described in Section 6.2.

The event count in each control and signal region is treated with a Poisson probability density function. The systematic uncertainties on the expected background yields are included as nuisance parameters, constrained to be Gaussian with a width determined from the size of the uncertainty. Correlations in the nuisance parameters between the control and signal regions, and background processes are taken into account. The Poisson probability density function also includes free parameters to scale the expected contribution from top, WW and, where relevant, ZV in the control regions. A likelihood is formed as the product of these probability density functions and the constraints on the nuisance parameters. The free parameters and the nuisance parameters are adjusted to maximise the likelihood.

7 Systematic Uncertainties

Systematic uncertainties have an impact on the estimates of the backgrounds and signal event yields in the control and signal regions. The relative sizes of these sources of systematic uncertainty in SR-$m_{T2}$ and SR-WW are detailed in Table 3.

The ‘MC statistics’ uncertainties arise from the limited number of simulated events in the signal and control regions. The largest contributions are due to the simulated background samples in the signal regions.

The dominant experimental systematic uncertainties, labelled ‘jet’ in Table 3, come from the propagation of the jet energy scale calibration [82–87] and resolution [88] uncertainties. The ‘lepton’ uncertainties include lepton reconstruction, identification and trigger efficiencies, as well as lepton energy and momentum measurements [71, 89–91]. Jet and lepton energy scale uncertainties are propagated to the
$E_T^{\text{miss}}$ evaluation. An additional ‘soft term’ uncertainty is associated with energy deposits not assigned to any reconstructed objects. The ‘$b$-tagging’ row refers to the uncertainties on the $b$-jet identification efficiency and charm and light-flavour jet rejection factors [92]. The ‘fake lepton’ uncertainties arise from the data-driven estimates of the fake-lepton background described in Section 6.2. The dominant sources are $E_T^{\text{miss,rel}}$ and $\eta$ dependences of the fake rates, difference between the light and heavy flavour jets, and the statistics of the control samples. The uncertainty on the integrated luminosity is $\pm 2.8\%$. It is derived, following the same methodology as that detailed in Ref. [93], from a preliminary calibration of the luminosity scale derived from beam-separation scans performed in November 2012.

Generator modelling uncertainties are obtained by comparing the results from POWHEG plus HERWIG to MC@NLO generators for top events, and POWHEG to SHERPA for diboson events. Parton showering uncertainties are extracted in top events by comparing POWHEG plus HERWIG with POWHEG plus PYTHIA. Special $\bar{t}t$ samples are generated using AcerMC with PYTHIA to evaluate the uncertainties related to the amount of initial and final-state radiation. The effects of all these uncertainties are summarised in the "theory & modelling" field of Table 3. The dominant contribution comes from the difference between POWHEG and SHERPA for diboson production.

Signal cross sections are calculated to NLO in the strong coupling constant. Their uncertainties are taken from an envelope of cross section predictions using different PDF sets and factorisation and renormalisation scales, as described in Ref. [94].

8 Results

Figures 6 and 7 show the comparison between data and the SM prediction for key kinematical variables in different signal regions. Tables 4 and 5 compare the observed yields in each signal region with those predicted for the SM background. Good agreement is observed across all channels.

Limits are set on the visible cross-section for possible non-SM processes in each channel, $\sigma_{\text{vis}} = \sigma \cdot \epsilon \cdot A$, where $A$ and $\epsilon$ are the analysis acceptance and efficiency, respectively. Upper limits are calculated at 95% confidence level (CL) using the modified frequentist CL$_s$ prescription [95] by comparing the number of observed events in data with the SM expectation using the profile likelihood ratio as test statistic. All systematic uncertainties and their correlations are taken into account via nuisance parameters.

9 Interpretation

In the absence of an excess over the SM background expectations, 95% confidence-level exclusion limits are set on the slepton, chargino and neutralino masses within the specific scenarios considered. Since the SRs are not mutually exclusive, the SR with the best expected exclusion limit is chosen for each model point.

Direct slepton scenario Figure 8 shows 95% CL exclusion regions for the direct production of right-handed (a), left-handed (b), and both right- and left-handed (c) selectrons and smuons of equal mass in the $m_{\tilde{e}_1} - m_{\tilde{\ell}}$ plane obtained from the $e^+e^-$ and $\mu^+\mu^-$ channels of SR-$m_{T2,90}$ and SR-$m_{T2,110}$. Each plot shows the 95% CL$_s$ expected (dashed black) and observed (solid red) limits, including all uncertainties except the theoretical uncertainty on the signal cross section. The solid yellow band indicates the impact of experimental uncertainties on the expected limits whereas the dashed red lines around the observed limit show the changes in the observed limit as the signal cross-sections are scaled up and down by the 1$\sigma$ theoretical uncertainties. A common value for left and right-handed selectron and smuon mass between 90 GeV and 320 GeV is excluded for a massless neutralino, where these numbers correspond to the observed value minus the signal theoretical uncertainty. The sensitivity decreases as the value of
Figure 6: Distributions of (a) $m_{ll}$ and (b) $E_T^{miss,rel}$ in SR-WWa, and $m_{T2}$ in (c) SR-WWb and (d) SR-WWc. The expected distributions from the $WW$ and $t\bar{t}$ processes are corrected with data-driven scale factors obtained in Section 6. The hashed regions represent the sum of systematic and statistical uncertainties arising from limited numbers of MC events. The effect of limited data events in the CR is included in the systematic uncertainty. The component $ZV$ includes the contributions from $WZ$ and $ZZ$ events. All statistical uncertainties are added in quadrature whereas the systematic uncertainties are obtained after taking full account of all correlations between sources, backgrounds and channels. The right-most bin of (b) includes overflow. Illustrative SUSY benchmark models are super-imposed.

$m_{\tilde{t}} - m_{\tilde{\chi}_1^0}$ decreases, which in turn lowers the $m_{T2}$ end point towards that of the SM backgrounds. For a 100 GeV neutralino, sleptons with masses between 160 GeV and 320 GeV are excluded. The present result cannot be directly compared with the previous ATLAS slepton limits in Ref. [35] which used a flavour-blind signal region and searched for a single-slepton flavour with both right-handed and left-handed contributions.

Chargino-to-slepotn scenario The direct $\tilde{\chi}^+_1$ pair production limits are set for the simplified model. The resulting limit for $\tilde{\chi}^+_1\tilde{\chi}^-_1$ production is illustrated in Fig. 8 (d). Chargino masses between 130 GeV and 450 GeV are excluded at 95% CL for a 20 GeV neutralino.
Figure 7: Distributions of $E_{T}^{\text{miss,rel}}$ in the di-electron (a), di-muon (b), electron-muon (c) in SR-$m_{T2}>90$. The expected distributions from the $WW$, $t\bar{t}$ and $ZV$ processes are corrected with data-driven scale factors obtained in Section 6. The hashed regions represent the sum of systematic and statistical uncertainties arising from limited numbers of MC events. The effect of limited data events in the CR is included in the systematic uncertainty. The component $ZV$ includes the contributions from $WZ$ and $ZZ$ events. All statistical uncertainties are added in quadrature whereas the systematic uncertainties are obtained after taking full account of all correlations between sources, backgrounds and channels. The right-most bin of each plot includes overflow. Illustrative SUSY benchmark models are super-imposed.

Chargino-to-$W$ scenario The 95% CL limits on the cross-section with respect to the simplified-model cross-section with bino-like $\tilde{\chi}_{1}^{0}$ and wino-like $\tilde{\chi}_{1}^{\pm}$ are presented in the $m_{\tilde{\chi}_{1}^{0}}-m_{\tilde{\chi}_{1}^{\pm}}$ plane in Figure 9 (a) and (b) for the signal region best contributing to the limit. The most sensitive region is $140 \leq m_{\tilde{\chi}_{1}^{0}} \leq 210$ GeV and $0 \leq m_{\tilde{\chi}_{1}^{\pm}} \leq 40$ GeV where an average observed (expected) 95% CL exclusion limit for $\sigma/\sigma_{\text{SUSY}}$ of 2.5 (2.0) is obtained. In this region, the $\tilde{\chi}_{1}^{\pm}$ cross section is still high (0.3–1.2 pb) and the $W$ bosons are boosted and therefore distinguishable from the $WW$ background. Figure 9 (c) shows the observed and expected 95% CL$_{s}$ upper limits on the cross section as a function of $m_{\tilde{\chi}_{1}^{\pm}}$ for a massless $\tilde{\chi}_{1}^{0}$, normalised to the model cross-section. The SRs with the smallest expected exclusion cross-section are SR-$WWa$ for $m_{\tilde{\chi}_{1}^{\pm}} = 100$ GeV, SR-$WWb$ for 110–160 GeV and SR-$WWc$ for 170–250 GeV. The
Table 4: Observed and expected numbers of events in regions SR-\(m_{T2,90}\) and SR-\(m_{T2,110}\) separated by lepton flavour. The first two rows of the signal expectation are direct slepton production with degenerate left- and right-handed sleptons masses, and the last two rows are chargino production with intermediate sleptons and sneutrinos. Also shown are the observed and expected 95% CL upper limits on the visible cross-section, \(\sigma_{\text{vis}}^{95}\), for non-SM events.

| SR-\(m_{T2,90}\) | \(e^+e^-\) & \(e^\mu^\pm\) & \(\mu^+\mu^-\) & all |
|---|---|---|---|---|
| Observed | 15 | 19 | 19 | 53 |
| Background total | \(16.6 \pm 2.3\) & \(20.7 \pm 3.2\) & \(22.4 \pm 3.3\) & \(59.7 \pm 7.3\) |
| WW | \(9.3 \pm 1.6\) & \(14.1 \pm 2.2\) & \(12.6 \pm 2.0\) & \(36.1 \pm 5.1\) |
| ZV (\(V = W\) or \(Z\)) | \(6.3 \pm 1.5\) & \(0.8 \pm 0.3\) & \(7.3 \pm 1.7\) & \(14.4 \pm 3.2\) |
| Top | \(0.9^{+1.1}_{-0.9}\) & \(5.6 \pm 2.1\) & \(2.5 \pm 1.8\) & \(8.9 \pm 3.9\) |
| Higgs | \(0.11 \pm 0.04\) & \(0.19 \pm 0.05\) & \(0.08 \pm 0.04\) & \(0.38 \pm 0.08\) |
| Fake | \(0.00^{+0.18}_{-0.00}\) & \(0.00^{+0.14}_{-0.00}\) & \(0.00^{+0.15}_{-0.00}\) & \(0.00^{+0.28}_{-0.00}\) |

Signal expectation

\((m_{\tilde{e}}, m_{\tilde{\chi}_1^0}) = (191, 90)\) GeV

\(21.6\) & \(0\) & \(21.6\) & \(43.2\)

\((m_{\tilde{e}}, m_{\tilde{\chi}_1^0}) = (251, 10)\) GeV

\(12.2\) & \(0\) & \(12.5\) & \(24.7\)

\((m_{\tilde{\chi}_1^+, m_{\tilde{\chi}_1^0}}) = (350, 0)\) GeV

\(11.7\) & \(16.6\) & \(10.5\) & \(38.8\)

\((m_{\tilde{\chi}_1^+, m_{\tilde{\chi}_1^0}}) = (425, 75)\) GeV

\(4.3\) & \(6.7\) & \(4.4\) & \(15.4\)

Observed \(\sigma_{\text{vis}}^{95}\) (fb) | \(0.44\) & \(0.51\) & \(0.47\) & \(0.81\)

Expected \(\sigma_{\text{vis}}^{95}\) (fb) | \(0.50^{+0.22}_{-0.15}\) & \(0.57^{+0.25}_{-0.17}\) & \(0.58^{+0.25}_{-0.17}\) & \(1.00^{+0.41}_{-0.38}\)

| SR-\(m_{T2,110}\) | \(e^+e^-\) & \(e^\mu^\pm\) & \(\mu^+\mu^-\) & all |
|---|---|---|---|---|
| Observed | 4 | 5 | 4 | 13 |
| Background total | \(6.1 \pm 2.2\) & \(4.4 \pm 2.0\) & \(6.3 \pm 2.4\) & \(16.9 \pm 6.0\) |
| WW | \(2.7 \pm 1.5\) & \(3.6 \pm 2.0\) & \(2.9 \pm 1.6\) & \(9.1 \pm 4.9\) |
| ZV (\(V = W\) or \(Z\)) | \(2.7 \pm 1.4\) & \(0.2 \pm 0.1\) & \(3.4 \pm 1.8\) & \(6.3 \pm 3.3\) |
| Top | \(0.7 \pm 0.7\) & \(0.6 \pm 0.4\) & \(0.0 \pm 0.0\) & \(1.3 \pm 1.0\) |
| Higgs | \(0.05 \pm 0.03\) & \(0.12 \pm 0.04\) & \(0.05 \pm 0.02\) & \(0.22 \pm 0.05\) |
| Fake | \(0.00^{+0.09}_{-0.00}\) & \(0.00^{+0.13}_{-0.00}\) & \(0.00^{+0.12}_{-0.00}\) & \(0.00^{+0.28}_{-0.00}\) |

Signal expectation

\((m_{\tilde{e}}, m_{\tilde{\chi}_1^0}) = (191, 90)\) GeV

\(12.3\) & \(0\) & \(12.0\) & \(24.3\)

\((m_{\tilde{e}}, m_{\tilde{\chi}_1^0}) = (251, 10)\) GeV

\(10.5\) & \(0\) & \(11.2\) & \(21.7\)

\((m_{\tilde{\chi}_1^+, m_{\tilde{\chi}_1^0}}) = (350, 0)\) GeV

\(9.5\) & \(14.0\) & \(8.7\) & \(32.2\)

\((m_{\tilde{\chi}_1^+, m_{\tilde{\chi}_1^0}}) = (425, 75)\) GeV

\(3.7\) & \(1.1\) & \(3.8\) & \(8.5\)

Observed \(\sigma_{\text{vis}}^{95}\) (fb) | \(0.27\) & \(0.35\) & \(0.28\) & \(0.54\)

Expected \(\sigma_{\text{vis}}^{95}\) (fb) | \(0.33^{+0.16}_{-0.09}\) & \(0.33^{+0.16}_{-0.09}\) & \(0.33^{+0.16}_{-0.10}\) & \(0.62^{+0.23}_{-0.16}\)

excluded cross-section is above the model cross-section by a factor 1.9–2.8 in the range 100–190 GeV and then degrades gradually to 4.7 when reaching a \(\tilde{\chi}_1^\pm\) mass of 250 GeV. The best sensitivity is obtained for the \((m_{\tilde{\chi}_1^+, m_{\tilde{\chi}_1^0}}) = (100, 0)\) GeV mass point where \(\sigma/\sigma_{\text{SUSY}} = 1.79\).

**GMSB model point** The CLs value is also calculated for the GMSB model point where the chargino is the NLSP \([m(\tilde{\chi}_1^\pm) = 110 \text{ GeV}, m(\tilde{\chi}_1^0) = 113 \text{ GeV} \text{ and } m(\tilde{\chi}_2^0) = 130 \text{ GeV}]\) [40]. The observed CLs value is found to be 0.52 using the SR-WWa region, which the most sensitive signal region for this point. The expected and observed 95% CL limit on \(\sigma/\sigma_{\text{SUSY}}\) are 2.6 and 2.9, respectively.
Table 5: Observed and expected numbers of events in SR-WWa, b and c. The first three rows of the signal expectation are simplified models, and the last row is the GMSB model of Ref. [40]. Also shown are the observed and expected 95% CL upper limits on the visible cross-section, $\sigma_{vis}$, for non-SM events. N/A means not applicable.

<table>
<thead>
<tr>
<th></th>
<th>SR-WWa</th>
<th>SR-WWb</th>
<th>SR-WWc</th>
</tr>
</thead>
<tbody>
<tr>
<td>Observed</td>
<td>123</td>
<td>16</td>
<td>9</td>
</tr>
<tr>
<td>Background total</td>
<td>$117.9 \pm 14.6$</td>
<td>$13.6 \pm 2.3$</td>
<td>$7.4 \pm 1.5$</td>
</tr>
<tr>
<td>Top</td>
<td>$15.2 \pm 6.6$</td>
<td>$2.7 \pm 1.1$</td>
<td>$1.0 \pm 0.7$</td>
</tr>
<tr>
<td>WW</td>
<td>$98.6 \pm 14.6$</td>
<td>$10.2 \pm 2.1$</td>
<td>$5.9 \pm 1.3$</td>
</tr>
<tr>
<td>$ZV (V = W$ or $Z)$</td>
<td>$3.4 \pm 0.8$</td>
<td>$0.26^{+0.31}_{-0.26}$</td>
<td>$0.29 \pm 0.14$</td>
</tr>
<tr>
<td>Higgs</td>
<td>$0.76 \pm 0.14$</td>
<td>$0.21 \pm 0.06$</td>
<td>$0.10 \pm 0.04$</td>
</tr>
<tr>
<td>fake</td>
<td>$0.02^{+0.33}_{-0.02}$</td>
<td>$0.26^{+0.30}_{-0.26}$</td>
<td>$0.12^{+0.17}_{-0.12}$</td>
</tr>
<tr>
<td>Signal expectation (m$_{\tilde{\chi}<em>1^\pm}$, m$</em>{\tilde{\chi}_1^0}$) = (100, 0) GeV</td>
<td>31</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>(m$_{\tilde{\chi}<em>1^\pm}$, m$</em>{\tilde{\chi}_1^0}$) = (140, 20) GeV</td>
<td>N/A</td>
<td>8.2</td>
<td>N/A</td>
</tr>
<tr>
<td>(m$_{\tilde{\chi}<em>1^\pm}$, m$</em>{\tilde{\chi}_1^0}$) = (200, 0) GeV</td>
<td>N/A</td>
<td>N/A</td>
<td>3.3</td>
</tr>
<tr>
<td>(m$_{\tilde{\chi}<em>1^\pm}$, m$</em>{\tilde{\chi}_1^0}$) = (110, 113) GeV</td>
<td>18</td>
<td>4.3</td>
<td>N/A</td>
</tr>
<tr>
<td>Observed $\sigma_{vis}$ (fb)</td>
<td>1.94</td>
<td>0.58</td>
<td>0.43</td>
</tr>
<tr>
<td>Expected $\sigma_{vis}$ (fb)</td>
<td>$1.77^{+0.66}_{-0.49}$</td>
<td>$0.51^{+0.21}_{-0.15}$</td>
<td>$0.37^{+0.18}_{-0.11}$</td>
</tr>
</tbody>
</table>

10 Summary

This note presented searches for slepton and chargino pair production in final states with two leptons, missing transverse momentum, and no jets performed using 20.3 fb$^{-1}$ of proton-proton collision data at $\sqrt{s} = 8$ TeV recorded with the ATLAS experiment at the Large Hadron Collider.

No significant excesses over the Standard Model predictions are observed. In scenarios where sleptons decay directly into the lightest neutralino and a charged lepton, a common value for left and right-handed slepton masses between 90 GeV and 320 GeV is excluded at 95% confidence level for a massless neutralino. In the scenario of chargino pair production, with wino-like charginos decaying into the lightest neutralino via an intermediate slepton, chargino masses between 130 GeV and 450 GeV are excluded at 95% confidence level for a 20 GeV neutralino. In the scenario of chargino pair production followed by the $\tilde{\chi}_1^+ \rightarrow W^+ \chi_1^0$ decay, the excluded cross-section is above the model cross-section by a factor 1.9–2.8 in the $\tilde{\chi}_1^+$ mass range 100–190 GeV and then degrades gradually to 4.7 when reaching a $\tilde{\chi}_1^+$ mass of 250 GeV. Best sensitivity is obtained for the $(m_{\tilde{\chi}_1^\pm}, m_{\tilde{\chi}_1^0}) = (100, 0)$ GeV mass point where $\sigma/\sigma_{SUSY} = 1.8$.

In the case of the GMSB model point, the observed 95% CL limit on $\sigma/\sigma_{SUSY}$ is 2.9.

References

Figure 8: 95% CL exclusion limits for (a) right-handed, (b) left-handed, and (c) both right- and left-handed (mass degenerate) selectron and smuon production in the $m_{\tilde{e}}$–$m_{\tilde{\mu}}$ plane. (d) 95% CL exclusion limits for $\tilde{\chi}_1^\pm$ pair production in the simplified model with sleptons and sneutrinos with $m_{\tilde{\chi}_1^\pm} = m_{\tilde{\chi}_1^\pm} = (m_{\tilde{e}_1^\pm} + m_{\tilde{\mu}_1^\pm})/2$. The dashed and solid lines show the 95% CL expected and observed limits, respectively, including all uncertainties except for the theoretical signal cross-section uncertainty (PDF and scale). The solid band around the expected limit shows the ±1σ result where all uncertainties, except those on the signal cross-sections, are considered. The ±1σ lines around the observed limit represent the results obtained when moving the nominal signal cross-section up or down by the ±1σ theoretical uncertainty. Illustrated also are the LEP limits [38] on the mass of the right-handed smuon $\mu_R$ in (a)–(c), and on the mass of the chargino in (d). The blue line in (d) indicates the limit from the previous analysis with the 7 TeV data [35].


Figure 9: Observed (a) and expected (b) 95% CL upper limits of the cross-section obtained from SR-WWa–c for simplified models with bino-like $\tilde{\chi}^0_1$ and wino-like $\tilde{\chi}^\pm_1$ in the $m_{\tilde{\chi}^0_1}$–$m_{\tilde{\chi}^\pm_1}$ plane. (c) Observed and expected 95% CL upper limits of the cross-section as a function of $m_{\tilde{\chi}^\pm_1}$ for massless $\tilde{\chi}^0_1$ normalised to the simplified-model cross-section.


Additional Material

Figure 10: Signal regions contributing to the exclusion limit in the plane of (a) slepton mass and the lightest neutralino mass for combined right-handed selectrons and smuons, (b) slepton mass and the lightest neutralino mass for combined left-handed selectrons and smuons, (c) slepton mass and the lightest neutralino mass for combined left-handed and right-handed selectrons and smuons, and (d) chargino mass and the lightest neutralino mass. The different colors show which signal region, SR-$m_{T2,90}$ or SR-$m_{T2,110}$, has the highest expected sensitivity at a given mass point.
Figure 11: Signal regions contributing to the exclusion limit in the $m_{\tilde{\chi}_0} - m_{\tilde{\chi}_\pm}$ plane. The different colors show which signal region, SR-WWa, SR-WWb or SR-WWc, has the highest expected sensitivity at a given mass point.

Figure 12: Observed (a) and expected (b) CL_s values from SR-WWa–c for simplified models with bino-like $\tilde{\chi}_0^0$ and wino-like $\tilde{\chi}_\pm^1$ in the $m_{\tilde{\chi}_0} - m_{\tilde{\chi}_\pm}$ plane.

<table>
<thead>
<tr>
<th>$(m_\ell, m_{\tilde{\chi}_0})$</th>
<th>(191, 90) GeV</th>
<th>(250, 10) GeV</th>
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<td>55</td>
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<td>54</td>
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<tr>
<td>SR-$m_{T2,110}$</td>
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<td>10.5</td>
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</table>

Table 6: Expected numbers of signal events after each step of the event selection for slepton-pair production benchmark model points, $(m_\ell, m_{\tilde{\chi}_0}) = (191, 90)$ GeV and (250, 10) GeV, with common left- and right-handed slepton masses. A total of 5000 events are generated in each sample. The numbers are scaled to correspond to an integrated luminosity of 20.3 fb$^{-1}$. 27
Figure 13: 95% exclusion limit for the mode with intermediary sleptons in the plane with the chargino mass and the lightest neutralino mass. (Left) The numbers in the plot quote the 95% CL excluded limits on the model cross section in pb. (Right) The number in the plot quote the CL$_s$ value at a given mass point.

Figure 14: 95% exclusion limit for combined right-handed selectrons and smuons. (Left) The numbers in the plot quote the 95% CL excluded limits on the model cross section in fb. (Right) The number in the plot quote the CL$_s$ value at a given mass point.
Figure 15: 95% exclusion limit for combined left-handed selectrons and smuons. (Left) The numbers in the plot quote the 95% CL excluded limits on the model cross section in fb. (Right) The number in the plot quote the CL_s value at a given mass point.

Figure 16: 95% exclusion limit for combined right-handed and left-handed selectrons and smuons. (Left) The numbers in the plot quote the 95% CL excluded limits on the model cross section in fb. (Right) The number in the plot quote the CL_s value at a given mass point.
Table 7: Expected numbers of signal events after each step of the event selection for chargino-pair production with intermediary slepton benchmark model points, \((m_{\tilde{\chi}^\pm_1}, m_{\tilde{\chi}^0_1}) = (350, 0) \text{ GeV} \) and \((425, 75) \text{ GeV} \). A total of 40000 events are generated in each sample. The numbers are scaled to correspond to an integrated luminosity of 20.3 fb\(^{-1}\).

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<td>7</td>
<td>11</td>
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<td>9</td>
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Table 8: Expected numbers of signal events after each step of the event selection for benchmark model points in the SR-WW. The numbers are scaled to correspond to an integrated luminosity of 20.3 fb\(^{-1}\).

The signal models S1, S2 and S3 are chargino-pair production with wino-like \(\tilde{\chi}^+_1\) and bino-like \(\tilde{\chi}^0_1\) with \((m_{\tilde{\chi}^+_1}, m_{\tilde{\chi}^0_1}) = (100, 0) \text{ GeV}, (140, 20) \text{ GeV} \) and \((200, 0) \text{ GeV} \), respectively. The GMSB model has \(m_{\tilde{\chi}^+_1} = 110 \text{ GeV}, m_{\tilde{\chi}^0_1} = 113 \text{ GeV} \), and the LSP is a massless gravitino.