A Search for the Top Squark in the Decay $\tilde{t} \rightarrow b\tilde{\chi}_1^{\pm}$ with the ATLAS Detector

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Abstract

This thesis presents results in the search for a scalar partner of the top quark in an $R$-parity conserving supersymmetric extension of the standard model. The top squark is assumed to decay into a $b$ quark and a chargino, and the chargino is assumed to decay into a neutralino and a $W$ boson. For both decays the branching ratio is set to 100% and the chargino mass is assumed to be equal to twice the neutralino mass, i.e. $M_{\tilde{\chi}^\pm_1} = 2M_{\tilde{\chi}^0_1}$. The search is performed by analyzing the data recorded by the ATLAS detector in 2012, with an integrated luminosity of 20.3 fb$^{-1}$ of proton-proton collisions at a center of mass energy of $\sqrt{s} = 8$ TeV. Two different strategies are presented, starting with a cut and count experiment. This cut based strategy did not have enough sensitivity and resulted in the choice for a shape fit approach. The performance of the shape fit, using the $CL_s$ technique, resulted in an excluded region in the mass grid with the $M_{\tilde{\chi}^\pm_1} = 2M_{\tilde{\chi}^0_1}$ mass hypothesis of $M_{\tilde{\chi}^\pm_1} = 100$ GeV, $M_{\tilde{\chi}^0_1} = 50$ GeV and $240$ GeV $< \mathit{M}_t < 430$ GeV at 95% CL.
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1 Introduction

In particle physics matter is studied at a subatomic level. At this subatomic level there are two types of elementary particles, matter particles which are fermions and force mediators which are bosons. The theory that describes these elementary particles and their interactions is the standard model of particle physics. Even though the standard model is one of the most successful theories in physics, there are a few shortcomings for which various theories that could extend the standard model are proposed.

One of the most promising theories that extends the standard model is supersymmetry. In supersymmetry an additional symmetry is introduced that relates fermions and bosons. Consequently, the number of particles in a supersymmetric theory is doubled as for every fermion there is an additional boson and for every boson there is an additional fermion.

One of the main goals of particle accelerator experiments, like the Large Hadron Collider (LHC), is the observation of new phenomena that could confirm the existence of supersymmetry.

This thesis presents a search for the supersymmetric partner of the top quark using data recorded by the ATLAS detector in 2012, with an integrated luminosity of 20.3 fb\(^{-1}\) of proton-proton collisions at a center of mass energy of \(\sqrt{s} = 8\) TeV. The first sections contain a theoretical introduction, in Section 2 a summary of the standard model of particle physics is given, followed by an introduction to supersymmetry in Section 3. This section introduces the supersymmetric partners of the standard model particles that are under investigation in this analysis.

In Section 4 the LHC and its experiments are described. The subsequent section gives an overview of the ATLAS detector and all its subdetectors. Additionally, in this section the process of reconstructing particles from the measurements done by the various ATLAS subdetectors is explained.

A detailed overview of the analysis is given in Section 6, which introduces the decay mode under investigation and the assumptions that are made in this supersymmetric extension of the standard model. Additionally, this section contains an overview of the relevant standard model backgrounds and a list of preselection criteria that are used to suppress these backgrounds.

Two different strategies are used in this thesis. The first strategy is an based on a cut and count method, for which an optimization procedure is performed. In this cut and count experiment one sided cuts are applied to reduce standard model backgrounds and enhance the signal selection efficiency, after which these signal and background yields are compared. This procedure, including a list of variables with high discriminating power between the signal from supersymmetry and the standard model backgrounds, is given in Section 7.

In order to improve the sensitivity that is reached with the optimization of the cut and count experiment, a shape fit is designed and described in Section 8. In this shape fit a shape comparison is performed between the signal and the background distributions of one variable. The increase in sensitivity for the shape fit is due to the information of the distribution that is lost in the cut and count method when applying a one-sided cut.

Last, the conclusion of the results of this analysis and perspectives are presented in Section 9.
2 The Standard Model of Particle Physics

There are four fundamental forces in nature discovered so far. The standard model of particle physics combines the electromagnetic, the weak and the strong forces in one theory, and describes the dynamics and interactions of elementary particles [1]. An overview of the particles of the standard model is shown in Figure 2.1.

The elementary particles are divided into fermions and bosons. The fermions are the building blocks of matter and consist of three families, or generations, of leptons and quarks. The leptons include the electron, the muon and the tau (e, µ, τ) which carry the elementary charge $-e$. Each of these charged leptons is paired with an additional chargeless neutrino ($\nu_e, \nu_\mu, \nu_\tau$), which carry the same leptonic quantum number.

The quarks are divided in up-type and down-type quarks. The up-type quarks consist of the up, the charm and the top quark (u, c, t) and carry an electric charge of $+\frac{2}{3}e$. The down-type quarks are the down, the strange and the bottom quark (d, s, b) and carry an electric charge of $-\frac{1}{3}e$.

The bosons consist of the vector gauge bosons which are the force carriers, and the scalar Higgs boson. The photon $\gamma$ is the force carrier of the electromagnetic interactions, described by quantum electrodynamics which is explained in Section 2.1. The $W^\pm$ and $Z$ bosons are the mediators of weak interactions and together with electromagnetic interactions are described in the electroweak theory in Section 2.2. The strong interactions are mediated by the gluons and are described by quantum chromodynamics explained in Section 2.4.

Attempts have been made to include interactions with gravity in the standard model which comes with the graviton as additional force carrier, however, these theories have not yet been verified by experiments [2].

Figure 2.1: Summary of the particles in the standard model. The fermions are displayed in the first three columns, where each column represents a different family or generation. The vector bosons are combined in the fourth column and the last column contains the Higgs boson.

2.1 Quantum Electrodynamics

Quantum electrodynamics (QED) is the quantum theory of electromagnetic interactions. This theory describes the interactions between spin-1/2 fermions and are mediated by the photon.
The Dirac Lagrangian, that describes the dynamics of fermions, is given by
\[ \mathcal{L} = \bar{\psi} (i\gamma^\mu \partial_\mu - m) \psi, \] (2.1)
where \( \psi \) is a Dirac spinor, \( \bar{\psi} = \psi^\dagger \gamma^0 \) is the adjoint spinor and \( \gamma^\mu \) (\( \mu = 0, 1, 2, 3 \)) are the Dirac matrices.

The Lagrangian is assumed to be invariant under \( U(1)_{EM} \) transformations, given by the local phase transformation
\[ \psi \rightarrow \psi' = \psi e^{iq\alpha(x)}, \] (2.2)
where \( \alpha(x) \) is a local phase that depends on the space-time coordinates \( x^\mu \) and \( q \) is equal to the electric charge of the fermion.

To keep the Lagrangian invariant under these transformations a covariant derivative \( D_\mu \), that replaces the ordinary derivative \( \partial_\mu \), containing a gauge field \( A^\mu \) is introduced and given by
\[ \partial_\mu \rightarrow D_\mu = \partial_\mu + iqA_\mu(x). \] (2.3)

The simultaneous transformation of both \( \psi \) and \( A^\mu \) follows as
\[ A^\mu \rightarrow A'_\mu = A^\mu - \partial_\mu \alpha(x) \] (2.4)
keeps the physics invariant and introduces the coupling between the fermion and the gauge fields, where the strength of the coupling is given by the charge \( q \). In addition to the Dirac Lagrangian a free Lagrangian for \( A^\mu \) is added, which is given by the Proca Lagrangian
\[ \mathcal{L} = -\frac{1}{4} F_{\mu\nu} F^{\mu\nu} + \frac{1}{2} m_A^2 A^\mu A^\mu, \] (2.5)
where \( m_A \) is the mass term of the gauge field and \( F_{\mu\nu} \) is the field strength tensor given by
\[ F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu. \] (2.6)

The mass term of the Proca Lagrangian is not invariant under the gauge transformations discussed, therefore, the mass of the gauge field must be equal to zero, which is in accordance with the massless photon. This results in the final Lagrangian for QED
\[ \mathcal{L}_{QED} = \bar{\psi} (i\gamma^\mu \partial_\mu - m) \psi - qA_\mu \bar{\psi} \gamma^\mu \psi - \frac{1}{4} F_{\mu\nu} F^{\mu\nu}. \] (2.7)

### 2.2 Electroweak Theory

The electromagnetic and weak interactions are unified in one model, the electroweak theory. The symmetry governing the electroweak interactions is \( SU(2)_L \times U(1)_Y \), where the \( L \) denotes the coupling to left handed \( SU(2)_L \) weak isospin doublets, defined by Eq. (2.10) and Eq. (2.11) and \( Y \) is the weak hypercharge. The hypercharge is related to the third component of the weak isospin \( T_3 \) and the charge \( Q \) by
\[ Q = T_3 + Y. \] (2.8)

The Lagrangian that describes the dynamics of the electroweak theory can be split up in four parts
\[ \mathcal{L}_{EW} = \mathcal{L}_g + \mathcal{L}_f + \mathcal{L}_h + \mathcal{L}_y, \] (2.9)
consisting of a Lagrangian for the gauge bosons (\( \mathcal{L}_g \)) and the fermions (\( \mathcal{L}_f \)) which are described in this section, and the Higgs sector (\( \mathcal{L}_h \)) and the Yukawa Lagrangian (\( \mathcal{L}_y \)) that are described in Section 2.3.
The electroweak theory makes a distinction between left and right handed fermions. The fermions can be rewritten in terms of their chiral eigenstates $\psi_L$ and $\psi_R$ as

$$\psi = \frac{1 - \gamma_5}{2} \psi + \frac{1 + \gamma_5}{2} \psi = \psi_L + \psi_R,$$

(2.10) where $\gamma_5 = i\gamma^1\gamma^2\gamma^3\gamma^4$. The left handed fermions of the same generation are represented in weak isospin doublets given by

$$L = \left( \begin{array}{c} e_L \\ \nu_L \end{array} \right), \quad Q = \left( \begin{array}{c} u_L \\ d_L \end{array} \right).$$

(2.11)

The Lagrangian for the gauge fields is given by

$$L_g = -\frac{1}{4} W_{\mu \nu}^a W^{a\mu \nu} - \frac{1}{4} B_{\mu \nu} B^{\mu \nu}.$$  

(2.12)

The field strength tensors are expressed in the gauge fields $W^a_{\mu \nu}$ and $B_{\mu \nu}$ for $SU(2)_L$ and $U(1)_Y$, respectively, and given by

$$W_{\mu \nu}^a = \partial_\mu W_{\nu}^a - \partial_\nu W_{\mu}^a + g \epsilon_{abc} W_{\mu}^b W_{\nu}^c,$$

(2.13)

$$B_{\mu \nu} = \partial_\mu B_{\nu} - \partial_\nu B_{\mu}.$$  

where $g$ is the weak coupling constant and $\epsilon_{abc}$ are the structure constants for $SU(2)$, which are equal to the components of the three dimensional Levi-Civita tensor.

The Lagrangian for fermions is given by

$$L_f = \bar{\psi} D_\mu \gamma^\mu \psi + \bar{u}_R i D_\mu \gamma^\mu u_R + \bar{d}_R i D_\mu \gamma^\mu d_R + \bar{\nu}_L D_\mu \gamma^\mu \nu_L.$$  

(2.14)

The Lagrangian for fermions before electroweak symmetry breaking is

$$L_H = \bar{\phi} (D_\mu \phi)^\dagger D^\mu \phi - \frac{1}{2} \mu^2 (\phi^\dagger \phi)^2 - \lambda (\phi^\dagger \phi)^2, \quad (\mu^2 < 0, \lambda > 0).$$  

(2.17)

### 2.3 Higgs Mechanism

The gauge fields that are introduced in the electroweak theory are massless gauge eigenstates. However, experiments confirm the existence of three massive gauge bosons, the two charged $W^+$ and $W^-$ bosons with a mass of $M_W = 80.385 \pm 0.015$ GeV and the neutral $Z$ boson with a mass of $M_Z = 91.1876 \pm 0.0021$ GeV [3–6].

The Higgs mechanism generates the masses of these physical gauge bosons by spontaneously breaking the electroweak symmetry [7–9]. The same mechanism is used to generate the masses of fermions via Yukawa couplings.

The Higgs Lagrangian before electroweak symmetry breaking is

$$L_H = (D_\mu \phi)^\dagger (D^\mu \phi) - \mu^2 (\phi^\dagger \phi) - \lambda (\phi^\dagger \phi)^2, \quad (\mu^2 < 0, \lambda > 0).$$  

(2.17)
where $D_\mu$ is given by Eq. (2.15) and $\phi$ is a complex scalar doublet with hypercharge $Y = +1/2$ given by

$$\phi = \frac{1}{\sqrt{2}} \left( \phi_1 + i\phi_2 \right). \quad (2.18)$$

The Higgs potential has a characteristic ‘Mexican hat’ shape that is shown in Figure 2.2 and results in a non-zero vacuum expectation value. The choice of a vacuum state for $\phi$ will spontaneously break the electroweak symmetry, and is chosen to be

$$\phi_0 = \left( \phi^+ \phi^0 \right) = \frac{1}{\sqrt{2}} \left( 0 + h \right), \quad v^2 = -\frac{\mu^2}{\lambda}. \quad (2.19)$$

This particular combination of hypercharge and vacuum state for $\phi$ results in an unbroken $U(1)_{EM}$ symmetry, such that the photon remains massless. Consequently, the symmetry of the standard model reduces from $SU(3)_C \times SU(2)_L \times U(1)_Y$ to $SU(3)_C \times U(1)_{EM}$ after electroweak symmetry breaking.

![Figure 2.2: The Higgs potential given by $\mu^2(\phi^\dagger \phi) + \lambda(\phi^\dagger \phi)^2, \mu^2 < 0, \lambda > 0$.](image)

The complex scalar $\phi$ can be expressed in terms of the vacuum expectation value $v$ and a real field $h$

$$\phi = \frac{1}{\sqrt{2}} \begin{pmatrix} 0 \\ v + h \end{pmatrix}. \quad (2.20)$$

The kinetic term $(D_\mu \phi)^\dagger (D^\mu \phi)$ of Eq. (2.17) can be rewritten in terms of the physical gauge fields and the Higgs field. The mass terms for the gauge fields are given by

$$\frac{1}{8} v^2 \left( 2g^2 W^+ \mu W^- \mu + (g^2 + g'^2) Z^2 \mu + 0 \cdot A^3_\mu \right), \quad (2.21)$$

where the massless gauge eigenstates mix into the physical gauge bosons by

$$W^\pm_\mu = \frac{1}{\sqrt{2}} \left( W^1_\mu + i W^2_\mu \right),$$

$$Z_\mu = \frac{g' W^3_\mu + g B_\mu}{\sqrt{g^2 + g'^2}},$$

$$A_\mu = \frac{g W^3_\mu - g' B_\mu}{\sqrt{g^2 + g'^2}}.$$
The Higgs part, omitting all constant terms, now contains
\[
\frac{1}{2} (\partial_\mu h)^2 - \frac{1}{2} m_h^2 h^2 - \lambda v h^3 - \frac{\lambda}{4} h^4,
\] (2.22)
including a kinetic, a mass, a three-point interaction and a four-point interaction term.

The Higgs boson was the last particle needed to complete the standard model of particle physics, and was observed by both ATLAS and CMS in July of 2012 [10][11].

**Fermion Masses**

The absence of mass terms in the fermion sector is a consequence of the gauge symmetry of the electroweak theory. The right and left handed fermion fields transform differently under $SU(2)_L \times U(1)_Y$, which forbids a Dirac mass term of the form
\[
m \bar{\psi} \psi = m( \bar{\psi}_L \psi_R + \bar{\psi}_R \psi_L ).
\] (2.23)

To generate the fermion masses, a coupling of fermions with the Higgs field has to be added in a Yukawa Lagrangian. This Lagrangian is given by
\[
L_Y = \lambda_u^{ij} \bar{Q}_i \phi d_R^j + \lambda_d^{ij} \bar{Q}_i \phi^c u_R^j + \lambda_e^{ij} \bar{L}_i \phi e_R^j + h.c.
\] (2.24)

where $i$ and $j$ are family indices, $\phi^c$ is the conjugate Higgs doublet and $\lambda_u^{ij}$, $\lambda_d^{ij}$ and $\lambda_e^{ij}$ are the Yukawa couplings for up type quarks, down type quarks and leptons, respectively.

After electroweak symmetry breaking $\phi$ is given by Eq. (2.20), this introduces mass terms where the fermion masses are given by
\[
M_{ij}^f = \frac{\lambda_f^{ij} v}{\sqrt{2}}, \quad f = \{u, d, e\}.
\] (2.25)

The fermion fields that are in the Yukawa Lagrangian are flavor eigenstates and the coupling between different generations of quarks or leptons is allowed. To get the physical mass of the fermions, the mass matrix which has $M_{ij}^f$ as elements must be diagonalized. This diagonalization results in flavor eigenstates of fermions that are a linear combination of mass eigenstates.

For down-type quarks the linear combination is represented in matrix form, the Cabibbo-Kobayashi-Maskawa (CKM) matrix [12]. This matrix mixes the two different states and is given by
\[
\begin{bmatrix}
V_{ud} & V_{us} & V_{ub} \\
V_{cd} & V_{cs} & V_{cb} \\
V_{td} & V_{ts} & V_{tb}
\end{bmatrix}
\begin{bmatrix}
d' \\
s' \\
b'
\end{bmatrix}
= \begin{bmatrix}
d \\
s \\
b
\end{bmatrix},
\] (2.26)

where the primed quarks are flavor eigenstates.

For the up-type quarks the flavor and mass eigenstates coincide. This is done by exploiting the freedom to rotate the up-type flavor eigenstates such that they are equal to their mass eigenstates. The choice to do this for the up-type quarks is purely arbitrary, and it could have been done for the down-type quarks such that the up-type flavor eigenstates mix into their mass eigenstates with a similar matrix.

Additionally, the elements of the CKM matrix are related to the probability that a given up-type quark decays into a certain down-type quark or vice versa.

For the lepton sector, however, in the original standard model the mass matrix $M_{ij}^e$ is diagonal. Since the observation of neutrino oscillations, which is driven by the small mass differences between the different neutrinos, this is known to be false [13]. The equivalent for the CKM matrix is the Pontecorvo-Maki-Nakagawa-Sakata (PMNS) matrix [14].
2.4 Quantum Chromodynamics

Quarks are fermions that in addition to electric charge carry a color charge: red \((r)\), green \((g)\) or blue \((b)\). The electromagnetic interactions of the quarks are described by QED as discussed in Section 2.1. The strong interactions of quarks are described by quantum chromodynamics (QCD) and involve the interaction of particles with a color charge. The mediators of QCD are the gluons.

The gauge transformations under which QCD is invariant are the local \(SU(3)_C\) transformations given by

\[
\psi(x) \rightarrow \psi'(x) = \exp \left( -g_s \frac{\lambda_a}{2} \alpha^a(x) \right) \psi(x),
\]

where \(g_s\) is the strong coupling constant and \(\lambda_a\) are the eight Gell-Mann matrices which satisfy the commutation relation

\[
[\lambda_a, \lambda_b] = 2i f_{abc} \lambda_c,
\]

involving the \(SU(3)_C\) structure constants \(f_{abc}\).

The full QCD Lagrangian is given by

\[
\mathcal{L}_{QCD} = \sum_{i,\alpha} \bar{\psi}_i^\alpha \left( i \gamma^\mu D_\mu - m_i \right) \psi_i^\alpha - \frac{1}{4} G_{\mu \nu}^a G^{a \mu \nu},
\]

where \(\alpha\) denotes the quark index and \(\alpha\) the color index, \(D_\mu\) is the covariant derivative and \(G_{\mu \nu}^a\) are the eightfold gluon field strength tensors.

The gluon field strength tensor is expressed in the gluon fields \(G_\mu^a\) as

\[
G_{\mu \nu}^a = \partial_\mu G^a_\nu - \partial_\nu G^a_\mu + g_s f_{abc} G^b_\mu G^c_\nu,
\]

and the covariant derivative is given by

\[
D_\mu = \partial_\mu - ig_s \frac{\lambda_a}{2} G^a_\mu.
\]

The last term in \(G_{\mu \nu}^a\) is a consequence of the non-abelian group structure of \(SU(3)_C\), which result in self-interaction terms for the gluons. This implies that the gluons, like quarks, have a color charge.

To give an overview of the different interactions, the Lagrangian can be rewritten as a decomposition in gluon fields

\[
\mathcal{L}_{QCD} = -\frac{1}{4} \left( \partial_\mu G^a_\nu - \partial_\nu G^a_\mu \right) \left( \partial_\mu G^a_\nu - \partial_\nu G^a_\mu \right) + \sum_i \bar{\psi}_i^\alpha \left( i \gamma^\mu D_\mu - m_i \right) \psi_i^\alpha

+ g_s G_{\mu}^a \sum_i \bar{\psi}_i^\alpha \gamma_\mu \left( \frac{\lambda_a}{2} \right)_{\alpha \beta} \psi_i^\beta

- \frac{g_s}{2} f_{abc} \left( \partial_\mu G^a_\nu - \partial_\nu G^a_\mu \right) G^b_\mu G^c_\nu - \frac{g_s^2}{4} f_{abc} f_{ade} G^b_\mu G^e_\nu G^d_\mu G^e_\nu.
\]

The first line contains the kinetic terms for the gluons and quarks, the second line describes the three-point interaction of two quarks and a gluon, and the last line contains the three-point and four-point self-interaction terms for the gluon fields.
The Strong Coupling: Confinement and Asymptotic Freedom

Only colorless bound states of quarks have been observed in nature, this phenomenon is called color confinement. The two basic combinations that result in a colorless state are called baryons and mesons. Baryons are the combination of three quarks with each a different color to result in a colorless state. The mesons are a quark anti-quark pair, where a color and its own anti-color makes a colorless state.

Confinement is the result of the behavior of the strong coupling, shown in Figure 2.3. The evolution of coupling constants as a function of the probing energy \( Q \) can be calculated using the renormalization group equations. The strong coupling evolves differently over \( Q \) compared to the electromagnetic or weak coupling constants. This is a consequence of the additional interactions in QCD due to the gluon self-interactions and makes the strong coupling constant strong at low energy or large distances and weak at high energy or small distances.

![Figure 2.3: The evaluation of the strong coupling constant as a function of the probing energy \( Q \).](image)

Two quarks in a bound state that are close together act as free particles, this is known as asymptotic freedom. When the distance between the two quarks increases virtual gluons are exchanged between the two quarks which can be seen as a color flux tube. After the distance between the quarks increases, the amount of energy needed to sustain the flux tube becomes larger. At a certain distance it is energetically more favorable to create a quark anti-quark pair, resulting in two bound quark pairs, than to sustain the flux tube.

An additional consequence of the behavior of the strong coupling constant is that at energies below a few GeV, QCD becomes a non-perturbative theory. In this region non-perturbative methods are used to model quark and gluon interactions.
3 Supersymmetry

The standard model of particle physics is a theory that accurately describes nature. Measurements show agreement of experiment and theory with high precision, however, there are a few shortcomings to the standard model.

There is a large variety in theories to extend the standard model that could explain these shortcomings. Some examples are grand unified theories which unify all known forces in one theory, but also quantum gravity and more complex theories like string theory are investigated.

One of the most studied extensions of the standard model is supersymmetry [16, 17]. The theoretical elegance of supersymmetry comes from the extension of the Coleman-Mandula theorem. The Coleman-Mandula theorem is a no-go theorem in physics which states that space-time and internal symmetries, like the symmetries of the standard model, only combine in a trivial way [18]. Haag, Lopuszanski and Solnius proved that there is one additional allowed symmetry. This symmetry relates bosons and fermions and is called supersymmetry [19].

In addition, supersymmetry offers solutions to some of the shortcomings of the standard model in a fairly natural way, which shall be discussed in Section 3.2.

As shown in the precedent chapters, the dynamics and interactions of particles are described by a Lagrangian which is symmetric under certain transformations. In supersymmetry the transformation relates bosons and fermions and is given by

\[ \hat{Q}|f\rangle = |b\rangle, \quad \hat{Q}|b\rangle = |f\rangle, \]

where \( f \) and \( b \) denote a fermion or boson, and \( \hat{Q} \) is the generator of the supersymmetry transformation.

Under this operation the spin of a particle is shifted by 1/2, which results in fermions transforming in scalar bosons and the vector bosons transform into spin-1/2 Majorana fermions.

The combination of a fermion and a boson that transform into each other under the operation of \( \hat{Q} \) is called a superfield. The two particles in a superfield have the same mass and internal quantum numbers except for spin. It is not possible to combine any two standard model particles in one superfield, which implies that all the standard model particles have an additional supersymmetric partner.

The supersymmetric partner of the electron is a scalar electron, which is charged and should have a mass of 0.511 MeV. This particle has a clear signature in detectors at particle accelerators and should have been observed by past experiments. The lack of observation of supersymmetric particles leads to the conclusion that supersymmetry, if it exists, is a broken symmetry. If supersymmetric particles exist they must be heavier than their standard model partners.

The exact mechanism that breaks supersymmetry is not known and a general method involving the addition of a soft breaking term to the Lagrangian is further explained in Section 3.1.3.

3.1 The Minimal Supersymmetric Standard Model

The minimal supersymmetric standard model respects the same \( SU(3)_C \times SU(2)_L \times U(1)_Y \) symmetry as the standard model with the addition of supersymmetric particles. The standard model particles and their supersymmetric partners are combined in two types of superfields:

- **Chiral superfields** contain the matter content and consist of the Higgs doublet and the fermion fields of the standard model, and their supersymmetric partners.
- **Massless vector superfields** contain the mediators and consist of the massless gauge fields and their supersymmetric partners.
The scalar supersymmetric partners get an \( s \) prefix, the spin-1/2 particles get an \( \text{ino} \) suffix and are called gauginos. All symbols for supersymmetric particles are denoted with a tilde. An overview of the superfields can be found in Table 3.1 and Table 3.2.

<table>
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<th>Names</th>
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<th>spin-( \frac{1}{2} )</th>
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<th>( SU(2)_L )</th>
<th>( U(1)_Y )</th>
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<td>2</td>
<td>( \frac{1}{6} )</td>
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<td>(-\frac{3}{3} )</td>
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<td></td>
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<tr>
<td></td>
<td>( \tilde{d} ) ( \tilde{d}^*_R ) ( d_R^\dagger )</td>
<td>3</td>
<td>1</td>
<td>( \frac{1}{3} )</td>
<td></td>
<td></td>
</tr>
<tr>
<td>sleptons, leptons</td>
<td>( L ) ((\nu_e, \tilde{e}_L)) ((\nu_e, e_L))</td>
<td>1</td>
<td>2</td>
<td>(-\frac{1}{2} )</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>( \tilde{e} ) ( \tilde{e}^*_R ) ( e_R^\dagger )</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Higgs, higgsinos</td>
<td>( H_1 ) ((H_1^+, H_1^0)) ((\tilde{H}_1^+, \tilde{H}_1^0))</td>
<td>1</td>
<td>2</td>
<td>(-\frac{1}{2} )</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>( H_2 ) ((H_2^0, H_2^-)) ((\tilde{H}_2^0, \tilde{H}_2^-))</td>
<td>1</td>
<td>2</td>
<td>( \frac{1}{2} )</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 3.1: The chiral superfields of the minimal supersymmetric standard model.

<table>
<thead>
<tr>
<th>Names</th>
<th>Superfield</th>
<th>spin-( \frac{1}{2} )</th>
<th>spin-1</th>
<th>( SU(3)_C )</th>
<th>( SU(2)_L )</th>
<th>( U(1)_Y )</th>
</tr>
</thead>
<tbody>
<tr>
<td>gluino, gluon</td>
<td>( G^a ) ( \tilde{g} ) ( g )</td>
<td>8</td>
<td>1</td>
<td>0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>winos, W bosons</td>
<td>( W^i ) ( \tilde{\omega}_i ) ( W_i )</td>
<td>1</td>
<td>3</td>
<td>0</td>
<td></td>
<td></td>
</tr>
<tr>
<td>bino, B boson</td>
<td>( B ) ( \tilde{b} ) ( B )</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 3.2: The massless vector superfields of the minimal supersymmetric standard model.

### 3.1.1 Higgs Sector and Gauge Anomalies

As can be seen in Table 3.1, an additional Higgs doublet is introduced in the minimal supersymmetric standard model. This additional Higgs doublet is required to solve the gauge anomalies that are introduced in this theory.

To have a consistent gauge invariant theory all gauge anomalies must cancel out. The condition for the anomaly in the electroweak theory to cancel out is

\[
\text{Tr} \left[ T^3_2 Y \right] = \text{Tr} \left[ Y^3 \right] = 0, \tag{3.2}
\]

where the traces run over all the left-handed fermions of the theory. The consequence of the fermionic partner of the Higgs doublet is that this relation is not satisfied. The addition of a Higgs doublet with the same hypercharge but with opposite sign is required to regain an anomaly free theory.

The introduction of the second Higgs doublet has a few implications. First is the addition of a second vacuum expectation value \( v_2 \), and second is four additional degrees of freedom. These degrees of freedoms are represented by four additional Higgs bosons. The five Higgs bosons now include the light and heavy \( CP \) even \( h^0 \) and \( H^0 \), the \( CP \) odd \( A^0 \) and the charged \( H^+ \) and \( H^- \).

The mass eigenstates of the supersymmetric partners of the bosons are a combination of the higgsinos, binos and winos. The charged \( W^\pm \) and \( \tilde{H}^\pm \) mix into the charginos \( \tilde{\chi}_1^\pm \) and \( \tilde{\chi}_2^\pm \), and neutral \( W^0 \), \( \tilde{B}^0 \), \( \tilde{H}_1^0 \) and \( \tilde{H}_2^0 \) mix into the neutralinos \( \tilde{\chi}_1^0, \tilde{\chi}_2^0, \tilde{\chi}_3^0 \) and \( \tilde{\chi}_4^0 \).
3.1.2 Superpotential and $R$-parity

The Lagrangian of the minimal supersymmetric standard model can be split up into four parts and is given by

$$\mathcal{L}_{\text{SUSY}} = \mathcal{L}_{\text{kin}} + \mathcal{L}_{\text{int}} + \mathcal{L}_W + \mathcal{L}_{\text{soft}}, \quad (3.3)$$

including a kinetic ($\mathcal{L}_{\text{kin}}$), an interaction ($\mathcal{L}_{\text{int}}$), a super potential ($\mathcal{L}_W$) and a soft breaking ($\mathcal{L}_{\text{soft}}$) Lagrangian.

The kinetic Lagrangian is given by

$$\mathcal{L}_{\text{kin}} = \sum_i \left[ (D_\mu S^*_i)(D^\mu S_i) + i\bar{\psi}_i \gamma^\mu D_\mu \psi_i \right] + \sum_a \left[ -\frac{1}{4} F^a_{\mu\nu} F^{\mu\nu}_a + \frac{i}{2} \lambda_a \gamma^\mu D_\mu \lambda_a \right]. \quad (3.4)$$

The first line contains the sum over all standard model fermions $\psi_i$ and their scalar partner $S_i$, and the two Higgs doublets and their fermion partners. The second line is a sum over all the gauge fields with strength tensor $F^a_{\mu\nu}$ and their Majorana fermion partners $\lambda_a$.

The interactions between the particles in the chiral and massless vector superfields are given in the interaction Lagrangian

$$\mathcal{L}_{\text{int}} = -\sqrt{2} \sum_{i,a} g_a \left( S^*_i T^a \bar{\psi}_{Li} \lambda_a + \text{h.c.} \right) - \frac{1}{2} \sum_a \left( \sum_i g_a S^*_i T^a S_i \right)^2, \quad (3.5)$$

where $g_a$ and $T^a$ are the coupling constants and generators of the relevant gauge symmetry. These interaction terms are fully specified by the gauge symmetries and supersymmetry and no adjustable parameters are present.

The freedom in the construction of a supersymmetric Lagrangian is the construction of a superpotential. This superpotential describes the scalar potential and Yukawa interactions between fermions and scalars. From the superpotential, the Lagrangian $\mathcal{L}_W$ is obtained by

$$\mathcal{L}_W = -\sum_i \left| \frac{\partial W}{\partial z_i} \right|^2 - \frac{1}{2} \sum_{ij} \left( \bar{\psi}_{L_i} \frac{\partial^2 W}{\partial z_i \partial z_j} \psi_{L_j} + \text{h.c.} \right), \quad (3.6)$$

where $z$ is a chiral superfield. This superpotential is a function containing terms with two or three chiral superfields and the most general form that is invariant under the symmetries of the standard model is

$$W = \mu H_1 H_2 + \lambda_L H_1 L \bar{e} + \lambda_D H_1 Q \bar{d} + \lambda_U H_2 Q \bar{u} + \lambda_1 L \bar{L} \bar{e} + \lambda_2 LQ \bar{d} + \lambda_3 \bar{u} \bar{d} \bar{d}, \quad (3.7)$$

where family indices are supressed. The various $\lambda$ constants are the Yukawa couplings which can be $3 \times 3$ matrices mixing the interactions of the three families and $\mu$ is the equivalent of the standard model Higgs boson mass.

A problem arises in the terms on the second line of Eq. (3.7), they imply lepton and baryon number violation. Lepton and baryon number violation are never observed and the experiments on the lifetime of a proton in the decay mode $p \to e^+\pi^0$ give a lower limit of $8.2 \times 10^{33}$ years [20].

To satisfy the constraints on lepton and baryon number violation, the concept of $R$-parity is introduced. The definition of $R$-parity is given by the relation

$$R = (-1)^{3(B-L)+2s}, \quad (3.8)$$
where $L$ and $B$ are lepton and baryon number, and $s$ is the spin of the particle. This results in an even $R$-parity ($R = +1$) for standard model particles, and an odd $R$-parity ($R = -1$) for supersymmetric particles.

The conservation of this multiplicative quantum number implies that supersymmetric particles are created or annihilated in pairs, or that supersymmetric particles decay into one standard model and one supersymmetric particle. Heavy supersymmetric particles decay into lighter ones, until the lightest supersymmetric particle is reached. This particle is stable as it is unable to decay into two lighter standard model particles without violating the assumption of $R$-parity conservation.

### 3.1.3 Spontaneous Breaking of Supersymmetry

As discussed before, supersymmetry must be a broken symmetry, resulting in different masses for standard model particles and their supersymmetric partners. The mechanism that spontaneously breaks supersymmetry is not understood. In order to keep the minimal supersymmetric standard model as general as possible a soft breaking term $\mathcal{L}_{\text{soft}}$ is added to the supersymmetric Lagrangian. This breaking term parametrizes the masses of the scalar particles and gauginos. The most general soft breaking term is given by

$$
\mathcal{L}_{\text{soft}} = -\frac{1}{2} \left( M_1 \tilde{b} \tilde{b} + M_2 \tilde{\omega} \tilde{\omega} + M_3 \tilde{\tilde{g}} \tilde{\tilde{g}} + \text{c.c.} \right) \\
- \left( \bar{\tilde{u}} u Q H_2 - \bar{\tilde{d}} d Q H_1 - \bar{\tilde{e}} e L H_1 + \text{c.c.} \right) \\
- Q^\dagger m_Q^2 Q - \tilde{L}^\dagger m_L^2 \tilde{L} - \bar{\tilde{u}} m_u^2 \tilde{u} - \bar{\tilde{d}} m_d^2 \tilde{d} - \bar{\tilde{e}} m_e^2 \tilde{e}^\dagger \\
- m_{H_1}^2 H_1^* H_1 - m_{H_2}^2 H_2^* H_2 - (b H_1 H_2 + \text{c.c.}).
$$

(3.9)

In this equation the mass terms for binos, winos and gluinos are given by $M_i$. The trilinear couplings $a_f$ are complex $3 \times 3$ matrices in family space. The mass matrices $m_f$ are square third order hermitian matrices. Finally $m_{H_1}, m_{H_2}$ and $b$ are the mass terms for the Higgs sector.

The characteristic mass scale ($m_{\text{soft}}$) up to which this breaking mechanism is valid should be in the order of a TeV. Masses much higher than this scale result in an unnatural theory as explained in Section 3.2.

One problem this soft breaking mechanism introduces is the large number of free parameters. The total number of masses, phases and mixing angles that cannot be reduced any further add up to 105.

### 3.2 Solutions of Supersymmetry to the Standard Model Shortcomings

Supersymmetry offers solutions for a few shortcomings of the standard model. The three shortcomings that are discussed here are the hierarchy problem, the absence of particles that provide a dark matter candidate and grand unified theories.

#### The Hierarchy Problem

The hierarchy problem addresses the large difference between the mass of the Higgs boson and its radiative corrections. The Yukawa coupling given in Eq. (2.24) include a mass term for fermions and an interaction term with the Higgs boson in the form of

$$
\mathcal{L}_{hf} = -\lambda_f \tilde{f} \frac{h}{\sqrt{2}} f.
$$

(3.10)
Figure 3.1: The radiative correction to the Higgs mass for a top quark loop (left) and a top squark loop (right).

These interactions appear in loop diagrams concerning radiative corrections to the Higgs mass and take the form of

$$\Delta m_h^2 \sim \frac{|\lambda_f|^2}{8\pi^2} \left[ \Lambda^2 + m_f^2 \right],$$  \hspace{1cm} (3.11)

where $\Lambda$ is the cutoff scale used to regulate the momentum integral of the loop. The major contributor to these corrections is the top quark for which $\lambda_t \approx 1$ and is shown in Figure 3.1.

This cutoff scale should go to infinity, however, it can be replaced by a value at which the standard model is expected to be invalid. At the Planck scale gravity becomes strong and cannot be ignored. If there is no new theory at a lower energy scale, the Planck scale is expected to be the point at which the standard model is invalid.

Replacing $\Lambda$ with the Planck mass, the radiative corrections become

$$M_P = \sqrt{\frac{\hbar c}{G}} = 1.22 \times 10^{19} \text{ GeV}, \quad \Lambda^2 = M_P^2 \approx 10^{38} \text{ GeV}^2,$$  \hspace{1cm} (3.12)

The measured Higgs mass is 126 GeV [10]. To regain this mass after radiative corrections a fine tuning parameter $\delta M_h^2$ is needed in the order of $10^{38}$ GeV.

Supersymmetry allows for a natural solution with the introduction of scalar partners for fermions. These scalar particles appear in additional loop diagrams that are included in the radiative corrections. The loop for a top squark is shown in Figure 3.1. The loop diagrams for a top quark and a top squark have the same form and only differ in a minus sign due to Fermi statistics. The resulting factor for the radiative corrections of a top quark and top squark is

$$\Delta M_h^2 \sim \frac{|\lambda_f|^2}{4\pi^2} \left( \Lambda^2 + m_f^2 \right) - \frac{\lambda_s}{4\pi^2} \left( \Lambda^2 + m_s^2 \right),$$  \hspace{1cm} (3.13)

where the coupling of fermions and scalars should be equal ($|\lambda_f|^2 = \lambda_s$). This results in a correction term that depends on the mass difference of standard model and supersymmetric particles

$$\Delta M_h^2 \sim \frac{|\lambda_f|^2}{4\pi^2} (m_f^2 - m_s^2).$$  \hspace{1cm} (3.14)

To keep the minimal supersymmetric standard model natural, the mass difference between fermions and scalar particles should not exceed the order of a TeV.

**Dark Matter**

From the observation of large astronomical objects, astrophysicists concluded that the universe is filled with dark matter and dark energy, which cannot be observed by conventional methods.
The latest results given by the Planck Collaboration \cite{21} on the energy and matter content of the universe are

\[ \Omega_b = 0.022242 \]
\[ \Omega_c = 0.11805 \]
\[ \Omega_\Lambda = 0.6964 \]

where the baryonic (\(\Omega_b\)), cold dark matter (\(\Omega_c\)) and dark energy (\(\Omega_\Lambda\)) density parameters are defined as the matter or energy density \(\rho\) divided by the critical density \(\rho_c\).

The problem of dark matter cannot be solved using standard model particles alone. In an \(R\)-parity conserving supersymmetric model a candidate for the cold dark matter comes out naturally as the lightest stable supersymmetric particle. This particle must have a mass in the range of 10 GeV up to 10 TeV to be a suited candidate to solve the problem of dark matter.

**Grand Unified Theories**

Grand unified theories try to unify the three forces of the standard model in one force. Some examples of grand unified theories are \(SU(5)\) \cite{22}, the smallest simple Lie group which contains the standard model

\[ SU(5) \supset U(1)_Y \times SU(2)_L \times SU(3)_C \quad (3.15) \]

or \(SO(10)\) \cite{23}

\[ SO(10) \supset SU(5) \supset U(1)_Y \times SU(2)_L \times SU(3)_C. \quad (3.16) \]

To unify the three forces of the standard model in one encompassing force, the coupling constants of the three independent interaction must converge. The evolution of the coupling constants are shown for the standard model and the minimal supersymmetric standard model in Figure 3.2.

The evolution of the coupling constants for the standard model without the introduction of new physics shows no sign of a good convergence. After the introduction of supersymmetric particles and the extra interactions of the minimal supersymmetric standard model, the coupling constants converge around an energy of \(10^{16}\) GeV, which could be the energy scale for unification of the three forces.

![Figure 3.2: The evaluation of coupling constants for electromagnetic (\(\alpha_1\)), weak (\(\alpha_2\)) and strong interactions (\(\alpha_3\)).](image-url)
The Large Hadron Collider (LHC) is a large proton-proton collider built between 1998 and 2008 at CERN near Geneva, Switzerland. The accelerator has a total circumference of 27 kilometer and a depth up to 175 meter underground [24].

Currently four main and few minor experiments are recording the results of the colliding proton beams. The four main experiments include the two general purpose detectors, A Toroidal LHC Apparatus (ATLAS) and Compact Muon Solenoid (CMS). The third experiment, LHC-beauty (LHCb), is specialized in $b$-physics and performs measurements with a special single arm forward detector. The fourth experiment, A Large Ion Collider Experiment (ALICE), is used for measurements on quark-gluon plasma created by colliding heavy ions.

The process of getting two proton beams in the LHC accelerator starts with a bottle of hydrogen gas, i.e. protons. After the protons are obtained, they are accelerated by a chain of pre-accelerators which is shown in Figure 4.1.

![Figure 4.1: The LHC and the chain of pre-accelerators at the CERN accelerator complex.](image)

The chain starts with the linear accelerator LINAC 2 which accelerates the protons up to 50 MeV. After LINAC 2 the protons are further accelerated by the Proton Synchrotron Booster to 1.4 GeV, which is followed by the Proton Synchrotron that increases the energy to 25 GeV. In the final step of the pre-accelerator chain the protons are accelerated to 450 GeV by the Super Proton Synchrotron after which they are injected in the beam pipes of the LHC. In the LHC the protons were accelerated to an energy of 3.5 TeV in 2011 and 4 TeV in 2012, and collide at the interaction points.

A total of 1232 identical 14.3 meter long superconducting dipole magnets are employed to deliver a magnetic field of 8.3 T, bending the path of protons and keeping them in the circular accelerator. Additional quadruple and sextuple magnets are required to focus and maintain stability of the proton beams.

At the start-up in 2008, a magnet quench caused by faulty electric connections between dipole magnets resulted in severe damage to the accelerator. Adjustments to the connections had to be made to run at the design center of mass energy of 14 TeV. These adjustments were
postponed until a long maintenance period and for safety reasons it was decided to run at reduced energies.

The proton bunches cross at the interactions points in correspondence to the four detectors that record the results of the collisions. The amount of collisions that are produced in the bunch crossings is given by the instantaneous luminosity

\[ L = \frac{f N_1 N_2 N_b}{4 \pi \sigma_x \sigma_y}, \]  

(4.1)

where \( f \) is the bunch crossing rate, \( N_1 \) and \( N_2 \) are the number of protons per bunch, \( N_b \) is the number of bunches per proton beam and the two \( \sigma \) variables are the \( x \) and \( y \) component of the transverse dimension of a proton bunch. At the LHC, the bunch spacing is 50 ns, resulting in a bunch crossing rate of 20 MHz. The total number of bunches per beam is 1380, each containing up to \( 10^{11} \) protons. The transverse dimension of the bunches is approximately \( 17 \times 17 \mu\text{m}^2 \). A peak instantaneous luminosity of \( L = 7.73 \cdot 10^{33} \text{cm}^{-2}\text{s}^{-1} \) was reached during the 2012 running.

The integrated luminosity is the integral over time of the instantaneous luminosity and expresses the total amount of data recorded by the experiments. The integrated luminosity of 2012 recorded by the ATLAS detector is 21.3 fb\(^{-1} \) and a time evolution is shown in Figure 4.2. From the recorded data of 21.3 fb\(^{-1} \), a total of 20.3 fb\(^{-1} \) is usable for offline analysis as specified by the Good Run List.

![Figure 4.2: The total data recorded in 2012 by the ATLAS detector.](image)

The center of mass energy of 8 TeV reached in 2012 results in an increased allowed phase space for creation of particles at the collisions compared to the 7 TeV in 2011. Consequently, the data recorded in 2012 has more potential in the search for new physics than the data recorded in 2011.

The LHC is currently in a long shutdown period dedicated to maintenance and upgrades. After shutdown the beam energy will go up to 6.5 TeV and turn on of the machine is planned for 2015.
The ATLAS Detector

The ATLAS detector is one of the general purpose experiments running at the LHC \cite{26}. Two of the main goals of the ATLAS detector are the discovery of the Higgs boson and the measurement of its properties, and the search for new phenomena that cannot be explained with the physics of the standard model.

5.1 Coordinate System

The ATLAS detector uses a characteristic coordinate system that exploits the symmetry of the detector. The origin of the coordinate system coincides with the interaction point. The $z$ axis is coaxial with the beam pipe. The azimuthal angle $\phi$ determines the angle in the transverse plane and runs from $-\pi$ to $+\pi$. Last, the pseudorapidity $\eta$ is defined as

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

where $\theta$ is the polar angle. In hadron collider physics the pseudorapidity is preferred over the polar angle for two reasons. First, the particle production is approximately constant as a function of $\eta$, and second, the difference in pseudorapidity between two particles is independent of a Lorentz boost along the $z$ axis.

5.2 Detector Layout

The detector is composed of different layers surrounding the interaction point. The innermost layer is the inner tracking detector that measures the tracks of charged particles. A superconducting solenoid magnet surrounds the inner tracking detector and provides the magnetic field in this region. The inner detector and solenoid magnet are surrounded by a layer of calorimeters, which measure the energy and direction of flight of electrons, photons and hadrons. The outermost layer of the ATLAS detector is the muon spectrometer, which identifies muons and measures their tracks and momenta. The magnetic field for the muons is supplied by a toroidal magnet, which is incorporated in the volume of the muon spectrometer.

The different subdetectors are subdivided into three different sections in $\eta$. The central barrel section coaxial with the beam axis has the interaction point at the center. The barrel section is closed by two end-cap sections at either side. The barrel section has an approximate coverage of $|\eta| < 1.5 - 2.0$ and the end-caps extend the total coverage up to $|\eta| < 4.9$.

5.2.1 Magnet System

Two different magnet systems are employed to produce the magnetic field required to bend the tracks of charged particles in the inner detector and muon spectrometer. The curvature of measured tracks can be used to determine the momentum of these particles.

The magnetic field for the inner detector is produced by a thin superconducting solenoid magnet. This 5.8 m long solenoid has an inner radius of 2.46 m and delivers an average field of 2 T at the central part of the inner detector.

The muon spectrometer has eight large superconducting barrel toroids. The whole system has an inner radius of 9.4 m, an outer radius of 20.1 m and a length of 25.3 m. The barrel toroids deliver a peak magnetic field of 3.9 T. The end-cap toroids have an inner radius of 1.65 m, an outer radius of 10.7 m and deliver a peak field of 4.1 T.

The magnetic field supplied by the barrel toroid has a coverage of $|\eta| < 1.0$, the end-cap toroids cover $1.4 < |\eta| < 2.7$ and in the transition region $1.0 < |\eta| < 1.4$ a combination of both field is used.
Both magnet systems are cooled using liquid helium at 4.5 K to keep the solenoid and toroids in a superconducting state.

5.2.2 Inner Detector

The inner detector is the tracking detector closest to the interaction point and it is equipped with two high granularity subsystems, the silicon pixel and silicon micro strip detectors, and a continuous tracking volume consisting of the transition radiation tracker. An overview of the inner detector is shown in Figure 5.1.

![Figure 5.1: The inner detector of ATLAS consisting of a silicon pixel, silicon micro strip (SCT) and transition radiation tracker (TRT).](image)

For each bunch crossing at the interaction point, multiple interactions can occur. The tracks that are reconstructed in the inner detector with high precision are used to determine the various interaction vertices. In general there is one hard scattering per bunch crossing, which is associated with the tracks containing the highest combined transverse energy and is considered the primary vertex. All other interaction in the bunch crossing are called pile up interactions and generally contain soft strongly interacting particles.

An important aspect of the inner detector is the measurement of impact parameters with respect to the primary vertex and the reconstruction of secondary vertices for heavy flavor and $\tau$ tagging. Hadrons containing heavy flavor quarks, especially $b$ quarks, have a relative long lifetime which allows them to travel short distances inside the detector before decaying. The tracks reconstructed from the decay products of these hadrons can be used to determine the decay vertex. The same technique can be used to identify $\tau$ leptons, which typically travel a few hundred micrometers from the interaction vertex.

The inner detector has an outer radius of 1.15 m and a length of 7 m which is subdivided in a barrel segment ($\pm 0.8$ m) and two end-cap segments. The coverage in $\eta$, number of channels.
and resolution of the different parts of the inner detector are summarized in Table 5.1.

<table>
<thead>
<tr>
<th>System</th>
<th>Position</th>
<th>Area [m²]</th>
<th>Resolution σ [µm]</th>
<th>Channels [×10⁶]</th>
<th>η coverage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pixels</td>
<td>B-layer</td>
<td>0.2</td>
<td>$R\phi = 10, z = 115$</td>
<td>16</td>
<td>±2.5</td>
</tr>
<tr>
<td></td>
<td>2 barrel layers</td>
<td>1.4</td>
<td>$R\phi = 10, z = 115$</td>
<td>81</td>
<td>±1.7</td>
</tr>
<tr>
<td></td>
<td>3 end-cap discs</td>
<td>0.7</td>
<td>$R\phi = 10, z = 115$</td>
<td>43</td>
<td>1.7 − 2.5</td>
</tr>
<tr>
<td>SCT</td>
<td>4 barrel layers</td>
<td>34.4</td>
<td>$R\phi = 17, z = 580$</td>
<td>3.2</td>
<td>±1.4</td>
</tr>
<tr>
<td></td>
<td>9 end-cap wheels</td>
<td>26.7</td>
<td>$R\phi = 17, z = 580$</td>
<td>3.0</td>
<td>1.4 − 2.5</td>
</tr>
<tr>
<td>TRT</td>
<td>Axial barrel straws</td>
<td>130 (per straw)</td>
<td>0.1</td>
<td>±0.7</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Radial end-cap straws</td>
<td>130 (per straw)</td>
<td>0.32</td>
<td>0.7 − 2.5</td>
<td></td>
</tr>
</tbody>
</table>

Table 5.1: Parameters of the pixel detector, semiconductor tracker (SCT) and transition radiation tracker (TRT). The resolutions depend on the angle of incidence with respect to the different detector elements [26].

The Pixel Detector

The innermost subsystem of the inner detector is the pixel detector, consisting of silicon modules with a high granularity grid of pixels. Each pixel has a surface area of $50 \times 400 \, \mu m^2$ and a thickness of 250 µm. The barrel segment consists of three layers. The innermost layer, the B-layer, is located approximately 5 cm from the interaction point, consists of $16 \times 10^6$ pixels and increases the resolution of the measurement on secondary vertices. The two outer barrels are located at radii approximately of 9 and 12 cm and consist of $81 \times 10^6$ pixels.

Three end-cap discs consisting of a $43 \times 10^6$ pixels are located at radii between approximately 9 and 15 cm.

The Semiconductor Tracker

The semiconductor tracker consist of modules each containing two planes of sensor strips in a stereo setup with a relative angle of 40 mrad. Each plane of sensors contain 768 strips with an area of $80 \, \mu m \times 120 \, mm$ and a thickness of $285 \pm 15 \, \mu m$.

The four barrel layers are designed to typically give eight hits, resulting in four space-points. Each barrel layer gives a precision measurement in $R\phi$ and the stereo setup is used to obtain a measurement of $z$.

In the nine end-caps the strips are placed radially in a stereo setup, which provides precision measurements in the $R\phi$ plane.

The Transition Radiation Tracker

The transition radiation tracker is a gaseous detector consisting of 4 mm radius straws. The barrel section has 50000 straws placed parallel to the beam axis and divided in the center, resulting in 100000 channels. The end-caps contain 320000 radially placed straws in wheels around the beam axis.

The resolution of each individual straw is $130 \, \mu m$, including a $30 \, \mu m$ error from residual misalignment of the detector.

An additional aspect of this tracker is the identification of charged particles using their emitted transition radiation. When passing the boundary of two different homogeneous media, charged particles emit transition radiation. The amount of transition radiation for ultrarelativistic particles is proportional to the Lorentz factor $\gamma$. Due to this $\gamma$ dependence of the transition radiation, it is possible to identify particles of different masses. The signal strength
in the sensor wires of the detector is enhanced by the transition radiation and for a given energy will be higher for light particles, making it possible to identify electrons and positrons and distinguish them from charged hadrons.

5.2.3 Calorimeters

The ATLAS detector is equipped with an electromagnetic and hadronic calorimeter with the purpose of measuring the direction and energy of electrons, photons and hadrons.

The electromagnetic calorimeter is designed to absorb photons and electrons, which will produce an electromagnetic shower in this subdetector. By interacting with the detector material, electrons will emit brehmsstrahlung and photons will produce electron-positron pairs. The electromagnetic shower is stopped if the energy of the particles is low enough to be absorbed by the material.

The typical momentum of muons created in the collisions is in the GeV range. In this energy range muons are minimum ionizing particles and will not shower in the calorimeters.

The hadronic calorimeter is designed to absorb hadrons, preventing all particles except muons to enter the outer layers of the ATLAS detector.

An overview of the calorimeters is shown in Figure 5.2.

Figure 5.2: Overview of the electromagnetic and hadronic calorimeters in the ATLAS detector.

The Electromagnetic Calorimeter

The electromagnetic calorimeter is a lead / liquid argon sampling calorimeter with a characteristic accordion geometry. A sampling calorimeter consists of two different materials, a dense absorber to stimulate the shower production and a scintillator as active medium to measure the energy contained in the electromagnetic shower. The electromagnetic calorimeter uses lead as absorber and liquid argon as active medium. The calorimeter is divided into a barrel section ($|\eta| < 1.475$) and two end-caps ($1.375 < |\eta| < 3.2$).

The thickness of an electromagnetic calorimeter is expressed in radiation lengths $X_0$, which
is the mean distance after which electrons have a residual energy of \( E_0/e \), where \( E_0 \) is the initial energy and \( e \) is Euler’s number [27]. Additionally, \( 9/7 \ X_0 \) is the mean free path for pair production from a photon.

The electromagnetic calorimeter is thicker than \( 22 \ X_0 \) for the barrel and \( 33 \ X_0 \) for the end-caps, enough to contain the electromagnetic shower caused by highly energetic electrons and photons.

A special presampler detector is installed in front of the electromagnetic calorimeter and consists of a layer of active liquid argon. The thickness of the presampler is 1.1 cm for the barrel and 0.5 cm for the end-caps and covers \(|\eta| < 1.8\). This subsystem provides a first sampling of the electromagnetic shower and is used to correct for energy loss in the material upstream to the calorimeter.

The design energy resolution and coverage of the electromagnetic and hadronic calorimeters are listed in Table 5.2. Due to the amount of material in front of the electromagnetic calorimeter the resolution reduces for \( 1.37 < |\eta| < 1.52 \).

<table>
<thead>
<tr>
<th>Subdetector</th>
<th>Energy resolution</th>
<th>Coverage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electromagnetic barrel calorimeter</td>
<td>( \frac{\sigma E}{E} = 10% \oplus 0.7% )</td>
<td>(</td>
</tr>
<tr>
<td>Electromagnetic end-cap calorimeter</td>
<td>( \frac{\sigma E}{E} = 10% \oplus 0.7% )</td>
<td>(1.375 &lt;</td>
</tr>
<tr>
<td>Hadronic barrel/end-cap calorimeter</td>
<td>( \frac{\sigma E}{E} = 50% \oplus 3% )</td>
<td>(</td>
</tr>
<tr>
<td>Forward calorimeter</td>
<td>( \frac{\sigma E}{E} = 100% \oplus 10% )</td>
<td>(3.1 &lt;</td>
</tr>
</tbody>
</table>

Table 5.2: The design energy resolutions of the ATLAS calorimeters. The \( \oplus \) sign denotes addition in quadrature [26].

The Hadronic Calorimeter

The hadronic calorimeter, which cover \(|\eta| < 4.9\), consists of multiple sampling calorimeters that employ a variety of materials.

The barrel (\(|\eta| < 1.0\)) and extended barrel (\(0.8 < |\eta| < 1.7\)) hadronic calorimeters use iron as absorber and scintillating tiles as active medium. In the hadronic end-cap calorimeters copper plates are the absorbers, liquid argon is the active medium and extends the total coverage to \(|\eta| < 3.2\).

The forward region (\(3.1 < |\eta| < 4.9\)) is covered by a liquid argon sampling calorimeter which employs as absorber copper in the first section for electromagnetic interactions and tungsten in the outer two sections for hadronic interactions. The forward calorimeter has to withstand a high level of radiation due to the increased rate of particle production in these regions.

The thickness of a hadronic calorimeter is expressed in interaction lengths which gives the scale at which secondary hadrons are created in inelastic interactions with nuclei [27]. The interaction length is given by

\[
\lambda = \frac{A}{\sigma_i N_0 \rho}, \tag{5.2}
\]

where \( A \) is the mass of one mole of material, \( \sigma_i \) the inelastic scattering cross section, \( N_0 \) Avogadro’s number and \( \rho \) the density of the material.

At \( \eta = 0 \) the total thickness is \( 11 \lambda \) of which 1.5 \( \lambda \) are due to supports around the calorimeter. This thickness is enough for hadrons to deposit all their energy and reduce the number of punch throughs to the muon spectrometer.
5.2.4 Muon Spectrometer

The muon spectrometer is the outermost layer of the ATLAS detector which covers $|\eta| < 2.7$ and is shown in Figure 5.3. This subdetector measures the tracks of all charged particles passing through the calorimeters, and consist of tracking chambers at large distances from the interaction point.

The barrel section consist of three concentric cylindrical layers at radii of approximately 5 m, 7.5 m and 10 m. The end-caps consist of three wheels at a distance from the interaction point $|z|$ of approximately 7.4 m, 14 m and 21.5 m.

![Figure 5.3: The muon spectrometer and toroid magnet system of the ATLAS detector.](image)

The muon spectrometer employs various technologies to cope with the varying particle rates of the different regions in $\eta$.

The barrel section contains monitored drift tubes and resistive plate chambers and in the end-caps monitored drift tubes, cathode strip chambers and thin gap chambers are used.

The monitored drift tubes are used for tracking in the entire muon spectrometer, except for $2.0 < |\eta| < 2.7$ in the inner wheel of the end-cap segment. The monitored drift tubes consist of multiple single wire drift tubes that achieve an individual resolution of $80 \mu m$. Single wire drift tubes are combined into drift chambers with two times four monolayers for the innermost region and two times three monolayers for the two outer regions, which improves the resolution to $35 \mu m$ in $z$.

For the inner wheel of the end-caps, cathode strip chambers are used and cover $2.0 < |\eta| < 2.7$. The cathode strip chambers are multiwire proportional chambers giving a measurement in $R$ and $\phi$ by an orthogonal configuration of anode wires and pickup strips. The achieved spatial resolution is $40 \mu m$.

The muon spectrometer plays a key role in selecting events to be recorded to permanent storage, this online selection is called triggering which is further explained in Section 5.3.
information for the triggers is provided by the resistive plate chambers and thin gap chambers. The resistive plate chambers cover $|\eta| < 1.05$ and consist of two rectangular plates as electrodes with pickup strips mounted at the back. To get a measurement of $\phi$ and $\eta$ one set of pickup strips is placed parallel and one set of pickup strips is placed orthogonally with respect to the monitored drift tubes.

The thin gap chambers are multiwire proportional chambers with a coverage of $1.05 < |\eta| < 2.4$. The thin gap chambers provide a measurement of $\eta$ and $\phi$ by radially placed anode wires and cathode strips placed orthogonally with respect to these anode wires.

### 5.3 Trigger and Data Acquisition

The ATLAS detector has a three step online triggering system to extract the events of interest from the large quantity of events produced at the LHC. The triggers are designed to reduce the initial 20 MHz bunch crossing rate to a more manageable 400 Hz for permanent storage, without losing the interesting events. A schematic overview of the trigger and data acquisition is shown in Figure 5.4 and consist of a Level-1 (L1), Level-2 (L2) and the third level (L3) trigger which is called the event filter.

![Figure 5.4: Schematic overview of the trigger and data acquisition system. The initial event selection is done by the fast Level 1 trigger. Subsequently, the slower High Level Trigger performs a more elaborate investigation of the event provided by the information of the Level 1 trigger to make a selection of events for permanent storage.](image)

The L1 trigger is hardware based and makes the initial decision to keep or reject an event. The decision is based on information from the trigger chambers of the muon spectrometer and the calorimeters. Information from neighboring cells of the calorimeter are merged to reduce the granularity.
The L1 trigger searches for high transverse momentum leptons and photons, clusters in the calorimeters and large missing and transverse energy. The L1 trigger defines regions of interest in the $\eta\phi$ plane where these objects have been identified. These regions of interest are used by the subsequent stages of the trigger.

The L1 trigger is designed to make a fast initial decision based on the rough information of the detector for which the latency is less than 2.5 $\mu$s and the accepted event rate is 75 kHz. During this decision period all data from the detector is pipelined. After the L1 trigger selects an event, the event information is written to the readout drives followed by the readout buffers. This information will be accessible to the L2 and L3 triggers and kept until the event is either rejected or written to permanent storage.

The L2 trigger is a software based trigger with dedicated algorithms which look at the detector information at full granularity in the regions of interest seeded by the L1 trigger objects, accounting for 1 – 2% of the data of an event. The L2 trigger is designed to reduce the event rate below 3.5 kHz and has an average latency of approximately 40 ms.

The final stage of the triggering system, the L3 event filter, reduces the rate to approximately 400 Hz and has an average processing time of 4 s. This time is used to fully reconstruct the event using the ATLAS reconstruction software and access the latest calibration and alignment information. After the L3 trigger decides to keep the event, the data will be written to a mass storage device for offline analysis. The event size of approximate 1.5 MB corresponds to an output rate of approximately 600 MB/s.

5.4 Identification of Particles in the ATLAS Detector

The identification of particles is required to analyse the proton-proton collisions provided by the LHC and recorded by the ATLAS detector. For this identification the measurements provided by the different subdetectors are combined and a schematic representation is shown in Figure 5.5. The particles that are identified in the ATLAS detector are leptons, photons and hadrons.

If a track in the inner detector can be matched to a cluster of energy deposition in the electromagnetic calorimeter, it will be identified as an electron. In the absence of a matching track, the cluster of energy deposition in the electromagnetic calorimeter is identified as a photon.

Muons leave tracks in the inner detector and muon spectrometer. Muons do not shower in the electromagnetic and hadronic calorimeter, however, they are minimum ionizing particles and will lose some of their energy traversing these subdetectors. Taus decay a few hundred micrometers from the interaction vertex due to their relative long lifetime and will be identified indirectly through its leptonic or hadronic decay products.

As explained in Section 2.4, quarks and gluons are confined to bound states, and will immediately go through a hadronization process after production. They create a highly collimated spray of hadrons, called a jet. Hadrons deposit all their energy by interacting with the material of the hadronic calorimeter. Additionally, charged hadrons leave tracks in the inner detector and deposit energy in the electromagnetic calorimeter.

Weakly interacting particles, like the neutrino, can be indirectly observed exploiting the conservation of momentum. All individual partons inside the proton have no transverse momentum before the collision. Consequently, the total transverse momentum in one single event should be zero. Weakly interacting particles leave the detector without interacting, which results in a non-zero total transverse momentum. The missing transverse momentum ($E_T^{\text{miss}}$) is used to regain a zero total transverse momentum in these cases, and represents the presence of weakly interacting particles in the final state.

In this analysis the particles that are expected in the final state are exactly one electron or
one muon, four jets, one neutrino and two neutralinos which behave like neutrinos.

**Figure 5.5: The main signatures in the ATLAS detector.**

### 5.4.1 Selection of Identified Particles

**Electrons**

An identified electron, that consist of a matching track and cluster of energy, is required to deposit most of its energy in the electromagnetic calorimeter with an electromagnetic fraction greater than 0.8.

Furthermore, electrons are required to be identified with certain quality criteria: loose, medium or tight. These criteria rely on information from the shower shape in the electromagnetic calorimeter.

The loose criteria have a higher selection efficiency. However they are characterized by a lower purity, having an higher misidentification probability. The tighter criteria will result in a lower misidentification probability, however, this reduces the selection efficiency. Therefore, the quality selection is a trade-off between the purity and efficiency of reconstructed electrons.

Two categories of electrons are used:

- **Loose electrons** are used to veto events with multiple leptons. Additionally, these electrons are involved in the process where overlapping reconstructed particles are removed which is further explained in Section 5.4.2. These electrons pass the loose quality criteria, have a geometric acceptance of $|\eta| < 2.47$ and are required to have a minimum transverse momentum of $p_T > 10$ GeV.

- **Signal electrons** are used in the final analysis. These electrons have the same geometric acceptance as loose electrons, are required to pass the tight quality criteria and have minimal transverse momentum of $p_T > 20$ GeV.
Muons

Muons are reconstructed using the “Chain 1” algorithm, which performs a statistical combination of the track parameters for the individual inner detector and muon spectrometer tracks.

Two categories of muons are used:

- Loose muons are used to veto events with additional leptons and in the removal of overlapping particles (Section 5.4.2). These muons are required to have a geometric acceptance of \(|\eta| < 2.4\), a minimum transverse momentum of \(p_T > 10\) GeV and a quality requirement on the track of the inner detector.

- Signal muons that are used in the final analysis are loose muons with an increased transverse momentum cut of \(p_T > 20\) GeV and have requirements on the impact parameters of the track. The impact parameters are the transverse \((d_0)\) and longitudinal \((z_0)\) distances between the track of a muon and the primary interaction vertex of the event. The requirements on signal muons are \(|z_0| < 1\) mm and \(|d_0| < 0.2\) mm.

Jets

For the reconstruction of jets, ATLAS uses the anti-
\(k_T\) jet identification algorithm. This algorithm uses the information of the calorimeters to form clusters of energy deposition which are reconstructed as jets. The anti-
\(k_T\) algorithm is characterized by a distance parameter \(R = 0.4\) which gives the minimum distance between the center of two distinct jets.

Jets are required to have a geometric acceptance of \(|\eta| < 2.5\) and a minimum transverse momentum of \(p_T > 25\) GeV.

Jets that originate from \(b\) quarks are separated from other jets by means of \(b\) tagging as mentioned in Section 5.2.2. The \(b\) tagging algorithm is a multivariate method which uses the jet parameters such as track impact parameters and secondary reconstructed vertex as input. The algorithm provides an output ranging from 0 to 1, which is interpreted as the probability of a jet to originate from a \(b\) quark.

Missing Transverse Momentum

In reconstructed events the missing transverse momentum \(E_T^{\text{miss}}\) is determined with an algorithm which calculates the vectorial sum of all the transverse momentum in the event. All the identified particles in the event are taken into account, and are considered in a specific order: electrons, photons, taus, jets and muons.

After all the identified particles are used, the transverse momentum of the remaining topological clusters in the calorimeter that are not assigned to any reconstructed particle are combined in an additional term which represents the soft particles.

5.4.2 Removal of Overlapping Particles

Two particles are said to overlap if they are reconstructed in the same area in the \(\eta\phi\) plane of the detector. Specific criteria are defined to resolve the problem of overlapping particles and are characterized by the angular distance of two particles \(p_1\) and \(p_2\) given by

\[
\Delta R(p_1, p_2) = \sqrt{(\phi(p_1) - \phi(p_2))^2 + (\eta(p_1) - \eta(p_2))^2}. \tag{5.3}
\]

All loose particles are used in these criteria and the transverse momentum constraints on jets is reduced to 20 GeV. This procedure contains the following steps:
1. If an electron and a $b$-jet are found within $\Delta R < 0.2$, the electron is interpreted as a non-isolated electron and is removed. This electron could be the result of decaying hadrons in the $b$-jet.

2. Because electrons leave a cluster of energy deposition in the calorimeter, every electron will also be identified as a jet. If an electron and a light flavor jet are found within $\Delta R < 0.2$ the particle is identified as an electron and the jet is removed.

3. If a muon and a jet are found within $\Delta R < 0.4$, the particle is interpreted as a jet and the muon as non-isolated and removed. This muon could be the result of a decaying hadron in the jet.

4. If an electron and a jet are found within $0.2 < \Delta R < 0.4$ the electron is non-isolated and removed.
6 Analysis Overview

6.1 Phenomenology of the Top Squark

As discussed in Section 3 the masses of the supersymmetric particles must be higher than their standard model partners. In order to keep the minimal supersymmetric standard model a natural theory and free of large radiative corrections to the Higgs mass, the masses of the supersymmetric particles, and in particular the mass of the top squark, should not exceed the soft breaking scale $m_{\text{soft}}$ as explained in Section 3.2.

General searches for squarks using data recorded by the ATLAS detector in 2011 and 2012 have set limits on the first and second generation squark masses up to approximately 1.5 TeV [28]. However, the production cross section of a pair of top squarks is an order of magnitude smaller with respect to the production cross section of the light quark superpartners and gluinos, as can be seen in Figure 6.1. Consequently, the existence of a top squark with masses that are even comparable with the top quark mass are not yet excluded and can be observed using the data recorded in 2012 by the ATLAS detector.

![Figure 6.1: Pair production cross section in proton-proton collisions at a center of mass energy of $\sqrt{S} = 8\,\text{TeV}$ for various combinations of supersymmetric particles [29–31].](image)

This analysis assumes an $R$-parity conserving minimal supersymmetric standard model scenario and investigates the decay of a top squark pair where both top squarks decay into a $b$ quark and a chargino. Subsequently, the chargino decays to a $W$ boson and a neutralino

$$\tilde{t} \rightarrow b\tilde{\chi}^\pm \rightarrow bW^{\pm}\tilde{\chi}^0.$$  \hspace{1cm} (6.1)

The full decay is shown in Figure 6.2 where in the final state a semileptonic decay of the $W$ bosons is required.
The top squark might decay in other particles, for example a top quark and a neutralino. However, a simplification of the model investigated in this analysis assumes a 100% branching ratio for both the \( \tilde{t} \rightarrow b \tilde{\chi}^\pm_1 \) and the \( \tilde{\chi}^\pm_1 \rightarrow W^\pm \tilde{\chi}_0^1 \) decay, as additional decay modes are covered by other analyses.

For the leptonic decay of the \( W \) boson, the lepton is required to be either an electron or a muon. This decay mode is chosen for its clear signature in the detector, as the ATLAS triggers are designed to recognize high \( p_T \) electrons and muons with a very high efficiency.

A choice for a dileptonic final state would result in a cleaner signature for the triggers. However, this will reduce the number of selected events by approximately a factor of seven, as the branching ratio for a \( W \) to an electron or a muon and a neutrino is 10.80%, whereas the decay into hadrons has a branching ratio of 67.60% [6].

### 6.2 Mass Constraints of the Supersymmetric Particles

The signature of the top squark decay in the ATLAS detector largely depends on the masses and mass differences of the top squark, the chargino and the neutralino. These three arbitrary masses can be represented in a three dimensional mass grid. In order to reduce the complexity of such a mass grid, a mass constraint is placed on these three unknown masses, which will reduce the number of free parameters to two.

These constraints can take various forms and subdivide the three dimensional mass grid into different two dimensional regions. The following three constraints are considered in this analysis.

**The \( M_{\tilde{\chi}_1^\pm} = 106 \text{ GeV} \) Mass Grid**

In the first mass grid the mass constraint takes the form of a fixed mass. In this grid the chargino mass is assumed to be 106 GeV, where this value for \( M_{\tilde{\chi}_1^\pm} \) is set just above the limit obtained by LEP [32].

**The \( M_{\tilde{\chi}_1^\pm} = 150 \text{ GeV} \) Mass Grid**

In the second mass grid the chargino mass is fixed to a value of 150 GeV. This mass grid is the next mass grid in a list of mass grids which subdivide the three dimensional grid in slices of fixed chargino mass.
The $M_{\tilde{\chi}^\pm} = 2M_{\tilde{\chi}^0}$ Mass Grid

The main mass grid that is under investigation in this analysis simplifies the three-dimensional parameter space by requiring a chargino mass that is equal to twice the neutralino mass, i.e. $M_{\tilde{\chi}^\pm} = 2M_{\tilde{\chi}^0}$. This mass grid is shown in Figure 6.3, in which there are different regions that will be explained further on.

This relation between the chargino and neutralino mass is motivated by assuming unification of the three couplings at the mass scale of $10^{16}$ GeV [6]. With this assumption, the relation between $M_1$ and $M_2$ that appear in the soft breaking term given by Eq. (3.9) is approximated by

$$M_1 \approx \frac{5}{3} \tan^2(\theta_W)M_2 \approx \frac{1}{2}M_2,$$

(6.2)

where $\theta_W$ is the Weinberg angle. In the limit of

$$M_Z \ll |\mu \pm M_i|, \ i = 1, 2,$$

(6.3)

the lightest neutralino and chargino masses are given by

$$M_{\tilde{\chi}^0_1} \approx M_1 - \frac{M_Z^2 \sin^2(\theta_W)}{\mu^2 - M_1^2} [M_1 + \mu \sin(2\beta)]$$

$$M_{\tilde{\chi}^\pm_1} \approx M_2 - \frac{M_Z^2}{\mu^2 - M_2^2} [M_2 + \mu \sin(2\beta)],$$

(6.4)

where $\tan \beta = v_1/v_2$ is the ratio of the vacuum expectation values of the two Higgs doublets. Comparing the two mass terms in Eq. (6.4) and using Eq. (6.2) shows in good approximation a relation of the two masses as $M_{\tilde{\chi}^\pm} = 2M_{\tilde{\chi}^0}$.

Figure 6.3: The four different regions in the $M_{\tilde{\chi}^\pm} = 2M_{\tilde{\chi}^0}$ mass grid: (i) the diagonal region, (ii) the virtual $W$ boson region, (iii) the intermediate top squark mass region and (iv) the high top squark mass region.

In this mass grid there are regions with kinematic similarities in the final state. A choice was made to form four distinct regions which are shown in Figure 6.3 and consist of:

![Figure 6.3](image-url)
(i) The Diagonal Region
The decay mode is kinematically forbidden when $M_t < M_{\tilde{t}^\pm} + m_b$, where $m_b$ is the $b$ quark mass. The main characteristic of this region is the production of soft $b$ quarks, that are not reconstructed or identified as $b$-jets.

(ii) Virtual $W$ Region
This region is characterized by a mass difference between the chargino and neutralino of
\[
\Delta(M_{\tilde{\chi}^\pm_1}, M_{\tilde{\chi}^0_1}) = M_{\tilde{\chi}^\pm_1} - M_{\tilde{\chi}^0_1} < M_W.
\] (6.5)
This mass difference results in a $W$ bosons that is emitted off-shell, as there is not enough phase space for the chargino to decay into a neutralino and an on-shell $W$.

(iii) The Intermediate Mass Region
The intermediate mass region in the grid starts at the top quark mass and the upper bound is set to a top squark mass of approximately 400 GeV. In this region the signal is similar to the top quark and has a relative high production cross section compared to the higher top squark masses. The production cross section of a top squark pair with $M_t = m_t$ is in the order of 10% of the $tt$ production cross section.

(iv) The High Mass Region
The high mass region begins at a top squark mass of approximately 400 GeV. In this region it is harder to find a signal from supersymmetry in the large standard model backgrounds due to the small top squark pair production cross section, which is driven by the high top squark mass.

However, due to the high top squark mass there is a lot of phase space for relatively highly energetic jets and leptons, which can be used to distinguish between a standard model process and the top squark decay.

A dedicated analysis is currently performed on this mass grid, for which the results are shown in Figure 6.4. This figure presents the exclusion limit at 95% CL which are represented by contours. The method used for limit setting is further described in Section 8.4.

As can be seen in Figure 6.4 this analysis does not cover region (ii) specified in Figure 6.3, therefore, this study will focus on the virtual $W$ region of the mass grid. The masses of the supersymmetric particles in this analysis are assumed to be $M_{\tilde{\chi}^\pm_1} = 100$ GeV, $M_{\tilde{\chi}^0_1} = 50$ GeV and a mass range for the top squark of $275$ GeV $M_{\tilde{t}} < 500$ GeV.

6.3 Standard Model Backgrounds
In order to find evidence for supersymmetry in the data, a good knowledge of the standard model backgrounds is required. The standard model backgrounds are composed of all results of proton-proton interactions that involve processes predicted by the standard model and produce a final state indistinguishable from the top squark decay. The standard model backgrounds that are relevant for this analysis are:

Top anti-top quark pair production ($tt$)
The most dominant standard model background is the production of a top anti-top quark pair. Due to its large mass, the top quark decays into a $W$ boson and a quark before hadronization, where the quark is a $b$ quark almost 100% of the time ($|V_{tb}|^2 \approx 1$). The top quark pair decay shares the exact same final state as the top squark decay, and the production cross section of this process is $253^{+13}_{-15}$ pb [34,35].
Figure 6.4: The expected (black dashed) and observed (red solid) 95% CL excluded region as a function of $M_{\tilde{t}}$ and $M_{\tilde{\chi}_1^0}$ with the assumption of $M_{\tilde{\chi}_1^\pm} = 2M_{\tilde{\chi}_1^0}$. The yellow band around the expected exclusion represent the ±σ results where all uncertainties except the theoretical signal cross-section uncertainties are included. The dotted red lines represent the ±σ results when varying the signal cross-section with the theoretical uncertainty. The blue area and the dashed grey lines are results from previous analyses [33].

**W boson production in association with jets** ($W$ + jets)

The $W$ + jets background contains jets produced by quarks and gluons in association with a $W$ boson. The majority of the jets produced in this background originate from light flavor quarks.

The large production cross section for a $W$ of 12 nb reduces approximately half an order of magnitude in case of radiation in the form of an additional jet [36,37]. The production cross section where the additional jet originates from a $c$ quark, a $b$ quark or a gluon that produces a $c\bar{c}$ or $b\bar{b}$ pair ranges from 0.1 pb to 15 pb [38,39].

**Single top quark production**

The single top quark is produced through the weak interactions and produces less jets than the top squark decay and only results in the same final state in the presence of initial or final state radiation, or with the associate production of a vector boson. The most dominant production process is the $t$ channel with a cross section of $87.8^{+3.4}_{-1.5}$ pb [40]. Two additional production processes are the associated production of a $W$ boson and the $s$-channel with a cross section of $22.4 \pm 1.5$ pb [41] and $5.61 \pm 0.22$ pb [42], respectively.

**Vector boson pair production (Dibosons)**

The diboson background consist of a pair of vector gauge bosons, where the three co-
Binations that are allowed by the standard model are $WW$, $WZ$ and $ZZ$ with a cross section of 66.1 pb, 38.5 pb and 13.1 pb [37], respectively.

t\bar{t} with associate vector boson production ($t\bar{t} + V$)
The $t\bar{t}+V$ background also produces the same final state as the top squark decay, however, the cross section of this process is small. The production cross sections for $t\bar{t} + W$ and $t\bar{t} + Z$ are 0.232 pb and 0.206 pb [43], respectively.

Z boson production in association with jets ($Z + \text{jets}$)
The $Z + \text{jets}$ background produces two isolated leptons, which is easy to reject with a veto on a second lepton. In order to produce the same final state as the top squark, one of the two leptons should be misidentified as a jet.

Multijet production (QCD)
In the LHC the proton-proton collisions produce a lot of strongly interacting particles which result in a multijet background that contain a large number of jets. In order to be a relevant background for the top squark decay mode a jet from a charged hadron must be misidentified as a lepton.

The contribution of this background is easily reduced to a negligible amount by preselection criteria as will be explained in Section 6.5.1.

6.4 Monte Carlo Simulations
In order to find evidence for the existence of the top squark, events containing the top squark signal and each of the standard model backgrounds described in the previous section have been simulated by Monte Carlo generators. These generators start by simulating the results of proton-proton collisions. Subsequently, the response of the detector to the particles that emerge from the proton-proton collision is simulated after which the generated event is reconstructed.

The $W + \text{jets}$ background is further subdivided in $W + \text{light flavor jets}$ and $W + \text{heavy flavor jets}$, where the heavy flavors include the $c$ quark and the $b$ quark. This subdivision is done to separate events where light flavor jets are mistagged and reconstructed as $b$-jets and events that actually contain $b$-jets.

The amount of background and signal events generated varies by process, and to make a proper comparison with the number of observed events that are recorded by the ATLAS detector a normalization is required. This normalization is given by

$$\mathcal{N} = \frac{L\sigma}{N_{\text{gen}}}$$

where $\mathcal{N}$ is the normalization, $L$ is the integrated luminosity equal to 20.3 fb$^{-1}$, $\sigma$ is the production cross section of the process considered and $N_{\text{gen}}$ is the number of generated events in the Monte Carlo sample. This will result in the number expected events in the generated samples that is in accordance with an integrated luminosity of 20.3 fb$^{-1}$.

In addition to an overall normalization, different weights are applied to the events in the Monte Carlo samples in order to correct for the discrepancy between the simulations and the recorded data. These weights are event based and are determined by certain conditions. The two weights that are used in all the background and the signal samples are the pile up weight to correct for pile up conditions and $b$-tag weight to correct for $b$-tagging efficiency.

A recent study showed that the generator used for the simulation of $t\bar{t}$ events overestimates the transverse momentum of the $t\bar{t}$ system with respect to the data [44]. To account for this
overestimation and improve the agreement of the Monte Carlo simulations and the data an additional weight is applied to the simulated $t\bar{t}$ events, which depend on the transverse momentum of the $t\bar{t}$ system and is given in Table 6.1.

6.5 Event Selection

As explained in Section 5.3, the events of interest can be selected by a number of triggers. In this analysis a combination of triggers is used that are appropriate for the top squark decay mode.

The requirement for one isolated electron or muon and missing transverse energy in the final state motivates the choice for a combination of lepton and missing transverse energy triggers. These triggers are combined for a maximum trigger efficiency.

For electrons two triggers are used: $EF_{e24vhi\_medium1}$ that selects isolated electrons with $p_T > 24$ GeV or $EF_{e60\_medium1}$ for electrons with no isolation requirement and $p_T > 60$ GeV. Similar triggers are used for the muons: $EF_{\mu24i\_tight}$ for isolated muons with $p_T > 24$ GeV or $EF_{\mu36\_tight}$ for muons with no isolation requirement and $p_T > 36$ GeV.

For the missing transverse energy the trigger $EF_{xe80\_tclw\_loose}$ is used to select events with $E_T^{miss} > 80$ GeV.

6.5.1 Preselection Criteria

In order to reduce the standard model backgrounds that are easy to suppress, a few preliminary selections are applied which are summarized in Table 6.2 and explained in this section.

The triggers select events with a lepton and some missing transverse energy. Additionally the final state contains at least four jets, resulting in a selection of events with $n_{jets} \geq 4$.

The kinematics of the $b$ quarks depend on the mass difference $\Delta M(t, \tilde{\chi}_1^\pm)$, and in the region of interest for this analysis, this mass difference is at least 175 GeV. This relatively large mass difference results in high transverse momentum $b$ quarks which are easily reconstructed as $b$-jets. Therefore, in this $b$-jet rich region of the mass grid, preselected events are required to contain at least two $b$-jets, i.e. $n_{b\_jet} \geq 2$.

To reduce the effects of soft pile up jets in the selected events, all jets are required to have a transverse momentum of at least 25 GeV. Furthermore, the top squark decay mode will give four jets with a typical transverse momentum larger than the standard model backgrounds. Tighter transverse momentum requirements are applied to the three leading jets with increasing values. The final values for the transverse momenta of the four leading jets are $p_T > 80, 60, 40$ and 25 GeV.

### Table 6.1: The weights that are applied to the generated $t\bar{t}$ events to correct for the mismodeled transverse momentum of the $t\bar{t}$ system.

<table>
<thead>
<tr>
<th>$p_T$ $t\bar{t}$ system [GeV]</th>
<th>Event weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p_T &lt; 40$</td>
<td>0.97</td>
</tr>
<tr>
<td>$40 &lt; p_T &lt; 170$</td>
<td>0.95</td>
</tr>
<tr>
<td>$170 &lt; p_T &lt; 340$</td>
<td>0.83</td>
</tr>
<tr>
<td>$p_T &gt; 340$</td>
<td>0.73</td>
</tr>
</tbody>
</table>

### Table 6.2: A summary of all preselection criteria used in this analysis.

<table>
<thead>
<tr>
<th>Preselection criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>$n_{jet}$ ≥ 4</td>
</tr>
<tr>
<td>$n_{b_jet}$ ≥ 2</td>
</tr>
<tr>
<td>$p_T(j_1)$ &gt; 80 GeV</td>
</tr>
<tr>
<td>$p_T(j_2)$ &gt; 60 GeV</td>
</tr>
<tr>
<td>$p_T(j_3)$ &gt; 40 GeV</td>
</tr>
<tr>
<td>$p_T(j_4)$ &gt; 25 GeV</td>
</tr>
<tr>
<td>$E_T^{miss}$ &gt; 100 GeV</td>
</tr>
<tr>
<td>$</td>
</tr>
<tr>
<td>$</td>
</tr>
<tr>
<td>$E_T^{miss}/\sqrt{H_T}$ &gt; 5 GeV$^{1/2}$</td>
</tr>
<tr>
<td>$n$ isolated tracks = 1</td>
</tr>
</tbody>
</table>
The missing transverse energy trigger selects events with $E_T^{\text{miss}} > 80$ GeV, however the requirement of the missing transverse energy is increased to 100 GeV to account for a possible mismatch between the online $E_T^{\text{miss}}$ measurement used by the triggers and the offline $E_T^{\text{miss}}$ reconstruction used in the analysis, since the offline reconstruction is more accurate.

Missing transverse energy can be the result of mismeasured energy in a jet due to calorimeter inconsistencies and resolutions. Consequently, the magnitude of the missing transverse energy depends on the energy of the jets. The resolution of the jet energy scales with $\sqrt{E}$ and a good approximation of the significance of the missing transverse energy is given by

$$E_T^{\text{miss}} / \sqrt{H_T}, \quad H_T = \sum_{i=1}^{4} p_T(j_i).$$

This significance is required to be greater than 5 GeV$^{1/2}$.

In case jets are the source of this fake missing transverse energy, the $E_T^{\text{miss}}$ will point in the same direction as these jets. Therefore an angular requirement is placed with respect to the missing transverse energy and the two leading jets

$$|\Delta \phi(j_i, E_T^{\text{miss}})| = |\phi(j_i) - \phi(E_T^{\text{miss}})| > 0.8, \quad i = 1, 2.$$  

The last three preselection criteria will result in a reduction of the multijet background to a negligible magnitude.

The final preselection criteria in Table 6.2 is a requirement on the number of isolated tracks. The lepton that comes from the leptonically decaying $W$ boson is considered to be either an electron or a muon, and result in an isolated track in the inner detector and muon spectrometer. Events that contain more than one isolated track are removed from the selected events.
7 Optimization of a Cut and Count Method

In searches for supersymmetry a general strategy is the implementation of a cut and count method. In a cut and count experiment a selection of cuts are applied to variables with a large discrimination power between signal from supersymmetry and the standard model backgrounds. These cuts are introduced to reduce the number of events from standard model backgrounds whilst maximizing the signal selection efficiency, making it a signal enriched region or signal region in short. To find evidence for supersymmetry the expected background and signal yields are compared to the number of observed events in the signal region.

A shape comparison is performed in order to choose variables with large discriminating power. In this method the shapes of the distributions for the background and the signal are compared. For the standard model backgrounds only $t\bar{t}$ is considered as it is the most important background.

The quantification of the discrimination power is done by use of the separation power \[45\]. The separation power describes the difference between a signal and a background distribution and is given by the integral

$$S = \frac{1}{2} \int_{x_i}^{x_f} \frac{(b(x) - s(x))^2}{s(x) + b(x)} \, dx,$$

where $s(x)$ and $b(x)$ are the signal and the background distributions, respectively. For the signal and the background distributions the histograms for the $t\bar{t}$ sample and the signal samples of the top squark are used. Consequently, the integral transforms into a sum over the bins of the histograms, given by

$$S = \frac{1}{2} \sum_{i=1}^{n_{\text{bins}}} \frac{(b_i - s_i)^2}{b_i + s_i}.$$

This method makes a distinction between good discrimination power in the bulk and in the tail of a distribution, as the difference in bin content between the $t\bar{t}$ and a signal samples are weighted by the sum of these values. This weight will be large in the bulk and smaller in the tail of the distributions.

The separation power of the variables with the most discrimination power are summarized in Table 7.1, and are further described in the following section.

<table>
<thead>
<tr>
<th>$M_{\tilde{t}}$ [GeV]</th>
<th>275</th>
<th>300</th>
<th>350</th>
<th>400</th>
<th>450</th>
<th>500</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_{\text{eff}}$</td>
<td>0.029</td>
<td>0.058</td>
<td>0.152</td>
<td>0.264</td>
<td>0.366</td>
<td>0.492</td>
</tr>
<tr>
<td>$E_{\text{T}}^{\text{miss}}$</td>
<td>0.036</td>
<td>0.059</td>
<td>0.124</td>
<td>0.209</td>
<td>0.289</td>
<td>0.371</td>
</tr>
<tr>
<td>$p_T(LF_{j1})$</td>
<td>0.039</td>
<td>0.031</td>
<td>0.033</td>
<td>0.027</td>
<td>0.027</td>
<td>0.031</td>
</tr>
<tr>
<td>$m_T$</td>
<td>0.048</td>
<td>0.044</td>
<td>0.057</td>
<td>0.052</td>
<td>0.060</td>
<td>0.064</td>
</tr>
<tr>
<td>$p_T(bj_2)$</td>
<td>0.073</td>
<td>0.097</td>
<td>0.193</td>
<td>0.251</td>
<td>0.320</td>
<td>0.363</td>
</tr>
<tr>
<td>$p_T(bj_1)$</td>
<td>0.081</td>
<td>0.111</td>
<td>0.223</td>
<td>0.302</td>
<td>0.381</td>
<td>0.458</td>
</tr>
<tr>
<td>$p_T(bj_1) + p_T(bj_2)$</td>
<td>0.102</td>
<td>0.134</td>
<td>0.259</td>
<td>0.348</td>
<td>0.437</td>
<td>0.510</td>
</tr>
<tr>
<td>$R_{\ell d}$</td>
<td>0.106</td>
<td>0.120</td>
<td>0.159</td>
<td>0.181</td>
<td>0.192</td>
<td>0.208</td>
</tr>
<tr>
<td>$aM_{T2}$</td>
<td>0.241</td>
<td>0.302</td>
<td>0.417</td>
<td>0.460</td>
<td>0.533</td>
<td>0.566</td>
</tr>
</tbody>
</table>

Table 7.1: A summary of the separation power of the most discriminating variables. The variables are ordered from small to large separation power for the $M_{\tilde{t}} = 275$ GeV signal sample.
7.1 Overview of the Most Discriminating Variables

The variables that are considered for the construction of a signal region are shown in Table 7.1.

As explained in section 6.5.1, the kinematics of the \( b \)-quarks that emerge from the \( \tilde{t} \to b \tilde{\chi}_1^{\pm} \) decay are determined by the mass difference between the top squark and the chargino. In case of a top anti-top quark pair, the kinematics of the \( b \) quark are determined by the mass difference between the top quark and the \( W \) boson.

For the region of interest in this analysis, the minimum mass difference between the top squark and the chargino is 175 GeV, whereas for \( t\bar{t} \) the mass difference is fixed and equal to \( m_t - M_W = 93.1 \) GeV [6]. This difference between the top squark pair and the top anti-top quark pair decay represents itself in the transverse momenta of the two \( b \)-jets in the final state of these decays, and therefore are investigated. In addition, the scalar sum of these two transverse momenta is considered, as this combination has a higher separation power than either \( p_T(bj_1) \) or \( pT(bj_2) \), as can be seen in Table 7.1.

Due to the relative high top squark mass compared to the top quark mass there is more phase space available for the decay products, which typically result in a higher transverse momenta for the final state particles. For this reason three variables are used that in combination with the transverse momenta of the \( b \)-jets contain the information of the full final state of the decay.

In addition to the two \( b \)-jets, two jets from the hadronically decaying \( W \) boson are required, which in general originate from light flavor quarks. The transverse momentum of the leading light flavor jet \( p_T(LFj_1) \) has the most discrimination power of these two jets and is considered as one of the variables in the construction of a signal region.

As mentioned previously, in the top squark decay mode two neutralinos and a neutrino are created that escape the detector without interacting, which results in missing transverse energy. The relevant standard model backgrounds generally produce only one neutrino. This results in a difference in the magnitude of the missing transverse energy, \( E_T^{\text{miss}} \), which has a good separation power between the signal and \( t\bar{t} \) samples, as shown in Table 7.1.

A variable that gives a measure of the total energy in the expected final state is the effective mass, which is given by

\[
M_{\text{eff}} = E_T^{\text{miss}} + p_T(l) + \sum_{i=1}^{4} p_T(j_i). \tag{7.3}
\]

This variable is highly correlated with the previously described variables, however, has a good separation power and contains information about the fourth jet and the lepton that still remained unused.

The distributions of these six variables are shown in Figure 7.1 where the histograms for the \( t\bar{t} \) background and two signal samples with \( M_{\tilde{t}} = 275 \) or 500 GeV, \( M_{\tilde{\chi}_1^{\pm}} = 100 \) GeV and \( M_{\tilde{\chi}_0^1} = 50 \) GeV are normalized to unity and combined for comparison.

7.1.1 The Transverse Mass

The transverse mass is the transverse component of the invariant mass of a system of two particles that originate from the same parent particle. The variable \( m_T \) that is used in this analysis is the transverse mass of the leptonically decaying \( W \) boson, and combines the lepton and the neutrino.

The choice for the transverse mass rather than the invariant mass is due to the neutrino, as only the transverse component of the momentum of the neutrino is indirectly measurable and is represented by \( E_T^{\text{miss}} \).

The transverse mass is given by

\[
m_T^2 = 2p_T(l)E_T^{\text{miss}}\left(1 - \cos(\Delta\phi(l, E_T^{\text{miss}}))\right), \tag{7.4}
\]
Figure 7.1: The distributions for (a) $p_T(b_1)$, (b) $p_T(b_2)$, (c) $p_T(b_1) + p_T(b_2)$, (d) $p_T(LF_1)$, (e) $E_T^{\text{miss}}$ and (f) $M_{\text{eff}}$, comparing the $t\bar{t}$ background with the two signal samples at the edge of the region of interest with $M_{\tilde{t}} = 275, 500$ GeV, $M_{\chi_1^\pm} = 100$ GeV and $M_{\chi_0} = 50$ GeV. The distributions are normalized to unity and combined in one plot for comparison.
where the masses of the two particles are neglected, as these are small in comparison to the energies produced by the LHC.

The distributions for the standard model backgrounds after applying the preselection criteria are shown in Figure 7.2. The distribution of $m_T$ for a pure $W \rightarrow l\ell$ sample can be used to determine $M_W$, as it has an end-point at the $W$ mass. This is represented in the plot in Figure 7.2 as a peak just before $m_T = M_W$ and drops sharply after the $W$ mass.

In Figure 7.2 a global scale factor ($\mu_{t\bar{t}}$) is applied to the $t\bar{t}$ Monte Carlo sample to improve the agreement between data and simulations at preselection level, as the Monte Carlo tends to overestimate the data. This scale factor is only applied at preselection level and a proper background normalization procedure is introduced in Section 8.

At the preselection level the total standard model background yield is expected to be 16633, whereas the signal yield peaks at 743 for the signal sample with $M_{\tilde{t}} = 275$ GeV, $M_{\tilde{\chi}^\pm} = 100$ GeV and $M_{\tilde{\chi}_1^0} = 50$ GeV. Consequently, the expected signal yield is in the order of a percent of the total background yield, which is too small to create an artificial excess of top squark events using a global scale factor.

For the top squark decay two additional particles, the two neutralinos, do not interact in the detector and contribute to the missing transverse energy. Consequently, the transverse mass is expected to be higher for the top squark decay, which can be seen in Figure 7.3a. The peak of the $m_T$ distribution is shifted to the right, and the size of the shift depends on to the top squark, the chargino and the neutralino masses.

Figure 7.2: The transverse mass $m_T$ of the leptonically decaying $W$ boson after applying the preselection criteria. The Monte Carlo distributions for the various standard model backgrounds processes are normalized to $20.3\, \text{fb}^{-1}$ and a global scale factor $\mu_{t\bar{t}} = 0.9$ is applied to the $t\bar{t}$ background sample to improve data and Monte Carlo agreement.

For the top squark decay two additional particles, the two neutralinos, do not interact in the detector and contribute to the missing transverse energy. Consequently, the transverse mass is expected to be higher for the top squark decay, which can be seen in Figure 7.3a. The peak of the $m_T$ distribution is shifted to the right, and the size of the shift depends on to the top squark, the chargino and the neutralino masses.
In the region of interest for this analysis the $W$ boson originating from the chargino decay is emitted off-shell. Consequently, $m_T$ will not peak at $M_W$ as is shown in Figure 7.3b.

![Figure 7.3: The comparison of the distributions, which are normalized to unity, for $t\bar{t}$ and signal samples with an on-shell and an off-shell $W$. The signal samples with an on-shell $W$ are shown in (a) with masses equal to $M_\tilde{t} = 300$ GeV, $M_{\tilde{\chi}_1^\pm} = 200$ GeV, $M_{\tilde{\chi}_1^0} = 100$ GeV for Signal (i) and $M_\tilde{t} = 450$ GeV, $M_{\tilde{\chi}_1^+} = 300$ GeV, $M_{\tilde{\chi}_1^0} = 150$ GeV for Signal (ii). The signal samples with an off-shell $W$ are shown in (b) with masses equal to $M_\tilde{t} = 275$ GeV, $M_{\tilde{\chi}_1^+} = 100$ GeV and $M_{\tilde{\chi}_1^0} = 50$ GeV for Signal (i) and $M_\tilde{t} = 500$ GeV, $M_{\tilde{\chi}_1^+} = 100$ GeV and $M_{\tilde{\chi}_1^0} = 50$ GeV for Signal (ii).]

For a signal sample where the $W$ boson produced in the chargino decay is on-shell, a cut on the transverse mass after $M_W$ significantly reduces the standard model backgrounds while keeping the decrease in signal selection efficiency to a minimum. For a signal sample with an off-shell emitted $W$ boson, such a cut would also significantly reduce the signal selection efficiency. For this reason the implementation of a veto, where events within a certain mass window around $M_W$ are removed from the selection, was found to be most optimal.

The vetoed mass window is an asymmetric window around $M_W$: $60$ GeV < $m_T$ < $90$ GeV. In order to keep enough signal events the mass window cannot be too wide and the asymmetry of the mass window is motivated by the asymmetric peak around $M_W$ for the standard model background distributions of $m_T$, as shown in Figure 7.2.

After the application of the preselection criteria the signal selection efficiency for this mass window ranges from 0.809 up to 0.821 for the top squark samples and the standard model background selection efficiency is 0.662.

Other mass windows where considered and the full study is summarized in Appendix A.

### 7.1.2 The Asymmetric Stransverse Mass

As discussed in the previous section, the end point of the distribution of the transverse mass can be used to determined the mass of a parent particle.

In the case of one unobserved particle, such as the neutrino in the decay $W \rightarrow l\nu$, the missing transverse energy is assumed to originate from the neutrino and can be used in the calculation of $m_T$. However, this assumption does not hold when introducing decay modes with multiple invisible particles, as the missing transverse energy cannot be decomposed into these original multiple components.
A generalization of the transverse mass to a topology with two invisible particles is called the stransverse mass or $M_{T^2}$ [46]. This stransverse mass is defined as

$$m_{T^2} \equiv \min\left[\max(m_{T,a}, m_{T,b})\right], \quad \vec{p}_{T,a} + \vec{p}_{T,b} = E_{T}^{\text{miss}},$$

where $\vec{p}_{T,a}$ and $\vec{p}_{T,b}$ are the transverse momenta of the two invisible particles, for which their combination is required to be equal to the missing transverse energy.

For one combination of $\vec{p}_{T,a}$ and $\vec{p}_{T,b}$ the transverse masses $m_{T,a}$ and $m_{T,b}$ are calculated and the maximum of the two is chosen. This is done for different combinations of $\vec{p}_{T,a}$ and $\vec{p}_{T,b}$ that satisfy $\vec{p}_{T,a} + \vec{p}_{T,b} = E_{T}^{\text{miss}}$, and the minimum of all the possible combinations is defined as $m_{T^2}$.

The asymmetric $M_{T^2}$, $aM_{T^2}$, is introduced to describe the transverse mass for a dileptonic decay of $t\bar{t}$ in the case where one of the two leptons is misidentified [47]. The situation is shown in Figure 7.4 where the missing or unmeasured particles in the final state are marked by the gray dashed circles.

In the calculation of $aM_{T^2}$, the visible particles for the $t\bar{t}$ decay are one $b$-jet for the top quark with the misidentified lepton, and the lepton and $b$-jet for the second top quark. The missing lepton in the calculation of $aM_{T^2}$ is taken into account by assuming that one of the transverse masses given in Eq. 7.5 is in agreement with the mass of the $W$ boson. The distribution of $aM_{T^2}$ for $t\bar{t}$ has an end-point at the top quark mass.

The stransverse mass is in general a good variable in searches for new phenomena that cannot be described by the standard model and introduce particles that do not interact with the detector. In the $R$-parity conserving supersymmetric model investigated in this analysis, the supersymmetric particles are created in pairs and the lightest particle is stable and escapes the detector. Therefore, together with the neutrino, the missing transverse energy is the combination of three missing momentum vectors and as a result values for the asymmetric stransverse mass will typically be higher for signal samples in comparison to the standard model backgrounds. This can be seen in the comparison of two top squark signals and $t\bar{t}$ in Figure 7.5.

---

**Figure 7.4:** The situation where one lepton is misidentified in a dileptonic decay of $t\bar{t}$. The particles that are missing in the final state to fully reconstruct the top quark pair system are marked by the gray dashed circles.

**Figure 7.5:** The distributions of $aM_{T^2}$, normalized to unity, for $t\bar{t}$ and the two signal samples with $M_{\tilde{g}} = 275$, 500 GeV, $M_{\tilde{\chi}^\pm_1} = 100$ GeV and $M_{\tilde{\chi}^0_1} = 50$ GeV.
7.1.3 A Novel Discriminating Variable: The Ratio Between Lepton and b-jet Transverse Momenta

One of the variables that was found to be powerful in the distinction between $t\bar{t}$ and the top squark signal is a ratio of transverse momenta of the lepton and a $b$-jet [48]. This relation is given by

$$R_{bl} = \frac{p_T(l)}{p_T(l) + p_T(bj)},$$

(7.6)

where for $t\bar{t}$ both the lepton and $b$-jet are required to originate from the same leptonically decaying top quark. To choose the $b$-jet of interest, first a distinction has to be made between the two $b$-jets that originate from the top quarks and the two additional jets that originate from the hadronically decaying $W$ boson.

As discussed in Section 5.2.2, multivariate methods are used to determine the probability of a jet originating from a $b$ quark, which is reflected in a so-called $MV1$ value for each individual jet that runs from 0 to 1. The two jets that are considered as the two $b$-jets in this decay are the two jets with the highest $MV1$ value, which generally are the two leading $b$-jets. The two remaining jets are considered to be the additional jets from the hadronically decaying $W$ boson.

In order to find the $b$-jet of interest for the calculation of $R_{bl}$, a $\chi^2$ minimization is applied, given by

$$\chi^2 = \frac{(M_{jj} - M_W)^2}{\Delta M_W^2} + \frac{(M_{jjb} - m_t)^2}{\Delta m_t^2}.$$  \hspace{1cm} (7.7)

In this equation the invariant mass of the system containing the two jets is given by $M_{jj}$ and is compared to the mass of the $W$ boson, which is equal to $M_W = 80.4$ GeV. In the second term $M_{jjb}$ is the invariant mass of the system containing the two jets and either one of the $b$-jets and is compared to the top quark mass $m_t = 173$ GeV. Both quantities are weighted by the mass width of these two particles, equal to $\Delta M_W = 2.1$ GeV and $\Delta m_t = 2.0$ GeV for the $W$ boson and the top quark, respectively [6].

One of the assumptions of this procedure is the correct extraction of the two $b$-jets and two jets that are expected to come from the hadronically decaying $W$ boson. This assumption is proven by the distribution of $M_{jj}$ which, as expected, peaks around the $W$ mass and is shown in Figure 7.6.

The $b$-jet that is compatible with the hadronic top quark decay minimizes Eq. (7.7), and the $b$-jet that maximizes this equation is used in the calculation of $R_{bl}$. The distribution of $R_{bl}$ for $t\bar{t}$ and two signal samples is shown in Figure 7.7, where for comparison again the distributions are normalized to unity. As can be seen in this figure, the distribution for a top squark is more centered to the left ($R_{bl} < 0.3$) whereas the distribution for the $t\bar{t}$ background sample is centered around $R_{bl} \approx 0.3$.

The comparison of the data with the Monte Carlo simulations is shown in Figure 7.8.

7.2 The Optimization Procedure

As discussed previously, to find evidence for supersymmetry the expected background and signal yields are compared to the number of observed events in a signal enriched region. This signal region is defined by a set of cuts that are applied on variables which should give an optimal signal selection efficiency and reduce the relevant standard model backgrounds.

To create a signal region an optimization procedure is used that calculates a figure of merit for a large amount of cut combinations on the most discriminating variables described in the preceding section. This figure of merit reflects the performance of the cuts and from this the most optimal combination of cuts can be found.
Figure 7.6: The invariant mass of the system of the two jets that are assumed to originate from the hadronically decaying $W$ boson. The Monte Carlo distributions for the various standard model backgrounds processes are normalized to 20.3 fb$^{-1}$ and a global scale factor $\mu_{tt} = 0.9$ is applied to the $t\bar{t}$ background sample to improve data and Monte Carlo agreement.

Figure 7.7: The distributions, normalized to unity, of $R_{bl}$ for $t\bar{t}$ and the two signal samples with $M_{\tilde{t}} = 275, 500$ GeV, $M_{\tilde{\chi}^\pm} = 100$ GeV and $M_{\tilde{\chi}^0_1} = 50$ GeV.
Figure 7.8: The distribution of $R_{bl}$ after the application of preselection criteria. The Monte Carlo distributions for the various standard model backgrounds processes are normalized to $20.3 \text{ fb}^{-1}$ and a global scale factor $\mu_{t\bar{t}} = 0.9$ is applied to the $t\bar{t}$ background sample to improve data and Monte Carlo agreement.

The figure of merit that is used in this analysis is the sensitivity $S$ given by

$$S = \frac{s}{\sqrt{s + b + (0.2b)^2}},$$

(7.8)

where $s$ and $b$ are the signal and the background yields, respectively. This figure of merit is generally used in studies that try to exclude phenomena described by physics that cannot be explained by the standard model. The set of cuts that maximize this figure of merit has the most optimal performance in an effort to distinguish between signal-like and background-like events.

The term $(0.2b)^2$ in the denominator of Eq. (7.8) is due to the systematic uncertainties. For the systematics uncertainties a simplified model is used where the systematics are estimated and applied as flat systematics, i.e. independent on the variables that are considered. The total systematics are assumed to be

20% correlated systematics
These systematics are due to the uncertainties in the jet energy scale and jet energy resolution. These systematics are the result of the uncertainties of the energy measurement in the calorimeters and affect all signal and background samples, hence they are treated as correlated systematics.

10% uncorrelated systematics
The uncorrelated systematics are due to the uncertainty on individual properties of the background and signal samples. This includes for example the theoretical uncertainty on the calculation of the production cross section or the generator uncertainties in the Monte Carlo simulations.
To get a reasonable estimate on the performance of the various cut combinations that could be used to construct a signal region, only the dominant 20% of systematics are applied in the optimization procedure.

The variables that were considered in this optimization are only a selection of the variables shown in Table 7.1, as some of these variables were discarded due to correlations, and in addition a reduction of the total number of variables was needed for the more practical reason of a limited maximum number of cut combinations.

The scalar sum of transverse momenta of the two leading $b$-jets performed better than $p_T(b_{j1})$ or $p_T(b_{j2})$, and therefore their sum is used in the optimization rather than the individual transverse momenta of these two jets. In addition, as discussed previously, the effective mass given by Eq. (7.3) is highly correlated with the transverse momenta of the four leading jets and the missing transverse energy, and was found to be ineffective.

From the comparison plots that are shown in Section 7.1 a range of cut values that will improve the sensitivity for each individual variable is estimated, and are summarized in Table 7.2. The optimization procedure runs through all the possible combinations and determines the signal and the background yields. Subsequently, the sensitivity $S$ given by Eq. (7.8) is calculated for every set of cuts, and the set of cuts that maximize $S$ is extracted.

### Table 7.2: The cut ranges for the most discrimination variables that are used in the optimization procedure. All variables are also allowed to be excluded, i.e. $< 1$ for $R_{bl}$ and $> 0$ GeV for the rest of the variables.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Range</th>
<th>Step size</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p_T(b_{j1}) + p_T(b_{j2})$</td>
<td>$&gt; 150-400$ GeV</td>
<td>25 GeV</td>
</tr>
<tr>
<td>$p_T(LF_{j1})$</td>
<td>$&gt; 60-120$ GeV</td>
<td>20 GeV</td>
</tr>
<tr>
<td>$aM_{T2}$</td>
<td>$&gt; 175-250$ GeV</td>
<td>25 GeV</td>
</tr>
<tr>
<td>$E_T^{miss}$</td>
<td>$&gt; 100-200$ GeV</td>
<td>10 GeV</td>
</tr>
<tr>
<td>$R_{bl}$</td>
<td>$&lt; 0.05-0.7$</td>
<td>0.05</td>
</tr>
</tbody>
</table>

7.2.1 Results and Conclusion of the Optimization of a Cut and Count Method

The results of the optimization procedure are summarized in Table 7.3, which include the signal yields, the background yields, and the sensitivity given by Eq. (7.8). The most optimal cuts for the six assumed signal samples in this analysis are shown in Table 7.4. A visual representation of the achieved sensitivities is presented in Figure 7.9, where only the six combinations of cuts summarized in Table 7.4 are allowed to be applied for all the signal samples in the mass grid.

### Table 7.4: The set of most optimal cuts for the investigated signal samples that are obtained by the optimization procedure.

<table>
<thead>
<tr>
<th>$M_{\tilde{t}}$ [GeV]</th>
<th>275</th>
<th>300</th>
<th>350</th>
<th>400</th>
<th>450</th>
<th>500</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p_T(b_{j1}) + p_T(b_{j2})$ [GeV]</td>
<td>$&gt; 200$</td>
<td>225</td>
<td>300</td>
<td>325</td>
<td>325</td>
<td>400</td>
</tr>
<tr>
<td>$p_T(LF_{j1})$ [GeV]</td>
<td>$&gt; 80$</td>
<td>100</td>
<td>100</td>
<td>120</td>
<td>120</td>
<td>100</td>
</tr>
<tr>
<td>$E_T^{miss}$ [GeV]</td>
<td>$&gt; 100$</td>
<td>110</td>
<td>100</td>
<td>110</td>
<td>180</td>
<td>160</td>
</tr>
<tr>
<td>$aM_{T2}$ [GeV]</td>
<td>$&gt; 175$</td>
<td>175</td>
<td>200</td>
<td>200</td>
<td>250</td>
<td>250</td>
</tr>
<tr>
<td>$R_{bl}$</td>
<td>$&lt; 0.2$</td>
<td>0.2</td>
<td>0.2</td>
<td>0.2</td>
<td>0.25</td>
<td>0.2</td>
</tr>
</tbody>
</table>
From Figure 7.9 it can be concluded that the cuts that are obtained in this procedure are dedicated to the virtual $W$ region of the mass grid as the most optimal performance is achieved for the masses of the supersymmetric particles of $M_{\tilde{\chi}^\pm_1} = 100$ GeV, $M_{\tilde{\chi}^0_1} = 50$ GeV and $250$ GeV $< M_{\tilde{t}} < 550$ GeV.

The yields for the signal samples and standard model background that are summarized in Table 7.3 follow an expected trend. For increasing top squark masses the background and the signal yields decrease as a result of a tighter most optimal set of cuts, as shown in Table 7.4. This is the result of a decreasing production cross section of a top squark pair that is driven by the increase in top squark mass. In order to suppress enough standard model background at these high top squark masses, tighter cuts must be applied. In this tight scenario there is less sensitivity as is shown in Table 7.3 and Figure 7.9.

To get a conclusion using the most optimal set of cuts obtained, the sensitivity should be at least greater than or equal to three. Combining all the results presented in this section concludes that not enough sensitivity is reached with the selected variables and cut ranges in order to give a definitive conclusion. The optimization procedure of a cut and count experiment proved to be too challenging for the virtual $W$ region of the $M_{\tilde{\chi}^\pm_1} = 2M_{\tilde{\chi}^0_1}$ mass grid. For this reason it was decided to change the strategy to a shape fit analysis. The results obtained from the optimization procedure are used as a starting point in the construction of a signal region in this shape fit analysis, which shall be discussed in the following section.

<table>
<thead>
<tr>
<th>$M_{\tilde{t}}$ [GeV]</th>
<th>$S$</th>
<th>$s$</th>
<th>$b$</th>
</tr>
</thead>
<tbody>
<tr>
<td>275</td>
<td>1.49</td>
<td>70</td>
<td>217</td>
</tr>
<tr>
<td>300</td>
<td>1.58</td>
<td>58</td>
<td>169</td>
</tr>
<tr>
<td>350</td>
<td>1.73</td>
<td>58</td>
<td>153</td>
</tr>
<tr>
<td>400</td>
<td>1.49</td>
<td>27</td>
<td>75</td>
</tr>
<tr>
<td>450</td>
<td>1.29</td>
<td>17</td>
<td>52</td>
</tr>
<tr>
<td>500</td>
<td>1.12</td>
<td>11</td>
<td>37</td>
</tr>
</tbody>
</table>

Table 7.3: The results of the optimization procedure. For each signal sample of interest the top squark mass $M_{\tilde{t}}$, the sensitivity $S$, the signal yield $s$ and the background yield $b$ are given.
Figure 7.9: The achieved sensitivities in the optimization procedure as calculated with Eq. (7.8). Only the six combinations of cuts summarized in Table 7.4 are allowed to be applied for each individual signal sample in the mass grid.
8 A Shape Fit Analysis Using the Variable $R_{bl}$

As discussed in the previous section, the optimization procedure of a cut and count method did not reach the desired sensitivity to give a definitive conclusion for the virtual $W$ region of the $M_{\tilde{\chi}_1^\pm} = 2M_{\tilde{\chi}_1^0}$ mass grid. The virtual $W$ region proved to be too challenging compared to the other regions in this mass grid which were defined in Section 6.3 as the signal looks more like the top quark decay which results in a lower discrimination power between the signal and the background.

It was decided to change the analysis strategy from a cut and count method to a shape fit, which employs a multi-binned likelihood method. This shape fit analysis depends on a shape comparison of the standard model background and the top squark signal distributions.

Before performing the shape fit it is important to further reduce the standard model backgrounds with respect to the preselection criteria which were defined in Section 6.5.1. In order to find the optimal cut values for the most discriminating variables an optimization procedure is used. The figure of merit that will be used in this optimization procedure is given by

$$S = \frac{s}{\sqrt{s + b}},$$

(8.1)

where $s$ and $b$ are the number of signal and background events, respectively. This figure of merit will result in a looser set of cuts compared to the figure of merit used for the optimization of a cut and count method which is given by Eq. (7.8).

The variables and ranges that are used in the optimization procedure for the shape fit analysis are the same as for the optimization of the cut and count method and are summarized in Table 7.2. The cuts that are found to be most optimal using the figure of merit shown in Eq. (8.1) are given in Table 8.1. The number of expected background and expected signal events are shown in Table 8.2 together with the sensitivity $S$ that is calculated with Eq. (8.1).

<table>
<thead>
<tr>
<th>$M_{\tilde{t}}$ [GeV]</th>
<th>275</th>
<th>300</th>
<th>350</th>
<th>400</th>
<th>450</th>
<th>500</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p_T(bj_1)+p_T(bj_2)$ [GeV]</td>
<td>&gt; 150</td>
<td>150</td>
<td>225</td>
<td>250</td>
<td>300</td>
<td>325</td>
</tr>
<tr>
<td>$p_T(LFj_1)$ [GeV]</td>
<td>&gt; 0</td>
<td>0</td>
<td>80</td>
<td>80</td>
<td>80</td>
<td>100</td>
</tr>
<tr>
<td>$aMT_2$ [GeV]</td>
<td>&gt; 175</td>
<td>175</td>
<td>175</td>
<td>175</td>
<td>200</td>
<td>200</td>
</tr>
<tr>
<td>$E_T^{miss}$ [GeV]</td>
<td>&gt; 100</td>
<td>100</td>
<td>110</td>
<td>120</td>
<td>120</td>
<td>130</td>
</tr>
<tr>
<td>$R_{bl}$</td>
<td>&lt; 0.5</td>
<td>0.45</td>
<td>0.4</td>
<td>0.4</td>
<td>0.4</td>
<td>0.4</td>
</tr>
</tbody>
</table>

Table 8.1: The set of cuts for the signal samples of interest obtained in the optimization procedure for the shape fit analysis. These cuts were found to be the most optimal using the figure of merit given by Eq. (8.1).

The variable that will be used for fitting is the variable $R_{bl}$, described in Section 7.1.3, which is developed especially for the signal of a top squark including a virtual $W$ boson. This variable has a good discrimination power between the standard model background and a signal from supersymmetry for both low and high top squark masses as can be seen in Table 7.1.

8.1 The Construction of a Signal Region for the Shape Fit Analysis

In the construction of a signal region for the shape fit analysis no cut is applied on the variable $R_{bl}$, since the whole distribution is required to perform a shape comparison.

For the remaining variables the correlations with $R_{bl}$ are studied to see if any of these variables has an impact on the shape of the distribution of $R_{bl}$. The cuts that enter the signal
region should remove the contribution of the standard model background and not alter the
distribution of the signal from a top squark. Affecting the shape of the signal could have a
negative impact on the sensitivity of \( R_{bl} \) if these cuts remove signal events in the region of the
distribution with a high discrimination power between signal and background.

The correlation plots of the variables with \( R_{bl} \) are shown in Figure 8.1 and Figure 8.2
In these correlation plots \( R_{bl} \) is on the x axis and the variable \( aM_{T2}, E_{T}^{\text{miss}}, p_T(LF_{j1}) \) and
\( p_T(b_{j1}) + p_T(b_{j2}) \) are on the y axis. All the distributions are normalized to unity to compare
the signal and the background contours. The standard model background is represented by the
color scale and the signal samples with \( M_{\tilde{t}+} = 100 \text{ GeV}, M_{\tilde{t}0} = 50 \text{ GeV} \) and \( M_{\tilde{t}} = 275 \) or
500 GeV are represented by the black boxes, where the area of a box scales with the magnitude
of the bin content.

The correlation plots in Figure 8.1, Figure 8.2a and
Figure 8.2b show no correlation between \( R_{bl} \) and \( aM_{T2}, E_{T}^{\text{miss}} \) or \( p_T(LF_{j1}) \).

The cut values that are incorporated in the signal
region for the shape fit are represented by red lines in
these figures. For \( aM_{T2} \) the most optimal value found
for lower top squark masses is used, which is equal to
175 GeV.

Considering that the missing transverse energy is
one of the key characteristics of the top squark decay a
choice was made to place the cut at \( E_{T}^{\text{miss}} = 120 \text{ GeV}, \)
which coincides with the most optimal value found
for higher top squark masses.

From Figure 8.2a and Figure 8.2b it can be concluded that there is no possible cut for \( p_T(LF_{j1}) \) that
would remove the bulk of the standard model background distribution and not significantly affect the
shape of the signal. Therefore it was decided to discard a cut on the transverse momentum of the leading
light flavor jet.

From Figures 8.2a and 8.2d it can be concluded that there is a correlation between \( R_{bl} \) and
\( p_T(b_{j1}) + p_T(b_{j2}) \). This correlation affects the shape of the distribution for \( R_{bl} < 0.3 \), which is
the region of the distribution where the signal and the background shapes differ the most.

To further investigate this correlation, the correlations for both \( p_T(b_{j1}) \) and \( p_T(b_{j2}) \) are shown in Figure 8.3. These plots show that the correlation of \( p_T(b_{j1}) + p_T(b_{j2}) \) with \( R_{bl} \)
originates mostly from the correlation of the transverse momentum of the leading b-jet.

In order to reduce the effects of this correlation, a choice was made to cut only on the
transverse momentum of the second leading b-jet. As this variable was not included in the
optimization procedure of the shape fit, the cut value was determined using the correlation
plots only. The choice was made to cut for \( p_T(b_{j2}) > 60 \text{ GeV}, \) which leaves the bulk of the
signal unaffected as shown in Figure 8.3a and Figure 8.3d.

<table>
<thead>
<tr>
<th>( M_{\tilde{t}} ) [GeV]</th>
<th>( S )</th>
<th>( s )</th>
<th>( b )</th>
</tr>
</thead>
<tbody>
<tr>
<td>275</td>
<td>6.39</td>
<td>255</td>
<td>1333</td>
</tr>
<tr>
<td>300</td>
<td>6.22</td>
<td>236</td>
<td>1207</td>
</tr>
<tr>
<td>350</td>
<td>5.16</td>
<td>139</td>
<td>587</td>
</tr>
<tr>
<td>400</td>
<td>3.62</td>
<td>85</td>
<td>468</td>
</tr>
<tr>
<td>450</td>
<td>2.60</td>
<td>45</td>
<td>250</td>
</tr>
<tr>
<td>500</td>
<td>2.00</td>
<td>29</td>
<td>178</td>
</tr>
</tbody>
</table>

Table 8.2: The results of the optimization procedure for the shape fit.
For each signal sample in the region of interest the top squark mass \( M_{\tilde{t}} \), the sensitivity \( S \) calculated using
Eq. (8.1), the signal yield \( s \) and the
background yield \( b \) is shown.
Figure 8.1: The correlation plots with on the $x$ axis $R_{bl}$ and on the $y$ axis $aM_{T2}$ for (a) and (b) and $E_{T}^{\text{miss}}$ for (c) and (d). All signal samples shown in this figure have $M_{\tilde{\chi}_{\pm}} = 100$ GeV and $M_{\tilde{\chi}_{0}} = 50$ GeV, the plots on the left have $M_{t} = 275$ GeV and the plots on the right have $M_{t} = 500$ GeV. All distributions are normalized to unity for comparison.
Figure 8.2: The correlation plots with on the $x$ axis $R_{bl}$ and on the $y$ axis $p_T(LF_{j_1})$ for (a) and (b) and $p_T(b_{j_1}) + p_T(b_{j_2})$ for (c) and (d). All signal samples shown in this figure have $M_{\tilde{\chi}^\pm_1} = 100$ GeV and $M_{\tilde{\chi}^0_1} = 50$ GeV, the plots on the left have $M_{\tilde{t}} = 275$ GeV and the plots on the right have $M_{\tilde{t}} = 500$ GeV. All distributions are normalized to unity for comparison.
Figure 8.3: The correlation plots with on the $x$ axis $R_{bl}$ and on the $y$ axis $p_T(bj_1)$ for (a) and (b) and $p_T(bj_2)$ for (c) and (d). All signal samples shown have $M_{\tilde{\chi}^\pm} = 100$ GeV and $M_{\tilde{\chi}^0_1} = 50$ GeV, the plots on the left have $M_{\tilde{t}_L} = 275$ GeV and the plots on the right have $M_{\tilde{t}_L} = 500$ GeV. All distributions are normalized to unity for comparison.
The procedure to choose a final binning is merging adjacent bins with comparable sensitivities. It was decide to merge all the bins for $R_{bl} > 0.45$, as there is no significant discrimination power in this region of the distribution. For the remaining part of the distribution five additional bins were proposed, resulting in the following bins: 0.00-0.10, 0.10-0.15, 0.15-0.25, 0.25-0.35, 0.35-0.45 and 0.45-1.00. The distributions of the standard model background, the top squark signals and the sensitivities with these merged bins are shown in Figure 8.5.

8.2 A Semi-Data Driven Background Normalization: Control Regions and Validation Regions

As discussed in Section 6, the Monte Carlo simulations tend to overestimate the observed data. In order to rely less on the Monte Carlo a semi-data driven background normalization procedure is used by introducing so-called control regions. These control regions are used to obtain a normalization or scale factor for the dominant standard model backgrounds. In addition to control regions, validation regions are introduced to validate the scale factors obtained by this method. After validation, the scale factors can be propagated to the signal region to get a normalization factor for the standard model backgrounds which improves the agreement between data and Monte Carlo. A schematic view of this method is shown in Figure 8.6.

The control and the validation regions are required to satisfy the following conditions:

1. The signal, the control and the validation regions must be orthogonal with respect to one another, which means that an event that is used in one region cannot be used in a second region.

2. The signal contamination in the control and the validation region, which is the number of expected signal events in these regions, must be kept to a minimum. The scale factors that are used to normalize the standard model backgrounds are calculated using the data. If a large signal contribution is expected in the control region, the resulting scale factors will be too large. For the validation regions a disagreement between data and Monte Carlo could be explained by signal in the case of a large signal contamination.

3. The control and the validation regions must be as close as possible to the signal region, which means that the selection of cuts that define the control and the validation regions must be as similar to the signal region as possible.

The scale factors that are obtained by this method depend on the cuts of the control region. To have a consistent scale factor for the signal region, the cuts of the control region should be as similar to the signal region as possible. Additionally, in order to properly validate the scale factors, the cuts that define the validation region should also be as close as possible to the signal region and the control region.

The two dominant standard model backgrounds that are present in this shape fit analysis are the $t\bar{t}$ and the $W +$ jets backgrounds. Two distinct control regions are introduced in which these backgrounds are dominant to extract the scale factors $\mu_{t\bar{t}}$ and $\mu_{W+\text{jets}}$. For the construction of the control regions the distribution of the transverse mass $m_T$ is used in order to satisfy the orthogonality condition. As discussed in Section 7.1.1 the distribution of $m_T$ peaks around $M_W$ for the $t\bar{t}$ and $W +$ jets backgrounds. For this reason a veto of $60 \text{ GeV} < m_T < 90 \text{ GeV}$ is applied in the signal region. This mass window is used for the two control regions.

The mass window in $m_T$ is used as a $t\bar{t}$ control region, where all other criteria from the signal region carry over. With the inversion of the $m_T$ veto as only difference between the signal region and the $t\bar{t}$ control region, conditions 1 and 3 are automatically satisfied, and the signal contamination will be discussed at the end of this section.
Figure 8.4: The expected yields and sensitivities for $R_{bl}$ with a fine binning ($\Delta R_{bl} = 0.05$) for signal samples with $M_{\tilde{\chi}^\pm} = 100$ GeV, $M_{\tilde{\chi}^0} = 50$ GeV and $M_{\tilde{t}}$ equal to (a) 275 GeV, (b) 300 GeV, (c) 350 GeV, (d) 400 GeV, (e) 450 GeV and (f) 500 GeV. The sensitivities are calculated with Eq. (7.8).
Figure 8.5: The expected yields and sensitivities for $R_{bl}$ with the final binning used in the shape fit for signal samples with $M_{\tilde{\chi}^\pm} = 100$ GeV, $M_{\tilde{\chi}^0} = 50$ GeV and $M_t$ equal to (a) 275 GeV, (b) 300 GeV, (c) 350 GeV, (d) 400 GeV, (e) 450 GeV and (f) 500 GeV. The sensitivities are calculated with Eq. (7.8).
The control region for $W + \text{jets}$, like the $t\bar{t}$ control region, uses the mass window of $60 \text{ GeV} < m_T < 90 \text{ GeV}$. In order to satisfy the orthogonality condition and enhance the $W + \text{jets}$ contribution in this region with respect to $t\bar{t}$, a different $b$-jet multiplicity requirement is applied. The majority of the $W + \text{jets}$ background is expected to contain jets originating from light flavor quarks. Therefore, a $b$-jet veto is applied in this region, i.e. $n_{b\text{-jet}} = 0$. The cut on the transverse momentum of the second leading $b$-jet is dropped as there are no $b$-tagged jets in this region.

In the construction of the two validation regions a different $b$-jet multiplicity with respect to the two control regions is considered. Both regions require a $b$-jet multiplicity of $n_{b\text{-jet}} = 1$. Furthermore, one of the validation regions uses the $m_T$ mass window like the control regions, and one validation region uses the mass veto in $m_T$ like the signal region.

The definitions of the signal region, the two control regions and the two validation regions are summarized in Table 8.3.

<table>
<thead>
<tr>
<th>Region</th>
<th>$n_{b\text{-jet}}$</th>
<th>$E_{\text{miss}}^T$ [GeV]</th>
<th>$p_T(b_{j2})$ [GeV]</th>
<th>$aM_{T2}$ [GeV]</th>
<th>$m_T$ veto / cut</th>
</tr>
</thead>
<tbody>
<tr>
<td>SR</td>
<td>$&gt; 2$</td>
<td>120</td>
<td>60</td>
<td>175</td>
<td>veto</td>
</tr>
<tr>
<td>CR $t\bar{t}$</td>
<td>$&gt; 2$</td>
<td>120</td>
<td>60</td>
<td>175</td>
<td>cut</td>
</tr>
<tr>
<td>CR $W + \text{jets}$</td>
<td>0</td>
<td>120</td>
<td>0</td>
<td>175</td>
<td>cut</td>
</tr>
<tr>
<td>VR Veto</td>
<td>1</td>
<td>120</td>
<td>0</td>
<td>175</td>
<td>veto</td>
</tr>
<tr>
<td>VR Window</td>
<td>1</td>
<td>120</td>
<td>0</td>
<td>175</td>
<td>cut</td>
</tr>
</tbody>
</table>

Table 8.3: The definitions for the signal region (SR), the control region for $t\bar{t}$ (CR $t\bar{t}$), the control region for $W + \text{jets}$ (CR $W + \text{jets}$) and the two validation regions (VR Veto and VR Window). The last column shows if a two-sided cut or a veto is applied for the mass window $60 \text{ GeV} < m_T < 90 \text{ GeV}$.

The expected signal yields and the nominal standard model expectations in the control
Table 8.4: The expected signal yields for an integrated luminosity of 20.3 fb$^{-1}$ in the control regions and the validation regions. For each signal sample $M_{\tilde{t}} = 100$ GeV, $M_{\tilde{\chi}^0_1} = 50$ GeV and the top squark mass is given in the table. For comparison the nominal standard model background yields (SM) before scaling are given in the bottom row.

<table>
<thead>
<tr>
<th>$M_{\tilde{t}}$ [GeV]</th>
<th>CR $t\bar{t}$</th>
<th>CR $W +$ jets</th>
<th>VR Veto</th>
<th>VR Window</th>
</tr>
</thead>
<tbody>
<tr>
<td>275</td>
<td>52.7</td>
<td>3.3</td>
<td>93.6</td>
<td>20.1</td>
</tr>
<tr>
<td>300</td>
<td>53.3</td>
<td>2.7</td>
<td>90.2</td>
<td>19.0</td>
</tr>
<tr>
<td>350</td>
<td>39.7</td>
<td>2.1</td>
<td>66.9</td>
<td>16.3</td>
</tr>
<tr>
<td>400</td>
<td>26.1</td>
<td>2.2</td>
<td>50.0</td>
<td>10.3</td>
</tr>
<tr>
<td>450</td>
<td>14.8</td>
<td>0.7</td>
<td>30.1</td>
<td>6.9</td>
</tr>
<tr>
<td>500</td>
<td>9.4</td>
<td>0.4</td>
<td>19.4</td>
<td>4.1</td>
</tr>
<tr>
<td>SM</td>
<td>537.9</td>
<td>1734.1</td>
<td>2902.3</td>
<td>1380.4</td>
</tr>
</tbody>
</table>

and the validation regions are shown in Table 8.4. As can be seen in this table the signal contamination in the two validation regions and the $W +$ jets control region is negligible. This is an effect of the zero and one $b$-jet requirement for these regions, as the top squark signal samples of interest are expected to have a high abundance of $b$-jets.

In the $t\bar{t}$ control region the signal contamination from the signal samples with a relative light top squark mass ($M_{\tilde{t}} < 350$ GeV) is considerably larger, and peaks around 10% for the signal sample with $M_{\tilde{t}} = 300$ GeV, $M_{\tilde{\chi}^\pm_1} = 100$ GeV and $M_{\tilde{\chi}^0_1} = 50$ GeV.

8.3 The Scaling of the $t\bar{t}$ and the $W +$ Jets Backgrounds

In order to estimate the scale factors for the $t\bar{t}$ and the $W +$ jets backgrounds, the HistFitter package is used [49]. This package does a simultaneous fit in the two control regions to calculate the scale factors $\mu_{t\bar{t}}$ and $\mu_{W + jets}$. The larger signal contamination in the $t\bar{t}$ control region is considered in the fit performed by HistFitter, and despite the resulting reduction in sensitivity it still provides a reliable scale factor for $t\bar{t}$.

The HistFitter package takes into account the statistical and systematic uncertainties in the fitting procedure. The systematic uncertainties include a 10% uncorrelated systematic uncertainty due to the individual properties of the signal and the backgrounds, e.g. the theoretical uncertainty on the production cross section or the Monte Carlo generator uncertainties, and 20% correlated systematic uncertainty which is driven by the jet energy resolution and scale. The systematic uncertainties are applied as flat systematics, i.e. not depending on the measured quantities, and are constrained to a Gaussian distribution.

The resulting yields for the standard model backgrounds after the application of the scale factors are shown in Table 8.5. The extracted scale factors from the control regions are $\mu_{t\bar{t}} = 0.75$ and $\mu_{W + jets} = 0.82$.

In addition to the yields that are presented in Table 8.5, the distributions for $aM_{T2}$, $E_T^{\text{miss}}$ and $R_4$ before and after scaling are shown in Figure 8.7 and Figure 8.8 for the validation region with the veto on $m_T$ and the validation region with the two-sided cut on $m_T$, respectively. These figures are a visual representation of the agreement of data and Monte Carlo. From these figures it can be concluded that there is a good agreement between data and Monte Carlo in the validation regions after the background scaling. This validates the extrapolation of the scale factors $\mu_{t\bar{t}}$ and $\mu_{W + jets}$ to the signal region as explained in Section 8.2, and results in reliable yields for the standard model background in this signal region.

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Figure 8.7: The distributions, normalized to an integrated luminosity of 20.3 fb$^{-1}$, of (from top to bottom) $aM_T^2$, $E_T^{\text{miss}}$, and $R_{bl}$ before (left) and after (right) scaling in the validation region with the veto on $m_T$. The scale factors that are obtained from the control regions are equal to $\mu_{\tilde{t}\tilde{t}} = 0.75$ and $\mu_{W+\text{jets}} = 0.82$. 
Figure 8.8: The distributions, normalized to an integrated luminosity of 20.3 fb\(^{-1}\), of (from top to bottom) \(aM_{T2}\), \(E_{T}\)\(_{\text{miss}}\) and \(R_{bl}\) before (left) and after (right) scaling in the validation region VR Window. The scale factors that are obtained from the control regions are equal to \(\mu_{t\bar{t}} = 0.75\) and \(\mu_{W+jets} = 0.82\).
Table 8.5: The background fit results for the $t\bar{t}$ control region (CR $t\bar{t}$), the $W$ + jets control region (CR $W$ + jets), the validation region with a veto on $m_T$ (VR Veto) and the validation region with a cut on $m_T$ (VR Window), for an integrated luminosity of 20.3 fb$^{-1}$. The errors shown are the statistical plus systematic uncertainties.

<table>
<thead>
<tr>
<th>channel</th>
<th>CR $t\bar{t}$</th>
<th>CR $W$ + jets</th>
<th>VR Veto</th>
<th>VR Window</th>
</tr>
</thead>
<tbody>
<tr>
<td>Observed events</td>
<td>428</td>
<td>1417</td>
<td>2402</td>
<td>1123</td>
</tr>
<tr>
<td>background events</td>
<td>$428 \pm 21$</td>
<td>$1417 \pm 39$</td>
<td>$2339 \pm 77$</td>
<td>$1108 \pm 38$</td>
</tr>
<tr>
<td>$t\bar{t}$ events</td>
<td>$259 \pm 29$</td>
<td>$119 \pm 13$</td>
<td>$913 \pm 103$</td>
<td>$434 \pm 49$</td>
</tr>
<tr>
<td>$t\bar{t} + V$ events</td>
<td>$3.98 \pm 0.87$</td>
<td>$1.19 \pm 0.26$</td>
<td>$12.6 \pm 2.8$</td>
<td>$4.07 \pm 0.89$</td>
</tr>
<tr>
<td>Single top events</td>
<td>$63.3 \pm 13.9$</td>
<td>$20.6 \pm 4.5$</td>
<td>$187 \pm 41$</td>
<td>$74.6 \pm 16.4$</td>
</tr>
<tr>
<td>Diboson events</td>
<td>$11.2 \pm 2.5$</td>
<td>$46.6 \pm 10.2$</td>
<td>$95.3 \pm 20.9$</td>
<td>$47.0 \pm 10.3$</td>
</tr>
<tr>
<td>$W$ + jets (HF) events</td>
<td>$76.3 \pm 7.8$</td>
<td>$417 \pm 42$</td>
<td>$700 \pm 71$</td>
<td>$344 \pm 35$</td>
</tr>
<tr>
<td>$W$ + jets (LF) events</td>
<td>$14.1 \pm 0.8$</td>
<td>$809 \pm 46$</td>
<td>$402 \pm 23$</td>
<td>$201 \pm 11$</td>
</tr>
<tr>
<td>$Z$ + jets events</td>
<td>$0.31 \pm 0.07$</td>
<td>$3.65 \pm 0.80$</td>
<td>$28.8 \pm 6.3$</td>
<td>$3.09 \pm 0.68$</td>
</tr>
</tbody>
</table>

8.4 Discovery, Exclusion and the $CL_s$ Technique

The processes that are involved in the proton-proton collisions are of a stochastic nature. An excess in the number of observed events in comparison to the standard model expectations can either indicate a sign of physics that cannot be explained by the standard model or a statistical fluctuation of the standard model backgrounds. Consequently, to get a definitive conclusion given the number of expected and observed events there is need for a statistical procedure.

These procedures start by defining a test statistic which captures the entire observation in one single number. This test statistic could be as simple as the number of observed events, however, generally more complex functions are used that reach a higher sensitivity with the same signal region. An example is a likelihood ratio given by

$$Q = \frac{L_{s+b}}{L_b},$$

where the likelihood function $L$ is a combined probability to estimate a certain parameter of interest, for example the signal strength $\mu$, given a set of $n$ measurements $(x_1, x_2, \ldots, x_n)$, i.e.

$$L(x_1, x_2, \ldots, x_n|\mu) = \prod_{i=1}^{n} P(\mu|x_i).$$

The likelihood ratio expresses the agreement of data to the signal plus background hypothesis given by the likelihood $L_{s+b}$, when compared to the background only hypothesis given by the likelihood $L_b$.

Two arbitrary probability density functions are shown in Figure 8.9, one for the signal plus background scenario $P(Q|s + b)$ and one for a background only scenario $P(Q|b)$. These probability density functions are used to either exclude one of the hypotheses or claim a discovery. In addition to the two distributions that are shown in Figure 8.9, the observed test statistic that would be representing the data is given by $Q_{obs}$.

The discovery of a theory involving physics that cannot be described by the standard model is specified by a $p$-value, $p_b$, which is the probability of obtaining a value for the background test statistic that is higher than $Q_{obs}$. This $p$-value must be extremely small such that it is unlikely the observations are a result of the background only hypothesis. In order to claim a
Figure 8.9: The description of a hypothesis test where a background only hypothesis is compared to a signal plus background scenario with probability distribution functions $P(Q|b)$ and $P(Q|s+b)$, respectively. The observed value for the test statistic $Q$ is given by $Q_{\text{obs}}$ and the definitions for the $p$-values $p_b$ and $p_{s+b}$ are further described in this section.

discovery, this value should be lower than or equal to $p_b \leq 5.7 \times 10^{-7}$, which corresponds to five standard deviations in a Gaussian distribution.

For the exclusion of a new theory, the observed value for the test statistic is compared to the distribution of the signal plus background hypothesis. For exclusion the $p$-value $p_{s+b}$ is used, which is equal to the probability of finding a value for the signal plus background test statistic lower than $Q_{\text{obs}}$. An exclusion can be claimed at 95% confidence level when the $p$-value is lower than or equal to $p_{s+b} \leq 0.05$, corresponding to two standard deviations in a Gaussian distribution.

The expected discovery potential of the signal region used in the shape fit analysis is given in Table 8.6. For each signal sample and each of the six bins that were defined in Section 8.1 the expected $p$-values and the corresponding number of standard deviations of a Gaussian distribution are given. The yields that are used for the calculation of the $p$-values are given in Table 8.8 in the following section. From Table 8.6 it can be concluded that there is no discovery potential for this signal region.

The observed $p$-values and corresponding number of standard deviations of a Gaussian distribution are given in Table 8.7. From these $p$-values it can be concluded that there is a good agreement between the observed data and the standard model expectations. Due to the absence of an excess in the distribution of $R_{bl}$ and the poor discovery potential, a choice was made to perform an exclusion test for the signal from a top squark decay in the virtual $W$ region of the $M_{\tilde{\chi}^\pm_1} = 2M_{\tilde{\chi}^0_1}$ mass grid.

The method that is used in this analysis to perform an exclusion test is a powerful technique for the exclusion of a theory that describes new physics, in the case where the signal is expected to be small compared to the large standard model backgrounds [50]. This technique, the $CL_s$
method, involves the confidence level of a signal only hypothesis and can be written as

\[ CL_s = P(Q_{s+b} \leq Q_{\text{obs}} | Q_b \leq Q_{\text{obs}}) = \frac{P(Q \leq Q_{\text{obs}} | s + b)}{P(Q \leq Q_{\text{obs}} | b)}. \] (8.4)

The term in the numerator on the right hand side of Eq. [8.4] is the confidence level for a signal plus background scenario, \( CL_{s+b} \), which is given by

\[ CL_{s+b} = \int_{-\infty}^{Q_{\text{obs}}} P(Q|s + b)dQ = p_{s+b}. \] (8.5)

The value of \( CL_{s+b} \) corresponds to the yellow area in Figure 8.9.

The term in the denominator of Eq. [8.4] is the confidence level for a background only scenario, \( CL_b \), and is given by

\[ CL_b = \int_{-\infty}^{Q_{\text{obs}}} P(Q|b)dQ = 1 - p_b. \] (8.6)

The value of \( CL_b \) is equal to \( 1 - p_b \), where \( p_b \) corresponds to the green area in Figure 8.9.

Combining Eq. (8.5) and Eq. (8.6) results in

\[ CL_s = \frac{CL_{s+b}}{CL_b} = \frac{p_{s+b}}{1 - p_b}. \] (8.7)

This value is the confidence level for a signal only hypothesis, which is equal to the confidence level of the signal plus background hypothesis but normalized to the confidence level of the background only hypothesis. The signal hypothesis can be rejected at 95% confidence level for \( CL_s \) values lower than or equal to \( CL_s \leq 0.05 \).

For this analysis the exclusion test is performed using the HistFitter package, which calculates the \( CL_s \)-values using the shape fit and the signal region defined in this analysis.

To calculate the \( CL_s \) values the default test statistic of the LHC is used, which is the one-sided profile-likelihood function. This function is based on the likelihood \( L(\mu, \theta) \), where \( \mu \) is the signal strength and the nuisance parameters are represented by \( \theta \) [51], which are all the parameters that are of no interest. In this analysis these parameters represent the systematic uncertainties.

<table>
<thead>
<tr>
<th>( M_f ) [GeV]</th>
<th>bin 1</th>
<th>bin 2</th>
<th>bin 3</th>
<th>bin 4</th>
<th>bin 5</th>
<th>bin 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>275</td>
<td>0.198 (0.849\sigma)</td>
<td>0.076 (1.436\sigma)</td>
<td>0.036 (1.799\sigma)</td>
<td>0.124 (1.157\sigma)</td>
<td>0.192 (0.872\sigma)</td>
<td>0.319 (0.472\sigma)</td>
</tr>
<tr>
<td>300</td>
<td>0.123 (1.160\sigma)</td>
<td>0.033 (1.834\sigma)</td>
<td>0.038 (1.777\sigma)</td>
<td>0.132 (1.117\sigma)</td>
<td>0.232 (0.732\sigma)</td>
<td>0.346 (0.396\sigma)</td>
</tr>
<tr>
<td>350</td>
<td>0.123 (1.160\sigma)</td>
<td>0.033 (1.834\sigma)</td>
<td>0.079 (1.411\sigma)</td>
<td>0.200 (0.841\sigma)</td>
<td>0.292 (0.547\sigma)</td>
<td>0.388 (0.284\sigma)</td>
</tr>
<tr>
<td>400</td>
<td>0.157 (1.005\sigma)</td>
<td>0.085 (1.369\sigma)</td>
<td>0.190 (0.879\sigma)</td>
<td>0.300 (0.523\sigma)</td>
<td>0.386 (0.291\sigma)</td>
<td>0.425 (0.188\sigma)</td>
</tr>
<tr>
<td>450</td>
<td>0.245 (0.689\sigma)</td>
<td>0.187 (0.889\sigma)</td>
<td>0.293 (0.543\sigma)</td>
<td>0.379 (0.308\sigma)</td>
<td>0.421 (0.199\sigma)</td>
<td>0.455 (0.114\sigma)</td>
</tr>
<tr>
<td>500</td>
<td>0.198 (0.849\sigma)</td>
<td>0.296 (0.536\sigma)</td>
<td>0.375 (0.319\sigma)</td>
<td>0.424 (0.190\sigma)</td>
<td>0.448 (0.131\sigma)</td>
<td>0.470 (0.075\sigma)</td>
</tr>
</tbody>
</table>

Table 8.6: The results of the discovery test where for each signal sample the chargino and neutralino masses are 100 GeV and 50 GeV, respectively, and the top squark mass is given in the first column. For each bin the expected \( p \)-value is given and the corresponding number of standard deviations is shown between parentheses.
Table 8.7: The observed p-values and corresponding standard deviations in a Gaussian distribution for the six different bins. A p-value of 0.5 is given for bins where the number of expected standard model background events exceeds the number of observed events.

<table>
<thead>
<tr>
<th>bin 1</th>
<th>bin 2</th>
<th>bin 3</th>
<th>bin 4</th>
<th>bin 5</th>
<th>bin 6</th>
</tr>
</thead>
<tbody>
<tr>
<td>p-value</td>
<td>0.299</td>
<td>0.5</td>
<td>0.409</td>
<td>0.5</td>
<td>0.495</td>
</tr>
<tr>
<td>σ</td>
<td>0.526</td>
<td>-</td>
<td>0.231</td>
<td>-</td>
<td>0.013</td>
</tr>
</tbody>
</table>

uncertainties, the statistical uncertainties and the two backgrounds scale factors μ_{t\bar{t}} and μ_{W+jets}. The profile-likelihood ratio is given by

\[ \lambda(\mu) = \frac{L(\mu, \hat{\theta})}{L(\hat{\mu}, \hat{\theta})}. \]  

(8.8)

In this equation the denominator is the maximized likelihood function given by the parameters \( \hat{\mu} \) and \( \hat{\theta} \). In the numerator the parameters \( \hat{\theta} \) denote the values for \( \theta \) that maximize \( L \) for a given \( \mu \), and are thus depending on \( \mu \).

Furthermore, an asymptotic approximation is used in the calculation of the p-values. This method makes use of Wilk’s Theorem \cite{52}, which states that the likelihood ratio can be approximated by an asymptotic formula given by

\[ -2 \log(\lambda(\mu)) = \chi^2. \]  

(8.9)

8.5 The Results for the Exclusion in the \( M_{\tilde{\chi}_1^\pm} = 2M_{\tilde{\chi}_1^0} \) Mass Grid

The resulting yields for the standard model backgrounds in the signal region are summarized in Table 8.8. After the scaling of the t\bar{t} and the W + jets backgrounds the data and Monte Carlo predictions are in good agreement as was concluded in the preceding chapter by the p-values that were obtained in the discovery test. Additionally, the distribution of \( R_{\mu} \) is shown in Figure 8.10 where no excess is observed.

<table>
<thead>
<tr>
<th>channel</th>
<th>SR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Observed events</td>
<td>925</td>
</tr>
<tr>
<td>Fitted background events</td>
<td>928 ± 28</td>
</tr>
<tr>
<td>Fitted t\bar{t} events</td>
<td>545 ± 58</td>
</tr>
<tr>
<td>Fitted t\bar{t} + V events</td>
<td>13.4 ± 3.0</td>
</tr>
<tr>
<td>Fitted Single top events</td>
<td>154 ± 34</td>
</tr>
<tr>
<td>Fitted Diboson events</td>
<td>25.1 ± 5.6</td>
</tr>
<tr>
<td>Fitted W + jets (HF) events</td>
<td>156 ± 16</td>
</tr>
<tr>
<td>Fitted W + jets (LF) events</td>
<td>29.4 ± 1.7</td>
</tr>
<tr>
<td>Fitted Z + jets events</td>
<td>4.40 ± 0.99</td>
</tr>
</tbody>
</table>

Table 8.8: The yields in the signal region, for an integrated luminosity of 20.3 fb\(^{-1}\), after extrapolation of the scale factors \( \mu_{t\bar{t}} = 0.75 \) and \( \mu_{W+jets} = 0.82 \). The errors shown are statistical plus systematic uncertainties.

The resulting yields in this signal region are used to calculate the expected and observed \( CL_s \) values, where for the expected \( CL_s \) value the number of observed events is set equal to the

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Figure 8.10: The distribution of $R_{dt}$, normalized to an integrated luminosity of 20.3 fb$^{-1}$ after the application of the scale factors $\mu_{tt} = 0.75$ and $\mu_{W+jets} = 0.82$ which are obtained from the control regions.

number of expected standard model background events. All these values are combined in one plot where a contour represents the expected and observed exclusion at 95% confidence level. The exclusion plot for the $M_{\tilde{\chi}^\pm_1} = 2M_{\tilde{\chi}^0_1}$ mass grid is shown in Figure 8.11.

As can be seen in this exclusion plot, the expected and observed exclusion are in good agreement. The region addressed by this analysis is the virtual W boson region ($\Delta M(\tilde{\chi}^\pm_1, \tilde{\chi}^0_1) < M_W$) and an optimization was done using signal samples with chargino and neutralino masses of $M_{\tilde{\chi}^\pm_1} = 100$ GeV and $M_{\tilde{\chi}^0_1} = 50$ GeV. In this region an exclusion is observed for a top squark mass range of 240 GeV < $M_{\tilde{t}}$ < 430 GeV.

8.6 The Exclusion for the $M_{\tilde{\chi}^\pm_1} = 106$ GeV and $M_{\tilde{\chi}^\pm_1} = 150$ GeV Hypotheses

As discussed in Section 6.2, two additional hypotheses were considered. In these mass grids the chargino mass is constrained to $M_{\tilde{\chi}^\pm_1} = 106$ GeV, which is just above the limit set by LEP [32], and $M_{\tilde{\chi}^\pm_1} = 150$ GeV. The signal region defined in this analysis is obtained after an optimization procedure and study of the behavior of variables for signal samples in the virtual W boson region of the $M_{\tilde{\chi}^\pm_1} = 2M_{\tilde{\chi}^0_1}$ mass grid. Nevertheless, it is interesting to see the performance of this signal region in the two additional mass grids.

The performance in the $M_{\tilde{\chi}^\pm_1} = 150$ GeV is not optimal and only a few signal samples in this mass grid are excluded. The expected and observed $CL_s$ values are shown in Figure 8.12 where signal samples with $CL_s \leq 0.05$ are considered to be excluded at 95% confidence level.

For the implementation of the shape fit in the $M_{\tilde{\chi}^\pm_1} = 106$ GeV mass grid the exclusion plot is shown in Figure 8.13. An exclusion is reached for $M_{\tilde{\chi}^0_1} < 85$ GeV and 220 GeV < $M_{\tilde{t}}$ < 420 GeV. However, one area is not included in this contour which is due to the signal sample with $M_{\tilde{\chi}^0_1} = 1$ GeV, $M_{\tilde{\chi}^\pm_1} = 150$ GeV and $M_{\tilde{t}} = 300$ GeV that is not excluded at 95% confidence.
The expected and observed exclusion limits at 95% confidence level (CL) for the $M_{\tilde{t}} = 2M_{\tilde{\chi}^0}$ mass grid. The limits are obtained by the implementation of a shape fit on the variable $R_{bl}$ in the signal region summarized in Table 8.3. The uncertainties considered are statistical, 20% correlated systematic and 10% uncorrelated systematic uncertainty. The yellow band around the expected exclusion represents the expected $\pm\sigma$ results.

In order to investigate the behavior of this signal sample the expected $CL_s$, the observed $CL_s$, the signal yield and background yield of this particular signal sample and the neighboring signal samples are summarized in Table 8.9. From the information in this table no definitive conclusion can be made on the reason why the signal sample with $M_{\tilde{t}} = 300$ GeV, $M_{\tilde{\chi}^\pm} = 106$ GeV and $M_{\tilde{\chi}^0} = 1$ GeV is not excluded.

Additionally, in Figure 8.14 plots are shown which display the sensitivity per bin, where the sensitivity is calculated with Eq. (7.8). From these figures it can be concluded that the signal sample with $M_{\tilde{t}} = 300$ GeV, $M_{\tilde{\chi}^\pm} = 106$ GeV and $M_{\tilde{\chi}^0} = 1$ GeV is not excluded because of the poor sensitivity in the second bin, which for other signal samples is the most sensitive bin in the distribution of $R_{bl}$.
Figure 8.12: The (a) expected and (b) observed \( CL_s \) values for the \( M_{\tilde{\chi}^\pm} = 150 \) GeV mass grid with the signal region defined in Table 8.3. All white spaces in these plots represent the absence of a signal sample. Signal samples with \( CL_s < 0.05 \) are considered to be excluded at 95% confidence level.
Figure 8.13: The expected and observed exclusion limits at 95% confidence level (CL) for the $M_{\tilde{t}\tilde{\chi}_1^\pm} = 106$ GeV mass grid. The limits are obtained by the implementation of a shape fit on the variable $R_{\text{bl}}$ in the signal region summarized in Table 8.3. The uncertainties considered are statistical, 20% correlated systematic and 10% uncorrelated systematic uncertainty. The yellow band around the expected exclusion represents the expected ±σ results.

<table>
<thead>
<tr>
<th>$M_t$ [GeV]</th>
<th>$M_{\tilde{t}\tilde{\chi}_1^\pm}$ [GeV]</th>
<th>$M_{\tilde{\chi}_1^0}$ [GeV]</th>
<th>exp. $CL_s$</th>
<th>obs. $CL_s$</th>
<th>signal</th>
<th>background</th>
</tr>
</thead>
<tbody>
<tr>
<td>250</td>
<td>106</td>
<td>1</td>
<td>0.0215</td>
<td>0.0321</td>
<td>240</td>
<td>928</td>
</tr>
<tr>
<td>250</td>
<td>106</td>
<td>35</td>
<td>0.0349</td>
<td>0.0306</td>
<td>190</td>
<td>928</td>
</tr>
<tr>
<td>300</td>
<td>106</td>
<td>1</td>
<td>0.1086</td>
<td>0.36</td>
<td>234</td>
<td>928</td>
</tr>
<tr>
<td>300</td>
<td>106</td>
<td>35</td>
<td>0.003</td>
<td>0.0036</td>
<td>210</td>
<td>928</td>
</tr>
<tr>
<td>350</td>
<td>106</td>
<td>1</td>
<td>0.0105</td>
<td>0.0102</td>
<td>181</td>
<td>928</td>
</tr>
<tr>
<td>350</td>
<td>106</td>
<td>35</td>
<td>0.0121</td>
<td>0.006</td>
<td>185</td>
<td>928</td>
</tr>
</tbody>
</table>

Table 8.9: The non-excluded signal point $M_t = 300$ GeV, $M_{\tilde{t}\tilde{\chi}_1^\pm} = 106$ GeV and $M_{\tilde{\chi}_1^0} = 1$ GeV and the adjacent signal samples. The table includes the expected (exp.) and observed (obs.) $CL_s$ values, the signal yield and the background yield.
Figure 8.14: The background and signal yields for the non-excluded signal sample and the adjacent signal points of the mass grid with the assumption of $M_{\tilde{t}} = 106$ GeV. The sensitivities are calculated with Eq. (7.8).
9 Conclusion and Perspectives

In this thesis the results of the search for the top squark are presented. The search is performed using the data recorded by the ATLAS detector with an integrated luminosity of 20.3 fb\(^{-1}\) at a proton-proton center of mass energy of \(\sqrt{s} = 8\) TeV.

The decay mode that is under investigation in this thesis is the decay of a top squark and includes a chargino and a neutralino. These particles are introduced in an \(R\)-parity conserving supersymmetric extension of the standard model. The decay mode of the top squark is given by \(\tilde{t} \rightarrow b\chi_{1}^{\pm} \) followed by the decay \(\chi_{1}^{\pm} \rightarrow W^{\pm}\chi_{1}^{0}\), and for both decays a branching ratio of 100\% is assumed.

There are three unknown parameters in this model which are represented by the masses of the three supersymmetric particles. In order to reduce this complex three-dimensional parameter space a mass constraint is introduced. The main constraint of this thesis relates the chargino and the neutralino mass by \(M_{\chi_{1}^{\pm}} = 2M_{\chi_{1}^{0}}\). The region of the \(M_{\chi_{1}^{\pm}} = 2M_{\chi_{1}^{0}}\) mass grid on which this thesis focuses is defined by the inequality \(\Delta(M_{\chi_{1}^{\pm}}, M_{\chi_{1}^{0}}) < M_{W}\), which results in a \(W\) boson that is emitted off-shell in the chargino decay.

A reinterpretation of this analysis is given by introducing two additional hypotheses which are defined by the mass constraints \(M_{\chi_{1}^{\pm}} = 106\) GeV and \(M_{\chi_{1}^{\pm}} = 150\) GeV.

Two strategies are tested to exclude or confirm the existence of the top squark in the virtual \(W\) region of the \(M_{\chi_{1}^{\pm}} = 2M_{\chi_{1}^{0}}\) mass grid. The first strategy is based on a cut and count method for which an optimization procedure is performed. This procedure resulted in a too low sensitivity to give a definitive conclusion and a second strategy is introduced. To increase the sensitivity of the cut and count method a shape fit analysis is introduced. The results of the optimization of the cut and count method are used as a starting point for this shape fit strategy.

The shape fit employs a shape comparison using the variable \(R_{\tilde{t}b}\), which was introduced in Section 7.1.3 and constructed especially for the virtual \(W\) region of the \(M_{\chi_{1}^{\pm}} = 2M_{\chi_{1}^{0}}\) mass grid. This variable is highly discriminating between signal from supersymmetry and the relevant standard model backgrounds. The \(CL_s\) technique, as described in Section 8.4, is used to give an exclusion limit in the hypotheses with the three introduced mass constraints.

In the mass grid described by the constraint \(M_{\chi_{1}^{\pm}} = 2M_{\chi_{1}^{0}}\) an exclusion is observed for \(M_{\chi_{1}^{\pm}} = 100\) GeV, \(M_{\chi_{1}^{0}} = 50\) GeV and a top squark mass range of \(250\) GeV < \(M_{\tilde{t}} < 430\) GeV at 95\% confidence level.

In the \(M_{\chi_{1}^{\pm}} = 106\) GeV mass grid a signal is excluded for \(M_{\chi_{1}^{0}} < 85\) GeV and \(220\) GeV < \(M_{\tilde{t}} < 420\) GeV at 95\% confidence level, with the exception of a small region around \(M_{\chi_{1}^{0}} = 1\) GeV and \(M_{\tilde{t}} = 300\) GeV. The sensitivity for the signal sample that is not excluded is too low as the variable \(R_{\tilde{t}b}\) did not have enough discrimination power compared to the adjacent signal points.

For the hypothesis with the mass constraint \(M_{\chi_{1}^{\pm}} = 150\) GeV the shape fit with the signal region that is defined for the \(M_{\chi_{1}^{\pm}} = 2M_{\chi_{1}^{0}}\) mass grid does not have enough sensitivity. Only a few signal points around \(M_{\tilde{t}} = 400\) GeV are excluded at 95\% confidence level.

The exclusion reached for the \(M_{\chi_{1}^{\pm}} = 2M_{\chi_{1}^{0}}\) mass grid is in accordance with the goals set in this analysis. Nevertheless, some improvements are proposed.

First, a simplified model for the systematic uncertainties is introduced in this analysis. The systematics are treated as flat systematics, which are independent of any assumptions throughout the analysis, for example the preselection criteria or the bins used for the shape fit on \(R_{\tilde{t}b}\). The first improvement that should be made is a proper handling of the systematic uncertainties that are present, which means that the systematic uncertainties should vary depending on the...
measurements in an event.

Second, the shape fit with the signal region specified for the $M_{\tilde{\chi}_1^\pm} = 2M_{\tilde{\chi}_1^0}$ does not perform optimal for the $M_{\tilde{\chi}_1^\pm} = 150$ GeV mass grid. In order to increase the sensitivity in this mass grid an optimization procedure on the variables that are defined in the signal region for the $M_{\tilde{\chi}_1^\pm} = 2M_{\tilde{\chi}_1^0}$ mass grid should be done to gain more optimal cuts for this hypothesis.

Third, the shape fit performs good for the hypothesis with the $M_{\tilde{\chi}_1^\pm} = 106$ GeV mass constraint. However, in the observed excluded region one signal sample is not excluded, which results in the small non-excluded area that can be seen in the lower part of Figure 8.13. For this signal sample the variable $R_{bd}$ has a lower sensitivity in the bins that are most sensitive for the neighboring signal points. The decrease in sensitivity of this signal sample compared to the adjacent signal points is not understood and a further investigation of the origin of this decrease should be done.

Last, the upcoming run in 2015 with a proton-proton center of mass energy of $\sqrt{s} = 13$ GeV will result in more data that can be used for analysis. This will increase the performance of the shape fit and due to the increased center of mass energy compared to the 2012 data, extends the reach of this signal region to higher top squark masses.
References


Appendices
A The Study of a Veto in the Transverse Mass Distribution

In Section 7.1.1 the transverse mass of the leptonically decaying W boson is introduced. In general this variable has a good discrimination power between the top squark signal and the standard model backgrounds, and the introduction of a cut would significantly reduce the contribution of standard model backgrounds.

In the region of interest of this analysis, the top squark signal samples contain a W boson that is emitted off-shell in the $\tilde{\chi}_1^\pm \rightarrow W^\pm \tilde{\chi}_1^0$ decay. A characteristic property of these signal samples is the absence of a peak in the distribution of the transverse mass as shown in Figure A.1. A cut on $m_T$ would significantly reduce the signal selection efficiency for the signal samples including a virtual W boson.

To improve the signal selection efficiency in comparison to the application of a one-sided cut, a veto in the transverse mass distribution is investigated. This appendix summarizes the results of three different mass windows and for comparison a cut on $m_T$ is included. The three mass windows and the cut on $m_T$ are listed in Table A.1.

| Veto A       | $50 \text{ GeV} < m_T < 100 \text{ GeV}$ |
| Veto B       | $65 \text{ GeV} < m_T < 85 \text{ GeV}$  |
| Veto C       | $60 \text{ GeV} < m_T < 90 \text{ GeV}$  |
| Cut A        | $m_T > 100 \text{ GeV}$                 |

Table A.1: The three mass windows in the transverse mass distribution that are investigated for the signal samples with a W boson that is emitted off-shell. Additionally, a one-sided cut is included for comparison.

All three mass windows are asymmetric around the W mass $M_W = 80.385 \text{ GeV}$ as the distribution for $t\bar{t}$, shown in Figure A.1, has an asymmetric peak around the W boson mass. The distributions for the $t\bar{t}$ sample and two signal samples after the application of the vetos and the cut can be seen in Figure A.2, where the signal samples have $M_{\tilde{t}} = 275$ or 500 GeV, $M_{\tilde{\chi}^\pm_1} = 100 \text{ GeV}$ and $M_{\tilde{\chi}^0_1} = 50 \text{ GeV}$.

Veto A is chosen to fully veto the peak of the $t\bar{t}$ distribution, Veto B removes only a small mass window around the maximum of the peak and Veto C performs in between Veto A and Veto B.

The resulting signal and background selection efficiencies are summarized in Table A.2 and are expressed as $\varepsilon = N/N_{\text{preselection}}$, where $N_{\text{preselection}}$ is the number of selected events after applying the preselection criteria as defined in Section 6.5.1 and $N$ is the number of preselected events that pass the veto or the cut requirement.

A cut in $m_T$ at 100 GeV would result in a standard model background selection efficiency to 0.1 and an average signal selection efficiency of approximately 0.2, from which can be concluded that a cut on $m_T$ is too tight for this region of the $M_{\tilde{\chi}^\pm_1} = 2M_{\tilde{\chi}^0_1}$ mass grid.

Veto A removes a lot of preselected signal events and was not considered. While Veto B has a good signal selection efficiency, the reduction of the number of selected background events was considered to be more optimal in Veto C. Therefore, Veto C was found to have the best performance and is included in the analysis.
Figure A.1: The distributions of the transverse mass, normalized to unity, for $t\bar{t}$ and two signal samples with $M_t = 275$ or 500 GeV, $M_{\tilde{\chi}^\pm} = 100$ GeV and $M_{\tilde{\chi}_1^0} = 50$ GeV.

<table>
<thead>
<tr>
<th>$M_t$ [GeV]</th>
<th>Veto A</th>
<th>Veto B</th>
<th>Veto C</th>
<th>Cut A</th>
</tr>
</thead>
<tbody>
<tr>
<td>275</td>
<td>0.6987</td>
<td>0.8791</td>
<td>0.8155</td>
<td>0.1794</td>
</tr>
<tr>
<td>300</td>
<td>0.6844</td>
<td>0.8727</td>
<td>0.8090</td>
<td>0.1845</td>
</tr>
<tr>
<td>350</td>
<td>0.6921</td>
<td>0.8717</td>
<td>0.8135</td>
<td>0.1964</td>
</tr>
<tr>
<td>400</td>
<td>0.6828</td>
<td>0.8766</td>
<td>0.8121</td>
<td>0.1994</td>
</tr>
<tr>
<td>450</td>
<td>0.6980</td>
<td>0.8801</td>
<td>0.8155</td>
<td>0.2393</td>
</tr>
<tr>
<td>500</td>
<td>0.6973</td>
<td>0.8856</td>
<td>0.8211</td>
<td>0.2635</td>
</tr>
<tr>
<td>$t\bar{t}$</td>
<td>0.5005</td>
<td>0.7670</td>
<td>0.6659</td>
<td>0.1275</td>
</tr>
<tr>
<td>$tt + V$</td>
<td>0.5985</td>
<td>0.8191</td>
<td>0.7385</td>
<td>0.2526</td>
</tr>
<tr>
<td>Single top</td>
<td>0.5016</td>
<td>0.7655</td>
<td>0.6651</td>
<td>0.0980</td>
</tr>
<tr>
<td>Dibosons</td>
<td>0.5117</td>
<td>0.7644</td>
<td>0.6695</td>
<td>0.0992</td>
</tr>
<tr>
<td>$Z +$ jets</td>
<td>0.8738</td>
<td>0.9458</td>
<td>0.9181</td>
<td>0.0451</td>
</tr>
<tr>
<td>$W +$ jets (HF)</td>
<td>0.4952</td>
<td>0.7597</td>
<td>0.6582</td>
<td>0.0846</td>
</tr>
<tr>
<td>$W +$ jets (LF)</td>
<td>0.4862</td>
<td>0.7495</td>
<td>0.6455</td>
<td>0.0758</td>
</tr>
<tr>
<td>Standard Model Combined</td>
<td>0.4998</td>
<td>0.7495</td>
<td>0.6624</td>
<td>0.1067</td>
</tr>
</tbody>
</table>

Table A.2: The signal and background selection efficiencies after the application of the vetos and the cut summarized in Table A.1. The efficiency is given by $\varepsilon = N/N_{\text{preselection}}$, where $N_{\text{preselection}}$ is the number of events that pass the preselection criteria, and $N$ is the number of preselected events that pass the veto or the cut criteria. The standard model background samples for $W +$ jets is split into a heavy flavor (HF) and a light flavor (LF) sample.
Figure A.2: The distribution of the transverse mass, normalized to unity, for $t\bar{t}$ and two signal samples after the application of (a) Veto A, (b) Veto B, (c) Veto C and (d) Cut A as summarized in Table A.1. The signal samples shown have masses for the supersymmetric particles of $M_{\tilde{t}} = 275$ or 500 GeV, $M_{\tilde{\chi}^\pm_1} = 100$ GeV and $M_{\tilde{\chi}^0_1} = 50$ GeV.
B  Preselection Variables Before and After Background Scaling

Figure B.1: The distributions, normalized to an integrated luminosity of 20.3 fb$^{-1}$, of (from top to bottom) $n_{\text{jet}}$, $p_T(j_1)$ and $p_T(j_2)$ before (left) and after (right) scaling in the validation region with the veto on $m_T$. The scale factors that are obtained from the control regions are equal to $\mu_{t\bar{t}} = 0.75$ and $\mu_{W+\text{jets}} = 0.82$. 
Figure B.2: The distributions, normalized to an integrated luminosity of 20.3 fb$^{-1}$, of (from top to bottom) $p_T(j_3)$, $p_T(j_4)$ and $\Delta\phi(j_1, E_T^{\text{miss}})$ before (left) and after (right) scaling in the validation region with the veto on $m_T$. The scale factors that are obtained from the control regions are equal to $\mu_{t\bar{t}} = 0.75$ and $\mu_{W^+ +\text{jets}} = 0.82$. 
Figure B.3: The distributions, normalized to an integrated luminosity of 20.3 fb$^{-1}$, of (from top to bottom) $\Delta\phi(j_2, E_T^{\text{miss}})$, $E_T^{\text{miss}}/\sqrt{H_T}$ and $m_T$ before (left) and after (right) scaling in the validation region with the veto on $m_T$. The scale factors that are obtained from the control regions are equal to $\mu_{t\bar{t}} = 0.75$ and $\mu_{W^{+}\text{jets}} = 0.82$. 

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Figure B.4: The distributions, normalized to an integrated luminosity of 20.3 fb$^{-1}$, of (from top to bottom) $n_{\text{jet}}$, $p_T(j_1)$ and $p_T(j_2)$ before (left) and after (right) scaling in the validation region with a two-sided cut on $m_T$. The scale factors that are obtained from the control regions are equal to $\mu_{t\bar{t}} = 0.75$ and $\mu_{W+jets} = 0.82$. 

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Figure B.5: The distributions, normalized to an integrated luminosity of 20.3 fb$^{-1}$, of (from top to bottom) $p_T(j_3)$, $p_T(j_4)$ and $\Delta \phi(j_1, E_{\text{miss}})$ before (left) and after (right) scaling in the validation region with a two-sided cut on $m_T$. The scale factors that are obtained from the control regions are equal to $\mu_t = 0.75$ and $\mu_{W+\text{jets}} = 0.82$. 

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Figure B.6: The distributions, normalized to an integrated luminosity of 20.3 fb$^{-1}$, of (from top to bottom) $\Delta \phi(j_2, E^\text{miss}_T)$, $E^\text{miss}_T / \sqrt{H_T}$ and $m_T$ before (left) and after (right) scaling in the validation region with two-sided cut on $m_T$. The scale factors that are obtained from the control regions are equal to $\mu_t = 0.75$ and $\mu_W + \text{jets} = 0.82$. 

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