Search for the supersymmetric partner of the top quark with a mass of 250 GeV

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July 4, 2014

Abstract

We searched for the supersymmetric partner of the top quark assuming it to have a mass of 250 GeV, decaying into a $b$ quark and a chargino, where the chargino decays into a $W$ and a neutralino. The chargino is assumed to have a mass of 106 GeV and the neutralino a mass of 1 GeV. Some of the main motivations for supersymmetry and the theory behind supersymmetry itself are explained in Chapter 2. Monte Carlo simulations provided the modelling of signal and background events. A number of requirements, that are described in Chapter 4, were optimised to reduce the background and keep as much signal events as possible. Then these cuts were applied to 20 fb$^{-1}$ of data recorded by ATLAS at a $\sqrt{s} = 8$ TeV. After this a discovery test was performed computing a standard deviation of 2.3$\sigma$ and an exclusion test computing a CLs $> 99\%$. This can be found in Chapter 6. For a discovery the standard deviation has to have a minimum of 5$\sigma$ and for an exclusion CLs has to be $> 95\%$. This means the top squark with a mass of 250 GeV can be excluded. Further searches can be performed for stops of different masses.
Contents

1 Introduction 3

2 Theory 3
   2.1 Introduction to SUSY 3
   2.2 Particles and Sparticles 6

3 The ATLAS Detector 7

4 Event Selection 9

5 Asymmetric Distribution of $\Delta \phi$ between the leading jet and $E_T^{\text{miss}}$ 13

6 Discovery or Exclusion 14
   6.1 Poisson Distribution 14
   6.2 Results on Experimental Data 16

7 Conclusion and discussion 17
1 Introduction

The Standard Model (SM) describes all known elementary particles: fermions (quarks and leptons) and bosons ($W^\pm, Z, \gamma$, gluons and the Higgs boson). Fermions are matter and antimatter particles and bosons are force particles which mediate the interaction between fermions. Quantum chromodynamics (QCD) describes the strong interactions while the electromagnetic and weak interactions are described by the electroweak theory (EWT). With the discovery of the Higgs boson in 2012 [1], which implies the existence of the Higgs field, the SM has been confirmed. The Higgs field explains why when symmetries say fundamental particles should be massless they however do have mass and ensures the electroweak radiative corrections to not become infinite. The SM has been tested to predict the experimental measurements of particle physics to a precision of greater than .1%, but it is still incomplete. Examples are the large quadratically contribution to the Higgs boson mass, dark matter and the three gauge couplings which do not meet at high energy. These problems can be solved by an additional theory, supersymmetry (SUSY).

SUSY introduces supersymmetric partners of the particles of the Standard Model, which have the same mass and quantum number but a different spin. However, no supersymmetric partner has (yet) been observed at the LHC, so SUSY must be a broken symmetry with a non-zero mass difference between the particles and their corresponding SUSY partners. Up until now a range of masses of the top squark has been excluded, but there is a non-excluded gap at a mass of 250 GeV.

We search for the supersymmetric partner of the top quark, $\tilde{t}$, with a mass of 250 GeV, which decays with an assumed branching ratio of 100% to a $b$ jet and a chargino and the chargino decays with an assumed branching ratio of 100% to a $W$ and a neutralino. The chargino mass is assumed to be 106 GeV and neutralino mass 1 GeV. Monte Carlo (MC) simulations are used to model signal events and background events. Signal events represent the top squarks and background events represent the SM processes that have a final state similar to the topology of the top squark signal. The background events can be characterised by different kinematics with respect to signal events, so cuts can be placed at different observables with the purpose of rejecting the background while keeping as much signal as possible. These cuts are optimised by a figure of merit, after which a discovery or an exclusion of the top squark can be expected. Next the same cuts are applied to 20 fb$^{-1}$ of data recorded by ATLAS at a $\sqrt{s} = 8$ TeV and two tests are performed, i.e. a discovery test and an exclusion test.

2 Theory

2.1 Introduction to SUSY

One of the problems of the Standard Model is the large quadratically divergent contribution to the Higgs boson mass shown as the top diagram in Figure 1. This contribution is of order $O(10^{18}$ GeV), while the Higgs mass is measured to be 126 GeV [1]. To cancel the quadratically divergent contribution to the Higgs boson mass a mass counterterm, $\delta M_h^2$, is introduced and has to have a magnitude of order $10^{16}$.

$$ M_h^2 = M_h^2 + \frac{\lambda}{4\pi^2} \Lambda^2 + \delta M_h^2 $$
Equation 1 shows the definition of the Higgs mass squared, where $M_h^2$ is the Higgs boson mass, $M_{h0}^2$ is the "bare" Higgs boson mass, i.e. before corrections, $\Lambda$ is a momentum cutoff to regulate the loop integral which must be of order Planck scale and $\delta M_h^2$ is the mass counterterm [2]. Due to the unnaturalness of this cancellation and due to the fact that it must occur at every order in perturbation theory this cancellation is one of the main motivations for supersymmetry (SUSY).

SUSY is a theory which contains in addition to the Higgs field, $h$, both fermions, $\psi$, and massive scalars, $\phi$. A recalculation of the one-loop contribution to $M_h^2$ shown in Equation 1 with this Lagrangian gives Equation 2 (this equation only contains the interesting terms), with $g_F$ the fermion coupling, $m_F$ the fermion mass, $g_S$ the scalar coupling and $m_S$ the scalar mass.

$$M_h^2 \sim M_{h0}^2 + \frac{g_F^2}{4\pi^2}(\Lambda^2 + m_F^2) - \frac{g_S^2}{4\pi^2}(\Lambda^2 + m_S^2)$$ (2)

Fermi statistics causes the relative minus sign between the fermion and scalar contributions to the Higgs boson mass-squared. When $g_S = g_F$ equation 2 turns into an easier contribution to the Higgs boson mass.

$$M_h^2 \sim M_{h0}^2 + \frac{g_F^2}{4\pi^2}(m_F^2 - m_S^2)$$ (3)

This is a well behaved contribution as long as the fermion and scalar masses don’t differ too much. Therefore, SUSY solves the quadratic contribution at every order of perturbation theory by means of an additional symmetry. [2]

Supersymmetry relates fermions and bosons. It introduces particles with the same quantum number and the same mass as the particles in the Standard Model, but with differing spin. SUSY combines particles into a superfield containing fields differing by 1/2 unit of spin. The scalar superfield is the simplest example of a superfield, which includes a complex scalar, $S$, and a two-component Majorana fermion, $\psi$. A Majorana fermion is a fermion which is equal to its charge conjugate, $\psi^c = \psi$. The scalar superfield has a Lagrangian that depends on just one mass term, the mass term is the same for the scalar as for the fermion. The Lagrangian is invariant under transformations which take the fermion into the scalar and the other way around. Since the
fermions and bosons are partners due to SUSY, the same coupling applies to both the scalar and
fermion interactions and the cancellation of quadratic divergences occurs automatically. Now,
there is no supersymmetric scalar partner observed at the LHC for any of the fermions in the
Standard Model so supersymmetry must be a broken symmetry. Supersymmetry breaking is
based on a non-zero mass splitting between the particles of a superfield. [2]

The simplest supersymmetric model of the SM is called the Minimal Supersymmetric Standard
Model (MSSM) and is a direct supersymmetrization of the SM except for the fact that it has two
Higgs doublet fields. The MSSM contains the smallest number of new particle states and new
interactions consistent with phenomenology. The MSSM gauge symmetry group for the theory
is the same as the Standard Model gauge group $SU(3)_C \times SU(2)_L \times U(1)_Y$, which consists of 12
gauge bosons: 8 gluons, 3 weak bosons and one photon. $C$ represents colour, $L$ isospin and $Y$
hypercharge. In the SM there are no baryon and lepton number violating interactions, since they
are forbidden to contribute to dimension- 4 operators by the gauge symmetries and are supressed
by factors of some heavy mass scale in dimension- 6 operators where they first arise, but in the
MSSM the baryon and lepton number are no longer conserved. However, without baryon number
and lepton number conservation the lifetime of a proton would be $10^{-2}$ seconds. Observations
show it will take more than $10^{33} - 10^{34}$ years for a proton to decay so the number violating terms
need to be forbidden by a symmetry to not re-appear at higher orders of perturbation theory to
get a reasonable lifetime of a proton. This symmetry is called R-parity which state that Standard
Model particles have R-parity +1 and their SUSY partners have R-parity -1 and can be defined
as Equation 4. [2]

$$R \equiv (-1)^{3(B-L)+s}$$

Here $B$ is the baryon number, $L$ the lepton number and $s$ the spin of the particle. R-parity is a
multiplicative quantum number so SUSY partners can only be pair produced from SM particles.
These SUSY particles (sparticles) are highly unstable and cause a decay chain. Because of R-parity
conservation there has to be a lightest SUSY partner (LSP) at the end of the decay chain which
has to be stable and initiated by the decay of a heavy unstable SUSY particle. The LSP has to
be electrically and colour neutral to be consistent with cosmological constraints [3]. Because it is
a neutral particle, it leaves the detector undetected directly (like the neutrino) and may therefore
be a candidate for the non baryonic dark matter, also known as the Weakly Interacting Massive
Particle (WIMP), which is a about a quarter of the total energy density of the known universe. In
this search the LSP is referred to as the neutralino, $\tilde{\chi}^0$, which will be explained in subsection 2.2.
The candidate for dark matter is another main motivation for supersymmetry.

Besides the cancellation of the quadratically divergent contribution and the explanation for
dark matter, another motivation for supersymmetry is presented in the following. For the Grand
Unified Theory (GUT), a theory where the three gauge interactions are merged into one single
force, a meeting of the three gauge couplings is required at high energy. Coupling constants
represent the strength of the force exerted in an interaction. In gauge theory coupling constants
scale with energy according to a specific function. This way a coupling constant at any energy
can be predicted if it is measured at one energy scale. At one loop Equation 5 holds,
\[
\frac{1}{\alpha_i(Q)} = \frac{1}{\alpha_i(M)} + \frac{b_i}{2\pi} \log\left(\frac{M}{Q}\right)
\]
with \(i = \{1, 2, 3\}\). \(b_i\) depends on the numbers \(N_g\) (number of generations) and \(N_H\) (number of Higgs doublets), where in the Standard Model \(N_g = 3\) and \(N_H = 1\). With \(M = M_Z\) and the measured values of the coupling constants at the Z-pole and having the couplings evolved to high energy, Figure 2 is obtained. There is no meeting of the coupling constants at high energy, however with the introduction of SUSY a meeting of the coupling constants is possible. In SUSY

\[\text{Figure 2: Gauge couplings experimentally measured at the Z-pole in the Standard Model. } \alpha_i^* \equiv \frac{5}{3} \alpha_i \text{ (the relevant coupling in Grand Unified Theories).} \]

\[\text{Figure 3: Gauge couplings experimentally measured at the Z-pole in a low energy SUSY model, with the SUSY thresholds at } 1 \text{ TeV. } \alpha_i^* \equiv \frac{5}{3} \alpha_i \text{ (the relevant coupling in Grand Unified Theories).} \]

\(b_i\) depends on the numbers \(N_g\) and \(N_H\), with \(N_g = 3\) and \(N_H = 2\). The coupling constants scale as in Figure 3, with the SUSY thresholds taken to be at 1 TeV, and meet at a scale around \(10^{16}\) GeV. [2]

\[2.2 \text{ Particles and Sparticles} \]

The fermions of the Standard Model, quarks and leptons, are shown in Table 1, and in Table 2 their supersymmetric spin-zero (boson) partners, squarks and sleptons, are shown. The Higgs boson and the gauge bosons (\(\gamma, W^\pm, Z\) and gluons) have fermionic partners in SUSY, which have 'ino' added to the name of their corresponding SM particle. The mass eigenstates of the charged and neutral gauginos and higgsinos are called charginos, \(\tilde{\chi}^\pm\), and neutralinos, \(\tilde{\chi}^0\), respectively. More information about the naming of the SUSY particles can be found in Ref. [3]. The large mixing between the partners of the left-handed and right-handed top quark reduces the mass of the lightest stop mass eigenstate. Therefore, the top squark, \(\tilde{t}\), might be the lightest of the squarks [4].

\[6\]
Table 1: Quarks and leptons of the Standard Model.

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<thead>
<tr>
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<tr>
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<td>$\tilde{u}$</td>
<td>$\tilde{c}$</td>
<td>$\tilde{t}$</td>
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<td>$\tilde{d}$</td>
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<td>$\tilde{e}$</td>
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<tr>
<td>$\tilde{\nu}_e$</td>
<td>$\tilde{\nu}_\mu$</td>
<td>$\tilde{\nu}_\tau$</td>
</tr>
</tbody>
</table>

Table 2: Squarks and sleptons of SUSY.

| $\tilde{u}$ | $\tilde{c}$ | $\tilde{t}$ |
| $\tilde{d}$ | $\tilde{s}$ | $\tilde{b}$ |
| $\tilde{e}$ | $\tilde{\mu}$ | $\tilde{\tau}$ |
| $\tilde{\nu}_e$ | $\tilde{\nu}_\mu$ | $\tilde{\nu}_\tau$ |

3 The ATLAS Detector

Every 50 ns two bunches of billions of protons pass through each other in the ATLAS (A Toroidal LHC ApparatuS) detector in the Large Hadron Collider (LHC), providing proton-proton collisions with a $\sqrt{s}$ up to 14 TeV. The ATLAS detector measures the particles coming out of these collisions. ATLAS is cylindrically symmetric and is composed of different layers, a cut-away view is displayed in Figure 4. The inner detector (ID) is provided by a 2 T magnetic field from a thin surrounding superconducting solenoid. The ID provides pattern recognition, momentum and vertex measurements and electron identification. The next layer is the liquid-argon (LAr) electromagnetic calorimeter (ECAL), which measures the energy of occurring electromagnetic particles. Many different segments in the ECAL provide two different measurement regions, i.e. the pseudo-
dorapidity range $|\eta| < 2.5$ for accurate measuring and the range $2.5 < |\eta| < 4.9$ for less accurate measuring. The hadronic calorimeter (HCAL), composed of a scintillator-tile calorimeter and two LAr calorimeters, is surrounding the ECAL and measures the energy of hadronic particles in the range $|\eta| < 4.9$. The calorimeters are surrounded by the muon spectrometers that are placed in an air-core toroid system with an eight-fold azimuthal symmetry. The toroid system provides a magnetic field causing muons to be deflected allowing their energy to be measured.

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The coordinate system of ATLAS is defined as follows: the origin is where the collision takes place, the $z$-axis is in the beam direction and the $x$-$y$ plane is the transverse plane to the beam direction, where the positive $x$-axis is pointing towards the center of the LHC and the positive $y$-axis is pointing upwards. The angle around the $z$-axis is the azimuthal angle $\phi$ and the polar angle $\theta$ is the angle of a particle relative to the beam axis. The pseudorapidity $\eta = -\ln \tan(\theta/2)$ is a massless approximation of rapidity, $y = \frac{1}{2} \ln \frac{E+p_z}{E-p_z}$, a Lorentz invariant variable. Variables in the transverse plane are the transverse energy, $E_T$, the transverse momentum, $p_T$, and the missing transverse energy, $E_T^{\text{miss}}$. The total initial energy in the transverse plane is zero, but there can be a non-zero total final energy in the transverse plane, caused by for example non-detectable WIMPs or neutrinos. The energy of all the missing particles in total is referred to as missing transverse energy. The distance $\Delta R$ between two objects in the detector in the pseudorapidity-azimuthal angle space is defined as $\Delta R = \sqrt{\Delta \eta^2 + \Delta \phi^2}$. [6]

Figure 5 presents a scheme of the cross section of the ATLAS detector showing the trace of a photon. [7]
direction of the particle since positive and negative particles are curved in opposite directions. Quarks that are created will hadronise and will be recognised by the ID as jets. Electromagnetic particles (photons and electrons) and hadrons collide with the dense material of the electromagnetic calorimeter and the hadronic calorimeter respectively. When particles hit the calorimeter, they decay into other particles which will also decay until all the energy is deposited. The energy of the original particle is reconstructed by summing the energies of the newly created particles. Muons pass both the tracker and the calorimeters and are therefore the only charged particles which are detected in the muon chambers what they generally pass as well. As muons will not deposit all their energy in the detector, their energy is calculated by looking at the curve of their path caused by the magnetic field. [8]

4 Event Selection

The top squark decay considered in this search decays into a \( b \) quark and a chargino. A \( b \) quark can easily be distinguished from the other quarks due to the longer lifetime of the hadrons that contain a \( b \) quark. One lepton in the form of an electron or a muon in the final state is required and although this rejects quite a few stop events, all events with only hadrons in the final state which are not from stop decays will also be rejected. A large amount of background can be distinguished by the requirement of the decay of the top squark into a \( b \) quark and the requirement of one lepton in the final state.

\[
\tilde{t} \rightarrow b \tilde{\chi}^\pm \rightarrow b \tilde{\chi}^0 W.
\]

Figure 6: Scheme of the decay of a stop quark with \( \tilde{t} \rightarrow b \tilde{\chi}^\pm \rightarrow b \tilde{\chi}^0 W \). The lepton is an electron or a muon.

In Figure 6 a scheme of the considered decay of the top squark is shown. The cross section of a pair of top squarks with both a mass of 250 GeV is \( \sigma_{\tilde{t}\tilde{t}} = 5.6 \) pb. Both the top squarks decay into a \( b \) quark and a chargino with a branching ratio of 100%, where the chargino decays into a \( W \) and a neutralino also with a branching ratio of 100%. One \( W \) decays into a lepton and a neutrino and the other \( W \) decays into two quarks. This decay chain contains 4 jets originating from the two \( b \) quarks and the two quarks from the hadronically decaying \( W \). A missing transverse energy is produced by the neutrino and the two neutralinos that escape the detector without interacting. The requirements that focus on this decay are presented in Table 3. The particles are ranked in order of decreasing momentum, \( p_T \).

After these preselection requirements, the main background will be due to top quark pair production, a scheme is shown in Figure 7. This process has a cross section of \( \sigma_{tt} = 241 \pm 42 \) pb [9]. The second main background is due to the events where a \( W \) and jets are produced together,
Preselection requirements

<table>
<thead>
<tr>
<th>Requirement</th>
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<tbody>
<tr>
<td>Number of jets $\geq 4$</td>
</tr>
<tr>
<td>$E_T^{\text{miss}} &gt; 100$ GeV</td>
</tr>
<tr>
<td>$p_T$ of jet 1 $&gt; 60$ GeV</td>
</tr>
<tr>
<td>$p_T$ of jet 2, 3, 4 $&gt; 25$ GeV</td>
</tr>
<tr>
<td>Number of $b$ jets $\geq 2$</td>
</tr>
<tr>
<td>$p_T$ of the lepton $&gt; 25$ GeV</td>
</tr>
</tbody>
</table>

Table 3: Preselection requirements to focus on the assumed decay.

Figure 7: Scheme of the decay of a top quark, the main background process.

Figure 8: Scheme of $W + 2$ jets, the second main background process.

a scheme is shown in Figure 8. The cross section of a process with the production of a $W$ together with four jets is $\sigma_{W + \text{jets}} = 0.019 \pm 0.011$ nb [10]. The jets can originate from light flavoured (LF) quarks (up, down, strange) or heavy flavoured (HF) quarks (bottom, charm). The $t\bar{t}$ events have the same topology in the final state as the top squark decay, only the missing transverse energy is due to one neutrino. The $W + \text{jets}$ event shown in Figure 8 has the jets only coming from the gluon splitting or extra gluon or quark radiation and the missing transverse energy from a neutrino.

For the search of the top squark the number of observed background events has to be greatly reduced with additional cuts on kinematic variables, while keeping as much signal events as possible. The significance of a set of cuts is determined by Equation 6, where $\text{sig}$ is the significance, $S$ the number of signal events, $B$ the number of background events and 0.2 represents the 20% systematic uncertainty due to calibration of the jet energy measurement by ATLAS.

$$\text{sig} = \frac{S}{\sqrt{B + (0.2 \times B)^2}}$$

The optimal cut value is the one that maximises the significance. The additional cuts have been chosen after an optimisation procedure with the purpose to maximise the significance and are shown in Table 4.

- Jet 1 is the jet with the highest $p_T$, i.e. the leading jet, lepton is the required lepton, i.e. an electron or a muon, and $b$ jet 2 is the next-to-leading $b$ jet.
- $M_T^2$ [11] is a kinematic variable designed to identify the $t\bar{t}$ background where both top quarks decay leptonically as $t \rightarrow bW \rightarrow b\ell\nu$, but one lepton is lost because it is not reconstructed,
<table>
<thead>
<tr>
<th>Additional cuts</th>
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<tbody>
<tr>
<td>$180 \text{ GeV} &lt; M_{T2}^a &lt; 250 \text{ GeV}$</td>
</tr>
<tr>
<td>$120 \text{ GeV} &lt; m_{lep}^T &lt; 180 \text{ GeV}$</td>
</tr>
<tr>
<td>$p_T$ of $b$ jet 2 &gt; 80 GeV</td>
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<tr>
<td>$E_{T, \text{sig}} &gt; 5.8$</td>
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<tr>
<td>$\sqrt{s_{\text{min}}} &lt; 1090 \text{ GeV}$</td>
</tr>
<tr>
<td>$\Delta\eta(\text{lepton, jet}\ 1) &lt; 1.6$</td>
</tr>
</tbody>
</table>

Table 4: Cuts that are applied to the signal and background events.

out of the detector acceptance or not identified. This decay is shown in Figure 9, where the missing particles are indicated with a dashed line. The top quark with the detected lepton at the end of its decay is said to be the first top quark and the top quark with the missing lepton is the second top quark. At the decay of the first top quark the $b$ jet and the detected lepton are the visible particle, $b_1 + l$, and the neutrino is the missing transverse energy, $p_1$, where at the decay of the second top quark, the $b$ jet is the visible particle, $b_2$, and the $W$ is the missing transverse energy, $p_2$. Equation 7 shows the definition of $M_{T2}^a$,

$$M_{T2}^a = \min\{\max[M_T(\vec{p}_b^1 + \vec{p}_l^T), M_T(\vec{p}_b^2, \vec{p}_2^T)]\}$$

(7)

The lepton is paired with the one of the two $b$ jets whose combination produces a smaller $M_{T2}^a$ and the variable is calculated by minimising over all possible combinations of $\vec{p}_1^T$ and $\vec{p}_2^T$.

- $m_{lep}^T$ is the transverse mass of the $W$ from the top quark decay that decays into a lepton and a neutrino. $m_{lep}^T = \sqrt{2p_T^{lep}E_{miss}^T(1 - \cos\phi)}$
\[- |\Delta \phi (\text{jet } 1, E_{\text{miss}}^T)| = |\phi_{\text{jet}1} - \phi_{E_{\text{miss}}^T}| \]

\[- |\Delta \phi (\text{lepton, jet } 1)| = |\phi_{\text{lepton}} - \phi_{\text{jet}1}| \]

\[- \Delta \eta (\text{lepton, jet } 1) = \eta_{\text{lepton}} - \eta_{\text{jet}1} \]

\[- E_{\text{miss}}^T_{\text{sig}} \] is the significance of $E_{\text{miss}}^T$ and is defined as in Equation 8, where $H_T^4 = \sum_{i=1}^{4} p_T(jet_i)$.

$$E_{\text{miss}}^T_{\text{sig}} = \frac{E_{\text{miss}}^T}{\sqrt{H_T^4}}$$ (8)

$\sqrt{s}_{\text{min}}^{(\text{sub})}$ is a variable that describes the hard scattering of an event without including underlying event effects (UE), initial state radiation (ISR) and multiple parton interactions (MPI) [12]. The visible particles of the event are divided in two groups: the subsystem and the upstream system. The subsystem consists of the visible particles that are guaranteed not to originate from UE and the upstream system consists of the remaining visible particles. The subsystem has $n_{\text{sub}}$ particles and has a total energy and momentum of $E_{(\text{sub})}$ and $\vec{P}_{(\text{sub})}$ respectively. Analogously the upstream system has a total energy and momentum of $E_{(\text{up})}$ and $\vec{P}_{(\text{up})}$. The invisible particles of the event are assumed to originate only from within the subsystem and have total momentum $\vec{P}_{\text{miss}}^T$. Equation 9 shows the definition of $\sqrt{s}_{\text{min}}^{(\text{sub})}$, where $M_{\text{miss}}^{\text{sub}} = \sum_{i=1}^{n_{\text{sub}}} m_i$. A more detailed illustration of $\sqrt{s}_{\text{min}}^{(\text{sub})}$ along with its derivation can be found in Ref. [12].

$$\sqrt{s}_{\text{min}}^{(\text{sub})} (M_{\text{miss}}^{\text{sub}}) = \left\{ \left( \sqrt{M_{\text{sub}}^2 + P_{T(\text{sub})}^2} + \sqrt{(M_{\text{miss}}^{\text{sub}})^2 + (P_{T(\text{miss}})^2) \right)^2 - (\vec{P}_{T(\text{sub})} + \vec{P}_{T(\text{miss})})^2 \right\}^\frac{1}{2} \quad (9)$$

In Figure 10 to 13 distributions of the most discriminating variables are shown. In each figure the preselection cuts are applied and three additional cuts chosen from Table 4. In Table 5 the chosen cuts for each of the figures can be found. The cutting threshold value of each distribution is indicated by an arrow pointing towards the area that will be left after applying the cut. The region that will be rejected contains a very low signal-to-background ratio as opposed to the region indicated by the arrow. Figure 10 to 13 show that the cuts in Table 4 are the optimal values to maximise the signal significance.

<table>
<thead>
<tr>
<th>Figure</th>
<th>Additional cuts</th>
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<tbody>
<tr>
<td>Figure 10</td>
<td>$m_T^{lep} &gt; 120$ GeV, $p_T$ of b jet 2 &gt; 80 GeV, $</td>
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<tr>
<td>Figure 11</td>
<td>$M_{T2}^2 &gt; 180$ GeV, $p_T$ of b jet 2 &gt; 80 GeV, $</td>
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<tr>
<td>Figure 12</td>
<td>$M_{T2}^2 &gt; 180$ GeV, $m_T^{lep} &gt; 120$ GeV, $</td>
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<tr>
<td>Figure 13</td>
<td>$M_{T2}^2 &gt; 180$ GeV, $m_T^{lep} &gt; 120$ GeV, $p_T$ of b jet 2 &gt; 80 GeV</td>
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Table 5: The cuts applied at each of the Figures 10 to 13.
Figure 10: The distribution of \( M_{T2} \) with the preselection cuts and the cuts \( m_{T}^{lep} > 120 \) GeV, \( p_T \) of \( b \) jet 2 > 80 GeV and \( |\Delta \phi(\text{jet 1, } E_T^{miss})| < 3.0 \). The cut \( M_{T2} > 180 \) GeV is indicated by an arrow.

Figure 11: The distribution of \( m_{T}^{lep} \) with the preselection cuts and the cuts \( M_{T2} > 180 \) GeV, \( p_T \) of \( b \) jet 2 > 80 GeV and \( |\Delta \phi(\text{jet 1, } E_T^{miss})| < 3.0 \). The cut \( m_{T}^{lep} > 120 \) GeV is indicated by an arrow.

Figure 12: The distribution of \( p_T \) of \( b \) jet 2 with the preselection cuts and the cuts \( M_{T2} > 180 \) GeV, \( m_{T}^{lep} > 120 \) GeV and \( |\Delta \phi(\text{jet 1, } E_T^{miss})| < 3.0 \). The cut \( p_T \) of \( b \) jet 2 > 80 GeV is indicated by an arrow.

Figure 13: The distribution of \( \Delta \phi(\text{jet 1, } E_T^{miss}) \) with the preselection cuts and the cuts \( M_{T2} > 180 \) GeV, \( m_{T}^{lep} > 120 \) GeV and \( p_T \) of \( b \) jet 2 > 80 GeV. The cut \( |\Delta \phi(\text{jet 1, } E_T^{miss})| < 3.0 \) is indicated by an arrow.

5 Asymmetric Distribution of \( \Delta \phi \) between the leading jet and \( E_T^{miss} \)

Figure 14 shows the distribution of \( \Delta \phi \) between the leading jet and \( E_T^{miss} \) after all the cuts shown in Table 3 and Table 4 except for the requirement \( |\Delta \phi(\text{jet 1, } E_T^{miss})| < 3.0 \). As can be seen in the figure more signal events have a positive \( \Delta \phi \), while the background events show a symmetric
distribution. A cut only on negative $\Delta \phi$ between the leading lepton and $E_T^{\text{miss}}$ would mean a higher significance, but there is no physical reason to do this. Bidimensional scatterplots are made to study correlations between $\Delta \phi$ and the three most discriminating variables of Table 4, $M_T^2$, $m_T^{\text{lep}}$, and the $p_T$ of $b$ jet 2. The asymmetric distribution of signal events is already present after the cuts on these variables as can be seen from Figure 13. The variable which shows to contribute the most to an asymmetric $\Delta \phi$ between the leading jet and $E_T^{\text{miss}}$ is $m_T^{\text{lep}}$. The scatterplot is shown in Figure 15. The cuts that are applied are the preselection cuts, $M_T^2 > 180$ GeV and $p_T$ of $b$ jet 2 $> 80$ GeV. At lower transverse mass ($m_T^{\text{lep}} < 120$ GeV) a bit more signal events are situated at negative $\Delta \phi$ and for $m_T^{\text{lep}} > 120$ GeV slightly more signal events are situated at positive $\Delta \phi$, which suggests more signal events will have a positive $\Delta \phi$ after the cut. Still this variable shows no striking evidence for the asymmetric distribution of $\Delta \phi$ between the leading jet and $E_T^{\text{miss}}$ of signal events. The asymmetric distribution is interpreted as a statistical fluctuation of the MC simulation. The cut on $\Delta \phi$ between the leading jet and $E_T^{\text{miss}}$ is therefore kept symmetric.

6 Discovery or Exclusion

6.1 Poisson Distribution

After applying all the cuts of Table 4 we expect $21.8 \pm 4.2$ signal events and $9.8 \pm 0.6$ background events. Two different tests are performed, i.e. a discovery test and an exclusion test.

In Figure 16 the Poisson distribution for a discovery with an expected background of 10 events is shown. If there is a discovery the SM is not enough to explain the observed number of data events and this number will deviate more than $5\sigma$ [13] from the expected number of background events. This means the integral above the number of data events has to be smaller than $5.7 \times 10^{-7}$. The minimum number of data events that would need to be observed for a discovery is 31 events and
is indicated by the red arrow in Figure 16. With the expected number of signal and background events a number of 32 data events is expected. The integral above this number is calculated to be $1.0 \times 10^{-7}$ (5.2σ). This means with the expected event numbers a discovery can be achieved.

In Figure 17 the Poisson distribution for exclusion is shown. The mean is at 32, which is the sum of the number of background and the number of signal events. For an exclusion of the top squark of 250 GeV the observed number of data events will be compatible with the expected number of background events. To determine if an exclusion is obtained the CLs is calculated, the confidence level in the signal, and has to be greater than 95% [13] (2σ) for an exclusion. To calculate the CLs the integral of the Poisson distribution shown in Figure 17 above the observed number of data events is determined. To have an exclusion a number of 23 of data events or less is needed, which is indicated by the red arrow in Figure 17. With an expected number of background events of 10 a CLs > 99% (4.2σ) is expected. This means with the expected event numbers an exclusion can be achieved.

![Poisson Distribution for Discovery](image)

Figure 16: The Poisson distribution for a discovery. The number of background events is the mean and is indicated by the dotted arrow, the number of data events is indicated by a blue arrow and the minimum number of events needed for a discovery is indicated by a red arrow.

Up to now, only poissonan statistical uncertainty was considered. However, ATLAS measurements are characterised by statistical uncertainty of the MC simulation and systematic uncertainty due to calibration of the jet energy measurement. The statistical uncertainty of the available Monte Carlo simulation statistic for background is 6% and the systematic uncertainty is the same as in
Equation 6, 20%. To also take these uncertainties into account in the discovery and exclusion toy MC experiments [14] are computed. The total uncertainty is \( \epsilon_{tot} = \sqrt{\epsilon_{stat}^2 + \epsilon_{syst}^2} = 21\% \). A total of \( 10^7 \) toy experiments determine the standard deviation of the expected background and signal events to be \( 4.5\sigma \) (which corresponds to an integral of \( 4.2 \times 10^{-6} \)). The CLs is determined to be \( > 99\% \ (4.0\sigma) \). With the uncertainties taken into account only an evidence \( (> 3\sigma) \) for a discovery can be concluded, but not a discovery itself. However, an exclusion can still be concluded.

![Poisson Distribution for Exclusion](image)

**Figure 17:** The Poisson distribution for an exclusion. The number of background events plus the number of signal events is the mean and is indicated by the dotted arrow, the number of data events is indicated by a blue arrow and the maximum number of events needed for a discovery is indicated by a red arrow.

### 6.2 Results on Experimental Data

The same cuts are applied to 20 fb\(^{-1}\) of data recorded by ATLAS at a \( \sqrt{s} = 8 \) TeV which yield an observed number of 17 events. The integral of the Poisson distribution of Figure 16 above 17 is calculated to be \( 2.0 \times 10^{-2} \ (2.3\sigma) \). This is not close to a discovery, it is not even evidence \( (3\sigma) \) for a discovery. From \( 10^6 \) toy experiments assuming 21\% systematic uncertainty on the expected background events, the probability is determined to be \( 5.4 \times 10^{-2} \ (1.6\sigma) \), which also concludes no discovery is made. To see if there is proof for an exclusion instead, CLs is calculated and is equal to \( > 99\% \ (3.1\sigma) \). This is more than the 95\% needed for an exclusion. Considering systematic uncertainties, \( 10^6 \) toy experiments give a result of \( > 99\% \ (2.6\sigma) \), which is also more than 95\%. 

16
The top squark with a mass of 250 GeV can be excluded.

## 7 Conclusion and discussion

We searched for a top squark with a mass of 250 GeV. The decay of the top squark is assumed to have a branching ratio of 100% into a $b$ quark and a chargino of mass 106 GeV. The chargino decays with an assumed branching ratio of 100% to a $W$ and a neutralino of mass 1 GeV. One lepton was required in the final state. The background and signal events were simulated with a Monte Carlo simulation. To the background and signal events the following cuts were applied:

- number of jets $\geq 4$
- $E_T^{\text{miss}} > 100$ GeV
- $p_T$ of jet 1 $> 60$ GeV
- $p_T$ of jet 2, 3, 4 $> 25$ GeV
- number of $b$ jets $\geq 2$
- 180 GeV $< M_T^2 < 250$ GeV
- 120 GeV $< m_{lep}^T < 180$ GeV
- $p_T$ of jet 2 $> 80$ GeV
- $|\Delta \phi (\text{jet 1, } E_T^{\text{miss}})| < 3.0$
- $|\Delta \phi (\text{lepton, jet 1})| < 1.6$
- $E_{T,\text{sig}}^{\text{miss}} > 5.8$
- $\sqrt{s}^{(\text{sub})}_{\text{min}} < 1090$ GeV
- $\Delta \eta (\text{lepton, jet 1}) < 1.6$

The cuts provided an expected number of 21.8 $\pm$ 4.2 of signal events and an expected number of 9.8 $\pm$ 0.6 of background events. After this the cuts were applied to 20 fb$^{-1}$ of data recorded by ATLAS at a $\sqrt{s} = 8$ TeV during 2012. This resulted in 17 observed data events. With the results of this search the standard deviation is determined to be 2.3$\sigma$, so no discovery is made. CLs is determined to be $> 99\%$, which is more than the 95% needed for an exclusion. The top squark of 250 GeV is proven to be excluded.

The distribution of $\Delta \phi$ between the leading jet and $E_T^{\text{miss}}$ of signal is a somewhat asymmetric distribution, more signal events have a positive $\Delta \phi$ in stead of a negative $\Delta \phi$. A cut at only negative $d \phi$ would mean a higher significance, but there is no physical reason to do so. An investigation on a possible unknown correlation between $\Delta \phi$ between the leading jet and $E_T^{\text{miss}}$ and another variable leaded to the assumption that the asymmetric distribution is due to statistical fluctuations. More research to this variable can lead to an answer to the asymmetric distribution of the signal events.
The top squark of mass 250 GeV is proven to be excluded, even with the statistical and systematic error taken into account. This does not mean supersymmetry does not exist. In the future the LHC will operate again and at higher energy, producing more data in a wider energy range. Further search for the top squark can be performed at different masses of the top squark, chargino and neutralino to look for evidence for SUSY.
References


