Search for scalar top quark pair production in natural gauge mediated supersymmetry models with the ATLAS detector in pp collisions at $\sqrt{s} = 7$ TeV


DOI
10.1016/j.physletb.2012.07.010

Publication date
2012

Document Version
Final published version

Published in
Physics Letters B

Citation for published version (APA):

General rights
It is not permitted to download or to forward/distribute the text or part of it without the consent of the author(s) and/or copyright holder(s), other than for strictly personal, individual use, unless the work is under an open content license (like Creative Commons).
1. Introduction

Supersymmetry (SUSY) [1–9] provides an extension to the Standard Model (SM) which can resolve the hierarchy problem. For each known boson or fermion, SUSY introduces a particle (sparticle) with identical quantum numbers except for a difference of half a unit of spin. The non-observation of the sparticles implies that SUSY is broken and the superpartners are generally heavier than the SM partners. In the framework of a generic R-parity conserving minimal supersymmetric extension of the SM (MSSM) [10–14], SUSY particles are produced in pairs and the lightest supersymmetric particle (LSP) is stable.

The scalar partners of right-handed and left-handed quarks, \( \tilde{q}_R \) and \( \tilde{q}_L \), can mix to form two mass eigenstates. In the case of the scalar top quark (\( \tilde{t}_1 \) stop), large mixing effects due to the Yukawa coupling, \( y_t \), and the trilinear coupling, \( A_t \), can lead to one top mass eigenstate, \( \tilde{t}_1 \), that is significantly lighter than other squarks. Consequently, the \( \tilde{t}_1 \) could be produced with large cross sections at the LHC via direct pair production.

Light stop masses are favoured by arguments of ‘naturalness’ of electroweak symmetry breaking [15], because of the possibly large coupling between the \( \tilde{t}_1 \) and the Higgs boson, \( h \). In particular, radiative corrections to the Higgs boson mass mainly arise from the stop–top loop diagrams including top Yukawa and three-point stop–stop–Higgs interactions.

In gauge mediated SUSY breaking (GMSB) models [16–21], gauge interactions (messengers) are responsible for the appearance of soft supersymmetry breaking terms. If the characteristic scale of the mass of the messenger fields is about 10 TeV, an upper bound on \( m_\chi \) of about 400 GeV is found when imposing the absence of significant (\( \sim 10\% \)) fine tuning [15]. In GMSB, the gravitino \( \chi \) is the LSP (in general \( m_\chi \ll 1 \) keV). The experimental signatures are largely determined by the nature of the next-to-lightest SUSY particle (NLSP). For several GMSB models the NLSP is the lightest neutralino, \( \tilde{\chi}_1^0 \), promptly decaying to its lighter SM partner through gravitino emission. Neutralinos are mixtures of gaugino (\( \tilde{B}, \tilde{W}^0 \)) and higgsino (\( \tilde{H}_u^0, \tilde{H}_d^0 \)) gauge-eigenstates, and therefore the lightest neutralino decays to either a \( \gamma \), \( Z \) or Higgs boson. If the \( \tilde{\chi}_1^0 \) is higgsino-like, it decays either via \( \tilde{\chi}_1^0 \rightarrow h\tilde{\tilde{\nu}} \) or \( \tilde{\chi}_1^0 \rightarrow Z\tilde{\tilde{e}} \). Light higgsinos lead to a large higgsino component in \( \tilde{\chi}_1^0 \) and a small mass difference between \( \tilde{\chi}_1^0 \) and \( \tilde{\tilde{\chi}}_1^\pm \). In particular, if the higgsino mass (\( |m_\mu| \)) is much smaller than the gaugino masses (pure higgsino case), \( \tilde{\chi}_1^0 \) and \( \tilde{\tilde{\chi}}_1^\pm \) are almost degenerate such that the \( (\tilde{\tilde{f}}\tilde{f}') \) sector resulting from the chargino decay \( \tilde{\chi}_1^\pm \rightarrow \tilde{\chi}_1^0 f f' \) is very soft.

In this Letter, a search for direct stop pair production is presented, assuming a GMSB model where the \( \tilde{\chi}_1^0 \) is purely higgsino-like and is lighter than the \( \tilde{\tilde{\nu}}_1 \) [22]. The model parameters are

\[
m_{\tilde{q}_1} = m_{\tilde{b}_1} = -A_t/2; \quad \tan \beta = 10,
\]

where \( m_{\tilde{q}_1} \) and \( m_{\tilde{b}_1} \) are the soft SUSY breaking masses for the left- and right-handed third-generation squarks, respectively, and \( \tan \beta \) is the ratio of the vacuum expectation values of up-type and down-type Higgs field. In these scenarios, masses of first
and second generation squarks and gluinos (superpartners of the gluons) are above 2 TeV, the \( t \) mass eigenstates are such that \( m_{\tilde{t}_2} \gg m_{\tilde{t}_1} \) and only \( \tilde{t}_1 \)-pair production is considered in what follows. Stops decay either via \( \tilde{t}_1 \rightarrow b \tilde{\chi}_1^+ \) or, if kinematically allowed, via \( \tilde{t}_1 \rightarrow t \tilde{\chi}_1^{0(2)} \). For the scenarios considered, the subsequent decay \( \tilde{\chi}_1^0 \rightarrow Z\tilde{\chi}_1^0 \) has a branching ratio (BR) between 1 and 0.65 for \( m_{\tilde{t}_1} \) between 100 GeV and 350 GeV [23]. Thus, the expected signal is characterised by the presence of two jets originating from the hadronisation of the \( b \)-quarks (\( b \)-jets), decay products of \( Z \) (or \( h \)) bosons and large missing transverse momentum — its magnitude is here referred to as \( E_T^{\text{miss}} \) — resulting from the undetected gravitinos.

This search uses data recorded between March and August 2011 by the ATLAS detector at the LHC. After the application of beam, detector, and data quality requirements, the dataset corresponds to a total integrated luminosity of \( 2.05 \pm 0.08 \text{ fb}^{-1} \) [24,25]. To enhance the sensitivity to the aforementioned SUSY scenarios, events are required to contain energetic jets, of which one must be identified as a \( b \)-jet, large \( E_T^{\text{miss}} \) and two opposite-sign, same flavour leptons (\( \ell = e, \mu \)) with invariant mass consistent with the \( Z \) boson mass, \( m_Z \). This is the first search for scalar top quarks decaying via \( Z \) bosons in GMSB models. General searches for supersymmetric particles in events with a \( Z \) boson, energetic jets and missing transverse momentum have been reported by the CMS Collaboration [26]. Searches for direct stop pair production have been performed at the CDF and D0 experiments assuming different SUSY mass spectra and decay modes (see for example Refs. [27] and [28]).

### 2. The ATLAS detector

The ATLAS detector [29] consists of inner tracking devices surrounded by a superconducting solenoid, electromagnetic and hadronic calorimeters, and a muon spectrometer with a toroidal magnetic field.

The inner detector system, in combination with the 2 T field from the solenoid, provides precision tracking of charged particles for \( |\eta| < 2.5 \) [2]. It consists of a silicon pixel detector, a silicon microstrip detector and a straw tube tracker that also provides transition radiation measurements for electron identification. The calorimeter system covers the pseudorapidity range \( |\eta| < 4.9 \). It is composed of sampling calorimeters with either liquid argon (LAr) or scintillating tiles as the active media. The muon spectrometer surrounds the calorimeters. It consists of a set of high-precision tracking chambers placed within a magnetic field generated by three large superconducting eight-coil toroids. The spectrometer, which has separate trigger chambers for \( |\eta| < 2.4 \), provides muon identification and measurement for \( |\eta| < 2.7 \).

### 3. Simulated event samples

Simulated event samples are used to aid in the description of the background, as well as to determine the detector acceptance, the reconstruction efficiencies and the expected event yields for the SUSY signal.

---

1. ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the centre of the detector and the z-axis coinciding with the axis of the beam pipe. The x-axis points from the IP to the centre of the LHC ring, and the y-axis points upward. Cylindrical coordinates \((r, \phi)\) are used in the transverse plane, \(\phi\) being the azimuthal angle around the beam pipe. The pseudorapidity is defined in terms of the polar angle \( \theta \) as \( \eta = -\ln \tan(\theta/2) \). The distance \( \Delta R \) in the \( \eta - \phi \) space is defined as \( \Delta R = \sqrt{(\Delta \eta)^2 + (\Delta \phi)^2} \).
lated, such that the $p_T$ sum of tracks ($\Sigma p_T$, not including the electron track), within a cone in the $(\eta, \phi)$ plane of radius $\Delta R = 0.2$ around the candidate must be less than 10% of the electron $p_T$.

Muons are reconstructed using an algorithm [57] which combines the inner detector and the muon spectrometer information (combined muons). A muon is selected for the analysis only if it has $p_T > 10$ GeV and $|\eta| < 2.4$, and the sum of the transverse momenta of tracks within a cone of $\Delta R = 0.2$ around it is less than 1.8 GeV. To reject cosmic rays, muons are required to have longitudinal and transverse impact parameters within 1 mm and 0.2 mm of the primary vertex, respectively.

Following the object reconstruction described above, overlaps between jet candidates and leptons are resolved. Any jet within a distance $\Delta R = 0.2$ of a candidate electron is discarded. Any remaining lepton within $\Delta R = 0.4$ of a jet is discarded.

The $E_T^{miss}$ is calculated from the vectorial sum of the transverse momenta of jets (with $p_T > 20$ GeV and $|\eta| < 4.5$), electrons and muons — including non-isolated muons [58]. The four vectors of calorimeter clusters not belonging to other reconstructed objects are also included.

During 40% of the data-taking period, a localised electronics failure in the LAr barrel calorimeter created a dead region in the second and third calorimeter layers ($\Delta \eta \times \Delta \phi \simeq 1.4 \times 0.2$) in which, on average, 30% of the incident energy is not measured. If a jet with $p_T > 50$ GeV or an electron candidate falls in this region, the event is rejected. The loss in signal acceptance is less than 10% for the models considered.

5. Event selection

The data are selected with a three-level trigger system based on the presence of leptons. Two trigger paths are considered: a single electron trigger, reaching a plateau efficiency for electrons with $p_T \geq 25$ GeV, and a combined muon + jet trigger, reaching a plateau efficiency for muons with $p_T > 20$ GeV and jets with $p_T \geq 60$ GeV.

Events must pass basic quality criteria against detector noise and non-collision backgrounds [54] are required to have a reconstructed primary vertex associated with five or more tracks; when more than one such vertex is found, the vertex with the largest summed $p_T^2$ of the associated tracks is chosen.

The selections applied in this analysis are listed below:

- To ensure full efficiency of the trigger, events are selected if they contain at least one electron with $p_T > 25$ GeV or one muon with $p_T > 20$ GeV.
- Exactly two same flavour opposite-sign leptons ($ee$, $\mu\mu$) are required, such that their invariant mass $m_{\ell\ell}$ is within the $Z$ mass range (86 GeV < $m_{\ell\ell}$ < 96 GeV). Events with additional electron or muon candidates are vetoed.
- Events must include at least one jet with $p_T > 60$ GeV and one additional jet with $p_T > 50$ GeV.
- At least one jet with $p_T > 50$ GeV and $|\eta| < 2.5$ is required to be $b$-tagged.

Two signal regions, referred to as SR1 and SR2, are defined using two different $E_T^{miss}$ threshold requirements in order to maximise the sensitivity across the $t\bar{t}Z^0$ mass plane. For SR1, $E_T^{miss} > 50$ GeV is required and it is chosen for models with $\Delta m = m_{t\bar{t}} - m_{Z^0}$ larger than 100 GeV or $m_{t\bar{t}} < 300$ GeV, where moderate missing transverse momentum is expected. SR2 is optimised for small $\Delta m$ scenarios and events are required to have $E_T^{miss} > 80$ GeV.

The signal efficiencies, which include the $Z \rightarrow ee, \mu\mu$ BR, acceptance and detector effects, vary across the $t\bar{t}Z^0$ mass plane.

6. Background estimation

The main SM processes contributing to the background are, in order of importance, top quark pair and single top quark production, followed by the associated production of $Z$ bosons and heavy-flavour jets — referred to as $Z + hf$.

The top background is evaluated using control regions (CRs) that are the same as the SRs with the exception of the $m_{\ell\ell}$ requirement (modified to 15 GeV < $m_{\ell\ell}$ < 81 GeV or $m_{\ell\ell}$ > 101 GeV). Depending on the corresponding signal region, CRs are labelled as CR1 and CR2. In both cases, negligible yields from the targeted SUSY signals are expected. The background estimation in each SR is obtained by multiplying the number of events observed in the corresponding CR — corrected using simulations for non-top backgrounds — by a transfer factor, defined as the ratio of the MC-predicted yield in the signal region to that in the control region:

\[
N_{SR}^{top} = \frac{N_{CR}^{top,MC}}{N_{CR}^{top,MC}} \frac{N^{obs}_{CR} - N^{non-top,MC}_{CR}}{N^{obs}_{SR} - N^{non-top,MC}_{SR}}
\]  

(2)

where $N^{obs}_{CR}$ denotes the observed yield in the CR. For each CR, the contribution from other SM processes accounts for less than 10% of the total. The estimate based on this approach benefits from a cancellation of systematic uncertainties that are correlated between SRs and CRs. The distribution of $m_{\ell\ell}$ for CR1 is shown in Fig. 1. The experimental uncertainties, described in Section 7, are displayed. They include effects due to jet energy scale and resolution [54] (JES), $b$-tagging [55] and lepton identification (ID) efficiencies [56, 57, 59]. The number of expected events for 2.05 fb$^{-1}$ of integrated luminosity as predicted by the MC simulation is in good agreement with data for both CRs without introducing data/MC scaling factors.

The topology of $Z + hf$ production events is similar to that of the signal, especially in low $t\bar{t}Z^0$ mass scenarios. Therefore the background from the $Z + hf$ process is estimated from MC simulation and validated in a control region where events passing all SR selection criteria except for a reversed $E_T^{miss}$ cut ($E_T^{miss} < 50$ GeV)
are considered. Possible signal contamination in the control region varies across the \(t_1 - \chi_{1}^0\) mass range. As an example, for \(m_{\chi_1^0} \lesssim 100\) GeV, the contamination is 5% (80%) of the total predicted SM background for \(m_{\chi_1^0} \simeq 350\) (150) GeV. In Fig. 2 the \(E_T^{\text{miss}}\) distribution is shown in the range 0–50 GeV for \(ee + \mu\mu\) final states. The number of events observed in data is in good agreement with the SM expected yields within experimental uncertainties.

Backgrounds from W + jets and multi-jet production, referred to as “fake-lepton” contributions, are subdominant. In this case, events passing the selection contain at least one misidentified or non-isolated lepton (collectively called “fakes”). The fake-lepton background estimate is obtained using the data-driven approach described in Ref. [60]. The probability of misidentifying a jet as a signal lepton is estimated in control regions dominated by multi-jet events where exactly one pre-selected lepton, at least one b-tagged jet and low \(E_T^{\text{miss}}\) are required.

Finally, background contributions from diboson, Ztt, Wtt and t\(\bar{t}\)b\(\bar{t}\) events — referred to as ‘Others’ — are estimated from MC simulation. They account for less than 3% of the total SM background in either SR.

7. Systematic uncertainties

Various systematic uncertainties affecting the background rates and signal yields have been considered. The values quoted in the following refer to \(ee\) and \(\mu\mu\) channels summed.

Systematic uncertainties on the top background expectations vary between 11% and 13% depending on the SR and are dominated by the residual uncertainties on the shape of the kinematic distributions of top quark events. The uncertainties are evaluated using additional MC samples. A\(\text{CEREC}\) [40] is used to evaluate the impact of initial and final state radiation parameters (varied as in Ref. [61]), PYTHIA for the choice of fragmentation model, POWHEG [39] for the choice of generator. Experimental uncertainties on the b-tagging efficiency, JES and lepton ID efficiency account for about 4% in either SR.

The dominant uncertainties on the \(Z + hf\) background estimates from simulation arise from the uncertainty on the production cross section used to normalise the MC yields. A ±55% uncertainty on the total production cross section is evaluated from the direct \(Z + hf\) inclusive measurement described in Ref. [62] and takes into account differences between data, M\(\text{C\text{F}}\)M [63] and AL\(\text{P\text{G}}\)E\(\text{N}\).

The dashed band represents the experimental uncertainties including effects due to JES, b-tagging and lepton ID efficiency.

Table 1

<table>
<thead>
<tr>
<th></th>
<th>SR1</th>
<th>SR2</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>ee channel</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Data</td>
<td>39</td>
<td>20</td>
</tr>
<tr>
<td>SM</td>
<td>36.2 ± 8.5</td>
<td>14.1 ± 3.0</td>
</tr>
<tr>
<td>Top</td>
<td>23.8 ± 4.8</td>
<td>11.9 ± 2.8</td>
</tr>
<tr>
<td>(Z + hf)</td>
<td>9.4 ± 7.0</td>
<td>0.9 ± 0.8</td>
</tr>
<tr>
<td>Fake lepton</td>
<td>2.4 ± 0.9</td>
<td>1.1 ± 0.6</td>
</tr>
<tr>
<td>Others</td>
<td>0.3 ± 0.5</td>
<td>0.2 ± 0.2</td>
</tr>
<tr>
<td><strong>(\mu\mu) channel</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Data</td>
<td>47</td>
<td>23</td>
</tr>
<tr>
<td>SM</td>
<td>55 ± 12</td>
<td>26.6 ± 5.1</td>
</tr>
<tr>
<td>Top</td>
<td>40.4 ± 6.2</td>
<td>22.9 ± 4.3</td>
</tr>
<tr>
<td>(Z + hf)</td>
<td>14.2 ± 9.9</td>
<td>3.3 ± 2.6</td>
</tr>
<tr>
<td>Fake lepton</td>
<td>0.00 ± 0.08</td>
<td>0.00 ± 0.07</td>
</tr>
<tr>
<td>Others</td>
<td>0.7 ± 0.7</td>
<td>0.3 ± 0.3</td>
</tr>
<tr>
<td><strong>ee + (\mu\mu)</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Data</td>
<td>86</td>
<td>43</td>
</tr>
<tr>
<td>SM</td>
<td>92 ± 19</td>
<td>40.7 ± 6.0</td>
</tr>
<tr>
<td>Top</td>
<td>64.3 ± 7.7</td>
<td>34.8 ± 5.0</td>
</tr>
<tr>
<td>(Z + hf)</td>
<td>24 ± 16</td>
<td>4.2 ± 3.2</td>
</tr>
<tr>
<td>Fake lepton</td>
<td>2.4 ± 0.9</td>
<td>1.1 ± 0.6</td>
</tr>
<tr>
<td>Others</td>
<td>1.2 ± 1.2</td>
<td>0.6 ± 0.6</td>
</tr>
</tbody>
</table>

95% C.L. upper limits: observed (expected)

| Events \(95%\)   | 37.2 (40.6)  | 19.8 (17.8)  |
| Visible \(95\)   | 18.2 (19.8)  | 9.7 (8.7)    |

The number of observed and expected SM background events in the two SRs are summarised in Table 1, for \(ee\) and \(\mu\mu\) channels summed. The \(ee\) and \(\mu\mu\) contributions are also shown separately for illustration. In all SRs, the SM expectation and observation agree within uncertainties.

In Fig. 3 the distributions of \(E_T^{\text{miss}}\) in SR1 (full spectrum) and SR2 (\(E_T^{\text{miss}} > 80\) GeV), summing the \(ee\) and \(\mu\mu\) channels, are
9. Conclusions

In summary, results of a search for direct scalar top quark pair production in pp collisions at $\sqrt{s} = 7$ TeV, based on 2.05 fb$^{-1}$ of ATLAS data are reported. Scalar top quarks are searched for in events with two same flavour opposite-sign leptons ($e, \mu$) with invariant mass consistent with the $Z$ boson mass, large missing transverse momentum and jets in the final state, where at least one of the jets is identified as originating from a $b$-quark. The results are in agreement with the SM prediction and are interpreted in the framework of $R$-parity conserving ‘natural’ gauge mediated SUSY scenarios. Stop masses up to 310 GeV are excluded for $115 \text{ GeV} < m_{\tilde{\chi}_1^0} < 230 \text{ GeV}$ at 95% C.L., reaching an exclusion of $m_{\tilde{t}_1} < 330 \text{ GeV}$ for $m_{\tilde{\chi}_1^0} = 190 \text{ GeV}$. Stop masses below 240 GeV are excluded for $m_{\tilde{t}_1} > m_{\tilde{\chi}_1^0}$.

Acknowledgements

We thank CERN for the very successful operation of the LHC, as well as the support staff from our institutions without whom ATLAS could not be operated efficiently.

We acknowledge the support of ANPCyT, Argentina; YerPhI, Armenia; ARC, Australia; BMWF, Austria; ANAS, Azerbaijan; SSTC, Belarus; CNPq and FAPESP, Brazil; NSERC and CFI, Canada; CERN; CONICYT, Chile; CAS, MOST and NSFC, China; COLCIENCIAS, Colombia; MSMT CR, MPO CR and VSC CR, Czech Republic; DNRF, DNSRC and Lundbeck Foundation, Denmark; ARTEMIS, European Union; IN2P3-CNRS, CEA-DSM/Irfu, France; GNAS, Georgia; BMBF, DFG, MPG and AvH Foundation, Germany; GSI, HGF, MPG and AVH Foundation, Germany; GSI, Hessen, Greece; ISF, MINERVA, GIF, DIP and Benoziyo Center, Israel; INFN, Italy; MEXT and JSPS, Japan; CNRS, Morocco; FOM and NWO, Netherlands; RCN, Norway; MNiSW, Poland; GRCIES and FCT, Portugal; MERYS (MECTS), Romania; MES of Russia and ROSATOM, Russian Federation; JINR; MSTD, Serbia; MSSR, Slovakia; ARRS and MVZT, Slovenia; DST/NRF, South Africa; MICINN, Spain; SRC and Wallenberg Foundation, Sweden; SER, SNSF and Cantons of Bern and Geneva, Switzerland; NSC, Taiwan; TAEK, Turkey; STFC, the Royal Society and Leverhulme Trust, United Kingdom; DOE and NSF, United States.

The crucial computing support from all WLCG partners is acknowledged gratefully, in particular from CERN and the ATLAS Tier-1 facilities at TRIUMF (Canada), NDGF (Denmark, Norway, Sweden), CC-IN2P3 (France), KIT/GridKA (Germany), INFN-CNAF (Italy), NL-T1 (Netherlands), PIC (Spain), ASGC (Taiwan), RAL (UK) and BNL (USA) and in the Tier-2 facilities worldwide.

Open access

This article is published Open Access at sciedirect.com. It is distributed under the terms of the Creative Commons Attribution License 3.0, which permits unrestricted use, distribution, and reproduction in any medium, provided the original authors and source are credited.

References
