ATLAS Collaboration

Search for light top squark pair production in final states with leptons and b-jets with the ATLAS detector in √s=7 TeV proton-proton collisions


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1. Introduction

Supersymmetry (SUSY) [1–9] is an extension of the Standard Model (SM) which naturally resolves the hierarchy problem by introducing supersymmetric partners to the known fermions and bosons. In a framework of 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. In a large variety of models the LSP is the lightest neutralino, $\tilde{\chi}^0_1$, which only interacts weakly. The scalar partners of right-handed and left-handed quarks (squarks) can mix to form two mass eigenstates ($\tilde{t}_1, \tilde{t}_2$). In particular, the lightest top squark (stop, $\tilde{t}_1$), could have a mass similar to, or lower than, the top quark (t) mass.

In this Letter, a search for direct stop pair production is presented targeting these scenarios. A SUSY particle mass hierarchy is assumed such that $m_{\tilde{t}_1} \geq m_{\tilde{t}_2} > m_{\tilde{\chi}^0_1}$ and the stop decays exclusively into a $b$-quark and a chargino ($\tilde{t}_1 \rightarrow \tilde{\chi}^\pm_1 b$). The chargino subsequently decays via a virtual or real $W$ boson ($\tilde{\chi}^\pm_1 \rightarrow W^{(*)}\tilde{\chi}^0_1$). The masses of all other supersymmetric particles, including the mass of $\tilde{t}_2$, are assumed to be above the TeV scale. In the case where $m_{\tilde{t}_1} \sim m_t$, direct stop pair production will lead to final states very similar to SM $t\bar{t}$ events, which form the dominant background. In the first stage of the analysis the stop pair production (including stop pairs) is reconstructed from final states which contain exclusively one or two leptons ($\ell = e, \mu$), $b$-jets, light-flavour jets, and large missing transverse momentum. The use of event-based mass scale variables allows discrimination between stop pairs and the $t\bar{t}$ background. The results are interpreted in three MSSM scenarios where stop and neutralino masses are varied and different assumptions are made about the chargino–neutralino mass difference: gaugino universality ($m_{\tilde{\chi}^\pm_1} = 2 \times m_{\tilde{\chi}^0_1}$); fixed chargino mass of 106 GeV (above the present exclusion limit from LEP [15]); and fixed stop mass of 180 GeV with variations of the chargino–neutralino mass difference. Previous results for direct production of top squark pairs in the same MSSM scenarios have been presented by the CDF [16] and ATLAS Collaborations [17].

2. The ATLAS detector

The ATLAS detector is described in detail elsewhere [18]. It comprises an inner detector (ID) surrounded by a thin superconducting solenoid, a calorimeter system and an extensive muon spectrometer embedded in a toroidal magnetic field. The ID tracking system consists of a silicon pixel detector, a silicon microstrip detector (SCT), and a transition radiation tracker (TRT). It provides tracking information for charged particles in a pseudorapidity $|\eta| < 2.5$ and allows efficient identification of jets.
originating from b-hadron decays using impact parameter measurements to reconstruct secondary decay vertices. The ID is immersed in a 2 T axial magnetic field and is surrounded by high-granularity liquid-argon (LAr) sampling electromagnetic calorimeters. An iron/scintillator tile calorimeter provides hadronic energy measurements in the central pseudorapidity range (|η| < 1.7). In the forward regions (1.5 < |η| < 4.9), it is complemented by two end-cap calorimeters using LAr as the active material and copper or tungsten as an absorber. The muon spectrometer (MS) surrounds the calorimeters and consists of three large superconducting eight-coil toroids, a system of tracking chambers, and detectors for triggering. The MS is segmented into barrel (|η| < 1.05) and end-cap regions (1.05 < |η| < 2.7).

3. Simulated event samples

Monte Carlo (MC) simulated event samples are used to develop and validate the analysis procedure and to help evaluate the SM backgrounds in the signal regions. Production of top quark pairs is simulated with MC@NLO [19–21], using a top quark mass of 172.5 GeV and the next-to-leading-order (NLO) parton distribution function (PDF) set CT10 [22]. Samples of W and Z/γ ∗ production, with accompanying light- and heavy-flavour jets, and t ¯t with additional b-jets (tibb) are generated using ALPGEN [23]. Samples of Zt, Wt and WWt are generated with MadGraph [24] interfaced to PYTHIA [25]. Diboson (WW, WZ, ZZ) production is generated with HERWIG [26]. Single top production is generated with MCHLO for the s- and t + W-channels, and AcerMC [27] for the t-channel. Fragmentation and hadronisation modelling for the ALPGEN and MC@NLO samples are performed by HERWIG, using JIMMY [28] for the underlying event. ALPGEN and HERWIG++ [29] samples are used to assess the systematic uncertainties associated with the choice of generator for tt production, and AcerMC samples are used to assess the uncertainties associated with initial and final state radiation (ISR/FSR). The choice of PDF depends on the generator: the MSTW2007 LO [30] set is used with HERWIG, CTEQ6L1 [31] with ALPGEN. The background predictions are normalised to the theoretical cross sections, in ing of the vector sum of the pT of the reconstructed electrons, muons and jets, and all energy clusters with |η| < 4.9 not associated with such objects.

Electrons must additionally pass the “tight” electron criteria of Ref. [39], and be isolated such that the scalar pT sum of tracks within a cone of ΔR = 0.2 around the electron candidate (not including the electron track) must be less than 10% of the electron pT. Muons must also be isolated such that the pT sum of tracks (not including the muon track) within ΔR = 0.2 is less than 1.8 GeV. Jets are further required to lie within |η| < 2.5 and must have more than 75% of pT-weighted ID tracks associated to the primary vertex. This reduces the presence of jets arising from uncorrelated soft collisions (pile-up) and discards jets without reconstructed tracks.

A b-tagging algorithm [43] is used to identify jets containing a b-hadron decay. The algorithm uses a multivariate technique based on the properties of the secondary vertex, of tracks within the jet, and of the jet itself. The nominal b-tagging efficiency, determined from tt MC events, is on average 60%, with a misidentification rate of 3%.

5. Signal region definitions

The data are selected with a three-level trigger system. The events used in this search satisfied single-lepton trigger requirements that varied with the data-taking period. The highest electron trigger has an efficiency of ~97% for electrons with pT > 25 GeV. The muon trigger reaches an efficiency plateau of ~90% in the end-caps for muons with pT > 20 GeV. The equivalent efficiency in the barrel region is ~75% due to a lower geometrical acceptance for the muon trigger chambers in this region. Collision events are selected by requiring at least one reconstructed vertex with at least five associated tracks with pT > 400 MeV, consistent with the beam spot position. Two signal regions are defined containing either exclusively one or two charged leptons (ℓ = e, μ) in the final state, referred to hereafter as the 1- and 2-lepton channels respectively. A total integrated luminosity of 4.7 ±0.2 fb−1 is used, following the beam, detector and data-quality requirements as described in Refs. [44,45].

In the 1-lepton channel, events are required to contain the minimum number of objects expected from the t → W/¯Wb/¯b decay. Exactly one lepton is required, which must have pT > 25 GeV (20 GeV) for the electron (muon) channel and fulfill the trigger requirements. Events with an additional electron
Fig. 1. The 1-lepton channel $m_{\text{had}}$ distribution after all requirements except those on $m_{\text{had}}$ and $\sqrt{s}_{\text{min}}$ (a), and the $\sqrt{s}_{\text{min}}$ distribution after all requirements except that on $\sqrt{s}_{\text{min}}$ (b). For the 2-lepton channel, the $m_{\ell\ell}$ distribution is shown after all requirements except those on $m_{\ell\ell}$ and $\sqrt{s}_{\text{min}}$ (c), and the $\sqrt{s}_{\text{min}}$ distribution, before the requirements on $\sqrt{s}_{\text{min}}$ itself (d). The last bin in each histogram contains the integral of all events with values greater than the upper axis bound. The hatched bands display the total uncertainties on the background expectation and the dashed lines show the expected distributions for two signal models. The bottom panels show the ratio of data to the expected background (points) and the total uncertainty on the background (hatched area).

(muon) with $p_T > 20$ GeV (10 GeV) are rejected to ensure no events are classified as belonging to both 1- and 2-lepton channels. A minimum of four jets are required in the event, at least two of which must pass the $b$-tagging requirements and at least two must fail them. Events are required to have a missing transverse momentum of $E_{\text{T}}^{\text{miss}} > 40$ GeV. Background from multi-jet processes, in which jets are misidentified as leptons, is rejected by requiring that the transverse mass of the lepton-$E_{\text{T}}^{\text{miss}}$ system, $m_T = \sqrt{2p_T E_{\text{T}}^{\text{miss}} - 2p_T p_{\text{miss}}}·$, is larger than 30 GeV.

The invariant mass of the hadronic top decay products ($m_{\text{had}}$) is used as an additional discriminating variable. In scenarios where the stop is lighter than the top, $m_{\text{had}}$ will tend to be lower than for background $t\bar{t}$ processes, as illustrated in Fig. 1(a). Since there is an ambiguity as to which $b$-jet arises from the hadronic top decay (and additional ambiguities at higher jet multiplicities), the hadronic decay products are tagged using the following algorithm: for every possible combination of light and $b$-tagged jets in the event, the invariant masses $m_{\text{had}} W$ (of two light jets, $m_{jj}$), $m_{\ell W}$ (assuming that the lepton and $E_{\text{T}}^{\text{miss}}$ arise from the $W \rightarrow \ell\nu$ decay), $m_{\text{had}}$ and $m_{\ell\ell}$ (the leptonic top mass) are calculated. A $t\bar{t}$ estimator of $P_{\text{tot}} = P(m_{\text{had}} W)P(m_{\ell W})P(m_{\ell\ell})P(m_{\text{had}})$ is assigned to this combination, where $P(m)$ is related to the probability for reconstructing a particle of mass $m$, assuming a Gaussian probability density function with mean values taken from Ref. [46] and widths from MC simulation. The combination which maximises $P_{\text{tot}}$ is assigned one $b$-jet and two light-flavour jets (one $b$-jet, the lepton and $E_{\text{T}}^{\text{miss}}$) as arising from the hadronic (leptonic) decay of the top quark.
Events are then required to have $m_{\text{had}}^{\text{sub}} < \hat{\mu} - 0.5\hat{\sigma}$, where $\hat{\mu}$ and $\hat{\sigma}$ are the mean and width respectively of a Gaussian fit to the $m_{\text{had}}^{\text{sub}}$ distribution in a 40 GeV window around the top mass. This approach is taken to reduce some of the systematic uncertainties affecting the shape of this distribution, as detailed in Section 6.

In the 2-lepton channel, the following requirements are imposed to ensure that the event contains the required number of objects consistent with the $t\bar{t} \to WbW\bar{b} \to \ell\nu b\bar{b}$ decay. Exactly two oppositely-charged leptons are required to pass the selection described in Section 4. For same-flavour pairs, the highest $p_T$ lepton is required to have $p_T > 25$ GeV (20 GeV) for electrons (muons). In the case of different-flavour pairs, either the electron must have $p_T > 25$ GeV or the muon $p_T > 20$ GeV. At least two jets are required in the event, of which the two with highest $p_T$ are assumed to originate from the $t\bar{t}$ process. At least one of these two jets is required to be $b$-tagged. The event is required to fulfill $E_{\text{T}}^{\text{miss}} > 40$ GeV and the invariant mass of the two leptons ($m_{\ell\ell}$) must satisfy $30 < m_{\ell\ell} < 81$ GeV to increase the discrimination against the background, as illustrated in Fig. 1(c). In order to distinguish between stop and top pair production the mass scale subsystem variable $\sqrt{S}_{\text{min}}^{\text{(sub)}}$ [47] is employed. Conceptually, the variable is constructed by dividing an event’s topology into a subsystem comprising both the visible and invisible particles originating from the hard-scattering process of interest and a set of other visible particles labelled as coming from other, “upstream”, processes such as the underlying event or ISR. With these definitions, the minimum invariant mass compatible with the subsystem is

$$\sqrt{S}_{\text{min}}^{\text{(sub)}} = \left( \sqrt{m_{\text{sub}}^2 + p_T^{\text{(sub)}}^2} + \sqrt{(m_{\text{miss}}^2 + E_{\text{T}}^{\text{miss}})^2} \right)^2 - (p_T^{\text{(sub)}} + E_{\text{T}}^{\text{miss}})^2 \right)^{1/2},$$

where $m_{\text{sub}}$ and $p_T^{\text{(sub)}}$ are the invariant mass and the transverse momentum of the visible subsystem particles. The variable $m_{\text{miss}}$ is the scalar sum of the invisible particle masses in the event. The final term in Eq. (1) is a two-dimensional vector sum representing the boost correction in the transverse plane caused by upstream processes. In this analysis $\sqrt{S}_{\text{min}}^{\text{(sub)}}$ is calculated making the hypothesis that each event arises from $t\bar{t}$ production, with the invisible subsystem comprising one or two neutrinos, and therefore $m_{\text{miss}} = 0$ in Eq. (1). With this assumption, the reconstructed $\sqrt{S}_{\text{min}}^{\text{(sub)}}$ distribution for $t\bar{t}$ background events is expected to peak at around $m_{\ell\ell} = 2m_t \approx 345$ GeV. On the other hand, stop pair production will peak at lower values if the mass difference between the stop and the neutralino is less than the top mass, as illustrated in Figs. 1(b) and 1(d). Signal events are therefore selected by imposing an upper limit on $\sqrt{S}_{\text{min}}^{\text{(sub)}}$.

In the 1-lepton channel, the visible subsystem comprises the single lepton, two light-flavour jets and two $b$-jets. In events where combinatorial ambiguities arise, the subsystem objects are chosen which give the highest estimator in the algorithm described above. In the 2-lepton channel, the two leptons and the two leading jets are used. In both channels, the upper limit on $\sqrt{S}_{\text{min}}^{\text{(sub)}}$ has been chosen to maximise the expected signal efficiency with respect to background rejection, across a range of scenarios described in Section 1. In the 1-lepton channel, the optimal requirement is $\sqrt{S}_{\text{min}}^{\text{(sub)}} < 250$ GeV, defining a signal region referred to hereafter as 1LSR. In the 2-lepton channel two signal regions are defined, the first requiring $\sqrt{S}_{\text{min}}^{\text{(sub)}} < 225$ GeV (2LSR1). The invariant mass of the two leptons and two jets ($m_{\ell\ell\ell\ell}$) was also found to be a useful discriminating variable. Imposing $m_{\ell\ell\ell\ell} < 140$ GeV in combination with $\sqrt{S}_{\text{min}}^{\text{(sub)}} < 235$ GeV was found to give the optimal performance and defines a second signal region (2LSR2).

### 6. Background estimation

The dominant SM background process in the 1-lepton (2-lepton) channel arises from single-lepton (dilepton) $t\bar{t}$ decays, comprising 60% (80%) of the total background. The second most significant background in the 1-lepton (2-lepton) channel arises from $W(\gamma^*)$ production in association with jets from heavy-flavour quarks. For both channels, similar methods are used to estimate these backgrounds. For each channel and background process a control region is defined that is rich in the background of interest. The region is kinematically similar to the signal region but distinct from it, such that the signal and control regions have no events in common. For a control region containing $N_{\text{obs}}^{\text{sub}}$ observed events (corrected for the contamination from other backgrounds), the number of events in the signal region is calculated as $N_{\text{SR}} = N_{\text{SR}}^{\text{CR}} \times (N_{\text{SR}}^{\text{CR}}/N_{\text{MC}}^{\text{CR}})$, where $N_{\text{SR}}^{\text{CR}}$ and $N_{\text{MC}}^{\text{CR}}$ are the MC-based estimates in the signal and control regions respectively. The advantage of this method is that many systematic uncertainties partially cancel.

In the 1-lepton channel, the $t\bar{t}$ background (including dileptonic $Wt$ decays) is determined using a control region identical to the signal region except that $\sqrt{S}_{\text{min}}^{\text{(sub)}} > 101$ GeV and $\sqrt{S}_{\text{min}}^{\text{(sub)}} < 325$ GeV, with 94% purity of $t\bar{t}$ events. The $Z + jets$ background, with $Z$ decaying to any of the three lepton flavours, is determined in a region requiring two same-flavour leptons, $81 < m_{\ell\ell} < 101$ GeV and $\sqrt{S}_{\text{min}}^{\text{(sub)}} < 225$ GeV, with a $Z$ purity of 90%.

The contribution to the background from events where a jet is misidentified as a lepton, or where a lepton from a $b$- or c-hadron decay is selected (referred to as “fake” lepton background), is estimated using a data-driven technique in both channels [39,48]. The probability of such a misidentification is estimated by relaxing the electron and muon identification criteria to obtain control samples dominated by multi-jet production. In the 1-lepton channel, the main contribution is from multi-jet events. In the 2-lepton channel, the dominant contribution is from processes containing one real and one fake lepton, such as $W + jet$ or single-lepton $t\bar{t}$ decays. The contribution from events containing two fake leptons was found to be negligible.

Other less significant processes in the 1-lepton channel include $Z(\gamma^*) + jets$ and single top quark production. Diboson and $ttX$ ($X = W, Z, Wb, bb$) production give a minor contribution to both channels. The contribution to the total background from these processes (referred to as “Others” in the following and in Fig. 1) is 2.5% (2%) in the 1-lepton (2-lepton) channel, and is taken directly from the MC predictions.
7. Systematic uncertainties

The effect of the jet energy scale (JES) uncertainty on the final event yield is calculated by shifting the $p_T$ of all jets up and down by $p_T$ and $\eta$ dependent factors, which are 5–3% for jets with $p_T$ of 20–60 GeV. Repeating the analysis with these $p_T$ shifts applied to the MC simulation leads to variations on the final background estimate of 6–10% depending on the signal region. The uncertainty due to the jet energy resolution (JER) is calculated by smearing the $p_T$ of each jet by factors depending on the jet $p_T$ and $\eta$. The smearing on a single jet is typically around 10%, and results in an overall uncertainty of 1–10%. Systematic uncertainties in the lepton identification efficiency amount to 1%. The uncertainty on the $E_T^{miss}$ due to the energy scale of the clusters in the calorimeter not associated with jets and electrons is evaluated using the method described in Ref. [49], extended to include pile-up uncertainties. The effect is up to 9% on the total background estimate depending on the signal region. The uncertainty due to b-tagging is evaluated by varying the b-tagging efficiency and mis-tag rates within the uncertainties of the measured values [50–52], giving an effect of 1% in all signal regions. The uncertainty associated with pile-up re-weighting is evaluated by varying the number of interactions per bunch-crossing by 10%. The overall effect on the predicted background yield is at most 3%.

Uncertainties related to the overall normalisation of the top background are reduced compared to estimates based purely on MC simulation by employing the method described in Section 6. Residual uncertainties related to the shape of the predicted kinematic distributions are described in the following. Theoretical uncertainties on the top background are evaluated by comparing event yields from MC@NLO to those from POWHEG with the same parton shower model (HERWIG). The parton shower uncertainties are then calculated by comparing samples generated with the HERWIG and PYTHIA parton shower models, with the same generator (POWHEG). The uncertainty due to ISR/FSR is assessed using AcerMC samples with variations of PYTHIA parameters related to the ISR branching phase-space and the FSR low-$p_T$ cutoff. These variations are chosen to produce jet activity in $t\bar{t}$ events that is consistent with the data [53,54]. The total uncertainty on the $t\bar{t}$ estimate due to these effects amounts to 10–15%. Uncertainties due to the PDF choice and errors are found to be negligible.

In the 1-lepton channel, the theoretical uncertainty in the $W$ estimate due to variations of the factorisation, renormalisation and matching scales is found to be 15%. Similar uncertainties on the $Z/\gamma^*\nu$ contribution in the 2-lepton channel is 9% (2%) in 2LSR1 (2LSR2).

Uncertainties on the data-driven background from fake leptons arise from the lepton fake rate determination and from the definition of the fake-enriched control regions. The effect is between 45–84% of the fake contribution.

Theoretical uncertainties on the stop pair production cross section are taken from an envelope of predictions which use different PDF sets and factorisation and renormalisation scales, as described in Ref. [55]. Signal uncertainties on JES (10–30%), JER (1–30%) and b-tagging (5–10%) vary depending on the sparticle masses and the signal channel considered. They are treated as fully correlated with their respective background uncertainties. Finally, the luminosity uncertainty is 3.9%.

8. Results and interpretation

Table 1 shows the observed number of events in data and the SM predictions for the signal regions of the 1- and 2-lepton channels. In all SRs, the data are in good agreement with the SM expectations.

The results are translated into 95% confidence-level (CL) upper limits on contributions from new physics using the CL$_s$ prescription [56] with a profile log-likelihood ratio as a test statistic [57], where the parameter to describe the non-SM signal strength is constrained to be non-negative in the fit. As shown in Table 1, the three signal regions are used to set limits on the visible cross section of the new physics models, $\sigma_{vis} = \sigma \times A \times e$, where $\sigma$ is the total production cross section for any non-SM signal, $A$ is the acceptance defined by the fraction of events passing the geometric and kinematic selections at particle level, and $e$ is the detector reconstruction, identification and trigger efficiency. Results are interpreted in the MSSM scenarios described in Section 6. In order to maximise the sensitivity of the analysis, results from the 1- and 2-lepton channels are combined using the following method: for each signal point, the 2-lepton signal region (2LSR1 or 2LSR2) which yields the lowest expected CL$_s$ value is chosen. This region is then statistically combined with the 1LSR by multiplying the respective likelihood functions. Correlated sys-
Fig. 2. Exclusion limits at 95% CL for the scenarios described in the text. The dashed (solid) lines show the expected (observed) limits, including all uncertainties except for the theoretical signal cross section uncertainty (PDF and scale). The bands around the expected limits show the ±1σ results. The lines around the observed limits represent the results obtained when moving the nominal signal cross section up or down by the ±1σ theoretical uncertainty. In (c), results are compared to previous limits from the Tevatron [16], where the lowest neutralino mass considered was 44 GeV (dotted line), and from ATLAS [17].

9. Conclusions

A search has been performed for top squarks with masses near to, or less than, the top quark mass. Good agreement is observed between data and the SM predictions in all channels. The results allow limits to be set on the stop mass, assuming that \( \tilde{t}_1 \rightarrow \tilde{\chi}_1^\pm b \) is the only allowed decay mode, followed by \( \tilde{\chi}_1^\pm \rightarrow W^{(*)}\tilde{\chi}_1^0 \). For
scenarios in which \( m_{\tilde{\chi}^0_1} \approx 2 \times m_{\tilde{\chi}^0_1} \), stop masses between 120–167 GeV are excluded for \( m_{\tilde{\chi}^0_1} = 55 \) GeV. For a fixed stop mass of 180 GeV, a region around \( m_{\tilde{\chi}^0_1} = 70 \gev, m_{\tilde{\chi}^0_1} = 140 \gev \) is excluded. In the scenario where \( m_{\tilde{\chi}^0_1} = 106 \gev \), neutralino masses of 70 GeV are excluded for 125 < \( m_{\tilde{\chi}^0_1} < 155 \) GeV, significantly extending previous limits in such scenarios.

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