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Search for Direct Top Squark Pair Production in Final States with One Isolated Lepton, Jets, and Missing Transverse Momentum in $\sqrt{s} = 7$ TeV $pp$ Collisions Using 4.7 fb$^{-1}$ of ATLAS Data

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(ATLAS Collaboration)

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A search is presented for direct top squark pair production in final states with one isolated electron or muon, jets, and missing transverse momentum in proton-proton collisions at $\sqrt{s} = 7$ TeV. The measurement is based on 4.7 fb$^{-1}$ of data collected with the ATLAS detector at the LHC. Each top squark is assumed to decay to a top quark and the lightest supersymmetric particle (LSP). The data are found to be consistent with standard model expectations. Top squark masses between 230 GeV and 440 GeV are excluded with 95% confidence for massless LSPs, and top squark masses around 400 GeV are excluded for LSP masses up to 125 GeV.

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Weak scale supersymmetry (SUSY) [1–9] is an extension to the standard model (SM) that provides a solution to the hierarchy problem by introducing supersymmetric partners of all SM particles. In the framework of a generic R-parity conserving minimal supersymmetric extension of the SM [10–14], SUSY particles are produced in pairs, and the lightest supersymmetric particle (LSP) is stable and can be a dark matter candidate. In a large variety of models, the LSP is the lightest neutralino, $\tilde{\chi}_1^0$, which only interacts weakly and thus escapes detection.

Light top squarks (stop) are suggested by naturalness arguments [15,16]. Searches for direct top stop pair production have been previously reported by the CDF and D0 experiments [17,18]. Searches for stops via $g \rightarrow t\bar{t}$ production have been reported by the ATLAS [19–21] and CMS [22,23] Collaborations. In this Letter, one stop mass eigenstate $(\tilde{t}_1)$ is assumed to be significantly lighter than the other stops. A search is presented for directly pair-produced stops, which are each assumed to decay to a top quark and the LSP. The signature for such a signal is characterized by a top quark pair ($t\bar{t}$) produced in association with possibly large missing transverse momentum, the magnitude of which is referred to as $E_T^{\text{miss}}$, from the undetected LSPs. The analysis targets final states where one top quark decays hadronically and the other semileptonically.

The ATLAS detector [24] has a solenoid, surrounding the inner tracking detector (ID), a calorimeter, as well as a barrel and two end cap toroidal magnets supporting the muon spectrometer. The ID consists of silicon pixel, silicon microstrip, and transition radiation detectors and provides precision tracking of charged particles for pseudorapidity $|\eta| < 2.5$ [25]. The calorimeter, placed outside the solenoid, covers $|\eta| < 4.9$ and is composed of sampling electromagnetic and hadronic calorimeters with either liquid argon or scintillating tiles as the active media. The muon spectrometer surrounds the calorimeters and consists of a system of precision tracking chambers in $|\eta| < 2.7$, and detectors for triggering in $|\eta| < 2.4$.

The analysis is based on data recorded by the ATLAS detector in 2011 corresponding to 4.7 fb$^{-1}$ of integrated luminosity with the LHC operating at a $pp$ center-of-mass energy of 7 TeV. The data were collected requiring either a single lepton (electron or muon) or an $E_T^{\text{miss}}$ trigger. The combined trigger efficiency is >98% for the chosen selection criteria on leptons and $E_T^{\text{miss}}$. Requirements that ensure the quality of beam conditions, detector performance, and data are imposed.

Monte Carlo (MC) event samples using the full ATLAS detector simulation [26] based on the GEANT4 program [27] are used to aid in the description of the background and to model the SUSY signal. The effect of multiple $pp$ interactions per bunch crossing is also simulated [28]. Production of top quark pairs is simulated with MC@NLO 4.01 [29,30], alternatively using ALPGEN 2.14 [31] and PowHeg HVQ patch 4 [32–34]. The data modeling is improved for high jet multiplicities by reweighting the MC@NLO sample to match the jet multiplicity distribution in ALPGEN. Uncertainties associated with initial- and final-state radiation (ISR and FSR) [35] are assessed using ACERMC 3.7 [36] samples. A top quark mass of 172.5 GeV is used consistently.

$W$ and $Z/\gamma^*$ production in association with jets are each modeled with ALPGEN. Diboson $VV$ ($WW$, $WZ$, and $ZZ$) production is simulated with ALPGEN and cross-checked with HERWIG 6.520 [37]. Single top production is modeled with MC@NLO, and $t\bar{t}$ events produced in association with $W$, $Z$, or $W$ ($t\bar{t} + V$) are generated with MADGRAPH 5 [38]. Next-to-leading-order (NLO) parton density functions (PDFs) CT10 [39] are used with all NLO MC samples. For all other samples,

*Full author list given at the end of the article.
TABLE I. Selection requirements defining the SRA–SRE.

<table>
<thead>
<tr>
<th>Requirement</th>
<th>SRA</th>
<th>SRB</th>
<th>SRC</th>
<th>SRD</th>
<th>SRE</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E^{\text{miss}}_T [\text{GeV}]$</td>
<td>150</td>
<td>150</td>
<td>150</td>
<td>225</td>
<td>275</td>
</tr>
<tr>
<td>$E^{\text{miss}}_T / \sqrt{H_T} [\text{GeV}^{1/2}]$</td>
<td>7</td>
<td>9</td>
<td>11</td>
<td>11</td>
<td>11</td>
</tr>
<tr>
<td>$m_T [\text{GeV}]$</td>
<td>120</td>
<td>120</td>
<td>120</td>
<td>130</td>
<td>140</td>
</tr>
</tbody>
</table>

LO PDFs are used: MRSTmcal [40] with HERWIG, and CTEQ6L1 [41] with ALPGEN and MADGRAPH. Fragmentation and hadronization for the ALPGEN and MC@NLO samples are performed with HERWIG, using JIMMY 4.31 [42] for the underlying event, and for the MADGRAPH samples PYTHIA 6.425 [43] is used. The $t\bar{t}$, single top and $t\bar{t} + V$ production cross sections are normalized to approximate next-to-next-to-leading order (NNLO) [44], next-to-next-to-leading-logarithmic accuracy (NLO + NNLL) [45–47] and NLO [48] calculations, respectively. QCD NNLO FEWZ [49] inclusive W and Z cross sections are used for the normalization of the $W + j$ets and $Z + j$ets processes. Expected diboson yields are normalized using NLO QCD predictions obtained with MCFM [50,51].

Stop pair production is modeled using Herwig++ 2.5.2 [52]. The $t\bar{t}$ is chosen to be mostly the partner of the right-handed top quark, and the $\chi^0_1$ to be almost a pure bino. A signal grid is generated with a step size of 50 GeV both for the stop and LSP mass values. Signal cross sections are calculated to NLO in the strong coupling constant, including the resummation of soft gluon emission at next-to-leading-logarithmic accuracy (NLO + NLL) [53–55]. The nominal cross section and the uncertainty are taken from an envelope of cross-section predictions using different PDF sets and factorization and renormalization scales [56]. The $t\bar{t}t\bar{t}$ cross section for $m_{t\bar{t}} = 400$ GeV is $(0.21 \pm 0.03)$ pb.

Events must pass basic quality criteria to reject detector noise and noncollision backgrounds [57,58] and are required to have $\geq 1$ reconstructed primary vertex associated with five or more tracks with transverse momentum $p_T > 0.4$ GeV. Events are retained if they contain exactly one muon [59] with $|\eta| < 2.4$ and $p_T > 20$ GeV or one electron passing “tight” [60] selection criteria with $|\eta| < 2.47$ and $p_T > 25$ GeV. Leptons are required to be isolated from other particles. The scalar sum of the transverse momenta of tracks above 1 GeV within a cone of size $\Delta R = 0.2$ around the lepton candidate is required to be $<10\%$ of the electron $p_T$, and $<1.8$ GeV for the muon. Events are rejected if they contain additional leptons passing looser selection criteria [61]. Jets are reconstructed from three-dimensional calorimeter energy clusters using the anti-$k_T$ jet clustering algorithm [62] with a radius parameter of 0.4. The jet energy is corrected for the effects of calorimeter noncompensation and inhomogeneities using $p_T$- and $\eta$-dependent calibration factors based on MC simulations and validated with extensive test-beam and collision-data studies [63]. To suppress jet background originating from uncorrelated soft collisions, $\geq 75\%$ of the summed $p_T$ of all tracks associated to a jet must come from tracks associated to the selected primary vertex. Events with four or more jets with $|\eta| < 2.5$ and $p_T > 80, 60, 40$, and 25 GeV are selected. At least one jet needs to be identified as a $b$-jet, which is a jet containing a $b$-hadron decay. These are identified using the “MV1” $b$-tagging algorithm [64] which exploits both impact parameter and secondary vertex information. An operating point is employed corresponding to an average $75\% b$-tagging efficiency and to a $<2\%$ misidentification rate for light-quark or gluon jets for jets with $p_T > 20$ GeV and $|\eta| < 2.5$ in $t\bar{t}$ MC events.

Ambiguities between overlapping leptons and jets are resolved by discarding either the jet or lepton candidates [61].

Events with one muon are selected using a kinematic likelihood ratio

$$R = \frac{P_{\mu}}{P_{\text{tot}}},$$

where $P_{\mu}$ is the probability of one muon and $P_{\text{tot}}$ is the probability of any particle. The cut is $R > 0.015$.

Events with two muons are selected using a two-dimensional kinematic likelihood ratio

$$R = \frac{P_{\mu\mu}}{P_{\text{tot}}},$$

where $P_{\mu\mu}$ is the probability of two muons and $P_{\text{tot}}$ is the probability of any particle. The cut is $R > 0.015$.

Events with three or four muons are selected using a three-dimensional kinematic likelihood ratio

$$R = \frac{P_{\mu\mu\mu\mu}}{P_{\text{tot}}},$$

where $P_{\mu\mu\mu\mu}$ is the probability of three or four muons and $P_{\text{tot}}$ is the probability of any particle. The cut is $R > 0.015$.

Events with one electron are selected using a one-dimensional kinematic likelihood ratio

$$R = \frac{P_{e}}{P_{\text{tot}}},$$

where $P_{e}$ is the probability of one electron and $P_{\text{tot}}$ is the probability of any particle. The cut is $R > 0.015$.

Events with two electrons are selected using a two-dimensional kinematic likelihood ratio

$$R = \frac{P_{e\mu\mu}}{P_{\text{tot}}},$$

where $P_{e\mu\mu}$ is the probability of two electrons and $P_{\text{tot}}$ is the probability of any particle. The cut is $R > 0.015$.

Events with three or four electrons are selected using a three-dimensional kinematic likelihood ratio

$$R = \frac{P_{e\mu\mu\mu}}{P_{\text{tot}}},$$

where $P_{e\mu\mu\mu}$ is the probability of three or four electrons and $P_{\text{tot}}$ is the probability of any particle. The cut is $R > 0.015$.

TABLE II. Numbers of observed events in the five signal regions and three background control regions, as well as their estimated values and all (statistical and systematic) uncertainties from a fit to the control regions only, for the electron and muon combined channel. The expected numbers of signal events for $m_{t\bar{t}} = 400$ GeV (500 GeV) and $m_{W} = 1$ GeV for benchmark points 1 (2) are listed for comparison. The central values of the fitted sum of backgrounds in the control regions agree with the observations by construction. Furthermore, $p_T$-values and 95% CLs, observed (expected) upper limits on beyond-SM events are given, using simultaneous fits including one SR at a time and all CRs.

<table>
<thead>
<tr>
<th>Regions</th>
<th>SRA</th>
<th>SRB</th>
<th>SRC</th>
<th>SRD</th>
<th>SRE</th>
<th>2-lep TR</th>
<th>1-lep TR</th>
<th>1-lep WR</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t\bar{t}$</td>
<td>36</td>
<td>5</td>
<td>27</td>
<td>11</td>
<td>2</td>
<td>4.9</td>
<td>1.3</td>
<td>109</td>
</tr>
<tr>
<td>$t\bar{t} + V, \text{ single top}$</td>
<td>2.9</td>
<td>0.7</td>
<td>2.5</td>
<td>0.6</td>
<td>1.6</td>
<td>0.9</td>
<td>0.4</td>
<td>7.2</td>
</tr>
<tr>
<td>$V + \text{jets}, VV$</td>
<td>2.5</td>
<td>1.3</td>
<td>1.7</td>
<td>0.8</td>
<td>0.4</td>
<td>0.3</td>
<td>0.1</td>
<td>1.6</td>
</tr>
<tr>
<td>Multijet</td>
<td>0.4</td>
<td>0.4</td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
<td>0.3</td>
<td>0.0</td>
<td>0.0</td>
</tr>
<tr>
<td>Total background</td>
<td>42</td>
<td>6</td>
<td>31</td>
<td>4</td>
<td>13</td>
<td>6.4</td>
<td>1.8</td>
<td>118</td>
</tr>
<tr>
<td>Signal benchmark 1 (2)</td>
<td>25.6</td>
<td>8.8</td>
<td>23.0</td>
<td>8.1</td>
<td>17.6</td>
<td>13.5</td>
<td>7.1</td>
<td>1.7</td>
</tr>
<tr>
<td>Observed events</td>
<td>38</td>
<td>25</td>
<td>15</td>
<td>8</td>
<td>5</td>
<td>118</td>
<td>421</td>
<td>228</td>
</tr>
<tr>
<td>$p_T$-values</td>
<td>0.5</td>
<td>0.5</td>
<td>0.3</td>
<td>0.2</td>
<td>0.0</td>
<td>0.4</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>Obs. (exp.) $N_{\text{BSM}}&lt;$</td>
<td>15.1</td>
<td>17.2</td>
<td>10.1</td>
<td>13.8</td>
<td>10.9</td>
<td>8.4</td>
<td>8.2</td>
<td>8.2</td>
</tr>
</tbody>
</table>

211803-2
based on their separation $\Delta R$. The measurement of $E_T^{\text{miss}}$ is based on the transverse momenta of all electron and muon candidates, all jets after overlap removal, and all calorimeter energy clusters not associated to such objects. The background is reduced by requiring $\Delta \phi^{\text{min}} > 0.8$, where $\Delta \phi^{\text{min}}$ is the minimum azimuthal separation between the two highest $p_T$ jets and the missing transverse momentum direction. A requirement on the three-jet mass $m_{jjj}$ of the hadronically decaying top quark specifically rejects the dileptonic $t\bar{t}$ background, where both $W$ bosons from the top quarks decay leptonically. The jet-jet pair having invariant mass $>60$ GeV and the smallest $\Delta R$ is selected to form the hadronically decaying $W$ boson.

The mass $m_{jjj}$ is reconstructed including a third jet closest in $\Delta R$ to the hadronic $W$ boson momentum vector and 130 GeV $< m_{jjj} < 205$ GeV is required.

Five signal regions (SRA–SRE) are defined in order to optimize the sensitivity for different stop and LSP masses. For increasing stop mass and increasing mass difference between stop and LSP, the requirements are tightened on $E_T^{\text{miss}}$, on the ratio $E_T^{\text{miss}}/\sqrt{H_T}$, where $H_T$ is the scalar sum of the momenta of the four selected jets with highest $p_T$, and on the transverse mass $m_T$ [65], as shown in Table I. The number of observed events in each SR after applying all selection criteria are given in Table II.

The product of the kinematic acceptance, detector, and reconstruction efficiency ($A \cdot e$) varies between 4% and 0.3% for SRA and between 3% and 0.01% for SRE as the stop-LSP mass difference varies between 550 GeV and 200 GeV.

The dominant background arises from dileptonic $t\bar{t}$ events in which one of the leptons is either not identified, is outside the detector acceptance, or is a hadronically decaying $\tau$ lepton. In all these cases, the $t\bar{t}$ decay products include two or more high-$p_T$ neutrinos, resulting in large $E_T^{\text{miss}}$ and $m_T$. Three control regions (CRs) enriched in dileptonic $t\bar{t}$ events (2-lep TR), single-leptonic $t\bar{t}$ events (1-lep TR), and $W +$ jets events (1-lep WR) are designed to normalize the corresponding backgrounds using data. The 2-lep TR differs from the SRs by selecting events with exactly two leptons, applying no requirements on $m_T$, $E_T^{\text{miss}}/\sqrt{H_T}$ and $m_{jjj}$, and by requiring $E_T^{\text{miss}} > 125$ GeV. The 1-lep TR and 1-lep WR have selection criteria identical to SRA, except the $m_T$ requirement is changed to 60 $< m_T < 90$ GeV and the 1-lep WR has a $b$-jet veto instead of a $b$-jet requirement. $t\bar{t}$ production accounts for $>90\%$ of events in the top CRs and $W +$ jets production for $>60\%$ in the $W$ CR. The signal contamination reaches a maximum of 8% in the 2-lep TR for $m_{t\bar{t}} = 200$ GeV. The multijet background, which mainly originates from jets misidentified as leptons, is estimated using the matrix method [61]. Other background contributions ($VW$, $t\bar{t} + V$, and single top) are estimated using MC simulation normalized to the theoretical cross sections. The $Z +$ jets background is found to be negligible.

FIG. 1 (color online). Top: $E_T^{\text{miss}}$ distributions for the 2-lep TR. Center: $E_T^{\text{miss}}$ distributions for SRA. Bottom: $m_T$ distribution for the preselection requirements (see text). All plots show the electron and muon combined channel, before normalization fits. Hatched areas indicate the combined uncertainty due to MC sample size and the jet energy scale.

Good agreement is observed between data and the SM prediction before using the CRs to normalize the $t\bar{t}$ and $W +$ jets backgrounds. As an example, Fig. 1 shows the agreement of the $E_T^{\text{miss}}$ distributions in the 2-lep TR, and the $E_T^{\text{miss}}$ distribution in SRA. In addition, the $m_T$ distribution for a looser requirements region—$E_T^{\text{miss}} > 40$ GeV and no requirements on $E_T^{\text{miss}}/\sqrt{H_T}$ and $m_{jjj}$ (preselection)—is shown.

Simultaneous fits to the numbers of observed events in the three CRs and one SR at a time are performed to
SRs are based on the PowHeg and ALPGEN, different showering models (HERWIG and PYTHIA), and by varying ISR or FSR parameters. The observation in the SRs, a second set of simultaneous fits including one SR at a time and all CRs is performed. To obtain the best expected combined exclusion limits, a mapping in the stop-LSP mass plane is constructed by selecting the SR with the lowest expected \( \text{CL}_{s} \) value for each grid point. The expected and observed 95% \( \text{CL}_{s} \) exclusion limits are displayed in Fig. 2. Stop masses are excluded between 230 GeV and 440 GeV for massless LSPs, and stop masses around 400 GeV are excluded for LSP masses up to 125 GeV. These values are derived from the \( -1\sigma \) model-dependent upper limit contour. These stop mass limits significantly extend previous results [17,18].

In summary, a search for stop pair production is presented in final states with one isolated lepton, jets, and missing transverse momentum in \( \sqrt{s} = 7 \) TeV \( pp \) collisions corresponding to 4.7 fb\(^{-1}\) of ATLAS 2011 data. Each stop is assumed to decay to a top quark and a long-lived undetected neutral particle. No significant excess of events above the rate predicted by the standard model is observed and 95% \( \text{CL}_{s} \) upper limits are set on the stop mass in the stop-LSP mass plane, significantly extending previous stop-mass limits.

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[25] ATLAS and CMS use a right-handed coordinate system with its origin at the nominal interaction point in the center of the detector and the z axis along the beam pipe. Cylindrical coordinates (r, φ) are used in the transverse plane, φ being the azimuthal angle around the beam pipe. The pseudorapidity η is defined in terms of the polar angle θ by η = − ln tan(θ/2), and ΔR = √(Δη)² + (Δφ)².

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