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DOI
10.1103/PhysRevLett.109.211803

Publication date
2012

Document Version
Final published version

Published in
Physical Review Letters

Citation for published version (APA):

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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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(Received 13 August 2012; published 20 November 2012)

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.

DOI: 10.1103/PhysRevLett.109.211803 PACS numbers: 12.60.Jv, 13.85.Rm, 14.80.Ly

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 stop pair production have been previously reported by the CDF and D0 experiments [17,18]. Searches for stops via $g\tilde{g}$ 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 squarks. 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]. 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 $Z$, $W$, or $WW$ ($t\bar{t} + V$) 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,
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.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 + jets and Z + jets 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 \( \tilde{t}_1 \) is chosen to be mostly the partner of the right-handed top quark, and the \( \tilde{\chi}_1^0 \) 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 \( \tilde{t}_1\tilde{t}_1 \) cross section for \( m_{\tilde{t}_1} = 400 \text{ GeV} \) is \( (0.21 \pm 0.03) \text{ pb} \).

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 \( p_T > 0.4 \text{ GeV} \). Events are retained if they contain exactly one muon [59] with \( |\eta| < 2.4 \) and \( p_T > 20 \text{ GeV} \) or one electron passing “tight” [60] selection criteria with \( |\eta| < 2.47 \) and \( p_T > 25 \text{ GeV} \). 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 \( p_T^{\gamma} \) 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 \( 25 \text{ GeV} \) 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 \( p_T > 20 \text{ GeV} \) 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].

<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{min}_{T}\text{[GeV]} )</td>
<td>150</td>
<td>150</td>
<td>150</td>
<td>225</td>
<td>275</td>
</tr>
<tr>
<td>( E^\text{min}_{T}/\sqrt{H_T} \text{[GeV}^{1/2}\text{]} )</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>120</td>
<td>140</td>
</tr>
</tbody>
</table>

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 \( m_{\tilde{t}} = 400 \text{ GeV} \) (500 GeV) and \( m_{\tilde{\chi}^0_1} = 1 \text{ GeV} \) 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, \( p_0^\text{-values} \) and 95% CL, 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 ± 5</td>
<td>27 ± 4</td>
<td>11 ± 2</td>
<td>4.9 ± 1.3</td>
<td>1.3 ± 0.6</td>
<td>109 ± 10</td>
<td>364 ± 23</td>
<td>59 ± 19</td>
</tr>
<tr>
<td>( t\bar{t} + V ), single top</td>
<td>2.9 ± 0.7</td>
<td>2.5 ± 0.6</td>
<td>1.6 ± 0.3</td>
<td>0.9 ± 0.3</td>
<td>0.4 ± 0.1</td>
<td>7.2 ± 1.3</td>
<td>18 ± 3</td>
<td>6.1 ± 1.6</td>
</tr>
<tr>
<td>( V + \text{jets}, VV )</td>
<td>2.5 ± 1.3</td>
<td>1.7 ± 0.8</td>
<td>0.4 ± 0.1</td>
<td>0.3 ± 0.1</td>
<td>0.1 ± 0.1</td>
<td>1.6 ± 0.8</td>
<td>38 ± 11</td>
<td>162 ± 23</td>
</tr>
<tr>
<td>Multijet</td>
<td>0.4 ± 0.4</td>
<td>0.3 ± 0.3</td>
<td>0.3 ± 0.3</td>
<td>0.3 ± 0.3</td>
<td>0.0 ± 0.0</td>
<td>1.7 ± 0.7</td>
<td>0.8 ± 0.8</td>
<td></td>
</tr>
<tr>
<td>Total background</td>
<td>42 ± 6</td>
<td>31 ± 4</td>
<td>13 ± 2</td>
<td>6.4 ± 1.4</td>
<td>1.8 ± 0.7</td>
<td>118 ± 10</td>
<td>421 ± 20</td>
<td>228 ± 15</td>
</tr>
<tr>
<td>Signal benchmark 1 (2)</td>
<td>25.6(8.8)</td>
<td>23.0(8.1)</td>
<td>17.5(6.9)</td>
<td>13.5(6.2)</td>
<td>7.1(4.5)</td>
<td>1.7(0.6)</td>
<td>2.3(0.6)</td>
<td>0.4(0.1)</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_0^\text{-values} )</td>
<td>0.50</td>
<td>0.50</td>
<td>0.32</td>
<td>0.24</td>
<td>0.015</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Obs. (exp.) ( N_{\text{BSM}} )</td>
<td>15.1(17.2)</td>
<td>10.1(13.8)</td>
<td>10.8(9.2)</td>
<td>8.4(7.0)</td>
<td>8.2(4.6)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
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 $0.3\%$ for SRA and between $3\%$ and $0.01\%$ for SRE as reconstruction efficiency ($A \cdot e$).

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 $m_{jj} = 200$ GeV. The multijet background, which mainly originates from jets misidentified as leptons, is estimated using the matrix method [61]. Other background contributions ($VV$, $t\bar{t} + V$, and single top) are estimated using MC simulation normalized to the theoretical cross sections. The $Z +$ jets background is found to be negligible.

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
normalize the $t\bar{t}$ and $W + \text{jets}$ background estimates as well as to search for an excess from a potential signal contribution. The 1-lep and 2-lep TRs have $t\bar{t}$ normalizations that float independently and that are found to be in good agreement with each other. The $t\bar{t}$ estimates in the SRs are based on the 2-lep TR, as this minimizes the extrapolation uncertainties in the fit. Systematic uncertainties are treated as nuisance parameters with Gaussian probability density functions.

The dominant systematic uncertainties in the fitted $t\bar{t}$ background estimate are theoretical and modeling uncertainties, which affect the event kinematics and thus the extrapolation from the CR to the various SRs. They are determined by using different generators (MC@NLO, PowHeg and ALPGEN), different showering models (HERWIG and PYTHIA), and by varying ISR or FSR parameters, and amount to 10–30%. Electroweak single top production is associated with an 8% theoretical uncertainty [45–47] and the $t\bar{t} + V$ background has a 30% uncertainty [48]. The difference between ALPGEN and HERWIG predictions is used to assess the uncertainty on the diboson background, and the uncertainty on the multijet background is based on the matrix method. Both of these uncertainties are estimated as 100%.

Experimental uncertainties affect the signal and background yields, including those normalized in CRs. They are estimated by aid of MC events and are dominated by uncertainties in the jet energy scale, jet energy resolution, and $b$-tagging. Uncertainties related to the trigger and lepton reconstruction and identification (momentum and energy scales, resolutions and efficiencies) give smaller contributions. Other small uncertainties are due to modeling of multiple $pp$ interactions, the integrated luminosity, and the limited numbers of MC and data events. The uncertainty on $A \cdot \epsilon$ varies between 9% and 16% as the simulated stop-LSP mass difference varies between 550 GeV (SRE) and 250 GeV (SRA and SRB).

Table II shows the results of the background fit to the CRs, extrapolated to the SRs. The fitted numbers of $t\bar{t}$ and $W + \text{jets}$ events are compatible with the MC predictions, with factors of 1.01 and 0.90 applied, respectively. To assess the agreement between the SM expectation and the observation in the SRs, a second set of simultaneous fits including one SR at a time and all CRs is performed. The $p_0$-values (probing the background-only hypothesis) obtained are given in Table II. No significant excess of events is found.

One-sided exclusion limits are derived using the $CL_s$ method [66], based on the same simultaneous fit method but taking the predicted signal contamination in the CRs into account. To obtain the best expected combined exclusion limit, a mapping in the stop-LSP mass plane is constructed by selecting the SR with the lowest expected $CL_s$ value for each grid point. The expected and observed 95% $CL_s$ 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 $-1\sigma$ theory observed limit contour. These stop mass limits significantly extend previous results [17,18]. Limits on beyond-SM contributions are derived from the same simultaneous fit but without signal model-dependent inputs (i.e., without signal contamination in the CRs, and without signal systematic uncertainties). The resulting limits are shown at the bottom of Table II.

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% $CL_s$ upper limits are set on the stop mass in the stop-LSP mass plane, significantly extending previous stop-mass limits.

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, NRC and CFI, Canada; CERN;
CONICYT, Chile; CAS, MOST, and NSFC, China; COLCIENCIAS, Colombia; MSMT CR, MPO CR, and VSC CR, Czech Republic; DNB, DAFNE, and Lundbeck Foundation, Denmark; EPLANET, ERC, European Union; IN2P3-CNRS, CEA-DSM/IRFU, France; GNSF, Georgia; BMBF, DFG, HGF, MPG, and AvH Foundation, Germany; GSRT, Greece; ISF, INHER, GIF, DIP, and Benoziyo Center, Israel; INFN, Italy; MEXT and JSPS, Japan; CNRST, Morocco; FOM and NWO, Netherlands; RCN, Norway; MNiSW, Poland; GRICES and FCT, Portugal; MERSYS (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 ERC, Switzerland; NSC, Taiwan; TAEK, Turkey; STFC, the Royal Society and Leverhulme Trust, United Kingdom; and 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, and 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.

[25] ATLAS uses 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 = √(Δη² + Δφ²).

\[ m_T = \sqrt{p_T^2 + E_T^{\text{miss}}^2 (1 - \cos(\Delta \phi))}, \]
where $\Delta \phi$ is the azimuthal angle between the lepton and missing momentum direction.
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