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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

The ATLAS Collaboration

Abstract

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 $230\,\mathrm{GeV}$ and $440\,\mathrm{GeV}$ are excluded with 95% confidence for massless LSPs, and top squark masses around $400\,\mathrm{GeV}$ are excluded for LSP masses up to $125\,\mathrm{GeV}$.

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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 (MSSM) [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 $\tilde{g}\tilde{g}$ 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 $E_{\mathrm{T}}^{\mathrm{miss}}$, 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 endcap 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 $E_{\mathrm{T}}^{\mathrm{miss}}$ trigger. The combined trigger efficiency is $> 98\%$ for the chosen selection criteria on leptons and $E_{\mathrm{T}}^{\mathrm{miss}}$. 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/FSR) [35] are assessed using `AcerMC 3.7` [36] samples. A top quark mass of 172.5 GeV is used consistently. W and Z/γ^* 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) 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 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+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 $m_{\tilde{t}_1} = 400$ GeV is (0.21 ± 0.03) pb.

Events must pass basic quality criteria to reject detector noise and non-collision backgrounds [57, 58] and are required to have ≥ 1 reconstructed primary vertex associated with five or more tracks with transverse momentum $p_{\mathrm{T}} > 0.4$ GeV. Events are retained if they contain exactly one muon [59] with $|\eta| < 2.4$ and $p_{\mathrm{T}} > 20$ GeV or one electron passing 'tight' [60] selection criteria with $|\eta| < 2.47$ and $p_{\mathrm{T}} > 25$ 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 non-compensation and inhomogeneities using p_{T}- and η-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 $p_{\mathrm{T}} > 80$, 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/gluon jets for jets with $p_{\mathrm{T}} > 20$ 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] based on their separation ΔR. The measurement of $E_{\mathrm{T}}^{\mathrm{miss}}$ 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 $\Delta\phi_{\min} > 0.8$, where $\Delta\phi_{\min}$ 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 ΔR is selected to form the hadronically decaying W boson. The mass m_{jjj} is reconstructed including a third jet closest in ΔR to the hadronic W boson momentum vector and 130 GeV $< m_{jjj} <$ 205 GeV is required.

Five signal regions (SR A–E) 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 $E_{\mathrm{T}}^{\mathrm{miss}}$, on the ratio $E_{\mathrm{T}}^{\mathrm{miss}}/\sqrt{H_{\mathrm{T}}}$, 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.

TABLE I. Selection requirements defining the SR A–E.

Requirement	SR A	SR B	SR C	SR D	SR E
$E_{\mathrm{T}}^{\mathrm{miss}}$ [GeV] $>$	150	150	150	225	275
$E_{\mathrm{T}}^{\mathrm{miss}}/\sqrt{H_{\mathrm{T}}}$ [GeV$^{1/2}$] $>$	7	9	11	11	11
m_{T} [GeV] $>$	120	120	120	130	140

The product of the kinematic acceptance, detector and reconstruction efficiency $(A \cdot \epsilon)$ varies between 4% and 0.3% for SR A and between 3% and 0.01% for SR E as the stop-LSP mass difference varies between 550 GeV and 250 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 τ lepton. In all these cases, the $t\bar{t}$ decay products include two or more high-p_{T} neutrinos, resulting in large $E_{\mathrm{T}}^{\mathrm{miss}}$ 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}, $E_{\mathrm{T}}^{\mathrm{miss}}/\sqrt{H_{\mathrm{T}}}$ and m_{jjj}, and by requiring $E_{\mathrm{T}}^{\mathrm{miss}} > 125$ GeV. The *1-lep TR* and *1-lep WR* have selection criteria identical to SR A, except the m_{T} requirement is changed to $60 < m_{\mathrm{T}} < 90$ 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 $m_{\tilde{t}_1} = 200$ 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 $E_{\mathrm{T}}^{\mathrm{miss}}$ distributions in the *2-lep TR*, and the $E_{\mathrm{T}}^{\mathrm{miss}}$ distribution in SR A. In addition, the m_{T} distribution for a looser requirements region — $E_{\mathrm{T}}^{\mathrm{miss}} > 40$ GeV and no requirements on $E_{\mathrm{T}}^{\mathrm{miss}}/\sqrt{H_{\mathrm{T}}}$ and m_{jjj} (pre-selection) — 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+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/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 (SR E) and 250 GeV (SR A and B).

Table II shows the results of the background fit to the

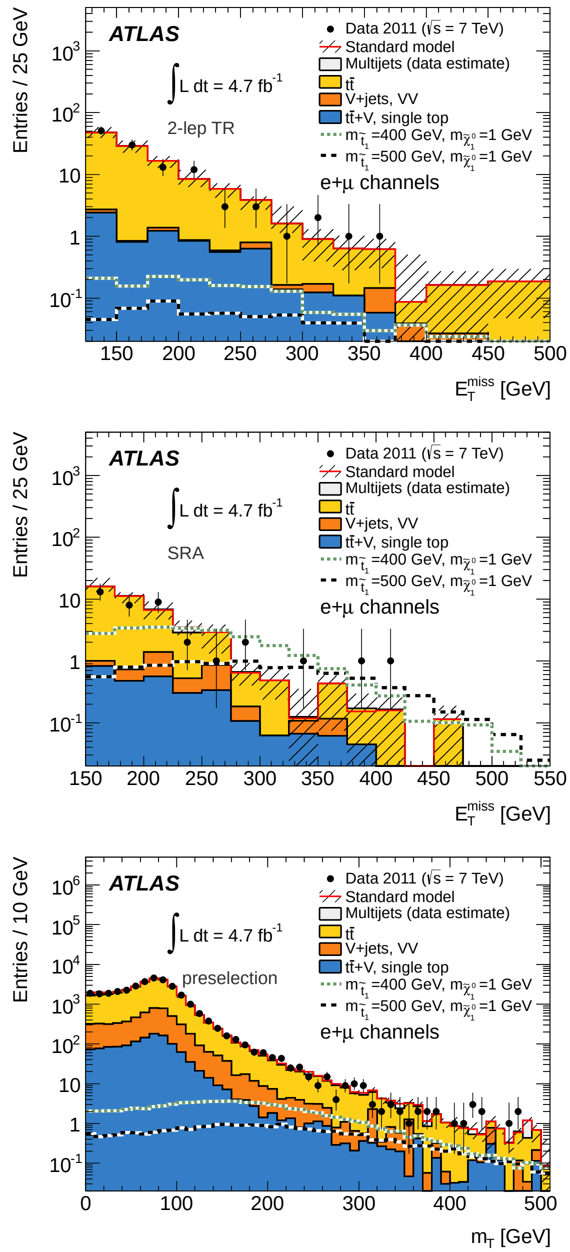

FIG. 1. Top: $E_{\mathrm{T}}^{\mathrm{miss}}$ distributions for the *2-lep TR*. Center: $E_{\mathrm{T}}^{\mathrm{miss}}$ distributions for SR A. Bottom: m_{T} distribution for the pre-selection requirements (see text). All plots show the electron and muon combined channel, before normalization fits. Hatched areas indicate the combined uncertainty due to MC sample size and the jet energy scale.

CRs, extrapolated to the SRs. The fitted numbers of $t\bar{t}$ and W+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

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 $m_{\tilde{t}_1} = 400$ GeV (500 GeV) and $m_{\tilde{\chi}_1^0} = 1$ 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_0-values and 95% CL$_s$ observed (expected) upper limits on beyond-SM events are given, using simultaneous fits including one SR at a time and all CRs.

Regions	SR A	SR B	SR C	SR D	SR E	*2-lep TR*	*1-lep TR*	*1-lep WR*
$t\bar{t}$	36 ± 5	27 ± 4	11 ± 2	4.9 ± 1.3	1.3 ± 0.6	109 ± 10	364 ± 23	59 ± 19
$t\bar{t} + V$, single top	2.9 ± 0.7	2.5 ± 0.6	1.6 ± 0.3	0.9 ± 0.3	0.4 ± 0.1	7.2 ± 1.3	18 ± 3	6.1 ± 1.6
V+jets, VV	2.5 ± 1.3	1.7 ± 0.8	0.4 ± 0.1	0.3 ± 0.1	0.1 ± 0.1	1.6 ± 0.8	38 ± 11	162 ± 23
Multijet	0.4 ± 0.4	0.3 ± 0.3	0.3 ± 0.3	0.3 ± 0.3	$0.0^{+0.3}_{-0.0}$	$0.0^{+0.6}_{-0.0}$	1.7 ± 1.7	0.8 ± 0.8
Total background	42 ± 6	31 ± 4	13 ± 2	6.4 ± 1.4	1.8 ± 0.7	118 ± 10	421 ± 20	228 ± 15
Signal benchmark 1 (2)	25.6 (8.8)	23.0 (8.1)	17.5 (6.9)	13.5 (6.2)	7.1 (4.5)	1.7 (0.6)	2.3 (0.6)	0.4 (0.1)
Observed events	38	25	15	8	5	118	421	228
p_0-values	0.50	0.50	0.32	0.24	0.015	-	-	-
Obs. (exp.) $N_{\mathrm{BSM}} <$	15.1 (17.2)	10.1 (13.8)	10.8 (9.2)	8.4 (7.0)	8.2 (4.6)	-	-	-

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 $-1\,\sigma^{\mathrm{SUSY}}_{\mathrm{theory}}$ 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.

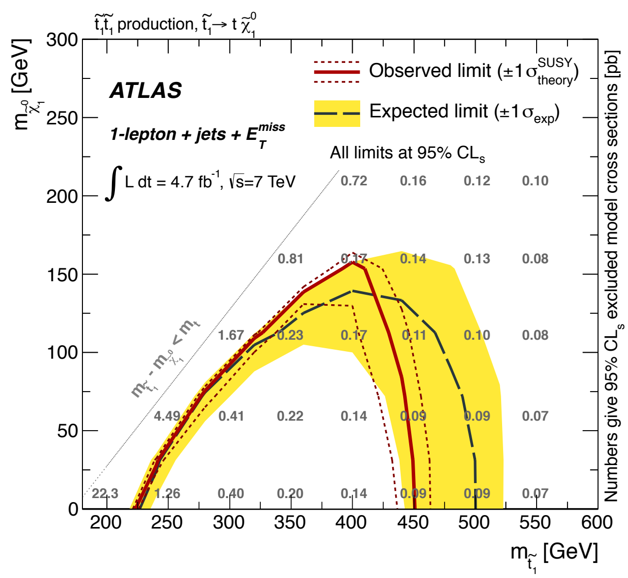

FIG. 2. Expected (dashed) and observed (solid curve) 95% CL$_s$ excluded region (under the curve) in the plane of $m_{\tilde{\chi}_1^0}$ vs. $m_{\tilde{t}_1}$, assuming $BR(\tilde{t}_1 \rightarrow t\tilde{\chi}_1^0) = 100\%$. All uncertainties except the signal cross-section uncertainties are included. The contours of the shaded band around the expected limit are the $\pm 1\,\sigma$ results. The dotted lines around the observed limit illustrate the change in the observed limit as the nominal signal cross section is scaled up and down by the theoretical uncertainty. The overlaid numbers give the 95% CL$_s$ upper limit on the signal cross section, in pb.

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[65] m_{T} is defined as $m_{\mathrm{T}}^2 = 2p_{\mathrm{T}}^{\mathrm{lep}} E_{\mathrm{T}}^{\mathrm{miss}}(1 - \cos(\Delta\phi))$, where $\Delta\phi$ is the azimuthal angle between the lepton and missing

momentum direction.

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