Search for supersymmetry using final states with one lepton, jets, and missing transverse momentum with the ATLAS detector in $\sqrt{s} = 7$ TeV pp collisions

The ATLAS Collaboration

Many extensions of the standard model predict the existence of new colored particles, such as the squarks ($\tilde{q}$) and gluinos ($\tilde{g}$) of supersymmetric (SUSY) theories, which could be accessible at the LHC. The dominant SUSY production channels are squark-(anti)squark, squark-gluino, and gluino-gluino pair production. Squarks and gluinos are expected to decay to quarks and gluons and the SUSY partners of the gauge bosons (charginos, $\tilde{\chi}^\pm$, and neutralinos, $\tilde{\chi}^0$), leading to events with energetic jets. In R-parity conserving SUSY models, the lightest supersymmetric particle (LSP) is stable and escapes detection, giving rise to events with significant missing transverse momentum. In decay chains with charginos ($\tilde{q}_L \rightarrow q \tilde{\chi}^\pm$, $\tilde{g} \rightarrow q \bar{q} \tilde{\chi}^\pm$), chargino decay to the LSP can produce a high-momentum lepton. Currently, the most stringent limits on squark and gluino masses come from the LHC [3] and from the Tevatron [4–8].

This Letter reports on a search for events with exactly one isolated high-transverse momentum ($p_T$) electron or muon, at least three high-$p_T$ jets, and significant missing transverse momentum. An exact definition of the signal region will be given elsewhere in this Letter. From an experimental point of view, the requirement of an isolated lepton suppresses the QCD multijet background and facilitates triggering on interesting events. In addition to the signal region, three control regions are considered for the most important standard model backgrounds. A combined fit to the observed number of events in these four regions, together with an independent estimate of jets misidentified as leptons in QCD multijet events, is used to search for an excess of events in the signal region.

The analysis is sensitive to any new physics leading to such an excess, and is not optimized for any particular model of SUSY. The results are interpreted within the MSUGRA/CMSSM (minimal supergravity/constrained minimal supersymmetric standard model) framework [7, 8] in terms of limits on the universal scalar and gaugino mass parameters $m_0$ and $m_{1/2}$. These are presented for fixed values of the universal trilinear coupling parameter $A_0 = 0$ GeV, ratio of the vacuum expectation values of the two Higgs doublets $\tan \beta = 3$, and Higgs mixing parameter $\mu > 0$, in order to facilitate comparison with previous results.

The ATLAS detector [9] is a multipurpose particle physics apparatus with a forward-backward symmetric cylindrical geometry and near $4\pi$ coverage in solid angle [10]. The inner tracking detector (ID) consists of a silicon pixel detector, a silicon microstrip detector (SCT), and a transition radiation tracker (TRT). The ID is surrounded by a thin superconducting solenoid providing a 2 T magnetic field, and by high-granularity liquid-argon (LAr) sampling electromagnetic calorimeters. An iron-scintillator tile calorimeter provides hadronic coverage in the central rapidity range. The end-cap and forward regions are instrumented with LAr calorimeters for both electromagnetic and hadronic measurements. The muon spectrometer (MS) surrounds the calorimeters and consists of three large superconducting toroids, a system of precision tracking chambers, and detectors for triggering.

The data used in this analysis were recorded in 2010 at the LHC at a center-of-mass energy of 7 TeV. Application of beam, detector, and data-quality requirements results in a total integrated luminosity of 35 pb$^{-1}$, with an estimated uncertainty of 11% [11]. The data have been selected with single lepton ($e$ or $\mu$) triggers. The detailed trigger requirements vary throughout the data-taking period, but the thresholds are always low enough to ensure that leptons with $p_T > 20$ GeV lie in the efficiency plateau.

Fully simulated Monte Carlo event samples are used to develop and validate the analysis procedure, compute detector acceptance and reconstruction efficiency, and aid in the background determination. Samples of events for background processes are generated as described in detail in Ref. [12]. For the major backgrounds, top quark pair and W+jets production, MC@NLO [13] v3.41 and
ALPGEN [14] v2.13 are used. Further samples include QCD multijet events, single top production, diboson production, and Drell-Yan dilepton events.

Monte Carlo signal events are generated with Herwig++ [15] v2.4.2. The SUSY particle spectra and decay modes are calculated with ISAJET [16] v7.75. The SUSY samples are normalized using next-to-leading order (NLO) cross sections as determined by Prospino [17] and a GEANT4 based [19] detector simulation [20].

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Jets are reconstructed using the anti-

The calculation of the missing transverse momentum, \( E_T^{\text{miss}} \), is based on the modulus of the vectorial sum of the \( p_T \) of the reconstructed objects (jets with \( p_T > 20 \) GeV, but over the full calorimeter coverage \(| \eta | < 4.9 \), and the selected lepton), any additional non–isolated muons and the calorimeter clusters not belonging to reconstructed objects.

Events are required to have at least one reconstructed primary vertex with at least five associated tracks. The selection criteria for signal and control regions are based on Monte Carlo studies prior to examining the data. The signal region is defined as follows. At least one identified electron or muon with \( p_T > 20 \) GeV is required. Events are rejected if they contain a second identified lepton with \( p_T > 20 \) GeV, because they are the subject of a future analysis. At least three jets with \( p_T > 30 \) GeV are required, the leading one of which must have \( p_T > 60 \) GeV.

In order to reduce the background of events with fake \( E_T^{\text{miss}} \) from mismeasured jets, the missing transverse momentum vector \( E_T^{\text{miss}} \) is required not to point in the direction of any of the three leading jets: \( \Delta \phi (\ell, E_T^{\text{miss}}) > 0.2 \) (i = 1, 2, 3). The transverse mass between the lepton and the missing transverse momentum vector, \( m_T = \sqrt{2 \cdot p_T \cdot E_T^{\text{miss}} : (1 - \cos (\Delta \phi (\ell, E_T^{\text{miss}})))} \), is required to be larger than 100 GeV. \( E_T^{\text{miss}} \) must exceed 125 GeV and must satisfy \( E_T^{\text{miss}} > 0.25 m_{\text{eff}} \), where the effective mass \( m_{\text{eff}} \) is the scalar sum of the \( p_T \) of the three leading jets, the \( p_T \) of the lepton, and \( E_T^{\text{miss}} \). Finally, a cut is applied on the effective mass: \( m_{\text{eff}} > 500 \) GeV. The efficiency for the SUSY signal in the MSSUGRA/CMSSM model defined earlier varies between 0.01% for \( m_{1/2} = 100 \) GeV and 4% for \( m_{1/2} = 350 \) GeV, with a smaller dependence on \( m_0 \), for the electron channel and the muon channel separately. The inefficiency is dominated by the leptonic branching fractions in the SUSY signal.

Backgrounds from several standard model processes could contaminate the signal region. Top quark pair production and W+jets production backgrounds are estimated by including events in three control regions, using Monte Carlo simulations to derive the background in the signal region from the control regions. The background determination of QCD multijet production with a jet misidentified as an isolated lepton is purely data driven. Remaining backgrounds from other sources are estimated with simulations.

The three control regions have identical lepton and jet selection criteria as the signal region. The top control region is defined by a window in the two-dimensional plane of 30 GeV < \( E_T^{\text{miss}} < 80 \) GeV and 40 GeV < \( m_T < 80 \) GeV and by requiring that at least one of the three leading jets is tagged as a b-quark jet. For the b-tagging, the secondary vertex algorithm SV0 [22] is used, which, for \( p_T = 60 \) GeV jets, provides an efficiency of 50% for b-quark jets and a mistag rate of 0.5% for light-quark jets. The W control region is defined by the same window in the \( E_T^{\text{miss}} - m_T \) plane, but with the requirement that none of the three hardest jets is b-tagged. The QCD mult-
tijet control region is defined by demanding low missing transverse momentum, $E_{T}^{miss} < 40$ GeV, and low transverse mass, $m_T < 40$ GeV. This QCD control region is only used to estimate the QCD multijet background contribution to other background regions but not to the signal region. Instead, the electron and muon identification criteria are relaxed, obtaining a “loose” control sample that is dominated by QCD jets. A loose-tight matrix method, in close analogy to that described in Ref. [12], is then used to estimate the number of QCD multijet events with fake leptons in the signal region after final selection criteria: $0.0^{+0.5}_{-0.0}$ in the muon channel and $0.0^{+0.3}_{-0.0}$ in the electron channel.

Data are compared to expectations in Figure 1. The standard model backgrounds in the figure are normalized to the theoretical cross sections, except for the multijet background which is normalized to data in the QCD multijet control region. The data are in good agreement with the standard model expectations. After final selection, one event remains in the signal region in the electron channel and one event remains in the muon channel. Figure 1 also shows the expected distributions for the MSUGRA/CMSSM model point $m_0 = 360$ GeV and $m_{1/2} = 280$ GeV.

A combined fit to the number of observed events in the signal and control regions is performed. The assumption that the Monte Carlo is able to predict the backgrounds in the signal region from the control regions is validated by checking additional control regions at low $m_T$ and at low $E_{T}^{miss}$. The defined control regions are not completely pure, and the combined fit takes the expected background cross-contaminations into account. The likelihood function of the fit can be written as:

$$L(n|s,b,\theta) = P_b \times P_W \times P_T \times P_Q \times C_{Syst},$$

where $n$ represents the number of observed events in data, $s$ is the SUSY signal to be tested, $b$ is the background, and $\theta$ represents the systematic uncertainties, which are treated as nuisance parameters with a Gaussian probability density function. The four $P$ functions in the right hand side are Poisson probability distributions for event counts in the defined signal (S) and control regions (W, T, and Q for W, top pair and QCD multijets respectively), and $C_{Syst}$ represents the constraints on systematic uncertainties, including correlations.

The dominant sources of systematic uncertainties in the background estimates arise from Monte Carlo modeling of the shape of the $E_{T}^{miss}$ and $m_T$ distributions in signal and control regions. These uncertainties are determined by variation of the Monte Carlo generator, as well as by variations of internal generator parameters. Finite statistics in the background control regions also contributes to the uncertainty. Experimental uncertainties are varied within their determined range and are dominated by the jet energy scale uncertainty $\delta E$, $b$-tagging uncertainties, and the uncertainty on the luminosity.

Systematic uncertainties on the SUSY signal are esti-
mated by variation of the factorization and renormalization scales in Prospino and by including the parton density function (PDF) uncertainties using the eigenvector sets provided by CTEQ6 [27]. Uncertainties are calculated separately for the individual production processes. Within the relevant kinematic range, typical uncertainties resulting from scale variations are 10–16%, whereas PDF uncertainties vary from 5% for $q\bar{q}$ production to 15–30% for $gg$ production.

The result of the combined fit to signal and control regions, leaving the number of signal events free in the signal region while not allowing for a signal contamination in the other regions, is shown in Table I. The observed number of events in data is consistent with the standard model expectation.

Limits are set on contributions of new physics to the signal region. These limits are obtained from a second combined fit to the four regions, this time allowing for a signal contamination in the other regions, leaving the number of signal events free in the signal region. These limits are obtained from a second model expectation.

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FIG. 2: Observed and expected 95% CL exclusion limits, as well as the ±1σ variation on the expected limit, in the combined electron and muon channels. Also shown are the published limits from CMS [3], CDF [4], and D0 [5, 6], and the results from the LEP experiments [29].

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TABLE I: Numbers of observed events in the signal and background control regions, as well as their estimated values from the fit (see text), for the electron (top part) and muon (bottom part) channels. The central values of the fitted sum of backgrounds in the control regions agree with the observations by construction. For comparison, nominal Monte Carlo expectations are given in parentheses for the signal region, the top control region and the W QCD region.

<table>
<thead>
<tr>
<th>Electron channel</th>
<th>Signal region</th>
<th>Top region</th>
<th>W region</th>
<th>QCD region</th>
</tr>
</thead>
<tbody>
<tr>
<td>Observed events</td>
<td>1</td>
<td>80</td>
<td>202</td>
<td>1464</td>
</tr>
<tr>
<td>Fitted top events</td>
<td>1.34 ± 0.52 (1.29)</td>
<td>65 ± 12 (63)</td>
<td>32 ± 16 (31)</td>
<td>40 ± 11</td>
</tr>
<tr>
<td>Fitted W/Z events</td>
<td>0.47 ± 0.40 (0.46)</td>
<td>11.2 ± 4.6 (10.2)</td>
<td>161 ± 27 (146)</td>
<td>170 ± 34</td>
</tr>
<tr>
<td>Fitted QCD events</td>
<td>0.0^{-0.3}_{+0.0}</td>
<td>3.7 ± 7.6</td>
<td>9 ± 20</td>
<td>1254 ± 51</td>
</tr>
<tr>
<td>Fitted sum of background events</td>
<td>1.81 ± 0.75</td>
<td>80 ± 9</td>
<td>202 ± 14</td>
<td>1464 ± 38</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Muon channel</th>
<th>Signal region</th>
<th>Top region</th>
<th>W region</th>
<th>QCD region</th>
</tr>
</thead>
<tbody>
<tr>
<td>Observed events</td>
<td>1</td>
<td>93</td>
<td>165</td>
<td>346</td>
</tr>
<tr>
<td>Fitted top events</td>
<td>1.76 ± 0.67 (1.39)</td>
<td>85 ± 11 (67)</td>
<td>42 ± 19 (33)</td>
<td>50 ± 10</td>
</tr>
<tr>
<td>Fitted W/Z events</td>
<td>0.49 ± 0.36 (0.71)</td>
<td>7.7 ± 3.3 (11.6)</td>
<td>120 ± 26 (166)</td>
<td>71 ± 16</td>
</tr>
<tr>
<td>Fitted QCD events</td>
<td>0.0^{-0.5}_{+0.0}</td>
<td>0.3 ± 1.2</td>
<td>3 ± 12</td>
<td>225 ± 22</td>
</tr>
<tr>
<td>Fitted sum of background events</td>
<td>2.25 ± 0.94</td>
<td>93 ± 10</td>
<td>165 ± 13</td>
<td>346 ± 19</td>
</tr>
</tbody>
</table>

[10] 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, θ, φ) are used in the transverse plane, φ being the azimuthal angle around the beam pipe. The pseudorapidity is defined in terms of the polar angle θ as η = − ln(tan(θ/2)).

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