Search for supersymmetry using final states with one lepton, jets, and missing transverse momentum using 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 (\( \tilde{q}_L \to q\tilde{\chi}^\pm \), \( \tilde{\chi}^0 \to q\bar{q}\tilde{\chi}^\mp \)), 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 electron or muon 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 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, \( \tan \beta = 3 \), \( \mu > 0 \) and for equal squark and gluino masses, gluino masses below 700 GeV are excluded at 95% confidence level.

PACS numbers: 12.60.Jv, 14.80.Ly

ALPGEN\textsuperscript{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++\textsuperscript{15} v2.4.2. The SUSY particle spectra and decay modes are calculated with ISAJET\textsuperscript{16} v7.75. The SUSY samples are normalized using next-to-leading order (NLO) cross sections as determined by Prospino\textsuperscript{17} and a GEANT4 based\textsuperscript{19} detector simulation\textsuperscript{20}.

Criteria for electron and muon identification closely follow those described in Ref.\textsuperscript{21}. Electrons in the signal region are required to pass the “tight” selection criteria, with $p_T > 20$ GeV and $|\eta| < 2.47$. Events are always vetoed if a “medium” electron is found in the electromagnetic calorimeter transition region, $1.37 < |\eta| < 1.52$.

Muons are required to be identified either in both ID and MS systems (combined muons) or as a match between an extrapolated ID track and one or more segments in the MS. The ID track is required to have at least one pixel hit, more than five SCT hits, and a number of TRT hits that varies with the pixel hit, more than five SCT hits, and a number of TRT hits that varies with the pixel hit, $R$.

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The inputs to this algorithm are clusters of calorimeter material and other effects using calibration factors obtained from Monte Carlo and validated with extensive test-beam and collision-data studies\textsuperscript{23}. If a jet and a “medium” electron are both identified within a distance $\Delta R < 0.2$ of each other, the jet is discarded. Furthermore, identified “medium” electrons or muons are only considered if they satisfy $\Delta R > 0.4$ with respect to the closest remaining jet. Events are discarded if they contain any jet failing basic quality selection criteria, which reject detector noise and non-collision backgrounds\textsuperscript{24}.

The calculation of the missing transverse momentum, $E_T^{miss}$, 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 $E_T^{miss}$ from mismeasured jets, the missing transverse momentum vector $E_T^{miss}$ is required not to point in the direction of any of the three leading jets: $\Delta \phi(j_i, E_T^{miss}) > 0.2$ ($i = 1, 2, 3$). The transverse mass between the lepton and the missing transverse momentum vector, $m_T = \sqrt{2 \cdot p_T \cdot E_T^{miss} \cdot (1 - \cos(\Delta \phi(\ell, E_T^{miss}))}$, is required to be larger than 100 GeV. $E_T^{miss}$ must exceed 125 GeV and must satisfy $E_T^{miss} > 0.25 m_{\text{eff}}$, 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 $E_T^{miss}$. Finally, a cut is applied on the effective mass: $m_{\text{eff}} > 500$ GeV. The efficiency for the SUSY signal in the MSUGRA/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 from a combined fit to the number of observed 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 < $E_T^{miss}$ < $80$ 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\textsuperscript{25} 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 $E_T^{miss} - m_T$ plane, but with the requirement that none of the three hardest jets is $b$-tagged. The QCD mul-
tjet control region is defined by demanding low missing
transverse momentum, $E_T^{\text{miss}} < 40$ GeV, and low trans-
verse mass, $m_T < 40$ GeV. This QCD control region is
only used to estimate the QCD multijet background con-
tribution to other background regions but not to the sig-
nal 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 multi-
jet 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 selec-
tion, one event remains in the signal region in the elec-
tron channel and one event remains in the muon chan-
nel. 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 as-
sumption that the Monte Carlo is able to predict the
backgrounds in the signal region from the control re-
gions is validated by checking additional control regions
at low $m_T$ and at low $E_T^{\text{miss}}$. The defined control re-
gions are not completely pure, and the combined fit takes
the expected background cross-contaminations into ac-
count. The likelihood function of the fit can be written
as: $L(n | s, b, \theta) = P_b \times P_W \times P_T \times P_Q \times C_{\text{Syst}}$, 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
$C_{\text{Syst}}$ represents the constraints on systematic uncertain-
ties, including correlations.

The dominant sources of systematic uncertainties in
the background estimates arise from Monte Carlo mod-
eling of the shape of the $E_T^{\text{miss}}$ 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. Fi-
nite statistics in the background control regions also con-
tributes to the uncertainty. Experimental uncertainties
are varied within their determined range and are domi-
nated by the jet energy scale uncertainty [20], $b$-tagging
uncertainties, and the uncertainty on the luminosity.

Systematic uncertainties on the SUSY signal are esti-

\begin{figure}
\centering
\includegraphics[width=0.8\textwidth]{figure1.png}
\caption{Top: $E_T^{\text{miss}}$ distribution after lepton and jet selection.
Center: $m_T$ distribution after lepton and jet selection. Bottom:
Effective mass distribution after final selection criteria except for
the cut on the effective mass itself. All plots are made for
the electron and muon channel combined. Yellow bands indicate
the uncertainty on the Monte Carlo prediction from finite Monte
Carlo statistics and from the jet energy scale uncertainty.}
\end{figure}
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 $\bar{q}q$ production to 15–30% for $\bar{q}g$ 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 in all four regions, and leaving all nuisance parameters free. The limits are then derived from the profile likelihood ratio, $\Lambda(s) = -2(\ln L(n|\hat{s}, \hat{b}, \hat{\theta}) - \ln L(n|\hat{s}, \hat{b}, \theta))$, where $\hat{s}$, $\hat{b}$ and $\hat{\theta}$ maximize the likelihood function and $b$ and $\theta$ maximize the likelihood for a given choice of $s$. In the fit, $s$ and $\hat{s}$ are constrained to be non-negative. The test statistic is $\Lambda(s)$. The exclusion $p$-values are obtained from this using pseudo-experiments and the limits set are one-sided upper limits [28].

From the fit to a model with signal events only in the signal region, a 95% CL upper limit on the number of events from new physics in the signal region can be derived. This number is 2.2 in the electron channel and 2.5 in the muon channel. This corresponds to a 95% CL upper limit on the effective cross section for new processes in the signal region, including the effects of experimental acceptance and efficiency, of 0.065 pb for the electron channel and 0.073 pb for the muon channel.

Within the MSUGRA/CMSSM framework, the results are interpreted as limits in the $m_0 - m_{1/2}$ plane, as shown in Figure 2. For the model considered and for equal squark and gluino masses, gluino masses below 700 GeV are excluded at 95% CL. The limits depend only moderately on $\tan \beta$.

In summary, the first ATLAS results on searches for supersymmetry with an isolated electron or muon, jets, and missing transverse momentum have been presented. In a data sample corresponding to 35 pb$^{-1}$, no significant deviations from the standard model expectation are observed. Limits on the cross section for new processes within the experimental acceptance and efficiency are set. For a chosen set of parameters within MSUGRA/CMSSM, and for equal squark and gluino masses, gluino masses below 700 GeV are excluded at 95% CL. These ATLAS results exceed previous limits set by other experiments [3, 6].

We wish to thank CERN for the efficient commissioning and operation of the LHC during this initial high-energy data-taking period 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; DNRF, DNSRC and Lundbeck Foundation, Denmark; ARTEMIS, European Union; IN2P3-CNRS, CEA-DSM/IRFU, France; GNAS, Georgia; BMBF, DFG, HGF, MPG and AvH Foundation, Germany; GSRT, Greece; ISF, MINERVA, GIF, DIP and Benoziyo Center, Israel; INFN, Italy; MEXT and JSPS, Japan; CNRS, Morocco; FOM and NWO, Netherlands; RCU, 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 Cantons of Bern and Geneva, Switzerland; NSC, Taiwan; TAEK, Turkey; STFC, the Royal Society and Leverhulme Trust, United Kingdom; DOE and NSF, United States of America.

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, 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.
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 and QCD control 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</td>
<td>65 ± 12</td>
<td>32 ± 16</td>
<td>40 ± 11</td>
</tr>
<tr>
<td>Fitted W/Z events</td>
<td>0.47 ± 0.40</td>
<td>11.2 ± 4.6</td>
<td>161 ± 27</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</td>
<td>85 ± 11</td>
<td>42 ± 19</td>
<td>50 ± 10</td>
</tr>
<tr>
<td>Fitted W/Z events</td>
<td>0.49 ± 0.36</td>
<td>7.7 ± 3.3</td>
<td>120 ± 26</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, 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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