Search for squarks and gluinos using final states with jets and missing transverse momentum with the ATLAS detector in $\sqrt{s} = 7$ TeV proton–proton collisions

**ATLAS Collaboration**

**Abstract**

A search for squarks and gluinos in final states containing jets, missing transverse momentum and no electrons or muons is presented. The data were recorded by the ATLAS experiment in $\sqrt{s} = 7$ TeV proton–proton collisions at the Large Hadron Collider. No excess above the Standard Model background expectation was observed in 35 pb$^{-1}$ of analysed data. Gluino masses below 500 GeV are excluded at the 95% confidence level in simplified models containing only squarks of the first two generations, a gluino octet and a massless neutralino. The exclusion increases to 870 GeV for equal mass squarks and gluinos. In MUGRA/CMS models with $\tan\beta = 3$, $A_0 = 0$ and $\mu > 0$, squarks and gluinos of equal mass are excluded below 775 GeV. These are the most stringent limits to date.

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1. Introduction

Many extensions of the Standard Model (SM) include heavy coloured particles, some of which could be accessible at the LHC. The squarks and gluinos of supersymmetric theories [1] are one example of such particles. This Letter presents the first ATLAS search for squarks and gluinos in final states containing only jets and large missing transverse momentum. Interest in this final state is motivated by the large number of $R$-parity conserving models [2] in which squarks, $\tilde{q}$, and gluinos, $\tilde{g}$, can be produced in pairs ($\tilde{q}\tilde{g}$, $\tilde{g}\tilde{g}$) and can generate that final state in their decays $\tilde{q} \rightarrow q\tilde{\chi}_1^0$ and $\tilde{g} \rightarrow q\tilde{q}\tilde{\chi}_1^0$ to weakly interacting neutralinos, $\tilde{\chi}_1^0$, which escape the detector unseen. The analysis presented here is based on a study of purely hadronic final states; events with reconstructed electrons and muons are vetoed to avoid overlap with a related ATLAS search [3] which requires them. The search strategy was optimised for maximum exclusion in the $(m_{\tilde{g}}, m_{\tilde{q}})$-plane for a set of simplified models in which all other supersymmetric particles (except for the lightest neutralino) were given masses beyond the reach of the LHC. Though interpreted in terms of supersymmetric models, the main results of this analysis (the data and expected background event counts in the signal regions) are relevant for excluding any model of new physics that predicts jets in association with missing transverse momentum. Currently, the most stringent limits on squark and gluino masses are obtained at the LHC [4] and at the Tevatron [5–9].

2. The ATLAS detector and data samples

The ATLAS detector [10] is a multipurpose particle physics apparatus with a forward–backward symmetric cylindrical geometry and nearly 4$\pi$ coverage in solid angle. The layout of the detector is dominated by four superconducting magnet systems, which comprise a thin solenoid surrounding inner tracking detectors and three large toroids supporting a large muon tracker. The calorimeters are of particular importance to this analysis. In the pseudorapidity region $|\eta| < 3.2$, high-granularity liquid-argon (LAr) electromagnetic (EM) sampling calorimeters are used. An iron-scintillator tile calorimeter provides hadronic coverage over $|\eta| < 1.7$. The end-cap and forward regions, spanning $1.5 < |\eta| < 4.9$, are instrumented with LAr calorimetry for both EM and hadronic measurements.

The data sample used in this analysis was taken in 2010 with the LHC operating at a centre-of-mass energy of 7 TeV. Application of beam, detector and data-quality requirements resulted in a total integrated luminosity of 35 pb$^{-1}$. The detailed trigger specification varied throughout the data-taking period, partly as a consequence of the rapidly increasing LHC luminosity, but always guaranteed a trigger efficiency above 97% for events with a reconstructed jet with transverse momentum ($p_T$) exceeding 120 GeV and more than 100 GeV of missing $p_T$.

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1 ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point in the centre of the detector and the $z$-axis along the beam pipe. Cylindrical coordinates $(r, \phi)$ are used in the transverse plane, $\phi$ being the azimuthal angle around the beam pipe. The pseudorapidity $\eta$ is defined in terms of the polar angle $\theta$ by $\eta = -\ln \tan(\theta/2)$.
3. Object reconstruction

Jet candidates are reconstructed using the anti-$k_T$ jet clustering algorithm [11,12] with a distance parameter of 0.4. The inputs to this algorithm are clusters of calorimeter cells seeded by those with energy significantly above the measured noise. Jet momenta are constructed by performing a four-vector sum over these cell clusters, treating each as an $(E, \mathbf{p})$ four-vector with zero mass. These jets are corrected for the effects of calorimeter non-compensation and inhomogeneities by using $p_T$- and $\eta$-dependent calibration factors based on Monte Carlo (MC) corrections validated with extensive test-beam and collision-data studies [13]. Only jet candidates with $p_T > 20$ GeV and $|\eta| < 4.9$ are subsequently retained.

Electron candidates are required to have $p_T > 10$ GeV, to have $|\eta| < 2.47$, to pass the ‘medium’ electron shower shape and track selection criteria of Ref. [14], and to be outside problematic regions of the calorimeter. Muon candidates are required to have $p_T > 10$ GeV and $|\eta| < 2.4$. The sum of the transverse momenta of charged particle tracks within a cone of radius $\Delta R = \sqrt{(\Delta \eta)^2 + (\Delta \phi)^2} < 0.2$ around the muon trajectory is required to be less than 1.8 GeV.

Following the steps above, overlaps between candidate jets with $|\eta| < 2.5$ and leptons are resolved using the method of Ref. [15] as follows. First, any such jet candidate lying within a distance $\Delta R < 0.2$ of an electron is discarded. Then the whole event is rejected if any electron candidate remains in the calorimeter transition region $1.37 < |\eta| < 1.52$ between barrel and end-cap. Finally, any lepton candidate remaining within a distance $\Delta R = 0.4$ of such a jet candidate is discarded.

The measurement of the missing transverse momentum two-vector $\vec{P}_T^\text{miss}$ (and its magnitude $E_T^\text{miss}$) is then based on the transverse momenta of all remaining jet and lepton candidates and all calorimeter clusters not associated to such objects. Following this, all jet candidates with $|\eta| > 2.5$ are discarded. Thereafter, the remaining lepton and jet candidates are considered “reconstructed”, and the term “candidate” is dropped.

4. Event selection

Following the object reconstruction described above, events are discarded if any electrons or muons remain, or if they have any jets failing quality selection criteria designed to suppress detector noise and non-collision backgrounds [16], or if they lack a reconstructed primary vertex associated with five or more tracks.

In order to achieve maximal reach over the $(m_\tilde{g}, m_\tilde{q})$-plane, several signal regions are defined. When production of squark pairs $\tilde{q}\tilde{q}$ is dominant, only a small number of jets (one per squark from $q \rightarrow \tilde{q} \tilde{g}$) is expected. The optimal strategy for the $\tilde{q}\tilde{q}$ region therefore makes requirements on two jets only. When production involves gluinos ($\tilde{g}\tilde{g}$ and $\tilde{g}\tilde{q}$), extra jets are expected from $g \rightarrow q\bar{q} \chi^0_1$. In these regions, requiring at least three jets yields better sensitivity. The higher total cross section in the associated $\tilde{g}\tilde{g}$ region where both species are accessible permits the use of tighter criteria than in the $\tilde{g}\tilde{q}$ region. Four signal regions A, B, C and D are therefore defined (targeting light-$\tilde{q}\tilde{q}$, heavy-$\tilde{g}\tilde{g}$, $\tilde{g}\tilde{g}$ and $\tilde{g}\tilde{q}$ production, respectively) as shown in Table 1. In this table, $\Delta \phi$ (jet, $E_T^\text{miss}$)_{min} is the smallest of the azimuthal separations between $E_T^\text{miss}$ and jets with $p_T > 40$ GeV (up to a maximum of three, in descending order of $p_T$, whether pre-selected or not). The variable $m_{T2}$ [17–19] is defined to be the maximal lower bound on the mass of a pair-produced particle which decays into one of the pre-selected jets and a massless undetected particle, assuming the two undetected particles are the only source of the event $E_T^\text{miss}$. The effective mass, $m_{\text{eff}}$, is defined as the sum of $E_T^\text{miss}$ and the magnitudes of the transverse momenta of the two highest $p_T$ jets (in signal region A) or three highest $p_T$ jets (in signal regions C and D). The $\tilde{q}\tilde{q}$ channel has two signal regions, A and B, because the $m_{T2}$ distribution has the best expected reach in $m_\tilde{q}$, but $m_{\text{eff}}$ offers better coverage for lighter squarks.

5. Backgrounds, simulation and normalisation

Standard Model background processes contribute to the event counts in the signal regions. The dominant sources are: $W +$ jets, $Z+$ jets, top pair, multi-jet and single top production. Non-collision backgrounds are negligible. The majority of the $W +$ jets background is composed of $W \rightarrow \tau \nu$ events, or $W \rightarrow l \nu$ events in which no electron or muon candidate is reconstructed. The largest part of the $Z+$ jets background comes from the irreducible component in which $Z \rightarrow \nu\bar{\nu}$ generates large $E_T^\text{miss}$. Hadronic $\tau$ decays in $t\bar{t} \rightarrow b\bar{b}v\nu\gamma$ can generate large $E_T^\text{miss}$ and pass the jet and lepton requirements at a non-negligible rate. The multi-jet background in the signal regions is predominantly caused by poor reconstruction of jet energies in calorimeters leading to ‘fake’ missing transverse momentum. There is also a contribution from neutrinos when events contain semileptonic decays of heavy quarks. Extensive validation of MC against data has been performed for each of these background sources and for a wide variety of control regions. The excellent agreement found motivates an approach in which the systematic uncertainties on the $W +$ jets, $Z +$ jets and top background estimates are derived from the validation against data, while the central values for those estimates are taken from MC simulation to reduce sensitivity to correlations between data-driven estimates for different backgrounds. In contrast, the multi-jet background is normalised to data in control regions as described below.

Production of $W$ and $Z$ bosons, in association with jets, was simulated with ALPGEN [20] v2.13 at leading order (LO) and up to $2 \rightarrow 5$ partons using CTEQ6L1 PDFs [21]. Both were separately normalised to the next-to-next-to-leading-order inclusive $W$ and $Z$ cross sections from FEWZ [22,23] v2.0. Both resulting samples were found to be consistent with a variety of data-derived estimates, including methods based on: re-simulation of reconstructed leptons as hadronically decaying taus; removal of leptons from $W(l\nu)$ + jet and $Z(l\ell)$ + jet events; and by comparing MC predictions to data in control regions enriched with background events.

Production of top quarks (both singly and in pairs, assuming $m_{\text{top}} = 172.5$ GeV) was simulated with MC@NLO [24,25] v3.41 using CTEQ6.6 next-to-leading-order (NLO) PDFs [26]. This estimate was found to be consistent with a data-driven cross-check based on replacement of reconstructed muons in the corresponding single-lepton channels with simulated hadronic $\tau$ decays. Agreement was also found after reweighting the $t\bar{t}$ MC according to experimentally measured $b$-tag weights.

Simulated multi-jet events were generated both with PYTHIA [27] v6.4.21, which uses 2 $\rightarrow$ 2 LO matrix elements (ME) with the MRST2007 LO+ PDF set [28], and with ALPGEN implementing the exact LO ME for up to 2 $\rightarrow$ 5 partons. The normalisation of these samples was fixed by a scaling designed to achieve a match to data in control regions obtained by reversing the $\Delta \phi$ requirements. After this scaling, both sets of simulations were in agreement within the experimental uncertainties, and therefore only PYTHIA multi-jet simulations are used further in this analysis. The resulting simulation was found to be consistent with a data-driven estimate in which high $E_T^\text{miss}$ events were generated from data by smearing low $E_T^\text{miss}$ events on a jet-by-jet basis with measured jet energy resolution functions. This latter technique has
no MC dependencies: it provides a completely independent determination of the multi-jet background using only quantities measured from the data. Additional control regions having reversed $E_T^{miss}/m_{eff}$ requirements were used as further checks on the normalisation.

Supersymmetric events were generated with HERWIG++ [29] v2.4.2. These samples were normalised using NLO cross sections determined by PROSPINO [30] v2.1.

All non-PYTHIA samples used HERWIG++ or HERWIG-6.510 [31] to simulate parton showering and fragmentation, while JIMMY [32] v4.31 was used to generate the underlying event. All samples were produced using an ATLAS 'tune' [33] and a full detector simulation [34].

6. Systematic uncertainties

The primary sources of systematic uncertainties in the background estimates are: the luminosity determination, the jet energy scale (JES), the jet energy resolution (JER), the MC modelling, the jet energy resolution (JES), the jet energy scale inter-calibration, the rate the JES uncertainty. Systematic uncertainties associated with mis-

<table>
<thead>
<tr>
<th>Pre-selection</th>
<th>Number of required jets</th>
<th>$\geq 2$</th>
<th>$\geq 2$</th>
<th>$\geq 3$</th>
<th>$\geq 3$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leading jet $p_T$ [GeV]</td>
<td>$&gt; 120$</td>
<td>$&gt; 120$</td>
<td>$&gt; 120$</td>
<td>$&gt; 120$</td>
<td></td>
</tr>
<tr>
<td>Other jet(s) $p_T$ [GeV]</td>
<td>$&gt; 40$</td>
<td>$&gt; 40$</td>
<td>$&gt; 40$</td>
<td>$&gt; 40$</td>
<td></td>
</tr>
<tr>
<td>$E_T^{miss}$ [GeV]</td>
<td>$&gt; 100$</td>
<td>$&gt; 100$</td>
<td>$&gt; 100$</td>
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<td></td>
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</table>

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<tr>
<th>Final selection</th>
<th>$\Delta \phi (\text{jet}, \overrightarrow{E_T^{miss}})_{\text{min}}$</th>
<th>$&gt; 0.4$</th>
<th>$&gt; 0.4$</th>
<th>$&gt; 0.4$</th>
<th>$&gt; 0.4$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_T/m_{eff}$</td>
<td>$&gt; 0.3$</td>
<td>$-$</td>
<td>$&gt; 0.25$</td>
<td>$&gt; 0.25$</td>
<td></td>
</tr>
<tr>
<td>$m_{eff}$ [GeV]</td>
<td>$&gt; 500$</td>
<td>$-$</td>
<td>$&gt; 500$</td>
<td>$&gt; 1000$</td>
<td></td>
</tr>
<tr>
<td>$m_{12}$ [GeV]</td>
<td>$-$</td>
<td>$&gt; 300$</td>
<td>$-$</td>
<td>$-$</td>
<td></td>
</tr>
</tbody>
</table>

<table>
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<tr>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
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</table>

This Letter reports a search for new physics in final states containing high-$p_T$ jets, missing transverse momentum and no electrons or muons. Good agreement is seen between the numbers of events observed in the four signal regions and the numbers of events expected from SM sources. Signal regions A, B, C and D exclude non-SM cross sections within acceptance of 1.3, 0.35, 1 and 0.11 pb respectively at 95% confidence.

There are five parameters which are needed to specify a particular MSUGRA/CMSSM model. They are the universal scalar mass, $m_0$, the universal gaugino mass $m_{1/2}$, the universal trilinear scalar coupling, $A_0$, the ratio of the vacuum expectation values of the two Higgs fields, $\tan \beta$, and the sign of the higgsino mass parameters, $\mu$. 
Table 2
Expected and observed numbers of events in the four signal regions. Uncertainties shown are due to “MC statistics, statistics in control regions, other sources of uncorrelated systematic uncertainty, and also the jet energy resolution and lepton efficiencies” $[u]$, the jet energy scale $[j]$, and the luminosity $[L]$. Totals are correct within rounding errors.

<table>
<thead>
<tr>
<th>Signal region A</th>
<th>Signal region B</th>
<th>Signal region C</th>
<th>Signal region D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Multi-jet</td>
<td>$7.0 , ^{+5}_{-4}(u+j)$</td>
<td>$0.6 , ^{+3}_{-2}(u+j)$</td>
<td>$0.2 , ^{+5}_{-4}(u+j)$</td>
</tr>
<tr>
<td>W+jets</td>
<td>$50 , ^{+35}_{-24}(j) \pm 5(L)$</td>
<td>$4.4 , ^{+2.3}_{-1.5}(j) \pm 0.5(L)$</td>
<td>$1.1 , ^{+0.7}_{-0.8}(j) \pm 0.1(L)$</td>
</tr>
<tr>
<td>Z+jets</td>
<td>$52 , ^{+32}_{-24}(j) \pm 6(L)$</td>
<td>$4.1 , ^{+2.3}_{-1.5}(j) \pm 0.5(L)$</td>
<td>$0.8 , ^{+0.7}_{-0.8}(j) \pm 0.1(L)$</td>
</tr>
<tr>
<td>(t) and (t)</td>
<td>$10 , ^{+0}_{-0}(j) \pm 1(L)$</td>
<td>$0.9 , ^{+0.1}_{-0.1}(j) \pm 0.1(L)$</td>
<td>$0.3 , ^{+0.1}_{-0.1}(j) \pm 0.0(L)$</td>
</tr>
<tr>
<td>Total SM</td>
<td>$118 , ^{+72}_{-56}(j) \pm 12(L)$</td>
<td>$10.0 , ^{+4.5}_{-2.9}(j) \pm 1.0(L)$</td>
<td>$8.8 , ^{+5.0}_{-4.6}(j) \pm 0.9(L)$</td>
</tr>
<tr>
<td>Data</td>
<td>87</td>
<td>11</td>
<td>66</td>
</tr>
</tbody>
</table>

Fig. 1. The distributions of $m_{\text{eff}}$ (separately for the $\geq 2$ and $\geq 3$ jet regions) and $m_{T2}$ are shown for data and for the expected SM contributions after application of all selection criteria — cuts on the variables themselves are indicated by the red arrows. Also shown is the $E_{\text{T}}^{\text{miss}}$ distribution after the $\geq 2$ jet preselection cuts only. For comparison, each plot includes a curve showing the expectation for an MSUGRA/CMSSM reference point with $m_0 = 200$ GeV, $m_{1/2} = 190$ GeV, $A_0 = 0$, $\tan\beta = 3$ and $\mu > 0$. This reference point is also indicated by the star on Fig. 3. Below each plot the ratio of the data to the SM expectation is provided. Black vertical bars show the statistical uncertainty from the data, while the yellow band shows the size of the Standard Model MC uncertainty. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this Letter.)

The results are interpreted in both a simplified model containing only squarks of the first two generations, a gluino octet and a massless neutralino, as well as in MSUGRA/CMSSM models with $\tan\beta = 3$, $A_0 = 0$ and $\mu > 0$. In the simplified model, gluino masses below 500 GeV are excluded at the 95% confidence level with the limit increasing to 870 GeV for equal mass squarks and gluinos. In the MSUGRA/CMSSM models equal mass squarks and gluinos below 775 GeV are excluded.
and squark mass are displayed at 100 GeV intervals. The different model assumptions given in the legend. Contours of constant gluino mass are displayed at 100 GeV intervals. Assume illustrative only as some are derived in the context of MSUGRA/CMSSM or may not be known.

Fig. 2. 95% C.L. exclusion limits in the ($m_{\tilde{g}}$, $m_{\tilde{q}}$) plane together with existing limits [5–9] and contours showing the total supersymmetric cross section, for the simplified squark–gluino model with massless $\tilde{\chi}_1^0$. Comparison with existing limits is illustrative only as some are derived in the context of MSUGRA/CMSSM or may not assume $m_{\tilde{g}} = 0$.

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