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

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Aad, G
Abbott, B
Abdallah, J
et al.

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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

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 \cite{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 hadrons produced in `$t$-channel' decays of squarks, $\tilde{q}$, and gluinos, $\tilde{g}$, as well as the complexity of the decay products. 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 \cite{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. 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 \cite{4} and at the Tevatron \cite{5–9}.

2. The ATLAS detector and data samples

The ATLAS detector \cite{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 $p_T$.

\footnote{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 $(\rho, \phi)$ 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 $(E, \vec{p})$ 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 failing quality selection criteria designed to suppress detector noise discarded if any electrons or muons remain, or if they have any jets.

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 $\Delta R = \sqrt{(\Delta \eta)^2 + (\Delta \phi)^2} = 0.2$ around the muon trajectory is required to be less than 1.8 GeV.

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 $(m_\tilde{g}, m_\tilde{\chi}^0)$-plane, several signal regions are defined. When production of squark pairs $\tilde{g}\tilde{g}$ is dominant, only a small number of jets (one per squark from $q \rightarrow q\tilde{\chi}^0_1$) is expected. The optimal strategy for the $\tilde{g}\tilde{g}$ region therefore makes requirements on two jets only. When production involves gluinos ($\tilde{g}\tilde{g}$ and $\tilde{q}\tilde{q}$), extra jets are expected from $g \rightarrow q\tilde{\chi}^0_1$. 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 $\tilde{g}\tilde{g}$ region. Four signal regions A, B, C and D are therefore defined (targeting light-$\tilde{q}$, heavy-$\tilde{q}$, $\tilde{g}\tilde{g}$ and $\tilde{q}\tilde{q}$ production, respectively) as shown in Table 1. In this table, $\Delta p_T$ 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 $m_{\tilde{t}_2}$ [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 $m_{\tilde{t}_2}$ 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 candidare is reconstructed. The largest part of the Z + jets background comes from the irreducible component in which $Z \rightarrow \ell^+\ell^-$ generates large $E_T^{\text{miss}}$. Hadronic $\tau$ decays in $t\bar{t} \rightarrow b\bar{b}t\nuqq$ 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 to 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 $W/(l)+j$ and $Z/(l)+j$ 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 to 2 LO matrix elements (ME) with the MSTW2007 LO* PDF set [28], and with ALPGEN implementing the exact LO ME for up to 2 to 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
by variation of the factorisation and renormalisation scales in function have also been incorporated where appropriate.

The uncertainty on the estimated top background is dominated by and nominal MC is taken as the systematic uncertainty on the JER.

The number of observed data events and the number of SM events expected from SM sources. Signal regions A, B, C and D exclude non-SM cross sections within acceptance of 1.3, 0.35, 1.1 and 0.11 pb respectively at 95% confidence.

Systematic uncertainties on the SUSY signal were estimated by variation of the factorisation and renormalisation scales in PROSPINO between half and twice their default values and by considering the PDF uncertainties provided by CTEQ6. Uncertainties were calculated for individual production processes (e.g. $q\bar{q}$, $g\bar{g}$, etc.).

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7. Results, interpretation and limits

The number of observed data events and the number of SM events expected to enter each of the signal regions are shown in Table 2. The background model is found to be in good agreement with the data, and the distributions of $m_{\text{eff}}$, $m_{t\bar{t}}$, and $E_T^{\text{miss}}$ are shown in Fig. 1.

An interpretation of the results is presented in Fig. 2 as a 95% confidence exclusion region in the $(m_{\tilde{g}}, m_{\tilde{q}})$-plane for the simplified set of models with $m_{\tilde{q}} = 0$ for which the analysis was optimised. In these models the gluino mass and the masses of the squarks of the first two generations are set to the values shown in the figure. All other supersymmetric particles, including the squarks of the third generation, are decoupled by being given masses of 5 TeV. ISASUSY from ISAJET [37] v7.80 was used to calculate the decay tables, and to guarantee consistent electroweak symmetry breaking. The SUSY Les Houches Accord files for the models used may be found online [38]. The results are also interpreted in the $\tan \beta = 3$, $A_0 = 0$, $\mu > 0$ slice of MSUGRA/CMSSM2 [39–44] in Fig. 3.

These figures also show the variation of the expected limit in response to ±1σ fluctuations of the SM expectation including the stated systematic uncertainties. The character of the statistic which is used to construct the exclusion regions in the $(m_{\tilde{g}}, m_{\tilde{q}})$ and CMSSM planes varies as a function of position. Specifically, at each point in those planes, only the data from a single signal region (A, B, C or D) is used to form that statistic, where the region was chosen based on the best expected sensitivity. For a given signal region, the statistic is defined to be the log of the profile likelihood ratio [45,46] for the observed event count in that region, assuming a non-negative signal contribution. A detailed description of how this is done and how the correlated and uncorrelated nuisance parameters representing systematic uncertainties are incorporated may be found in the Higgs chapter of Ref. [15]. Plots showing where each signal region is dominant may be found in [38]. All signal regions contribute to the exclusion and to its boundary in the $(m_{\tilde{g}}, m_{\tilde{q}})$-plane. Region D is dominant near the CMSSM boundary. Pseudo-experiments are used to compute one-sided upper limits on the signal contribution and guarantee exact coverage. In the simplified model, changing the $\chi^0_1$ mass from 0 to 100 GeV reduces the number of selected events by only $\lesssim 20\%$ near the exclusion curve so only slightly modifies the excluded region in the $(m_{\tilde{g}}, m_{\tilde{q}})$-plane. In the CMSSM, varying $A_0$ to 300 GeV, $\tan \beta$ to 30 or $\mu$ to $-\mu$ leads to significant (~5%) changes, among the strongly interacting particles, only in the stop and sbottom masses. Accordingly, the exclusion limits are not strongly sensitive to these parameters.

8. Summary

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, 1.1 and 0.11 pb respectively at 95% confidence.

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**Table 1**

Criteria for admission to each of the four overlapping signal regions A–D. All variables are defined in Section 4.

<table>
<thead>
<tr>
<th>Pre-selection</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of required jets</td>
<td>$\geq 2$</td>
<td>$\geq 2$</td>
<td>$\geq 3$</td>
<td>$\geq 3$</td>
</tr>
<tr>
<td>Leading jet $p_T$ [GeV]</td>
<td>$&gt; 120$</td>
<td>$&gt; 120$</td>
<td>$&gt; 120$</td>
<td>$&gt; 120$</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>
</tr>
<tr>
<td>$E_T^{\text{miss}}$ [GeV]</td>
<td>$&gt; 100$</td>
<td>$&gt; 100$</td>
<td>$&gt; 100$</td>
<td>$&gt; 100$</td>
</tr>
</tbody>
</table>

---

2 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 parameter, $\mu$. 

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**Figure 1**

Graph showing the dependence of the systematics on the SUSY signal.

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**Figure 2**

Graph showing the 95% confidence exclusion region in the $(m_{\tilde{g}}, m_{\tilde{q}})$-plane.

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**Figure 3**

Graph showing the variation of the expected limit in response to ±1σ fluctuations of the SM expectation including the stated systematic uncertainties.
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>7.1 ± 1.1([u + j])</td>
<td>0.6 ± 0.2([u + j])</td>
<td>0.2 ± 0.1([u + j])</td>
</tr>
<tr>
<td>W+jets</td>
<td>50 ± 11([u + j]) ± 5([C])</td>
<td>4.4 ± 3.2([u + j]) ± 0.5([C])</td>
<td>35 ± 9([u + j]) ± 4([C]) ± 0.1([C])</td>
</tr>
<tr>
<td>Z+jets</td>
<td>52 ± 21([u + j]) ± 4([C])</td>
<td>4.1 ± 2.9([u + j]) ± 0.5([C])</td>
<td>27 ± 12([u + j]) ± 3([C]) ± 0.1([C])</td>
</tr>
<tr>
<td>(t) and (t)</td>
<td>10 ± 0([u + j]) ± 1([C])</td>
<td>0.9 ± 0.1([u + j]) ± 0.1([C])</td>
<td>17 ± 1([u + j]) ± 2([C]) ± 0.1([C])</td>
</tr>
<tr>
<td>Total SM</td>
<td>118 ± 25([u + j]) ± 12([C])</td>
<td>10.0 ± 4.3([u + j]) ± 1.0([C])</td>
<td>88 ± 18([u + j]) ± 9([C]) ± 0.1([C])</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.
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 \(\chi_1^0\). Comparison with existing limits is illustrative only as some are derived in the context of MSUGRA/CMSSM or may not assume \(m_{\tilde{g}} = 0\).

Fig. 3. 95% C.L. exclusion limits in the \((m_0, m_{1/2})\) plane of MSUGRA/CMSSM for which \(\tan \beta = 3\), \(A_0 = 0\) and \(\mu > 0\). Also shown are existing limits [7–9,4] having the different model assumptions given in the legend. Contours of constant gluino and squark mass are displayed at 100 GeV intervals.

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ATLAS Collaboration


Also at California Institute of Technology, Pasadena CA, United States.

Also at Group of Particle Physics, University of Montreal, Montreal QC, Canada.

Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan.

Also at Institut für Experimentalphysik, Universität Hamburg, Hamburg, Germany.

Also at Manhattan College, New York NY, United States.

Also at School of Physics and Engineering, Sun Yat-sen University, Guangzhou, China.

Also at Academia Sinica Grid Computing, Institute of Physics, Academia Sinica, Taipei, Taiwan.

Also at High Energy Physics Group, Shandong University, Shandong, China.

Also at Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom.

Also at Section de Physique, Université de Genève, Geneva, Switzerland.

Also at Departamento de Fisica, Universidade de Minho, Braga, Portugal.

Also at Department of Physics and Astronomy, University of South Carolina, Columbia SC, United States.

Also at KFKI Research Institute for Particle and Nuclear Physics, Budapest, Hungary.

Also at Institute of Physics, Jagiellonian University, Krakow, Poland.

Also at Department of Physics, Oxford University, Oxford, United Kingdom.

Also at DSM/IRFU, CEA Saclay, Gif-sur-Yvette, France.

Also at Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France.

Also at Department of Physics, Nanjing University, Jiangsu, China.

Deceased.