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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

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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 MSUGRA/CMSSM 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.

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 in which squarks and gluinos can be produced in pairs $\{\tilde{g}\tilde{g}, \tilde{q}\tilde{q}, \tilde{q}\tilde{g}\}$ and can generate that final state in their decays $\tilde{q} \rightarrow q\tilde{\chi}_1^0$ and $\tilde{g} \rightarrow qq\tilde{\chi}_1^0$ 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 [2] which requires a lepton. 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 [3] and at the Tevatron [4] .

2. The ATLAS Detector and Data Samples

The ATLAS detector [5] is a multipurpose particle physics apparatus with a forward-backward symmetric cylindrical geometry and nearly 4π coverage in solid angle.[1] 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 guarantees a trigger efficiency above 97% for events with a reconstructed jet with transverse momentum ($p_{\rm T}$) exceeding 120 GeV and more than 100 GeV of missing $p_{\rm T}$.

3. Object Reconstruction

Jet candidates are reconstructed by using the anti-k_t jet clustering algorithm [6] 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 $p_{\rm T}$- and η-dependent calibration factors based on Monte Carlo (MC) corrections validated with extensive test-beam and collision-data studies [7]. Only jet candidates with $p_{\rm T} > 20$ GeV and $|\eta| < 4.9$ are retained hereafter.

Electron candidates are required to have $p_{\rm T} > 10$ GeV, to have $|\eta| < 2.47$, to pass the 'medium' electron shower shape and track selection criteria of Ref. [8], and to be outside problem-

[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, ϕ) are used in the transverse plane, ϕ being the azimuthal angle around the beam pipe. The pseudorapidity η is defined in terms of the polar angle θ by $\eta = -\ln\tan(\theta/2)$.

atic regions of the calorimeter. Muon candidates are required to have $p_{\mathrm{T}} > 10$ 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. [9] 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 $\vec{P}_{\mathrm{T}}^{\mathrm{miss}}$ (and its magnitude $E_{\mathrm{T}}^{\mathrm{miss}}$) 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 against detector noise and against non-collision backgrounds [10], 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 $\tilde{q} \to q\tilde{\chi}_1^0$) 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 $\tilde{q}\tilde{g}$), extra jets are expected from $\tilde{g} \to qq\tilde{\chi}_1^0$. In these regions, requiring at least three jets yields better sensitivity. The higher total cross section in the associated $\tilde{q}\tilde{g}$ 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 thus defined (targeting light-$\tilde{q}\tilde{q}$, heavy-$\tilde{q}\tilde{q}$, $\tilde{g}\tilde{g}$ and $\tilde{g}\tilde{q}$ production, respectively) as shown in Table 1. In this table, $\Delta\phi(\text{jet}, \vec{P}_{\mathrm{T}}^{\mathrm{miss}})_{\min}$ is the smallest of the azimuthal separations between $\vec{P}_{\mathrm{T}}^{\mathrm{miss}}$ and jets with $p_{\mathrm{T}} > 40$ GeV (up to a maximum of three, in descending order of p_{T}, whether pre-selected or not). The variable m_{T2} [11] 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 $\vec{P}_{\mathrm{T}}^{\mathrm{miss}}$. The effective mass, m_{eff}, is defined as the sum of $E_{\mathrm{T}}^{\mathrm{miss}}$ 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_{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, QCD multi-jet (hereafter, the expression "multi-jet" is dropped) and single top production. Non-collision backgrounds are negligible. The majority of the W+jets background is composed of $W \to \tau\nu$ events, or $W \to l\nu$ 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 $Z \to \nu\bar{\nu}$ generates large $E_{\mathrm{T}}^{\mathrm{miss}}$. Hadronic τ decays in $t\bar{t} \to b\bar{b}\tau\nu qq$ can generate large $E_{\mathrm{T}}^{\mathrm{miss}}$ and pass the jet and lepton requirements at a non-negligible rate. The QCD 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 leptonic 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 both the shape and the normalisation of the W+jets, Z+jets and top backgrounds are taken from MC simulation. In contrast, the QCD background is normalised to data in control regions as described below.

		A	B	C	D
Pre-selection	Number of required jets	≥ 2	≥ 2	≥ 3	≥ 3
	Leading jet p_{T} [GeV]	> 120	> 120	> 120	> 120
	Other jet(s) p_{T} [GeV]	> 40	> 40	> 40	> 40
	$E_{\mathrm{T}}^{\mathrm{miss}}$ [GeV]	> 100	> 100	> 100	> 100
Final selection	$\Delta\phi(\text{jet}, \vec{P}_{\mathrm{T}}^{\mathrm{miss}})_{\min}$	> 0.4	> 0.4	> 0.4	> 0.4
	$E_{\mathrm{T}}^{\mathrm{miss}}/m_{\mathrm{eff}}$	> 0.3	–	> 0.25	> 0.25
	m_{eff} [GeV]	> 500	–	> 500	> 1000
	m_{T2} [GeV]	–	> 300	–	–

Table 1: Criteria for admission to each of the four overlapping signal regions A to D. All variables are defined in §4.

Production of W and Z bosons, in association with jets, was simulated with ALPGEN [12] v2.13 at leading order (LO) and up to $2 \to 5$ partons using CTEQ6L1 PDFs [13]. Both were separately normalised to the next-to-next-to-leading-order inclusive W and Z cross sections from FEWZ [14] 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 $Z(ll)$+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 $m_{\mathrm{top}} = 172.5$ GeV) was simulated with MC@NLO [15] v3.41 using CTEQ6.6 next-to-leading-order (NLO) PDFs [16]. 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 τ decays. Agreement was also found after reweighting the $t\bar{t}$ MC according to experimentally measured b-tag weights.

Simulated QCD events were generated both with PYTHIA [17] v6.4.21, which uses $2 \to 2$ LO matrix elements (ME) with the MRST2007 LO* PDF set [18], and with ALPGEN implement-

	Signal region A	Signal region B	Signal region C	Signal region D
QCD	$7\ ^{+8}_{-7}$[u+j]	$0.6\ ^{+0.7}_{-0.6}$[u+j]	$9\ ^{+10}_{-9}$[u+j]	$0.2\ ^{+0.4}_{-0.2}$[u+j]
W+jets	50 ± 11[u] $^{+14}_{-10}$[j] $\pm$ 5[$\mathcal{L}$]	4.4 ± 3.2[u] $^{+1.5}_{-0.8}$[j] $\pm$ 0.5[$\mathcal{L}$]	35 ± 9[u] $^{+10}_{-8}$[j] $\pm$ 4[$\mathcal{L}$]	1.1 ± 0.7[u] $^{+0.2}_{-0.3}$[j] $\pm$ 0.1[$\mathcal{L}$]
Z+jets	52 ± 21[u] $^{+15}_{-11}$[j] $\pm$ 6[$\mathcal{L}$]	4.1 ± 2.9[u] $^{+2.1}_{-0.8}$[j] $\pm$ 0.5[$\mathcal{L}$]	27 ± 12[u] $^{+10}_{-6}$[j] $\pm$ 3[$\mathcal{L}$]	0.8 ± 0.7[u] $^{+0.6}_{-0.0}$[j] $\pm$ 0.1[$\mathcal{L}$]
$t\bar{t}$ and t	10 ± 0[u] $^{+3}_{-2}$[j] $\pm$ 1[$\mathcal{L}$]	0.9 ± 0.1[u] $^{+0.4}_{-0.3}$[j] $\pm$ 0.1[$\mathcal{L}$]	17 ± 1[u] $^{+6}_{-4}$[j] $\pm$ 2[$\mathcal{L}$]	0.3 ± 0.1[u] $^{+0.2}_{-0.1}$[j] $\pm$ 0.0[$\mathcal{L}$]
Total SM	118 ± 25[u] $^{+32}_{-23}$[j] $\pm$ 12[$\mathcal{L}$]	10.0 ± 4.3[u] $^{+4.0}_{-1.9}$[j] $\pm$ 1.0[$\mathcal{L}$]	88 ± 18[u] $^{+26}_{-18}$[j] $\pm$ 9[$\mathcal{L}$]	2.5 ± 1.0[u] $^{+1.0}_{-0.4}$[j] $\pm$ 0.2[$\mathcal{L}$]
Data	87	11	66	2

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 [$\mathcal{L}$].

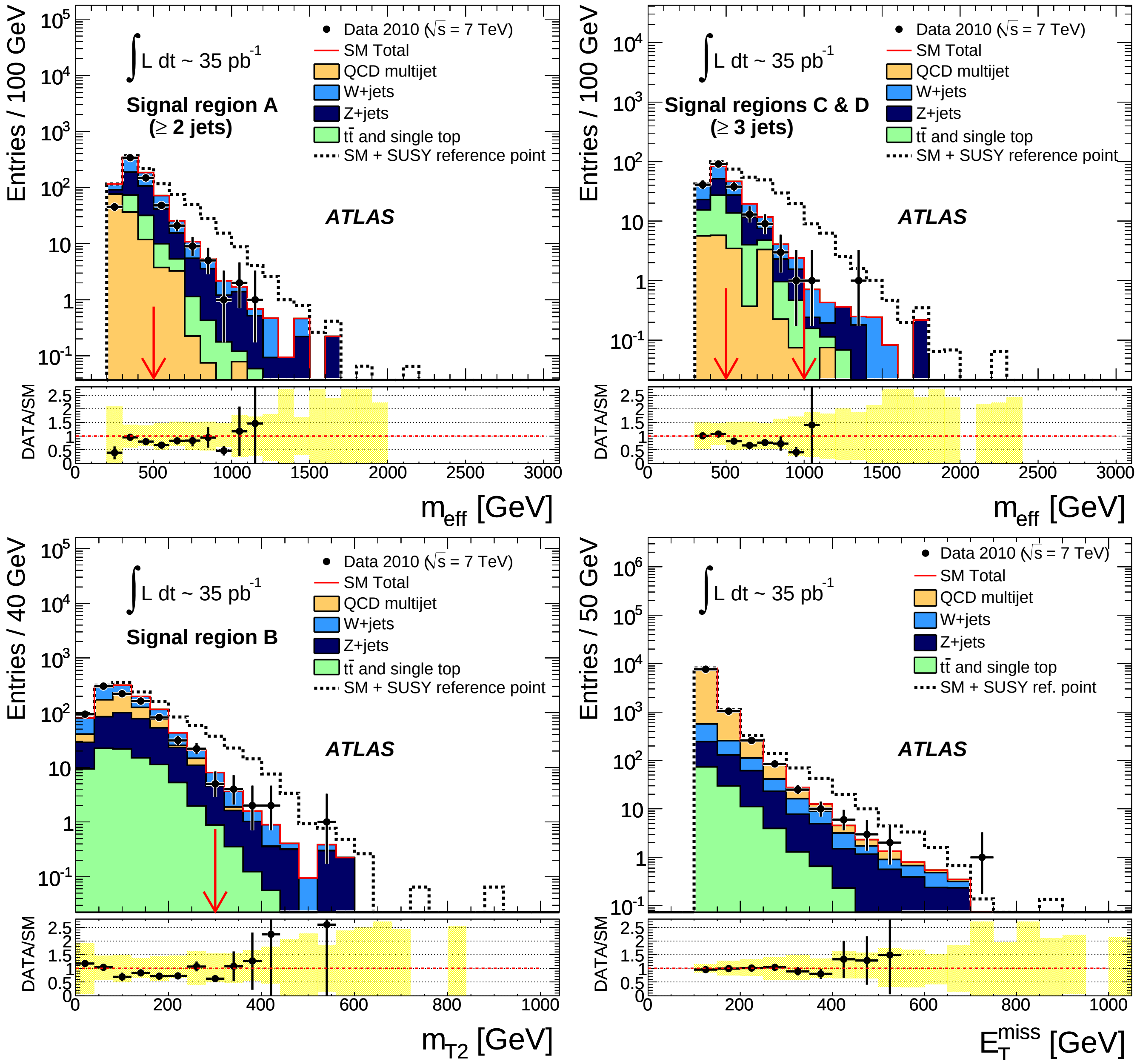

Figure 1: The distributions of m_{eff} (separately for the ≥ 2 and ≥ 3 jet regions) and m_{T2} are shown for data and for the expected SM contributions after application of all selection criteria – cuts on the variables themselves are indicated by the red arrows. Also shown is the $E_{\mathrm{T}}^{\mathrm{miss}}$ 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 Figure 3. Below each plot may be seen the ratio of the data to the SM expectation. Black vertical bars show the statistical uncertainty from the data, while the yellow band shows the size of the Standard Model MC uncertainty.

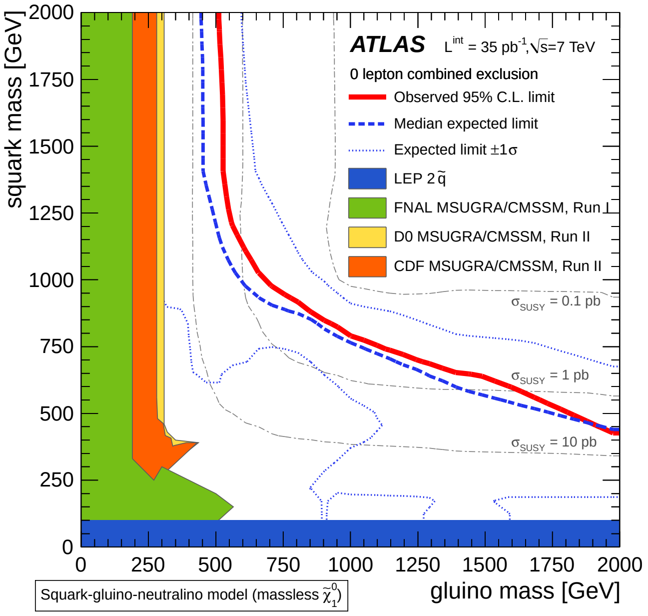

Figure 2: 95% C.L. exclusion limits in the $(m_{\tilde{g}}, m_{\tilde{q}})$ plane together with existing limits [4]. Comparison with existing limits is illustrative only as some are derived in the context of MSUGRA/CMSSM or may not assume $m_{\tilde{\chi}_1^0} = 0$.

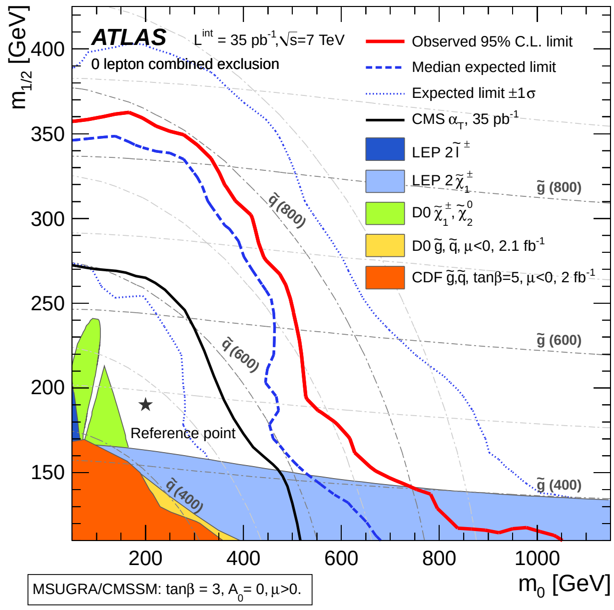

Figure 3: 95% C.L. exclusion limits in the $\tan\beta = 3$, $A_0 = 0$ and $\mu > 0$ slice of MSUGRA/CMSSM, together with existing limits [3, 4] with the different model assumptions given in the legend.

ing 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 QCD simulations are used further in this analysis. The resulting QCD simulation was found to be consistent with a data-driven QCD estimate in which high $E_{\mathrm{T}}^{\mathrm{miss}}$ events were generated from data by smearing low $E_{\mathrm{T}}^{\mathrm{miss}}$ 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 QCD background using only quantities measured from the data. Additional control regions having reversed $E_{\mathrm{T}}^{\mathrm{miss}}/m_{\mathrm{eff}}$ requirements were used as further checks on the normalisation.

Supersymmetric events were generated with HERWIG++ [19] v2.4.2. These samples were normalised using NLO cross sections determined by PROSPINO [20] v2.1.

All non-PYTHIA samples used HERWIG++ or HERWIG-6.510 [21] to simulate parton showering and fragmentation, while JIMMY [22] v4.31 was used to generate the underlying event. All samples were produced using an ATLAS 'tune' [23] and a full detector simulation [24].

6. Systematic Uncertainties

The primary sources of systematic uncertainties in the background estimates are: the jet energy scale (JES), the jet energy resolution (JER), the luminosity determination, the MC modelling, the lepton efficiencies, the extrapolation from control regions into signal regions, and the finite statistics of the MC samples and control regions. The uncertainty on the luminosity determination is estimated to be 11% [25]. The JES uncertainty has been measured from the complete 2010 data set using the techniques described in Ref. [7] and, though p_{T} and η dependent, is around 7%. The JER measured in data [26] was applied to all MC simulated jets and was propagated to $\vec{P}_{\mathrm{T}}^{\mathrm{miss}}$. The difference between the re-calibrated and nominal MC is taken as the systematic uncertainty due to this effect. The uncertainty on the estimated top background is dominated by the JES uncertainty. Systematic uncertainties associated with misidentification of leptons, jet energy scale inter-calibration, the rate of leptonic b-decays and the non-Gaussian tail of the jet response function have also been incorporated where appropriate.

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. $\tilde{q}\tilde{q}$, $\tilde{g}\tilde{g}$, etc.).

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_{eff}, m_{T2} and $E_{\mathrm{T}}^{\mathrm{miss}}$ are shown in Figure 1.

An interpretation of the results is presented in Figure 2 as a 95% confidence exclusion region in the $(m_{\tilde{g}}, m_{\tilde{q}})$-plane for the simplified set of models with $m_{\tilde{\chi}_1^0} = 0$ 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 [27] 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 [28]. The results are also interpreted in the $\tan\beta = 3$, $A_0 = 0$, $\mu > 0$ slice of MSUGRA/CMSSM [29] in Figure 3.

These figures also show the variation of the expected limit in response to $\pm 1\sigma$ fluctuations of the SM expectation including the stated systematic uncertainties. The exclusion regions are constructed using a profile likelihood ratio method. Pseudo-experiments are used to compute one-sided upper limits on the signal contribution, which is assumed to be non-negative. At each point in the $(m_{\tilde{g}}, m_{\tilde{q}})$ and CMSSM planes, the chosen test statistic is the likelihood ratio corresponding to the number of observed events in the signal region whose expected sensitivity was largest. Plots showing where each signal region is dominant may be found in [30]. 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. In the simplified model, changing the $\tilde{\chi}_1^0$ 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 μ to $-\mu$ leads to significant ($\sim 5\%$) 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.

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.

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