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Search for new phenomena in final states with large jet multiplicities and missing transverse momentum using $\sqrt{s} = 7$ TeV pp collisions with the ATLAS detector

The ATLAS Collaboration

Abstract: Results are presented of a search for any particle(s) decaying to six or more jets in association with missing transverse momentum. The search is performed using 1.34 fb^{-1} of $\sqrt{s} = 7$ TeV proton-proton collisions recorded by the ATLAS detector during 2011. Data-driven techniques are used to determine the backgrounds in kinematic regions that require at least six, seven or eight jets, well beyond the multiplicities required in previous analyses. No evidence is found for physics beyond the Standard Model. The results are interpreted in the context of a supersymmetry model (MSUGRA/CMSSM) where they extend previous constraints.

Keywords: Hadron-Hadron Scattering

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Contents

1 Introduction

Many extensions of the Standard Model predict the existence of TeV-scale states that rapidly decay to a large number of strongly interacting particles in association with one or more stable, weakly interacting particles. If such states are kinematically accessible with the proton-proton collisions at the LHC [1], they will be characterised by events with many hadronic jets with unbalanced momenta in the plane perpendicular to the beams due to the unobserved weakly interacting particles.

The most sensitive direct searches [2–8] have been previously performed at the LHC by the ATLAS and CMS collaborations in selections requiring jets and missing transverse momentum ($E_{\mathrm{T}}^{\mathrm{miss}}$). These analyses required a varying number of jets from as few as one [4, 7, 8], to as many as $\geq$4 [5].

The delivery of a large ($>\mathrm{fb}^{-1}$) integrated luminosity makes it possible to extend those searches to final states with at least six, seven or even eight jets. Selecting events with larger jet multiplicities provides increased sensitivity to models that predict many-body decays or sequential cascade decays to many strongly interacting particles. Such models include supersymmetric [9–17] (SUSY) models that have gluinos with masses near the TeV scale and relatively heavy squarks.

Standard Model predictions must be determined with particular care for large jet multiplicities. The background from multi-jet events, in which the momentum imbalance results from jet mismeasurement, is evaluated using entirely data-driven methods. Electroweak and top contributions are obtained from a mixture of control measurements, and transfer factors calculated from sophisticated multi-leg Monte Carlo simulations [18–21]. A detailed description of the background determination can be found in section 5.

Events containing high transverse momentum ($p_{\rm T}$) electrons or muons are vetoed in order to reduce backgrounds from (semi-leptonically) decaying top quarks or W bosons. Other complementary searches have been performed by the ATLAS collaboration in final states with $E_{\rm T}^{\rm miss}$ and lower jet multiplicity requirements [2, 4, 5], in conjunction with b-jet tagging [3], hard electrons and/or muons [22–24] or photons [25].

While the results are presented in the context of MSUGRA/CMSSM [26–31], the analysis is sensitive to any new states that decay into large numbers of jets in association with weakly interacting particles which escape the detector unseen.

2 The ATLAS detector and data samples

The ATLAS experiment [32] is a multipurpose particle physics detector 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 a barrel and two end-cap 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 for $|\eta| < 1.7$. 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 during the first half of 2011 with the LHC operating at a centre-of-mass energy of $\sqrt{s}$ =7 TeV. Application of beam, detector and data-quality requirements resulted in an integrated luminosity of $1.34 \pm 0.05\,{\rm fb}^{-1}$. The analysis makes use of dedicated multi-jet triggers, the details of which changed during the data-taking period as a consequence of increasing LHC luminosity. In all cases the trigger efficiency was greater than 95% for events with either at least four jets with $p_{\rm T} > 80$ GeV, or at least five jets with $p_{\rm T} > 55$ GeV.

3 Object reconstruction

The definitions of jets, leptons (e and μ) and missing transverse momentum follow closely those of previous ATLAS searches [5, 24].

Jet candidates are reconstructed using the anti-k_t jet clustering algorithm [33, 34] with distance parameter 0.4. The inputs to this algorithm are clusters of calorimeter cells [35] seeded by those with energy significantly above the measured noise. Jet momenta are constructed by performing a four-vector sum over these topological clusters of calorimeter cells, treating each as an $(E, \vec{p})$ four-vector with zero mass. These jets are corrected for the

[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 $\eta = -\ln\tan(\theta/2)$.

effects of calorimeter non-compensation and inhomogeneities by using p_{T}- and η-dependent calibration factors based on Monte Carlo (MC) simulations validated with extensive test-beam and collision-data studies [36]. Only jet candidates with $p_{\mathrm{T}} > 20\,\mathrm{GeV}$ and $|\eta| < 4.9$ are retained. During the data-taking period, a localized electronics failure in the LAr barrel calorimeter created an electronically dead region in the second and third calorimeter layers, approximately 1.4×0.2 in $\Delta\eta \times \Delta\phi$, in which on average 30% of incident jet energy is lost. The impact on reconstruction efficiency for $p_{\mathrm{T}} > 20\,\mathrm{GeV}$ jets is found to be negligible. Since the energy response for jets in the problematic region is underestimated due to this extra dead area, a correction factor is applied to the jet transverse momenta. Events are rejected if the correction applied to any jet candidate provides a contribution to $E_{\mathrm{T}}^{\mathrm{miss}}$ that is greater than both $10\,\mathrm{GeV}$ and $0.1\,E_{\mathrm{T}}^{\mathrm{miss}}$. When identification of jets containing heavy flavour quarks is required, either to make measurements in control regions or for cross checks, a tagging algorithm exploiting both impact parameter and secondary vertex information is used [37].

Electron candidates are required to have $p_{\mathrm{T}} > 20\,\mathrm{GeV}$ and $|\eta| < 2.47$, to pass the 'medium' electron shower shape and track selection criteria of ref. [38], and to be outside problematic regions of the calorimeter. Muon candidates are required to have $p_{\mathrm{T}} > 10\,\mathrm{GeV}$ and $|\eta| < 2.4$.[2]

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 electron and muon candidates, all jets which are not also electron candidates with $|\eta| < 4.5$, and all calorimeter clusters with $|\eta| < 4.5$ not associated to such objects.

Following the steps above, overlaps between candidate jets with $|\eta| < 2.8$ and leptons are resolved as follows. First, any such jet candidate lying within a distance $\Delta R < 0.2$ of an electron is discarded, where $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$. Then any lepton candidate remaining within a distance $\Delta R = 0.4$ of such a jet candidate is discarded. Thereafter, all jet candidates with $|\eta| > 2.8$ are discarded, and the remaining electron, muon and jet candidates are retained as reconstructed objects.

4 Event selection

Following the object reconstruction described in section 3, events are discarded if any electrons or muons remain, or if they contain any jet failing quality selection criteria designed to suppress detector noise and non-collision backgrounds [39], or if they lack a reconstructed primary vertex with five or more associated tracks.

Four different signal regions (SRs) are defined as shown in table 1. The use of multiple signal regions provides sensitivity in different areas of the MSUGRA/CMSSM plane. Furthermore, the complementarity of the selections may be enhanced in new models not

[2] When defining control regions that require the presence of one or more leptons, additional requirements are applied. Electrons must pass the 'tight' selection criteria of ref. [38], and the sum Σ of the transverse momentum of tracks within a cone of $\Delta R = 0.2$ around the electron must satisfy $\Sigma / p_{\mathrm{T}}(e) < 0.1$. Muons must have longitudinal and transverse impact parameters within 1 mm and 0.2 mm of the primary vertex, respectively, and must have $\Sigma < 1.8\,\mathrm{GeV}$.

Signal region	7j55	8j55	6j80	7j80
Jet p_T	$> 55\,\text{GeV}$		$> 80\,\text{GeV}$	
Jet $\lvert\eta\rvert$	< 2.8			
ΔR_{jj}	> 0.6 for any pair of jets			
Number of jets	≥ 7	≥ 8	≥ 6	≥ 7
$E_{\mathrm{T}}^{\mathrm{miss}}/\sqrt{H_T}$	$> 3.5\,\text{GeV}^{1/2}$			

Table 1. Definitions of the four signal regions.

explicitly considered here. The combinations of jet multiplicities and p_{T} thresholds are chosen such that all four SRs have trigger efficiencies in excess of 95% and acceptances greater than 2% - 3% for kinematically accessible MSUGRA/CMSSM models. Differences caused by jet merging and splitting between the offline and online selections can lead to trigger inefficiencies. A separation of $\Delta R_{jj} > 0.6$ between all jets with p_{T} above the threshold for the SR is required to maintain acceptable trigger efficiency.

The final selection variable is $E_{\mathrm{T}}^{\mathrm{miss}}/\sqrt{H_{\mathrm{T}}}$, the ratio of magnitude of the missing transverse momentum to the square root of the scalar sum H_{T} of transverse momenta of all jets with $p_{\mathrm{T}} > 40\,\text{GeV}$ and $|\eta| < 2.8$. This ratio provides a measure of the size of the missing transverse momentum relative to the resolution due to stochastic variations in the measured jet energies.

5 Backgrounds, simulation and normalisation

Standard Model processes contribute to the event counts in the signal regions. The dominant backgrounds are multi-jet production, including those from purely strong interaction processes and fully hadronic decays of $t\bar{t}$; semi- and fully-leptonic decays of $t\bar{t}$; and leptonically-decaying W or Z bosons produced in association with jets. Non-fully-hadronic top, and W and Z are collectively referred to as 'leptonic' backgrounds, and can contribute to the signal regions when no e or μ leptons are produced (for example $Z \to \nu\nu$ or hadronic $W \to \tau\nu$ decays) or when they are produced but out of acceptance or not reconstructed. Contributions from the hadronic decays of W and Z bosons are negligible.

The selection cuts were chosen such that the background from the multi-jet processes can be determined from supporting measurements. In events dominated by jet activity, the ATLAS $E_{\mathrm{T}}^{\mathrm{miss}}$ resolution is approximately proportional to $\sqrt{H_{\mathrm{T}}}$. The ratio $E_{\mathrm{T}}^{\mathrm{miss}}/\sqrt{H_{\mathrm{T}}}$ is therefore almost invariant under changes in the jet multiplicity N_{jet}, as will be shown later.

The shape of the $E_{\mathrm{T}}^{\mathrm{miss}}/\sqrt{H_{\mathrm{T}}}$ distribution for the multi-jet background is therefore determined from data using control regions CR with smaller jet multiplicities than the SRs. The control regions are assumed to be dominated by Standard Model processes, an assumption that is corroborated by the agreement of multi-jet cross section measurements with up to six jets [40] with Standard Model predictions. The signal 'contamination' contributes less than 1% to the higher multiplicity CRs for relevant, unexcluded MSUGRA/CMSSM points. The basic shape of the $E_{\mathrm{T}}^{\mathrm{miss}}/\sqrt{H_{\mathrm{T}}}$ distribution is encapsulated in transfer factors

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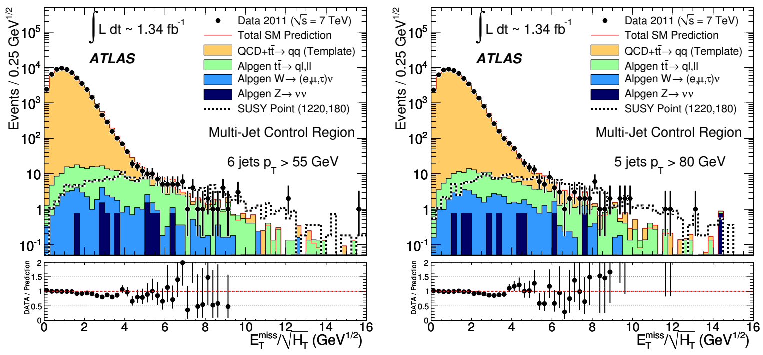

(a) (b)

Figure 1. The distribution of the variable $E_{\rm T}^{\rm miss}/\sqrt{H_T}$ for control regions requiring (a) exactly six jets with $p_{\rm T} > 55\,{\rm GeV}$ or (b) exactly five jets with $p_{\rm T} > 80\,{\rm GeV}$. Overlaid are templates taken from selections requiring (a) exactly five jets with $p_{\rm T} > 55\,{\rm GeV}$ or (b) exactly four jets with $p_{\rm T} > 80\,{\rm GeV}$. These templates are normalised to the data in the region with $E_{\rm T}^{\rm miss}/\sqrt{H_T} < 1.5$. The background estimation includes the ALPGEN Monte-Carlo prediction for the 'leptonic' Standard Model backgrounds. For illustrative purposes the plots also contain the distribution expected for an example MSUGRA/CMSSM point with $m_0 = 1220\,{\rm GeV}$ and $m_{1/2} = 180\,{\rm GeV}$. In all ratio plots (lower), in regions with very low numbers of events, some points may lie off the shown range and for bins with no observed events no ratio is shown. For $t\bar{t}$ backgrounds the labels 'qq' and 'ql,ll' represent fully hadronic and non-fully-hadronic decays respectively.

$T_{\rm j,p}$, defined to be the ratio of the number of events in the control region, ${\rm CR}^{+}_{\rm j,p}$, with a certain number, j, of jets above a $p_{\rm T}$ threshold p and $E_{\rm T}^{\rm miss}/\sqrt{H_{\rm T}} > 3.5{\rm GeV}^{1/2}$ to the number in the control region, ${\rm CR}^{-}_{\rm j,p}$, with the same j, p and $E_{\rm T}^{\rm miss}/\sqrt{H_{\rm T}} < 1.5\,{\rm GeV}^{1/2}$. The $T_{\rm j,p}$ are calculated after subtracting the predicted contributions of the 'leptonic' backgrounds from the measured counts. The signal region prediction is found by applying a $T_{\rm j,p}$, with the same p as the signal region and $j = 5$ when $p = 55\,{\rm GeV}$ and $j = 4$ when $p = 80\,{\rm GeV}$, to the number of events (after subtracting the expected contribution from 'leptonic' background sources) satisfying signal region multiplicity requirements but with $E_{\rm T}^{\rm miss}/\sqrt{H_{\rm T}} < 1.5\,{\rm GeV}^{1/2}$.

The validity of the assumption of $E_{\rm T}^{\rm miss}/\sqrt{H_{\rm T}}$ invariance has been tested with data, using a series of additional CRs with either smaller jet multiplicities than the SRs, or at smaller values of $E_{\rm T}^{\rm miss}/\sqrt{H_{\rm T}}$ (between $1.5\,{\rm GeV}^{1/2}$and $3.0\,{\rm GeV}^{1/2}$) or both. Templates are formed from data selections with lower values of $N_{\rm jet}$ and correcting for 'leptonic' contamination. After scaling by the appropriate normalisation the shapes of the $E_{\rm T}^{\rm miss}/\sqrt{H_{\rm T}}$ distributions in these CRs are found to be well described by these templates (see figures 1 and 2 for examples). The numbers of events in each of six different CRs are found to be correctly predicted to within $\sim 10\% - 20\%$. The residual differences are included in the systematic uncertainty associated with the method.

The backgrounds from multi-jet processes are cross checked using another data-driven technique [2, 5] which smears the energies of individual jets from low-$E_{\rm T}^{\rm miss}$ multi-jet 'seed' events in data. Separate smearing functions are defined for b-tagged and non-b-tagged

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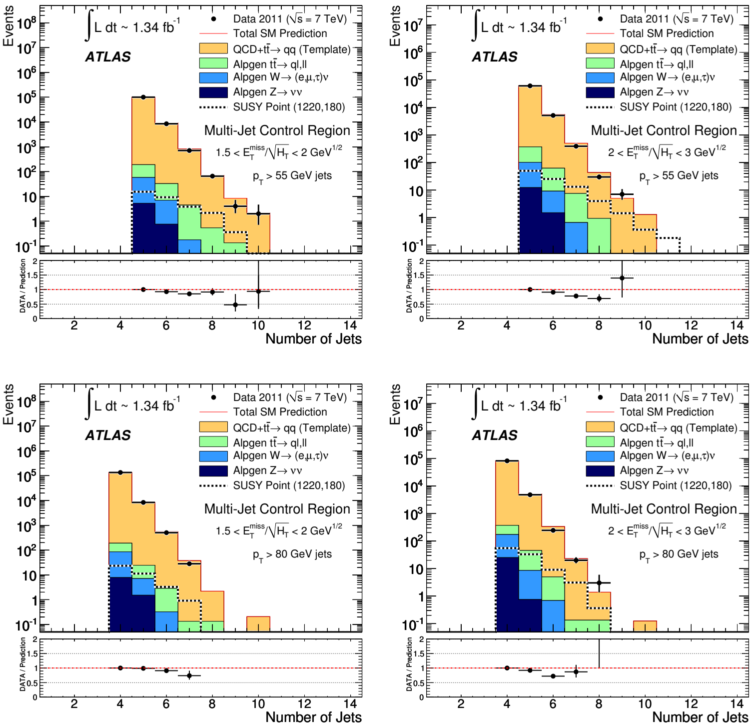


Figure 2. Observed and predicted jet multiplicity distributions for jets with $p_{\mathrm{T}} > 55\,\mathrm{GeV}$ (upper) and with $p_{\mathrm{T}} > 80\,\mathrm{GeV}$ (lower) in four example control regions defined by $1.5\,\mathrm{GeV}^{1/2} < E_{\mathrm{T}}^{\mathrm{miss}}/\sqrt{H_{\mathrm{T}}} < 2\,\mathrm{GeV}^{1/2}$ (left) and $2\,\mathrm{GeV}^{1/2} < E_{\mathrm{T}}^{\mathrm{miss}}/\sqrt{H_{\mathrm{T}}} < 3\,\mathrm{GeV}^{1/2}$ (right). Overlaid are templates taken from selections requiring $E_{\mathrm{T}}^{\mathrm{miss}}/\sqrt{H_{\mathrm{T}}} < 1.5\,\mathrm{GeV}^{1/2}$ which are normalised to the data in the lowest jet multiplicity bin shown. The background estimation includes the `ALPGEN` Monte-Carlo prediction for the 'leptonic' Standard Model backgrounds. For illustrative purposes the plots also contain the distribution expected for an example MSUGRA/CMSSM point with $m_0 = 1220\,\mathrm{GeV}$ and $m_{1/2} = 180\,\mathrm{GeV}$.

jets, with each modelling both the Gaussian core and the non-Gaussian tail of the jet response. The functions are based on simulations and are verified with data in three-jet control regions in which the $\vec{P}_{\mathrm{T}}^{\mathrm{miss}}$ can be associated with the fluctuation of a particular jet. The agreement between the two methods is satisfactory within uncertainties, and so the prediction used in what follows is that based on $E_{\mathrm{T}}^{\mathrm{miss}}/\sqrt{H_{\mathrm{T}}}$ shape invariance.

Monte Carlo simulations are used to determine the transfer factors used to estimate the 'leptonic' Standard Model backgrounds, and to assess sensitivity to specific SUSY signal models. When used for 'leptonic' background estimation, the resulting transfer factors connect CRs and SRs with similar selection requirements. Theoretical uncertainties, including those arising from the use of Leading Order (LO) generators, are therefore reduced. All Monte Carlo samples employ a GEANT4 [41] based detector simulation [42], and are reconstructed with the same algorithms as the data. The simulations include the effects of multiple proton-proton interactions per bunch crossing.

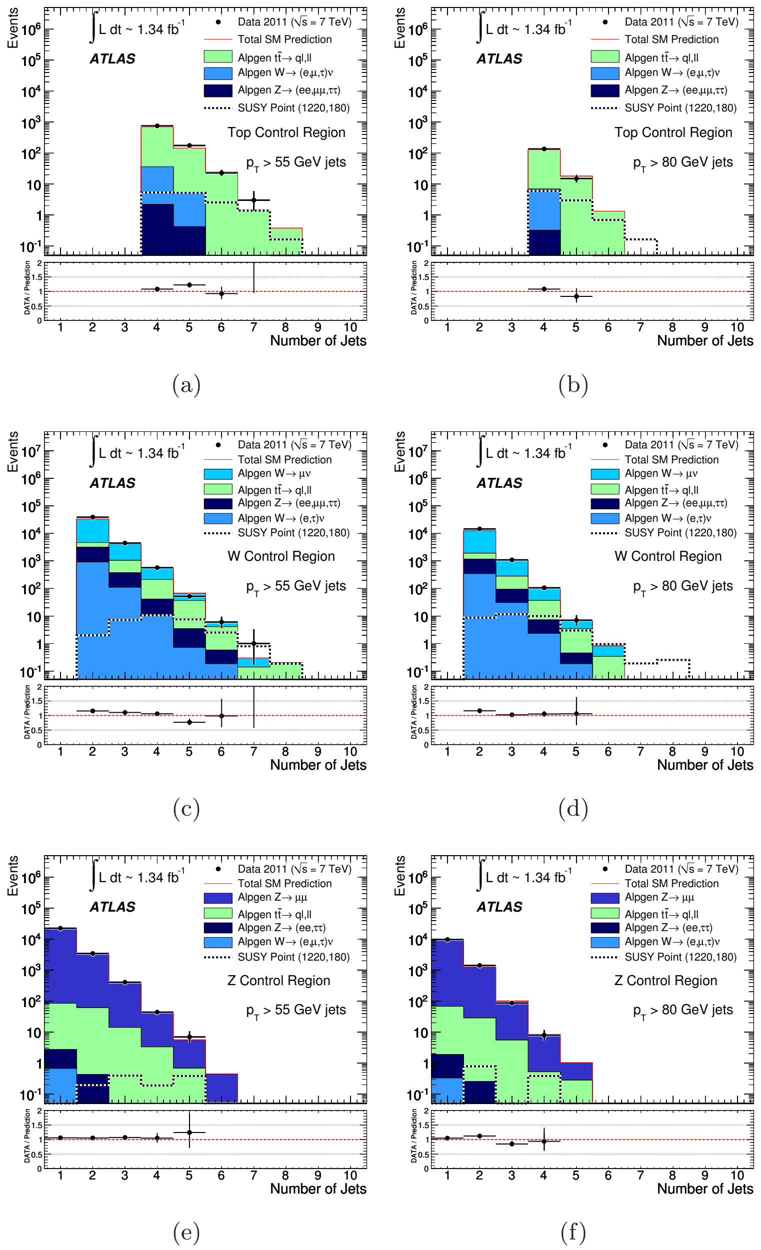


Figure 3. The multiplicity of jets with $p_{\mathrm{T}} > 55\,\mathrm{GeV}$ (left) or $p_{\mathrm{T}} > 80\,\mathrm{GeV}$ (right) for events in various control regions. Top row: top-quark enhanced control regions requiring at least one b-tagged jet, a single isolated muon with $p_T > 20\,\mathrm{GeV}$ and $|\eta| < 2.4$ and $40 < m_{\mathrm{T}} < 100\,\mathrm{GeV}$. Middle row: W-boson enhanced region (as for top, but with b-jet veto). Bottom row: $Z \to \mu\mu$ enhanced region.

To estimate the contribution from 'leptonic' $t\bar{t}$ events, control regions are defined with exactly one $p_{\mathrm{T}} > 20\,\mathrm{GeV}$ muon, transverse mass[3] in the range $40\,\mathrm{GeV} < m_{\mathrm{T}}(\mu, \vec{P}_{\mathrm{T}}^{\mathrm{miss}}) < 100\,\mathrm{GeV}$, and at least one b-tagged jet. The jet multiplicity distributions for this initial

[3] The transverse mass is defined by $m_{\mathrm{T}}^2(a,b) = m_a^2 + m_b^2 + 2\left(E_{\mathrm{T}}^{(a)} E_{\mathrm{T}}^{(b)} - \vec{p}_{\mathrm{T}}^{\,(a)} \cdot \vec{p}_{\mathrm{T}}^{\,(b)}\right)$, where $E_T^2 = p_{\mathrm{T}}^2 + m^2$. The massless representation is used for $\vec{P}_{\mathrm{T}}^{\mathrm{miss}}$.

control selection are shown in figures 3(a) and 3(b). The control regions, $CR^{t\bar{t}}_{j,p}$, are then formed by including the leptons in the jet multiplicity, j, and requiring $E^{\rm miss}_{\rm T}/\sqrt{H_{\rm T}} > 3.5\,{\rm GeV}^{1/2}$. The contribution in each SR is calculated from the corresponding $CR^{t\bar{t}}_{j,p}$ (with the same j,p) in each case using a transfer factor evaluated using ALPGEN [18] v2.13 $t\bar{t}$ Monte Carlo, the PDF set CTEQ6L1 [43] and up to three (and as a cross check, up to five) additional outgoing partons in the matrix elements. Parton showering, fragmentation and hadronization for all ALPGEN samples is performed with HERWIG [44, 45], while JIMMY [46] is used to simulate the underlying event.

The vector boson processes $Z \to \nu\nu$ and $W \to \ell\nu$ provide small contributions to the signal regions when produced in association with jets. The $W \to \ell\nu$ + jets background is evaluated using an ALPGEN-based simulation with up to five additional partons in the matrix elements. Control regions are defined with selections similar to the $CR^{t\bar{t}}_{j,p}$ but with a b-jet veto to reduce contamination from $t\bar{t}$. The jet multiplicity distributions for the W-enhanced selection can be found in figures 3(c) and 3(d).

The $Z \to \nu\nu$ + jets background is calculated using an ALPGEN-based simulation with up to five additional partons in the matrix elements. There are sufficient $Z \to \mu^+\mu^-$ events in data to verify the Monte Carlo predictions for multiplicities in the range $1 \le N_{\rm jet} \le 5$ (figures 3(e) and 3(f)). The ratio of cross sections $R_n \equiv \frac{\sigma(V+(n+1)\,{\rm jets})}{\sigma(V+n\,{\rm jets})}$ is found, both in simulations and in data, to be nearly constant.[4] The values of R_n for $N_{\rm jet} \in \{5, 6, 7\}$ have been cross checked against SHERPA [19–21] with COMIX [53] and agreement found at the 20% level.

Backgrounds from other sources such as single top or diboson production, which have been evaluated using Monte Carlo simulations, and those from non-collision sources are found to be negligible.

MSUGRA/CMSSM particle spectra and decay modes are calculated with ISAJET [54] v7.75. Samples are generated with HERWIG++ [55] v2.4.2. The cross sections are normalised using the next-to-leading-order predictions of PROSPINO [56] v2.1.

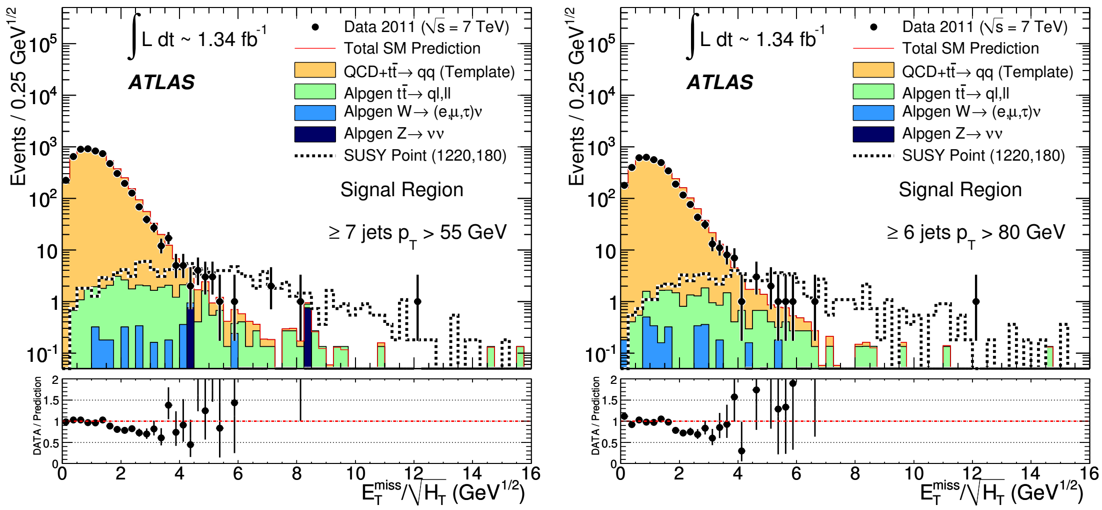
6 Systematic uncertainties

Systematic uncertainties arise through the imperfect modelling of the multi-jet $E^{\rm miss}_{\rm T}/\sqrt{H_{\rm T}}$ distribution, the use of MC-derived transfer factors relating observations in the control regions to 'leptonic' background expectations in the signal regions, and from the calculation of the SUSY signal.

For the multi-jet contribution, systematic uncertainties are determined to account for the residual dependence of the $E^{\rm miss}_{\rm T}/\sqrt{H_{\rm T}}$ distribution on $N_{\rm jet}$ (as described in section 5), the fraction of jets containing b quarks and the response in problematic areas of the calorimeter. A special study performed to quantify the effect of the dead area of the calorimeter found that after applying the correction-based veto described in section 3 the uncertainty is less than 5%.

Jets containing heavy flavour (b and c) quarks can include neutrinos and hence have broader resolution functions. The size of the systematic uncertainty resulting from heavy

[4] See also ref. [47–52].



(a) (b)

Figure 4. The distribution of the variable $E_{\mathrm{T}}^{\mathrm{miss}}/\sqrt{H_T}$ for events with (a) seven or more jets with $p_{\mathrm{T}} > 55\,\mathrm{GeV}$ or (b) six or more jets with $p_{\mathrm{T}} > 80\,\mathrm{GeV}$. Overlaid are the hadronic background templates plus the ALPGEN Monte-Carlo prediction for the 'leptonic' Standard Model backgrounds. For illustrative purposes the plots also contain the distribution expected for an example MSUGRA/CMSSM point with $m_0 = 1220\,\mathrm{GeV}$ and $m_{1/2} = 180\,\mathrm{GeV}$.

flavour (b-jet) contributions, including those from fully-hadronic $t\bar{t}$, is determined as follows. Separate values of T are calculated for events with at least one b jet and for non-b-tagged sub-samples, and their individual contributions to the SRs are determined. The differences with respect to the flavour-blind determination actually used are 8% – 15% depending on SR, and are included as a systematic uncertainty.

The transfer factors calculated for the 'leptonic' backgrounds have systematic uncertainties due to the finite number of Monte Carlo events generated, the jet energy scale, the jet energy resolution, the lepton identification efficiency, the b-tag efficiency, and the effect of multiple proton-proton interactions per bunch crossing.

Theoretical uncertainties on the SUSY signal were estimated from variation of the factorisation and renormalisation scales in PROSPINO between half and twice the mean outgoing sparticle mass and by considering the PDF uncertainties provided by CTEQ6.6 [57]. Uncertainties were calculated for individual production processes (e.g. $\tilde{q}\tilde{q}$, $\tilde{g}\tilde{g}$, etc.) and are typically 30% – 40% for models in the vicinity of the limits expected to be set by this analysis. For the signal samples, the combined experimental systematic uncertainties from jet energy scale, resolution, and cleaning are typically 15% – 20%. The 3.7% luminosity uncertainty [58, 59] is included but is negligible.

7 Results, interpretation and limits

The measured $E_{\mathrm{T}}^{\mathrm{miss}}/\sqrt{H_{\mathrm{T}}}$ distributions for two of the signal regions are shown in figure 4 prior to the final $E_{\mathrm{T}}^{\mathrm{miss}}/\sqrt{H_{\mathrm{T}}} > 3.5\,\mathrm{GeV}^{1/2}$ requirement. The number of observed events

Signal region	7j55	8j55	6j80	7j80
Multi-jets	26 ± 5.2	2.3 ± 0.7	19 ± 4	1.3 ± 0.4
$t\bar{t} \to q\ell, \ell\ell$	10.8 ± 6.7	$0^{+4.3}$	6.0 ± 4.6	$0^{+0.13}$
W + jets	0.95 ± 0.45	$0^{+0.13}$	0.34 ± 0.24	$0^{+0.13}$
Z + jets	$1.5^{+1.8}_{-1.5}$	$0^{+0.75}$	$0^{+0.75}$	$0^{+0.75}$
Total Standard Model	39 ± 9	$2.3^{+4.4}_{-0.7}$	26 ± 6	$1.3^{+0.9}_{-0.4}$
Data	45	4	26	3
$N^{95\%}_{\mathrm{BSM,max}}$	26.0	11.2	16.3	6.0
$\sigma^{95\%}_{\mathrm{BSM,max}} \times \epsilon/\,\mathrm{fb}$	19.4	8.4	12.2	4.5
p_{SM}	0.30	0.36	0.49	0.16

Table 2. Results for each of the four signal regions for $1.34\,\mathrm{fb}^{-1}$. The expected number of Standard Model events are given for each of the following sources: multi-jet (including fully hadronic $t\bar{t}$), semi- and fully-leptonic top combined, and W and Z bosons (separately) in association with jets, as well as the total Standard Model expectation. Where small event counts in control regions have not made it possible to determine a central value for the expectation, an asymmetric bound is given instead. The number of observed events is also shown. The final three rows show the statistical quantities described in the text.

for each of the signal regions is shown in table 2. The Standard Model expectations are also shown, together with their combined statistical and systematic uncertainties. The data are found to be in good agreement with the background model and no excess is observed. table 2 shows the 95% confidence level upper bound $N^{95\%}_{\mathrm{BSM,max}}$ on the number of events originating from sources other than the Standard Model, the corresponding upper limit $\sigma^{95\%}_{\mathrm{BSM,max}} \times \epsilon$ on the cross section times efficiency within acceptance (which equals the limit on the observed number of signal events divided by the luminosity) and the p-value for the Standard Model-only hypothesis (p_{SM}).

An interpretation of these results is presented in figure 5 as a 95% confidence level exclusion region in the $\tan\beta = 10$, $A_0 = 0$, $\mu > 0$ slice of MSUGRA/CMSSM.[5] Data from the four SRs are used to set the limits, taking the SR with the best expected limit at each point in parameter space. The limit for each SR is obtained by comparing the observed event count with that expected from Standard Model background plus SUSY signal processes, taking into account uncertainties in the expectation including those which are correlated between signal and background (for instance jet energy scale uncertainties). The exclusion regions are obtained using the $\mathrm{CL_s}$ prescription [60]. Acceptance times efficiency values are tabulated for typical points elsewhere [61].

[5]A particular MSUGRA/CMSSM model point is specified by five parameters: 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 μ.

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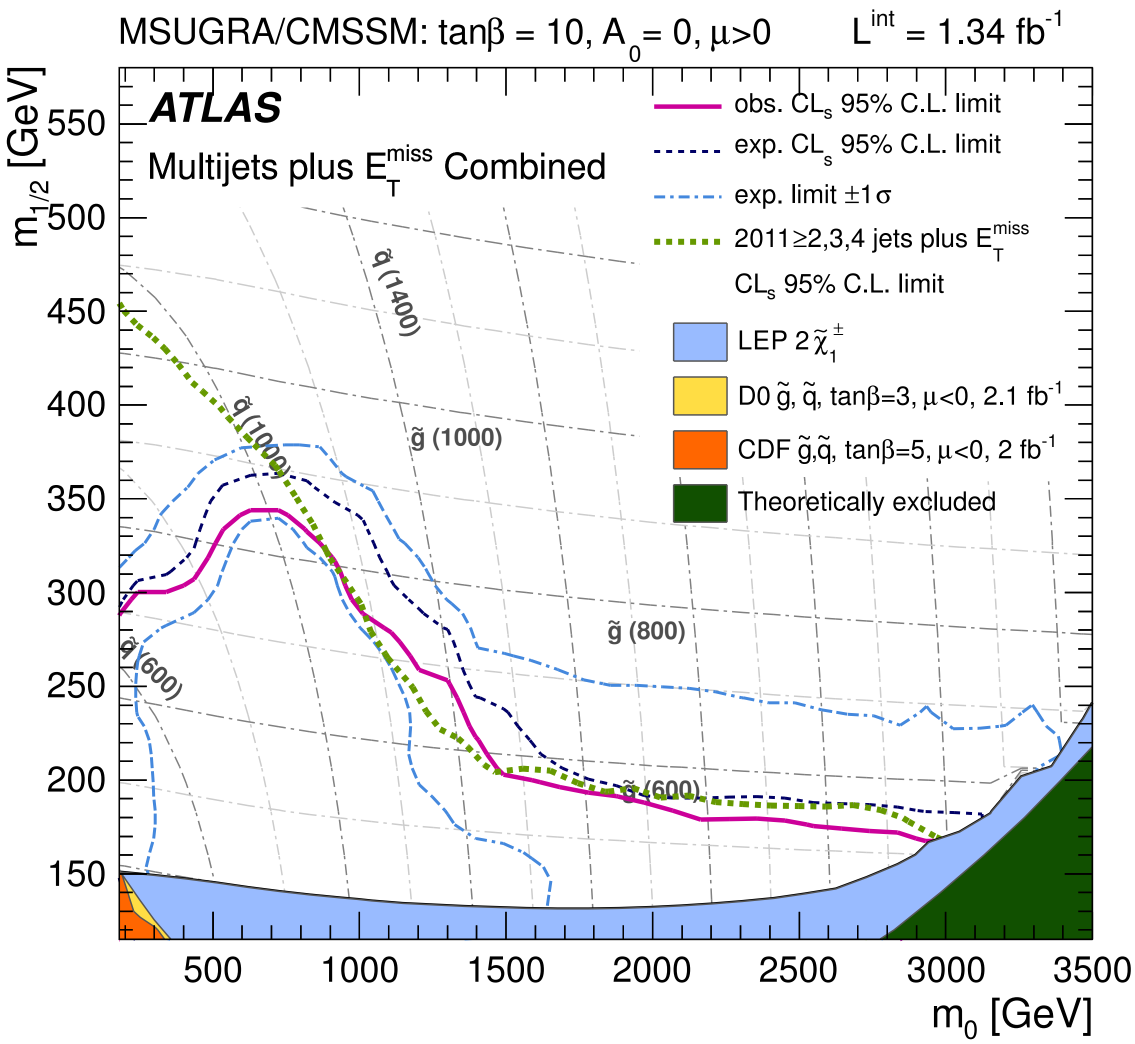

Figure 5. Combined exclusion bounds in the $\tan\beta = 10, A_0 = 0, \mu > 0$ slice of the MSUGRA/CMSSM space. Gluinos with masses below 520 GeV, and gluinos with masses below 680 GeV under the assumption that $m_{\rm squark} = 2 \times m_{\rm gluino}$ are excluded at the 95% confidence level. Limits from individual SRs can be found elsewhere [61]. Recent limits from ATLAS [5], as well as previous limits from D0 and CDF [62–65] and LEP [66, 67] are also shown.

8 Summary

A search for new phenomena has been performed using events containing missing transverse momentum and much larger jet multiplicities than have been previously considered, up to eight or more jets. The dominant Standard Model background contributions have been determined from the data themselves. The sub-dominant 'leptonic' backgrounds are measured using multiple control regions together with Monte Carlo transfer factors.

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No evidence for physics beyond the Standard Model has been observed in a data sample from early 2011 corresponding to an integrated luminosity of $1.34\,\mathrm{fb}^{-1}$. Limits are set on MSUGRA/CMSSM models excluding at the 95% confidence level gluinos with masses below 520 GeV, and gluinos with masses below 680 GeV under the assumption that $m_{\mathrm{squark}} = 2 \times m_{\mathrm{gluino}}$. This result extends those set by previous ATLAS analyses.

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