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Hunt for new phenomena using large jet multiplicities and missing transverse momentum with ATLAS in $4.7\,\text{fb}^{-1}$ of $\sqrt{s} = 7$ TeV proton-proton collisions

The ATLAS collaboration

Abstract: Results are presented of a search for new particles decaying to large numbers of jets in association with missing transverse momentum, using $4.7\,\text{fb}^{-1}$ of pp collision data at $\sqrt{s} = 7$ TeV collected by the ATLAS experiment at the Large Hadron Collider in 2011. The event selection requires missing transverse momentum, no isolated electrons or muons, and from $\geq$6 to $\geq$9 jets. No evidence is found for physics beyond the Standard Model. The results are interpreted in the context of a MSUGRA/CMSSM supersymmetric model, where, for large universal scalar mass m_0, gluino masses smaller than 840 GeV are excluded at the 95% confidence level, extending previously published limits. Within a simplified model containing only a gluino octet and a neutralino, gluino masses smaller than 870 GeV are similarly excluded for neutralino masses below 100 GeV.

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1 Introduction

Many extensions of the Standard Model of particle physics predict the presence of TeV-scale strongly interacting particles that decay to lighter, weakly interacting descendants. Any such weakly interacting particles that are massive and stable can contribute to the dark matter content of the universe. The strongly interacting parents would be produced in the proton-proton interactions at the Large Hadron Collider (LHC), and such events would be characterized by significant missing transverse momentum $E_{\mathrm{T}}^{\mathrm{miss}}$ from the unobserved weakly interacting daughters, and jets from emissions of quarks and/or gluons.

In the context of R-parity conserving [1–5] supersymmetry [5–10], the strongly interacting parent particles are the squarks $\tilde{q}$ and gluinos $\tilde{g}$, they are produced in pairs, and the lightest supersymmetric particles can provide the stable dark matter candidates [11, 12]. Jets are produced from a variety of sources: from quark emission in supersymmetric cascade decays, production of heavy Standard Model particles (W, Z or t) which then decay hadronically, or from QCD radiation. Examples of particular phenomenological interest include models where squarks are significantly heavier than gluinos. In such models the gluino pair production and decay process

$$\tilde{g} + \tilde{g} \to \left(t + \bar{t} + \tilde{\chi}_1^0\right) + \left(t + \bar{t} + \tilde{\chi}_1^0\right)$$

can dominate, producing large jet multiplicities when the resulting top quarks decay hadronically. In the context of MSUGRA/CMSSM models, a variety of different cascade decays, including the $\tilde{g}\tilde{g}$ initiated process above, can lead to large jet multiplicities.

A previous ATLAS search in high jet multiplicity final states [13] examined data taken during the first half of 2011, corresponding to an integrated luminosity of $1.34\,\mathrm{fb}^{-1}$. This paper extends the analysis to the complete ATLAS 2011 pp data set, corresponding to $4.7\,\mathrm{fb}^{-1}$, and includes improvements in the analysis and event selection that further increase sensitivity to models of interest.

Events are selected with large jet multiplicities ranging from ≥ 6 to ≥ 9 jets, in association with significant $E_{\mathrm{T}}^{\mathrm{miss}}$. Events containing high transverse momentum (p_{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 $E_{\mathrm{T}}^{\mathrm{miss}}$ and one or more leptons [14, 15]. Further searches have been carried out by ATLAS using events with at least two, three or four jets [16], or with at least two b-tagged jets [17]. Searches have also been performed by the CMS collaboration, including a recent analysis in fully hadronic final states [18].

2 The ATLAS detector and data samples

The ATLAS experiment [19] is a multi-purpose 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 spectrometer. 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 April–October 2011 with the LHC operating at a proton-proton centre-of-mass energy of $\sqrt{s} = 7$ TeV. Application of beam, detector and data-quality requirements resulted in a corresponding integrated luminosity of $4.7 \pm 0.2\,\mathrm{fb}^{-1}$ [20]. The analysis makes use of dedicated multi-jet triggers that required either at least four jets with $p_{\mathrm{T}} > 45$ GeV or at least five jets with $p_{\mathrm{T}} > 30$ GeV,

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

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where the energy is measured at the electromagnetic scale[2] and the jets must have $|\eta| < 3.2$. In all cases the trigger efficiency was greater than 98% for events satisfying the offline jet multiplicity selections described in section 4.

3 Object reconstruction

The jet, lepton and missing transverse momentum definitions are based closely on those of ref. [13], with small updates to account for evolving accelerator and detector conditions.

Jet candidates are reconstructed using the anti-k_t jet clustering algorithm [21, 22] with radius parameter of 0.4. The inputs to this algorithm are clusters of calorimeter cells seeded by cells with energy significantly above the noise level. Jet momenta are reconstructed 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. The jet energies are corrected for the 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 [23]. Only jet candidates with $p_{\mathrm{T}} > 20$ GeV and $|\eta| < 4.9$ are retained. Further corrections are applied to any jet falling in problematic areas of the calorimeter. The event is rejected if, for any jet, this additional correction leads to a contribution to $E_{\mathrm{T}}^{\mathrm{miss}}$ that is greater than both 10 GeV and $0.1\,E_{\mathrm{T}}^{\mathrm{miss}}$. These criteria, along with selections against non-collision background and calorimeter noise, lead to a loss of signal efficiency of $\sim$8% for the models considered. 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. Jets are tagged for $|\eta| < 2.5$ and the parameters of the algorithm are chosen such that 70% of b-jets and $\sim$1% of light flavour or gluon jets, are selected in $t\bar{t}$ events in Monte Carlo simulation [24]. Jets initiated by charm quarks are tagged with about 20% efficiency.

Electron candidates are required to have $p_{\mathrm{T}} > 20$ GeV and $|\eta| < 2.47$, and to satisfy the 'medium' electron shower shape and track selection criteria of ref. [14]. Muon candidates are required to have $p_{\mathrm{T}} > 10$ GeV and $|\eta| < 2.4$. Additional requirements are applied to muons when defining leptonic control regions. In this case muons must have longitudinal and transverse impact parameters within 1 mm and 0.2 mm of the primary vertex, respectively, and the sum of the transverse momenta of other tracks within a cone of $\Delta R = 0.2$ around the muon must be less than 1.8 GeV, where $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$.

The measurement of the missing transverse momentum two-vector $\vec{p}_{\mathrm{T}}^{\mathrm{miss}}$ and its magnitude (conventionally denoted $E_{\mathrm{T}}^{\mathrm{miss}}$) is then based on the transverse momenta of all electron and muon candidates, all jets with $|\eta| < 4.5$ which are not also electron candidates, and all calorimeter clusters with $|\eta| < 4.5$ not associated to such objects [25].

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

[2]The electromagnetic scale is the basic calorimeter signal scale for the ATLAS calorimeters. It has been established using test-beam measurements for electrons and muons to give the correct response for the energy deposited in electromagnetic showers, although it does not correct for the lower response of the calorimeter to hadrons.

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Signal region	**7j55**	**8j55**	**9j55**	**6j80**	**7j80**	**8j80**
Number of isolated leptons (e, μ)	$= 0$					
Jet p_{T}	$> 55\,\mathrm{GeV}$			$> 80\,\mathrm{GeV}$		
Jet $\lvert\eta\rvert$	< 2.8					
Number of jets	≥ 7	≥ 8	≥ 9	≥ 6	≥ 7	≥ 8
$E_{\mathrm{T}}^{\mathrm{miss}}/\sqrt{H_{\mathrm{T}}}$	$> 4\ \mathrm{GeV}^{1/2}$					

Table 1. Definitions of the six signal regions.

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electron is discarded, 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 they contain any jet failing quality criteria designed to suppress detector noise and non-collision backgrounds, or if they lack a reconstructed primary vertex with five or more associated tracks.

For events containing no isolated electrons or muons, six non-exclusive signal regions (SRs) are defined as shown in table 1. The first three require at least seven, eight or nine jets, respectively, with $p_{\mathrm{T}} > 55$ GeV; the latter three require at least six, seven or eight jets, respectively, with $p_{\mathrm{T}} > 80$ GeV. The final selection variable is $E_{\mathrm{T}}^{\mathrm{miss}}/\sqrt{H_{\mathrm{T}}}$, the ratio of the magnitude of the missing transverse momentum to the square root of the scalar sum H_{T} of the transverse momenta of all jets with $p_{\mathrm{T}} > 40$ GeV and $|\eta| < 2.8$. This ratio is closely related to the significance of the missing transverse momentum relative to the resolution due to stochastic variations in the measured jet energies [25]. The value of $E_{\mathrm{T}}^{\mathrm{miss}}/\sqrt{H_{\mathrm{T}}}$ is required to be larger than 4 $\mathrm{GeV}^{1/2}$ for all signal regions.

A previous ATLAS analysis of similar final states [13] required jets to be separated by $\Delta R > 0.6$ to ensure that the trigger efficiency was on its plateau. It has since been demonstrated that the requirement of an offline jet multiplicity at least one larger than that used in the trigger is sufficient to achieve a 98% trigger efficiency. Investigations on the enlarged data sample, in comparison to the previous incarnation of the strategy used here, allow various improvements to be made; in particular, the requirement on jet-jet separation is modified so as to increase the acceptance for signal models of interest by a factor two to five, without introducing any significant trigger inefficiency.

The dominant backgrounds are multi-jet production, including 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 $t\bar{t}$, and W and Z are collectively referred to as 'leptonic' backgrounds. Contributions from gauge boson pair and single top quark production are negligible. The determination of the multi-jet and 'leptonic' backgrounds is described in sections 6 and 7, respectively.

5 Monte Carlo simulations

Monte Carlo simulations are used as part of the 'leptonic' background determination process, and to assess sensitivity to specific SUSY signal models. The 'leptonic' backgrounds are generated using `Alpgen2.13` [26] with the PDF set `CTEQ6L1` [27]. Fully-leptonic $t\bar{t}$ events are generated with up to five additional partons in the matrix element, while semi-leptonic $t\bar{t}$ events are generated with up to three additional partons in the matrix element. W + jets and $Z \to \nu\bar{\nu}$ + jets are generated with up to six additional partons, and the $Z \to \ell^+\ell^-$ + jets (for $\ell \in \{e, \mu, \tau\}$) process is generated with up to five additional partons in the matrix element. In all cases, additional jets are generated via parton showering, which, together with fragmentation and hadronization, is performed by `Herwig` [28, 29]. `Jimmy` [30] is used to simulate the underlying event. The W + jets, Z + jets and $t\bar{t}$ backgrounds are normalized according to their inclusive theoretical cross sections [31, 32]. The estimation of the 'leptonic' backgrounds in the signal regions is described in detail in section 7.

Supersymmetric production processes are generated using `Herwig++2.4.2` [33]. Signal cross sections are calculated to next-to-leading order in the strong coupling constant α_S, including the resummation of soft gluon emission at next-to-leading-logarithmic accuracy (NLO+NLL) [34–38].[3] An envelope of cross-section predictions is defined using the 68% confidence-level (CL) ranges of the `CTEQ6.6` [39] (including the α_S uncertainty) and `MSTW2008 NLO` [40] PDF sets, together with independent variations of the factorization and renormalization scales by factors of two or one half. The nominal cross-section value is then taken to be the midpoint of the envelope, and the uncertainty assigned is half the full width of the envelope, following closely the PDF4LHC recommendations [41]. MSUGRA/CMSSM particle spectra and decay modes are calculated with `ISAJET++7.75` [42]. For illustrative purposes, plots of kinematic quantities show the distribution expected for an example MSUGRA/CMSSM point that has not been excluded in previous searches. This reference point is defined by[4]: $m_0 = 2960$ GeV, $m_{1/2} = 240$ GeV, $A_0 = 0$, $\tan\beta = 10$, and $\mu > 0$.

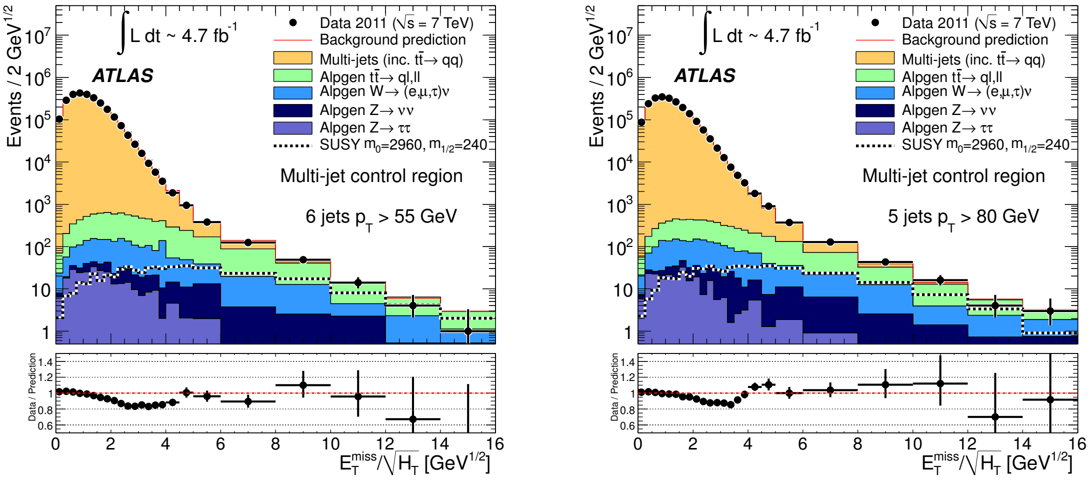
All Monte Carlo samples employ a detector simulation [43] based on `GEANT4` [44] and are reconstructed with the same algorithms as the data.

6 Multi-jet backgrounds

The dominant background at intermediate values of $E_{\mathrm{T}}^{\mathrm{miss}}$ is multi-jet production including purely strong interaction processes and fully hadronic decays of $t\bar{t}$. These processes are not

[3] The NLL correction is used for squark and gluino production when the average of the squark masses in the first two generations and the gluino mass lie between 200 GeV and 2 TeV. In the case of gluino-pair (associated squark-gluino) production processes, the calculations were extended up to squark masses of 4.5 TeV (3.5 TeV). For masses outside this range and for other types of production processes (i.e. electroweak and associated strong and electroweak), cross sections at NLO accuracy obtained with `Prospino2.1` [34] are used.

[4] 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.



(a) (b)

Figure 1. $E_{\mathrm{T}}^{\mathrm{miss}}/\sqrt{H_{\mathrm{T}}}$ distributions in example multi-jet control regions. (a) For exactly six jets with $p_{\mathrm{T}} > 55$ GeV, compared to a prediction based on the $E_{\mathrm{T}}^{\mathrm{miss}}/\sqrt{H_{\mathrm{T}}}$ distribution for exactly five jets with $p_{\mathrm{T}} > 55$ GeV. (b) For exactly five jets with $p_{\mathrm{T}} > 80$ GeV, compared to a prediction based on four jets with $p_{\mathrm{T}} > 80$ GeV. The multi-jet predictions have been normalized to the data in the region $E_{\mathrm{T}}^{\mathrm{miss}}/\sqrt{H_{\mathrm{T}}} < 1.5$ GeV$^{1/2}$ after subtraction of the predicted 'leptonic' backgrounds. The most important 'leptonic' backgrounds are also shown, based on MC simulations. Variable bin sizes are used with bin widths (in units of GeV$^{1/2}$) of 0.25 (up to 4), 0.5 (from 4 to 5), 1 (from 5 to 6), and then 2 thereafter. The error bars on the data points show the Poisson coverage interval corresponding to the number of data events observed in each bin.

reliably predicted with existing Monte Carlo calculations, and so their contributions must be determined from collision data. Indeed, the selection cuts have been designed such that multi-jet processes can be determined reliably from supporting measurements.

The method for determining the multi-jet background from data is motivated by the following considerations. In events dominated by jet activity, including hadronic decays of top quarks and gauge bosons, the $E_{\mathrm{T}}^{\mathrm{miss}}$ resolution is approximately proportional to $\sqrt{H_{\mathrm{T}}}$, and is almost independent of the jet multiplicity. The distribution of the ratio $E_{\mathrm{T}}^{\mathrm{miss}}/\sqrt{H_{\mathrm{T}}}$ has a shape that is almost invariant under changes in the jet multiplicity, as shown in figure 1. The multi-jet backgrounds therefore can be determined using control regions with lower $E_{\mathrm{T}}^{\mathrm{miss}}/\sqrt{H_{\mathrm{T}}}$ and/or lower jet multiplicity than the signal regions.[5] 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 [45] with Standard Model predictions.

As an example, the estimation of the background expected in the 8j55 signal region is obtained as follows. A template describing the shape of the $E_{\mathrm{T}}^{\mathrm{miss}}/\sqrt{H_{\mathrm{T}}}$ distribution is obtained from those events that contain exactly six jets, using the same 55 GeV p_{T} threshold as the target signal region. That six-jet $E_{\mathrm{T}}^{\mathrm{miss}}/\sqrt{H_{\mathrm{T}}}$ template is normalized to the number

[5] Residual variations in the shape of the $E_{\mathrm{T}}^{\mathrm{miss}}/\sqrt{H_{\mathrm{T}}}$ are later used to quantify the systematic uncertainty associated with the method, as described in section 6.1.

of eight-jet events observed in the region $E_{\mathrm{T}}^{\mathrm{miss}}/\sqrt{H_{\mathrm{T}}} < 1.5$ GeV$^{1/2}$ after subtraction of the 'leptonic' background expectation. The normalized template then provides a prediction for the multi-jet background for the 8j55 signal region for which $E_{\mathrm{T}}^{\mathrm{miss}}/\sqrt{H_{\mathrm{T}}} > 4$ GeV$^{1/2}$.

A similar procedure is used for each of the signal regions, and can be summarized as follows. For each jet p_{T} threshold $p_< \in \{55 \text{ GeV}, 80 \text{ GeV}\}$, control regions are defined for different numbers n_{jet} of jets found above $p_<$. The number of events $N_{p_<,n_{\mathrm{jet}}}(s_{\min}, s_{\max})$ for which $E_{\mathrm{T}}^{\mathrm{miss}}/\sqrt{H_{\mathrm{T}}}$ (in units of GeV$^{1/2}$) lies between $s_{\min}$ and $s_{\max}$ is determined, and the predicted 'leptonic' contributions $L_{p_<,n_{\mathrm{jet}}}(s_{\min}, s_{\max})$ subtracted

$$N^{\not{L}}_{p_<,n_{\mathrm{jet}}}(s_{\min}, s_{\max}) = N_{p_<,n_{\mathrm{jet}}}(s_{\min}, s_{\max}) - L_{p_<,n_{\mathrm{jet}}}(s_{\min}, s_{\max}).$$

Transfer factors

$$T_{p_<,n_{\mathrm{jet}}} = \frac{N^{\not{L}}_{p_<,n_{\mathrm{jet}}}(4, \infty)}{N^{\not{L}}_{p_<,n_{\mathrm{jet}}}(0, 1.5)}$$

connect regions with the same $p_<$ and n_{jet} with different $E_{\mathrm{T}}^{\mathrm{miss}}/\sqrt{H_{\mathrm{T}}}$. The multi-jet prediction for the signal region is found from the product of the $T_{p_<,n_{\mathrm{jet}}}$, with the same $p_<$ as the signal region and $n_{\mathrm{jet}} = 6$ when $p_< = 55$ GeV ($n_{\mathrm{jet}} = 5$ when $p_< = 80$ GeV) times the number of events (after subtracting the expected contribution from 'leptonic' background sources) satisfying signal region jet multiplicity requirements but with $E_{\mathrm{T}}^{\mathrm{miss}}/\sqrt{H_{\mathrm{T}}} < 1.5$ GeV$^{1/2}$.

6.1 Systematic uncertainties on multi-jet backgrounds

The method is validated by determining the accuracy of predictions for regions with jet multiplicities and/or $E_{\mathrm{T}}^{\mathrm{miss}}/\sqrt{H_{\mathrm{T}}}$ smaller than those chosen for the signal regions. Figure 1 shows that the shape of the $E_{\mathrm{T}}^{\mathrm{miss}}/\sqrt{H_{\mathrm{T}}}$ distribution for $p_< = 55$ GeV and $n_{\mathrm{jet}} = 6$ is predicted to an accuracy of better than 20% from that measured using a template with the same value of $p_<$ and $n_{\mathrm{jet}} = 5$. Similarly, the distribution for $p_< = 80$ GeV and $n_{\mathrm{jet}} = 5$ can be predicted for all $E_{\mathrm{T}}^{\mathrm{miss}}/\sqrt{H_{\mathrm{T}}}$ using a template with $n_{\mathrm{jet}} = 4$. The templates are normalized for $E_{\mathrm{T}}^{\mathrm{miss}}/\sqrt{H_{\mathrm{T}}} < 1.5$ GeV$^{1/2}$, and continue to provide a good prediction of the distribution out to values of $E_{\mathrm{T}}^{\mathrm{miss}}/\sqrt{H_{\mathrm{T}}}$ of 4 GeV$^{1/2}$ and beyond. Additional validation regions are defined for each $p_<$ and for jet multiplicity requirements equal to those of the signal regions, but for the intermediate values of $(s_{\min}, s_{\max})$ of (1.5, 2), (2, 2.5) and (2.5, 3.5). Residual inaccuracies in the predictions are used to quantify the systematic uncertainty from the closure of the method. Those uncertainties are in the range 15%–25%, depending on $p_<$ and $E_{\mathrm{T}}^{\mathrm{miss}}/\sqrt{H_{\mathrm{T}}}$.

The mean number of proton-proton interactions per bunch crossing $\langle\mu\rangle$ increased during the 2011 run, reaching $\langle\mu\rangle = 16$ at the start of proton fills for runs late in the year. Sensitivity to those additional interactions is studied by considering the jet multiplicity as a function of $\langle\mu\rangle$, and of the number of reconstructed primary vertices. The consistency of the high-p_{T} tracks within the selected jets with a common primary vertex is also investigated. The effect of additional jets from pile-up interactions is found to be significant for low-p_{T} jets but small for jets with $p_{\mathrm{T}} > 45$ GeV, and negligible for the jet selection used for the SRs.

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The presence of multiple in-time and out-of-time pp interactions also leads to a small but significant deterioration of the $E_{\mathrm{T}}^{\mathrm{miss}}$ resolution. The effectiveness of the $E_{\mathrm{T}}^{\mathrm{miss}}/\sqrt{H_{\mathrm{T}}}$ template method described above is tested separately for subsets of the data with different values of the instantaneous luminosity, and hence of $\langle\mu\rangle$. Good agreement is found separately for each subset of the data. Since the data set used to form the template has the same pile-up conditions as that used to form the signal regions, the changing shape of the $E_{\mathrm{T}}^{\mathrm{miss}}$ resolution is included in the data-driven determination and does not lead to any additional systematic uncertainty.

Due to the presence of neutrinos produced in the decay of hadrons containing bottom or charm quarks, events with heavy-flavour jets exhibit a different $E_{\mathrm{T}}^{\mathrm{miss}}$ distribution. To quantify the systematic uncertainty associated with this difference, separate templates are defined for events with at least one b-tagged jet and for those with none. The sum of the predictions for events with and without b-tagged jets is compared to the flavour-blind approach, and the difference is used to characterize the systematic uncertainty from heavy flavour (10%–20%). Other systematic uncertainties account for imperfect knowledge of: the subtracted 'leptonic' contributions (10%), the potential trigger inefficiency (2%), and imperfect response of the calorimeter in problematic areas (1%).

The backgrounds from multi-jet processes are cross checked using another data-driven technique [16] which smears the energies of individual jets from low-$E_{\mathrm{T}}^{\mathrm{miss}}$ multi-jet 'seed' events in data. Separate smearing functions are defined for b-tagged and non-b-tagged jets, with each modelling both the Gaussian core and the non-Gaussian tail of the jet response, including the loss of energy from unobserved neutrinos. The jet smearing functions are derived from `GEANT4` [44] simulations [43]. The Gaussian core of the function is tuned to di-jet data, and the non-Gaussian tails 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. There is agreement within uncertainties between the background predicted by this jet-smearing method and the primary method based on the shape invariance of $E_{\mathrm{T}}^{\mathrm{miss}}/\sqrt{H_{\mathrm{T}}}$.

7 'Leptonic' backgrounds

Non-fully-hadronic (i.e. semi-leptonic or di-leptonic) $t\bar{t}$, and W and Z production are collectively referred to as 'leptonic' backgrounds. The process $Z \to \nu\nu$ + jets contributes to the signal regions since it produces jets in association with $E_{\mathrm{T}}^{\mathrm{miss}}$. Leptonic $t\bar{t}$ and W decays contribute to the signal regions when hadronic τ decays allow them to evade the lepton veto, with smaller contributions from events in which electrons or muons are produced but are not reconstructed.

The 'leptonic' background predictions employ the Monte Carlo simulations described in section 5. To reduce uncertainties from Monte Carlo modelling and detector response, it is desirable to normalize the background predictions to data using control regions (CR) and cross-check them against data in other validation regions (VR). These control regions and validation regions are designed to be distinct from, but kinematically close to, the signal regions. Each is designed to provide enhanced sensitivity to a particular background process.

The control and validation regions are defined as shown in table 2. By using control regions that are kinematically similar to the signal regions, theoretical uncertainties, includ-

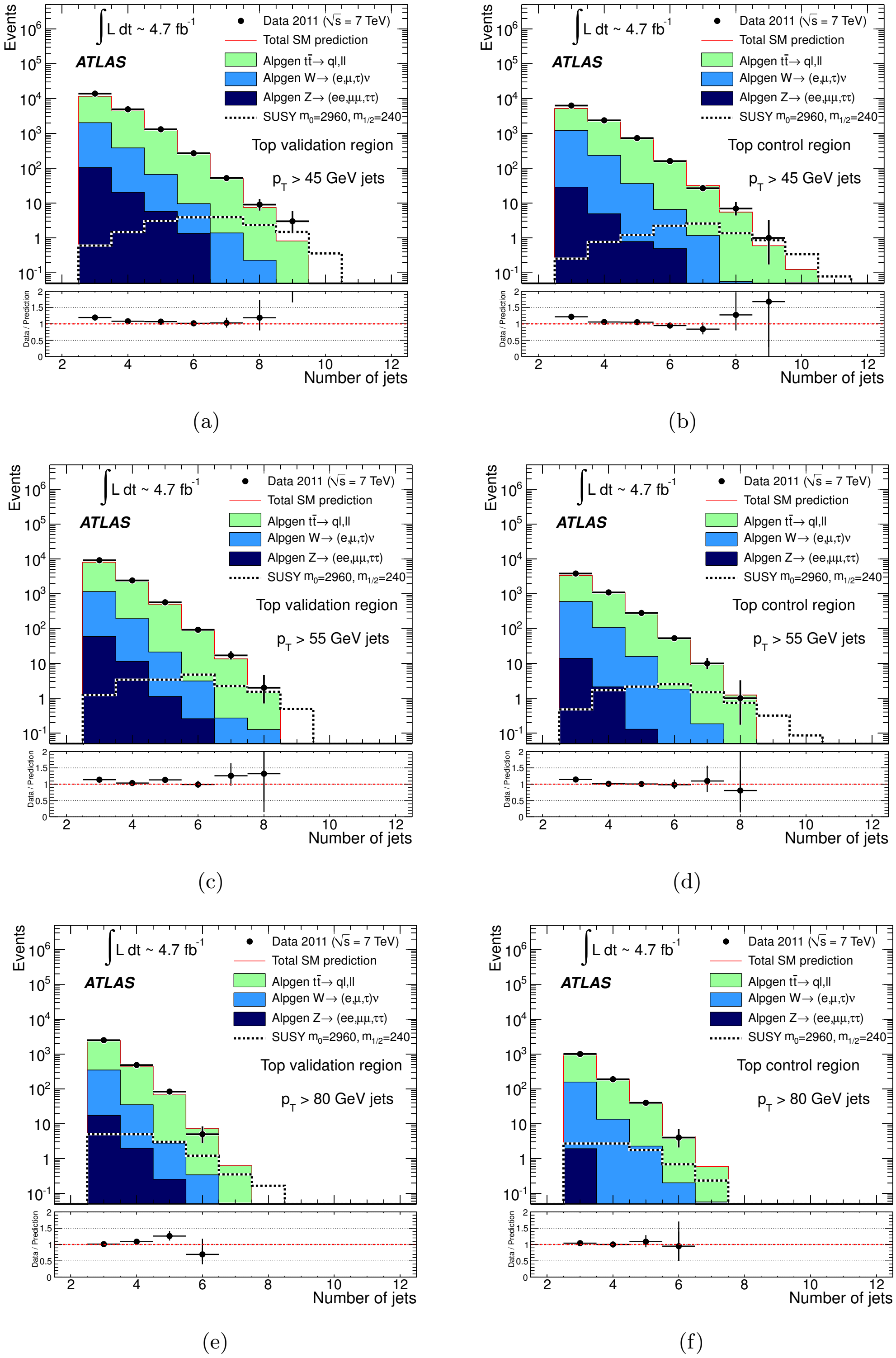

Figure 2. Jet multiplicity distributions for the $t\bar{t}$ + jets validation regions (left) and control regions (right) before any jet multiplicity requirements, for a jet p_T threshold of 45 GeV (top), 55 GeV (middle) and 80 GeV (bottom).

	$t\bar{t}$ + jets	W + jets	Z + jets
Muon kinematics	$p_{\mathrm{T}} > 20$ GeV, $\lvert\eta\rvert < 2.4$		
Muon multiplicity	$= 1$		$= 2$
Electron multiplicity	$= 0$		
b-tagged jet multiplicity	≥ 1	$= 0$	—
m_{T} or $m_{\mu\mu}$	50 GeV $< m_{\mathrm{T}} <$ 100 GeV		80 GeV $< m_{\mu\mu} <$ 100 GeV
VR $\rightarrow$ CR transform	$\mu \rightarrow$ jet		$\mu \rightarrow \nu$
Jet p_{T}, $\lvert\eta\rvert$, multiplicity (CR)	As in table 1.		
$E_{\mathrm{T}}^{\mathrm{miss}}/\sqrt{H_{\mathrm{T}}}$ (CR)			

Table 2. Definitions of the validation regions and control regions for the 'leptonic' backgrounds: $t\bar{t}$ + jets, W + jets and Z + jets. The validation regions VR are defined by the first five selection requirements. A long dash '—' indicates that no requirement is made. The control regions CR differ from the VR in their treatment of the muons, and by having additional requirements on jets and $E_{\mathrm{T}}^{\mathrm{miss}}/\sqrt{H_{\mathrm{T}}}$, as shown in the final two rows.

ing those arising from the use of a leading-order (LO) generator, are reduced. The $t\bar{t}$ + jets and W + jets validation regions each require a single muon and no electrons. For the $t\bar{t}$ process the single-muon selection is primarily sensitive to the semi-leptonic decay.[6] The $t\bar{t}$ + jets validation region is further enhanced by the requirement of at least one b-tagged jet, whereas for W + jets enhancement a b-tag veto is applied. Since it is dominantly through hadronic τ decays that W and $t\bar{t}$ contribute to the signal regions, the corresponding control regions are created by recasting the muon as a (τ-)jet. For $Z \rightarrow \nu\nu$ + jets the validation regions select events from the closely related process $Z \rightarrow \mu\mu$ + jets. The related control regions are formed from these validation regions by recasting the muons as neutrinos.

In detail, for those control regions where the Monte Carlo simulations predict at least one event for $4.7\,\mathrm{fb}^{-1}$, the leptonic background prediction s_i for each signal region from each background is calculated by multiplying the number of data events c_i^{data} found in the corresponding control region by a Monte Carlo-based factor t_i^{MC}

$$s_i = c_i^{\mathrm{data}} \times t_i^{\mathrm{MC}}.$$

This transfer factor is defined to be the ratio of the number of MC events found in the signal region to the number of MC events found in the control region

$$t_i^{\mathrm{MC}} = \frac{s_i^{\mathrm{MC}}}{c_i^{\mathrm{MC}}}.$$

In each case, the event counts are corrected for the expected contamination by the other background processes. Whenever less than one event is predicted in the control region,

[6] The procedure is also sensitive to those di-leptonic $t\bar{t}$ decays in which one lepton was not observed in the VR. After the VR $\rightarrow$ CR replacement ($\mu \rightarrow$ jet), the procedure captures the leading di-leptonic $t\bar{t}$ contributions to the SR.

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the Monte Carlo prediction for the corresponding signal region is used directly, without invoking a transfer factor.

For the $t\bar{t}$ + jets background, the validation region requires exactly one isolated muon, at least one b-tagged jet, and no selected electrons. The transverse mass for the muon transverse momentum $\vec{p}_{\mathrm{T}}^{\mu}$ and the missing transverse momentum two-vector $\vec{p}_{\mathrm{T}}^{\mathrm{miss}}$ is calculated using massless two-vectors

$$m_{\mathrm{T}}^2 = 2|\vec{p}_{\mathrm{T}}^{\mu}||\vec{p}_{\mathrm{T}}^{\mathrm{miss}}| - 2\vec{p}_{\mathrm{T}}^{\mu} \cdot \vec{p}_{\mathrm{T}}^{\mathrm{miss}} \, ,$$

and must satisfy 50 GeV $< m_{\mathrm{T}} <$ 100 GeV. Figure 2 shows the jet multiplicity in the $t\bar{t}$ validation regions, and it is demonstrated that the Monte Carlo provides a good description of the data.

The $t\bar{t}$ control regions used to calculate the background expectation differ from the validation regions as follows. Since the dominant source of background is from hadronic τ decays in the control regions, the muon is used to mimic a jet, as follows. If the muon has sufficient p_{T} to pass the jet selection threshold $p_{<}$, the jet multiplicity is incremented by one. If the muon p_{T} is larger than 40 GeV it is added to H_{T}. The selection variable $E_{\mathrm{T}}^{\mathrm{miss}}/\sqrt{H_{\mathrm{T}}}$ is then recalculated, and required to be larger than the threshold value of 4 GeV$^{1/2}$. Distributions of the jet multiplicity in the $t\bar{t}$ control regions may also be found in figure 2.

The W + jets validation regions and control regions are defined in a similar manner to those for $t\bar{t}$ + jets, except that a b-jet veto is used rather than a b-jet requirement (see table 2). Figure 3 shows that the resulting jet multiplicity distributions are well described by the Monte Carlo simulations.

The Z + jets validation regions are defined (as shown in table 2) requiring precisely two muons with invariant mass $m_{\mu\mu}$ consistent with m_Z. The dominant backgrounds from Z + jets arise from decays to neutrinos, so in forming the Z + jets control regions from the validation regions, the vector sum of the $\vec{p}_{\mathrm{T}}$ of the muons is added to the measured $\vec{p}_{\mathrm{T}}^{\mathrm{miss}}$, to model the $E_{\mathrm{T}}^{\mathrm{miss}}$ expected from $Z \to \nu\nu$ events. The selection variable $E_{\mathrm{T}}^{\mathrm{miss}}/\sqrt{H_{\mathrm{T}}}$ is then recalculated and required to be greater than 4 GeV$^{1/2}$ for events in the control region. Figure 4 shows that the resulting jet multiplicity distributions in both validation and control regions are well described by the Monte Carlo simulations.

For each of the 'leptonic' backgrounds further comparisons are made between Monte Carlo and data using the lower jet p_{T} threshold of 45 GeV, showing agreement within uncertainties for all multiplicities (up to nine jets for $t\bar{t}$, see figures 2(a) and 2(b). The `Alpgen` Monte Carlo predictions for Z + jets and W + jets were determined with six additional partons in the matrix element calculation, and cross checked with a calculation in which only five additional partons were produced in the matrix element — in each case with additional jets being produced in the parton shower. The two predictions are consistent with each other and with the data, providing further supporting evidence that the parton shower offers a sufficiently accurate description of the additional jets.

7.1 Systematic uncertainties on 'leptonic' backgrounds

The use of control regions is effective in reducing uncertainties from Monte Carlo modelling and detector response. When predictions are taken directly from the Monte Carlo, the

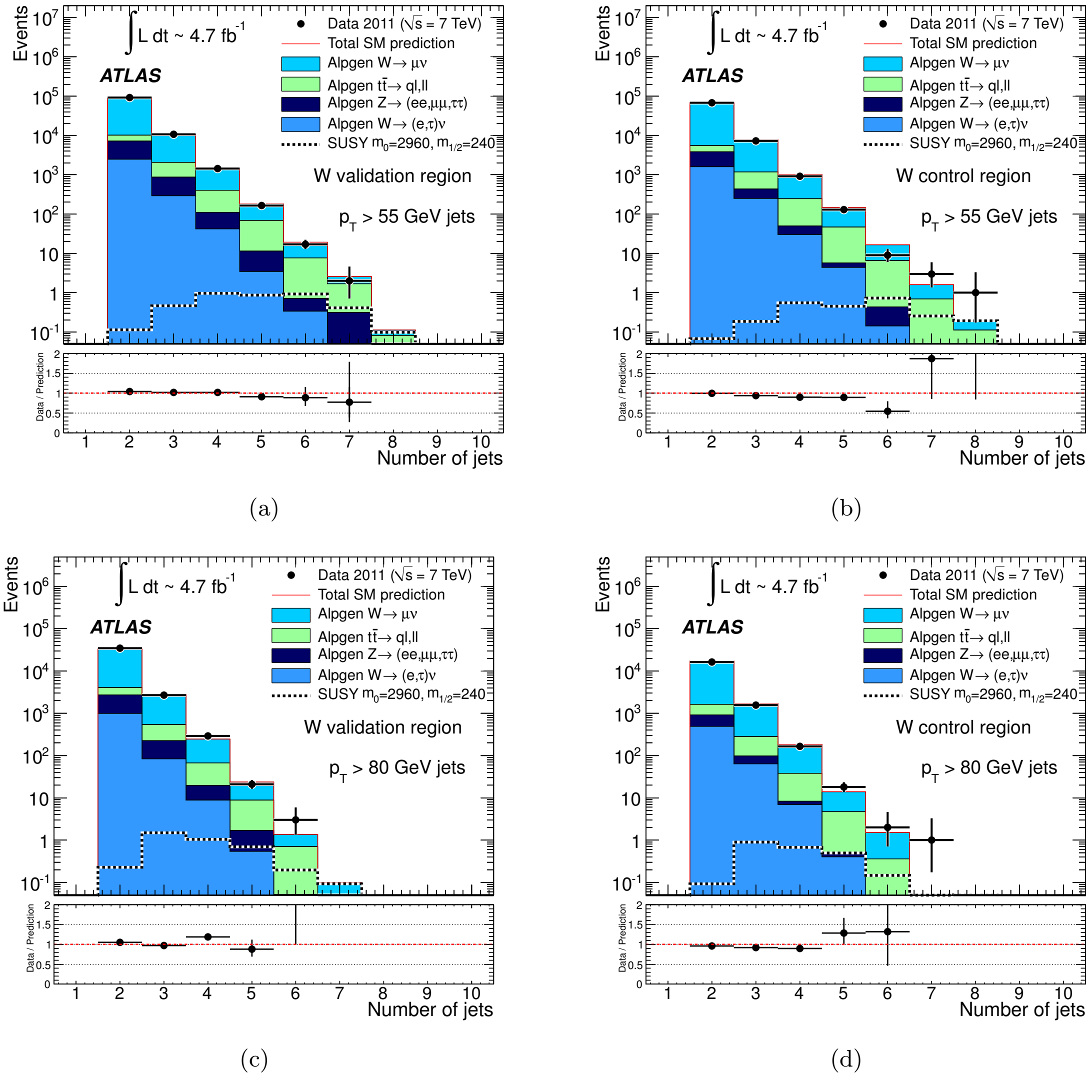


Figure 3. Jet multiplicity distributions for the $W^{\pm}$ + jets validation regions (left) and control regions (right) before any jet multiplicity requirements, and for a jet p_{T} threshold of 55 GeV (top) and 80 GeV (bottom).

'leptonic' background determinations are subject to systematic uncertainties from Monte Carlo modelling of: the jet energy scale (JES, 40%), the jet energy resolution (JER, 4%), the number of multiple proton-proton interactions (3%), the b-tagging efficiency (5% for $t\bar{t}$), the muon trigger and reconstruction efficiency and the muon momentum scale. The numbers in parentheses indicate the typical values of the SR event yield uncertainties prior to the partial cancellations that result from the use of control regions.

The JES and JER uncertainties are calculated using a combination of data-driven and Monte Carlo techniques [23], using the complete 2011 ATLAS data set. The calculation accounts for the variation in the uncertainty with jet p_{T} and η, and that due to nearby jets. The Monte Carlo simulations model the multiple proton-proton interactions with a

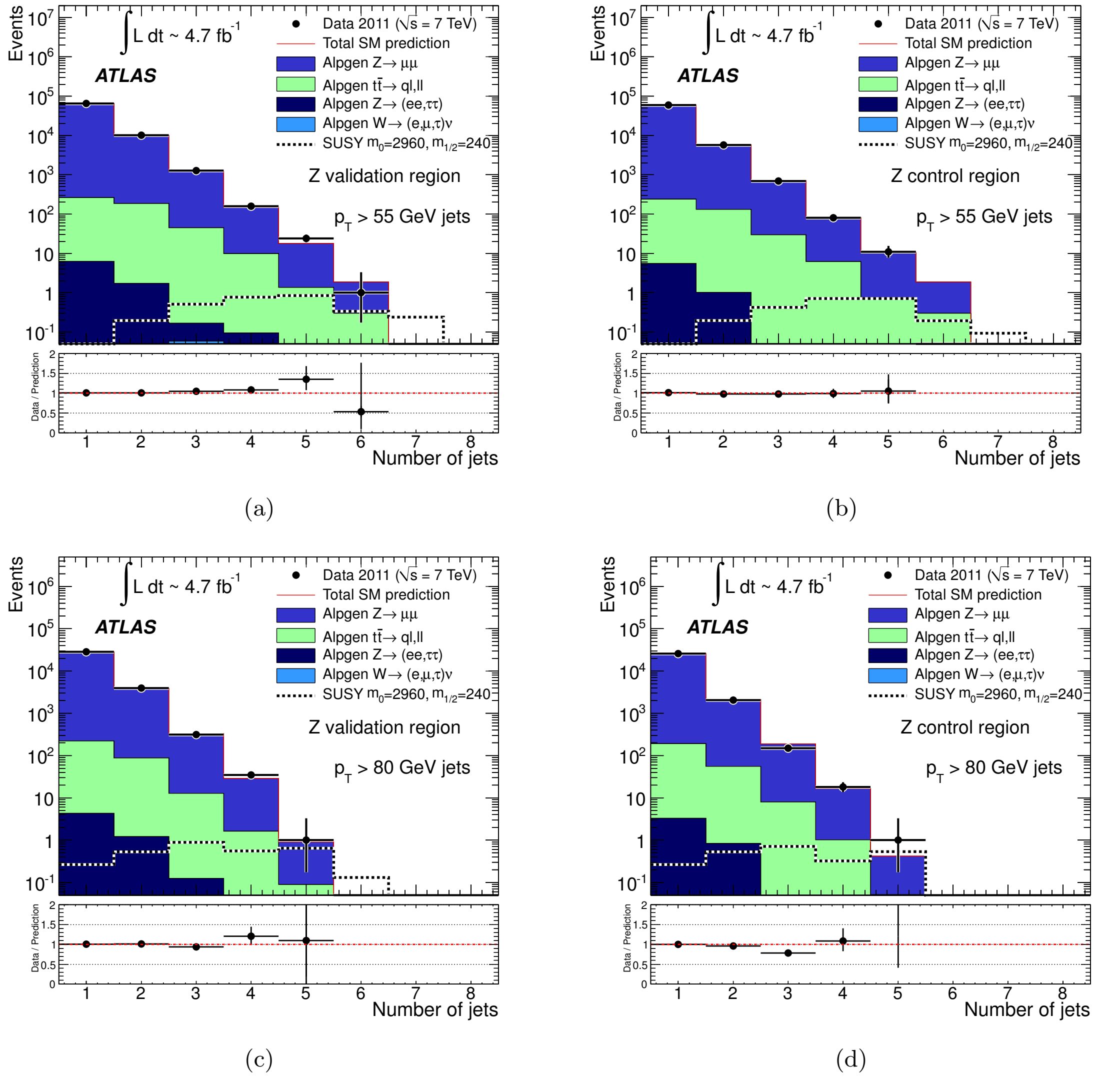


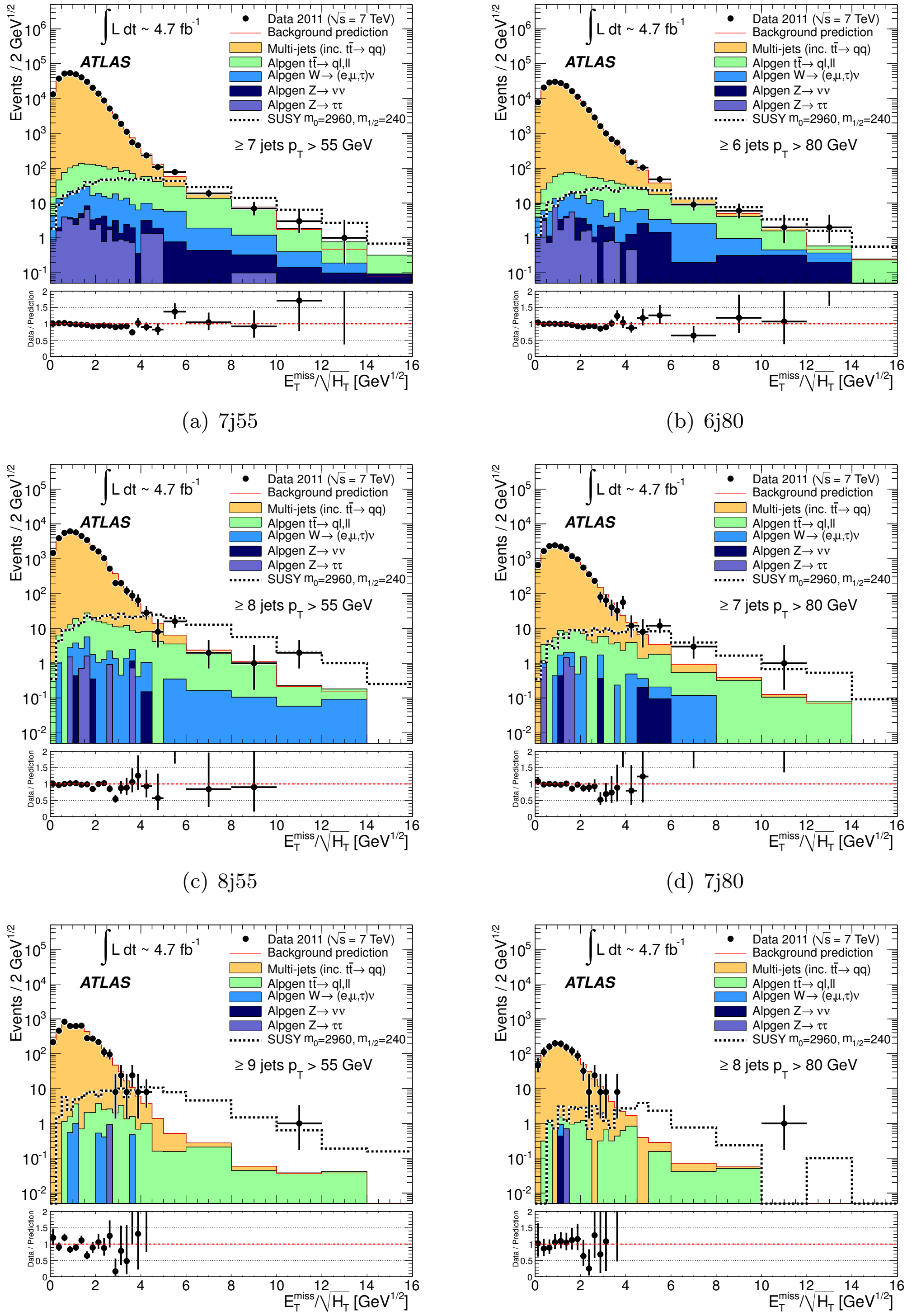
Figure 4. As for figure 3 but for the Z + jets validation regions and control regions.

varying value of $\langle\mu\rangle$ which is well matched to that in the data. The residual uncertainty from pile-up interactions is determined by reweighting the Monte Carlo samples so that $\langle\mu\rangle$ is increased or decreased by 10%. The uncertainty in the integrated luminosity is 3.9% [20].

When transfer factors are used to connect control regions to signal regions, the effects of these uncertainties largely cancel in the ratio. For example, the impact of the jet energy scale uncertainty is reduced to $\approx 6\%$.

8 Results, interpretation and limits

Figure 5 shows the $E_{\mathrm{T}}^{\mathrm{miss}}/\sqrt{H_{\mathrm{T}}}$ distributions after applying the jet selections for the six different signal regions (see table 1) prior to the final $E_{\mathrm{T}}^{\mathrm{miss}}/\sqrt{H_{\mathrm{T}}} > 4\ \mathrm{GeV}^{1/2}$ requirement. Figure 6 shows the jet multiplicity distributions for the two different jet p_{T} thresholds after the final $E_{\mathrm{T}}^{\mathrm{miss}}/\sqrt{H_{\mathrm{T}}}$ requirement. It should be noted that the signal regions are

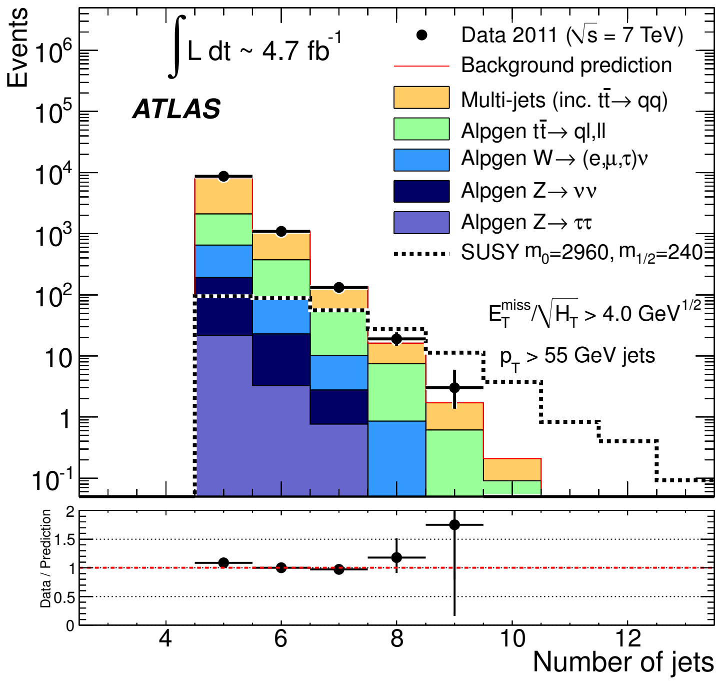


(a) 7j55 (b) 6j80

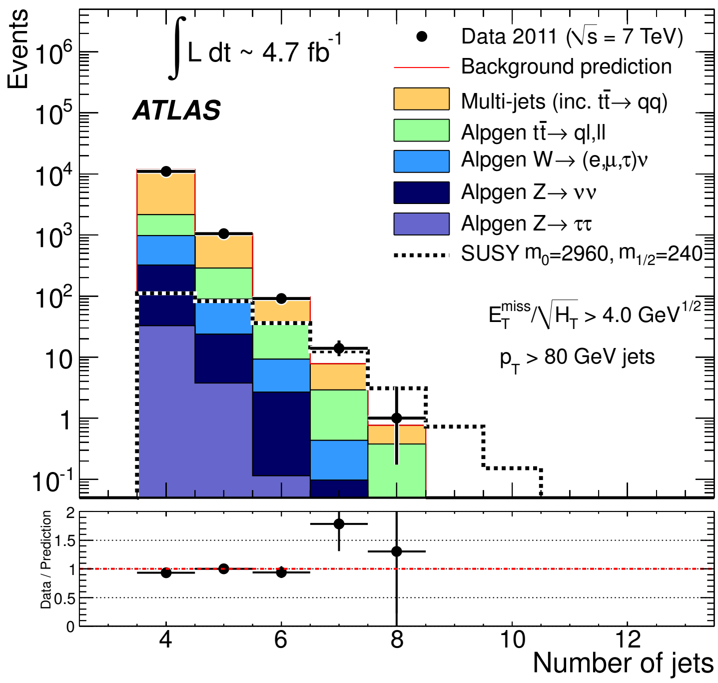
(c) 8j55 (d) 7j80

(e) 9j55 (f) 8j80

Figure 5. The distribution of the variable $E_T^{\text{miss}}/\sqrt{H_T}$ for each of the six different signal regions defined in table 1, prior to the final $E_T^{\text{miss}}/\sqrt{H_T} > 4$ GeV$^{1/2}$ requirement.



(a)



(b)

Figure 6. The distribution of jet multiplicity for jets with $p_{\mathrm{T}} > 55$ GeV (a) and those with $p_{\mathrm{T}} > 80$ GeV (b). Only events with $E_{\mathrm{T}}^{\mathrm{miss}}/\sqrt{H_{\mathrm{T}}} > 4$ GeV$^{1/2}$ are shown.

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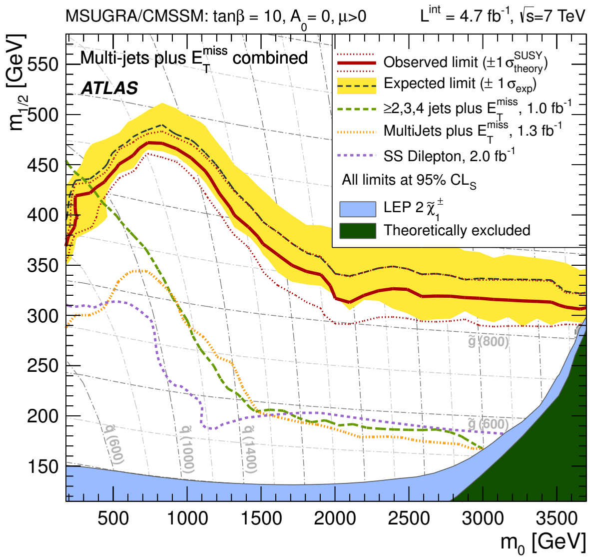
Signal region	**7j55**	**8j55**	**9j55**	**6j80**	**7j80**	**8j80**
Multi-jets	91±20	10±3	1.2±0.4	67±12	5.4±1.7	0.42±0.16
$t\bar{t} \to q\ell, \ell\ell$	55±18	5.7±6.0	0.70±0.72	24±13	2.8±1.8	0.38±0.40
W + jets	18±11	0.81±0.72	0+0.13	13±10	0.34±0.21	0+0.06
Z + jets	2.7±1.6	0.05±0.19	0+0.12	2.7±2.9	0.10±0.17	0+0.13
Total Standard Model	**167±34**	**17±7**	**1.9±0.8**	**107±21**	**8.6±2.5**	**0.80±0.45**
Data	**154**	**22**	**3**	**106**	**15**	**1**
$N^{95\%}_{\mathrm{BSM,max}}$ (exp)	72	16	4.5	46	8.4	3.5
$N^{95\%}_{\mathrm{BSM,max}}$ (obs)	64	20	5.7	46	15	3.8
$\sigma^{95\%}_{\mathrm{BSM,max}} \cdot A \cdot \epsilon$ (exp) [fb]	15	3.4	0.96	9.8	1.8	0.74
$\sigma^{95\%}_{\mathrm{BSM,max}} \cdot A \cdot \epsilon$ (obs) [fb]	14	4.2	1.2	9.8	3.2	0.81
p_{SM}	0.64	0.27	0.28	0.52	0.07	0.43

Table 3. Results for each of the six signal regions for an integrated luminosity of $4.7\,\mathrm{fb}^{-1}$. The expected numbers of Standard Model events are given for each of the following sources: multi-jet (including fully hadronic $t\bar{t}$), semi- and fully-leptonic $t\bar{t}$ decays combined, and W and Z bosons (separately) in association with jets, as well as the total Standard Model expectation. The uncertainties on the predictions show the combination of the statistical and systematic components. 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 numbers of observed events are also shown. The final five rows show the statistical quantities described in the text. Both the expected (exp) and the observed (obs) values are shown for $N^{95\%}_{\mathrm{BSM,max}}$ and $\sigma^{95\%}_{\mathrm{BSM,max}} \times A \times \epsilon$.

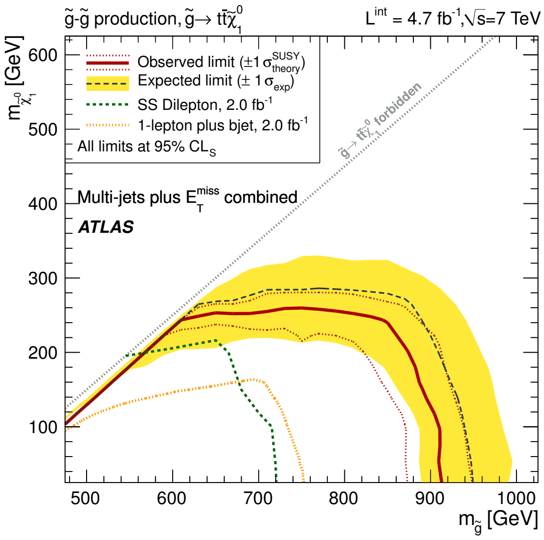
not exclusive. For example, in figure 5, all plots contain the same event at $E_{\mathrm{T}}^{\mathrm{miss}}/\sqrt{H_{\mathrm{T}}} \sim 11\ \mathrm{GeV}^{1/2}$. The 'leptonic' backgrounds shown in the figures are those calculated from the Monte Carlo simulation, using the MC calculation of the cross section and normalized to $4.7\,\mathrm{fb}^{-1}$. The number of events observed in each of the six signal regions, as well as their Standard Model background expectations are shown in table 3. Good agreement is observed between SM expectations and the data for all six signal regions. Table 3 also 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 $\sigma^{95\%}_{\mathrm{BSM,max}} \times A \times \epsilon$ 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}).

In the absence of significant discrepancies, limits are set in the context of two supersymmetric (SUSY) models. The first is the $\tan\beta = 10$, $A_0 = 0$ and $\mu > 0$ slice of the MSUGRA/CMSSM parameter space. The second is a simplified SUSY model with only a gluino octet and a neutralino $\tilde{\chi}_1^0$ within kinematic reach. Theoretical uncertainties on the SUSY signals are estimated as described in section 5. Combined experimental systematic uncertainties on the signal yield from jet energy scale, resolution, and event cleaning are approximately 25%. Acceptance times efficiency values are tabulated elsewhere [50].

The limit for each signal region is obtained by comparing the observed event count with that expected from Standard Model background plus SUSY signal processes, taking into



(a) MSUGRA/CMSSM



(b) $\tilde{g} - \tilde{\chi}_1^0$ simplified model

Figure 7. Combined 95% CL exclusion curves for the $\tan\beta = 10$, $A_0 = 0$ and $\mu > 0$ slice of MSUGRA/CMSSM (a) and for the simplified gluino-neutralino model (b). The dashed grey and solid red lines show the 95% CL expected and observed limits respectively, including all uncertainties except the theoretical signal cross section uncertainty (PDF and scale). The shaded yellow band around the expected limit shows its $\pm1\sigma$ range. The $\pm1\sigma$ lines around the observed limit represent the result produced when moving the signal cross section by $\pm1\sigma$ (as defined by the PDF and scale uncertainties). The contours on the MSUGRA/CMSSM model show values of the mass of the gluino and the mean mass of the squarks in the first two generations. Exclusion limits are also shown from previous ATLAS searches with $\geq$2, 3 or 4 jets plus $E_{\mathrm{T}}^{\mathrm{miss}}$ [16], multi-jets plus $E_{\mathrm{T}}^{\mathrm{miss}}$ [13] or with same-sign dileptons [46] and from LEP [47, 48] in (a). The lower plot shows limits from ATLAS searches with same-sign dileptons [46] or with one-lepton plus b-jet [49].

account all uncertainties on the Standard Model expectation, including those which are correlated between signal and background (for instance jet energy scale uncertainties) and all but theoretical cross section uncertainties (PDF and scale) on the signal expectation. The combined exclusion regions are obtained using the CL_s prescription [51], taking the signal region with the best expected limit at each point in parameter space. The 95% confidence level (CL) exclusion in the $\tan\beta = 10$, $A_0 = 0$ and $\mu > 0$ slice of MSUGRA/CMSSM is shown in figure 7. The $\pm 1\,\sigma$ band surrounding the expected limit shows the variation anticipated from statistical fluctuations and systematic uncertainties on SM and signal processes. The uncertainties on the supersymmetric signal cross section from PDFs and higher-order terms are calculated as described in section 5, and the resulting signal cross section uncertainty is represented by $\pm 1\sigma$ lines on either side of the observed limit.[7]

The analysis substantially extends the previous exclusion limits [13, 16, 17] for $m_0 > 500$ GeV. For large m_0, the analysis becomes independent of the squark mass, and the lower bound on the gluino mass is extended to almost 840 GeV for large $m_{\tilde{q}}$.[8] In the simplified model gluinos are pair-produced and decay with unit probability to $t + \bar{t} + \tilde{\chi}_1^0$. In this context, the 95% CL exclusion bound on the gluino mass is 870 GeV for neutralino masses up to 100 GeV.

9 Summary

A search for new physics is presented using final states containing large jet multiplicities in association with missing transverse momentum. The search uses the full 2011 pp LHC data set taken at $\sqrt{s} = 7$ TeV, collected with the ATLAS detector, which corresponds to an integrated luminosity of $4.7\,\text{fb}^{-1}$.

Six non-exclusive signal regions are defined. The first three require at least seven, eight or nine jets, with $p_T > 55$ GeV; the latter three require at least six, seven or eight jets, with $p_T > 80$ GeV. In all cases the events are required to satisfy $E_T^{\text{miss}}/\sqrt{H_T} > 4\ \text{GeV}^{1/2}$, and to contain no isolated high-p_T electrons or muons. Investigations on the enlarged data sample have resulted in improvements compared to a previous measurement using a similar strategy. In particular, inclusion of events with smaller jet-jet separation increases the acceptance for signal models of interest by a factor two to five, without significantly increasing the systematic uncertainty.

The Standard Model multi-jet background is determined using a template-based method that exploits the invariance of $E_T^{\text{miss}}/\sqrt{H_T}$ under changes in jet multiplicity, cross-checked with a jet-smearing method that uses well reconstructed multi-jet seed events from data. The other significant backgrounds — $t\bar{t}$ + jets, W + jets and Z + jets — are determined using a combination of data-driven and Monte Carlo-based methods.

In each of the six signal regions, agreement is found between the Standard Model prediction and the data. In the absence of significant discrepancies, the results are interpreted

[7] Previous analyses have a slightly different presentation of the effect of the signal cross section uncertainty. In refs. [13, 16, 17] the effect of the signal cross section uncertainty was folded into the displayed limits and so was not shown separately.

[8] Limits on sparticle masses quoted in the text are those from the lower edge of the $1\,\sigma$ signal cross section band rather than the central value of the observed limit, so can be considered conservative.

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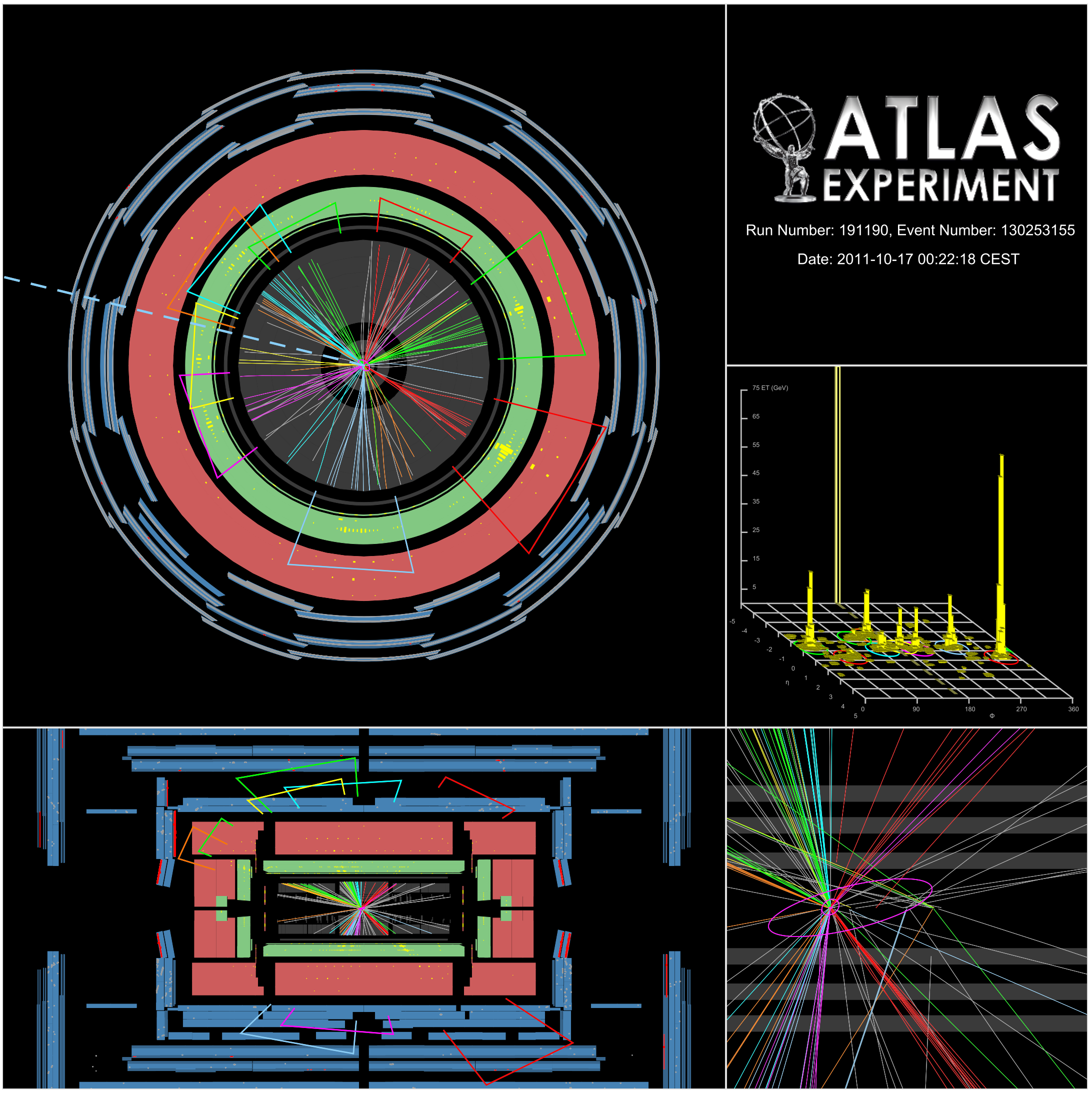

Figure 8. A display of an event which passes the 9j55 and 7j80 signal region selections. The event has $E_{\mathrm{T}}^{\mathrm{miss}}/\sqrt{H_{\mathrm{T}}}$ of 4.1 GeV$^{1/2}$, $\mathrm{H_T}$ of 1.47 TeV and $E_{\mathrm{T}}^{\mathrm{miss}}$ of 157 GeV.

as limits in the context of R-parity conserving supersymmetry. Exclusion limits are shown for MSUGRA/CMSSM, for which, for large m_0, gluino masses smaller than 840 GeV are excluded at the 95% confidence level. For a simplified supersymmetric model in which both of the pair-produced gluinos decay via the process $\tilde{g} \to t + \bar{t} + \tilde{\chi}_1^0$, gluino masses smaller than about 870 GeV are similarly excluded for $\tilde{\chi}_1^0$ masses up to 100 GeV.

A Event displays

A display of an event that passes the 9j55 and 7j80 signal region selections can be found in figure 8. A display of an event that passes all signal region selections can be found in figure 9.

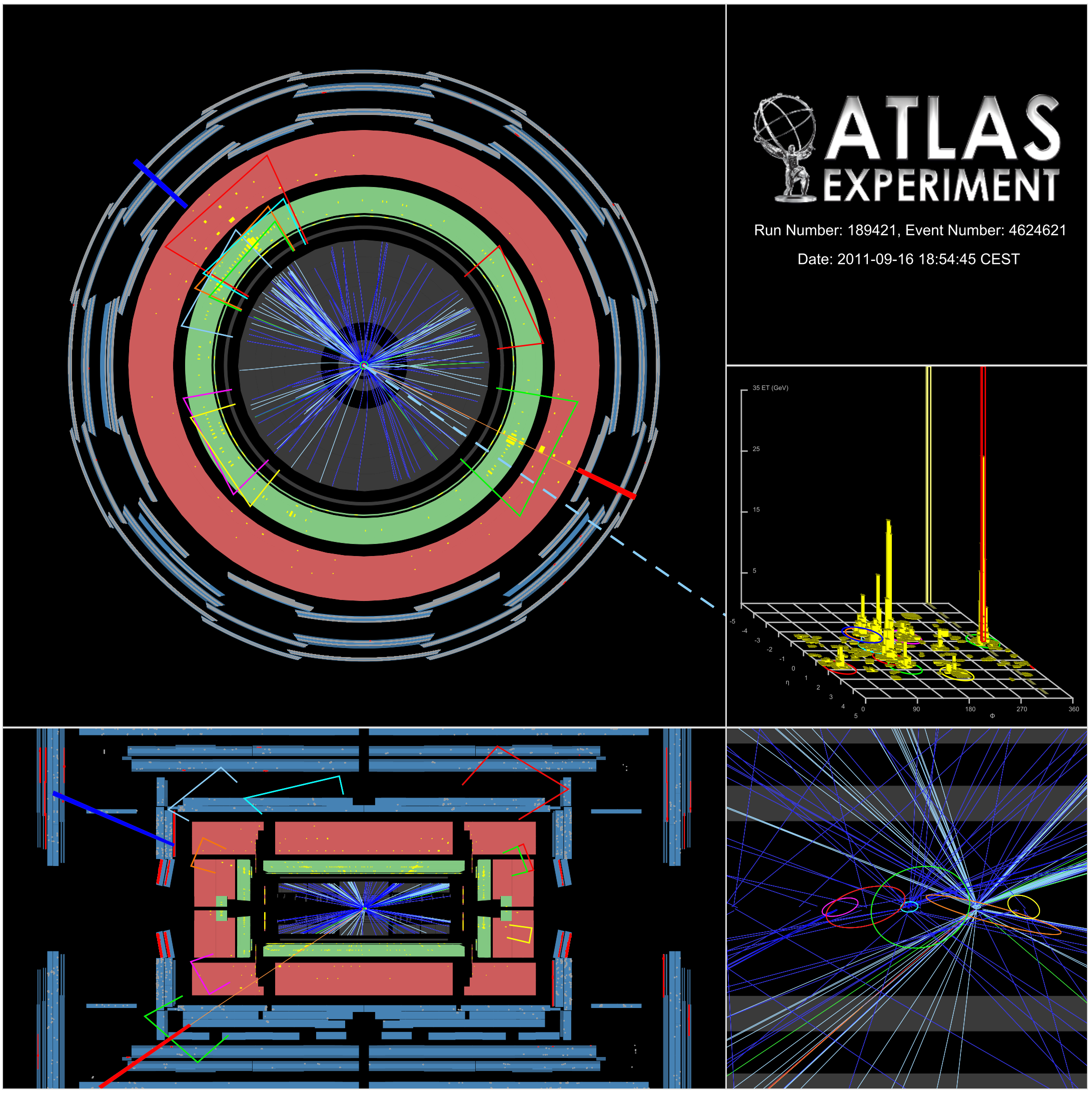

Figure 9. A display of an event which passes all signal region selections. The event has $E_{\mathrm{T}}^{\mathrm{miss}}/\sqrt{H_{\mathrm{T}}}$ of 11.6 $\mathrm{GeV}^{1/2}$, $\mathrm{H_T}$ of 1.17 TeV and $E_{\mathrm{T}}^{\mathrm{miss}}$ of 397 GeV. One of the jets, with $\mathrm{p_T}$ of 107 GeV is b tagged. The event also contains a muon with $\mathrm{p_T}$ of 90 GeV, overlapping with a jet.

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A. Tua[139], A. Tudorache[25a], V. Tudorache[25a], J.M. Tuggle[30], M. Turala[38], D. Turecek[127], I. Turk Cakir[3e], E. Turlay[105], R. Turra[89a,89b], P.M. Tuts[34], A. Tykhonov[74], M. Tylmad[146a,146b], M. Tyndel[129], G. Tzanakos[8], K. Uchida[20], I. Ueda[155], R. Ueno[28], M. Ugland[13], M. Uhlenbrock[20], M. Uhrmacher[54], F. Ukegawa[160], G. Unal[29], A. Undrus[24], G. Unel[163], Y. Unno[65], D. Urbaniec[34], G. Usai[7], M. Uslenghi[119a,119b], L. Vacavant[83], V. Vacek[127], B. Vachon[85], S. Vahsen[14], J. Valenta[125], P. Valente[132a], S. Valentinetti[19a,19b], S. Valkar[126], E. Valladolid Gallego[167], S. Vallecorsa[152], J.A. Valls Ferrer[167], H. van der Graaf[105], E. van der Kraaij[105], R. Van Der Leeuw[105], E. van der Poel[105], D. van der Ster[29], N. van Eldik[29], P. van Gemmeren[5], I. van Vulpen[105], M. Vanadia[99], W. Vandelli[29], A. Vaniachine[5], P. Vankov[41], F. Vannucci[78], R. Vari[132a], T. Varol[84], D. Varouchas[14], A. Vartapetian[7], K.E. Varvell[150], V.I. Vassilakopoulos[56], F. Vazeille[33], T. Vazquez Schroeder[54], G. Vegni[89a,89b], J.J. Veillet[115], F. Veloso[124a], R. Veness[29], S. Veneziano[132a], A. Ventura[72a,72b], D. Ventura[84], M. Venturi[48], N. Venturi[158], V. Vercesi[119a], M. Verducci[138], W. Verkerke[105], J.C. Vermeulen[105], A. Vest[43], M.C. Vetterli[142,d], I. Vichou[165], T. Vickey[145b,ai], O.E. Vickey Boeriu[145b], G.H.A. Viehhauser[118], S. Viel[168], M. Villa[19a,19b], M. Villaplana Perez[167], E. Vilucchi[47], M.G. Vincter[28], E. Vinek[29], V.B. Vinogradov[64], M. Virchaux[136,*], J. Virzi[14], O. Vitells[172], M. Viti[41], I. Vivarelli[48], F. Vives Vaque[2], S. Vlachos[9], D. Vladoiu[98], M. Vlasak[127], A. Vogel[20], P. Vokac[127], G. Volpi[47], M. Volpi[86], G. Volpini[89a], H. von der Schmitt[99], J. von Loeben[99], H. von Radziewski[48], E. von Toerne[20], V. Vorobel[126], V. Vorwerk[11], M. Vos[167], R. Voss[29], T.T. Voss[175], J.H. Vossebeld[73], N. Vranjes[136], M. Vranjes Milosavljevic[105], V. Vrba[125], M. Vreeswijk[105], T. Vu Anh[48], R. Vuillermet[29], I. Vukotic[115], W. Wagner[175], P. Wagner[120], H. Wahlen[175], S. Wahrmund[43], J. Wakabayashi[101], S. Walch[87], J. Walder[71], R. Walker[98], W. Walkowiak[141], R. Wall[176], P. Waller[73], C. Wang[44], H. Wang[173], H. Wang[32b,aj], J. Wang[151], J. Wang[55], R. Wang[103], S.M. Wang[151], T. Wang[20], A. Warburton[85], C.P. Ward[27], M. Warsinsky[48], A. Washbrook[45], C. Wasicki[41], P.M. Watkins[17], A.T. Watson[17], I.J. Watson[150], M.F. Watson[17], G. Watts[138], S. Watts[82], A.T. Waugh[150], B.M. Waugh[77], M. Weber[129], M.S. Weber[16], P. Weber[54], A.R. Weidberg[118], P. Weigell[99], J. Weingarten[54], C. Weiser[48], H. Wellenstein[22], P.S. Wells[29], T. Wenaus[24], D. Wendland[15], Z. Weng[151,w], T. Wengler[29], S. Wenig[29], N. Wermes[20], M. Werner[48], P. Werner[29], M. Werth[163], M. Wessels[58a], J. Wetter[161], C. Weydert[55], K. Whalen[28], S.J. Wheeler-Ellis[163], A. White[7], M.J. White[86], S. White[122a,122b], S.R. Whitehead[118], D. Whiteson[163], D. Whittington[60], F. Wicek[115], D. Wicke[175], F.J. Wickens[129], W. Wiedenmann[173], M. Wielers[129], P. Wienemann[20], C. Wiglesworth[75], L.A.M. Wiik-Fuchs[48], P.A. Wijeratne[77], A. Wildauer[167], M.A. Wildt[41,s], I. Wilhelm[126], H.G. Wilkens[29], J.Z. Will[98], E. Williams[34], H.H. Williams[120], W. Willis[34], S. Willocq[84], J.A. Wilson[17], M.G. Wilson[143], A. Wilson[87], I. Wingerter-Seez[4], S. Winkelmann[48], F. Winklmeier[29], M. Wittgen[143], M.W. Wolter[38], H. Wolters[124a,h], W.C. Wong[40], G. Wooden[87], B.K. Wosiek[38], J. Wotschack[29], M.J. Woudstra[82], K.W. Wozniak[38], K. Wraight[53], C. Wright[53], M. Wright[53], B. Wrona[73], S.L. Wu[173], X. Wu[49], Y. Wu[32b,ak], E. Wulf[34], B.M. Wynne[45], S. Xella[35], M. Xiao[136], S. Xie[48], C. Xu[32b,z], D. Xu[139], B. Yabsley[150], S. Yacoob[145b], M. Yamada[65], H. Yamaguchi[155], A. Yamamoto[65], K. Yamamoto[63], S. Yamamoto[155], T. Yamamura[155], T. Yamanaka[155], J. Yamaoka[44], T. Yamazaki[155], Y. Yamazaki[66], Z. Yan[21], H. Yang[87], U.K. Yang[82], Y. Yang[60], Z. Yang[146a,146b], S. Yanush[91], L. Yao[32a], Y. Yao[14], Y. Yasu[65], G.V. Ybeles Smit[130], J. Ye[39], S. Ye[24], M. Yilmaz[3c], R. Yoosoofmiya[123], K. Yorita[171], R. Yoshida[5], C. Young[143], C.J. Young[118], S. Youssef[21], D. Yu[24], J. Yu[7], J. Yu[112], L. Yuan[66], A. Yurkewicz[106], B. Zabinski[38], R. Zaidan[62], A.M. Zaitsev[128], Z. Zajacova[29], L. Zanello[132a,132b], A. Zaytsev[107], C. Zeitnitz[175], M. Zeman[125], A. Zemla[38], C. Zendler[20], O. Zenin[128], T. Ženiš[144a], Z. Zinonos[122a,122b], S. Zenz[14], D. Zerwas[115], G. Zevi della Porta[57], Z. Zhan[32d], D. Zhang[32b,aj], H. Zhang[88], J. Zhang[5], X. Zhang[32d], Z. Zhang[115], L. Zhao[108], T. Zhao[138], Z. Zhao[32b], A. Zhemchugov[64], J. Zhong[118], B. Zhou[87], N. Zhou[163], Y. Zhou[151], C.G. Zhu[32d], H. Zhu[41], J. Zhu[87], Y. Zhu[32b], X. Zhuang[98], V. Zhuravlov[99], D. Zieminska[60],

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R. Zimmermann[20], S. Zimmermann[20], S. Zimmermann[48], M. Ziolkowski[141], R. Zitoun[4], L. Živković[34], V.V. Zmouchko[128,*], G. Zobernig[173], A. Zoccoli[19a,19b], M. zur Nedden[15], V. Zutshi[106] and L. Zwalinski[29].

[1]: University at Albany, Albany NY, U.S.A.
[2]: Department of Physics, University of Alberta, Edmonton AB, Canada
[3]: [(a)]Department of Physics, Ankara University, Ankara; [(b)]Department of Physics, Dumlupinar University, Kutahya; [(c)]Department of Physics, Gazi University, Ankara; [(d)]Division of Physics, TOBB University of Economics and Technology, Ankara; [(e)]Turkish Atomic Energy Authority, Ankara, Turkey
[4]: LAPP, CNRS/IN2P3 and Université de Savoie, Annecy-le-Vieux, France
[5]: High Energy Physics Division, Argonne National Laboratory, Argonne IL, U.S.A.
[6]: Department of Physics, University of Arizona, Tucson AZ, U.S.A.
[7]: Department of Physics, The University of Texas at Arlington, Arlington TX, U.S.A.
[8]: Physics Department, University of Athens, Athens, Greece
[9]: Physics Department, National Technical University of Athens, Zografou, Greece
[10]: Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan
[11]: Institut de Física d'Altes Energies and Departament de Física de la Universitat Autònoma de Barcelona and ICREA, Barcelona, Spain
[12]: [(a)]Institute of Physics, University of Belgrade, Belgrade; [(b)]Vinca Institute of Nuclear Sciences, University of Belgrade, Belgrade, Serbia
[13]: Department for Physics and Technology, University of Bergen, Bergen, Norway
[14]: Physics Division, Lawrence Berkeley National Laboratory and University of California, Berkeley CA, U.S.A.
[15]: Department of Physics, Humboldt University, Berlin, Germany
[16]: Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern, Switzerland
[17]: School of Physics and Astronomy, University of Birmingham, Birmingham, U.K.
[18]: [(a)]Department of Physics, Bogazici University, Istanbul; [(b)]Division of Physics, Dogus University, Istanbul; [(c)]Department of Physics Engineering, Gaziantep University, Gaziantep; [(d)]Department of Physics, Istanbul Technical University, Istanbul, Turkey
[19]: [(a)]INFN Sezione di Bologna; [(b)]Dipartimento di Fisica, Università di Bologna, Bologna, Italy
[20]: Physikalisches Institut, University of Bonn, Bonn, Germany
[21]: Department of Physics, Boston University, Boston MA, U.S.A.
[22]: Department of Physics, Brandeis University, Waltham MA, U.S.A.
[23]: [(a)]Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro; [(b)]Federal University of Juiz de Fora (UFJF), Juiz de Fora; [(c)]Federal University of Sao Joao del Rei (UFSJ), Sao Joao del Rei; [(d)]Instituto de Fisica, Universidade de Sao Paulo, Sao Paulo, Brazil
[24]: Physics Department, Brookhaven National Laboratory, Upton NY, U.S.A.
[25]: [(a)]National Institute of Physics and Nuclear Engineering, Bucharest; [(b)]University Politehnica Bucharest, Bucharest; [(c)]West University in Timisoara, Timisoara, Romania
[26]: Departamento de Física, Universidad de Buenos Aires, Buenos Aires, Argentina
[27]: Cavendish Laboratory, University of Cambridge, Cambridge, U.K.
[28]: Department of Physics, Carleton University, Ottawa ON, Canada
[29]: CERN, Geneva, Switzerland
[30]: Enrico Fermi Institute, University of Chicago, Chicago IL, U.S.A.
[31]: [(a)]Departamento de Física, Pontificia Universidad Católica de Chile, Santiago; [(b)]Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso, Chile

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[32]: [(a)] Institute of High Energy Physics, Chinese Academy of Sciences, Beijing; [(b)] Department of Modern Physics, University of Science and Technology of China, Anhui; [(c)] Department of Physics, Nanjing University, Jiangsu; [(d)] School of Physics, Shandong University, Shandong, China
[33]: Laboratoire de Physique Corpusculaire, Clermont Université and Université Blaise Pascal and CNRS/IN2P3, Aubiere Cedex, France
[34]: Nevis Laboratory, Columbia University, Irvington NY, U.S.A.
[35]: Niels Bohr Institute, University of Copenhagen, Kobenhavn, Denmark
[36]: [(a)] INFN Gruppo Collegato di Cosenza; [(b)] Dipartimento di Fisica, Università della Calabria, Arcavata di Rende, Italy
[37]: AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, Krakow, Poland
[38]: The Henryk Niewodniczanski Institute of Nuclear Physics, Polish Academy of Sciences, Krakow, Poland
[39]: Physics Department, Southern Methodist University, Dallas TX, U.S.A.
[40]: Physics Department, University of Texas at Dallas, Richardson TX, U.S.A.
[41]: DESY, Hamburg and Zeuthen, Germany
[42]: Institut für Experimentelle Physik IV, Technische Universität Dortmund, Dortmund, Germany
[43]: Institut für Kern- und Teilchenphysik, Technical University Dresden, Dresden, Germany
[44]: Department of Physics, Duke University, Durham NC, U.S.A.
[45]: SUPA - School of Physics and Astronomy, University of Edinburgh, Edinburgh, U.K.
[46]: Fachhochschule Wiener Neustadt, Johannes Gutenbergstrasse 32700 Wiener Neustadt, Austria
[47]: INFN Laboratori Nazionali di Frascati, Frascati, Italy
[48]: Fakultät für Mathematik und Physik, Albert-Ludwigs-Universität, Freiburg i.Br., Germany
[49]: Section de Physique, Université de Genève, Geneva, Switzerland
[50]: [(a)] INFN Sezione di Genova; [(b)] Dipartimento di Fisica, Università di Genova, Genova, Italy
[51]: [(a)] E.Andronikashvili Institute of Physics, Tbilisi State University, Tbilisi; [(b)] High Energy Physics Institute, Tbilisi State University, Tbilisi, Georgia
[52]: II Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen, Germany
[53]: SUPA - School of Physics and Astronomy, University of Glasgow, Glasgow, U.K.
[54]: II Physikalisches Institut, Georg-August-Universität, Göttingen, Germany
[55]: Laboratoire de Physique Subatomique et de Cosmologie, Université Joseph Fourier and CNRS/IN2P3 and Institut National Polytechnique de Grenoble, Grenoble, France
[56]: Department of Physics, Hampton University, Hampton VA, U.S.A.
[57]: Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge MA, U.S.A.
[58]: [(a)] Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg; [(b)] Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg; [(c)] ZITI Institut für technische Informatik, Ruprecht-Karls-Universität Heidelberg, Mannheim, Germany
[59]: Faculty of Applied Information Science, Hiroshima Institute of Technology, Hiroshima, Japan
[60]: Department of Physics, Indiana University, Bloomington IN, U.S.A.
[61]: Institut für Astro- und Teilchenphysik, Leopold-Franzens-Universität, Innsbruck, Austria
[62]: University of Iowa, Iowa City IA, U.S.A.
[63]: Department of Physics and Astronomy, Iowa State University, Ames IA, U.S.A.
[64]: Joint Institute for Nuclear Research, JINR Dubna, Dubna, Russia
[65]: KEK, High Energy Accelerator Research Organization, Tsukuba, Japan
[66]: Graduate School of Science, Kobe University, Kobe, Japan

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[67]: Faculty of Science, Kyoto University, Kyoto, Japan
[68]: Kyoto University of Education, Kyoto, Japan
[69]: Department of Physics, Kyushu University, Fukuoka, Japan
[70]: Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata, Argentina
[71]: Physics Department, Lancaster University, Lancaster, U.K.
[72]: [(a)]INFN Sezione di Lecce; [(b)]Dipartimento di Matematica e Fisica, Università del Salento, Lecce, Italy
[73]: Oliver Lodge Laboratory, University of Liverpool, Liverpool, U.K.
[74]: Department of Physics, Jožef Stefan Institute and University of Ljubljana, Ljubljana, Slovenia
[75]: School of Physics and Astronomy, Queen Mary University of London, London, U.K.
[76]: Department of Physics, Royal Holloway University of London, Surrey, U.K.
[77]: Department of Physics and Astronomy, University College London, London, U.K.
[78]: Laboratoire de Physique Nucléaire et de Hautes Energies, UPMC and Université Paris-Diderot and CNRS/IN2P3, Paris, France
[79]: Fysiska institutionen, Lunds universitet, Lund, Sweden
[80]: Departamento de Fisica Teorica C-15, Universidad Autonoma de Madrid, Madrid, Spain
[81]: Institut für Physik, Universität Mainz, Mainz, Germany
[82]: School of Physics and Astronomy, University of Manchester, Manchester, U.K.
[83]: CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France
[84]: Department of Physics, University of Massachusetts, Amherst MA, U.S.A.
[85]: Department of Physics, McGill University, Montreal QC, Canada
[86]: School of Physics, University of Melbourne, Victoria, Australia
[87]: Department of Physics, The University of Michigan, Ann Arbor MI, U.S.A.
[88]: Department of Physics and Astronomy, Michigan State University, East Lansing MI, U.S.A.
[89]: [(a)]INFN Sezione di Milano; [(b)]Dipartimento di Fisica, Università di Milano, Milano, Italy
[90]: B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk, Republic of Belarus
[91]: National Scientific and Educational Centre for Particle and High Energy Physics, Minsk, Republic of Belarus
[92]: Department of Physics, Massachusetts Institute of Technology, Cambridge MA, U.S.A.
[93]: Group of Particle Physics, University of Montreal, Montreal QC, Canada
[94]: P.N. Lebedev Institute of Physics, Academy of Sciences, Moscow, Russia
[95]: Institute for Theoretical and Experimental Physics (ITEP), Moscow, Russia
[96]: Moscow Engineering and Physics Institute (MEPhI), Moscow, Russia
[97]: Skobeltsyn Institute of Nuclear Physics, Lomonosov Moscow State University, Moscow, Russia
[98]: Fakultät für Physik, Ludwig-Maximilians-Universität München, München, Germany
[99]: Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München, Germany
[100]: Nagasaki Institute of Applied Science, Nagasaki, Japan
[101]: Graduate School of Science and Kobayashi-Maskawa Institute, Nagoya University, Nagoya, Japan
[102]: [(a)]INFN Sezione di Napoli; [(b)]Dipartimento di Scienze Fisiche, Università di Napoli, Napoli, Italy
[103]: Department of Physics and Astronomy, University of New Mexico, Albuquerque NM, U.S.A.
[104]: Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, Netherlands
[105]: Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam, Netherlands

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[106]: Department of Physics, Northern Illinois University, DeKalb IL, U.S.A.
[107]: Budker Institute of Nuclear Physics, SB RAS, Novosibirsk, Russia
[108]: Department of Physics, New York University, New York NY, U.S.A.
[109]: Ohio State University, Columbus OH, U.S.A.
[110]: Faculty of Science, Okayama University, Okayama, Japan
[111]: Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman OK, U.S.A.
[112]: Department of Physics, Oklahoma State University, Stillwater OK, U.S.A.
[113]: Palacký University, RCPTM, Olomouc, Czech Republic
[114]: Center for High Energy Physics, University of Oregon, Eugene OR, U.S.A.
[115]: LAL, Université Paris-Sud and CNRS/IN2P3, Orsay, France
[116]: Graduate School of Science, Osaka University, Osaka, Japan
[117]: Department of Physics, University of Oslo, Oslo, Norway
[118]: Department of Physics, Oxford University, Oxford, U.K.
[119]: [(a)]INFN Sezione di Pavia; [(b)]Dipartimento di Fisica, Università di Pavia, Pavia, Italy
[120]: Department of Physics, University of Pennsylvania, Philadelphia PA, U.S.A.
[121]: Petersburg Nuclear Physics Institute, Gatchina, Russia
[122]: [(a)]INFN Sezione di Pisa; [(b)]Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy
[123]: Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh PA, U.S.A.
[124]: [(a)]Laboratorio de Instrumentacao e Fisica Experimental de Particulas - LIP, Lisboa, Portugal; [(b)]Departamento de Fisica Teorica y del Cosmos and CAFPE, Universidad de Granada, Granada, Spain
[125]: Institute of Physics, Academy of Sciences of the Czech Republic, Praha, Czech Republic
[126]: Faculty of Mathematics and Physics, Charles University in Prague, Praha, Czech Republic
[127]: Czech Technical University in Prague, Praha, Czech Republic
[128]: State Research Center Institute for High Energy Physics, Protvino, Russia
[129]: Particle Physics Department, Rutherford Appleton Laboratory, Didcot, U.K.
[130]: Physics Department, University of Regina, Regina SK, Canada
[131]: Ritsumeikan University, Kusatsu, Shiga, Japan
[132]: [(a)]INFN Sezione di Roma I; [(b)]Dipartimento di Fisica, Università La Sapienza, Roma, Italy
[133]: [(a)]INFN Sezione di Roma Tor Vergata; [(b)]Dipartimento di Fisica, Università di Roma Tor Vergata, Roma, Italy
[134]: [(a)]INFN Sezione di Roma Tre; [(b)]Dipartimento di Fisica, Università Roma Tre, Roma, Italy
[135]: [(a)]Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Energies - Université Hassan II, Casablanca; [(b)]Centre National de l'Energie des Sciences Techniques Nucleaires, Rabat; [(c)]Faculté des Sciences Semlalia, Université Cadi Ayyad, LPHEA-Marrakech; [(d)]Faculté des Sciences, Université Mohamed Premier and LPTPM, Oujda; [(e)]Faculté des sciences, Université Mohammed V-Agdal, Rabat, Morocco
[136]: DSM/IRFU (Institut de Recherches sur les Lois Fondamentales de l'Univers), CEA Saclay (Commissariat a l'Energie Atomique), Gif-sur-Yvette, France
[137]: Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz CA, U.S.A.
[138]: Department of Physics, University of Washington, Seattle WA, U.S.A.
[139]: Department of Physics and Astronomy, University of Sheffield, Sheffield, U.K.
[140]: Department of Physics, Shinshu University, Nagano, Japan
[141]: Fachbereich Physik, Universität Siegen, Siegen, Germany
[142]: Department of Physics, Simon Fraser University, Burnaby BC, Canada
[143]: SLAC National Accelerator Laboratory, Stanford CA, U.S.A.

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144: [(a)]Faculty of Mathematics, Physics & Informatics, Comenius University, Bratislava; [(b)]Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice, Slovak Republic
145: [(a)]Department of Physics, University of Johannesburg, Johannesburg; [(b)]School of Physics, University of the Witwatersrand, Johannesburg, South Africa
146: [(a)]Department of Physics, Stockholm University; [(b)]The Oskar Klein Centre, Stockholm, Sweden
147: Physics Department, Royal Institute of Technology, Stockholm, Sweden
148: Departments of Physics & Astronomy and Chemistry, Stony Brook University, Stony Brook NY, U.S.A.
149: Department of Physics and Astronomy, University of Sussex, Brighton, U.K.
150: School of Physics, University of Sydney, Sydney, Australia
151: Institute of Physics, Academia Sinica, Taipei, Taiwan
152: Department of Physics, Technion: Israel Institute of Technology, Haifa, Israel
153: Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv, Israel
154: Department of Physics, Aristotle University of Thessaloniki, Thessaloniki, Greece
155: International Center for Elementary Particle Physics and Department of Physics, The University of Tokyo, Tokyo, Japan
156: Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo, Japan
157: Department of Physics, Tokyo Institute of Technology, Tokyo, Japan
158: Department of Physics, University of Toronto, Toronto ON, Canada
159: [(a)]TRIUMF, Vancouver BC; [(b)]Department of Physics and Astronomy, York University, Toronto ON, Canada
160: Institute of Pure and Applied Sciences, University of Tsukuba,1-1-1 Tennodai,Tsukuba, Ibaraki 305-8571, Japan
161: Science and Technology Center, Tufts University, Medford MA, U.S.A.
162: Centro de Investigaciones, Universidad Antonio Narino, Bogota, Colombia
163: Department of Physics and Astronomy, University of California Irvine, Irvine CA, U.S.A.
164: [(a)]INFN Gruppo Collegato di Udine; [(b)]ICTP, Trieste; [(c)]Dipartimento di Chimica, Fisica e Ambiente, Università di Udine, Udine, Italy
165: Department of Physics, University of Illinois, Urbana IL, U.S.A.
166: Department of Physics and Astronomy, University of Uppsala, Uppsala, Sweden
167: Instituto de Física Corpuscular (IFIC) and Departamento de Física Atómica, Molecular y Nuclear and Departamento de Ingeniería Electrónica and Instituto de Microelectrónica de Barcelona (IMB-CNM), University of Valencia and CSIC, Valencia, Spain
168: Department of Physics, University of British Columbia, Vancouver BC, Canada
169: Department of Physics and Astronomy, University of Victoria, Victoria BC, Canada
170: Department of Physics, University of Warwick, Coventry, U.K.
171: Waseda University, Tokyo, Japan
172: Department of Particle Physics, The Weizmann Institute of Science, Rehovot, Israel
173: Department of Physics, University of Wisconsin, Madison WI, U.S.A.
174: Fakultät für Physik und Astronomie, Julius-Maximilians-Universität, Würzburg, Germany
175: Fachbereich C Physik, Bergische Universität Wuppertal, Wuppertal, Germany
176: Department of Physics, Yale University, New Haven CT, U.S.A.
177: Yerevan Physics Institute, Yerevan, Armenia
178: Domaine scientifique de la Doua, Centre de Calcul CNRS/IN2P3, Villeurbanne Cedex, France

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[a]: Also at Laboratorio de Instrumentacao e Fisica Experimental de Particulas - LIP, Lisboa, Portugal
[b]: Also at Faculdade de Ciencias and CFNUL, Universidade de Lisboa, Lisboa, Portugal
[c]: Also at Particle Physics Department, Rutherford Appleton Laboratory, Didcot, U.K.
[d]: Also at TRIUMF, Vancouver BC, Canada
[e]: Also at Department of Physics, California State University, Fresno CA, U.S.A.
[f]: Also at Novosibirsk State University, Novosibirsk, Russia
[g]: Also at Fermilab, Batavia IL, U.S.A.
[h]: Also at Department of Physics, University of Coimbra, Coimbra, Portugal
[i]: Also at Department of Physics, UASLP, San Luis Potosi, Mexico
[j]: Also at Università di Napoli Parthenope, Napoli, Italy
[k]: Also at Institute of Particle Physics (IPP), Canada
[l]: Also at Department of Physics, Middle East Technical University, Ankara, Turkey
[m]: Also at Louisiana Tech University, Ruston LA, U.S.A.
[n]: Also at Dep Fisica and CEFITEC of Faculdade de Ciencias e Tecnologia, Universidade Nova de Lisboa, Caparica, Portugal
[o]: Also at Department of Physics and Astronomy, University College London, London, U.K.
[p]: Also at Group of Particle Physics, University of Montreal, Montreal QC, Canada
[q]: Also at Department of Physics, University of Cape Town, Cape Town, South Africa
[r]: Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan
[s]: Also at Institut für Experimentalphysik, Universität Hamburg, Hamburg, Germany
[t]: Also at Manhattan College, New York NY, U.S.A.
[u]: Also at School of Physics, Shandong University, Shandong, China
[v]: Also at CPPM, Aix-Marseille Université and CNRS/IN2P3, Marseille, France
[w]: Also at School of Physics and Engineering, Sun Yat-sen University, Guanzhou, China
[x]: Also at Academia Sinica Grid Computing, Institute of Physics, Academia Sinica, Taipei, Taiwan
[y]: Also at Dipartimento di Fisica, Università La Sapienza, Roma, Italy
[z]: Also at DSM/IRFU (Institut de Recherches sur les Lois Fondamentales de l'Univers), CEA Saclay (Commissariat a l'Energie Atomique), Gif-sur-Yvette, France
[aa]: Also at Section de Physique, Université de Genève, Geneva, Switzerland
[ab]: Also at Departamento de Fisica, Universidade de Minho, Braga, Portugal
[ac]: Also at Department of Physics and Astronomy, University of South Carolina, Columbia SC, U.S.A.
[ad]: Also at Institute for Particle and Nuclear Physics, Wigner Research Centre for Physics, Budapest, Hungary
[ae]: Also at California Institute of Technology, Pasadena CA, U.S.A.
[af]: Also at Institute of Physics, Jagiellonian University, Kracow, Poland
[ag]: Also at LAL, Université Paris-Sud and CNRS/IN2P3, Orsay, France
[ah]: Also at Department of Physics and Astronomy, University of Sheffield, Sheffield, U.K.
[ai]: Also at Department of Physics, Oxford University, Oxford, U.K.
[aj]: Also at Institute of Physics, Academia Sinica, Taipei, Taiwan
[ak]: Also at Department of Physics, The University of Michigan, Ann Arbor MI, U.S.A.
[*]: Deceased

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