



# Search for new phenomena with the monojet and missing transverse momentum signature using the ATLAS detector in $\sqrt{s} = 7$ TeV proton–proton collisions <sup>☆</sup>

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## ABSTRACT

A search for new phenomena in events featuring a high energy jet and large missing transverse momentum in proton–proton collisions at  $\sqrt{s} = 7$  TeV is presented using a dataset corresponding to an integrated luminosity of  $33 \text{ pb}^{-1}$  recorded with the ATLAS detector at the Large Hadron Collider. The number of observed events is consistent with the Standard Model prediction. This result is interpreted in terms of limits on a model of Large Extra Dimensions.

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## 1. Introduction

Events composed of one high transverse energy jet and large missing transverse momentum constitute one of the simplest and most striking signatures that can be observed at a hadron collider. The main Standard Model (SM) contribution to this “monojet” final state is Z boson plus jet production where the Z boson decays to two undetected neutrinos. Processes involving physics beyond the Standard Model have been suggested as additional sources of monojet events, including Large Extra Dimension (LED) scenarios [1], Split Supersymmetry [2–4], and pair production of Dark Matter particles in association with a jet [5–7]. In this Letter, the data are interpreted in the context of a LED model.

Large Extra Dimensions have been proposed as a way to remove the hierarchy problem [8] and to explain why gravity is so much weaker than the other forces. In the LED scenario of Arkani-Hamed, Dimopoulos, and Dvali (ADD) [1], gravity propagates in the  $(4+n)$ -dimensional bulk of space–time, while the other SM fields are confined to our usual four dimensions. The observed large difference in the characteristic mass scale of gravity (Planck mass) and the electroweak scale ( $W$  boson mass) is the result of the four-dimensional interpretation of the Planck scale. The four-dimensional Planck scale,  $M_{Pl}$ , is related to the fundamental  $(4+n)$ -dimensional Planck scale,  $M_D$ , by  $M_{Pl}^2 \sim M_D^{2+n} R^n$ , where  $n$  and  $R$  are the number and size of the extra dimensions, respectively. An appropriate choice of  $R$  for a given  $n$  allows for a value of  $M_D$  close to the electroweak scale. The extra spatial dimensions are compactified, resulting in a Kaluza–Klein tower of massive graviton modes. At hadron colliders, these graviton modes can be produced in association with a jet. The production processes include  $qg \rightarrow qG$ ,  $gg \rightarrow gG$ , and  $q\bar{q} \rightarrow gG$ , where  $G$  stands

for graviton,  $q$  for quark, and  $g$  for gluon. As gravitons do not interact with the detector, these processes give rise to a monojet signature in the final state.

Previous monojet searches performed in Run I and Run II at the Tevatron [9,10] found no evidence of physics beyond the Standard Model.

## 2. The ATLAS detector and data samples

The ATLAS detector [11] at the LHC covers nearly the entire solid angle around the collision point. It consists of an inner tracking detector surrounded by a thin superconducting solenoid, electromagnetic and hadronic calorimeters, and an external muon spectrometer incorporating three large superconducting toroid magnets. A three-level trigger system is used to select interesting events for recording and subsequent offline analysis. Only data for which all subsystems described above are fully operational are used. Applying these requirements to  $pp$  collision data taken at a centre-of-mass energy of  $\sqrt{s} = 7$  TeV with stable beam conditions during the 2010 LHC run results in a data sample with a time-integrated luminosity of  $33 \text{ pb}^{-1}$ , determined with an uncertainty of 3.4% [12,13].

## 3. Object reconstruction

Jet candidates are reconstructed using the anti- $k_t$  jet clustering algorithm [14,15] with a distance parameter of 0.4. The inputs to this algorithm are clusters of calorimeter cells seeded by those with energies significantly above the measured noise. Jet momenta are constructed by performing a four-vector sum over these cell clusters, treating each cluster as an  $(E, \vec{p})$  four-vector with zero mass. The resulting jet energies are corrected for the effects of calorimeter non-compensation and inhomogeneities by

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using  $p_T$ - and  $\eta$ -dependent<sup>1</sup> calibration factors based on Monte Carlo (MC) simulations and validated with extensive test-beam and collision-data studies [16].

Electron candidates are required to have  $p_T > 20$  GeV and  $|\eta| < 2.47$ , and to pass the *medium* electron shower shape and track selection criteria described in [17]. Muon candidates are required to have  $p_T > 10$  GeV and  $|\eta| < 2.4$  and to pass the *combined* reconstruction criteria described in [17], which include the association of a stand-alone muon spectrometer track to an inner detector track. Muons are required to be isolated to reduce the background contribution from jet “punch through” which consists of particles originating from a high  $p_T$  jet, going through the calorimeter and reaching the muon spectrometer. The sum of the transverse momenta of the tracks not associated with the muon in a cone of radius  $R = 0.2$  in  $\eta$ - $\phi$  space around the muon direction is required to be less than 1.8 GeV.

The measurement of the magnitude of the missing transverse momentum ( $E_T^{\text{miss}}$ ) is done using all energy deposits in the calorimeter up to  $|\eta|$  of 4.5. These clusters are calibrated taking into account the different response of the calorimeters to hadrons compared to electrons or photons, as well as dead material and out-of-cluster energy losses [18].

#### 4. Event selection

Events must be accepted by an  $E_T^{\text{miss}}$  trigger [19] with a nominal threshold of 40 GeV, evaluated using energy depositions in the calorimeters. The trigger is over 99% efficient for events with a reconstructed  $E_T^{\text{miss}}$  above 120 GeV. The efficiency of the  $E_T^{\text{miss}}$  trigger was determined with events selected using a muon trigger. Events are then required to pass a set of basic kinematic selections that are aimed at reducing electroweak, non-collision, and detector-induced backgrounds. These selections require the event to have a monojet topology characterized by one unbalanced high  $p_T$  jet resulting in large  $E_T^{\text{miss}}$ .

The selections are:

- Events are required to have a reconstructed primary vertex with at least five associated tracks. This ensures that the recorded event is consistent with a proton–proton collision.
- The highest  $p_T$  jet is required to have a charge fraction  $f_{\text{ch}} = \sum p_T^{\text{track,jet}} / p_T^{\text{jet}} > 0.02$ , where  $\sum p_T^{\text{track,jet}}$  is the scalar sum of the transverse momenta of tracks associated with the primary vertex within a cone of radius  $R = 0.4$  around the jet axis, and  $p_T^{\text{jet}}$  is the transverse momentum as determined from calorimetric measurements. Furthermore, events are rejected if they contain any other jet with an electromagnetic fraction<sup>2</sup>  $f_{\text{em}} < 0.10$ , or any jet in the pseudorapidity range  $|\eta| < 2$  with  $f_{\text{em}} > 0.95$  and a charge fraction  $f_{\text{ch}} \leq 0.05$ . The requirement  $f_{\text{em}} < 0.10$  suppresses jets produced by cosmic rays or beam halo muons that interact in the hadronic calorimeter. The latter requirements reject events in which beam halo muons deposit a large amount of energy in the electromagnetic calorimeter while keeping a high efficiency for jets originating from  $pp$  collisions.
- Additional selections to reject events with detector noise and non-collision backgrounds are applied: events are rejected if

any jet with  $p_T > 20$  GeV and  $|\eta| < 4.5$  does not pass all of the additional quality selection criteria described in Ref. [20].

- Events are required to have no identified electrons or muons according to the selection criteria stated above. Although the signal selection vetoes leptons, control regions with identified leptons are used in this analysis to evaluate the agreement between the MC predictions and the data.

Although the results of this analysis are interpreted in this Letter in terms of the LED model, the event selections have not been tuned to maximize the sensitivity to any particular theoretical model. To maintain sensitivity to a wide range of models, two sets of kinematic selections, LowPt and HighPt, are defined. The LowPt selections are chosen such that the  $E_T^{\text{miss}}$  trigger with the highest integrated luminosity is fully efficient. Using lower jet  $p_T$  and  $E_T^{\text{miss}}$  selections has been motivated in the past to set limits on the pair production of Dark Matter particles [5]. The HighPt cuts are motivated by a potential increase in sensitivity in models such as ADD where there is a benefit from reducing the number of background events. However, enough events in the data control samples must be left to validate the MC predictions.

The LowPt (HighPt) selections are:

- Highest jet  $p_T > 120$  GeV and  $|\eta| < 2.0$  ( $p_T > 250$  GeV and  $|\eta| < 2.0$ ).
- Second highest jet  $p_T < 30$  GeV and  $|\eta| < 4.5$  ( $p_T < 60$  GeV and  $|\eta| < 4.5$ ). The threshold is raised for the HighPt region to preserve signal acceptance.
- $E_T^{\text{miss}} > 120$  GeV ( $E_T^{\text{miss}} > 220$  GeV).
- For the HighPt selection,  $\Delta\phi(\text{jet2}, E_T^{\text{miss}}) > 0.5$ , where jet2 is the second highest  $p_T$  jet, and the third highest jet is required to have  $p_T < 30$  GeV. The number of events in which the large value of  $E_T^{\text{miss}}$  is caused by a mis-measurement of the second-leading jet is reduced by requiring a large azimuthal separation between the direction of the second-leading jet and the missing transverse momentum.

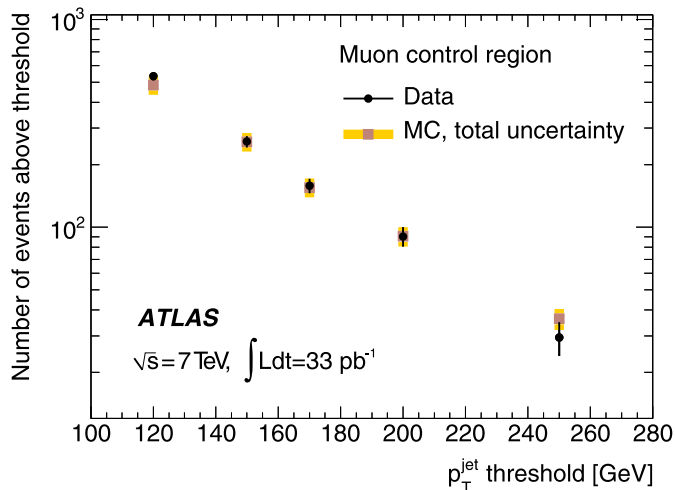
#### 5. Background estimate and comparison with data

The SM background to the monojet signature is dominated by  $Z(\rightarrow \nu\bar{\nu}) + \text{jets}$  and  $W + \text{jets}$  production, and includes contributions from  $Z/\gamma^*(\rightarrow \ell^+\ell^-) + \text{jets}$  ( $\ell = e, \mu, \tau$ ), multi-jet,  $t\bar{t}$ , and  $\gamma + \text{jets}$  processes. The  $W/Z$  plus jets backgrounds are estimated using Monte Carlo event samples normalized to data in control regions. The multi-jets background contribution is determined from data in the case of the LowPt analysis, while multi-jets MC simulation is employed for the HighPt selection. Potential contributions from beam-related background and cosmic rays are estimated using data. The remaining SM backgrounds from  $t\bar{t}$  and  $\gamma + \text{jets}$  are determined using simulated samples. These processes, which contribute a negligible number of events in both the LowPt region and the HighPt region, will not be discussed further.

Samples of simulated  $Z(\rightarrow \nu\bar{\nu}) + \text{jets}$ ,  $Z/\gamma^*(\rightarrow \ell^+\ell^-) + \text{jets}$ , and  $W(\rightarrow \ell\nu) + \text{jets}$  events are generated using ALPGEN v2.13 [21] interfaced to HERWIG v6.510 [22] for parton shower and fragmentation, and to JIMMY v4.31 [23] to model underlying event contributions. The CTEQ6L1 [24] parton distribution functions (PDFs) are employed, and the cross sections are initially normalized to predictions calculated to next-to-next-to-leading order (NNLO) in perturbative QCD as determined by the FEWZ [25] program using MSTW2008 PDFs [26]. These MC predictions are subsequently normalized using control samples in data as detailed below. Multi-jets background contributions are simulated using LO perturbative QCD matrix elements for  $2 \rightarrow 2$  processes plus parton shower in the leading logarithmic approximation, as implemented in PYTHIA

<sup>1</sup> ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the centre of the detector and the  $z$ -axis along the beam pipe. The  $x$ -axis points from the IP to the centre of the LHC ring, and the  $y$ -axis points upward. Cylindrical coordinates  $(r, \phi)$  are used in the transverse plane,  $\phi$  being the azimuthal angle around the beam pipe. The pseudorapidity is defined in terms of the polar angle  $\theta$  as  $\eta = -\ln \tan(\theta/2)$ .

<sup>2</sup> Fraction of the energy measured in the electromagnetic calorimeter.



**Fig. 1.** Observed number of events (black circles) in the muon control sample compared to the sum of the different  $W/Z$  plus jets predictions (squares) as a function of the highest jet  $p_T$  threshold, in events with no second-leading jet with  $p_T > 60$  GeV. The band indicates the total systematic uncertainty on the MC prediction.

v6.421 [27], with the ATLAS-MC09 tuning that uses the MRST 2007 LO\* PDFs [28]. All the MC samples are produced using the ATLAS detector simulation software [29] based on GEANT4 [30].

The SM MC predictions for the dominant  $W/Z$  plus jets background processes suffer from sizeable theoretical uncertainties. These uncertainties are related to the parton distribution functions, the renormalization and factorization scales in the perturbative QCD calculations, the modeling of the parton showers, the underlying event contributions, and the fragmentation of partons into hadrons. In addition, the MC predictions are affected by the limited knowledge of the absolute jet energy scale and resolution [31], trigger efficiency, and the total integrated luminosity [12]. In this analysis,  $W/Z$  plus jets data control samples are used to normalize the MC predictions, resulting in a significant reduction of their systematic uncertainties.

The data control samples are selected by removing the lepton veto from the requirements described previously. These samples with an identified electron or muon are dominated by  $W(\rightarrow e\nu) + \text{jets}$  and  $W(\rightarrow \mu\nu) + \text{jets}$  events but also include contributions from  $W(\rightarrow \tau\nu) + \text{jets}$  and  $Z/\gamma^*(\rightarrow \ell^+\ell^-) + \text{jets}$  processes. A small contamination from  $t\bar{t}$  production is subtracted using MC. The normalization factors are obtained for a given set of kinematic selections by taking the ratio of the number of events observed in the data to the number of events predicted by the MC. The kinematic selections are varied from  $E_T^{\text{miss}} > 120$  GeV and leading jet  $p_T > 120$  GeV up to  $E_T^{\text{miss}} > 220$  GeV and leading jet  $p_T > 250$  GeV. The  $p_T$  threshold on the jet veto is also increased from 0 GeV (no threshold) to the nominal LowPt and HighPt thresholds of 30 GeV and 60 GeV, respectively. The dependence of the normalization factors on the kinematic selections is discussed later.

The muon candidate sample is used to normalize the  $W(\rightarrow \mu\nu) + \text{jets}$ ,  $Z(\rightarrow \nu\bar{\nu}) + \text{jets}$ , and  $Z/\gamma^*(\rightarrow \mu^+\mu^-) + \text{jets}$  MC predictions. To emulate these backgrounds where muons are not identified and leave very little energy in the calorimeters, the  $E_T^{\text{miss}}$  is not corrected to take into account the momentum of the identified muons. For the LowPt selections, a normalization factor of  $0.99 \pm 0.06$  is obtained. For the HighPt region, the small number of events left after applying the selections results in a large statistical uncertainty on the normalization factor. To reduce this uncertainty, the number of events in the control sample is increased by lowering the  $E_T^{\text{miss}}$  and highest jet  $p_T$  thresholds to 180 and 200 GeV,

respectively. This results in a normalization factor of  $0.91 \pm 0.10$ . Since the kinematic selections are slightly lower than those of the signal region, the dependence of the normalization factor on the selections was studied. No significant dependence was observed as the  $E_T^{\text{miss}}$ , highest jet  $p_T$ , and jet veto thresholds were varied.

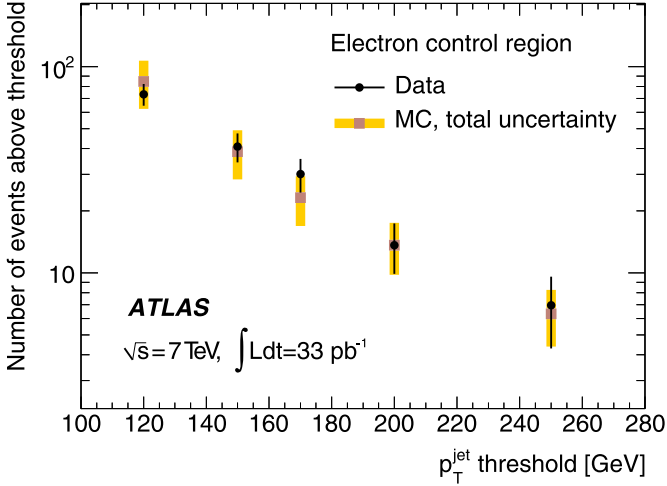
For the muon candidate sample, a comparison is shown in Fig. 1 between the data and the  $W/Z$  plus jets MC predictions normalized for the HighPt region as a function of the leading jet  $p_T$  threshold in events with no second-leading jet with  $p_T$  above 60 GeV.

The background calculation procedure described above makes the assumption, which is supported by the MC simulation, that the normalization used for  $W(\rightarrow \ell\nu) + \text{jets}$  backgrounds is valid for  $Z/\gamma^*(\rightarrow \ell^+\ell^-) + \text{jets}$  backgrounds. Since the largest background comes from  $Z(\rightarrow \nu\bar{\nu}) + \text{jets}$  events and the contribution from the rest of the  $Z + \text{jets}$  backgrounds is very small, the relevant assumption is that the normalization factor used for the  $Z(\rightarrow \nu\bar{\nu}) + \text{jets}$  background should be the same as the one used for the  $W(\rightarrow \mu\nu) + \text{jets}$  background. This assumption is tested by constructing samples with a set of selections aimed specifically at identifying  $Z$  and  $W$  bosons in events with jets and  $E_T^{\text{miss}}$ : the  $W(\rightarrow \mu\nu)$  candidate events are required to have an identified muon with  $p_T > 20$  GeV, transverse mass<sup>3</sup> in the region  $40 < m_T < 100$  GeV,  $E_T^{\text{miss}} > 100$  GeV, a leading jet with  $p_T$  above 100 GeV, and no additional jets with  $p_T > 30$  GeV. The  $Z/\gamma^*(\rightarrow \mu^+\mu^-) + \text{jets}$  data control samples are selected by requiring two oppositely charged leptons with  $p_T > 20$  GeV, a dilepton invariant mass in the range  $71 < M_{\ell^+\ell^-} < 111$  GeV,  $E_T^{\text{miss}} > 100$  GeV, a leading jet with  $p_T$  above 100 GeV, and no additional jets with  $p_T > 30$  GeV. The  $E_T^{\text{miss}}$  is not corrected for the presence of the two muons. The normalization factors are found to be  $0.91 \pm 0.13$  for the  $W(\rightarrow \mu\nu)$  sample, and  $0.88 \pm 0.18$  for the  $Z/\gamma^*(\rightarrow \mu^+\mu^-)$  sample. These values are consistent with the normalization factors used for the background calculation.

The electron candidate sample is used to normalize the  $W(\rightarrow e\nu) + \text{jets}$ ,  $Z/\gamma^*(\rightarrow e^+e^-) + \text{jets}$ , and  $W(\rightarrow \tau\nu) + \text{jets}$  MC predictions. Here, the electron is included in the  $E_T^{\text{miss}}$  calculation since an unidentified electron can deposit a large amount of energy in the calorimeters. This means that the  $E_T^{\text{miss}}$  selection is qualitatively different in the two samples even though the same value of the threshold is used. As a result, the number of events obtained in the two samples are not expected to be the same. For the LowPt kinematic selections, a normalization factor of  $0.92 \pm 0.24$  is obtained. For the HighPt kinematic selections, the procedure used previously for the muons of lowering the jet  $p_T$  and  $E_T^{\text{miss}}$  thresholds is followed and yields a normalization factor of  $1.0 \pm 0.3$ . No significant kinematic selection dependence of the normalization factor was observed. For the electron candidate sample, a comparison is shown in Fig. 2 between the data and the  $W/Z$  plus jets MC predictions as a function of the leading jet  $p_T$  threshold in events with no second-leading jet with  $p_T$  above 60 GeV.

The normalization factor used for the electron backgrounds is also used for the  $W(\rightarrow \tau\nu \rightarrow \text{had.} + X) + \text{jets}$  backgrounds since the MC predicts that after all selections, the dominant fully hadronic  $\tau$ -lepton decay channel produces a similar reconstructed signal in the control region as that of the electron channel. The systematic difference in the normalization factors of the two channels is much smaller than the uncertainties associated with the electron background normalization, and is therefore neglected. The remaining small  $W(\rightarrow \tau\nu) + \text{jets}$  background contribution with a

<sup>3</sup> The transverse mass is defined as  $m_T = \sqrt{2p_T^{\text{lepton}}E_T^{\text{miss}}(1 - \cos \Delta\phi)}$ , where  $\Delta\phi$  is the azimuthal separation between the directions of the lepton and the missing transverse momentum.



**Fig. 2.** Observed number of events (black circles) in the electron control sample compared to the sum of the different  $W/Z$  plus jets predictions (squares) as a function of the highest jet  $p_T$  threshold, in events with no second-leading jet with  $p_T > 60$  GeV. The band indicates the total uncertainty on the MC prediction.

muon from the  $\tau$ -lepton decay is found to have a normalization factor consistent, within uncertainties, with the value extracted from the muon control sample.

The total uncertainty on the electroweak background includes the uncertainties on the normalization factors given above, a 3% uncertainty on the lepton identification efficiency and a 2% uncertainty from the subtraction of the  $t\bar{t}$  contribution. Other experimental and theoretical uncertainties, that include the jet energy scale, jet energy resolution, luminosity, parton distribution functions, are cancelled, overall, by the normalization of the MC prediction to the data.

The multi-jets background with large  $E_T^{\text{miss}}$  originates mainly from the misreconstruction of the energy of the second-leading jet in the calorimeters, resulting in a monojet signature. In such events, the  $E_T^{\text{miss}}$  direction is generally aligned with the second-leading jet in the event. To estimate this background, a jets enriched data control sample is defined using the LowPt selection without the veto on the second-leading jet  $p_T$  and requiring  $\Delta\phi(\text{jet}2, E_T^{\text{miss}}) < 0.5$ . Events with more than two jets with  $p_T$  above 30 GeV are excluded. Small contributions from SM processes are subtracted according to the MC predictions. In the case of  $W/Z$  plus jets processes, the predictions are corrected with the normalization factors derived above for the relevant kinematic selections.

The measured  $p_T$  distribution of the second-leading jet in the jets enriched control sample is used to estimate the multi-jets background in the LowPt analysis. This estimate is compared to PYTHIA which has to be scaled by a factor  $1.13 \pm 0.04$  to match the data. The number of multi-jets background events is obtained from a linear extrapolation below the threshold of  $p_T < 30$  GeV. Several functional forms are considered to fit the data, and the difference with respect to the nominal result is included in the systematic uncertainties. In the LowPt analysis, a total of  $24 \pm 5(\text{stat.}) \pm 14(\text{syst.})$  multi-jets background events are expected, in agreement with the  $19 \pm 7(\text{stat.})$  events predicted by PYTHIA. For the HighPt analysis, an estimation of the multi-jets background from data is not possible due to the small number of events. The PYTHIA MC predicts a negligible contribution.

The cosmic ray and beam-related backgrounds are estimated from empty and unpaired proton bunches in the collider that fulfill the event selection criteria. This estimate also accounts for the probability of overlaps between background contributions and genuine proton–proton collisions leading to monojet signatures. A to-

**Table 1**

Number of observed events and predicted background events, including statistical and systematic uncertainties. The statistical uncertainties are due to limited MC statistics. The dominant systematic uncertainties come from the limited statistics in the data control regions. The systematic uncertainties on  $W(\rightarrow \mu\nu) + \text{jets}$ ,  $Z/\gamma^*(\rightarrow \mu^+\mu^-) + \text{jets}$ , and  $Z(\rightarrow \nu\bar{\nu}) + \text{jets}$  predictions are fully correlated. Similarly, the systematic uncertainties on  $W(\rightarrow e\nu) + \text{jets}$ ,  $W(\rightarrow \tau\nu) + \text{jets}$ , and  $Z/\gamma^*(\rightarrow \tau^+\tau^-) + \text{jets}$  are fully correlated.

	Background predictions $\pm$ (stat.) $\pm$ (syst.)	
	LowPt selection	HighPt selection
$Z(\rightarrow \nu\bar{\nu}) + \text{jets}$	$357 \pm 12 \pm 25$	$25.4 \pm 2.6 \pm 2.8$
$W(\rightarrow \tau\nu) + \text{jets}$	$139 \pm 5 \pm 36$	$7.8 \pm 1 \pm 2.3$
$W(\rightarrow \mu\nu) + \text{jets}$	$70 \pm 4 \pm 5$	$3.8 \pm 0.6 \pm 0.4$
$W(\rightarrow e\nu) + \text{jets}$	$59 \pm 3 \pm 15$	$3.0 \pm 0.7 \pm 0.9$
Multi-jets	$24 \pm 5 \pm 14$	–
$Z/\gamma^*(\rightarrow \tau^+\tau^-) + \text{jets}$	$2.6 \pm 0.5 \pm 0.7$	–
$Z/\gamma^*(\rightarrow \mu^+\mu^-) + \text{jets}$	$1.9 \pm 0.4 \pm 0.1$	–
top	$0.96 \pm 0.04 \pm 0.2$	–
$\gamma + \text{jets}$	$0.35 \pm 0.17 \pm 0.5$	–
$Z/\gamma^*(\rightarrow e^+e^-) + \text{jets}$	–	–
Non-collision background	$2.4 \pm 0.5 \pm 1.1$	–
Total background	$657 \pm 15 \pm 62$	$40 \pm 2.9 \pm 4.8$
Events in Data ( $33 \text{ pb}^{-1}$ )	611	39

tal of  $2.4 \pm 1.1$  non-collision background events are predicted in the LowPt analysis, while the contribution in the HighPt region is negligible.

The SM background predictions are summarized in Table 1 and are found to be consistent with the number of observed events in the data of 611 and 39 for the LowPt and HighPt selections, respectively. The main systematic uncertainties in the electroweak backgrounds come from the normalization uncertainties, which are dominated by the statistics in the data control samples. The statistical uncertainties listed in Table 1 come from the limited number of events in the MC samples. A comparison of the SM predictions to the measured  $E_T^{\text{miss}}$  and leading-jet  $p_T$  distributions are provided in Figs. 3 and 4, respectively. Good agreement is observed in all cases. The results of  $\chi^2$  tests performed on the distributions of Figs. 3 and 4 lead to  $\chi^2$  per degree of freedom values in the range between 0.4 and 1.2.

## 6. Data interpretation and limits

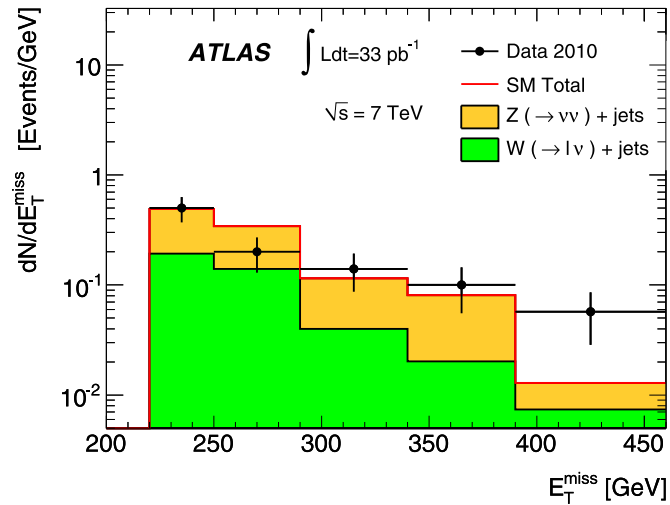
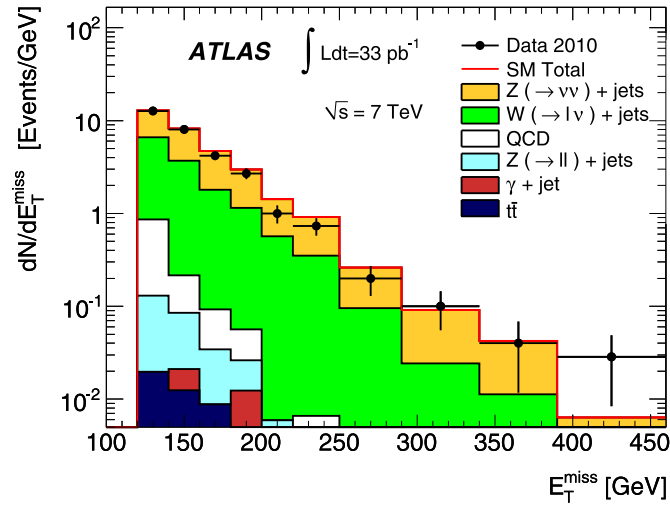
Since the number of events observed in the LowPt and HighPt regions are found to be consistent with the background predictions, as shown in Table 1, 95% confidence level (CL) upper limits are set on the cross-section times acceptance and on the value of  $M_D$  as a function of the number of extra dimensions. All limits are computed using the  $CL_s$  modified frequentist approach [32].

The 95% CL upper limits on cross section times acceptance are calculated considering the systematic uncertainties on the backgrounds and on the integrated luminosity. The resulting values are 3.26 pb and 0.51 pb for the LowPt and HighPt analysis, respectively.

To obtain limits on the ADD parameters  $M_D$  and  $R$ , model-dependent uncertainties on the signal cross sections and acceptances must be determined and included in the limit calculation.

For graviton production in the ADD scenario, a low-energy effective field theory [33] with energy scale  $M_D$  is used to calculate the signal cross section considering the contribution of different graviton mass modes. Signal samples corresponding to a number of extra dimensions varying between 2 and 6 are considered, with the renormalization and factorization scales set to  $\frac{1}{2}M_G^2 + p_T^2$ , where  $M_G$  is the graviton mass and  $p_T$  denotes the transverse momentum of the recoiling parton. The samples are generated using the PYTHIA MC program with the ATLAS MC09 tuning defining all parameters including the MRST2007 LO\* PDF set. The yields for



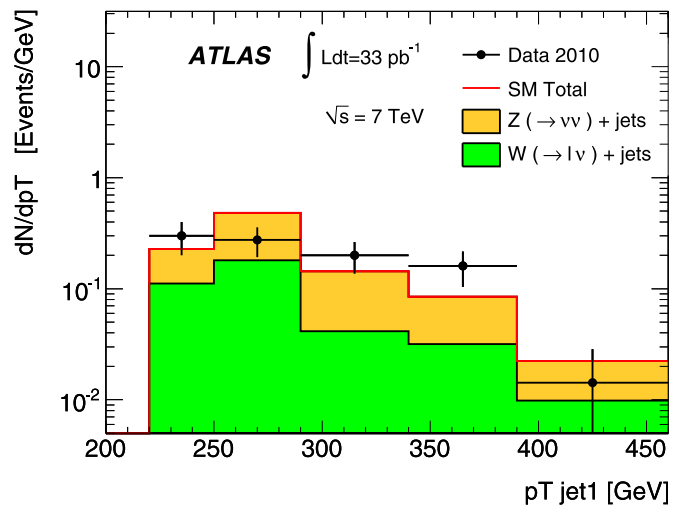
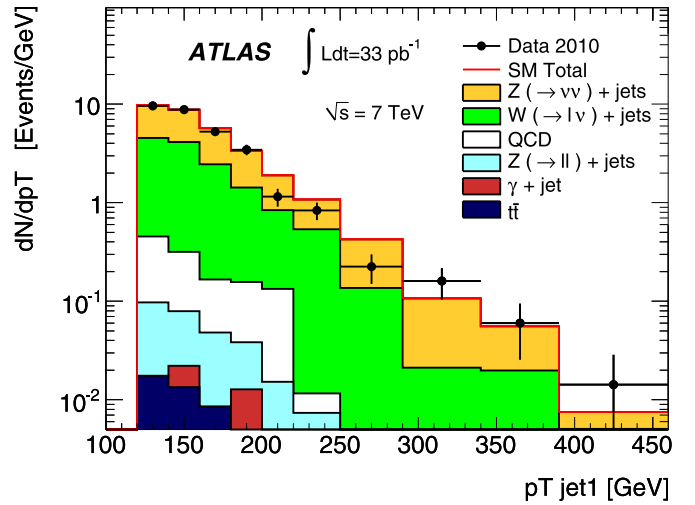


**Fig. 3.** Measured  $E_T^{\text{miss}}$  distributions for the LowPt (top) and HighPt (bottom) analyses compared to background predictions. Only statistical uncertainties on the data are shown. The systematic uncertainties on the total number of predicted events are 9% for the LowPt region and 12% for the HighPt region.

CTEQ6.6 PDFs [34] are obtained by reweighting these samples. All generated samples are passed through the full detector simulation, and are reconstructed and analyzed with the same analysis chain as for the data.

The approximation used in the calculation of the signal cross sections is expected to be valid only if the scales involved in the hard interaction are significantly smaller than  $M_D$ . An estimate of the relative importance of the signal predictions in the unknown ultra-violet kinematic region can be made by evaluating the cross section after rejecting events for which  $\hat{s} > M_D^2$ . A substantial contribution to the cross section from the region of phase space where  $\hat{s}$  is comparable to or larger than  $M_D^2$  would indicate that the model does not provide reliable predictions. In the case of 2 to 4 extra dimensions, and for the HighPt selections, the change in the accepted cross section varies between 2 and 28%, respectively. The effect is larger when the number of dimensions is increased, and can be as large as 60% for 6 dimensions. In this analysis, only predictions for up to 4 extra dimensions are therefore considered.

Systematic uncertainties that affect the production cross section include the PDF and scale uncertainties. The former are evaluated by studying the variations of the cross section obtained between

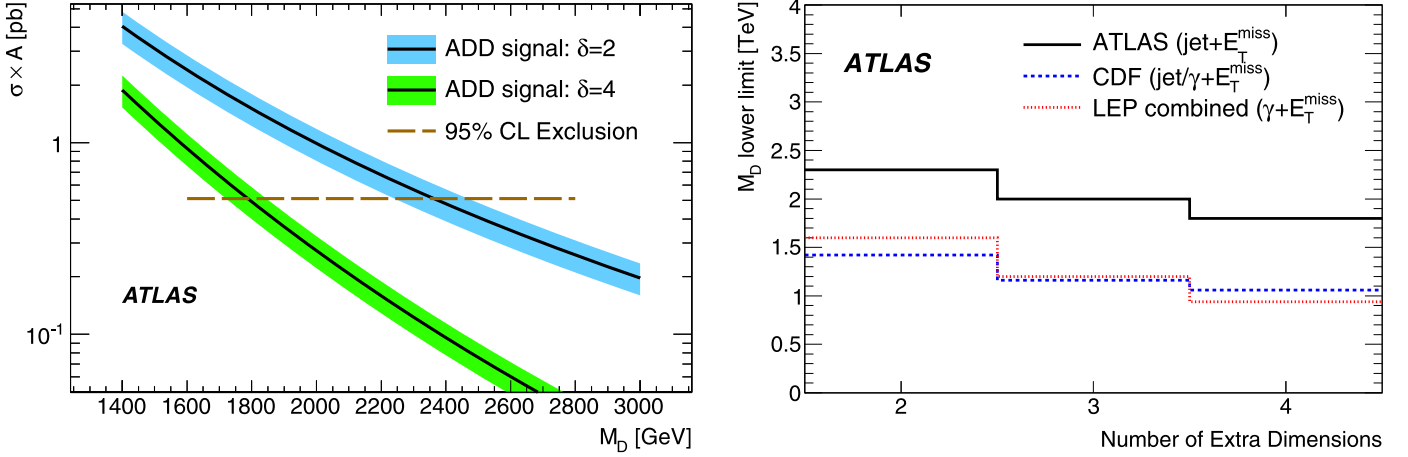


**Fig. 4.** Measured leading-jet  $p_T$  distributions for the LowPt (top) and HighPt (bottom) analyses compared to background predictions. Only statistical uncertainties on the data are shown. The systematic uncertainties on the total number of predicted events are 9% for the LowPt region and 12% for the HighPt region.

the nominal CTEQ6.6 value and its 44 error sets.<sup>4</sup> The uncertainty on the cross section related to the choice of renormalization and factorization scales is estimated by varying the scales upward and downward by a factor of two from their nominal value.

Systematic uncertainties affecting the signal acceptance are estimated as follows. The uncertainty coming from the modeling of initial and final state radiation (ISR/FSR) is estimated by varying the simulation parameters controlling ISR and FSR within a range that is consistent with experimental data [35]. The jet energy scale (JES) and resolution (JER) are varied by their uncertainties ([31] and [36]), and their impact on the signal acceptance is evaluated. The contributions of the PDF and scale uncertainties to the acceptance uncertainty are evaluated using the methods described above. The systematic uncertainty from the modeling of the pile-up is studied by comparing MC samples simulated without pile-up and with and average of two interactions per bunch crossing, corresponding to the average number of interactions per crossing observed in the 2010 data.

<sup>4</sup> The errors provided by CTEQ correspond to 90% confidence intervals. Here, they are rescaled to correspond to 68% intervals.



**Fig. 5.** Left: Signal cross section times acceptance as a function of  $M_D$  predicted by the effective ADD theory for 2 and 4 extra dimensions. The bands surrounding the curves reflect the systematic uncertainties. The observed limit is shown as a dashed line. Right: 95% CL observed lower limits on  $M_D$  for different numbers of extra dimensions for ATLAS, CDF [37], and LEP [38–42].

**Table 2**

Systematic uncertainties (in %) on ADD graviton signal yields for the LowPt and HighPt kinematic regions, respectively.

Source	LowPt (%)	HighPt (%)
PDFs	6	7
ISR/FSR	13	13
$Q^2$ scale	11	11
JES	5	6
JER	3	1
Pile-up	3	2
Luminosity	3	3
Total systematics	20	20

Finally, the uncertainty of 3.4% on the luminosity is also included. The values of all the signal-related systematic uncertainties considered above are given in Table 2, where all correlations are taken into account.

Signal cross sections times acceptance predicted by the effective theory for 2 and 4 extra dimensions are shown on the left side of Fig. 5 as a function of  $M_D$ . The bands around the curves reflect the uncertainties described previously. The cross section times acceptance limit of 0.51 pb is also shown for illustrative purposes.

To compute the 95% CL limits on ADD model parameters, all signal systematic uncertainties are considered and the  $CL_s$  approach mentioned above is used. Since the HighPt selections provide the best expected limits, they are used to set the observed limits. The 95% CL observed limits on  $M_D$  are shown on the right side of Fig. 5. Table 3 lists the 95% CL lower (upper) limits on  $M_D$  ( $R$ ), obtained with the CTEQ6.6 PDF set. Using the nominal MRST PDF set, the limits are 2.3, 2.0, and 1.8 TeV for 2, 3, and 4 extra dimensions, respectively. The expected limits are within 5% of the observed values.

Finally, to quantify the remaining sensitivity of the observed limits on  $M_D$  to the ultra-violet behavior of the theory for the different number of extra dimensions, the 95% CL limits on  $M_D$  are re-calculated using the truncated phase space region with  $\hat{s} < M_D^2$ . This translates into no significant change in the case of 2 and 3 extra dimensions and reduces the quoted limit for the case of 4 extra dimensions by 10%.

## 7. Conclusion

A search for new physics in final states containing a high- $p_T$  jet and missing transverse momentum is performed using  $33 \text{ pb}^{-1}$  of

**Table 3**

95% CL observed lower (upper) limits on  $M_D$  ( $R$ ) for  $\delta = 2-4$ , using a dataset corresponding to an integrated luminosity of  $33 \text{ pb}^{-1}$ . These results are obtained using the HighPt selection, and CTEQ6.6 PDF set. The expected limits are within 5% of the observed values.

$\delta$	$M_D$ [TeV]	$R$ [pm]
2	2.3	$9.2 \times 10^7$
3	2.0	$1.1 \times 10^3$
4	1.8	4.1

$pp$  collision data collected by the ATLAS detector. Good agreement is observed between the data and Standard Model predictions in the two kinematic regions studied in this analysis. 95% CL upper limits on cross section times acceptance are found to be 3.26 pb and 0.51 pb for the LowPt and HighPt analysis, respectively.

The results are then interpreted in terms of the ADD LED scenario where  $M_D$  values between 2.3 TeV and 1.8 TeV are excluded at the 95% confidence level for a number of extra dimensions varying from 2 to 4, respectively.

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