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A measurement of the ratio of the W and Z cross sections with exactly one associated jet in pp collisions at √s = 7 TeV with ATLAS

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A measurement of the ratio of the W and Z cross sections with exactly one associated jet in pp collisions at $\sqrt{s} = 7$ TeV with ATLAS ☆

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ABSTRACT

The ratio of production cross sections of the W and Z bosons with exactly one associated jet is presented as a function of jet transverse momentum threshold. The measurement has been designed to maximise cancellation of experimental and theoretical uncertainties, and is reported both within a particle-level kinematic range corresponding to the detector acceptance and as a total cross-section ratio. Results are obtained with the ATLAS detector at the LHC in pp collisions at a centre-of-mass energy of 7 TeV using an integrated luminosity of 33 pb^{-1}. The results are compared with perturbative leading-order, leading-log, and next-to-leading-order QCD predictions, and are found to agree within experimental and theoretical uncertainties. The ratio is measured for events with a single jet with $p_{\mathrm{T}} > 30$ GeV to be $8.73 \pm 0.30(\mathrm{stat}) \pm 0.40(\mathrm{syst})$ in the electron channel, and $8.49 \pm 0.23(\mathrm{stat}) \pm 0.33(\mathrm{syst})$ in the muon channel.

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1. Introduction

Measurements of vector bosons V where $V = W$ or Z produced in association with one or more jets (V + jet) [1–4] provide an important test of the Standard Model (SM) description of the strong interaction in perturbative quantum chromodynamics (QCD). This is particularly important in the kinematic region accessible at the LHC in order to understand the physics at or above the electroweak symmetry-breaking scale. Production of vector bosons is also a significant source of background for studies of other SM processes, including studies of top quark properties, searches for the Higgs boson, as well as in many searches for physics beyond the Standard Model. Measurements of the kinematic properties and dynamics of V + jet processes and comparisons to theoretical predictions are therefore of significant interest. Individual measurements of kinematic observables in W + jet [4] and Z + jet events are limited by systematic uncertainties common to both. Measurement of the ratio was first proposed in Ref. [5] to exploit the cancellation of theoretical and experimental uncertainties, therefore building the foundations for a high precision test of the Standard Model. In the present measurement, this ratio is measured, for states involving exactly one jet, as a function of the minimum jet transverse momentum. In addition to testing the predictions of perturbative QCD at various energy scales, the measurement provides model-independent sensitivity to new physics coupling to leptons and jets.

This Letter describes a measurement of the ratio of the production cross sections in the electron and muon decay channels of the W and Z gauge bosons in association with exactly one jet with transverse momentum $p_{\mathrm{T}} > 30$ GeV. The measurement was performed in the active fiducial volume of the detector and in a kinematic range where events are well-measured, hence minimising any model-dependence. The results were corrected to facilitate direct comparison to theoretical predictions at the particle level. Following the detector acceptance, the fiducial regions were defined by $p_{\mathrm{T}}^{\mathrm{lepton}} > 20$ GeV, $p_{\mathrm{T}}^{\nu} > 25$ GeV, $p_{\mathrm{T}}^{\mathrm{jet}} > 30$ GeV, $|\eta^{\mathrm{jet}}| < 2.8$,[1] and for electrons by $1.52 < |\eta| < 2.47$ or $|\eta| < 1.37$ and for muons by $|\eta| < 2.4$. Events with a second jet with $p_{\mathrm{T}} > 30$ GeV within this fiducial region were rejected.[2] The selected jet was required to be isolated from electrons by requiring $\Delta R^{e,\mathrm{jet}} > 0.6$ (where $\Delta R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2}$). Requirements are made on the boson masses specific to their reconstruction. For the W, the transverse mass defined by the lepton ℓ and neutrino ν transverse momenta and angles as $m_{\mathrm{T}} = \sqrt{2p_{\mathrm{T}}^{\ell}p_{\mathrm{T}}^{\nu}(1 - \cos(\phi^{\ell} - \phi^{\nu}))}$ was required to satisfy $m_{\mathrm{T}} > 40$ GeV. The dilepton invariant mass of the Z was required to be within the range $71 < m_{\ell\ell} < 111$ GeV.

[1] The nominal pp interaction point at the centre of the detector is defined as the origin of a right-handed coordinate system. The positive x-axis is directed from the interaction point to the centre of the LHC ring. The positive y-axis points upwards, while the beam direction defines the z-axis. The azimuthal angle ϕ is measured around the beam axis and the polar angle θ from the z-axis. The pseudorapidity is defined as $\eta = -\ln\tan(\theta/2)$.

[2] This veto is not expected to significantly affect fixed-order predictions for V + jet cross sections within the presented range of jet p_{T} measurements.

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Particle-level jets were defined as jets reconstructed in simulated events by applying the anti-k_t jet reconstruction algorithm [6] with a radius parameter $R = 0.4$ to all final state particles with a lifetime longer than 10 ps (including muons and non-interacting particles). Particle-level electrons were defined by including the energy of all radiated photons within a cone of $\Delta R = 0.1$ around each electron. The results are compared to perturbative leading-order [7] (LO), leading-log [8] (LL), and next-to-leading-order [9] (NLO) QCD calculations.

2. The ATLAS detector

The ATLAS detector [10,11] consists of an inner detector tracking system (ID) surrounded by a superconducting solenoid providing a 2 T magnetic field, electromagnetic and hadronic calorimeters, and a muon spectrometer (MS). The ID consists of pixel and silicon microstrip detectors inside a transition radiation tracker (TRT). The electromagnetic calorimeter is a lead liquid-argon (LAr) detector in the barrel ($|\eta| < 1.475$) and the end-cap ($1.375 < |\eta| < 3.2$) regions. Hadron calorimetry is based on two different detector technologies. The barrel ($|\eta| < 0.8$) and extended barrel ($0.8 < |\eta| < 1.7$) calorimeters are composed of scintillator/steel, while the hadronic end-cap calorimeters ($1.5 < |\eta| < 3.2$) are LAr/Cu. The forward calorimeters ($3.1 < |\eta| < 4.9$) are instrumented with LAr/Cu and LAr/W, providing electromagnetic and hadronic energy measurements, respectively. The MS is based on three large superconducting toroids and a system of three stations of trigger chambers and precision tracking chambers.

3. Simulated event samples

Simulated event samples were used to correct signal yields for detector effects, for some of the background estimates, and for comparison of the results to theoretical expectations. Samples of $W \to \ell\nu + N_{\text{parton}}$ and $Z \to \ell\ell + N_{\text{parton}}$ (where $\ell = e, \mu, \tau$) were generated using Alpgen v2.13 [8] with the MLM matching scheme [12], interfaced to Herwig v6.510 [13] for parton shower and fragmentation processes, and to Jimmy v4.31 [14] for the underlying event simulation. The CTEQ6L1 [15] parton density functions (PDFs) were used for samples generated with Alpgen. Additional inclusive samples were generated using Pythia 6.4.21 [7] using the MRST 2007 LO* [16] PDF for the same processes. The underlying event was generated with the ATLAS MC09 tune [17] for the Alpgen and Pythia samples. A Powheg v1.01p4 [18] NLO matrix element calculation with the CTEQ6.6M [19] PDF set and CTEQ6L1 Pythia parton showering and underlying event was used to generate $t\bar{t}$ samples. The radiation of photons from charged leptons was treated in Herwig and Pythia using Photos v2.15.4 [20], and Tauola v1.0.2 [21] was used for tau decays. The Powheg sample used the ATLAS MC09 tune with one parameter adjusted.[3] Inclusive samples of charm and bottom quark production were generated with Pythia 6.4.21. To reproduce the detector conditions, samples were also generated with multiple inelastic non-diffractive interactions overlaid on top of the hard-scattering event; the number of additional interactions followed a Poisson distribution with a mean of approximately two [22]. These MC samples were then re-weighted such that the distribution of the number of primary vertices matched that of the data. All samples were passed through the ATLAS detector simulation [23] performed using GEANT4 [24] and were subjected to the same reconstruction and analysis chain as the data.

[3] The cutoff for multiple parton interactions, PARP (82), was adjusted from 2.3 to 2.1 GeV, suitable for the CTEQ6L1 PDF.

Predictions for the W + one jet and Z + one jet cross sections at NLO were obtained with MCFM [9] with the same jet algorithm and kinematic selection requirements as applied to the data. A correction to particle level was applied to the MCFM predictions using Pythia to account for initial and final state radiation, underlying event, and hadronization. Renormalisation and factorisation scales were set to $H_T/2$, where H_T is the scalar sum of the p_T of the unclustered partons, the lepton and the neutrino. The CTEQ6.6M [19] PDF was used for the NLO calculations.

4. Data and event selection

The data used in this analysis were collected in the period March to October 2010. Basic requirements on beam, detector, stable trigger conditions and data quality resulted in a data set corresponding to an integrated luminosity $\mathcal{L} = 33\ \text{pb}^{-1}$. The criteria for event selection and lepton identification followed those employed for the W and Z inclusive cross-section measurement [25] with a few differences to account for the jet selection and to optimise cancellation of systematic uncertainties in the ratio.

In the electron channel, events were selected using a trigger logic that required the presence of at least one electromagnetic cluster in the calorimeter with transverse energy $E_T = E\sin(\theta)$ above 15 GeV in the region $|\eta| < 2.5$. Electron candidates were required to be matched to a track with silicon pixel and strip measurements in the ID, to have $E_T > 20$ GeV, and be within the fiducial region, avoiding the calorimeter barrel and end-cap transition regions. Candidates were required to satisfy standard "tight" or "medium" criteria [25]. Candidates satisfying lateral shower containment, shape and width criteria with minimal leakage into the hadronic calorimeter were classified as "medium". Candidates satisfying additional pixel and impact parameter criteria which also satisfied further requirements on the ratio of cluster energy to track momentum and on the ratio of high-threshold hits to the total number of TRT hits were classified as "tight".

In the muon channel, events were selected with a trigger system which identified muon candidates by the presence of hit patterns in the MS, consistent with a muon track with $p_T > 10$ GeV or $p_T > 13$ GeV (depending on the data period). The measured transverse momentum in the MS was required to satisfy $p_T > 10$ GeV to reject backgrounds from decays in flight. Muon candidates were required to have independent momentum measurements in both the ID and MS, which were then combined. Candidates which satisfied $p_T > 20$ GeV and were found to be within the fiducial region were classified as "medium".

Muons were additionally classified as "tight" if they satisfied all of the following additional criteria: the impact parameter with respect to the nominal beam axis was consistent with prompt muon production, the ID track satisfied additional hit quality criteria, the independent ID and MS track p_T measurements were consistent, and the muon was isolated by requiring the $\sum p_T$ of all tracks within $\Delta R < 0.2$ of the muon to be less than 1.8 GeV.

Events were required to have at least one reconstructed primary vertex with three or more associated tracks consistent with the nominal luminous region. The vertex with the largest $\sum p_T^2$ of associated tracks was assumed to be the primary vertex and was required to be within 150 mm of the centre of the detector along the beam direction.

The missing transverse energy (E_T^{miss}) was calculated from the energy deposits of calorimeter cells grouped into three-dimensional clusters [26] following the prescription in Ref. [25]. These clusters were corrected to account for the different response to hadrons compared to electrons or photons, as well as dead material and energy losses [27]. The E_T^{miss} was also corrected for measured muon momenta and their energy depositions in the

calorimeter. To calculate m_{T}, the (x, y) components of the neutrino momentum were inferred from the corresponding $E_{\mathrm{T}}^{\mathrm{miss}}$ components.

Events containing W boson candidates were selected by requiring one electron or muon satisfying "tight" selection criteria with no other "medium" leptons in the event, $E_{\mathrm{T}}^{\mathrm{miss}} > 25$ GeV and $m_{\mathrm{T}} > 40$ GeV. Events containing Z candidates were selected by requiring at least one lepton satisfying "tight" requirements and an additional same flavour, opposite charge lepton satisfying at least "medium" criteria, for which the pair was required to satisfy $71 < m_{\ell\ell} < 111$ GeV. The less stringent requirements on the second lepton reduced the systematic uncertainty on the lepton identification within the ratio measurement. These W and Z selections were defined to ensure mutual exclusivity.

The jet reconstruction efficiency in simulated data control samples [28] was found to be close to 100% for jets with $p_{\mathrm{T}} > 30$ GeV. Events containing jets arising from detector noise or cosmic rays were rejected [29]. A p_{T}- and η-dependent correction factor, derived from simulated events, was applied to the p_{T} of each jet to provide an average energy scale correction [30]. Jets were required to be reconstructed within $|\eta| < 2.8$ and with $p_{\mathrm{T}} > 30$ GeV. To avoid double-counting of electrons as jets, the closest jet within $\Delta R < 0.2$ of an electron candidate was not considered. Selected jets were required to be isolated from selected "medium" electrons by requiring $\Delta R(e, \mathrm{jet}) > 0.6$, to prevent a distortion of the jet energy response and of the jet reconstruction efficiency due to the proximity of the electron's electromagnetic shower. Jets from multiple interactions in a bunch crossing were suppressed by requiring jets with associated tracks have a good jet-vertex fraction ($JVF > 0.75$) [4]. This algorithm used track-jet association within a cone of $\Delta R(\mathrm{track}, \mathrm{jet}) < 0.4$. The JVF was computed for each jet as the scalar sum p_{T} of all associated tracks which also originated from the primary vertex divided by the scalar sum p_{T} of all the associated tracks. Events were required to have exactly one jet satisfying the above criteria with transverse momentum above the jet p_{T} threshold. Events containing a second jet with a good JVF and $p_{\mathrm{T}} > 30$ GeV were rejected.

Applying these W (Z) selection criteria, 12 112 (948) events and 12 995 (1376) events were retained in the electron and muon channels respectively.

5. Background estimation

Two categories of background events were considered, originating from either QCD multijet or electroweak processes. The electroweak background contributions in both channels were estimated from the simulated event samples as a fraction f_{ewk} of the total multijet-subtracted event yield, which has the advantage that there is no reliance on the measured absolute luminosity, and reduces the systematic uncertainty from detector effects on the acceptance. The multijet contributions were estimated using template methods based on simulated electroweak and multijet-enriched data samples, and were also expressed as a fraction f_{multijet} of the total event yield. The background contributions were derived in the electron and muon channels for W and Z selections separately for each jet p_{T} threshold value. They were subtracted from the total event yield N_{tot} from Table 1 using,

$$N_{\mathrm{sig}} = N_{\mathrm{tot}} \cdot (1 - f_{\mathrm{multijet}})(1 - f_{\mathrm{ewk}}) \quad (1)$$

to obtain the signal event yield N_{sig}. The yields and breakdown of background predictions are shown in Table 1.

The background contribution from multijet processes in the electron channel originates from events with jets misidentified as electrons and the mismeasurement of calorimetric energy resulting in large $E_{\mathrm{T}}^{\mathrm{miss}}$. This background contribution was estimated by using a partially data-driven method [25].

Table 1
Predicted and observed event yields in data in the electron and muon channels for the W and Z selections for $\mathcal{L} = 33$ pb^{-1}. Background estimates are quoted for a jet p_{T} threshold of 30 GeV. "Other" includes contributions from diboson and single top events. The total statistical uncertainties on predictions are quoted.

Process	$W \to e\nu$	$Z \to ee$
$W \to e\nu$	9340 ± 40	3 ± 1
$Z \to ee$	106 ± 3	880 ± 10
$W \to \tau\nu$	191 ± 6	0.2 ± 0.2
$t\bar{t}$	33 ± 1	1.9 ± 0.2
$Z \to \tau\tau$	19 ± 1	0.3 ± 0.1
Multijet	1800 ± 60	2.9 ± 0.6
Other	58 ± 2	1.1 ± 0.1
Total	$11\,550 \pm 70$	880 ± 10
Data N_{tot}	12 112	948

Process	$W \to \mu\nu$	$Z \to \mu\mu$
$W \to \mu\nu$	$11\,860 \pm 40$	4 ± 2
$Z \to \mu\mu$	360 ± 6	1370 ± 40
$W \to \tau\nu$	234 ± 6	0.3 ± 0.6
$Z \to \tau\tau$	22 ± 1	0.3 ± 0.6
$t\bar{t}$	35 ± 1	3 ± 2
Multijet	380 ± 70	4 ± 4
Other	117 ± 1	8 ± 3
Total	$13\,010 \pm 80$	1380 ± 40
Data N_{tot}	12 995	1376

The multijet background within the $W \to e\nu$ sample selection was estimated by fitting templates to the low $E_{\mathrm{T}}^{\mathrm{miss}}$ control region $15 < E_{\mathrm{T}}^{\mathrm{miss}} < 55$ GeV. The $E_{\mathrm{T}}^{\mathrm{miss}}$ templates for signal and electroweak processes were derived from Monte Carlo simulations, while the template for the multijet contribution was extracted from data by inverting the "tight" electron identification criteria which are not correlated with the $E_{\mathrm{T}}^{\mathrm{miss}}$. The result of this fit was the relative contribution of the multijet background [25] to the data. This estimate was performed for each jet p_{T} threshold considered.

The multijet background in the $Z \to ee$ channel was estimated with a similar fit using the di-electron invariant mass distribution. Templates for signal and electroweak processes were derived from Monte Carlo simulated events, while the template describing the multijet contribution was obtained by inverting two of the "medium" selection criteria of the Z selection.

For the W selection in the electron channel, the electroweak contributions mainly originate from $W \to \tau\nu$ events where the τ decays to an electron, and $t\bar{t}$ where one or more W decay to an electron. For the Z selection, they similarly come from $t\bar{t}$ events, and from $Z \to \tau\tau$ where both τ leptons decay to electrons. Finally, W and Z production also constitute significant background to each other, due to events in which one electron from the Z was not reconstructed, or when a W event contains an additional electron candidate. The total electroweak background fraction in the electron channel was approximately 3.4% for the selected W candidates, and less than 1% for the Z candidates.

The multijet background to $W \to \mu\nu + \mathrm{jet}$ events is estimated from the number of events passing all signal selections except isolation, and efficiencies derived from control samples in data for signal and multijet events required to pass the isolation requirement.

To estimate the multijet backgrounds for the Z in the muon channel, non-isolated muon pairs were selected in the simulated multijet sample. By comparing the dimuon invariant mass distribution for this sample and a non-isolated sample in data, a scale

factor was derived that was used to normalise a simulated background sample with the isolation requirement applied.

For the W selection in the muon channel, the electroweak backgrounds mainly originate from decays $W \to \tau\nu$ with the τ decaying to a muon and $Z \to \mu\mu$ where one muon fails to be reconstructed. The $Z \to \tau\tau$ and $t\bar{t}$ processes where one or both W boson(s) decay to a muon, contribute a smaller background fraction. For the Z selection in the muon channel, the dominant electroweak backgrounds arise from $Z \to \tau\tau$ and $t\bar{t}$ events with two real muons in the final state. The total electroweak background fraction in the muon channel was approximately 5% for the selected W candidates, and less than 1% for the Z candidates.

6. Correction to particle-level yield

The number of events after selection and background subtraction ($N_{\text{sig}}^{\ell,V}$) for each lepton ℓ and boson V was corrected for the detector effects and selection efficiencies back to the particle level ($N_{\text{part}}^{\ell,V}$). This corrected yield can be directly compared to theoretical predictions at the particle level. The corresponding correction factors from detector to particle level were computed for each jet p_{T} threshold in the electron and muon channels for the W and Z selections separately.

Yields were corrected with multiplicative factors which include trigger efficiency ($\epsilon_{\text{trig}}^{\ell}$), lepton identification efficiency (ϵ^{ℓ}), and boson reconstruction and resolution (C_V^{ℓ}). The number of signal events for each boson at particle level was then obtained using

$$N_{\text{part}}^{\ell,V} = \frac{N_{\text{sig}}^{\ell,V}}{\epsilon_{\text{trig}}^{\ell} \times \epsilon^{\ell} \times C_V^{\ell}}, \tag{2}$$

where the boson corrections C_V^{ℓ} correct the observed phase space to the fiducial phase space defined above, accounting for the resolution of leptons and $E_{\text{T}}^{\text{miss}}$.

Trigger and identification efficiencies were binned to account for variations in detector response. These efficiencies were binned in E_T and η for electrons and η and ϕ for muons. Efficiencies were found to be independent of the jet multiplicity and jet p_{T}. Therefore, a single efficiency map was used for all jet p_{T} thresholds.

The methods used to derive these efficiencies and corrections were similar for the electron and muon channels. The trigger efficiency and identification efficiency were measured using a sample of unbiased leptons obtained by selecting a well-identified tag lepton in $Z \to \ell\ell$ candidate events. The boson reconstruction correction C_V^{ℓ} was computed using the ALPGEN event generator. The PYTHIA Monte Carlo, used for comparison, was found to produce a consistent correction factor.

By measuring the ratio, almost complete cancellation of jet resolution effects was achieved. A small correction C_{jet}^{ℓ} was applied to the ratio to account for remaining non-cancelling effects due to lepton selection, jet selection criteria, and isolation criteria. The ratio measured was then the ratio of yields corrected to particle level and finally corrected for these remaining effects:

$$R_{\text{jet}} = \frac{N_{\text{part}}^{\ell,W}}{N_{\text{part}}^{\ell,Z}} \times C_{\text{jet}}^{\ell}. \tag{3}$$

The jet correction for the muon channel C_{jet}^{μ} is shown in Fig. 1. Systematic uncertainties from this correction were evaluated on the ratio itself. The jet correction C_{jet}^{ℓ} accounts for the difference of the ratio when calculated in terms of jets defined at particle level and reconstructed jets. The correction factor is different from unity if an offset exists between W + jet and Z + jet events in the jet p_{T} migration from particle level to detector level. This offset

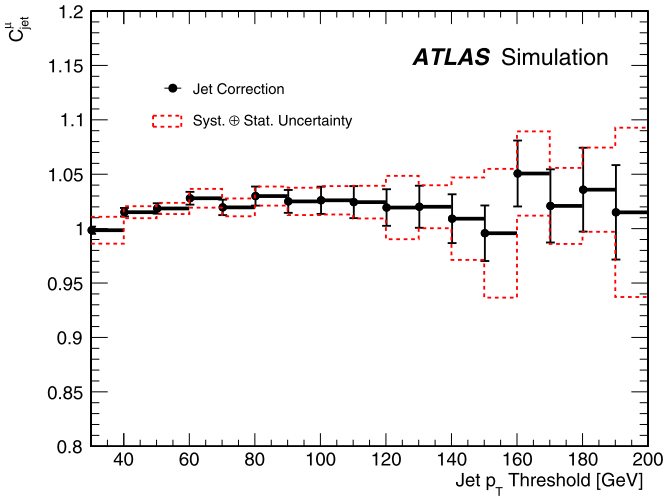

Fig. 1. Detector jet spectrum correction (C_{jet}^{μ}) on R_{jet} in the muon channel derived from ALPGEN. The uncertainty is shown as a dashed line, it accounts for the difference between PYTHIA and ALPGEN generators.

is due to the different requirements applied in the W + jet and Z + jet selections prior to the jet selections, placing the jets into slightly different phase space regions for the numerator and the denominator of the measurement. Performing the measurement as a function of p_{T} threshold instead of differentially removes the effects of migration across the upper bin edge.

7. Systematic uncertainties

To evaluate cancellations of systematic uncertainties which occur in the ratio, the correlations between W and Z systematic effects must be considered. Correlations between the measurements at each jet p_{T} threshold must also be accounted for. The effects of systematic uncertainties were therefore evaluated by measuring the relative change in the ratio R_{jet} from each source.

The total systematic uncertainty ranges from 4% at low jet p_{T} to 15% for the largest p_{T} threshold studied. For jet p_{T} thresholds of greater than 50 GeV the statistical uncertainty dominates the total measurement uncertainty.

The sources of systematic uncertainties on R_{jet} were grouped into uncertainties on the boson reconstruction (including lepton trigger, reconstruction and identification efficiencies, as well as lepton and $E_{\text{T}}^{\text{miss}}$ scales and resolutions), on jet-related corrections, multijet and electroweak background predictions, and generator-related uncertainties.

In the muon channel, where the background was small, the uncertainty on R_{jet} from the background estimation was approximately 1% for the whole jet p_{T} range. In the electron channel, the uncertainty increases as a function of jet p_{T} threshold. This is due to the larger background in the electron channel and the limited statistics used to compute backgrounds for high jet p_{T} thresholds.

Systematic uncertainties on the multijet background fractions were estimated by varying the criteria used to derive the background fractions. Each systematic uncertainty includes a component from the statistical uncertainty on the estimate of the background fraction.

The estimate of the electroweak background is affected by systematic effects from the event selection criteria. Samples with and without multiple pp interactions included in the simulation were also compared.

The lepton trigger efficiency and identification uncertainties were estimated following the procedure documented in Ref. [25]. The uncertainty on the ratio from lepton identification efficiencies

was directly obtained by scaling the single lepton identification efficiencies by their uncertainties, taking cancellations into account. A contribution to the uncertainty on the identification efficiency was assigned from the difference between its value derived in data and Monte Carlo. The total identification uncertainty was 1.1% (1.7%) for electrons (muons) independent of jet p_{T} thresholds.

The uncertainties on the scale and resolution of lepton energies and $E_{\mathrm{T}}^{\mathrm{miss}}$ were propagated to evaluate their effects on boson reconstruction by smearing the simulated signal samples using a Gaussian with a width corresponding to the nominal uncertainties. The resulting variations in R_{jet} were applied as systematic uncertainties.

Uncertainties on the jet energy scale (JES) and jet energy resolution (JER) were determined by comparing data and simulations [30]. The JES uncertainty includes components from calibration and jet sample composition differences. The JES calibration uncertainty varies with $|\eta|$ and p_{T}, and ranges from 4% to 8%. The JES and JER were measured with di-jet events, which have different proportions of quark and gluon initiated jets than events containing vector bosons. Therefore, an uncertainty was assigned to account for the difference in calorimeter response between jets in $V+$jet events and the di-jet events used for calibration, ranging from 2 to 5%, and was added in quadrature to the JES calibration uncertainty. The total JES uncertainty ranges from approximately 10% at 20 GeV to 5% at 100 GeV.

To compute the effect of the JER uncertainty on the ratio R_{jet}, jets were smeared according to a Gaussian with a width corresponding to the JER. The effect of the JES uncertainty on the ratio was obtained in a similar manner, but in this case, shifting the jet energy by its uncertainty. The ratio was recomputed applying these variations simultaneously to the numerator and denominator. The change was applied as a systematic uncertainty. The uncertainties on R_{jet} due to the JER and JES were approximately 0.5% and 2% respectively. The contribution to the uncertainty on the ratio from the small component of heavy flavour jets is covered by the total JES uncertainty.

To account for systematics associated with the modelling of the signal at particle level, correction factors were re-computed with samples generated with Pythia instead of Alpgen, and the observed variation was applied as a systematic uncertainty. Systematic uncertainties were assigned from this variation to the following corrections: (C_{jet}^{ℓ}), the boson reconstruction correction C_{V}^{ℓ}, and the electroweak background estimation f_{ewk}. At large jet p_{T} threshold, where the statistical uncertainty on the measurement dominates the total uncertainty, this systematic uncertainty is limited by the statistics of the samples used and is the dominant systematic uncertainty.

The uncertainties due to multiple pp interactions are dominated by uncertainties on the efficiency of the *JVF* algorithm. It was confirmed that the results obtained with simulated signal samples which include this effect were consistent with those obtained from samples which contained no additional interactions in the simulation. The residual difference on R_{jet} between samples with and without multiple interactions included was used as the systematic error from this *JVF* requirement.

Corrections to the simulation for hadronisation and the underlying event on the NLO parton-level calculation were computed with Pythia as a function of jet p_{T} threshold. The impact of this correction on R_{jet} was 1 to 6% for the electrons and 1 to 4% for the muons. The slightly larger variation for the electrons was due to the jet-electron isolation and the jet isolation veto included in the corrections.

The uncertainty on the correction of the MCFM cross-section ratio predictions for fragmentation, hadronisation and underlying event effects was estimated by comparing the Pythia AMBT1 [31] tune with the AMBT1 tune with increased underlying event activity, and without any underlying event. The uncertainty due to initial and final state radiation (ISR/FSR) was evaluated by varying the Pythia parameters controlling ISR and FSR [7]. For the ISR the variation ranges used were similar to the ranges used in the Perugia Soft and Perugia Hard tunes. For the FSR the variation ranges were similar to the ranges used in the Perugia 2011 radHi and Perugia 2011 radLo tunes [32].

Table 2
Summary of the systematic uncertainties on R_{jet} for the electron and muon channels. The value of each of the systematics for jet p_{T} thresholds of 30 and 100 GeV is shown. For the muon channel, the identification efficiency is included in the Boson reconstruction category.

Systematic uncertainties on R_{jet} (%) Electron channel	$p_{\mathrm{T}} > 30$ GeV	$p_{\mathrm{T}} > 100$ GeV
Trigger	0.5	0.5
Boson reconstruction	3.7	2.4
Identification efficiency	1.1	1.1
JVF	0.0	0.6
JES/JER	1.5	1.7
Multijet background	1.0	3.6
Electroweak background	1.3	1.2
Total non-generator	4.5	5.0
Generator	1.2	3.4
Total	4.6	6.1
Muon channel	$p_{\mathrm{T}} > 30$ GeV	$p_{\mathrm{T}} > 100$ GeV
Trigger	1.0	1.0
Boson reconstruction	2.5	2.4
JVF	1.7	0.2
JES/JER	2.0	1.9
Multijet background	0.4	0.1
Electroweak background	0.1	0.1
Total non-generator	3.8	3.2
Generator	1.4	2.7
Total	4.0	4.2

Renormalisation and factorisation scale uncertainties were estimated by varying the scales in all combinations, up and down, by a factor of two. Although these variations are arbitrary, they are motivated by the dependence of the behaviour of the NLO $W+$jet and $Z+$jet cross-section on the scale. This choice has a minimal impact on the uncertainty of the R_{jet} prediction. Systematic uncertainties from imperfect knowledge of PDFs were computed by summing in quadrature the dependence on each of the 22 eigenvectors characterising the CTEQ6.6 PDF set; the uncertainty in α_{s} was also taken into account. An alternative PDF set, MSTW2008 [33], with its set of 68% C.L. eigenvectors was also examined, and the envelope of the uncertainties from CTEQ6.6 and MSTW2008 was used as the PDF uncertainty.

All systematic uncertainties were added in quadrature to obtain the total systematic uncertainty. A summary of sources of systematic uncertainties and their relative contributions to R_{jet} is shown in Fig. 2 and in Table 2.

8. Results

The ratio R_{jet} was measured in the fiducial region of the ATLAS detector defined by the jet p_{T} threshold and selection criteria. The present measurements were corrected back to the particle level and within the defined kinematic range. The electron and muon measurements were performed in slightly different phase space, due to the different η range and electron-jet isolation requirements, as well as for the different QED treatment between electron and muon definitions. The observed signal yields were corrected to recover the yield at particle level as described in Section 6.

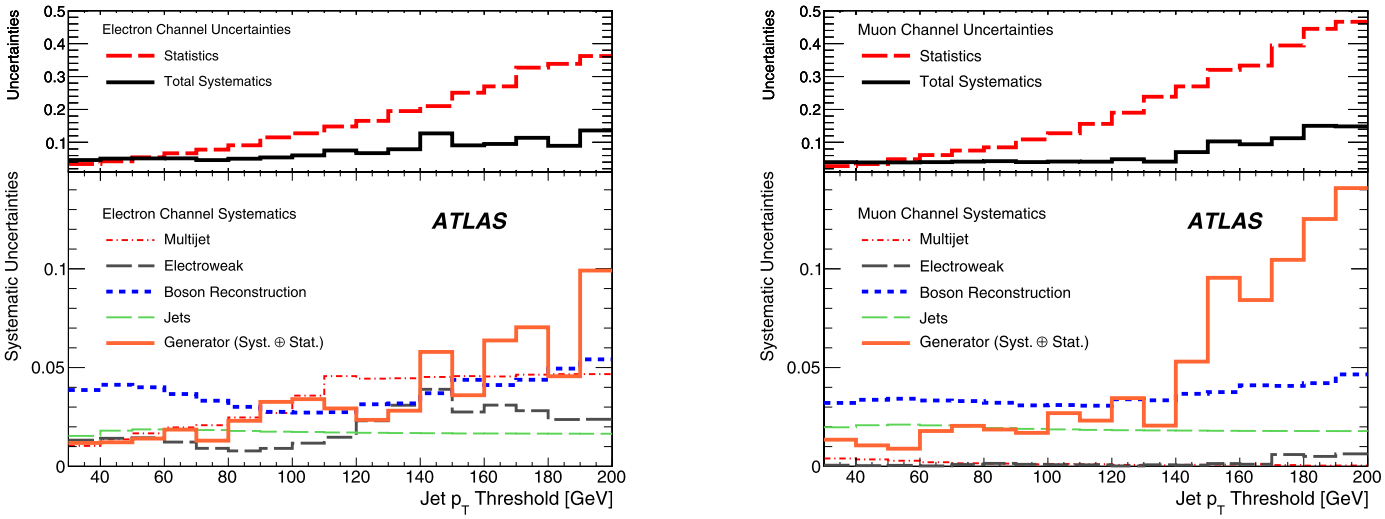

Fig. 2. Relative systematic uncertainties on R_{jet} in the electron channel (left) and in the muon channel (right). The top plot displays the total systematic and statistics uncertainty (shown as dashed line) versus jet p_{T} threshold. The lower plot shows the breakdown of the systematic uncertainties. Boson reconstruction contains the uncertainties related with the leptons and $E_{\text{T}}^{\text{miss}}$ (including trigger and lepton identification). Jets contains systematics of the jet correction as well as the jet energy scale and resolution. Uncertainties from each group were added in quadrature.

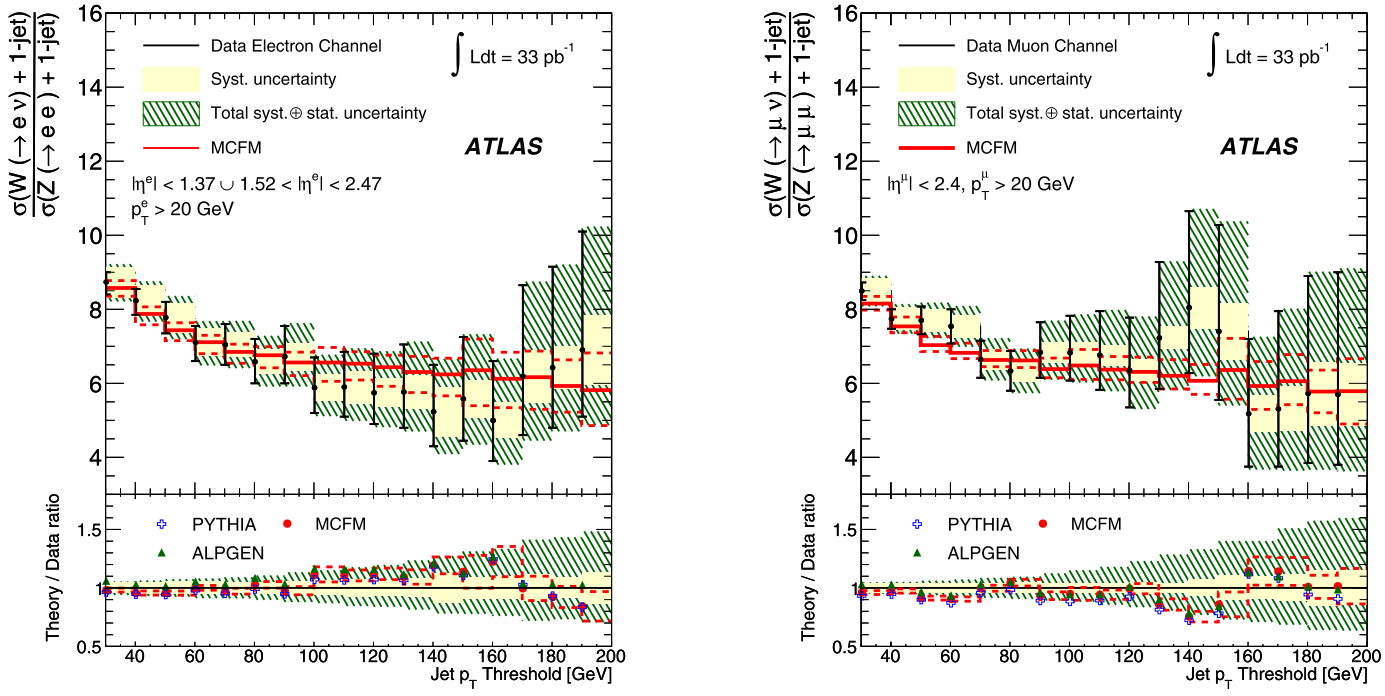

Fig. 3. Results for R_{jet} in the electron channel (left) and in the muon channel (right) for their respective fiducial regions. The results are compared to NLO predictions from MCFM (corrected to particle level using Pythia). Data are shown as black points at the lower bin edge corresponding to the jet p_{T} threshold with black error bars indicating the statistical uncertainties. The central band shows all systematic uncertainties added in quadrature and the larger hatched band shows statistical and systematic uncertainties added in quadrature. The theory uncertainty (dashed line) shown on the MCFM prediction includes uncertainties from PDF and renormalisation and factorisation scales. Note that these threshold data and their associated uncertainties are correlated between bins.

The corrected ratio R_{jet} of the production cross sections in the leptonic (electron or muon) decays of the gauge bosons W and Z in association with exactly one jet is shown in Fig. 3 as a function of the jet p_{T} threshold for the electron (left) and muon (right) channels. As the jet p_{T} threshold increases, the ratio R_{jet} is expected to decrease as the effective scale of the interaction becomes large compared to the difference in boson masses. This dependence is observed in the data. The values for the lowest jet p_{T} threshold of 30 GeV are:

$$R_{\text{jet}}(e) = 8.73 \pm 0.30(\text{stat}) \pm 0.40(\text{syst}),$$

$$R_{\text{jet}}(\mu) = 8.49 \pm 0.23(\text{stat}) \pm 0.33(\text{syst}).$$

The statistical uncertainties were evaluated by repeating the measurement with Monte Carlo pseudo-experiments assuming Poisson distributed data with a mean at the observed yield. Both electron and muon channel results are individually compatible with the theoretical predictions.

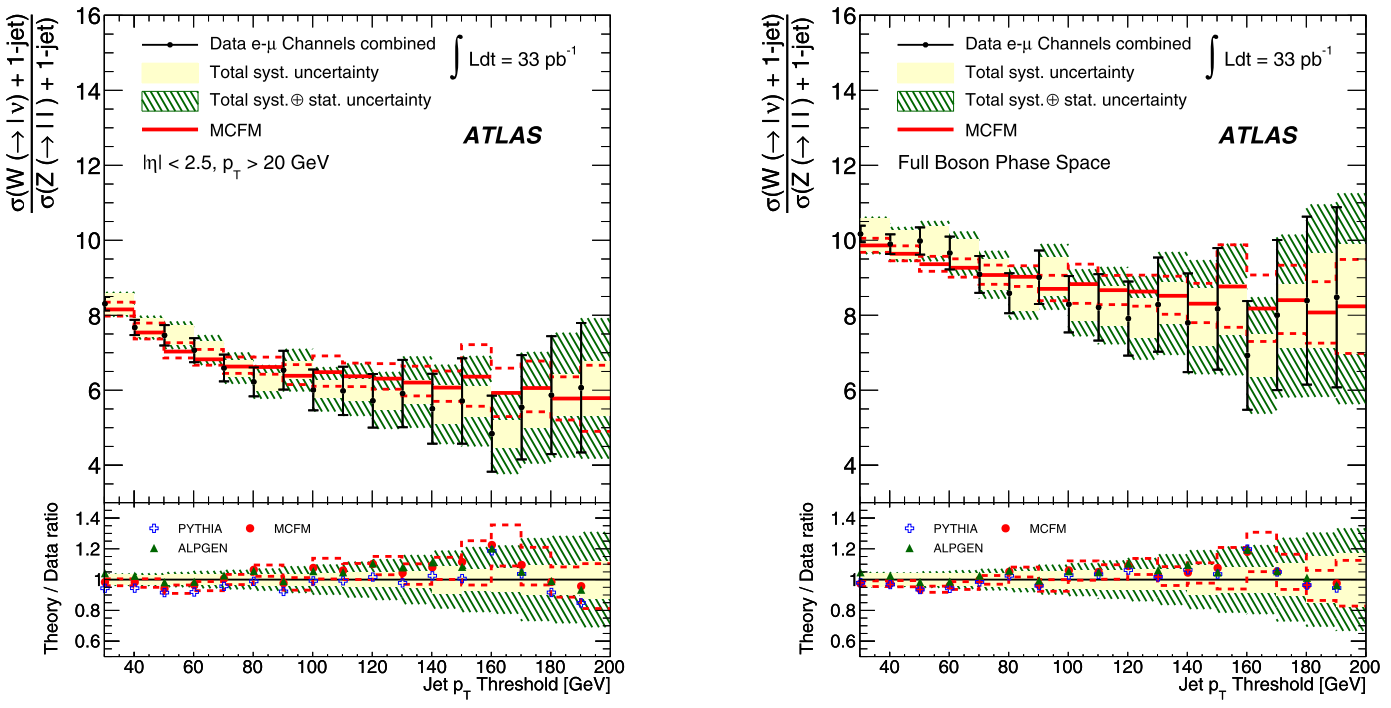

Fig. 4. Left: Combined electron and muon results for R_{jet} in a common fiducial region. The results are compared to predictions from MCFM (corrected to particle level). Data are shown with black error bars indicating the statistical uncertainties. The central band shows all systematic uncertainties added in quadrature and the larger hatched band shows statistical and systematic uncertainties added in quadrature. The theory uncertainty (dashed line) includes contributions from PDF and renormalisation and factorisation scales. Right: Combined electron and muon results for R_{jet} extrapolated to the total phase space. Note that these threshold data and their associated uncertainties are correlated between bins.

Table 3
Measured R_{jet} in the electron, muon and combined channels. The extrapolation to a common fiducial region for the combination decreases the value of the ratio for both channels. Values are reported with statistical and systematic uncertainties, respectively.

Jet p_{T} threshold (GeV)	Electron fiducial $\lvert\eta^e\rvert < 2.47$ (excl. $1.37 < \eta < 1.52$)	Muon fiducial $\lvert\eta^\mu\rvert < 2.4$	Combined $\lvert\eta^\ell\rvert < 2.5$	Boson full phase space
30	$8.73 \pm 0.3 \pm 0.40$	$8.49 \pm 0.23 \pm 0.33$	$8.29 \pm 0.18 \pm 0.28$	$10.13 \pm 0.22 \pm 0.45$
40	$8.23 \pm 0.35 \pm 0.41$	$7.74 \pm 0.26 \pm 0.30$	$7.67 \pm 0.20 \pm 0.24$	$9.89 \pm 0.26 \pm 0.38$
50	$7.77 \pm 0.42 \pm 0.39$	$7.7 \pm 0.37 \pm 0.30$	$7.46 \pm 0.27 \pm 0.25$	$9.97 \pm 0.36 \pm 0.39$
60	$7.10 \pm 0.47 \pm 0.36$	$7.54 \pm 0.46 \pm 0.30$	$7.07 \pm 0.32 \pm 0.24$	$9.64 \pm 0.43 \pm 0.39$
70	$7.04 \pm 0.55 \pm 0.32$	$6.64 \pm 0.49 \pm 0.27$	$6.59 \pm 0.35 \pm 0.22$	$9.07 \pm 0.49 \pm 0.41$
80	$6.58 \pm 0.6 \pm 0.33$	$6.33 \pm 0.53 \pm 0.27$	$6.22 \pm 0.38 \pm 0.23$	$8.58 \pm 0.53 \pm 0.46$
90	$6.72 \pm 0.77 \pm 0.36$	$6.83 \pm 0.74 \pm 0.27$	$6.53 \pm 0.51 \pm 0.23$	$9.02 \pm 0.71 \pm 0.51$
100	$5.88 \pm 0.75 \pm 0.35$	$6.82 \pm 0.87 \pm 0.28$	$6.02 \pm 0.54 \pm 0.23$	$8.33 \pm 0.75 \pm 0.48$
110	$5.90 \pm 0.87 \pm 0.44$	$6.76 \pm 1.05 \pm 0.28$	$6.01 \pm 0.64 \pm 0.28$	$8.25 \pm 0.88 \pm 0.53$
120	$5.74 \pm 0.95 \pm 0.38$	$6.34 \pm 1.20 \pm 0.31$	$5.72 \pm 0.71 \pm 0.26$	$7.93 \pm 0.98 \pm 0.52$
130	$5.76 \pm 1.12 \pm 0.45$	$7.22 \pm 1.72 \pm 0.30$	$5.95 \pm 0.89 \pm 0.31$	$8.31 \pm 1.25 \pm 0.55$
140	$5.23 \pm 1.1 \pm 0.66$	$8.04 \pm 2.17 \pm 0.56$	$5.62 \pm 0.93 \pm 0.50$	$7.94 \pm 1.31 \pm 0.76$
150	$5.58 \pm 1.4 \pm 0.50$	$7.40 \pm 2.37 \pm 0.76$	$5.70 \pm 1.13 \pm 0.40$	$8.15 \pm 1.62 \pm 0.67$
160	$4.99 \pm 1.35 \pm 0.47$	$5.17 \pm 1.72 \pm 0.48$	$4.83 \pm 1.01 \pm 0.36$	$6.92 \pm 1.44 \pm 0.56$
170	$6.19 \pm 2.02 \pm 0.70$	$5.30 \pm 2.09 \pm 0.59$	$5.53 \pm 1.39 \pm 0.53$	$7.97 \pm 2.00 \pm 0.84$
180	$6.42 \pm 2.17 \pm 0.57$	$5.72 \pm 2.54 \pm 0.86$	$5.86 \pm 1.57 \pm 0.55$	$8.38 \pm 2.24 \pm 1.25$
190	$6.9 \pm 2.5 \pm 0.94$	$5.70 \pm 2.65 \pm 0.84$	$6.04 \pm 1.72 \pm 0.72$	$8.43 \pm 2.40 \pm 1.46$

Electron and muon channel results were compatible and were therefore combined to reduce the statistical and uncorrelated systematic uncertainties on the result. Each channel was extrapolated to a common phase space, defined as $|\eta_\ell| < 2.5$ before any QED radiation (Born level) with PYTHIA. The electron channel was further corrected for the effect on the acceptance of the electron-jet isolation requirements. This extrapolation to a common fiducial region decreases the value of the ratio for both channels primarily due to the more central distribution of leptons from the Z. The results were combined using a Bayesian approach [34] in the combination of systematic uncertainties accounting for correlations between them. The systematic uncertainties from $E_{\text{T}}^{\text{miss}}$, jet energy scale and resolution and electroweak background sources were considered fully correlated between the electron and muon channels. The combined result is shown in Fig. 4 (left). The value of R_{jet} for the lowest jet p_{T} threshold of 30 GeV is found to be $8.29 \pm 0.18(\text{stat}) \pm 0.28(\text{syst})$.

The combined results were also extrapolated to the full phase space, correcting for regions of geometric and kinematic acceptance not measured (only the requirement on the invariant mass of the Z and veto on additional jets were retained), and presented as a function of jet p_{T} threshold. For this extrapolation, the W and Z acceptance factors were calculated at particle level using ALPGEN, and their ratio was applied as a correction to R_{jet}. This

extrapolation to the full phase space increases the value of the ratio for both channels primarily due to additional kinematic acceptance for the W. Fig. 4 (right) shows the result in the full boson acceptance phase space for the combined electron and muon channels. Due to the additional uncertainty on the correction to the generator-level acceptance, this result has larger total uncertainty than the results obtained in the fiducial regions. No significant discrepancy between data and theory is observed in any of these results.

9. Conclusions

This Letter presents a first measurement of the ratio of the production cross sections of the gauge bosons W and Z in association with exactly one jet. Results are presented as a function of jet p_{T} threshold, in both the electron and muon decay modes of the W and Z vector bosons. The measurement was corrected for all detector effects back to the particle level and presented within a fiducial phase space for electrons and muons. The ratio was measured to be $8.73 \pm 0.30(\mathrm{stat}) \pm 0.40(\mathrm{syst})$ in the electron channel, and $8.49 \pm 0.23(\mathrm{stat}) \pm 0.33(\mathrm{syst})$ in the muon channel at a jet p_{T} threshold of 30 GeV (Table 3). Results have also been extrapolated to $|\eta| < 2.5$ and combined, yielding $8.29 \pm 0.18(\mathrm{stat}) \pm 0.28(\mathrm{syst})$, and extrapolated to the full phase of the boson and combined giving $10.13 \pm 0.22(\mathrm{stat}) \pm 0.45(\mathrm{syst})$. The design of the measurement allows a cancellation of many theoretical and systematic uncertainties. These results are provided as a function of jet p_{T} threshold from 30 to 200 GeV, exploring the transition region of electroweak scale breaking in the perturbative jet production. This measurement builds the foundations of a high precision test of the Standard Model, and provides model-independent sensitivity to new physics coupling to leptons and jets. Comparisons with LO and NLO perturbative QCD predictions were made and found to be in agreement with data over the jet p_{T} threshold range covered by this measurement.

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