Measurement of the production cross section for W-bosons in association with jets in pp collisions at $\sqrt{s} = 7$ TeV with the ATLAS detector

The ATLAS Collaboration

Abstract

This Letter reports on a first measurement of the inclusive $W$+jets cross section in proton-proton collisions at a centre-of-mass energy of 7 TeV at the LHC, with the ATLAS detector. Cross sections, in both the electron and muon decay modes of the $W$ boson, are presented as a function of jet multiplicity and of the transverse momentum of the leading and next-to-leading jets in the event. Measurements are also presented of the ratio of cross sections $\sigma(W+\geq n)/\sigma(W+\geq n-1)$ for inclusive jet multiplicities $n=1$–4. The results, based on an integrated luminosity of 1.3 pb$^{-1}$, have been corrected for all known detector effects and are quoted in a limited and well-defined range of jet and lepton kinematics. The measured cross sections are compared to particle-level predictions based on perturbative QCD. Next-to-leading order calculations, studied here for $n \leq 2$, are found in good agreement with the data. Leading-order multiparton event generators, normalized to the NNLO total cross section, describe the data well for all measured jet multiplicities.

1. Introduction

The study of massive vector boson ($V$, where $V = W$ or $Z$) production in association with one or more jets ($V$+jets) is an important test of quantum chromodynamics (QCD). In addition, $V$+jets processes are a significant background to studies of Standard Model processes such as $t\bar{t}$ or single-top production, as well as searches for the Higgs boson and for physics beyond the Standard Model. Measurements of the cross section and kinematic properties of $V$+jets processes and comparisons to theoretical predictions are therefore of significant interest. This Letter reports on a first measurement at the Large Hadron Collider (LHC) of the $W$+jets cross section in proton-proton (pp) collisions at a centre-of-mass energy ($\sqrt{s}$) of 7 TeV, in both electron and muon decay modes of the $W$-boson, with the ATLAS detector. The measurement is based on an integrated luminosity of approximately 1.3 pb$^{-1}$.

The cross section measurements are presented as a function of jet multiplicity and of the transverse momentum ($p_T$) of the leading and next-to-leading jets in each event. Measurements are also presented of the ratio of cross sections $\sigma(W+\geq n)/\sigma(W+\geq n-1)$ for inclusive jet multiplicities $n=1$–4. The results have been corrected for all known detector effects and are quoted in a limited and well-defined range of jet and lepton kinematics, fully covered by the detector acceptance, so as to avoid model-dependent extrapolations and to facilitate comparisons with theoretical predictions. Previous measurements of $W$+jets production in proton-antiproton collisions at $\sqrt{s} = 1.96$ TeV were published by the CDF Collaboration [1]. Theoretical calculations at next-to-leading order (NLO) in perturbative QCD (pQCD) have been computed for up to four jets for $W$ production [2,3]. Comparisons are made in this Letter with NLO pQCD calculations for $n \leq 2$; higher jet multiplicities are compared only to leading-order (LO) calculations.

2. The ATLAS Detector

The ATLAS detector [4,5] consists of an inner tracking system (inner detector, or ID) surrounded by a thin superconducting solenoid providing a 2T magnetic field, electromagnetic and hadronic calorimeters and a muon spectrometer (MS). The ID consists of pixel and silicon microstrip (SCT) detectors, surrounded by the transition radiation

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adjusted from 2.3 to 2.1 GeV, suitable for the CTEQ6L1 PDF.

The electromagnetic calorimeter is a lead liquid-argon (LAr) detector. Hadron calorimetry is based on two different detector technologies, with scintillatortiles or LAr as active media, and with either steel, copper, or tungsten as the absorber material. The MS is based on three large superconducting toroids arranged with an eight-fold azimuthal coil symmetry around the calorimeters, and a system of three stations of chambers for the trigger and for precise measurements. The nominal pp interaction point at the centre of the detector is defined as the origin of a right-handed coordinate system. The positive z-axis is defined by the direction from the interaction point to the centre of the LHC ring, with the positive y-axis pointing upwards, while the beam direction defines the z-axis. The azimuthal angle $\phi$ is measured around the beam axis and the polar angle $\theta$ is the angle from the z-axis. The pseudorapidity is defined as $\eta = -\ln \tan(\theta/2)$.

3. Simulated Event Samples

Simulated event samples were used for most of the background estimates, for the correction of the signal yield for detector effects and for comparisons of the results for detector effects to theoretical expectations. The detector simulation was performed using GEANT4. The simulated event samples are summarised in Table 1. The ALPGEN samples were generated with the MLM matching scheme and interfaced to HERWIG v6.510 for parton shower and fragmentation processes and to JIMMY v4.31 for underlying event simulation. Parton density functions (PDF) were: CTEQ6L1 for the ALPGEN and SHERPA samples, MRST 2007 LO+ for PYTHIA, and MSTW2008 for FEWZ. For the POWHEG samples, the PDF set was CTEQ6.6M for the NLO matrix element calculations, while CTEQ6L1 was used for the parton showering and underlying event via the POWHEG interface to PYTHIA. The radiation of photons from charged leptons was treated in HERWIG and PYTHIA using PHOTOS v2.15.4 for PYTHIA, and MSTW2008 for FEWZ. For the POWHEG samples, PYTHIA inclusive vector boson production, and PYTHIA QCD samples. The POWHEG sample used the ATLAS MC09 tune for the ALPGEN samples, PYTHIA inclusive vector boson production, and PYTHIA QCD samples. The POWHEG sample used the ATLAS MC09 tune with one parameter adjusted. The AMBT1 tune was used for the PYTHIA W+jets samples. The samples generated with SHERPA used the default underlying event tune. Samples were generated with minimum bias interactions overlaid on top of the hard-scattering event in order to account for the multiple pp interactions in the same beam crossing (pile-up) experienced in the data. The number of minimum bias interactions followed a Poisson distribution with a mean of two. These samples were then reweighted such that the distribution of the number of primary vertices matched that of the data.

4. Data and Event Selection

The data used in this analysis were collected from March to August 2010. Application of beam, detector, and data-quality requirements resulted in a total integrated luminosity of $1.3 \text{ pb}^{-1}$. The uncertainty on the luminosity determination is estimated to be $11\%$.

Criteria for electron and muon identification, as well as for event selection, followed closely those for the $W$ boson inclusive cross section analysis [27].

In the electron channel, a hardware-based level-one trigger system selected events containing one or more electron candidates, based on the presence of a cluster in the electromagnetic calorimeter with a transverse energy ($E_T$) greater than 14 GeV; this is the only difference in the electron channel with respect to the $W$ inclusive cross section analysis, and was motivated by the fact that, for this larger dataset, this trigger was the lowest-threshold, useful electromagnetic trigger without any additional higher-level trigger requirements. The impact of the trigger efficiency was negligible for electrons with $E_T > 20$ GeV. In the offline analysis, electrons were required to pass the standard “tight” electron selection criteria [27] with $E_T > 20$ GeV and $|\eta| < 2.47$; electrons in the transition region between the barrel and endcap calorimeter ($1.37 < |\eta| < 1.52$) were rejected. Events were also rejected if there was a second electron passing the “medium” electron selection criteria and the same kinematic selections as above.

In the muon channel, the hardware-based trigger selected events containing one or more muon candidates, based on hit patterns in the MS, corresponding to $p_T > 10$ GeV. Offline, the muons were required to be identified in both ID and MS subsystems and to have $p_T > 20$ GeV and $|\eta| < 2.4$. The ID track was required to have $\geq 2$ hits in the pixel detector, $\geq 6$ hits in the SCT and, for tracks with $|\eta| < 2.0$, $\geq 1$ hit in the TRT. The muon impact parameter with respect to the primary vertex was required to be $< 0.1$ mm and $< 10$ mm in the $r-\phi$ and $r-z$ planes, respectively. The first of these requirements was added to further reduce non-prompt muons from decays of hadrons, and muons from cosmic rays. The difference between the ID and MS $p_T$, corrected for the mean energy loss in upstream material, was required to satisfy $|p_T^{\text{ID}} - p_T^{\text{MS}}| < 0.5 \times p_T^{\text{ID}}$. Compared to the criteria used in Ref. [27], this scaled requirement reduced the background from decays-in-flight of hadrons and improved the signal efficiency at high $p_T$. As in Ref. [27], the muons were required to be isolated, following a track-based isolation, but the cone size was reduced from $\Delta R = 0.4$ to $\Delta R = 0.2$ (where $\Delta R = \sqrt{(\Delta \eta)^2 + (\Delta \phi)^2}$ of the muon) and the isolation requirement was changed from $\Sigma p_T^{\text{ID}}/p_T < 0.2$ to $\Sigma p_T^{\text{ID}} < 1.8$ GeV to improve the QCD background rejection. With these optimised cuts, the QCD background was reduced by a factor of 1.7 for the inclusive 1-jet sample. In addition, a number of requirements were added on the tracks inside the isolation cone: the difference between the z position of the track extrapolated to the beam line and 2
the z coordinate of the primary vertex was required to be < 1 cm, and the total number of hits in the pixel and SCT detectors was required to be ≥ 4. These additional requirements further improved the rejection of QCD background. Events were rejected if there was a second muon passing the same kinematic selections and isolation requirements as above.

The calculation of missing transverse energy (E_{T}^{miss}) and transverse mass (M_{T}) followed the prescription in Ref. [27]. M_{T} was defined by the lepton and neutrino p_{T} as M_{T} = \sqrt{(2\hat{\nu}_{T}E_{T}^{miss}/(1 - \cos(\phi - \phi'))), where the (x, y) components of the neutrino momentum were inferred from the corresponding E_{T}^{miss} components. E_{T}^{miss} was calculated from the energy deposits of calorimeter cells inside three-dimensional clusters [28]. These clusters were then corrected to take into account the different response to hadrons compared to electrons or photons, as well as dead material and out-of-cluster energy losses [29]. In the muon channel, E_{T}^{miss} was corrected for the muon momentum. Events were required to have E_{T}^{miss} > 40 GeV. After requiring ≥ 1 primary vertex with ≥ 3 associated tracks in the event, the primary vertex was required to be within 150 nm along the beam direction relative to the centre of the detector. In events with multiple vertices along the beam axis, the vertex with the largest \sum_{i} \rho_{T,i}^{2} of associated tracks was taken as the primary event vertex. Starting from approximately 9.6 × 10^{6} triggered events in each of the electron and muon channels, these selection criteria reduced the sample to 4216 and 4911 events, respectively.

Jets were reconstructed using the anti-kt algorithm [30] with a radius parameter R = 0.4 [31]. The efficiency for reconstructing jets was found to be approximately 98% in simulation for jet p_{T} of 20 GeV, rising to close to 100% efficiency for 30 GeV jets. Jets arising from detector noise or cosmic rays were rejected [32]. To take into account the differences in calorimeter response to electrons and hadrons, a p_{T} and η-dependent factor, derived from simulated events, was applied to each jet to provide an average energy scale correction [31] back to particle-level. Jets were required to have |η| < 2.8 and p_{T} > 20 GeV. All jets within ΔR < 0.5 of an electron or muon (that passed the lepton identification requirements) were removed, regardless of the jet p_{T} or η.

Jets from pile-up interactions were removed by a cut on the jet-vertex fraction (JVF) which was computed for each jet in the event. After associating tracks to jets with a simple matching in ΔR(track, jet), requiring ΔR < 0.4, the JVF was computed for each jet as the scalar sum p_{T} of all matched tracks from the primary vertex divided by the total jet-matched track p_{T} from all vertices. Jets which fell outside of the fiducial tracking region (|η| < 2.5) or which had no matching tracks were not considered for the JVF cut. Jets for which JVF < 0.75 were rejected. The application of the JVF cut reduced the sensitivity of the measured jet multiplicity distribution to additional jets from pile-up.

### 5. Signal and Background Yields

The major background processes in the electron channel are QCD and leptonic backgrounds. The latter consist of W → τν where the tau decays to an electron, Z → ee where one electron is not identified and hadronic energy in the event is mismeasured, and semileptonic t\bar{t} decays (t \rightarrow bq\nu Q \bar{c}v). The QCD background in the electron channel has two components, one where a hadronic jet passes the electron selection and additional energy mis-
measurement in the event results in large $E_T^{\text{miss}}$, and the other where a bottom- or charm-hadron decays to an electron. For the muon channel, the main backgrounds arise from semileptonic heavy flavour decays in multijet events and from the leptonic background from the following sources: $W \to \tau\nu$ where the tau decays to a muon, $Z \to \mu\mu$ where one muon is not identified, and semileptonic $t\bar{t}$ decays in the muon channel. The contributions of single-top and diboson production to the measured cross section have been estimated to be slightly smaller than the $W \to \tau\nu$ background, and are not subtracted from the data.

The number of leptonic background events surviving the above selection cuts was estimated with simulated event samples: ALPGEN for vector boson samples (PYTHIA was used for $W \to \tau\nu + \text{jets}$) and POWHEG for $t\bar{t}$ background. The simulated leptonic background samples were normalised to the integrated luminosity of the data using the predicted NNLO or NLO+NNLL cross sections. The number of QCD background events was estimated by fitting, in each jet multiplicity bin, the $E_T^{\text{miss}}$ distribution in the data (without the $E_T^{\text{miss}}$ and $M_{T}$ cuts) to a sum of two templates: one for the QCD background and another which included signal and the leptonic backgrounds. In both muon and electron channels, the shapes for the second template were obtained from simulation. In the electron channel, the template for the QCD background was obtained from the data because the mechanisms by which a jet fakes an electron are difficult to simulate. This template was derived from a data sample where looser electron identification criteria were applied on the shower shapes and the track-cluster matching requirements were inverted. The QCD background was computed from the results of the template fit. In the electron channel, the fit was performed in the region $E_T^{\text{miss}} > 10$ GeV due to the poor understanding of the background below 10 GeV. The fit to the $E_T^{\text{miss}}$ distribution was used only to determine the QCD background normalisation, taking into account contributions from lepton background and signal in the low $E_T^{\text{miss}}$ region. The $W+\text{jet}$ signal yield for the cross section calculation was derived as the difference between the observed number of events in the signal region and the sum of background components. Figure 4 shows the $E_T^{\text{miss}}$ distribution for events with one jet, with the fitted contributions from all background sources in the electron and muon channels respectively, after all the other selection requirements (except for the $M_{T}$ cut) have been applied. The residual difference in $E_T^{\text{miss}}$ between the data and the QCD template in the control region is covered by the systematic uncertainties. The number of observed events and the estimated number of background events are summarised in Table 2.

The yield of signal events was corrected back to the particle level, taking into account detector and reconstruction efficiency. The dominant corrections in the electron channel come from electron reconstruction efficiency ($\approx 20\%$ correction). In the muon channel, the dominant corrections come from trigger and reconstruction efficiency (corrections of $\approx 10-20\%$ and $\approx 10\%$ respectively). The corrections were computed using the ALPGEN $W+\text{jets}$ event generator plus full detector simulation, restricting the events to the same phase space as the data analysis. The phase space requirements were applied to generated quantities. In this analysis, particle-level jets were constructed in simulated events by applying the jet finder to all final state particles (excluding muons and neutrinos) with a lifetime longer than 10 ps, whether produced directly in the $pp$ collision or from the decay of particles with shorter lifetimes. Correction factors were computed as one-dimensional functions of jet multiplicity and $p_T$ of the leading and next-to-leading jets, and were treated as independent. Migration of events across bins of jet multiplicity $M_{T}$ cuts) to a sum

The correction factor for the trigger efficiency was obtained directly from the data as follows. In the electron channel, events were triggered either by an independent $E_T^{\text{miss}}$ trigger or a loose electron trigger with an approximately 5 GeV threshold. The full $W+\text{jets}$ selection was carried out in essentially the same way as described above in order to isolate a pure electron sample. The main difference was in the QCD background estimation, which was done with templates for the shape of the electron isolation distribution, where the isolation variable was defined as the sum of transverse energy in a cone of $\Delta R = 0.4$ around the electron divided by the transverse energy of the electron. These templates were obtained by inverting one or more of the electron shower shape requirements. The electron trigger efficiency was found to be close to 100% in both data and simulation. In the muon channel, the trigger efficiency was computed with a sample of unbiased offline reconstructed muons from $Z \to \mu\mu$ decays. Average trigger efficiencies of $82.0 \pm 1.4\%$ and $86.9 \pm 0.1\%$ were obtained in data and simulation, respectively; the difference between data and simulation comes from a mismodelling of both the efficiency of the forward muon chambers and of the programming of the muon trigger electronics. The trigger efficiency (and its uncertainty) from the data was used for the correction factor.

6. Systematic Uncertainties

The primary sources of systematic uncertainty in the cross section for both electron and muon channels are uncertainties in the integrated luminosity and in the jet energy scale $\Delta R$. In the electron channel, the uncertainty due to the QCD background shape is also important. Both electron and muon channels are affected by uncertainties
Uncertainties in the jet energy scale (JES) and jet energy resolution (JER) were determined primarily from simulations \[31\]. The JES uncertainty varies as a function of \( p_T \) and \( \eta \), and ranges from around 10% at 20 GeV to about 8% at 100 GeV. The JER uncertainty is 14% of the jet energy resolution. To take into account the differences in calorimeter response to quark- and gluon-initiated jets, an additional uncertainty of 5% was added in quadrature in calorimeter response to quark- and gluon-initiated jets, which was obtained from the data. To correct for the systematic deviation of the JES due to nearby jets in the lepton channel, the jet energy scale (JES) uncertainty, based on the average difference in simulation of the calorimeter response between jets in the \( W + \text{jets} \) samples compared to those in the dijet samples (on which the JES calibration is based). Uncertainties in the JES due to nearby jets in \( W + \text{jets} \) events were also studied but found to be small. To estimate the impact of the JES uncertainty, jet energies in the simulated events were shifted by the JES uncertainty, and the \( E_T^{\text{miss}} \) vector was recomputed. In addition, calorimeter clusters not associated to a jet or electron, such as those coming from the underlying event, were scaled using a \( p_T \)-dependent uncertainty \[27\], ranging from \( \pm 20\% \) for \( p_T \approx 500 \text{ MeV} \) to \( \pm 5\% \) at high \( p_T \). Similarly the jet energies were smeared with a Gaussian representing the JER uncertainty and the \( E_T^{\text{miss}} \) vector was recomputed. The full analysis was repeated with these variations, and the cross sections were recomputed; the change in the cross section was taken as the systematic uncertainty. The impact of the JES and \( E_T^{\text{miss}} \) uncertainties on the cross section uncertainty was approximately 10%.

A significant source of uncertainty in the electron channel is the potential bias in the sample selection for building the template shape of the QCD background; with the current selection requirements, the contribution from semileptonic heavy flavour decays is underestimated. The size of the effect was determined with simulated events by comparing the background estimates from two templates: one based on the electron selection used for this cross section measurement and the other based on the selection used for the QCD background estimation in the electron channel. The resulting uncertainty on the QCD background estimate, including significant contributions from the limited statistics of the simulated event samples, was as high as 50%, but the effect on the cross section for the inclusive 1-jet bin was about 5%. The fit region for the QCD background was varied by \( \pm 5 \text{ GeV} \) to account for shape differences in the low \( E_T^{\text{miss}} \) region; the resulting uncertainty on the cross section was 1 – 2%.

The uncertainty in the electron identification efficiency was taken from the inclusive cross section measurement \[27\]. By examining the reconstruction efficiency in simulated events as a function of the \( \Delta R \) separation between the jet and the electron, the reconstruction efficiency was found to be consistent with the value in Ref. \[27\]. Furthermore, in the region \( \Delta R > 0.5 \), the efficiency was found to be constant as a function of \( \Delta R \) and as a function of jet multiplicity. The uncertainty in the muon reconstruction efficiency was estimated by comparing the efficiency measured with simulated events to that measured in the data with muons from \( Z \to \mu \mu \) decays, following a method similar to that described in Ref. \[27\]. The resulting uncer-


<table>
<thead>
<tr>
<th>Electron channel process</th>
<th>$N_{\text{jet}} \geq 0$</th>
<th>$N_{\text{jet}} \geq 1$</th>
<th>$N_{\text{jet}} \geq 2$</th>
<th>$N_{\text{jet}} \geq 3$</th>
<th>$N_{\text{jet}} \geq 4$</th>
</tr>
</thead>
<tbody>
<tr>
<td>QCD</td>
<td>130 $^{+20}_{-16}$</td>
<td>100 $^{+20}_{-40}$</td>
<td>45 $^{+7}_{-20}$</td>
<td>18 $^{+3}_{-8}$</td>
<td>-</td>
</tr>
<tr>
<td>$W \rightarrow \tau\nu$</td>
<td>113 $^{+11}_{-7}$</td>
<td>25 $^{+16}_{-5}$</td>
<td>4 $^{+2}_{-4}$</td>
<td>0.5 $^{+0.4}_{-0.6}$</td>
<td>-</td>
</tr>
<tr>
<td>$Z \rightarrow ee$</td>
<td>10 $^{+8}_{-7}$</td>
<td>7 $^{+6}_{-6}$</td>
<td>3 $^{+2}_{-2}$</td>
<td>1 $^{+1}_{-1}$</td>
<td>-</td>
</tr>
<tr>
<td>$t\bar{t}$</td>
<td>17 $^{+2}_{-1}$</td>
<td>17 $^{+2}_{-1}$</td>
<td>17 $^{+2}_{-1}$</td>
<td>14 $^{+2}_{-1}$</td>
<td>-</td>
</tr>
<tr>
<td>Observed in Data</td>
<td>4216</td>
<td>987</td>
<td>276</td>
<td>83</td>
<td>-</td>
</tr>
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</table>

<table>
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<tr>
<th>Muon channel process</th>
<th>$N_{\text{jet}} \geq 0$</th>
<th>$N_{\text{jet}} \geq 1$</th>
<th>$N_{\text{jet}} \geq 2$</th>
<th>$N_{\text{jet}} \geq 3$</th>
<th>$N_{\text{jet}} \geq 4$</th>
</tr>
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<tr>
<td>QCD</td>
<td>30 $^{+20}_{-14}$</td>
<td>20 $^{+13}_{-13}$</td>
<td>4 $^{+10}_{-4}$</td>
<td>2 $^{+2}_{-2}$</td>
<td>1 $^{+1}_{-1}$</td>
</tr>
<tr>
<td>$W \rightarrow \tau\nu$</td>
<td>133 $^{+12}_{-12}$</td>
<td>24 $^{+6}_{-6}$</td>
<td>5 $^{+2}_{-2}$</td>
<td>0.9 $^{+0.5}_{-0.5}$</td>
<td>0.4 $^{+0.3}_{-0.3}$</td>
</tr>
<tr>
<td>$Z \rightarrow \mu\mu$</td>
<td>170 $^{+14}_{-14}$</td>
<td>30 $^{+4}_{-4}$</td>
<td>8 $^{+1}_{-1}$</td>
<td>2 $^{+0.5}_{-0.5}$</td>
<td>0.6 $^{+0.2}_{-0.2}$</td>
</tr>
<tr>
<td>$t\bar{t}$</td>
<td>18 $^{+2}_{-2}$</td>
<td>18 $^{+2}_{-2}$</td>
<td>18 $^{+2}_{-2}$</td>
<td>16 $^{+2}_{-2}$</td>
<td>11 $^{+1}_{-1}$</td>
</tr>
<tr>
<td>Observed in Data</td>
<td>4911</td>
<td>1049</td>
<td>292</td>
<td>95</td>
<td>36</td>
</tr>
</tbody>
</table>

Table 2: Summary of background yields and observed number of events for the electron and muon channels with systematic uncertainties, excluding the luminosity uncertainty. Statistical uncertainties are negligible compared to systematic uncertainties. The uncertainty in the backgrounds due to the luminosity uncertainty is 11% for all backgrounds except for the QCD background, since it was normalised to the data. The measurement was not performed in the inclusive 4-jet bin in the electron channel because of the poor signal-to-background ratio.

tainties in the cross section were approximately 5.5% in both electron and muon channels.

Other uncertainties which were considered include the trigger efficiency, jet reconstruction efficiency, lepton momentum scale and resolution, pile-up, and biases in the procedure for correcting for detector effects (for example, by comparing correction factors obtained with ALPGEN to those obtained with SHERPA). Their effect on the cross section was found to be smaller than the uncertainties described above. For example, the uncertainty on the electron energy resolution was based on extrapolations from test-beam measurements [27] and had a < 0.1% effect on the cross section. All of the above systematic uncertainties (except for the bias in the template shape for the QCD background in the electron channel) were also applied to the estimates of the QCD and leptonic backgrounds in both electron and muon channels. In addition, for the leptonic backgrounds the uncertainty in the NNLO cross sections was taken to be 5% for $W/Z$ production as in Ref. [27]. The $t\bar{t}$ cross section uncertainty was taken to be approximately 7%, amounting to the sum in quadrature of PDF uncertainties (3%) and uncertainties estimated by varying renormalisation and factorisation scales (6%) [33, 34].

The systematic uncertainties in the cross section measurement are summarised in Table 3 for $N_{\text{jet}} \geq 1$; most of the uncertainties are approximately independent of jet multiplicity, except for the uncertainty due to the jet energy scale and resolution, and the QCD background in the electron channel. The dominant systematic uncertainties are shown as a function of jet multiplicity and leading jet $p_T$ in Figure 2. Both distributions are similar for electron and muon channels; the uncertainty is therefore shown as a function of jet multiplicity for the electron channel and as a function of leading jet $p_T$ for the muon channel. The main contribution to the other uncertainties in the electron channel comes from the QCD background (especially at high jet multiplicities), the electron identification efficiency and the electron energy scale. For the muon channel, the main contribution is from the muon reconstruction efficiency.

In the cross section ratio measurement, the uncertainty due to the jet energy scale uncertainty remains the dominant effect, amounting to approximately 10% on the ratio. The luminosity uncertainty does not completely cancel in the ratio because the background estimates are affected by the luminosity uncertainty and the background levels vary as a function of jet multiplicity.

### 7. Results and Conclusions

The measured $W$+jets cross section (multiplied by the leptonic branching ratio) and the cross section ratios are shown as a function of corrected jet multiplicity in Tables 4 and 5 respectively, as well as in Figures 3 and 4. The measurement was not performed in the inclusive 4-jet bin in the electron channel because of the poor signal-to-background ratio. The cross sections are quoted in the limited kinematic region: $E_T^\ell > 20$ GeV, $|\eta^\ell| < 2.8$, $E_T^j > 20$ GeV, $|\eta^j| < 2.47$ (excluding 1.37 < $|\eta^j|$ < 1.52), $|\eta^{\nu}| < 2.4$, $p_T^{\nu} > 25$ GeV, $M_T > 40$ GeV, $\Delta R_{l\ell} > 0.5$, where $l$, $\ell$, $j$ and $\nu$ denote lepton, jet and neutrino, respectively. The quantities $p_T^{\ell}$, $|\eta^j|$, and $M_T$ include the energy of all radiated photons within $\Delta R = 0.1$ around the lepton. The $W$+jets
The systematic uncertainty in the MCFM cross section (times leptonic branching ratio) is shown as a function of the $p_T$ of the leading and next-to-leading jets in the event in Figure 5; the leading jet is shown for $N_{\text{jet}} \geq 1$ and the next-to-leading jet is shown for $N_{\text{jet}} \geq 2$.

Also shown in Figures 3, 4, and 5 are particle-level expectations from PYTHIA, ALPGEN and SHERPA simulations as well as a calculation using MCFM v5.8 [35]. PYTHIA is LO, while ALPGEN and SHERPA match higher-order predictions due to fragmentation was estimated by comparing the AMBT1 [19] event generator tune with the tune from JIMMY [10] as well as by varying the AMBT1 tune to increase the underlying event activity by approximately 10%. Renormalisation and factorisation scale uncertainties were estimated by varying the scales, in all combinations, up and down, by factors of two. PDF uncertainties were computed by summing in quadrature the dependence on each of the 22 eigenvectors characterising the CTEQ6.6 PDF set; the uncertainty in

### Table 3: Summary of the systematic uncertainties in the cross section.

<table>
<thead>
<tr>
<th>Effect</th>
<th>Range</th>
<th>Cross Section Uncertainty (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jet energy scale and $E_T^{\text{miss}}$</td>
<td>±10% (dependent on jet $\eta$ and $p_T$) $\oplus$ 5%</td>
<td>+11, -9</td>
</tr>
<tr>
<td>Jet energy resolution</td>
<td>14% on each jet</td>
<td>±1.0</td>
</tr>
<tr>
<td>Electron trigger</td>
<td>±0.5%</td>
<td>±0.7</td>
</tr>
<tr>
<td>Electron identification</td>
<td>±5.2%</td>
<td>±5.5</td>
</tr>
<tr>
<td>Electron energy scale</td>
<td>±3%</td>
<td>+3.9, -4.7</td>
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<tr>
<td>Pile-up removal cut</td>
<td>$4 - 7%$ in lowest $p_T$ bin</td>
<td>±1.9</td>
</tr>
<tr>
<td>Residual pile-up effects</td>
<td>from simulation</td>
<td>±2.2</td>
</tr>
<tr>
<td>QCD background shape</td>
<td>from template variation</td>
<td>-1.5, +5.2</td>
</tr>
<tr>
<td>Luminosity</td>
<td>±11%</td>
<td>-10, +13</td>
</tr>
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</table>

<table>
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<tr>
<th>Effect</th>
<th>Range</th>
<th>Cross Section Uncertainty (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jet energy scale and $E_T^{\text{miss}}$</td>
<td>±10% (dependent on jet $\eta$ and $p_T$) $\oplus$ 5%</td>
<td>+11, -9</td>
</tr>
<tr>
<td>Jet energy resolution</td>
<td>14% on each jet</td>
<td>±1.8</td>
</tr>
<tr>
<td>Muon trigger</td>
<td>±2.5% in barrel, ±2.0% in endcap</td>
<td>±1.6</td>
</tr>
<tr>
<td>Muon reconstruction</td>
<td>±5.6%</td>
<td>-5.4, +5.9</td>
</tr>
<tr>
<td>Muon momentum scale</td>
<td>±1%</td>
<td>+2, -0.9</td>
</tr>
<tr>
<td>Muon momentum resolution</td>
<td>±5% in barrel, ±9% in endcap</td>
<td>±1.4</td>
</tr>
<tr>
<td>Pile-up removal cut</td>
<td>$4 - 7%$ in lowest $p_T$ bin</td>
<td>±1.7</td>
</tr>
<tr>
<td>Residual pile-up effects</td>
<td>from simulation</td>
<td>±1.4</td>
</tr>
<tr>
<td>Luminosity</td>
<td>±11%</td>
<td>-11, +13</td>
</tr>
</tbody>
</table>

The MCFM results were obtained with the same jet algorithm and same kinematic selection requirements as applied to the data. 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 and of the lepton and neutrino from the $W$ decay. The PDFs were CTEQ6L1 [11] and CTEQ6.6M [15] for the LO and NLO calculations, respectively. Corrections for hadronisation and underlying event were computed with PYTHIA as a function of leading and next-to-leading jet $p_T$. Hadronisation and underlying event corrections ranged from $-10\%$ to $-4\%$ and $+10\%$ to $+4\%$, respectively, for jet $p_T \approx 20$ GeV to jet $p_T > 80$ GeV. The partial cancellation of hadronisation and underlying event corrections results in an overall correction of approximately 4%. The effect of final state QED radiation from the electron or muon was computed with PYTHIA and ALPGEN (both using PHOTOS) and with SHERPA, comparing the acceptance before radiation with the acceptance after radiation, but summing up the photons within $\Delta R = 0.1$ around the lepton. This factor ($\approx 1 - 2\%$) was applied as a correction to the MCFM prediction.

The systematic uncertainty in the MCFM cross sections due to fragmentation was estimated by comparing PYTHIA with HERWIG. Underlying event uncertainties were estimated by comparing the AMBT1 [19] event generator tune with the tune from JIMMY [10] as well as by varying the AMBT1 tune to increase the underlying event activity by approximately 10%. Renormalisation and factorisation scale uncertainties were estimated by varying the scales, in all combinations, up and down, by factors of two. PDF uncertainties were computed by summing in quadrature the dependence on each of the 22 eigenvectors characterising the CTEQ6.6 PDF set; the uncertainty in
Figure 2: Summary of the systematic uncertainties on the cross section measurement shown as a function of jet multiplicity in the electron channel (left) and leading-jet $p_T$ in the muon channel (right). The jet energy scale uncertainty includes the uncertainty on $E^{miss}_T$. The main contribution to the "sum of other uncertainties" in the electron channel comes from the QCD background (especially at high jet multiplicities), the electron identification efficiency and the electron energy scale. For the muon channel, the main contribution is from the muon reconstruction efficiency.

Figure 3: $W$+jets cross-section results as a function of corrected jet multiplicity. Left: electron channel. Right: muon channel. The cross sections are quoted in a limited and well-defined kinematic region, described in the text. For the data, the statistical uncertainties are shown by the vertical bars, and the combined statistical and systematic uncertainties are shown by the hashed regions. Note that the uncertainties are correlated from bin to bin. Also shown are predictions from PYTHIA, ALPGEN, SHERPA and MCFM, and the ratio of theoretical predictions to data (PYTHIA is not shown in the ratio). The theoretical uncertainties are shown only for MCFM, which provides NLO predictions for $N_{jet} \leq 2$ and a LO prediction for $N_{jet} = 3$. 
and are quoted in a limited and well-defined range of jet multiplicities with (in order) statistical, systematic, and luminosity uncertainties. The cross sections are quoted in a limited and well-defined kinematic region, described in the text. The measurement was not performed in the inclusive 4-jet bin in the electron channel because of the poor signal-to-background ratio. Theoretical predictions from MCFM are also shown, with all uncertainties combined. MCFM provides NLO predictions for $N_{\text{jet}} \leq 2$ and a LO prediction for $N_{\text{jet}} = 3$.

Table 4: The measured cross section times leptonic branching ratio for $W$+jets in the electron and muon channels as a function of corrected jet multiplicity with (in order) statistical, systematic, and luminosity uncertainties. The cross sections are quoted in a limited and well-defined kinematic region, described in the text. The measurement was not performed in the inclusive 4-jet bin in the electron channel because of the poor signal-to-background ratio. Theoretical predictions from MCFM are also shown, with all uncertainties combined. MCFM provides NLO predictions for $N_{\text{jet}} \leq 2$ and a LO prediction for $N_{\text{jet}} = 3$.

<table>
<thead>
<tr>
<th>Jet multiplicity</th>
<th>$W \rightarrow e\nu$ (nb)</th>
<th>MCFM $W \rightarrow e\nu$ (nb)</th>
<th>$W \rightarrow \mu\nu$ (nb)</th>
<th>MCFM $W \rightarrow \mu\nu$ (nb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\geq 0$</td>
<td>$4.53 \pm 0.07^{+0.35 +0.58}_{-0.30 -0.47}$</td>
<td>$5.08^{+0.11}_{-0.30}$</td>
<td>$4.58 \pm 0.07^{+0.38 +0.61}_{-0.32 -0.48}$</td>
<td>$5.27^{+0.11}_{-0.32}$</td>
</tr>
<tr>
<td>$\geq 1$</td>
<td>$0.84 \pm 0.03^{+0.13 +0.11}_{-0.10 -0.09}$</td>
<td>$0.81^{+0.02}_{-0.04}$</td>
<td>$0.84 \pm 0.03^{+0.11 +0.11}_{-0.09 -0.09}$</td>
<td>$0.84^{+0.02}_{-0.04}$</td>
</tr>
<tr>
<td>$\geq 2$</td>
<td>$0.21 \pm 0.01^{+0.04 +0.03}_{-0.03 -0.02}$</td>
<td>$0.21^{+0.01}_{-0.02}$</td>
<td>$0.23 \pm 0.02^{+0.04 +0.03}_{-0.03 -0.02}$</td>
<td>$0.21^{+0.01}_{-0.02}$</td>
</tr>
<tr>
<td>$\geq 3$</td>
<td>$0.047 \pm 0.007^{+0.014 +0.008}_{-0.011 -0.006}$</td>
<td>$0.05 \pm 0.02$</td>
<td>$0.064 \pm 0.008^{+0.016 +0.010}_{-0.014 -0.008}$</td>
<td>$0.05 \pm 0.02$</td>
</tr>
<tr>
<td>$\geq 4$</td>
<td>-</td>
<td>-</td>
<td>$0.019 \pm 0.005 \pm 0.006^{+0.004}_{-0.003}$</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 5: The measured cross section ratio for $W$+jets in the electron and muon channels as a function of corrected jet multiplicity with (in order) statistical and systematic uncertainties. The cross section ratios are quoted in a limited and well-defined kinematic region, described in the text. The measurement was not performed in the inclusive 4-jet bin in the electron channel because of the poor signal-to-background ratio. Theoretical predictions from MCFM are also shown, with all uncertainties combined. MCFM provides NLO predictions for $N_{\text{jet}} \leq 2$ and a LO prediction for $N_{\text{jet}} = 3$.

<table>
<thead>
<tr>
<th>Jet multiplicity</th>
<th>$W \rightarrow e\nu$</th>
<th>MCFM $W \rightarrow e\nu$</th>
<th>$W \rightarrow \mu\nu$</th>
<th>MCFM $W \rightarrow \mu\nu$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\geq 1/ \geq 0$</td>
<td>$0.185 \pm 0.007^{+0.025}_{-0.019}$</td>
<td>$0.159^{+0.006}_{-0.005}$</td>
<td>$0.183 \pm 0.007^{+0.023}_{-0.020}$</td>
<td>$0.160^{+0.006}_{-0.005}$</td>
</tr>
<tr>
<td>$\geq 2/ \geq 1$</td>
<td>$0.250 \pm 0.019^{+0.019}_{-0.010}$</td>
<td>$0.255^{+0.017}_{-0.022}$</td>
<td>$0.274 \pm 0.020^{+0.018}_{-0.011}$</td>
<td>$0.255^{+0.017}_{-0.021}$</td>
</tr>
<tr>
<td>$\geq 3/ \geq 2$</td>
<td>$0.224 \pm 0.037 \pm 0.022$</td>
<td>$0.241^{+0.108}_{-0.061}$</td>
<td>$0.278 \pm 0.041^{+0.024}_{-0.020}$</td>
<td>$0.242^{+0.104}_{-0.061}$</td>
</tr>
<tr>
<td>$\geq 4/ \geq 3$</td>
<td>-</td>
<td>-</td>
<td>$0.297 \pm 0.088^{+0.037}_{-0.026}$</td>
<td>-</td>
</tr>
</tbody>
</table>

$\alpha_s$ was also taken into account. An alternative PDF set, MSTW2008 [13], with its set of 68% C.L. eigenvectors was also examined, and the envelope of the uncertainties from CTEQ6.6 and MSTW2008 was taken as the final PDF uncertainty. The total resulting uncertainties are given in Tables 4 and 5.

In conclusion, this Letter presents a measurement of the $W$+jets cross section as a function of jet multiplicity in $pp$ collisions at $\sqrt{s} = 7$ TeV in both electron and muon decay modes of the $W$ boson, based on an integrated luminosity of 1.3 pb$^{-1}$ recorded with the ATLAS detector. Measurements are also presented of the ratio of cross sections $\sigma(W+ \geq n)/\sigma(W+ \geq n - 1)$ for inclusive jet multiplicities $n = 1 - 4$, and of the $p_T$ distribution of the leading and next-to-leading jets in the event. The results have been corrected for all known detector effects and are quoted in a limited and well-defined range of jet and lepton kinematics. This range is fully covered by the detector acceptance, so as to avoid model-dependent extrapolations and to facilitate comparisons with theoretical predictions. As expected, the PYTHIA samples considered, which contain a $2 \rightarrow 1$ matrix element merged with a $2 \rightarrow 2$ matrix element and a leading-logarithmic parton shower, does not provide a good description of the data for jet multiplicities greater than one. Good agreement is observed with the predictions of the multi-parton matrix element generators ALPGEN and SHERPA. Calculations based on $O(\alpha_s^2)$ matrix elements in MCFM (available for jet multiplicities $n \leq 2$) are also in good agreement with the data.

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References

Figure 5: W+jets cross-section as a function of the $p_T$ of the two leading jets in the event. The $p_T$ of the leading jet is shown for events with $\geq 1$ jet while the $p_T$ of the next-to-leading jet is shown for events with $\geq 2$ jets. Left: electron channel. Right: muon channel. The cross sections are quoted in a limited and well-defined kinematic region, described in the text. For the data, the statistical uncertainties are shown by the vertical bars, and the combined statistical and systematic uncertainties are shown by the hashed regions. Also shown are theoretical predictions from PYTHIA, ALPGEN, SHERPA and MCFM, and the ratio of theoretical predictions to data (PYTHIA is not shown in the ratio). The theoretical uncertainties are shown only for MCFM, which provides NLO predictions for $N_{\text{jet}} \leq 2$ and a LO prediction for $N_{\text{jet}} = 3$. 

\[ W+\nu_e \rightarrow W+\text{ jets} \quad \text{Data 2010, } \sqrt{s} = 7 \text{ TeV} \]

ATLAS
The ATLAS Collaboration

G. Aad\textsuperscript{18}, B. Abbott\textsuperscript{111}, J. Abbal\textsuperscript{11},
A.A. Abdelalim\textsuperscript{49}, A. Abdesselam\textsuperscript{118}, O. Abdinov\textsuperscript{10},
B. Abi\textsuperscript{112}, M. Abolins\textsuperscript{88}, H. Abramowicz\textsuperscript{153}, H. Abreu\textsuperscript{115},
E. Aceti\textsuperscript{98a,98b}, B.S. Achariya\textsuperscript{16a,16b,16}, M. Ackers\textsuperscript{99},
D.L. Adams\textsuperscript{24}, T.N. Addy\textsuperscript{1}, J. Adelman\textsuperscript{175},
M. Aderholz\textsuperscript{39}, S. Adomeit\textsuperscript{98}, P. Adragna\textsuperscript{75}, T. Adye\textsuperscript{129},
A. Aeshy\textsuperscript{22}, J.A. Aguilar-Saavedra\textsuperscript{124a,88},
M. Aharnouche\textsuperscript{84}, S.P. Ahlen\textsuperscript{41}, A. Ahmed\textsuperscript{148},
M. Ahsan\textsuperscript{40}, G. Aielli\textsuperscript{133a,133b}, T. Akgd\textsuperscript{18a},
T.P.A. Akesson\textsuperscript{99}, G. Akimoto\textsuperscript{155,49}, A.V. Akimov\textsuperscript{94},
M.S. Alam\textsuperscript{41}, M.A. Alam\textsuperscript{76}, S. Albran\textsuperscript{96}, A. Aleksa\textsuperscript{29},
I.N. Aleksandrov\textsuperscript{65}, M. Aleppo\textsuperscript{80a,80b,97}, F. Alessandrini\textsuperscript{89a},
C. Alexe\textsuperscript{25a}, G. Alexander\textsuperscript{153}, G. Andreat\textsuperscript{49},
T. Alexopoulos\textsuperscript{60}, M. Alhroob\textsuperscript{20}, M. Aliev\textsuperscript{15},
G. Alimonti\textsuperscript{89a}, J. Alison\textsuperscript{120}, M. Aliyev\textsuperscript{10}, P.P. Allport\textsuperscript{73},
S.E. Allwood-Spiers\textsuperscript{53}, J. Almond\textsuperscript{82,102b},
A. Alonso\textsuperscript{124a,124b}, A. Alou\textsuperscript{76}, J. Alonso\textsuperscript{14},
M.G. Alvigg\textsuperscript{102a,102b}, K. Amako\textsuperscript{66}, P. Amara\textsuperscript{29},
C. Amelung\textsuperscript{14}, V.V. Ammosov\textsuperscript{128}, A. Amorim\textsuperscript{124a,6},
G. Amorós\textsuperscript{167}, N. Amram\textsuperscript{153}, C. Anastopoulos\textsuperscript{139},
T. Andeen\textsuperscript{14}, C.F. Anders\textsuperscript{90}, K.J. Anderson\textsuperscript{90},
A. Andreazza\textsuperscript{89a,89b}, V. Andrei\textsuperscript{89a,89b}, M.-L. Andreux\textsuperscript{55},
X.S. Anduaga\textsuperscript{70}, A. Angerani\textsuperscript{34}, F. Anghinolfi\textsuperscript{29},
N. Anjos\textsuperscript{124a}, A. Anmovi\textsuperscript{47}, A. Antonaki\textsuperscript{8},
S. Antonelli\textsuperscript{164a,164b}, J. Antos\textsuperscript{76}, F. Anul\textsuperscript{14},
S. Aoun\textsuperscript{43}, L. Aperio Bella\textsuperscript{4}, R. Apoll\textsuperscript{118}, G. Arabidze\textsuperscript{68},
I. Aracena\textsuperscript{143}, Y. Aral\textsuperscript{46}, A.T.H. Arce\textsuperscript{44},
J.P. Archambault\textsuperscript{89a}, S. Arrufio\textsuperscript{155,155}, J.-F. Arguin\textsuperscript{141},
E. Arik\textsuperscript{98a,*}, M. Arik\textsuperscript{89a,18a}, A.J. Armbruster\textsuperscript{81},
K.E. Arms\textsuperscript{109}, S.R. Armstrong\textsuperscript{9}, O. Arnaez\textsuperscript{8},
C. Arnauld\textsuperscript{115}, A. Artonam\textsuperscript{95}, G. Artoni\textsuperscript{132a,132b},
D. Arutinov\textsuperscript{20}, S. Asai\textsuperscript{155}, R. Asfandiyarv\textsuperscript{172}, S. Ask\textsuperscript{27},
B. Asman\textsuperscript{146a,146b}, L. Asquith\textsuperscript{9}, K. Assamagan\textsuperscript{74},
A. Astbury\textsuperscript{169}, A. Astvatsatov\textsuperscript{128}, G. Ation\textsuperscript{25},
B. Aubert\textsuperscript{4}, B. Auerbach\textsuperscript{175}, E. Auge\textsuperscript{115}, K. Augsten\textsuperscript{127},
M. Aurousseau\textsuperscript{4}, N. Austin\textsuperscript{73}, R. Avramidou\textsuperscript{91},
D. Axen\textsuperscript{168}, C. Ay\textsuperscript{94}, G. Azuelos\textsuperscript{93,d}, Y. Azuma\textsuperscript{155},
M.A. Baak\textsuperscript{99}, G. Baccagli\textsuperscript{89a}, C. Bacci\textsuperscript{133a,134b},
A.M. Bach\textsuperscript{14}, H. Bach\textsuperscript{136}, K. Bach\textsuperscript{29}, G. Bach\textsuperscript{29},
M. Backes\textsuperscript{9}, E. Bades\textsuperscript{25a}, P. Bagna\textsuperscript{132a,132b},
S. Bahinipati\textsuperscript{2}, Y. Bai\textsuperscript{12a,20}, D.C. Bailey\textsuperscript{158}, T. Bain\textsuperscript{158},
J.T. Baines\textsuperscript{120}, O.K. Baker\textsuperscript{175}, S. Baker\textsuperscript{77},
F. Baltasar Dos Santos Pedro\textsuperscript{29}, E. Banas\textsuperscript{98},
P. Banerjee\textsuperscript{93}, Sw. Banerjee\textsuperscript{169}, D. Banf\textsuperscript{89a,89c},
A. Bangert\textsuperscript{137}, V. Bansal\textsuperscript{119}, H.S. Bansli\textsuperscript{17}, L. Barak\textsuperscript{75},
S.P. Baranov\textsuperscript{94}, A. Barashkoi\textsuperscript{64}, A. Barbaro Galtieri\textsuperscript{14},
T. Barber\textsuperscript{27}, E.L. Barberio\textsuperscript{96}, D. Barberis\textsuperscript{90a,50b},
M. Barbero\textsuperscript{19}, D.Y. Bardin\textsuperscript{65}, T. Barillas\textsuperscript{99},
M. Barisonzi\textsuperscript{174}, T. Barklow\textsuperscript{143}, N. Barlow\textsuperscript{27},
B.M. Barnett\textsuperscript{129}, R.M. Barnett\textsuperscript{144}, A. Barocelli\textsuperscript{134a},
A.J. Bar\textsuperscript{118}, F. Barich\textsuperscript{80}, J. Barreiro Guimarães da Costa\textsuperscript{57}, P. Barrillon\textsuperscript{115}, R. Bartoldus\textsuperscript{143}, A.E. Barton\textsuperscript{71},
D. Bartsch\textsuperscript{20}, R.L. Bates\textsuperscript{53}, L. Batkova\textsuperscript{44a},
J.R. Batley\textsuperscript{27}, A. Battaglia\textsuperscript{16}, M. Battistin\textsuperscript{29},
G. Battistoni\textsuperscript{89a}, F. Bauer\textsuperscript{136}, H.S. Bawa\textsuperscript{143}, B. Bear\textsuperscript{158},
}
Physics, Box 19059, Arlington, TX 76019, United States of America
8 University of Athens, Nuclear & Particle Physics, Department of Physics, Panepistimiopolis, Zografiou, GR 15771 Athens, Greece
9 National Technical University of Athens, Physics Department, 9-Iroon Polytechni, GR 15780 Zografiou, Greece
10 Institute of Physics, Azerbijan Academy of Sciences, H. Javid Avenue 33, AZ 143 Baku, Azerbaijan
11 Institut de Fisica d’Altes Energies, IFAE, Edifici Cu, Universitat Autonoma de Barcelona, ES - 08193 Bellaterra (Barcelona), Spain
12 University of Belgrade(8), Institute of Physics, P.O. Box 57, 11001 Belgrade; Vinca Institute of Nuclear Sciences(6), M. Petrovic Alasa 12-14, 11000 Belgrade, Serbia, Serbia
13 University of Bergen, Department for Physics and Technology, Allegaten 55, NO - 5007 Bergen, Norway
14 Lawrence Berkeley National Laboratory and University of California, Physics Division, MS05B-6227, 1 Cyclops Road, Berkeley, CA 94720, United States of America
15 Humboldt University, Institute of Physics, Berlin, Newtonstr. 15, D-12489 Berlin, Germany
16 University of Bern, Albert Einstein Center for Fundamental Physics, Laboratory for High Energy Physics, Sidlerstrasse 5, CH - 3012 Bern, Switzerland
17 University of Birmingham, School of Physics and Astronomy, Edgbaston, Birmingham B15 2TT, United Kingdom
18 Bogazici University(a), Faculty of Sciences, Department of Physics, TR - 80815 Bebek-Istanbul; Dagus University(b), Faculty of Arts and Sciences, Department of Physics, 34722, Kadikoy, Istanbul;
(c)Gaziantep University, Faculty of Engineering, Department of Physics Engineering, 27310, Sehitkamil, Gaziantep, Turkey; Istanbul Technical University(d), Faculty of Arts and Sciences, Department of Physics, 34469, Maslak, Istanbul, Turkey
19 INFN Sezione di Bologna(a); Università di Bologna, Dipartimento di Fisica(b), viale C. Berti Pichat, 6/2, IT - 40127 Bologna, Italy
20 University of Bonn, Physikalisches Institut, Nussallee 12, D - 53115 Bonn, Germany
21 Boston University, Department of Physics, 590 Commonwealth Avenue, Boston, MA 02215, United States of America
22 Brandeis University, Department of Physics, MS057, 415 South Street, Waltham, MA 02454, United States of America
23 Universidade Federal do Rio De Janeiro, COPPE/EE/IF (c), Caixa Postal 68528, Ilha do Fundao, BR - 21945-970 Rio de Janeiro; (d)Universidade de Sao Paulo, Instituto de Fisica, R.do Matao Trav. R.187, Sao Paulo - SP, 05508 - 900, Brazil
24 Brookhaven National Laboratory, Physics Department, Bldg. 510A, Upton, NY 11973, United States of America
25 National Institute of Physics and Nuclear Engineering(a)Bucharest-Magurele, Str. Atomistilor 407, P.O. Box MG-6, R-077125, Romania; University Politehnica Bucharest(b), Rectorat - AN 001, 313 Splaiul Independentei, sector 6, 060042 Bucuresti; West University(c) in Timisoara, Bd. Vasile Parvan 4, Timisoara, Romania
26 Universidad de Buenos Aires, FCEyN, Dto. Fisica, Pab I - C. Universitaria, 1428 Buenos Aires, Argentina
27 University of Cambridge, Cavendish Laboratory, J J Thomson Avenue, Cambridge CB3 0HE, United Kingdom
28 Carleton University, Department of Physics, 1125 Colonel By Drive, Ottawa ON K1S 5B6, Canada
29 CERN, CH - 1211 Geneva 23, Switzerland
30 University of Chicago, Enrico Fermi Institute, 5640 S. Ellis Avenue, Chicago, IL 60637, United States of America
31 Pontificia Universidad Catolica de Chile, Facultad de Fisica, Departamento de Fisica(c), Avda. Vicuna Mackenna 4860, San Joaquìn, Santiago; Universidad Tecnica Federico Santa Maria, Departamento de Fisica(b), Avda. España 1680, Casilla 110-V, Valparaiso, Chile
32 Institute of High Energy Physics, Chinese Academy of Sciences(a), P.O. Box 918, 19 Yuquan Road, Shijing Shan District, CN - Beijing 100049; University of Science & Technology of China (USTC), Department of Modern Physics(c), Hefei, CN - Anhui 230026; Nanjing University, Department of Physics(c), Nanjing, CN - Jiangsu 210093; Shandong University, High Energy Physics Group(d), Jinan, CN - Shandong 250100, China
33 Laboratoire de Physique Corpusculaire, Clermont Universitè, Université Blaise Pascal, CNRS/IN2P3, FR - 63177 Aubiere Cedex, France
34 Columbia University, Nevis Laboratory, 136 So. Broadway, Irvington, NY 10533, United States of America
35 University of Copenhagen, Niels Bohr Institute, Blegdamsvej 17, DK - 2100 Kobenhavn 0, Denmark
36 INFN Gruppo Collegato di Cosenza(a); Università della Calabria, Dipartimento di Fisica(b), IT-87036 Arcavacata di Rende, Italy
37 Faculty of Physics and Applied Computer Science of the AGH-University of Science and Technology, (FPACS, AGH-UST), al. Mickiewicza 30, PL-30059 Cracow, Poland
38 The Henryk Niewodniczanski Institute of Nuclear Physics, Polish Academy of Sciences, ul. Radzikowskiego 152, PL - 31342 Krakow, Poland
39 Southern Methodist University, Physics Department, 106 Fondren Science Building, Dallas, TX 75275-0175, United States of America
40 University of Texas at Dallas, 800 West Campbell Road, Richardson, TX 75080-3021, United States of America
41 DESY, Notkestr. 85, D-22603 Hamburg and Platanallee 6, D-15738 Zeuthen, Germany
Costiera 11, IT-34014, Trieste; Università di Udine, Dipartimento di Fisica\(^{(o)}\), via delle Scienze 208, IT - 33100 Udine, Italy

University of Illinois, Department of Physics, 1110 West Green Street, Urbana, Illinois 61801, United States of America

University of Uppsala, Department of Physics and Astronomy, P.O. Box 516; SE -751 20 Uppsala, Sweden

Instituto de Física Corpuscular (IFIC) Centro Mixto UVEG-CSIC, Apdo. 22085 ES-46071 Valencia, Dept. Física At. Mol. y Nuclear; Dept. Ing. Electrónica; Univ. de Valencia, and Inst. de Microelec\(\)tronica de Barcelona (IMB-CNMCSCIC) 08193 Bellaterra, Spain

University of British Columbia, Department of Physics, 6224 Agricultural Road, CA - Vancouver, B.C. V6T 1Z1, Canada

University of Victoria, Department of Physics and Astronomy, P.O. Box 3055, Victoria B.C., V8W 3P6, Canada

Waseda University, WISE, 3-4-1 Okubo, Shinjuku-ku, Tokyo, 169-8555, Japan

The Weizmann Institute of Science, Department of Particle Physics, P.O. Box 26, IL - 76100 Rehovot, Israel

University of Wisconsin, Department of Physics, 1150 University Avenue, WI 53706 Madison, Wisconsin, United States of America

Julius-Maximilians-University of Würzburg, Physikalisches Institute, Am Hubland, 97074 Würzburg, Germany

Bergische Universität, Fachbereich C, Physik, Postfach 100127, Gauss-Strasse 20, D- 42097 Wuppertal, Germany

Yerevan Physics Institute, Alikhanian Brothers Street 2, AM - 375036 Yerevan, Armenia

Centre de Calcul CNRS/IN2P3, Domaine scientifique de la Doua, 27 bd du 11 Novembre 1918, 69622 Villeurbanne Cedex, France

Also at LIP, Portugal

Also at Faculdade de Ciencias, Universidade de Lisboa, Portugal

Also at CPPM, Marseille, France.

Also at TRIUMF, Vancouver, Canada

Also at FPACS, AGH-UST, Cracow, Poland

Now at Universita’ dell’Insubria, Dipartimento di Fisica e Matematica

Also at Department of Physics, University of Coimbra, Portugal

Also at CPPM, Marseille, France

Also at TRIUMF, Vancouver, Canada

Also at FPACS, AGH-UST, Cracow, Poland

Now at Universita’ dell’Insubria, Dipartimento di Fisica e Matematica

Also at Department of Physics, University of Coimbra, Portugal

Also at CERN

Also at Università di Napoli Parthenope, Napoli, Italy

Also at Institute of Particle Physics (IPP), Canada

Also at Università di Napoli Parthenope, via A. Acton 38, IT - 80133 Napoli, Italy

Louisiana Tech University, 305 Wisteria Street, P.O. Box 3178, Ruston, LA 71272, United States of America

Also at Universidade de Lisboa, Portugal

At California State University, Fresno, USA

Also at TRIUMF, 4004 Wesbrook Mall, Vancouver, B.C. V6T 2A3, Canada

Also at Faculdade de Ciencias, Universidade de Lisboa, Portugal and at Centro de Física Nuclear da Universidade de Lisboa, Portugal

Also at FPACS, AGH-UST, Cracow, Poland

Also at California Institute of Technology, Pasadena, USA

Louisiana Tech University, Ruston, USA

Also at University of Montreal, Montreal, Canada

Now at Chonnam National University, Chonnam, Korea 500-757

Also at Institut für Experimentalphysik, Universität Hamburg, Luruper Chaussee 149, 22761 Hamburg, Germany

Also at Manhattan College, NY, USA

Also at School of Physics and Engineering, Sun Yat-sen University, China

Also at Taiwan Tier-1, ASGC, Academia Sinica, Taipei, Taiwan

Also at School of Physics, Shandong University, Jinan, China

Also at California Institute of Technology, Pasadena, USA

Also at Rutherford Appleton Laboratory, Didcot, UK

Also at school of physics, Shandong University, Jinan

Also at Rutherford Appleton Laboratory, Didcot, UK

Also at TRIUMF, Vancouver, Canada

Now at KEK

Also at Departamento de Física, Universidade de Minho, Portugal

University of South Carolina, Columbia, USA

Also at KFKI Research Institute for Particle and Nuclear Physics, Budapest, Hungary

University of South Carolina, Dept. of Physics and Astronomy, 700 S. Main St, Columbia, SC 29208, United States of America

Also at Institute of Physics, Jagiellonian University, Cracow, Poland

Louisiana Tech University, Ruston, USA

Also at Centro de Física Nuclear da Universidade de Lisboa, Portugal

Also at Institut für Experimentalphysik, Universität Hamburg, Hamburg, Germany

University of South Carolina, Columbia, USA

Transfer to LHCb 31.01.2010

Also at Oxford University, Department of Physics, Denys Wilkinson Building, Keble Road, Oxford OX1 3RH, United Kingdom

Also at school of physics and engineering, Sun Yat-sen University, China

Determine the Muon T0s using 2009 and 2010 beam splash events for MDT chambers and for each mezzanine card, starting from 2009/09/15

Also at CEA

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Also at LPNHE, Paris, France

has been working on Muon MDT noise study and calibration since 2009/10, contact as Tiesheng Dai and Muon convener

Also at Nanjing University, China

* Deceased