Measurement of the cross-section and charge asymmetry of W bosons produced in proton–proton collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector

ATLAS Collaboration

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Measurement of the cross-section and charge asymmetry of $W$ bosons produced in proton–proton collisions at $\sqrt{s} = 8$ TeV with the ATLAS detector

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This paper presents measurements of the $W^+ \rightarrow \mu^+ \nu$ and $W^- \rightarrow \mu^- \nu$ cross-sections and the associated charge asymmetry as a function of the absolute pseudorapidity of the decay muon. The data were collected in proton–proton collisions at a centre-of-mass energy of 8 TeV with the ATLAS experiment at the LHC and correspond to a total integrated luminosity of 20.2 fb$^{-1}$. The precision of the cross-section measurements varies between 0.8% to 1.5% as a function of the pseudorapidity, excluding the 1.9% uncertainty on the integrated luminosity. The charge asymmetry is measured with an uncertainty between 0.002 and 0.003. The results are compared with predictions based on next-to-next-to-leading-order calculations with various parton distribution functions and have the sensitivity to discriminate between them.

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1 Introduction

Measurements of the $W^+$ and $W^-$ boson cross-sections in hadron collisions are a sensitive probe of quantum chromodynamics (QCD). High-precision predictions at next-to-next-to-leading-order (NNLO) accuracy in QCD are available to compare with data. Of particular interest is the ability of such measurements to discriminate between different parton distribution functions (PDFs) [1–7], because the $W$ boson rapidity $y$ is strongly correlated with the initial-state parton momentum fractions $x$. In high-energy proton–proton collisions, the main production mechanism of single $W$ bosons is a valence quark annihilating with a sea antiquark. The $W$ bosons are preferentially produced with a boost in the direction of the incoming valence quark, as the quark is more likely to be at a higher $x$ than the corresponding antiquark. Since the PDFs of $u$ and $d$ quarks in the proton differ (largely due to there being two valence $u$ quarks and one valence $d$ quark), there is a production asymmetry between $W^+$ and $W^-$ bosons (referred to in this paper as the $W$ boson charge asymmetry), which also varies as a function of rapidity. The boson rapidity cannot be determined unambiguously in leptonic decays of the $W$ boson because the decay neutrino passes through the detector unobserved. The charge asymmetry can instead be measured as a function of the decay lepton’s pseudorapidity $\eta_{\ell}$, which is strongly correlated with the $W$ boson rapidity.

The $W$ boson charge asymmetry was measured in proton–antiproton collisions by the CDF and D0 collaborations [8–10]. It was also measured, along with the individual cross-sections, in proton–proton collisions at the LHC by the ATLAS Collaboration at centre-of-mass energies of $\sqrt{s} = 5$ TeV [11] and 7 TeV [2], by the CMS Collaboration at $\sqrt{s} = 7$ and 8 TeV [12–14], and by the LHCb Collaboration at $\sqrt{s} = 7$ and 8 TeV [15–17].

This paper presents measurements of the integrated fiducial cross-sections for $W^+ \rightarrow \mu^+\nu$ and $W^- \rightarrow \mu^-\bar{\nu}$, as well as the differential cross-sections, $d\sigma_{W^+}/d\eta_{\mu}$ and $d\sigma_{W^-}/d\eta_{\mu}$, as a function of $|\eta_{\mu}|$, where $\eta_{\mu}$ is the pseudorapidity of the decay muon. The data used were collected in proton–proton collisions at a centre-of-mass energy of $\sqrt{s} = 8$ TeV with the ATLAS experiment at the LHC and correspond to a total integrated luminosity of 20.2 fb$^{-1}$ [18]. The muon decay channel ($W \rightarrow \mu\nu$) is particularly well suited for this measurement due to good lepton identification and small contributions from background processes. In addition, a measurement of the $W$ boson charge asymmetry $A_{\mu}$ is presented, also as a function of $|\eta_{\mu}|$. The asymmetry is defined in terms of the $W^+$ and $W^-$ differential cross-sections as

$$A_{\mu} = \frac{d\sigma_{W^+}/d\eta_{\mu} - d\sigma_{W^-}/d\eta_{\mu}}{d\sigma_{W^+}/d\eta_{\mu} + d\sigma_{W^-}/d\eta_{\mu}}. \tag{1}$$

The measurements are performed in a fiducial phase space, which is defined by the kinematics and geometrical acceptance of the muon. All measurements are compared with predictions from a calculation performed at NNLO accuracy using the DYNNLO program [19]. The DYNNLO predictions are produced with six different PDF sets.

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1 ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point in the centre of the detector and the $z$-axis coinciding with the axis of the beam pipe. The $x$-axis points from the interaction point to the centre of the LHC ring, and the $y$-axis points upward. Cylindrical coordinates $(r, \phi)$ are used in the transverse plane, $\phi$ being the azimuthal angle around the beam pipe. The pseudorapidity is defined in terms of the polar angle $\theta$ as $\eta = -\ln \tan(\theta/2)$. The rapidity $y$ of a system is defined in terms of its energy $E$ and its longitudinal momentum $p_z$ as $y = (1/2) \ln [(E + p_z)/(E - p_z)]$. Angular separations between particles or reconstructed objects are measured in $\eta$–$\phi$ space using $\Delta R = \sqrt{(\Delta \eta)^2 + (\Delta \phi)^2}$. 

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2 The ATLAS detector

The ATLAS detector [20] at the LHC covers nearly the entire solid angle around the collision point. It consists of an inner tracking detector (ID) surrounded by a thin superconducting solenoid, electromagnetic and hadronic calorimeters, and a muon spectrometer (MS) incorporating three large superconducting toroid magnets. The ID is immersed in a 2 T axial magnetic field and provides charged-particle tracking in the range $|\eta| < 2.5$. A high-granularity silicon pixel detector typically provides three measurements per track and is followed by a silicon microstrip tracker, which usually provides four three-dimensional measurement points per track. These silicon detectors are complemented by a transition radiation tracker, which enables radially extended track reconstruction up to $|\eta| = 2.0$.

The calorimeter system covers the pseudorapidity range $|\eta| < 4.9$. Electromagnetic calorimetry is provided by barrel and endcap high-granularity lead/liquid-argon (LAr) sampling calorimeters in the $|\eta| < 3.2$ region. A thin LAr presampler, covering $|\eta| < 1.8$, corrects for energy loss in the material upstream of the calorimeters. Hadronic calorimetry is provided in the $|\eta| < 1.7$ region by the steel/scintillator tile calorimeter, segmented into three barrel structures, and in the endcap region by two copper/LAr calorimeters. The forward regions $3.1 < |\eta| < 4.9$ are covered by copper/LAr and tungsten/LAr calorimeter modules optimised for electromagnetic and hadronic measurements, respectively.

The MS has separate trigger and precision tracking chambers measuring the deflection of muons in a magnetic field generated by superconducting air-core toroids. The precision chamber system covers the region $|\eta| < 2.7$ with three layers of monitored drift tubes, complemented by cathode-strip chambers in the forward regions $2.0 < |\eta| < 2.7$, where the background is highest. There is a transition between the barrel and endcap muon detectors around $|\eta| = 1.05$. The muon trigger system covers the range of $|\eta| < 2.4$ with resistive-plate chambers in the barrel and thin-gap chambers in the endcap regions.

A three-level trigger system [21, 22] selected candidate events in 2012. The level-1 trigger was implemented in hardware and used a subset of detector information to reduce the event rate to a design value of at most 75 kHz. This was followed by two software-based trigger levels which together reduced the event rate to about 400 Hz.

3 Analysis methodology

3.1 Description of the measurements

The integrated cross-sections for $W^+ \rightarrow \mu^+ \nu$ and $W^- \rightarrow \mu^- \bar{\nu}$ production are measured in a fiducial phase space defined at the particle level by requiring the muon transverse momentum $p_T^\mu$ to be greater than 25 GeV and the neutrino transverse momentum $p_T^\nu$ to be greater than 25 GeV. The absolute muon pseudorapidity is required to be less than 2.4. The $W$ boson transverse mass is

$$m_T = \sqrt{2p_T^\mu p_T^\nu (1 - \cos (\phi^\mu - \phi^\nu))},$$

where $\phi^\mu$ and $\phi^\nu$ are the azimuthal angles of the muon and neutrino, respectively. For this analysis, $m_T$ must be at least 40 GeV, both at reconstruction and particle level. The requirements on fiducial quantities are defined before the emission of final-state photon radiation (i.e. at the ‘Born level’).
The differential cross-sections and charge asymmetry are measured in the same fiducial phase space as for the integrated measurement. These are measured in 11 bins of absolute muon pseudorapidity between 0 and 2.4 with bin edges at 0, 0.21, 0.42, 0.63, 0.84, 1.05, 1.37, 1.52, 1.74, 1.95, 2.18, and 2.4. The bin edges are identical to those used in the ATLAS 7 TeV measurement [2].

3.2 Data and simulated event samples

The data for this analysis comprise the entire ATLAS $\sqrt{s} = 8$ TeV data set recorded between April and December 2012, corresponding to an integrated luminosity of 20.2 fb$^{-1}$. The average number of proton–proton interactions per bunch crossing $\langle \mu \rangle$ was 20.7. Only events recorded with stable beams and the detector operating well are selected. The relative uncertainty of the LHC proton beam energy of $\pm 0.1\%$ [23] has no significant effect on the results.

Events from Monte Carlo (MC) simulations, including simulation of the ATLAS detector, are used for the background estimation and to correct the measured data for detector acceptance, efficiency, and resolution effects.

The $W \rightarrow \mu \nu$ signal process was simulated using Powheg-Box [24, 25] at next-to-leading order (NLO) in perturbative QCD using the CT10 set of PDFs [26] and interfaced to Pythia 8.170 [27] with the AU2 set of tuned parameters [28] to simulate the parton shower, hadronisation, and underlying event and to PhoRos [29] to simulate final-state photon radiation (FSR). This is referred to as Powheg+Pythia8 in this paper. An alternative signal sample was simulated using NLO Sherpa 1.4 [30] and the CT10 PDF set to cross-check the results obtained using Powheg+Pythia8 and to evaluate systematic uncertainties in the signal modelling.

Powheg+Pythia8 with the CT10 PDF set was used to simulate the background processes $W \rightarrow \tau \nu$ and $Z \rightarrow \mu \mu$ (with the AU2 tune set) and Powheg+Pythia6 [31, 32] also with the CT10 PDF set was used to simulate the $t\bar{t}$ process (with the P2011C tune set [33]). The $Z \rightarrow \tau \tau$ process was simulated using Alpgen [34] with the CTEQ6L1 PDF set [35] interfaced to Herwig [36] to simulate the parton shower and Jimmy [37] to model the underlying event. The single-top process in the s-channel and $Wt$-channels was simulated with MC@NLO [38] interfaced to Jimmy. The t-channel is generated with AcerMC [39] interfaced to Pythia. The backgrounds from the diboson processes $WW$, $WZ$, and $ZZ$ were simulated using Herwig at leading order with the CTEQ6L1 PDF set. In all cases, the Geant4 [40] program was used to simulate the passage of particles through the ATLAS detector [41]. The multijet background is estimated using a data-driven technique, described in Section 3.4. A $b\bar{b} \rightarrow \mu X$ MC sample, simulated using Pythia8 with the AU2 tune set, is used to cross-check the data-driven estimation.

Differences in reconstruction, trigger, and isolation efficiencies between MC simulations and data are evaluated using a tag-and-probe method [42] and are corrected by reweighting the MC simulated events. The muon reconstruction efficiencies are parameterised versus $\eta$ and $\phi$, the muon isolation efficiencies versus $\eta$ and transverse momentum $p_T$, and the muon trigger efficiencies versus $\eta$, $\phi$, and $p_T$. The reconstruction, trigger and isolation efficiencies are evaluated separately for positive and negative muons. This is particularly necessary in the case of the trigger efficiencies, which differ by up to 3% (depending on $\eta$) between positive and negative muons, much greater than the total uncertainty in the cross-section from other sources. Corrections are also applied to MC events for the description of the muon momentum scales and resolution, which are determined from fits to the observed mass distributions of $Z \rightarrow \mu \mu$ candidates in data and MC simulations [42]. To correct for charge-dependent biases of the muon momentum scale due to residual misalignments in the ID and MS, an additional momentum-dependent correction parameterised
versus $\eta$ and $\phi$ is applied. An associated uncertainty corresponding to the full size of the correction is included.

All simulated samples are normalised using their respective inclusive cross-sections at higher orders in perturbative QCD. The $W$ and $Z$ predictions are scaled to the NNLO calculation obtained with DYNLO v1.5 [19, 43] and the MSTW2008 PDF set [44]. The production of top quarks is normalised using the prediction at NNLO+NNLL precision from the Top++2.0 program for $t\bar{t}$ [45–51], to the calculations in Refs. [52–54] for single top quarks, and for diboson production to the NLO calculations following the procedure described in Ref. [55].

The effect of multiple interactions per bunch crossing (pile-up) is simulated by overlaying minimum-bias MC events generated with Pythia8 (with the A2 tune set) [56]. The simulated event samples are reweighted to describe the distribution of the number of pile-up events in the data. The MC simulations are also reweighted to better describe the distribution of the longitudinal position of the primary proton–proton collision vertex [57] in data.

### 3.3 Event selection

Candidate $W \rightarrow \mu\nu$ events are selected with the requirement that at least one of two single-muon triggers are satisfied. A high-threshold trigger requires muons to have $p_T > 36$ GeV, whilst a low-threshold trigger requires $p_T > 24$ GeV alongside the requirement that the muon must be isolated from additional nearby tracks.

Muon candidates are reconstructed by combining tracks measured in both the ID and the MS [42]. The $p_T$ of the ID track is required to be greater than 25 GeV and the absolute pseudorapidity to be less than 2.4. Track quality requirements are imposed for muon identification and background suppression. The transverse impact parameter significance is required to be less than 3 to ensure that the muon candidates originate from a primary proton–proton interaction vertex. The muon candidates are also required to be isolated, satisfying $I_\mu < 0.1$, where $I_\mu$ is the scalar sum of the $p_T$ of tracks within a cone of size $\Delta R = 0.4$ around the muon (excluding the muon track) divided by the $p_T$ of the muon. Events are required to contain exactly one muon candidate satisfying the above criteria.

To reduce background contamination, in particular from multijet processes, events are required to have missing transverse momentum $E_T^{\text{miss}}$ greater than 25 GeV. The $E_T^{\text{miss}}$ is reconstructed using energy depositions in the calorimeters and tracks reconstructed in the inner detector and muon spectrometer [58]. It is defined as the absolute value of the negative of the vectorial sum of the transverse momenta of reconstructed objects (e.g. electrons, muons, jets) and tracks not associated with these objects. These are labelled the hard and soft terms, respectively.

The $W$ boson transverse mass $m_T$ is required to be larger than 40 GeV. This variable is defined analogously to Eq. (2) with $p_T^\nu$ replaced by $E_T^{\text{miss}}$ and $\phi^\nu$ replaced by the azimuthal angle related to the $E_T^{\text{miss}}$.

### 3.4 Estimation of backgrounds

The backgrounds from all sources other than multijet processes are estimated using the MC samples detailed in Section 3.2. The $Z \rightarrow \mu\mu$ process with one of the muons not identified contributes between 1% and 8% of selected data events, depending on the value of $|\eta_{\mu}|$. This is the largest background for $|\eta_{\mu}| \gtrsim 1.4$. The contribution from $W \rightarrow \tau\nu$ where the $\tau$-lepton decays into a muon is 2% of the selected
data events and approximately constant as a function of $|\eta_\mu|$. The backgrounds from $Z \rightarrow \tau\tau$, $t\bar{t}$, and the diboson processes $WW$, $WZ$, and $ZZ$ each amount to less than 0.3% of the selected data.

Multijet processes contribute between 2% and 4% of the selected data and are the largest sources of background for $|\eta_\mu| \lesssim 1.4$. The number and properties of the background events arising from multijet processes are estimated using a data-driven template-fit technique, similar to that used in Ref. [59]. A multijet-dominated sample is obtained from data by selecting events passing the nominal selection except that the muon fails the isolation criterion. For this purpose, events satisfying a trigger without an isolation requirement are used. Multijet templates are constructed from this sample for each distribution of interest by subtracting the residual contribution from signal and other background sources, estimated from MC simulations. The normalisations of the multijet templates in the signal region are obtained by fitting the templates to data in three discriminating variables: $E_T^{\text{miss}}$, $m_T$, and the ratio $p_T^\mu/m_T$. The fits are performed in two phase-space regions (fitting regions) in which the selections on $E_T^{\text{miss}}$ and $m_T$ are relaxed in order to enrich the multijet background contribution. The isolation requirement in the fitting regions is the same as for the signal selection. A requirement that the $W$ transverse momentum be less than 30 GeV is introduced in one fitting region to remove a region poorly modelled by signal MC simulations. The normalisation of the multijet template is allowed to float in each of the fits and the total MC-based signal plus background is kept constant. The multijet normalisation in the signal selection is extracted using each discriminating variable in both fitting regions (a total of six estimates). It is assumed that the normalisations of the templates in the fitting regions are the same as for the signal selection.

The composition of processes contributing to the multijet events varies as a function of $I_\mu$, and therefore so does the template shape. To account for this, templates are constructed in a series of mutually exclusive intervals in $I_\mu$, and the fits described above are performed for each (i.e. for each template six fits are performed). The normalisation estimate extracted in each $I_\mu$ interval (for a particular discriminating variable and fitting region) is used to extrapolate to an isolation value of 0.05, which is the average isolation of multijet events in the signal region as estimated using the $b\bar{b} \rightarrow \mu X$ MC simulation.

The central value of the multijet background is chosen to be the average of the extrapolated curves at $I_\mu = 0.05$, and the spread gives one component of the systematic uncertainty, which is estimated to be bin-to-bin correlated and 50% charge correlated. This uncertainty component includes the effects from the choice of the discriminating variable and the definition of the fitting regions. Another component arises from the effect of the cross-section uncertainty on the signal simulation contribution in the fitting regions ($\pm 5\%$). The fit is repeated varying this and the deviation from the nominal normalisation is taken as an uncertainty, which is again treated as being charge and bin-to-bin correlated. The fit also has a statistical uncertainty, which is treated as being uncorrelated between charges and bins. This is largely due to the limited number of data events for the multijet templates passing the signal selection in each interval of $I_\mu$. The size of the multijet systematic uncertainty is reported in Section 4. The above procedure is performed separately in each bin of muon pseudorapidity. A summary of the most important backgrounds including systematic uncertainties is given in Table 1.

Figure 1 shows the muon $\eta$, muon $p_T$, and $W$ transverse mass distributions of selected events with positive muons (left) and with negative muons (right). The data are compared with the sum of MC and data-based estimates for the signal and the backgrounds. The predictions are normalised to the luminosity of the data, after first normalising each MC cross-section to a corresponding higher-order prediction. A normalisation shift between data and MC simulations of approximately 1% is observed for the positive muon plots. This is covered by the uncertainty in the MC signal prediction due to the cross-section uncertainty. Otherwise, the combined prediction describes the data well and within the uncertainties.
Figure 1: The muon $\eta$ (top), muon $p_T$ (centre), and $W$ boson transverse mass (bottom) distributions of selected events with positive muons (left) and negative muons (right). The statistical uncertainties of the data points are smaller than the size of the markers.
Table 1: The number of data events after event selection for $W^+ \rightarrow \mu^+\nu$ and $W^- \rightarrow \mu^-\bar{\nu}$ and the percentage of selected data that each of the three major backgrounds constitutes.

<table>
<thead>
<tr>
<th></th>
<th>$W^+ \rightarrow \mu^+\nu$</th>
<th>$W^- \rightarrow \mu^-\bar{\nu}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of events</td>
<td>Data</td>
<td>50 390 184</td>
</tr>
<tr>
<td>Percentage of data</td>
<td>Multijet</td>
<td>2.4 ± 0.3</td>
</tr>
<tr>
<td></td>
<td>$W \rightarrow \tau\nu$</td>
<td>1.9 ± 0.1</td>
</tr>
<tr>
<td></td>
<td>$Z \rightarrow \mu\mu$</td>
<td>3.1 ± 0.2</td>
</tr>
<tr>
<td></td>
<td>Others</td>
<td>0.62 ± 0.02</td>
</tr>
</tbody>
</table>

3.5 Obtaining the fiducial cross-sections

The fiducial $W^\pm$ differential cross-sections in bin $i$ of pseudorapidity $(d\sigma_{W^\pm}/d\eta_{\mu})_i$ are obtained from

$$\left(\frac{d\sigma_{W^\pm}}{d\eta_{\mu}}\right)_i = \frac{N_{\text{data},i} - N_{\text{bkg},i}}{\Delta\eta_i \cdot C_{W^\pm,i} \cdot \int L dt},$$

where $N_{\text{data},i}$ is the number of selected candidate events in data, $N_{\text{bkg},i}$ is the number of background events estimated using the methods described in Section 3.4, $\Delta\eta_i$ is the width of bin $i$, and $\int L dt$ is the integrated luminosity. The results are provided as a function of absolute pseudorapidity, where $\Delta|\eta_{\mu}| = 2 \cdot \Delta\eta_i$. The term $C_{W^\pm,i}$ is a factor (different for positive and negative channels) which corrects for the various detector inefficiencies and resolution effects. This is estimated using $W \rightarrow \mu\nu$ signal MC simulations and defined for each bin $i$ as the number of reconstructed events satisfying the same selection criteria as data divided by the number of generated events in the fiducial phase space. The charge asymmetry is then evaluated in each absolute pseudorapidity bin using Eq. (1). A bin-by-bin correction method is used as the purity of each bin is 99% or larger, where the bin purity is defined as the ratio of events generated and reconstructed in a certain bin to all events reconstructed in that bin (where all events are in the generator-level fiducial phase space).

The integrated fiducial cross-sections ($\sigma_{W^\pm}$) are obtained using one global correction factor, $C_{W^\pm}$, (i.e. the total number of reconstructed events satisfying the same selection criteria as data divided by the total number of generated events in the integrated fiducial phase space). The values are also obtained by summing the differential cross-sections as a function of $|\eta_{\mu}|$ and the results are consistent. Table 2 lists the $C_{W^\pm,i}$ values with their associated systematic uncertainties as a function of $|\eta_{\mu}|$ and gives the integrated global correction factor $C_{W^\pm}$, each for $W^+$ and $W^-$.  

4 Systematic uncertainties

This section describes the sources of systematic uncertainty considered for the cross-section and the asymmetry measurements. The size of these uncertainties as a function of $|\eta_{\mu}|$ is provided in Figures 2 and 3. The data statistical uncertainties are also shown and are small compared with the total systematic uncertainty. Table 3 lists the $W^+ \rightarrow \mu^+\nu$ and $W^- \rightarrow \mu^-\bar{\nu}$ cross-sections and the asymmetry as a function
Table 2: The $C_{W^\pm,j}$ values with their associated systematic uncertainties as a function of $|\eta_\mu|$ and the integrated global correction factor $C_{W^\pm}$, each for $W^+$ and $W^-$. 

| $|\eta_\mu|$ | $W^+ \rightarrow \mu^+\nu$ | $W^+ \rightarrow \mu^+\nu$ |
|---|---|---|
| 0.00–0.21 | $0.508 \pm 0.004$ | $0.505 \pm 0.004$ |
| 0.21–0.42 | $0.684 \pm 0.004$ | $0.679 \pm 0.004$ |
| 0.42–0.63 | $0.702 \pm 0.005$ | $0.702 \pm 0.005$ |
| 0.63–0.84 | $0.611 \pm 0.004$ | $0.613 \pm 0.005$ |
| 0.84–1.05 | $0.603 \pm 0.004$ | $0.601 \pm 0.005$ |
| 1.05–1.37 | $0.795 \pm 0.006$ | $0.796 \pm 0.007$ |
| 1.37–1.52 | $0.848 \pm 0.008$ | $0.845 \pm 0.007$ |
| 1.52–1.74 | $0.861 \pm 0.009$ | $0.856 \pm 0.007$ |
| 1.74–1.95 | $0.856 \pm 0.009$ | $0.855 \pm 0.008$ |
| 1.95–2.18 | $0.792 \pm 0.008$ | $0.794 \pm 0.009$ |
| 2.18–2.40 | $0.802 \pm 0.008$ | $0.812 \pm 0.011$ |

Integrated $0.736 \pm 0.003$ $0.727 \pm 0.003$

of the absolute pseudorapidity of the muon, along with the data statistical uncertainties and dominant systematic uncertainties. Most sources of systematic uncertainty are treated as being correlated between the positive and negative muon channels, and therefore their relative impact is reduced for the asymmetry measurement.

![Figure 2: The relative systematic uncertainty from each source for the $W^+$ (left) and $W^-$ (right) differential cross-sections as a percentage of the differential cross-section. Also shown are the total systematic and statistical uncertainties.](image)

Experimental sources of uncertainty are possible mis-modelling of the muon momentum scale, resolution, or charge-dependent bias as well as of the reconstruction, trigger, and isolation efficiencies. Such uncertainties form a small but non-negligible fraction of the total uncertainty, 0.5% or less of the differential cross-section. A test is performed to check the compatibility of the cross-sections measured separately in positive and negative muon pseudorapidity; this is an important cross-check of the correction procedure. A
Figure 3: The systematic uncertainty from each source for the $W$ boson charge asymmetry as an absolute difference from the central value. Also shown are the total systematic and statistical uncertainties.

Further small uncertainty (up to 0.4% depending on the $|\eta_{\mu}|$ bin) is added to cover the small differences observed. This uncertainty is treated as being uncorrelated between charges and propagated to the asymmetry measurement. The above uncertainties are combined in the column labelled ‘Muon Reconstruction’ in Table 3. Additional sources of uncertainty are the mis-modelling of the pile-up event activity and of the primary vertex longitudinal position, both of which are small.

Uncertainties from the mis-modelling of the missing transverse momentum also contribute substantially to the total systematic uncertainty in the cross-section, although they are reduced for the asymmetry measurements. These include mis-modelling in the jet energy scale and resolution, as well as of the momentum balance between the soft term and the total transverse momentum of the hard objects in $Z \rightarrow \mu\mu$ calibration events [58]. The muon-related uncertainties in the missing transverse momentum are treated as being fully correlated with those of the signal muon and are part of the muon systematic uncertainties. The sum of all soft-term uncertainties is the largest or second largest contributor (depending on the $|\eta_{\mu}|$ bin) to the total uncertainty in the differential cross-sections but is significantly less important for the asymmetry measurement. The hard-term uncertainties are small for both the cross-section and asymmetry measurements.

Uncertainties due to the mis-modelling of the background processes are also considered. For the backgrounds modelled with MC simulations, these are estimated by varying their normalisation within theoretical uncertainties and observing the effect on the final measurements. The cross-section uncertainty for the $Z \rightarrow \mu\mu$ process and the $W \rightarrow \tau\nu$ process is 5% [60]. The cross-section uncertainty for $t\bar{t}$ production is 6% [45–51], and for single top production 7% [52–54]. The cross-section uncertainty for diboson production is 5% for $WW$ and $ZZ$ production and 7% for $WZ$ production [55].

As mentioned in Section 3.4, there are three components of the uncertainty in the multijet background normalisation. The two correlated uncertainties are larger for the cross-section measurements (totalling around 0.5%), whilst the effect of the statistical component is larger for the asymmetry measurement.

The statistical uncertainty due to the limited number of MC events for the other backgrounds and for the signal process is small for the cross-section measurement (less than 0.2%) but becomes significant for
the asymmetry measurement (around one third of the total uncertainty), as it is completely uncorrelated between positive and negative channels.

Theoretical sources of uncertainty arise from the choice of PDF interfaced to the POWHEG+PYTHIA8 signal MC simulations (the CT10 PDF set). This uncertainty is estimated by reweighting the POWHEG+PYTHIA8 events to the nominal values of the CT14 [1] and MSTW2008nlo68cl [44] PDF sets using the LHAPDF interface [61]. The PDF uncertainty is small for both the fiducial cross-section and asymmetry measurements.

The alternative SHERPA signal sample is used to estimate an uncertainty from POWHEG+PYTHIA8 related to the modelling of the matrix elements that impact kinematics, as well as the underlying event activity and hadronisation (which affects the $E_{\text{T}}^{\text{miss}}$ measurement). The difference between the dressed-level $C_{\text{W}}$ values obtained using the POWHEG+PYTHIA8 and SHERPA simulations is assigned as a systematic uncertainty and is labelled as ‘Modelling’ in Table 3. The dressed-level is defined by combining the four-momentum of each muon after photon FSR with that of photons radiated within a cone defined by $\Delta R = 0.1$ around the muon. This is one of the largest systematic uncertainties for both the cross-section (up to 1% at large $|\eta_{\mu}|$) and the asymmetry measurements. The uncertainty in the luminosity is 1.9% [18]. For the asymmetry, the uncertainty in the luminosity is fully correlated between $W^+$ and $W^-$ and therefore cancels out completely.

5 Theoretical predictions

The $W^+$ and $W^-$ integrated and differential cross-sections and the $W$ boson charge asymmetry are compared with theoretical predictions from an optimised version of the DYNNLO generator [19], which simulates initial-state QCD corrections to NNLO accuracy at leading order in the electroweak couplings with parameters set according to the $G_{\mu}$ scheme [62]. The input parameters (the Fermi constant $G_F$, the masses and widths of the $W$ and $Z$ bosons, and the CKM matrix elements) are taken from Ref. [63]. The DYNNLO predictions are calculated with the PDF sets from CT14 NNLO [1], ATLASepWZ2016 [2], HERAPDF2.0 [3], NNPDF3.1 [4], PDF4LHC15 [5] and MMHT2014 NNLO [6]. The renormalisation and factorisation scales are set equal to the invariant mass of the muon–neutrino pair.

Uncertainties in the DYNNLO prediction due the choice of scales are evaluated by varying the factorisation and renormalisation scales independently by factors of 0.5 and 2 from their nominal values. The uncertainty on the CT14 NNLO prediction is evaluated using the corresponding PDF error sets.

6 Results

The measured integrated fiducial cross-sections multiplied by the branching fraction for the decay into a muon and a neutrino are listed in Table 4, along with the associated uncertainties which are dominated by the 1.9% uncertainty in the luminosity. Also provided is the sum of the $W^+ \to \mu^+\nu$ and $W^- \to \mu^-\bar{\nu}$ integrated cross-sections and their ratio, the total uncertainties on which are 2.1% and 0.3% respectively. The data are compared with the NNLO predictions from DYNNLO, the total uncertainties on which are dominated by the component from the PDF uncertainty. Data and theory agree well and within the uncertainties. The results presented in Table 4 are consistent, within about one standard deviation, with
Table 3: Size of cross-sections (differential in $\eta_\mu$) and asymmetry, as a function of $|\eta_\mu|$. The central values are provided along with the statistical and dominant systematic uncertainties: the data statistical uncertainty (Data Stat.), the $E_{\text{T}}^{\text{miss}}$ uncertainty, the uncertainties related to muon reconstruction (Muon Reco.), those related to the background, those from MC statistics (MC Stat.), and modelling uncertainties. The uncertainties of the cross-sections are given in percent and those of the asymmetry as an absolute difference from the nominal.

| $|\eta_\mu|$ | $d\sigma_{W_\mu^+}/d\eta_\mu$ [pb] | $d\sigma_{W_\mu^-}/d\eta_\mu$ [pb] | $A_\mu$ |
|----------|-------------------------------------|-------------------------------------|-------|
| 0.00–0.21 | 630.3 | 493.7 | 0.1215 |
| 0.21–0.42 | 635.2 | 489.6 | 0.1294 |
| 0.42–0.63 | 641.6 | 485.8 | 0.1383 |
| 0.63–0.84 | 638.1 | 474.3 | 0.1473 |
| 0.84–1.05 | 642.8 | 465.0 | 0.1605 |
| 1.05–1.37 | 654.7 | 455.7 | 0.1792 |
| 1.37–1.52 | 661.0 | 439.7 | 0.2011 |
| 1.52–1.74 | 662.3 | 427.3 | 0.2156 |
| 1.74–1.95 | 661.8 | 410.2 | 0.2347 |
| 1.95–2.18 | 657.5 | 389.1 | 0.2565 |
| 2.18–2.40 | 641.5 | 368.3 | 0.2706 |
Table 4: The measured fiducial production cross-sections times branching ratio for \( W^+ \rightarrow \mu^+ \nu \) and \( W^- \rightarrow \mu^- \bar{\nu} \), their sum, and their ratio for both data and the predictions from DYNNLO (CT14 NNLO PDF set).

<table>
<thead>
<tr>
<th></th>
<th>Data</th>
<th>DYNNLO (CT14 NNLO PDF set)</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \sigma (W^+ \rightarrow \mu^+ \nu) ) [pb]</td>
<td>( 3110 \pm 0.5 ) (stat.) ( \pm 29 ) (syst.) ( \pm 59 ) (lumi.)</td>
<td>( 3015 \pm 92 ) (PDF) ( \pm 15 ) (scale)</td>
</tr>
<tr>
<td>( \sigma (W^- \rightarrow \mu^- \bar{\nu}) ) [pb]</td>
<td>( 2137 \pm 0.4 ) (stat.) ( \pm 22 ) (syst.) ( \pm 41 ) (lumi.)</td>
<td>( 2105 \pm 53 ) (PDF) ( \pm 10 ) (scale)</td>
</tr>
<tr>
<td>Sum [pb]</td>
<td>( 5247 \pm 0.6 ) (stat.) ( \pm 50 ) (syst.) ( \pm 100 ) (lumi.)</td>
<td>( 5120 \pm 140 ) (PDF) ( \pm 23 ) (scale)</td>
</tr>
<tr>
<td>Ratio</td>
<td>( 1.4558 \pm 0.0004 ) (stat.) ( \pm 0.0040 ) (syst.)</td>
<td>( 1.4320 \pm 0.0100 ) (PDF) ( \pm 0.0007 ) (scale)</td>
</tr>
</tbody>
</table>

those measured using \( W \) boson decays in the electron channel in data at a centre-of-mass energy of 8 TeV [64].

The \( W^+ \) and \( W^- \) fiducial cross-sections, differential in muon pseudorapidity, multiplied by the branching fraction for the decay into a muon and a neutrino, are shown as a function of absolute muon pseudorapidity in Figure 4. These are presented with systematic and total uncertainties. The data statistical uncertainties are smaller than the size of the markers. The cross-section values are detailed in Table 3. The measured cross-sections are compared with theoretical predictions obtained using DYNNLO.

In the top plots of Figure 4, DYNNLO is shown with its associated total theoretical uncertainty, and from the PDF uncertainty (evaluated with the CT14 NNLO error sets). The component from the PDF uncertainty dominates the total and is shown separately. The data precision is similar to the intrinsic theoretical uncertainty from scale variations but is much higher than the uncertainty from the PDF. Therefore the data are useful for constraining and evaluating the performance of different PDF sets. In the bottom plots the data are compared with the central values of each PDF set described above. The statistical uncertainties of the DYNNLO predictions are indicated by error bars.

The measured \( W \) boson charge asymmetry as a function of absolute muon pseudorapidity is presented in Figure 5. The values are detailed in Table 3. Again the data are shown with its total systematic uncertainty. In Figure 5 (left) the data are compared with the prediction from DYNNLO in which the CT14 NNLO PDF set is used. The DYNNLO prediction is also shown with its associated total theoretical uncertainty, along with the component from the PDF set, which dominates. In Figure 5 (right) the data are compared with the central prediction from the six PDF sets considered. The statistical uncertainties of the DYNNLO predictions are indicated by error bars. The ratios of the data to the corresponding prediction are shown in the lower panels. The comparison with ATLASepWZ2016 and NNPDF3.1 is of particular interest as both include information from the ATLAS 7 TeV measurement [2], which is expected to be largely uncorrelated with the current data being presented. It is observed that its central value is generally closer to the data than the alternatives, other than HERAPDF2.0 which performs about as well.
Figure 4: The $W^+$ (left) and $W^-$ (right) fiducial cross-sections, differential in muon pseudorapidity multiplied by the branching fraction for the decay into a muon and a neutrino are shown as a function of the absolute muon pseudorapidity. The data are presented with systematic and total uncertainties (the data statistical uncertainties are smaller than the size of the markers) and are compared with the predictions from DYNNLO. In the top two plots, the CT14 NNLO PDF set is used, and DYNNLO is shown with its associated total theoretical uncertainty. In the bottom two plots, the data are compared with the central values of six different PDF sets described in the text. The statistical uncertainties of the DYNNLO predictions are indicated by error bars. The ratios of the data to the corresponding prediction are shown in the lower panels.
Figure 5: The $W$ boson charge asymmetry as a function of absolute muon pseudorapidity. The data are presented with systematic and total uncertainties (the data statistical uncertainties are smaller than the size of the markers). In the left plot, the data are compared with the prediction from DYNNLO in which the CT14 NNLO PDF set is used. The DYNNLO prediction is also shown with its associated total theoretical uncertainty, along with the component from the PDF set. In the right plot, the data are compared with the central prediction from DYNNLO produced using a selection of PDFs. The statistical uncertainties of the DYNNLO predictions are indicated by error bars. The ratios of the data to the corresponding prediction are shown in the lower panels.
7 Conclusion

Fiducial cross-sections for $W^+ \rightarrow \mu^+ \nu$ and $W^- \rightarrow \mu^- \bar{\nu}$ and the $W$ boson charge asymmetry are measured differentially as a function of the absolute muon pseudorapidity using $20.2 \text{ fb}^{-1}$ of data from proton–proton collisions at a centre-of-mass energy of 8 TeV with the ATLAS experiment at the LHC. The muon and neutrino transverse momenta are required to be greater than 25 GeV and the $W$ boson transverse mass to be greater than 40 GeV. A precision of 0.8–1.5% is achieved for the cross-section values, depending on the pseudorapidity, whilst an uncertainty between 0.002 and 0.003 (in absolute units) is obtained for the asymmetry. The integrated fiducial $W^+$ production cross-sections are also determined. The measurements are compared to predictions at NNLO accuracy in QCD computed with the DYNNLO program. The precision of the measurement is better than both the uncertainties on the PDF sets as well as the spread between different sets, showing the sensitivity of the measurement to discriminate between them and serve as input to improve the knowledge on the proton structure.

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References


The ATLAS Collaboration

1Department of Physics, University of Adelaide, Adelaide; Australia.
2Physics Department, SUNY Albany, Albany NY; United States of America.
3Department of Physics, University of Alberta, Edmonton AB; Canada.
4(a)Department of Physics, Ankara University, Ankara; (b)Istanbul Aydin University, Istanbul; (c)Division of Physics, TOBB University of Economics and Technology, Ankara; Turkey.
5LAPP, Université Grenoble Alpes, Université Savoie Mont Blanc, CNRS/IN2P3, Annecy; France.
6High Energy Physics Division, Argonne National Laboratory, Argonne IL; United States of America.
7Department of Physics, University of Arizona, Tucson AZ; United States of America.
8Department of Physics, University of Texas at Arlington, Arlington TX; United States of America.
9Physics Department, National and Kapodistrian University of Athens, Athens; Greece.
10Physics Department, National Technical University of Athens, Zografou; Greece.
11Department of Physics, University of Texas at Austin, Austin TX; United States of America.
12(a)Bahcesehir University, Faculty of Engineering and Natural Sciences, Istanbul; (b)Istanbul Bilgi University, Faculty of Engineering and Natural Sciences, Istanbul; (c)Department of Physics, Bogazici University, Istanbul; (d)Department of Physics Engineering, Gaziantep University, Gaziantep; Turkey.
13Institute of Physics, Azerbaijan Academy of Sciences, Baku; Azerbaijan.
14Institut de Física d’Altes Energies (IFAE), Barcelona Institute of Science and Technology, Barcelona; Spain.
15(a)Institute of High Energy Physics, Chinese Academy of Sciences, Beijing; (b)Physics Department, Tsinghua University, Beijing; (c)Department of Physics, Nanjing University, Nanjing; (d)University of Chinese Academy of Science (UCAS), Beijing; China.
16Institute of Physics, University of Belgrade, Belgrade; Serbia.
17Department for Physics and Technology, University of Bergen, Bergen; Norway.
18Physics Division, Lawrence Berkeley National Laboratory and University of California, Berkeley CA; United States of America.
19Institut für Physik, Humboldt Universität zu Berlin, Berlin; Germany.
20Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern; Switzerland.
21School of Physics and Astronomy, University of Birmingham, Birmingham; United Kingdom.
22Facultad de Ciencias y Centro de Investigaciones, Universidad Antonio Nariño, Bogota; Colombia.
23(a)INFN Bologna and Universita’ di Bologna, Dipartimento di Fisica; (b)INFN Sezione di Bologna; Italy.
24Physikalisches Institut, Universität Bonn, Bonn; Germany.
25Department of Physics, Boston University, Boston MA; United States of America.
26Department of Physics, Brandeis University, Waltham MA; United States of America.
27(a)Transilvania University of Brasov, Brasov; (b)Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest; (c)Department of Physics, Alexandru Ioan Cuza University of Iasi, Iasi; (d)National Institute for Research and Development of Isotopic and Molecular Technologies, Physics Department, Cluj-Napoca; (e)University Politehnica Bucharest, Bucharest; (f)West University in Timisoara, Timisoara; Romania.
28(a)Faculty of Mathematics, Physics and Informatics, Comenius University, Bratislava; (b)Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice; Slovak Republic.
29Physics Department, Brookhaven National Laboratory, Upton NY; United States of America.
30Departamento de Física, Universidad de Buenos Aires, Buenos Aires; Argentina.
31California State University, CA; United States of America.
32Cavendish Laboratory, University of Cambridge, Cambridge; United Kingdom.
33(a)Department of Physics, University of Cape Town, Cape Town; (b)Department of Mechanical
Engineering Science, University of Johannesburg, Johannesburg; \( ^{(c)} \) School of Physics, University of the Witwatersrand, Johannesburg; South Africa.

Department of Physics, Carleton University, Ottawa ON; Canada.

\( ^{(a)} \) Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Energies - Université Hassan II, Casablanca; \( ^{(b)} \) Faculté des Sciences, Université Ibn-Tofail, Kénitra;\( ^{(c)} \) Faculté des Sciences Semlalia, Université Cadi Ayyad, LPHEA-Marrakech; \( ^{(d)} \) Faculté des Sciences, Université Mohamed Premier and LPTPM, Oujda; \( ^{(e)} \) Faculté des sciences, Université Mohammed V, Rabat; Morocco.

\( ^{(a)} \) CERN, Geneva; Switzerland.

Enrico Fermi Institute, University of Chicago, Chicago IL; United States of America.

\( ^{(a)} \) LPC, Université Clermont Auvergne, CNRS/IN2P3, Clermont-Ferrand; France.

\( ^{(a)} \) Nevis Laboratory, Columbia University, Irvington NY; United States of America.

\( ^{(a)} \) Niels Bohr Institute, University of Copenhagen, Copenhagen; Denmark.

\( ^{(a)} \) Dipartimento di Fisica, Università della Calabria, Rende; \( ^{(b)} \) INFN Gruppo Collegato di Cosenza, Laboratori Nazionali di Frascati; Italy.

\( ^{(a)} \) Physics Department, Southern Methodist University, Dallas TX; United States of America.

\( ^{(a)} \) Department of Physics, University of Texas at Dallas, Richardson TX; United States of America.

\( ^{(a)} \) National Centre for Scientific Research "Demokritos", Agia Paraskevi; Greece.

\( ^{(a)} \) Dipartimento di Fisica, Università della Calabria, Rende; \( ^{(b)} \) Oskar Klein Centre, Stockholm; Sweden.

\( ^{(a)} \) Deutsches Elektronen-Synchrotron DESY, Hamburg and Zeuthen; Germany.

\( ^{(a)} \) Lehrstuhl für Experimentelle Physik IV, Technische Universität Dortmund, Dortmund; Germany.

\( ^{(a)} \) Institut für Kern- und Teilchenphysik, Technische Universität Dresden, Dresden; Germany.

\( ^{(a)} \) Department of Physics, Duke University, Durham NC; United States of America.

\( ^{(a)} \) SUPA - School of Physics and Astronomy, University of Edinburgh, Edinburgh; United Kingdom.

\( ^{(a)} \) INFN e Laboratori Nazionali di Frascati, Frascati; Italy.

\( ^{(a)} \) Physikalisches Institut, Albert-Ludwigs-Universität Freiburg, Freiburg; Germany.

\( ^{(a)} \) II. Physikalisches Institut, Georg-August-Universität Göttingen, Göttingen; Germany.

\( ^{(a)} \) Département de Physique Nucléaire et Corpusculaire, Université de Genève, Genève; Switzerland.

\( ^{(a)} \) Dipartimento di Fisica, Università di Genova, Genova; \( ^{(b)} \) INFN Sezione di Genova; Italy.

\( ^{(a)} \) II. Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen; Germany.

\( ^{(a)} \) SUPA - School of Physics and Astronomy, University of Glasgow, Glasgow; United Kingdom.

\( ^{(a)} \) LPSC, Université Grenoble Alpes, CNRS/IN2P3, Grenoble INP, Grenoble; France.

\( ^{(a)} \) Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge MA; United States of America.

\( ^{(a)} \) Department of Modern Physics and State Key Laboratory of Particle Detection and Electronics, University of Science and Technology of China, Hefei; \( ^{(b)} \) Institute of Frontier and Interdisciplinary Science and Key Laboratory of Particle Physics and Particle Irradiation (MOE), Shandong University, Qingdao; \( ^{(c)} \) School of Physics and Astronomy, Shanghai Jiao Tong University, KLPPAC-MoE, SKLPPC, Shanghai; \( ^{(d)} \) Tsung-Dao Lee Institute, Shanghai; China.

\( ^{(a)} \) Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg; \( ^{(b)} \) Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg; Germany.

\( ^{(a)} \) Faculty of Applied Information Science, Hiroshima Institute of Technology, Hiroshima; Japan.

\( ^{(a)} \) Department of Physics, Chinese University of Hong Kong, Shatin, N.T., Hong Kong; \( ^{(b)} \) Department of Physics, University of Hong Kong, Hong Kong; \( ^{(c)} \) Department of Physics and Institute for Advanced Study, Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong; China.

\( ^{(a)} \) Department of Physics, National Tsing Hua University, Hsinchu; Taiwan.

\( ^{(a)} \) Department of Physics, Indiana University, Bloomington IN; United States of America.

\( ^{(a)} \) INFN Gruppo Collegato di Udine, Sezione di Trieste, Udine; \( ^{(b)} \) ICTP, Trieste; \( ^{(c)} \) Dipartimento
Politecnico di Ingegneria e Architettura, Università di Udine, Udine; Italy.
67(a) INFN Sezione di Lecce; (b) Dipartimento di Matematica e Fisica, Università del Salento, Lecce; Italy.
68(a) INFN Sezione di Milano; (b) Dipartimento di Fisica, Università di Milano, Milano; Italy.
69(a) INFN Sezione di Napoli; (b) Dipartimento di Fisica, Università di Napoli, Napoli; Italy.
70(a) INFN Sezione di Pavia; (b) Dipartimento di Fisica, Università di Pavia, Pavia; Italy.
71(a) INFN Sezione di Pisa; (b) Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa; Italy.
72(a) INFN Sezione di Roma; (b) Dipartimento di Fisica, Sapienza Università di Roma, Roma; Italy.
73(a) INFN Sezione di Roma Tor Vergata; (b) Dipartimento di Fisica, Università di Roma Tor Vergata, Roma; Italy.
74(a) INFN Sezione di Roma Tre; (b) Dipartimento di Matematica e Fisica, Università Roma Tre, Roma; Italy.
75(a) INFN-TIFPA; (b) Università degli Studi di Trento, Trento; Italy.
76 Institut für Astro- und Teilchenphysik, Leopold-Franzens-Universität, Innsbruck; Austria.
77 University of Iowa, Iowa City IA; United States of America.
78 Department of Physics and Astronomy, Iowa State University, Ames IA; United States of America.
79 Joint Institute for Nuclear Research, Dubna; Russia.
80(a) Departamento de Engenharia Elétrica, Universidade Federal de Juiz de Fora (UFJF), Juiz de Fora; (b) Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio de Janeiro; (c) Universidade Federal de São João del Rei (UFSJ), São João del Rei; (d) Instituto de Física, Universidade de São Paulo, São Paulo; Brazil.
81 KEK, High Energy Accelerator Research Organization, Tsukuba; Japan.
82 Graduate School of Science, Kobe University, Kobe; Japan.
83(a) AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, Krakow; (b) Marian Smoluchowski Institute of Physics, Jagiellonian University, Krakow; Poland.
84 Institute of Nuclear Physics Polish Academy of Sciences, Krakow; Poland.
85 Faculty of Science, Kyoto University, Kyoto; Japan.
86 Kyoto University of Education, Kyoto; Japan.
87 Research Center for Advanced Particle Physics and Department of Physics, Kyushu University, Fukuoka; Japan.
88 Institute of Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata; Argentina.
89 Physics Department, Lancaster University, Lancaster; United Kingdom.
90 Oliver Lodge Laboratory, University of Liverpool, Liverpool; United Kingdom.
91 Department of Experimental Particle Physics, Jožef Stefan Institute and Department of Physics, University of Ljubljana, Ljubljana; Slovenia.
92 School of Physics and Astronomy, Queen Mary University of London, London; United Kingdom.
93 Department of Physics, Royal Holloway University of London, Egham; United Kingdom.
94 Department of Physics and Astronomy, University College London, London; United Kingdom.
95 Louisiana Tech University, Ruston LA; United States of America.
96 Fysiska institutionen, Lunds universitet, Lund; Sweden.
97 Centre de Calcul de l’Institut National de Physique Nucléaire et de Physique des Particules (IN2P3), Villeurbanne; France.
98 Departamento de Física Teórica C-15 and CIAFF, Universidad Autónoma de Madrid, Madrid; Spain.
99 Institut für Physik, Universität Mainz, Mainz; Germany.
100 School of Physics and Astronomy, University of Manchester, Manchester; United Kingdom.
101 CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille; France.
102 Department of Physics, University of Massachusetts, Amherst MA; United States of America.
103 Department of Physics, McGill University, Montreal QC; Canada.
104 School of Physics, University of Melbourne, Victoria; Australia.
105 Department of Physics, University of Michigan, Ann Arbor MI; United States of America.
106 Department of Physics and Astronomy, Michigan State University, East Lansing MI; United States of America.
107 B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk; Belarus.
108 Research Institute for Nuclear Problems of Byelorussian State University, Minsk; Belarus.
109 Group of Particle Physics, University of Montreal, Montreal QC; Canada.
110 P.N. Lebedev Physical Institute of the Russian Academy of Sciences, Moscow; Russia.
111 Institute for Theoretical and Experimental Physics of the National Research Centre Kurchatov Institute, Moscow; Russia.
112 National Research Nuclear University MEPhI, Moscow; Russia.
113 D.V. Skobeltsyn Institute of Nuclear Physics, M.V. Lomonosov Moscow State University, Moscow; Russia.
114 Fakultät für Physik, Ludwig-Maximilians-Universität München, München; Germany.
115 Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München; Germany.
116 Nagasaki Institute of Applied Science, Nagasaki; Japan.
117 Graduate School of Science and Kobayashi-Maskawa Institute, Nagoya University, Nagoya; Japan.
118 Department of Physics and Astronomy, University of New Mexico, Albuquerque NM; United States of America.
119 Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen; Netherlands.
120 Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam; Netherlands.
121 Department of Physics, Northern Illinois University, DeKalb IL; United States of America.
122 (a) Budker Institute of Nuclear Physics and NSU, SB RAS, Novosibirsk; (b) Novosibirsk State University Novosibirsk; Russia.
123 Institute for High Energy Physics of the National Research Centre Kurchatov Institute, Protvino; Russia.
124 Department of Physics, New York University, New York NY; United States of America.
125 Ochanomizu University, Otsuka, Bunkyo-ku, Tokyo; Japan.
126 Ohio State University, Columbus OH; United States of America.
127 Faculty of Science, Okayama University, Okayama; Japan.
128 Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman OK; United States of America.
129 Department of Physics, Oklahoma State University, Stillwater OK; United States of America.
130 Palacký University, RCPTM, Joint Laboratory of Optics, Olomouc; Czech Republic.
131 Center for High Energy Physics, University of Oregon, Eugene OR; United States of America.
132 LAL, Université Paris-Sud, CNRS/IN2P3, Université Paris-Saclay, Orsay; France.
133 Graduate School of Science, Osaka University, Osaka; Japan.
134 Department of Physics, University of Oslo, Oslo; Norway.
135 Department of Physics, Oxford University, Oxford; United Kingdom.
136 LPNHE, Sorbonne Université, Paris Diderot Sorbonne Paris Cité, CNRS/IN2P3, Paris; France.
137 Department of Physics, University of Pennsylvania, Philadelphia PA; United States of America.
138 Konstantinov Nuclear Physics Institute of National Research Centre "Kurchatov Institute", PNPI, St. Petersburg; Russia.
139 Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh PA; United States of America.
140 (a) Laboratório de Instrumentação e Física Experimental de Partículas - LIP; (b) Departamento de Física, Faculdade de Ciências, Universidade de Lisboa, Lisboa; (c) Departamento de Física, Universidade de
Coimbra, Coimbra;\(^{(d)}\) Centro de Física Nuclear da Universidade de Lisboa, Lisboa;\(^{(e)}\) Departamento de Física, Universidade do Minho, Braga;\(^{(f)}\) Universidad de Granada, Granada (Spain);\(^{(g)}\) Dep Física and CEFITECT of Faculdade de Ciências e Tecnologia, Universidade Nova de Lisboa, Caparica; Portugal.

\(^{141}\) Institute of Physics of the Czech Academy of Sciences, Prague; Czech Republic.
\(^{142}\) Czech Technical University in Prague, Prague; Czech Republic.
\(^{143}\) Charles University, Faculty of Mathematics and Physics, Prague; Czech Republic.
\(^{144}\) Particle Physics Department, Rutherford Appleton Laboratory, Didcot; United Kingdom.
\(^{145}\) IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette; France.
\(^{146}\) Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz CA; United States of America.
\(^{147}(a)\) Departamento de Física, Pontificia Universidad Católica de Chile, Santiago;\(^{(b)}\) Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso; Chile.
\(^{148}\) Department of Physics, University of Washington, Seattle WA; United States of America.
\(^{149}\) Department of Physics and Astronomy, University of Sheffield, Sheffield; United Kingdom.
\(^{150}\) Department of Physics, Shinshu University, Nagano; Japan.
\(^{151}\) Department Physik, Universität Siegen, Siegen; Germany.
\(^{152}\) Department of Physics, Simon Fraser University, Burnaby BC; Canada.
\(^{153}\) SLAC National Accelerator Laboratory, Stanford CA; United States of America.
\(^{154}\) Physics Department, Royal Institute of Technology, Stockholm; Sweden.
\(^{155}\) Departments of Physics and Astronomy, Stony Brook University, Stony Brook NY; United States of America.
\(^{156}\) Department of Physics and Astronomy, University of Sussex, Brighton; United Kingdom.
\(^{157}\) School of Physics, University of Sydney, Sydney; Australia.
\(^{158}\) Institute of Physics, Academia Sinica, Taipei; Taiwan.
\(^{159}(a)\) E. Andronikashvili Institute of Physics, Iv. Javakhishvili Tbilisi State University, Tbilisi;\(^{(b)}\) High Energy Physics Institute, Tbilisi State University, Tbilisi; Georgia.
\(^{160}\) Department of Physics, Technion, Israel Institute of Technology, Haifa; Israel.
\(^{161}\) Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv; Israel.
\(^{162}\) Department of Physics, Aristotle University of Thessaloniki, Thessaloniki; Greece.
\(^{163}\) International Center for Elementary Particle Physics and Department of Physics, University of Tokyo, Tokyo; Japan.
\(^{164}\) Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo; Japan.
\(^{165}\) Department of Physics, Tokyo Institute of Technology, Tokyo; Japan.
\(^{166}\) Tomsk State University, Tomsk; Russia.
\(^{167}\) Department of Physics, University of Toronto, Toronto ON; Canada.
\(^{168}(a)\) TRIUMF, Vancouver BC;\(^{(b)}\) Department of Physics and Astronomy, York University, Toronto ON; Canada.
\(^{169}\) Division of Physics and Tomonaga Center for the History of the Universe, Faculty of Pure and Applied Sciences, University of Tsukuba, Tsukuba; Japan.
\(^{170}\) Department of Physics and Astronomy, Tufts University, Medford MA; United States of America.
\(^{171}\) Department of Physics and Astronomy, University of California Irvine, Irvine CA; United States of America.
\(^{172}\) Department of Physics and Astronomy, University of Uppsala, Uppsala; Sweden.
\(^{173}\) Department of Physics, University of Illinois, Urbana IL; United States of America.
\(^{174}\) Instituto de Física Corpuscular (IFIC), Centro Mixto Universidad de Valencia - CSIC, Valencia; Spain.
\(^{175}\) Department of Physics, University of British Columbia, Vancouver BC; Canada.
\(^{176}\) Department of Physics and Astronomy, University of Victoria, Victoria BC; Canada.
Also at Instituto de Física Teórica, IFT-UAM/CSIC, Madrid; Spain.
Also at Istanbul University, Dept. of Physics, Istanbul; Turkey.
Also at Joint Institute for Nuclear Research, Dubna; Russia.
Also at LAL, Université Paris-Sud, CNRS/IN2P3, Université Paris-Saclay, Orsay; France.
Also at Louisiana Tech University, Ruston LA; United States of America.
Also at LPNHE, Sorbonne Université, Paris Diderot Sorbonne Paris Cité, CNRS/IN2P3, Paris; France.
Also at Manhattan College, New York NY; United States of America.
Also at Moscow Institute of Physics and Technology State University, Dolgoprudny; Russia.
Also at National Research Nuclear University MEPhI, Moscow; Russia.
Also at Physics Dept, University of South Africa, Pretoria; South Africa.
Also at Physikalisches Institut, Albert-Ludwigs-Universität Freiburg, Freiburg; Germany.
Also at School of Physics, Sun Yat-sen University, Guangzhou; China.
Also at The City College of New York, New York NY; United States of America.
Also at The Collaborative Innovation Center of Quantum Matter (CICQM), Beijing; China.
Also at Tomsk State University, Tomsk, and Moscow Institute of Physics and Technology State University, Dolgoprudny; Russia.
Also at TRIUMF, Vancouver BC; Canada.
Also at Universita di Napoli Parthenope, Napoli; Italy.
* Deceased