Measurements of $W$ and $Z$ boson production in $pp$ collisions at $\sqrt{s} = 5.02$ TeV with the ATLAS detector

The ATLAS Collaboration

Measurements of fiducial integrated and differential cross sections for inclusive $W^+$, $W^-$ and $Z$ boson production are reported. They are based on $25.0 \pm 0.5$ pb$^{-1}$ of $pp$ collision data at $\sqrt{s} = 5.02$ TeV collected with the ATLAS detector at the CERN Large Hadron Collider. Electron and muon decay channels are analysed, and the combined $W^+$, $W^-$ and $Z$ integrated cross sections are found to be $\sigma_{W^+} = 2266 \pm 9$ (stat) $\pm 29$ (syst) $\pm 43$ (lumi) pb, $\sigma_{W^-} = 1401 \pm 7$ (stat) $\pm 18$ (syst) $\pm 27$ (lumi) pb, and $\sigma_Z = 374.5 \pm 3.4$ (stat) $\pm 3.6$ (syst) $\pm 7.0$ (lumi) pb, in good agreement with next-to-next-to-leading-order QCD cross-section calculations. These measurements serve as references for Pb+Pb interactions at the LHC at this nucleon–nucleon centre-of-mass energy.
1 Introduction

Measurements of $W^\pm$ and $Z$ boson production at hadron colliders provide a benchmark for the understanding of quantum chromodynamics (QCD) and electroweak (EW) processes. Predictions for the differential and fiducial cross sections are available up to next-to-next-to-leading-order (NNLO) accuracy in QCD and include EW corrections at next-to-leading-order (NLO) accuracy [1–3]. The rapidity distribution of EW boson production is sensitive to the underlying QCD dynamics and, in particular, to the parton distribution functions (PDFs) which define the initial kinematics of the hard process. Therefore, measurements of weak-boson production offer an excellent opportunity to test models of parton dynamics.

The ATLAS, CMS and LHCb collaborations have measured $W^\pm$ and $Z$ boson production in proton–proton ($pp$) collisions at centre-of-mass energies of $\sqrt{s} = 7$, 8 and 13 TeV [4–7]. These measurements provide precision tests of the QCD theory and PDFs, which can be complemented with measurements at the additional centre-of-mass energy $\sqrt{s} = 5.02$ TeV.

This paper describes measurements of the production cross sections times leptonic branching ratios for the inclusive $W^+ \to \ell^+\nu$, $W^- \to \ell^-\nu$ and $Z \to \ell^+\ell^-$ ($\ell = e, \mu$) processes. Integrated and differential cross sections are measured in a fiducial phase space defined by detector acceptance and lepton kinematics. For $W^\pm$ bosons the decay lepton charge asymmetry is also determined. All measurements are performed with $pp$ collision data corresponding to an integrated luminosity of $25.0 \text{ pb}^{-1}$, collected at $\sqrt{s} = 5.02$ TeV with the ATLAS detector. The data were recorded during the autumn of 2015. The peak instantaneous luminosity delivered by the LHC was $L = 3.8 \times 10^{32} \text{ cm}^{-2}\text{s}^{-1}$ and the mean number of $pp$ interactions per bunch crossing (hard scattering and pile-up events) was 1.5. Therefore, this dataset is characterised by a relatively low pile-up contribution as compared to the measurements of weak-boson production performed at higher centre-of-mass energies by ATLAS.

In addition, the measurement of $W^\pm$ and $Z$ boson production in $pp$ collisions at the centre-of-mass energy $\sqrt{s} = 5.02$ TeV is an important reference for weak-boson production in heavy-ion collisions. The LHC has provided both proton–lead ($p+$Pb) and lead–lead (Pb+Pb) collisions at the centre-of-mass energy per nucleon pair $\sqrt{s_{\text{NN}}} = 5.02$ TeV. Published results from the ATLAS and CMS collaborations are currently available for $W^\pm$ and $Z$ boson production [8–11] in Pb+Pb collisions at $\sqrt{s_{\text{NN}}} = 2.76$ TeV and $Z$ boson production [12, 13] in the $p+$Pb system at $\sqrt{s_{\text{NN}}} = 5.02$ TeV.

2 The ATLAS detector

The ATLAS experiment [14] is a multipurpose particle detector with a forward–backward symmetric cylindrical geometry. It consists of an inner tracking detector surrounded by a thin superconducting solenoid, electromagnetic and hadronic calorimeters, and a muon spectrometer incorporating three large superconducting air-core toroid magnets with eight coils each.

The inner-detector system (ID) is immersed in a 2 T axial magnetic field and provides charged-particle tracking in the pseudorapidity range $|\eta| < 2.5$. At small radii, a high-granularity silicon pixel detector

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1 Throughout this paper, $Z/\gamma^*$ boson production is referred to as $Z$ boson production.

2 ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point (IP) in the centre of the detector and the $z$-axis along the beam pipe. The $x$-axis points from the IP to the centre of the LHC ring, and the $y$-axis points upward. Cylindrical coordinates $(r, \phi)$ are used in the transverse plane, $\phi$ being the azimuthal angle around the $z$-axis. The pseudorapidity is defined in terms of the polar angle $\theta$ as $\eta = -\ln \tan(\theta/2)$. 
covers the interaction region and typically provides four measurements per track. It is followed by the silicon microstrip tracker, which usually provides eight measurement points per track. These silicon detectors are complemented by a gas-filled straw-tube transition radiation tracker, which enables track reconstruction up to $|\eta| = 2.0$. The transition radiation tracker also provides electron identification information based on the fraction of hits (out of ~ 35 in total) with an energy deposit above a threshold indicative of transition radiation.

The calorimeter system covers the pseudorapidity range $|\eta| < 4.9$. Within the region $|\eta| < 3.2$, electromagnetic (EM) calorimetry is provided by high-granularity lead/liquid-argon (LAr) calorimeters, with an additional thin LAr presampler covering $|\eta| < 1.8$ to correct for upstream energy-loss fluctuations. The EM calorimeter is divided into a barrel section covering $|\eta| < 1.475$ and two endcap sections covering $1.375 < |\eta| < 3.2$. For $|\eta| < 2.5$ it is divided into three layers in depth, which are finely segmented in $\eta$ and $\phi$. Hadronic calorimetry is provided by a steel/scintillator-tile calorimeter, segmented into three barrel structures within $|\eta| < 1.7$ and two copper/LAr hadronic endcap calorimeters covering $1.5 < |\eta| < 3.2$. The solid-angle coverage is completed with forward copper/LAr and tungsten/LAr calorimeter modules in $3.1 < |\eta| < 4.9$, optimised for electromagnetic and hadronic measurements, respectively.

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The muon spectrometer (MS) comprises separate trigger and high-precision tracking chambers measuring the deflection of muons in the magnetic field generated by the toroid magnets. 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 region. The muon trigger system covers the range $|\eta| < 2.4$ with resistive plate chambers in the barrel, and thin gap chambers in the endcap regions.

In 2015, the ATLAS detector had a two-level trigger system [15]. The level-1 trigger is implemented in hardware and uses a subset of detector information to reduce the event rate to a value of at most 75 kHz. This is followed by a software-based high-level trigger which reduces the event rate to about 1 kHz.

### 3 Simulated event samples

Samples of Monte Carlo (MC) simulated events are used to evaluate the selection efficiency for signal events and the contribution of several background processes to the analysed dataset. All of the samples are processed with the Geant4-based simulation [16, 17] of the ATLAS detector. Dedicated efficiency and calibration studies with data are used to derive correction factors to account for residual differences between experiment and simulation, as is subsequently described.

The processes of interest, specifically events containing $W^\pm$ or $Z$ bosons, were generated with the Powheg-Box v2 MC program [18] interfaced to the Pythia 8.186 parton shower model [19]. The CT10 PDF set [20] was used in the matrix element, while the CTEQ6L1 PDF set [21] was used with the AZNLO [22] set of generator-parameter values (tune) for the modelling of non-perturbative effects in the initial-state parton shower. The Photos++ v3.52 program [23] was used for QED radiation from electroweak vertices and charged leptons. Samples of top-quark pair ($t\bar{t}$) and single-top-quark production were generated with the Powheg-Box v2 generator, which uses NLO matrix element calculations together with the CT10f4 PDF set [24]. Top-quark spin correlations were preserved for all top-quark processes. The parton shower, fragmentation, and underlying event were simulated using Pythia 6.428 [25] with the CTEQ6L1 PDF set and the corresponding Perugia 2012 tune (P2012) [26]. The top-quark mass was set to 172.5 GeV. The EvtGen v1.2.0 program [27] was used to model bottom and charm hadron decays for all versions of Pythia. Diboson processes were simulated using the Sherpa v2.1.1 generator [28]. They were calculated for up to...
one (ZZ) or zero (WW, WZ) additional partons at NLO QCD accuracy and up to three additional partons at LO. In addition, the Sherpa diboson sample cross section is scaled to account for the cross section change when the $G_{\mu}$ scheme [29] is used instead of the native one for the EW parameters, resulting in an effective value of $\alpha \approx 1/132$. Multiple overlaid $pp$ collisions were simulated with the soft QCD processes of Pythia v8.186 using the A2 tune [30] and the MSTW2008LO PDF set [31]. For the comparison with data in differential distributions and the evaluation of single-boson EW backgrounds for the cross-section calculations, the single-boson simulations are normalised to the results of NNLO QCD calculations [2, 3], with uncertainties of 3%. The simulations of all other processes are normalised to the predictions of NLO QCD calculations, with uncertainties of 10% for the diboson and top-quark processes.

4 Object definitions and event selection

This section describes the reconstruction of electrons, muons and hadronic recoil objects, and the selection of $W$ and $Z$ bosons. Candidate events are required to have at least one primary vertex reconstructed from at least three tracks with $p_T > 400$ MeV and to pass a trigger selection, which requires a single electron or muon candidate with a $p_T$ threshold of 15 GeV or 14 GeV, respectively. In addition, a loose likelihood-based identification requirement [32, 33] is applied in the electron trigger.

Electron candidates are required to have $p_T > 20$ (25) GeV in the $Z$ ($W$) boson analysis and $|\eta| < 2.47$. Candidates within the transition region between barrel and endcap calorimeters (1.37 < $|\eta|$ < 1.52) are rejected. In addition, medium likelihood-based identification and tight isolation requirements are applied [32, 33]. Muon candidates must satisfy $p_T > 20$ (25) GeV in the $Z$ ($W$) boson analysis and $|\eta| < 2.4$ and pass the requirements of medium identification and tight isolation [34]; both criteria were optimised for 2015 analysis conditions.

Additional requirements are imposed on the significance of the transverse impact parameter, $d_0$, such that $|d_0|/\sigma_{d_0} < 5$ (3) for electron (muon) candidates. To ensure that lepton candidates originate from the primary vertex, a requirement is also placed on the longitudinal impact parameter, $z_0$, multiplied by the sine of the track polar angle, $\theta$, such that the absolute value is smaller than 0.5 mm.

Events with $Z$ boson candidates are selected by requiring exactly two opposite-charge electrons or muons, at least one of which is matched to a lepton selected at trigger level. The dilepton invariant mass must satisfy the fiducial requirement $66 < m_{\ell\ell} < 116$ GeV.

Events with $W$ boson candidates are selected by requiring exactly one electron or muon that is matched to a lepton selected at trigger level. In events where a $W$ boson is produced and decays leptonically, the full event kinematic reconstruction is not possible due to the presence of an (anti-)neutrino that escapes direct detection. A measure of the missing transverse momentum corresponding to the neutrino, $p_T^\nu$, can be inferred from information about the hadronic system recoiling against the $W$ boson. The hadronic recoil is the vector sum of all calorimeter energy clusters excluding the deposits from the decay muon or electron, and is further described below. The transverse projection of the recoil onto the $r$–$\phi$ plane, $\vec{u}_T$, is used together with the decay lepton transverse momentum $\vec{p}_T^\ell$ for the calculation of the missing transverse momentum vector,

$$\vec{E}_T^{\text{miss}} = - \left( \vec{u}_T + \vec{p}_T^\ell \right),$$
whose magnitude is denoted $E_{\text{miss}}^T$. The transverse mass of the lepton-$E_{\text{miss}}^T$ system is defined as

$$m_T = \sqrt{2p_T^\ell E_{\text{miss}}^T \left(1 - \cos \Delta \phi_{\ell, E_{\text{miss}}^T}\right)}$$

where $\Delta \phi_{\ell, E_{\text{miss}}^T}$ is the azimuthal angle between $\vec{p}_T^\ell$ and $\vec{E}_{\text{miss}}^T$.

Fiducial selections $E_{\text{miss}}^T > 25$ GeV and $m_T > 40$ GeV, optimised for the multi-jet background reduction, are required for events with $W$ boson candidates.

The general structure of the algorithm used for hadronic recoil reconstruction is introduced in Ref. [35], where three-dimensional topological clusters [36] calibrated at the hadronic scale are used as inputs to the algorithm. In this measurement, the hadronic recoil is reconstructed using particle flow objects [37] as inputs. The ATLAS particle flow algorithm provides an improved $E_{\text{miss}}^T$ resolution compared to the algorithm using only topological clusters, and makes the measurement less sensitive to pile-up by separating the charged-hadron contribution from the neutral hadronic activity [37]. The charged activity is measured by the ID and the related tracks from charged hadrons can be matched to a vertex. From all charged hadrons, only calorimetric clusters associated with a track originating from the reconstructed primary vertex are retained as input to the hadronic recoil algorithm. The neutral hadronic activity is represented by clusters without an associated track, and is also used in the recoil algorithm.

5 Detector performance corrections

5.1 Lepton calibration and efficiency

The electron energy calibration is primarily obtained from the simulation by employing multivariate techniques [38]. The signal $Z \rightarrow ee$ MC simulation is used for deriving the data energy scale calibration and resolution corrections for the simulation. The energy resolution is corrected with additional factors no larger than about 1% in the barrel and up to 2% in the endcap region of the detector in order to account for a slightly worse resolution observed in the data. The energy scale is corrected by applying a per-electron energy scale factor to the data derived from a comparison of the electron-pair invariant mass between the simulation and the data. This procedure was found to be sensitive to the pile-up distribution in data due to different settings used for the signal readout from the EM calorimeters [39]. Therefore, a special set of scale correction factors was derived for this dataset.

Electron candidates used for the analysis are required to satisfy selection criteria related to reconstruction, identification, isolation and trigger. For each of these requirements, the efficiency of the selection is measured in data with the tag-and-probe method in $Z \rightarrow e^+e^-$ events, as described in Ref. [33], and compared with the simulation. Data-to-simulation ratios of efficiencies are used as scale factors to correct the simulation for the observed differences. Measurements are performed as a function of the electron $p_T$ and $\eta$ for electrons selected in the analysis. All uncertainties related to efficiency are classified as either correlated or uncorrelated, and are propagated accordingly to the final measurement uncertainty.

The electron reconstruction efficiency is in the range 95–99% both in the data and simulation and is typically measured with a precision of 2%. The data-to-simulation ratio is up to 2% (5%) different.
from unity in the barrel (endcap) calorimeter and is measured typically with 2% precision for \( p_T \) in the range \( \sim 30–50 \text{ GeV} \) and 5% for \( p_T > 60 \text{ GeV} \). The efficiency of an electron to further pass the medium identification definition varies from 85% to 95% and is measured with 2% precision. This efficiency differs from the efficiency measured in the MC simulation by up to 5%. The isolation efficiency is measured with a precision of 5% and agrees with the simulated value within 2%. Data-to-simulation correction factors for identification and isolation efficiencies are measured with a precision of 2–6%. Finally, the trigger efficiency data-to-simulation ratio is found to deviate from unity by 0.5–3% and is measured with a precision of up to 2%.

Various selection requirements related to muon trigger, reconstruction, identification and isolation are imposed on muon candidates used in the analysis. The efficiency of the selection criteria is measured in data with the tag-and-probe method in \( Z \rightarrow \mu^+\mu^- \) events \([15, 34]\) and compared with the simulation. Ratios of the efficiencies determined in data and simulation are applied as scale factors to correct the simulated events. For muons with \( p_T > 20 \text{ GeV} \), the correction factors measured as a function of muon \( p_T \) have typically an uncertainty of 1–2% and do not deviate from a constant value by more than 3%. Therefore, the \( p_T \) dependence of the scale factors is neglected, and they are evaluated only as a function of muon \( \eta \).

The muon trigger efficiency in the endcap region of the detector (\( 1.05 < |\eta| < 2.4 \)) is measured to be around 90%, and the values obtained in data and simulation agree well. However, in the barrel region (\( |\eta| < 1.05 \)) the trigger efficiency determined in the simulation varies from 70% to 85%, while the efficiency measured in data is lower by 5–15%, which results in sizeable scale factors. The combined reconstruction and identification efficiency for medium-quality muons typically exceeds 99% in both the data and simulation with good agreement between the two measurements. The efficiency of the isolation selection is found to be 97–98% in the MC simulation and it differs from the efficiency measured in the data by about 2% in the most central (\( |\eta| < 0.6 \)) and most forward detector regions (\( 1.74 < |\eta| < 2.4 \)).

All measurements of lepton efficiency corrections are limited in their precision by the number of \( Z \rightarrow \ell^+\ell^- \) candidates available in the \( \sqrt{s} = 5.02 \text{ TeV} \) dataset.

Figure 1 summarises the reconstruction, identification, isolation and trigger efficiencies for electron and muon candidates obtained from the tag-and-probe method.

Figure 2 shows the invariant mass distribution of the dilepton system for electron and muon candidates from \( Z \rightarrow \ell^+\ell^- \) boson decays after applying scale factors to the MC simulation. The data points are compared with simulation including \( Z \) boson signal and background components. The electron candidates in the data, shown on the left panel, are calibrated using calorimeter settings and calibration correction factors optimised for low-pile-up conditions. Good agreement between the data and the simulation is found for both channels.

### 5.2 Recoil calibration

In events with \( W \) or \( Z \) boson production, the hadronic recoil gives a measure of the boson transverse momentum. The calibration of the recoil is performed using dilepton events from decays of \( Z \) bosons produced in \( pp \) collisions at \( \sqrt{s} = 5.02 \text{ TeV} \), as information about the \( Z \) boson transverse momentum can be obtained with high precision from the measurements of lepton momenta and compared with the measurement from hadronic recoil. The recoil resolution is studied using \( u_\perp \), the projection of \( \vec{u}_T \) onto the axis – in the transverse plane – perpendicular to the \( Z \) boson \( \vec{p}_T \). The resolution is given by the standard
deviation of the $u_\perp$ distribution, $\sigma_{u_\perp}$. The transverse momentum scale response of the recoil can be studied using the bias defined as $u_\parallel + p_T^Z$, where $u_\parallel$ is the projection of $u_T$ onto the axis defined by $p_T^Z$, and is quantified via the average of the bias distribution. Differences between the responses in data and simulation are less than $\sim 2$ GeV, while up to $\sim 20\%$ differences in the resolution are observed.

Following the procedure described in Ref. [35], in situ corrections to the resolution and the scale of $u_T$ are obtained in $Z$ events and are applied to the $W$ boson event candidates, as a function of $p_T^W$. The corrections
Equation (1) describes corrections applied to the recoil response in simulation. It includes a shift which brings the average value of $u_{\parallel}$ in the simulation closer to the one in data, taking into account differences in the bias. In addition, it corrects the response distribution for resolution differences (last term in the equation). The resolution correction is directly described by Eq. (2) where it is applied to the $u_{\perp}$ distribution in the simulation. The impact of the calibration on the scale and resolution in events where a $Z$ boson decays to a dimuon pair is shown in Figure 3. The distributions are shown for the simulation before and after applying the corrections and for data. Agreement of the distributions from simulation with data distributions is improved after applying the calibration, and residual differences are covered by the systematic uncertainties described in Section 8.

Figure 3: Distributions of (a) $u_{\parallel} + p_{T}^{Z}$ and (b) $u_{\perp}$ in data and $Z \rightarrow \mu^{+}\mu^{-}$ MC simulation before (squares) and after (circles) recoil calibration. The shaded band in the ratio panels represents the statistical uncertainty of the data sample, while the error bars represent the systematic uncertainty associated with the calibration procedure.

6 Background determination

6.1 $W$ channels

The reported cross-section measurements correspond to inclusive Drell–Yan production of single vector bosons which decay leptonically. Background processes that contribute to the $W^{\pm}$ boson production
measurement are EW processes producing $W^\pm \rightarrow \tau^\pm \nu$, $Z \rightarrow \ell^+ \ell^-$, $Z \rightarrow \tau^+ \tau^-$ decays, EW diboson (WW, WZ, ZZ) production, as well as top-quark production and multi-jet processes. The multi-jet background includes various processes such as semileptonic decays of heavy-flavour hadrons or in-flight decays of kaons and pions for the muon channel, as well as photon conversions or misidentified hadrons for the electron channel. The background contributions from EW and top-quark production are evaluated using simulated event samples, while the multi-jet contribution is estimated with a data-driven method similar to the one described in Ref. [5].

Although multi-jet background events are well rejected by the lepton isolation requirements, their contribution to the signal region is still sizeable because of the very large production cross sections for multi-jet processes. This contribution is estimated from template fits to data in kinematic distributions: lepton $p_T$, $E_T^{miss}$ and $m_T$. The fits are performed in a phase-space region defined by the full event selection with a looser lepton $p_T$ requirement of $p_T > 20$ GeV and with the requirements on $E_T^{miss}$ and $m_T$ removed. An additional requirement on the transverse component of the hadronic recoil, $u_T < 30$ GeV, is placed to ensure better agreement of the event kinematics between the fit region and the signal region.

Template distributions for signal, EW and top-quark background processes are constructed by applying the fit-region selection to samples of simulated events. Templates enriched in contributions from multi-jet processes are built using events in data with non-isolated leptons selected by inverting the isolation requirement described in Section 4. The normalisation factors of template distributions for signal, EW and top-quark backgrounds, as well as the multi-jet background, are extracted from a fit to the data. The fits are repeated with multi-jet background templates constructed from different intervals in a track-based (muon channel) or calorimeter-based (electron channel) isolation variable. Finally, a linear extrapolation to the signal region is performed as a function of the selected isolation variable, accounting also for the difference in kinematic selections between the fit region and the signal region.

Following this procedure, multi-jet background processes are estimated to contribute around 0.9% of the $W^+ \rightarrow e^+ \nu$ sample and 1.4% of the $W^- \rightarrow e^- \nu$ sample, while in the muon channel they represent around 0.1% of the $W^+ \rightarrow \mu^+ \nu$ sample and 0.2% of the $W^- \rightarrow \mu^- \nu$ sample.

Figure 4: Distributions of $E_T^{miss}$ used to extract multi-jet yields in the (a) electron and (b) muon channels after performing the template fits. Only the statistical uncertainties of the data are shown.
The largest background contributions to the decay modes studied come from the production of single EW bosons decaying via other decay channels. The $Z \rightarrow e^+e^-$ background represents 0.1% of the $W^+ \rightarrow e^+\nu$ sample and 0.2% of the $W^- \rightarrow e^-\nu$ sample, while the $Z \rightarrow \mu^+\mu^-$ background amounts to 2.8% and 3.8% in the $W^+ \rightarrow \mu^+\nu$ and $W^- \rightarrow \mu^-\nu$ samples, respectively. The $W^\pm \rightarrow \tau^\pm\nu$ background contributes around 1.8% to the samples selected in both channels and the $Z \rightarrow \tau^+\tau^-$ background contributes approximately 0.1%. Contributions from top-quark production ($t\bar{t}$ and single top quarks) are estimated to be at the level of 0.1–0.2% in both channels. Similarly, diboson processes represent approximately 0.1% of the selected event samples.

Figures 5 and 6 show detector-level lepton pseudorapidity distributions for positive and negative electron and muon candidates from $W$ boson decays. Good agreement is found between the data and the sum of signal and background contributions.
6.2 Z channels

Background contributions to the Z boson sample are expected from $Z \rightarrow \tau^+\tau^-$, diboson and $W$ boson decay processes, top-quark pair production, and the multi-jet background. The EW and top-quark contributions are evaluated from dedicated simulation samples, whereas the upper limit on the amount of the multi-jet background is estimated.

Diboson background contributes 0.08% in the muon channel and 0.14% in the electron channel. The $Z \rightarrow \tau^+\tau^-$ background is found to be at the level of 0.07% in both decay channels. The top-quark background is at the level of 0.06% in the electron channel and 0.08% in the muon channel. The $W$ boson background is found to be below 0.01% in both channels.

The contribution of the multi-jet background in the muon channel is estimated from samples that simulate $b\bar{b}$ and $c\bar{c}$ production. The study yields an estimate at the level of <0.01%. A previous ATLAS measurement at $\sqrt{s} = 7$ TeV [4] estimated the multi-jet contribution at the level of 0.02–0.15% for the electron channel and 0.09% for the muon channel. As it is expected that this contribution increases with pile-up and since that measurement was done with higher pile-up than the current analysis, the multi-jet background is considered to be negligible in this analysis.

![Figure 7](image_url)

Figure 7: Detector-level lepton-pair rapidity distributions in the (a) electron and (b) muon channels. Background contributions are negligible using a linear scale. Only the statistical uncertainties of the data are shown.

Figure 7 shows detector-level dilepton rapidity distributions for electron and muon candidates from Z boson decays. Good agreement is found between the data and the sum of signal and background contributions.

Table 1 summarises background contributions to the $W^+$, $W^-$ and Z boson candidate samples.

7 Measurement procedure

The integrated and differential $W$ and Z boson production cross sections are measured within a fiducial phase space defined as follows:

- for $W$ production: $p_T^\ell > 25$ GeV, $p_T^{\mu} > 25$ GeV, $|\eta_\ell| < 2.5$, $m_T > 40$ GeV
Table 1: Background contributions as a percentage of the total for the $W^+$, $W^-$ and $Z$ candidate samples in the electron (muon) channels.

<table>
<thead>
<tr>
<th>Background</th>
<th>$W^+ \rightarrow e^+\nu$ ($W^+ \rightarrow \mu^+\nu$) [%]</th>
<th>$W^- \rightarrow e^-\nu$ ($W^- \rightarrow \mu^-\nu$) [%]</th>
<th>$Z \rightarrow e^+e^-$ ($Z \rightarrow \mu^+\mu^-$) [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z \rightarrow \ell^+\ell^-$, $\ell = e, \mu$</td>
<td>0.1 (2.8)</td>
<td>0.2 (3.8)</td>
<td>–</td>
</tr>
<tr>
<td>$W^\pm \rightarrow \ell^\pm\nu$, $\ell = e, \mu$</td>
<td>–</td>
<td>–</td>
<td>&lt;0.01 (&lt;0.01)</td>
</tr>
<tr>
<td>$W^\pm \rightarrow \tau^\pm\nu$</td>
<td>1.8 (1.8)</td>
<td>1.8 (1.8)</td>
<td>&lt;0.01 (&lt;0.01)</td>
</tr>
<tr>
<td>$Z \rightarrow \tau^+\tau^-$</td>
<td>0.1 (0.1)</td>
<td>0.1 (0.1)</td>
<td>0.07 (0.07)</td>
</tr>
<tr>
<td>Multi-jet</td>
<td>0.9 (0.1)</td>
<td>1.4 (0.2)</td>
<td>&lt;0.01 (&lt;0.01)</td>
</tr>
<tr>
<td>Top quark</td>
<td>0.1–0.2 (0.1–0.2)</td>
<td>0.1–0.2 (0.1–0.2)</td>
<td>0.06 (0.08)</td>
</tr>
<tr>
<td>Diboson</td>
<td>0.1 (0.1)</td>
<td>0.1 (0.1)</td>
<td>0.14 (0.08)</td>
</tr>
</tbody>
</table>

- for $Z$ production: $p_T^\ell > 20$ GeV, $|\eta_\ell| < 2.5$, $66 < m_{\ell\ell} < 116$ GeV.

Integrated fiducial cross sections in the electron and muon channels are calculated using:

$$
\sigma_{\text{fid}, W^\pm \rightarrow \ell^\pm\nu[Z \rightarrow \ell^+\ell^-]} = \frac{N_{W[Z]} - B_{W[Z]}}{C_{W[Z]} \cdot L_{\text{int}}},
$$

where $N_{W[Z]}$ and $B_{W[Z]}$ are the number of selected events in data and the expected number of background events, respectively. The integrated luminosity of the sample is $L_{\text{int}} = 25.0 \pm 0.5$ pb$^{-1}$, determined with the method described in Ref. [40]. A correction for the event detection efficiency is applied with the factor $C_{W[Z]}$, which is obtained from the signal simulation as:

$$
C_{W[Z]} = \frac{N_{W[Z]}^{\text{MC, sel}}}{N_{W[Z]}^{\text{MC, fid}}},
$$

Here, $N_{W[Z]}^{\text{MC, sel}}$ is the number of events which pass the signal selection at the detector level, corrected for the observed differences between data and simulation such as in reconstruction, identification, isolation, and trigger efficiencies. The denominator $N_{W[Z]}^{\text{MC, fid}}$ is computed applying the fiducial requirements to the generator-level leptons originating from $W$ and $Z$ boson decays. The measurement is corrected for QED final-state radiation effects by applying these requirements to the lepton momenta before photon radiation.

The uncertainty associated with the $C_{W[Z]}$ correction is dominated by experimental systematic uncertainties, described in Section 8. Uncertainties in $C_{W[Z]}$ of theoretical origin comprise uncertainties induced by the PDFs, by the description of the $W$ and $Z$ boson transverse momentum distributions, by the implementation of the NLO QCD matrix element and its matching to the parton shower, and by the modelling of the parton shower, hadronisation and underlying event. These uncertainties are discussed in Ref. [4], where they are evaluated to be smaller than 0.2% and thus are negligible at the present level of precision.

The procedure described above is extended to the measurement of differential cross sections as a function of the decay lepton pseudorapidity in $W$ boson production, and as a function of the lepton-pair rapidity in $Z$ boson production. The dependence of cross sections on these kinematic variables is particularly sensitive to the choice of PDFs. For $W$ production, following Ref. [4], the lepton $|\eta|$ boundaries are defined as:

- 0 – 0.21 – 0.42 – 0.63 – 0.84 – 1.05 – 1.37 – 1.74 – 1.95 – 2.18 – 2.50;
Table 2: Correction factors $C_{W|Z}$ used to calculate integrated and differential $W$ and $Z$ boson production cross sections. The integrated $C_{W|Z}$ factors are shown with the sum in quadrature of statistical and systematic uncertainties. For the differential $C_{W|Z}$ factors, the spread of values across lepton $|\eta|$ or $|y_{\ell\ell}|$ intervals is shown.

<table>
<thead>
<tr>
<th>Channel</th>
<th>$C_W (W^+ \rightarrow e^+\nu)$</th>
<th>$C_W (W^- \rightarrow e^-\nu)$</th>
<th>$C_Z$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Integrated cross-section measurements</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electron channel</td>
<td>$0.657 \pm 0.006$</td>
<td>$0.667 \pm 0.005$</td>
<td>$0.522 \pm 0.007$</td>
</tr>
<tr>
<td>Muon channel</td>
<td>$0.723 \pm 0.011$</td>
<td>$0.720 \pm 0.010$</td>
<td>$0.780 \pm 0.007$</td>
</tr>
<tr>
<td>Differential cross-section measurements</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Electron channel</td>
<td>$0.55$–$0.80$</td>
<td></td>
<td>$0.52$–$0.62$</td>
</tr>
<tr>
<td>Muon channel</td>
<td>$0.55$–$0.85$</td>
<td></td>
<td>$0.60$–$0.82$</td>
</tr>
</tbody>
</table>

for $Z$ boson production, the lepton-pair $|y_{\ell\ell}|$ boundaries are defined as:

- $0$ – $0.5$ – $1.0$ – $1.5$ – $2.0$ – $2.5$.

For the measurement of these cross sections, the $C_{W|Z}$ factors are computed separately for each lepton $|\eta|$ or $|y_{\ell\ell}|$ interval by applying the corresponding requirements on the reconstructed lepton kinematics in the numerator, and on the generator-level kinematics in the denominator. Migrations between rapidity intervals are negligible due to the very good angular resolution with which charged-particle tracks associated with leptons are reconstructed, and the good lepton momentum and energy resolutions. The $C_{W|Z}$ factors for the measurements of integrated and differential cross sections are summarised in Table 2.

8 Measurement uncertainties

8.1 Lepton calibration and efficiency corrections

Uncertainties in the determination of lepton trigger, reconstruction, identification and isolation efficiency scale factors affect the measurements through the correction factors $C_{W|Z}$.

The uncertainties of the electron efficiency measurements are propagated to the cross-section measurements with separate contributions from reconstruction, identification, trigger and isolation efficiencies. For the $W^\pm \rightarrow e^\pm\nu$ channels the efficiency determination contributes a systematic uncertainty of 0.8% to the fiducial cross-section measurements, while for the $Z \rightarrow e^+e^-$ channel this contribution is 1.3%. Systematic effects related to the electron $p_T$ scale and resolution are subdominant, yielding an uncertainty at the level of 0.3% for the $W^\pm \rightarrow e^\pm\nu$ channels and less than 0.2% for the $Z \rightarrow e^+e^-$ channel. Uncertainties in the modelling of the electron charge identification are at the level of 0.1%, and neglected for the cross section measurements. Their impact on the asymmetry measurements is however sizeable and included in the final results.

In the muon channels, the statistical components of the scale factor uncertainties are propagated to the measurements via MC pseudo-experiments, while systematic components are propagated as a single variation fully correlated across all muon $|\eta|$ intervals. The single largest contribution to the systematic uncertainty of fiducial cross-section measurements in the $W^\pm \rightarrow \mu^\pm\nu$ channels is 1.4% and comes from the determination of the muon trigger efficiency. For measurements in the $Z \rightarrow \mu^+\mu^-$ channel the largest systematic uncertainty is contributed by the muon isolation efficiency measurement and amounts to 0.7%.

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Uncertainties coming from the muon $p_T$ scale and resolution are below 0.2% for both $W^\pm \rightarrow \mu^\pm\nu$ channels and the $Z \rightarrow \mu^+\mu^-$ channel.

### 8.2 Hadronic recoil corrections

The uncertainty assigned to the hadronic recoil calibration is conservatively defined from the full size of the corrections, which are derived using events with Z boson production. In these events, the impact of the correction on the $u_\perp$ and $u_\parallel + p_T^Z$ distributions varies between a few percent and $\sim 20\%$ in the range $[-15, +15]$ GeV, which dominates the reported cross-section measurements. After applying this correction to events with $W^+$ and $W^-$ production, the resulting uncertainties on the cross-section measurements are at the level of 0.5% for both the muon and electron channels.

### 8.3 Background evaluation

Uncertainties in the evaluation of EW and top-quark backgrounds in the $W^\pm \rightarrow e^\pm\nu$ and $W^\pm \rightarrow \mu^\pm\nu$ channels are estimated by varying the respective normalisation cross sections. For single-boson production, the size of the cross-section variations is obtained from higher-order QCD calculations, while for diboson and top-quark processes the uncertainty in the cross sections is conservatively taken as 10%. The resulting uncertainties in the measurements in both the $W^\pm \rightarrow e^\pm\nu$ and $W^\pm \rightarrow \mu^\pm\nu$ channels are below 0.2%. Uncertainties related to the multi-jet background evaluation arise from the statistical precision of the multi-jet templates and uncertainty in the normalisations of the subtracted EW and top-quark contamination. These contributions are propagated through linear extrapolations over the isolation variables to the signal region. The related uncertainties in the measurements are evaluated to be 0.7–0.8% in the $W^\pm \rightarrow e^\pm\nu$ channels and not more than 0.2% in the $W^\pm \rightarrow \mu^\pm\nu$ channels.

In both the $Z \rightarrow \mu^+\mu^-$ and $Z \rightarrow e^+e^-$ channels, the uncertainty associated with the background subtraction is negligible, since all individual background contributions are below 0.2% of the selected data sample.

### 8.4 Luminosity calibration

Luminosity measurements in ATLAS are calibrated using dedicated van der Meer scans [40]. The analysis of data from the scan performed in $pp$ collisions at $\sqrt{s} = 5.02$ TeV, which uses the LUCID-2 detector for the baseline luminosity measurements [41], yields a relative systematic uncertainty of 1.9% in the measured luminosity.

### 9 Results

#### 9.1 Channel combination

Results of measurements in the electron and muon channels are summarised in Table 3 for $W^+$ boson production, Table 4 for $W^-$ boson production and Table 5 for $Z$ boson production. In these tables, the statistical uncertainty is defined from the variance of the background-subtracted number of observed events, and the systematic uncertainty includes all uncertainty components described above, except for
Table 3: Measured fiducial $W^+ \rightarrow \ell^+ \nu$ differential and integrated cross sections for electron and muon channels.

| $|\eta_\ell|_{\text{min}}$ | $|\eta_\ell|_{\text{max}}$ | $d\sigma/d|\eta_\ell|$ $d\sigma_{\text{stat}}$ $d\sigma_{\text{syst}}$ $d\sigma_{\text{lumi}}$ | $W^+ \rightarrow e^+ \nu$ $d\sigma/d|\eta_\ell|$ $d\sigma_{\text{stat}}$ $d\sigma_{\text{syst}}$ $d\sigma_{\text{lumi}}$ | $W^+ \rightarrow \mu^+ \nu$ $d\sigma/d|\eta_\ell|$ $d\sigma_{\text{stat}}$ $d\sigma_{\text{syst}}$ $d\sigma_{\text{lumi}}$ |
|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|
| 0.00 | 0.21 | 448 | 8 | 10 | 8 | 473 | 9 | 15 | 9 |
| 0.21 | 0.42 | 463 | 8 | 10 | 9 | 472 | 8 | 11 | 9 |
| 0.42 | 0.63 | 453 | 8 | 10 | 9 | 493 | 8 | 11 | 9 |
| 0.63 | 0.84 | 460 | 8 | 10 | 9 | 460 | 9 | 12 | 9 |
| 0.84 | 1.05 | 466 | 9 | 11 | 9 | 478 | 9 | 13 | 9 |
| 1.05 | 1.37 | 469 | 7 | 10 | 9 | 478 | 6 | 10 | 9 |
| 1.37 | 1.52 | – | – | – | – | 482 | 9 | 12 | 9 |
| 1.52 | 1.74 | 460 | 9 | 14 | 9 | 482 | 7 | 10 | 9 |
| 1.74 | 1.95 | 454 | 9 | 14 | 8 | 472 | 8 | 10 | 9 |
| 1.95 | 2.18 | 453 | 9 | 14 | 8 | 443 | 7 | 10 | 9 |
| 2.18 | 2.50 | 370 | 7 | 14 | 7 | 371 | 7 | 9 | 7 |
| 0.00 | 2.50 | 2243 | 13 | 27 | 42 | 2303 | 12 | 36 | 44 |

Table 4: Measured fiducial $W^- \rightarrow \ell^- \nu$ differential and integrated cross sections for electron and muon channels.

| $|\eta_\ell|_{\text{min}}$ | $|\eta_\ell|_{\text{max}}$ | $d\sigma/d|\eta_\ell|$ $d\sigma_{\text{stat}}$ $d\sigma_{\text{syst}}$ $d\sigma_{\text{lumi}}$ | $W^- \rightarrow e^- \nu$ $d\sigma/d|\eta_\ell|$ $d\sigma_{\text{stat}}$ $d\sigma_{\text{syst}}$ $d\sigma_{\text{lumi}}$ | $W^- \rightarrow \mu^- \nu$ $d\sigma/d|\eta_\ell|$ $d\sigma_{\text{stat}}$ $d\sigma_{\text{syst}}$ $d\sigma_{\text{lumi}}$ |
|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|----------------|
| 0.00 | 0.21 | 322 | 7 | 7 | 6 | 341 | 8 | 10 | 6 |
| 0.21 | 0.42 | 316 | 7 | 7 | 6 | 314 | 7 | 6 | 6 |
| 0.42 | 0.63 | 303 | 7 | 7 | 6 | 327 | 7 | 6 | 6 |
| 0.63 | 0.84 | 294 | 7 | 7 | 6 | 303 | 7 | 7 | 6 |
| 0.84 | 1.05 | 300 | 7 | 7 | 6 | 306 | 7 | 8 | 6 |
| 1.05 | 1.37 | 280 | 5 | 6 | 5 | 290 | 5 | 5 | 6 |
| 1.37 | 1.52 | – | – | – | – | 276 | 7 | 6 | 5 |
| 1.52 | 1.74 | 270 | 7 | 9 | 5 | 272 | 6 | 5 | 5 |
| 1.74 | 1.95 | 260 | 7 | 9 | 5 | 245 | 6 | 5 | 5 |
| 1.95 | 2.18 | 255 | 7 | 9 | 5 | 253 | 5 | 5 | 5 |
| 2.18 | 2.50 | 220 | 6 | 10 | 4 | 219 | 5 | 5 | 4 |
| 0.00 | 2.50 | 1393 | 10 | 17 | 26 | 1412 | 9 | 22 | 28 |

The electron and muon channel measurements are combined using the Best Linear Unbiased Estimate (BLUE) method [42], accounting for the correlations of the systematic uncertainties across the channels and measurement bins. The $|\eta_\ell|$ and $|y_{\ell\ell}|$ distributions for the electron channel, muon channel and combined results are shown in Figures 8 and 9 for $W$ and $Z$ bosons, respectively, and the results are listed in Tables 6–8. In the interval $1.37 < |\eta_\ell| < 1.52$, only the muon channel measurements for $W$ boson production are...
Table 5: Measured fiducial $Z \rightarrow \ell^+\ell^-$ differential and integrated cross sections for electron and muon channels.

| $|y_{\ell\ell}|$ | $|y_{\ell\ell}|$ | $\frac{d\sigma}{dy_{\ell\ell}}$ | $\delta\sigma_{\text{stat}}$ | $\delta\sigma_{\text{syst}}$ | $\delta\sigma_{\text{lumi}}$ |
|-----------------|-----------------|-------------------|-----------------|-----------------|-----------------|
| [pb]            | [pb]            | [pb]              | [pb]            | [pb]            | [pb]            |
| 0.0 0.5         | 99.9 2.5        | 1.6              | 1.9             | 105.2 2.4       | 1.1             | 2.0             |
| 0.5 1.0         | 100.3 2.7       | 1.6              | 1.9             | 101.9 2.3       | 1.0             | 1.9             |
| 1.0 1.5         | 89.2 2.7        | 1.4              | 1.7             | 89.8 2.1        | 0.8             | 1.7             |
| 1.5 2.0         | 59.6 2.4        | 1.2              | 1.1             | 61.0 1.8        | 0.6             | 1.1             |
| 2.0 2.5         | 19.6 1.3        | 0.7              | 0.4             | 20.3 1.2        | 0.2             | 0.4             |
| 0.0 2.5         | 369.0 5.3       | 4.7              | 6.9             | 377.9 4.4       | 3.4             | 7.1             |

The combination yields $\chi^2$/d.o.f = 19.3/10 for the $W^+$ boson results, $\chi^2$/d.o.f = 15.1/10 for the $W^-$ boson results, and $\chi^2$/d.o.f = 3.0/5 for the $Z$ boson results. A simultaneous combination of all measurements, accounting for the correlation of the experimental systematic uncertainties between the $W$ and $Z$ measurement results for a given lepton flavour, gives $\chi^2$/d.o.f = 37.5/25, corresponding to a probability of 5.2%. In view of this remaining discrepancy and of the general trend of the muon channel cross sections to be higher than the electron channel ones, the systematic uncertainties are scaled such that $\chi^2$/d.o.f = 1; Tables 6–8 include this scaling. The measured ratio of fiducial $W^+$ and $W^-$ production cross sections, as well as ratios of fiducial $W^\pm$ and $Z$ production cross sections, are summarised in Table 9.

Figure 8: Differential (a) $W^+$ and (b) $W^-$ boson production cross sections as a function of absolute decay lepton pseudorapidity, for the electron, muon and combined results. Statistical and systematic errors are shown as corresponding bars and shaded bands. The luminosity uncertainty is not included. The lower panel shows the ratio of channels to the combined differential cross section in each bin. In the lower panel, error bars represent statistical uncertainties in the ratio, while the shaded band represents systematic uncertainties in the combined differential cross sections.

The measurements of differential $W^+$ and $W^-$ production cross sections allow the extraction of the $W$
Table 6: Combined fiducial $W^+ \rightarrow \ell^+ \nu$ differential and integrated cross sections.

| $|\eta_{\ell}|_{\text{min}}$ | $|\eta_{\ell}|_{\text{max}}$ | $d\sigma/d|\eta_{\ell}|$ [pb] | $\delta\sigma_{\text{stat}}$ [pb] | $\delta\sigma_{\text{syst}}$ [pb] | $\delta\sigma_{\text{lumi}}$ [pb] |
|----------------|----------------|----------------|----------------|----------------|----------------|
| 0.00 | 0.21 | 456 | 6 | 11 | 9 |
| 0.21 | 0.42 | 467 | 6 | 9 | 9 |
| 0.42 | 0.63 | 471 | 6 | 9 | 9 |
| 0.63 | 0.84 | 460 | 6 | 10 | 9 |
| 0.84 | 1.05 | 471 | 6 | 11 | 9 |
| 1.05 | 1.37 | 474 | 5 | 9 | 9 |
| 1.37 | 1.52 | 482 | 9 | 15 | 9 |
| 1.52 | 1.74 | 474 | 6 | 11 | 9 |
| 1.74 | 1.95 | 465 | 6 | 11 | 9 |
| 1.95 | 2.18 | 446 | 6 | 10 | 9 |
| 2.18 | 2.50 | 371 | 5 | 10 | 7 |
| 0.00 | 2.50 | 2266 | 9 | 29 | 43 |

Table 7: Combined fiducial $W^- \rightarrow \ell^- \nu$ differential and integrated cross sections.

| $|\eta_{\ell}|_{\text{min}}$ | $|\eta_{\ell}|_{\text{max}}$ | $d\sigma/d|\eta_{\ell}|$ [pb] | $\delta\sigma_{\text{stat}}$ [pb] | $\delta\sigma_{\text{syst}}$ [pb] | $\delta\sigma_{\text{lumi}}$ [pb] |
|----------------|----------------|----------------|----------------|----------------|----------------|
| 0.00 | 0.21 | 329 | 5 | 8 | 6 |
| 0.21 | 0.42 | 315 | 5 | 6 | 6 |
| 0.42 | 0.63 | 315 | 5 | 6 | 6 |
| 0.63 | 0.84 | 298 | 5 | 6 | 6 |
| 0.84 | 1.05 | 303 | 5 | 7 | 6 |
| 1.05 | 1.37 | 286 | 4 | 5 | 6 |
| 1.37 | 1.52 | 276 | 7 | 7 | 5 |
| 1.52 | 1.74 | 272 | 4 | 6 | 5 |
| 1.74 | 1.95 | 249 | 4 | 5 | 5 |
| 1.95 | 2.18 | 253 | 4 | 6 | 5 |
| 2.18 | 2.50 | 219 | 4 | 6 | 4 |
| 0.00 | 2.50 | 1401 | 7 | 18 | 27 |

Table 8: Combined fiducial $Z \rightarrow \ell^+ \ell^-$ differential and integrated cross sections.

| $|y_{\ell\ell}|_{\text{min}}$ | $|y_{\ell\ell}|_{\text{max}}$ | $d\sigma/d|y_{\ell\ell}|$ [pb] | $\delta\sigma_{\text{stat}}$ [pb] | $\delta\sigma_{\text{syst}}$ [pb] | $\delta\sigma_{\text{lumi}}$ [pb] |
|----------------|----------------|----------------|----------------|----------------|----------------|
| 0.0 | 0.5 | 103.0 | 1.7 | 1.2 | 1.9 |
| 0.5 | 1.0 | 101.3 | 1.8 | 1.1 | 1.9 |
| 1.0 | 1.5 | 89.6 | 1.7 | 0.9 | 1.7 |
| 1.5 | 2.0 | 60.5 | 1.4 | 0.7 | 1.1 |
| 2.0 | 2.5 | 20.0 | 0.9 | 0.4 | 0.4 |
| 0.0 | 2.5 | 374.5 | 3.4 | 3.6 | 7.0 |
Figure 9: Differential $Z$ boson production cross section as a function of absolute lepton-pair rapidity, for the electron, muon and combined results. Statistical and systematic errors are shown as corresponding bars and shaded bands. The luminosity uncertainty is not included. The lower panel shows the ratio of channels to the combined differential cross section in each bin. In the lower panel, error bars represent statistical uncertainties in the ratio, while the shaded band represents systematic uncertainties in the combined differential cross sections.

Table 9: Ratios of integrated $W$ and $Z$ production cross sections.

| $R_{W^+/W^-}^{fid}$ | $1.617 \pm 0.012$ (stat) $\pm 0.003$ (syst) |
| $R_{W/Z}^{fid}$ | $9.81 \pm 0.13$ (stat) $\pm 0.01$ (syst) |
| $R_{W^+/Z}^{ fid}$ | $6.06 \pm 0.08$ (stat) $\pm 0.01$ (syst) |
| $R_{W^-/Z}^{ fid}$ | $3.75 \pm 0.05$ (stat) $\pm 0.01$ (syst) |

boson charge asymmetry, as a function of the absolute pseudorapidity of the decay lepton:

$$A_{\ell}(|\eta_{\ell}|) = \frac{d\sigma_{W^+}/d|\eta_{\ell}| - d\sigma_{W^-}/d|\eta_{\ell}|}{d\sigma_{W^+}/d|\eta_{\ell}| + d\sigma_{W^-}/d|\eta_{\ell}|}.$$ 

Uncertainties in $A_{\ell}$ are calculated considering all sources of correlated and uncorrelated systematic uncertainties in the differential cross sections. The resulting dependence of $A_{\ell}$ on $|\eta_{\ell}|$ measured in the electron and muon channels is presented in Figure 10 together with the combined values, while the combined results are summarised with the corresponding uncertainties in Table 10. Good agreement between the two channels is found.

9.2 Comparison with theoretical predictions

The measured cross sections are compared with theoretical predictions obtained using a modified version of DYNNLO 1.5 [2, 3] optimised for speed of computation. The calculation is performed at $O(\alpha^3_S)$ in QCD and at leading order in the EW theory, with parameters set according to the $G_\mu$ scheme [29]. The input parameters (the Fermi constant $G_F$, the masses and widths of $W$ and $Z$ bosons, and the CKM matrix elements) are taken from Ref. [43]. The DYNNLO predictions are calculated using the NNLO PDF sets from CT14NNLO [44], NNPDF3.1 [45], MMHT14NNLO68CL [46] and HERAPDF2.0 [47]. All considered
Table 10: Charge asymmetry for W bosons as a function of absolute pseudorapidity of the decay lepton.

| $|\eta_\ell|_{\text{min}}$ | $|\eta_\ell|_{\text{max}}$ | $A_\ell$ | $\delta A_{\text{stat}}$ | $\delta A_{\text{syst}}$ |
|-----------------|-----------------|--------|-----------------|-----------------|
| 0.00            | 0.21            | 0.163  | 0.010           | 0.001           |
| 0.21            | 0.42            | 0.195  | 0.009           | 0.001           |
| 0.42            | 0.63            | 0.201  | 0.009           | 0.001           |
| 0.63            | 0.84            | 0.213  | 0.010           | 0.001           |
| 0.84            | 1.05            | 0.218  | 0.010           | 0.001           |
| 1.05            | 1.37            | 0.248  | 0.008           | 0.001           |
| 1.37            | 1.52            | 0.272  | 0.014           | 0.002           |
| 1.52            | 1.74            | 0.271  | 0.009           | 0.001           |
| 1.74            | 1.95            | 0.300  | 0.010           | 0.001           |
| 1.95            | 2.18            | 0.276  | 0.010           | 0.001           |
| 2.18            | 2.50            | 0.256  | 0.010           | 0.001           |

Figure 10: Charge asymmetry for W bosons as a function of absolute decay lepton pseudorapidity, for the electron, muon and combined results. Statistical and systematic errors are shown as corresponding bars and shaded bands (not visible for most points). The lower panel shows the ratio of channels to the combined charge asymmetry in each bin. In the lower panel, error bars represent statistical uncertainties in the ratio, while the shaded band represents systematic uncertainties in the combined charge asymmetry.

PDF sets except HERAPDF2.0 are evaluated from global fits which include to varying extents the LHC measurements of W/Z boson, Drell-Yan, top-quark and inclusive jet production. The renormalisation and factorisation scales, respectively denoted as $\mu_r$ and $\mu_f$, are set equal to the decay lepton-pair invariant mass, $m_{l\nu}$ or $m_{l\ell}$. Uncertainties in these predictions are derived as follows. PDF uncertainties are evaluated from the variations of the NNLO PDFs (the PDF uncertainties of CT14nnlo are rescaled from 90% confidence level to 68% confidence level). Scale uncertainties are defined by the envelope of the variations obtained by changing $\mu_r$ and $\mu_f$ by a factor of two with respect to their nominal values and imposing $0.5 \leq \mu_r/\mu_f \leq 2$. The uncertainty induced by the strong coupling constant is estimated by varying $\alpha_S$ by $\pm 0.001$ around the central value of $\alpha_S(m_Z) = 0.118$, following the prescription of Ref. [44]; the effect of these variations is estimated by comparing the CT14NNLO AS_0117 and CT14NNLO AS_0119 PDF sets to CT14NNLO. Finally,
intrinsic limitations of the NNLO calculations for fiducial cross-section predictions lead to systematic differences between results from different programs, as explained in Ref. [48]. Therefore, an additional uncertainty of 0.7%, estimated from a comparison of predictions calculated with Fewz 3.1 and DYNNLO, is assigned. Theory uncertainties are dominated by our knowledge of the proton PDFs.

Differential cross sections for W and Z boson production are shown in Figures 11 and 12 as a function of $|\eta_\ell|$ and $|y_{\ell\ell}|$, respectively. The cross sections are compared for the combined measurement and theoretical predictions calculated with the CT14NNLO, NNPDF3.1, MMHT14NNLO68CL and HERAPDF2.0 PDF sets, with uncertainties assigned as described above. In some regions of phase space, a comparison of the differential cross sections shows systematic deviations of the predictions obtained with recent PDF sets from the measured values. These deviations are largest for $W^+$ boson production and at central rapidity for $Z$ boson production.

The measured lepton charge asymmetry for $W$ bosons shown in Figure 13 is compared with predictions calculated with the PDF sets mentioned previously. In most of the $|\eta_\ell|$ range considered, the predictions from all PDF sets tend to underestimate the measured asymmetry by a few percent.

Figure 11: Differential cross sections for (a) $W^+$ and (b) $W^-$ boson production as a function of absolute decay lepton pseudorapidity compared with theoretical predictions. Statistical and systematic errors are shown as corresponding bars and shaded bands on the data points. The luminosity uncertainty is not included. Only the dominant uncertainty (PDF) is displayed for the theory. The lower panel shows the ratio of predictions to the measured differential cross section in each bin, and the shaded band shows the sum in quadrature of statistical and systematic uncertainties of the data.
Figure 12: Differential cross section for $Z$ boson production as a function of absolute lepton-pair rapidity compared with theoretical predictions. Statistical and systematic errors are shown as corresponding bars and shaded bands on the data points. The luminosity uncertainty is not included. Only the dominant uncertainty (PDF) is displayed for the theory. The lower panel shows the ratio of predictions to the measured differential cross section in each bin, and the shaded band shows the sum in quadrature of statistical and systematic uncertainties of the data.

Figure 13: Charge asymmetry for $W$ bosons as a function of absolute decay lepton pseudorapidity compared with theoretical predictions. Statistical and systematic errors are shown as corresponding bars and shaded bands on the data points. Only the dominant uncertainty (PDF) is displayed for the theory. The lower panel shows the ratio of predictions to the measured differential cross section in each bin, and the shaded band shows the sum in quadrature of statistical and systematic uncertainties of the data.
10 Summary

Fiducial cross sections are reported for inclusive $W^+$, $W^-$ and $Z$ boson production in $pp$ collisions at the centre-of-mass energy $\sqrt{s} = 5.02$ TeV. The measurement is based on data taken by the ATLAS detector at the LHC corresponding to an integrated luminosity of 25.0 pb$^{-1}$. Cross sections are reported in the electron and muon decay channels, integrated over the fiducial regions and differentially. The fiducial region is defined using lepton kinematics and detector acceptance. The differential cross sections for $W^\pm \rightarrow \ell^\pm \nu$ boson production are measured as a function of absolute lepton pseudorapidity while for $Z \rightarrow \ell^+ \ell^-$ bosons they are reported as a function of absolute dilepton rapidity in the mass window $66 < m_{\ell\ell} < 116$ GeV. For $W^\pm$ bosons the decay lepton charge asymmetry as a function of absolute lepton pseudorapidity is also measured.

The electron and muon channel results are found to agree within the measurement precision, and are therefore combined considering all sources of correlated and uncorrelated uncertainties. The combined fiducial $W^+$, $W^-$, and $Z$ cross sections are measured with a precision of 1.2–1.7%. Both the integrated and differential cross sections are compared with next-to-next-to-leading-order QCD calculations including next-to-leading-order electroweak corrections, and using various PDF sets. A comparison of the differential cross sections shows 1–2$\sigma$ deviations from the predictions obtained with many of the recent PDF sets.

These results provide the first measurement of $W^\pm$ and $Z$ boson production cross sections at the centre-of-mass energy $\sqrt{s} = 5.02$ TeV and complement previous measurements at $\sqrt{s} = 7$, 8 and 13 TeV. They constitute a reference for measurements of $W^\pm$ and $Z$ boson production in heavy-ion collisions collected at $\sqrt{s_{NN}} = 5.02$ TeV by the LHC experiments.
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References


The ATLAS Collaboration

5 LAPP, Université Grenoble Alpes, Université Savoie Mont Blanc, CNRS/IN2P3, Annecy; France.
6 High Energy Physics Division, Argonne National Laboratory, Argonne IL; United States of America.
7 Department of Physics, University of Arizona, Tucson AZ; United States of America.
8 Department of Physics, University of Texas at Arlington, Arlington TX; United States of America.
9 Physics Department, National and Kapodistrian University of Athens, Athens; Greece.
10 Physics Department, National Technical University of Athens, Zografou; Greece.
11 Department of Physics, University of Texas at Austin, Austin TX; United States of America.
12 Bahcesehir University, Faculty of Engineering and Natural Sciences, Istanbul; Istanbul Bilgi University, Faculty of Engineering and Natural Sciences, Istanbul; Bogazici University, Istanbul; Department of Physics Engineering, Gaziantep University, Gaziantep; Turkey.
13 Institute of Physics, Azerbaijan Academy of Sciences, Baku; Azerbaijan.
14 Instituto de Física d’Altes Energies (IFAE), Barcelona Institute of Science and Technology, Barcelona; Spain.
15 Institute of High Energy Physics, Chinese Academy of Sciences, Beijing; Physics Department, Tsinghua University, Beijing; Department of Physics, Nanjing University, Nanjing; University of Chinese Academy of Science (UCAS), Beijing; China.
16 Institute of Physics, University of Belgrade, Belgrade; Serbia.
17 Department for Physics and Technology, University of Bergen, Bergen; Norway.
18 Physics Division, Lawrence Berkeley National Laboratory and University of California, Berkeley CA; United States of America.
19 Institut für Physik, Humboldt Universität zu Berlin, Berlin; Germany.
20 Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern; Switzerland.
21 School of Physics and Astronomy, University of Birmingham, Birmingham; United Kingdom.
22 Centro de Investigaciones, Universidad Antonio Nariño, Bogota; Colombia.
23 Dipartimento di Fisica e Astronomia, Università di Bologna, Bologna; INFN Sezione di Bologna; Italy.
24 Physikalisches Institut, Universität Bonn, Bonn; Germany.
25 Department of Physics, Boston University, Boston MA; United States of America.
26 Department of Physics, Brandeis University, Waltham MA; United States of America.
27 Transilvania University of Brasov, Brasov; Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest; Department of Physics, Alexandru Ioan Cuza University of Iasi, Iasi; National Institute for Research and Development of Isotopic and Molecular Technologies, Physics Department, Cluj-Napoca; University Politehnica Bucharest, Bucharest; West University in Timisoara, Timisoara; Romania.
28 Faculty of Mathematics, Physics and Informatics, Comenius University, Bratislava; Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice; Slovak Republic.
29 Physics Department, Brookhaven National Laboratory, Upton NY; United States of America.
30 Departamento de Física, Universidad de Buenos Aires, Buenos Aires; Argentina.
31 Cavendish Laboratory, University of Cambridge, Cambridge; United Kingdom.
32 Department of Physics, University of Cape Town, Cape Town; Department of Mechanical Engineering Science, University of Johannesburg, Johannesburg; School of Physics, University of the Witwatersrand, Johannesburg; South Africa.
33 Department of Physics, Carleton University, Ottawa ON; Canada.
34 Faculté des Sciences Ain Chock, Réseau Universitaire de Physique des Hautes Energies - Université Hassan II, Casablanca; Centre National de l’Energie des Sciences Techniques Nucleaires (CNESTEN),
Rabat;\textsuperscript{(c)}Faculté des Sciences Semlalia, Université Cadi Ayyad, LPHEA-Marrakech;\textsuperscript{(d)}Faculté des Sciences, Université Mohamed Premier and LPTPM, Oujda;\textsuperscript{(e)}Faculté des sciences, Université Mohammed V, Rabat; Morocco.

35CERN, Geneva; Switzerland.

36Enrico Fermi Institute, University of Chicago, Chicago IL; United States of America.

37LPC, Université Clermont Auvergne, CNRS/IN2P3, Clermont-Ferrand; France.

38Nevis Laboratory, Columbia University, Irvington NY; United States of America.

39Niels Bohr Institute, University of Copenhagen, Copenhagen; Denmark.

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

41Physics Department, Southern Methodist University, Dallas TX; United States of America.

42Physics Department, University of Texas at Dallas, Richardson TX; United States of America.

43\textsuperscript{(a)}Department of Physics, Stockholm University;\textsuperscript{(b)}Oskar Klein Centre, Stockholm; Sweden.

44Deutsches Elektronen-Synchrotron DESY, Hamburg and Zeuthen; Germany.

45Lehrstuhl für Experimentelle Physik IV, Technische Universität Dortmund, Dortmund; Germany.

46Institut für Kern- und Teilchenphysik, Technische Universität Dresden, Dresden; Germany.

47Department of Physics, Duke University, Durham NC; United States of America.

48SUPA - School of Physics and Astronomy, University of Edinburgh, Edinburgh; United Kingdom.

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

50\textsuperscript{(a)}Dipartimento di Fisica, Università dell’Insubria, Varese;\textsuperscript{(b)}INFN Sezione di Varese; Italy.

51\textsuperscript{(a)}Institut für Kernphysik, Universität zu Köln, Köln;\textsuperscript{(b)}Center of Excellence for Astroparticle Physics, Bonn; Germany.

52\textsuperscript{(a)}IPN Orsay, CNRS/IN2P3, Université Paris-Saclay, Orsay; France.

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

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

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

56\textsuperscript{(a)}INFN Gruppo Collegato di Udine, Sezione di Trieste, Udine;\textsuperscript{(b)}ICTP, Trieste;\textsuperscript{(c)}Dipartimento di Chimica, Fisica e Ambiente, Università di Udine, Udine; Italy.

57\textsuperscript{(a)}INFN Sezione di Pavia;\textsuperscript{(b)}Dipartimento di Fisica, Università di Pavia, Pavia; Italy.
INFN Sezione di Pisa;\(^{(a)}\) Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa; Italy.

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

INFN Sezione di Roma Tor Vergata;\(^{(b)}\) Dipartimento di Fisica, Università di Roma Tor Vergata, Roma; Italy.

INFN Sezione di Roma Tre;\(^{(a)}\) Dipartimento di Matematica e Fisica, Università Roma Tre, Roma; Italy.

INFN-TIFPA;\(^{(b)}\) Università degli Studi di Trento, Trento; Italy.

Institut für Astro- und Teilchenphysik, Leopold-Franzens-Universität, Innsbruck; Austria.

University of Iowa, Iowa City IA; United States of America.

Department of Physics and Astronomy, Iowa State University, Ames IA; United States of America.

Joint Institute for Nuclear Research, Dubna; Russia.

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 do Rei (UFSJ), São João do Rei;\(^{(d)}\) Instituto de Física, Universidade de São Paulo, São Paulo; Brazil.

KEK, High Energy Accelerator Research Organization, Tsukuba; Japan.

Graduate School of Science, Kobe University, Kobe; Japan.

AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, Krakow;\(^{(b)}\) Marian Smoluchowski Institute of Physics, Jagiellonian University, Krakow; Poland.

Institute of Nuclear Physics Polish Academy of Sciences, Krakow; Poland.

Faculty of Science, Kyoto University, Kyoto; Japan.

Kyoto University of Education, Kyoto; Japan.

Research Center for Advanced Particle Physics and Department of Physics, Kyushu University, Fukuoka; Japan.

Instituto de Física La Plata, Universidad Nacional de La Plata and CONICET, La Plata; Argentina.

Physics Department, Lancaster University, Lancaster; United Kingdom.

Oliver Lodge Laboratory, University of Liverpool, Liverpool; United Kingdom.

Department of Experimental Particle Physics, Jožef Stefan Institute and Department of Physics, University of Ljubljana, Ljubljana; Slovenia.

School of Physics and Astronomy, Queen Mary University of London, London; United Kingdom.

Department of Physics, Royal Holloway University of London, Egham; United Kingdom.

Department of Physics and Astronomy, University College London, London; United Kingdom.

Louisiana Tech University, Ruston LA; United States of America.

Fysiska institutionen, Lunds universitet, Lund; Sweden.

Centre de Calcul de l’Institut National de Physique Nucléaire et de Physique des Particules (IN2P3), Villeurbanne; France.

Departamento de Física Teorica C-15 and CIAFF, Universidad Autónoma de Madrid, Madrid; Spain.

Institut für Physik, Universität Mainz, Mainz; Germany.

School of Physics and Astronomy, University of Manchester, Manchester; United Kingdom.

CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille; France.

Department of Physics, University of Massachusetts, Amherst MA; United States of America.

Department of Physics, McGill University, Montreal QC; Canada.

School of Physics, University of Melbourne, Victoria; Australia.

Department of Physics, University of Michigan, Ann Arbor MI; United States of America.

Department of Physics and Astronomy, Michigan State University, East Lansing MI; United States of America.

B.I. Stepanov Institute of Physics, National Academy of Sciences of Belarus, Minsk; Belarus.

Research Institute for Nuclear Problems of Byelorussian State University, Minsk; Belarus.
<table>
<thead>
<tr>
<th>Page</th>
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<tbody>
<tr>
<td>107</td>
<td>Group of Particle Physics, University of Montreal, Montreal QC; Canada.</td>
</tr>
<tr>
<td>108</td>
<td>P.N. Lebedev Physical Institute of the Russian Academy of Sciences, Moscow; Russia.</td>
</tr>
<tr>
<td>109</td>
<td>Institute for Theoretical and Experimental Physics (ITEP), Moscow; Russia.</td>
</tr>
<tr>
<td>110</td>
<td>National Research Nuclear University MEPhI, Moscow; Russia.</td>
</tr>
<tr>
<td>111</td>
<td>D.V. Skobeltsyn Institute of Nuclear Physics, M.V. Lomonosov Moscow State University, Moscow; Russia.</td>
</tr>
<tr>
<td>112</td>
<td>Fakultät für Physik, Ludwig-Maximilians-Universität München, München; Germany.</td>
</tr>
<tr>
<td>113</td>
<td>Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), München; Germany.</td>
</tr>
<tr>
<td>114</td>
<td>Nagasaki Institute of Applied Science, Nagasaki; Japan.</td>
</tr>
<tr>
<td>115</td>
<td>Graduate School of Science and Kobayashi-Maskawa Institute, Nagoya University, Nagoya; Japan.</td>
</tr>
<tr>
<td>116</td>
<td>Department of Physics and Astronomy, University of New Mexico, Albuquerque NM; United States of America.</td>
</tr>
<tr>
<td>117</td>
<td>Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen; Netherlands.</td>
</tr>
<tr>
<td>118</td>
<td>Nikhef National Institute for Subatomic Physics and University of Amsterdam, Amsterdam; Netherlands.</td>
</tr>
<tr>
<td>119</td>
<td>Department of Physics, Northern Illinois University, DeKalb IL; United States of America.</td>
</tr>
<tr>
<td>120</td>
<td>(a) Budker Institute of Nuclear Physics and NSU, SB RAS, Novosibirsk; (b) Novosibirsk State University Novosibirsk; Russia.</td>
</tr>
<tr>
<td>121</td>
<td>Institute for High Energy Physics of the National Research Centre Kurchatov Institute, Protvino; Russia.</td>
</tr>
<tr>
<td>122</td>
<td>Department of Physics, New York University, New York NY; United States of America.</td>
</tr>
<tr>
<td>123</td>
<td>Ohio State University, Columbus OH; United States of America.</td>
</tr>
<tr>
<td>124</td>
<td>Faculty of Science, Okayama University, Okayama; Japan.</td>
</tr>
<tr>
<td>125</td>
<td>Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman OK; United States of America.</td>
</tr>
<tr>
<td>126</td>
<td>Department of Physics, Oklahoma State University, Stillwater OK; United States of America.</td>
</tr>
<tr>
<td>127</td>
<td>Palacký University, RCPTM, Joint Laboratory of Optics, Olomouc; Czech Republic.</td>
</tr>
<tr>
<td>128</td>
<td>Center for High Energy Physics, University of Oregon, Eugene OR; United States of America.</td>
</tr>
<tr>
<td>129</td>
<td>LAL, Université Paris-Sud, CNRS/IN2P3, Université Paris-Saclay, Orsay; France.</td>
</tr>
<tr>
<td>130</td>
<td>Graduate School of Science, Osaka University, Osaka; Japan.</td>
</tr>
<tr>
<td>131</td>
<td>Department of Physics, University of Oslo, Oslo; Norway.</td>
</tr>
<tr>
<td>132</td>
<td>Department of Physics, Oxford University, Oxford; United Kingdom.</td>
</tr>
<tr>
<td>133</td>
<td>LPNHE, Sorbonne Université, Paris Diderot Sorbonne Paris Cité, CNRS/IN2P3, Paris; France.</td>
</tr>
<tr>
<td>134</td>
<td>Department of Physics, University of Pennsylvania, Philadelphia PA; United States of America.</td>
</tr>
<tr>
<td>135</td>
<td>Konstantinov Nuclear Physics Institute of National Research Centre &quot;Kurchatov Institute&quot;, PNPI, St. Petersburg; Russia.</td>
</tr>
<tr>
<td>136</td>
<td>Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh PA; United States of America.</td>
</tr>
<tr>
<td>137</td>
<td>(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) Departamento de Física Teórica y del Cosmos, Universidad de Granada, Granada (Spain); (g) Dep Física and CEFITEC of Faculdade de Ciências e Tecnologia, Universidade Nova de Lisboa, Caparica; Portugal.</td>
</tr>
<tr>
<td>138</td>
<td>Institute of Physics, Academy of Sciences of the Czech Republic, Prague; Czech Republic.</td>
</tr>
<tr>
<td>139</td>
<td>Czech Technical University in Prague, Prague; Czech Republic.</td>
</tr>
<tr>
<td>140</td>
<td>Charles University, Faculty of Mathematics and Physics, Prague; Czech Republic.</td>
</tr>
</tbody>
</table>
Particle Physics Department, Rutherford Appleton Laboratory, Didcot; United Kingdom.

IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette; France.

Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz CA; United States of America.

(a) Departamento de Física, Pontificia Universidad Católica de Chile, Santiago; (b) Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso; Chile.

Department of Physics, University of Washington, Seattle WA; United States of America.

Department of Physics and Astronomy, University of Sheffield, Sheffield; United Kingdom.

Department of Physics, Shinshu University, Nagano; Japan.

Department Physik, Universität Siegen, Siegen; Germany.

Department of Physics, Simon Fraser University, Burnaby BC; Canada.

SLAC National Accelerator Laboratory, Stanford CA; United States of America.

Physics Department, Royal Institute of Technology, Stockholm; Sweden.

Departments of Physics and Astronomy, Stony Brook University, Stony Brook NY; United States of America.

Department of Physics and Astronomy, University of Sussex, Brighton; United Kingdom.

School of Physics, University of Sydney, Sydney; Australia.

Institute of Physics, Academia Sinica, Taipei; Taiwan.

(a) E. Andronikashvili Institute of Physics, Iv. Javakhishvili Tbilisi State University, Tbilisi; (b) High Energy Physics Institute, Tbilisi State University, Tbilisi; Georgia.

Department of Physics, Technion, Israel Institute of Technology, Haifa; Israel.

Raymond and Beverly Sackler School of Physics and Astronomy, Tel Aviv University, Tel Aviv; Israel.

Department of Physics, Aristotle University of Thessaloniki, Thessaloniki; Greece.

International Center for Elementary Particle Physics and Department of Physics, University of Tokyo, Tokyo; Japan.

Graduate School of Science and Technology, Tokyo Metropolitan University, Tokyo; Japan.

Department of Physics, Tokyo Institute of Technology, Tokyo; Japan.

Tomsk State University, Tomsk; Russia.

Department of Physics, University of Toronto, Toronto ON; Canada.

(a) TRIUMF, Vancouver BC; (b) Department of Physics and Astronomy, York University, Toronto ON; Canada.

Division of Physics and Tomonaga Center for the History of the Universe, Faculty of Pure and Applied Sciences, University of Tsukuba, Tsukuba; Japan.

Department of Physics and Astronomy, Tufts University, Medford MA; United States of America.

Department of Physics and Astronomy, University of California Irvine, Irvine CA; United States of America.

Department of Physics and Astronomy, University of Uppsala, Uppsala; Sweden.

Department of Physics, University of Illinois, Urbana IL; United States of America.

Instituto de Física Corpuscular (IFIC), Centro Mixto Universidad de Valencia - CSIC, Valencia; Spain.

Department of Physics, University of British Columbia, Vancouver BC; Canada.

Department of Physics and Astronomy, University of Victoria, Victoria BC; Canada.

Fakultät für Physik und Astronomie, Julius-Maximilians-Universität Würzburg, Würzburg; Germany.

Department of Physics, University of Warwick, Coventry; United Kingdom.

Waseda University, Tokyo; Japan.

Department of Particle Physics, Weizmann Institute of Science, Rehovot; Israel.

Department of Physics, University of Wisconsin, Madison WI; United States of America.

Fakultät für Mathematik und Naturwissenschaften, Fachgruppe Physik, Bergische Universität
Wuppertal, Wuppertal; Germany.
\textsuperscript{180}Department of Physics, Yale University, New Haven CT; United States of America.
\textsuperscript{181}Yerevan Physics Institute, Yerevan; Armenia.

\textsuperscript{a} Also at Borough of Manhattan Community College, City University of New York, NY; United States of America.
\textsuperscript{b} Also at California State University, East Bay; United States of America.
\textsuperscript{c} Also at Centre for High Performance Computing, CSIR Campus, Rosebank, Cape Town; South Africa.
\textsuperscript{d} Also at CERN, Geneva; Switzerland.
\textsuperscript{e} Also at CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille; France.
\textsuperscript{f} Also at Département de Physique Nucléaire et Corpusculaire, Université de Genève, Genève; Switzerland.
\textsuperscript{g} Also at Departament de Física de la Universitat Autònoma de Barcelona, Barcelona; Spain.
\textsuperscript{h} Also at Departamento de Física Teórica y del Cosmos, Universidad de Granada, Granada (Spain); Spain.
\textsuperscript{i} Also at Departamento de Física, Instituto Superior Técnico, Universidade de Lisboa, Lisboa; Portugal.
\textsuperscript{j} Also at Department of Applied Physics and Astronomy, University of Sharjah, Sharjah; United Arab Emirates.
\textsuperscript{k} Also at Department of Financial and Management Engineering, University of the Aegean, Chios; Greece.
\textsuperscript{l} Also at Department of Physics and Astronomy, University of Louisville, Louisville, KY; United States of America.
\textsuperscript{m} Also at Department of Physics and Astronomy, University of Sheffield, Sheffield; United Kingdom.
\textsuperscript{n} Also at Department of Physics, California State University, Fresno CA; United States of America.
\textsuperscript{o} Also at Department of Physics, California State University, Sacramento CA; United States of America.
\textsuperscript{p} Also at Department of Physics, King’s College London, London; United Kingdom.
\textsuperscript{q} Also at Department of Physics, St. Petersburg State Polytechnical University, St. Petersburg; Russia.
\textsuperscript{r} Also at Department of Physics, Stanford University; United States of America.
\textsuperscript{s} Also at Department of Physics, University of Fribourg, Fribourg; Switzerland.
\textsuperscript{t} Also at Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa; Italy.
\textsuperscript{u} Also at Giessen University, Faculty of Engineering, Giessen; Turkey.
\textsuperscript{v} Also at Graduate School of Science, Osaka University, Osaka; Japan.
\textsuperscript{x} Also at Hellenic Open University, Patras; Greece.
\textsuperscript{y} Also at Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest; Romania.
\textsuperscript{z} Also at II. Physikalisches Institut, Georg-August-Universität Göttingen, Göttingen; Germany.
\textsuperscript{aa} Also at Instituto Catalan de Recerca i Estudis Avancats, ICREA, Barcelona; Spain.
\textsuperscript{ab} Also at Institut für Experimentalphysik, Universität Hamburg, Hamburg; Germany.
\textsuperscript{ac} Also at Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen; Netherlands.
\textsuperscript{ad} Also at Institute for Particle and Nuclear Physics, Wigner Research Centre for Physics, Budapest; Hungary.
\textsuperscript{ae} Also at Institute of Particle Physics (IPP); Canada.
\textsuperscript{af} Also at Institute of Physics, Academia Sinica, Taipei; Taiwan.
\textsuperscript{ag} Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku; Azerbaijan.
\textsuperscript{ah} Also at Institute of Theoretical Physics, Ilia State University, Tbilisi; Georgia.
\textsuperscript{ai} Also at Instituto de Física Teórica de la Universidad Autónoma de Madrid; Spain.
\textsuperscript{aj} Also at Istanbul University, Dept. of Physics, Istanbul; Turkey.
\textsuperscript{ak} Also at LAL, Université Paris-Sud, CNRS/IN2P3, Université Paris-Saclay, Orsay; France.
\textsuperscript{al} 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 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