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

ATLAS Collaboration

CERN, 1211 Geneva 23, Switzerland

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 in QCD and electroweak (EW) processes. Predictions for the differential and fiducial cross sections are available up to next-to-next-to-leading-order QCD cross-section calculations. These measurements serve as references for Pb+Pb interactions at the LHC at $\sqrt{s_{NN}} = 5.02$ TeV.

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

* e-mail: atlas.publications@cern.ch

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 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 $L = 3.8 \times 10^{32}$ cm$^{-2}$ 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 $\sqrt{s_{NN}} = 5.02$ 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 $\sqrt{s_{NN}} = 2.76$ TeV and $Z$ boson production [12, 13] in the $p+Pb$ system at $\sqrt{s_{NN}} = 5.02$ 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 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 $\sim 35$ 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.

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 v8.186 parquet 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 ($ZZ$, $WW$) or zero ($WZ$) 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].
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. The (anti-)neutrinos from $W^\pm \rightarrow \ell^\pm v$ decays escape direct detection. A measure of the neutrino transverse momentum, $p_T^\nu$, 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 $E_{T}^{\text{miss}}$. The transverse mass of the lepton-$E_{T}^{\text{miss}}$ system is defined as

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

where $\Delta \phi_{\ell,E_{T}^{\text{miss}}}$ is the azimuthal angle between $\vec{p}_T^\ell$ and $\vec{E}_{T}^{\text{miss}}$. The $W$ boson candidate events are selected by requiring $E_{T}^{\text{miss}} > 25$ GeV and $m_T > 40$ GeV. These event selection requirements are optimised to reduce background contributions from multi-jet processes.

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 $E_{T}^{\text{miss}}$ 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.

Measurements of muon momenta can be biased by the detector alignment and resolution, distortions of the magnetic field or imprecise estimates of the amount of passive material in the detector. Corrections of the muon momentum scale and resolution, which are applied to the simulation, are derived as a function of the muon $\eta$ and $\phi$ using $Z \rightarrow \mu^+\mu^-$ events [34]. The correction factors are chosen such that they minimise the $\chi^2$ between the muon-pair invariant mass distributions in data and simulation.
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 to 50 GeV and 5% for $p_T >$ 60 GeV. The efficiency of an electron to further pass the medium identification definition varies from 85 to 95% and is measured with 2% precision. The electron isolation efficiency is measured with a precision of 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 $\sqrt{s} = 5.02$ TeV dataset.

Figure 1 summarises the reconstruction, identification, isolation and trigger efficiencies 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 $\sqrt{s} = 5.02$ 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 $\vec{p}_T$ onto the axis – 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 $\vec{u}_T$ onto the axis defined by $\vec{p}_T$, 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 $\sqrt{u_T}$ are obtained in $Z$ events and are applied to the $W$ boson event candidates, as a function of $p_T^W$. The corrections applied to the simulation are obtained as a function of $p_T^Z$:

$$u_\parallel^{W,\text{corr}} = \left( u_\parallel^Z + p_T^Z \right)^{\text{data}} - \left( u_\parallel^Z + p_T^Z \right)^{\text{MC}} + \left( u_\parallel^Z \right)^{\text{data}}$$

$$u_\perp^{W,\text{corr}} = u_\perp^{W,\text{MC}} \cdot \frac{\sigma_{u_\perp}^{\text{data}}}{\sigma_{u_\perp}^{\text{MC}}}.$$  \hspace{1cm} (1)

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 Fig. 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 calibrations.
tion, and residual differences are covered by the systematic uncertainties described in Sect. 8.

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 $W^\pm \to \tau^\pm \nu$, $Z \to \ell^+ \ell^-$, $Z \to \tau^+ \tau^-$ 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 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 $p_T$, $E_T^{\text{miss}}$ 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 $E_T^{\text{miss}}$ 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 Sect. 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. Examples of post-fit template $E_T^{\text{miss}}$ distributions, which are used to extract multi-jet yields in the electron and muon channels, are presented in Fig. 4.

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

The largest background contributions to the decay modes studied come from the production of single EW bosons decaying via other decay channels. The $Z \to e^+e^-$ background represents 0.1% of the $W^+ \to e^+\nu$ sample and 0.2% of the $W^- \to e^-\nu$ sample, while the $Z \to \mu^+\mu^-$ background amounts to 2.8% and 3.8% in the $W^+ \to \mu^+\nu$ and $W^- \to \mu^-\nu$ samples, respectively. The $W^\pm \to \tau^\pm\nu$ background contributes around 1.8% to the samples selected in both channels and the $Z \to \tau^+\tau^-$ 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 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.
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>$W^\pm \rightarrow \ell^+\nu$, $\ell = e, \mu$</td>
<td>–</td>
<td>–</td>
<td>$&lt;$0.01 ($&lt;$0.01)</td>
</tr>
<tr>
<td>$W^\pm \rightarrow \tau^+\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>

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, $p_T^\nu > 25$ GeV, $|\eta_\ell| < 2.5$, $m_T > 40$ GeV.
- 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:

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

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 described in Sect. 3 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 $C_{W[Z]}$ factors also account for the difference in acceptance between detector-level requirements on lepton $|\eta_\ell|$ and the fiducial selection of $|\eta_\ell| < 2.5$.

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 the measurement of differential cross sections, the formula given in Eq. (3) is adjusted so that the cross sections are divided by the width of the corresponding interval in absolute pseudorapidity or rapidity. For $W$ production, following Ref. [4], the lepton $|\eta|$ boundaries are defined as:

- $0 \sim 0.21 \sim 0.42 \sim 0.63 \sim 0.84 \sim 1.05 \sim 1.37 \sim 1.52 \sim 1.74 \sim 1.95 \sim 2.18 \sim 2.50$;

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

- $0 \sim 0.5 \sim 1.0 \sim 1.5 \sim 2.0 \sim 2.5$.

For the measurement of these cross sections, the $C_{W[Z]}$ factors are computed separately for each lepton $|\eta|$ or $|\gamma_{\ell\ell}|$ 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.

The uncertainty associated with the $C_{W[Z]}$ correction is dominated by experimental systematic uncertainties, described in Sect. 8. For the differential $C_W$ factors, the relative size of statistical and systematic uncertainties added in quadrature varies in the range 1.1–2.5% (1.7–3%), while the uncertainties in differential $C_Z$ factors are in the range 1.6–3.5% (0.9–1.2%) in the electron (muon) channel.
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 $|y_C|$ intervals is shown, while their uncertainties are described in the text.

<table>
<thead>
<tr>
<th>Channel</th>
<th>$C_W(W^+ \rightarrow \ell^+\nu)$</th>
<th>$C_W(W^- \rightarrow \ell^-\nu)$</th>
<th>$C_Z$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron channel</td>
<td>0.657 ± 0.006</td>
<td>0.667 ± 0.005</td>
<td>0.522 ± 0.007</td>
</tr>
<tr>
<td>Muon channel</td>
<td>0.723 ± 0.011</td>
<td>0.720 ± 0.010</td>
<td>0.780 ± 0.007</td>
</tr>
</tbody>
</table>

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 size of acceptance corrections included in the integrated correction factors is 7% (3%) for the $W$ boson measurements and 14% (5%) for the $Z$ boson measurements in the electron (muon) channel. In the case of differential $W$ boson measurements, only the $C_W$ factor in the interval $2.18 < |\eta_\ell| < 2.5$ includes an acceptance correction of 9% for $W^\pm \rightarrow e^\pm\nu$ processes and 40% for $W^\pm \rightarrow \mu^\pm\nu$ processes. On the other hand, all differential $C_Z$ factors include an acceptance correction which varies from 6% to 28% for the $Z \rightarrow e^+e^-$ channel and up to 53% for the $Z \rightarrow \mu^+\mu^-$ channel.

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 divided into contributions correlated across electron $|\eta|$ and $p_T$ intervals and uncorrelated ones, and are propagated to the cross-section measurements accordingly. 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%. 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 ~20% in the range $[-15, +15]$ GeV, which dominates the reported cross-section measurements. After applying this correction to events with $W^\pm$ and $W^\mp$ 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. The largest sources of uncertainty are systematic effects related to the van der Meer scan procedure and the long-term stability of the luminosity calibration.

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 the luminosity uncertainty, which is given separately. The systematic uncertainties coming from lepton efficiency corrections are measured as a function of lepton $\eta$ and $p_T$, and include a significant statistical component due to the number of $Z$ events used to derive the corrections. This statistical component is substantially reduced for the integrated cross sections compared to the differential ones.

The data tables provided in this paper contain compact summaries of the measurement uncertainties. A complete breakdown of systematic uncertainties and their correlated components is provided in HEPData [42].

The electron and muon channel measurements are combined using the Best Linear Unbiased Estimate (BLUE) method [43], accounting for the correlations of the systematic uncertainties across the channels and measurement bins. The $|\eta|\ell$ and $|\eta\ell\ell|$ distributions for the electron channel, muon channel and combined results are shown in Figs. 8 and 9 for $W$ and $Z$ bosons, respectively, and the results are listed in Tables 6, 7 and 8. In the interval $1.37 < |\eta| < 1.52$, only the muon channel measurements for $W$ boson production are used. 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

| $|\eta|\ell$ | $|\eta\ell\ell|$ | $\delta\sigma_{stat}$ [pb] | $\delta\sigma_{syst}$ [pb] | $\delta\sigma_{lumi}$ [pb] | $\delta\sigma_{stat}$ [pb] | $\delta\sigma_{syst}$ [pb] | $\delta\sigma_{lumi}$ [pb] |
|----------------|----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| 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 $W^+ \to \ell^+ \nu$ differential and integrated cross sections for electron and muon channels

| $|\eta_\ell|_{\text{min}}$ | $|\eta_\ell|_{\text{max}}$ | $W^+ \to e^+ \nu$ | $W^+ \to \mu^+ \nu$ |
|-------------------------|-------------------------|----------------|----------------|
| $d\sigma/d|\eta_\ell|$ [pb] | $d\sigma/d|\eta_\ell|$ [pb] | $\delta\sigma_{\text{stat}}$ [pb] | $\delta\sigma_{\text{syst}}$ [pb] | $\delta\sigma_{\text{lumi}}$ [pb] | $\delta\sigma_{\text{stat}}$ [pb] | $\delta\sigma_{\text{syst}}$ [pb] | $\delta\sigma_{\text{lumi}}$ [pb] |
| 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 | 6 | 6 |
| 0.84 | 1.05 | 300 | 7 | 7 | 6 | 306 | 7 | 6 | 6 |
| 1.05 | 1.37 | 280 | 5 | 6 | 5 | 290 | 5 | 6 | 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 | 4 |
| 2.18 | 2.50 | 220 | 6 | 10 | 4 | 219 | 5 | 5 | 4 |
| 0.00 | 2.50 | 1393 | 10 | 17 | 26 | 1412 | 9 | 22 | 28 |

Table 5: Measured fiducial $Z \to \ell^+ \ell^-$ differential and integrated cross sections for electron and muon channels

| $|y_{\ell\ell}|_{\text{min}}$ | $|y_{\ell\ell}|_{\text{max}}$ | $Z \to e^+ e^-$ | $Z \to \mu^+ \mu^-$ |
|---------------------------|---------------------------|----------------|----------------|
| $d\sigma/d|y_{\ell\ell}|$ [pb] | $d\sigma/d|y_{\ell\ell}|$ [pb] | $\delta\sigma_{\text{stat}}$ [pb] | $\delta\sigma_{\text{syst}}$ [pb] | $\delta\sigma_{\text{lumi}}$ [pb] | $\delta\sigma_{\text{stat}}$ [pb] | $\delta\sigma_{\text{syst}}$ [pb] | $\delta\sigma_{\text{lumi}}$ [pb] |
| 0.0 | 0.5 | 99.9 | 2.9 | 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 |

Fig. 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.

Uncertainties in the efficiency corrections are scaled such that $\chi^2$/d.o.f = 1; the correction uncertainties are scaled by a common factor, preserving the uncertainty correlations as a function of lepton $p_T$ and $\eta$ for this source. Tables 6, 7 and 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.
The measurements of differential $W^+$ and $W^-$ production cross sections allow the extraction of the $W$ 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 Fig. 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 $O(\alpha_s^2)$ 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

---

Fig. 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 systematic uncertainties in the ratio, while the shaded band represents systematic uncertainties in the combined differential cross sections.

---

Table 6 Combined fiducial $W^+ \rightarrow \ell^+\nu$ differential and integrated cross sections

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

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

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

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

| $|y_{\ell\ell}|_{\text{min}}$ | $|y_{\ell\ell}|_{\text{max}}$ | $Z \rightarrow \ell^+\ell^-$ | $d\sigma/d|y_{\ell\ell}|$ [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             |

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

<table>
<thead>
<tr>
<th>$R_{W^+}/W^-$</th>
<th>$R_{W^+}/Z$</th>
<th>$R_{W^+}/W^-$</th>
<th>$R_{W^+}/Z$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$1.617 \pm 0.012 \text{ (stat)} \pm 0.003 \text{ (syst)}$</td>
<td>$9.81 \pm 0.13 \text{ (stat)} \pm 0.01 \text{ (syst)}$</td>
<td>$6.06 \pm 0.08 \text{ (stat)} \pm 0.01 \text{ (syst)}$</td>
<td>$3.75 \pm 0.05 \text{ (stat)} \pm 0.01 \text{ (syst)}$</td>
</tr>
</tbody>
</table>
Fig. 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.

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           |

$G_F$, the masses and widths of $W$ and $Z$ bosons, and the CKM matrix elements) are taken from Ref. [44]. The DYNNLO predictions are calculated using the NNLO PDF sets from CT14NNLO [45], NNPDF3.1 [46], MMHT14NNLO68CL [47], HERAPDF2.0 [48] and ABMP16 [49]. All considered 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, $m_{\ell\ell}$ or $m_\ell$.

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. [45]; 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. [50]. 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.

The uncertainty of the LHC proton beam energy is estimated to be 0.1% [51] and induces typically an uncertainty of 0.1% in the cross-section predictions, which is negligible compared to other theoretical uncertainties discussed above.

Differential cross sections for $W$ and $Z$ boson production are shown in Figs. 11 and 12 as a function of $|\eta_\ell|$ and $|y_\ell|$, respectively. The cross sections are compared for the combined measurement and theoretical predictions calculated with the CT14NNLO, NNPDF3.1, MMHT14NNLO68CL, HERAPDF2.0 and ABMP16 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 Fig. 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.

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 $W^{\pm} \to \ell^{\pm}\nu\ell$ boson production are measured as a function of absolute lepton pseudorapidity while for $Z \to \ell^+\ell^-$ bosons they are...
reported as a function of absolute dilepton rapidity in the mass window $66 < m_{ll} < 116$ 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%, excluding the luminosity uncertainty. Both the integrated and differential cross sections are compared with next-to-next-to-leading-order QCD calculations using various PDF sets. A comparison of the differential cross sections shows 1–2σ 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.
Acknowledgements
We thank CERN for the very successful operation of the LHC, as well as the support staff from our institutions without whom ATLAS could not be operated efficiently. We acknowledge the support of ANPCyT, Argentina; YerPhI, Armenia; ARC, Australia; BMWFW and FWF, Austria; ANAS, Azerbaijan; SSTC, Belarus; CNPq and FAPESP, Brazil; NSERC, NRC and CFI, Canada; CERN; CONICYT, Chile; CAS, MOST and NSFC, China; COLCIENCIAS, Colombia; MSMT CR, MPO CR and VSC CR, Czech Republic; DNRF and DNSRC, Denmark; IN2P3-CNRS, CEA-DRF/IRFU, France; SRNSFG and CEA-DRF/IRFU, Georgia; Hong Kong SAR, China; ISF and Benoziyo Center, Israel; INAF, Italy; MEXT and JSPS, Japan; CNRST, Morocco; NWO, Netherlands; RGC, Hong Kong SAR, China; ISF and Benoziyo Center, Israel; INFN, Italy; MEXT and JSPS, Japan; CNRST, Morocco; NWO, Netherlands; RCN, Norway; MNiSW and NCN, Poland; FCT, Portugal; MEHEP, Romanian; MES of Russia and NRC KI, Russian Federation; JINR; MESTD, Serbia; MSSR, Slovakia; ARRS and MIZS, Slovenia; DST/NRF, South Africa; MINECO, Spain; SRC and Wallenberg Foundation, Sweden; SERI, SNSF and Cantons of Bern and Geneva, Switzerland; MOST, Taiwan; TAEK, Turkey; STFC, United Kingdom; DOE and NSF, United States of America. In addition, individual groups and members have received support from BCKDF, CANARIE, CRC and Compute Canada, Canada; COST, ERC, ERDF, Horizon 2020, and Marie Skłodowska-Curie Actions, European Union; Investissements d’Avenir Labex and Idex, ANR, France; DFG and AvH Foundation, Germany; Herakleitos, Thales and Aristeia programmes co-financed by EU-ESF and the Greek NSF, Greece; BSF-NSF and GIF, Israel; CERCA Programme Generalitat de Catalunya, Spain; The Royal Society and Leverhulme Trust, United Kingdom. The crucial computing support from all WLCG partners is acknowledged gratefully, in particular from CERN, the ATLAS Tier-1 facilities at TRIUMF (Canada), NDGF (Denmark, Norway, Sweden), CC-IN2P3 (France), KIT/GridKA (Germany), INFN-CNAF (Italy), NL-T1 (Netherlands), PIC (Spain), ASGC (Taiwan), RAL (UK) and BNL (USA), the Tier-2 facilities worldwide and large non-WLCG resource providers. Major contributors of computing resources are listed in Ref. [52].

Data Availability Statement
This manuscript has no associated data or the data will not be deposited. [Authors’ comment: All ATLAS scientific output is published in journals, and preliminary results are made available in Conference Notes. All are openly available, without restriction on use by external parties beyond copyright law and the standard conditions agreed by CERN. Data associated with journal publications are also made available: tables and data from plots (e.g. cross section values, likelihood profiles, selection efficiencies, cross section limits, ...) are stored in appropriate repositories such as HEPDATA (http://hepdata.cedar.ac.uk/). ATLAS also strives to make additional material related to the paper available that allows a reinterpretation of the data in the context of new theoretical models. For example, an extended encapsulation of the analysis is often provided for measurements in the framework of RIVET (http://rivet.hepforge.org/). This information is taken from the ATLAS Data Access Policy which is a public document that can be downloaded from http://opendata.cern.ch/record/413 [opendata.cern.ch].]

Open Access
This article is distributed under the terms of the Creative Commons Attribution 4.0 International License (http://creativecommons.org/licenses/by/4.0/), which permits unrestricted use, distribution, and reproduction in any medium, provided you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made. Funded by SCOAP³.

References
(a) Faculty of Mathematics, Physics and Informatics, Comenius University, Bratislava, Slovakia; (b) Department of Subnuclear Physics, Institute of Experimental Physics of the Slovak Academy of Sciences, Kosice, Slovak Republic

Physics Department, Brookhaven National Laboratory, Upton, NY, USA

Departamento de Física, Universidad de Buenos Aires, Buenos Aires, Argentina

Cavendish Laboratory, University of Cambridge, Cambridge, UK

(a) Department of Physics, University of Cape Town, Cape Town, South Africa; (b) Department of Mechanical Engineering Science, University of Johannesburg, Johannesburg, South Africa; (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, Morocco; (b) Centre National de l’Energie des Sciences Techniques Nuclaires (CENESTEN), Rabat, Morocco; (c) Faculté des Sciences Semlalia, Université Cadi Ayyad, LPHEA-Marrakech, Marrakech, Morocco; (d) Faculté des Sciences, Université Mohamed Premier and LPTPM, Oujda, Morocco; (e) Faculté des sciences, Université Mohammed V, Rabat, Morocco

CERN, Geneva, Switzerland

Enrico Fermi Institute, University of Chicago, Chicago, IL, USA

LPC, Université Clermont Auvergne, CNRS/IN2P3, Clermont-Ferrand, France

Nevis Laboratory, Columbia University, Irvington, NY, USA

Niels Bohr Institute, University of Copenhagen, Copenhagen, Denmark

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

Physics Department, Southern Methodist University, Dallas, TX, USA

Physics Department, University of Texas at Dallas, Richardson, TX, USA

(a) Department of Physics, Stockholm University, Stockholm, Sweden; (b) Oskar Klein Centre, Stockholm, Sweden

Deutsches Elektronen-Synchrotron DESY, Hamburg and Zeuthen, Germany

Lehrstuhl für Experimentelle Physik IV, Technische Universität Dortmund, Dortmund, Germany

Institut für Kern- und Teilchenphysik, Technische Universität Dresden, Dresden, Germany

Department of Physics, Duke University, Durham, NC, USA

SUPA-School of Physics and Astronomy, University of Edinburgh, Edinburgh, UK

INFN e Laboratori Nazionali di Frascati, Frascati, Italy

Physikalisches Institut, Albert-Ludwigs-Universität Freiburg, Freiburg, Germany

II. Physikalisches Institut, Georg-August-Universität Göttingen, Göttingen, Germany

Département de Physique Nucléaire et Corpusculaire, Université de Genève, Geneva, Switzerland

(a) Dipartimento di Fisica, Università di Genova, Genoa, Italy; (b) INFN Sezione di Genova, Genoa, Italy

II. Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen, Germany

SUPA-School of Physics and Astronomy, University of Glasgow, Glasgow, UK

LPC, Université Grenoble Alpes, CNRS/IN2P3, Grenoble INP, Grenoble, France

Laboratory for Particle Physics and Cosmology, Harvard University, Cambridge, MA, USA

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

(a) Kirchhoff-Institut für Physik, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany; (b) Physikalisches Institut, Ruprecht-Karls-Universität Heidelberg, Heidelberg, Germany

Faculty of Applied Information Science, Hiroshima Institute of Technology, Hiroshima, Japan

(a) Department of Physics, Chinese University of Hong Kong, Shatin, NT, Hong Kong; (b) Department of Physics, University of Hong Kong, Hong Kong, China; (c) Department of Physics and Institute for Advanced Study, Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong, China

Department of Physics, National Tsing Hua University, Hsinchu, Taiwan

Department of Physics, Indiana University, Bloomington, IN, USA

(a) INFN Gruppo Collegato di Udine, Sezione di Trieste, Udine, Italy; (b) ICTP, Trieste, Italy; (c) Dipartimento di Chimica, Fisica e Ambiente, Università di Udine, Udine, Italy
INFN Sezione di Lecce, Lecce, Italy; Dipartimento di Matematica e Fisica, Università del Salento, Lecce, Italy
Dipartimento di Fisica, Università di Milano, Milan, Italy
INFN Sezione di Napoli, Naples, Italy; Dipartimento di Fisica, Università di Napoli, Naples, Italy
INFN Sezione di Pavia, Pavia, Italy; Dipartimento di Fisica, Università di Pavia, Pavia, Italy
INFN Sezione di Roma, Rome, Italy; Dipartimento di Fisica, Sapienza Università di Roma, Rome, Italy
INFN Sezione di Roma Tor Vergata, Rome, Italy; Dipartimento di Fisica, Università di Roma Tor Vergata, Rome, Italy
INFN Sezione di Roma Tre, Rome, Italy; Dipartimento di Matematica e Fisica, Università Roma Tre, Rome, Italy
INFN-TIFPA, Povo, Italy; Università degli Studi di Trento, Trento, Italy
Institut für Astro- und Teilchenphysik, Leopold-Franzens-Universität, Innsbruck, Austria
University of Iowa, Iowa City, IA, USA
Department of Physics and Astronomy, Iowa State University, Ames, IA, USA
Joint Institute for Nuclear Research, Dubna, Russia
Graduate School of Science, Kobe University, Kobe, Japan
Faculty of Physics and Applied Computer Science, AGH University of Science and Technology, Kraków, Poland; Marian Smoluchowski Institute of Physics, Jagiellonian University, Kraków, Poland
Institute of Nuclear Physics Polish Academy of Sciences, Kraków, 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 de La Plata, Universidad Nacional de La Plata and CONICET, La Plata, Argentina
Physics Department, Lancaster University, Lancaster, UK
Oliver Lodge Laboratory, University of Liverpool, Liverpool, UK
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, UK
Department of Physics, Royal Holloway University of London, Egham, UK
Department of Physics and Astronomy, University College London, London, UK
Louisiana Tech University, Ruston, LA, USA
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, UK
CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille, France
Department of Physics, University of Massachusetts, Amherst, MA, USA
Department of Physics, McGill University, Montreal, QC, Canada
School of Physics, University of Melbourne, Parkville, VIC, Australia
Department of Physics, University of Michigan, Ann Arbor, MI, USA
Department of Physics and Astronomy, Michigan State University, East Lansing, MI, USA
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
Group of Particle Physics, University of Montreal, Montreal, QC, Canada
P.N. Lebedev Physical Institute of the Russian Academy of Sciences, Moscow, Russia
Institute for Theoretical and Experimental Physics (ITEP), Moscow, Russia
National Research Nuclear University MEPhI, Moscow, Russia
D.V. Skobeltsyn Institute of Nuclear Physics, M.V. Lomonosov Moscow State University, Moscow, Russia

Springer
112 Fakultät für Physik, Ludwig-Maximilians-Universität München, Munich, Germany
113 Max-Planck-Institut für Physik (Werner-Heisenberg-Institut), Munich, Germany
114 Nagasaki Institute of Applied Science, Nagasaki, Japan
115 Graduate School of Science and Kobayashi-Maskawa Institute, Nagoya University, Nagoya, Japan
116 Department of Physics and Astronomy, University of New Mexico, Albuquerque, NM, USA
117 Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, The Netherlands
118 Nikhef National Institute for Subatomic Physics, University of Amsterdam, Amsterdam, The Netherlands
119 Department of Physics, Northern Illinois University, De Kalb, IL, USA
120 (a) Budker Institute of Nuclear Physics and NSU, SB RAS, Novosibirsk, Russia; (b) Novosibirsk State University, Novosibirsk, Russia
121 Institute for High Energy Physics of the National Research Centre Kurchatov Institute, Protvino, Russia
122 Department of Physics, New York University, New York, NY, USA
123 Ohio State University, Columbus, OH, USA
124 Faculty of Science, Okayama University, Okayama, Japan
125 Homer L. Dodge Department of Physics and Astronomy, University of Oklahoma, Norman, OK, USA
126 Department of Physics, Oklahoma State University, Stillwater, OK, USA
127 Palacký University, RCPTM, Joint Laboratory of Optics, Olomouc, Czech Republic
128 Center for High Energy Physics, University of Oregon, Eugene, OR, USA
129 LAL, Université Paris-Sud, CNRS/IN2P3, Université Paris-Saclay, Orsay, France
130 Graduate School of Science, Osaka University, Osaka, Japan
131 Department of Physics, University of Oslo, Oslo, Norway
132 Department of Physics, Oxford University, Oxford, UK
133 LPNHE, Sorbonne Université, Paris Diderot Sorbonne Paris Cité, CNRS/IN2P3, Paris, France
134 Department of Physics, University of Pennsylvania, Philadelphia, PA, USA
135 Konstantinov Nuclear Physics Institute of National Research Centre “Kurchatov Institute”, PNPI, St. Petersburg, Russia
136 Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh, PA, USA
137 (a) Laboratório de Instrumentação e Física Experimental de Partículas-LIP, Lisbon, Portugal; (b) Departamento de Física, Faculdade de Ciências, Universidade de Lisboa, Lisbon, Portugal; (c) Departamento de Física, Universidade de Coimbra, Coimbra, Portugal; (d) Centro de Física Nuclear da Universidade de Lisboa, Lisbon, Portugal; (e) Departamento de Física, Universidade do Minho, Braga, Portugal; (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
138 Institute of Physics, Academy of Sciences of the Czech Republic, Prague, Czech Republic
139 Czech Technical University in Prague, Prague, Czech Republic
140 Faculty of Mathematics and Physics, Charles University, Prague, Czech Republic
141 Particle Physics Department, Rutherford Appleton Laboratory, Didcot, UK
142 IRFU, CEA, Université Paris-Saclay, Gif-sur-Yvette, France
143 Santa Cruz Institute for Particle Physics, University of California Santa Cruz, Santa Cruz, CA, USA
144 (a) Departamento de Física, Pontificia Universidad Católica de Chile, Santiago, Chile; (b) Departamento de Física, Universidad Técnica Federico Santa María, Valparaiso, Chile
145 Department of Physics, University of Washington, Seattle, WA, USA
146 Department of Physics and Astronomy, University of Sheffield, Sheffield, UK
147 Department of Physics, Shinshu University, Nagano, Japan
148 Department Physik, Universität Siegen, Siegen, Germany
149 Department of Physics, Simon Fraser University, Burnaby, BC, Canada
150 SLAC National Accelerator Laboratory, Stanford, CA, USA
151 Physics Department, Royal Institute of Technology, Stockholm, Sweden
152 Departments of Physics and Astronomy, Stony Brook University, Stony Brook, NY, USA
153 Department of Physics and Astronomy, University of Sussex, Brighton, UK
154 School of Physics, University of Sydney, Sydney, Australia
155 Institute of Physics, Academia Sinica, Taipei, Taiwan
E. Andronikashvili Institute of Physics, Iv. Javakhishvili Tbilisi State University, Tbilisi, Georgia; 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

TRIUMF, Vancouver, BC, Canada; 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, USA

Department of Physics and Astronomy, University of California Irvine, Irvine, CA, USA

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

Department of Physics, University of Illinois, Urbana, IL, USA

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, UK

Waseda University, Tokyo, Japan

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

Department of Physics, University of Wisconsin, Madison, WI, USA

Fakultät für Mathematik und Naturwissenschaften, Fachgruppe Physik, Bergische Universität Wuppertal, Wuppertal, Germany

Department of Physics, Yale University, New Haven, CT, USA

Yerevan Physics Institute, Yerevan, Armenia

Also at Borough of Manhattan Community College, City University of New York, NY, USA

Also at California State University, East Bay, USA

Also at Centre for High Performance Computing, CSIR Campus, Rosebank, Cape Town, South Africa

Also at CERN, Geneva, Switzerland

Also at CPPM, Aix-Marseille Université, CNRS/IN2P3, Marseille, France

Also at Département de Physique Nucléaire et Corpusculaire, Université de Genève, Geneva, Switzerland

Also at Departamento de Física de la Universitat Autonoma de Barcelona, Barcelona, Spain

Also at Departamento de Física Teorica y del Cosmos, Universidad de Granada, Granada (Spain), Spain

Also at Departamento de Física, Instituto Superior Técnico, Universidade de Lisboa, Lisbon, Portugal

Also at Department of Applied Physics and Astronomy, University of Sharjah, Sharjah, United Arab Emirates

Also at Department of Financial and Management Engineering, University of the Aegean, Chios, Greece

Also at Department of Physics and Astronomy, University of Louisville, Louisville, KY, USA

Also at Department of Physics and Astronomy, University of Sheffield, Sheffield, UK

Also at Department of Physics, California State University, Fresno, CA, USA

Also at Department of Physics, California State University, Sacramento, CA, USA

Also at Department of Physics, King’s College London, London, UK

Also at Department of Physics, St. Petersburg State Polytechnical University, St. Petersburg, Russia

Also at Department of Physics, Stanford University, USA

Also at Department of Physics, University of Fribourg, Fribourg, Switzerland

Also at Department of Physics, University of Michigan, Ann Arbor, MI, USA

Also at Dipartimento di Fisica E. Fermi, Università di Pisa, Pisa, Italy

Also at Giresun University, Faculty of Engineering, Giresun, Turkey

Also at Graduate School of Science, Osaka University, Osaka, Japan
x Also at Hellenic Open University, Patras, Greece
y Also at Horia Hulubei National Institute of Physics and Nuclear Engineering, Bucharest, Romania
z Also at II Physikalisches Institut, Georg-August-Universität Göttingen, Göttingen, Germany

aa Also at Institutio Catalana de Recerca i Estudis Avancats, ICREA, Barcelona, Spain
ab Also at Institut für Experimentalphysik, Universität Hamburg, Hamburg, Germany
ac Also at Institute for Mathematics, Astrophysics and Particle Physics, Radboud University Nijmegen/Nikhef, Nijmegen, The Netherlands
ad Also at Institute for Particle and Nuclear Physics, Wigner Research Centre for Physics, Budapest, Hungary
ae Also at Institute of Particle Physics (IPP), Canada
af Also at Institute of Physics, Academia Sinica, Taipei, Taiwan
ag Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan
ah Also at Institute of Theoretical Physics, Ilia State University, Tbilisi, Georgia
ai Also at Instituto de Física Teórica de la Universidad Autónoma de Madrid, Spain
aj Also at Istanbul University, Dept. of Physics, Istanbul, Turkey
ak Also at LAL, Université Paris-Sud, CNRS/IN2P3, Université Paris-Saclay, Orsay, France
al Also at Louisiana Tech University, Ruston, LA, USA
am Also at LPNHE, Sorbonne Université, Paris Diderot Sorbonne Paris Cité, CNRS/IN2P3, Paris, France
an Also at Manhattan College, New York, NY, USA
ao Also at Moscow Institute of Physics and Technology State University, Dolgoprudny, Russia
ap Also at National Research Nuclear University MEPhI, Moscow, Russia
aq Also at Physikalisches Institut, Albert-Ludwigs-Universität Freiburg, Freiburg, Germany
ar Also at School of Physics, Sun Yat-sen University, Guangzhou, China
as Also at The City College of New York, New York, NY, USA
at Also at The Collaborative Innovation Center of Quantum Matter (CICQM), Beijing, China
au Also at Tomsk State University, Tomsk, and Moscow Institute of Physics and Technology State University, Dolgoprudny, Russia
av Also at TRIUMF, Vancouver, BC, Canada
aw Also at Universita di Napoli Parthenope, Naples, Italy
\* Deceased