Z boson production in $p + $Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV measured with the ATLAS detector

G. Aad et al.*
(Received 23 July 2015; revised manuscript received 23 September 2015; published 30 October 2015)

The ATLAS Collaboration measures the inclusive production of $Z$ bosons via their decays into electron and muon pairs in $p + $Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV at the Large Hadron Collider. The measurements are made using data corresponding to integrated luminosities of 29.4 and 28.1 nb$^{-1}$ for $Z \to ee$ and $Z \to \mu\mu$, respectively. The results from the two channels are consistent and combined to obtain a cross section times the $Z \to l\ell$ branching ratio, integrated over the rapidity region $|y_Z| < 3.5$, of 139.8 $\pm$ 4.8 (statistical) $\pm$ 6.2 (systematic) $\pm$ 3.8 (luminosity) nb. Differential cross sections are presented as functions of the $Z$ boson rapidity and transverse momentum and compared with models based on parton distributions both with and without nuclear corrections. The centrality dependence of $Z$ boson production in $p + $Pb collisions is measured and analyzed within the framework of a standard Glauber model and the model’s extension for fluctuations of the underlying nucleon-nucleon scattering cross section.

DOI: 10.1103/PhysRevC.92.044915

PACS number(s): 25.75.Bh, 25.75.Dw, 14.70.Hp

I. INTRODUCTION

The study of electroweak bosons in $p + $Pb collisions at the Large Hadron Collider (LHC) at CERN has demonstrated that the production rate of non–strongly interacting particles scales with the number of nucleon-nucleon collisions, $N_{\text{coll}}$. This has been observed for photons [1], $W$ bosons [2,3], and $Z$ bosons [4,5]. The momentum and rapidity distributions of $Z$ bosons are consistent with PYTHIA [6] simulations of $pp$ collisions multiplied by the average nuclear thickness function, $\langle T_{AA}\rangle$, which is equivalent to $\langle N_{\text{coll}} \rangle$ divided by the total nucleon-nucleon cross section [4]. $Z$ boson production in $p + $Pb collisions was found to be consistent with next-to-leading-order perturbative quantum chromodynamics (NLO QCD) calculations that disregard nuclear modifications in the treatment of parton distribution functions (PDFs). However, nuclear modification is not excluded within the precision of the measurement [7]. The production of $Z$ bosons, examined as a function of centrality, was also found to scale with $\langle N_{\text{coll}} \rangle$.

To differentiate between initial- and final-state effects in heavy-ion collisions, the study of $p + $Pb collisions is used at the LHC. One would expect that hot and dense QCD medium cannot be formed in such collisions, unlike in the $p + $Pb case, and that modifications to final-state particles relative to nucleon-nucleon collisions should originate from the initial state of the nucleus. This assumption was challenged by the very first results from $p + $Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV produced at the LHC in 2012. Results on multiparticle correlations, published for three LHC experiments [8–14], revealed collective behavior in $p + $Pb collisions similar to that previously measured in heavy-ion collision systems. The yields of jets measured by ATLAS scale with $\langle N_{\text{coll}} \rangle$ when measured inclusively for all centralities but show significant deviations from binary scaling when considered in centrality selections [15]. The CMS Collaboration has measured dijet pseudorapidity distributions and found them to agree better with predictions that include nuclear PDF modifications than with predictions that do not include nuclear effects [16]. The CMS Collaboration has also recently measured the production of $W$ bosons in $p + $Pb collisions and observed hints of nuclear modifications of the PDF [17]. Collectively, these results have highlighted the need for a better understanding of the initial conditions of $p + $Pb collisions.

Unlike symmetric $p + $Pb collisions, in $p + $Pb collisions nuclear modifications of the PDFs in the lead nucleus create an asymmetry in the rapidity-dependent cross section of $Z$ bosons; this presents an attractive observable for the study of initial-state nuclear conditions. The centrality-dependent yield of $Z$ bosons is a well-suited probe to test our understanding of $p + $Pb collision geometry. The LHCB Collaboration has made a first exploratory measurement of $Z$ bosons at far forward and backward rapidities [18] based on an integrated luminosity of 1.6 nb$^{-1}$.

This paper presents the results of the measurement of $Z$ boson production in $p + $Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV using the ATLAS detector. The yield of $Z$ bosons is measured as a function of their transverse momentum $p_T^Z$, rapidity in the center-of-mass frame ($y_Z^\text{CM}$), and centrality. The leptonic

1 ATLAS uses a right-handed coordinate system with its origin at the nominal interaction point in the center of the detector and the $z$ axis along the beam pipe. The $x$ axis points from the interaction point to the center of the LHC ring, and the $y$ axis points upward. Cylindrical coordinates $(r,\phi)$ are used in the transverse plane, $\phi$ being the azimuthal angle around the beam pipe. The rapidity in the laboratory frame is given by $y^\text{lab} = \frac{1}{2} \ln \frac{E^+ + p_T^+}{E^- + p_T^-}$ and pseudorapidity is defined as $\eta = -\ln \tan(\theta/2)$. Positive rapidity corresponds to the direction the proton beam travels, “proton-going,” and negative rapidity is referred to as “Pb-going.” In this convention the asymmetric beam energies result in a center of mass shifted to rapidity, $y^* = y^\text{lab} - 0.465$. 

*Full author list given at the end of the article.
decays of the Z boson ($Z \rightarrow ee$ and $Z \rightarrow \mu\mu$) are used for its reconstruction. In the muon channel it is possible to reconstruct the Z boson in the rapidity range $-3 < y^Z < 2$, while in the electron channel this range can be extended to $|y^Z| < 3.5$. The larger acceptance in rapidity for $Z \rightarrow ee$ candidates is possible because of the larger acceptance of the ATLAS calorimeters compared to the muon spectrometer (MS, Secs. II and III B). The efficiency of Z boson reconstruction is calculated from detector simulations (Sec. III D). Backgrounds in each channel are estimated using simulations and data-driven methods (Sec. III E). Results measured in the dimuon and dielectron decay channels are combined after accounting for uncertainties and their correlations (Sec. III G). The measured cross sections and centrality-dependent yields are compared to models of proton-lead collisions composed of 82 pp and 126 pn collisions in which the production of Z bosons is obtained using perturbative QCD calculations.

II. THE ATLAS DETECTOR

The ATLAS detector [19] at the LHC covers nearly the entire solid angle around the collision point. It consists of an inner tracking detector surrounded by a thin superconducting solenoid, electromagnetic and hadronic calorimeters, and an MS. The inner detector (ID) system is immersed in a 2-T axial magnetic field and provides charged particle tracking in the pseudorapidity range $|\eta| < 2.5$. It comprises a high-granularity silicon pixel detector covering the collision region, surrounded by a silicon microstrip tracker and a transition radiation tracker. The calorimeters cover the range $|\eta| < 4.9$. Within the region $|\eta| < 3.2$, electromagnetic calorimetry is provided by barrel and endcap high-granularity lead liquid-argon (LAr) calorimeters, with an additional thin LAr presampler covering $|\eta| < 1.8$. Behind the electromagnetic calorimeter there is a steel/scintillator sampling hadronic calorimeter covering $|\eta| < 1.7$, and LAr hadronic calorimeters extend the coverage to $|\eta| < 4.9$. Forward electromagnetic calorimeters (FCals) are located in the range $3.1 < |\eta| < 4.9$. Electrons may be reconstructed over the entire electromagnetic calorimeter system, $|\eta| < 4.9$.

The MS comprises separate trigger and high-precision tracking chambers that measure the deflection of muons in a magnetic field generated by superconducting air-core toroids. The precision chambers cover the region $|\eta| < 2.7$ with three layers of monitored drift tube chambers, complemented by cathode strip chambers in the innermost layer of the forward region. The muon trigger system covers the range $|\eta| < 2.4$, with resistive plate chambers in the barrel ($|\eta| < 1.05$) and thin gap chambers in the endcap regions ($1.05 < |\eta| < 2.4$).

The ATLAS detector has a three-level trigger system [20]: the hardware-based level 1 (L1) trigger and the software-based high-level trigger, which is subdivided into the level 2 (L2) trigger and the event filter. Single-electron and single-muon triggers are used to acquire the data analyzed in this paper. Minimum-bias events are selected based on signals in the minimum-bias trigger scintillators (MBTS) that detect charged particles in the range $2.1 < |\eta| < 3.9$.

III. ANALYSIS

A. Data sample

This analysis uses the 2013 ATLAS $p + $Pb collision data at $\sqrt{s_{NN}} = 5.02$ TeV, produced from a 4-TeV proton beam and a 1.57-TeV-per-nucleon lead beam. The asymmetric energy of the beams resulted in a shift of the center-of-mass by 0.465 units of rapidity relative to the laboratory frame. After 60% of the data were recorded the directions of the proton and lead beams were reversed. Results obtained in the two data periods are found to be consistent with each other. In this paper all data from both periods are presented using the convention that the proton beam travels forward in the positive-rapidity direction.

Following stringent data-quality requirements, the $Z \rightarrow ee$ and $Z \rightarrow \mu\mu$ analyses use samples corresponding to integrated luminosity values of $29.4 \pm 0.8$ and $28.1 \pm 0.8$ nb$^{-1}$, respectively. The luminosity measurement for the 2013 $p + $Pb data is calibrated based on dedicated beam-separation scans. Systematic uncertainties similar to those studied for the calculation of pp luminosity [21] are calculated. The combination of these systematic uncertainties results in a total uncertainty in the ATLAS luminosity scale during proton-lead collisions at $\sqrt{s_{NN}} = 5.02$ TeV of 2.7%. Minimum-bias $p + $Pb collisions were selected by a trigger based on a signal in both MBTS counters. Minimum-bias events are required to have the time measured in each MBTS be consistent within 10 ns and a reconstructed collision vertex within 175 mm of the nominal collision point in the longitudinal direction [22].

B. Lepton reconstruction

Electron candidates are first identified by the L1 trigger as a cluster of cells in the electromagnetic calorimeter, formed into $(\Delta \phi \times \Delta \eta) = 0.1 \times 0.1$ trigger towers, within the range $|\eta| < 2.5$ and with the cluster transverse energy exceeding 5 GeV. The high-level trigger then incorporates tracking information from the ID and imposes electron identification requirements on the electron candidates. A trigger for at least one electron candidate with $E_T > 15$ GeV and satisfying loose identification requirements is used to select events.

In the off-line analysis, electron candidates within $|\eta| < 4.9$ are selected using the ATLAS reconstruction algorithm [23]. Electrons with $|\eta| < 2.47$, referred to as midrapidity electrons, require the matching of a track to an energy cluster in the electromagnetic calorimeter. In addition to the reconstruction requirements, further electron identification selections based primarily on the shower shape in the electromagnetic calorimeter are made to reject background. Electron identification requirements used in previous ATLAS analyses [23] are used to provide quality classification of electrons based on the tightness of the identification criteria they satisfy. The triggering electron is required to have $E_T > 20$ GeV, to be outside the pseudorapidity interval $1.37 < |\eta| < 1.52$ (a transition region between the barrel and the endcap calorimeters which contains a relatively large amount of inactive material), and to satisfy tight identification quality requirements. If the other electron is within $|\eta| < 2.47$, it must have $E_T > 10$ GeV and satisfy loose quality requirements. Forward electrons are those reconstructed within the range $2.5 < |\eta| < 4.9$ based on energy deposited in the FCal [23]. There is no tracking
in this region, so the electron candidate reconstruction and identification are derived solely from the calorimeter signal and do not have an associated charge. Forward electrons are required to have \( E_T > 20 \) GeV. Of \( Z \rightarrow ee \) decays with \(|\gamma^*_Z| < 3.5\), approximately 82% fall into the fiducial acceptance defined by the electron \( p_T \) and \( \eta \) requirements.

Muon candidates are first identified at the L1 trigger, based on hits in either the resistive plate chamber or the thin gap chamber. The high-level trigger then reconstructs muon tracks in the vicinity of the detector region reported by the L1 trigger. The L2 trigger uses an algorithm to perform a fast reconstruction of muons, which is then refined in the event filter by incorporating the hits in the ID tracking as well as those in the MS tracking. Events containing at least one muon with \( p_T \) greater than 8 GeV are accepted by the high-level trigger.

For the \( Z \rightarrow \mu\mu \) analysis, muons are identified from candidates reconstructed in both the MS and the ID [24]. Muons are reconstructed separately in the MS and ID and a \( \chi^2 \)-minimization procedure is used to obtain combined muon kinematic information. To reduce background from jets, each muon is required to pass a loose track-based isolation selection. Tracks are considered in a cone of size \( \Delta R = \sqrt{(\Delta \eta)^2 + (\Delta \phi)^2} = 0.3 \) around the direction of the muon. The muon is considered isolated if the scalar sum of the \( p_T \) of these tracks, excluding the muon, is less than 50% of the muon \( p_T \). The efficiency of this selection is greater than 99%. The triggering muon is required to have \( p_T > 20 \) GeV and be within \(|\eta| < 2.4\). The second muon must be within \(|\eta| < 2.47 \) and have \( p_T > 10 \) GeV. Approximately 68% of Z bosons with \(-3 < y^*_Z < 2\) fall into the fiducial acceptance defined by the muon kinematic requirements.

C. Centrality

In addition to measuring the Z boson cross section, the Z boson yield per minimum-bias event is measured for different centrality selections. In order to characterize the \( p + Pb \) collision geometry, each event is assigned a centrality based on the total transverse energy measured in the FCal on the Pb-going side of the detector region reported by the L1 trigger. The L2 trigger uses an algorithm to perform a fast reconstruction of muons, which is then refined in the event filter by incorporating the hits in the ID tracking as well as those in the MS tracking. Events containing at least one muon with \( p_T \) greater than 8 GeV are accepted by the high-level trigger.

For the \( Z \rightarrow \mu\mu \) analysis, muons are identified from candidates reconstructed in both the MS and the ID [24]. Muons are reconstructed separately in the MS and ID and a \( \chi^2 \)-minimization procedure is used to obtain combined muon kinematic information. To reduce background from jets, each muon is required to pass a loose track-based isolation selection. Tracks are considered in a cone of size \( \Delta R = \sqrt{(\Delta \eta)^2 + (\Delta \phi)^2} = 0.3 \) around the direction of the muon. The muon is considered isolated if the scalar sum of the \( p_T \) of these tracks, excluding the muon, is less than 50% of the muon \( p_T \). The efficiency of this selection is greater than 99%. The triggering muon is required to have \( p_T > 20 \) GeV and be within \(|\eta| < 2.4\). The second muon must be within \(|\eta| < 2.47 \) and have \( p_T > 10 \) GeV. Approximately 68% of Z bosons with \(-3 < y^*_Z < 2\) fall into the fiducial acceptance defined by the muon kinematic requirements.

60–90%. For the study of the \( y^*_Z \) distribution as a function of centrality (see Sec. IV B), larger bins are used: 0–10%, 10–40%, and 40–90%. For the most peripheral collisions, centrality greater than 90%, centrality modeling, and associated geometric quantities are not well constrained. Pileup events, those containing multiple \( p + Pb \) interactions from the same bunch crossing, are removed by rejecting events in which more than one primary vertex is reconstructed. The fraction of candidate events which is removed from the centrality-selected Z boson yield analysis due to pileup rejection is approximately 5%. Diffractive events are identified by a rapidity gap (defined by the absence of calorimeter energy clusters) of greater than two units on the Pb-going side of the detector and excluded. This leads to a rejection of less than 0.1% of Z boson candidate events. The total number of minimum-bias events corresponding to the luminosity sampled by the trigger, \( N_{\text{evt}} \), is used to define the Z boson yield per event in each centrality selection.

Besides its sensitivity to the event geometry, the \( \Sigma E_T^{\text{FCal}} \) for a fixed geometry may also be affected by the presence of a hard scattering process in the event. In particular, the calculation of centrality for \( Z \rightarrow ee \) events in which there is a forward electron in the Pb-going-side FCal is biased by the energy of the electron. This is corrected by subtracting the transverse energy of the electron from \( \Sigma E_T^{\text{FCal}} \). The subtraction procedure is found to effectively recover the correct centrality of minimum-bias events into which simulated \( Z \rightarrow ee \) decays containing electrons in the Pb-going-side FCal were overlaid.

In addition to the case where there is a Z-decay electron in the Pb-going-side FCal, \( \Sigma E_T^{\text{FCal}} \) may be more subtly biased in all Z boson events. The presence of a Z boson (or any hard process) is correlated with a higher transverse energy of the underlying event. Consequently, more energy may be deposited in the Pb-going-side FCal in events containing a hard scattering process than in those that do not contain one. This causes a bias in the centrality-dependent yield, as the Z boson yield is enhanced in the more central events but depleted in the more peripheral ones. This effect, referred to as a centrality bias, has been noted for yields of hard processes in \( d + Au \) collisions at \( \sqrt{s_{NN}} = 200 \) GeV by the PHENIX Collaboration [28] and \( p + Pb \) collisions at \( \sqrt{s_{NN}} = 5.02 \) TeV by the ALICE Collaboration [29].

A correction to the centrality-dependent yields of hard processes in \( d + Au \) collisions at \( \sqrt{s_{NN}} = 200 \) GeV has been studied by the PHENIX Collaboration [28] (the correction is also calculated for \( p + Pb \) at \( \sqrt{s_{NN}} = 5.02 \) TeV). The centrality bias correction used by the PHENIX Collaboration is based on the modeling of an increase in the mean particle multiplicity produced by the specific NN collision that undergoes a hard scattering. Recently, similar calculations of a centrality bias have been made in which all NN collisions may contribute to an increase in the particle multiplicity [30]. The increase in multiplicity stemming from each NN collision is taken to be proportional to the contribution from that collision to the \( E_T \) in the event. This model is applied to the ATLAS \( p + Pb \) centrality classification for the standard Glauber analysis as well as the GGCF models and, thus, used to calculate corrections to the hard process yield measured in a given centrality bin. Because the \( N_{\text{part}} \) probability distribution varies


less steeply in the GGCF models than in the standard Glauber model, the centrality bias corrections are closer to unity for the GGCF cases. The corrections from Ref. [30] are shown in Fig. 1. The reciprocals of the corrections are applied as multiplicative factors to the centrality-dependent $Z$ boson yields.

Using $Z$ bosons measured in ATLAS, data-driven centrality bias corrections may be calculated and compared with the results in Ref. [30]. To do so, the corrections are calculated by comparing the transverse energy deposited in the FCal in events selected by the minimum-bias trigger and in $Z$ boson events from $pp$ collisions (in which there is no centrality to consider). This effect is studied in $pp$ collisions at $\sqrt{s} = 2.76$ TeV and $\sqrt{s} = 7$ TeV from the 2011 LHC run. At both energies a significant increase in the mean transverse energy deposited in the FCal is observed and, within the uncertainties of the measurement, found to be independent of the $Z$ boson kinematics. A single value is interpolated from the $\sqrt{s} = 2.76$ TeV and $\sqrt{s} = 7$ TeV data for $\sqrt{s_{NN}} = 5.02$ TeV. The interpolation is performed using both logarithmic and linear expressions, and the difference between them contributes to the systematic uncertainty. A correction is made to account for the shifted center of mass in the $p + Pb$ system, which changes the effective FCal acceptance in $\eta$ compared to $pp$. From this procedure an additive shift to $\Sigma E_T^{\text{FCal}}$ of $2.0 \pm 0.5$ GeV is calculated. In each $p + Pb$ $Z \rightarrow \ell\ell$ event this value is subtracted from $\Sigma E_T^{\text{FCal}}$ and the resulting value used to determine a corrected centrality of the event. The centrality-dependent yield may be constructed, according to the method described in Sec. III E, using both the subtracted and the unsubtracted $\Sigma E_T^{\text{FCal}}$ values and their ratio is then comparable to a centrality bias correction factor that may be compared to those calculated in Ref. [30]. As shown in Fig. 1, within the uncertainties this data-based method is compatible with the model calculations.

### D. Monte Carlo (MC) simulation corrections

The trigger, reconstruction, and identification efficiencies of electrons and muons as well as the muon isolation efficiency are evaluated by an MC simulation complemented by data-driven estimates of these quantities. Using the POWHEG generator [31] (with the CT10 PDF [32]) interfaced to PYTHIA8 [6] for simulation of the parton shower, approximately 10 million $Z \rightarrow ee$ and 4 million $Z \rightarrow \mu\mu$ events were simulated. The $Z$ bosons were generated from $pp$ and $pn$ collisions, which were added together with weights 82/208 and 126/208, respectively, corresponding to the numbers of protons and neutrons in the Pb ion. The response of the ATLAS detector to the generated particles was modeled using GEANT4 [33,34]. Due to the dependence of electron identification and reconstruction efficiency on the detector occupancy, simulated $Z \rightarrow ee$ events were overlaid with data events selected with the minimum-bias trigger and then reconstructed.

To cross-check the efficiencies calculated in the MC simulation, a “tag-and-probe” technique is employed. The tag is defined as a fully reconstructed high-quality triggered lepton, whereas the probe is a lepton candidate to which triggering, reconstruction, or quality requirements are not applied. Using tag-and-probe pairs with an invariant mass $m_{\ell\ell}$ consistent with selection of $Z$ bosons, the efficiency of the probe with additional requirements is calculated. The mass window used depends on the background present in the probe sample and ranges from $80 < m_{\ell\ell} < 100$ to $87 < m_{\ell\ell} < 95$ GeV. For example, the electron trigger efficiency is measured from high-quality reconstructed electron probes selected without an a priori trigger requirement, and the MS reconstruction efficiency is measured from charged-particle tracks in the ID without an a priori MS signal requirement. The MC simulation is scaled to match the efficiencies determined with the data-driven tag-and-probe method. The factors used to scale the MC electron response are derived from the 2013 $p + Pb$ data set. Muon reconstruction is insensitive to the differences between 2013 $p + Pb$ and 2012 $pp$ conditions and therefore the scale factors for muons are taken from $Z \rightarrow \mu\mu$ events collected in the 2012 $pp$ data set [24]. The scale factors for the $Z \rightarrow ee$ ($Z \rightarrow \mu\mu$) MC events deviate from unity by less than $5\%$ (1%).

The trigger efficiencies of electrons and muons depend on $\eta$ and have average values of approximately 95% and 83%, respectively. The reconstruction and identification efficiency of the more stringently selected electrons is approximately 75%, whereas the reconstruction and identification efficiency for the looser-quality midrapidity electrons is approximately 88% and the forward-electron efficiency is about 65%. These values depend on $\eta$ and $p_T$. The muon reconstruction efficiency is approximately 95%, depending on $\eta$.

Correction factors for the yields of $Z \rightarrow ee$ and $Z \rightarrow \mu\mu$ candidates are calculated from the MC simulations as functions of $p_T^\ell$, $y_\ell$, and $p + Pb$ centrality. These corrections take into account the cumulative losses due to the trigger, reconstruction, and identification efficiency as well as the kinematic acceptance of decay leptons. The correction is defined relative to all generated $Z$ bosons within the mass window $66 < m_{\ell\ell} < 116$ GeV. The total efficiency for reconstructing a produced $Z$ boson, including acceptance, is approximately 55% for
$Z \rightarrow ee$ and 65% for $Z \rightarrow \mu\mu$. Following the subtraction of background (see Sec. III E) and application of the correction factor, a corrected yield of Z bosons is obtained in each bin of $p_T^Z$ and $y_Z$. The uncertainty of the correction factor follows from the uncertainty of the data-driven tag-and-probe checks of the MC, primarily due to the relatively low number of tag-and-probe events in the data. The uncertainty associated with the lepton identification efficiency is the dominant uncertainty for both the $Z \rightarrow ee$ and the $Z \rightarrow \mu\mu$ analyses. This uncertainty is approximately 10% for $Z \rightarrow ee$ (rising as high as 15% for pairs including a forward electron) and 1.5% for $Z \rightarrow \mu\mu$. The sizable uncertainty for $Z \rightarrow ee$ is primarily driven by the limited size of the tag-and-probe 2013 $p + Pb$ data set. The other uncertainties are typically less than 2% in both channels.

### E. Yield extraction

To form $Z \rightarrow ee$ candidates, all electrons found in triggered events are paired with each other. When both electrons are at midrapidity ($|\eta| < 2.47$), the unlike-sign charged pairs with an invariant mass satisfying $66 < m_{ee} < 116$ GeV are accepted as signal Z boson candidates. The like-sign pairs in this window are used to estimate the combinatorial background, created primarily by jets. In total, 1647 unlike-sign pairs and 52 like-sign pairs are reconstructed. The like-sign pairs are composed of combinatorial background and $Z \rightarrow ee$ decays in which one of the electrons has misreconstructed charge. The contribution from pairs with misreconstructed charge is estimated, using the MC simulation, to be half of the like-sign pairs, and the remainder is taken as an estimate of the background. Pairs made of one midrapidity electron and one nontrigging forward electron have a larger contribution from background and so an invariant mass window of $80 < m_{ee} < 100$ GeV is used to select Z boson candidates. To facilitate combination of all $Z \rightarrow ee$ candidates, an acceptance correction is made to account for the smaller mass window. No charge requirement is made for these candidates because the nontrigging electron is outside the acceptance of the ID and therefore does not have a reconstructed charge. There are 264 such candidates, of which an estimated 5% are background based on a fit of the invariant mass distribution. The fit is performed in the range $60 < m_{ee} < 120$ GeV using a signal shape from the MC simulation and several background parametrizations assuming exponential or polynomial descriptions of the background. The mass distributions of $Z \rightarrow ee$ candidates are shown in Figs. 2(a) and 2(b), along with the reconstructed MC simulation of the same quantity. The estimated background is subtracted from the signal candidates differentially in rapidity, transverse momentum, and centrality.

A similar procedure is also followed to select $Z \rightarrow \mu\mu$ candidates with an invariant mass of $66 < m_{\mu\mu} < 116$ GeV. This selection yields 2032 unlike-sign charged candidates and 4 like-sign pairs; their mass distribution is shown in Fig. 2(c). The MC simulation describes the data well in both lepton channels. The slight shift of the mass peak visible between the data and the simulation for dielectron events has only a very small effect on the calculation of corrections based on the MC simulation and is incorporated into the systematic uncertainty associated with electron reconstruction.

Based on the like-sign pairs and MC simulation of charge misreconstruction, the uncertainty from the background subtraction is approximately 1% in the $Z \rightarrow ee$ channel for pairs in which both electrons are at midrapidity; in pairs involving a forward electron the uncertainty ranges from 5% to 20% based on fits of the invariant mass distribution. The background uncertainty in the $Z \rightarrow \mu\mu$ yield is negligible. The largest source of correlated background in both lepton decay channels is the decay of $Z \rightarrow \tau\tau$ events into dielectron and dimuon pairs. These are simulated and reconstructed just as $Z \rightarrow ee$ and $Z \rightarrow \mu\mu$ are but are found to have a negligible contribution following the analysis procedures.

### F. Systematic uncertainties

The dominant source of uncertainty in the $Z \rightarrow ee$ measurement stems from imperfect knowledge of the efficiency
of the electron identification requirements. The uncertainty is driven by the limited number of events available for the tag-and-probe analysis, which had to rely on 2013 $p + \text{Pb}$ collision data because the electron reconstruction performance changed due to detector conditions and occupancy compared to earlier $pp$ collision data. The uncertainty is larger in pairs involving a forward-electron, and the sample has a lower purity than the sample of midrapidity electrons. Other electron uncertainties are significantly smaller and are associated with the trigger efficiency, electron reconstruction efficiency and energy resolution, background subtraction (which becomes significant for forward electrons), and charge misreconstruction. In addition, a small uncertainty stems from possible differences between the simulated $y_\gamma^*$ distribution and the one measured in the data. The $Z \to ee$ systematic uncertainties depend on $p_T^Z$, $y_\gamma^*$, and $p + \text{Pb}$ centrality and are summarized in Table I.

The conditions of muon reconstruction in the 2013 $p + \text{Pb}$ collision data closely resemble those in $pp$ collisions described in Ref. [24]. The small uncertainties from the more abundant $pp$ data are used in this analysis. An uncertainty of 1%, based on the performance of the muon reconstruction in high-pileup $pp$ collisions, is associated with the scale factors to account for possible differences between the data sets. The uncertainties depend on $p_T^\mu$, $y_\gamma^*$, and $p + \text{Pb}$ centrality and are summarized in Table I.

In addition to the $Z$ boson measurement uncertainties, a 2.7% uncertainty is associated with the luminosity calculation. For the centrality-dependent yields that are scaled by $\langle T_{\text{AA}} \rangle$ the uncertainties of the Glauber model calculations are taken from Ref. [22].

The cross section in each leptonic decay channel is defined for the mass window $66 < m_Z < 116$ GeV, the rapidity ranges $|y_\gamma^*| < 3.5$ for $Z \to ee$ and $-3 < y_\gamma^* < 2$ for $Z \to \mu\mu$, and the full decay lepton kinematic phase space. The $Z \to ee$ and $Z \to \mu\mu$ yields, corrected for acceptance and efficiency, are used to calculate the cross section in each channel, and a good agreement between the two is observed as shown for the $y_\gamma^*$ distributions in Fig. 3.

The two decay channel results are combined to one set of $Z \to \ell\ell$ data using the method described in Refs. [35,36]. The technique uses a $\chi^2$ minimization procedure with a nuisance parameter formalism to combine the data sets coherently. The procedure distinguishes those systematic uncertainty sources that are uncorrelated bin to bin, uncorrelated across data sets, and fully correlated bin to bin and across data sets. In this way, combined points are calculated to optimize the overall agreement of the data sets, given the correlation of the uncertainties. This may result in differences in the combined $Z \to \ell\ell$ data points relative to the $Z \to ee$ data points in rapidity regions in which there are no $Z \to \mu\mu$ data points. Following this, an integrated cross section for the region $|y_\gamma^*| < 3.5$ is defined for the combined $Z \to \ell\ell$ points based on both the $Z \to ee$ and the $Z \to \mu\mu$ data even though the $Z \to \mu\mu$ data are limited to $-3 < y_\gamma^* < 2$. The systematic uncertainties associated with the combined results are fully correlated bin to bin in each distribution. They are

TABLE I. Relative systematic uncertainties (in percent) associated with the measurement of $Z \to ee$. The uncertainties typically increase at the more forward rapidities. Background includes charge misreconstruction, and electron reconstruction includes resolution. The last two rows refer only to pairs where one of the electrons was reconstructed in the range $3.1 < |y| < 4.9$.

<table>
<thead>
<tr>
<th>Source</th>
<th>Uncertainty range (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electron ID</td>
<td>6–14</td>
</tr>
<tr>
<td>Electron reconstruction</td>
<td>1–3</td>
</tr>
<tr>
<td>Electron trigger</td>
<td>1–2</td>
</tr>
<tr>
<td>Background</td>
<td>1–3</td>
</tr>
<tr>
<td>MC $y_Z^*$ shape</td>
<td>0–2</td>
</tr>
<tr>
<td>Forward-electron reconstruction</td>
<td>4–15</td>
</tr>
<tr>
<td>Forward-electron background</td>
<td>2–10</td>
</tr>
</tbody>
</table>

G. Lepton channel combination

The cross section in each leptonic decay channel is defined for the mass window $66 < m_Z < 116$ GeV, the rapidity ranges $|y_\gamma^*| < 3.5$ for $Z \to ee$ and $-3 < y_\gamma^* < 2$ for $Z \to \mu\mu$, and the full decay lepton kinematic phase space. The $Z \to ee$ and $Z \to \mu\mu$ yields, corrected for acceptance and efficiency, are used to calculate the cross section in each channel, and a good agreement between the two is observed as shown for the $y_\gamma^*$ distributions in Fig. 3.

The two decay channel results are combined to one set of $Z \to \ell\ell$ data using the method described in Refs. [35,36]. The technique uses a $\chi^2$ minimization procedure with a nuisance parameter formalism to combine the data sets coherently. The procedure distinguishes those systematic uncertainty sources that are uncorrelated bin to bin, uncorrelated across data sets, and fully correlated bin to bin and across data sets. In this way, combined points are calculated to optimize the overall agreement of the data sets, given the correlation of the uncertainties. This may result in differences in the combined $Z \to \ell\ell$ data points relative to the $Z \to ee$ data points in rapidity regions in which there are no $Z \to \mu\mu$ data points. Following this, an integrated cross section for the region $|y_\gamma^*| < 3.5$ is defined for the combined $Z \to \ell\ell$ points based on both the $Z \to ee$ and the $Z \to \mu\mu$ data even though the $Z \to \mu\mu$ data are limited to $-3 < y_\gamma^* < 2$. The systematic uncertainties associated with the combined results are fully correlated bin to bin in each distribution. They are

TABLE II. Relative systematic uncertainties (in percent) associated with the measurement of $Z \to \mu\mu$.

<table>
<thead>
<tr>
<th>Source</th>
<th>Uncertainty range (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Muon ID &amp; reconstruction</td>
<td>1.5</td>
</tr>
<tr>
<td>Muon trigger</td>
<td>1–2</td>
</tr>
<tr>
<td>Background</td>
<td>&lt;1</td>
</tr>
<tr>
<td>$p_T^\mu$ resolution</td>
<td>&lt;1</td>
</tr>
<tr>
<td>MC $y_Z^*$ shape</td>
<td>&lt;1.5</td>
</tr>
</tbody>
</table>
TABLE III. The measured integrated cross section (in nb) for several rapidity ranges, for $Z \rightarrow \mu\mu$, $Z \rightarrow ee$, and the combined $Z \rightarrow \ell\ell$. The first uncertainty listed is statistical, and the second systematic. There is an additional 2.7% luminosity uncertainty for each cross section. Cross sections predicted by the models (see text) are also listed. Uncertainties listed with the model calculations are the PDF and scale uncertainties added in quadrature.

<table>
<thead>
<tr>
<th>$y_Z$</th>
<th>$[-2.0]$</th>
<th>$[0.2]$</th>
<th>$[-3.2]$</th>
<th>$[-3.5, 3.5]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Z \rightarrow \mu\mu$</td>
<td>$54.2 \pm 1.6 \pm 1.3$</td>
<td>$45.3 \pm 2.1 \pm 0.9$</td>
<td>$118.2 \pm 3.3 \pm 2.6$</td>
<td>N/A</td>
</tr>
<tr>
<td>$Z \rightarrow ee$</td>
<td>$55.1 \pm 1.8 \pm 5.9$</td>
<td>$46.5 \pm 2.2 \pm 5.0$</td>
<td>$121 \pm 3 \pm 13$</td>
<td>$143 \pm 5 \pm 17$</td>
</tr>
<tr>
<td>$Z \rightarrow \ell\ell$</td>
<td>$54.4 \pm 1.3 \pm 1.4$</td>
<td>$45.9 \pm 1.4 \pm 1.4$</td>
<td>$119.3 \pm 2.2 \pm 3.4$</td>
<td>$139.8 \pm 4.8 \pm 6.2$</td>
</tr>
<tr>
<td>CT10 (NLO)</td>
<td>$47.4 \pm 0.9$</td>
<td>$46.8 \pm 0.9$</td>
<td>$110.8 \pm 2.9$</td>
<td>$132.2 \pm 3.3$</td>
</tr>
<tr>
<td>CT10 + EPS09 (NLO)</td>
<td>$48.7 \pm 1.0$</td>
<td>$43.5 \pm 1.1$</td>
<td>$108.6 \pm 3.1$</td>
<td>$127.4 \pm 3.6$</td>
</tr>
<tr>
<td>MSTW2008 (NNLO)</td>
<td>$48.3^{+1.2}_{-0.9}$</td>
<td>$47.9^{+1.2}_{-0.9}$</td>
<td>$113.5^{+2.8}_{-2.2}$</td>
<td>$135.2^{+3.4}_{-2.7}$</td>
</tr>
</tbody>
</table>

approximately 3% at midrapidity and rise to about 10% at forward and backward rapidity.

IV. RESULTS

A. $Z \rightarrow \ell\ell$ cross section

From the combined $Z \rightarrow ee$ and $Z \rightarrow \mu\mu$ data a total cross section of $139.8 \pm 4.8$ (statistical) $\pm 6.2$ (systematic) $\pm 3.8$ (luminosity) nb is obtained in the $|y_Z| < 3.5$ acceptance. Based on the MC simulation (and the models discussed below) this acceptance covers approximately 99.5% of the total $Z \rightarrow \ell\ell$ cross section. Restricting the results to the smaller rapidity interval of $-3 < y_Z < 2$, the cross section is $119.3 \pm 2.2$ (statistical) $\pm 3.4$ (systematic) $\pm 3.2$ (luminosity) nb. Table III lists the integrated cross section in the larger and

FIG. 4. (Color online) (a) The $d\sigma/dy_Z$ distribution from $Z \rightarrow \ell\ell$, shown along with several model calculations in the upper panel. Bars indicate statistical uncertainty, and shaded boxes systematic uncertainty, of the data; uncertainties of model calculations are not shown. (b)–(d) Ratios of the data to the models. Uncertainties of the model calculations (scale and PDF uncertainties added in quadrature) are shown as bands around unity in each panel. An additional 2.7% luminosity uncertainty of the cross section is not shown.

FIG. 5. (Color online) (a) The differential cross section of $Z$ boson production multiplied by the Bjorken $x$ of the parton in the lead nucleus, $x_{Pb}d\sigma/dx_{Pb}$, as a function of $x_{Pb}$ using $Z \rightarrow \ell\ell$ events shown along with several model calculations. Bars indicate statistical uncertainty, and shaded boxes systematic uncertainty, of the data; uncertainties of the model calculations are not shown. (b)–(d) Ratios of the data to the models. Uncertainties of the model calculations are shown as bands around unity in each panel. There is an additional 2.7% luminosity uncertainty of the cross section.
smaller rapidity ranges as measured for each channel and their combination.

The measured cross section may be compared to a $p + \text{Pb}$ model prediction composed of a linear sum of the nucleon-nucleon cross sections: $82 \sigma(pp \rightarrow Z + X) + 126 \sigma(\text{pn} \rightarrow Z + X)$, corresponding to the numbers of protons and neutrons in the Pb ion. The value of $\sigma(\text{pn} \rightarrow Z + X)$ is 2% higher than that of $\sigma(pp \rightarrow Z + X)$ in all models discussed below. Calculating the baseline nucleon-nucleon cross sections using the CT10 PDF at NLO, as in the corresponding MC simulation, the model yields values of 132.2 $\pm$ 3.3 nb in the range $|y_Z^*| < 3.5$ and 110.8 $\pm$ 2.9 nb for $-3 < y_Z^* < 2$, where the uncertainties are the sums in quadrature of PDF and scale (renormalization and factorization) uncertainties. Using the MSTW2008 PDF, calculated with FEWZ [37] at next-to-next-to-leading order (NNLO), cross sections of $135.2^{+3.4}_{-2.7}$ nb are obtained for $|y_Z^*| < 3.5$ and $113.5^{+3.8}_{-2.8}$ nb for $-3 < y_Z^* < 2$. At NLO the results from MSTW2008 are very close to the CT10 results. In addition to the simple model of the $p + \text{Pb}$ $Z$ boson cross section as a linear sum of nucleon-nucleon cross sections, calculations are performed incorporating nuclear corrections of the PDF. Including the EPS09 modifications [38] to the CT10 PDF results in cross sections of $127.4 \pm 3.6$ and $108.6 \pm 3.1$ nb, respectively.

For a more detailed understanding of $Z$ boson production, the measured cross section as a function of the $Z$ boson rapidity is presented in Fig. 4 and compared to model calculations. The data are seen to be strongly asymmetric about $y_Z^* = 0$. The CT10 + EPS09 calculations come closest to reproducing the shape of the measured $y_Z^*$ differential cross section. A $\chi^2$ test of compatibility between the data and the model shapes (irrespective of normalization) finds that the CT10 + EPS09 shape of the $y_Z^*$ distribution gives a $p$ value of 0.79. The unmodified CT10 calculation and MSTW2008 calculations have $p$ values of 0.07 and 0.01, respectively. A Kolmogorov-Smirnov test was also performed and resulted in probabilities of 0.96, 0.09, and 0.07 for CT10 + EPS09, CT10, and MSTW2008 model calculations. This is consistent with the preference for the observation of nuclear correction effects as in the $\chi^2$ test.

Nuclear modification of PDFs is fundamentally related to the Bjorken $x$ of the relevant parton. At leading order, $x_p$ in the proton and $x_{\text{Pb}}$ in the lead nucleus are related to the reconstructed $Z$ boson kinematics by

$$x_p = \frac{m_{\ell\ell} e^{y_Z^*}}{\sqrt{S_{NN}}} , \quad x_{\text{Pb}} = \frac{m_{\ell\ell} e^{-y_Z^*}}{\sqrt{S_{NN}}} .$$

The resulting $x_{\text{Pb}}$ distribution is shown in Fig. 5 and compared to model calculations.

Figure 6 shows the $p_T^Z$ distributions for $-3 < y_Z^* < 2$ and, separately, for $-2 < y_Z^* < 0$ and $0 < y_Z^* < 2$. These are compared to the baseline CT10 model. The $p_T^Z$ dependence is less sensitive to nuclear effects and a good agreement between the experimental measurement and the MC simulation shape is observed.

### B. Centrality-dependent yield

Results are presented for the centrality-dependent $Z$ boson yield. If the rate of $Z$ boson production were consistent with geometric expectations, then the $Z$ boson yield divided by $\langle N_{\text{coll}} \rangle$ should be independent of centrality. To investigate
this, the yield of Z bosons per event scaled by \(\langle N_{\text{coll}} \rangle\), within \(-3 < y^{*}_Z < 2\), is displayed as a function of \(\langle N_{\text{part}} \rangle\) in Fig. 7. The yield is independent of centrality defined using the standard Glauber model. Using the GGCF centrality models increases \(\langle N_{\text{coll}} \rangle\) in central events and reduces it in peripheral events; consequently, the yield divided by \(\langle N_{\text{coll}} \rangle\) is reduced in central events and increased in peripheral events. Figure 7 also shows the yield without the application of the centrality bias corrections discussed in Sec. III.C.

The ATLAS Collaboration has previously measured the inclusive charged-hadron multiplicity in \(p + Pb\) collisions as a function of centrality [22], and the centrality dependence of that quantity is similar to that observed in the present measurement. In order to quantify the similarity, the ratio \((dN_{Z}/dy^{*}_{Z})/(dN_{ch}/d\eta)\) is plotted vs \(\langle N_{\text{part}} \rangle\) in Fig. 8. The charged-particle yield is expected to scale with \(\langle N_{\text{part}} \rangle\) and the Z boson yield with \(\langle N_{\text{coll}} \rangle = \langle N_{\text{part}} \rangle - 1\), and so the ratio is fit to a function with the form \(a \cdot ((N_{\text{part}}) - 1)/\langle N_{\text{part}} \rangle\). This

\[N_{\text{coll}} = 29 \text{ nb}^{-1}\]
function describes the data well for the GGCF cases, and less so for the standard Glauber model.

To further investigate the behavior observed in the rapidity differential cross section, the $y^*_Z$ dependence of the $Z$ boson yield in different centrality bins is also measured, as shown in Fig. 9. The differences between the data and the model are larger in central collisions. The $\langle N_{\text{coll}}\rangle$-scaled ratio of central to peripheral data, $R_{\text{CP}}$, defined as

$$R_{\text{CP}}(y^*_Z) = \frac{\langle N_{\text{coll}}\rangle_{\text{peripheral}}}{\langle N_{\text{coll}}\rangle_{\text{central}}} \times \frac{dN_Z^\text{central}/dy^*_Z}{dN_Z^\text{peripheral}/dy^*_Z},$$

is used to observe changes in the rapidity distribution for different centrality bins in a model-independent way and is shown in Fig. 9. Events with 40–90% centrality define the peripheral event selection, and two central selections, 0–10% and 10–40%, are compared with it. A linear fit of the $R_{\text{CP}}(y^*_Z)$ for 0–10% centrality results in a slope of $-0.11 \pm 0.04$, which suggests that the $y^*_Z$ distribution may be different in most central events compared to peripheral events. For 10–40% centrality, the slope is $-0.05 \pm 0.03$.

V. SUMMARY

The $Z$ boson production cross section has been measured in $p + $Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV with the ATLAS detector at the LHC, using $Z \to \ell^+\ell^-$ ($Z \to \mu^+\mu^-$) decays in a 29.4-nb$^{-1}$ (28.1-nb$^{-1}$) data sample. It is found to be significantly higher than predictions based on perturbative QCD calculations. Disregarding the difference in overall normalization, the shapes of the $y^*_Z$ and $x_{NB}$-dependent cross sections are somewhat better described by models that include nuclear modification of the lead nucleus PDF compared to those that do not, although models without nuclear modification are not excluded. Following the application of a centrality bias correction, the centrality-dependent yield is found to scale with $\langle N_{\text{coll}}\rangle$. In addition, the centrality dependence of the $y^*_Z$ distribution was studied, and the asymmetry in $y^*_Z$ was found to be slightly larger in more central events. Integrated over $y^*_Z$, the centrality dependence appears to be consistent with binary scaling and is similar to the production of inclusive charged particles.

ACKNOWLEDGMENTS

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; BMWF 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; MZMT CR, MPO CR, and VSC CR, Czech Republic; DNRF, DNSRC, and Lundbeck Foundation, Denmark; EPLANET, ERC, and NSRF, European Union; IN2P3-CNRS, CEA-DSM/IRFU, France; GNSF, Georgia; BMBF, DFG, HGF, MPG, and AvH Foundation, Germany; GSRT and NSRF, Greece; RGC, Hong Kong SAR, China; ISF, MINEVA, GIF, I-CORE, and Benoziyo Center, Israel; INFN, Italy; MEXT and JSPS, Japan; CNRST, Morocco; FOM and NWO, The Netherlands; BRF and RCN, Norway; MNISw and NCN, Poland; GRICES and FCT, Portugal; MNE/IFA, Romania; MES of Russia and NRC KI, Russian Federation; JINR; MSTD, Serbia; MSSR, Slovakia; ARRS and MIZŠ, Slovenia; DST/NRF, South Africa; MINECO, Spain; SRC and Wallenberg Foundation, Sweden; SER, SNSF, and Cantons of Bern and Geneva, Switzerland; NRC Taiwan; TAEK, Turkey; STFC, the Royal Society and Leverhulme Trust, United Kingdom; and DOE and NSF, United States of America. The crucial computing support from all WLCG partners is acknowledged gratefully, in particular, from CERN and the ATLAS Tier-1 facilities at TRIUMF (Canada), NDGF (Denmark, Norway, Sweden), CC-IN2P3 (France), KIT/GridKA (Germany), INFN-CNAF (Italy), NL-T1 (The Netherlands), PIC (Spain), ASGC (Taiwan), RAL (UK), and BNL (USA) and in the Tier-2 facilities worldwide.
14 Department for Physics and Technology, University of Bergen, Bergen, Norway
15 Physics Division, Lawrence Berkeley National Laboratory and University of California, Berkeley CA, United States of America
16 Department of Physics, Humboldt University, Berlin, Germany
17 Albert Einstein Center for Fundamental Physics and Laboratory for High Energy Physics, University of Bern, Bern, Switzerland
18 School of Physics and Astronomy, University of Birmingham, Birmingham, United Kingdom
19a Department of Physics, Bogazici University, Istanbul
19b Department of Physics Engineering, Gaziantep University, Gaziantep
19c Department of Physics, Dogus University, Istanbul, Turkey
20 INFN Sezione di Bologna
20a Dipartimento di Fisica e Astronomia, Università di Bologna, Bologna, Italy
21 Physikalisches Institut, University of Bonn, Bonn, Germany
22 Department of Physics, Boston University, Boston MA, United States of America
23 Department of Physics, Brandeis University, Waltham MA, United States of America
24a Universidade Federal do Rio De Janeiro COPPE/EE/IF, Rio De Janeiro
24b Electrical Circuits Department, Federal University of Juiz de Fora (UFJF), Juiz de Fora
24c Federal University of Sao Joao del Rei (UFSJ), Sao Joao del Rei
24d Instituto de Fisica, Universidade de Sao Paulo, Sao Paulo, Brazil
25 Physics Department, Brookhaven National Laboratory, Upton NY, United States of America
26a National Institute of Physics and Nuclear Engineering, Bucharest
26b West University in Timisoara, Timisoara, Romania
27 Departamento de Física, Universidad de Buenos Aires, Buenos Aires, Argentina
28 Cavendish Laboratory, University of Cambridge, Cambridge, United Kingdom
29 Department of Physics, Carleton University, Ottawa ON, Canada
30 CERN, Geneva, Switzerland
31 Enrico Fermi Institute, University of Chicago, Chicago IL, United States of America
32a Departamento de Física, Pontificia Universidad Católica de Chile, Santiago
32b Departamento de Física, Universidad Técnica Federico Santa María, Valparaíso, Chile
33a Institute of High Energy Physics, Chinese Academy of Sciences, Beijing
33b Department of Modern Physics, University of Science and Technology of China, Anhui
33c Department of Physics, Nanjing University, Jiangsu
33d School of Physics, Shandong University, Shandong
33e Department of Physics and Astronomy, Shanghai Key Laboratory for Particle Physics and Cosmology, Shanghai Jiao Tong University, Shanghai
34 Physics Department, Tsinghua University, Beijing 100084, China
35 Laboratoire de Physique Corpusculaire, Clermont Université and Université Blaise Pascal and CNRS/IN2P3, Clermont-Ferrand, France
36 Nevis Laboratory, Columbia University, Irvington NY, United States of America
37a Niels Bohr Institute, University of Copenhagen, Kobenhavn, Denmark
37b INFN Gruppo Collegato di Cosenza, Laboratori Nazionali di Frascati
37c Dipartimento di Fisica, Università della Calabria, Rende, Italy
38 AGH University of Science and Technology, Faculty of Physics and Applied Computer Science, Krakow
38a Institute of Nuclear Physics Polish Academy of Sciences, Krakow, Poland
39 Marian Smoluchowski Institute of Physics, Jagiellonian University, Krakow, Poland
40 Physics Department, Southern Methodist University, Dallas TX, United States of America
41 Physics Department, University of Texas at Dallas, Richardson TX, United States of America
42 DESY, Hamburg and Zeuthen, Germany
43 Institut für Experimentelle Physik IV, Technische Universität Dortmund, Dortmund, Germany
44 Institut für Kern- und Teilchenphysik, Technische Universität Dresden, Dresden, Germany
45 Department of Physics, Duke University, Durham, NC, United States of America
46 SUPA - School of Physics and Astronomy, University of Edinburgh, Edinburgh, United Kingdom
47 INFN Laboratori Nazionali di Frascati, Frascati, Italy
48 Fakultät für Mathematik und Physik, Albert-Ludwigs-Universität, Freiburg, Germany
49 Section de Physique, Université de Genève, Geneva, Switzerland
50 INFN Sezione di Genova
50a Dipartimento di Fisica, Università di Genova, Genova, Italy
51a E. Andronikashvili Institute of Physics, Iv. Javakhishvili Tbilisi State University, Tbilisi
51b High Energy Physics Institute, Tbilisi State University, Tbilisi, Georgia
52 II Physikalisches Institut, Justus-Liebig-Universität Giessen, Giessen, Germany
School of Physics, University of the Witwatersrand, Johannesburg, South Africa

Department of Physics, Stockholm University

The Oskar Klein Centre, Stockholm, Sweden

Departments of Physics & Astronomy and Chemistry, 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

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, The 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

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

TRIUMF, Vancouver BC

Department of Physics and Astronomy, York University, Toronto, ON, Canada

Faculty of Pure and Applied Sciences, University of Tsukuba, Tsukuba, Japan

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

Centro de Investigaciones, Universidad Antonio Nariño, Bogota, Colombia

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

INFN Gruppo Collegato di Udine, Sezione di Trieste, Udine

ICTP, Trieste

Dipartimento di Chimica, Fisica e Ambiente, Università di Udine, Udine, Italy

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

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

Instituto de Física Corpuscular (IFIC) and Departamento de Física Atómica, Molecular y Nuclear and Departamento de Ingeniería Electrónica y Instituto de Microelectrónica de Barcelona (IMB-CNM), University of Valencia and CSIC, Valencia, Spain

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

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

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

Waseda University, Tokyo, Japan

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

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

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

Fachbereich C Physik, Bergische Universität Wuppertal, Wuppertal, Germany

Department of Physics, Yale University, New Haven, CT, United States of America

Yerevan Physics Institute, Yerevan, Armenia

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

Also at Department of Physics, King’s College London, London, United Kingdom

Also at Institute of Physics, Azerbaijan Academy of Sciences, Baku, Azerbaijan

Also at Novosibirsk State University, Novosibirsk, Russia

Also at TRIUMF, Vancouver, BC, Canada

Also at Department of Physics, California State University, Fresno CA, United States of America

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

Also at Departamento de Fisica e Astronomia, Faculdade de Ciencias, Universidade do Porto, Portugal

Also at Tomsk State University, Tomsk, Russia

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

Also at Universita di Napoli Parthenope, Napoli, Italy

Also at Institute of Particle Physics (IPP), Canada

Also at Particle Physics Department, Rutherford Appleton Laboratory, Didcot, United Kingdom

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

Also at Louisiana Tech University, Ruston, LA, United States of America

Also at Instituto Catalana de Recerca i Estudis Avancats, ICREA, Barcelona, Spain

Also at Department of Physics, National Tsing Hua University, Taiwan

Also at Department of Physics, The University of Texas at Austin, Austin, TX, United States of America

Also at Institute of Theoretical Physics, Ilia State University, Tbilisi, Georgia

Also at CERN, Geneva, Switzerland