Measurement of Z Boson Production in Pb-Pb Collisions at $\sqrt{s_{NN}} = 2.76$ TeV with the ATLAS Detector

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The ATLAS experiment has observed 1995 Z boson candidates in data corresponding to 0.15 nb^{-1} of integrated luminosity obtained in the 2011 LHC Pb + Pb run at $\sqrt{s_{NN}} = 2.76$ TeV. The Z bosons are reconstructed via dielectron and dimuon decay channels, with a background contamination of less than 3%. Results from the two channels are consistent and are combined. Within the statistical and systematic uncertainties, the per-event Z boson yield is proportional to the number of binary collisions estimated by the Glauber model. The elliptic anisotropy of the azimuthal distribution of the Z boson with respect to the event plane is found to be consistent with zero.

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Extensive studies of heavy ion (HI) collisions carried out by the experiments at the Relativistic Heavy Ion Collider (RHIC) at BNL, and the Large Hadron Collider (LHC) at CERN, have established that the hot and dense matter produced in HI collisions causes a significant modification of the energetic color-charge carriers propagating through such a medium [1,2]. An understanding of this phenomenon requires measuring the unmodified production rates of the particles before they lose energy. The best candidates to perform such measurements are particles that do not interact via the strong force. The PHENIX experiment at RHIC measured the properties of photons [3]. At the LHC, the CMS experiment reported results on photons and W bosons [4,5]. The number of these bosons was found to scale with the number of incoherent nucelon-nucleon collisions. Both the ATLAS and CMS Collaborations have reported measurements of $Z \to \mu\mu$ production at $\sqrt{s_{NN}} = 2.76$ TeV [6,7], which show, within a limited statistical precision, the same scaling behavior. This Letter presents a precise measurement of Z boson production in Pb + Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV, using the dielectron and dimuon decay channels. The Z boson production rate is measured as a function of centrality, rapidity (y^Z), transverse momentum (p_T^Z), and orientation with respect to the event plane [8].

The ATLAS detector [9] 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 a muon spectrometer incorporating three superconducting toroid magnet systems.

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The inner detector system (ID) is immersed in a 2 T axial magnetic field and provides charged particle tracking in the range $|\eta| < 2.5$. The high-granularity silicon pixel detector covers the vertex region and is surrounded by the silicon microstrip tracker and the transition radiation tracker.

The calorimeters cover the range $|\eta| < 4.9$. Within the region $|\eta| < 3.2$, electromagnetic calorimetry is provided by barrel and end-cap high-granularity lead liquid-argon (LAr) calorimeters, with an additional thin LAr presampler covering $|\eta| < 1.8$. The electromagnetic calorimeter is backed by a hadronic calorimeter. Forward calorimeters (FCal) are located in the range $3.1 < |\eta| < 4.9$.

The muon spectrometer (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 tubes (MDT), complemented by cathode strip chambers (CSC) 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, and thin gap chambers in the end-cap regions.

This analysis uses the 2011 LHC Pb + Pb collision data at $\sqrt{s_{NN}} = 2.76$ TeV, obtained by the ATLAS experiment with integrated luminosity of approximately 0.15 nb^{-1}. The data sample for this study was collected using a three-level trigger system [10], which selected events with electron or muon candidates.

Electron candidates were identified at the first trigger level ($L1$) 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 $|\eta| < 2.5$, excluding the transition region between calorimeter sections ($1.37 < |\eta| < 1.52$). The cluster transverse energy was required to exceed $E_T = 14$ GeV.

Muon candidates were selected using all three trigger levels. The $L1$ muon trigger searched for patterns of hits in the trigger chambers consistent with muons. If a muon had p_T exceeding 4 GeV, the event was accepted for further processing by the high-level trigger (HLT). The $L1$ muon algorithm also identified regions of interest (RoI) within the detector to be investigated by the HLT. In the HLT, the track parameters of each muon were recalculated by including the precision data from the MDT or CSC in the RoI defined by the previous trigger level. Muon candidates were reconstructed either solely from the MS or using combined data from the MS and ID. In addition to the events selected using the RoI-based muon trigger, the reconstruction was performed over the whole MS by the HLT to identify muons with $p_T > 10$ GeV. The full scan searched all events in which a neutral particle signal was detected in each of two zero degree calorimeters (ZDC) ($|\eta| > 8.3$), or which contained an energy deposition in the calorimeters of $E_T > 10$ GeV.

In addition to the single-lepton trigger, each event had to pass the minimum-bias (MB) event selection, which required a timing signal coincidence of better than 3 ns between the MB trigger scintillators ($2.1 < |\eta| < 3.8$), as well as the reconstruction of a collision vertex in the ID. The total number of sampled events is $(1.03 \pm 0.02) \times 10^9$ [11].

Analyzed events are divided into centrality classes. Centrality reflects the overlap volume of the two colliding nuclei. Collisions with a small (large) impact parameter are referred to as central (peripheral). The overlap volume is closely related to the average number of participant nucleons which scatter inelastically in each nuclear collision $\langle N_{\text{part}} \rangle$, and to the average number of binary collisions between the nucleons of the colliding nuclei $\langle N_{\text{coll}} \rangle$. Equivalently, $\langle N_{\text{coll}} \rangle$ may be defined as the average nuclear thickness function $\langle T_{\text{AA}} \rangle$ multiplied by the total inelastic $p + p$ cross section of 64 ± 5 mb [12].

The Pb + Pb collision centrality is measured using the scalar sum of transverse energy ($\sum E_T$) deposited in the FCal, calibrated at the electromagnetic energy scale [13]. The fraction of events with more than one Pb + Pb collision is estimated not to exceed 0.05%, except for the most central 5% of events in which the fraction does not exceed 0.5%. A cut on the FCal energy of $\sum E_T < 3.8$ TeV is applied to prevent contamination by events with multiple Pb + Pb interactions. Glauber model calculations relate centrality to $\langle N_{\text{part}} \rangle$ and $\langle N_{\text{coll}} \rangle$, following the procedure documented in Ref. [14]. In the present sample, $\langle N_{\text{coll}} \rangle$ ($\langle N_{\text{part}} \rangle$) ranges from 1683 ± 130 (382 ± 2) for the most central class, 0%–5%, to 78 ± 7 (46 ± 3) for the most peripheral class, 40%–80%.

The efficiencies of the electron and muon triggers are evaluated from 5.5×10^7 events selected with the MB trigger during the 2011 run. The MB trigger required a transverse energy deposition of $E_T > 50$ GeV in the calorimeters or a coincidence of both ZDC signals and a track in the ID. The average trigger efficiency for muons with $p_T > 10$ GeV decreases from $(98.2 \pm 0.5)\%$ in peripheral events to $(90.9 \pm 0.5)\%$ in central events, where the ID occupancy is higher. The average trigger efficiency for electrons with $|\eta| < 2.5$ and $E_T > 20$ GeV is $(98.1 \pm 0.1)\%$, independent of centrality. The trigger efficiency for $Z \rightarrow \mu\mu$ decays ranges from $(99.0 \pm 0.6)\%$ in peripheral events to $(95.0 \pm 0.9)\%$ in central events. For $Z \rightarrow ee$ decays the efficiency is $(99.9 \pm 0.1)\%$ independent of centrality.

For the $Z \rightarrow ee$ analysis, electron candidates are formed using the standard ATLAS reconstruction algorithm [15], requiring the matching of a track to an energy cluster in the electromagnetic calorimeter. Electron selection is limited to $|\eta| < 2.5$ and both electrons are required to have $E_T > 20$ GeV. Following the reconstruction requirements, further electron identification cuts are made to reject background. The standard electron identification cuts [15] used in the $p + p$ environment are not suited to the Pb + Pb environment due to the large underlying event (UE) energy deposition in the calorimeter. To address this, a different set of cuts has been developed to accommodate the modification of the calorimeter variables by the presence of the UE. The cuts used are based on the energy balance between the track momentum and cluster energy (E/p), as well as calorimeter shower shape variables. Furthermore, the UE energy is estimated (following Ref. [16]) and subtracted on an electron-by-electron basis to recover the proper electron energy.

The electron combined reconstruction and identification efficiency is evaluated in a Monte Carlo simulation using electrons from 7×10^5 PYTHIA (version 6.425) [17] $p + p \rightarrow Z \rightarrow ee$ events with $66 < m_Z < 116$ GeV and $|y^Z| < 2.5$ embedded into Pb + Pb events generated by the HIJING event generator (version 1.38b) [18]. The response of the ATLAS detector to the generated particles is modeled using GEANT4 [19,20]. The combined reconstruction and identification efficiency for electrons of $E_T > 20$ GeV ranges from 72% to 76% from central to peripheral events, with a common absolute uncertainty of 5.4%.

For the $Z \rightarrow ee$ analysis, all electrons found in triggered events are paired with each other, requiring that at least one electron in the pair matches a trigger object. The opposite-sign charged pairs with an invariant mass satisfying $66 < m_{ee} < 102$ GeV are accepted as signal Z boson candidates. The same-sign pairs in this window are taken as an estimate of the combinatorial background. In total, 772 opposite-sign pairs and 42 same-sign pairs are reconstructed.

In the $Z \rightarrow \mu\mu$ analysis, single muons are reconstructed with several levels of quality [21]. High quality muons are reconstructed in both the MS and ID with consistent angular measurements, as well as with a good match to the event vertex. At least one muon in each pair, matched to the trigger, is required to be of such quality. If the second muon in the pair has hit patterns in the MS and ID satisfying criteria of high reconstruction quality, the minimum p_T threshold is set to 10 GeV for both muons. If the second muon fails this condition, both muons are required to satisfy $p_T > 20$ GeV.

The muon combined reconstruction and identification efficiency is evaluated using muons from 5.3×10^5 PYTHIA $p + p \rightarrow Z \rightarrow \mu\mu$ events with $66 < m_Z < 116$ GeV and $|y^Z| < 2.5$ embedded into HIJING events. For muons with $p_T > 20$ GeV, $|\eta| < 2.5$ and associated to the event vertex, the reconstruction efficiency of the MS varies from $(97 \pm 1)\%$ to $(98 \pm 1)\%$ from central to peripheral events. Requiring a match between the MS and ID reduces the efficiency to $(89 \pm 1)\%$ and $(91 \pm 1)\%$, respectively, due to track loss in the ID, predominantly at $|\eta| > 1.5$.

As in the $Z \rightarrow ee$ analysis, an invariant mass window of $66 < m_{\mu\mu} < 102$ GeV is used to define oppositely charged muon pairs as Z boson candidates and same-sign charged pairs as a background estimate. In total, 1223 opposite-sign candidates and 14 same-sign pairs are reconstructed in the $Z \rightarrow \mu\mu$ channel.

The invariant mass distributions of the selected pairs together with estimated combinatorial backgrounds for all p_T^Z and $y^Z < 2.5$ are shown in Fig. 1, compared with the simulation normalized to the number of pairs in the region $66 < m_{\ell\ell} < 102$ GeV ($\ell = e, \mu$). In order to calculate the yield, the combinatorial background estimated with the same-sign pairs must be subtracted. Backgrounds from electroweak processes and top pair decays [22] are small compared to the combinatorial backgrounds, and their contribution is accounted for in the systematic uncertainty related to the background.

The main sources of systematic uncertainty in both measurement channels are associated with the precision to which the corrections applied to the data can be calculated. In the $p + p$ environment, the muon reconstruction efficiencies in data and simulation agree to 1% (2% for $p_T < 15$ GeV) [23]. The MS maintains low occupancy in the Pb + Pb environment. The difference in the fraction of muons reconstructed only in the MS, between data and simulation is used to estimate the systematic uncertainty on the reconstruction efficiency. To evaluate the uncertainty on the efficiency of the electron identification cuts stemming from the simulation, the efficiency is computed from the HI data using a tag-and-probe technique [15] and compared to the efficiency computed from simulation. The systematic uncertainty due to momentum resolution is estimated by introducing additional momentum smearing to the simulation. The efficiency (resolution) uncertainties are $\approx 5.5\%$ (2.5%) for $Z \rightarrow \mu\mu$, and 8% (2.5%) in $Z \rightarrow ee$; these estimates vary with p_T^Z and y^Z.

The trigger efficiency uncertainties are estimated by using alternative methods and comparing their results with those obtained from the MB data set. For this comparison the simulation trigger efficiency is used, as well as the conditional trigger efficiency of a second lepton in a triggered pair reconstructed as a Z boson.

For each $Z \rightarrow ll$ analysis, correction factors to account for the efficiency (relative to Z bosons produced with $66 < m_Z < 116$ GeV) and detector resolution within the selected acceptance based on the simulation are calculated differentially in event centrality, p_T^Z, and y^Z. In each decay channel, the correction factor is applied and the background, estimated by the same-sign pairs, is subtracted. The two measurements are averaged with weights set by their respective uncertainties.

The fully corrected y^Z distribution is shown in Fig. 2. No centrality dependence of this shape is observed. The data are compared to a model composed of PYTHIA events normalized to the $Z \rightarrow ll$ cross section in $p + p$ collisions at $\sqrt{s_{NN}} = 2.76$ TeV taken from next-to-next-to-leading-order (NNLO) calculations used in Ref. [24] and scaled by $\langle T_{AA} \rangle$. Using the same computational approach as in

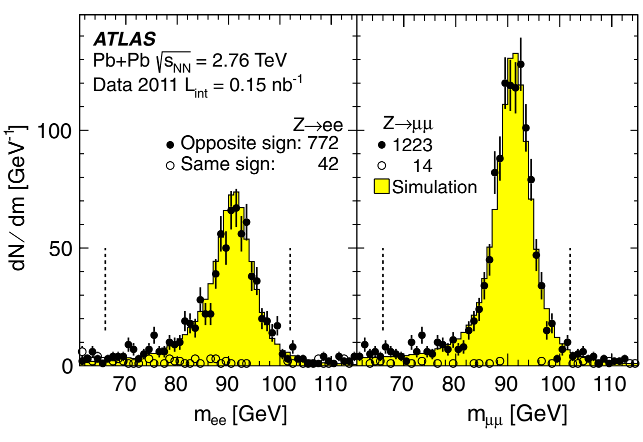

FIG. 1 (color online). The invariant mass distributions of $Z \rightarrow ee$ (left) and $Z \rightarrow \mu\mu$ (right) candidates, integrated over momentum, rapidity, and centrality. Bars represent the statistical uncertainty. The number of pairs with $66 < m_{\ell\ell} < 102$ GeV (marked by the vertical dashed lines) is listed. The simulation is weighted to match the centrality distribution in data and normalized in the region $66 < m_{\ell\ell} < 102$ GeV.

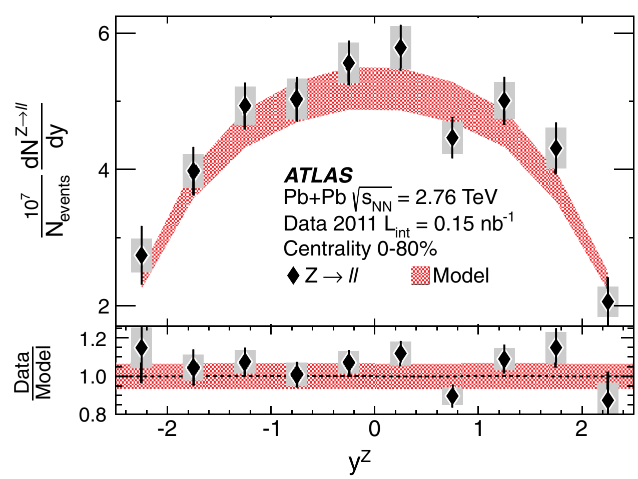

FIG. 2 (color online). The corrected per-event rapidity distribution of measured Z bosons. Bars and boxes represent statistical and systematic uncertainties, respectively. The data are compared to the model distribution shown as a band whose width is the normalization uncertainty.

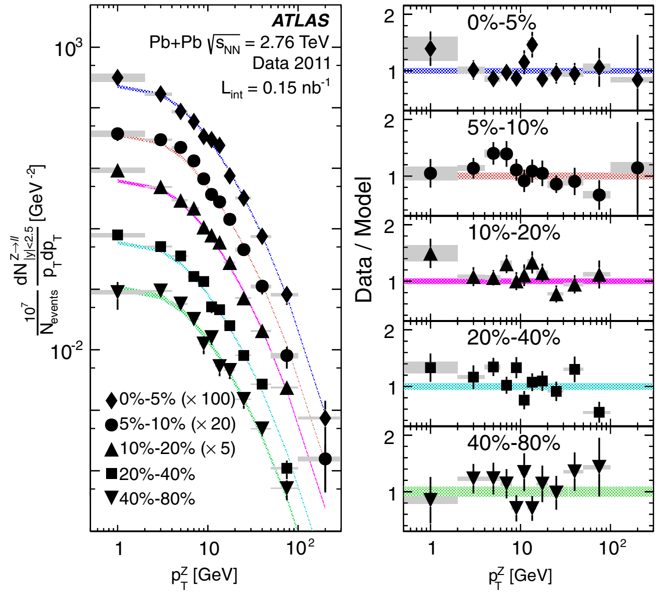

FIG. 3 (color online). Left: corrected per-event p_T^Z spectra of measured Z bosons in five centrality classes. The data are compared to a PYTHIA simulation normalized to the NNLO $p + p$ cross section and scaled by $\langle T_{AA}\rangle$, shown as bands. Right: ratios of the data to the model in each centrality class. Bars represent statistical uncertainties, boxes represent systematic uncertainties, and bands represent the normalization uncertainty.

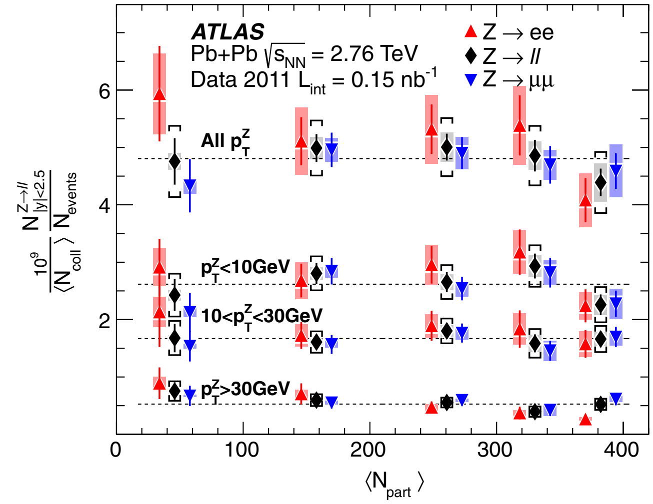

FIG. 4 (color online). Centrality dependence of Z boson yields divided by $\langle N_{coll}\rangle$. Results for ee (upward pointing triangles) and $\mu\mu$ (downward pointing triangles) channels are shifted left and right, respectively, from their weighted average (diamonds). Bars and boxes represent statistical and systematic uncertainties, respectively. For the combined results, the brackets show the combined uncertainty including the uncertainty on $\langle N_{coll}\rangle$, and the dashed lines show the results of fits, using a constant.

Ref. [24] but incorporating $p + n$ and $n + n$ collisions would increase the cross section by 3%. The shape is well reproduced by PYTHIA, and the integrated yield is in good agreement with the $\langle T_{AA}\rangle$-scaled NNLO cross section.

The fully corrected p_T distributions in five centrality classes are shown in the left panel of Fig. 3 along with the model prediction. The shape as a function of p_T^Z is well reproduced by PYTHIA. The right panel of Fig. 3 shows the ratios of the data to the PYTHIA prediction scaled by $\langle T_{AA}\rangle$. The ratios are constant within uncertainties for all centrality classes over the range of measured p_T^Z.

To further examine the binary collision scaling of the data, the Z boson per-event yields, divided by $\langle N_{coll}\rangle$, are shown in Fig. 4 as a function of $\langle N_{part}\rangle$, in several p_T^Z bins. The figure demonstrates that the $Z \to ee$ and $Z \to \mu\mu$ results are consistent within their uncertainties for all p_T^Z and centrality regions. Within the statistical significance of the data sample, the Z boson per-event yield obeys binary collision scaling.

The elliptic anisotropy v_2 of the Z boson is defined as $v_2 = \langle\cos 2(\phi - \Psi_2)\rangle/\sigma_2$, where ϕ is the azimuthal angle of the Z boson momentum vector and Ψ_2 is the azimuthal angle of the event plane, the plane containing the momentum vectors of both lead nuclei and measured with resolution σ_2 [25]. The v_2 values measured in the two decay channels are consistent and are combined. The main uncertainty on the v_2 measurement arises from the event plane (EP) resolution, which is measured from the difference of Ψ_2 determined using the two sides of the FCal at positive and negative rapidities [25]. To ensure that the jets associated with Z boson production do not affect the determination of Ψ_2, the EP resolution is also measured comparing the FCal signal on the side which may be affected by a recoiling jet to the one of the unaffected side. A systematic uncertainty of 12 mrad is assigned for possible EP distortion.

The v_2 of the Z boson is shown in Fig. 5 as a function of $|y^Z|$, p_T^Z, and $\langle N_{part}\rangle$. The averaged v_2 of the Z boson has been measured to be $v_2 = -0.015 \pm 0.018(\text{stat}) \pm 0.014(\text{sys})$, which indicates an isotropic distribution. This observation is an independent measurement consistent with $Z \to ll$ yields being unaffected by the medium in HI collisions.

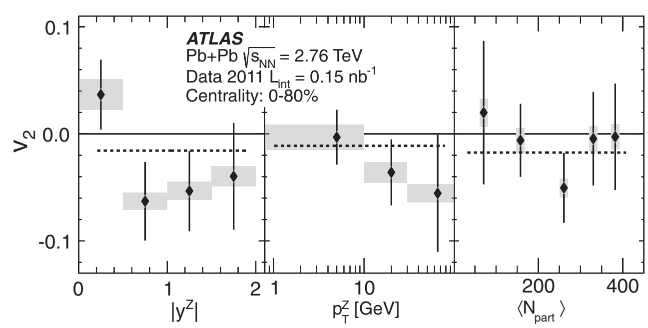

FIG. 5. v_2 as a function of $|y^Z|$ (left), p_T^Z (center), and $\langle N_{part}\rangle$ (right). Bars and boxes represent statistical and systematic uncertainties, respectively. The dashed lines show the results of constant fits to the v_2 values, considering only statistical uncertainties.

Using the ATLAS detector, Z boson production has been measured in Pb + Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV using 0.15 nb^{-1} of integrated luminosity collected in the 2011 LHC physics run. Within $|y^Z| < 2.5$, and $66 < m_{\ell\ell} < 102$ GeV, a total of 772 and 1223 Z boson candidates are reconstructed in the $Z \to ee$ and $Z \to \mu\mu$ channels, respectively. The combinatorial background is at the level of 5% in the dielectron channel and 1% for the dimuon channel. The Z boson production yield integrated over $|y^Z| < 2.5$ is consistent between the two channels in all measured p_T and centrality regions. The momentum and rapidity distributions of the Z bosons are consistent with PYTHIA simulations of Z boson production in $p + p$ collisions scaled to the NNLO cross section and multiplied by $\langle T_{\mathrm{AA}} \rangle$. Within the uncertainties the Z boson yield is found to be proportional to $\langle N_{\mathrm{coll}} \rangle$. The elliptic anisotropy of the Z boson measured as a function of rapidity, p_T^Z and $\langle N_{\mathrm{part}} \rangle$ is consistent with zero within the uncertainties of the measurements.

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