Z Boson Production in p +Pb Collisions measured by the ATLAS Experiment

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Abstract

The measurement of Z bosons in heavy ion collisions is an excellent tool for probing the nucleus at the partonic level. The inclusive yield provides a stringent test of binary collision scaling. Recent ATLAS results demonstrate such scaling in Pb+Pb collisions. The 2013 p+Pb physics run at the LHC providing more than 30 nb^{-1} of collisions at an energy of $\sqrt{s_{NN}} = 5.02 \text{ TeV}$ has made a detailed study of Z boson production in proton+nucleus interactions possible for the first time. These data may confirm binary scaling in the p+Pb system and help to clarify the present ambiguity of centrality classifications in proton+nucleus collisions. Furthermore, the momentum and rapidity differential yields of Z bosons allow the detection of modification of the initial state present in such collisions.

Keywords: ATLAS, p+Pb, Z Bosons

The measurement of Z boson production in p +Pb collisions is a way to compare the initial state effects between p +Pb and Pb+Pb collisions at the LHC. The Z bosons are reconstructed using the $Z \rightarrow \mu^+\mu^-$ decay channel in the rapidity range $-2.5 < y^Z < 2.5$ in the laboratory coordinate frame. Positive rapidity corresponds to the direction the proton beam travelled, “p-going”, and negative rapidity is referred to as “Pb-going”. Midway through the p +Pb running the directions of the proton and lead beams were reversed; the results obtained in the two data periods were found to be consistent with each other and are combined. In this convention, the asymmetric beams resulted in a centre of mass shifted to rapidity $y_{CM}=0.465$ in the laboratory frame. The data sample for this study was collected with the ATLAS detector [1] using a three-level trigger system, which selected events with electron or muon candidates. Following stringent data quality requirements, the $Z \rightarrow e^+e^-$ and $Z \rightarrow \mu^+\mu^-$ analyses draw on samples corresponding to integrated luminosity values of $29.1 \pm 1.0 \text{ nb}^{-1}$ and $27.8 \pm 0.9 \text{ nb}^{-1}$, respectively.

Results measured in the di-electron and di-muon decay channels are combined accounting for uncertainty correlations, and the Z boson production rates are presented as a function of event centrality, p_T^Z and y^Z . The measured cross-sections are compared to NNLO pQCD calculations, and the centrality dependence of the Z boson yield per event is compared to the centrality dependence of the total charged multiplicity. The analysis is discussed in greater detail in Ref. [2].

To form $Z \rightarrow e^+e^-$ candidates, all electrons found in triggered events are paired with each other. The triggering electron is required to have $E_T > 20 \text{ GeV}$, and $|\eta| < 1.37$ or $1.52 < |\eta| < 2.47$, and must satisfy tight reconstruction quality requirements. The other electron must have $E_T > 10 \text{ GeV}$, may be anywhere in $|\eta| < 2.47$, and must satisfy looser quality requirements. Similarly, muon candidates were selected in the region $|\eta| < 2.4$, with the requirement that the triggering muon must have $p_T > 20 \text{ GeV}$ and the other muon $p_T > 10 \text{ GeV}$. Opposite-sign charged pairs with an invariant mass satisfying $66 < m_{\ell\ell} < 116 \text{ GeV}$ 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, 1652 (52) opposite-sign (same-sign) pairs are reconstructed in the $Z \rightarrow e^+e^-$ channel and 2095 (37) opposite-sign (same-sign) pairs in the $Z \rightarrow \mu^+\mu^-$ channel. Additionally, electrons were reconstructed between $2.5 < |\eta| < 4.9$ based on energy deposited in the forward calorimeters. These electrons are required to have $E_T > 20 \text{ GeV}$. Pairs made with one mid-rapidity triggering electron and one forward electron ($2.5 < |\eta| < 4.9$) with an invariant mass $80 < m_{ee} < 100 \text{ GeV}$ were also selected as Z boson candidates. There were 264 such candidates, of which an estimated 5% are background based on a fit of the invariant mass distribution.

Figure 1: The $d\sigma/dp_T$ (left) and $d\sigma/dy$ (right) distributions for $Z \rightarrow \ell^+ \ell^-$ in the data compared with CT10 (scaled to have the total cross-section predicted by MSTW2008 at NNLO). The lower panel are their ratios. The bars indicate statistical uncertainty and the shaded boxes systematic uncertainty. The systematic uncertainties are correlated bin-by-bin. There is an overall scale uncertainty of 3.4% stemming from the luminosity measurement that is not shown. The Figure is from Ref. [2].

The trigger, reconstruction, and identification efficiencies of both electrons and muons are evaluated by a Monte Carlo simulation (MC) complemented by data-driven estimates of the same quantities. Using the POWHEG generator [3] (utilizing the CT10 PDF [4]) with showering from PYTHIA8 [5], 10 million $Z \rightarrow e^+ e^-$ and 4 million $Z \rightarrow \mu^+ \mu^-$ events were simulated. The Z bosons were generated from both pp and pn collisions, and are 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 is modeled using GEANT4 [6, 7]. From the MC, correction factors for the yields of $Z \rightarrow e^+ e^-$ and $Z \rightarrow \mu^+ \mu^-$ candidates are calculated as functions of p_T^Z , y^Z , and p +Pb centrality. This correction takes into account the cumulative losses due to trigger, reconstruction, and identification efficiency as well as the kinematic acceptance limits of the daughter leptons. The correction is defined relative to all generated Z bosons within the mass window $66 < m_{\ell\ell} < 116$ GeV. Following the subtraction of background and application of the correction factor, a corrected yield of Z bosons is obtained in each bin of p_T^Z and y^Z . After correction, the $Z \rightarrow e^+ e^-$ and $Z \rightarrow \mu^+ \mu^-$ are combined using the method described in Ref. [8].

In order to characterize the p +Pb collision geometry each event is assigned a centrality classification based on the total transverse energy measured in the forward calorimeter on the Pb-going side ($-4.9 < \eta < -3.2$). A standard Glauber model [9] approach is used to calculate the mean number of participating nucleons in the collision, $\langle N_{\text{part}} \rangle$ (in the p +Pb system the mean number of inelastic nucleon-nucleon collisions, $\langle N_{\text{coll}} \rangle$, is $\langle N_{\text{part}} \rangle - 1$). In addition, a Glauber-Gribov model [10, 11], an extension to the Glauber model, is also implemented. To maintain the integrity of the centrality classification and the related calculation of $\langle N_{\text{part}} \rangle$, in the centrality binned part of this analysis only events within 0-90% centrality are studied. Pile-up events containing multiple p +Pb interactions and diffractive events, identified by a rapidity gap defined by the absence of calorimeter energy clusters, are removed. The cross-section is defined for the mass window $66 < m_Z < 116$ GeV, and the full decay lepton kinematic phase-space. The p_T and rapidity differential cross-sections are shown in Figure 1. The cross-section may be compared to a baseline model based on NNLO pQCD calculations constructed as $\sigma(p+Pb \rightarrow Z \rightarrow \ell^+ \ell^-) = 82 \times \sigma(pp \rightarrow Z \rightarrow \ell^+ \ell^-) + 126 \times \sigma(pn \rightarrow Z \rightarrow \ell^+ \ell^-)$. The nucleon-nucleon cross-sections, $\sigma(pp \rightarrow Z \rightarrow \ell^+ \ell^-)$ and $\sigma(pn \rightarrow Z \rightarrow \ell^+ \ell^-)$, are obtained by following the calculations in Ref. [12]. To consider this baseline cross-section differentially the high statistics MC generated using the CT10 PDF is taken at generator level and scaled to the NNLO total cross-section. The model is shown alongside the data in Figure 1. This naive model underestimates the data at backward rapidity (in the Pb-going beam direction).

Results are also presented for the centrality differential Z boson yields in the left panel of Figure 2. The centrality dependence is roughly consistent with binary collision scaling using the standard Glauber model centrality definitions. Charged particle production as a function of $\langle N_{\text{part}} \rangle$ in p +Pb collisions [13] displays a similar trend and is plotted alongside the Z boson yield in the right panel of Figure 2. To quantify the similarity between the Z boson, within $|y^Z| < 2.5$, and inclusive charged particle yields, the ratio $\frac{dN_Z/dy}{dN_{ch}/dy}$ is plotted vs $\langle N_{\text{part}} \rangle$ in Figure 3. The charged particle

Figure 2: Left: The yield of Z bosons per event scaled by $\langle N_{\text{coll}} \rangle$ as a function of $\langle N_{\text{part}} \rangle$. Each panel uses a different Glauber model configuration in calculating $\langle N_{\text{part}} \rangle$ (and $\langle N_{\text{coll}} \rangle$); displayed from top to bottom are: the standard Glauber model with no Gribov fluctuations, Glauber-Gribov with $\Omega=0.55$, and Glauber-Gribov with $\Omega=1.01$. The bars indicate statistical uncertainty and the shaded boxes systematic uncertainty. The systematic uncertainties are correlated bin-by-bin. The $\langle N_{\text{coll}} \rangle$ uncertainty plotted does not include the bin-by-bin fully correlated uncertainty stemming from the uncertainty on $\sigma_{N+N \rightarrow X}$. The $\sigma_{N+N \rightarrow X}$ uncertainty is plotted on the NNLO prediction point. The Figure is from Ref. [2]. Right: The similar quantity for inclusive charged particle multiplicity scaled by $\langle N_{\text{part}} \rangle/2$ (in place of $\langle N_{\text{coll}} \rangle$) from Ref. [13].

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 of the form $a \cdot (\langle N_{\text{part}} \rangle - 1) / \langle N_{\text{part}} \rangle$ which describes the data well. To further understand the rapidity shape seen in Figure 1, the yields of Z boson per event as a function of the Z rapidity are plotted separately for different centrality categories in Figure 4. The rapidity asymmetry is found to be strongly present in central collisions, and less so in peripheral collisions.

ATLAS has measured the total integrated and differential cross-sections of Z boson production in p+Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV using both the di-electron and di-muon channels. The total measured cross-section is compared to a baseline pQCD model in which nuclear binding and motion effects are neglected. The transverse momentum differential cross-section shows no shape modification relative to the simple model, however the rapidity differential cross-section shows a significant asymmetry compared to the simple model. A relative excess in the Z boson differential cross-section is seen in the backward (Pb-going) part of the rapidity distribution. This asymmetry is more pronounced in central events and is apparently absent in peripheral events which are roughly symmetric about the centre of mass.

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Figure 3: The ratio $\frac{dN_Z/dy}{dN_{ch}/dy}$ (for $|y^Z| < 2.5$) as a function of $\langle N_{part} \rangle$. The values of the ratio themselves are wholly independent of the definition of $\langle N_{part} \rangle$, but each point is plotted three times on the x-axis corresponding to the three different Glauber implementations. A fit of the form $a(\langle N_{part} \rangle - 1)/\langle N_{part} \rangle$, is shown to be in good agreement with the data. Statistical uncertainties are plotted as bars. For readability, systematic uncertainties (shaded boxes) are plotted only on the $\Omega=0.55$ set of points and the fit is to these points. The Figure is from Ref. [2].

Figure 4: The Z boson yield per event scaled by $\langle N_{coll} \rangle$ as a function of y^Z , for three centrality bins. The bars indicate statistical uncertainty and the shaded boxes systematic uncertainty. The systematic uncertainties are correlated bin-by-bin. The shaded boxes plotted at $2 \cdot 10^{-9}$, represent the uncertainty (it is a scale uncertainty evaluated at $2 \cdot 10^{-9}$) from $\langle N_{coll} \rangle$ for each centrality bin in the appropriate color, and the overall uncertainty due to the uncertainty on $\sigma_{N+N \rightarrow X}$ is shown in black. The means of each distribution, $\langle y^Z \rangle$, are listed. The Figure is from Ref. [2].

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