Vector-boson production in p+Pb collisions measured with ATLAS at the LHC

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Abstract
Electroweak–boson production processes (W, Z and photon) provide access to the earliest moments of heavy–ion collisions. Furthermore, because they do not undergo strong interactions, they are sensitive to the initial–state geometry of the collision and potentially the details of the nuclear parton distribution functions. ATLAS results on vector–boson yields have demonstrated binary collision scaling in Pb+Pb collisions. In p+Pb collisions, the measurement of vector bosons provides possible constraints on the nuclear parton distribution functions and insights into the details of the initial collision geometry. We report on the latest results of vector–boson production in p+Pb collisions at $\sqrt{s_{\text{NN}}}=5.02$ TeV. Production yields of Z and W bosons and lepton charge asymmetry of W bosons are presented as a function of pseudo-rapidity and centrality. The vector–boson yields are compared to calculations incorporating different parton distribution function sets, as well as different centrality calculations.

Keywords:
proton–lead collisions, electroweak bosons, parton distribution functions, lepton charge asymmetry

1. Introduction
Collisions between lead (Pb) ions at the Large Hadron Collider (LHC) are thought to create strongly interacting matter at temperatures well above the QCD critical temperature. The Relativistic Heavy Ion Collider (RHIC) has established [1] that at such temperatures, strongly interacting matter is expected to take the form of quark–gluon plasma (QGP). The energetic color charge carriers produced in hard–scattering processes during the initial stages of nuclear collisions are expected to lose energy in the QGP. Both RHIC and LHC experiments have reported a suppression of charged hadron yields by a factor of two at high transverse momenta in heavy-ion (HI) collisions [2, 3, 4, 5]. On the other hand particles, which are created in hard scatterings and whose products do not interact via the strong force, provide an alternative means to investigate the phenomenon of energy loss in the QGP. Electroweak bosons ($V=\gamma, W, Z$) provide additional ways to study partonic energy loss in HI collisions. They do not interact strongly with the medium, thus offer a means to calibrate the energy of jets in V–jet events. Moreover, in principle, electroweak bosons are an excellent tool for studying nuclear parton distribution functions (PDF) in a multi–nucleon environment.

The ATLAS collaboration [6] has measured V boson production at $\sqrt{s_{\text{NN}}}=2.76$ TeV in Pb+Pb collisions. These results demonstrated per–event yield scaling with a number of binary collisions. This has been observed for prompt photons [7], W bosons [8], and Z bosons [9]. The V boson production has been found
consistent with the NLO QCD predictions incorporating the PDF sets that do not account for nuclear effects. However, the nuclear modification is not excluded within the precision of those measurements.

Unlike in symmetric Pb+Pb collisions, in the p+Pb system nuclear modifications of the PDF in the Pb nucleus result in an asymmetry in the rapidity–dependent cross section of bosons; this presents an attractive observable for the study of initial–state nuclear conditions. The centrality–dependent yield of V bosons is a well suited probe to test understanding of p+Pb collision geometry.

Therefore, in this report, the most recent measurements on W and Z boson production in the p+Pb system at $\sqrt{s_{NN}} = 5.02$ TeV are discussed. They are based on the entire statistics of p+Pb data collected by the ATLAS experiment in 2013.

2. Z boson production

The Z boson production has been measured in p+Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV using data corresponding to integrated luminosity of $\sim 29$ nb$^{-1}$ [10]. The Z bosons were reconstructed via the di-electron and di-muon decay channels. Results from the two channels have been found consistent and could be combined to obtain a total cross-section times the $Z \rightarrow \ell \ell$ branching ratio of $139.8 \pm 4.8$ (stat.) $\pm 6.2$ (syst.) $\pm 3.8$ (lumi.) nb within the fiducial acceptance region defined by $|y_{Z}| < 3.5$, where $y_{Z}$ is pseudorapidity of the Z boson in the center-of-mass system.

In the left panel of Fig. 1 the per–event yield of Z bosons divided by a number of nucleon–nucleon collisions, $\langle N_{\text{coll}} \rangle$, is displayed as a function of centrality represented by a number of participants, $\langle N_{\text{part}} \rangle$. If the rates 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. The yield is independent of centrality defined using the standard Glauber model shown in the upper panel of Fig. 1. In other two panels centrality is defined using the Glauber–Gribov Color Fluctuation (GGCF) [11] models which increase $\langle N_{\text{coll}} \rangle$ in central events and reduce it in peripheral ones, consequently the yield divided by $\langle N_{\text{coll}} \rangle$ is reduced in central events and increased in peripheral ones.

![Graphs showing Z and W boson production rates per nucleon–nucleon collision ($N_{\text{coll}}$) and per minimum–bias events taken in the corresponding centrality class in the fiducial acceptance of the ATLAS detector as a function of the number of participants, $N_{\text{part}}$. The three panels are for three centrality association models, Glauber model in the upper panel, GGCF ($\omega_{NN} = 0.11$) in the middle panel and GGCF ($\omega_{NN} = 0.2$) in the lower panel. The upper panel for W boson production shows also the rates measured for the $W^{+}$ (diamonds) and $W^{-}$ (squares) separately. Results of the Pownw-based model using CT10 PDF [13] and the natural ratio of neutrons and protons in Pb nuclei are also shown. Open markers show the data without centrality bias correction.](image)

The presence of the Z boson is correlated with a larger transverse energy of the underlying event. Consequently, more energy may be deposited in the forward calorimeter on the Pb-going side in events containing...
a hard scattering process than in those coming from soft production. This causes a bias as the boson yield is enhanced in the more central events but depleted in the more peripheral ones. The centrality bias correction is calculated assuming the average yield from hard scattering processes in each nucleon–nucleon collision and is proportional to the contribution from that collision. This correction significantly changes the trend of the data, especially for the Glauber model in the upper panel of Fig. 1. Predictions based on the NLO QCD calculations using CT10 PDF [13] and the natural ratio of neutrons and protons in Pb nuclei are also shown. They are in good agreement with the standard Glauber model.

3. W boson production

W boson production in the muon decay mode has been measured in p+Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV using 28.1 ± 0.8 nb$^{-1}$ of data [12]. The production yields have been calculated within the fiducial region defined by muon pseudorapidity, $0.1 < |\eta| < 2.4$, muon transverse energy, $p_T > 25$ GeV, missing transverse momentum, $E_T^{miss} > 25$ GeV and transverse mass of the muon and missing transverse momentum, $m_T > 40$ GeV.

The right panel of Fig. 1 shows the W boson production rates per minimum–bias event per $\langle N_{coll} \rangle$ in the fiducial acceptance of the ATLAS detector as a function of $\langle N_{part} \rangle$. The upper plot uses the standard Glauber model, while the middle and the lower plots use the GGCF model extensions with the parameter of fluctuations $\omega_{fc} = 0.11$ and 0.2, respectively. Inclusive $W^\pm$ boson production yields are shown with open markers. Filled markers represent the same data after applying the centrality bias correction. After applying this correction, the yield per binary collision is approximately constant with $\langle N_{part} \rangle$ for the standard Glauber model. In the lower plots the data production rate per collision diminishes with $\langle N_{part} \rangle$, and shows a clear negative slope for the $\omega_{fc} = 0.2$ case. The results of the CT10 calculations are shown as dashed lines and are the same in all panels. The upper plot also shows the yields separately measured for $W^+$ and $W^-$ bosons. The production rate of the $W^+$ boson is larger than of the $W^-$ boson, which is also consistent with the CT10 model calculations.

The fully corrected $W$ boson production cross section as a function of the muon pseudorapidity is shown in Fig. 2 in three centrality intervals: 40–90% (peripheral), 10–40% (mid–central) and 0–10% (central). The production rates of the $W$ bosons in the corresponding centrality intervals are corrected for the centrality bias and divided by $\langle N_{coll} \rangle$ from the Glauber model. The cross section is measured separately for $W^+$ and $W^-$ bosons and these show differences in the positive and negative pseudorapidity. The difference between the charges is shown in the lower panel as a lepton charge asymmetry $A_{\mu}(\eta)$ defined by

$$A_{\mu}(\eta) = \frac{dN_{W^+}/d\eta - dN_{W^-}/d\eta}{dN_{W^+}/d\eta + dN_{W^-}/d\eta},$$

where $N_{W^+}(N_{W^-})$ is a corrected number of $W^+$($W^-$) bosons. The shape of the curves is partially due to the centre-of-mass system shift of approximately 0.465 which is a consequence of the asymmetric energy of the proton and Pb beams in the laboratory frame. In addition there is a natural pseudorapidity dependence to the lepton charge asymmetry due to the valence $u$ quarks which produce $W^+$ bosons having on average a higher fraction of the proton momentum. This effect is symmetric in pseudorapidity for $pp$ collisions, however in the $p+Pb$ system the charge asymmetry is also sensitive to the difference in the quark content of the proton and neutrons which are found in the Pb nucleus, and this leads to the dependence on lepton pseudorapidity.

The measurements in Fig. 2 are compared to the results of Powheg calculations. In peripheral collisions the model calculations are lower than the data for all values of muon pseudorapidity. This may be due to the difficulty in definitively determining $\langle N_{coll} \rangle$ for a given centrality bin. There appears to be a dependence of the shape of the pseudorapidity distributions of both positively and negatively charged muons from $W$ bosons on centrality. The middle panels, displaying the ratios of the measured muon pseudorapidity distribution coming from $W^\pm$ bosons to that calculated with the model, suggest the presence of a slope in the most central collisions, which does not appear in peripheral collisions.

The asymmetries shown in the lower panels of Fig. 2 agree between the data and model, except in the Pb–going direction (negative pseudorapidity) in the most central collisions. The shape modification of the
pseudorapidity distribution with centrality present in the $W$ boson data is similar to the trend observed in the $Z$ boson data [10].

4. Conclusions

Measurements of $Z$ and $W$ boson production have been reported based on $p+Pb$ data collected at $\sqrt{s_{NN}} = 5.02$ TeV by the ATLAS experiment at the LHC. Predictions based on perturbative QCD calculations reproduce the data well, except for the Pb-going direction, where there appears to be an excess above the model. The yields of electroweak bosons per nucleon–nucleon collision are approximately constant as a function of $\langle N_{\text{part}} \rangle$ for the Glauber model and show a negative slope for the GGCF model calculations with $\omega_{\perp} = 0.2$.

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References