PROCEEDINGS OF SCIENCE

Production of electroweak bosons in Pb+Pb, p+Pb and pp collisions with the ATLAS detector

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Electroweak bosons produced in ultrarelativistic heavy-ion collisions serve as excellent probes of the collision geometry and centrality. Their production rates should be unaffected by final-state effects. Due to the correlation between the kinematics of quarks from incoming nuclei and the rapidity of produced electroweak bosons, they also provide insight into nuclear modifications of parton distribution functions (PDFs). We present the latest ATLAS results on massive electroweak boson production in Pb+Pb and pp collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV using data collected by the ATLAS experiment in 2015. The yields of W and Z bosons produced per inelastic Pb+Pb collision are compared to cross-sections measured in pp collisions and used to construct nuclear modification factors. A comparison of the measured yields and cross-sections to calculations obtained with various (nuclear) PDF sets is also presented. Also selected results on prompt photon production in p+Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 8.16$ TeV are discussed.

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1. Introduction

Electroweak (EW) bosons, and in case of Z/W also their leptonic decay products, do not interact strongly. Therefore if formed in a hard parton-parton interaction at a very early stage of the Pb+Pb or p+Pb collision they carry out, unmodified by the surrounding medium, information about the geometry of the collision and possible nuclear modifications of the parton distribution functions (PDFs) of a free nucleon.

2. Z and W boson production

Z and W boson production has been recently studied by the ATLAS [1] experiment in pp [2] and in Pb+Pb [3, 4] collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV with an integrated luminosities of 25 pb^{-1} and 0.49 nb^{-1}, respectively. In either case the Z/W bosons were reconstructed in their leptonic ($\ell = e, \mu$) decay channels, $Z \to \ell^+\ell^-$ and $W^\pm \to \ell^\pm\nu$, and both channels were then combined.

The integrated and differential Z and W boson production cross-sections in both pp and Pb+Pb collisions are measured within a fiducial phase space defined as follows:

- for Z production: $p_{\mathrm{T}}^{\ell} > 20$ GeV, $|\eta_\ell| < 2.5$ and $66 < m_{\ell\ell} < 116$ GeV,
- for W production: $p_{\mathrm{T}}^{\ell} > 22$ GeV, $p_{\mathrm{T}}^{\nu} > 25$ GeV, $|\eta_\ell| < 2.5$ and $m_{\mathrm{T}} > 40$ GeV,

where p_{T}^{ℓ} is the transverse momentum of the charged lepton, η_ℓ its pseudorapidity, p_{T}^{ν} the transverse momentum of the (anti)neutrino, $m_{\ell\ell}$ invariant mass of the two charged leptons from Z decay, and $m_{\mathrm{T}} = \sqrt{2p_{\mathrm{T}}^{\ell}p_{\mathrm{T}}^{\nu}(1-\cos\Delta\phi)}$ is the transverse mass of W boson decay products, with $\Delta\phi$ being the azimuthal angle between the charged lepton ℓ and the (anti)neutrino.

Differential cross-section for the Z boson production as a function of the absolute rapidity of the charged lepton pair, $|y_{\ell\ell}|$ in pp collisions is shown in Fig. 1(left). The measured cross-section is compared to several NNLO QCD predictions mentioned in the legend. Most of the predictions describe the measured cross-section at forward rapidities, however they all underestimate the data at central rapidity.

The measured differential cross-sections for the production of $W^\pm$ bosons as a function of η_ℓ are used to obtain the lepton charge asymmetry, defined as

$$A_\ell = \frac{\mathrm{d}N_{W^+\to\ell^+\nu_\ell}/\mathrm{d}\eta_\ell \; - \; \mathrm{d}N_{W^-\to\ell^-\bar{\nu}_\ell}/\mathrm{d}\eta_\ell}{\mathrm{d}N_{W^+\to\ell^+\nu_\ell}/\mathrm{d}\eta_\ell \; + \; \mathrm{d}N_{W^-\to\ell^-\bar{\nu}_\ell}/\mathrm{d}\eta_\ell}$$

and shown in Fig. 1(right). The measured lepton charge asymmetry in pp collisions is compared to several NNLO QCD predictions listed in the legend. There is good agreement between data and predictions within the total uncertainties. The measurement of Z/W boson production in pp collisions serves as a reference for studies of more complex systems, such as e.g. Pb+Pb collisions.

An effective nucleon-nucleon (NN) cross-section for the process X in A+A collisions, further referred to as normalised production yield, is defined using the total number of inelastic A+A collisions (N_{evt}) and the mean nuclear thickness function $\langle T_{AA}\rangle$ as $\sigma_X^{\mathrm{NN}} = N_X/N_{\mathrm{evt}}/\langle T_{AA}\rangle$. In Fig. 2(left) the normalised Z boson yield in Pb+Pb collisions as a function of absolute rapidity is compared between the combined measurement and NLO QCD theoretical calculations listed in the legend.

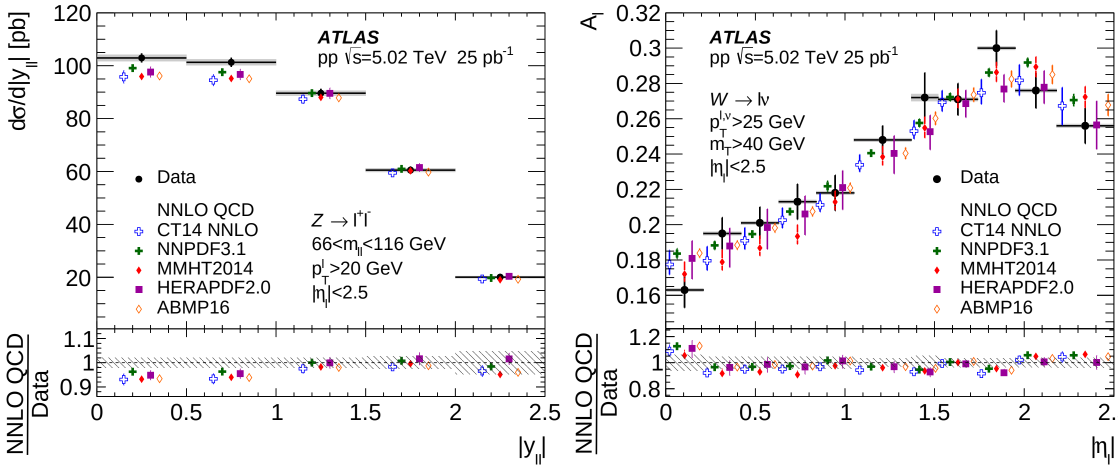

Figure 1: (left) Differential cross-section for Z boson production in pp collisions as a function of absolute lepton-pair rapidity compared with theoretical predictions. (right) Charge asymmetry for W bosons production in pp collisions as a function of absolute charged lepton pseudorapidity compared with theoretical predictions. In both plots statistical and systematic uncertainties are shown as corresponding bars and shaded bands on the data points. The luminosity uncertainty is not included. Taken from Ref. [2].

All calculations lie 1-3σ below the data in all intervals of rapidity integrated over event centrality. Calculations that are using nuclear PDFs deviate from the data even stronger than calculations based on the CT14 PDF set. Figure 2(right) shows the normalised Z boson yield in Pb+Pb collisions as a function of rapidity for three centrality intervals. The results are consistent with each other within the statistical uncertainties. The currently available statistics precludes making a more definitive statement about possible modification of the Z boson rapidity distribution with centrality. Differences between σ_X^{NN} and σ_X^{pp} may arise due to nuclear effects including the isospin effect and

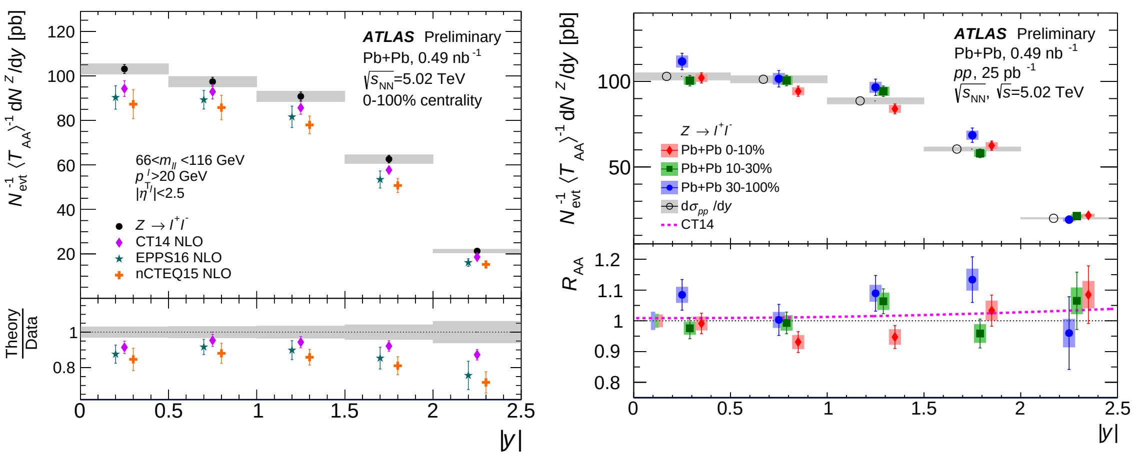

Figure 2: (left) Rapidity dependence of the normalised Z boson yield in Pb+Pb collisions compared with theoretical predictions. The error bars on the data points indicate the statistical uncertainties and the shaded boxes show the systematic uncertainties. (right) Normalised Z boson yields in Pb+Pb collisions versus rapidity measured in three centrality classes indicated in the legend. The differential Z boson cross-sections measured in pp are shown by open circles. The lower panel shows the R_{AA} and the contribution from the isospin effect calculated with CT14 NLO (dashed line). The shaded boxes at unity indicate the combined uncertainty from the pp data added in quadrature to the $\langle T_{AA}\rangle$ uncertainty. Taken from Ref. [3].

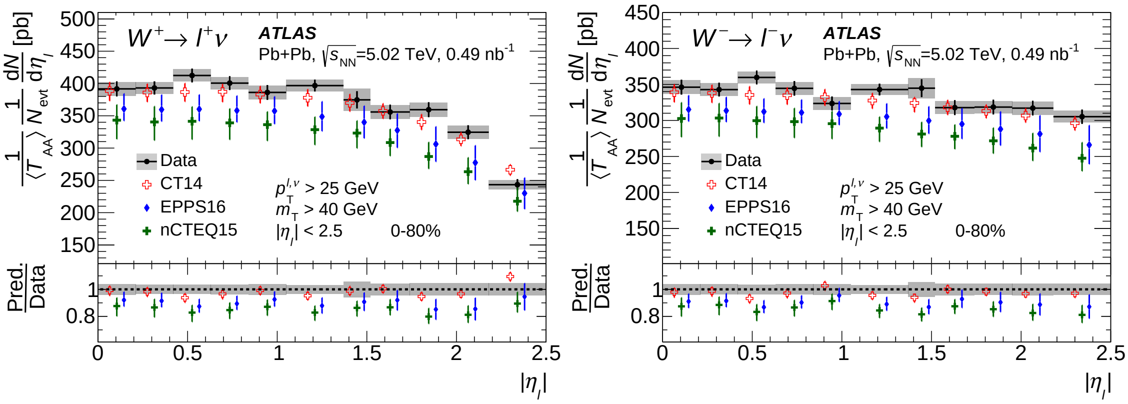

Figure 3: Differential normalised production yields for W^+ (left) and W^- (right) bosons as a function of $|\eta_\ell|$ for the combined electron and muon channels. Error bars show statistical uncertainties, whereas systematic uncertainties are shown as shaded boxes. Systematic uncertainties related to $\langle T_{AA}\rangle$ are not included. The measured distributions are compared with theory predictions listed in the legend. Taken from Ref. [4].

inaccuracies in the description of the nuclear geometry and are usually quantified using the nuclear modification factor defined as $R_{\mathrm{AA}} = \sigma_X^{\mathrm{NN}}/\sigma_X^{pp}$. In the lower panel of Fig. 2(right) the R_{AA} is shown for all three centrality classes. The trend observed in the data is consistent with the isospin effect expected only from the different valence quark content of protons and neutrons in the Pb nucleus. The expected contribution of the isospin effect to the R_{AA} is shown by the dashed line.

Figure 3 shows a comparison of combined differential normalised production yields for W^+ and W^- bosons with theoretical predictions obtained at NLO QCD as a function of charged-lepton absolute pseudorapidity. The predictions take into account the isospin effect. All predictions provide a good description of the shapes of the measured $|\eta_\ell|$ distributions. The prediction based on the free nucleon PDF set differs by 2-3% in normalisation compared with the data, while the predictions based on nPDFs underestimate the measured yields by 10 -20%.

Figure 4(left) compares the normalised production yields of W^+ and W^- bosons as a function of the average number of participants, $\langle N_{\mathrm{part}}\rangle$, for the combined electron and muon channels. The normalised production yields for W^+ bosons are about 10% higher than the yields for W^- bosons. The data are also compared with theoretical predictions based on the CT14 NLO PDF set, which include the isospin effect. The normalised production yields for $W^\pm$ bosons do not change with $\langle N_{\mathrm{part}}\rangle$ for mid-central and central collisions represented by $\langle N_{\mathrm{part}}\rangle$ values above 200. In this range of centralities, the measured yields are in good agreement with the predictions, while for mid-peripheral and peripheral collisions corresponding to $\langle N_{\mathrm{part}}\rangle < 200$, there is a slight excess of $W^\pm$ bosons in data in comparison with the theory predictions. The effect grows as $\langle N_{\mathrm{part}}\rangle$ decreases. It is largest in the most peripheral bin and amounts to 1.7 (0.8) standard deviations for $W^-(W^+)$ boson production. After combining the two bins with the lowest $\langle N_{\mathrm{part}}\rangle$ values, the excess in measured normalised production yields over the theory predictions is 1.7 (0.9) standard deviations for $W^-(W^+)$ bosons. It was checked whether the events from the lowest $\langle N_{\mathrm{part}}\rangle$ bin could be contaminated by a contribution from photonuclear background. No significant enhancement of events with asymmetric signals in the Zero Degree Calorimeters on either side of ATLAS was seen.

It was recently argued in Ref. [5] that the value of R_{AA} in peripheral A+A collisions is expected to be modified due to a biased classification of the event geometry, as specified by the centrality

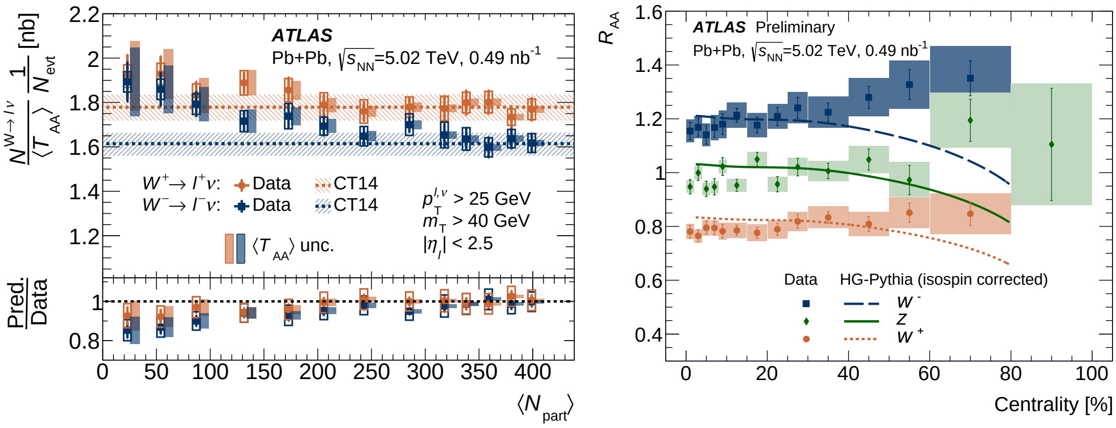

Figure 4: (left) Normalised production yields of $W^{\pm}$ bosons as a function of $\langle N_{\text{part}} \rangle$ shown for the combination of electron and muon decay channels. Predictions calculated using the CT14 NLO PDF set are shown as the horizontal bands. Error bars show statistical uncertainties, whereas systematic uncertainties are shown as the boxes around the data points. The systematic uncertainties due to $\langle T_{AA} \rangle$ are not included in those boxes, and are shown as separate shaded boxes plotted to the right of the data points for better visibility. In the lower panel the ratios of the predictions to the data are displayed, and the boxes around the data points show the sum in quadrature of statistical and systematic uncertainties of the data. (right) The R_{AA} in centrality intervals compared with the HG-PYTHIA model [5] scaled by the isospin factor obtained from the CT14 NLO PDF calculation. Taken from Ref. [4, 3].

assignment, for events containing a hard process. In that analysis, the value of R_{AA} without any nuclear effects was determined using the HG-PYTHIA model, which describes A+A collisions using the HIJING event generator [6] and superimposes a PYTHIA 6.4 event [7] for each hard sub-interaction specified by the generator. The HG-PYTHIA prediction was demonstrated to describe the ALICE measurement of charged-hadron R_{AA} in peripheral Pb+Pb collisions [8]. In Fig. 4(right), the R_{AA} factors for $W^{\pm}$ and Z bosons measured as a function of centrality percentile are compared with theoretical predictions calculated with the CT14 NLO PDF set multiplied by the HG-PYTHIA prediction of the R_{AA} factor taken from Ref. [8]. The impact of re-evaluating the bias for centrality classes defined in the ATLAS centrality determination procedure is found to be negligible. Due to the different interplay of the hard process and soft production for events with jet production and EW boson production, it is not clear that the centrality bias in this analysis is expected to be the same as in the ALICE measurement. The observed trend of R_{AA} factors with centrality goes in the opposite direction to the effect of centrality bias predicted by HG-PYTHIA for charged-hadron production.

3. Prompt photon production

Measurements of prompt photon production offer a way to isolate the initial-state effects because the final-state photons do not interact strongly. These initial-state effects include the degree to which PDFs are modified in a nuclear environment, as well as potential modification due to an energy loss arising through interactions of the partons traversing the nucleus prior to the hard scattering.

Recently ATLAS has studied the prompt photon production [9] in collisions of proton and lead beams of energies 6.5 TeV and 2.51 TeV, respectively, resulting in the nucleon-nucleon centre-of-

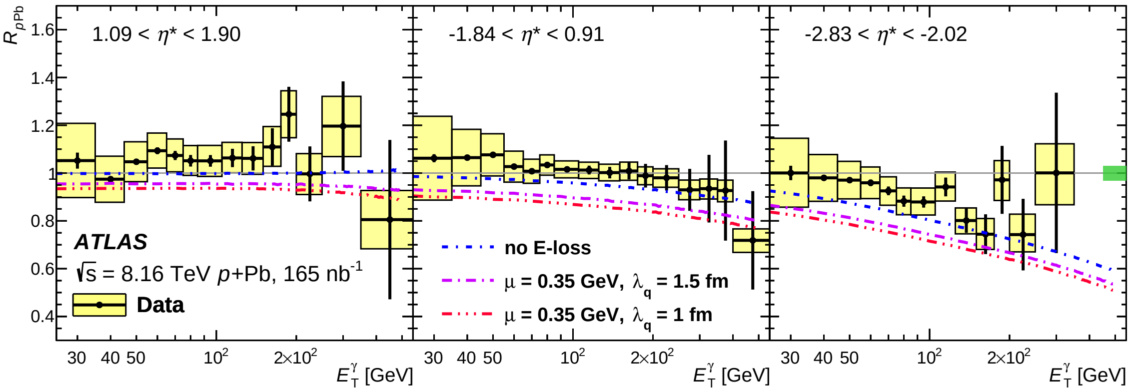

Figure 5: Nuclear modification factor $R_{p\mathrm{Pb}}$ for isolated, prompt photons as a function of photon transverse energy E_{T}^{γ}, shown for different centre-of-mass pseudorapidity, η^*, regions. The data are compared with an initial-state energy-loss calculations. In all plots, the yellow bands and vertical bars correspond to total systematic and statistical uncertainties in the data respectively. Taken from Ref. [9].

mass energy $\sqrt{s_{\mathrm{NN}}} = 8.16$ TeV and a rapidity boost of this frame by ± 0.465 units relative to the ATLAS laboratory frame, depending on the direction of the Pb beam. By convention, the results are reported as a function of photon pseudorapidity in the nucleon-nucleon collision frame, η^*, with positive η^* corresponding to the proton beam direction, and negative to the Pb beam direction.

Figure 5 shows the nuclear modification factor $R_{p\mathrm{Pb}}$ as a function of the prompt photon transverse energy, E_{T}^{γ}, in three η^* intervals. At forward rapidities ($1.09 < \eta^* < 1.90$), the $R_{p\mathrm{Pb}}$ value is consistent with unity, indicating that nuclear effects are small. At mid-rapidity, nuclear effects are similarly small and consistent with unity at low E_{T}^{γ}, but at higher E_{T}^{γ}, there is a hint that $R_{p\mathrm{Pb}}$ is lower. The $R_{p\mathrm{Pb}}$ measurements are also compared with an initial-state energy-loss model prediction (for references see [9]). In this model, the energetic partons undergo multiple scattering in the cold nuclear medium, and thus lose energy due to this medium-induced gluon bremsstrahlung, before the hard collision. The calculation is performed with a parton-gluon momentum transfer $\mu = 0.35$ GeV and mean free path for quarks $\lambda_q = 1.5$ fm. Alternative calculations with a shorter path length ($\lambda_q = 1$ fm), and a control version with no initial-state energy loss, are also considered. The data disfavour a large suppression of the cross-section from initial-state energy-loss effects.

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