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# Heavy electroweak boson production in Pb+Pb and *pp* collisions with ATLAS

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Electroweak bosons produced in Pb+Pb collisions are an excellent tool to constrain initial-state effects which affect hard-scattering process rates in nucleon-nucleon interactions. The production yields of massive electroweak bosons, observed via their leptonic decay channels, offer a high-precision test of the binary collision scaling expected in the Pb+Pb system and a way to quantify nuclear modifications of the parton distribution functions. The large sample of Pb+Pb data at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV obtained by the ATLAS experiment in 2015, and the corresponding high-statistics *pp* data at the same collision energy used as a baseline, allow for a detailed experimental study of these phenomena and comparisons to predictions from a variety of theoretical calculations. This report presents the latest ATLAS results on electroweak boson production, including updated results on $Z$ boson production and high-precision $W$ boson results in Pb+Pb collisions.

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## 1. Introduction

The production of heavy electroweak ($W$ and $Z$) bosons in heavy-ion collisions occurs at the earliest stage. These bosons do not carry colour charge and are thus not expected to interact with the quark–gluon plasma (QGP) formed in ultrarelativistic nucleus–nucleus collisions. Therefore, their production should follow a scaling with the average nuclear overlap function, $\langle T_{\mathrm{AA}} \rangle$. Studies of this scaling can be used to gain insight on the collision centrality and geometry. In addition, the $W$ and $Z$ boson production mechanisms are sensitive to details of the nucleon structure and underlying dynamics of quantum chromodynamics (QCD). In particular, rapidity differential measurements can provide information about parton distribution functions (PDFs) and nuclear modifications of them (nPDFs). The studies of nuclear effects present in nucleus–nucleus collisions require also reference measurements in proton–proton ($pp$) collisions at the same centre-of-mass energy.

This report presents measurements of $W$ and $Z$ boson production using data from 0.49 nb$^{-1}$ of lead–lead (Pb+Pb) collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV [1, 2] and 25 pb$^{-1}$ of $pp$ collisions at $\sqrt{s} =$ 5.02 TeV [3] taken with the ATLAS detector [4]. The measurements use leptonic decay channels ($W^{\pm} \to \ell^{\pm}\nu$, $Z \to \ell^{+}\ell^{-}$ where $\ell = e, \mu$), because decays of heavy electroweak bosons produce leptons with high transverse momentum, $p_{\mathrm{T}}$, which are not affected by the presence of QGP. In addition, the lepton reconstruction algorithms in ATLAS provide good angular and momentum resolutions.

The modifications of heavy electroweak boson production in Pb+Pb collisions relative to $pp$ collisions can be quantified by the nuclear modification factor:

$$R_{\mathrm{AA}} = \frac{N_{\mathrm{AA}}/N_{\mathrm{evt}}}{\langle T_{\mathrm{AA}} \rangle \cdot \sigma^{pp}_{W[Z]}} \tag{1.1}$$

where $N_{\mathrm{AA}}/N_{\mathrm{evt}}$ is the electroweak boson yield measured per minimum-bias Pb+Pb collision, while $\sigma^{pp}_{W[Z]}$ is the electroweak boson production cross-section measured in $pp$ collisions at the same energy. These cross-sections are measured in the following way:

$$\sigma^{pp}_{W[Z]} = \frac{N_{W[Z]} - B_{W[Z]}}{C_{W[Z]} \cdot \mathscr{L}}. \tag{1.2}$$

Here, $N_{W[Z]}$ and $B_{W[Z]}$ represent the number of $W/Z$ boson candidates observed in data and the number of estimated background events, respectively, while $\mathscr{L}$ denotes the integrated luminosity of the data sample. The correction factors $C_{W[Z]}$ account for detector inefficiencies related to lepton reconstruction, identification, isolation and triggers.

## 2. Measurements in *pp* collisions

For the measurement of $Z$ boson production in $pp$ collisions, candidate events are selected using high-$p_{\mathrm{T}}$ single-lepton triggers. Reconstructed leptons are required to pass a kinematic selection, as well as reconstruction quality and isolation requirements, to suppress contributions from background processes. Candidates for $Z \to \ell^{+}\ell^{-}$ events are constructed from pairs of oppositely charged leptons with an invariant mass in the range $66 < m_{\ell\ell} < 116$ GeV. At least one of the leptons is required to match the trigger. After the full event selection, contributions from background



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processes are estimated at the level of 0.3% of the data sample for both the electron and muon channels, and are subtracted.

Events for the $W$ boson measurement are selected with the same triggers as for the $Z$ boson measurement, but are required to have exactly one lepton passing kinematic, quality and isolation requirements. This condition allows to reduce the contribution from $Z \to \ell^+\ell^-$ events in the data sample. Other background processes, such as top-quark production or QCD multi-jet production, are suppressed by requiring a sizeable missing transverse momentum, $E_{\mathrm{T}}^{\mathrm{miss}}$, and transverse mass, $m_{\mathrm{T}}$, of the event. In this measurement, $E_{\mathrm{T}}^{\mathrm{miss}}$ is calculated from information about the hadronic system recoiling against the $W$ boson, which is reconstructed using a particle flow algorithm [5]. The background contributions remaining after applying the event selection vary between 3 and 6% depending on the measurement channel, and are subtracted.

The $W$ and $Z$ boson production cross-sections are measured in fiducial phase-space volumes, separately in the electron and muon channels. The channel cross-sections are combined using the Best Linear Unbiased Estimate method [6], which allows to account for correlations of systematic uncertainties across channels. Figures 1 and 2 show the combined differential cross-sections for $Z$ and $W$ boson production, respectively. The measurements are compared with theoretical predictions calculated at next-to-next-to-leading order (NNLO) in QCD using a version of DYNNLO 1.5 [7, 8] optimised for speed of computation. Several sets of predictions are obtained using different PDF sets: CT14 NNLO [9], NNPDF3.1 [10], MMHT14 NNLO [11] and HERAPDF2.0 [12]. All of the predictions are below the measured $Z$ boson cross-sections at central rapidities ($|y_{\ell\ell}| < 1$), but show a better agreement with the data at larger rapidities. The predictions also tend to underestimate the measured $W$ boson cross-sections, with the exception of HERAPDF2.0.

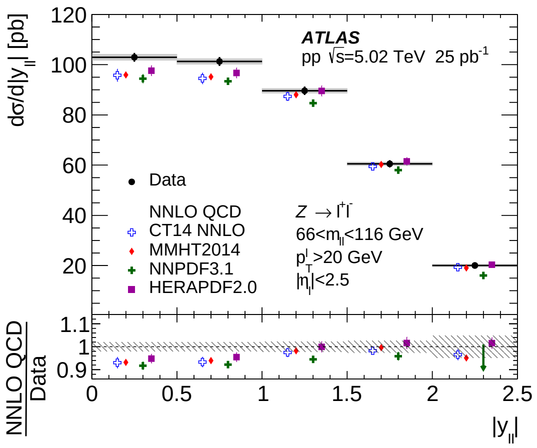


**Figure 1:** Differential cross-section for $Z$ boson production as a function of absolute lepton-pair rapidity compared with theoretical predictions. The lower panel shows the ratio of predictions to the measured differential cross section in each bin [3].

## 3. Measurements in Pb+Pb collisions

The measurements of $W$ and $Z$ boson production in Pb+Pb collisions presented in this report are performed only using the muon decay channel. The event selections are similar to the mea-

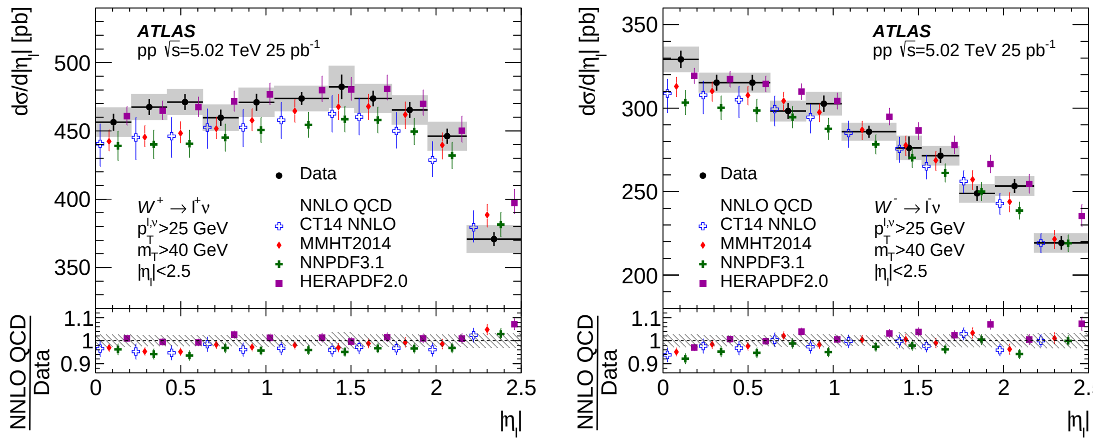


**Figure 2:** Differential cross-sections for $W^+$ (left) and $W^-$ (right) boson production as a function of absolute decay lepton pseudorapidity compared with theoretical predictions. The lower panel shows the ratio of predictions to the measured differential cross section in each bin [3].

surements in *pp* collisions, but have some differences. For selecting $Z$ boson candidates in Pb+Pb collisions, the reconstructed muons are not required to pass an isolation selection which results in slightly larger background contributions, at the level of 0.5%. In the case of the $W$ boson measurement, the missing transverse momentum is calculated only from charged-particle tracks, because the resolution of calorimetric $E_{\mathrm{T}}^{\mathrm{miss}}$ reconstruction is deteriorating with collision centrality. Nevertheless, background contributions are much higher than in *pp* collisions, mainly due to the large underlying event activity which increases with centrality.

The $W$ boson yields are measured in a similar fiducial phase-space volume as the *pp* cross-sections, differing only in the requirement on the absolute lepton pseudorapidity. On the other hand, the $Z$ boson yields are extrapolated to the full phase space of lepton kinematics. Figure 3 presents the $W$ and $Z$ boson yields measured per minimum-bias Pb+Pb collision and divided by $\langle T_{\mathrm{AA}}\rangle$. The yields are measured as a function of the average number of nucleons participating in the collision, $\langle N_{\mathrm{part}}\rangle$, which corresponds to a given centrality interval. Both the $W$ and $Z$ boson yields do not depend on centrality in most of the considered range, and are in agreement with theoretical predictions calculated at next-to-leading order in QCD using the CT10 PDF set [13] and scaled to NNLO accuracy. The only hint of deviation is observed in the most peripheral centrality interval for both $W$ and $Z$ bosons. The $R_{\mathrm{AA}}$ for $Z$ boson production is also presented, however the *pp* cross-sections used to calculate it are only preliminary [14]. In addition, measurements of rapidity differential $W$ boson yields have been performed, but with the current experimental uncertainties they show only little sensitivity to nPDFs [1].

## 4. Summary

This report presents a summary of recent ATLAS measurements of heavy electroweak boson production in *pp* and Pb+Pb collisions at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV.

In *pp* collisions, differential cross-sections for $W$ and $Z$ bosons production are measured with a precision of a few percent. Predictions calculated at NNLO in QCD using various modern PDF

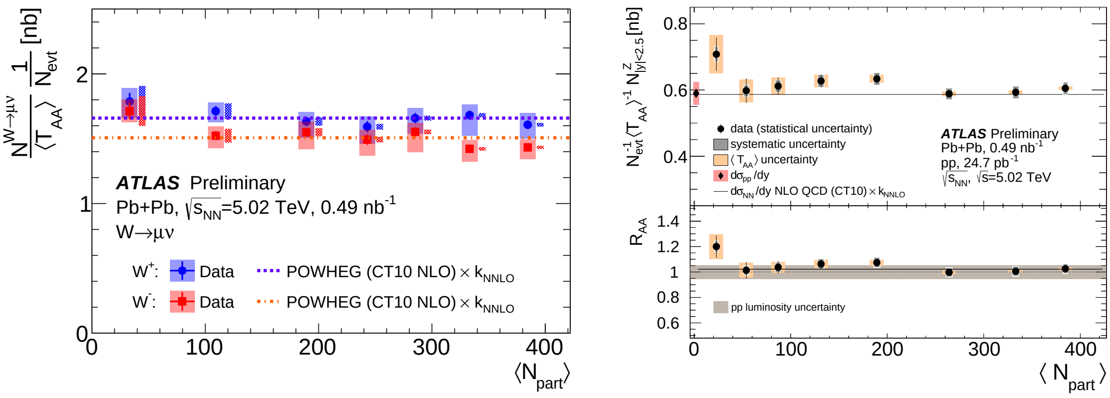


**Figure 3:** Fiducial $W$ (left) and $Z$ (right) boson yields per minimum-bias event divided by $\langle T_{\mathrm{AA}} \rangle$ as a function of $\langle N_{\mathrm{part}} \rangle$ [1, 2]. In the left figure, the filled boxes around data points represent systematic and statistical uncertainties added in quadrature, while the systematic uncertainties related to the $\langle T_{\mathrm{AA}} \rangle$ are represented by the hatched area shifted along the x-axis for better visibility. In the right figure, the bottom panel shows the $R_{\mathrm{AA}}$ calculated using *pp* cross-sections taken from Ref. [14].

sets tend to underestimate the data.

In Pb+Pb collisions, the yields of $W$ and $Z$ bosons are observed to scale with $\langle T_{\mathrm{AA}} \rangle$ in most of the considered centrality ranges, and they are in agreement with expectations.

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