Measurement of W- and Z-boson production in p–Pb collisions at $\sqrt{s_{\rm NN}} = 5.02$ TeV with ALICE at the LHC

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Abstract. In hadronic collisions, electroweak bosons (W and Z) are produced in initial hard scattering processes and they are not affected by the strong interaction. In proton–proton collisions, they have been suggested as standard candles for luminosity monitoring and their measurement can improve the evaluation of detector performances. In nucleus-nucleus and proton–nucleus collisions, electroweak bosons provide a check at first order the validity of binary collision scaling, while small deviations allow studying the nuclear modifications of parton distribution functions. In ALICE, the production of W and Z bosons is measured via the contribution of W-boson decays to the inclusive $p_{\rm T}$-differential muon yield and the invariant mass of unlike-sign muon pairs from Z-boson decays, respectively, at large rapidities. This paper reports on the production cross sections of muons from W muonic decay and of Z boson in p–Pb collisions at $\sqrt{s_{\rm NN}} = 5.02$ TeV, which are compared to the theoretical calculations, and on the W-boson yields normalized to the average number of binary nucleon-nucleon collisions as a function of the event activity.

1. Introduction

The high collision energies available at the Large Hadron Collider (LHC) at CERN allow for an abundant production of hard probes, such as heavy quarks, quarkonia, high $p_{\rm T}$ jets and electroweak bosons ($W^{\pm}$, Z^0). Due to large masses of electroweak bosons, they are produced in initial hard parton scattering processes, with a formation time of the order of $1/{\rm M} \sim 0.002 - 0.003$ fm/c and, having a lifetime of 0.08-0.10 fm/c, thus decay before the formation of the quark-gluon plasma (QGP), which is a deconfined phase of QCD matter that is formed in high-energy heavy-ion collisions. Furthermore, their leptonic decay products do not interact strongly with the hot and dense QCD medium. In proton-proton collisions, precise theoretical predictions of the W- and Z-boson production make them good standard candles for the luminosity measurement. Moreover, they can be used to constrain the parton distribution functions (PDFs) at high momentum transfer (Q^2). In proton-nucleus and nucleus-nucleus collisions, precise measurements of W- and Z-boson production can constrain the modification of the parton distribution functions in the nucleus (nPDFs) [1] and at first order they can be used to test the scaling of hard particle production with the number of binary nucleon-nucleon collisions [2].

2. Experimental apparatus and data sample

The ALICE experiment is equipped with two magnets and various detectors for triggering, tracking and particle identification [3, 4]. Muons are reconstructed in the muon spectrometer, which covers the pseudo-rapidity range $-4 < \eta_{\rm lab} < -2.5$, consists of a thick front absorber, a dipole magnet, five tracking stations, a muon filter and two trigger stations. The inner tracking system consists of six layers of silicon detectors covering the range $|\eta_{\rm lab}| < 0.9$. In this analysis, the interaction vertex is measured with the two innermost layers, which are equipped with Silicon Pixel Detectors (SPD). The number of clusters in the outer layer of the SPD (CL1) can be used to characterize the event activity. Two arrays of scintillators placed at both sides of the interaction point, the VZERO detector (V0A ($2.8 < \eta_{\rm lab} < 5.1$) and V0C ($-3.7 < \eta_{\rm lab} < -1.7$)), provide the trigger and an additional event activity estimation. A third estimation of the event activity is obtained with the Zero Degree Calorimeters (ZNA and ZNC) located at both sides of the detector at 112.5 m from the main interaction point along the beam line. Due to the energy asymmetry of the proton and lead colliding beams at the LHC, the centre-of-mass system of nucleon-nucleon collisions is shifted by $\Delta y = 0.465$ in the direction of the proton beam, with respect to the laboratory frame. Experimental data have been collected with two beam configurations (p-Pb and Pb-p) by inverting the orbits of the two particle species. The rapidity regions covered by the muon spectrometer in the two cases are $2.03 < y^{\mu}_{\rm cms} < 3.53$ (forward, p-going direction) and $-4.46 < y^{\mu}_{\rm cms} < -2.96$ (backward, Pb-going direction).

The data have been collected at $\sqrt{s_{\rm NN}} = 5.02$ TeV with minimum bias (MB), high-$p_{\rm T}$ single-muon (MSH) and low-$p_{\rm T}$ di-muon (MUL) triggers. The MB trigger is defined requiring hits in both sides of the VZERO detector in coincidence with the beam counters. The MSH trigger is defined by asking, in addition to the MB condition, for a high transverse momentum muon with $p_{\rm T} \gtrsim 4.2$ GeV/c in the trigger system of the spectrometer. The MUL is a coincidence of MB trigger and an unlike-sign muon pair selected with $p_{\rm T} \gtrsim 0.5$ GeV/c for each of them. The MSH and MUL data samples are used for W- and Z-boson analysis, respectively. The integrated luminosity for the forward and backward rapidity measurements are 5.03 ± 0.18 nb^{-1} and 5.81 ± 0.20 nb^{-1} [5], respectively. The track in the muon tracking system is required to be in the geometrical acceptance ($-4 < \eta_{\rm lab} < -2.5$), to have a polar angle measured at the end of the front absorber of $170^\circ < \theta_{\rm abs} < 178^\circ$ and match a tracklet in the trigger stations in order to reject the remaining contamination from hadrons. Furthermore, the correlation between momentum and distance of closest approach (DCA) to the interaction vertex was used to remove beam-gas collisions and secondary particles produced in the absorber.

3. W-boson measurement

The present analysis is based on the extraction of the W-boson contribution from the transverse momentum distribution of inclusive muons. At high $p_{\rm T}$, the main contributions to the yield of inclusive muons come from the muonic decays of W bosons, the di-muon decays of Z^0/γ^* bosons and the semi-muonic decays of beauty hadrons. The yield of muons from W-boson decays can be obtained through a fit based on suitable parameterizations of the different components. The distribution of muons from intermediate vector boson decays is described by Monte Carlo (MC) templates obtained from POWHEG simulations [6]. The isospin dependence of the W-boson differential cross-section [7] is accounted for by simulating separately p-p and p-n collisions and then summing the results together according to:

$$\frac{1}{N_{\text{p-Pb}}} \cdot \frac{\mathrm{d}N_{\text{p-Pb}}}{\mathrm{d}p_{\rm T}} = \frac{Z_{\rm Pb}}{A_{\rm Pb}} \cdot \frac{1}{N_{\text{p-p}}} \cdot \frac{\mathrm{d}N_{\text{p-p}}}{\mathrm{d}p_{\rm T}} + \frac{A_{\rm Pb} - Z_{\rm Pb}}{A_{\rm Pb}} \cdot \frac{1}{N_{\text{p-n}}} \cdot \frac{\mathrm{d}N_{\text{p-n}}}{\mathrm{d}p_{\rm T}} \tag{1}$$

where $A_{\rm Pb} = 208$ and $Z_{\rm Pb} = 82$. The generation of muons from Z^0/γ^* decays is performed in an equivalent way. For the description of the background at low $p_{\rm T}$ ($10 < p_{\rm T} < 40$ GeV/c), which originates from the decays of beauty hadrons, three approaches are adopted: MC templates based on pQCD calculations with FONLL [8], functional form, which was already successfully adopted for analogous measurements by the ATLAS experiment at the LHC [9] and another function derived from the second term of the parameterization used by ATLAS, which can be written as $f(p_{\rm T}) = a \cdot \frac{e^{b \cdot \sqrt{p_{\rm T}}}}{p_{\rm T}^{c}}$. The different contributions are summed together in the fit function:

$$f(p_{\rm T}) = N_{\mu\leftarrow{\rm HF}} \cdot f_{\mu\leftarrow{\rm HF}}(p_{\rm T}) + N_{\mu\leftarrow{\rm W}} \cdot f_{\mu\leftarrow{\rm W}}(p_{\rm T}) + N_{\mu\leftarrow{\rm Z^0}/\gamma^*} \cdot f_{\mu\leftarrow{\rm Z^0}/\gamma^*}(p_{\rm T}) \qquad (2)$$

where $f_{\mu\leftarrow{\rm HF}}$ can be either a functional form or the MC template for muons from heavy-flavour decays, and $f_{\mu\leftarrow{\rm W}}$ and $f_{\mu\leftarrow{\rm Z^0}/\gamma^*}$ are the MC templates for muons from W and $\rm Z^0/\gamma^*$ boson decays, respectively. The number of muons from W decays ($N_{\mu\leftarrow{\rm W}}$) is a free parameter, while the ratio $N_{\mu\leftarrow{\rm Z^0}/\gamma^*}/N_{\mu\leftarrow{\rm W}}$ is fixed to the value obtained with POWHEG. Figure 1 presents three examples of the combined fit for μ^+ by varying heavy-flavour background description.

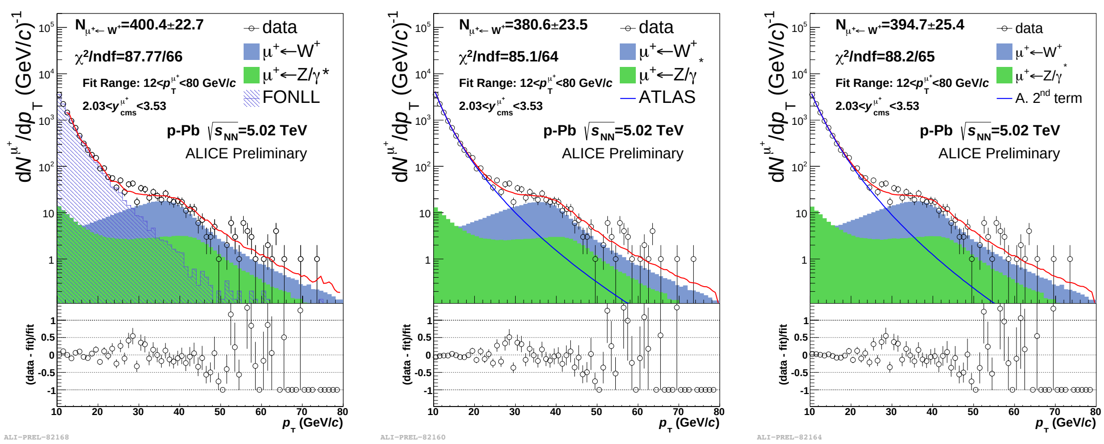

Figure 1. Examples of the combined fit to the inclusive $p_{\rm T}$-spectrum of μ^+ at forward rapidity. Heavy-flavour templates based on FONLL [8] (left), the ATLAS function [9] (middle) and the 2^{nd} term (second addend) of the ATLAS function (right). The errors on the yields represent the statistical uncertainties.

The uncertainty on the background description is determined by using either FONLL-based MC templates or functional forms and by varying the $p_{\rm T}$ range in the fit. The relative contribution of $\rm Z^0/\gamma^*$ is varied based on POWHEG and PYTHIA [10] predictions. The effect of the detector alignment is taken into account by producing the templates using different residual alignment assumptions. The signal was extracted several times by varying the above conditions and the final result is chosen as the weighted average of all of the trials. The systematic uncertainties are given by the RMS of the trials. It is worth noting that POWHEG does not account for the nuclear modification of the PDFs. Hence, the signal extraction using PYTHIA with EPS09 parameterization of the nuclear PDFs [11] was included in the calculation of the systematic uncertainties.

After signal extraction, the yields of muons from W-boson decays are corrected for acceptance times efficiency (88% for forward, 76% for backward). The measured production cross-sections of muons from W-boson decays at forward and backward rapidity in p-Pb collisions are shown in Figure 2 and compared with theoretical predictions based on NLO pQCD calculations with CT10 PDFs [12] and modified CT10 PDFs with the EPS09 parametrization of nuclear effects. Both of the theoretical predictions with and without EPS09 agree with the measurement within uncertainties.

The yield of muons from W-boson decays can also be extracted per event activity interval. It is corrected for acceptance times efficiency and normalized to the number of equivalent MB event. Thus, the normalized yield can be divided by the average number of binary nucleon-nucleon collisions $\langle N_{\rm coll}\rangle$ in each event activity interval, in order to obtain the yield per binary collision. The average number of binary collisions $\langle N_{\rm coll}\rangle$ is determined from a Glauber-model based analysis in the case of V0A, V0C and CL1 estimators, while for the ZN estimator it is computed with a hybrid approach, assuming that the particle density at mid-rapidity is proportional to the number of nucleons participating in the collision, $N_{\rm part}$ [2]. The measured yields of muons from W-boson decays over $\langle N_{\rm coll}\rangle$ in p–Pb collisions at forward and backward rapidities are shown in Figure 3 as a function of event activity. The results present a flat trend as function of event activity, and are similar for the three estimators within uncertainties.

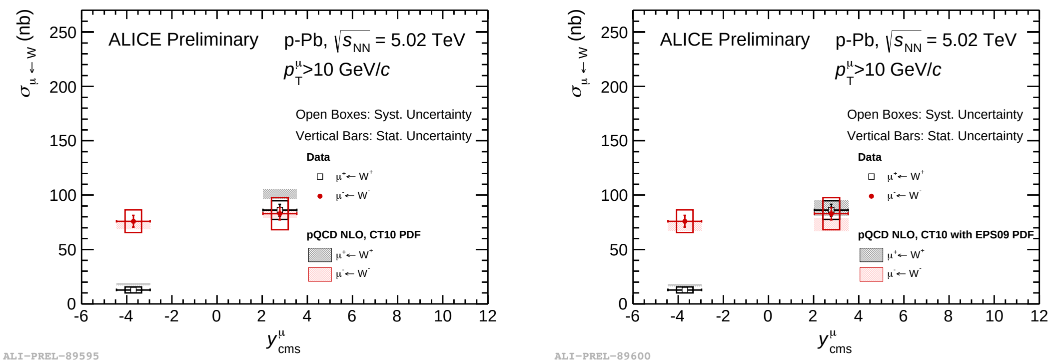

Figure 2. The cross section of muons from W-boson decays compared with pQCD [1] calculations with CT10 PDFs [12] (left) and CT10 PDFs including nuclear effects EPS09 [11] (right) at forward and backward rapidity. The cut of $p_{\rm T} > 10$ GeV/c is added.

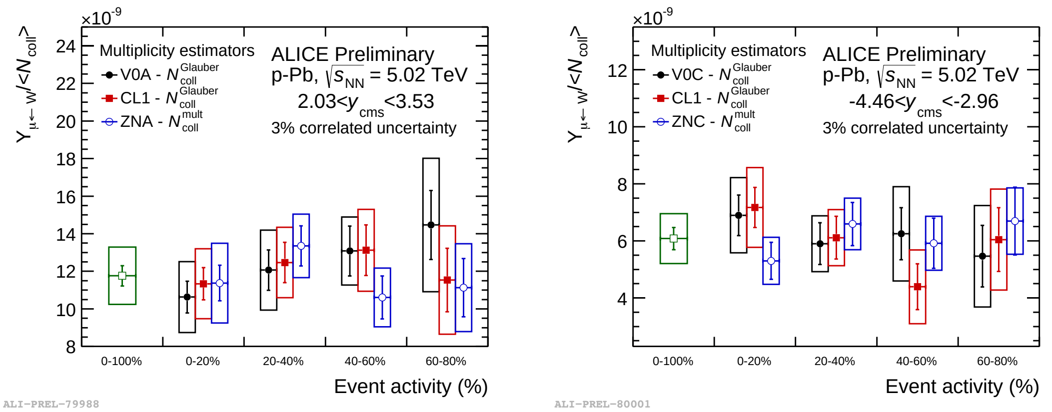

Figure 3. Muon yields from W-boson decays normalized to the average number of binary collisions as a function of event activity at forward (left) and backward (right) rapidity. The green points represent the values in minimum-bias collisions.

4. Z-boson measurement

The signal of Z boson is seen as a peak around 90 GeV/c^2 in the invariant-mass distribution of unlike-sign muon pairs, selected according to the criterion described in section 2 and with

$p_{\rm T} > 20$ GeV/c in order to reduce background from lower mass resonances decay and of the semi-leptonic decay of charm and beauty hadrons. It was verified that loosening the requirement on the minimum $p_{\rm T}$ of the muons to 10 GeV/c does not introduce any additional unlike-sign muon pair with $m_{\mu\mu} > 40$ GeV/c^2. The invariant mass distribution is shown in Figure 4. 22 (2) candidates with $m_{\mu\mu} > 60$ GeV/c^2 were reconstructed at forward (backward) rapidity in p–Pb collisions. At forward rapidity, the distribution is compared with expectations from the POWHEG simulations with CT10 PDFs and EPS09 nPDFs. The parameters were extracted from a fit using the Crystal-Ball function [13], which consists of a Gaussian core with power-law tails on both sides. A good agreement within the experimental uncertainties between data and POWHEG is obtained. The contribution to the invariant-mass distribution from the combinatorial background can be estimated using the like-sign dimuon distribution: no candidates were found in the region $60 < m_{\mu\mu} < 120$ GeV/c^2. A 0.1% upper limit for this contribution is obtained by extrapolating the like-sign dimuon distribution at low mass to the region of interest. Contributions from other physics processes, like the semi-leptonic decay of $c\bar{c}$, $b\bar{b}$ and $t\bar{t}$ pairs and the muonic decay of τ pairs in the process ($Z \rightarrow \tau\tau \rightarrow \mu\mu$), is estimated using MC simulations to be less than 0.7% (0.4%) at forward and backward rapidity, respectively.

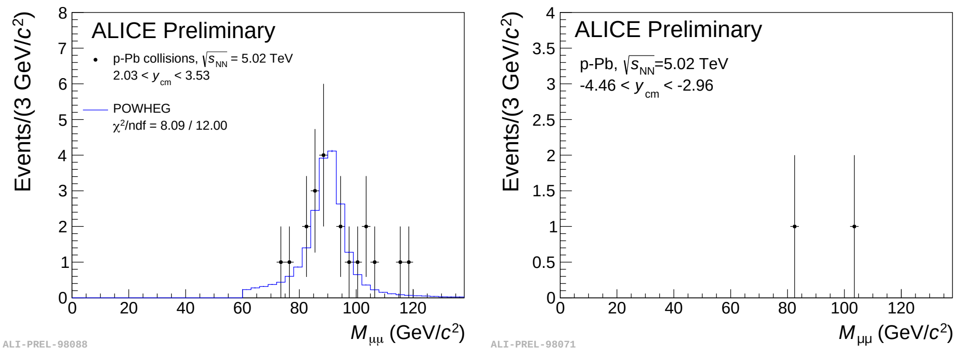

Figure 4. Invariant-mass distribution of unlike-sign muon pairs with $p_{\rm T} > 20$ GeV/c in the p-going (left panel) and Pb-going (right panel) direction. The blue line represents the distribution obtained using POWHEG simulation with CT10 PDFs and EPS09 nPDFs and normalized to the number of Z candidates in the data.

The measured number of candidates is corrected by the acceptance times efficiency (78% for forward, 61% for backward) with a relative systematic uncertainty (1% for forward, 2% for backward). The measured production cross section of muons from Z-boson decays at forward and backward rapidity in p-Pb collisions is shown in Figure 5 (left) and compared with next-to-next-to leading order (NNLO) Fully Exclusive W and Z (FEWZ) [14] predictions with CT10nlo [15], CTEQ6m [16], JR09NNLO [17] and MSTW2008NNLO [18] with and without nPDFs. Since there are few candidates at backward rapidity, limiting the measurement statistical precision, an upper limit of the cross section is also evaluated. The ratio of the measured cross sections (obtained by ALICE and LHCb [19]) to FEWZ are shown in Figure 5 (right). The measurements of ALICE are in agreement with theoretical calculations at both rapidity regions.

5. Conclusion

The production cross section of muons from W- and Z-boson decays at forward and backward rapidity has been measured in p-Pb collisions at $\sqrt{s_{\rm NN}} = 5.02$ TeV with the ALICE muon spectrometer. Theoretical predictions based on NLO pQCD and FEWZ calculations with CT10 PDFs agree with the measurement within uncertainties for W and Z boson, respectively. Taking into account the EPS09 parametrization of nuclear effects on the PDFs further improves the

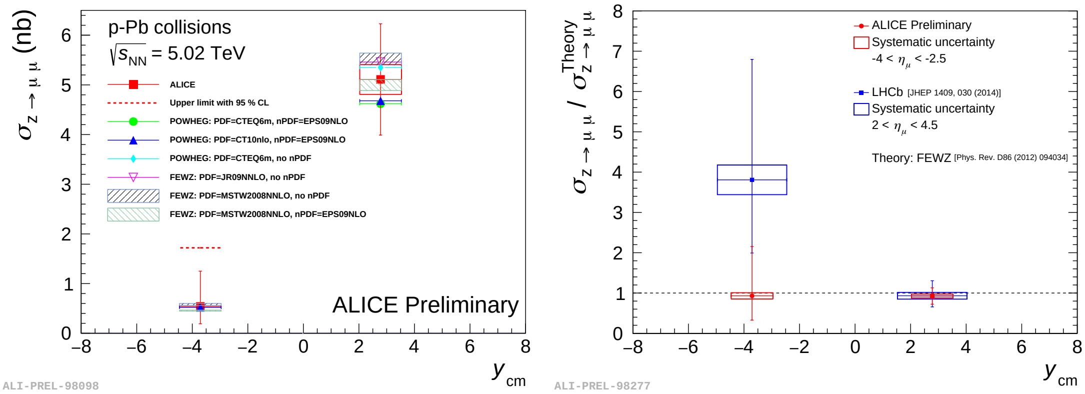

Figure 5. (Left) The cross section of muons from Z-boson decays compared to FEWZ [14] calculations with different PDFs with and without nuclear effects EPS09 [11]. (Right) The ratio of cross section to FEWZ calculation measured by the ALICE collaboration is compared with those obtained by the LHCb collaboration [19].

agreement between theoretical predictions and the measurements at forward rapidity where shadowing is expected to be important. The ALICE measurement on Z-boson agrees with the results from LHCb [19] at forward and backward rapidities, whereas CMS [20, 21] and ATLAS [22] results indicate that electroweak bosons favour the modification of the PDFs at mid-rapidity. The yield of muons from W-boson decays in different event activity scales with $\langle N_{\rm coll} \rangle$ within the experimental uncertainties.

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References

[1] Paukkunen H and Salgado C A 2011 *JHEP* **03** 071
[2] Adam J *et al.* (ALICE Collaboration) 2015 *Phys. Rev.* C **91** 064905
[3] Aamodt K *et al.* (ALICE Collaboration) 2008 *JINST* **3** S08002
[4] Abelev B *et al.* (ALICE Collaboration) 2014 *Int.J.Mod.Phys.* A **29** 1430044
[5] Adam J *et al.* (ALICE Collaboration) 2015 *JHEP* **11** 127
[6] Alioli S, Nason P, Oleari C and Re E 2008 *JHEP* **07** 060
[7] Conesa del Valle Z, CERN-THESIS-2007-102
[8] Cacciari M, Greco M and Nason P 1998 *JHEP* **05** 007
[9] Aad G *et al.* (ATLAS Collaboration) 2011 ATLAS-CONF-2011-078
[10] Sjostrand T, Mrenna S and Skands P 2006 *JHEP* **05** 026
[11] Eskola K J, Paukkunen H and Salgado C A 2009 *JHEP* **04** 065
[12] Lai H L *et al.* 2010 *Phys.Rev.* D **82** 074024
[13] Gaiser J 1982 PhD thesis (http://www.slac.stanford.edu/cgi-wrap/getdoc/slac-r-255.pdf)
[14] Gavin R, Li Y, Petriello F and Quackenbush S 2011 *Comput. Phys. Commun.* **182** 2388-2403
[15] Lai H L, Guzzi M, Huston J, Li Z, Nadolsky P M, Pumplin J and Yuan C P 2010 *Phys. Rev.* D **82** 074024
[16] Nadolsky P M *et al.* 2008 *Phys. Rev.* D **78**(1) 013004
[17] Jimenez-Delgado P and Reya E 2009 *Phys. Rev.* D **79** 074023
[18] Martin A D, Stirling W J, Thorne R S and Watt G 2009 *Eur. Phys. J.* C **63** 189-285
[19] Aaij R *et al.* (LHCb Collaboration) 2014 *JHEP* **09** 030
[20] Khachatryan V *et al.* (CMS Collaboration) 2015 *Phys. Lett.* B **750** 565-586
[21] Khachatryan V *et al.* (CMS Collaboration) 2016 *Phys. Lett.* B **759** 36-57
[22] Aad G *et al.* (ATLAS Collaboration) 2015 *Phys. Rev.* C **92** 044915