The Compact Muon Solenoid Experiment
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Mailing address: CMS CERN, CH-1211 GENEVA 23, Switzerland

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CMS results on electroweak probes from LHC Run1

Anna Julia Zsigmond for the CMS Collaboration

Abstract

Electroweak boson production is an important benchmark process in high-energy heavy-ion collisions at the LHC. The Z and W bosons do not participate in the strong interaction and their leptonic decays provide medium-blind probes of the initial state of the collisions. Final results on Z boson production in PbPb collisions compared to pp collisions are presented. The centrality dependence confirms the binary scaling of hard probes in heavy-ion collisions and the differential cross sections show that initial state effects are small compared to the statistical precision of the available data. Measurements of the W and Z boson production in pPb collisions, combining both the muon and electron decay channels are also presented. The data are compared to theory predictions for nuclear modifications of the parton distributions and show a clear sensitivity to these effects.

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Anna Julia Zsigmond (for the CMS Collaboration)

Wigner RCP, Budapest, Hungary

Abstract

Electroweak boson production is an important benchmark process in high-energy heavy-ion collisions at the LHC. The Z and W bosons do not participate in the strong interaction and their leptonic decays provide medium-blind probes of the initial state of the collisions. Final results on Z boson production in PbPb collisions compared to pp collisions are presented. The centrality dependence confirms the binary scaling of hard probes in heavy-ion collisions and the differential cross sections show that initial state effects are small compared to the statistical precision of the available data. Measurements of the W and Z boson production in pPb collisions, combining both the muon and electron decay channels are also presented. The data are compared to theory predictions for nuclear modifications of the parton distributions and show a clear sensitivity to these effects.

Keywords: CMS, heavy-ion collisions, pA collisions, electroweak bosons

1. Introduction

Z and W boson production plays an important role in high-energy physics measurements and became accessible in heavy-ion collisions for the first time at the LHC. Electroweak bosons are essentially not modified by the hot and dense medium produced in nucleus-nucleus collisions because they decay before the medium is formed. Studies of their leptonic decay modes provide access to the geometric scaling properties of the collisions because leptons do not participate in the strong interaction and pass through the medium unperturbed. However, the production of electroweak bosons can be modified compared to pp collisions because of initial state effects in collisions involving nuclei. The parton distribution functions (PDFs) of bound nucleons can be different from those of free protons, which together with the fact that nuclei contain neutrons beside protons, can modify the observed cross sections.

Based on the first set of PbPb collision data from 2010 at a center-of-mass energy per nucleon pair of $\sqrt{s_{NN}} = 2.76$ TeV, the CMS Collaboration reported results on isolated photon, Z and W boson production [1, 2, 3]. In this paper, the finalized results on Z bo-

son production are presented based on the second set of PbPb collisions recorded in 2011 and pp collisions at the same center-of-mass energy from 2013 [4]. The pPb collision data recorded in 2013 provide the best possibility to constrain nuclear PDFs (nPDFs) in a previously unexplored region of phase space. The updated results on Z boson production cross section [5] and the finalized results on W boson production [6] in pPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV are also presented.

2. Z bosons in PbPb and pp collisions at 2.76 TeV

The Z bosons are identified through their leptonic decays to muon or electron pairs. Signal candidates are selected by requiring an opposite charge lepton pair in the 60–120 GeV/ c^2 invariant mass range with both leptons having $p_T > 20$ GeV/ c and found to be in $|\eta^\mu| < 2.4$ for muons or $|\eta^e| < 1.44$ for electrons. The dimuon rapidity is limited to $|y| < 2$, while the dielectron rapidity is kept in the $|y| < 1.44$ range. Simulations are used to determine the acceptance, efficiency and resolution corrections. The PYTHIA 6 [7] generator is used to produce Z boson signal events that are embedded in

Figure 1: Nuclear modification of Z bosons in PbPb collisions as a function of centrality, rapidity and transverse momentum comparing the muon and electron channel results.

minimum bias PbPb background events produced by the HYDJET [8] generator in order to simulate the effect of the high-multiplicity environment of heavy-ion collisions. For pp collisions, the PYTHIA 6 simulation is used without embedding.

The corrected Z boson yield is normalized by the number of minimum bias events or by the integrated luminosity in the two datasets. The results from the muon and electron decay channels agree within the statistical uncertainties and a combination is performed in the common kinematic region of $|y| < 1.44$. The results for the normalized Z boson yield in PbPb collisions for the combined dilepton channel as a function of centrality and transverse momentum are consistent with predictions from the POWHEG [9] generator. The results as a function of rapidity are compared with predictions from [10] using CT10 PDF set [11] with and without the nuclear effects from EPS09 nPDF set [12] and an agreement is found with both predictions.

The nuclear modification factor (R_{AA}) is calculated by dividing the corrected yield from PbPb collisions by the cross section measured in pp collisions and divided by the nuclear overlap function (T_{AA}), which is proportional to the average number of binary nucleon-nucleon collisions (N_{coll}). Figure 1 shows the R_{AA} of Z boson production as a function of centrality, rapidity and transverse momentum. In every event class, it is compatible with unity and the integrated values are 1.06 ± 0.05 (stat.) ± 0.08 (syst.) in the dimuon and 1.02 ± 0.08 (stat.) ± 0.15 (syst.) in the dielectron channel. From the centrality dependence, one can confirm that the Z boson production in PbPb collisions scales with N_{coll} . The results as a function of y and p_T are compatible with unity within uncertainties and no sig-

nificant initial state nuclear effects are visible with the current amount of data.

3. Z bosons in pPb collisions at 5.02 TeV

Due to the LHC magnet system, the p and Pb beam energies were different that resulted in a $\Delta y = 0.465$ shift of the nucleon-nucleon center-of-mass frame compared to the laboratory frame. The Z boson results are presented in the center-of-mass frame with positive rapidity values corresponding to the proton fragmentation region. The Z boson candidates are selected as an opposite charge muon or electron pair in the 60–120 GeV/ c^2 mass range where both leptons have $p_T > 20$ GeV/ c and are within the $|\eta_{lab}| < 2.4$ muon detector coverage. Embedded simulated samples are used to determine the efficiency and resolution corrections. The signal events are generated by PYTHIA 6 taking into account the nucleon content of the Pb nucleus and the pPb background events are generated by HIJING [13]. The acceptance correction is calculated from POWHEG simulation with CT10 free proton PDF set and interfaced with PYTHIA 6 parton shower.

The corrected results from the muon and electron decay channel are in agreement and a combination is performed. The measured inclusive Z boson production cross section in pPb collisions is $\sigma_{pPb \rightarrow Z \rightarrow \mu\mu} = 138.1 \pm 2.4$ (stat.) ± 8.6 (syst.) ± 4.8 (lumi.) nb using the calibrated integrated luminosity [14]. The POWHEG simulation predicts 136.1 ± 6.8 nb after multiplying by the number of nucleons in the Pb nucleus ($A = 208$), which corresponds to the hypothesis of binary collision scaling in pPb collisions. The inclusive result is in a good agreement with the NLO pQCD prediction.

The measured differential cross section as a function of rapidity in the center-of-mass frame is compared to predictions from MCFM generator [15] in the top of Figure 2. The MCFM predictions are calculated with MSTW2008NLO free proton PDF set [16] with and without the nuclear modification from EPS09 or DSSZ nPDF sets [12, 17] and multiplied by A . The measured differential cross section is consistent with all theory predictions within uncertainties that are entirely dominated by the statistical uncertainties however, better agreement is observed with the nPDF predictions.

Figure 2: Z boson production cross section as a function of rapidity and forward-backward asymmetry in pPb collisions.

The forward-backward asymmetry, defined as $d\sigma(+y)/d\sigma(-y)$, is expected to be more sensitive to nuclear effects [10], because normalization uncertainties cancel both in theory and in experiment. In the bottom of Figure 2 the measured forward-backward asymmetry is shown as a function of $|y_{\text{c.m.}}|$ compared to the MCFM predictions. The measurement is consistent with the presence of nuclear effects. However, due to the large statistical uncertainties, it is not able to distinguish between different nPDF sets.

4. W bosons in pPb collisions at 5.02 TeV

W boson candidate events are selected by requiring an isolated lepton with $p_T > 25$ GeV/c and opposite charge dilepton events are rejected. The number of leptons coming from W boson decays is extracted by fitting the missing transverse energy (E_T) distribution of the selected events. The shapes of E_T for the $W \rightarrow l\nu$ signal, the $W \rightarrow \tau\nu$ and $Z \rightarrow ll$ (with a missing lepton) backgrounds are provided by simulations and the shape of the QCD multi-jet background is modelled by a functional form which is shown to reproduce the E_T shape of events containing non-isolated leptons. In order to correct for lepton efficiencies, the W boson events are generated by PYTHIA 6 taking into account the nucleon content of the Pb nucleus and then embedded in pPb background events generated by HIJING.

The measured cross sections as a function of pseudo-rapidity in the laboratory frame (η_{lab}) in the muon and electron channels are found to be in good agreement, therefore their combination is performed. Since the cross section alone lacks discriminating power between different PDF sets, various asymmetries are determined to reduce both the experimental and theoretical uncertainties. Figure 3 shows the lepton charge asymmetry, as a function of η_{lab} compared to theoretical predictions. The predictions use the CT10 PDF set for the nucleons with or without the modification from EPS09 nPDF set as described in Ref. [10]. The lepton charge asymmetry is a sensitive probe of the down to up quark PDF ratio. In the proton fragmentation region, the data agrees well with the predictions, but in the Pb fragmentation region both predictions stand above the measurements. These results could be explained by assuming different nuclear modification of the down and up quarks in the Pb nucleus, which is assumed to respect isospin symmetry in most nPDF fits, such as EPS09. The forward-backward asymmetries for the different charges show a similar sign of possible difference between the down and up quark nPDFs as shown in Figure 3. The forward-backward asymmetry probes the small- x modification

Figure 3: Charge asymmetry and forward-backward asymmetry of positive and negative W bosons in pPb collisions as a function of pseudorapidity in the laboratory frame.

of the nPDF (shadowing) over the large- x modification (anti-shadowing). The measurement favors the EPS09 modified PDF as compared to the free proton PDF set.

5. Summary

We reported finalized results on Z boson production in PbPb and pp collisions at $\sqrt{s_{NN}} = 2.76$ TeV. The nuclear modification factor of Z bosons is consistent with unity and does not show any centrality, transverse momentum or rapidity dependence within the statistical uncertainties. These results confirm that the production of electroweak bosons in heavy-ion collisions scales with the number of elementary nucleon-nucleon collisions. Also presented updated measurements of Z boson production and finalized results on W boson production in pPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The results were compared to NLO theory predictions with and without nuclear modification of PDFs and show signs of nuclear effects. These measurements set significant constraints for the global fits of nPDFs in a previously unexplored region of the $Q^2 - x$ phase space.

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