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nPDF studies with electroweak bosons in pPb collisions at $\sqrt{s_{\rm NN}}$ = 8.16 TeV with the CMS experiment

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Yields of electroweak gauge bosons can be used to probe the nuclear parton distribution functions of quarks and antiquarks. Final results on W boson production in pPb collisions at a nucleon-nucleon center-of-mass energy of 8.16 TeV using the CMS detector will be presented. The muon decay channel is used to study both positive and negative W bosons as a function of muon pseudorapidity. Rapidity and charge asymmetries in the W yield are studied. Comparisons to theory calculations show that these data are sensitive to the presence of nuclear modifications to the parton distributions in the lead nucleus, and can help improve and constrain theoretical calculations.

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1. Introduction

Determining the exact internal structure of nucleons is one of the continuous efforts in particle physics. Nucleons are predominantly composed of three valence quarks at low energy scales (Q^2). When resolving the nucleon at higher Q^2, a more complex partonic structure is revealed, which is not yet precisely known. The structure is quantified by the parton distribution functions (PDFs) of the nucleon, which are the probability density functions for finding a parton within the nucleon with a given flavor, momentum fraction x at a given scale Q^2. The PDFs of a bound nucleon in a nucleus (nPDFs) are different from those of a free nucleon. Electroweak gauge bosons are considered to be sensitive probes of the PDFs and nPDFs, because they are produced in the early stages of the hadron collisions and do not interact with QCD matter: those probes keep information from the initial state of the collisions [1]. W boson production is sensitive to the isospin effect (different up and down quark content between proton and neutrons), because W bosons are mainly produced by quark-antiquark annihilation in the colliding hadrons, through $u\bar{d} \rightarrow W^+$ and $d\bar{u} \rightarrow W^-$. In addition, the comparison between the yields of W^+ and W^- bosons could give more information about the ratio of the up to down quark PDFs [2–4]. In pPb collisions at $\sqrt{s_{\mathrm{NN}}} = 8.16$ TeV, W boson production is expected to probe the quark nPDFs for $10^{-3} < x < 10^{-1}$ at high Q^2.

2. Reconstruction of W bosons

W boson measurements are performed in the $W^{\pm} \rightarrow \mu^{\pm}\nu_{\mu}$ decay channel, using pPb collision data collected with the CMS detector in 2016 run period with the integrated luminosity of 173.4 ± 8.7 nb^{-1} [5]. The detailed description of the CMS detector can be found in Ref. [6]. To select events with an isolated high-p_{T} muon, the presence of at least one muon candidate with $p_T > 12$ GeV$/c$ is required online by the triggering algorithm. The muon candidates are reconstructed with the combination of information from the muon systems and the inner tracker. Events are required to have a muon with transverse momentum larger than 25 GeV$/c$ and an absolute value of the pseudorapidity in laboratory frame less than 2.4. To select muons with good quality, standard tight selection criteria described in Ref. [7] are applied. To reduce further the jet-induced backgrounds, the selected muon is required to be isolated. The muon isolation parameter is defined as the p_{T} sum of photons, charged and neutral hadrons reconstructed by the particle flow (PF) algorithm [8], in a cone of radius $R = \sqrt{(\Delta\eta)^2 + (\Delta\phi)^2} = 0.3$ around the muon candidate, where $\Delta\eta$ and $\Delta\phi$ are the difference of pseudorapidity and azimuthal (in radians) distances from the muon to the PF particle. If the muon isolation is less than 15% of the muon p_{T}, the muon is considered isolated and used for the analysis. Finally, events with at least two isolated oppositely charged muons, each with $p_{\mathrm{T}} > 15$ GeV$/c$, are rejected, to veto Z boson events.

Since neutrinos are not detected by the CMS detector, we infer the presence of the neutrino from overall momentum imbalance in the transverse plane. In detail, missing transverse momentum ($p_{\mathrm{T}}^{\mathrm{miss}}$) is defined as the magnitude of the negative vector sum of the p_{T} vector of all reconstructed PF objects in an event. The $p_{\mathrm{T}}^{\mathrm{miss}}$ distribution is used to extract the signal yields and background fractions in 24 bins of the pseudorapidity of muons in center-of-mass frame. With the exception of the QCD multijet background, derived from data, the signal and backgrounds are all modeled from MC templates generated using the next-to-leading-order (NLO) generator POWHEG v2 [9–11].

3. Results

The W boson η^{μ}_{CM}-differential cross sections are defined as

$$\frac{d\sigma^{W^{\pm}\to\mu^{\pm}\nu_{\mu}}}{d\eta^{\mu}_{\mathrm{CM}}}(\eta^{\mu}_{\mathrm{CM}}) = \frac{N_{\mu}(\eta^{\mu}_{\mathrm{CM}})}{\mathscr{L}\Delta\eta^{\mu}_{\mathrm{CM}}}, \tag{3.1}$$

where $N_{\mu}(\eta^{\mu}_{\mathrm{CM}})$ is the efficiency-corrected muon yield in bins of the pseudorapidity η^{μ}_{CM} of muon in center-of-mass frame, $\mathscr{L}$ is the integrated luminosity, and $\Delta\eta^{\mu}_{\mathrm{CM}}$ is the width of the measured η^{μ}_{CM} bin.

To reduce correlated uncertainties and further investigate nuclear effects, forward-backward ratios (R_{FB}), defined as $N^{\pm}_{\mu}(+\eta^{\mu}_{\mathrm{CM}})/N^{\pm}_{\mu}(-\eta^{\mu}_{\mathrm{CM}})$, are computed for both positive and negative muons. Those R_{FB} values from data are compared to the CT14 free proton PDF [12], EPPS16 [13] and nCTEQ15 [14] nPDF calculations. The CT14 PDF is also used for the proton in the nPDF calculations. One difference between the nCTEQ15 and EPPS16 nPDF sets is that the latter includes LHC data (W and Z bosons, and dijets) while the former does not. As shown in Figure 1, the results for muons of both charges favor the predictions using nPDFs over those using CT14. Moreover, the uncertainties from experimental data are significantly smaller than the uncertainties from each nPDF. Consequently, these measurements are expected to constrain the quark and antiquark distributions in nuclei.

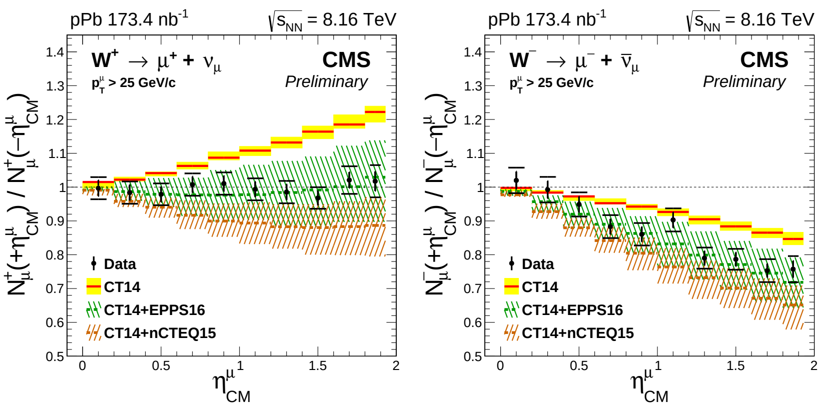

Figure 1: Forward-backward ratios for the positive (left) and negative (right) muons [5]. The brackets represent the quadratic sum of statistical and systematic uncertainties, while the error bars show the statistical uncertainties only. Calculations using CT14 [12] (red line), CT14+EPPS16 [13] (green line) and CT14+nCTEQ15 [14] (brown line), including their uncertainty bands at 68% confidence level.

Another variable, the muon charge asymmetry, defined as $(N^{+}_{\mu}-N^{-}_{\mu})/(N^{+}_{\mu}+N^{-}_{\mu})$, indicates the differences between the production of W^{+} and W^{-} bosons. As shown in Figure 2, the measurement of the muon charge asymmetry as a function of η^{μ}_{CM} is compared to the CT14 proton PDF and two nPDFs EPPS16 and nCTEQ15 similarly to the R_{FB}. Both PDF and nPDF calculations reproduce the present measurements within given uncertainties in the entire analysis range, because nuclear modifications of the PDFs are expected to cancel in this quantity.

Moreover, the theoretical uncertainties are also enlarged in the EPPS16 nPDF sets, as compared to the EPS09 nPDF sets used in the analysis at $\sqrt{s_{\mathrm{NN}}} = 5.02$ TeV [15]. To compare the

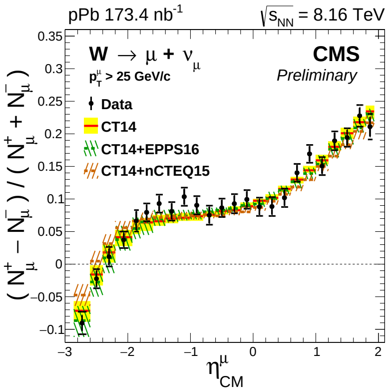

Figure 2: Muon charge asymmetry as a function of the muon pseudorapidity in the center-of-mass frame [5]. The brackets represent the quadratic sum of statistical and systematic uncertainties, while the error bars show the statistical uncertainties only. Calculations using CT14 [12] (red line), CT14+EPPS16 [13] (green line) and CT14+nCTEQ15 [14] (brown line), including their uncertainty bands at 68% confidence level.

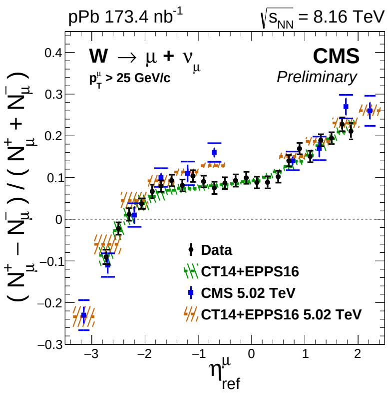

Figure 3: Comparison of the muon charge asymmetry measured at 8.16 TeV (black points) [5] and at 5.02 TeV (blue squares) [15]. The muon pseudorapidity has been shifted according to $\eta^{\mu}_{\rm ref} = \eta^{\mu}_{\rm CM} \pm \ln(8.16\ \text{TeV}\ /\sqrt{s_{\rm NN}})$ [16]. The brackets represent represent the quadratic sum of statistical and systematic uncertainties, while the error bars show the statistical uncertainties only. Calculations using with CT14+EPPS16 nPDF at 8.16 TeV (green line) and at 5.02 TeV (brown line) [13] , are also shown, including their uncertainty bands at 68% confidence level.

measurements of the lepton charge asymmetry at different collision energies, the shift in the lepton pseudorapidity by $\eta^{\mu}_{\rm ref} = \eta^{\mu}_{\rm CM} \pm \ln(8.16\ \text{TeV}\ /\sqrt{s_{\rm NN}})$ is used [16]. Figure 3 shows a good agreement between the muon charge asymmetry at $\sqrt{s_{\rm NN}} = 8.16$ TeV and $\sqrt{s_{\rm NN}} = 5.02$ TeV after using the rapidity shift.

4. Summary

CMS has measured the production of $W^{\pm}$ bosons in pPb collisions at $\sqrt{s_{\rm NN}} = 8.16$ TeV, in the $W^{\pm} \to \mu^{\pm}\nu_{\mu}$ decay channel. The cross section, forward-backward asymmetry and muon charge asymmetry have been measured as a function of the muon pseudorapidity in the center-of-mass frame. The cross sections and forward-backward asymmetries favor calculations using nPDFs over those using the free proton PDF CT14. They feature significantly lower experimental uncertainties than the nPDF ones and are expected to constrain the present models. The muon charge asymmetries in data and nPDF sets at different collision energies after shifting the muon pseudorapidity show a good agreement. Complementary studies of the Drell-Yan process in pPb collisions at $\sqrt{s_{\mathrm{NN}}} = 8.16$ TeV are ongoing and will be reported soon.

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