Productions of $Z$ and $W$ in Relativistic Heavy-Ion Collisions at the LHC

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The productions of massive gauge bosons, $Z^0$ and $W^+/W^-$ in heavy-ion reactions at the LHC provide an excellent tool to study the cold nuclear matter effects in high-energy nuclear collisions. In this paper we investigate $Z^0$ and $W^+/W^-$ productions in p+Pb and Pb+Pb at the LHC at NLO and NNLO with DYNNLO incorporating the nuclear PDFs (nPDFs) parametrization sets EPS09 and DSSZ within the framework of perturbative QCD. The numerical simulations of the transverse momentum spectra, rapidity dependence and related nuclear modification factors for $Z$ and $W$ particles as well as the charge asymmetry for $W$ boson are provided and confronted against the latest experimental data. It is found that the theoretical results with EPS09 and DSSZ nPDFs can give good descriptions of the recent data on $Z^0$ and $W^\pm$ particles in p+Pb and Pb+Pb within the experimental error bars, though some differences between results with EPS09 and DSSZ can be observed, especially in the rapidity dependence of the $Z^0$ yield. Theoretical predictions for future measurements on $Z$ and $W$ in p-Pb and Pb-Pb collisions at the LHC are also provided.

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I. INTRODUCTION

With the running of the Large Hadron Collider (LHC), the measurement of heavy gauge bosons $Z^0$ and $W^+/W^-$ in relativistic heavy-ion collisions has become available for the first time and attracted a lot of attentions [1–8]. Through the Drell-Yan mechanism [9], the gauge boson production with final state lepton pair would provide an interesting insight on perturbative quantum chromodynamics (pQCD) for both hadronic and nuclear collisions. It’s also noteworthy that in the heavy-ion collisions (HIC), the electro-weak boson production would be hardly affected by the evolution of the QCD matter, since the boson mean-free-path in the QCD matter is much longer than the size of the QCD medium [10–12]. Not like other probes with easily polluted final state signal, the gauge boson could be a good probe of initial cold nuclear matter (CNM) effects in high-energy nuclear collisions with this great superiority [13–17].

In this paper we focus on the CNM effects on the massive gauge boson production and investigate the yields of $Z^0$ and $W^+/W^-$ bosons in nuclear collisions at the next-to-leading order (NLO) and the next-to-next-to-leading order (NNLO) within the framework of pQCD by using the program DYNNLO [18]. Several important CNM effects such as the isospin effect, nuclear shadowing effect, anti-shadowing effect, EMC effect as well as Fermi motion effect will be included in the numerical simulations of heavy gauge boson productions by phenomenologically utilizing the nuclear parton distribution functions (nPDFs) parametrization sets EPS09 [19] and DSSZ [20]. The transverse momentum and rapidity dependence of $Z^0$ and $W^+/W^-$ yields in p+Pb and Pb+Pb collisions will be computed numerically and compared with the data at the LHC. The difference between results with EPS09 and DSSZ will be shown and their physics implications are discussed.

Our work is organized as follows: In Section III we discuss the gauge boson productions in hadronic collisions through the Drell-Yan mechanism and introduce the program DYNNLO. In Section IV we study the $Z^0$ boson production in heavy-ion collisions at LHC for both Pb+Pb at $\sqrt{s_{NN}} = 2.76$ TeV and p+Pb at $\sqrt{s_{NN}} = 5.02$ TeV. We calculate the $Z^0$ boson transverse momentum distribution, rapidity distribution, and the corresponding nuclear modification factor. The parton-flavor dependent nuclear modification effects on the gauge boson production are discussed. In Section V we focus on the $W^+/W^-$ boson production in HIC. The isospin effect on the $W^+$ transverse momentum distribution and the charge asymmetry are mainly discussed. In Section V we give the summary and conclusions.

II. Z AND W PRODUCTIONS IN HADRONIC COLLISIONS

Heavy gauge boson productions in elementary hadron-hadron reactions provide the baseline of studies on $Z$ and $W$ yields in high-energy nuclear collisions. Generally we consider the following inclusive hard-scattering reaction

$$h_1 + h_2 \rightarrow V + X$$

where $V = Z/\gamma$, $W^+$, or $W^-$ with high invariant mass. Take $Z^0/\gamma^*$ production as an example, in the parton model, the cross section $\sigma_{DY}$ for the Drell-Yan
(DY) process with $Z^0$ decaying to a lepton pair can be calculated by weighting the subprocess cross section $\sigma$ for $q\bar{q} \rightarrow Z \rightarrow ll$ (at the lowest order) with the parton distribution functions (PDFs) of quark $q(x, \mu)$ and that of anti-quark $\bar{q}(x, \mu)$, and then summing contributions of all quark-antiquark combinations in $h_1$ and $h_2$ as \[ \sigma_{DY} = \sum_f \int dx_1 dx_2 [q_1(x_1, \mu)q_2(x_2, \mu)] \times \sigma_{q\bar{q} \rightarrow V(q) \rightarrow ll}. \tag{2} \]

Here $V \rightarrow ll$ stands for the process of $Z/\gamma^* \rightarrow l^+l^-$. In calculating the massive gauge boson productions, higher order corrections to Eq. (2) play an important role. At the next-to-leading order (NLO) which gives perturbative expansions at $O(\alpha_s)$, there are two kinds of new contributions: (1) the real corrections, and (2) one-loop virtual corrections to the leading order (LO) subprocess; at the next-to-next-to-leading order (NNLO) which gives calculations at $O(\alpha_s^2)$, three kinds of contributions should be included: double real corrections, real-virtual corrections, and two-loop virtual corrections to the LO subprocess [18, 23–26]. In the last two decade, some numerical approaches of computing massive gauge boson productions in hadronic collisions at the NLO and NNLO have been developed [18, 23, 24, 27]. In this work, the Drell-Yan process cross sections of $Z^0$ and $W^+/W^-$ are calculated by using the NNLO computation program DYNNLO [18], which has taken into account finite-width effects, $\gamma-Z$ interference, the leptonic decay of the vector bosons as well as the corresponding spin correlations.

Besides considering the total yields of massive gauge bosons and their rapidity dependence, we may also investigate the transverse momentum spectra of these vector bosons. Although the lowest order of the DY process in Eq. (2) gives important contribution to the total yield, it does not give non-vanishing transverse momentum $p_T^V$. Therefore, when $p_T^V \neq 0$, the (N)NLO contributions of total yield are given by the (N)LO contributions to the final state $V+\text{jet}$. So the leading-order contribution for total cross sections (or rapidity distributions) of $Z^0$ is given by $q\bar{q} \rightarrow Z^0$, whereas for $Z^0$ transverse momentum distribution, the processes of $q\bar{q} \rightarrow V+g$ and $gg \rightarrow V+g$ provide the dominant contribution. It is also noted that in computing transverse momentum spectra at sufficiently small $p_T^V$, the resummation technique will be needed to get robust predictions [23, 32]. In this work we will focus on the massive gauge boson transverse momentum distribution at large $p_T^V$ region and will not include the contribution from resummation needed for small $p_T^V$ region.

In this paper to compute numerically heavy gauge boson productions at (N)NLO with DYNNLO (version 1.4), Martin-Stirling-Thorne-Watt (MSTW)2008 [33] sets of parton distribution functions (PDFs) are chosen, and the NNLO PDFs are used in calculations at $O(\alpha_s^2)$ and the NLO PDFs in that at the $O(\alpha_s)$. The renormalization scale ($\mu_R$) and the factorization scale ($\mu_F$) are both fixed at the value $\mu_R = \mu_F = m_V$ with $m_V$ the mass of the vector boson. One intensive study about the impact of the renormalization and factorization scales on the gauge boson rapidity distribution could be found in Ref. [34], and discussions about these scales on the transverse momentum spectrum calculation could be seen in Ref. [35]. Generally the calculations with higher order pQCD corrections have less dependence on the scale. In the following we will give the numerical results of massive gauge boson productions in $h+h$ collisions, where the errors in the Monte Carlo integration were provided by the DYNNLO program according to an estimate of the numerical errors in the Monte Carlo integration [18], and in this paper we have not included the errors associated with the uncertainties of PDFs (and nPDFs).

Recently, the productions of massive gauge bosons in

![FIG. 1: (Color online) The normalized $Z$ boson differential cross section as a function of $p_T^Z$ in p+p collisions at $\sqrt{s} = 7$ TeV. The ATLAS combined data are taken from Ref. [35].](image1)

![FIG. 2: (Color online) Top panel: the ratio of the normalized $Z$ boson differential cross section at $O(\alpha_s^2)$ to that at $O(\alpha_s)$ and ATLAS data [33]. Bottom panel: the deviation between theory for the $Z$ production at $O(\alpha_s^2)$ and ATLAS data [35].](image2)
the proton-proton collisions at $\sqrt{s} = 7$ TeV have been studied by measuring the transverse momentum distributions and the rapidity distribution of the gauge bosons. We confront the theoretical calculations with these measurements to test the validity of perturbative QCD calculations of the heavy gauge boson productions.

In Fig. 1 we compare the theoretical calculations of the normalized $Z^0$ differential cross section $(1/\alpha) d\sigma/dp_T^2$ with ATLAS measurement on $Z$ production combining the channel of $Z/\gamma^* \rightarrow ee$ with the channel of $Z/\gamma^* \rightarrow \mu\mu$ in the final state fiducial phase space, which is defined by the lepton pseudorapidity and transverse momentum, and by the invariant mass of the dilepton: $|\eta^*| < 2.4$, $p_T^\gamma > 20$ GeV and $66$ GeV < $m_{ll} < 116$ GeV \cite{35}. We see the $O(\alpha_s^2)$ results agree very well with the data in the region of $p_T^\gamma > 10$ GeV. To see the relative contributions of higher order corrections and the deviation between theory and experiment we plot in Fig. 2 the ratios of the $O(\alpha_s^2)$ results to the $O(\alpha_s)$ results and the ATLAS data to the $O(\alpha_s^2)$ results. It is observed that the $O(\alpha_s^2)$ calculations give about 10% ~ 40% more contributions than those of $O(\alpha_s)$ to the differential cross sections as a function of $p_T^\gamma$, and the differences between theory and data are rather small.

TABLE I: The total cross sections for massive gauge bosons in the fiducial volume in $p+p$ collisions at $\sqrt{s} = 7$ TeV.

| Vector Boson | $|\eta^*| < 2.4$ | $p_T^\gamma > 20$ GeV | $66$ GeV < $m_{ll} < 116$ GeV |
|--------------|----------------|----------------------|-----------------------------|
| $Z^0$ at $O(\alpha_s)$ | $0.45 \pm 0.0002$ | $0.458 \pm 0.0008$ | $O(\alpha_s^2)$ |
| $W^+$ at $O(\alpha_s)$ | $3.000 \pm 0.0016$ | $3.062 \pm 0.0092$ | $O(\alpha_s^2)$ |
| $W^-$ at $O(\alpha_s)$ | $2.025 \pm 0.001$ | $2.045 \pm 0.0048$ | $O(\alpha_s^2)$ |

In TABLE. I we list the theoretical simulation of the total cross sections of $Z^0$ and $W^+/W^-$ in the fiducial phase space at the NLO and NNLO for $p+p$ reactions at the LHC. It is seen that the total cross sections of the gauge bosons at the NNLO will be enhanced slightly as compared to those at the NLO.

The normalized differential cross sections as a function of $Z$ boson rapidity in the invariant mass interval $60$ GeV < $m_{ll} < 120$ GeV are measured by CMS collaboration \cite{36}. We show our numerical results with the CMS data in Fig. 3 and we find that both the $O(\alpha_s^2)$ and $O(\alpha_s)$ calculations have good agreements with the data. The values at $O(\alpha_s^2)$ are slightly larger than those at $O(\alpha_s)$, just like the case of total cross sections calculations.

The transverse momentum distribution of $W$ bosons is also studied and the theoretical calculations as well as the experimental data by ATLAS are illustrated in Fig. 4 where both theory and data are made in the fiducial phase space defined by the pseudorapidity and transverse momentum of charged lepton, the transverse momentum of neutrino and the transverse mass as $|\eta^*| < 2.4$, $p_T^\gamma > 20$ GeV, $p_T^\nu > 25$ GeV, $m_T = \sqrt{2p_T^\nu p_T^\gamma (1-\cos(\phi^\nu-\phi^\gamma))}$ > 40 GeV \cite{37}.

FIG. 3: (Color online) The normalized $Z$ boson differential cross section as a function of rapidity in $p+p$ at $\sqrt{s} = 7$ TeV. The CMS data are taken from Ref. \cite{36}.

FIG. 4: (Color online) The normalized $W$ boson differential cross section as a function of $p_T^W$ in $p+p$ collisions at $\sqrt{s} = 7$ TeV. The ATLAS combined data are taken from Ref. \cite{37}.

Fig. 11 demonstrate that the pQCD calculations of heavy gauge boson productions at the (N)NLO with DYNNLO can give satisfactory descriptions of the experimental data, and thus provide a very good theoretical tool to study the productions of the gauge bosons in relativistic heavy-ion collisions and related cold nuclear matter effects.

III. $Z^0$ BOSON PRODUCTION IN HEAVY-ION COLLISIONS

To extend the investigation of the gauge boson productions in $p+p$ collisions to that in $p+A$ and $A+A$ reactions cold nuclear matter (CNM) effects should be taken into account, even though final-state hot/dense QGP effects (which may exists in Pb+Pb collisions at the LHC) will

...
not affect the production of the gauge boson production due to its much larger mean-free-path relative to the size of the QGP [13, 14, 16, 17, 30, 38–40]. To include several CNM effects (such as shadowing, anti-shadowing, EMC effect, Fermi motion etc.) on heavy gauge boson productions we phenomenologically replace the parton distribution functions (PDFs) of the free proton with the nuclear parton distribution functions (nPDFs) [19, 20] in computing the cross sections in heavy-ion collisions. We note that the effect of parton energy loss in cold nuclear matter [11–13] has not been included in this approach and we may defer it in a future study.

Usually to construct a set of nPDFs we can choose a set of free PDFs \( f^p \) and then implement nuclear modifications on them. In this way the nPDFs can be obtained as [19, 20]

\[
f^A(x, \mu) = \frac{Z}{A} f^{p,A}(x, \mu) + \frac{N}{A} f^{n,A}(x, \mu) \tag{3}\]

where \( Z \) and \( N \) are the number of protons and neutrons in a nucleus with mass number \( A \). \( f^{p,A}(x, \mu) \) and \( f^{n,A}(x, \mu) \) are the bound proton and neutron PDFs for momentum fraction \( x \) and the scale \( \mu \) respectively. In parametrizations of nPDF such as EPS09 [19] and DSSZ [20] the nuclear modifications to the PDFs are defined through flavor and scale dependent factors \( R_f(x, \mu) \):

\[
f^{p,A}(x, \mu) = R_f(x, \mu) f^p(x, \mu), \tag{4}\]

while \( f^{n,A} \) can be derived from those of a bound proton by assuming the isospin symmetry as [19, 20],

\[
d^{p,A} = u^{p,A}, \quad d^{n,A} = d^{p,A} \tag{5}\]

the PDFs of other flavor partons in the bound proton and neutron PDFs are the same. In this paper, the nuclear PDFs are taken from EPS09 and DSSZ parametrization sets and the proton PDFs from MSTW2008.

When calculating the cross sections in p+A and A+A collisions one can use the Glauber model to obtain the geometry of nuclear collisions [44], and calculate the total number of nucleon-nucleon collision in a given centrality class \( \langle N_{coll} \rangle \) and the nuclear overlap function for minimal bias (MB) reactions \( \langle T_{AB} \rangle_{MB} \).

Recently the \( Z^0 \) boson productions in p+Pb collisions at \( \sqrt{s_{NN}} = 5.02 \text{ TeV} \) and in Pb+Pb collisions at \( \sqrt{s_{NN}} = 2.76 \text{ TeV} \) have been measured at the LHC. As the first example we study the transverse momentum distributions of \( Z^0 \) in heavy-ion collisions and the corresponding nuclear modification factors. Fig. 5 demonstrates the theoretical simulations of the yields \( d^2N/dydp_T \) of \( Z \rightarrow \mu\mu \) per MB event as a function of \( p_T \) in the Z boson rapidity range \(|y| < 2.0\) for Pb+Pb collisions at \( \sqrt{s_{NN}} = 2.76 \text{ TeV} \), and compares the theory with the CMS muon data, which have been measured in the \( Z^0 \) invariant mass interval \( 60 \text{ GeV} < m_{\mu\mu} < 120 \text{ GeV} \) [2, 8]. Our yields are obtained by multiplying cross section per nucleon-nucleon collisions by the average nuclear overlap function for minimum bias collisions

\[
\langle T_{AB} \rangle_{MB} = (5.66 \pm 0.35) \text{mb}^{-1}, \text{ which is the same as that used in [2]. We can see in Fig. 5 that the theory could give a decent description of the data in Pb+Pb collisions, though at very low } p_T \text{ region a resummation of leading log contributions may be needed for a more precise comparison.}

In Fig. 6 we plot the \( p_T^Z \) dependence of the \( \langle N_{coll} \rangle^{-1} \frac{d\sigma}{dp_T^Z} \) for the Z boson productions in p+p and Pb+Pb collisions at \( \sqrt{s_{NN}} = 2.76 \text{ TeV} \).

\[
\langle N_{coll} \rangle^{-1} \frac{d\sigma}{dp_T^Z} \text{ for the Z boson productions in p+p and Pb+Pb collisions at } \sqrt{s_{NN}} = 2.76 \text{ TeV}.
\]

The ratio as functions of other variables, such as rapidity can be defined similarly.

In Fig. 7 the \( R_{AA} \) as a function of \( p_T^Z \) is plotted. A small enhancement could be observed in the large \( p_T^Z \) re-
region (≈ 10–200 GeV) for both EPS09 and DSSZ nPDFs. Suppression related to the nuclear shadowing effects can only be seen at rather small $p_T$. To well understand the $R_{AA}(p_T^Z)$, we can make an analysis at the order $O(\alpha_s)$. At this order, we have the relationship [45] with the narrow width approximation as

$$
x_1 = \left( E_{T3} e^{y_3} + E_{T4} e^{y_4} \right) / \sqrt{s},
$$

$$
x_2 = \left( E_{T3} e^{-y_3} + E_{T4} e^{-y_4} \right) / \sqrt{s},
$$

where $y_3$ and $y_4$ are the rapidity of the vector boson $V$ and the parton recoiling against it, and $E_T$ is the particle transverse energy defined as $E_T = \sqrt{p_T^2 + m^2}$. In the central rapidity with $y_3 \sim y_4 \sim 0$, we derive a simple relationship

$$
x_1 = x_2 = \left( E_{T3} + E_{T4} \right) / \sqrt{s}.
$$

In the partonic process, with $p_{T3} = p_{T4}$ and by neglecting the parton mass one can obtain in the narrow width approximation that

$$
x_1 = x_2 = \frac{p_T + m^2 / s}{\sqrt{s}},
$$

which connects initial parton momentum and the gauge boson transverse momentum in the mid-rapidity region at leading order.

Because of the large mass of Z boson, the momentum fraction $x$ can not be too small in the mid-rapidity boson productions. Even with the minimum $p_T^Z$, for heavy-ion collisions at $\sqrt{s_{NN}} = 2.76$ TeV $x \sim m_Z / \sqrt{s_{NN}} \sim 0.033$ which is in the vicinity of anti-shadowing region for the EPS09 nPDFs. This underlies the enhancement at large $p_T^Z$ and the suppression at small $p_T^Z$.

Fig. 8 shows that the differences exist between the results of EPS09 and DSSZ nPDFs. For example, more enhancement is given by EPS09 in the region of $p_T^Z \lesssim 130$ GeV, but DSSZ gives persistent enhancement even when the yields of EPS09 go down in the larger $p_T^Z$ region ($>130$ GeV), which can be seen more obviously in the insert of Fig. 8. To have a deeper understanding of these differences we plot in Fig. 8 the flavor dependent factors of both EPS09 and DSSZ as $R_f(p_T^Z, \mu)$ by replacing the parton momentum fraction $x$ with $p_T^Z$, where the relation of $x$ and $p_T^Z$ is given by Eq. (9). One can observe that the nuclear modification factors of the $u$ and $d$ valence quarks are similar for EPS09 and DSSZ. However, obvious distinction could be found for $u$ sea quarks and $d$ sea quarks, especially for gluons. In the region of $p_T^Z \lesssim 130$ GeV, the nuclear PDF of $u$ sea quark is shadowed in DSSZ while it is anti-shadowed in EPS09, and the anti-shadowing effects for gluons are very weak in DSSZ but much stronger in EPS09. Because partonic subprocesses with at least one initial-state gluon (for example, $e^- e^+ \rightarrow u + Z^0$ and $e^- e^+ \rightarrow d + Z^0$ at LO) give dominant contributions to $Z^0$ production at large $p_T$, $R_{AA}(p_T^Z)$ could provide a good tool to distinguish different parametrizations of gluon distributions in nuclei [11]. In TABLE II we have listed the theoretical results and CMS data for $R_{AA}$.

| $p_T^Z$ (GeV) | $\mathcal{O}(\alpha_s^2)$ | $\mathcal{O}(\alpha_s^3)$ | CMS Data |
|---------------|----------------|----------------|----------|
| [0, 6]        | 0.943           | 0.922          | 0.84 ± 0.26 ± 0.12 |
| [6, 12]       | 1.031           | 0.9845         | 1.32 ± 0.34 ± 0.19 |
| [12, 36]      | 1.055           | 1.007          | 1.06 ± 0.31 ± 0.45 |

For p+Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV, the differential cross sections as a function of $p_T^Z$ are calculated in the Z boson invariant mass interval 66 GeV < $m_H$ < 116 GeV, as adapted by the ATLAS experiment [2] [33]. What should be mentioned for p-Pb collisions is that for the asymmetric collision system, the center of mass frame...
for the colliding nucleon pair is not the same as the laboratory frame. At the LHC, the relationship of rapidity between them is $y_{c.m.} = y_{lab} - 0.465$. Here we calculate the $p_T^Z$ distribution in the rapidity region $|y_{c.m.}| < 2$. In Fig. 9 we show results with EPS and DSSZ nPDFs at $O(\alpha_s^2)$ and find the difference is marginal.

The nuclear modification ratios $R_{pA}(p_T^Z)$ are plotted in Fig. 10 for EPS09 nPDFs, enhancements could be observed in the $p_T^Z$ region of about 10 $-$ 300 GeV. For DSSZ, suppressions exist in the region $p_T^Z \lesssim 40$ GeV and enhancements appear in the larger $p_T^Z$ region. Compared to results in Pb+Pb, the suppression and enhancement regions in p+Pb become wider because of the larger colliding energy $\sqrt{s_{NN}}$ in p+Pb. For example, with $p_T = 200$ GeV the Eq. (9) gives the parton momentum fraction $x \sim 0.083$ for p+Pb in the central rapidity $y_3 \sim y_1 \sim 0$, which is in the anti-shadowing region in EPS09. But the momentum fraction $x$ given by Eq. (10) may fall in the EMC region for Pb+Pb collisions at 2.76 TeV. Also we note the CNM effects will be less pronounced for p+Pb, the smaller colliding system as compared to those in Pb+Pb.

Next we focus on another important observable in Z boson productions, i.e. the Z boson rapidity distribution. The yields per MB event $dN/dy$ in Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV are calculated numerically and compared to the CMS data [2, 8] in Fig. 11. One can observe that results at $O(\alpha_s^2)$ and $O(\alpha_s)$ are close to each other, and $O(\alpha_s^2)$ calculations slightly enhance the total yields. The calculations agree with the data though experiment error bars are rather large and more measurement may be needed for a robust comparison.

In Fig. 12 we compare the differential cross section of $Z^0$ in Pb+Pb with that in p+p, and give the related nuclear modification ratios $R_{AA}(y^Z)$ in Fig. 13 $Z$ productions in both Pb+Pb and p+p exhibit a symmetric rapidity distributions. In Pb+Pb collisions, considerable distinction between results in EPS09 nPDFs and those in DSSZ nPDFs could be observed. Relative to that in p+p, the yield of Pb+Pb with EPS09 shows an enhancement in the mid-rapidity region (about $|y^Z| < 1$), but a suppression in the large rapidity region (about $1 < |y^Z| < 2$). However, the yield with DSSZ always gives a handsome suppression in the whole rapidity region we studied. For the convenience in TABLE III we list the CMS data on $R_{AA}(y^Z)$ and theoretical results with EPS09 and DSSZ.

To have a simple picture of this distinction one can look at the leading-order processes for $Z^0$ production. At LO, the $Z$ boson rapidity can be connected to the parton (quark and anti-quark) momentum fractions with the kinematic relations

$$x_1 = \frac{m_Z}{\sqrt{s_{NN}}}e^{y^Z}, \quad x_2 = \frac{m_Z}{\sqrt{s_{NN}}}e^{-y^Z}. \quad (10)$$

Then at $y^Z = 0$ one obtains $x_1 = x_2 = m_Z/\sqrt{s_{NN}} \sim 0.033$, at which the anti-shadowing effect is nearly peaked in EPS09 parametrization. Therefore the visible en-
hancement of $Z^0$ yield with EPS09 in Pb+Pb relative to that in p+p at $y^Z = 0$ originates mainly from the anti-shadowing effects. When going to the large $|y^Z|$ region, $Z$ bosons are produced with one of parton momentum fractions ($x_1$ or $x_2$) increasing and going to the EMC effect region, while the other decreasing and going to the shadowing region. As a consequence, a suppression gradually develops in the large $|y^Z|$ regime. For example, if we consider $Z$ boson production at $y^Z = 2$, then one gets $x_1 \sim 0.24$ and $x_2 \sim 0.0045$. For EPS09 nPDFs, $x_1$ has entered the EMC region, and $x_2$ has entered the shadowing region, so a suppression is observed at $y^Z = 2$ since both shadowing and EMC effects may reduce the total yield of Z gauge bosons.

To demonstrate the differences between EPS09 and DSSZ, we plot in Fig. 14 the factor $R_{f f}(y^Z, \mu)$ defined as

$$R_{f f}(y^Z, \mu) = \frac{1}{2} \left[ R_f(x_1, \mu) R_f(x_2, \mu) + R_f(x_2, \mu) R_f(x_1, \mu) \right],$$

where $x_{1,2}$ is related to $Z^0$ rapidity according to Eq. (10). One can see clearly in Fig. 14 that the three partonic subprocesses ($u + \bar{u} \to Z^0$, $d + \bar{d} \to Z^0$, $s + \bar{s} \to Z^0$) suffer similar nuclear modifications. They demonstrate that $R_{AA}(y^Z)$ results mainly from the nuclear modifications of quark and anti-quark, and thus provide an excellent observable to measure the nuclear modification of (anti-)quark distribution. On the contrary as we have discussed $R_{AA}(p_T^Z)$ (or $R_{pA}(p_T^Z)$) gives more information about the nuclear effects on gluons.

We also investigate the yields of $Z$ in p+Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV, and the results are shown in Fig. 15. $Z$ bosons are produced in the ATLAS mass window $66\text{ GeV}<m_Z<116\text{ GeV}$ [33,34]. Fig. 15 shows a forward-backward asymmetry of $Z$ boson rapidity distributions in p+Pb collisions. Compared to p+p at $\sqrt{s} = 5.02$ TeV, a suppression exists in the forward rapidity region and the enhancement shows up in the backward direction in p+Pb collisions. We have checked that the isospin effect just give a slight contribution to the nuclear modifications observed in $Z$ rapidity distribution, which implies the forward-backward asymmetry results mainly from other CNM effects, such as shadowing effect. In Fig. 15 the nuclear modification factors $R_{pA}(y^Z)$ are given. Using Eq. (10) one find at $y^Z = 0$, the momentum fractions of partons $x_1 = x_2 = m_Z/\sqrt{s_{NN}} \sim 0.018$, which is near the junction of the shadowing and anti-shadowing region of EPS09 nuclear modifications. Thus at $y^Z = 0$ one find the nuclear effects of Z boson with EPS09 are rather moderate. Moreover, when moving to the forward rapidity regime, parton distributions of the lead nucleus at smaller $x$ are depleted as compared to those in proton, we expect to get a suppression due to the shadowing effects. And when going to the backward regime, an enhancement occurs due to the anti-shadowing effects with the larger $x$ carried by partons in the lead nucleus. We also show the flavor dependent nuclear modification factor $R_f(y^Z, \mu)$ in Fig. 17 by replacing the parton momentum fraction $x_2$ (from the lead nucleon) with the boson rapidity $y^Z$ by using the Eq. (11). One can see that although nPDFs of valence quarks are essentially the same in EPS09 and in DSSZ, visible difference could be observed for nPDFs of sea quark distribution.

| TABLE III: Rapidity dependence of the nuclear modification ratios $R_{AA}(y^Z)$ for $Z$ boson as well as the CMS data [2]. |
|---|---|---|---|
| $|y^Z|$ | $O(\alpha_s^2)$ EPS09 | $O(\alpha_s^2)$ DSSZ | CMS |
| 0.2 | 0.993 | 0.961 | 1.00 ± 0.16 ± 0.14 |
| 0.5 | 1.037 | 0.961 | 1.03 ± 0.29 ± 0.15 |
| 1.0 | 1.018 | 0.965 | 0.98 ± 0.29 ± 0.14 |
| 2.0 | 0.954 | 0.959 | 0.97 ± 0.26 ± 0.14 |

FIG. 12: (Color online) The $Z$ boson differential cross section in p+p and Pb+Pb collisions at $O(\alpha_s)$ as a function of rapidity.

FIG. 13: (Color online) the nuclear modification factors $R_{AA}(y^Z)$ for the $Z$ boson production at $O(\alpha_s)$. 
and Pb+Pb collisions at $\sqrt{s}$ results of $\sqrt{s}$ One can observe that, as in collisions at lepton (muon at CMS) as transverse momentum and pseudo-rapidity of the charge that in the CMS experiment, which is defined by the

FIG. 14: (Color online) The flavor dependent factor $R_{fA}(y^Z, \mu)$ as functions of Z boson rapidity. The factorization scale is fixed at the boson mass.

The final state phase space is chosen to be the same as $Z$ (Fig. 4), the yields of $Z$ bosons production in p+p collisions. The green dotted-dash line stands for the result by only considering the isospin effect in p+Pb collisions.

IV. $W^\pm$ BOSON PRODUCTION IN HEAVY-ION COLLISIONS

In Section III we discussed Z production in nuclear collisions, with the same approach we can also investigate $W^\pm$ gauge boson production in heavy-ion collisions at NLO and NNLO with DYNNLO.

Firstly we study the transverse momentum distribution of W bosons production. We plot in Fig. 15 the $p_T^W$ differential cross sections calculated at $\mathcal{O}(\alpha_s^2)$ order. The results of $W^+$, $W^-$ and $W(=W^+ + W^-)$ in both p+p and Pb+Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV are shown. The final state phase space is chosen to be the same as that in the CMS experiment, which is defined by the transverse momentum and pseudo-rapidity of the charge lepton (muon at CMS) as $p_T > 25$ GeV and $|\eta| < 2.1$. One can observe that, as in collisions at $\sqrt{s} = 7$ TeV (see Fig. 4), the yields of $W^+$ and $W^-$ in p+p collisions at $\sqrt{s_{NN}} = 5.02$ TeV are quite different, which is a unique observable in $W^+/W^-$ production and is referred as the charge asymmetry in the W productions. The $W^+/W^-$ charge asymmetry originates from the asymmetry in proton parton distributions. For example, a dominant contribution to this asymmetry comes from the difference between parton distributions of u quark and d quark in a proton (more u quarks than d quarks), and a moderate contribution from the small deviation between PDFs of $\bar{u}$ and d. While other processes like $u + d \rightarrow W^+ + g$ and $d + \bar{u} \rightarrow W^- + g$ connect $W^+$ productions with u and d and $W^-$ with d and $\bar{u}$. When computing the transverse momentum spectra of the $W^+/W^-$ productions, the LO processes such as $u + d \rightarrow W^+ + g$ and $d + \bar{u} \rightarrow W^- + g$ connect $W^+$ productions with u and d and $W^-$ with d and $\bar{u}$. While other processes like $u + g \rightarrow W^+ + d$ and $d + g \rightarrow W^- + u$ also bring considerable contributions to the asymmetry of the $W^+/W^-$ productions. Therefore the measurement of W boson charge asymmetry might give very important constraints on the quark parton distribution functions (PDFs), especially the ratio $u(x)/d(x)$ or $\bar{u}(x)/\bar{d}(x)$.

However in Pb+Pb collisions the yield of $W^+$ is sup-
The differential cross section for $W$ production as a function of $W$ boson transverse momentum $p_T$ in $p+p$ and Pb+Pb collisions with $\sqrt{s_{NN}} = 2.76$ TeV at $O(\alpha_s^2)$. 

FIG. 19: (Color online) The nuclear modification factors $R_{AA}(p_T)$ for the $W$ production at $O(\alpha_s^2)$. 

pressed significantly as compared to that in $p+p$ reactions, whereas the yield of $W^-$ productions is strongly enhanced. The opposite trends of the $W^+/W^-$ productions in $A+A$ mainly result from the isospin effect of nuclear parton distributions, i.e. the existing of a lot neutrons in the large nucleus (such as Lead) should to a large extent increase the $d$ quark distribution in nuclei, and decrease $u$ quark distribution in nuclei. We emphasize that although the differential cross sections of $W^+$ and $W^-$ in $p+p$ are modified significantly relative to those in $p+p$, the alteration of the yield for total $W$ production in Pb+Pb is rather small.

In Fig. 19 we plot nuclear modification ratio $R_{AA}(p_T^W)$ at $O(\alpha_s^2)$. As we have discussed the isospin effect gives the dominant contribution to the distinct behaviors of $R_{AA}^{W^+}$ and $R_{AA}^{W^-}$. It is observed that both the suppression of the $W^+$ production and the enhancement of $W^-$ productions become stronger with the increasing $p_T^W$, which results mainly from the increasing $u - d$ asymmetry of PDFs at large momentum fraction $x$ when $p_T^W$ going up.

To dig deeper the isospin effect on the obvious separation of $R_{AA}^{W^+}$ and $R_{AA}^{W^-}$ we define the asymmetry ratio of parton PDFs in a proton as

$$r_{ud}(x) = \frac{u(x) - d(x)}{u(x) + d(x)},$$

$$r_{\bar{u}d}(x) = \frac{\bar{u}(x) - d(x)}{\bar{u}(x) + d(x)}.$$  

At LO the $W$ bosons are mainly produced through partonic subprocess with an initial-state gluon, such as $u + g \rightarrow W^+ + d$ and $\bar{d} + g \rightarrow W^- + \bar{u}$ for $W^+$ production and $d + g \rightarrow W^- + u$ and $\bar{u} + g \rightarrow W^+ + \bar{d}$ for $W^-$ production (actually the subprocess with an initial-state sea quark gives small contribution to the $W$ production). If only considering the isospin effect and neglecting the contributions of other nuclear effects, we obtain some simple relations as:

$$\frac{u^A(x)}{u^p(x)} \approx \frac{Z - N}{A} + \frac{2N}{A} \frac{1}{1 + r_{ud}(x)},$$

$$\frac{d^A(x)}{d^p(x)} \approx \frac{Z - N}{A} + \frac{2N}{A} \frac{1}{1 - r_{ud}(x)},$$  

where $f^A(x)$ is the parton distribution in nuclei and $f^p(x)$ is that in proton. More details could be found in the Appendix A. In Fig. 20 we plot $f^A(p_T^W) / f^p(p_T^W)$ by replacing the parton momentum fraction $x$ with $p_T^W$ according to Eq. (9). By comparing Fig. 19 with Fig. 20 we can see clearly that the isospin effect gives the most important contribution to $R_{AA}^{W^+}(p_T)$ and $R_{AA}^{W^-}(p_T)$.

Certainly other CNM effects, especially the (anti-)shadowing may also affect the $R_{AA}(p_T^W)$ of $W^+$, $W^-$ and total $W$. In Fig. 19 we give both the results with EPS09 and those with DSSZ nPDFs. Similar differences between the two nPDFs for $W^+$, $W^-$ and total $W$ could be observed, which is similar as we observed in the $Z$ production.

To complement the study of the $W$ production in Pb+Pb we also carry out the numerical simulations of the $W$ boson production in $p$+Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The $p_T^W$ differential cross sections are shown in Fig. 21 and the nuclear modification factors $R_{pA}(p_T^W)$ in Fig. 22. The calculations are made in the CMS final-state phase space defined as $p_T^W > 25$ GeV and $|\eta_{lab}| < 2.1$.

To study the difference of $W^+$ and $W^-$ in $p+p$ and heavy-ion collisions, CMS collaboration has measured the so-called the charge asymmetry observable defined as

$$A = \frac{N_{W^+} - N_{W^-}}{N_{W^+} + N_{W^-}}.$$  

Fig. 23 shows the dependence of the charge asymmetry observable on pseudorapidity of the absolute value of charged lepton at $O(\alpha_s)$ (NLO) and $O(\alpha_s^2)$ (NNLO) for both $p+p$ and Pb+Pb collisions. One could observe that for $p+p$ reactions, the charge asymmetry is always
positive in the whole region $|\eta^L| < 2.1$. For Pb+Pb, the charge asymmetry is positive in $|\eta^L| \lesssim 1$ and then decreases to be negative in $1 \lesssim |\eta^L| \lesssim 2.1$. And the NNLO calculations give negligible corrections to the NLO results. It is also found that in Pb+Pb collisions the charge asymmetry $A$ is also not very sensitive to the nPDFs, as we have shown in Fig. 18 already. Our theoretical calculation give a decent description of the CMS data [3].

In Fig. 21 we provide the numerical results on charge asymmetry as a function of the charged lepton pseudorapidity in p+\Lambda collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The results agree well with the CMS preliminary data [3]. The theoretical simulation of the charge asymmetry observable in p+p and Pb+Pb collisions at $5.02$ TeV are also plotted for comparison, which are also symmetric with $\eta_{\text{cm}}$, the charged lepton pseudorapidity in the center-of-mass frame.

It is interesting to observe that the curve of p+Pb collisions lying between those of p+p and Pb+Pb collisions.

To be specific, it goes gradually closer to the p+p curve in the forward direction, while it approaches to the Pb-Pb curve in the backward direction. As in our previous discussions, the differences among these curves mainly originate from the isospin effect. And the magnitude of the isospin effect is associated approximately to the parton distribution asymmetry ratios such as $r_{ud}(x)$. In p+Pb collisions, the W production at very forward region are dominated by partonic processes with nuclear distributions at very small momentum fraction $x$, where $r_{ud}(x)$ (or $r_{ud}(x)$) is rather small. So the isospin effect becomes weaker in that region. With similar discussions we can find that the charge asymmetry in the very backward region for Pb+Pb collisions will be very close to that for p+Pb collisions.

So far for the charge asymmetry of the $W$ production at the LHC, the charged lepton pseudorapidity distribution has been measured [6]. In this work, we further study another related measurement of the charge asym-
theoretical predictions for the charge asymmetry at p+p, p+Pb and Pb+Pb collisions taken from Ref. [6].

![Image](image_url)

**FIG. 25:** (Color online) The charge asymmetry \((N_{W^+} - N_{W^-})/(N_{W^+} + N_{W^-})\) as a function of the transverse momentum \(p_T\) in p+p, p+Pb and Pb+Pb at \(\sqrt{s_{NN}} = 5.02\) TeV. The CMS preliminary data for p+Pb collisions are taken from Ref. [6].

| W production Process | \(O(\alpha_s^2)\) | \(O(\alpha_s^2)\) | CMS norm. cross section [nb] | \(\Delta\eta\) |
|----------------------|-----------------|-----------------|-----------------------------|-----------------|
| \(pPb \to W^+\)      | 0.235           | 0.229           | 0.28 ± 0.02 ± 0.02          |                  |
| \(pPb \to W^-\)      | 0.212           | 0.205           | 0.27 ± 0.02 ± 0.02          |                  |
| \(pp \to W^+\)       | 0.316           | 0.305           | 0.34 ± 0.02 ± 0.02          |                  |
| \(pp \to W^-\)       | 0.178           | 0.175           | 0.18 ± 0.01 ± 0.01          |                  |

**TABLE IV:** The inclusive cross sections for \(W^+, W^-\) and total \(W\) at \(\sqrt{s_{NN}} = 2.76\) TeV, and the corresponding nuclear modification factor \(R_{AA}\). The CMS data are taken from Ref. [3].

If focusing on only the isospin effect and neglecting (smaller) contributions from other CNM effects, as discussed in the Appendix, we derive some simple relations such as

\[
\begin{align*}
    r_{ud}^{pA}(x) &\approx \frac{Z}{A} r_{ud}^{pp}(x), \\
    r_{ud}^{AA}(x) &\approx \frac{1}{2} \left[r_{ud}^{pp}(x) + r_{ud}^{AA}(x)\right],
\end{align*}
\]

and \(r_{ud}^{pp}(x) \equiv r_{ud}(x)\). We can also obtain similar relations for the ratio \(r_{ud}(x)\). In Fig. 26 we plot \(r_{ud}(p_T^W)\) and \(r_{ud}(p_T^W)\) given by Eq. (16) for p+p, p+Pb and Pb+Pb, where \(p_T^W\) is related to the momentum fraction \(x\) according to Eq. (9). Fig. 26 shows at small \(p_T^W\) (corresponding to small \(x\)) region, three curves are very close to each other. From Fig. 25 and Fig. 26 one can see that the charge asymmetry as a function of \(p_T^W\) might shed light on the parton distribution asymmetry ratios \(r_{ud}(x)\) and \(r_{ud}(x)\).
\( (N_{\text{coll}})^{-1} \sigma / \Delta \eta \) in the CMS final state phase space with \( \Delta \eta = 4.2 \) at the NNLO and the related nuclear modification factor \( R_{AA} \). CMS data are also provided for comparison. We can see that the NNLO calculations agree with the experimental data within the experiment error bars.

V. SUMMARY AND CONCLUSIONS

The massive gauge boson production and decaying to a lepton pair provide a clean process to test pQCD working at the LHC energies for both hadronic and nuclear levels. In heavy-ion reactions, since the final state interaction on the gauge boson production could be neglected, the weak vector boson could be a good probe of CNM effects, and the precise comparison between the theory and the experimental data may impose important constraints on the nuclear PDFs.

In this paper we have investigated heavy gauge bosons production in heavy-ion collisions at the LHC at NLO and NNLO with DYNNLO program within the framework of perturbative QCD. To consider the CNM effects, two recently published parametrization sets of nuclear parton distribution, EPS09 and DSSZ have been used in our simulations. We have provided the numerical results for the transverse momentum spectra and rapidity dependence of \( Z^0 \) and \( W^+/W^- \), the nuclear modification factors for \( W \) and \( Z \) particles as well as the charge asymmetry for \( W \) boson productions.

For \( Z \) production it is found that calculations at \( \mathcal{O}(\alpha_s^3) \) can give a satisfactory description of the transverse momentum spectrum of \( Z \) boson in \( p+\text{Pb} \) collisions recently measured by CMS Collaboration. And the theoretical predictions for \( Z \) boson \( p_T \) distribution in \( p+\text{Pb} \) and the yield of \( Z \) boson in \( p+\text{Pb} \) and \( \text{Pb}+\text{Pb} \) as a function of rapidity have been made. Differences between the results with EPS09 and DSSZ could be observed in the transverse momentum dependence and rapidity dependence of \( Z \) productions. It has been shown that the partonic subprocess with at least one initial-state gluon gives dominant contribution to the \( p_T \) distribution of \( Z \) boson, and thus \( Z^0 \) nuclear modification factor \( R(p_T) \) as a function of transverse momentum is an optimal tool to study the alterations of gluon distribution in nuclear. However, the CNM effects on \( Z \) yield as functions of the \( Z \) boson rapidity are dominated by the nuclear modifications on the (valence and sea) quark distributions, therefore \( R(g^2) \) may provide important information on the nuclear modifications of quark distribution functions.

The CNM effects on total \( W = (W^+ + W^-) \) production are similar to those in \( Z^0 \) production. However, for the separate production of \( W^+ \) or \( W^- \), the isospin effect gives the most important contribution to the modification of \( W^+ \) or \( W^- \) yield in both \( p+\text{A} \) collisions at \( \sqrt{s_{NN}} = 5.02 \) TeV and \( \text{Pb}+\text{Pb} \) at \( \sqrt{s_{NN}} = 2.76 \) TeV relative to that in elementary \( p+p \) reactions. We find that the parton distribution asymmetry ratios \( r_{ud}(x) \) and \( r_{\bar{u}\bar{d}}(x) \) for proton could reflect the magnitude of the isospin effect and provide an understanding of the overall trends of \( R_{AA}(p_T^W) \) and \( R_{pA}(p_T^W) \) for \( W \) production. In particular we have calculated the charge asymmetry \( (N_{W^+} - N_{W^-}) / (N_{W^+} + N_{W^-}) \) as a function of the charged lepton pseudorapidity in \( p+\text{Pb} \) and \( \text{Pb}+\text{Pb} \) collisions and compared them with the latest CMS measurement and a good agreement between theory and experiment has been seen. It is interesting to show that at the same colliding energy the charge asymmetry in \( p+\text{Pb} \) collision may approach to that in \( p+p \) collision at forward direction of the charge lepton pseudorapidity, but approach to that in \( \text{Pb}+\text{Pb} \) at backward direction. Theoretical predictions for the charge asymmetry \( (N_{W^+} - N_{W^-}) / (N_{W^+} + N_{W^-}) \) as a function of the transverse momentum in future heavy-ion experiments have been provided and it is shown that the charge asymmetry in \( p+p \), \( p+\text{Pb} \) and \( \text{Pb}+\text{Pb} \) may be more pronounced in large \( p_T^W \) region.

In the current study we have not included the possible effect of parton energy loss in cold nuclear matter on massive gauge boson production, which has been found to be rather small. Moreover, here we focused on \( Z^0 \) and \( W^\pm \) productions in minimum bias (MB) nuclear collisions and have not considered the centrality dependence of gauge boson productions in heavy-ion collisions. We may delegate these discussions to other works in the future.

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Appendix A: The isospin effect

For proton, one has

\[
\begin{align*}
    r_{ud}(x) & = \frac{u(x) - d(x)}{u(x) + d(x)}, \\
    \frac{u(x)}{d(x)} & = \frac{1 + r_{ud}(x)}{1 - r_{ud}(x)} = \frac{2}{1 - r_{ud}(x)} - 1, \\
    \frac{d(x)}{u(x)} & = \frac{1 + r_{ud}(x)}{1 - r_{ud}(x)} = \frac{2}{1 + r_{ud}(x)} - 1. 
\end{align*}
\]

For parton distributions in nucleus, if we only consider the isospin effect and neglect contributions of other CNM effects, then

\[
    u^A(x) \approx \frac{Z}{A} u(x) + \frac{N}{A} d(x),
\]
Furthermore we obtain
\begin{equation}
\frac{u^A(x)}{u^P(x)} \approx \frac{Z}{A} u(x) + \frac{N}{A} d(x),
\end{equation}
\begin{equation}
\frac{d^A(x)}{d^P(x)} \approx \frac{Z}{A} d(x) + \frac{N}{A} u(x),
\end{equation}
and
\begin{equation}
\frac{r_{ud}^{A A}(x)}{r_{ud}(x)} = \frac{u^A(x) - d^A(x)}{u^A(x) + d^A(x)},
\end{equation}
and
\begin{equation}
\frac{1}{2} [r_{ud}^{pp}(x) + r_{ud}^{A A}(x)] \approx \frac{Z}{A} r_{ud}^{pp}(x) \approx r_{ud}^{A A}(x).
\end{equation}
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