Dynamical simulation on production of $W^{\pm}$ and $Z^0$ bosons in p–p, p–Pb (Pb–p), and Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV with PACIAE

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In this paper, production of $Z^0$ and $W^\pm$ vector bosons in p–p, p–Pb (Pb–p), and Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV is dynamically simulated with a parton and hadron cascade model PACIAE. ALICE data of $Z^0$ production is found to be reproduced fairly well. A prediction for $W^\pm$ production is given in the same collision systems and at the same energy. An interesting isospin-effect is observed among those systems. This is the so called isospin effect.

I. INTRODUCTION

$W^\pm$ and $Z^0$ vector bosons are heavy particles with masses of $m_{W^\pm} = 80.39$ GeV/$c^2$ and $m_{Z^0} = 91.19$ GeV/$c^2$. They are mainly produced in the large momentum transferred hard partonic scattering processes at the early stage of the (ultra-)relativistic nuclear-nuclear collisions. Their main production processes are

$$\bar{u}d \to W^+,$$  $$u\pi \to W^-$$

and

$$u\pi \to Z^0,$$  $$d\bar{d} \to Z^0$$

in leading order approximation [2]. Therefore, the different abundance ratios of valence quarks $u$ and $d$ in p–p, p–Pb (Pb–p), and Pb–Pb collisions may result in difference on the ratio of $W^+$ and $W^-$ production yields among those systems. This is the so called isospin effect.

In comparing with the available datasets of $W^+/Z^0$ production at mid-rapidity [12, 13], in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV, respectively. A similar measurement of $W^\pm$ production in Pb–Pb collisions with ALICE is on the way. The $W^\pm$ and $Z^0$ production cross sections are also measured in p–Pb collisions at $\sqrt{s_{NN}} = 5.02$ and/or 8.16 TeV with ALICE and CMS [14, 15]. All those measurements are declared to be well reproduced by the leading-order (LO) and next-to-leading-order (NLO) perturbative Quantum Chromo Dynamics (pQCD) calculations [16, 17] using the CT14 Parton Distribution Function (PDF) set [18] with and without the parameterized nuclear modified PDF (nPDF) like EPPS16 [19]. As the experimental data analysis relies on templates calculated with LO pQCD, comparing experimental data to the LO or NLO pQCD predictions is incoherenceless. The study of $W^+/Z^0$ production in heavy-ion collisions with dynamical simulation may provide more differential understandings into the microscopic transport properties of the partonic system.
II. MODEL

A parton and hadron cascade model PACIAE [20] is employed in this paper to dynamically simulate $Z^0$ production in $p$–$p$ and Pb–Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV. The results are compared with that measured by ALICE [11]. Production of $W^\pm$ is predicted in the $p$–$p$, $p$–Pb (Pb–$p$), and Pb–Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV as well.

The PACIAE model is based on Pythia event generator (version 6.4.28) [21]. For $pp$ collisions, with respect to Pythia, the partonic and hadronic rescatterings are introduced in PACIAE, before string formation and after the hadronization, respectively. The final hadronic states are developed from the initial partonic hard scatterings followed by the parton and hadron rescattering stages. Thus, the PACIAE model provides a multi-stage transport description on the evolution of the collision system.

For heavy-ion collisions, the initial positions of nucleons in the colliding nucleus are described by the Woods-Saxon distribution and the number of participant (spectator) nucleons calculated by the Glauber model [3, 8]. Together with the initial momentum setup of $p_x = p_y = 0$ and $p_z = p_{\text{beam}}$ for each nucleon, a list containing the initial state of all nucleons in a given nucleus–nucleus collisioning system is constructed. A collision happened between two nucleons if their relative transverse distance is less than or equal to the minimum approaching distance: $D \leq \sqrt{\frac{\sigma_{\text{NN}}^{\text{LO}}}}{\pi}$. The collision time is calculated with the assumption of straight-line trajectories. All such nucleon pairs compose a nucleon-nucleon (NN) collision (time) list. A NN collision with least collision time is selected from the list and executed by Pythia (PYEVNW subroutine) with the hadronization temporarily turned-off and the strings as well as diquarks broken-up. The nucleon list and NN collision list are then updated. A new NN collision with least collision time is selected from the updated NN collision list and executed with repeating the aforementioned step until the NN collision list is empty.

With those procedures, the initial partonic state for a nucleus-nucleus collision is constructed. Then it proceeds into a partonic rescattering stage where the LO-pQCD parton-parton cross section [22, 23] is employed. After partonic rescatterings, the string is recovered and then hadronized with the Lund string fragmentation regime resulting in an intermediate hadronic state. Finally, the system proceeds into the hadronic rescattering stage and results in the final hadronic state of the collision system.

The $W^\pm/Z^0$ production yield is very low, e.g., $dN(Z^0)/dy \sim 10^{-9}$ at mid-rapidity in the most 20% central Pb–Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV. In our simulations, the relevant production channels are activated in a user controlled approach by setting $\text{MSEL}=0$ together with the following subprocesses switched on:

- $f_i \rightarrow W^+ + W^-$
- $f_i \gamma_j \rightarrow gW^+ + W^-$
- $f_i W^+ \rightarrow \gamma W^+ + W^-$
- $f_i g \rightarrow f_k W^+ + W^-$
- $f_i j \rightarrow Z^0W^+ + W^-$
- $f_i j \rightarrow W^+ W^-$
for $W^\pm$ production, and

$$f_i \bar{f}_i \rightarrow \gamma^*/Z^0$$
$$f_i \bar{f}_i \rightarrow g(\gamma^*/Z^0)$$
$$f_i \bar{f}_i \rightarrow \gamma(\gamma^*/Z^0)$$
$$f_i g \rightarrow f_i(\gamma^*/Z^0)$$
$$f_i \bar{f}_i \rightarrow (\gamma^*/Z^0)(\gamma^*/Z^0)$$
$$f_i \bar{f}_i \rightarrow Z^0W^+/W^−$$

for $Z^0$ production. In aforementioned equations $f$ refers to fermions (quarks) and its subscript stands for flavor code.

As $W^\pm$ and $Z^0$ bosons are nearly transparency in both the Quark Gluon Matter and Hadron Matter, they are not considered in the partonic rescattering and hardonic rescattering in the PACIAE simulations. Thus the results of $W^\pm$ and $Z^0$ productions from PACIAE simulations are nearly the same as the ones from PYTHIA simulations for p–p collisions.

The Monte Carlo simulation of $W^\pm/Z^0$ production described above is a triggered $W^\pm/Z^0$ production approach (a bias sampling technique). A normalization factor is needed to account for the trigger bias effect (the bias correction). To make a fair comparison to the experimental data, we use the rescaled distribution defined as follows

$$R(X) = X/X_{\text{ref}},$$

where $X$ denotes a given observed distribution, such as the rapidity density $dN/dy/\langle T_{AA} \rangle$. Here $X_{\text{ref}}$ is a chosen reference point in the distribution. The comparison between data and simulations will be presented on the rescaled distribution $R(X)$.

III. RESULTS AND DISCUSSIONS

The comparison of the rescaled $Z^0$ rapidity-differential density $R(dN_{Z^0}/dy/\langle T_{AA} \rangle)$ between PACIAE simulations and the ALICE measurements is shown in the left panel of Fig. [1] for 0–90% centrality class in Pb–Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV. The points on the plot, from the left to right, represent the results in rapidity intervals of $2.5 < y < 3, 2.5 < y < 4$ and $3 < y < 4$. In both data and simulations, the value in $2.5 < y < 4$ is chosen as the reference point. In this figure, the black full circles are the ALICE measurements \[1\], the red open triangles are PACIAE results with free proton PDF, and the green open squares are PACIAE results with EPS09 nPDF \[2\]. This panel shows that the ALICE measurements \[1\] are well reproduced by PACIAE dynamical simulations within uncertainties.

The right panel of Fig. [1] shows the centrality dependent of rescaled $R(dN_{Z^0}/dy/\langle T_{AA} \rangle)$ in the Pb–Pb collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV. The red open triangles are...
1.5 2 2.5 3
|y_{lab}|

0.6
0.8
1
1.2
1.4

R(dN/dy/ \langle T_{AA} \rangle)_{\text{minimum bias } p+Pb}

3.6 4 4.4 4.8
|y_{lab}|

0.4
0.8
1.2
1.6

R(dN/dy/ \langle T_{AA} \rangle)_{\text{minimum bias } Pb+p}

FIG. 3: The rescaled $\mu$ rapidity density ($dN/dy/ \langle T_{AA} \rangle$) as a function of $|y_{lab}|$, for $\mu^+$ and $\mu^-$ decayed from $W^+$ and $W^-$, in minimum bias $p$–Pb (left panel) and Pb–p (right panel) collisions at $\sqrt{s_{NN}} = 5.02$ TeV respectively.

PACIAE results with free proton PDF, and the green open squares are those with EPS09nPDF, while the ALICE data are indicated by the black full circles. Again, the ALICE data are well reproduced within error bars.

Similar model calculations for $\mu^\pm$ production in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV are shown in Fig. 2. In this figure and in following studies for Pb–Pb collisions, the calculations are made in event centralities $0$–$5\%$, $0$–$10\%$, $0$–$20\%$, $0$–$40\%$, and $0$–$90\%$ within the corresponding impact parameter intervals of $[0, 3.5]$, $[0, 4.94]$, $[0, 6.98]$, $[0, 9.88]$ and $[0, 14.96]$ fm to match the event geometries shown in ALICE data [5]. The $\langle N_{\text{part}} \rangle$ from optical Glauber calculations are, correspondingly, 378.6, 348.3, 298.1, 219.9 and 111.7.

This figure shows the centrality dependent $N/\langle T_{AA} \rangle$ (left panel), the corresponding $dN/dy/ \langle T_{AA} \rangle$ (in $2.4 < y < 4$, middle panel) and the rescaled distribution of $R(dN/dy/ \langle T_{AA} \rangle)$ (in $2.4 < y < 4$, right panel) obtained from PACIAE simulations with nPDF for $W^\pm$ decay $\mu^\pm$ in Pb–Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. The trends of the distributions shown in the left and middle panels are similar to what are shown in Fig. 13 in [12]. However the $\mu^\pm$ is obtained in the full $p_T$ phase space in PACIAE simulations while ATLAS measures that in $p_T > 25$ GeV/c, where the event reliability is very low.

Meanwhile, we present the model calculation for the rescaled distributions, which is defined in eq. (2), for $\mu^\pm$ from $W^\pm$ decays in $p$–Pb and Pb–p collisions at $\sqrt{s_{NN}} = 5.02$ TeV in Fig. 3. The results are presented in rapidity intervals of $[2.03$, $2.53]$, $[2.53$, $3.03]$, and $[3.03, 3.53]$. 

FIG. 4: The $\mu$ charge asymmetry in minimum bias $p$–$p$, $p$–$n$, $n$–$p$, and $n$–$n$ collisions at center of energy equal to 5.02 TeV is given in left panel with blue open squares, from left to right respectively. The black full circles in this panel are the same as blue ones but for minimum bias $p$–$p$, $p$–$Pb$, $Pb$–$p$ and $Pb$–$Pb$ collisions at $\sqrt{s_{NN}}=5.02$ TeV, respectively. Middle panel is the $\mu$ differential charge asymmetry in minimum bias $p$–Pb (black full circles) and Pb–p (blue open squares) collisions at $\sqrt{s_{NN}}=5.02$ TeV. The $\mu$ charge asymmetry as a function of $\langle N_{\text{part}} \rangle$ in Pb–Pb collisions at $\sqrt{s_{NN}}=5.02$ TeV is given in right panel.
in p–Pb collisions, and of [2.96, 3.46], [3.46, 3.96], and [3.96, 4.46] in Pb–p collisions. A rapidity shift Δy = 0.465 has been used to account for the asymmetric beam energy configurations. In these figures, different rapidity dependence for μ⁺ and μ⁻ are observed between the proton-going and Pb-going directions.

The asymmetry between W⁺ and W⁻ production yields, stemming from the isospin effect, can be studied with the asymmetry of their decay products μ⁺ and μ⁻ as follows

\[ A_\mu = \frac{Y_{\mu^-} - Y_{\mu^+}}{Y_{\mu^-} + Y_{\mu^+}} \]  \(\text{(3)}\)

The μ± charge asymmetries in minimum bias pp, pn, np, and nn collisions at \(\sqrt{s} = 5.02\) TeV are presented in the left panel of Fig. 4 as the blue open squares. The black full circles are the results form minimum bias p–Pb, Pb–p, and Pb–Pb collisions at \(\sqrt{s_{NN}} = 5.02\) TeV. In the middle panel of Fig. 4, we present the differential charge asymmetry as a function of \(y_{lab}\) of μ± in minimum bias p–Pb (black full circles) and Pb–p (blue open squares) collisions at \(\sqrt{s_{NN}} = 5.02\) TeV. The rapidity intervals presented here are the same as that in Fig. 3. The right panel of Fig. 4 shows the μ± asymmetry varying with \(\langle N_{\text{part}}\rangle\) in Pb–Pb collisions at \(\sqrt{s_{NN}} = 5.02\) TeV.

The hierarchy of the charge asymmetry observed in pp, pn, np and nn collisions shown in Fig. 4 can be understood by the variation of relative abundance of the valence u and d quarks in those colliding hadron objects. The similar trend observed with nuclear collision beams thus arises due to the increasing neutron abundance from pp to Pb–Pb collisions. The Pb-beam is more neutron-like than the proton-beam. Therefore, the sign flipping of \(A_\mu\) from p–Pb to Pb–p collisions shown in the middle panel of Fig. 4 is a natural outcome of the different valence kinematic dominance between proton-side and Pb-side detector acceptance regions.

The PACIAE simulations on rapidity distributions of μ⁺ (left panel) and μ⁻ (right panel) in the minimum bias p–Pb and Pb–p collisions at \(\sqrt{s_{NN}} = 5.02\) TeV are given in Fig. 5. The relations of \(y_{lab} = y_{cma} - 0.465\) and \(y_{lab} = y_{cma} + 0.465\) are used in p–Pb and Pb–p collisions, respectively.

Figure. 6 shows the PACIAE (with EPS09 nPDF) simulations on rapidity distributions of μ⁺ (left panel) and μ⁻ (right panel) for 0–10% (black full circles) and 0–90% (red open squares) in Pb–Pb collisions at \(\sqrt{s_{NN}} = 5.02\) TeV. The results are compared with that in pp (blue open circles) collisions at the same energy. It shows that the shape of the y-differential distribution in 0–90% Pb–Pb collisions is more similar to the distribution in pp than to that in the most 10% Pb–Pb. The rapidity plateau of μ⁻ is observed to be wider than μ⁺ in all the collision systems studied.

IV. SUMMARY AND ACKNOWLEDGMENT

The parton and hadron cascade model of PACIAE is employed simulating the dynamical production of W⁺/Z⁰ bosons in pp, p–Pb (Pb–p) and Pb–Pb collisions at \(\sqrt{s_{NN}} = 5.02\) TeV for first time in this paper. The rescaled \(dN/dy/\langle T_{\text{AA}}\rangle\) for Z⁰ bosons measured by ALICE in Pb–Pb collisions at \(\sqrt{s_{NN}} = 5.02\) TeV [1] are fairly reproduced. Simulations on μ± production are given for all collision systems. A sign-change of μ± charge asymmetry are observed in pp, pn, np, and nn collisions and in minimum bias p–Pb, Pb–p and Pb–Pb collisions at \(\sqrt{s_{NN}} = 5.02\) TeV, respectively. These interesting isospin-effect observations are worthwhile to be investigated further. Meanwhile, carrying out studies of W⁺/Z⁰ boson production in dynamical simulations with partonic transport effects may shed a light on the understanding of medium induced higher order effects in the future works.

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FIG. 5: The left and right panels are rapidity distributions of \( \mu^+ \) and \( \mu^- \) decayed from \( W^+ \) and \( W^- \), respectively. They are dynamically simulated in minimum bias p–Pb and Pb–p collisions at \( \sqrt{s_{NN}} = 5.02 \text{ TeV} \) by PACIAE model.

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FIG. 6: The rapidity distribution of $\mu^+$ (left panel) and $\mu^-$ (right panel) decayed from $W^+$ and $W^-$, respectively. They are dynamically simulated in 0–10% and 0–90% central classes Pb–Pb as well as pp collisions at $\sqrt{s_{NN}} = 5.02$ TeV by PACIAE model with EPS09nPDF.

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