

Strangeness production in p Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV in the PACIAE model

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We present a study of the single- and multistrange particle productions in p Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV using the PACIAE 4.0 model. The effects of color reconnection (CR), rope hadronization (RH), as well as partonic and hadronic rescatterings (PRS and HRS) on their productions are investigated. There are two kinds of CR considered: the multiparton-interactions-based CR (MPI-CR) and the quantum-chromodynamics-based CR (QCD-CR). The four mechanisms studied have little effect on kaon production. The QCD-CR scheme incorporating the junction topology gives an enhanced baryon production, but it is still not enough to describe the data of integrated yields of strange baryons. The combination of QCD-CR and the RH scheme together with flavor ropes (FR) and string shoving (SS) provides a good description for the data of strange baryon production. For the heavier Ξ and Ω baryons, an improved QCD-CR+FR scheme with stronger tension is required, whereas the QCD-CR+FR+SS scheme adequately describes Λ production. PRS has a weak effect, but HRS exerts a promoting effect on the production of multistrange baryons (Ξ and Ω).

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I. INTRODUCTION

The novel state of quark-gluon plasma (QGP, composed of quarks and gluons) was originally conjectured as a transient state of strongly interacting matter that existed just microseconds after the big bang [1]. In experiments at the BNL Relativistic Heavy Ion Collider (RHIC) and the CERN Large Hadron Collider (LHC), the QGP-related information is only hidden in the final hadronic state (FHS). Several observables are considered as evidence of QGP formation, including the mass hierarchy of the elliptic flow (v_2) at low transverse momentum (p_T) [2,3], the energy loss (jet quenching) [4], the polarization effect of Λ hyperons [5], the strangeness enhancement [6,7], etc. When QGP is formed, the chemically equilibrated system generates copious strange quark pairs through thermal gluon fusion processes, enhancing the

formation of multistrange hadrons especially [6,7]. Therefore, the strangeness enhancement, particularly that of multistrange baryons, is widely considered as a distinctive signature of QGP formation [8–10].

Proton-proton (pp) and proton-nucleus (pA) collisions serve as baselines for investigating QGP formation in heavy-ion collisions at energies available at RHIC and LHC. They are supported by ALICE observations of a significant enhancement in the strange hadron to pion yield ratio for high-multiplicity pp and pA collisions at LHC energies [11–14], which is similar to those observed in Pb-Pb [9,15,16] collisions at the same energies.

The universal characteristics of the strangeness-to-pion ratio as a function of multiplicity are interpreted through various models. The THERMUS model explains the reduced strange hadron yields in pp collisions via the canonical strangeness conservation [17]. The DIPSY model [18] employs Mueller's dipole formulation to describe strangeness production in a QCD-inspired approach, and accurately reproduces the yields of single-strange hadrons (K_s^0 and Λ). However, it systematically underestimates the multistrange baryons (Ξ and Ω). The model attributes the enhanced strangeness production to color ropes, which arise from interacting gluonic strings and increases the effective string tension [19,20]. The EPOS model [21] incorporates QGP formation in pp collisions through a core-corona treatment of particle interactions. The strangeness enhancement in heavy-ion collisions is interpreted within two complementary frameworks.

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The McGill group [22–25] attributes the effect to strong, long-lived color fields that fragment through baryon-junction loops and transient field fluctuations, explaining the high- p_T baryon/meson anomaly from RHIC to LHC. The Santiago [26] and St. Petersburg [27] teams instead emphasize string fusion: overlapping color strings form higher-tension “ropes” whose decay preferentially produces s -quark pairs, linking the local string density to the observed centrality-dependent rise of strange hadrons. In the Monte Carlo event generator PACIAE 2.0 [28], the mechanisms of single-string dynamics and multiple-string interactions, have successfully described the strange enhancement in pp [29] and Pb-Pb collisions [30]. Although current models successfully describe several aspects of the data, the underlying physics driving strangeness enhancement is not yet fully understood. This highlights the need for additional developments to obtain a complete microscopic description of strangeness production in small collision systems (pp and pA) and to evaluate its possible role in heavy-ion collisions.

Recently, a combined mechanism of the color reconnection (CR) [31] and rope hadronization (RH) [18,32] was used to explore the strangeness enhancement in pp collisions at $\sqrt{s_{NN}} = 13$ TeV [33]. This approach offers a novel perspective for understanding the microscopic dynamics of high-multiplicity pp collision events observed at the LHC within the string fragmentation framework. The enhancement of strangeness was also studied in pp collisions using nonperturbative mechanisms of RH, including string shoving (SS) and flavor ropes (FR) [34,35]. In the present study, we incorporate these aforementioned mechanisms into pPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV using the microscopic transport model PACIAE 4.0 [36], and we investigate the production of strange and multistrange hadrons.

The paper is organized as follows. We present the PACIAE 4.0 model setup focusing on its implementation of CR and RH mechanisms, along with the partonic and hadronic rescatterings (PRS and HRS) processes, in Sec. II. The multiplicity dependent $\langle dN/dy \rangle$ and the strange hadron-to-pion ratios are presented in Sec. III. Finally, in Sec. IV, we summarize the important results of the present work.

II. METHODOLOGY

A. PACIAE 4.0 model

PACIAE 4.0 [36] is a new version of the Monte Carlo event generator PACIAE [28,37] for simulating high-energy lepton-lepton, lepton-hadron, lepton-nucleus, hadron-hadron, hadron-nucleus, and nucleus-nucleus collisions. It comprises four distinct stages: (1) initial partonic state, (2) partonic rescatterings, (3) hadronization, and (4) hadronic rescatterings. PACIAE 4.0 is based on PYTHIA 8 [38–41]. The initial partonic state is generated by temporarily deactivating the Lund string fragmentation in PYTHIA. This initial state then undergoes elastic $2 \rightarrow 2$ partonic rescatterings with the leading-order perturbative QCD (LO-pQCD) cross sections [42,43]. Then the Lund string fragmentation regime is executed, converting the colored partons to color-neutral hadrons. Finally, the produced hadrons experience $2 \rightarrow 2$

hadronic rescatterings with experimentally and/or empirically determined cross sections [7,41,44].

B. Mechanisms of CR and RH

In nucleon-nucleon (NN) collisions, the multiparton interactions (MPI) stemming from the composite property of nucleons lead to an increase number of color charges and the number of strings in the system. The string rearrangement (reconnection) minimizing the total string length, which is a phenomenon known as color reconnection (CR) [31]. This mechanism is promising in the explanation of heavy-ion-like phenomena observed in high-multiplicity pp collisions [31,33,45]. In this work, two distinct CR models are implemented to address different aspects of string dynamics in the high-energy collisions. One is the default MPI-based CR (MPI-CR) which reduces the total string length by a complete merge of the partons of separate MPI systems with the merging possibility related to the p_T scale [41]. The other is QCD-based CR (QCD-CR), which determines the possibility of reconnection through the color symmetry principles of QCD [46]. In QCD-CR, a fraction of the string dipoles reconnect in junction configurations, which can enhance baryon production [46].

PACIAE 4.0 provides two hadronization models: The Lund string fragmentation regime and the phenomenological coalescence model. In this work, the former hadronization mechanism is chosen [47]. The rope hadronization (RH) framework [18] represents an advanced extension of the conventional Lund string fragmentation regime. It incorporates two distinct but complementary string interaction mechanisms: The flavor ropes (FR) formation and the string shoving (SS) dynamics. The FR mechanism allows the formation of ropes between overlapping strings in dense environments. The string ropes can be hadronized by larger effective string tension [48], which increases the tunneling probabilities of strange quark-antiquark and diquark-antidiquark pairs, enhancing the production of strange hadrons [18,19]. The SS mechanism [49,50] arises from the repulsive interaction between the chromoelectric fields of overlapping strings in the dense environment of heavy-ion collisions [41]. In the Lund string model, each string has a transverse extent with a Gaussian profile of its electric field. When multiple strings overlap, their fields repel each other, leading to a net “shoving” effect that pushes string pieces apart. This mechanism is particularly significant because it can generate collective-like behavior without requiring the formation of a quark-gluon plasma (QGP).

In proton-nucleus (pA) peripheral collisions, the string density is lower and the geometry is more asymmetric relative to central collisions, leading to stronger initial-state eccentricity. The shoving mechanism is more effective because strings at the edges experience unbalanced repulsive forces, while in central collisions the higher string density and more symmetric geometry result in a more isotropic force distribution, where individual repulsions tend to cancel out. This makes the shoving effect more pronounced in peripheral collisions, which is consistent with the observed centrality dependence of anisotropic flow (v_2) [51]. The same explanation is applicable

TABLE I. Values of various parameters in p Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV for PACIAE 4.0 model simulations.

Parameter	Value
MultipartonInteractions: Kfactor	1.1
MultiPartonInteractions: pT0Ref	1.3
StringPT: sigma	0.2
StringFlav: probQQtoQ	0.07
StringFlav: probStoUD	0.24
StringFlav: probSQtoQQ	0.18

to AA collisions. Therefore the shoving effect is stronger in peripheral AA collisions than in peripheral pA collisions because its string density is higher than that in pA collisions at a given energy. It is shown that SS would occur before FR [52]. Because the SS spatially pushes strings outward, reducing the string overlap, it will diminish the FR effect. The combined FR+SS will provide slightly smaller string tension compared to FR.

C. Model setup

Consistent with the ALICE experiment, the simulations of asymmetric p Pb collisions are performed in the laboratory frame (lab) with a beam energy of 4 TeV for projectile protons and 1.58 TeV per nucleon for target Pb nuclei [13,14,53], resulting in a collision energy of $\sqrt{s_{NN}} = 5.02$ TeV in the NN center-of-mass system (cms). The simulated events are chosen as the nonsingle diffractive (NSD) ones [13,14]. The tuned parameters used in this work are listed in Table I, while the other parameters are set as the default values. The meaning of these parameters is as follows:

- (1) MultipartonInteractions: Kfactor is a multiplicative factor of the parton-parton scattering cross sections in MPI.
- (2) MultiPartonInteractions: pT0Ref is the reference scale of the minimum p_T cutoff related to the regularization of the divergence of the QCD cross section for $p_T \rightarrow 0$.
- (3) StringPT: sigma corresponds to the width in the Gaussian p_x and p_y transverse momentum distributions for primary hadrons in the string fragmentation.
- (4) StringFlav: probQQtoQ is the suppression of diquark-antidiquark pair production compared to the quark-antiquark production in the string fragmentation.
- (5) StringFlav: probStoUD is the suppression of s quark pair production compared to the u or d pair production in the string fragmentation.
- (6) StringFlav: probSQtoQQ is the extra suppression of strange diquark production compared to the normal suppression of strange quark in the string fragmentation.

III. RESULTS AND DISCUSSIONS

In this work, the data analysis of identified hadrons is performed in the center-of-mass system. The rapidity interval

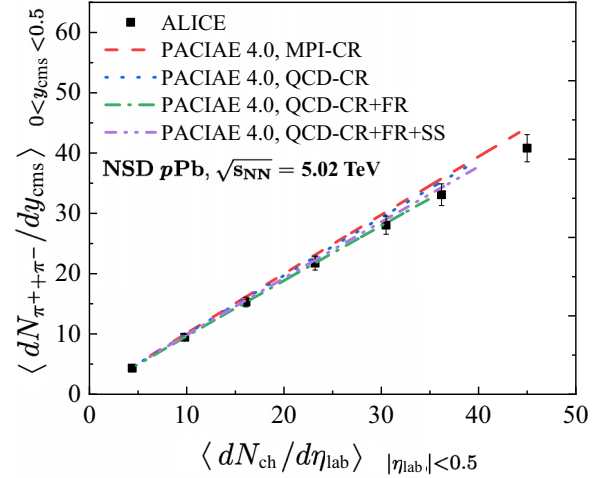


FIG. 1. Multiplicity dependent $\langle dN/dy_{cms} \rangle$ of π , varying with $\langle dN_{ch}/d\eta_{lab} \rangle_{|\eta_{lab}| < 0.5}$ in NSD p Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV. Four different CR and RH schemes are shown: MPI-CR, red dashed line; QCD-CR, blue dotted line; QCD-CR+FR, green dash-dotted line; QCD-CR+FR+SS, purple dash-dot-dotted line. The experimental data are taken from Ref. [13].

for π , K , Λ is $0 < y_{cms} < 0.5$ [13], while that of Ξ and Ω is $-0.5 < y_{cms} < 0$ [14]. With the tuned parameters, the multiplicity dependence of π yields versus the mean multiplicity densities of charged particles ($\langle dN_{ch}/d\eta \rangle$) within $|\eta_{lab}| < 0.5$ is presented in Fig. 1. The results of π from PACIAE 4.0 with four schemes of MPI-CR, QCD-CR, QCD-CR+FR, and QCD-CR+FR+SS are shown as the red dashed, blue dotted, green dash-dotted, and purple dash-dot-dotted lines, respectively. The ALICE data are shown by black squares with error bars [13]. The π yields from all four scenarios show reasonable agreement with experimental data, as expected. It demonstrates that the set parameters are rational.

We then analyze the dependence of K , Λ , Ξ , and Ω yields on the mean multiplicity densities of charged particles ($\langle dN_{ch}/d\eta \rangle$) within $|\eta_{lab}| < 0.5$ and compare those with the ALICE experimental data. As shown in Fig. 2(a), for the $\langle dN/dy \rangle$ distribution of kaons, the four mechanisms give rather similar results. For the strange baryons, we see from Figs. 2(b) to 2(d) that the MPI-CR scheme systematically underestimates particle production. The QCD-CR scheme enables baryon production through the junction structure formation, where three color flux tubes recombine, leading to enhanced baryon production. However, the results show that the QCD-CR scheme still underestimates the yield of strange baryons. The RH mechanism, when coupled with the QCD-CR, enhances the string tension, consequently increasing strange baryon production yields across all multiplicity classes. The combined QCD-CR+FR+SS scheme can provide slightly smaller string tension compared to the QCD-CR+FR scheme. More specifically, the experimental data of the Λ baryon can be reproduced by QCD-CR+FR+SS mechanisms, whereas the simulated results for Ξ and Ω are insufficient to match the experimental data. Therefore, it is necessary to use scheme QCD-CR+FR to adequately

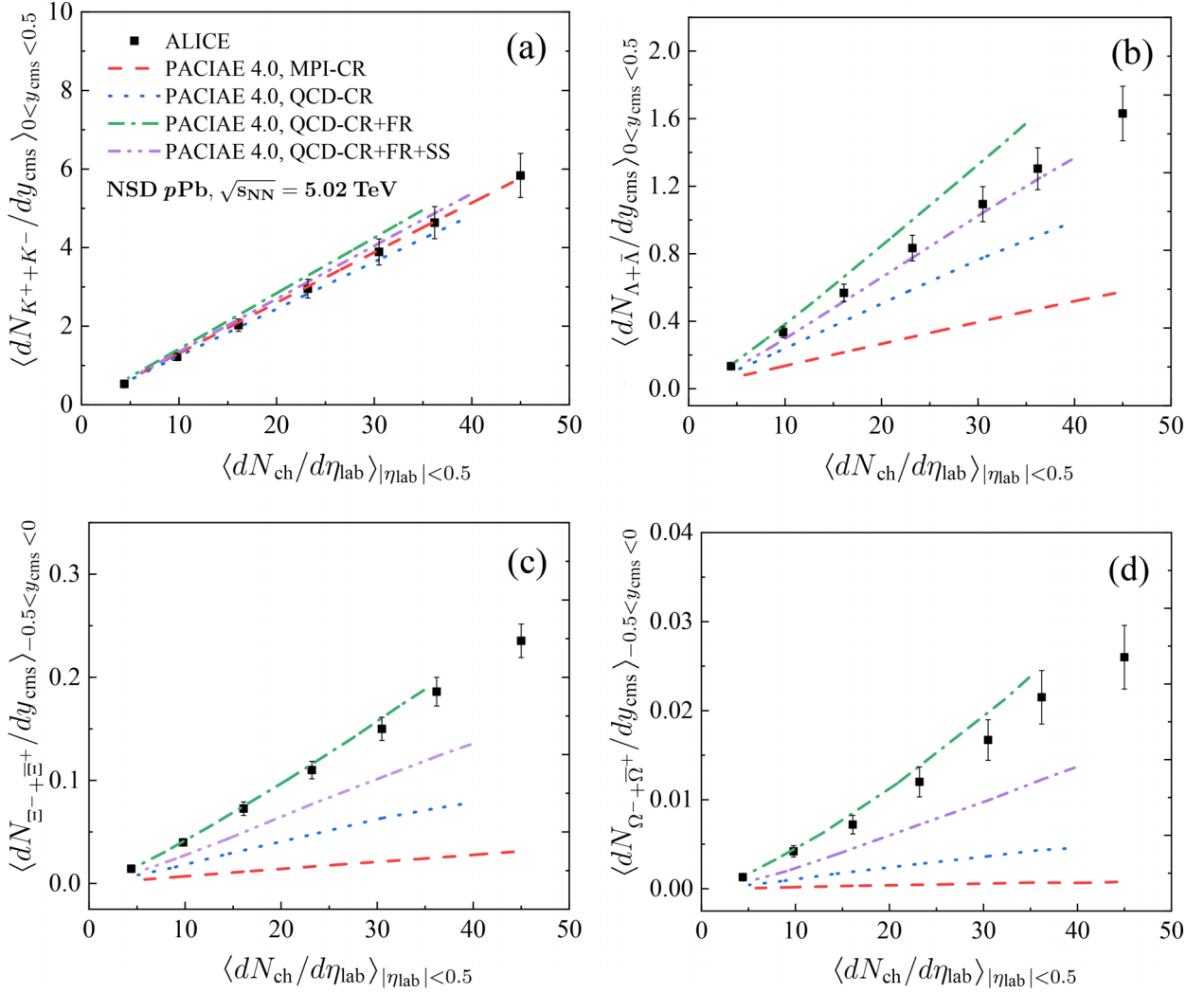


FIG. 2. Multiplicity dependent $\langle dN/dy_{\text{cms}} \rangle$ of K (a), Λ (b), Ξ (c), and Ω (d), varying with the $\langle dN_{\text{ch}}/d\eta_{\text{lab}} \rangle|_{|\eta_{\text{lab}}|<0.5}$ in NSD $p\text{Pb}$ collisions at $\sqrt{s_{\text{NN}}} = 5.02$ TeV. Four different CR and RH schemes are shown: MPI-CR, red dashed line; QCD-CR, blue dotted line; QCD-CR+FR, green dash-dotted line; QCD-CR+FR+SS, purple dash-dot-dotted line. The experimental data are taken from Refs. [13,14].

describe the experimental values. This indicates that heavier strange baryons require a stronger string tension for their production.

To investigate the strangeness enhancement observed by ALICE in $p\text{Pb}$ systems, we estimate the yield ratios of strange hadrons (K , Λ , Ξ , and Ω) to charged π . In Fig. 3, these ratios are plotted as a function of $\langle dN_{\text{ch}}/d\eta_{\text{lab}} \rangle|_{|\eta_{\text{lab}}|<0.5}$ with different simulation schemes and compared to the ALICE data [13,14]. It shows that the MPI-CR scheme and QCD-CR scheme systematically underestimate the ALICE data, except K/π . This is because both the MPI-CR scheme and QCD-CR scheme are not expected to generate sufficient baryons. The results of the QCD-CR+FR scheme overestimate the ALICE ratios for K/π and Λ/π . The data of these two strange particles show that the QCD-CR+FR+SS scheme gives a relatively better description. The ALICE data of multistrange baryons (Ξ and Ω) can be well described by the QCD-CR+FR scheme simulations. As the number of strange quarks increases (from

Λ to Ω), the simulated results show that a higher string tension is required.

We also study the effects of partonic and hadronic rescatterings (PRS and HRS), as in Ref. [54], on the strange hadron-to-pion ratios in PACIAE 4.0 with the QCD-CR+FR scheme. There are four combinations with and/or without both PRS and HRS. For clarity, we show only the results without both PRS and HRS and with PRS and HRS, respectively, in Fig. 4. We found that the baryon-to-pion ratios of Ξ and Ω from simulations with PRS and HRS are systematically higher than those without PRS and HRS, in contrast to the K/π and Λ/π ratios. It is mainly attributed to HRS, because PRS in this work is limited to elastic processes that do not significantly affect the flavor content of the final partonic state. In HRS, there exist inelastic processes involving strange hadrons [28,36,37], e.g., $\pi\Lambda \rightleftharpoons K\Xi$, $K\bar{\Lambda} \rightleftharpoons \pi\bar{\Xi}$, etc. At the same time, the direct production of single-strange hadrons K and Λ from hadronization is greater than that of multistrange

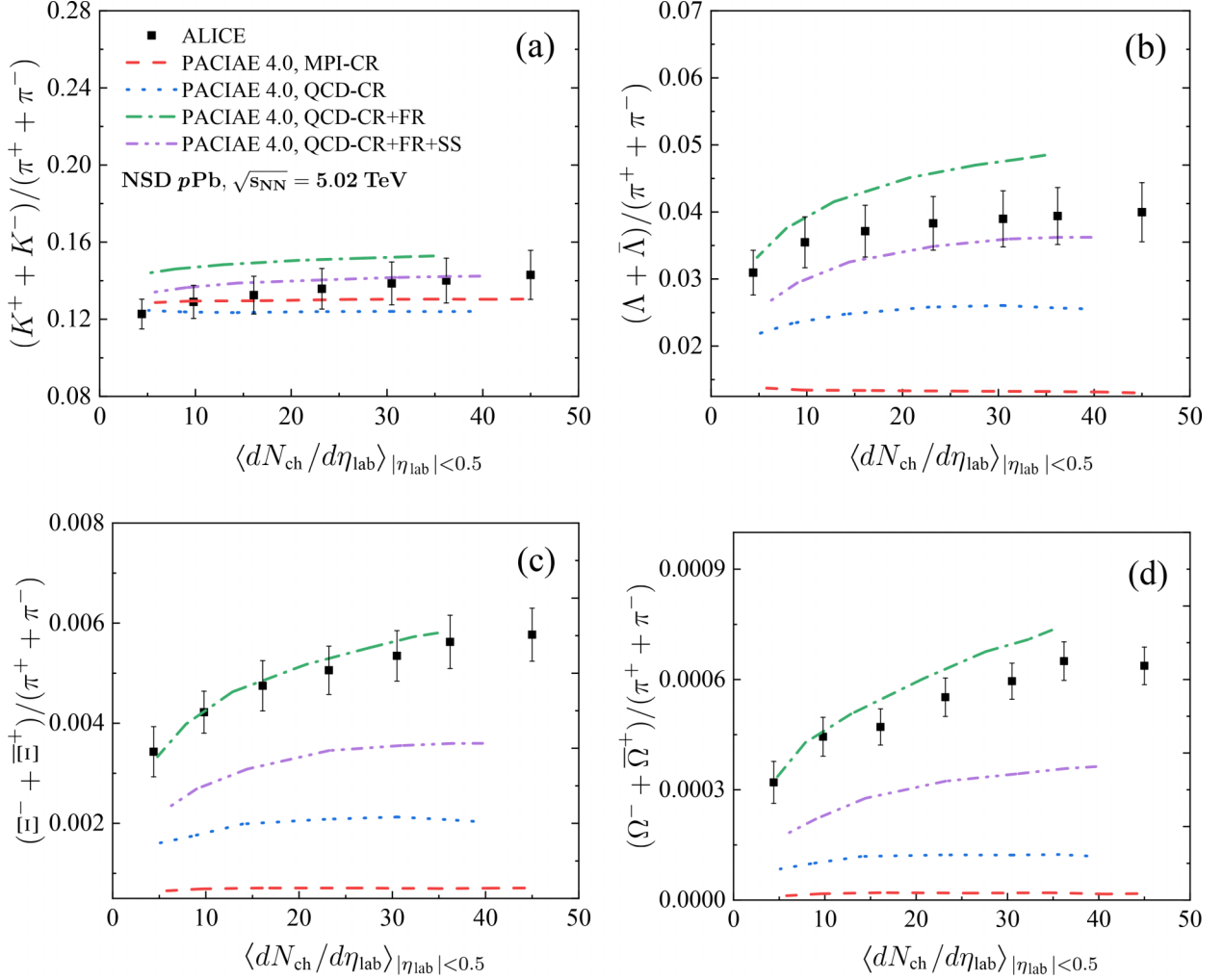


FIG. 3. The ratio of yields of strange hadrons [K (a), Λ (b), Ξ (c), and Ω (d)] to pions as a function of $\langle dN_{ch}/d\eta_{lab} \rangle_{|\eta_{lab}| < 0.5}$ in NSD p Pb collisions at $\sqrt{s_{NN}} = 5.02$ TeV using the PACIAE 4.0 model. Four different CR and RH schemes are shown: MPI-CR, red dashed line; QCD-CR, blue dotted line; QCD-CR+FR, green dash-dotted line; QCD-CR+FR+SS, purple dash-dot-dotted line. The experimental data are taken from Refs. [13,14].

baryons Ξ and Ω . Part of K and Λ could be converted to Ξ and Ω through the HRS.

IV. CONCLUSIONS

In this work, we employ the PACIAE 4.0 model with different selected physical mechanisms to investigate the multiplicity dependence of the strange hadrons $\langle dN/dy \rangle$ as well as the ratios of strange hadrons to charged pions, and compare them with the corresponding ALICE data. For the multiplicity-dependent $\langle dN/dy \rangle$ of kaons, four mechanisms give rather similar results. MPI-CR mechanism underestimates the yields of strange baryons (Λ , Ξ , and Ω). The QCD-CR scheme incorporating the junction topology gives an enhanced baryon production, but it is still not enough to describe the integrated yields of strange baryons. Furthermore, we found the combination of QCD-CR and the rope hadronization (RH) regime including flavor ropes (FR) and string shoving (SS) provides a good description of the production of strange baryons. The QCD-CR+FR+SS

scheme gives a good description of Λ , while for the heavier baryons (Ξ and Ω) it is necessary to incorporate a stronger tension QCD-CR+FR scheme for their production. The results of the ratios of strange baryons to pions also confirm the same conclusion as those for the yields. We also investigated the role of partonic and hadronic rescatterings. The results indicate that the effects of the PRS on the production of multistrange baryons can be neglected. However, the HRS exerts a promoting effect on the production of multistrange baryons (Ξ and Ω) due to the inelastic processes involved.

Our results demonstrate that the color-reconnection, rope hadronization, and two rescattering processes implemented in the PACIAE 4.0 model successfully reproduce the characteristic enhancement of strange particle production. These implementations provide novel approaches to investigate the phenomena of strangeness enhancement in the pA small collision system and fresh insights into its underlying mechanisms. The similar study is worth extending to the Pb-Pb collisions at LHC energies in the future.

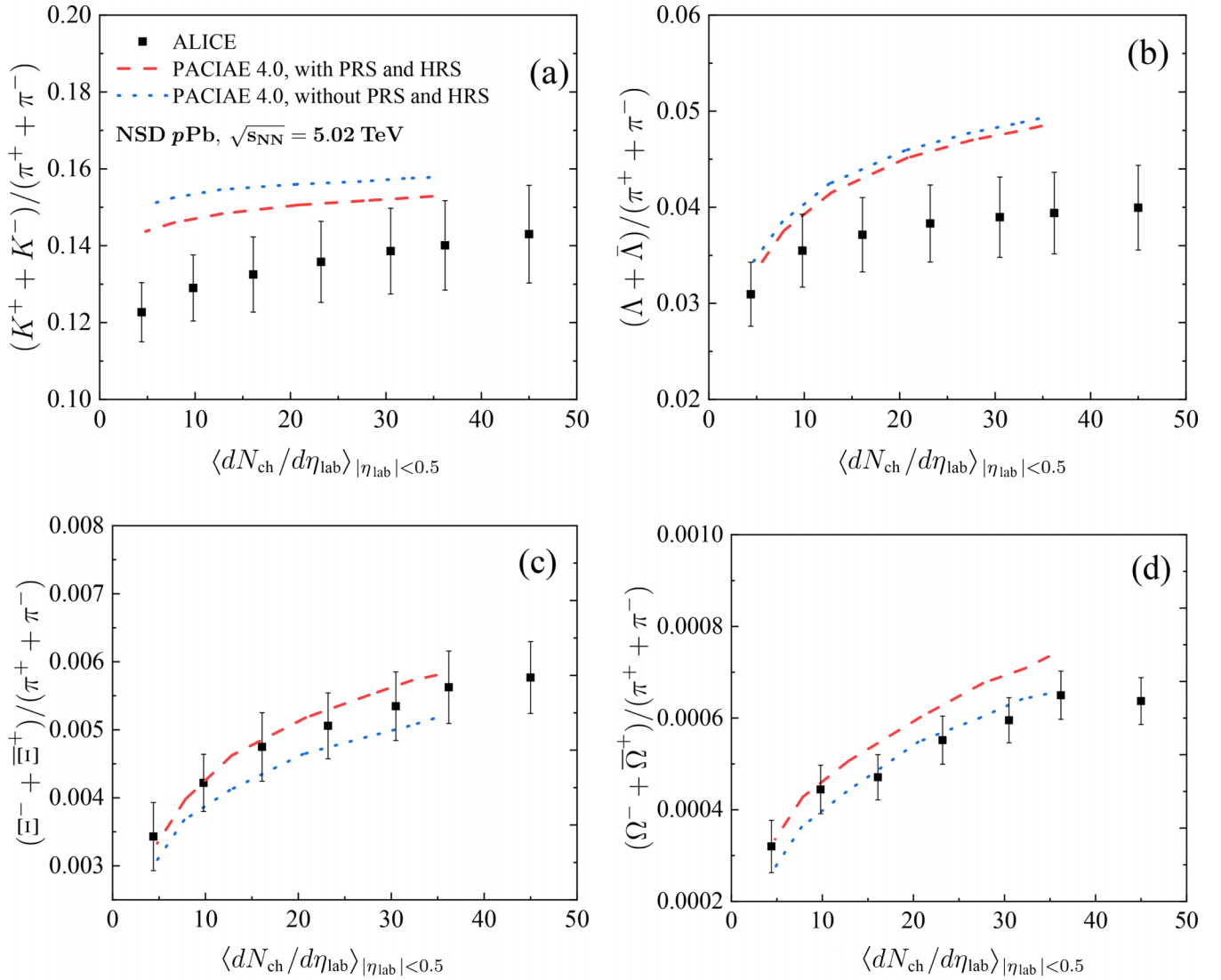


FIG. 4. The ratio of yields of strange hadrons [K (a), Λ (b), Ξ (c), and Ω (d)] to pions as a function of $\langle dN_{ch}/d\eta_{lab} \rangle_{|\eta_{lab}| < 0.5}$ in NSD $p\text{Pb}$ collisions at $\sqrt{s_{NN}} = 5.02$ TeV using PACIAE 4.0 with (red dashed line) and without (blue dotted line) both PRS and HRS processes. The QCD-CR+FR scheme is chosen. The experimental data are taken from Refs. [13,14].

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DATA AVAILABILITY

The data that support the findings of this article are not publicly available. The data are available from the authors upon reasonable request.

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