Effects of inelastic (re)scattering processes $s\bar{s}\rightarrow gg$ and $gg\rightarrow s\bar{s}$ on strange hadron production in pp collisions at RHIC and LHC energies*

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Abstract: The rapidity densities at mid-rapidity and the transverse momentum distributions for strange hadrons produced in pp collisions are analyzed using the modified PACIAE model by considering the effect of inelastic (re)scattering processes $s\bar{s}\rightarrow gg$ and $gg\rightarrow s\bar{s}$ in parton (re)scattering. The calculated results of the transverse momentum spectra of the strangeness fitting with data measured by STAR and ALICE Collaborations can be improved, especially at large transverse momentum levels. This demonstrates that the effect of inelastic (re)scattering processes of $s\bar{s}\rightarrow gg$ and $gg\rightarrow s\bar{s}$ is not negligible at RHIC and LHC energy levels.

Key words: strange particle, rapidity distribution, transverse momentum distribution, PACIAE model, inelastic (re)scattering process

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1 Introduction

PACIAE [1] is a parton and hadron cascade model for high energy hadron-hadron (hh) collisions at the hadronic level, which was originally based on the PYTHIA [2] model. In the PYTHIA model, a pp collision is decomposed into parton-parton collisions. The hard parton-parton interaction is described by the lowest-leading-order perturbative QCD (LO-pQCD). The soft parton-parton collision, the non-perturbative phenomenon, is considered empirically. The initial- and final-state QCD radiations, as well as the multiparton interactions, are considered. Therefore, the consequence of a pp collision is a parton multijet configuration composed of quarks (anti-quarks), di-quarks (anti-diquarks), and gluons, along with a few hadronic remnants. After that, the string construction and fragmentation (hadronization) are performed. And the hadronic final state for a pp collision is obtained eventually.

In Ref. [3], the modified PACIAE model was utilized to systematically investigate strange particle production in pp collisions at the energies available at the RHIC and LHC. We demonstrated [3] that the effect of the reduction mechanism of strange quark suppression and the parton and hadron rescatterings added in the PACIAE model are both important. Unfortunately, some problems, such as the transverse momentum spectra of ϕ meson and the heavy strange baryons (Λ and $\Xi^-+\bar{\Xi}^+$) at $\sqrt{s}$=0.9 TeV, did not fit well with the modified PACIAE model. For these species, the p_T spectra were found to be slightly harder (i.e. overestimated) than the data of ALICE Collaboration measured in the $p_T>1$ GeV/c region.

In this paper, we study the rapidity densities at mid-rapidity and the transverse momentum distributions of strange hadrons produced in pp collisions systematically using the modified PACIAE model by considering the effect of inelastic (re)scattering processes $s\bar{s}\rightarrow gg$ and $gg\rightarrow s\bar{s}$ in parton (re)scattering. It

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is found that the results are improved by considering the effect of the inelastic (re)scattering processes of $s\bar{s}\to gg$ and $gg\to s\bar{s}$.

This article is organized as follows. In Sec. 2, we briefly review the PACIAE model [1], and inelastic (re)scattering processes $gg\to s\bar{s}$ and $s\bar{s}\to gg$ in parton rescattering, as well as the reduction mechanism of strangeness quark suppression [4]. In Sec. 3, we use the modified PACIAE model and the effect of inelastic (re)scattering processes to reanalyze systematically the strangeness production in pp collisions at RHIC and LHC energies [5, 6]. Sec. 4 gives a summary and conclusion.

2 The strangeness production and the new modified PACIAE models

The research of strange hadron production always plays a special role in investigations of quark-gluon plasma (QGP) matter. Originally, this was motivated by the initial proposal that the strangeness enhancement in relativistic nucleus-nucleus collisions, relative to pp collisions, might provide a signature of QGP formation [7]. This opinion is based on the principle that the threshold for strange quark production in QGP is much smaller than that in hadronic matter. Although strangeness enhancement has been confirmed experimentally [8, 9], many new unexpected experimental findings and the development of theory [10] have altered the viewpoint on strangeness as an observable. Strange particles have also been instrumental in the exploration of new phenomena [11] that have appeared in heavy ion physics.

Following Large Hadron Collider (LHC) experiments, ALICE have recently reported on strange hadron production at $\sqrt{s}=0.9$ TeV [6]. These results open a new energy regime in which the properties of QCD matter (QGM) are studied. Strange hadron production is an important ingredient in understanding the nature of the strong force.

As a strange quark is heavier than up and down quarks, the yield of strange hadrons is generally suppressed compared with hadrons containing only up and/or down quarks. In the LUND string fragmentation scheme [12], the strange quark suppression factor (the parameter parj(2) in PYTHIA or λ denoted later), i.e., the suppression of strange quark pair production, relative to up (down) quark pair production, was assumed to be a constant. However, later experiments [13] have presented that this suppression factor is enhanced with increasing reaction energy. In Refs. [3, 4], the reduction mechanism of strange quark suppression was introduced in the LUCIAE model and the PACIAE model, respectively. By using this mechanism, they successfully described the strangeness enhancement in pp, p+A, and A+A collisions at SPS energies [4, 14], and in pp at STAR energy ($\sqrt{s}=200$ GeV) as well as ALICE energy ($\sqrt{s}=0.9$ TeV) [3]. LUCIAE is a hadron cascade model based on FRITIOF [15] with the firecracker model and hadronic rescattering added [16].

For the pp collision, the PACIAE model is different from the PYTHIA model in the addition of the parton initiation, parton rescattering before hadronization, and hadron rescattering after hadronization. Thus, the PACIAE model consists of the parton initiation, parton evolution (rescattering), hadronization, and four stages of hadron evolution (rescattering).

To create the parton initiation for a pp collision, the string fragmentation which occurs in the PYTHIA model is switched off temporarily in the PACIAE model. The di-quarks (anti-diquarks) are split randomly into quarks (antiquarks). Then the partonic initial state is obtained in the PACIAE model, instead of the hadronic final state in the PYTHIA model. This is just QGM formed in the parton initiation stage of a pp collision.

In the parton evolution stage, the rescattering among partons in QGM is only considered to be 2→2 LO-pQCD parton-parton (re)scattering [17]. Generally, one takes only elastic parton-parton interactions into account. However, the inelastic processes, $q\bar{q}\to gg$ and $gg\to q\bar{q}$, were involved already but their cross sections were set to zero. If one wishes to include the inelastic processes in the calculation, one has to let this become active (i.e., their cross sections obtained by means of LO-pQCD). The nine parton-parton interaction processes are included in the PACIAE model as follows

$$q_iq_j \to q_iq_j, \quad (1)$$
$$q_iq_i \to q_iq_i, \quad (2)$$
$$q_i\bar{q}_j \to q_i\bar{q}_j, \quad (3)$$
$$q_i\bar{q}_i \to q_j\bar{q}_j, \quad (4)$$
$$q_i\bar{q}_i \to q_i\bar{q}_i, \quad (5)$$
$$q_i\bar{q}_i \to gg, \quad (6)$$
$$gg \to q_i\bar{q}_i, \quad (7)$$
$$q_ig \to q_ig, \quad (8)$$
$$gg \to gg. \quad (9)$$

Where $q_{i(j)}$ ($\bar{q}_{i(j)}$) corresponds to quarks, and g corresponds to gluons. The sub-processes of (4), (6), and (7) are inelastic (re)scattering processes, and sub-processes of (6) and (7) are considered in this article, and are otherwise elastic. The sub-process of (4) is always negligible. The parton-parton differential cross section is calculated by means of LO-pQCD. The total cross section is obtained by integrating this differential cross section properly. With the differential and total cross sections, the parton rescattering is simulated by the Monte Carlo method until partonic freeze-out.

In the hadronization stage, the QGM formed after parton rescattering is hadronized by the LUND string fragmentation regime [2, 12] or the Monte Carlo coalescence model proposed in Ref. [1]. The LUND string fragmentation is used in this article.

The hadronic rescattering is simulated with the usual two-body elastic and/or inelastic collisions [16] until hadronic freeze-out. The rescatterings among π, K, p, n, ρ(ω), Δ, Λ, Σ, Ξ, J/ψ, and their antiparticles are considered for the moment.

In the PYTHIA model [2], the q$\bar{\text{q}}$ pair with quark mass m and transverse momentum p_{T} may be the first created quantum mechanically at one point and then it is tunnelled out to the classically allowed region. This tunnelling probability is calculated as:

$$\exp\left(-\frac{\pi m^2}{\kappa}\right)\exp\left(-\frac{\pi p_{\text{T}}^2}{\kappa}\right), \tag{10}$$

where the string tension is assumed to be a constant of $\kappa \approx$1 GeV/fm$\approx$ 0.2 GeV^2 [2, 12]. This probability implies a suppression of strange (heavy) quark production u:d:s:c$\approx$ 1:1:0.3:10^{-11}. Therefore the charm and heavier quarks are not expected to be produced in the soft string fragmentation process and only in the hard process or as a part of the initial- and final-state QCD radiations.

A reduction mechanism of strange quark suppression was introduced in Ref. [4] by assuming that the effective string tension increased with increasing reaction energy, and this mechanism which involves the PACIAE model [1], will be denoted as the modified PACIAE model to distinguish it from the default one. Hence the strange (heavy) quark production increases with increasing reaction energy. It was further assumed in Ref. [4] that the effective string tension variation with reaction energy could be considered as a function of number and hardening of the gluons in a single string as follows:

$$\kappa^{\text{eff}} = \kappa_0(1-\xi)^{-\alpha}, \tag{11}$$

$$\xi = \frac{\ln\left(\frac{k_{\text{Tmax}}^2}{s_0}\right)}{\ln\left(\frac{s}{s_0}\right)+\sum_{j=2}^{n-1}\ln\left(\frac{k_{\text{Tj}}^2}{s_0}\right)}, \tag{12}$$

where κ_0 is the string tension of the pure q$\bar{\text{q}}$ string, assumed to be $\sim$1 GeV/fm. Here it should be mentioned that the above Eq. (12) represents the deviation scale of the multigluon string from the pure string. The gluons in the multigluon string are ordered from 2 to $n-1$ because of the quark and antiquark on the ends of string with index 1 and n, respectively. k_{Tj}^2 (k_{Tmax}) is the transverse momentum of gluon j with $k_{\text{Tj}} > s_0$ (gluon's largest transverse momentum). The parameters α=3.5 GeV and $\sqrt{s_0}$=0.8 GeV are determined by fitting the hh collision data [4].

The strange quark suppression factor λ (i.e., parj(2) in PYTHIA) and the width σ (parj(21) in PYTHIA) of the Gaussian p_x and p_y transverse momentum distributions for primary hadrons in a string with effective string tension κ_1^{eff} are denoted by λ_1 and σ_1, respectively. These two quantities in a string with effective string tension κ_2^{eff}, λ_2 and σ_2, can be obtained by Eq. (10)

$$\lambda_2 = \lambda_1^{\frac{\kappa_1^{\text{eff}}}{\kappa_2^{\text{eff}}}}, \tag{13}$$

$$\sigma_2 = \sigma_1\left(\frac{\kappa_2^{\text{eff}}}{\kappa_1^{\text{eff}}}\right)^{1/2}. \tag{14}$$

In the PYTHIA model there are parameters, parj(1) and parj(3), related to strangeness production, besides parj(2) and parj(21). parj(1) stands for the suppression of diquark-antidiquark pair production compared with the quark-antiquark pair production. parj(3) refers to the extra suppression of strange diquark production compared with the normal suppression of strange quark production. For double strange particle (strange baryon) production, parj(1) and parj(3) have to be considered as well. It is easy to obtain parj(1) and parj(3) from the above equations.

The parameters parj(1), parj(2) and parj(3) can be tuned to reduce the strange quark suppression and parj(21) relates to the change of the width of its p_{T} distribution. Generally, one might first tune the parameters of parj(1), parj(2), parj(3), and parj(21) within the PACIAE model to fit the strange particle production data in a given nuclear collision system at a given energy. Then the resulting parj(1), parj(2), parj(3), parj(21) and effective string tension in the modified PACIAE model can be used to predict the strangeness production in the same reaction system at different energies, even in the different reaction systems.

3 Calculations and results

In this paper, the inelastic (re)scattering processes are included in the parton-parton rescattering stage of the new modified PACIAE model. As we aim to achieve the production of strangeness, the sub-processes of (6) and (7) are specified as follows:

$$s\bar{s}\rightarrow gg, \tag{15}$$

$$gg\rightarrow s\bar{s}, \tag{16}$$

where g stands for gluon, s($\bar{s}$) stands for strange (anti-strange) quark. In this article, the new modified PACIAE model with inelastic (re)scattering processes is used to systematically investigate the strange particle production in pp collisions at the energies available at the BNL RHIC and CERN LHC.

We first set the higher order and non-perturbative correction factor in parton-parton interaction K=3, and globally tuned the parameters parj(1), parj(2), parj(3) in default PACIAE with the effect of inelastic (re)scattering processes to fit the strange particle production data in NSD (non-single-diffractive) pp collisions at $\sqrt{s}$=200 GeV [5]. Strangeness rapidity densities results are shown in Table 1 and the transverse momentum spectra are presented in Fig. 1.

From Fig. 1, one could find that the strangeness results of the new modified PACIAE with the inelastic (re)scattering processes fit well the STAR data. This demonstrates that the effect of inelastic (re)scattering processes in the PACIAE model without the reduction mechanism of the strange quark suppression does not describe the strangeness production obviously.

The fitted parameters parj(1)=0.18, parj(2)=0.4, parj(3)=0.5, K=3 and the calculated κ^{eff}=1.3877 were then used to simulate the strange particle production in INEL (inelastic) pp reactions at $\sqrt{s}$=

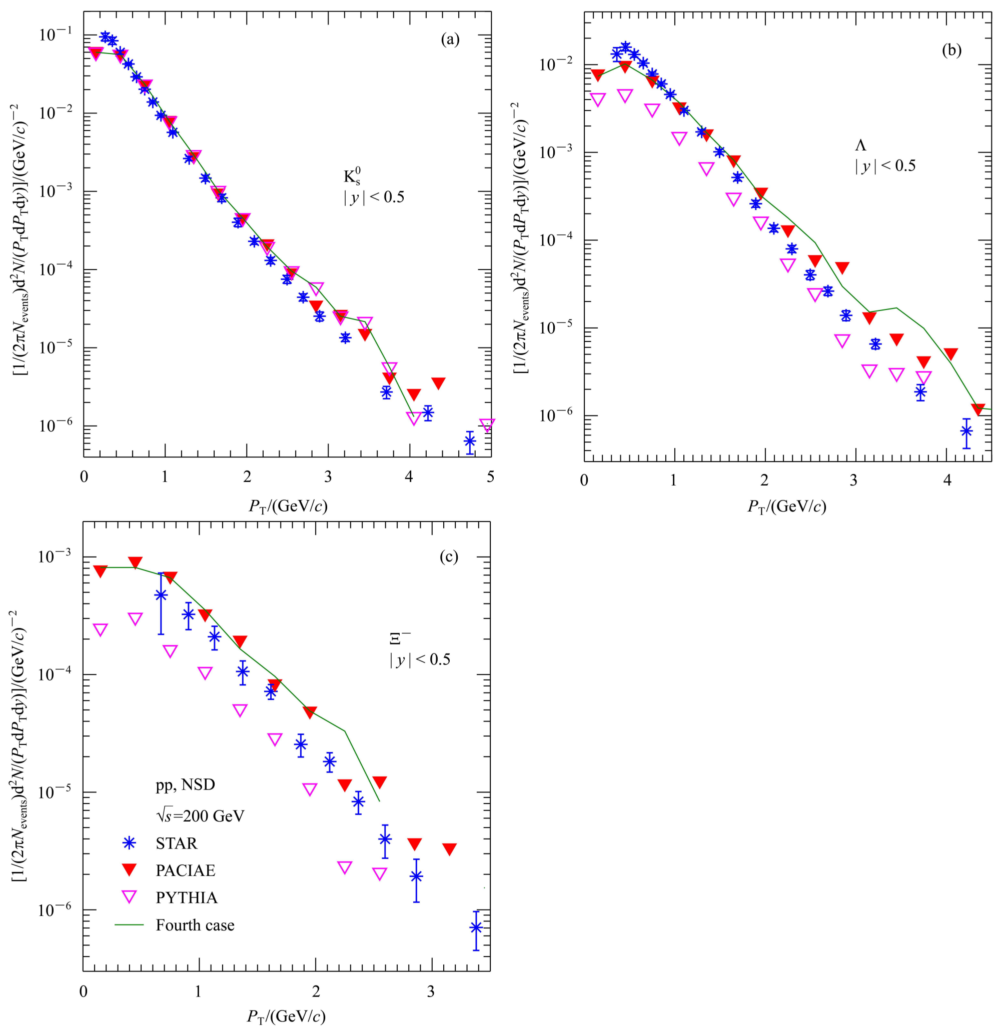

Fig. 1. (color online) The transverse momentum distribution of strange particles in NSD pp collisions at $\sqrt{s}$=200 GeV. Panels (a), (b), and (c) are for K_s^0, Λ, and Ξ^-, respectively. The STAR data are taken from Ref. [5].

900 GeV by using the new modified PACIAE model with the effect of inelastic (re)scattering processes. Strangeness rapidity densities results are shown in Table 2 and the transverse momentum spectra at $\sqrt{s}$=900 GeV are shown in Fig. 2. The corresponding results of the modified PACIAE model with and without [3] inelastic (re)scattering processes are also shown in Fig. 2, respectively.

From Fig. 2 and Table 2, one can find that the ALICE data are well reproduced by the new modified PACIAE with the inelastic (re)scattering processes. This demonstrates that the effect of inelastic (re)scattering processes in the new modified PACIAE model is important to describe the strangeness rapidity densities, especially at large transverse momentum regions. From the study, one finds that in order to fit the high $p_{\rm T}$ part of the strangeness spectrum, one should take the inelastic (re)scattering processes in parton-parton (re)scattering into account. Combining with Ref. [3], we can conclude that the effect of inelastic (re)scattering processes and the reduction mechanism of the strange quark suppression in the PACIAE model are not negligible at RHIC and LHC energies.

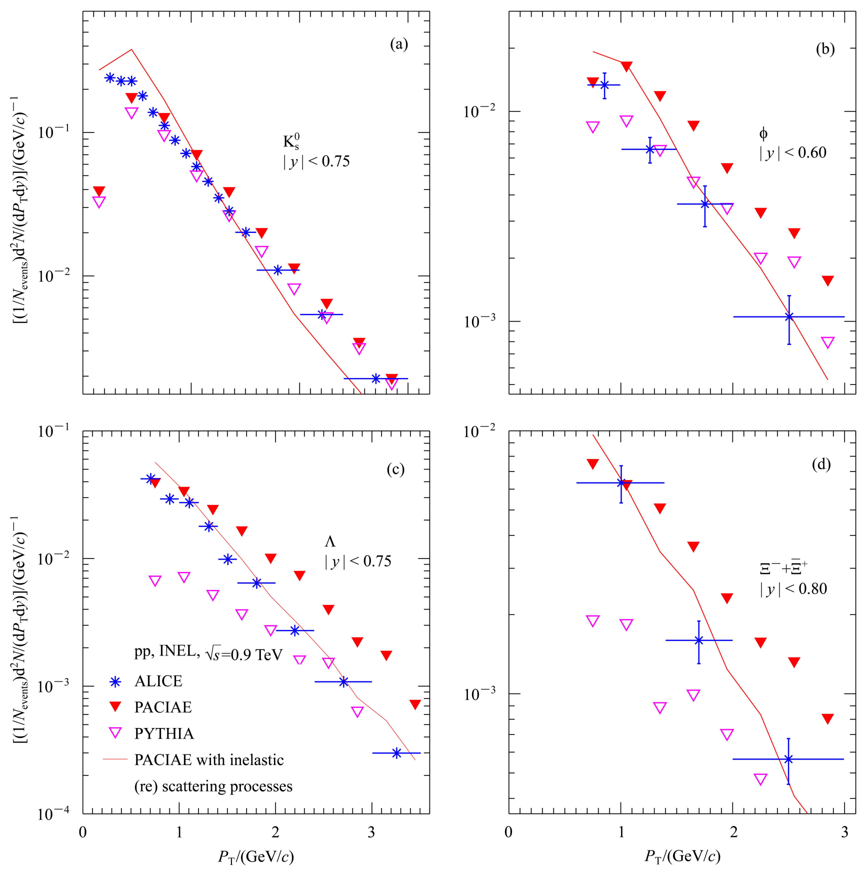

Fig. 2. (color online) The transverse momentum distributions of strange particles in INEL pp collisions at $\sqrt{s}$=900 GeV. Panels (a), (b), (c), and (d) were for K_s^0, ϕ, Λ, and $\Xi^-+\overline{\Xi}^+$, respectively. The ALICE data were taken from Ref. [6]

Table 1. Strange particle rapidity densities at mid-rapidity ($|y|<0.5$) in NSD pp collisions at $\sqrt{s}$=200 GeV. The STAR data are taken from Ref. [5].

	STAR	PACIAE from Ref. [3]	PYTHIA	PACIAE with inelastic (re)scattering processes
K_s^0	0.134±0.011	0.127	0.107	0.127
K^+	0.140±0.01	0.135	0.112	0.137
K^-	0.137±0.009	0.123	0.104	0.121
Λ	0.0385±0.0036	0.0360	0.0163	0.0372
$\overline{\Lambda}$	0.0351±0.0033	0.0350	0.0163	0.037
Ξ^-	0.0026±0.00092	0.00373	0.00106	0.00368
$\overline{\Xi}^+$	0.0029±0.001	0.00364	0.00099	0.0036
$\Omega^-+\overline{\Omega}^+$	0.00034±0.00019	0.00026	0.00005	0.00024

Table 2. Strange particle rapidity densities at mid-rapidity in INEL pp collisions at $\sqrt{s}$=900 GeV. The ALICE data are taken from Ref. [6].

	$\|y\|$	p_T/(GeV/c)	ALICE	PACIAE from Ref. [3]	PYTHIA	PACIAE with inelastic (re)scattering processes
K_s^0	<0.75	[0.2–3.0]	0.184 ± 0.0063	0.15	0.172	0.147
Φ	<0.60	[0.7–3.0]	0.021 ± 0.005	0.019	0.0134	0.0198
Λ	<0.75	[0.6–3.5]	0.048 ± 0.00412	0.043	0.0227	0.0434
$\overline{\Lambda}$	<0.75	[0.6–3.5]	0.047 ± 0.00539	0.043	0.0230	0.0424
$\Xi^-+\overline{\Xi}^+$	<0.80	[0.6–3.0]	0.0101 ± 0.00219	0.0086	0.00354	0.00856

4 Conclusions

In summary, we have utilized the new modifed PACIAE model with the effect of inelastic (re)scattering processes to analyze the production of strange particles in NSD and INEL pp collisions at $\sqrt{s}$=0.2 and 0.9 TeV, respectively. In our opinion, the effect of the inelastic (re)scattering processes involved in the new modified PACIAE model can significantly suppress the strangeness transverse momentum distributions at high p_T.

In Ref. [3], we demonstrate that the effect of the reduction mechanism of strange quark suppression and the parton and hadron rescatterings in the modified PACIAE model are important. But we also find that the transverse momentum spectra of ϕ mesons and the heavy strange baryons (Λ and $\Xi^-+\bar{\Xi}^+$) at $\sqrt{s}$ = 0.9 TeV, do not fit well with the ALICE data. For these species, the p_T spectra are found to be slightly harder (i.e. overestimated) than the data of the ALICE collaboration measured in the $p_T>1$ GeV/c region.

By considering the effect of inelastic (re)scattering processes, we re-analyzed the transverse momentum spectra of ϕ mesons and the heavy strange baryons (Λ and $\Xi^-+\bar{\Xi}^+$) at $\sqrt{s}$=0.2 and 0.9 TeV, respectively, in this paper. The calculated strangeness transverse momentum distributions in NSD pp collisions at $\sqrt{s}$=200 GeV coincide well with the STAR data. We also compared the transverse momentum distributions in INEL pp collisions at $\sqrt{s}$=0.9 TeV with the corresponding ALICE data. We obviously observe that the results of the new modified PACIAE model with the effect of inelastic (re)scattering processes are globally better than those of the default PYTHIA model and the modified PACIAE model from Ref. [3]. This may indicate the significant effect of inelastic (re)scattering processes in the parton-parton (re)scatterings stage of the PACIAE model. Combining with the discussion of Ref. [3], one finds that it not only indicates that both effects of the parton and hadron rescatterings and the reduction mechanism of strange quark suppression involved in the PACIAE model are important, but it also illustrates that the effect of inelastic (re)scattering processes in parton rescattering is also not negligible.

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References

1 SA Ben-Hao, ZHOU Dai-Mei, DONG Bao-Guo, YAN Yu-Liang, MA Hai-Liang, LI Xiao-Mei. J. Phys. G: Nucl. Part. Phys., 2009, **36**: 025007; YAN Yu-Liang, ZHOU Dai-Mei, DONG Bao-Guo, LI Xiao-Mei, MA Hai-Liang, SA Ben-Hao. Phys. Rev. C, 2009, **79**: 054902; SA Ben-Hao, ZHOU Dai-Mei, YAN Yu-Liang, LI Xiao-Mei, FENG Sheng-Qin, DONG Bao-Guo, CAI Xu, arXiv:1104.1238v1

2 Sjöstrand T, Mrenna S, Skands P, J. HEP & NP, 2006, **05**: 026 (in Chinese)

3 LONG Hai-Yan, FENG Sheng-Qin, ZHOU Dai-Mei, YAN Yu-Liang, MA Hai-Liang, SA Ben-Hao. Phys. Rev. C, 2011, **84**: 034905

4 TAI An, SA Ben-Hao. Phys. Lett. B, 1997, **409**: 393

5 Abelev B I et al. (STAR collaboration). Phys. Rev. C, 2007, **75**: 064901

6 Admodt K et al. (ALICE collaboration). Eur. Phys. J. C, 2011, **71**: 1594

7 Rafelski J. Phys. Rep., 1982, **88**: 331

8 Abbott T et al. (E802 collaboration). Phys. Rev. Lett., 1990, **64**: 847

9 Eiseman S E et al. (E810 collaboration). Phys. Lett. B, 1990, **248**: 254

10 Bratkovskaya E L et al. Phys. Rev. C, 2004, **69**: 054907

11 Blume C, Markert C. Progress in Particle and Nuclear Physics, 2011

12 Andersson B, Gustafson G, Ingelman G, Sjöstrand T. Phys. Rep., 1983, **97**: 31

13 Bocquet G et al. (UA1 collaboration). Phys. Lett. B, 1996, **366**: 447

14 TAI An, SA Ben-Hao. Phys. Rev. C, 1998, **57**: 261

15 Pi H. Comput. Phys. Commun., 1992, **71**: 173

16 SA Ben-Hao, TAI An. Comput. Phys. Commun., 1995, **90**: 121; TAI An, SA Ben-Hao. Comput. Phys. Commun., 1999, **116**: 353

17 Combridge B L, Kripfgang J, Ranft J. Phys. Lett. B, 1977, **70**: 234