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Particle Production at RHIC and LHC Energies

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The production of pion, kaon and proton was measured in Pb-Pb collisions at nucleus-nucleus center-of-mass energy $\sqrt{s_{NN}} = 2.76$ TeV by the ALICE experiment at Large Hadron Collider (LHC). The particle ratios of these species compared to the RHIC measurements are confronted to the hadron resonance gas (HRG) model and to simulations based on the event generators PYTHIA 6.4.21 and HIJING 1.36. It is found that the homogeneous particle-antiparticle ratios (same species) are fully reproducible by means of HRG and partly by PYTHIA 6.4.21 and HIJING 1.36. The mixed kaon-pion and proton-pion ratios measured at RHIC and LHC energies seem to be reproducible by the HRG model. On the other hand, the strange abundances are underestimated in both event generators. This might be originated to strangeness suppression in the event generators and/or possible strangeness enhancement in the experimental data. It is apparent that the values of kaon-pion ratios are not sensitive to the huge increase of $\sqrt{s_{NN}}$ from 200 (RHIC) to 2760 GeV (LHC). We conclude that the ratios of produced particle at LHC seem not depending on the system size.

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I. INTRODUCTION

Understanding the dynamical properties of hot and dense hadronic matter is one of the main motivations of the heavy-ion experiments, which are used to investigate the hadronic matter under extreme conditions [1–4] and to be confronted to the lattice QCD simulations [5]. Data from the Relativistic Heavy-Ion Collider (RHIC) has shown that the bulk matter created in such collisions can be quantitatively described by hydrodynamic approaches [4]. The created hot and dense partonic matter is conjectured to expands rapidly and accordingly cools down. This partonic state-of-matter is known as quark-gluon plasma (QGP) or colored quarks and gluons, in which quarks and gluons are supposed to have asymptotic freedom inside the typical size of a hadron. Over this path, QGP undergoes phase transition(s) back to the hadronic matter. Different thermal models can well reproduce the particle abundances [6–11], which are governed in the final state, i.e. at the chemical equilibrium, by two parameters, the chemical freeze-out temperature T_{ch} and the baryon chemical potential μ_b over a wide range of energies [11]. The latter also reflects the net-baryon content of the system and the nucleus-nucleus center-of-mass energy $\sqrt{s_{NN}}$. For seek of completeness, we mention here that the connection between μ_b and the center-of-mass energies smaller than that of the Alternating Gradient Synchrotron (AGS) is not as obvious as presented in Ref. [11].

That the particle abundances at AGS, Super Proton Synchrotron (SPS) and RHIC energies are consistent with the equilibrium populations [12] makes it possible to extract both freeze-out parameters over a wide range of $\sqrt{s_{NN}}$ from the fits of the measured particle ratios with the thermal models, in which the hadron interactions that might take place in the final state are not taken into account. The formation of resonances can only be materialized through strong interactions since the resonances (fireballs) are composed of lighter ones and so on [13]. In the case that all kinds of resonance interactions are taken into consideration by means of the S-matrix, which describes the scattering processes in the thermodynamic system, reduces the virtual term, so that the partition function turns to be reduced to the non-relativistic limit, especially at narrow width and/or low temperature T [14]. It was concluded that the resonance contributions to the partition function are the same as that of collisionless particles with some effective mass [14]. Furthermore, all possible interactions modifying the relative abundances are found negligible in the hadronic phase [14, 15]. In light of this, it is assumed that the hadron resonances with masses < 2 GeV would avoid the singularities expected at the Hagedorn temperature [16–19].

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The earliest idea about strangeness enhancement as a key signature of the QGP formation in the heavy-ion collisions has been proposed three decades ago [20]. During the hadronization process, T decreases from about 170 to few tens MeV, the dynamical mass of strange quark decreases as well [21?]. As a consequence of reducing the energy, which likely happen when QGP expands and cools down, the energy available to produce strange quark should not be enough and therefore the strange degrees of freedom in QGP is conjectured to equilibrate in short time-scales relative to those in the hadronic matter [23]. In other words, the averaged hadronic mass (~ 1 GeV) is much higher than the mass of the strange quark (~ 0.15 GeV). At SPS energy, there has been a large strangeness enhancement observed in the nucleus-nucleus (AA) and almost a negligible one in pA-collisions [24]. This has been cited as an experimental evidence for the QGP formation [24, 25]. The enhancement at AGS energy is considered as typical rescattering of the produced hadrons [26]. Assuming that the thermally equilibrated QGP hadronizes into a maximum entropy state, a test for the strange quark saturation in the early stages is provided by comparing the final state hadron yields to the thermal model predictions [27, 28].

Studying the ratios of particle yields helps in determining the freeze-out parameters and in eliminating the volume fluctuations. Furthermore, the dependence of the freeze-out surface on the initial conditions can be neglected. Using statistical model with the corresponding thermal parameters, predictions of the particle abundances at LHC energy are reported [29, 30]. Using the hadron resonance gas (HRG) model, three homogeneous ratios ($\bar{p}/p$, π^-/π^+ and K^-/K^+) are given in dependence on $\sqrt{s_{NN}}$ [31, 32]. The present work is an extension using recent measurements of pion, kaon and proton and their ratios in central Pb-Pb collisions at $\sqrt{s_{NN}} = 2.76$ TeV by the ALICE experiment [33] at LHC.

The present paper is organized as follows. Section II elaborates details about the HRG model and the event generators PYTHIA 6.4.21 and HIJING 1.36 [34, 35]. The results are discussed in section III. The conclusions are outlined in section IV.

II. THE MODEL

A. Hadron Resonance Gas Model

Treating hadron resonances as an ideal gas, the thermodynamic pressure in the hadronic phase, i.e. at temperatures below the critical one T_c [16–19] can be constructed. This should be valid for both collisionless (ideal) and interacting resonances. It has been shown that the thermodynamics of strongly interacting system (calculated in lattice Quantum Chromodynamics (QCD)) can be reproduced as a statistical system of an *ideal* gas composed of hadron resonances with masses ≤ 2 GeV [14, 36]. Based on this, the hadronic phase is effectively modelled as a non-interacting gas consisting of hadrons and resonances. The grand canonical partition function can be given as

$$Z(T, V) \;=\; \mathbf{Tr}\left[\exp^{-\mathbf{H}/\mathbf{T}}\right], \tag{1}$$

where the Hamiltonian $\mathbf{H}$ is given by summation over the kinetic energies of relativistic Fermi and Bose particles. $\mathbf{H}$ includes all relevant degrees of freedom of the confined interacting matter and interactions that result in the formation of the hadron resonances. In addition, it has been shown that this model gives a quite satisfactory description of the particle production in heavy-ion collisions and the thermodynamic quantities as measured in lattice QCD simulations [8–10, 14, 16–18]. Thus, the dynamics of the partition function at finite chemical potential μ and volume V can be calculated and expressed as summation over *single-particle partition* functions Z_i^1 of all hadrons and their resonances

$$\ln Z(T, \mu, V) \;=\; \sum_i \ln Z_i^1(T, \mu, V) = \sum_i \pm \frac{V g_i}{2\pi^2} \int_0^\infty k^2 dk \ln\left\{1 \pm \exp[(\mu_i - \varepsilon_i)/T]\right\}, \tag{2}$$

where $\varepsilon_i(k) = (k^2 + m_i^2)^{1/2}$ is the i-th particle dispersion relation, g_i is spin-isospin degeneracy factor and $\pm$ stands for bosons and fermions, respectively.

Before the discovery of QCD, a possible phase transition of massless pion gas to a new phase of matter was speculated. Based on statistical models such as Hagedorn [37, 38] and Bootstrap [39, 40] models, the thermodynamics of an ideal pion gas was analysed, extensively. After the discovery of QCD, the new state-of-matter was conjectured to be QGP. The physical picture was described as follows. At T_c, the additional degrees of freedom carried by QGP are released resulting in an increase in the thermodynamic quantities. The success of HRG in reproducing lattice QCD results at various quark flavors and masses and at vanishing and finite chemical potential (below T_c) has been reported in Refs. [8–10, 14, 16–18]. This led to a drastic change in the physical interpretation of the effective degrees of freedom. The thought that additional degrees of freedom might be released at $T > T_c$ has been modified. On the contrary, it was found that the system raises its effective degrees of freedom at $T < T_c$. In other words, the hadron phase should have much more degrees of freedom than the ones of the QGP phase. The former is to be described by couple hundreds of hadrons and their resonances, while the latter by much fewer degrees of freedom, i.e. quarks and gluons.

As introduced in Ref. [14], the whole spectrum of possible interactions might be represented by S-matrix. A recent review on the estimation of the excluded volume, which reflects a repulsive-type interaction, as a function of $\sqrt{s_{NN}}$ is given in Ref. [41] and the references therein. According to [14], the fugacity term can be expanded to include various kinds of interactions. In such a way, the S-matrix gives the plausible scattering processes taking place in the system of interest. It is found that including the hadron resonances with some effective masses has almost the same effect as that of a free gas with constituents having same mass. At high energy, the effective mass approaches the physical value. In other words, even strong interactions are taken into consideration through the inclusion of heavy hadron resonances. These conclusions suggest that the grand canonical partition function is able to simulate various types of interactions, when resonances with masses up to 2 GeV are included. As elaborated previously, this mass cut-off is supposed to avoid the Hagedorn singularity. A conclusive convincing prove has been presented through confronting HRG results to lattice QCD calculations [14, 16–19].

At finite temperature T and chemical potential of i-th particle μ_i, since no phase transition is present in the HRG model, the summation over all hadrons and their resonances results in the thermodynamic pressure in the hadronic phase

$$p(T,\mu_i) \;=\; \pm\frac{T}{2\pi^2}\sum_i^N g_i \int_0^\infty k^2 dk \ln\left\{1 \pm \exp[(\mu_i-\varepsilon_i)/T]\right\}, \tag{3}$$

where N is the total number of hadrons and resonances. The switching between hadron and quark chemistry is given by the correspondence between the *hadronic* chemical potentials and that of the quark constituents. For example, i-th particle would have the chemical potential $\mu_i = 3\, n_b\, \mu_q + n_s\, \mu_S$, where $n_b (n_s)$ being baryon (strange) quantum number. The chemical potential assigned to the *degenerate* light quarks is $\mu_q = (\mu_u + \mu_d)/2$ and the one assigned to strange quark reads $\mu_S = \mu_q - \mu_s$.

In the present work, the strangeness chemical potential μ_S is treated as a dependent parameter. Basically, it is calculated as a function of temperature T and baryon chemical potential μ_b, based on global conservation of strange quantum number in heavy-ion collisions [14]. Therefore and in order to assure vanishing strange charge, $\mu_S(\mu_b, T)$ has to be calculated, whenever μ_b and/or T are changed.

The particle number density is given by the derivative of Eq. 3 with respect to the chemical potential of interest

$$\langle n\rangle \;=\; \sum_i \frac{g_i}{2\pi^2}\int dk k^2 \frac{e^{(\mu_i-\varepsilon_i)/T}}{1\pm e^{(\mu_i-\varepsilon_i)/T}}. \tag{4}$$

The two parameters, T_{ch} and μ_b, are needed to explain the measured particle ratios at the chemical freeze-out takes place, i.e. particle productions equilibrates with particle annihilation. In rest frame of produced particle, the hadronic matter can be determined by constant degrees of freedom, for instance, $s/T^3(4/\pi^2) = const$ [42, 43]. The quantity in right-hand-side is assigned to 5 and 7 for two and three quark flavors, respectively. Because the chemical freeze-out is related to the particle creation, the abundances of different particle species are controlled by the chemical potential, which obviously depends on T. With increasing beam energy, T increase, while the baryon densities at mid-rapidity decrease. The estimation of the macroscopic parameters of the chemical freeze-out can be extracted from the measured particle ratio. These parameters collected over the last three decades seem to follow regular patterns as beam energy increases. The motivation of suggesting constant normalized entropy was the successful comparison to lattice QCD simulations with two and three flavors. At vanishing baryon chemical potential, it was found $s/T^3 = 5$ for two flavors and $s/T^3 = 7$ for three flavors. This finding was generalized to finite baryon chemical potential.

For a recent estimation of the chemical freeze-out parameters, T_{ch} and μ_b, the readers can consult Ref. [44–46]. A brief review on the predictions of thermal models for the hadron production in comparison to recent results from RHIC and LHC is presented in Ref. [47]. The much details on utilized models, which are missing here, can be deduced from literature. A recent review on the estimation of excluded volume as a function of $\sqrt{s_{NN}}$ is given in [41] and the references therein.

B. The Event Generation

1. *PYTHIA* 6.4.21

Although the experimental data shown in the present work are taken from the heavy-ion collisions, the comparison with PYTHIA 6.4.21, which is designed to generate multi-particle production in collisions between elementary particles, e^+e^-, pp and ep, would be possible at very high energies. The comparison with PYTHIA 6.4.21 is there to (dis)approve this. The difference between pp- and AA-collisions was supposed to disappear at LHC energies [31, 32], at least for particle ratios. We use PYTHIA 6.4.21 [48, 49] with the Perugia-0 tune [50] in the framework of AliRoot [51]. The bulk of PYTHIA multiplicities is formed in jets, i.e. in collimated bunches of hadrons or resonances decaying into further hadrons produced by the hadronization of partons [48, 49]. The relative proportion of strange particles is as expected small comparing with non-strange hadrons [52]. PYTHIA is capable of simulating for different processes including hard and soft interactions, parton distributions, initial/final–state parton showers, multiple interactions, fragmentation and decay.

As already discussed, the measured particle production is conjectured as an indicator for the formation of QGP, especially in heavy-ion collisions. In pp-collisions, the spatial and time evolution of the system is too short to assure initial conditions required to drive hadronic matter into partonic QGP. In Refs. [31, 32], we noticed that the collective flow of strongly interacting matter in heavy-ion collisions makes the HRG model underestimating the particle ratios measured in pp-collisions, especially at low energies. It was found that the differences between the particle ratios in pp- and AA-collisions almost disappear at the LHC energies. This shall be discussed in section III. In light of this, the comparison with PYTHIA remains an enlightening feature, especially at very high energy. Although, it gives comparable high-energy results as the ones from the heavy-ion collisions, its initial conditions would be reflected in the collective properties in the final state. This would include - among others - strangeness suppression, as the mass of strange quark is heavier than that of up and down quarks. Therefore, the production of strange hadrons is generally suppressed relative to hadrons containing up and down quarks only.

The data sample presented in the present work consists of 500 thousands minimum bias events for pp-collisions at 200 GeV and 2.76 TeV with 100 MeV $< p_t <$ 4500 MeV and $|y| < 0.5$.

2. *HIJING*

Taking into consideration the role of minijets in pp-, pA- and AA-interactions, the Heavy-Ion Jet INteraction Generator (HIJING) Monte Carlo model was developed in early 1990's [34, 35]. The version 1.36 is utilized in the present work. This combines a QCD-inspired model for jet production using Lund model for jet fragmentation [53, 54]. It is expected that hard or semi-hard parton scatterings with transverse momenta of a few GeV dominate the high-energy heavy-ion collisions. In light of this, HIJING provides a qualitative understanding of the interplay between soft string dynamics and hard QCD interactions. In particular, HIJING reproduces many inclusive spectra, two-particle correlations, as well as the observed flavour and multiplicity dependence of the average transverse momentum.

The nuclear shadowing and jet quenching are two important features of the HIJING event generator. The shadowing describes the modification of the free nucleon parton density. The parton shadowing is taken into account using a parametrization of the modification. It has been observed that at low-momentum fractions, the nuclear shadowing results in a decrease in the multiplicity.

With jet quenching it is meant the energy of partons in nuclear matter responsible for an increase of the particle multiplicity at central rapidity. Jet quenching is taken into account by an expected energy loss of partons traversing dense matter. A simple color configuration is assumed for the multi-jet system and the Lund fragmentation model is used for the hadronization. It is worthwhile to mention that HIJING does not consider the secondary interactions.

In order to generate the kinetic variables for hard scattering and associated radiations, the HIJING event generator uses some PYTHIA subroutines of tune 5.3. Also it implies JETSET 7.2 for jet fragmentation [53, 54]. The data sample presented in this work has the same characteristics as the ones of PYTHIA 6.4. 500 thousands minimum bias events for Pb-Pb collisions at 200 GeV and 2.76 TeV with 100 MeV $< p_t <$ 4500 MeV and $|y| <= 0.5$ are analysed.

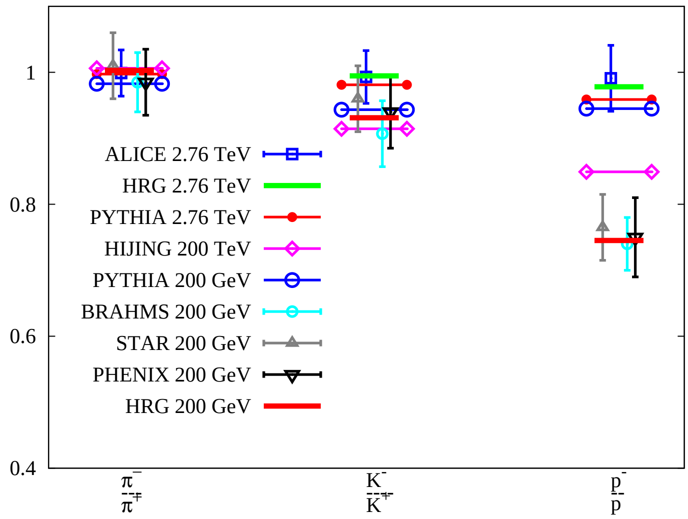

Fig. 1: The ratios π^-/π^+, K^-/K^+ and $\bar{p}/p$ measured in mid-rapidity Au-Au at RHIC [55–57] and mid-rapidity Pb-Pb at LHC [33] energies (symbols with error bars) are compared to the predictions from the HRG model (thick horizontal lines) and the event generators PYTHIA 6.4.21 and HIJING 1.36 (symbols with horizontal lines). At RHIC energy, the HRG model refers to $T_{ch} = 171$ MeV, $\mu_b = 8.4$ MeV and $\mu_S = 5.9$ MeV, while at LHC energy, $T_{ch} = 172$ MeV, $\mu_b = 6.3$ MeV and $\mu_S = 4.6$ MeV.

III. RESULTS

In Fig. 1, the ratios π^-/π^+, K^-/K^+ and $\bar{p}/p$ in Au-Au collisions at RHIC [55–57] and Pb-Pb collisions at LHC [33] energies (symbols with error bars) are compared with the HRG model (thick horizontal lines) and the event generators PYTHIA 6.4.21 and HIJING 1.36 (symbols with horizontal lines). The differences between the two even generators should be highlighted again. PYTHIA 6.4.21 simulations are principally related pp-collisions, while the HIJING 1.36 simulations are performed for Pb-Pb collisions in rapidity range $|y| <= 0.5$ with centrality $(0\% - 5\%)$ and $4500 > p_t > 100$ MeV. As introduced, the difference between the particle production in pp- and AA-collisions is likely to disappear at very high energy [31, 32], i.e. pp- and AA-results are conjectured to be nondistinguishable. It is obvious that the experimental measurements for particles to antiparticles ratios, i.e. same particle species, are well reproduced by HRG and both event generators. Furthermore, increasing energy narrows the difference between pp- and AA-results. This is also present in the left panels of Figs. 5, 6 and 7.

Calculating the chemical freeze-out parameters, T_{ch} and μ_b under the assumption of strangeness saturation has been discussed in previous section. At $\sqrt{s_{NN}} = 200$ GeV, it is found that $T_{ch} = 171$ MeV, and $\mu_b = 8.4$ MeV. The corresponding strange chemical potential reads $\mu_S = 5.9$ MeV. At ALICE energy $\sqrt{s_{NN}} = 2760$ GeV, it is found that $T_{ch} = 172$ MeV, $\mu_b = 6.3$ MeV and $\mu_S = 4.6$ MeV. The comparison with HIJING 1.36, PYTHIA 6.4.21 shows that the ALICE results (LHC energy) are well reproduced. We note that PYTHIA 6.4.21 overestimates RHIC results for $\bar{p}/p$ (π^-/π^+ and K^-/K^+ are well reproduced). This might be originated to the initial conditions in pp-collisions. In comparison with both event generators, the HRG model reproduces the experimental results at both RHIC and LHC energies.

The ratios of different species are named ad mixed ratios. Fig. 2 shows different mixed proton/pion ratios. It is apparent that PYTHIA 6.4.21 reproduces well the ALICE experimental results at 2.76 TeV (at LHC). The RHIC results at 200 GeV are not fully described. Both HIJING and HRG are almost identical in reproducing ALICE experimental data at 2.76 TeV. HRG seems to reproduce RHIC data well but overestimates LHC results. The latter is know is know as proton anomaly.

In Fig. 3, different mixed kaon/pion ratios are presented. It is apparent that both event generators PYTHIA 6.4.21 and HIJING 1.36 underestimate the experimental data, while the HRG model slightly overestimates them. This might be interpreted due to strangeness suppression in both event generators but enhancement in the experimental data. It is apparent that the experimental values of kaon-pion ratios are not sensitive to the huge increase of $\sqrt{s_{NN}}$ from 200 (RHIC) to 2760 GeV (LHC). This observation seems to support the assumption of QGP production and throughout strangeness enhancement.

A comparative study is summarized in Tab. I, where the present results on particle-antiparticle ratios are

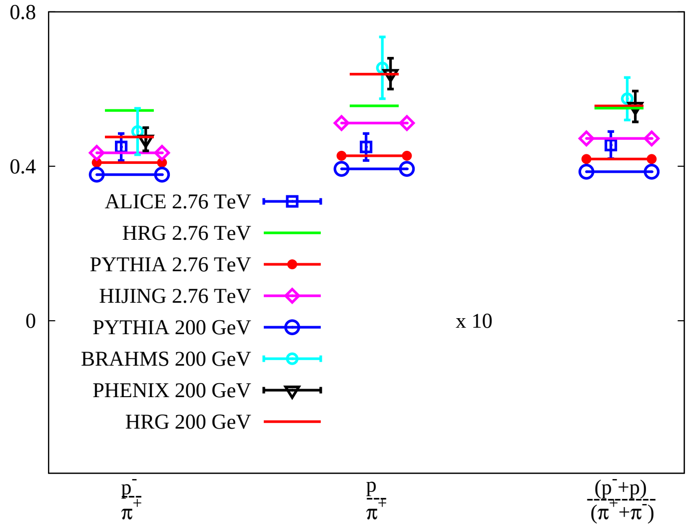

Fig. 2: Different mixed proton/pion ratios measured in mid-rapidity Au-Au at RHIC [55–57] and mid-rapidity Pb-Pb at LHC [33] are compared with HRG mdel and PYTHIA 6.4.21 and HIJING 1.36 event generators. Symbols are the same as in Fig. 1. All results are scaled by 10.

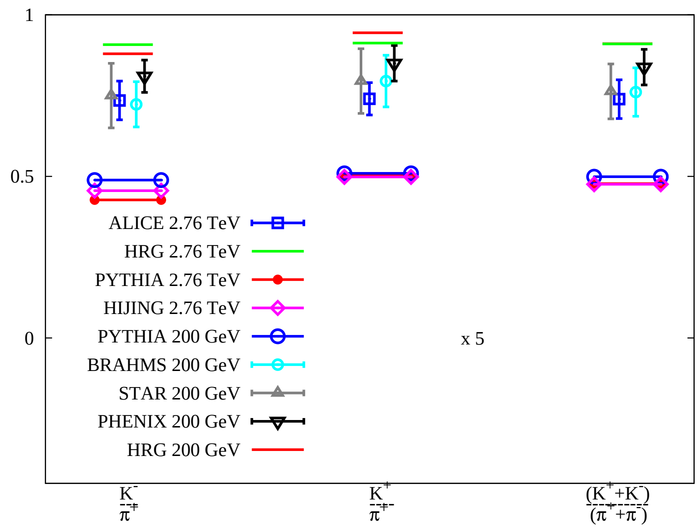

Fig. 3: Different mixed kaon-pion ratios measured in mid-rapidity Au-Au at RHIC [55–57] and mid-rapidity Pb-Pb at LHC [33] are compared to the HRG model and the event generators PYTHIA 6.4.21 and HIJING 1.36. Symbols are the same as in Figs. 1 and 2. The results are scaled by 5.

compared with the corresponding results reported in Ref. [29]. The values given here are the same drawn in Figs. 1-3. The mixed ratios are presented in Tab. II. The HRG model are confronted to previous studies [29, 30]. This is a satisfactorily agreement, especially with Ref. [29].

A. Comparison with CMS results

The CMS collaboration reported on the particle ratios π^-/π^+, K^-/K^+, $\bar{p}/p$, $(K^+ + K^-)/(\pi^+ + \pi^-)$ and $(\bar{p}+p)/(\pi^+ + \pi^-)$ [58] measured in pp-collisions at 0.9, 2.76 and 7 TeV. In Fig 4, we find a satisfactory agreement with the ALICE results [33] at LHC, especially for the homogeneous particle-antiparticle ratios, although both experiments have analysed different interacting systems. In the ALICE experiment, the particle ratios are calculated in Pb-Pb collisions at 2.76 TeV, while CMS utilized for this purpose *pp*-collisions. This is another evidence supporting the conclusions of Ref. [31, 32] that the difference between these two types of collisions is conjectured to disappear at very high energies. There is a substantial difference in the mixed particle ratios. While kaon-pion ratios measures by CMS are smaller than the ones by the ALICE experiments at LHC, we find that the values of the proton-pion ratios are qualitatively flipped. This behavior can be understood as follows. The strangeness enhancement as measured by the CMS experiment (pp-collisions) seems to be smaller than the measurements by the ALICE experiment (Pb-Pb collisions). As discussed above, the strangeness enhancement is supposed to reflect the formation of QGP. The increase in the CMS proton-pion ratios relative to the ALICE ratios might be interpreted by enriched proton contents in the Pb-Pb relative to pp-collisions.

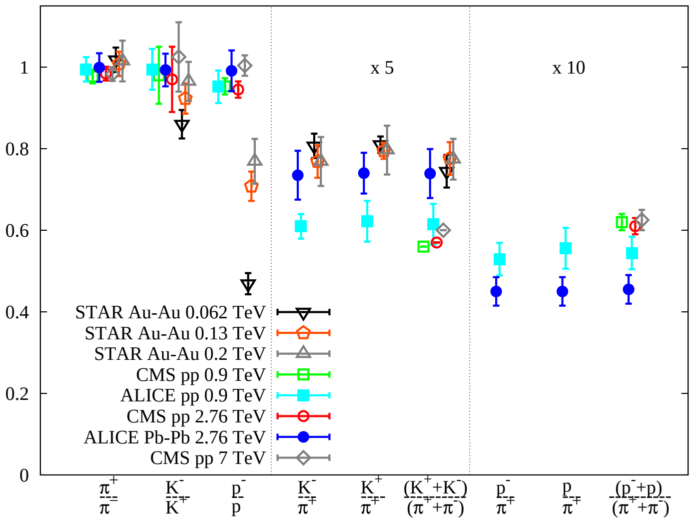

Fig. 4: The particle ratios measured in Pb-Pb collisions by the ALICE experiment [33] are compared with the results deduced from pp-collisions in the CMS experiment [58] (both at LHC) and Au-Au collisions from the STAR [55] experiment (at RHIC).

	K^-/K^+	π^+/π^-	$\bar{p}/p$	$\bar{\Lambda}/\Lambda$
HRG	0.994	0.9997	0.978	0.983
Ref. [29]	0.9998	0.9998	0.989	0.992

Tab. I: Ratios of K^-/K^+, π^+/π^-, $\bar{p}/p$, $\bar{\Lambda}/\Lambda$ (matter-to-antimatter) calculated from HRG model are compared with the results reported in Ref. [29].

	K^+/π^+	$K^-/\pi-$	p/π^-	p/π^+	Λ/p	Λ/π^-
HRG	0.182	0.181	0.092	0.056	0.437	0.024
Ref. [29]	0.180	0.179	0.091		0.473	
Ref. [30]	0.164	0.163		0.072		0.042

Tab. II: K^+/π^+, $K^-/\pi-$, p/π^-, p/π^+, Λ/p, Λ/π^- mixed ratios calculated from the HRG model are compared to the results reported in Ref. [29] and [30].

B. Energy dependence of particle ratios

Figs. 5, 6 and 7 present the energy dependence of different particle ratios. In Fig. 5, the π^-/π^+ (left panel), K^-/π^+ (middle panel) and $\bar{p}/\pi^+$ (right panel) ratios are given in dependence on $\sqrt{s_{NN}}$. It is obvious that the HRG calculations for π^-/π^+ reproduce well the experimental data at RHIC and LHC energies. This comparison has been introduced in Ref. [31, 32], as well. The energy dependence of K^-/π^+ ratio is given in the middle panel. Here, it is apparent that the experimental values are smaller than the calculated ones. In other words, the HRG model obviously overestimates the experimental data at both RHIC and LHC energies. For a

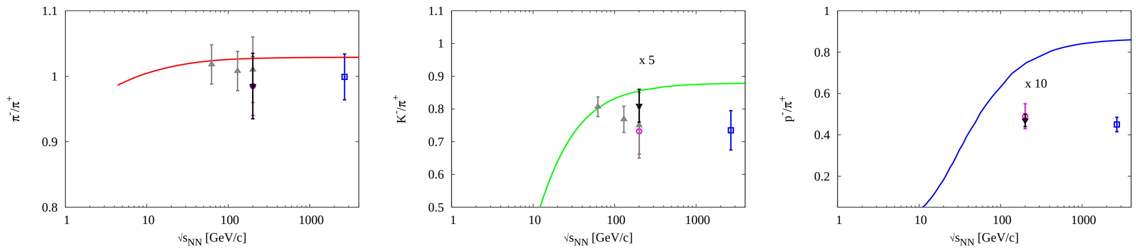

Fig. 5: Ratios of π^-/π^+, K^-/π^+ and $\bar{p}/\pi^+$ are given in dependence on $\sqrt{s_{NN}}$ and compared with experimental measurements in Au-Au collisions at RHIC [55–57] and Pb-Pb collisions at LHC [33] (symbols). Curves represent the results deduced from HRG model. At $\sqrt{s_{NN}} = 200$ GeV, the HRG model refers to $T_{ch} = 171$ MeV, $\mu_b = 8.4$ MeV and $\mu_S = 5.9$ MeV, while at $\sqrt{s_{NN}} = 2760$ GeV, $T_{ch} = 172$ MeV, $\mu_b = 6.3$ MeV and $\mu_S = 4.6$ MeV.

comparative purpose, we refer to Fig. 3, where it is depicted how the event generators underestimate this ratio at both energies, 200 and 2760 GeV, respectively. The $\bar{p}/\pi^+$ ratio is given in the right panel. Here, we find that the RHIC results are reproduced, while the LHC results are obviously overestimated by the HRG model.

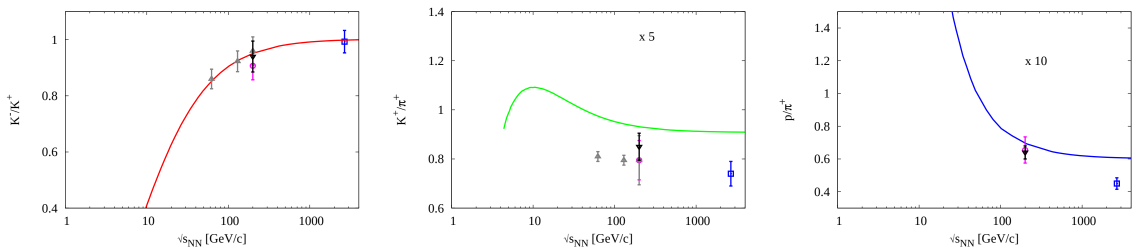

Fig. 6: Ratios of K^-/K^+, K^+/π^+, and p/π^+ are given in dependence on $\sqrt{s_{NN}}$ and compared with experimental measurements in Au-Au collisions at RHIC [55–57] and in Pb-Pb collisions LHC [33] (symbols). The curves represent for the HRG results.

In Fig. 6, homogeneous strange bosonic ratio of K^-/K^+ (left panel), mixed strange to non-strange bosonic ratio of K^+/π^+ (middle panel), and mixed baryon to non-strange boson p/π^+ ratio (right panel) are given in dependence on $\sqrt{s_{NN}}$. The HRG calculations for antikaon-to-kaon ratio K^-/K^+ agree well with the experimental results at both energies, 200 and 2760 GeV, respectively [31, 32]. The energy dependence of K^+/π^+ seems to be different than the one presented in Fig, 5 and left panel of Fig. 6. There is a peak (horn) at low energy. Then the ratio decreases slightly with increasing $\sqrt{s_{NN}}$. Once again, we find that the HRG model obviously overestimates the experimental results at both energies, 200 and 2760 GeV, respectively. Referring to Fig. 3, we recall that both event generators underestimate this ratio, as well. The HRG results on p/π^+ are presented in the right panel. It is apparent that the RHIC results are well described by the HRG model, while the LHC data are overestimated. Again, the values of K^+/π^+ and p/π^+ decrease with increasing $\sqrt{s_{NN}}$.

For completeness, we highlight that K^+/π^+ ratio shows a maximum (horn) at low $\sqrt{s_{NN}}$ and the HRG model in its standard configurations cannot explain this. Various models and approaches have been proposed, allegedly. One of the authors has propounded two resolutions. The first one depends on modifying phase-space [60, 61]. The second one implements difference quark occupation factors for light and strange quarks [62, 63].

Finally, the three remaining ratios $\bar{p}/p$ (left panel), $(K^++K^-)/(\pi^++\pi^-)$ (middle panel) and $(\bar{p}+p)/(\pi^++\pi^-)$ (right panel) are given in Fig. 7 as functions of $\sqrt{s_{NN}}$. Once again, the agreement between the experimental results (RHIC and LHC) and the HRG model on $\bar{p}/p$ is convincing [31, 32]. The kaon-to-pion ratio is obviously overestimated by the HRG model. Along the whole energy range, the HRG model gives about 30% higher values than the measured ratios. The event generators PYTHIA 6.4.21 and HIJING 1.36 underestimate this value at both energies, 200 and 2760 GeV, respectively. The proton-to-pion (right panel) is well reproduced by the HRG model, especially at RHIC energy, but once again overestimated at the LHC energy.

It is obvious that the strange ratios are overestimated by the HRG model. Furthermore, both event generators underestimate such ratios. This might be rooted back in the strangeness suppression in both event generators and/or the strangeness enhancement in the experimental data. We note that the values of kaon-pion ratios remain unaffected by the huge increase in $\sqrt{s_{NN}}$ from 200 (RHIC) to 2760 GeV (LHC). This experimental observations can be interpreted in favor of the assumption of QGP production and strangeness enhancement.

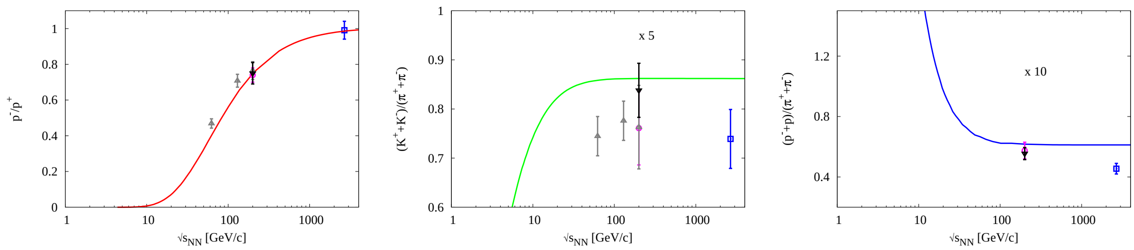

Fig. 7: Ratios of $\bar{p}/p$, $(K^+ + K^-)/(\pi^+ + \pi^-)$, and $(\bar{p}+p)/(\pi^+ + \pi^-)$ are given in dependence on $\sqrt{s_{NN}}$ and compared with experimental measurements in Au-Au collisions at RHIC [55–57] and in Pb–Pb collisions at LHC [33] (symbols). The curves represent the HRG results.

For completeness, we mention that a comparison between thermal model for particle production and results from RHIC and LHC has been introduced in Ref. [47]. The authors reported an apparent anomaly for proton and antiproton production. In the present work, we study the particle ratios and apparently the anomaly in the particle production is irrelevant. Nevertheless, in the thermal model [47], excluded volume and heavier resonances are utilized.

Strangeness suppression is probably related to limited phase-space [60, 61] available in string fragmentation. In thermal models, the occupation factor of different quark flavors has the influence to explain strange particle ratios over a wide range of energies [62, 63]. When extracting quark-antiquark creation probabilities in exclusive two-body production as implemented in the event generators, only a single quark-antiquark pair is likely. The observation reported here would reflect observe a suppression of strange quark-antiquark pairs compared to nonstrange ones, which seems to increase with increasing energy.

Signature for the QGP formation relies on strangeness enhancement [64]. In heavy-ion collisions, the strange quark (unlike up and down quarks) is not brought into interaction by the colliding nuclei. Therefore, observed strange quarks or antiquarks should be created from the kinetic energy of colliding nuclei or partons. That the mass of strange quarks is equivalent to the critical temperature would mean that their abundance is sensitive to initial conditions, hadronization and dynamics underlying QGP (deconfined phase).

C. pp- and AA-collisions

First, confronting AA-collisions to PYTHIA calculations has been practised by LHC collaborations [65, 66] and various authors [67, 68]. Second, in Ref. [42, 43], one of the authors has introduced first evidences that in the homogeneous particle ratios of pions, protons and kaons the differences between pp- and AA-collisions become negligibly small with increasing the nucleon-nucleon center-of-mass energies. Third, the multiplicities from pp- and AA-collisions are found possessing a global power law behavior [69].

The charge fluctuations in pp- and AA-collisions at RHIC and LHC energies are studied from different event generators (UrQMD, HIJING and HIJING/BB) [70]. The results are compared with independent emission from hadron gas and QGP phase. It has been concluded that a difference in the so-called D-measures (of charge fluctuations) from pp- and AA-collisions might be interpreted by rescattering effects.

Various experimental observations, such as, direct photon enhancement at low p_T, suppression of high p_T hadrons, scaling of elliptic flow, etc. imply formation of QGP, especially in central AA-collisions at RHIC energy [71]. In proposing these observations, the interactions of quarks and gluons with small momentum exchange, are obviously not taken into account, because of complications coupled with their estimation in QCD. As in AA-collisions, pp-collisions can be also classified according to centrality, where here parton pairs replaces nucleon pairs in defining centrality AA-collisions [72]. Pairs of partons from colliding proton pairs start interacting in very early stage of collisions [73].

Two quark-diquark strings can be excited between the two colliding protons. Alternatively, additional two gluons can be emitted (one from each proton). These can be converted into quark and antiquark at each proton, which in tern interacts with each other. Through gluon emissions, additional partonic interactions take place. All these define the centrality of pp-collision.

The phase space is an additional aspect of pp-collisions. The sampling of parton energy from a proton is given by the parton distribution function, which at low p_T, is less explored. Constraints from energy conservation law requires normalized energy momentum fractions (due to partons in each proton).

At ultra high-energy (low-x), i.e. LHC, the partons turn to actively participate in the particle production.

Thus, it is likely that QGP can also be formed and the various yields produced from coincident with the ones from AA-collisions.

IV. CONCLUSIONS

In the present work, we introduce a systematic comparison between experimental measurements, simulations and results from effective model. The simulations are based on two even generators HIJING and PYTHIA. We have discussed characteristics of each of them. The effective model is the thermal particle production, which principally constructed for heavy-ion collisions.

Two remarks are now in order. The first one is that the simulations with PYTHIA 6.4.21 are performed for pp-collisions. Therefore, the comparison with the heavy-ion collisions is given as a reference. From pp event generator and experiments, no concrete conclusion was derived. They are there to compare with. The second remark is that the HRG model counts for all baryonic and bosonic resonances with masses < 2 GeV, assures conserved strange degrees of freedom and characterizes the chemical freeze-out by constant s/T^3. The latter is conjectured to be valid over the entire range of $\sqrt{s_{NN}}$.

We conclude that

- The particle-antiparticle ratios are produced by the HRG model.
- The produced particle ratio seems not depending on the system size, especially at very high energies.
- To a large extend, both event generators are also able to reproduce these homogeneous ratios.
- In particle-antiparticle ratios, additional effects, mainly the volume fluctuations, the dependence on initial conditions and decay channels are almost eliminated. This seems not being the case in mixed ratios.
- The HRG model and the two event generators simulate well the baryon-boson ratios.
- Comparing to particle-antiparticle ratios, their production of mixed ratios is relatively less.
- On the other hand, both calculations and simulations do not agree with the strange ratios. The energy dependence, which is calculated by the HRG model reflects the tendency of each ratio with the change in $\sqrt{s_{NN}}$.

The strange quark flavors seem to play an essential role in explaining the discrepancy with the kaon-pion ratios. On one hand, the HRG model seems to overestimate the experimental results. On other hand, the PYTHIA 6.4.21 simulator, which is basically originated from pp-collisions, whose spatial and temporal evolutions are likely short to assure initial conditions driving the hadronic matter to the partonic QGP, seems to underestimate the experimental results. The HIJING simulator, which is basically based on Pb-Pb collisions, is also unable to reproduce these ratios. Another aspect regarding the production of strange ratios would be the threshold of strange quark production. Comparing to QGP, the threshold in the hadronic matter is relatively small. This effect would be enhanced in hadrons with multiple strange quarks. In heavy-ion collisions, the production of QGP is likely. Thus the strangeness enhancement in high energetic pp collisions would be a sign of a collective effect [59].

The relative large suppression of strange quark production in PYTHIA 6.4.21 and HIJING 1.36 would be originated in the absence of the correct inclusion of the strange production in current tunes of these event generators. It has been concluded in Ref. [52] that there is a large increase in the measured production cross section of strange particles as the energy increases from 0.9 to 7 TeV. Also, it is found that the difference between the predictions of strange particles production and measurements gets bigger as the particle mass and strangeness number increase.

Although the mixed ratios measured at RHIC and LHC energies are well generated by the HRG model, it is found that the strange abundances are underestimated in both event generators. This might be understood as a strangeness suppression in both event generators and/or a strangeness enhancement in the experimental data. We note that the experimental values of kaon-pion ratios are not sensitive to the huge jump in $\sqrt{s_{NN}}$ from 200 (RHIC) to 2760 GeV (LHC). This observation seems to support the assumption of QGP production and strangeness enhancement.

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