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STUDY OF $\pi\pi$ CORRELATIONS AT RHIC AND LHC ENERGIES IN pp COLLISIONS WITHIN THE QUARK–GLUON STRING MODEL

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The main goal of this work is to employ the Monte Carlo Quark–Gluon String Model (QGSM) for description of femtoscopic characteristics in pp collisions at RHIC and LHC. It was found that experimental data can be reasonably well described within the pure string model by increasing the string tension by a factor of two with energy rising from $\sqrt{s} = 200$ GeV to $\sqrt{s} = 900$ GeV. The double-Gaussian fit reveals the contributions from resonances and directly produced particles.

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INTRODUCTION

Experiments at RHIC have demonstrated that hot and dense matter with partonic collectivity has been formed in ultrarelativistic Au + Au collisions at $\sqrt{s} = 200$ GeV. Proton–proton collisions are conventionally used as a reference to compare with nuclear collisions and to understand the observed collective effects. The new interest in general features of pp collisions at ultrarelativistic energies appeared after the first publication of the Large Hadron Collider data at $\sqrt{s} = 900$ GeV and $\sqrt{s} = 7$ TeV.

The system created in ultrarelativistic pp collisions at RHIC and especially LHC energies can be similar to the system created in non-central heavy-ion collisions because of the large energy deposited in the overlapping region and therefore can also demonstrate the collective behavior. The strong argument supporting this point of view comes from the observation of the same momentum dependence of the femtoscopic radii in pp and Au + Au collisions by STAR experiment at RHIC [1].

The Bose–Einstein correlations for pp collisions at $\sqrt{s} = 900$ GeV obtained in the ALICE experiment [2] have been successfully described within the EPOS + hydro model [3]. It was shown that the hydrodynamic expansion drastically modifies the space-time behavior of the evolution compared to the «classical» EPOS scenario with independent decay of flux-tube strings.

The quark–gluon string model based on Gribov–Regge theory gives a good description of the collective flow effects in Au + Au collisions at RHIC energies; the tuning of QGSM for pp collisions at LHC energies allowed the authors to describe successfully the main characteristics of pp interactions, i.e., multiplicity, transverse momentum and (pseudo)rapidity distributions, up to top LHC energy $\sqrt{s} = 7$ TeV [4]. The aim of the present article is to study hadronization processes in pp collisions at ultrarelativistic energies using momentum correlations techniques with the QGSM model and to compare obtained results with the experimental data of RHIC and LHC. We try to understand to what extent one is able to describe the correlation functions (CFs) in ultrarelativistic pp collisions within the pure string model picture.

1. QGSM AND PARTICLE COORDINATES

The hadrons in QGSM are produced through the creation and decay of resonances, strings and minijets. The space-time evolution of the collisions starts from the interacting partons (quark, diquark and sea quarks) distributed randomly in the projectile-target overlapping region. The strings between them are stretching and decaying into the hadrons. Due to uncertainty principle it takes time to create a hadron from constituent quarks. It was supported by experiment that fast particles are created the last. In string models two definitions of formation time are accepted: the time when string is broken and all constituents of the hadron are created (constituent) or the time when the trajectories of hadron constituents (quarks) cross («yo-yo»). In this version of QGSM we are using the smallest formation time — constituent. The formation time t_i^* and coordinate z_i^* of ith hadron in the string center of mass can be expressed through its energy E_i^*, its longitudinal momentum p_{zi}^* and the longitudinal momenta/energies of all hadrons produced by the decay of this string:

$$t_i^* = \frac{1}{2\kappa}\left(M_s - 2\sum_{j=1}^{i-1} p_{zj}^*\right), \quad z_i^* = \frac{1}{2\kappa}\left(M_s - 2\sum_{j=1}^{i-1} E_j^*\right). \qquad (1)$$

Then we calculate t_i in the laboratory frame and make the propagation of the coordinates to this point (x_i, y_i, z_i, t_i): $a_i = a_{0i} + t_i p_{ai}/E_i$, $a = x, y, z$. We have studied the influence of the strength of string tension κ on the space-time distributions and the corresponding correlation functions. Note that κ acts as a scaling parameter of the particle formation time.

2. THE TWO-PION CORRELATION FUNCTIONS

The momentum correlations are usually studied with the help of correlation functions of two or more particles. Particularly, the two-particle correlation function $\mathrm{CF}\,(p_1, p_2) = A(p_1, p_2)/B(p_1, p_2)$ is defined as a ratio of the two-particle distribution from the same event $A(p_1, p_2)$ to the reference one. The reference distribution is typically constructed by mixing the particles from different events of a given class. In $\pi\pi$ correlations in pp collisions the Coulomb correction can be neglected.

In our simulations the weight of each particle pair is calculated according to quantum statistics, using particle four-momenta p_i and four-coordinates x_i of the emission points: $w = 1 + \cos\,(q \cdot \Delta x)$, where $q = p_1 - p_2$ and $\Delta x = x_1 - x_2$. The CF is defined as a ratio of the weighted histogram of the pair kinematic variables to the unweighted one.

The «ideal» case, $\mathrm{CF}_{\mathrm{ideal}}(p_1, p_2) = A(p_1, p_2, w)/A(p_1, p_2)$, uses unweighted pairs from the same events as the reference. A more realistic case, $\mathrm{CF}_{\mathrm{real}}(p_1, p_2) = A(p_1, p_2, w)/$

$B(p_1, p_2)$, uses unweighted mixed pairs from different events as the reference. There is a difference between the ideal pair distribution $A(p_1, p_2)$ and the mixed one $B(p_1, p_2)$ due to presence of momentum conservation for the pairs from the same event and absence of it in pairs from the mixed ones. This causes a smooth increase of $\mathrm{CF}_{\mathrm{real}}$ with q_{inv}, which reflects the fact that due to momentum conservation the probability of two particles emitted in the same direction is smaller than that of two particles emitted in opposite directions. We take this into account by using more complicated fitting procedure for the «realistic CF» than for the «ideal CF».

In both the STAR [1] and the ALICE [2] experiments the correlation function is fitted to a single Gaussian. However, the fit is unable to describe the peak at low q_{inv}. We fit the CFs by two different fitting functions: a single Gaussian, like in the experiment, and a double Gaussian (reflecting 2 sizes presented in the data, direct π and the resonance halo):

$$\mathrm{CF}_{\mathrm{single}}(q_{\mathrm{inv}}) = \left(1 + \lambda \exp\left(-R_{\mathrm{inv}}^2 q_{\mathrm{inv}}^2\right)\right) D\left(q_{\mathrm{inv}}\right), \quad (2)$$

$$\mathrm{CF}_{\mathrm{double}}(q_{\mathrm{inv}}) = \left(1 + \lambda_1 \exp\left(-R_{\mathrm{inv},1}^2 q_{\mathrm{inv}}^2\right) + \lambda_2 \exp\left(-R_{\mathrm{inv},2}^2\, q_{\mathrm{inv}}^2\right)\right) D(q_{\mathrm{inv}}), \quad (3)$$

where the function $D(q_{\mathrm{inv}})$ takes into account any non-femtoscopic correlations. The parameters $R_{\mathrm{inv}\,(1,2)}$ and $\lambda_{(1,2)}$ describe the sizes of pion sources and the correlation strength, respectively.

For the «realistic» case with mixed reference distribution we first approximate the non-femtoscopic correlations $\mathrm{CF}\,(p_1, p_2) = A(p_1, p_2)/B(p_1, p_2)$ by a polynomial $D(q_{\mathrm{inv}}) = a + bq_{\mathrm{inv}} + cq_{\mathrm{inv}}^2$. The parameters a, b, c are then fixed and the full correlation function $\mathrm{CF}\,(p_1, p_2) = A(p_1, p_2, w)/B(p_1, p_2)$ is fitted to Eq. (2) or Eq. (3). In order to reproduce the experimental fitting procedures, we will use a flat baseline $D(q_{\mathrm{inv}}) = 1$ for STAR energies, while for ALICE energies we can use either a flat or a polynomial baseline.

3. RESULTS AND CONCLUSIONS

The correlation functions of two identical charged pions have been calculated within the QGSM models in the mid-rapidity region. Calculations have been done for both the «ideal» and the «realistic» cases. We find that, using the realistic case with a mixed pair reference distribution, we get radii which are slightly larger than in the ideal case.

The obtained one-dimensional CFs are fitted to Eqs. (2) and (3) in different k_T ranges in Fig. 1 (200 GeV) and Fig. 2 (900 GeV). For 200 GeV the results are shown for both single- and double-Gaussian fitting with $\kappa = 1.32$ GeV/fm. We see that the double Gaussian describes the shape of the CF well. For 900 GeV our results can be compared to the experimental CF. Unlike the experiments, our baseline $D(q_{\mathrm{inv}})$ is flat at low q_{inv} for all k_t bins for both 200 and 900 GeV. The reason for this is the absence of jets in the present version of QGSM. By varying κ, one can get a good agreement with experiment. Results for $\kappa = 0.88$ GeV/fm and $\kappa = 2.64$ GeV/fm are shown in Fig. 2, with the latter giving best agreement with experiment.

The obtained R_{inv} fitting parameters are shown in Fig. 3. Radii from the single-Gaussian fit are close to experimental results. In order to make a model-independent comparison, the standard single-Gaussian fit with *flat* baseline was chosen similar to that in STAR and ALICE experiments. Higher k_t bins have smaller statistics, and larger deviation from experimental points.

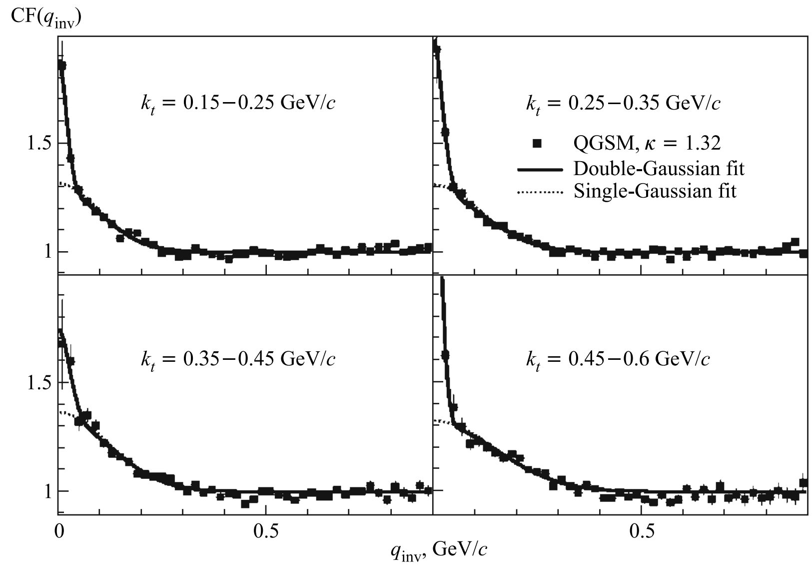

Fig. 1. The $\pi^+\pi^+$ CFs for pp at $\sqrt{s} = 200$ GeV in four k_T bins, using mixed pair reference distribution. Cuts are $|\eta| < 0.5$ and $0.12 < p_T < 0.8$ GeV/c. Calculations are performed with $\kappa = 1.32$ GeV/fm. Single-Gaussian and double-Gaussian fits are shown by dotted and full lines, respectively

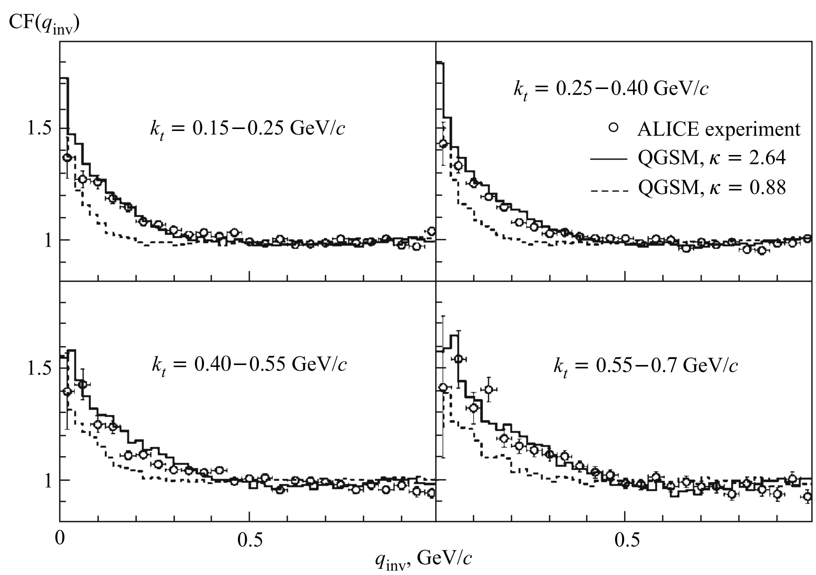

Fig. 2. The same as Fig. 1 but for $\sqrt{s} = 900$ GeV/c. Cuts are $|\eta| < 0.8$ and $0.15 < p_T < 1.0$ GeV/c. Calculations with $\kappa = 0.88$ GeV/fm (dashed line) and $\kappa = 2.64$ GeV/fm (full line) are compared to ALICE results [2] with multiplicity $7 \leqslant M \leqslant 11$

The double-Gaussian fit gives us two sets of radii, $R_{\text{inv},1}$ which is lower than for a single Gaussian, whereas $R_{\text{inv},2}$ is much larger. $R_{\text{inv},1}$ displays the radii of pions directly produced in the collision, while $R_{\text{inv},2}$ exhibits the radii of pions produced from resonance decays. This

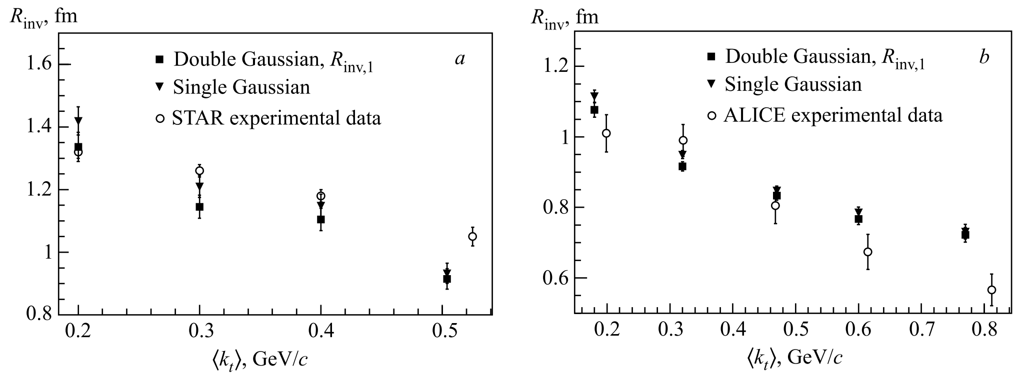

Fig. 3. The $\pi^+\pi^+$ correlation radii calculated by QGSM and compared with experimental data (STAR [1] and ALICE [2], flat baseline) at mid-rapidity in central pp collisions. We use $\kappa = 1.32$ GeV/fm for 200 GeV (*a*) and $\kappa = 2.64$ GeV/fm for 900 GeV (*b*)

can be confirmed by selecting only either direct pions or pions from resonance decays in our simulated data. Both cuts give correlation functions that are well fitted to a single Gaussian and give almost the same results as the two-Gaussian fit. The single-Gaussian fit, which does not include the low $q_{\rm inv}$ resonance peak, mostly describes the radii of direct pions and pions from short-lived resonances.

In conclusion, we find that the fitting values of both the STAR and ALICE experiments can be reproduced reasonably well by means of single-Gaussian fit. However, the two-Gaussian fitting approach reproduces the correlation function better while retaining a physical interpretation of the extracted parameters. At 900 GeV the shape of the obtained correlation functions can be directly compared with experimental data. Better description of the data is demonstrated for the lower k_t bins. To match the experimental results within the framework of independent strings, one has to increase the string tension from $\kappa = 1.32$ GeV/fm at $\sqrt{s} = 200$ GeV to $\kappa = 2.64$ GeV/fm at $\sqrt{s} = 900$ GeV. This can be taken as evidence for implementation of string-fusion processes in the model.

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