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Femtoscopic scales in $p+p$ and $p+\mathrm{Pb}$ collisions in view of the uncertainty principle

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ABSTRACT

A method for quantum corrections of Hanbury-Brown/Twiss (HBT) interferometric radii produced by semi-classical event generators is proposed. These corrections account for the basic indistinguishability and mutual coherence of closely located emitters caused by the uncertainty principle. A detailed analysis is presented for pion interferometry in $p+p$ collisions at LHC energy ($\sqrt{s}=7$ TeV). A prediction is also presented of pion interferometric radii for $p+\mathrm{Pb}$ collisions at $\sqrt{s}=5.02$ TeV. The hydrodynamic/hydrokinetic model with UrQMD cascade as 'afterburner' is utilized for this aim. It is found that quantum corrections to the interferometry radii improve significantly the event generator results which typically overestimate the experimental radii of small systems. A successful description of the interferometry structure of $p+p$ collisions within the corrected hydrodynamic model requires the study of the problem of thermalization mechanism, still a fundamental issue for ultrarelativistic $A+A$ collisions, also for high multiplicity $p+p$ and $p+\mathrm{Pb}$ events.

1. Introduction

The quantum-statistical enhancement of the pairs of identical pions produced with close momenta was observed first in $\bar{p}+p$ collisions in 1959 [1]. It took more than a decade to develop the method of pion interferometry based on the discovered phenomenon. This was done at the beginning of the 1970s by Kopylov and Podgoretsky [2]. Their theoretical analysis assumed the radiating source as consisting of independent incoherent emitters. In fact, such a representation is used for a long time for the analysis of the space–time structure of particle sources created in $\bar{p}+p$, $p+p$, $e^+ + e^-$ and $A+A$ collisions. The concept of independent emitters was applied to a further development of the interferometric method, in particular, to account for momentum-position correlations of the emitted particles [3–6] that, in turn, has resulted in a general interpretation of the measured radii as the homogeneity lengths in the Wigner functions [7–9]. This concept is important for a study of $A+A$ collision processes within the hydrodynamic approach. Also a detailed analysis of the particle final state (Coulomb) interactions brings the significant contribution to the traditional method of correlation femtoscopy [10,11].

In a recent paper [12] the correlation analysis is taken beyond the model of independent particle emitters. It is found that the uncertainty principle leads to (partial) indistinguishability of closely located emitters that fundamentally impedes their full independence and incoherence. The partial coherence of emitted particles is because of the quantum nature of particle emission and happens even if there is no specific mechanism to produce a coherent component of the source radiation. This effect leads to a reduction of the interferometry radii and suppression of the Bose–Einstein correlation functions. The effect is significant only for small sources with typical sizes less than 2 fm. We shall apply this approach [12] to the analysis of data in $p+p$ collisions at the LHC energy of $\sqrt{s}=7$ TeV, where the measured interferometry radii are just within the above scale. A simple estimate will be done also for $p+\mathrm{Pb}$, where the radii are larger and such corrections are less important.

A first attempt of the systematic theoretical analysis of the pion interferometry of $p+p$ collisions at the top RHIC and $\sqrt{s}=0.9$ TeV LHC energies was made in Ref. [13] within the quark–gluon string model (QGSM). It was found that, for a satisfactory description of the interferometry radii, one needs to reduce significantly the formation time by increasing the string tension value relative to the one fixed by the QGSM description of the spectra and multiplicity. Otherwise, the radii obtained within QGSM are too large compared to the measured ones. The similar result is obtained

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within UrQMD [14]. Hypothetically one can hope to reduce the predicted radii suggesting the other approach – the hydrodynamic mechanism of the bulk matter production in $p+p$ collisions, at least, for high multiplicity events. Then, to reproduce high multiplicity, the initially very small $p+p$ system has to be superdense at early times. This leads to very large collective velocity gradients, and so the homogeneity lengths should be fairly small. However, as we shall demonstrate, even at the maximally possible velocity gradients at the given multiplicity, one gets again an overestimate of the interferometry radii in $p+p$ collisions. The similar result is obtained in hydrodynamics in Ref. [15].[1] Therefore, one can conclude that the problem of theoretical description of the interferometry radii in $p+p$ collisions may be a general one for different types of event generators associated with various particle production mechanisms. Here we try to correct the results on interferometry from event generators using for this aim the quantum effects accounting for partial indistinguishability and mutual coherence of the closely located emitters due to the uncertainty principle [12].

In this Letter we employ the hydrokinetic model (HKM) [17,18] in its hybrid form [19] where the UrQMD hadronic cascade is considered as the semi-classical event generator at the post freeze-out ("afterburner") stage of the hydrodynamic/hydrokinetic evolution. We analyze two aspects of the analysis of $p+p$ collisions. The main one is: whether quantum corrections can help to describe the experimental data. If yes, it gives hope that it can be successfully applied for any event generator associated with another mechanisms of the particle production. The second aspect is more sophisticated: whether the typical hybrid models developed for $A+A$ collisions (here hybrid = hydrodynamic/hydrokinetic + hadronic cascade) with correspondingly modified initial conditions and with the above-mentioned quantum corrections can be real candidates to describe the bulk observables in $p+p$ collisions at LHC energies. For this aim we study the space–time structure of $p+p$ collisions, namely, analyze the multiplicity dependence of interferometry radii and volume as well as the p_T-behavior of the HBT radii. It is worth noting that a satisfactory description of the corresponding experimental data challenges the theoretical picture of $p+p$ collisions, however supporting the Landau pioneer suggestion [20] to use relativistic hydrodynamic theory for the hadron collisions with high multiplicity.

2. Hydrokinetic model: description and results for $p+p$ collisions

The hydrokinetic model [17–19] of $A+A$ collisions consists of several ingredients describing different stages of the evolution of matter in such processes. At the first stage of system's evolution the matter is supposed to be chemically and thermally equilibrated and its expansion is described within perfect $(2+1)$D boost-invariant relativistic hydrodynamics with the lattice QCD-inspired equation of state in the quark–gluon phase [21] matched with a chemically equilibrated hadron-resonance gas via crossover-type transition. The hadron-resonance gas consists of 329 well-established hadron states[2] made of u,d,s-quarks, including σ-meson ($f_0(600)$). With such an equilibrated evolution the system reaches the chemical freeze-out isotherm with the temperature $T_{ch} = 165$ MeV. At the second stage with $T < T_{ch}$, the hydrodynamically expanding hadron system gradually looses its (local) thermal and chemical equilibrium and particles continuously escape from the system. This stage is described within the hydrokinetic approach [17,18] to the problem of dynamical decoupling. In hHKM model [19] the hydrokinetic stage is matching with hadron cascade UrQMD one [23] at the isochronic hypersurface σ: $t = const$ (with $T_\sigma(r=0) = T_{ch}$), that guarantees the correctness of the matching (see [17–19] for details). The analysis provided in Ref. [19] shows a fairly small difference of the one- and two-particle spectra obtained in hHKM and in the case of the direct matching of hydrodynamics and UrQMD cascade at the chemical freeze-out hypersurface. Thus, in this Letter we utilize just the latter simplified "hybrid" variant for the afterburner stage.

Let us try to apply the above hydrokinetic picture to the LHC $p+p$ collisions at $\sqrt{s} = 7$ TeV aiming to get the minimal interferometry radii/volume at the given multiplicity bin. As it is known [17] the maximal average velocity gradient, and so the minimal homogeneity lengths can be reached for a Gaussian-like initial energy density profile. For the same aim we use the minimal transverse scale in ultra-high energy $p+p$ collision, close to the size of gluon spots [24] in a proton moving with a speed $v \approx c$. In detail, the initial boost-invariant tube for $p+p$ collisions has a Gaussian energy density distribution in the transverse plane $\epsilon_i(r)$ with width (rms) $R = 0.3$ fm [24] and, following Ref. [19], we attribute it to an initial proper time $\tau_0 = 0.1$ fm/c. At this time there is no initial transverse collective flow. The maximal initial energy density is defined by all charged particle multiplicity bin. The maximum initial energy density, $\epsilon_i(r=0)$, is determined in HKM, for selected experimental bins in multiplicity, by fitting of the mean charged particle multiplicity in those bins.

The correlation function for bosons in the UrQMD event generator is calculated according to

$$C(\mathbf{q}) = \frac{\sum_{i\neq j} \delta_\Delta(\mathbf{q} - \mathbf{p}_i + \mathbf{p}_j)(1 + \cos(p_j - p_i)(x_j - x_i))}{\sum_{i\neq j} \delta_\Delta(\mathbf{q} - \mathbf{p}_i + \mathbf{p}_j)} \tag{1}$$

where $\delta_\Delta(x) = 1$ if $|x| < \Delta p/2$ and 0 otherwise, with Δp being the bin size in histograms. The method (1) accounts for the smoothness approximation [25]. The output UrQMD 3D correlation histograms in the LCMS for different relative momenta $\mathbf{q} = \mathbf{p}_1 - \mathbf{p}_2$ are fitted with Gaussians at each $k_T = \frac{|\mathbf{p}_{1T} + \mathbf{p}_{2T}|}{2}$ bin

$$C(\mathbf{q}) = 1 + \lambda \cdot \exp\bigl(-R_{out}^2 q_{out}^2 - R_{side}^2 q_{side}^2 - R_{long}^2 q_{long}^2\bigr). \tag{2}$$

The interferometry radii $R_{out}(k_T)$, $R_{side}(k_T)$, $R_{long}(k_T)$ and the suppression parameter λ are extracted from this fit.

In Fig. 1 we demonstrate the results from hydrokinetic model for the pion interferometric radii, comparing them with the ones measured by the ALICE Collaboration at the LHC [26] in $p+p$ collisions at the energy $\sqrt{s} = 7$ TeV. As one can see there is a significant systematic overestimate of the predicted interferometry volume $V_{int} = R_{out} R_{side} R_{long}$ in $p+p$ collision even at the minimal homogeneity lengths possible for the given multiplicity classes. This is consistent with the results of the first paper devoted to the same topic "Pion interferometry testing the validity of hydrodynamical models" [27]. In what follows we shall try to improve the results of the semi-classical HKM event generator by means of the quantum corrections to them [12].

3. The quantum corrections to the hydrokinetic results

In [12] it is shown that, for small systems formed in particle collisions (e.g. pp, e^+e^-) where the observed interferometry radii are about 1–2 fm or smaller, the uncertainty principle doesn't allow one to distinguish completely between individual emission points. Also the phases of closely emitted wave packets are mutually coherent. All that is taken into account in the formalism of

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[1] The results for $p+p$ [16] obtained using EPOS 2.05 + hydro, need to be clarified since that version of EPOS underestimates the transverse energy per unit of rapidity [16].

[2] According to Particle Data Group compilation [22].