

# Transport model analysis of femtoscopy data at RHIC energies

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## Abstract

The pion source as seen through HBT correlations at RHIC energies is investigated within the UrQMD approach. We find that the calculated transverse momentum, centrality, and system size dependence of the Pratt-HBT radii  $R_L$  and  $R_S$  are reasonably well in line with experimental data. The predicted  $R_O$  values in central heavy ion collisions are larger as compared to experimental data. The corresponding quantity  $\sqrt{R_O^2 - R_S^2}$  of the pion emission source is somewhat larger than experimental estimates.

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In the quest to discover the high temperature phase of Quantum Chromodynamics (QCD), the Quark Gluon Plasma (QGP), the beam energies of accelerators have been boosted upwards from SIS, AGS, SPS, to RHIC. However, it is well known that the phase transition from hadrons to quarks might only occur in a small volume part of the system and within a rather short timespan in heavy ion collisions (HICs). This implies that the QGP drops formed at RHIC might be represented only by a few, locally thermally equilibrated drops of matter, in which quarks and gluons are de-confined. Thus, it is essential to probe the space-time structure of the (equilibrated?) source – the "region of homogeneity". Unfortunately, the small size and transient nature of the reactions preclude direct measurement of the time and/or position. Instead, correlations of two final-state particles at small relative momenta provide the most direct link to the size and lifetime of subatomic reactions. A well-established technique, the so-called "femtoscopy" or "HBT" in the heavy-ion community (in reference to Hanbury-Brown and Twiss's original work with photons) has been extensively used for HICs with energies from SIS, AGS, SPS, to RHIC [1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27, 28, 29, 30, 31].

Numerous HBT-measurements with various two-particle species have been pursued (see e.g. [1, 16] and references therein). Identically charged pion interferometry has been most extensively investigated. Basic, but important systematics of femtoscopic measurements from the AGS, SPS, and RHIC have been discovered [1, 7, 14, 16], such as the dependence of the HBT radii on system size, collision centrality, rapidity, transverse momentum, and particle mass. However, the existence of the so-called HBT-puzzle (i.e., the fact that model calculations that incorporate a phase transition to a new state of matter with many degrees of freedom significantly over-predict the observed source sizes) [1, 4, 19, 20, 21, 27, 28, 32, 33] drives us to a deeper and more systematical theoretical exploration. The Ultra-relativistic Quantum Molecular Dynamics (UrQMD, v2.2) transport model (employing hadronic and string degrees of freedom) (for details, the reader is referred to Refs.[34, 35, 36, 37]) and the analyzing program CRAB (v3.0 $\beta$ ) [38, 39, 40] are employed here as tools to analyze the two-particle interferometry. With this equipment, the excitation functions of the HBT radii of negatively charged pions are calculated systematically. In this paper, we focus on RHIC energies, where the biggest challenge is faced by the current theoretical models. The femtoscopy results at lower energies will be presented in a further study [41].

The correlation function of two particles is decomposed in Pratt's (so-called longitudinal

co-moving system "Out-Side-Long") three-dimensional convention (Pratt-radii). The three-dimensional correlation function is fit with the standard Gaussian form:

$$C(q_O, q_S, q_L) = 1 + \lambda \exp(-R_L^2 q_L^2 - R_O^2 q_O^2 - R_S^2 q_S^2 - 2R_{OL}^2 q_O q_L), \quad (1)$$

in which  $q_i$  and  $R_i$  are the components of the pair momentum difference  $\mathbf{q} = \mathbf{p}_2 - \mathbf{p}_1$  and the homogeneity length (Pratt-radii) in the  $i$  direction, respectively. The  $\lambda$  is the incoherence factor, which lies between 0 (complete coherence) and 1 (complete incoherence) in realistic HICs.  $R_{OL}$  represents the cross-term and is supposed to vanish at mid-rapidity under the assumption of a longitudinally boost invariant expansion and is also found to be negligible in our present calculations. Furthermore, in the present UrQMD calculations at RHIC energies, the Coulomb and other potential interactions are not considered (the "cascade mode" is used) due to the excessive computing times which would have been used otherwise. The Coulomb final state interactions are not taken into account in the analyzing program CRAB.

Fig. 1 gives the transverse momentum  $k_T$  dependence ( $\mathbf{k}_T = (\mathbf{p}_{1T} + \mathbf{p}_{2T})/2$ ) of the Pratt-radii  $R_L$  (left plots),  $R_O$  (middle plots), and  $R_S$  (right plots) at nucleon-nucleon center-of-mass energies  $\sqrt{s_{NN}} = 30, 62.4, 130,$  and  $200$  GeV (plots from top to bottom) in Au+Au reactions. The experimental results at energies  $\sqrt{s_{NN}} = 62.4, 130,$  and  $200$  GeV for central collisions ( $< 15\%$ ,  $< 10\%$ , and  $< 5\%$  of the total cross section  $\sigma_T$ , respectively) and at mid-rapidities ( $|\eta_{cm}| < 0.5$ ) are taken from Refs. [22, 23, 24, 25, 26]. The experimental error bars are shown as the sum of both statistical and systematic errors. The corresponding calculations with the same trigger- and acceptance- conditions as in the experiments are shown, as well as the lower energy case  $\sqrt{s_{NN}} = 30$  GeV for central collisions ( $< 15\%$  of  $\sigma_T$ ).

Both the absolute values and the decrease of the Pratt-radii  $R_L$  and  $R_S$  with transverse momentum is reproduced by the present model calculations very well. The origin of the decrease of the Pratt-radii with the increase of transverse momentum is still under discussion: it may be caused by the strong underlying transverse flow [24], or, by the temperature inhomogeneities within the hadron source (point of view of the hydrodynamics model) [31]. Here, it is also seen that the calculated  $k_T$ -dependence of  $R_S$  is somewhat flatter than that of  $R_L$ , which implies that flow effects on the  $k_T$ -dependence of the Pratt-radii can at least not be excluded. The UrQMD calculations of  $R_L$  and  $R_S$  reproduce the experimental data

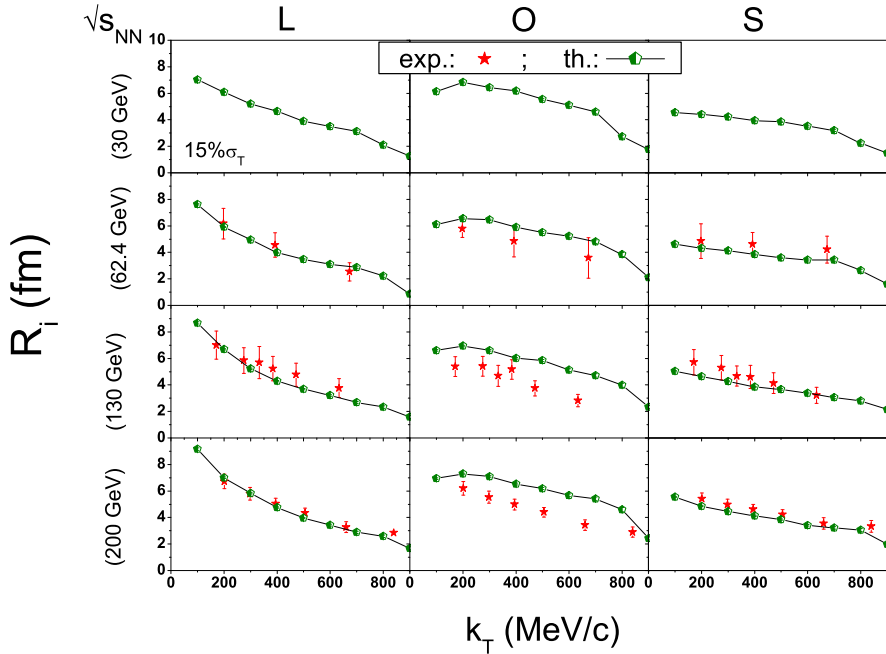


FIG. 1: Transverse momentum  $k_T$  dependence (at midrapidity) of the Pratt-radii  $R_L$ ,  $R_O$ , and  $R_S$  in Au+Au collisions at  $\sqrt{s_{NN}} = 30, 62.4, 130, \text{ and } 200$  GeV. Experimental data for the latter three cases are also shown [22, 23, 24, 25, 26]. The experimental errors are the sums of both statistical and systematic errors.

well within the error bars, while the calculated  $R_O$ 's are larger than the experimental data — the  $R_O$  is about 25% too large. We must conclude that at RHIC, larger ratios of  $R_O$  and  $R_S$  are seen from hadron transport model than expected. Similar observations have also been reported from other model calculations (c.f. [1, 19, 19, 20, 21, 42, 43, 44]). Ref. [28] has argued that the origin of this HBT-puzzle might be multifaceted.

Fig. 2 shows the  $k_T$ -dependence of the Pratt-radii in Au+Au reaction at  $\sqrt{s_{NN}} = 200$  GeV for four centralities: 0 – 5%, 10 – 20%, 30 – 50%, and 50 – 80% of total cross section. Here, a pseudo-rapidity cut  $|\eta_{cm}| < 0.5$  has been chosen. For better visibility, we have shifted in the figure the values of the radii by 0, 5, 10, and 15 fm for the four centralities. It is very interesting to see that our calculations for the centrality dependence of Pratt-radii are in reasonably good agreement with the experimental data. The important observation, however, is that the calculated  $R_O$  values tend to deviate from the data for central reactions

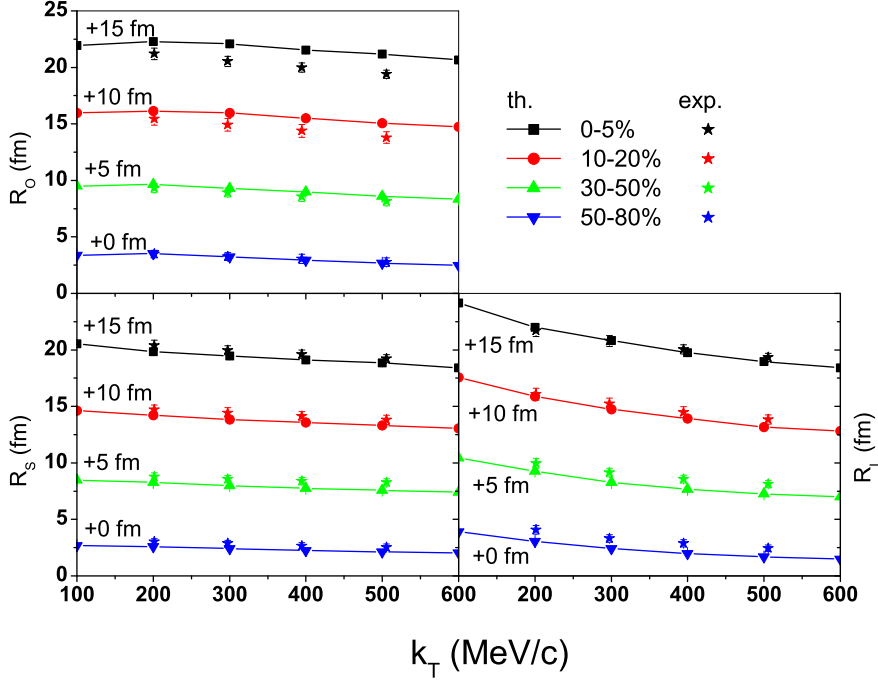


FIG. 2: Midrapidity  $k_t$ -dependence of Pratt-radii in Au+Au reaction at  $\sqrt{s_{NN}} = 200$  GeV for four centralities: 0 – 5%, 10 – 20%, 30 – 50%, and 50 – 80% of the total cross section, which are shifted by 15, 10, 5, and 0 fm, respectively. Experimental data are taken from Ref. [24].

by  $\approx 20\%$ , while they agree at midcentral and peripheral collisions.

The centrality dependence of the Pratt-radii can be seen more clearly from Fig. 3, which shows the Pratt-radii at  $k_T = 250 \sim 350$  MeV/c as a function of the number of participants  $N_{part}$ . The quantity  $\sqrt{R_O^2 - R_S^2}$  is also shown for comparison. In spite of the reasonable results on the centrality dependence of the Pratt-radii, the calculated quantity  $\sqrt{R_O^2 - R_S^2}$  obviously deviates from that extracted from data for the most central collisions: it is about twice as large as measured by experiments. The pion freeze-out volume  $V_f$  has been investigated thoroughly experimentally [7].  $V_f$  can be expressed as  $V_f = (2\pi)^{3/2} R_L R_S^2$ . The linear increase of  $V_f$  with  $N_{part}$  is expected. It can be explained reasonably well by the present model, although a smaller "thermal ellipse" is predicted due to a little shorter  $R_L$  and  $R_S$  values, as shown.

The calculations for central Cu+Cu collisions are shown in Fig. 3 (solid dots), which are in line with the centrality dependence of the HBT space-time structure calculated for Au+Au

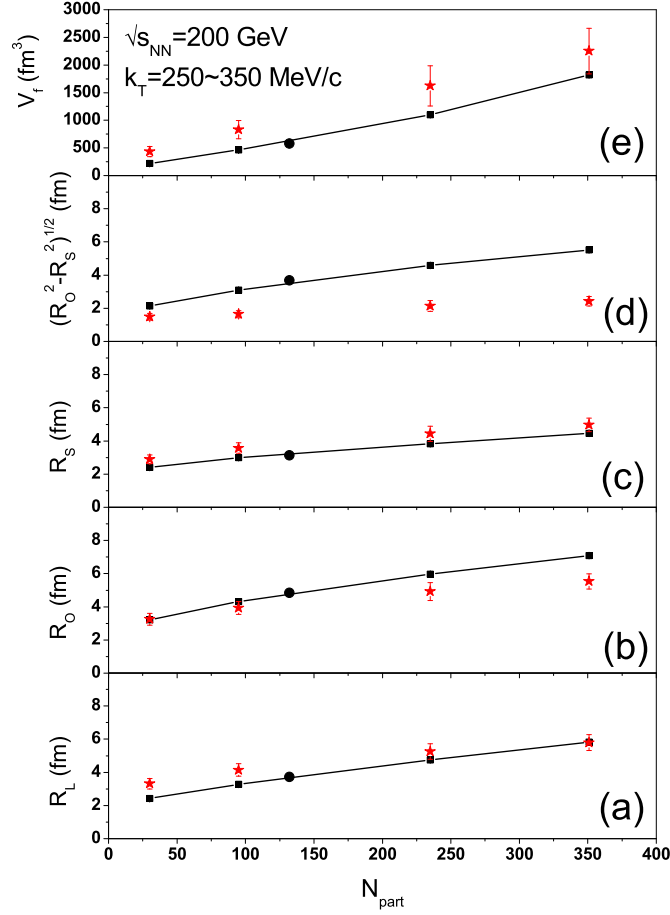


FIG. 3: Centrality dependence of the Pratt-radii ((a)-(c)), the quantity  $\sqrt{R_O^2 - R_S^2}$  (in (d)), and the freeze-out volume  $V_f$  ((e)) at  $k_T = 250 \sim 350 \text{ MeV}/c$ , in Au+Au collisions at  $\sqrt{s_{NN}} = 200 \text{ GeV}$ . Experimental data are taken from Ref. [24]. The calculated results for central Cu+Cu collisions shown with solid dots are perfectly located on the Au+Au systematic curves.

collisions. This implies that the participant multiplicity is a very good scaling variable, which drives the geometry (HBT radii) at mid-rapidity, at least for mid-size to heavy systems. In order to check this, the  $k_T$ -dependence of the ratios of the Pratt-radii between different systems is shown in Fig. 4. The radius ratios shown are from (a), Cu+Cu vs. p+p, (b), Au+Au vs. p+p, and (c), Au+Au vs. Cu+Cu. In order to read the figure more conveniently, the  $R_O$  and  $R_S$  ratios are shifted by 5 and 10, respectively. In the p+p calculation, the non-femtoscopic correlations at large relative momenta are also seen, that is, the pion correlations function saturates at large relative momentum, but the value is not equal to 1, which was

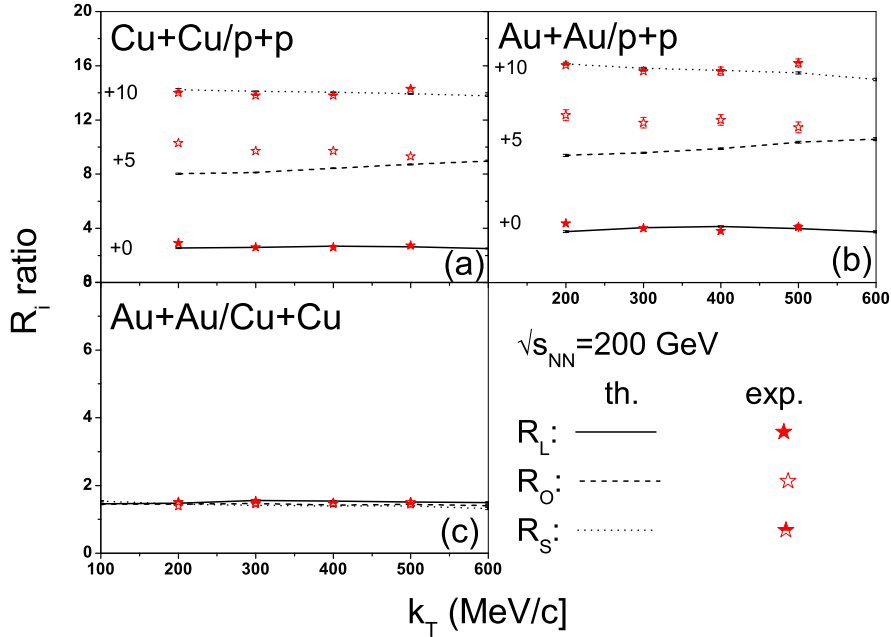


FIG. 4:  $k_T$ -dependence of the ratios of Pratt-radii between different systems: (a), Cu+Cu vs. p+p, (b), Au+Au vs. p+p, and (c), Au+Au vs. Cu+Cu. Central collisions at  $\sqrt{s_{NN}} = 200$  GeV and a mid-rapidity cut are chosen. In (a) and (b), the ratios are shifted by 5 and 10, respectively. The preliminary experimental data are taken from Ref. [14].

also implied by the preliminary data reported recently by Ref. [14]. We eliminate this effect by multiplying a constant into the parametrization of the correlation function. The  $R_L$  and  $R_S$  values in p+p collisions can be reproduced well, while the calculated  $R_O$  values are again larger than the experimental data, similar to the nucleus-nucleus collisions. This might be the origin of the whole puzzle, namely that the HBT-correlations are somewhat incorrectly put into the model in the elementary p+p dynamics. Figs. 4 (a) and (b) show that the calculated  $R_L$  and  $R_S$  ratios, reproduce the experimental data reasonably well. They are almost flat as a function of  $k_T$ , which means the  $k_T$ -dependence of the Pratt-radii still exists in the elementary p+p collisions at RHIC energies. Since the UrQMD model gives too large a  $R_O$  value in p+p collisions, the calculated  $R_O$ -ratio between Au+Au (or Cu+Cu) and p+p is smaller than the experimental data, in particular at low transverse momenta. This phenomenon disappears when we consider the Pratt-radii-ratios between two heavy systems, for examples, between Au+Au and Cu+Cu, in Fig. 3 (c). It is interesting to see that for

the Pratt-radii-ratios between Au+Au and Cu+Cu collisions, all radii-ratios are flat with  $k_T$  and approach  $\sim 1.4$ , which is equal to the ratio between the initial radii of nuclei.

To summarize, by using the CRAB program, we analyzed the evolution of the Pratt-radii  $R_L$ ,  $R_O$ , and  $R_S$  at RHIC energies in collisions simulated by the UrQMD transport model. The calculated transverse momentum-, centrality-, and system dependence of the Pratt-radii are in reasonable agreement with the experimental data. The calculated  $R_O$  values for central collisions are  $\sim 25\%$  larger as compared to experimental data. As a consequence, the extracted quantity  $\sqrt{R_O^2 - R_S^2}$  of the pion emission source is somewhat larger than experimental estimates.

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