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# HBT INTERFEROMETRY AND THE PARTON-HADRON PHASE TRANSITION

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## Abstract

We discuss predictions for the pion and kaon interferometry measurements in relativistic heavy ion collisions at SPS and RHIC energies. In particular, we confront relativistic transport model calculations that include explicitly a first-order phase transition from a thermalized quark-gluon plasma to a hadron gas with recent data from the RHIC experiments. We critically examine the *HBT-puzzle* both from the theoretical as well as from the experimental point of view. Alternative scenarios are briefly explained.

## 1 Introduction

This contribution is mainly based on results presented in Refs. [2, 3, 4]. We will briefly summarize the main conclusions obtained in these articles and then focus on a critical discussion of these results and their comparison to experimental data [5, 6] and look for possible solutions (of the *HBT-puzzle*).

One motivation to study two-particle correlations at small relative momenta is due to their predicted sensitivity to a phase transition from quark-gluon matter to hadronic matter [7, 8, 9, 10, 11]. In particular, for a first-order phase transition, larger hadronization times were expected to lead to considerably enhanced interferometry radii, characterizing the space-time extension of the particle-emitting source, compared to, for example, a purely hadronic scenario. Moreover, one is highly interested in the properties of such a phase transition as the critical temperature  $T_c$  or the latent heat. The radii should also depend on the initial specific entropy density or the initial thermalization time of the quark-gluon phase.

Here, we discuss relativistic transport calculations at RHIC energies that describe the initial dense stage by hydrodynamics [12] and the later more dilute stages by microscopic transport [13, 14] of the particles. The two models are matched at the hadronization hypersurface [15]. In the hadronic phase the particles are allowed to rescatter and to excite resonances based on cross sections as measured in vacuum. One example, the  $K\pi$  cross section, is shown

in Fig. 1. For the initial dense (hydrodynamical) phase of a QGP a bag model equation of state exhibiting a first-order phase transition is employed. Hence, a phase transition in local equilibrium that proceeds through the formation of a mixed phase, is considered. The details of this relativistic hybrid transport model can be found elsewhere [15].

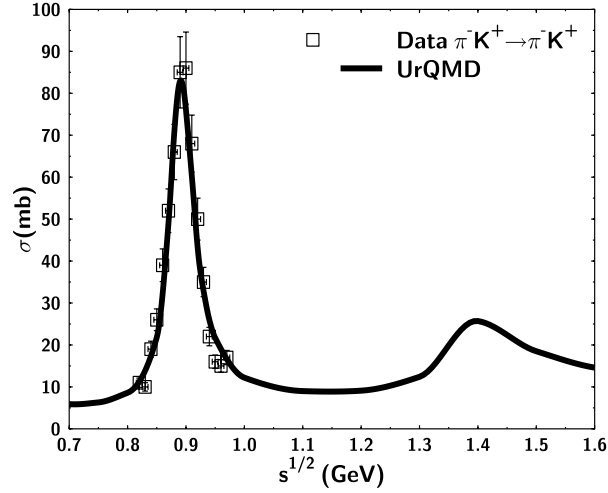


Fig. 1: Measured and modeled  $K^+ \pi^-$  cross section as a function of the center-of-mass energy  $\sqrt{s}$ . The large peak shows the  $K^*(892)$  resonance.

Fig. 2 shows a typical space-time evolution within this model. The contour lines of the freeze-out hypersurfaces of pions extend to rather large radii and times compared to the size of the mixed phase. In this hadronic phase many soft collisions take place that hardly modify the single-particle spectra but have a strong impact on the correlation functions that measure the final freeze-out state.

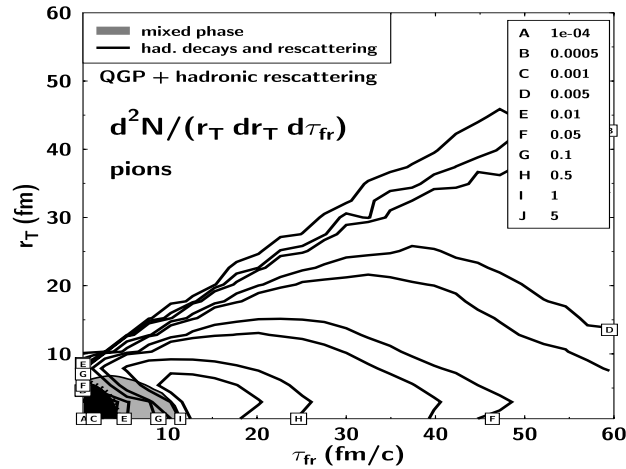


Fig. 2: Transverse radius - time plane showing contour lines of the freeze-out hypersurfaces. The grey-shaded area shows the extension of the mixed phase.

Studying this in detail lead to the following conclusions [2]: (i) The dissipative hadronic phase leads to a rather large duration of emission. (ii) The  $R_{\text{out}}/R_{\text{side}}$  ratio, thought to be a characteristic measure of this emission duration, increases with transverse momentum. (iii) The specific dependencies of the interferometry radii on the QGP properties are rather weak due to the dominance of the hadronic phase. This even leads to qualitative differences if calculations with and without this subsequent hadronic phase are compared (dependence on the critical temperature).

## 2 Why kaons?

The kaon correlations provide a severe test of the pion data and have several advantages [3, 4, 11]. In particular, the kaon density is much lower than the pion density [16]. Hence, multiparticle correlations that might play a role for the pions are of minor importance for the kaons. Also, the contributions from long-lived resonances are under better control for kaons. The  $R_{\text{out}}/R_{\text{side}}$  ratio for kaons is shown in Fig. 3. Most important is the strongly increased sensitivity to  $T_c$  and the specific entropy density (SPS vs. RHIC) at larger transverse momenta ( $K_T \sim 1 \text{ GeV}/c$ ). This enhanced sensitivity is also driven by a strong increase of the direct emission component (from the phase boundary) at high  $K_T$  as shown in Fig. 4. More and more kaons (up to  $\sim 30\%$ ) escape the initial stages (unperturbed by the hadronic phase).

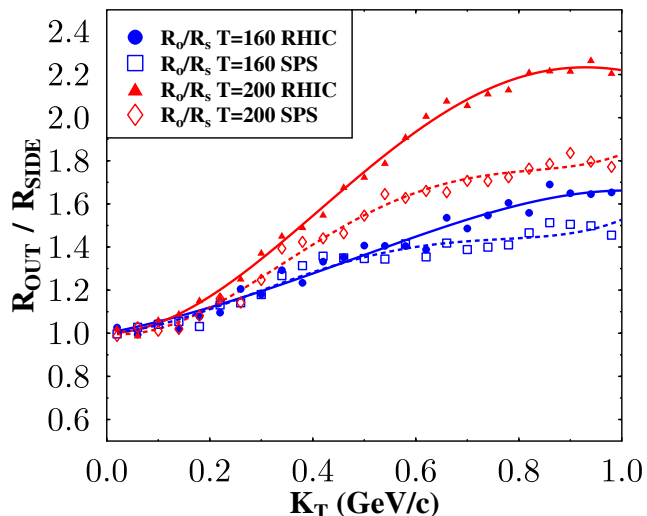


Fig. 3:  $R_{\text{out}}/R_{\text{side}}$  for kaons at RHIC (full symbols) and at SPS (open symbols), as a function of  $K_T$  for critical temperatures  $T_c \simeq 160 \text{ MeV}$  and  $T_c \simeq 200 \text{ MeV}$ , respectively.

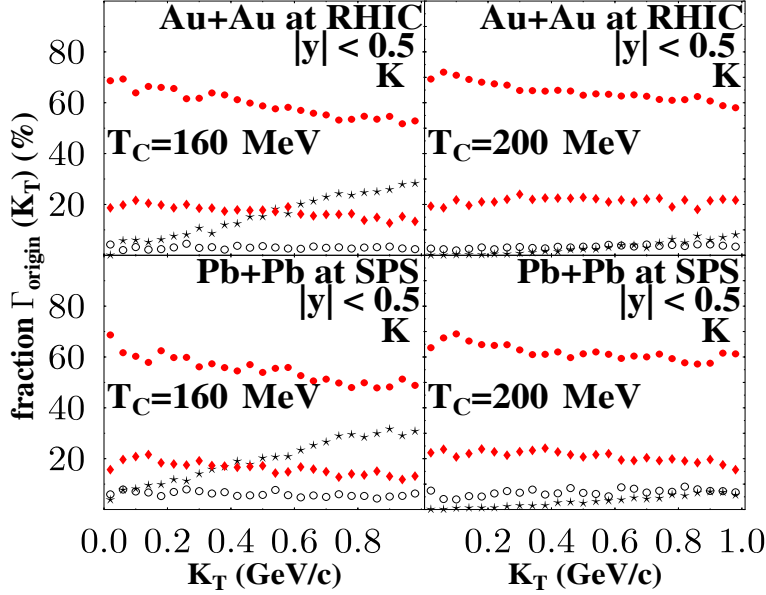


Fig. 4: Fraction of kaons  $\Gamma_{\text{origin}}$  that origin from a particular reaction channel prior to freeze-out. These are resonance decays (full circles), direct emission from the phase boundary (stars), elastic meson-meson (diamonds), or elastic meson-baryon (open circles) collisions. The upper and lower diagrams are for RHIC and SPS initial conditions for  $T_c \simeq 160$  MeV (left) and  $T_c \simeq 200$  MeV (right), respectively.

Fig. 5 shows the correlation parameters  $R_o$ ,  $R_s$ ,  $R_l$  and  $\lambda$  as obtained from the explicit calculation of the correlation functions [17] in the respective transverse momentum bins and subsequent fitting of these correlation functions to a Gaussian form of the correlator  $C_2 = 1 + \lambda \exp(-R_o^2 q_o^2 - R_s^2 q_s^2 - R_l^2 q_l^2)$ . Most important, we learn that even for a first-order phase transition scenario the interferometry radii are not unusually large. The transverse radii  $R_o$  and  $R_s$  are less than 7 fm. Moreover, we also note a strong effect of a finite momentum resolution (fmr) that has to be corrected for in the experimental analysis. The radii and the  $\lambda$  intercept parameter are reduced by the fmr. The reduction is stronger for higher  $K_T$ . Experimental data for the kaons from the RHIC experiments will be available soon. At the moment, the pion data are of great interest.

### 3 Pion interferometry radii - theory versus data

The table shows the experimental STAR data (average of  $\pi^-$  and  $\pi^+$  data plus generous error bars) [5] and the results of fitting the 3-dimensional correlation functions (as obtained from the transport calculations (RHIC initial condi-

tions,  $T_c \approx 160$  MeV) + *correlation after burner* (by Pratt) [17]) to a Gaussian correlator.

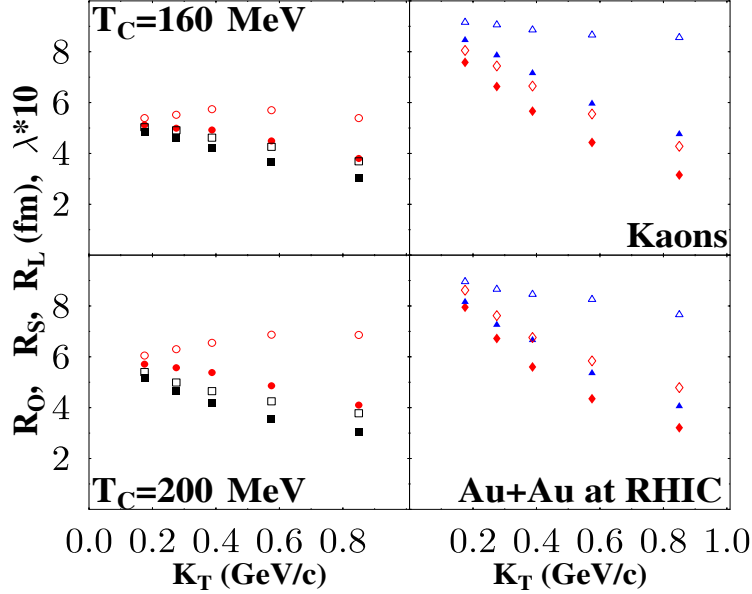


Fig. 5: Kaon HBT-parameters  $R_{\text{out}}$  (circles),  $R_{\text{side}}$  (squares),  $R_{\text{long}}$  (diamonds) and  $\lambda \cdot 10$  (triangles) as obtained from a  $\chi^2$  fit of  $C_2$  to an Gaussian *ansatz* for Au+Au collisions at RHIC as calculated with  $T_c \simeq 160$  MeV (top) and  $T_c \simeq 200$  MeV (bottom). Full and open circles correspond to calculations with and without taking momentum resolution effects into account, respectively.

		STAR	T	$T_{\text{fmr}}$
low $K_T1$	$R_{\text{out}}$	$5.9 \pm 0.5$	8.2	7.4
	$R_{\text{side}}$	$5.7 \pm 0.5$	5.7	5.4
	$R_{\text{out}}/R_{\text{side}}$	1.04	1.4	1.4
med. $K_T2$	$R_{\text{out}}$	$5.3 \pm 0.6$	8.0	6.8
	$R_{\text{side}}$	$5.3 \pm 0.5$	5.3	4.8
	$R_{\text{out}}/R_{\text{side}}$	1.0	1.5	1.4
high $K_T3$	$R_{\text{out}}$	$4.5 \pm 0.6$	7.7	6.1
	$R_{\text{side}}$	$5.1 \pm 0.6$	4.8	4.3
	$R_{\text{out}}/R_{\text{side}}$	0.88	1.6	1.4

Since the data are corrected they should be compared to the calculations (T) that do not take into account fmr. While the  $R_{\text{side}}$  radii appear to be described even too good the  $R_{\text{out}}$  radii are too large compared to the data. However, these pion radii are considerably smaller than the corresponding radii obtained from the coordinate-space points and using expressions for the Gaussian radius

parameters based on a saddle-point integration over the source function [2, 18]. Only the values presented in the table which are obtained from the complete calculation and the performed fits should be compared to data. The  $R_{\text{out}}/R_{\text{side}}$  ratio is also larger than unity for the fitted values and confirms the so-called *HBT-puzzle*, i.e., the RHIC data from STAR and PHENIX [5, 6] indicate a decreasing ratio with  $K_T$  (even below 1) and all calculations show only ratios larger 1. Note however, that the exp. data are consistent in the sense that they can be described by a single set of fit parameters [19]. On the other hand, there is presently no dynamical transport model describing this trend.

## 4 Discussion of the *HBT-puzzle*

### 4.1 Experimental Uncertainties and SPS data

The following list provides an overview which corrections enter the experimental data analysis. All of them are thought to be under relatively good control and accounted for in the systematic error bars. The numerous corrections illustrate the difficult, complex and challenging task to extract the *true* correlation parameters from the *raw* data. Without further commenting we list the corrections [5] (i) two-track resolution, (ii) particle identification (electrons, contributions from weak decays, e.g.  $\Lambda$ ), (iii) track splitting (one particle interpreted as two), (iv) track merging (two particles interpreted as one, requirement of separated tracks, affects low  $q$  pairs and reduces radii), (v) Coulomb corrections (should be under good control, except maybe influence of weak decay pions), (vi) momentum resolution (strong  $K_T$  dependent correction, reduces radii, see, e.g., Fig. 5), (vii) collider mode peculiarities (collision vertex, i.e., acceptance region varies event by event)

At the CERN-SPS, pion [20, 21, 22, 23] and kaon [24, 25] interferometry have been investigated for Pb+Pb collisions. While some data [21, 22] support an increasing  $R_{\text{out}}/R_{\text{side}}$  ratio with  $K_T$ , being larger than 1, new data from the CERES collaboration [23] indicate a similar trend as the RHIC data [5, 6] show. The former would mean a real qualitative change of the reaction dynamics from SPS to RHIC energies.

### 4.2 Model assumptions and uncertainties

Next, we provide a list of theoretical assumptions and uncertainties, that is by far not complete. (a) the hadronization process itself is usually modelled via a prescription, (b) the binary collision approximation (here only used for the later dilute stages after hadronization) requires in principle sufficiently low

particle densities, (c) the approximation *ideal* fluid dynamics (local thermal distributions, no dissipation) is certainly questionable, in particular if applied for the later dilute stages, (d) the limitations of *pure* hydrodynamical calculations as for example given due to the (pre/de)scription of the freeze-out, (e) the choice of the hadronization hypersurface to *switch* between models needs to be further elaborated (although it seems to be somehow a natural choice due to the limitations of the individual models), (f) the assumption of cylindrical symmetric transverse expansion and longitudinal scaling flow (should be justified at midrapidity and high energies), (g) the role of in-medium effects (both on the hadron properties or the equation of state), (h) the assumption that nucleation proceeds via hadronic bubbles (*well-mixed* phase scenario) may be questioned [see below], (i) the large number of hadronic states in the model equation of state may not be realized (they speed up the hadronization ( $\tau_H \sim \tau_i s_i / s_H(T_c)$ )) and reduce the time-delay signal. So neglecting them should even increase the observed differences.

Fig. 6, taken from Ref. [26] by Zschesche et al., addresses several uncertainties. First of all, the dependence on the latent heat (strong first-order vs. weak first-order vs. cross-over phase transition with a vanishing latent heat) is examined. Secondly, the effect of varying the choice of the freeze-out temperature  $T_f$  is investigated.

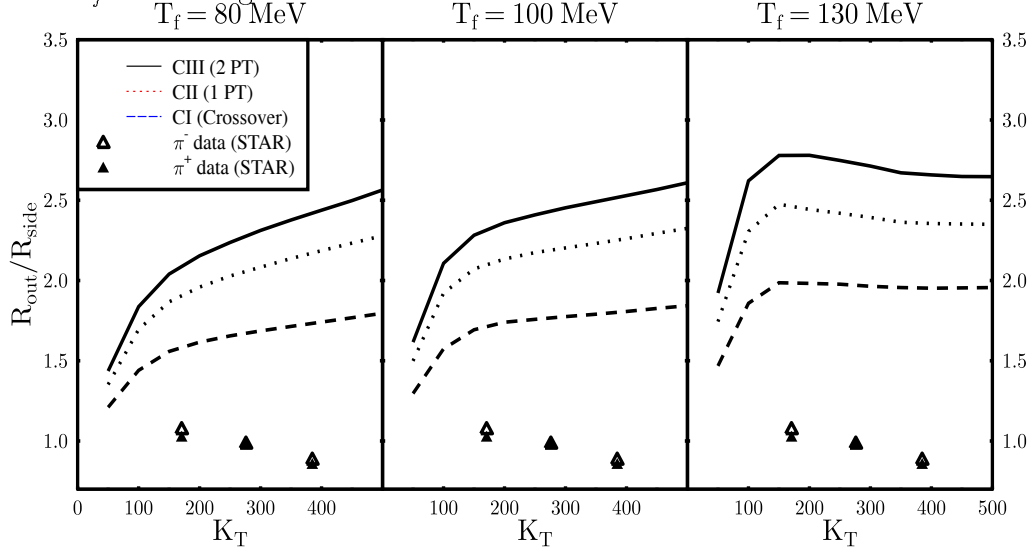


Fig. 6: Figure taken from [26] (Zschesche et al.). *Pure* hydrodynamical calculations with a strong first-order (solid line), a weaker first-order (dotted line), and a cross-over (dashed line) phase transition and different freeze-out temperatures  $T_f$ .

Although reducing the latent heat reduces the large  $R_{\text{out}}/R_{\text{side}}$  ratios, the  $K_T$



dependence of the data cannot be described. Lowering the freeze-out temperature also does not help in this approach. Even rather exotic initial conditions, for example, a collective flow prior to a typical equilibration time of the order of  $\tau_i \sim 1 \text{ fm}/c$ , do not provide a notable improvement [27]. What could help is a strongly opaque source (see also [4, 28]) that suppresses the spatial component in the *out* radius compared to the *side* radius (leaving out of the discussion the role of  $xt$ -correlations).

A completely different model scenario (illustrated in Fig. 7) is existent if the large expansion rate of the system leads to strong supercooling below a *spinodal* temperature  $T_S$  such that the system disintegrates rather instantaneously [29]. In this case of a *spinodal instability* the soft mixed phase vanishes. As a result the reaction times are quite short what should be reflected in the interferometry radii and their ratio. This has to be estimated in a quantitative way.

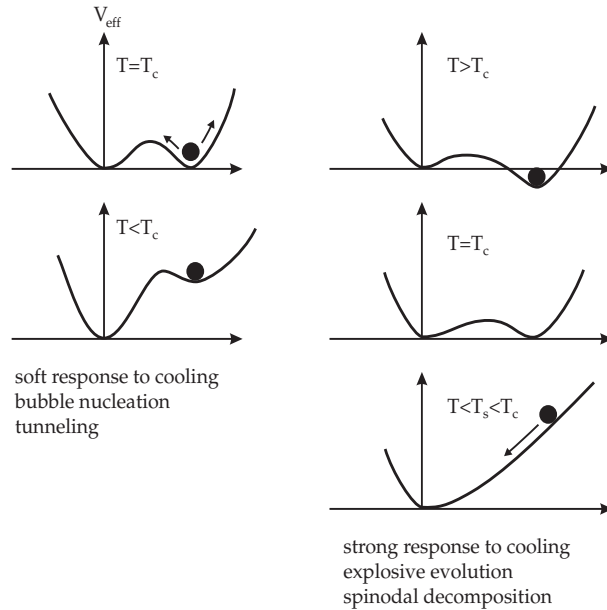


Fig. 7: Illustration of the effective potential for temperatures around the critical temperature  $T_c$  in the case of a *slow* nucleation via a mixed phase (*bubble nucleation*) (left) and in an *explosive* scenario that leads to supercooling down to a spinodal temperature  $T_s$  at or below which the system disintegrates rather instantaneously (right).

## 5 Summary

We demonstrated that the kaon interferometry measurements, in particular at high  $K_T$ , will provide an excellent probe of the space-time dynamics (close to the phase boundary). In addition they represent a severe test of the pion corre-

lations and may help to better understand the *HBT-puzzle*, i.e., the difference in the  $K_T$  dependence of the  $R_{\text{out}}/R_{\text{side}}$  ratio between the model predictions and the experimental (RHIC) data. A closer look showed us that the differences are due to the  $R_{\text{out}}$  radii (which are larger in the model calculations) while the  $R_{\text{side}}$  radii seem to be described reasonably. Finally, we discussed some possible origins of these differences.

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