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Review of Systematic Investigations of the Rout/Rside ratio in HBT at RHIC

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Review of Systematic Investigations of the $R_{\rm out}/R_{\rm side}$ ratio in HBT at RHIC

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Abstract. We review the significant difference in the ratio $R_{\rm out}/R_{\rm side}$ between experiment and theory in heavy-ion collisions at RHIC. This ratio is expected to be strongly correlated with the pion emission duration. Hydrodynamic models typically calculate a value that approximately equal to 1.5 and moderately dependent on k_T whereas the experiments report a value close to unity and independent of k_T. We review those calculations in which systematic variations in the theoretical assumptions were reported. We find that the scenario of second order phase transition or cross-over has been given insufficient attention, and may play an important role in resolving this discrepancy.

1. Introduction

Following the initial measurement of two-pion correlations by Goldhaber, Goldhaber, Lee, and Pais to extract the spatial dimension for pion production in proton-antiproton collision at the Bevatron [1], the technique of two particle correlations – referred to as HBT for the analogous technique in stellar interferometry pioneered by Hanbury Brown and Twiss [2] – has been used extensively to measure source dimensions in high energy and nuclear physics collisions. The technique is based upon the statistical interference and mutual Coulomb repulsion between pairs of pions emitted from a well defined region of space-time that leads to an enhancement in low-relative momentum. The enhanced probability, defined experimentally as the ratio of the relative momentum distribution of pairs from the same event to the distribution of pairs from mixed-events, is fit to multi-dimensional Gaussians to measure the rms source in multiple dimensions. Most modern analyses adopt the Bertsch-Pratt coordinate system [3, 4], in which $R_{\rm long}$ measures the source dimension along the beam momentum, $R_{\rm side}$ measures transverse to the beam and the pion pair momentum, and $R_{\rm out}$ measures transverse to the beam and parallel to the pion pair momentum.

The technique is particularly suited to heavy-ion collisions, where expectations of large source sizes and/or lifetimes have been suggested as potential signatures for the creation of a Quark-Gluon Plasma (QGP) state that would undergo a first order phase back to hadronic matter [3, 6]. In addition, the monotonic decrease of the $R_{\rm long}$ and $R_{\rm side}$ radii is expected for a rapid expansion of the system in the longitudinal and

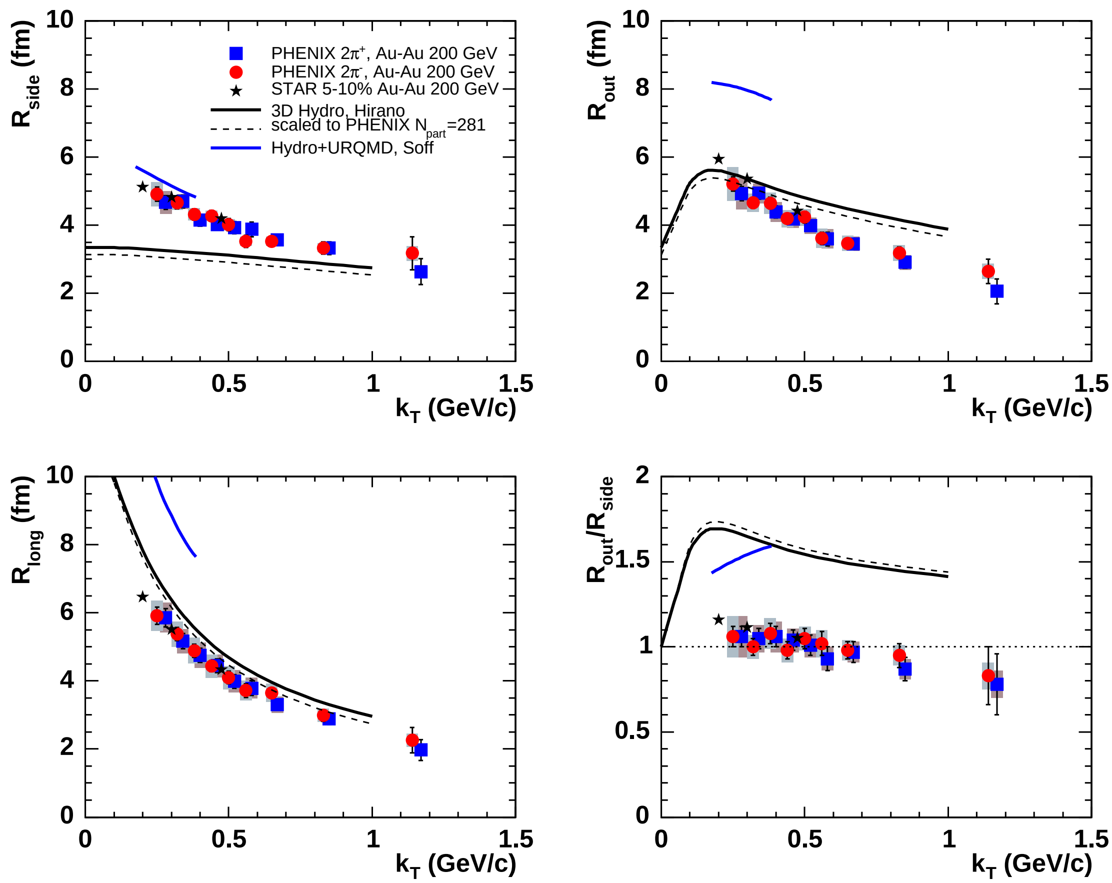

Figure 1. Comparison of the k_T dependence of Bertsch-Pratt radii and $R_{\text{out}}/R_{\text{side}}$ ratio measured by PHENIX, to the hydrodynamical and hybrid model calculations.

transverse directions. In this context, $R_{\text{long}}(k_T)$ provides a measure of the absolute time of the hadronic freeze-out [7] assuming boost invariant expansion, and $R_{\text{side}}(k_T)$ yields a measure the radial flow [8]. However, it is the ratio $R_{\text{out}}/R_{\text{side}}$ that has received the most attention for its ability to provide information on the emission duration.

Fig. 1 shows measurements of the three Bertsch-Pratt radii and the ratio $R_{\text{out}}/R_{\text{side}}$ by STAR and PHENIX [9, 10], compared to the hydrodynamic model of Hirano [11] and the hybrid hydro-UrQMD model [12]. These models display the typical range in predictions for $R_{\text{out}}/R_{\text{side}}$, from 1.5–2.0, whereas the data are close to unity and approximately independent of k_T. This discrepancy, taken together with the relative independence of the R_{side} radii over the range of energies accessible to the AGS, SPS, and RHIC, is referred to as the HBT Puzzle.

There has been a broad range of speculation on the possible solutions to the HBT puzzle. It is not the goal of this paper to review them all. Instead, this review will focus on the relatively few instances in the literature where this HBT Puzzle has been the subject of a systematic investigation to understand the impact of one or more variablea on the k_T dependence of the radii and the $R_{\text{out}}/R_{\text{side}}$ ratio. The variables that have been studied in this way are the partonic cross-sections, the inclusion of $x-t$ correlations, the critical temperature and latent heat, and the order and existence of a phase transition.

2. The role of x-t correlations

Before an investigation of the physical parameters in hydrodynamical and transport codes that may relate to the equation of state of the QGP, it is important to understand the implications of the sudden freeze-out approximation. In nearly all hydro models, the mean free path changes instantaneously from infinitesimal to infinite when the temperature of a hypersurface falls below a pre-determined freeze-out temperature. This unphysical approximation has a direct effect on the calculated value of R_{out}, as defined in Eq. 1,

$$R_{\text{out}}^2 = \tilde{x}^2 + \beta_T^2\tilde{\tau}^2 - 2\beta_T\tilde{x}\tilde{\tau}. \tag{1}$$

The x-t correlation enters as a signed quantity and can serve to increase or decrease the value of R_{out} depending on whether the freeze-out proceeds outside-in or inside-out, respectively. Calculations by Lin *et al.* using the AMPT code have found that the x-t contribution ($-2\beta_T\tilde{x}\tilde{\tau}$) is negative (inside-out cascade) and appreciable to the contribution from the purely spatial and purely temporal components [13]. The role of dynamical effects has been noted previously at lower energies using RQMD [14].

In order to make meaningful comparisons to the data, it will be necessary for hydrodynamic codes to employ a transport afterburner to calculate the freeze-out profile, or to apply a realistic parameterization of such a freeze-out profile. The hybrid approach of Soff *et al.* [12] shown in Fig. 1 is one example of this, but it does not lead to an improved agreement with the data.

3. Partonic Cross-sections

The possibility that the HBT radii may be sensitive to the elastic partonic cross-sections has been investigated by Lin using AMPT [13], and Molnar using MPC [15]. Although Lin reports a significant change in the correlation function, the fitted radii do not appear to depend significantly on partonic cross-sections in the range of 3–16 mb, as shown in Fig. 2. Using a fully Lorentz covariant transport code, but considering only the partonic stage Molnar finds a significant dependence in both R_{out} and R_{long} when the opacity is reduced to zero, and the radii measure the initial state geometry. However, for reasonable values of the opacity, corresponding to elastic cross-sections in the range of 3–7.5 mb, the relative variation in the radii is less than 5%.

4. Critical Temperature and Latent Heat

Soff *et al.* have investigated the dependence of the two-kaon correlation function while varying the critical temperature from 160 MeV to 200 MeV, corresponding to latent heats of 1.6 and 2.9 GeV [16]. Fig. 3 shows the slight reduction in the value of R_{out}

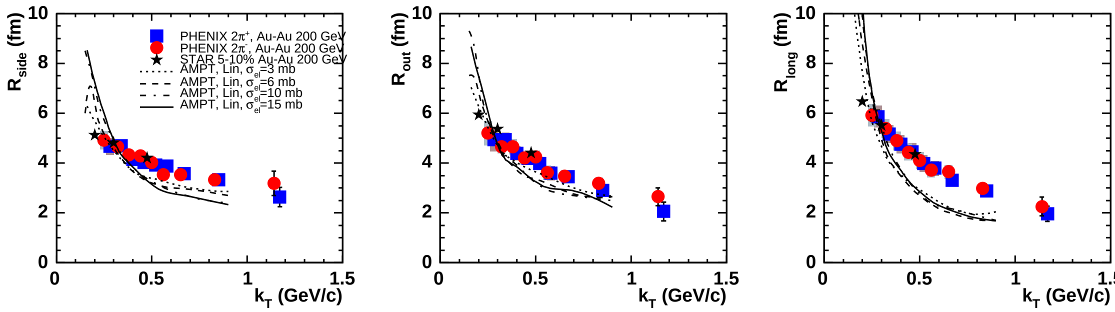

Figure 2. Comparison of the k_T dependence of Bertsch-Pratt radii and $R_{\rm out}/R_{\rm side}$ ratio measured by PHENIX, to the calculations performed with AMPT with partonic cross-sections of 3, 6, 10, and 15 mb.

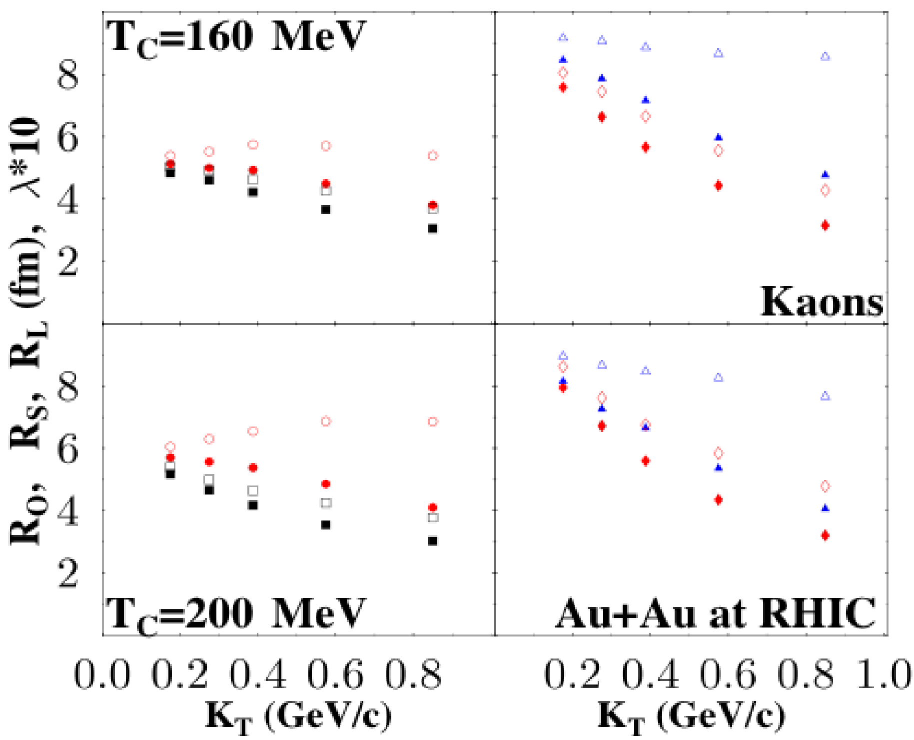

Figure 3. $R_{\rm side}$ (squares), $R_{\rm out}$ (circles), $R_{\rm long}$ (diamonds) and $\lambda * 10$ (triangles) vs. k_T for kaon HBT at critical temperatures of 160 MeV and 200 MeV. Filled symbols include a momentum resolution smearing of 2% of k_T.

relative to $R_{\rm side}$ for the smaller critical temperature and lower latent heat. This has been attributed to the shortened hadronic phase, as was shown for pions in [12].

Fig 3 also shows a significant dependence on the momentum resolution, shown as the difference between open and filled symbols. While this effect is significant for this study, it is highly dependent on the experiment. Most experiments perform a Monte Carlo simulation to apply a correction [9], or to incorporate the effect into systematic

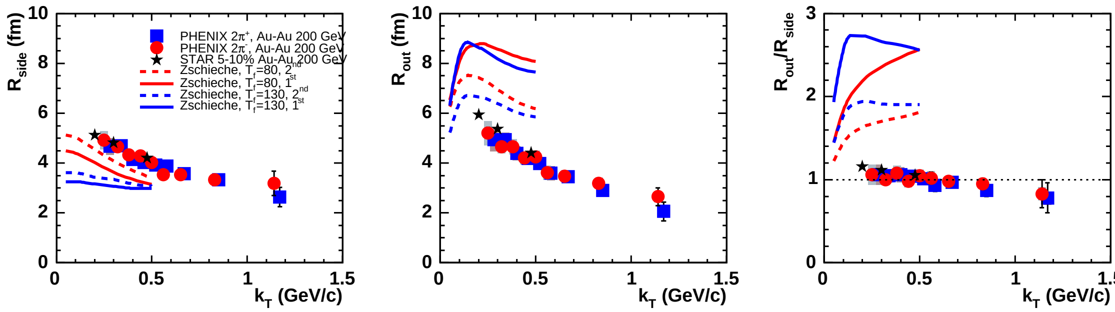

Figure 4. $R_{\rm out}$, $R_{\rm side}$, and $R_{\rm out}/R_{\rm side}$ vs. kT for chiral phase transition model of Zschiesche for first and second order phase transitions and critical temperatures of 80 and 130 MeV compared to measured values of PHENIX and STAR.

errors [10].

5. Transition Order

To date, there has been only one attempt to study the dependence of the HBT parameters on the transition order, albeit for a chiral transition rather than the deconfinement transition. Fig. 4 shows results for a two-dimensional calculation for two critical temperatures, 80 and 130 MeV for both first and second order transitions [17]. The authors find a significant decrease in the $R_{\rm out}$ and the hence $R_{\rm out}/R_{\rm side}$ for a second order phase transition. There is also a significant decrease in $R_{\rm out}/R_{\rm side}$ for the lower critical temperature in both cases.

6. Conclusions

In review, we find little dependence on the partonic cross-sections. There is a significant dependence of $R_{\rm out}/R_{\rm side}$ on the freeze-out profile as determined by the inclusion of x-t correlations, although there have been relatively few studies that have quantified this effect. Nevertheless, this is consistent with the view that the pion HBT measurements are mostly sensitive to the later stages of the collision. This situation may be different for kaons, where Soff [16] found that at 1 GeV/c $\sim 30\%$ of kaons are emitted directly from the phase boundary.

There appears to be a strong dependence on the critical and order of the transition temperature. Although none of the examples was shown to reproduce the data, we observed systematic reductions in the $R_{\rm out}/R_{\rm side}$ ratio of as much as 50% when either the critical temperature was lowered (latent heat reduced for first order transition) or a second order transition was assumed. This suggests that a small latent heat, or second order phase transition may be a necessary ingredient in any model that can give a complete description of the soft physics observable at RHIC.

No calculations of HBT radii have been performed for the case of a cross-over between the hadrons and deconfined quarks and gluons, despite the fact that recent LQCD calculations have demonstrated this to be a possibility some values of the dynamical quark masses [18]. This avenue of research appears worth pursuing. In closing, we wish to stress that any viable solution to the HBT puzzle must provide a complete characterization of all appropriate physics signatures accessible to us a RHIC.

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