Vol. 35 (2004) ACTA PHYSICA POLONICA B No 1

WHAT WE KNOW ABOUT HBT AT RHIC*

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(Received November 26, 2003)

The first measurements of the pion source dimensions for Au–Au collisions at RHIC gave no direct evidence for a large or long-lived source, as previously expected for a deconfinement phase transition. This result has proved to be something of a puzzle when taken in context with indications of jet suppression for central Au–Au collisions. With the goal of illuminating what we do not know, we review aspects of our understanding of the two-particle correlation measurements that have recently yielded to relatively new analysis techniques, in 3-pion correlations, non-identical particle correlations, and self-consistent treatments of the Coulomb interaction.

PACS numbers: 25.75.–q, 25.75.Gz

1. Introduction

Following the initial measurements of enhanced production of identical charged pions at small opening angle induced by Goldhaber, Lee and Pais [1], the technique of two-pion correlations has been used extensively to measure source sizes in elementary particle and heavy ion collisions over a range of systems and energies. The extracted Gaussian radii, often referred to as HBT radii, after the analogous technique of intensity interferometry pioneered by Hanbury-Brown and Twiss [2], are independent of energy, contrary to expectations of a large/long-lived pion source for a deconfinement phase transition [3,4]. Fig. 1 shows the k_{T} dependence of the Bertcsh–Pratt radii, where R_s measures the rms radius transverse to both the beam and the pion pair velocity, R_o measures transverse to the beam and parallel to the pair velocity, and R_l measures along the beam direction. The radii show no significant energy dependence, in the two transverse dimensions, and a

* Presented at the XXXIII International Symposium on Multiparticle Dynamics, Kraków, Poland, September 5–11, 2003.

monotonic increase with beam energy in the longitudinal direction. The k_{T} dependence, generally interpreted as resulting from the system expansion, also appears to be very similar for different beam energies.

The most striking non-feature of Fig. 1 is the absence of any strong increase in the ratio of R_o to R_s, predicted as an indication of long-lived pion source that would accompany a deconfinement phase transition. Recent calculations yield a ratio of R_o/R_s to close to a value of 1.5, for moderate values of k_{T}, still far above the values of unity measured by the RHIC experiments [7, 8]. This discrepancy between theory and experiment, referred to as the "HBT puzzle", has become a focal point for the community. While theorists have searched for explanations, experimentalists have struggled to reduce systematic errors. The latter effort, combined with higher statistics data sets has led to a reduction in overall systematics errors, and an improved understanding of the HBT parameters, in particular the chaoticity parameter, λ.

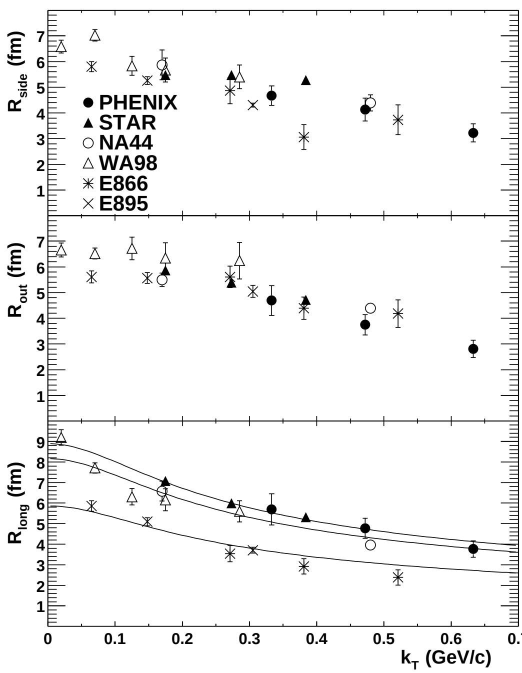

Fig. 1. Summary of HBT radii for pion pairs in heavy-ion collisions as a function of k_{T} measured at mid-rapidity for various energies from E895 ($\sqrt{s_{NN}} = 4.1$ GeV), E866 ($\sqrt{s_{NN}} = 4.9$ GeV), NA44, WA98 ($\sqrt{s_{NN}} = 17.3$ GeV), STAR, and PHENIX ($\sqrt{s_{NN}} = 130$ GeV). The bottom plot includes fits to $A/\sqrt{m_{\mathrm{T}}}$ for each energy region. The data are for π^- results except for the NA44 results, which are for π^+. Results are from [7] and references therein.

2. Measuring the chaoticity

For more than twenty years, two-pion correlations have been fit to the following form, $C_2(\boldsymbol{q}) = 1 + \lambda G(\boldsymbol{R}, \boldsymbol{q})$, where, $\boldsymbol{R}$ and $\boldsymbol{q}$ are the 4-vector fit-radius and relative momentum, respectively, and λ is a factor introduced to account for the fact that $C_2(\boldsymbol{q} = 0) < 1$, and G is the Gaussian representation of the source term. The two leading explanations for this fact have been the weak decay resonances from an outer halo that is too large to be resolved by experiments, and coherent pion production. A small contribution also results from the mis-identification of particles. Although a large component of coherent production is unlikely, until recently there had been no independent measure to constrain this contribution.

This changed with the theoretical work of Heinz and Zhang [9] and the subsequent measurement of the three-pion correlation function by the STAR collaboration [10]. In a three-pion correlation function, properly normalized as in Eq. (1), the halo and mis-dentified particle contributions cancel, and the intercept, $C_3(Q_3 = 0)$, provides a direct measure of the chaotic fraction, ε, as given by Eq. (2). The coherent contribution to the deviation of λ from unity is given by square of the coherent fraction, $1 - \lambda = (1 - \varepsilon)^2$.

$$r_3\left(Q_3\right) = \frac{\left(C_3\left(Q_3\right)-1\right)-\left(C_2\left(Q_{12}\right)-1\right)-\left(C_2\left(Q_{23}\right)-1\right)-\left(C_2\left(Q_{31}\right)-1\right)}{\sqrt{\left(C_2\left(Q_{12}\right)-1\right)\left(C_2\left(Q_{23}\right)-1\right)\left(C_2\left(Q_{31}\right)-1\right)}}\,, \tag{1}$$

$$\frac{1}{2}\, r_3\left(Q_3{=}0\right) = \sqrt{\varepsilon}\,\frac{3-2\varepsilon}{(2-\varepsilon)^{3/2}}\,. \tag{2}$$

Measurements of the three-pion correlation for central and mid-central 130 GeV Au–Au collisions by the STAR collaboration are shown in Fig. 2. The extrapolations to $Q_3 = 0$ are consistent with unity (fully chaotic source) for the central systems, and nearly consistent with unity for mid-central collisions. After accounting for an over-correction of the Coulomb interaction for decay products, the extracted chaotic fractions remain consistent with unity for the central collisions, and approximately 0.6 for mid-central collisions, a value which contributes 0.15 to the reduction of λ. Although the difference between central and mid-central extracted coherent fractions remains to be understood, the elimination of coherence as a possible explanation of $\lambda < 1$ in central collisions has important consequences for the treatment of the Coulomb final state interaction.

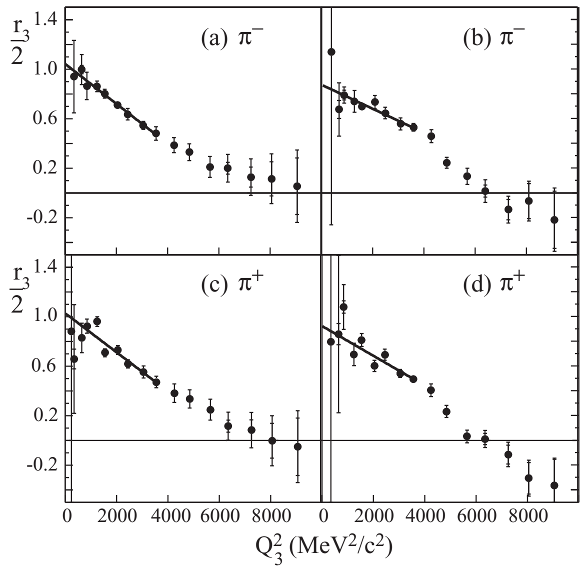

Fig. 2. 130 GeV Au–Au collisions measured by the STAR collaboration in (a) central and (b) mid-central π^- events and (c) central and (d) mid-central π^+ events.

3. Self-consistent treatment of the Coulomb interaction

Early analyses of two-pion correlations included only the affects of the Bose–Einstein interference. The treatment of the Coulomb final-state interaction was introduced by Zajc [11] in the form of the Gamow factor, the analytical calculation of relative momentum probability for charged particles emanating from a point source. Current analyses use an iterative correction procedure which calculates the Coulomb final state interaction over a finite source, but still assuming that all measured pion pairs are emanating from the same size source.

If, however, a substantial fraction of the pairs are daughters of long lived decays then the Coulomb interaction would be negligible for these pairs. Therefore the traditional full correction factor amounts to an *overcorrection*, as first noted by Bowler [12, 13] and applied to the experimental data of CERES [14].

The affects of this over-correction depend upon the experimental acceptance, in particular the $k_{\rm T}$ distribution of pairs. However, preliminary analyses by PHENIX and STAR have both discovered that the application of a self-consistent Coulomb correction has the largest affect on R_o, leading to an increase in the ratio R_o/R_s of approximately 10%, notable, but insufficient to eliminate the disagreement between theory and data.

4. Centrality dependence

Considering the challenge we face in understanding the HBT results, it is worth reviewing one remarkable feature of the HBT radii scaling with system size and/or centrality. The naive linear scaling with the number of participants to the one-third power ($N_{\rm part}^{1/3}$) has continued to describe the data from Bevelac energies [15], the AGS [16], and RHIC. Fig. 3 shows the strong linear dependence of the three Bertsch–Pratt radii with ($N_{\rm part}^{1/3}$) for Au–Au collisions at 200 GeV from PHENIX.

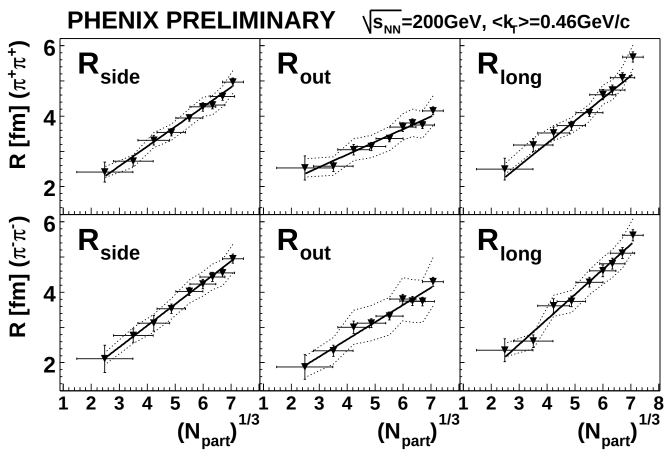

Fig. 3. Scaling of HBT parameters with number of participants ($N_{\rm part}$).

5. Conclusion and epilogue

Recent improvements in the treatment of the Coulomb correction supported by the first analysis of the three-pion correlation have led to significant reduction in the systematic errors associated with the determination the radii and their ratios. The discrepancy between theory and data for HBT at RHIC, while expected to be narrower with upcoming published data, will remain a challenge for the theoretical community (see paper by Sven Soff in these proceedings, p. 23).

In closing, we note that the similarity in $k_{\rm T}$ dependence may also apply across different systems, possibly extending all the way to proton–proton collisions. Fig. 4 shows the $k_{\rm T}$ dependence for STAR and PHENIX, compared to $1D$ and $2D$ HBT radii for NA27 and E735 [17, 18], with all radii normalized to their value at $k_{\rm T} \approx 1$. Note that the NA27 fit to a $1D$ Bessel Function is converted to the r.m.s. equivalent and compared to R_s values.

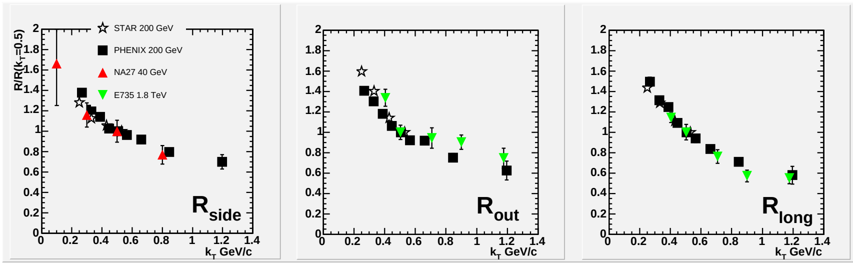

Fig. 4. Comparison of relative k_{T} dependence of heavy-ion and proton–proton HBT parameters. All radii are normalized to their values at $k_{\mathrm{T}} \approx 0.5$.

The E735 radius, R, and lifetime τ, are compared to R_l, consistent with the E735 interpretation for their acceptance, and the lifetime of emission, τ, is compared to R_o, which has the largest such contribution for STAR and PHENIX. Though crude at best, this comparison certainly calls out for improved measurements of HBT in proton–proton collisions.

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