AZIMUTHALLY-SENSITIVE INTERFEROMETRY AND THE SOURCE LIFETIME AT RHIC*

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Pion interferometry ("HBT") measurements relative to the reaction plane provide an estimate of the transverse source anisotropy at freeze-out, which probes the system dynamics and evolution duration. Measurements by the STAR Collaboration indicate that the source is extended increasingly out-of-plane with increasing impact parameter, suggesting a short evolution duration, roughly consistent with estimates based on azimuthally-integrated HBT measurements.

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1. Introduction

Two-particle intensity interferometry (Hanbury-Brown–Twiss, or HBT) analyses of relativistic heavy ion collisions represent the most direct experimental probes of the space-time structure of the source generated in such collisions [1]. At the Relativistic Heavy Ion Collider (RHIC), identical-pion HBT studies in Au + Au collisions [2–4] yielded an apparent source size quantitatively consistent with measurements at lower energies, in contrast to predictions of larger sources based on QGP formation [5]. In addition, hydrodynamical models, successful at RHIC in describing momentum-space quantities such as transverse momentum spectra and elliptic flow [11], have failed to reproduce the small HBT radii [6]. This "HBT puzzle" [7, 8] may arise because the system's lifetime is shorter than predicted by models.

In non-central collisions, the initial anisotropic collision geometry generates greater transverse pressure gradients in the reaction plane than perpendicular to it. This leads to preferential in-plane expansion (elliptic

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flow) [9–12] which diminishes the initial spatial anisotropy. The final (freeze-out) source shape should be sensitive to the evolution of the pressure gradients and the system lifetime; a long-lived source would be less out-of-plane extended and perhaps in-plane extended. Hydrodynamic calculations [13] predict a strong sensitivity of the HBT parameters to the early source conditions and show that, while the source may still be *out-of-plane* extended after hydrodynamic evolution, a subsequent rescattering phase [14] tends to make the source *in-plane*. Thus, the freeze-out source shape might discriminate between scenarios of the system's evolution.

Here, we present results of a measurement of azimuthally-sensitive HBT in Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV. We discuss how these results may be used to extract, in a model-dependent way, the geometric anisotropy of the source at freeze-out. Finally, we use this extracted geometry to estimate the evolution timescale of the system.

2. Measurement

The measurements were made using the STAR detector [15] at RHIC. Particle trajectories and momenta were reconstructed using a Time Projection Chamber (TPC) with full azimuthal coverage, located inside a 0.5 Tesla solenoidal magnet. Au + Au event samples of 0–5%, 5–10%, 10–20%, 20–30% and 30–80% of the total cross hadronic section (based on charged particle multiplicity) are presented here. The second-order event plane angle Ψ_2 [16] for each event was determined from the weighted sum of primary charged-particle transverse momenta ($\vec{p}_{\mathrm{T}}$) [17]. Within the resolution which we determine from the random subevent method [16], $\Psi_2 \approx \Psi_{\mathrm{rp}}$ (true reaction plane angle) or $\Psi_2 \approx \Psi_{\mathrm{rp}} + \pi$; *i.e.* the direction of the impact parameter vector is determined up to a sign [16], and the measured event plane is roughly coplanar with the true reaction plane [18].

Pions were selected according to their specific energy loss (dE/dx) in the TPC in the rapidity range $|y| < 0.5$. Pair-wise cuts to remove two-track merging and single-track splitting effects were applied to signal and background distributions [2].

Pairs of like-sign pions were placed into bins of $\Phi = \phi_{\mathrm{pair}} - \Psi_2$, where ϕ_{pair} is the azimuthal angle of the total pair momentum ($\boldsymbol{k} = \boldsymbol{p}_1 + \boldsymbol{p}_2$). Because we use the 2^{nd}-order event plane, Φ is only defined in the range $(0, \pi)$. For each bin, a three-dimensional correlation function is constructed in the "out-side-long" decomposition [19] of the relative momentum $\boldsymbol{q}$.

Finite reaction plane resolution and finite width of the Φ bins has the effect of reducing the measured oscillation amplitudes. A model-independent correction procedure [20] is applied to each $\boldsymbol{q}$-bin in the numerator and

denominator of each correlation function, the overall effect of which is to increase the amplitude of the oscillations of the HBT radii *vs* $\Phi(\sim 10$–$30\%)$.

To account for the effect of final-state Coulomb interactions, we adopt the approach first proposed by Bowler [21] and Sinyukov [22] and recently advocated by the CERES collaboration [23]. We fit each experimental correlation function to the form:

$$C(\boldsymbol{q}, \Phi) = N\,[(1-\lambda)\,1 + \lambda\,K(\boldsymbol{q})(1 + G(\boldsymbol{q}, \Phi))], \tag{1}$$

where the $(1-\lambda)$ and λ terms account for the non-participating and participating fractions of pairs, respectively, $K(Q_{\rm inv})$ is the square of the Coulomb wave-function, N is the normalization, and $G(\boldsymbol{q}, \Phi)$ is the Gaussian form [19]:

$$G(\boldsymbol{q}, \Phi) = \mathrm{e}^{-q_o^2 R_o^2(\Phi) - q_s^2 R_s^2(\Phi) - q_l^2 R_l^2(\Phi) - q_o q_s R_{os}^2(\Phi)}. \tag{2}$$

R_i^2 are the squared HBT radii, where the l, s, o subscripts indicate the long (parallel to beam), side (perpendicular to beam and total pair momentum) and out (perpendicular to q_l and q_s) decomposition of $\boldsymbol{q}$.

3. Results, Fourier coefficients and estimating eccentricity

Figure 1 shows the squared HBT radii as a function of Φ, for three centrality classes and $0.15 \le k_{\rm T} \le 0.6$ GeV/c. Curves correspond to a Fourier decomposition of the squared-radii oscillations according to [20, 24]

$$R^2_{\mu,n}(k_{\rm T}) = \begin{cases} \langle R^2_\mu(k_{\rm T}, \Phi)\cos(n\,\Phi)\rangle & (\mu = o, s, l)\,, \\ \langle R^2_\mu(k_{\rm T}, \Phi)\sin(n\,\Phi)\rangle & (\mu = o, s)\,. \end{cases} \tag{3}$$

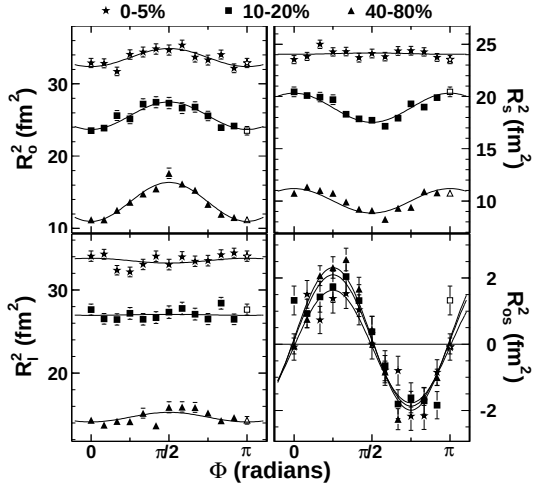


Fig. 1. Squared HBT radii measured relative to the reaction plane, for three selections of event centrality.

As expected [2], the 0^{th}-order Fourier coefficients (FCs), *i.e.* the mean value of the radii, indicate larger source sizes for more central collisions. We verified that the 0^{th}-order FC for R_o^2, R_s^2 and R_l^2 correspond to HBT radii obtained in an azimuthally-integrated analysis. Higher-order ($n > 2$) FCs were found to be negligible.

HBT radii directly measure homogeneity regions [1,26], which constitute only part of the "whole" source; hence, connections to the overall source geometry inevitably rely on a model. The so-called blast-wave model [27] has been relatively successful in describing soft physics observables (spectra, elliptic flow, azimuthally-integrated HBT) at RHIC. In the context of a generalized blast-wave, with spatial and flow anisotropies, a recent study [27] finds that the transverse source shape is related to $R_s^2(\Phi)$ as

$$\varepsilon \equiv \frac{\left(R_y^2 - R_x^2\right)}{\left(R_y^2 + R_x^2\right)} \approx \frac{1}{2}\frac{R_{s,2}^2}{R_{s,0}^2} \approx \frac{1}{2}\frac{R_{o,2}^2}{R_{s,0}^2} \approx \frac{1}{2}\frac{R_{os,2}^2}{R_{s,0}^2}\,. \tag{4}$$

Where R_x and R_y are the source length scales in and out of the reaction plane, respectively. The approximation becomes exact in the case of vanishing transverse flow [25,28]. In figure 2 are the 0^{th} and 2^{nd}-order FCs, as defined in Eq. (3), for three sources as calculated in the blast-wave. The sources have the same temperature, radial flow, timescales, and average size (all adjusted roughly to the values which best describe RHIC data), but differing ε. Changing from a round ($\varepsilon = 0$) to a deformed source increases the oscillations of the transverse radii (and, very slightly — note the scale) the longitudinal radius. Equation (4) arises from the observation that 2ε, indicated by small arrows on the right panels, approximately reproduces the relative oscillations in the transverse radii. Therefore, relying on the blast-wave model for context, we may estimate the freeze-out source shape.

Figure 3 shows the measured FCs, as a function of centrality, for three bins in k_{T}, quantifying the increasing size (left panels) and decreasing anisotropy (right panels) as the collision becomes more central. In figure 4, we compare the initial anisotropy, $\varepsilon_{\text{initial}}$, calculated with a Glauber model outlined in reference [29], with $\varepsilon_{\text{final}}$, estimated by applying Eq. (4) to the data of figure 3. We note that $\varepsilon_{\text{final}}$ has a meaningful sign, and its positive values indicate that the timescales and/or flow velocities of these collisions are not sufficiently large to fully quench the initial out-of-plane geometric anisotropy of the system.

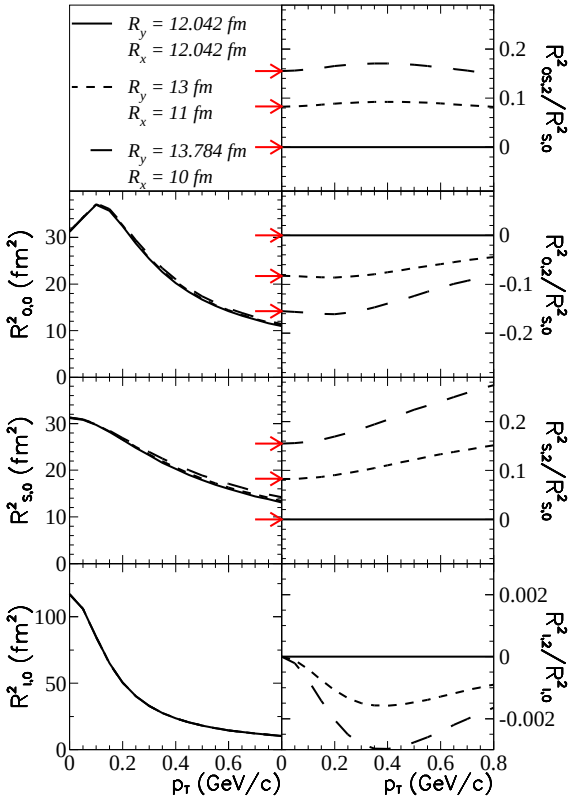


Fig. 2. Blast-wave [27] calculations of Fourier coefficients for the oscillations of squared HBT radii, for three sources of varying transverse eccentricity. Arrows indicate approximation of Eq. (4).

4. A connection to timescales

The data in figure 3 should provide useful constraints on timescales and evolution in transport models of heavy ion collisions. As a crude example, here we take the model-dependent data in figure 4 one step further. Motivated by hydrodynamical calculations [30], we assume that the transverse flow strength grows roughly linearly with time, and anisotropies in the flow field set in very early. Since there is no collective flow initially, the flow velocity and source extensions in (x) and out of (y) the reaction plane evolve with time as

$$\beta_{x,y}(t) = \frac{t}{\tau_0}\,\beta^{\mathrm{FO}}_{x,y} \quad \longrightarrow \quad R_{x,y}(t) = R^{\mathrm{Glauber}}_{x,y} + \frac{1}{2}\left(\frac{\beta^{\mathrm{FO}}_{x,y}}{\tau_0}\right) t^2. \qquad (5)$$

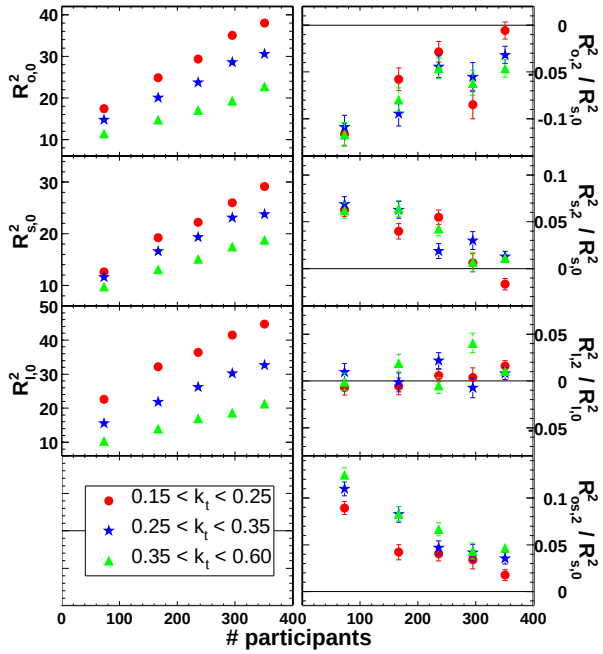


Fig. 3. Fourier coefficients for the oscillations of squared HBT radii, for 3 k_{T} bins, *versus* centrality (number of participating nucleons) measured by STAR. Left panels: means (0^{th}-order FC) of oscillations; right panels: relative 2^{nd}-order oscillation amplitudes. See text for details.

Here, β^{FO} is the flow velocity (at the edge of the source) at freeze-out, and τ_0 is the evolution time of the system — from initial overlap until freeze-out. From Eq. (5), we may calculate $\varepsilon(t)$ in this toy model.

For collisions between 10–20% of the cross-section (3^{rd} centrality bin in figures 3 and 4), the estimated initial and final anisotropies are indicated in figure 5. Estimates for $\beta^{\mathrm{FO}}_{x,y}$ were taken from blast-wave fits [27] to mid-central collisions at $\sqrt{s_{NN}} = 130$ GeV. In order to evolve ε, we must assume a value for τ_0. Blast-wave fits [27] to azimuthally-integrated longitudinal HBT radii suggest a rather short evolution time of ~ 9 fm/c. Assuming this value, we arrive at a consistent picture: as shown by the solid line in figure 5, at $t = \tau_0 = 9$ fm/c, ε has reached its measured value. On the other hand, using a significantly different value for τ_0 yields inconsistent results, as shown by the dashed and dotted lines. Thus, our measurements, in the context of this admittedly crude model, seem to provide corroborating evidence in the direction of evolution timescales on the order of 9 fm/c.

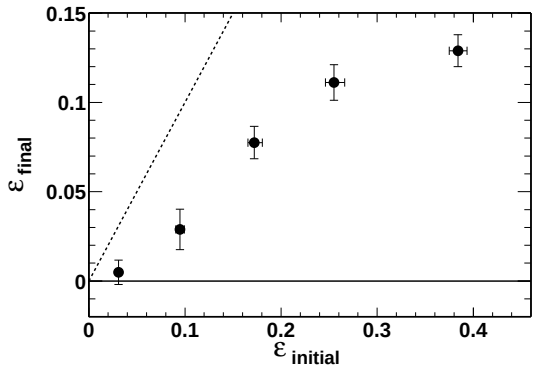


Fig. 4. Final (from HBT) *versus* initial (from Glauber) transverse source eccentricity, estimated from the data in Fig. 3 and Eq. (4). The line represents $\varepsilon_{\text{initial}} = \varepsilon_{\text{final}}$.

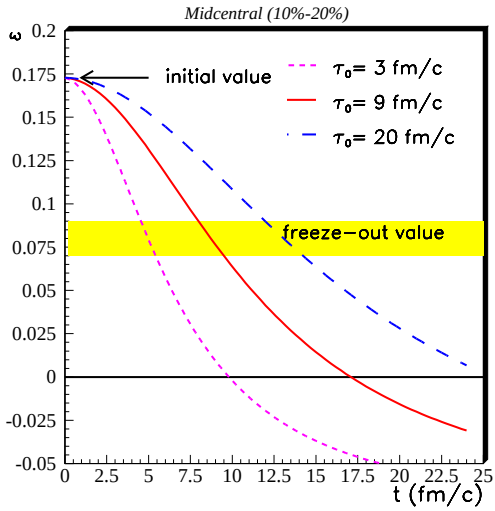


Fig. 5. Toy-model calculations for the evolution of the transverse eccentricity as a function of time. See text for details.

5. Summary

We have presented an analysis of azimuthally-sensitive pion interferometry for Au + Au collisions at RHIC. We observe clear 2^{nd}-order oscillations of the transverse HBT radii, and extract Fourier coefficients. Geometrically, as the impact parameter decreases, the 0^{th}-order FCs increase, indicating larger sources, and the relative oscillations decrease, suggesting rounder ones. More quantitative statements rely on model interpretations.

In the blast-wave model, the relative oscillations provide a good estimate of the source ellipticity at freeze-out. In this context, we find that the source at all centralities is extended out of the reaction plane (though not as much as the initial source), suggesting rather short evolution durations.

This data should provide strong constraints on dynamic models of heavy ion collisions, particularly as regards timescales and pressure anisotropies. To illustrate the point, we performed a toy model calculation which turned out to favor the rather short evolution timescales extracted via other means previously.

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