Azimuthal-Angle Dependence of Charged-Pion-Interferometry Measurements with Respect to Second- and Third-Order Event Planes in Au + Au Collisions at $\sqrt{s_{NN}} = 200$ GeV

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Charged-pion-interferometry measurements were made with respect to the second- and third-order event plane for Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV. A strong azimuthal-angle dependence of the extracted Gaussian-source radii was observed with respect to both the second- and third-order event planes. The results for the second-order dependence indicate that the initial eccentricity is reduced during the medium evolution, which is consistent with previous results. In contrast, the results for the third-order dependence indicate that the initial triangular shape is significantly reduced and potentially reversed by the end of the medium evolution, and that the third-order oscillations are largely dominated by the dynamical effects from triangular flow.

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The quark-gluon plasma (QGP), a state of nuclear matter in which quarks and gluons are deconfined, is produced in nuclear collisions at sufficiently high energy [1–4]. Once formed, the QGP expands, cools, and then freezes out into a collection of final-state particles. From extensive measurements of final-particle momenta and correlations, a detailed space-time picture of the evolution of the QGP is emerging [5,6], but detailed studies of the final space-time distribution of hadrons and an understanding of the dependence on the initial-collision geometry are needed to complete this picture.

Quantum-statistical interferometry of two identical particles, also known as Hanbury Brown–Twiss (HBT) interferometry [7,8], provides information on the space-time extent of the particle-emitting source. In heavy-ion collisions, hadron interferometry is sensitive to the space-time extent of the hadronic system at the time of the last scattering, referred to as kinetic freeze-out. In noncentral collisions of like nuclei, the initial density distribution is predominantly elliptical in shape, with additional fluctuations [9]. There is a larger pressure gradient along the minor axis (in plane) of the ellipse, compared to that along the major axis (out of plane), and this leads to a stronger expansion of the source within the in-plane direction. This phenomenon, elliptic flow, reduces the eccentricity of the spatial distribution in the transverse plane, and may even reverse the major and minor axes of the initial distributions. Previous results are consistent with the picture that the final distribution still retains the initial elliptical orientation, although with a smaller eccentricity upon freeze-out [10].

The full set of anisotropic moments of the flow is characterized by the Fourier coefficients of the azimuthal distribution of emitted particles: $dN/d\phi \propto 1 + 2\sum v_n \cos[n(\phi - \Psi_n)]$, where ϕ is the azimuthal angle of the particle, v_n is the strength of nth-order flow harmonic, and Ψ_n is the nth-order event plane, where Ψ_2 and Ψ_3 are independent [11]. Elliptic flow is defined by the second-order coefficient ($n = 2$), but triangular ($n = 3$), quadrangular ($n = 4$), and higher-order moments are also present and have been measured in both the spatial and momentum distributions in heavy-ion collisions [11–13]. While the higher-order even moments are needed to accurately describe the original elliptic shape, the odd moments arise predominantly through fluctuations in the initial spatial distribution or parity-odd processes, which are presumably small. Depending on strength of the fluctuations, flow profile, expansion time, and shear viscosity, these initial spatial fluctuations may be preserved until freeze-out [14,15].

In relativistic heavy-ion collisions, HBT interferometry with respect to different order event planes uniquely probes the magnitude of the initial-state fluctuations and the subsequent space-time evolution, thereby providing important constraints on the dynamics of the QGP. Here, we present results of azimuthal HBT measurements of charged pions with respect to the second-order event plane, as well as the first results with respect to the third-order event plane in Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV at central rapidity. The centrality and transverse momentum dependence are also presented.

This analysis is based on data collected in 2007 with the PHENIX detector [16]. Collision centrality was determined using the measured charge distribution in the beam-beam counters ($3.0 < |\eta| < 3.9$) [17]. The event planes Ψ_n were determined using the reaction plane detector (RXNP) covering forward and backward angles $1.0 < |\eta| < 2.8$ [18]. The event plane resolution $\mathrm{res}(\Psi_n)$ was estimated by the two-subevent method [19] using the Ψ_n correlation between the RXNP at forward and backward angles, where $\mathrm{res}(\Psi_n)$ is defined as $\langle\cos[n(\Psi_n - \Psi_{n,\mathrm{real}})]\rangle$. Track and momentum reconstruction of charged particles was performed by combining hits from the drift chamber and pad chambers in the central spectrometers ($|\eta| < 0.35$), where the momentum resolution is $\delta p/p \approx 1.3\% \oplus 1.2\% \times p$ [20]. Charged pions were identified by combining time of flight from the electromagnetic calorimeters [21] covering azimuthal angle $\Delta\phi = \pi/2$, with reconstructed momentum and trajectory in the magnetic field. Particles within 2 standard deviations of the peak of charged pions in mass-squared distributions were identified as pions up to a momentum of ~ 1 GeV$/c$.

The experimentally measured correlation function is defined as $A(q)/B(q)$, where $A(q)$ is the relative-momentum distribution of all combinations of identified pion pairs in the same event, and $B(q)$ is the event-mixed background distribution of pairs formed from pions from different events, but with similar event centralities, vertex positions, and second-order (third-order) event planes. To remove ghost tracks and detector inefficiencies, pairs with either $\Delta z < 5$ cm and $\Delta\phi < 0.07$ or $\Delta z < 70$ cm and $\Delta\phi < 0.02$ at the drift chamber were removed from the analysis, as were tracks separated by less than 17 cm at the front face of the electromagnetic calorimeters. The correlation functions were also binned according to the centrality of the event and the momentum of the pion pair. Positive and negative pion pairs were combined to cancel charge-dependent acceptance effect [22].

A three-dimensional analysis was performed with the Bertsch-Pratt parametrization assuming a Gaussian source [23,24],

$$G = \exp(-R_s^2 q_s^2 - R_o^2 q_o^2 - R_l^2 q_l^2 - 2R_{os}^2 q_s q_o). \quad (1)$$

In this framework, the relative momentum $\mathbf{q}$ is decomposed into q_l, q_o, and q_s, where q_l denotes the beam direction, q_o is perpendicular to q_l and parallel to the mean transverse momentum of the pair $\vec{k}_T = (\vec{p}_{1T} + \vec{p}_{2T})/2$, and q_s is perpendicular to both q_l and q_o. The R_μ ($\mu = s, o, l$) Gaussian parameters provide information on the size of the emission region in each direction, but R_o and (to a lesser extent) R_l include contributions from the emission duration and all are influenced by position-momentum correlations. The R_{os} is a cross term that arises from asymmetries in the emission region [25]. The analysis was performed in the longitudinally comoving system, where $p_{1z} = -p_{2z}$. The measured correlation functions were fit by

$$C_2 = N\{[\lambda(1 + G)]F_c + (1 - \lambda)\}, \quad (2)$$

where N is a normalization factor and F_c is the Coulomb correction factor evaluated using a Coulomb wave function [22,26]. Equation (2) is based on the core-halo model [27,28], which divides the source into two regions: a central core that contributes to the quantum interference and a long-range component that includes the decay of long-lived particles having a negligible Coulomb interaction and a quantum statistical interference that occurs in a relative momentum range that is too small to be resolved experimentally. The fraction of pairs in the core is given by λ.

Finite event-plane resolution reduces the oscillation amplitude of HBT radii relative to the event plane. In this analysis, a model-independent correction suggested in Ref. [29] was applied to $A(q)$ and $B(q)$. The correction factor is 54% (32%) for the second-order (third-order) event planes in 0%–10% centrality. As a cross-check, the oscillation amplitude was also corrected by dividing by $\mathrm{res}(\Psi_n)$ [30]. Both methods applied to the second- and third-order event-plane dependence are consistent within systematic uncertainties. The effect of momentum resolution was studied using GEANT simulations following previous analyses [22,31] and its impact is negligible on the extracted radii ($< 1\%$).

Systematic uncertainties were estimated by the variation of single track cuts, pair selection cuts, and input source size for the Coulomb wave function. Also incorporated were the variations when using alternate event-plane definitions from the forward, backward, and combined RXNPs. Total systematic uncertainties for R_s^2 and R_o^2 are not more than 5% (12%) and 7% (17%) for the second-order (third-order) event plane, respectively.

Figure 1 shows R_s^2, R_o^2, R_l^2, and R_{os}^2 for pions as functions of azimuthal angle ϕ with respect to Ψ_2 and Ψ_3 for two centrality bins, where $\langle k_T\rangle \approx 0.53$ GeV$/c$. The filled symbols show the extracted HBT radii and the open symbols are reflected by symmetry around $\phi - \Psi_n = 0$. For the 0%–10% bin, R_s^2 shows a very weak oscillation relative to both Ψ_2 and Ψ_3, while R_o^2 clearly exhibits a stronger oscillation. For the 20%–30% bin, R_s^2 and R_o^2 for Ψ_2 show opposite-sign oscillations, as expected for an elliptical source viewed from in-plane and out-of-plane axes [10]. For Ψ_3, R_s^2 shows a weaker angular dependence of the same sign as R_o^2.

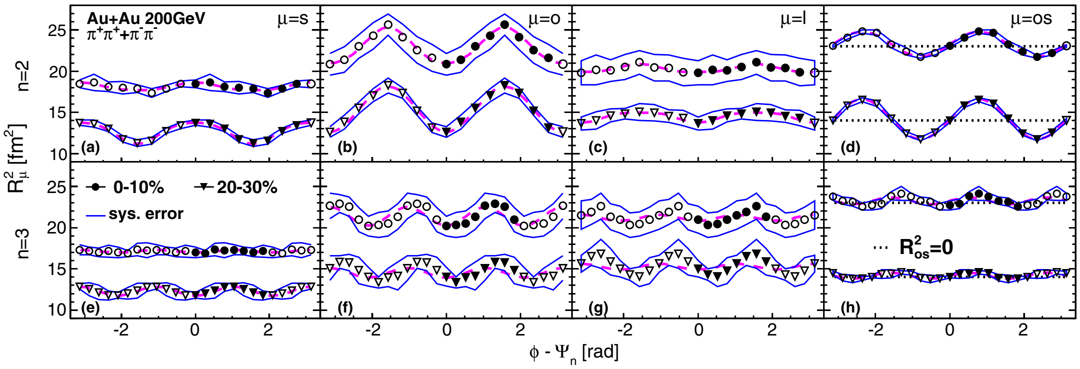

FIG. 1 (color online). The azimuthal dependence of R_s^2, R_o^2, R_l^2, and R_{os}^2 for charged pions in $0.2 < k_T < 2.0$ GeV/c with respect to second-(a)–(d) and third-order (e)–(h) event plane in Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV. The R_{os}^2 is plotted relative to dotted lines representing $R_{os}^2 = 0$. The filled symbols show the extracted HBT radii and the open symbols are reflected by symmetry around $\phi - \Psi_n = 0$. Bands of two thin lines show the systematic uncertainties and dashed lines show the fit lines by Eq. (3).

The oscillation amplitudes were extracted by fitting the angular dependence of R_μ^2 to the functional form,

$$R_\mu^2 = R_{\mu,0}^2 + 2\sum_{n=m,2m} R_{\mu,n}^2 \cos[n(\phi - \Psi_m)] \quad (\mu = s, o, l),$$
$$R_\mu^2 = 2\sum_{n=m,2m} R_{\mu,n}^2 \sin[n(\phi - \Psi_m)] \quad (\mu = os), \tag{3}$$

where $R_{\mu,n}^2$ are the Fourier coefficients [32].

Figure 2 shows the amplitudes relative to the average of R_s^2, R_o^2, and R_{os}^2, $2R_{\mu,n}^2/R_{\nu,0}^2$, as functions of initial eccentricity (ε_2) and triangularity (ε_3). Each ε_n is calculated by Monte Carlo Glauber simulation as given in Refs. [15,33]

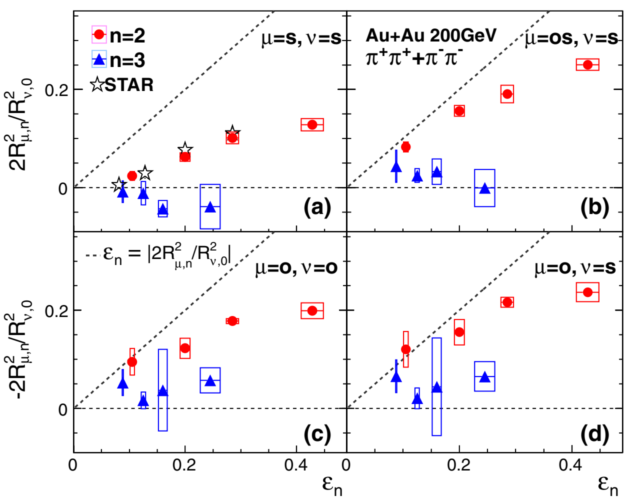

FIG. 2 (color online). The solid points are the oscillation amplitudes relative to the average of HBT radii for four different combinations (a) $2R_{s,n}^2/R_{s,0}^2$, (b) $2R_{os,n}^2/R_{s,0}^2$, (c) $2R_{o,n}^2/R_{o,0}^2$, and (d) $2R_{o,n}^2/R_{s,0}^2$, as a function of initial spatial anisotropy (ε_n), which are calculated using the Glauber model. Boxes show the systematic uncertainties. Open star symbols are the $\varepsilon_{\rm final}$ from STAR [10]. Dashed lines indicate the line of $\varepsilon_n = |2R_{\mu,n}^2/R_{\nu,0}^2|$.

and decreases with increasing centrality; however, the centrality dependence of ε_3 is weaker than that of ε_2.

The $2R_{s,2}^2/R_{s,0}^2$ [Fig. 2(a)] is sensitive to the final source eccentricity ($\varepsilon_{\rm final}$) at freeze-out [29], and approaches the whole source eccentricity in the limit of $k_T = 0$. Our results for the Ψ_2 dependence are consistent with the STAR experiment [10]. We note that the $\varepsilon_{\rm final}$ defined from R_s has a systematic uncertainty of 30% due to the assumption of space-momentum correlation in the blast-wave model [29]. The positive value of $\varepsilon_{\rm final}$ indicates that the source shape still retains the initial shape extended out of plane, though reduced in magnitude. Other combinations of $|2R_{\mu,2}^2/R_{\nu,0}^2|$ also have similar ε_n dependence, but are larger than $2R_{s,2}^2/R_{s,0}^2$. They include contributions from the emission duration and will have different sensitivity to the dynamics [34]. The $2R_{s,3}^2/R_{s,0}^2$ are less than or equal to zero, which seems to be an opposite trend to other combinations, as noted already in Fig. 1. For all amplitudes, the values for third order are small compared to those for second order.

It is well known that the HBT radii are influenced by the presence of dynamical correlations between momentum and spatial distributions at the time of freeze-out [35,36], as evident in the transverse pair momentum k_T dependence of the radii. Figure 3 shows these results for the third-order oscillation amplitudes. The $R_{o,3}^2/R_{o,0}^2$ decreases with k_T, whereas $R_{s,3}^2/R_{s,0}^2$ does not show a significant dependence.

Although the reduced third-order anisotropy in Fig. 3 may indicate small triangular deformation at freeze-out, its interpretation is complicated by the influence of dynamical correlations from the triangular flow [40]. To illustrate the different contributions of these effects, we show separately the k_T dependence for a source with radial symmetry and triangular flow ($\bar{\varepsilon}_3 = 0$, $\bar{v}_3 = 0.25$) and a source with triangular deformation and radial flow ($\bar{\varepsilon}_3 = 0.25$, $\bar{v}_3 = 0$) [37]. The model curves are taken from Ref. [40], but the radii are scaled by 0.3 to fit within the

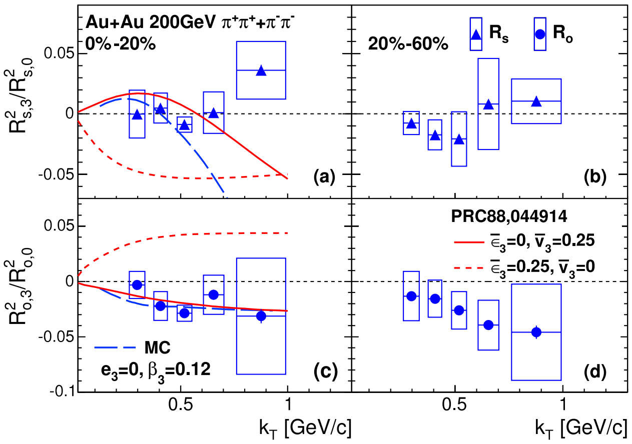

FIG. 3 (color online). k_T dependence of R_s^2 [(a),(b)] and R_o^2 [(c),(d)] amplitudes relative to their averages for the third-order event plane in two centrality bins. Calculations of the Gaussian source model [40] are shown as solid and short-dashed (red) curves, where the values are scaled by 0.3. Calculations using the Monte Carlo simulation are shown as long-dashed (blue) curves.

range of the data. The $R_{o,3}^2$ favors the deformed flow scenario, while the $R_{s,3}^2$ matches the deformed flow only at lower k_T.

To disentangle the relative contributions of spatial and flow anisotropy to the azimuthal dependence of HBT radii, we have performed a Monte Carlo simulation introducing the spatial anisotropy and collective flow with anisotropic modulation at freeze-out. The assumptions of this model are similar to those adopted in the blast-wave model [29,38], generalized for third-order modulation, and do not include effects such as viscosity and source opacity. The particle distributions in the transverse plane were parametrized with a Woods-Saxon function, $\Omega(r) = 1/\{1+\exp[(r-R)/a]\}$. To control the final source triangularity, we introduced a parameter e_3 into the radius parameter R in $\Omega(r)$ as follows:

$$R = R_0\{1 - 2e_3 \cos[3(\phi - \Phi)]\}, \tag{4}$$

$$\beta_T = \beta_0\{1 + 2\beta_3 \cos[3(\phi - \Phi)]\}, \tag{5}$$

where ϕ is the azimuthal angle of particle positions, Φ is the reference angle of the spatial anisotropy and triangular flow, and R_0 is the average radius. To take the collective flow into account, generated particles were boosted in the transverse radial direction with a velocity β_T in addition to their thermal velocities. We used a similar definition to the blast-wave model [29,38] as the flow rapidity $\rho(r) = (r/R)\tanh^{-1}(\beta_T)$. In Eq. (5), β_0 represents the average of radial flow and β_3 is used to control the flow anisotropy. We assume that the particles are emitted with a Gaussian time distribution with $\Delta\tau$ standard deviation, which affects R_o but not R_s. The effect of HBT interference was calculated by $\cos(\Delta\mathbf{x}\cdot\mathbf{q})$, where $\Delta\mathbf{x}$ and $\mathbf{q}$ are 4-vectors for relative distance and relative momentum of the pair. All other parameters except e_3 and β_3 were tuned to reproduce the strength of radial flow measured by m_T spectra [39] and the averages of HBT radii shown in Fig. 1. For this analysis $\Delta\tau$ was set to 3.5 fm/c (2.7 fm/c) for 0%–10% (20%–30%) to achieve better agreement with the average of R_o^2. A simulation result with $e_3 = 0$ and $\beta_3 = 0.12$ is shown in Fig. 3, displaying a trend that is qualitatively consistent with Ref. [40].

To understand how the data may constrain these values, we have performed a least-squares fit for e_3 and β_3. Figure 4 shows the contour plots of χ^2 defined by $\{([2R^2_{\mu,3}/R^2_{\mu,0}]^{\rm exp} - [2R^2_{\mu,3}/R^2_{\mu,0}]^{\rm sim})/E\}^2$, where E is the experimental uncertainty. The value of e_3 is well constrained by the measured value of R_s^2, and indicates that the final triangularity is very close to zero. The inclusion of R_o^2 favors a positive value for β_3 for 0%–10%, but does not add much information to 20%–30%, where a slightly negative value of e_3 is favored by R_s^2. We note that the discrepancy at high k_T remains, but the data integrated over k_T are primarily influenced by lower k_T pairs. Detailed comparison with a realistic hydrodynamic model (e.g., Refs. [40,41]) will be a key to fully understanding the results.

In summary, we have presented results on the azimuthal dependence of charged-pion HBT radii with respect to second- and third-order event planes in Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV. The results for the second-order event-plane dependence indicate that in noncentral events the source starts with an initial elliptical distribution and ends with an elliptical distribution at freeze-out, but with a diluted eccentricity due to the medium expansion. For the third-order event-plane results, the observed R_o^2 oscillation may come from flow anisotropy, but the small R_s^2 oscillation with the same sign as R_o^2 in noncentral collisions may imply that the source expansion with triangular flow inverts the initial triangular shape. A Monte Carlo simulation for an expanding triangular transverse distribution produced results consistent with this interpretation. Comparisons

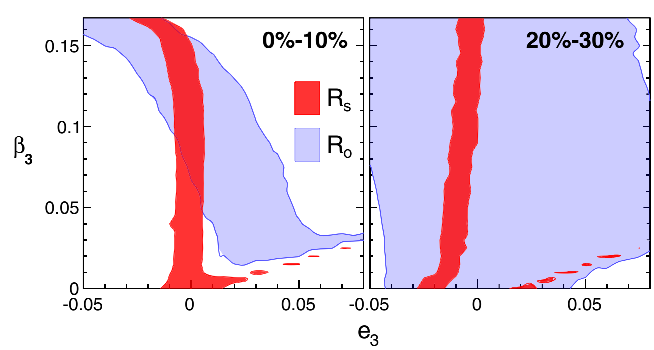

FIG. 4 (color online). χ^2 contours representing the difference between data and simulation in $2R^2_{\mu,2}/R^2_{\mu,0}$ ($\mu = s, o$), as functions of e_3 and β_3. Shaded areas represent χ^2 less than unity and constrained by the experimental uncertainty.

with an event-by-event hydrodynamic model will be needed to reveal the relation of spatial and hydrodynamical flow anisotropy at freeze-out, as well as to provide further constraints on the hydrodynamic evolution in relativistic heavy-ion collisions.

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