Azimuthally-differential pion femtoscopy in Cu+Au and Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV in the STAR experiment

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Anisotropic flow is sensitive to the properties of the systems created in heavy-ion collisions. Azimuthally-sensitive femtoscopy with respect to the first-order event plane is coupled with the directed flow, and probes the space-time structure of the particle-emitting source. The knowledge of the source tilt can give a helpful experimental handle on the origin of the anisotropic flow. In addition, the tilt angle dependence on different collision systems at the same energy can provide constraints on theoretical models.

In the experiment, this information can be extracted by measuring pion femtoscopic radii as a function of the pair emission angle with respect to the first-order event plane.

In this work, we present comparisons between the results of the radius oscillations of the pion-emitting sources at $\sqrt{s_{NN}} = 200$ GeV in symmetric (Au+Au) and asymmetric (Cu+Au) collisions measured with the STAR experiment, and those estimated in the UrQMD model.

Motivation

The medium originated from the collision of two nuclei can be tilted in the reaction plane. The beam axis and impact parameter vector define the reaction plane. The orientation of freeze-out distributions is interesting because it provides complementary information about the emission source. Tilt measurements could be used to test variety of different models.

In the article [1], a study of the emission region tilt behaviour was performed for different theoretical models. Several models predict that tilt decreases with increasing collision energy. This was observed in Au+Au collisions at low energies (2-6 AGeV) [2, 4]. Therefore, it is interesting to study the tilt at high energy collisions as well as to understand its behaviour for symmetric and asymmetric collisions at the same energy.

Femtoscopy technique

Femtoscopic measurements allow one to measure the size and shape of particle-emitting regions. In order to estimate the parameters of the emission sources, it is needed to construct a correlation function, $C(q) = \frac{A(q)}{B(q)}$. Here $A(q)$ is a distribution of the two-particle relative momentum q that contains quantum statistical correlations,

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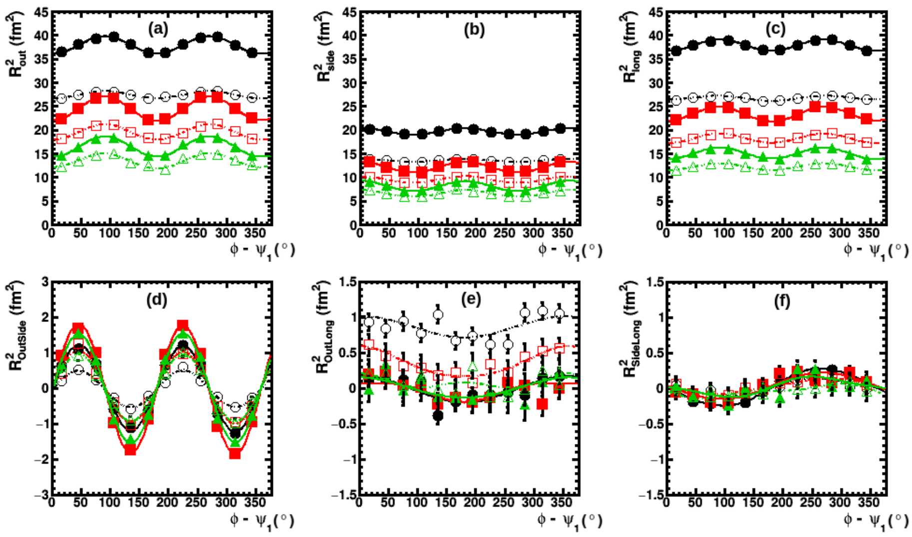

Fig. 1. The dependence of the squares of three-dimensional femtoscopic radii and cross components of the fit on the difference between the pair emission angle relative to the reaction plane angle ($\psi_1 = 0$) in the k_T range from 0.15 GeV/c to 0.35 GeV/c for different collision centralities: 0–20% (black circles), 20–40% (red squares), 40 - 80% (green triangles) in Au+Au (filled markers) and Cu+Au (hollow markers) collisions at 200 GeV/nucleon which were simulated with the UrQMD model.

and $B(q)$ is another distribution without quantum statistics. Quantum statistical correlations are usually not contained in Monte Carlo simulations, but can be introduced via: $weight = 1 + \cos(q \cdot \Delta x)$, where $\Delta x = x_1 - x_2$ is the relative four-coordinate. In the experiment $B(q)$ is the pair relative momentum distribution where particles are taken from different events with similar properties (event mixing technique). In the Ultra Relativistic Quantum Molecular Dynamics (UrQMD) model the unweighted pair relative momentum distribution, q, was used for $B(q)$. Assuming a Gaussian emission profile of the source, the correlation functions are fitted with the form:

$$C(q) = 1 + \lambda \exp\left[-\sum_{i,j=out,side,long} q_i q_j R_{ij}^2\right], \tag{1}$$

where λ is the correlation strength and q_i is the relative momentum of the pair in the i-th direction. The femtoscopic radii are related to regions of homogeneity [3]. To measure the tilt [4, 5] and probe the shape [5, 6] of the emission source one needs to use the azimuthally-differential femtoscopic measurements with respect to the particle pair emission angle and reaction plane angle. In UrQMD the reaction plane angle is always equal to zero. In STAR the reaction plane angle can be reconstructed by the different detectors: Zero Degree Calorimeter (ZDC), Beam-Beam Counter (BBC) (1st-order event plane) or Time Projection Chamber (TPC). Hence, the experimental azimuthaly-differential measurements need to take into account the non-zero reaction plane angle.

For the tilt extraction one could fit the radius oscillations with the following formulas:

$$R_{\mu}^{2}(\phi) = R_{\mu,0}^{2} + 2R_{\mu,1}^{2}\cos(\phi) + 2R_{\mu,2}^{2}\cos(2\phi) \tag{2}$$

for out, side, long and out-long fit components, and:

$$R_{\mu}^{2}(\phi) = R_{\mu,0}^{2} + 2R_{\mu,1}^{2}\sin(\phi) + 2R_{\mu,2}^{2}\sin(2\phi) \tag{3}$$

for out-side and side-long fit components.

Results and discussion

In this work, we present comparisons between the radius oscillations of the pion-emitting sources at $\sqrt{s_{NN}} = 200$ GeV in symmetric (Au+Au) and asymmetric (Cu+Au) collisions measured in the STAR experiment and those estimated from the UrQMD model.

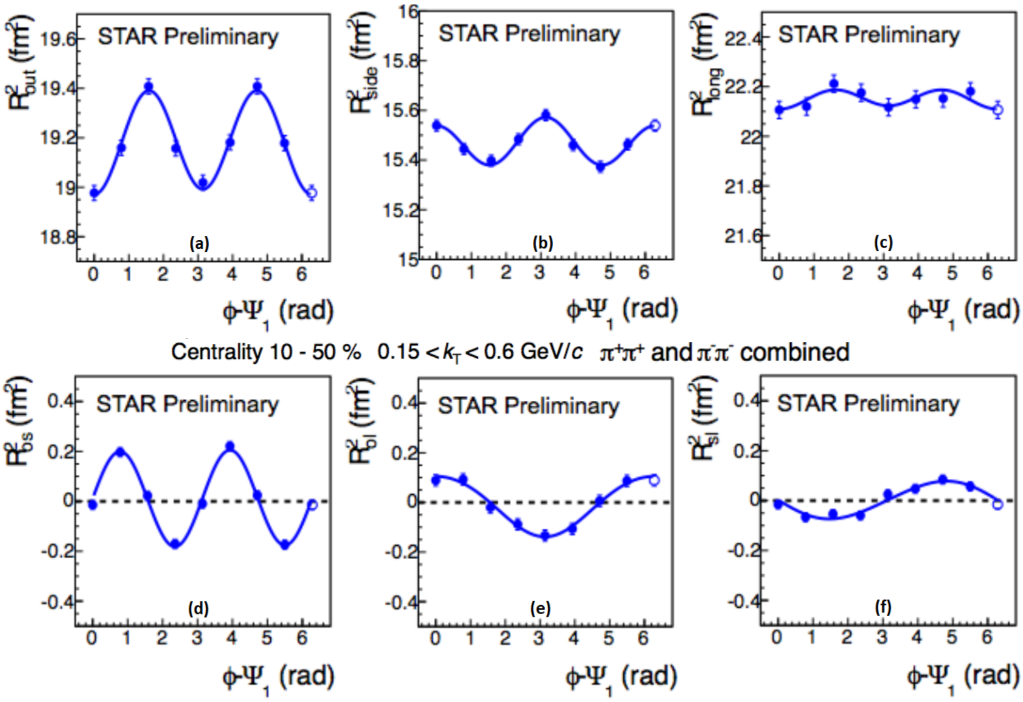

Fig. 2. The dependence of the squared three-dimensional femtoscopic radii and fit cross-components on the difference between a pair angle and an event plane angle in k_T range from 0.15 GeV/c to 0.6 GeV/c for 10–50% collision centrality in the Au+Au system at 200 GeV/nucleon. The values at $\phi = 0$ are redisplayed as open circles at $\phi = 2\pi$.

Simulations were performed with the UrQMD (3.4) [7, 8] transport model. For this work 10 million events for both Au+Au and Cu+Au collisions were simulated. Three centrality ranges (0-20, 20-40, 40-80%) and two ranges of pair transverse momentum (0.15 $< k_T$ (GeV/c) < 0.35, $0.35 < k_T$ (GeV/c) < 0.65) were used for Monte Carlo studies. Here centrality was defined by multiplicity of charged particles with p $>$ 100 MeV/c and $|\eta| < 1$. Values of multiplicity for centrality definition were taken from the experimental data. Figure 1 shows the dependence of the squared three-dimensional femtoscopic radii and cross-term components of the fit on the difference between the pair angle (ϕ) and the reaction plane angle (Ψ_1). It should be noted that in the UrQMD model the reaction plane angle is always equal to zero. According to expectation Cu+Au radii of the emission source is smaller than those for Au+Au. One can see that there are weak but non-zero cross-term components even for such energetic colliding systems. From Fig. 1(e) one can see the difference in the cross-term component of the three-dimensional fit between two colliding systems. The R_{ol} component measured for Cu+Au is shifted from zero due to the non-zero center-of-mass rapidity. The shift corresponds to the Au-going direction.

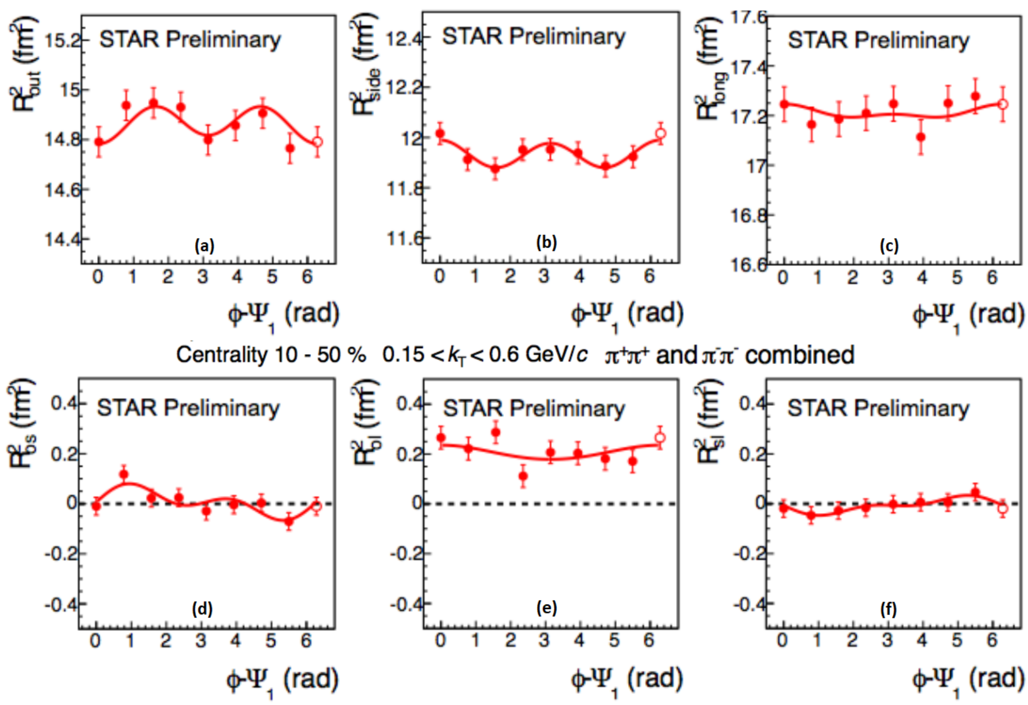

Fig. 3. The dependence of the squared three-dimensional femtoscopic radii and fit cross-components on the difference between a pair angle and an event plane angle in k_T range from 0.15 GeV/c to 0.6 GeV/c for 10–50% collision centrality in the Cu+Au system at 200 GeV/nucleon. The values at $\phi = 0$ are redisplayed as open circles at $\phi = 2\pi$.

The experimental results are presented for the 10-50% centrality range and for the pair transverse momentum range $0.15 < k_T$ (GeV/c) < 0.6. The data reported in this analysis were collected in 2011 (Au+Au) and 2012 (Cu+Au) with the STAR detector at RHIC. Events were selected to have the collision vertex position within ± 25 (30) cm from the center of the TPC in the beam direction and within 2 cm in the radial direction with respect to the center of the beam for Cu+Au (Au+Au) system. In this analysis, tracks with $0.15 < p_T$ (GeV/c) < 0.8 and $|\eta| < 1$ due to the detector acceptance were selected. Analyzed tracks were required to have the distance of closest approach to the primary vertex to be less than 3 cm, and have at least 15 TPC space points used in their reconstruction. For the pion identification TPC and Time-Of-Flight detectors were used. For the first-order event plane determination two ZDC were used, which located 18 m upstream and downstream of the interaction region. The ZDC measures energy depositions from the neutron spectators that flew out of the collision region.

Figures 2 and 3 show the dependence of the squared radii of the pion-emitting sources on the difference between the pair emission angle and the reaction plane angle for Au+Au and Cu+Au collision systems respectively. One can see a similar trend to that obtained in UrQMD. Figure 2 shows small but non-zero first-order oscillations in R_{ol} and R_{sl} components due to the emission source tilt signal, indicating that the source shape at freeze-out is tilted even at the top RHIC energy. It can be seen that oscillations are not clear from Fig. 3 because of the small statistics (approximately 45 million events) in Cu+Au collisions in comparison to the Au+Au collisions (approximately 430 million events) or due to the density asymmetry effects.

Conclusion

In this work the comparisons between experimental measurements and simulation calculations of the pion emission source radius oscillations were performed. For analysis two datasets were taken, Au+Au collisions as a symmetric system and Cu+Au collisions as an asymmetric system. The collision energy for both datasets is $\sqrt{s_{NN}} = 200$ GeV. The UrQMD model was used for Monte Carlo esimations of the particle-emitting source radii in Cu+Au and Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. According to theoretical expectation radii of the emission source for Au+Au system are larger than those for Cu+Au. The radius dependence on the difference between the pair angle and event plane angle shows small but non-zero first-order oscillations in R_{ol} and R_{sl} components due to the emission source tilt signal. One can see that the R_{ol} component in Cu+Au collisions shifts from zero due to the non-zero center-of-mass rapidity. The experimental data from STAR and simulations from the UrQMD model show similar trends.

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