Azimuthally-differential two-pion femtoscopy in Zr+Zr and Ru+Ru collisions at $\sqrt{s_{NN}} = 200$ GeV using the UrQMD model

Азимутально-чувствительная фемтоскопия пионов в Zr+Zr и Ru+Ru столкновениях при энергии $\sqrt{s_{NN}} = 200$ ГэВ в модели UrQMD

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Correlation femtoscopy allows one to estimate the spatial and temporal characteristics of the particle-emitting region formed in the relativistic heavy-ion collisions. Azimuthally-differential analysis is used to study shape and orientation of the source. In this work, collisions of isobaric nuclei Ru+Ru and Zr+Zr at $\sqrt{s_{NN}} = 200$ GeV are calculated using the UrQMD (Ultrarelativistic Quantum Molecular Dynamics) model and the azimuthally-differential two-pion femtoscopy relative to the second- and third-order event plane are performed. The extracted characteristics of the emission source are presented as a function of the pair transverse momentum, k_T, collision centrality and the pair emission angle. In the future, the obtained results can be compared with the STAR experimental data.

Корреляционная фемтоскопия позволяет оценить пространные и временные параметры области испускания частиц, которая образуется в столкновениях релятивистских тяжелых ионов. Азимутально-чувствительный анализ используется для изучения формы и ориентации источника. В этой работе сгенерированы столкновения ядер-изобар Ru+Ru и Zr+Zr при энергии $\sqrt{s_{NN}} = 200$ ГэВ, используя модель UrQMD (Ultrarelativistic Quantum Molecular Dynamics), и выполнена азимутально-чувствительная фемтоскопия пионов относительно плоскости события второго и третьего порядка. Извлеченные характеристики источника испускания пионов представлены как функция поперечного импульса пары частиц, центральности столкновений и азимутального угла пары. В дальнейшем, полученные результаты можно сравнить с эксперементальными данными эксперимента STAR.

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Introduction

The correlation femtoscopy provides information on final-state parameters of the particle-emitting source formed in heavy ion collisions. We present the results on the azimuthally-differential two-pion femtoscopy in Zr+Zr and Ru+Ru collisions at $\sqrt{s_{NN}} = 200$ GeV generated using the Ultrarelativistic Quantum Molecular Dynamics (UrQMD) model [1]. The $^{96}_{44}$Ru and $^{96}_{40}$Zr are isobaric nuclei with deformed shapes. In this work, we assume the absence of deformation for both nuclei and aim to study the impact of the initial nuclear charge on the femtoscopic parameters.

Correlation femtoscopy

The momentum correlations of two or more particles are sensitive to the spatio-temporal characteristics of the emission source due to quantum statistics effects. Two-particle correlation function is constructed as $C(\boldsymbol{q}) = A(\boldsymbol{q})/B(\boldsymbol{q})$ [2],where $A(\boldsymbol{q})$ and $B(\boldsymbol{q})$ are the relative three-momentum, $\boldsymbol{q} = \boldsymbol{p_1} - \boldsymbol{p_2}$, distribution for pairs of particles from the same event and from different events respectively. Only the numerator of the correlation function contains quantum statistical correlations. Since quantum statistics effects do not present in the Monte Carlo simulations, they are taken into account by calculating correlation function by adding weight to each pion pair [3]: $weight = 1 + cos(q \cdot \Delta x)$. Here $\Delta x = x_1 - x_2$ is the difference between particles four-coordinates and q is the relative four-momentum.

The relative momentum is decomposed in three projections $\boldsymbol{q} = (q_o, q_s, q_l)$ (*out, side, long*) using the Pratt-Bertsch parametrization [4, 5]. The "long" and "out" directions are pointing along the beam axis and the pair transverse momentum, $\boldsymbol{k_T} = (\boldsymbol{p_{T,1}} + \boldsymbol{p_{T,2}})/2$, respectively. The "side" direction is orthogonal to the other two. In order to extract the femtoscopic parameters, the correlation function is fitted by the following:

$$C(q_o, q_s, q_l) = N \cdot \Big(1 + \lambda \cdot \exp[-q_o^2 R_o^2 - q_s^2 R_s^2 - q_l^2 R_l^2 - 2 q_o q_s R_{os}^2]\Big), \qquad (1)$$

where N is the normalization factor, λ is the correlation strength and R_o, R_s, R_s are the femtoscopic radii in the out, side and long direction respectively and R_{os} is the out-side cross term ($R_{os} = R_{so}$). The R_{ol} and R_{sl} cross terms vanish due to the boost-invariance of the source and the symmetry of the correlation function in $q_o - q_l$ and $q_s - q_l$ planes, respectively [6].

In the azimuthally-differential analysis, the femtoscopic radii dependence on the azimuthal angle of pair momentum defined in transverse plane with respect to the event plane angle is studied. The event plane is an estimation of the reaction plane, which is defined by the vector of the impact parameter and the beam direction. In the UrQMD model the event plane angle is always equal to zero. In this work, the rotation of the event plane is performed, then second- and third-order event planes is reconstructed. The last one is done by adopting the technique used in the STAR experiment [7].

Collision centrality determination

The centrality of an event is defined by the percentile of the reaction total cross-section and characterized by the impact parameter, which is the distance between the centers of the two colliding nuclei. Experimentally, it can be estimated by the reference multiplicity calculated as a number of charged particles within the pseudorapidity region $|\eta| < 0.5$ having the momentum $p > 0.15$ GeV/c. That criteria roughly correspond to the experimental definition [8].

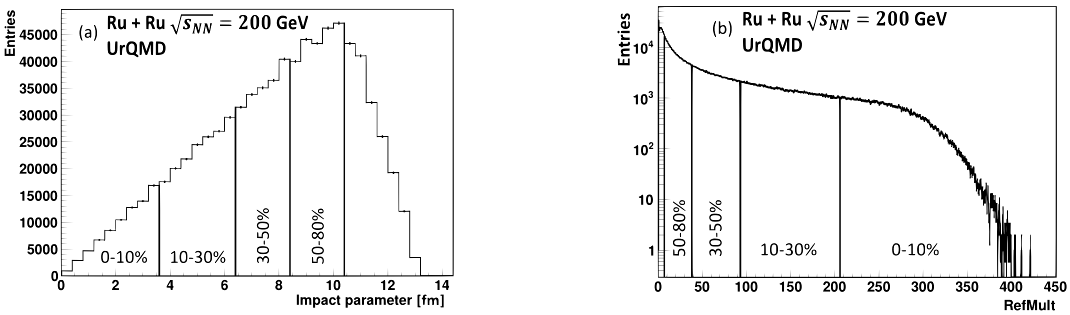

Fig. 1. The impact parameter (a) and reference multiplicity (b) distributions with estimated centrality boarders

Figures 1(a) and 1(b) show the impart parameter and reference multiplicity distributions, respectively. Each distribution shows the centrality classes corresponding to each of these parameters.

Results and discussion

In this work, the collisions of isobaric nuclei $^{96}_{44}$Ru+$^{96}_{44}$Ru and $^{96}_{40}$Zr+$^{96}_{40}$Zr are simulated using the UrQMD model. Data sets of 45 million events for Ru+Ru and 40 million events for Zr+Zr collisions are used in the study. The nuclear deformation of the ions and final-state interactions between produced particles are ommitted.

The analysis is performed in three centrality (0-10%, 10-30%, 30-50%) classes and four pair transverse momentum, k_T, (0.15-0.25 GeV/c, 0.25-0.35 GeV/c, 0.35-0.45 GeV/c, 0.45-0.55 GeV/c) ranges. Numerator and denominator of the correlation function are formed by pairs of pions from events of the same centrality class. In order to extract femtoscopic parameters, Equation 1 was used to fit the correlation functions. The correlation function and its fit are projected onto out, side and long axes and shown in Figure 2 (Top panel).

The impact of centrality determination on femtoscopic parameters is studied. Figure 2 (Bottom panel) shows the dependence of the radii on the pair transverse momentum and centrality for different centrality estimations. The femtoscopic radii obtained with the impact parameter centrality determination are systematically larger by about 1% than those with defined using reference multiplicity. This difference is within the typical systematic uncertainities measured in the experiment. Hence, the centrality defined using reference multiplicity will be used as a main one in this study. The decrease of the radii with increasing centrality is attributed to the geometry of the collisions – the overlapping region of two nuclei is smaller for the peripheral collisions. The radii decrease with increasing k_T due to decrease of the homogeneity regions sizes.

The radii dependence on the pair azimuthal angle with respect to second- and third-order event plane for $k_T = 0.25 - 0.35$ GeV/c is presented in Figure 3. We observe a difference of about 1% between the parameters obtained for Ru+Ru and Zr+Zr systems. Femtoscopic radii oscillate with azimuthal angle relative to the second-order event plane due to the shape of the overlapping area of two incoming nuclei. The third-order oscillations

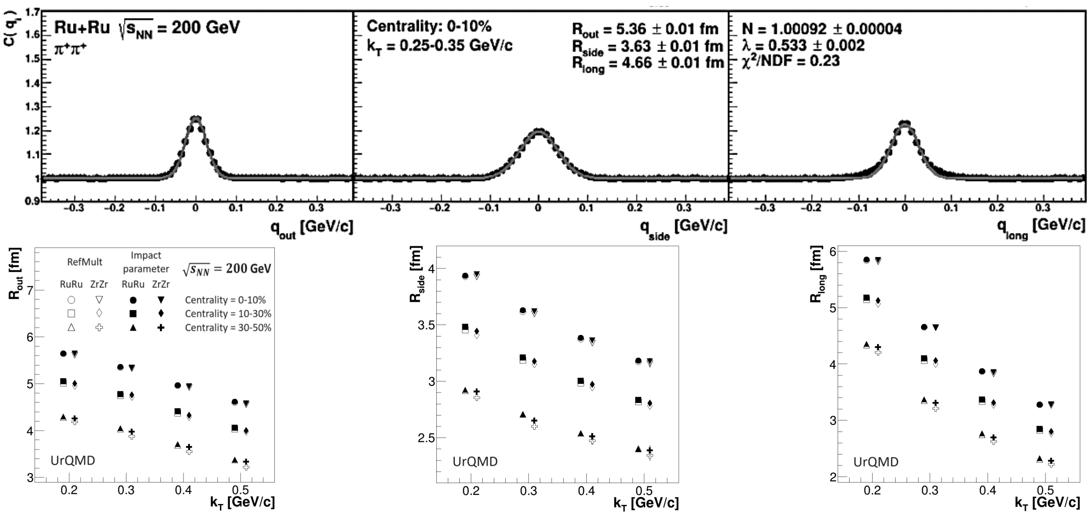

Fig. 2. Top panel. The example of correlation function (filled circles) and its fit (solid line) for 0-10% central Ru+Ru collisions at $\sqrt{s_{NN}} = 200$ GeV and $k_T = 0.25 - 0.35$ GeV/c. The centrality is determined via the impact parameter. Bottom panel. The dependence of the femtoscopic radii on the transverse momentum of the pair, k_t, and collision centrality. The centrality is estimated by the impact parameter (filled markers) and reference multiplicity (hollow markers).

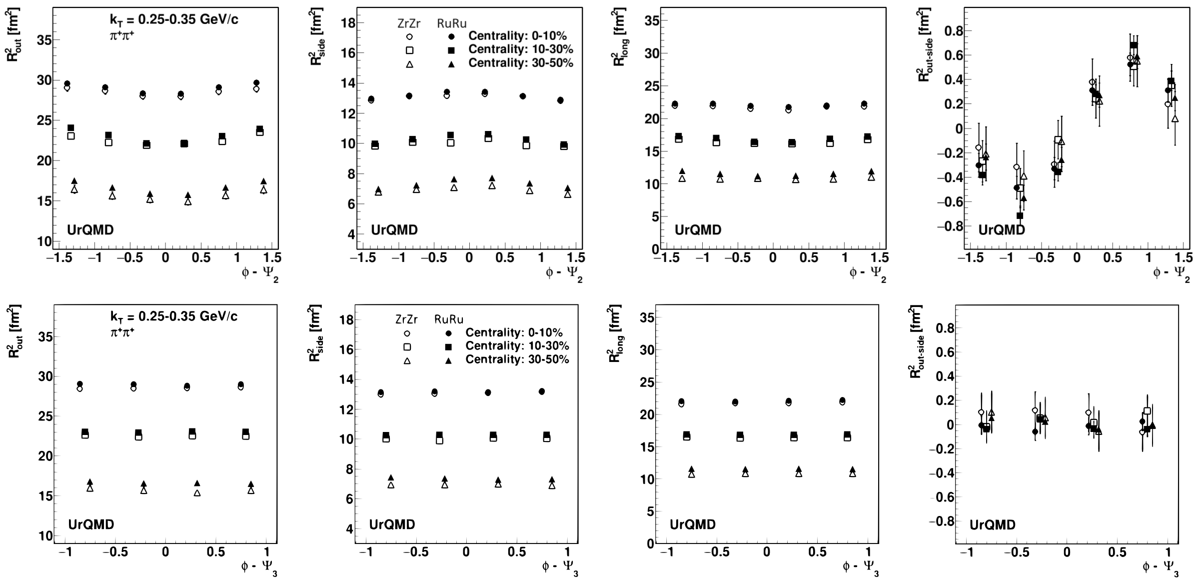

Fig. 3. The dependence of the squared femtoscopic radii and cross component R_{os} on the pair emission angle relative to the second- (top panel) and third-order (bottom panel) event plane in the k_T range from 0.25 to 0.35 GeV/c for different collision centralities.

of femtoscopic radii are absent (or weak) due to the absence of the nuclear deformation in this study. The corrections for the finite azimuthal angle bin width and event plane resolution should be applied to this results and may increase the radii oscillation amplitude.

Conclusions

In this analysis, the Ru+Ru and Zr+Zr collisions at $\sqrt{s_{NN}} = 200$ GeV were simulated using the UrQMD model. We have studied the influence of the centrality determination (charged particle multiplicity vs. impart parameter) on the femtoscopic parameters. The femtoscopic parameters for the centrality classes estimated via impact parameter are systematically larger by 1% than those obtain via charged particle multiplicity. We performed the azimuthally-differential analysis relative to the second- and third-order event planes. Only the second-order angular oscillations of femtoscopic radii were observed. The femtoscopic parameters obtained for Ru+Ru system are larger than those for Zr+Zr. The difference between them is about 1%. In the future work, the deformation of the nuclei will be taken into account and its impact on femtoscopic radii radii will be investigated.

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