Modeling of two-particle femtoscopic correlations at top RHIC energy

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Abstract. The spatial and temporal characteristics of particle emitting source produced in particle and/or nuclear collisions can be measured by using two-particle femtoscopic correlations. These correlations arise due to quantum statistics, Coulomb and strong final state interactions. In this paper we report on the calculations of like-sign pion femtoscopic correlations produced in p+p, p+Au, d+Au, Au+Au at top RHIC energy using Ultra Relativistic Quantum Molecular Dynamics Model (UrQMD). Three-dimensional correlation functions are constructed using the Bertsch-Pratt parametrization of the two-particle relative momentum. The correlation functions are studied in several transverse mass ranges. The emitting source radii of charged pions, \( R_{\text{out}} \), \( R_{\text{side}} \), \( R_{\text{long}} \), are obtained from Gaussian fit to the correlation functions and compared to data from the STAR and PHENIX experiments.

1. Introduction
The spatiotemporal structures of particle emitting source in high-energy collisions are essentially defined by the dynamics of the collision processes \cite{1}. The femtoscopy method allows to measure the spatial and temporal characteristics of emitting region in high-energy collisions. Such correlations arise due to quantum statistics, Coulomb and strong final state interactions.

We present calculations of the femtoscopic radii of two-pion correlations (referred to as Bose-Einstein, or Hanbury-Brown Twiss “HBT”, correlations) in p+p and central (0-10% centrality) p+Au, d+Au, Au+Au collisions at top RHIC energy \( \sqrt{s_{\text{NN}}} = 200 \) GeV. The Ultra Relativistic Quantum Molecular Dynamics Model (UrQMD) \cite{2,3,4,5} was used to simulate the ion collisions. The calculated femtoscopic radii for Au+Au collisions were compared to the STAR \cite{6} and PHENIX experimental data \cite{7}.

2. Femtoscopy
The method of femtoscopy is created to measure the space-time extents of the particle emitting region at freeze-out. It is based on measurements of identical particle correlations (usually pions). The femtoscopic correlations are calculated as a function of relative momentum, expressed as \( \mathbf{q} = \mathbf{p}_1 - \mathbf{p}_2 \). In order to estimate the particle emitting source parameters, one uses the correlation function, \( C(\mathbf{q}) \). It is constructed as follows:

\[
C(\mathbf{q}) = \frac{A(\mathbf{q})}{B(\mathbf{q})},
\]  

(1)
where $A(q)$ is a distribution of two-particle relative momentum that contains quantum statistical correlations, and $B(q)$ is the reference distribution that has all experimental effects (event, single-particle and pair-particle selection criteria) as the first one except for the absence of the Bose-Einstein correlations. Following the modern analysis techniques, we decompose the relative momentum of the pairs into the three projections, namely out, side and long, according to the Bettisch-Pratt parameterization \[8, 9\]. Correlation functions were constructed in longitudinally co-moving system (LCMS), where $p_{z1} + p_{z2} = 0$. Assuming a Gaussian emission profile of the source the correlations functions are fitted with the form \[11, 10\]:

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

(2)

where $\lambda$ is the fraction of correlated pairs and $q_i$ is the relative momentum of the pair in the $i$ direction. The longitudinal direction along the beam axis corresponds to the long term, the outward direction is pointing along the transverse component of the average momentum $k$ of a pair ($k_T = |p_{1T} + p_{2T}|/2$) and the sideward direction is orthogonal to both out and long. The effect of cross terms with $i \neq j$ in the HBT radii is negligible as the pseudorapidity cuts $|\eta| < 1$ are used. The HBT radii are related to regions of homogeneity. According to \[11\], $R_{\text{side}}$ contains information about geometry, $R_{\text{out}}$ convolutes the information about geometry and emission duration and $R_{\text{long}}$ contains information about system lifetime. The $m_T$ ($m_T = \sqrt{m_{z1}^2 + k_T^2}$) dependence of the femtoscopic radii shows the dynamic of the system and allows to probe the different regions of the homogeneity.

3. Results and Discussions

We present femtoscopic radii calculations of identical-pion correlations in p+p and central (0-10% centrality) p+Au, d+Au, Au+Au collisions at top RHIC energy $\sqrt{s_{NN}} = 200$ GeV using the UrQMD model. The collisions centrality was defined by comparing impact parameter and multiplicity distributions of charged particles within the typical acceptance of the collider experiments.

UrQMD is a microscopic many body approach and can be applied to study hadron-hadron, hadron-nucleus and heavy ion reactions at relativistic energies. The UrQMD does not contain quantum statistics correlations. In order to add these correlations, the simulated phase space points of charged pions at their freeze-out time were passed to a Correlation After Burner (CRAB) analyzing program \[12\].

Figure 1 shows the example of the projection in the outward direction of the correlation functions of charged pions calculated for d+Au (blue rombs) and Au+Au (green squares) collisions in the transverse mass range ($m_T = 0.2 - 0.4$ GeV/c$^2$) and corresponding to them fits.

Figure 2 shows the comparison of the $m_T$ dependence of the HBT radii obtained from UrQMD model (black triangles) and the data from STAR (blue circles) and PHENIX (red squares) experiments.

The $m_T$ dependence of $R_{\text{long}}$ and $R_{\text{side}}$ calculated from UrQMD qualitatively and quantitatively agrees with the experimental data. This suggests that the geometrical size of the particle emitting region and the medium lifetime are well reproduced by the model. From figure 2 it is seen that the $R_{\text{out}}$ obtained from the model is overestimated but qualitatively agrees with the experimental data. Since the $R_{\text{out}}/R_{\text{side}}$ ratio provides the information about the particle emission duration, one may conclude that emission duration of the charged pions not well reproduced in UrQMD.

Figure 3 shows the $m_T$ dependence of the charged pion femtoscopic radii for p+p (blue crosses), p+Au (red circles), d+Au (black triangles) and Au+Au (green squares) collisions obtained from the UrQMD model.
Figure 1. Example of the correlation function and projection of the three-dimensional Gaussian fit to it in the outward direction.

Figure 2. $R_{\text{out}}$ (a), $R_{\text{side}}$ (b) and $R_{\text{long}}$ (c) radii extracted from UrQMD model in comparison with STAR and PHENIX experiments.

Figure 3. The $m_T$ dependences of the $R_{\text{out}}$ (a), $R_{\text{side}}$ (b) and $R_{\text{long}}$ (c) obtained for p+p, p+Au, d+Au and Au+Au.

It is seen that for each transverse mass range the source radii following the next ordering: $R_i(\text{Au+Au}) > R_i(\text{d+Au}) > R_i(\text{p+Au}) \geq R_i(\text{p+p})$. This estimations may be used for the future measurements at Relativistic Heavy Ion Collider (RHIC) and for the correction of the transport properties of the UrQMD model.
4. Conclusions

The two-pion femtoscopic correlations for p+p and central p+Au, d+Au and Au+Au at top RHIC energy are studied with the Ultra Relativistic Quantum Molecular Dynamics Model. The transverse mass dependences of the femtoscopic radii $R_{out}, R_{side}, R_{long}$ were extracted. For Au+Au collisions the estimated from the model radii were compared to the experimental data from STAR and PHENIX.

The $m_T$ dependence of $R_{long}$ and $R_{side}$ radii obtained from UrQMD qualitatively and quantitatively agrees with the experimental data. The $R_{out}$ estimated by UrQMD are overestimated which means that the emission duration of charged pions is overestimated in the model meanwhile the geometrical size of the particle emitting region and the medium lifetime are well reproduced.

The estimations of the $m_T$ dependence of the charged pion radii have been done for p+p and central (0-10% centrality) p+Au, d+Au, Au+Au collisions. It was shown that for the given tranverse mass region $R_i(Au + Au) > R_i(d + Au) > R_i(p + Au) \geq R_i(p + p)$.

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