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Geometry and Dynamics in Heavy-Ion Collisions Seen by the Femtoscopy in the STAR Experiment

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Abstract

The geometry and the dynamics of the particle-emitting source in high-energy heavy-ion collisions can be inferred via femtoscopy measurement. Two-particle correlations at small relative momentum exploit quantum statistics and the final-state interactions which allow one to study the space-time characteristics of the source of the order of 10^{-15} m and 10^{-23} s, respectively. The RHIC Beam Energy Scan (BES) program covers a significant part of the QCD Phase Diagram using collisions of Au nuclei at eight beam energies in the range from 7.7 to 200 GeV, covering the baryon-rich region, which can be studied via baryon femtoscopy. Thus, two-baryon measurements together with two-meson and meson-baryon correlations provide complementary information about the source characteristics.

In this proceedings, the STAR preliminary results on femtoscopic observables of various particle combinations of protons, pions and kaons from Au+Au collisions at BES energies are presented. Determining how the properties of the particle-emitting source depend on collision energy is an important step towards understanding the physics of heavy-ion collisions. The BES program provides the possibility to study the energy dependence of the source sizes for various collision centralities. In addition to the source size, the measurements of non-identical particle combinations provide information about space-time asymmetries in emission process.

Keywords: femtoscopy, STAR, BES, correlations, heavy-ion collisions

1. Introduction

The Solenoidal Tracker at RHIC (STAR) [1] is a detector system at Relativistic Heavy Ion Collider (RHIC) located in Brookhaven National Laboratory (BNL). The analysis is based on the data collected during Beam Energy Scan (BES) program in years 2010 and 2011. Time Projection Chamber (TPC) [2] and Time Of Flight (TOF) [3] were used for particle tracking and identification in a pseudorapidity range of $|\eta| \leq 1.0$ and complete azimuthal symmetry.

[1] A list of members of the STAR Collaboration and acknowledgements can be found at the end of this issue.

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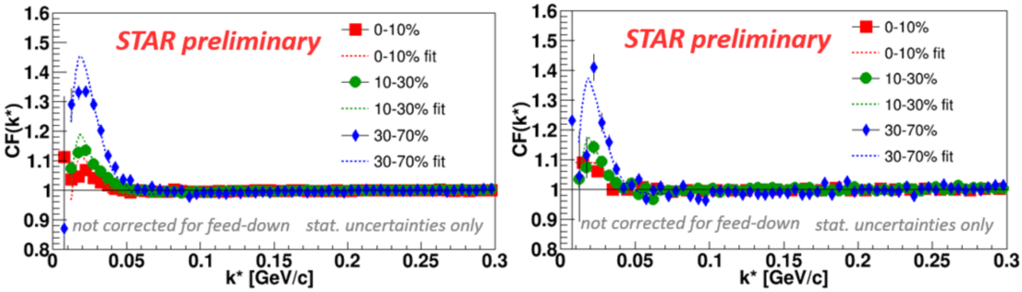

Fig. 1. Proton-proton (left) and antiproton-antiproton (right) correlation functions measured in Au+Au collisions at $\sqrt{s_{NN}}$ = 39 GeV.

2. Femtoscopy

The characteristics of the particle-emitting source cannot be measured directly. Femtoscopy allows one to measure the source properties through the correlation functions of particles produced in the collision.

Correlation function (Eq. 1) is defined as the ratio between the two-particle distribution function (Eq. 3) and two single-particle distribution functions (Eq. 2). Φ in (Eq. 3) describes the pair mutual interaction, $x_1, 2$ and $p_1, 2$ are space-time points of emission and four-momenta of analysed particles, respectively and $S(x, p)$ is the emission function that is used to describe the particle emission source.

$$C(p_1, p_2) = \frac{P_2(p_1, p_2)}{P_1(p_1)P_1(p_2)} \tag{1}$$

$$P_1(p) = E\frac{dN}{d^3p} = \int d^4x S(x, p) \tag{2}$$

$$P_2(p_1, p_2) = E_1E_2\frac{dN}{d^3p_1d^3p_2} = \int d^4x_1 S(x_1, p_1) d^4x_2 S(x_2, p_2)\Phi(x_2, p_2|x_1, p_1) \tag{3}$$

The correlation functions of identical particles are sensitive to Quantum Statistics effect and to Final-State Interactions (namely, Coulomb and Strong interactions), while the correlation functions of non-identical particle combinations are sensitive only to the Final State Interactions [4, 5, 6, 7].

Information about space-time asymmetry in the emission process can be provided by correlation functions of non-identical particle combinations, since their correlation function is sensitive to the space or time sequence of emission of different particle species [8].

This can be achieved using the spherical harmonics decomposition (Eq. 4), which employs tesseral spherical harmonics, Y_l^m, (terminology can be found in [9]) to express components of the correlation function, $C(q)$ that are sensitive to specific characteristics of the particle-emitting source. This analysis uses a C_0^0 and a $\Re C_1^1$ components to extract information about the size of the source and the space-time emission asymmetry, respectively [10, 11, 12, 13].

$$C(q) = \sum_{l,m} C_l^m(q) Y_l^m(\theta, \phi) \qquad C_l^m(q) = \int_\Omega C(q, \theta, \phi) Y_l^m(\theta, \phi) d\Omega \tag{4}$$

3. Geometry of the source

No significant difference can be seen between proton-proton ($p - p$) and antiproton-antiproton ($\bar{p} - \bar{p}$) correlation functions (Fig. 1) for Au+Au collisions at $\sqrt{s_{NN}}$ = 39 GeV where system is described by non-close-to-zero baryonic chemical potential.

The strength of the correlation between particles depends on the size of the source they were emitted from, i.e. the correlation is stronger for smaller sources. A centrality dependence of the source radius is

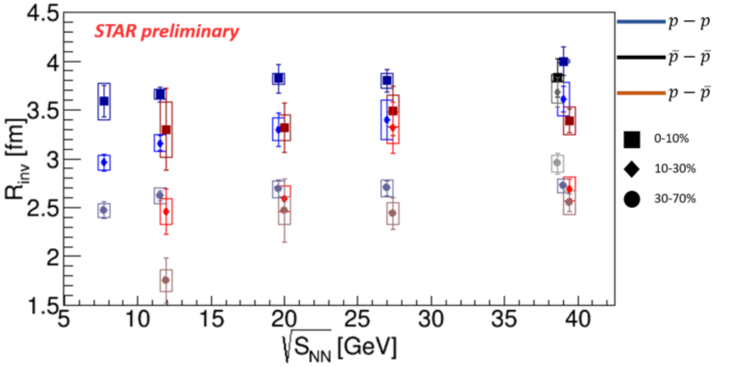

Fig. 2. Source radii extracted from proton-proton, antiproton-antiproton and proton-antiproton systems. Proton-antiproton points are offset by 0.5 GeV to the right and antiproton-antiproton points are offset by 0.5 GeV to the left for clarity.

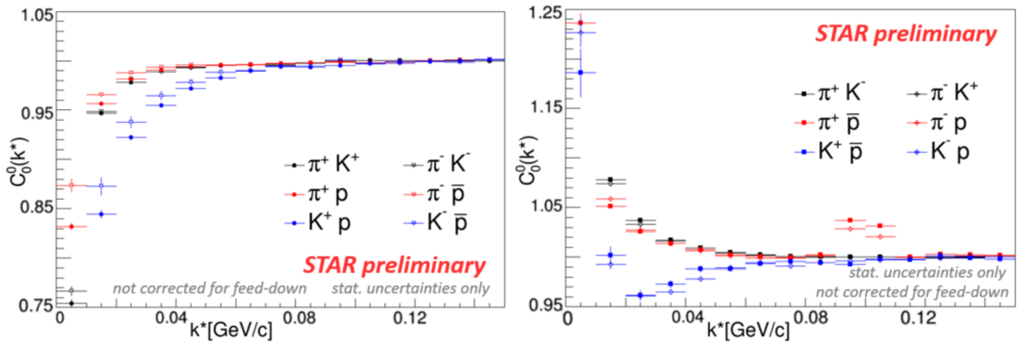

Fig. 3. C_0^0 component for like sign particle combinations (left) and unlike sign particle combinations (right) (0-10% centrality; Au+Au $\sqrt{s_{NN}}$ = 39 GeV data).

observed for all analyzed datasets but the dependence as a function of collision energy is weak, as shown in Fig. 2. Systematic uncertainties have been estimated based on the impact of purity correction on the fit results. The plot shows that the emitting-source radii extracted from $p-\bar{p}$ system are smaller than the corresponding radii from $p-p$ and $\bar{p}-\bar{p}$ systems. This difference may arise due to the different contamination to protons and antiprotons from weak decays. If this assumption is correct, applying a feed-down correction in all systems will reduce the observed difference [14].

The measured correlation function can be interpreted as an echo of the particle-emitting source as can be seen through the interaction between the analyzed particles: the results depend on the type of particle pairs that has been analyzed. Systems with like-sign particle combinations shown in left Fig. 3 are dominated by Coulomb interaction. The strength of the interaction depends on the Bohr radius of the pair [5, 6, 15] and the strongest correlation is observed for kaon-proton ($K-p$) system which has the lowest Bohr radius [16]. Figure 3 (right) shows unlike-sign particle combinations that also differ from each other, but due to different strong interaction a direct comparison of unlike-sign particle combinations cannot be performed. One can also see a peak at $k^* \approx 0.1$ GeV/c in pion-proton ($\pi-p$) that corresponds to the Λ^0 decay.

4. Dynamics of the source

$\Re C_1^1$ components of all particle combinations where analyzed particles have different masses ($\pi-K$, $\pi-p$ and $K-p$) deviate from zero (Fig. 4). This indicates that a space-time asymmetry signal is observed

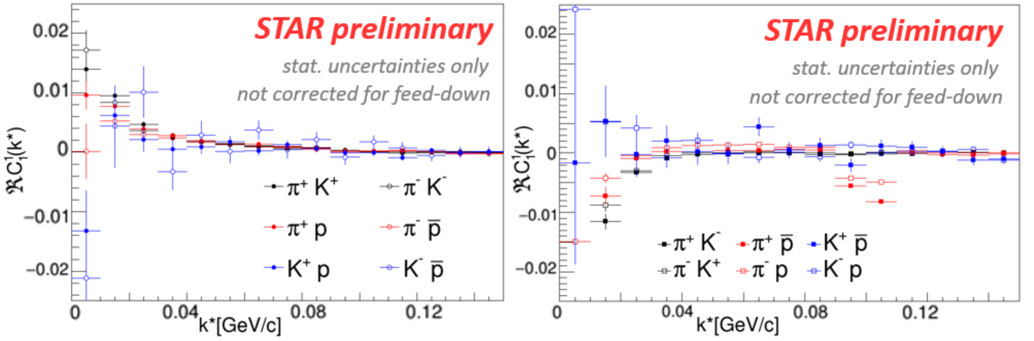

Fig. 4. $\Re C_1^1$ component for like sign particle combinations(left) and unlike sign particle combinations (right) (0-10% centrality; Au+Au $\sqrt{s_{NN}}$ = 39 GeV data).

for all centralities and collision energies in those systems.

By comparing shapes of $\Re C_1^1$ and C_0^0 (Fig. 3 and Fig. 4) components we can draw qualitative conclusions regarding the nature of the space-time asymmetry [8, 17]. In all cases we observe that those components have an opposite tendency, which according to the notation used in the analysis indicate a certain ordering of particles: lighter particles are emitted closer to the center of the source and/or later than heavier particles. It means that heavier particles have stronger push towards the edge of the source than lighter particles [13].

5. Summary

In these proceedings, it has been shown that there is a visible centrality, system and energy dependence of the source size at BES energies. For Au+Au collisions at $\sqrt{s_{NN}}$ = 39 GeV no significant difference between $p - p$ and $\bar{p} - \bar{p}$ pairs has been seen and the radii extracted from $p - \bar{p}$ system are believed to be different from other radii due to contamination from residual correlations. The strong interaction visible in $K - p$ system is not negligible and requires further analysis.

A clear emission asymmetry signal has been observed for particle combinations with different masses at BES energies which led to the conclusion that lighter particles are emitted closer to the center of the source and/or later than heavier particles.

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