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Geometry and Dynamics in Heavy-ion Collisions Seen by the Femtoscopy Method in the STAR experiment

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Geometry and dynamics of the source produced due to heavy-ion collisions at high energies can be studied via the femtoscopy method. Correlations of two particles at small relative momentum are sensitive to Quantum Statistics and the Final State Interactions. They allow one to study the source's space-time properties, which are of the order of 10^{-15} m and 10^{-23} s, respectively. Beam Energy Scan (BES) program conducted at the Relativistic Heavy Ion Collider (RHIC) covers an essential part of the QCD Phase Diagram with beams of Au ions accelerated to relativistic velocities. Already completed, the first phase of the BES program uses heavy-ions collided in the energy range $\sqrt{s_{NN}}$ from 7.7 to 200 GeV. It is a baryon-rich region that can be studied via femtoscopy methods with baryons. On the one hand, meson-meson correlations are the most commonly studied, and baryon-baryon systems, together with two-meson and meson-baryon correlations, provide complete information about source parameters. On the other hand, non-identical particle combination measurements complement our knowledge about space-time asymmetries during the emission process. Physics of heavy-ion collisions is successfully deduced basing on studies of the properties of the particle-emitting source and how they change with different collision energies. Such studies include various centralities of the collision. In this paper, the STAR preliminary results, including femtoscopic systems of various particle combinations such as protons, pions, and kaons produced from Au+Au collisions at BES energies, are discussed.

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1. Introduction

Solenoidal Tracker At RHIC (STAR) is an experiment realized at Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory (BNL), Upton. The STAR experiment's primary goal is to study the properties of matter created under extreme conditions (such as pressure, density) and learn about interactions between hadrons. For almost 20 years, STAR has been collecting data from various collisions of different ions at different energies: 7.7, 11.5, 19.6, 27, 39, 62.4, 130, and 200 GeV. The highest collision energy of Au nuclei is $\sqrt{s_{NN}}$ = 200 GeV, and it enables measurement of hot and dense matter after QGP formation. The Beam Energy Scan (BES) program [1], [2] which first part includes colliding energies below $\sqrt{s_{NN}}$ = 62.4 GeV, is mainly focused on the exploration of the QCD phase transition between Quark-Gluon Plasma (QGP) and a hadron gas and also to search for the Critical Point (CP) between first-order phase-transition and cross-over transition described by Quantum Chromodynamics (QCD).

2. Details of analysis

In order to define a femtoscopic correlation function [3], [4] in the case of identical particle combinations a Lonitudinally Co-Moving System (LCMS) is used which is defined as $p_{L,1} + p_{L,2} = 0$. $p_{L,1}$ and $p_{L,2}$ are longitudinal components of momentum for single particles. Using LCMS system the correlation function is defined using $Q_{\text{inv}} = \sqrt{(p_1 - p_2)^2 - (E_1 - E_2)^2}$ variable. In the case of nonidentical particle combinations Pair Rest Frame (PRF) reference is used which defined $k^* = p_1 = -p_2$ variable. PRF reference can be also used for identical pairs of particles and then $Q_{\text{inv}} = 2k^*$.
The definition of the correlation functions is as follows: $C(k^*) = \frac{A(k^*)}{B(k^*)}$ or $C(Q_{\text{inv}}) = \frac{A(Q_{\text{inv}})}{B(Q_{\text{inv}})}$. Correlated pairs of particles (from the same event enter) enter the numerator $A(k^*)$ or $A(Q_{\text{inv}})$ and uncorrelated pairs of particles (from different events) enter the denominator $B(k^*)$ or $B(Q_{\text{inv}})$ of the correlation function. All particles are measured and identified with two detectors: the Time Projection Chamber (TPC) and the Time of Flight (TOF).
The centrality selection is determined based on the uncorrected primary charged-particle multiplicity measured in the pseudorapidity region ($|Y| = |\frac{1}{2} ln \frac{E+p_z}{E-p_z}| < 0.5$) as given by the TPC detector. The fraction of this multiplicity distribution defines the centrality classes. The centrality class defined as $0 - 10\%$ corresponds to the most central collisions calculated in the amount of up to 10% of the total hadronic cross-section of the collision, while the $70 - 80\%$ bin is related to the most peripheral collisions. All particles are identified using the energy loss in the detector (dE/dx). Minimum Bias Au+Au collisions at the collision energy $\sqrt{s_{NN}}$ = 200 GeV (within the centrality up to 80%) are divided into three centrality classes: central (0-10%), mid-central (10-30%), and peripheral (30-80%). In the case of BES data, the same definitions of centrality classes were used. Pions are chosen in the transverse momentum range: $0.2 < p_T < 1.2$ GeV/c and kaons within $0.2 < p_T < 1.2$ GeV/c. Protons and antiprotons are chosen in the transverse momentum range: $0.4 < p_T < 2.5$ GeV/c. All particles are taken from the rapidity interval $|Y| < 0.5$. Each track is extrapolated to the primary vertex. If the shortest distance between the track and the vertex exceeds 1 cm, the track is excluded from the analysis chain. It removes a significant fraction of non-primary track candidates. Information derived from the TOF detector allows one to estimate the mass of

the particle. We require the mass square of pions to be between 0.01 and 0.03 GeV/c^2, of kaons within 0.21 and 0.28 GeV/c^2 and of protons to be between 0.76 and 1.03 GeV/c^2. The particle purity is not taken into account as it is estimated as almost 100%. The effects of track-splitting and track-merging are also taken into account.

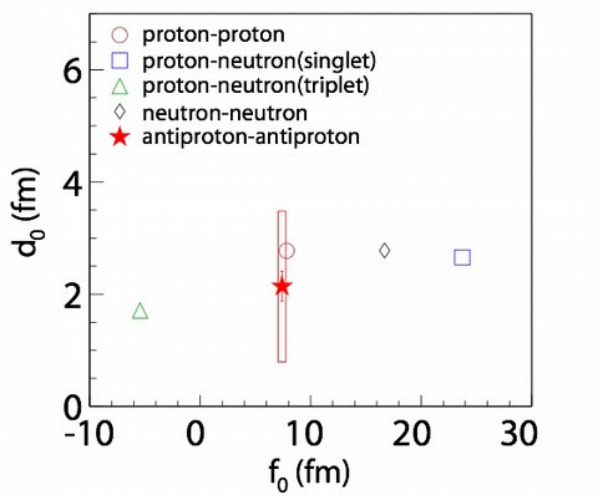

Figure 1: Parameters of strong interactions for different hadron pairs [5]

3. Geometry of the collision

As a result of the heavy-ion collision, a hot and dense system produces different types of particles. Using the femtoscopy method, it is possible to learn about the source's geometrical and dynamical properties. Geometrical parameters are related to sizes and dynamical ones to space-time emission sequence of particles of different species. Femtoscopy enables one to study of space characteristics of source emitting pairs of particles. Thus, it is impossible to explore the whole source's information but rather to its part, emitting considered pairs of particles. It explains why source sizes extracted from various studies are different depending on the considered system. So the geometry of heavy-ion collision can be studied via femtoscopic parameters describing source sizes of emission areas.

3.1 Results for Au + Au Collisions at $\sqrt{s_{NN}}$ = 200 GeV

STAR has measured correlation functions of proton-proton, antiproton-antiproton, and the ratio of proton-proton and antiproton-antiproton for collision energy $\sqrt{s_{NN}}$ = 200 GeV. Correlation functions for baryon-baryon and antibaryon-antibaryon pairs are assumed to be consistent with each other within uncertainties [5]. The scattering length, f_0 is a parameter that describes low-energy scattering, and d_0 is defined as the effective range of strong interaction between two particles. From these studies, parameters f_0 and d_0 are estimated for antiproton-antiproton pairs, and they are found to be consistent with those for proton-proton pairs (Fig. 1). Source sizes in the case

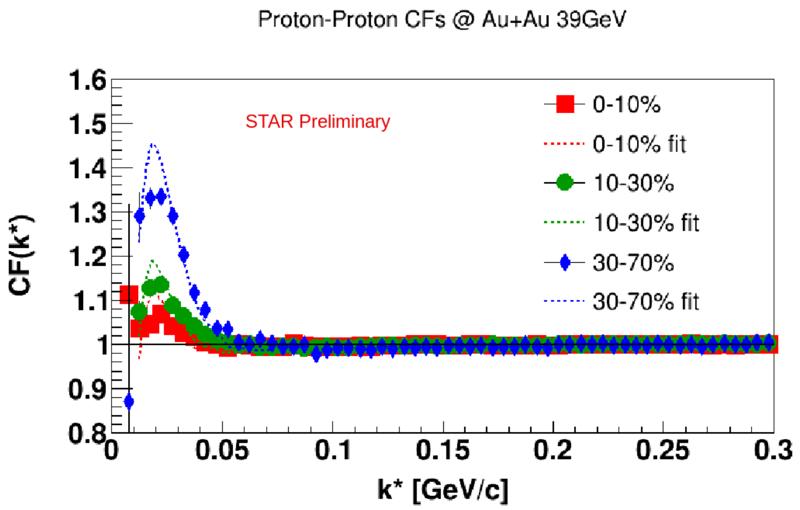

Figure 2: Proton-proton correlation functions for different centrality classes for $\sqrt{s_{NN}}$ = 39 GeV [6], [7]

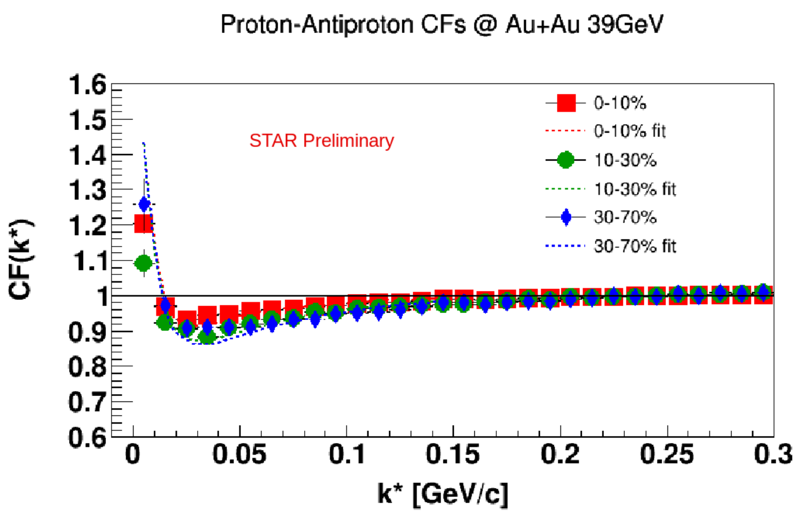

Figure 3: Proton-antiproton correlation functions for different centrality classes for $\sqrt{s_{NN}}$ = 39 GeV [6], [7]

of two protons or two antiprotons were found as $R_{pp} = 2.75 \pm 0.01(stat) \pm 0.04(syst.)fm$ and $R_{\bar{p}\bar{p}} = 2.80 \pm 0.02(stat) \pm 0.03(syst.)fm$.

3.2 Results for Au + Au Collisions for BES Program

Figure 2 shows results of proton-proton correlation functions for $\sqrt{s_{NN}}$ = 39 GeV for three different centralities. Figure 3 presents the results for proton-antiproton correlation functions for the same centrality classes. Centrality dependence is seen. Presented results indicate that source size strongly depends on collision centrality (in the case of more central collisions, more immense source is produced indicated by a weaker correlation signal, while in the case of more peripheral collisions, a smaller source and stronger correlation are measured). The correlation effect (width and magnitude of the correlation function) depends inversely proportional to the source size. Radii of the source also depend on collision energy. For higher collision energy more prominent source, and a weaker correlation is registered.

4. Dynamics of the Collision

The dynamics of the collision can be studied using femtoscopic methods using only non-identical particle combinations. It is possible to study the emission sequence in the case of distinguishable particles. Collision dynamics can be related to space and time aspects. The Femtoscopy method is sensitive to the emission asymmetries related to the spatial shifts (particles of different types statistically emitted from different areas of the emission source) and the time intervals between the two different particles' emissions. However, it is impossible to distinguish whether space and/or time asymmetry is deduced. In the case of such studies, the measured correlation function is determined using Spherical Harmonics decompositions. Thus, it is possible to study two components: $C00(k^*)$, which is consistent with the one-dimensional correlation function $C(k^*)$, and $C11(k^*)$, which is sensitive to the possible asymmetries in the emission process. Figure 4 shows correlation functions ($C11$ components) for pion-kaon systems for various collision centralities for collision energy $\sqrt{s_{NN}} = 39$ GeV. All $C11$ functions are different from zero value for small k^* intervals. It confirms emission asymmetries, proving that lighter particles (pions) are statistically emitted closer to the system's center and/or earlier than heavier particles (kaons). Such asymmetries are caused by the flow phenomenon, which affects particles differently with different masses.

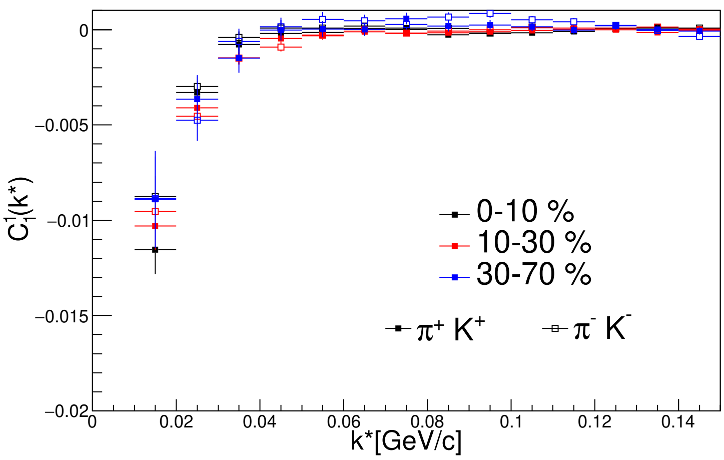

Figure 4: Pion-kaon correlation functions for different centrality classes for $\sqrt{s_{NN}} = 39$ GeV [7]

5. SUMMARY

This paper presents results describing geometrical and dynamical properties of source produced during heavy-ion collisions. In the context of geometrical properties, results of the proton-proton, antiproton-antiproton, and proton-antiproton femtoscopy for Au + Au collisions at $\sqrt{s_{NN}}$ =200 GeV and at BES program at STAR are discussed. Except for source sizes, these studies deliver the scattering length (f_0) and effective range (d_0) parameters of the strong interaction of protons and antiprotons. From studies performed in the BES program frame, invariant source sizes are extracted for proton-proton, proton-antiproton, and antiproton-antiproton pairs. The effect of residual correlations (including products of weak decays) in not taken into account, and it would be reflected in discrepancies between the source sizes estimated for identical and non-identical combinations of protons and antiprotons. Presented results underline the significance of changing source sizes with different collision centrality or collision energy. In the context of geometrical properties, results of pion-kaon correlations are discussed. They prove that emission differences of distinguishable particles can originate in both: spatial and time components. Both of them are the result of different emission properties for particles with different masses. Shown results confirm that lighter particles are on average emitted closer to the center of the system and /or earlier than heavier ones.

Acknowledgments

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