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STAR results on femtoscopy at the BES program

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Geometry and dynamics of the particle-emitting source in heavy-ion collisions can be inferred via the femtoscopy method. Two-particle correlations at small relative momentum exploit Quantum Statistics (QS) and the Final State Interactions (FSI), which allow one to study the space-time characteristics of the source of the order of 10^{-15} m and 10^{-23} s. The RHIC Beam Energy Scan (BES) program covers a significant part of the QCD Phase Diagram using Au nuclei collisions for several beam energies from 3.0 to 200 GeV, where the baryon-rich region is studied via femtoscopy. Together with meson ones, baryon measurements provide complementary information about the source created in the final states of interactions. The results of non-identical particles enable studies of space-time asymmetries in the emission process. Besides, femtoscopy enables the investigation of FSI between hadrons. The femtoscopic measurements of various particle combinations for different collision energies and centralities will be shown in these proceedings.

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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 more than 20 years, STAR has been collecting data from various collisions of different ions at different energies: $\sqrt{s_{NN}}$ = 7.7, 11.5, 14.5, 19.6, 27, 39, 54.4, 62.4, 130, and 200 GeV in the collider mode, and recently in the fixed target too, where the data has been available from $\sqrt{s_{NN}}$ = 4.5 GeV. The highest collision energy of Au nuclei is $\sqrt{s_{NN}}$ = 200 GeV, and it enables the measurement of hot and dense matter after QGP formation. The Beam Energy Scan (BES) program [1, 2] which 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 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 defines $k^* = p_1 = -p_2$ variable. The 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 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 pseudrapidity region ($|\eta| < 0.5$) 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 TPC detector (dE/dx). In the case of identical pion femtoscopy, following centrality bins are used: 0-5%, 5-10%, 10-15%, 15-20%, 20-25%, 25-30%. In case proton or nonidentical particle correlations (within the centrality up to 80%) minimum Bias Au+Au collisions are divided into three centrality classes: central (0-10%), mid-central (10-30%), and peripheral (30-80%).

Pions are chosen in the transverse momentum range: $0.2 < p_T < 2.0$ GeV/c and kaons within $0.2 < p_T < 2.0$ 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 $|Y| < 0.5$ for the collider mode and $-0.5 < Y < 1.5$ for the fixed-target mode. 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 $(\mathrm{GeV}/c^2)^2$, of kaons within 0.21 and 0.28 $(\mathrm{GeV}/c^2)^2$ and of protons to be between 0.76 and 1.03 $(\mathrm{GeV}/c^2)^2$. 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.

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 sequences of particles of different species. Femtoscopy enables one to study of space characteristics of particle pairs emitted from the source. Thus, it is impossible to explore the whole source's information but rather to its part, correlated pairs of emitting 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 pions femtoscopy at $\mathrm{Au}+\mathrm{Au}$ collisions for BES program

Identical pion correlations are performed in three-dimensional space where *long* component is determined by the beam axis, *out* component by the pair transverse momentum, and *side* component is perpendicular to their both. Figure 1 shows results from identical pion femtoscopy measured in the BES program. Upper plot shows $R^2_{out} - R^2_{side}$ measured as a function of collsion energy. There is visible and characteristic peak around $\sqrt{s_{NN}} \simeq 20$ GeV indicating a possible region of the phase transition. Bottom plot presents $\frac{R_{out}}{R_{side}}(\sqrt{s_{NN}})$ indicating a similar trend around the same collision energy.

There is a known trend for higher collision energies that the source is more prolonged in the transverse direction than in the longitudinal one ($R_{long} > R_{side}$), and for lower collision energies, the trend is opposite. Figure 2 shows the relation between R_{side} and R_{long} for different experimental facilities indicating that at $\sqrt{s_{NN}} = 4.5$ GeV the measured source is round-shaped.

3.2 Results for protons femtoscopy at $\mathrm{Au}+\mathrm{Au}$ collisions for BES program

Figure 3 shows results of proton-proton correlation functions for $\sqrt{s_{NN}} = 39$ GeV for three different centralities. Figure 4 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.

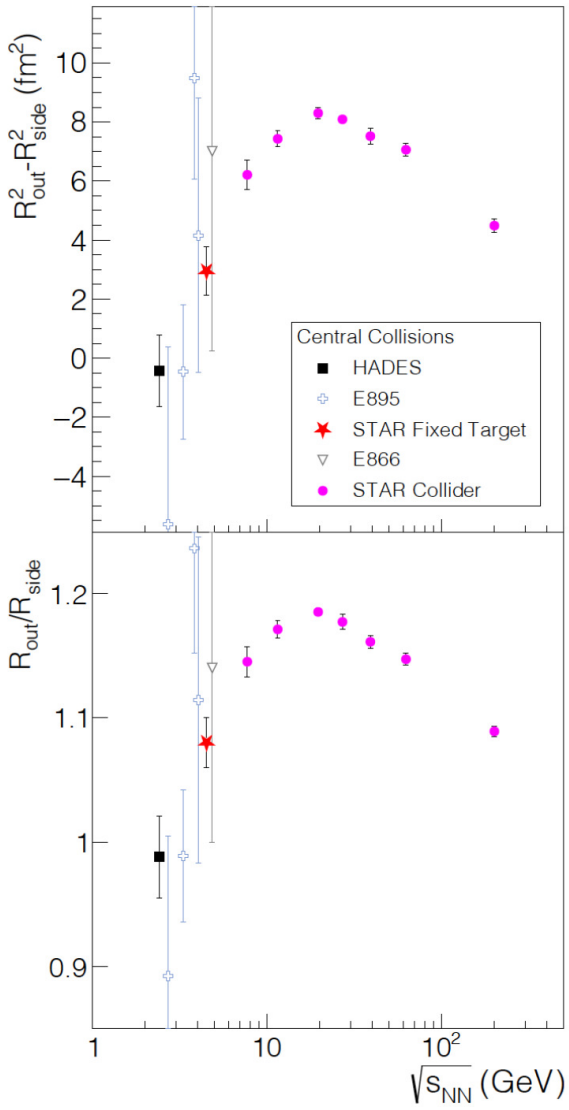

Figure 1: $R^2_{out} - R^2_{side}$ (top) and $\frac{R_{out}}{R_{side}}$ measured as a function of $\sqrt{s_{NN}}$ for identical pion interferometry results from the BES program [5]

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 [6]. Thus, it is possible to study two

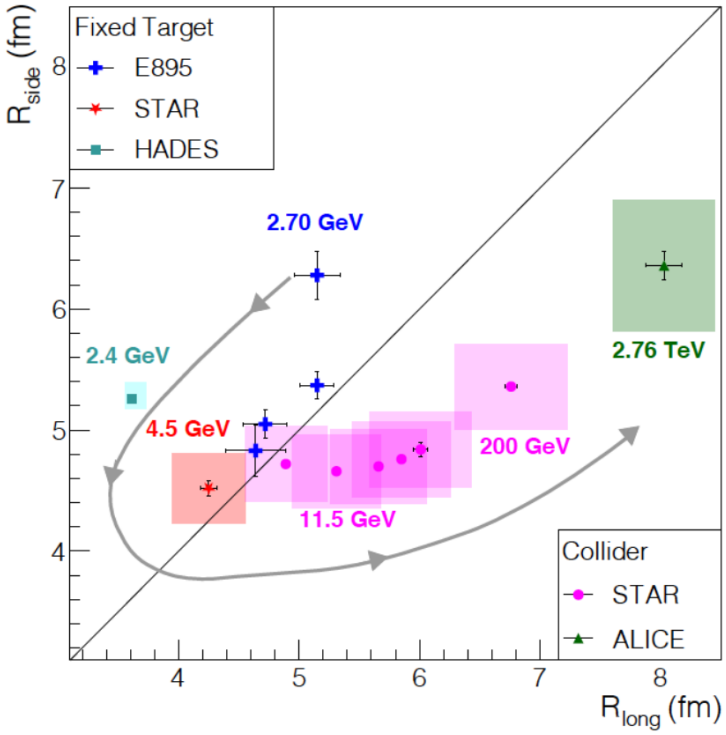

Figure 2: R_{side} and R_{long} measured for different collision energies for identical pion interferometry [5]

components: $C_0^0(k^*)$, which is consistent with the one-dimensional correlation function $C(k^*)$, and $C_1^1(k^*)$, which is sensitive to the possible asymmetries in the emission process. Figure 5 shows correlation functions (C_1^1 components) for pion-kaon systems for various collision centralities for collision energy $\sqrt{s_{NN}} = 39$ GeV. All C_1^1 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.

5. Summary

This paper presents results describing the geometrical and dynamical properties of the source produced during heavy-ion collisions. In the context of geometrical properties, results of the identical pions, proton-proton, antiproton-antiproton, and proton-antiproton femtoscopy for $\mathrm{Au}+\mathrm{Au}$ collisions at the BES program at STAR are discussed. For identical pion interferometry, the relation between source sizes in *out* and *side* directions are discussed as a possible signature of the phase transition. From studies performed in the BES program, invariant source sizes are extracted for proton-proton, proton-antiproton, and antiproton-antiproton pairs. The effect of residual correlations (including products of weak decays) is not considered, 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 change the source sizes with dif-

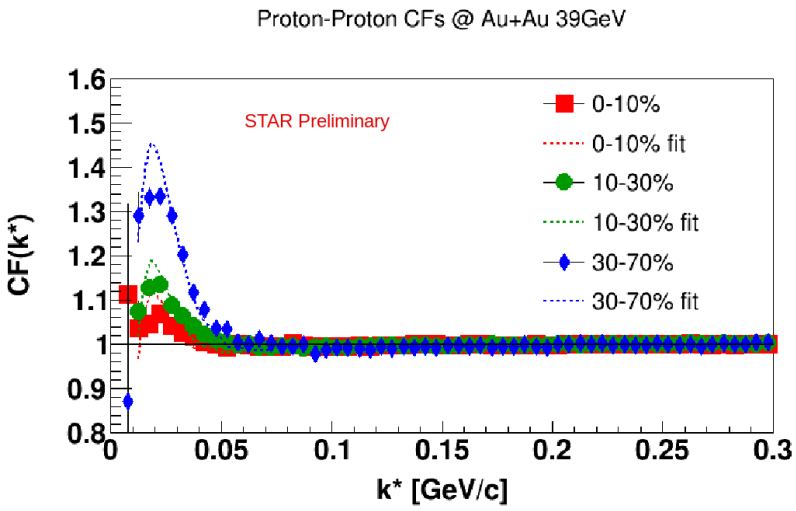

Figure 3: Proton-proton correlation functions for different centrality classes for $\sqrt{s_{NN}}$ = 39 GeV [7, 8]

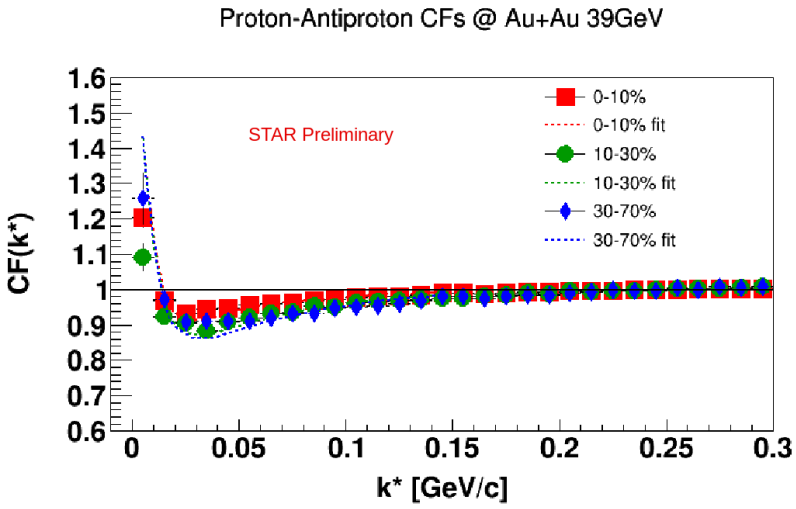

Figure 4: Proton-antiproton correlation functions for different centrality classes for $\sqrt{s_{NN}}$ = 39 GeV [7, 8]

ferent 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 system's center and /or earlier than heavier ones.

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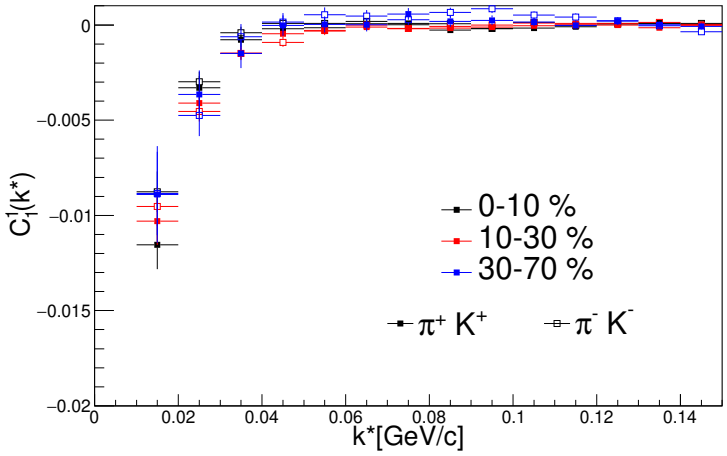

Figure 5: Pion-kaon correlation functions for different centrality classes for $\sqrt{s_{NN}}$ = 39 GeV [8]

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