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GEOMETRY AND DYNAMICS OF HEAVY-ION COLLISIONS MEASURED BY A FEMTOSCOPY METHOD*

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Geometrical and dynamical properties of the source created as a result of relativistic heavy-ion collisions at high energies can be accessed through the method of femtoscopy. Correlations of two particles at small relative momentum are sensitive to the effects of Quantum Statistics and of the Final State Interactions. They enable to explore space-time properties of the source (the order of 10^{-15} m and 10^{-23} s, respectively). Meson–meson correlations are the most commonly studied, and baryon–baryon pairs together with two-meson and meson–baryon correlations provide complete information about source parameters. Measurements of nonidentical particles complement our understanding of space-time asymmetries in the emission process. In this paper, the STAR results including systems of protons, pions and kaons produced in Au+Au collisions are shown.

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1. Introduction

Solenoidal Tracker At RHIC (STAR) is currently only one experiment conducted at Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory (BNL), Upton. The main goal of STAR is to study the properties of matter created under extreme conditions (such as pressure, density), and thus to learn about interactions between hadrons. For 20 years, STAR has been collecting data from various collisions of different ions at different energies: between 7.7 and 200 GeV. The Beam Energy Scan (BES) program [1, 2] which includes collision energies below $\sqrt{s_{NN}} = 62.4$ GeV is mainly focused on exploration of the QCD phase transition between Quark–Gluon Plasma (QGP) and a Hadron Gas (HG), and also to search for the

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Critical Point (CP) between first order phase transition and cross-over transition described by Quantum Chromodynamics (QCD). The highest collision energy of Au nuclei enables a measurement of GQP properties.

2. Details of analysis

To define a femtoscopic correlation function [3, 4] in the case of identical particle combinations, the Longitudinally Co-Moving System (LCMS) is used (longitudinal components of partcile's momentum $p_{\mathrm{L},1}$ and $p_{\mathrm{L},2}$ as $p_{\mathrm{L},1} + p_{\mathrm{L},2} = 0$). Then the correlation function is defined using $Q_{\mathrm{inv}} = \sqrt{(p_1 - p_2)^2 - (E_1 - E_2)^2}$ quantity. In the case of nonidentical particle combinations, the Pair Rest Frame (PRF) is used ($k^* = p_1 = -p_2$). For identical particles with identical masses: $Q_{\mathrm{inv}} = 2k^*$.

A correlation function is defined as: $C(k^*) = \frac{A(k^*)}{B(k^*)}$ (nonidentical particles) or $C(Q_{\mathrm{inv}}) = \frac{A(Q_{\mathrm{inv}})}{B(Q_{\mathrm{inv}})}$ (identical particles). Pairs of correlated particles (from the same event) enter the numerator $A(k^*)$ or $A(Q_{\mathrm{inv}})$ and uncorrelated pairs of particles (from different events) go into denominator $B(k^*)$ or $B(Q_{\mathrm{inv}})$ of the correlation function. In order to measure and identify different particle species, the Time Projection Chamber (TPC) and Time-of-Flight (TOF) detectors are used.

The centrality selection is done for mid-rapidity region ($|Y| = \frac{1}{2}\ln\frac{E+p_z}{E-p_z} < 0.5$) based on the uncorrected primary charged particle multiplicity provided by the TPC detector. The centrality classes are defined by the specific fraction of the multiplicity distribution. Minimum bias Au+Au collisions obtained for collision energy $\sqrt{s_{NN}} = 200$ GeV (within the centrality up to 80%) were collected in 2010, and then divided into three centrality bins: central (0–10%), midcentral (10–30%), and peripheral (30–80%). In the case of BES data, the same definitions of centrality intervals were used.

Considered intervals of transverse momentum for pions are: $0.2 < p_{\mathrm{T}} < 1.2$ GeV/c, for kaons: $0.2 < p_{\mathrm{T}} < 1.2$ GeV/c, for protons and antiprotons: $0.4 < p_{\mathrm{T}} < 2.5$ GeV/c, rapidity interval for all particle species: $|y| < 0.5$. Only primary track-candidates were included into analysis. TOF detector complements information from TPC and allows one to estimate the mass of particle, require m^2 of pions is between 0.01 and 0.03 GeV/c^2, of kaons within 0.21 and 0.28 GeV/c^2, and of protons between 0.76 and 1.03 GeV/c^2. The particle purity is estimated as almost 100%. The effect of tracks-splitting and -merging are also taken into account.

3. Geometry of collision

As a result of heavy-ion collision, a hot and dense system producing different particle species is created. Using the method of femtoscopy, one can discover both: geometrical and dynamical properties of the source. Geometrical quantities (for identical and nonidentical particle pairs) describe sizes, while dynamical ones (for nonidentical particle combinations only) space-time emission sequence. Femtoscopy enables one to study space-time characteristics of source via measurement of particle correlations. Thus, it is impossible to explore information related to the whole source but rather to its part emitting considered pairs of correlating particles.

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

Figure 1 (left) presents measured correlation functions of proton–proton (top), antiproton–antiproton (middle), and the ratio of proton–proton and antiproton–antiproton (bottom) for collision energy $\sqrt{s_{NN}} = 200$ GeV. Both correlation functions like-signs pairs are assumed to be consistent with each other within calculated uncertainties [5]. Two parameters describing properties of strong interactions are used: the scattering length,

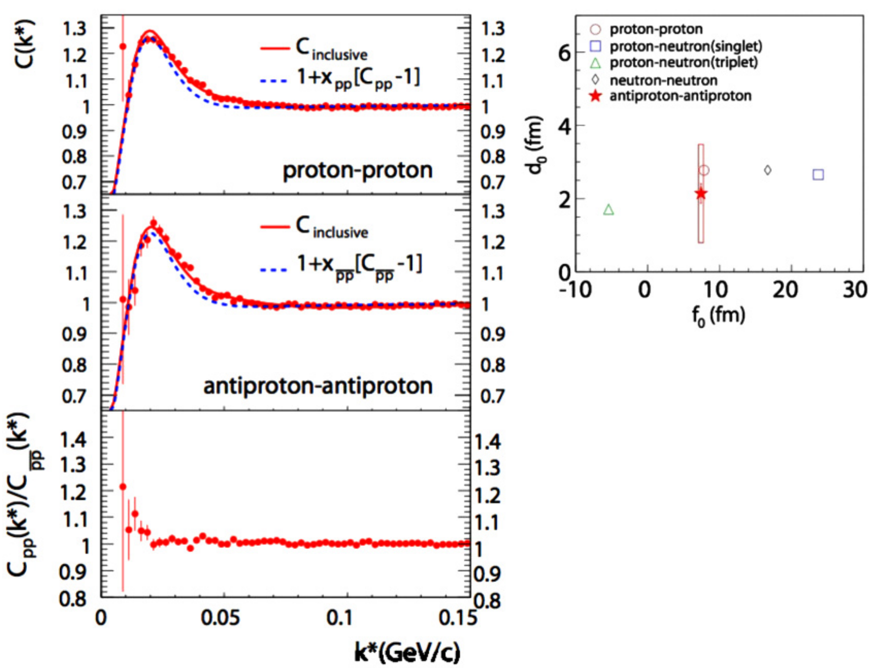

Fig. 1. p–p (top), $\bar{p}$–$\bar{p}$ (middle) and their ratio (bottom) for $\sqrt{s_{NN}} = 200$ GeV (left) and parameters of strong interactions for different hadron pairs (right) [5].

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. Both parameters: f_0 and d_0 are estimated for antiproton–antiproton pairs for the first time and they are found to be consistent with those for proton–proton pairs (Fig. 1 (right)). Source sizes in the case of two protons or two antiprotons were found as $R_{pp} = 2.75 \pm 0.01(\mathrm{stat.}) \pm 0.04(\mathrm{syst.})$ fm and $R_{\bar{p}\bar{p}} = 2.80 \pm 0.02(\mathrm{stat.}) \pm 0.03(\mathrm{syst.})$ fm.

3.2. Results for BES program

Figure 2 shows results of p–p and p–$\bar{p}$ correlation functions for $\sqrt{s_{NN}} = 39$ GeV for three different centralities. Centrality dependence is clearly visible. Table I lists the centrality dependence of protons and antiprotons source sizes measured for identical and nonidentical pairs. Results for identical particles are consistent with each other within uncertainties, and discrepancies between identical and nonidentical baryon pairs occur due to the measurements of residual correlations originating from weakly-decayed particles (which remain in the measured correlation function). Table II shows results of p–p and p–$\bar{p}$ systems for different collision energies.

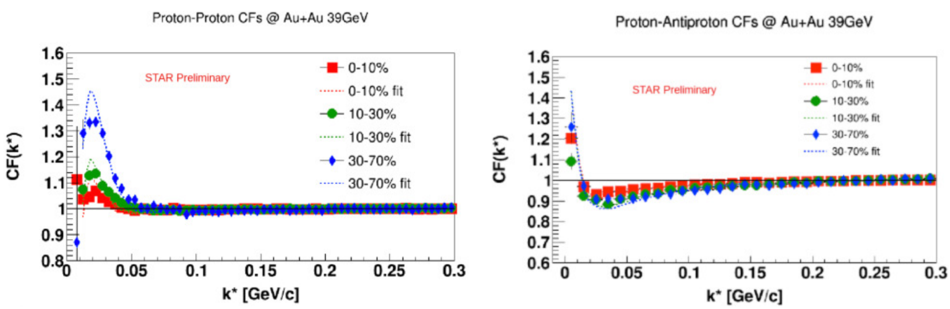

Fig. 2. Proton–proton (left) and proton–antiproton (right) correlation functions for different centrality classes for $\sqrt{s_{NN}} = 39$ GeV [6, 7].

TABLE I

Source sizes R_{inv} for various baryon (antibaryon) pairs with statistical and systematic uncertainties (due to purity correction only).

Centrality	R_{inv} p–p [fm]	R_{inv} $\bar{p}$–$\bar{p}$ [fm]	R_{inv} p–$\bar{p}$ [fm]
0–10%	$4.00 \pm 0.15 \pm 0.02$	$3.82 \pm 0.20 \pm 0.03$	$3.39 \pm 0.12 \pm 0.14$
10–30%	$3.61 \pm 0.13 \pm 0.17$	$3.68 \pm 0.15 \pm 0.11$	$2.69 \pm 0.10 \pm 0.12$
30–70%	$2.72 \pm 0.07 \pm 0.07$	$2.95 \pm 0.11 \pm 0.08$	$2.56 \pm 0.09 \pm 0.12$

TABLE II

Source sizes $R_{\rm inv}$ for various baryon pairs with error bars: statistical and systematic ones due to purity correction.

$\sqrt{s_{NN}}$ [GeV]	$R_{\rm inv}$ p–p [fm]	$R_{\rm inv}$ p–$\bar{p}$ [fm]
7.7	$3.59 \pm 0.16 \pm 0.19$	—
11.5	$3.66 \pm 0.08 \pm 0.05$	$3.30 \pm 0.42 \pm 0.28$
19.6	$3.82 \pm 0.15 \pm 0.06$	$3.32 \pm 0.25 \pm 0.13$
27	$3.80 \pm 0.12 \pm 0.08$	$3.49 \pm 0.25 \pm 0.16$
39	$4.00 \pm 0.15 \pm 0.02$	$3.39 \pm 0.12 \pm 0.14$

The source size strongly depends on collision centrality (more central collisions means bigger source and weaker correlation). Radii of source depend also on energy collision: higher collision energy means bigger source and weaker correlation.

4. Dynamics of collision

Dynamics of the collision studied by femtoscopic methods can be derived from nonidentical particles combinations only. It is possible to study emission sequence in the case of distinguishable particles. Collision dynamics can be related to both aspects: space and time. The method is sensitive to the emission asymmetries related to the spatial shifts (particles of different species are statistically emitted from different areas of the source) and to the time intervals between emissions of two different particles. However, it is impossible to distinguish between space and/or time scenario. The measured correlation function is determined using Spherical Harmonics decomponents, while two components are taken into account: $C00(k^*)$ — consistent with one-dimensional correlation function $C(k^*)$ and $C11(k^*)$ — sensitive to the

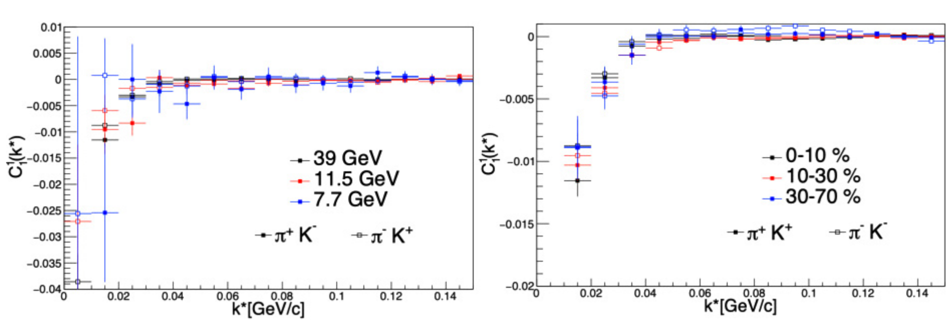

Fig. 3. Pion–kaon correlation functions for collision energies (left) and different centrality classes (right) for BES program [7].

possible asymmetries in the emission process. Figure 3 shows correlation functions (just $C11$ components) for pion–kaon systems as a function of collision centrality (for collision energy $\sqrt{s_{NN}} = 39$ GeV) and for various collision energy for BES program. All $C11$ functions differ from zero value for small k^* intervals and confirm emission asymmetries (lighter particles (pions) are statistically emitted closer to the systems center and/or earlier than heavier particles (kaons)). Such asymmetry is a result of flow.

5. Summary

Results describing geometrical and dynamical properties of source produced during heavy-ion collisions are presented in this paper. Geometrical sizes are derived from identical and nonidentical particle combinations and dynamical properties from nonidentical pairs only. In addition, parameters of strong interactions can be studied too. In the context of nonidentical particle species emission differences of distinguishable particles can have their origin 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 in average emitted closer to the systems center and/or earlier than heavier ones.

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REFERENCES

[1] G. Odyniec *et al.*, *J. Phys. G* **37**, 094028 (2010).
[2] M.M. Aggarwal *et al.*, `arXiv:1007.2613 [nucl-ex]`.
[3] V. Grishin, G. Kopylov, M. Podgoretskii, *Sov. J. Nucl. Phys.* **13**, 638 (1971).
[4] R. Lednicky, V.L. Lyuboshitz, *Sov. J. Nucl. Phys.* **35**, 770 (1982).
[5] L. Adamczyk *et al.*, *Nature* **527**, 345 (2015).
[6] H. Zbroszczyk *et al.*, *Acta Phys. Pol. B Proc. Suppl.* **12**, 205 (2019).
[7] S. Siejka *et al.*, *Nucl. Phys. A* **982**, 359 (2019).