

Strange hadron correlations in heavy-ion collisions at RHIC energies and below

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Abstract. 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 and the Final State Interactions (Coulomb and strong), which allow one to study the space-time characteristics of the source of the order of 10^{-15} m and 10^{-23} s. Femtosopic measurements allow one also to study FSI, especially the strong one, which is unknown for many two-particle systems. The RHIC program covers a significant part of the QCD phase diagram using collisions of Au nuclei for several beam energies from 7.7 to 200 GeV for which baryon-rich region is studied via femtoscopy. These measurements complement those obtained from AGS, SPS, and SIS experiments. Strange hadron measurements together with non-strange ones provide complementary information about source characteristics. Strangeness is a significant observable for many regimes of collision energies providing a complete view of strangeness production in heavy-ion collisions. These proceedings shows the femtosopic measurements of various strange particle combinations at different collision energies and centralities of the collision.

1 Introduction

For the last decades, many theoretical and experimental efforts have been devoted to study properties of strongly interacting matter described by the QCD phase diagram. At the Large Hadron Collider (LHC) and top Relativistic Heavy Ion Collider (RHIC) energies, the explored matter is described by high temperature and low baryon chemical potential and exists in the state of Quark-Gluon-Plasma (QGP). Hadron Gas (HG) transition to QGP is found to be of a smooth cross-over type. Many other areas of the QCD phase diagram, for significantly lower temperature and higher baryon chemical potential values are currently being explored by the HADES experiment conducted at Heavy Ion Synchrotron SIS18 at GSI and will be studied in the future by the CBM experiment at FAIR, currently under construction. Two experiments nowadays study areas of the phase diagram for intermediate temperature and baryon chemical potential: STAR conducted at RHIC with its Beam Energy Scan (BES) program [1], [2] and NA61/SHINE at the Super Proton Synchrotron (SPS). In this region, the phase transition from HG to QGP could be the first-order and ends at a Critical Point (CP). However, the CP has not been discovered yet, and its location is still unknown. Understanding the QCD phase diagram is one of the most essential goals in the field of relativistic heavy-ion physics. Several methods are proposed to study such baryon densities; two-particle correlations being one of them. Changes in the particle spectra shape as a function of

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collision energy can be studied to reveal changes in the kinetic freeze-out temperature of the hadrons from the medium and their mean transverse velocity. Momentum spectra can give partial information only. The bulk response of the produced system has a non-trivial structure in both space and time. By the measurement of particle correlations in the region of small relative velocities, the space-time information can be extracted. This method, called correlation femtoscopy, is widely used in heavy-ion collisions studies. Its name: femtoscopy is related to femto-scale (10^{-15} m = 1 fm), which can not be accessed by any other experimental technique, is a method originating from astronomy - HBT. By studying the space-time sizes of particle emission region as a function of beam energy, it is possible to infer the medium's energy density at the last re-scattering of the hadrons. These measurements can be sensitive to a softening in the equation of state, related to a first-order phase transition. STAR, as an example of a currently operating experiment for non-zero baryon chemical potential, performed detailed studies of two-pions femtoscopy for data collected in the frame of the BES-I program. With the relations between thermal and collective motions, between chemical and thermal freeze-out, with the effects of resonance production and secondary re-scattering, the system's final image of space-time evolution represents a very complex phenomenon, difficult to describe quantitatively.

RHIC, one of the largest accelerators in the world, is located at Brookhaven National Laboratory (BNL), Upton. Four facilities were located at RHIC: STAR, PHENIX, PHOBOS, and BRAHMS. Currently, STAR is the only running experiment. Solenoidal Tracker At RHIC (STAR) is an experiment, which 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 BES program 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 QGP and a hadron gas and also to search for the CP between first-order phase-transition and cross-over transition described by QCD.

The High-Acceptance Di-Electron Spectrometer (HADES) was originally designed to measure low mass di-electrons originating from the decay of vector mesons, HADES is also well suited to measure charged hadrons with good efficiency. The synchrotron SIS18 provides the beams with energies between 1 - 2 A GeV for heavy ions and up to 4.5 GeV for protons. Secondary pion beams with momenta up to 2 GeV/c are also available at this facility.

2 The femtoscopy method

Femtoscopy is a powerful tool which allows one to study through the effects of quantum statistics (QS) and the FSI, geometrical (source sizes), and the dynamical (space-time asymmetries in the emission process) properties of the expanding source. 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. Femtoscopy enables one to study 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. Therefore the geometry of heavy-ion collision can be studied via femtoscopic parameters describing source sizes of emission areas. In order to define a femtoscopic correlation function [3], [4] in the case of identical particle combinations a Longitudinally 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 the 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. 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) 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. If two particles are identical, the wave function must be adequately (anti-) symmetrized for pairs with even (odd) total pair spin. It is the QS effect. It is referred to as the Hanbury - Brown Twiss (HBT) effect, originating from the two astrophysicists' names that performed similar measurements for the correlation between photons from stars. Therefore, a correlation function in identical particles is sensitive to the QS effects (if there are considered bosons, they obey Bose-Einstein description; if they are fermions, they obey a Fermi-Dirac description). For pairs of hadrons, it will also contain the contribution from FSI. If both particles are charged ones, it will contain a contribution from Coulomb FSI. For pairs of charged hadrons, both types of FSI act at the same time. In traditional femtoscopy, considered usually for pions and kaons, the interaction is well known. For these pairs, the QS symmetrization is a dominating effect, the strong interaction is negligible, while the Coulomb FSI can be treated as a correction and can be considered with simplified methods. Besides, pions are the most abundantly produced particles in heavy-ion collisions, and the multiplicity of kaons is also large. The resulting experimental correlation function has excellent statistical precision. It can be fitted by a known theoretical formula, providing exact information about source sizes. A traditional femtoscopy method provides precise and detailed information relating to the source's space-time structure.

3 Results of nucleon-nucleon interactions for Au + Au collisions at $\sqrt{s_{NN}} = 200$ GeV

The study of nucleon-nucleon (N-N), nucleon-hyperon (N-Y), and hyperon-hyperon (Y-Y) interactions are fundamental to understand the physics of relativistic heavy-ion collisions, neutron stars and the existence of various exotic hadrons. A significant amount of N-N scattering data allows us to construct precise N-N potential models. However, the limited availability of N-Y scattering data and no scattering data for the Y-Y systems makes understanding the N-Y and Y-Y potentials complicated and challenging. Commonly, the experimental information on the bound states of strange baryons and nucleons (hypernuclei) is used to provide information on N-Y interactions. However, the extraction of strong interactions' parameters becomes difficult due to contamination by many-body effects. STAR has measured correlation functions of proton-proton, antiproton-antiproton, and the ratio of proton-proton and antiproton-antiproton for the 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], see Figure 1. 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 (Figure 2). Source sizes in the case of two protons or two antiprotons were found as $R_{pp} = 2.75 \pm 0.01(\text{stat}) \pm 0.04(\text{sys.})$ fm and $R_{\bar{p}\bar{p}} = 2.80 \pm 0.02(\text{stat}) \pm 0.03(\text{sys.})$ fm.

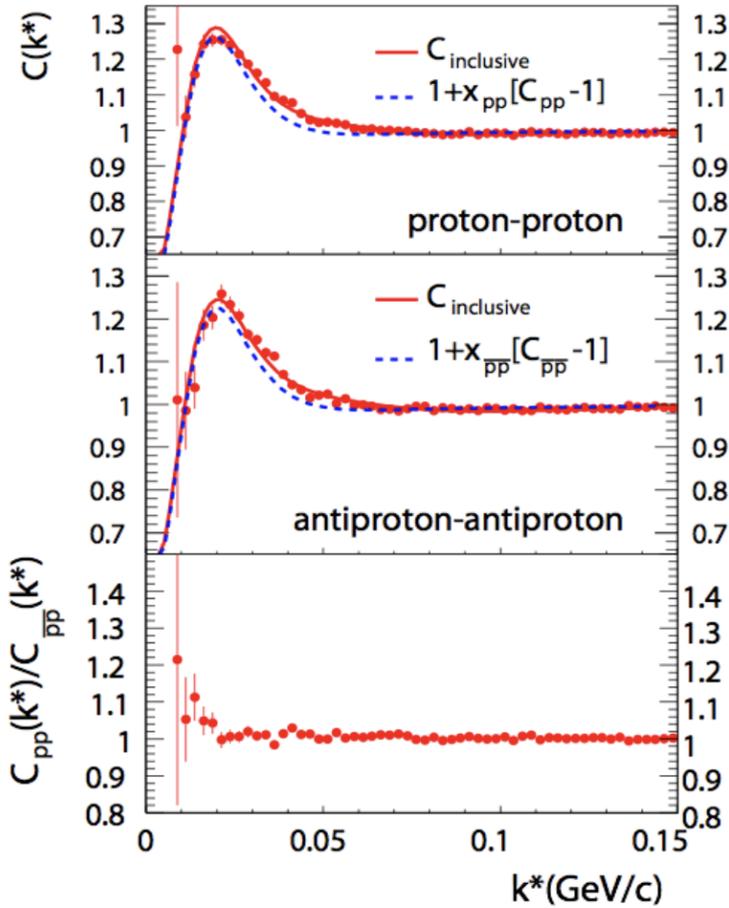


Figure 1. Proton-proton (top), antiproton-antiproton (middle) correlation functions and their ratio (bottom) for Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV. [5]

4 Strange baryon correlations

High-energy heavy-ion collisions provide a significant number of hyperons in each collision, which gives an excellent opportunity to study strong interactions. Using the $N - \Omega$ interaction, the shape of the two-particle correlation function at low relative momentum changes significantly with the strength of the $N - \Omega$ attraction. However, the Coulomb interaction in the $p - \Omega$ channel makes it challenging to access the strong interaction parameters directly from the measured two-particle correlation function. Therefore, a new measure, namely the ratio of the correlation functions between the peripheral (small) and central (large) collision systems, is proposed. This ratio provides direct access to the strong interaction between proton and Ω , independent of the model used for the emission source. The attractive nature of an $N - \Omega$ interaction leads to the possible existence of the $N - \Omega$ dibaryon. Such an $N - \Omega$ dibaryon is the most interesting candidate after the H-dibaryon [6]. Several attempts have been made to estimate the binding energy of the $N - \Omega$ state in different QCD-motivated

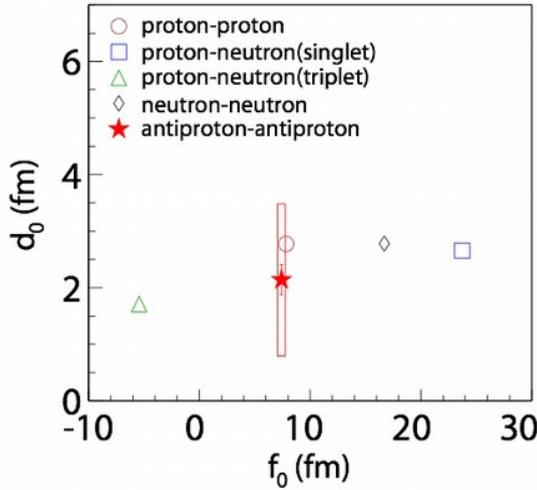


Figure 2. Parameters of strong interactions for different hadron pairs. [5]

models. The $N - \Omega$ dibaryon can be produced in high-energy heavy-ion collisions through the coalescence mechanism [7]. The measurement of the $p - \Omega$ correlation function for peripheral and central Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV, presented in Figure 3, provides insight into the existence of an $N - \Omega$ dibaryon.

In order to estimate the parameters of the strong interaction, it is better to use data from the experiment operating at lower collision energies due to the much lower contamination of the particle sample with the products from the decays. Such an example comes from the HADES experiment, where the parameters of the strong interaction between proton and lambdas pairs are estimated. The parameters were extracted from the measured correlation function that includes both: femtoscopic correlations and long-range correlations (LRC), seen as a slope for higher momentum difference. Long-range correlations are parametrized as $C_{LRC}(k) = 1 + ak + bk^2$. Figure 4 shows example of $p - p$ (top) and $p - \Lambda$ correlations functions. The source size of the region emitting proton-lambda pairs is estimated from distributions of the proton-proton system. Then, having estimated the source, determining f_0 and d_0 parameters was possible. The values are as following: $f_{0,NLO}^{S=0} = 2.91$ fm, $d_{0,NLO}^{S=0} = 2.78$ fm, $f_{0,NLO}^{S=1} = 1.54$ fm, $d_{0,NLO}^{S=1} = 2.72$ fm, and $f_{0,LO}^{S=0} = 1.91$ fm, $d_{0,LO}^{S=0} = 1.40$ fm, $f_{0,LO}^{S=1} = 1.23$ fm, $d_{0,LO}^{S=1} = 2.13$ fm.

5 Strange meson correlations

Examination of femtoscopic correlations between even lighter strange particles (e.g., charged and neutral kaons) for various collision energies is attributed to studies of strangeness production within different phase diagram regions. Inclusion of particle correlations between hyperons may be attributed to studies of the minimum collision energy required for heavier particle species to be produced. Considering the lightest strange particles – kaons, both: charged and neutral ones can extract different elements of information. It is very well known that a significant fraction of pions come from resonance decays after freeze-out, thus complicating the identical pion femtoscopic measurements. While the direct pion source may

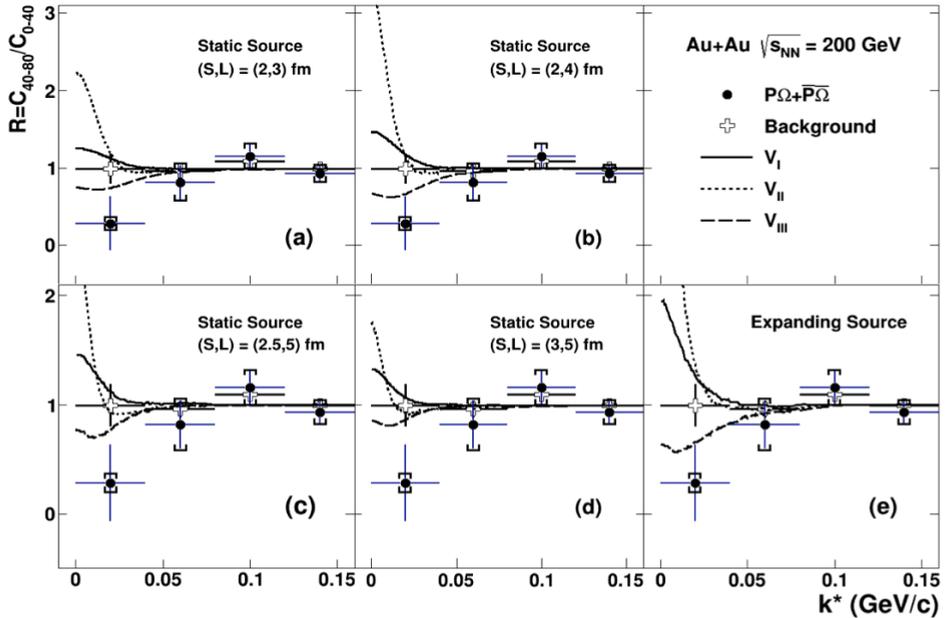


Figure 3. The solid circle represents the ratio (R) of the small system (40-80% collisions) to the large system (0-40% collisions) for proton-omega and $\bar{p} - \Omega$. The error bars correspond to the statistical errors, and caps correspond to systematic errors. The open crosses represent the ratio for background candidates from the side-band of omega invariant mass. Predictions for the ratio of the small system to the large system for $p - \Omega$ interaction potentials V_I , V_{II} and V_{III} for static source with different source sizes $(S, L) = (2,3)$, $(2,4)$, $(2.5, 5)$ and $(3,5)$ fm, where S and L are corresponding to small and large systems, are shown in (a), (b), (c) and (d) respectively. In addition, the prediction for the expanding source is shown in (e) [8].

be inherently non-Gaussian, the resonances extend the source size due to their finite lifetime, introduce an additional essentially non-Gaussian distortion in the two-pion correlator, and thus they reduce the fitted correlation strength. Kaon interferometry, on the other hand, suffers less from resonance contributions and could provide a cleaner signal for correlation studies than pions. Femtoscopic correlations for two identical charged pions or kaons are described by both QS effects and FSI: Coulomb and negligible strong one. Therefore, source characteristics derived from charged kaons studies ideally complement those learned from two-pions. An example of the correlation function for two neutral kaons for the most central Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV is shown in the Figure 5 (left), while the combination of neutral and positive kaon in the Figure 5 (right). The shape of the correlation function for identical and non-identical kaon pairs is different. The QS effects are dominant in the case of the both neutral kaons, QS (which relies on the Gaussian parameterization) is not sufficient to describe the shape of the correlation function around a dip structure around $q_{inv} = 0.1$ GeV/c. Only including the strong FSI (Lednický-Lyuboshitz parametrization) allows us to describe the area of the correlation function below the unity. The parameterization of the function for neutral and positive kaons only considers the strong interaction related to the presence of a_0 resonance.

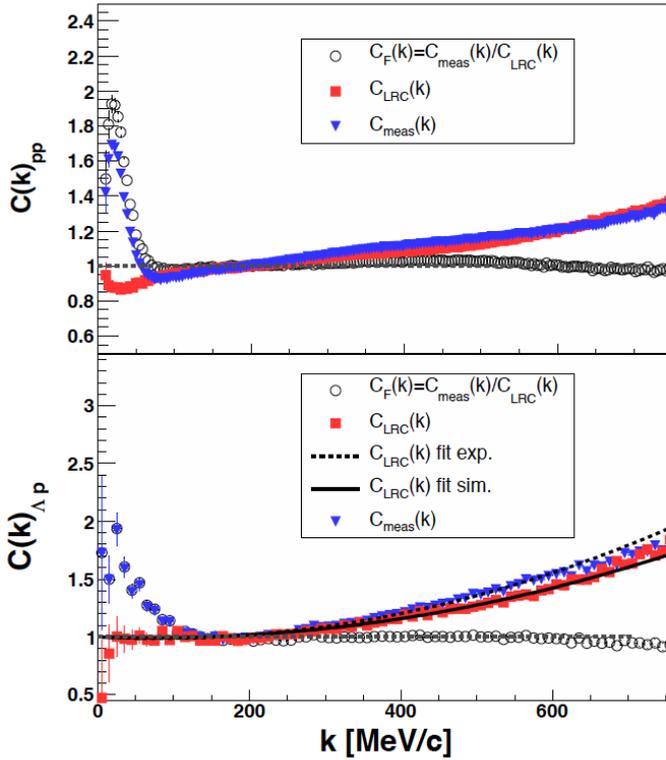


Figure 4. Proton-proton correlation function (top) used to extract source size and proton-lambda (bottom) correlation functions, femtoscopic correlations together with long-range correlation [9].

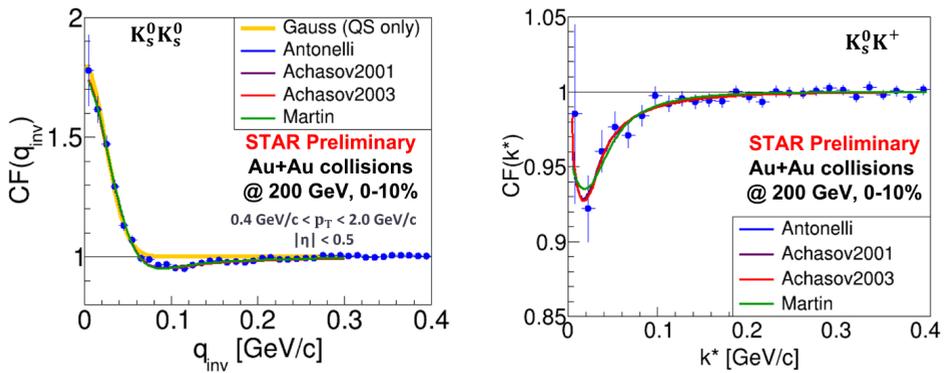


Figure 5. Two kaon correlations at Au+Au collisions at $\sqrt{s_{NN}} = 200$ GeV for neutral kaons (left) and combination of neutral and positive kaons (right) [10].

6 Summary

These proceedings presented femtoscopy results obtained for RHIC energies and below. The knowledge about N-N, N-Y, and Y-Y interactions is crucial to understanding the nature of elementary interactions responsible for building matter components, e.g., neutron stars. In the context of N-N and $\bar{N} - \bar{N}$ interactions, 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 were discussed. Except for source sizes, these studies delivered the scattering length (f_0) and effective range (d_0) parameters of the strong interaction of protons and antiprotons. Parameters of the strong interactions were also studied for $p - \Omega$ pairs; however, it was impossible to draw definitive conclusions due to insufficient statistics. It was also discussed that with the help of lower collision energies, studying elementary interactions can be conclusive and competitive with higher-energy experiments due to a much lower fraction of contaminated particles originating from decays. For example, HADES data were discussed to provide parameters of the strong interactions between $p - \Lambda$ pairs. In terms of strange meson correlations, strong interactions between neutral kaons and pairs of neutral and charged kaons were significant when the hypothesis about the possible formation of a_0 resonance as a tetraquark state.

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