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Femtoscopy in heavy-ion collision experiments at various μ_B

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Summary. — 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. Femtoscopic measurements allow one to study FSI, especially the Strong one, which is not studied for many two-particle systems. Various experiments at LHC, RHIC, and SIS-18 facilities cover a significant part of the QCD Phase Diagram using collisions of heavy ions for several beam energies, in which regions with different μ_B are studied via femtoscopy. Strange hadron measurements and non-strange ones provide complementary information about source characteristics. These proceedings exhibit the femtoscopic measurements of various particle combinations at different collision energies.

1. – Introduction

The femtoscopy method, inspired by the Hanbury Brown and Twiss technique from astronomy (HBT) [1], has been successfully used to study the properties of area-emitting pairs of correlated particles (fig. 1). It is known as the "length of homogeneity" [2] and refers to probing the geometric and dynamic properties of the phase-space cloud of particles. The correlation function is described by the Koonin-Pratt equation: $C(k^*, r^*) = \int S(r^*)|\Psi^2(r^*, k^*)|d^3r$, where k^* is the momentum of the first particle in the pair measured in the pair rest frame reference, r^* is the relative distance between two emission points, $S(r^*)$ is the source function, and $\Psi(k^*, r^*)$ is the wave function describing correlations due to Quantum Statistics and/or Final State Interactions. If the mechanisms of particle correlations are known, then the spatial properties of the cloud are determined. It is a classic example of non-interacting pairs of photons or two bosons (*e.g.*, mesons π). However, if only one knows how to describe the source function, then, thanks to two-particle correlations, the properties of the interactions in the final state are determined.

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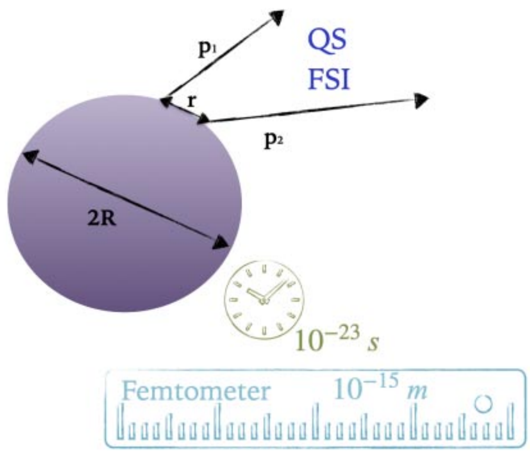

Fig. 1. – A schematic view of the phase-space cloud emitting pairs of particles, correlating due to Quantum Statistics and Final State Interactions, reveals the system's unique properties. Sizes are of the order of femtometers, and lifetimes are on the order of 10^{-23} s.

2. – QCD Phase Diagram

In recent years, femtoscopy has been successfully used to study interactions between many exotic particles, particularly those moderately produced in heavy-ion and elementary particle correlations. Additionally, femtoscopy stands out as one of the methods that allow researchers to study various areas of the still unexplored regions of the QCD phase diagram (fig. 2). The most well-known region is described by lattice QCD, which is related to high temperatures T and low, as well as very low, baryon chemical potentials μ_B. This region depicts the conditions of the Universe just moments after the Big Bang and is often referred to as the "Early Universe". The transition probed there, between the Hadron Gas (HG) and Quark-Gluon Plasma (QGP), is known as a "cross-over". Further regions of the QCD phase diagram are much less understood. The area of moderate

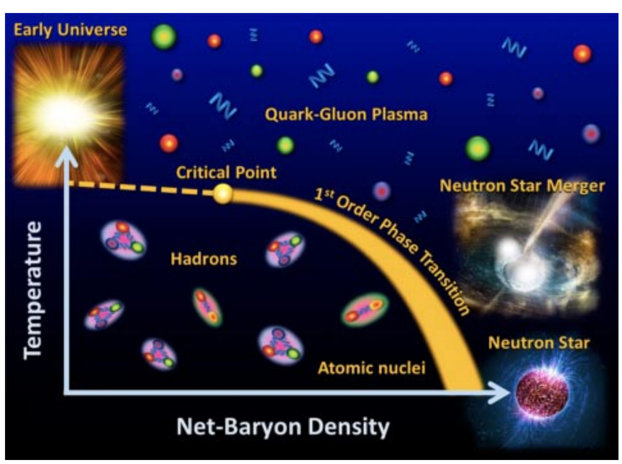

Fig. 2. – QCD phase diagram describing strongly interacting matter [2].

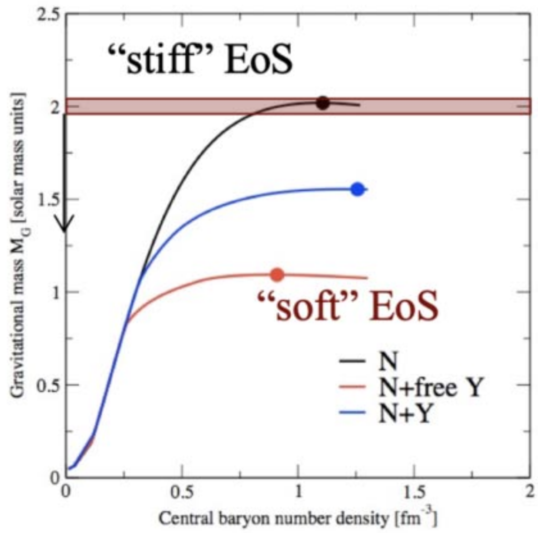

Fig. 3. – The difference between stiff and soft EoS resulting in the mass of NS.

T and μ_B, described by the first-order phase transition between HG and QGP, is still being explored. Moreover, the Critical Point (CP) between the cross-over transition and the first-order phase transition remains hypothetical and awaits discovery. The coldest area of the QCD phase diagram describes neutron star mergers (NSM) and the cores of neutron stars (NS).

3. – Neutron Stars and Neutron Star Mergers

The neutron star (NS) is a remnant of the gravitational collapse of massive stars during a supernova event. Its mass and radius typically range from 1 to 2 solar masses and 10 to 12 km, respectively. Central densities fall within the range of 4 to 8 times the normal nuclear matter saturation density, approximately $\epsilon_0 \simeq 2.7 \times 10^{14}\ g/cm^3$ ($\rho_0 \simeq 0.16 fm^{-3}$). The most suitable theoretical framework incorporates hyperons, which are expected to appear in the core of NS at densities around 2 to 3 ρ_0. The presence of hyperons softens the Equation of State (EoS), reducing the maximum NS mass (see fig. 3). However, observations of NSs with masses exceeding 2 solar masses are incompatible with such a soft EoS. While the existence of hyperons is energetically favorable, their presence softens the EoS and contradicts experimental results, posing the hyperon puzzle. One potential solution lies in the strong interactions between NS components, which can be elucidated through femtoscopy studies involving nucleon-nucleon (N-N), nucleon-hyperon (N-Y), and hyperon-hyperon (Y-Y) interactions. There is growing interest in Y-N and Y-Y interactions from an experimental perspective. Significant progress has also been made theoretically, notably through advancements in Lattice QCD. Despite numerous theoretical predictions, many experimental efforts focus on identifying evidence for bound states. The existence of hypernuclei, confirmed by attractive Y-N interactions, suggests the potential for binding hyperons to nucleons. Therefore, measuring Y-N and Y-Y interactions holds important implications for the potential formation of Y-N or Y-Y bound states, offering a promising avenue for resolving the puzzling mystery surrounding

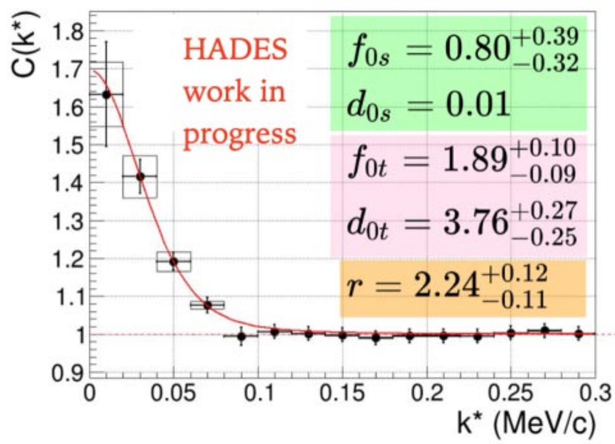

Fig. 4. – $p - \Lambda$ correlation function from Ag+Ag collisions at $\sqrt{s_{NN}} = 2.55$ GeV [3].

neutron stars. A precise knowledge of these interactions helps to explore the unknown structure of neutron stars. HADES (High Acceptance DielEctron Spectrometer) [3] is an experiment conducted at the SIS-18 accelerator at GSI, Darmstadt, Germany. HADES collects data from heavy ions (such as Au-Au, Ag-Ag) and elementary beams (protons, mesons like π). Its extensive physics program focuses on primordial dilepton probes, strangeness, and various aspects of heavy ions and hadronic physics.

In recent years, HADES has also become interested in femtoscopic correlation measurements. One of the recent areas attracting considerable attention is the N-Y interaction between protons and Λ hyperons. The only interaction between $p\Lambda$ is a strong one. To determine it, the Lednicky-Lyuboshits formalism is employed [4]. It uses two parameters, f_0 and d_0, scattering lengths and effective range of interaction, respec-

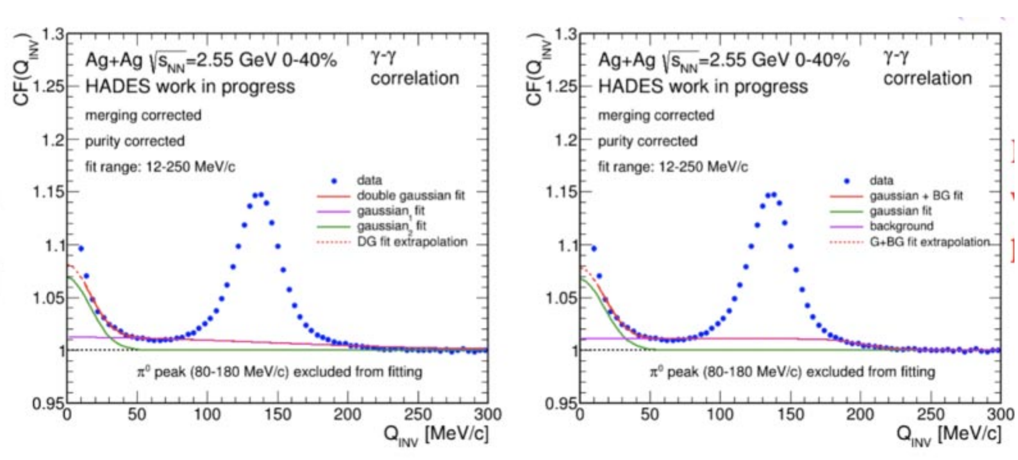

Fig. 5. – Two-photon correlation function for $0 - 40\%$ central collisions of Ag+Ag at $\sqrt{s_{NN}} = 2.55$ GeV with two different Gaussian fits applied [4].

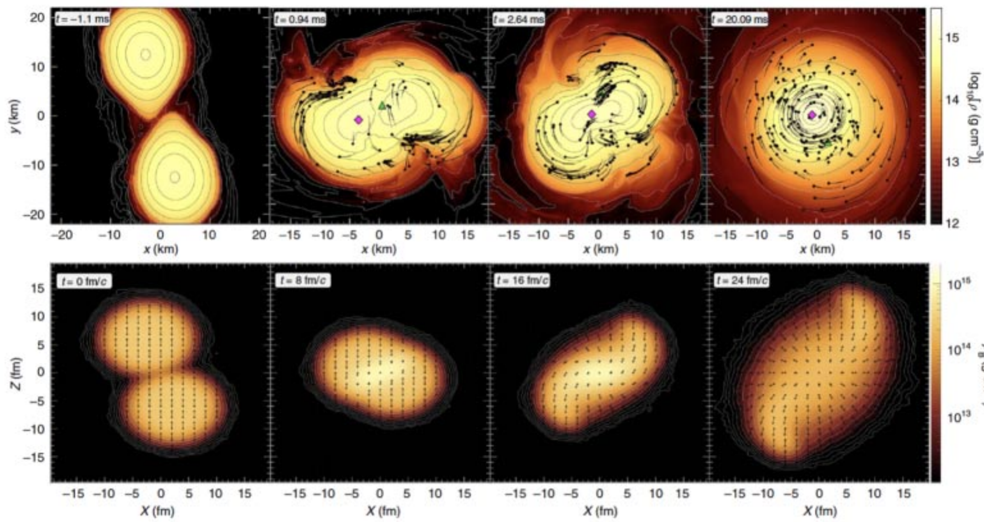

Fig. 6. – NSM (top) and heavy-ion collisions scenario from HADES environment [6].

tively. For the $p - \Lambda$ system, the following singlet and triplet proportions are made: $C(k^*) = \frac{1}{4}(1 + \lambda C(k^*, s = 0) + \frac{3}{4}(1 + \lambda C(k^*, s = 1))$. Then, the iterative fit is done to extract the following parameters: f_{0s}, d_{0s}, f_{0t}, d_{0t}, r (source size). More can be found in [4].

HADES is known for studying electromagnetic probes, primarily focusing on dilepton observables. These probes offer insights into various stages of the system's evolution following collision events, including information about early stages inaccessible to hadrons. This access allows for investigation before the freeze-out era. Figure 5 depicts the example of the $\gamma - \gamma$ correlation function from Ag+Ag collisions at $\sqrt{s_{NN}} = 2.55$ GeV. A prominent peak is visible around $Q_{inv} = 150$ MeV/c due to the decay of π^0 meson to two photons. The region where the contribution of direct (non-decayed) photons is expected is related to $Q_{inv} < 50$ MeV/c. More about preliminary results of photon's HBT can be found in [5].

HADES and future FAIR experiments (such as CBM, in conjunction with HADES) will explore the QCD region that describes the region of NSM. Figure 6 compares the visualization of the NSM (top) and heavy-ion collisions. While the geometric properties of these two systems differ significantly, the parameters describing their thermodynamic properties correspond to each other.

4. – Phase Transitions

One of the hottest topics in the heavy-ion collision community recently is the region of phase transitions between Hadron Gas (HG) and Quark-Gluon Plasma (QGP). Over a decade ago, the STAR (Solenoidal Tracker at RHIC) experiment proposed the Beam Energy Scan (BES) program. Its primary goals include searching for a threshold collision energy (by decreasing $\sqrt{s_{NN}}$) where the transition from HG to QGP is no longer present, identifying signatures of the first-order phase transition between HG and QGP, and investigating the still hypothetical Critical Point (CP). The femtoscopy method proves useful in this context. To search for possible signatures of the phase transition,

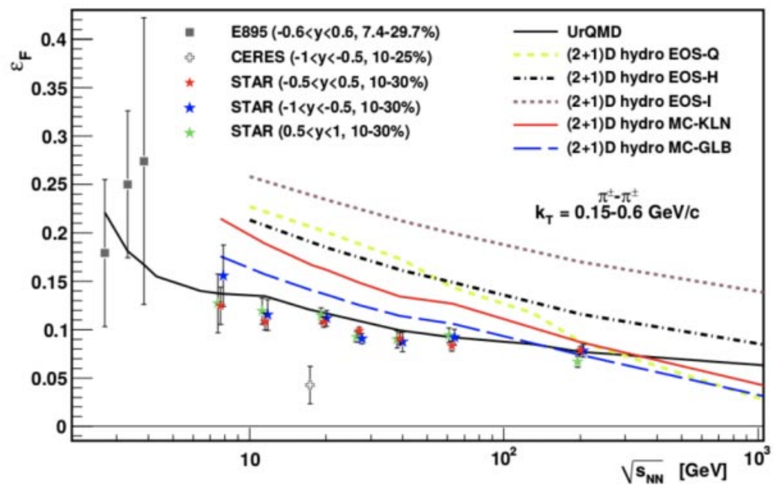

Fig. 7. – Excitation function of the final eccentricity for BES program [7].

the azimuthally-sensitive (asHBT) method is employed. asHBT measures the correlation function depending on the orientation of the reaction plane of the heavy-ion collision. From the parameters of the HBT radii, the final eccentricity parameter can be determined, which measures the system's evolution in time. Based on current results [7], it is inferred that up to $\sqrt{s_{NN}}$=7.7 GeV, the system undergoes a cross-over transition, a conclusion supported by comparison with various model predictions. Two approaches are necessary to deepen these studies. First, measurements should be performed with lower collision energies, which is likely to occur as the STAR experiment with the Fixed-Target (FXT) program descends to $\sqrt{s_{NN}}$=3 GeV. Aside from mesons π, other particle species should be validated; the next candidates are protons. STAR also plans to conduct an asHBT analysis for protons based on recent FXT data from Au-Au collisions.

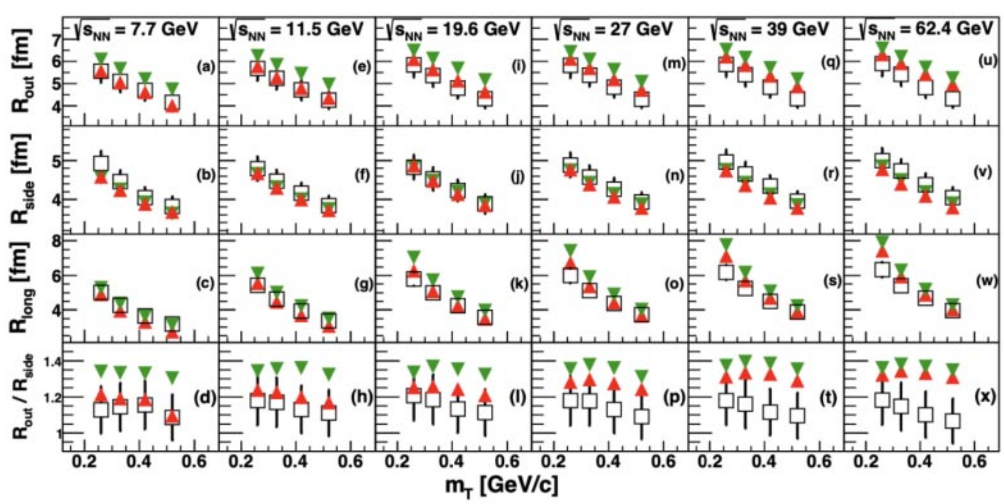

Fig. 8. – vHLEE+UrQMD predictions of two-pion correlations at STAR BES [8].

Additionally, the vHLLE+UrQMD models [8] are utilized to compare experimental STAR results with model predictions. Two different Equations of State (EoS) were tested: the first assumes a cross-over transition, while the second assumes a first-order phase transition. The comparison of model predictions with experimental results, especially for the R_{out}/R_{side} (R_{out} represents the source size in the direction compatible with the transverse pair momentum, while R_{side} is perpendicular to R_{out} and R_{long} which describes the system along the beam axis)) indicates that all measured results from STAR, down to $\sqrt{s_{NN}}$= 7.7 GeV are consistent with a cross-over transition.

5. – Early Universe

As mentioned earlier, the region of the QCD phase diagram successfully described by Lattice QCD is accessible through the ALICE experiment [9]. A significant collection of femtoscopic results from the LHC provides numerous insights into describing strong interactions between correlated hadrons.

6. – Summary

As discussed during many presentations at the WPCF 2023 conference, femtoscopy is a powerful tool for exploring not only the geometric and dynamic properties of the phase-space cloud of particles but also for providing insight into the description of strong interactions. Many systems are measured and accessed with various collision energies, which opens the door to studying various regions of the QCD phase diagram. Moreover, with femtoscopic observables, one can investigate the type of transition between HG and QGP. Experiments currently underway (such as HADES, STAR, ALICE) have already made significant contributions across various μ_B ranges. Future experiments, such as HADES combined with CBM, will additionally access the region of more dense nuclear matter and NS.

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