Two-particle femtoscopy at the HADES experiment

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Abstract. An experimental study of γ-γ, p-Λ, and p-cluster femtoscopic correlations from Ag+Ag collisions at $\sqrt{s_{NN}} = 2.55$ GeV has been conducted using the HADES detector. The results reveal an HBT-like structure for γ-γ correlations, provide estimations of strong interaction parameters for p-Λ correlations, and indicate potential decay signatures of light nuclei for p-cluster correlation functions.

1 Introduction

Over the past decades, the properties of dense matter have been widely concerned in connection with hypernuclei and hyperons. Their existence inside neutron stars softens the Equation of State (EoS), consequently limiting their masses to be lower than $2M_{\odot}$ (known as the "hyperon puzzle"). Low-energy relativistic collisions of heavy ions create very dense matter under conditions expected to be similar to neutron star mergers. To effectively establish an EoS for such matter, knowledge about strong interactions between matter elements is essential, particularly between nucleons and hyperons (e.g., p-Λ), as well as nucleons and clusters (e.g., p-d, p-t, or p-^{3}He). This can provide insights into the possible existence of hyperons in neutrons stars, along with a characterisation of potential excited and bound-states of light nuclei [1]. Created hadrons carry information available after thermal freeze-out, therefore photons with a long mean free path and emitted through the whole system's evolution are considered for studying earlier collision stages.

Femtoscopy [2] is a technique that allows the measurement of properties of a source area, having a lifespan of 10^{-23} seconds and a lifetime of femtometers (10^{-15} m), as well as interactions between particles through correlations between their momenta. To accomplish this, one can create correlation function, described as follows:

$$CF(q) = \int S(\vec{r}) \left|\Psi(q,\vec{r})\right|^2 dr^3 = \frac{\text{Same}(q)}{\text{Mixed}(q)} \tag{1}$$

where $q = \left|\vec{p_1} - \vec{p_2}\right|$ - momentum difference, $S(\vec{r})$ - source function, $\Psi(q,\vec{r})$ - 2-particle wave function, Same(q)/Mixed(q) - q distributions from same/mixed events respectively. In the case of one-dimensional analysis, either Q_{inv} for identical particles and k^* for non-identical can be used:

$$Q_{inv} = \sqrt{\left|\vec{p_1} - \vec{p_2}\right|^2 - (E_1 - E_2)^2} \quad ; \quad k^* = \frac{|\vec{p_1}^{\,*} - \vec{p_2}^{\,*}|}{2} \tag{2}$$

where: $\vec{p}$ - particle momentum, $\vec{p}^{\,*}$ - particle momentum in center-of-mass frame, E - particle's energy.

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The HADES experiment [3], located at the GSI/FAIR [4] scientific facility, is a fixed-target experiment, operating at low beam energies of a few A·GeV. The detector is optimized for the measurement of dielectrons, originating from light vector meson (ω, ρ, ϕ) decays. It is capable of reconstructing neutral particles thanks to electromagnetic calorimeter (ECAL) and achieves excellent proton-to-pion separation with precise Time-of-Flight detectors.

The presented femtoscopic studies were conducted using data from Ag+Ag collisions at $\sqrt{s_{NN}}$ = 2.55 GeV, collected by HADES in March 2019.

2 γ-γ femtoscopy

Hadron femtoscopy cannot probe the source at early evolution stages due to kinetic freeze-out. Such restriction does not apply to photons, being penetrative probes. Since photon emission is continuous through the system evolution, direct photons can be used to study the source at early times. Distinguishing between direct and decay photons in experiments poses a non-trivial problem, as the vast majority come from the $\pi^0 \longrightarrow \gamma\gamma$ decay. Because femtoscopy is sensitive to the emission time of studied particles, it can be used as a tool to isolate the contribution of direct photons. The γ candidates were selected by collecting hits in ECAL. Each candidate has to have an energy greater than 100 MeV, as well as $\beta = \frac{v}{c}$ within 2σ around the expected photon peak, centered at β=1.

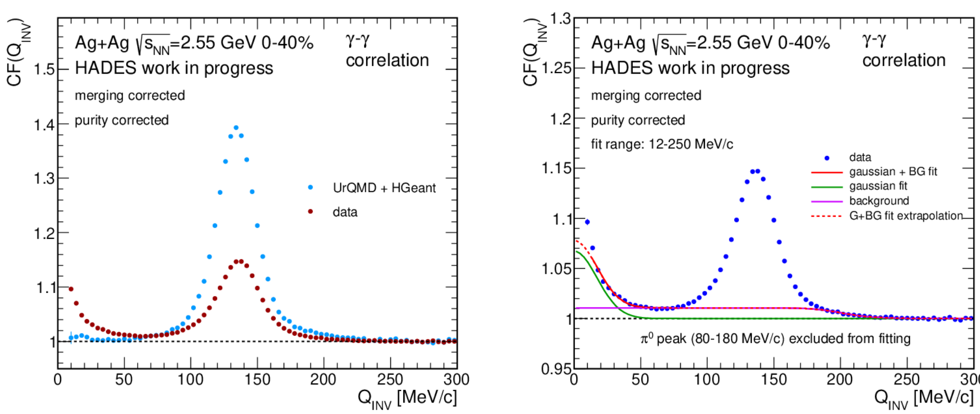

Figure 1: $\gamma - \gamma$ correlation function measured in Ag+Ag collisions at $\sqrt{s_{NN}}$ = 2.55 GeV with 0-40% centrality. A comparison between data and simulations is shown in the left panel. A fit of parametrization (3) to the experimental results is presented on the right. Only statistical uncertainties are shown.

Figure 1 presents the photon-photon correlation function obtained using data and UrQMD simulations with modeled detector response [5, 6]. The simulations do not include interactions between particles or quantum statistics effects, therefore serving as a benchmark of residual correlations and detector effects. For both series a π^0 residual peak is visible, located at its nominal mass ($\sim$ 135 MeV/c^2), as well as an enhancement of data over simulation at low relative momenta of Q_{inv} < 50 MeV/c region, reminiscent of the expected Bose-Einsten correlation. The correlation function was fitted with the parametrization:

$$CF(Q_{inv}) = 1 + \lambda e^{-Q_{inv}^2 R_{inv}^2} + \frac{a_0}{(1 + a_1 Q_{inv})^{a_2}} \tag{3}$$

where: R_{inv} - femtoscopic radius, λ - correlation strenghts, a_0, a_1, a_2 - parameters for the background factor. With such approach, a qualitative description of the correlation function can be achieved. The background contribution has an unknown origin, which, along with observed HBT-like peak and π^0 residual peak magnitude difference between simulations and experimental data, requires further investigation.

3 p-Λ femtoscopy

Although Λ hyperons are rare at HADES, due to the low energy of the collisions, they can be identified through the $\Lambda \longrightarrow p\pi^-$ decay channel (BR ~ 64%). Both charged particles were selected based on β - momentum dependence, within 2σ around the expected theoretical value, given by:

$$m_0 = p\sqrt{\frac{1}{\beta^2} - 1} \tag{4}$$

where: m_0 - particles rest mass, p - particles momentum, $\beta = \frac{v}{c}$. The off-vertex-decay topology [7] was exploited to reconstruct Λ hyperons and reduce the number of numerical combinatorics.

To extract values of strong interaction parameters the Lednicky-Luboshitz formalism [8] was utilized, featuring 6 free parameters: r_0 - femtoscopic radius, λ - correlation strength, f_{0s}, f_{0t} - scattering length (for singlet/triplet state) and d_{0s}, d_{0t} - effective radius (for singlet/triplet state). The fitting procedure was carried out iteratively, minimizing the χ^2 value for given set of parameters.

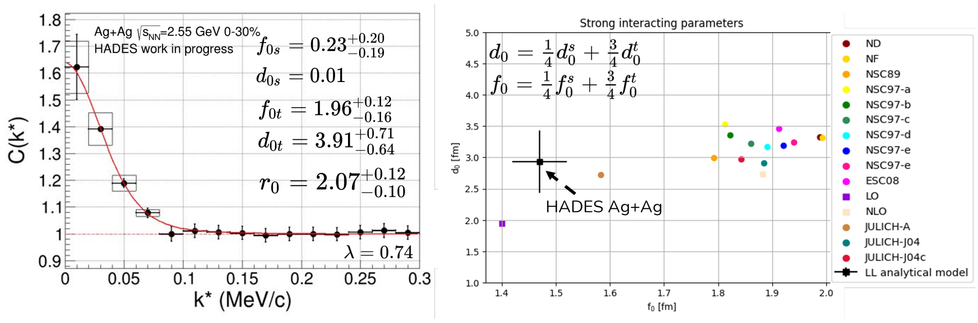

Figure 2: $p - \Lambda$ correlation function for Ag+Ag collisions at $\sqrt{s_{NN}} = 2.55$ GeV with 0-30% centrality with fitted analytical description is shown on the left. A comparison of average d_0 and f_0 to theoretical calculations is presented on the right.

Figure 2 shows the $p - \Lambda$ correlation function obtained from data, with fitted analytical description of the Lednicky-Luboshitz model and the best-fit parameter values and averaged values of d_0 and f_0 obtained with this analysis, compared to theoretical predictions [9]. The singlet state shows unexpectedly small values, therefore further studies are required.

4 p-cluster femtoscopy

Proton-cluster femtoscopy, in addition to probing the EoS of highly interacting matter, allows to study of the presence of decaying nuclear states. In the case of this analysis the CorAl [10] software package was used. The source was assumed to be Gaussian and predefined potentials were used. The p-p, p-d, p-t and p-^{3}He correlations have been investigated. The first two show a fair agreement with a theory, while the last two exhibit indications of possible contributions arising from the decays of light nuclei (^{4}He and ^{4}Li). More details can be found in [11].

5 Summary

A γ-γ correlation exhibits an enhancement at low Q_{inv}. In addition to the HBT-like peak another, wider contribution was observed. Their origin and physical interpretation requires further studies.

Strong interaction parameters have been determined via p-Λ correlations, separately for both spin states. The values obtained for the singlet state are noticeably smaller than for the triplet, which entails additional study.

Correlations between p and clusters can reveal signatures of the decays of light nuclei and a fair description of the obtained data by theoretical models has been observed.

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