The femtoscopy analysis of the p - Λ system obtained in heavy-ion collisions within the HADES experiment.

Narendra Rathod,* *for the HADES collaboration*

[1]Warsaw University of Technology, 00-662 Warsaw, Poland.

Abstract. The study investigates hyperons in dense matter, addressing the "hyperon puzzle" and its implications for neutron stars. Utilizing femtoscopy in Ag-Ag heavy-ion collisions at 1.58 AGeV within the HADES experiment, the analysis focuses on Λ (uds) strange quarks. By reconstructing Lambdas through $\Lambda \to \pi^- + p$ decay, the study measures the p - Λ correlation function, revealing a distinct peak and providing valuable insights into strong interaction parameters. The initial exploration of the nucleon-hyperon (N-Y) femtoscopic correlation signal is presented, with a focus on the ongoing nature of the contribution as a work in progress.

1 Introduction

Over the past decades, there has been significant interest in the properties of hyperons in dense matter, particularly in relation to hypernuclei and their role in neutron stars. Hyperons are believed to potentially exist in the inner layers of neutron stars, and their description depends heavily on the equation of state (EOS) of nuclear matter at supersaturation densities. The presence of hyperons in the core softens the EOS, leading to neutron stars with masses below 2M, where M is the mass of the sun. However, soft EOS typically predicts small radii, posing a challenge known as the "hyperon puzzle in neutron stars." To experimentally understand hyperon-nucleon interactions, the two-body system is considered. Femtoscopy, a technique involving two-particle correlations in momentum space, proves to be a powerful tool for exploring such phenomena and determining parameters of strong interaction and sizes in heavy-ion physics. It enables the measurement of the collision-generated system's space-time features, with a lifespan of 10^{-23} seconds and a spatial scale of femtometers (10^{-15} m). The analysis utilizes the HADES detectors at the GSI Helmholtz Center for Heavy-Ion Research in Darmstadt, Germany, focusing on Ag-Ag heavy-ion collisions at a kinetic energy of 1.58 AGeV. For the study of strong interactions, particles with strange quarks, such as Λ and K_s^0, are ideal. These strangeness-containing particles are produced infrequently in heavy-ion collisions at typical HADES energies. The analysis predominantly employs the off-vertex-decay or V_0 topology, reconstructing the secondary vertex.

2 Particle Identification via Time of Flight

Eq-1 functions as a valuable tool for deducing the rest mass of a particle by leveraging its momentum and velocity. The momenta of particles are determined using the Runge-Kutta

---

[*] e-mail: nsrathore.rajput@gmail.com

method [1]. Velocities are calculated based on trajectory lengths and time-of-flight measurements collected by either the RPC (Fig-1, right panel) or TOF (Fig-1, left panel) detector [1].

Importantly, the derived momenta inherently represent the momentum-to-charge ratios of these particles. As a result, the obtained mass values are effectively mass-to-charge ratios. This methodology is crucial for determining the rest masses of particles (m_0) within the analysis involving momentum (p) and $\beta \approx \frac{v}{c}$.

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

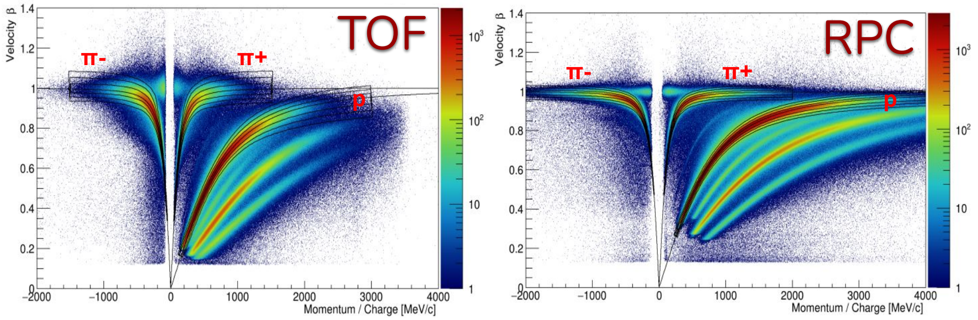

Figure 1. Velocity versus momentum-over-charge distributions of reconstructed charged particles are depicted in the left panel for the RPC detector and the right panel for the TOF detector. The solid lines indicate the ±1, 2, and 3σ (σ represents the standard deviation) selection regions for charged pions and protons [1].

3 Lambda reconstruction via Off-Vertex-Decay Topology

At typical HADES energies, the production of particles containing strangeness is exceptionally rare, even in the most central Ag(1.58A GeV)+Ag collisions, where a Λ hyperon is produced approximately once in every ten collisions. Identified proton and pion tracks are further considered for the reconstruction of Λ candidates. An off-vertex-decay or V_0 topology is defined based on the secondary vertex's displacement, characterized by parameters illustrated in Fig-2 (left panel). VDX represents the distance between the event vertex and the decay vertex, which is the midpoint of the vector connecting the trajectories of the daughter particles at their closest approach points. Two parameters, Distances of Closest Approach (DCAs) between the daughter particle trajectories and the event vertex, are also defined. The heavier daughter particle is labeled Dau1 (p), and the lighter one is Dau2 (π^-). These parameters quantify the distance from the primary event vertex where the hypothetical decay occurred, with larger values indicating actual weak decays instead of combinatorial background. The parameter MotVD measures the DCA between the hypothetical mother particle trajectory and the event vertex. Since the trajectories of daughter particles may not necessarily intersect in three-dimensional space, their DCA is quantified using another parameter called Minimum Track Distance (MTD). The final parameter is the opening angle between the two daughter particle trajectories, which is called A. The Off-Vertex-Decay Topology selected parameters are presented in Table-1. The reconstructed Λ hyperon is presented in

Parameters	**values**
VDX	**>65 mm**
Distance between the Dau1 and the primary vertex	**>8 mm**
Distance between the Dau2 and the primary vertex	**>24 mm**
MotVD	**<5 mm**
MTD	**<6 mm**
A	**>15^o**

Table 1. The final five selection criteria sets utilized in the reconstruction and analysis of Λ hyperons.

Fig-2 (right panel), where the event-mixing technique is used to eliminate background from the signal region. The obtained signal purity is about ≈90%.

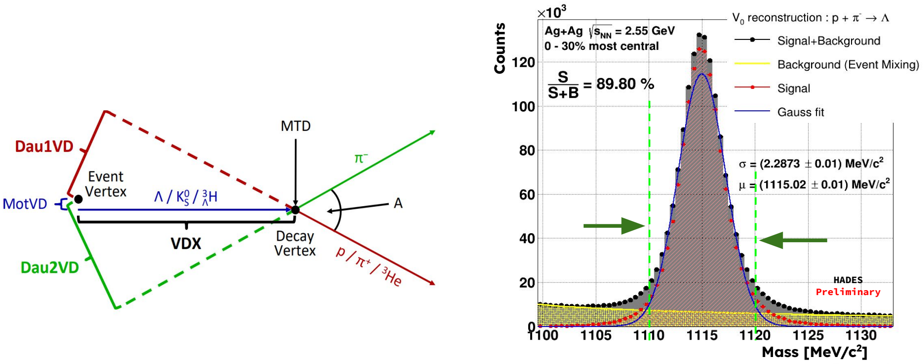

Figure 2. Schematic depictions of the Off-Vertex-Decay topology (left panel) and the invariant mass distribution of $p - \pi^-$ pairs from the 0-30% most central Ag(1.58A GeV)+Ag events (right panel).

4 $p - \Lambda$ femtoscopic correlation

The correlation technique is applied to a subset of the phase space of the selected particle pairs (p, Λ) to gain insights into an otherwise immeasurable region. The final state interaction of the emitted particles introduces an energy (momentum) dependence in this formalism. The particle femtoscopic correlation function (**C**), linked to the two-particle relative momentum (k^*) evaluated in the pair rest frame, is expressed as follows [2, 3] (see Eq-2).

$$C(k^*) = \frac{P(p_1^*, p_2^*)}{P(p_1^*)P(p_2^*)} = 1+\int S(\vec{r^*})[|\Psi(\vec{k^*}, \vec{r^*})|^2-1]d^3r^* \xrightarrow[Koonin-Pratt\ relation]{\int S(\vec{r^*})d^3r^*=1} \int S(\vec{r^*})|\Psi(\vec{k^*}, \vec{r^*})|^2 d^3r^* \tag{2}$$

Here, $P(p_1^*, p_2^*)$ represents the probability of the simultaneous detection of two particles with momentum p_1^* and p_2^*, evaluated in their center of mass, resulting in $k^* = |p_1^*$ - $p_2^*|/2$. $P(p_1^*)$ and $P(p_2^*)$ denote the single-particle emission probabilities, while $S(\vec{r^*})$ is the source function (or spatial probability density function). $S(\vec{r^*})$ is connected to the wave function of the relative motion of the particle pair, denoted as $\Psi(\vec{k^*}, \vec{r^*})$. The properties of the source function, along with the direction and intensity of the interaction, collectively influence the shape of the correlation function [4]. The correlation function shown in Fig-3 (left panel) is exclusively derived from simulations, capturing only the effects of the detector without inherent interaction information from the transport model. On the contrary, the red-colored points in Fig-3 (right panel) represent the correlation function obtained directly from experimental data. This data-driven correlation function is further refined using the double ratio correction method, leading to the black-colored points also depicted in Fig-3 (right panel). The femtoscopic correlation signal has been successfully extracted from HADES data. The next step involves the computation of this correlation function. To aid in this process, Lednicky and Lyuboshitz have introduced an analytical model specifically crafted for extracting parameters related to strong interactions and the corresponding source radii for particle pairs.

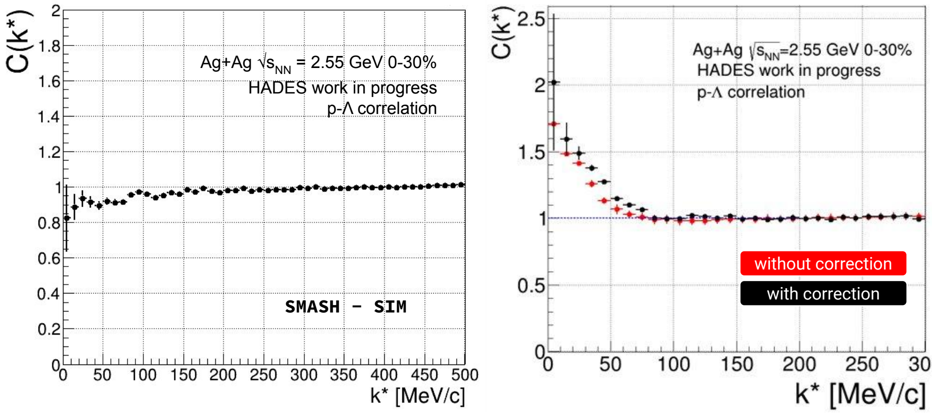

Figure 3. Experimental $p - \Lambda$ - correlation function extracted by HADES, Ag(1.58 AGeV/c)+Ag data, (**SMASH** simulation - left panel and **HADES** data - left panel). Correlation function before correction (red points) and after applying all detector corrections (black points).

Acknowledgement

This work was supported by the Grant of National Science Centre, Poland, No: 2020/38/E/ST2/00019. Studies were funded by IDUB-POB-FWEiTE-3, project granted by Warsaw University of Technology under the program Excellence Initiative: Research University (ID-UB).

References

[1] S. Spies, Ph.D. thesis, Frankfurt U. (2022)

[2] U. Heinz, B.V. Jacak, Annual Review of Nuclear and Particle Science **49**, 529 (1999), `https://doi.org/10.1146/annurev.nucl.49.1.529`

[3] M.A. Lisa, S. Pratt, R. Soltz, U. Wiedemann, Annual Review of Nuclear and Particle Science **55**, 357 (2005), `https://doi.org/10.1146/annurev.nucl.55.090704.151533`

[4] V.K. Semenova, E.V. Khyzhniak, G.A. Nigmatkulov, Journal of Physics: Conference Series **1390**, 012028 (2019)