INVESTIGATION OF THE EXCLUSIVE $pp \to ppKK$ PROCESS USING DATA COLLECTED BY HADES*

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Received 26 March 2025, accepted 27 March 2025, published online 12 May 2025

This study presents the exclusive analysis of the $pp \to ppK^+K^-$ reaction with data taken with the HADES detector in February 2022 at a center-of-mass energy of 3.47 GeV. A neural network-based particle identification was developed that compensates for simulation-experiment discrepancies through domain adversarial technique. The background was suppressed by means of kinematic refit with 4 overconstraints corresponding to the conservation of 4-momentum, which allowed us to obtain a high-purity sample of data with $S/B \approx 15$. Clear signals from $\phi(1020) \to K^+K^-$ and $\Lambda(1520) \to pK^-$ decays were observed with their parameters consistent with those published by the PDG. Moreover, the importance of K^+K^- non-resonant final-state interactions was confirmed. This paper discusses the details of our event selection, efficiency corrections, and presents a number of intermediate results.

DOI:10.5506/APhysPolBSupp.18.4-A9

1. Introduction

The High-Acceptance DiElectron Spectrometer (HADES) is a fixed-target particle detector at FAIR, primarily designed for detecting electron–positron pairs produced in medium-energy heavy-ion collisions [1]. The main objective of HADES is to investigate the properties of hot and dense hadronic matter, *e.g.* chiral symmetry restoration in the medium [2]. With its high acceptance and comprehensive particle identification (PID) systems, HADES is versatile and enables a wide range of studies, including hyperon production and elementary reactions induced by proton and pion beams.

* Presented at the Workshop at 1 GeV scale: From mesons to axions, Kraków, Poland, 19–20 September, 2024.

In the central region of the detector, that covers polar angles from 18° to 85°, particle momenta, charges, and trajectories are reconstructed by Mini-Drift Chambers (MDC), positioned on both sides of a magnetic field. Hadron identification in this area is facilitated primarily by two systems: (1) drift chambers, which allow for energy-loss measurement ($\mathrm{d}E/\mathrm{d}x$), and (2) two time-of-flight systems, TOF and RPC, which enable a measurement of particle velocities. In contrast, the forward area, which covers small polar angles, lacks magnetic field coverage along the particle path. As a result, momentum reconstruction and PID capabilities are limited in the forward detector. In most of the HADES analyses, all tracks reconstructed by the forward detector are assumed to stem from protons.

This paper addresses a study of the $pp \to ppK^+K^-$ reaction based on data taken at GSI by HADES using a proton beam with kinetic energy of 4.535 GeV. This channel provides valuable insights into the strangeness production mechanism. That includes refining the parameters of intermediate resonances, notably the $\phi(1020)$ and $\Lambda(1520)$, and assessing their contributions to the reaction. Specifically, the ratio of $\phi(1020)/K$ is of interest since it provides a measure of the area of strangeness conservation, which is used in the interpretation of data obtained in heavy-ion reactions [3]. Additionally, the non-resonant component can clarify the role of final-state interactions (FSI) in this process. The data presented here extends previous studies conducted at lower energies just above the reaction threshold [4].

The ultimate aim of this analysis is to extract differential cross sections and to perform a global fit to the data. This work presents some intermediate results as a step towards these broader objectives.

2. Event selection

A fully exclusive analysis was performed, where all four charged tracks are required to be detected and reconstructed in the HADES systems and one of the positive particles is allowed to hit the forward detector. Following a multiplicity cut $n_+ \geq 2$ and $n_- \geq 2$, the selection primarily relies on two methods: a neural network-based particle identification and a kinematic reconstruction of the reaction topology. The average pion production rate in p–p reactions at HADES is 1–2 orders of magnitude higher than the rates of kaon production. Consequently, processes such as $pp \to pp\pi\pi$ are the main sources of the background, and both selection methods are optimized to suppress this contamination while maintaining high kaon selection efficiency.

2.1. Particle identification

Conventionally, at HADES hadron identification is performed by a cut-based selection based on the reconstructed velocity-momentum correlations, which suffice for π/p separation, but is not enough for the case of 2 low-multiplicity kaons in the final state. Identification of kaons is further complicated because their distributions lie between those of pions and protons. To address this, a neural network-based PID procedure was developed that uses all particle information simultaneously. It is based on the Domain Adversarial Neural Network (DANN) technique [5], where the network is trained on both simulated (labeled) and experimental (unlabeled) datasets, reducing the effect of poor simulation quality. The algorithm takes all physical parameters of a particle as an input and outputs probabilities for the particle to be one of the five hadronic types: $\pi^-, \pi^+, K^-, K^+, p$, with the sum of probabilities equal to 1. To account for the significantly unbalanced abundances of kaons and pions, the importance of particle classes in the loss function was weighted inversely proportional to their estimated shares in the experimental dataset. It is worth noting that the usage of a neural network eases the selection procedure, as the suppression of certain classes can be adjusted with a single parameter — the cut on the output probability of the network. The PID quality was validated for experimental data using a tag-and-probe procedure. With the optimal probability cut, the efficiency and purity of negative pion selection were found to be above 98%, while kaon selection efficiency exceeded 80%.

2.2. Kinematic reconstruction

Further background suppression was achieved using a kinematic reconstruction package previously developed for HADES [6]. The main idea of the method is to find ideal particle parameters that satisfy certain constraint equations, simultaneously minimizing the difference between measured and ideal parameters in terms of detector resolutions: $\chi^2 = (\vec{y} - \vec{\eta})^T V^{-1} (\vec{y} - \vec{\eta})$, where $\vec{y}$ are measured parameters, $\vec{\eta}$ are ideal parameters, and V is the covariance error matrix. For this analysis, all momenta of initial- and final-state particles are known, allowing a fit imposing four-momentum conservation. To select signal events, the cuts on χ^2 values for two hypotheses were applied: $\chi^2_{ppKK} < 20$ and $\chi^2_{ppKK} < \chi^2_{pp\pi\pi}$, which further suppress pion contamination. These selection criteria result in a signal-to-background ratio of about 15, as illustrated in the χ^2 distribution in Fig. 1. After applying all the selection criteria, almost 150 thousand signal events remain in the dataset.

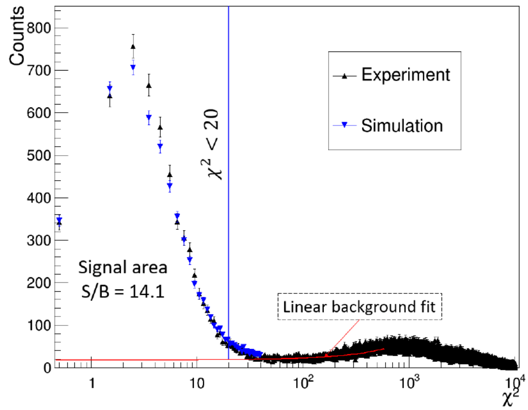

Fig. 1. Experimental χ^2 distribution with a linear background approximation. 3% of data.

3. Efficiency correction

Efficiency and acceptance corrections were derived from simulation, calculated as the ratio of selected to initially generated events within a given phase space region. For differential cross sections and other distributions, it is essential to parametrize efficiency according to the variables under study, as efficiency may vary significantly across bins. When experimental and simulated distributions over integrated degrees of freedom show substantial discrepancies, it may be beneficial to include them in the parametrization as well. Given the limited statistics presently available for the Monte Carlo simulated dataset, a balanced approach was adopted, in which the two-dimensional efficiency correction is used for all the studied distributions.

4. Results

Efficiency-corrected Dalitz distribution for the pK^+K^- system is shown in Fig. 2, where both the $\phi(1020) \to K^+K^-$ and $\Lambda(1520) \to pK^-$ resonances are distinctly visible. One of the Dalitz plot projections, the invariant mass distribution of K^+K^- pairs, is presented in Fig. 3. First, mass distributions of K^+K^- and pK^- were approximated by combinations of a Voigt function and a second-order polynomial. The resonance parameters of $\phi(1020)$ and $\Lambda(1520)$ extracted from the fit were found to be compatible within uncertainties with those reported by PDG.

The results of the fit were also used to determine the shares of the resonances in the final-state production cross section. The contribution of an intermediate $\Lambda(1520) \to pK^-$ resonance was estimated to be around 19%, and the contribution of a $\phi(1020) \to K^+K^-$ to be approximately 11%. After that, the production ratio of $\phi(1020)/K^- = 0.21 \pm 0.02$ was calculated from the yield of $\phi(1020)$, corrected for the branching ratio of $\phi(1020) \to K^+K^-$ decay, showing an enhancement similar to that seen in heavy-ion collisions at $\sqrt{s_{NN}} = 3.47$ GeV.

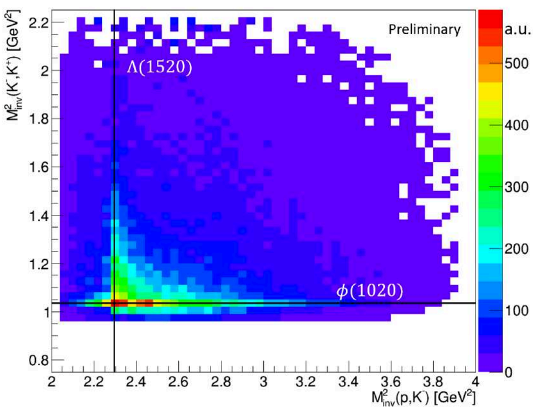

Fig. 2. Efficiency corrected Dalitz distribution of pK^+K^- system after kinematic refit.

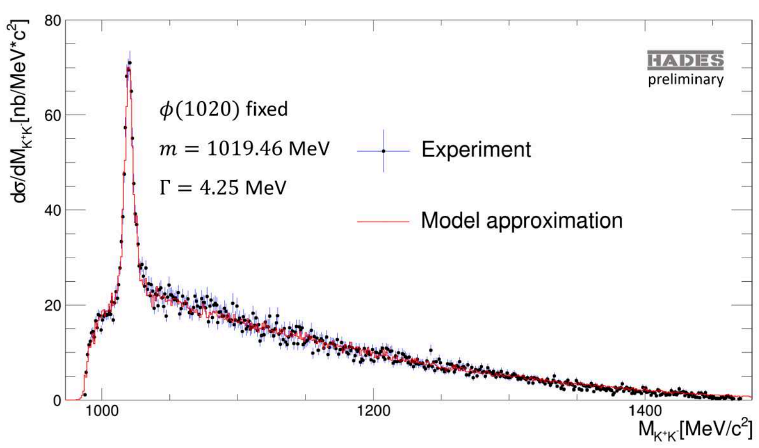

Fig. 3. Invariant mass distribution of K^+K^- pairs in comparison with an FSI-modified Monte-Carlo simulation.

The red histogram in Fig. 3 depicts an approximation of the measured K^+K^- invariant mass distribution with the Monte Carlo simulation. Generated phase-space distributed events were weighted by the amplitude that includes resonance contributions in the Breit–Wigner parametrization and the final-state interactions (FSI) of K^+K^- and pK^-. FSI were parametrized in a simplified re-scattering model $M = 1/(1 - iqa)$, where q is the relative momentum and a is the scattering length. The obtained K^+K^- scattering length $a_{K^+K^-} = (0.45 \pm 0.1) + i(0.1 \pm 0.1)$ fm was found to be not consistent with zero, which was previously unclear [4].

5. Summary

During the investigation of the $pp \to ppK^+K^-$ process with HADES at $\sqrt{s_{NN}} = 3.47$ GeV, we have obtained a clean data sample with an excellent signal-to-background ratio by exclusively reconstructing all final-state particles, using highly efficient NN-based PID and 4-constraint kinematic refit. Clear signals from the resonances $\phi(1020)$ and $\Lambda(1520)$ have been observed and their contributions to the reaction cross section have been measured. Additionally, the effects of final-state interactions have been studied which resulted in the K^+K^- scattering length measurement not consistent with zero. The results presented in this work are still preliminary, and a more refined analysis is expected to be published in the near future.

This work was supported by the NRW-FAIR network in the framework of a WP13, by the Ruhr-Universität Bochum, HADES Collaboration, and GSI Helmholtzzentrum in general.

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