PROCEEDINGS OF SCIENCE

pp scattering from standard to the unknown with PANDA@HADES

Jana Rieger*for the HADES collaboration and the PANDA@HADES collaboration

Department of Physics and Astronomy, Uppsala University,
Lägerhyddsvägen 1, 75237 Uppsala, Sweden

E-mail: jana.rieger@physics.uu.se

Hyperons and their electromagnetic decays have become one of the major objects of interest of the HADES experiment, providing access to the inner structure of those hadrons at the femtometer scale. With a recently collected data sample of reactions produced by a 4.5 GeV proton beam impinging on a liquid hydrogen target, a new avenue of such studies has opened up. Several steps are necessary in data pre-processing, such as quality assurance, calibration and normalization, before any data analysis can be performed. A "standard" reaction, namely elastic pp scattering, has been proven to be a versatile tool that can be applied to tackle those. A feasibility study for a planned measurement of the "unknown" Dalitz decay of the Σ^0 hyperon, produced in $pp \to pK^+\Sigma^0$ reactions, is performed. This would be the first measurement of an electromagnetic Dalitz decay of a hyperon. Two complementary analysis strategies are developed for this purpose. Preliminary simulation studies show that a pioneering measurement of the $\Sigma^0 \to \Lambda e^+e^-$ decay is feasible.

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1. Introduction

One of the most challenging questions in contemporary physics is how hadrons are built from quarks. This means that we do not yet understand the structure of one of the most abundant particles of our world, the nucleon. But what if we change the nucleon a little bit? Would that extend our picture? Hyperons are similar to nucleons but contain one or several strange quarks. By studying the unstable hyperons and their decays, we can gather valuable information about their inner structure. This inner structure is quantified by electromagnetic form factors. Especially by studying hyperon Dalitz decays ($Y^* \rightarrow Ye^+e^-$), where a hyperon Y^* decays into a lighter hyperon Y and a virtual photon that produces an electron-positron pair, basic particle quantities such as charge radii and magnetic dipole moments become accessible [1].
One of the main goals of the FAIR Phase-0 project PANDA@HADES is to enable such studies. In particular the beam time in spring of 2022 was dedicated to hyperon physics. Elastic pp scattering for which the cross section is known, is used for commissioning of the new detectors as well as for an absolute luminosity measurement, paving the way for hyperon analyses. The application of pp elastic scattering for monitoring purposes and normalization of the data, as well as a preliminary feasibility study for measuring the Σ^0 Dalitz decay are presented here.

2. The HADES Experiment

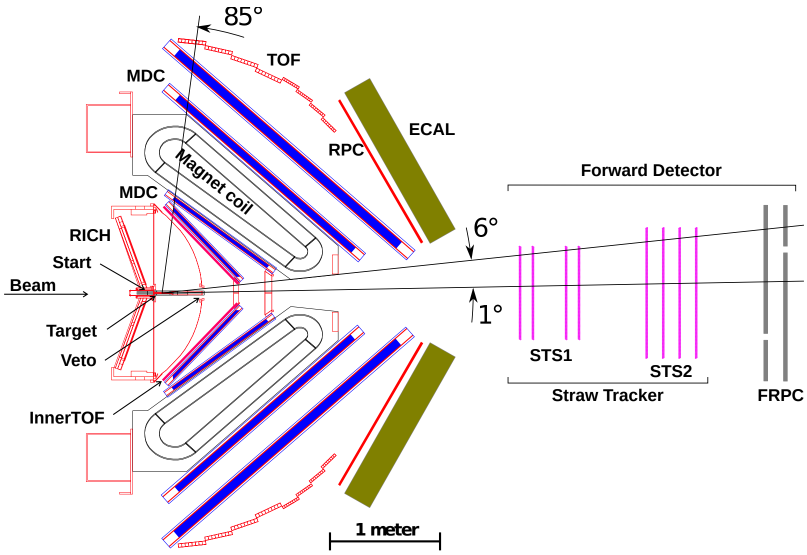

Figure 1: Schematic drawing of HADES and the hyperon upgrade. [3]

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The High Acceptance Di-Electron Spectrometer (HADES) [2] in the upgraded hyperon configuration [3] has taken data in Spring 2022. A proton beam of $T = 4.5$ GeV kinetic energy was provided by the upgraded SIS18 synchrotron [8], impinging on a liquid hydrogen target. A schematic drawing of the HADES setup used to collect the spring 2022 data is shown in Figure 1. After passing the Start detector the beam hits the target. The reaction products can either be detected in the main HADES or the Forward Detector. The latter has been added to facilitate hyperon measurements by extending the acceptance for protons in the forward direction. HADES is featuring the Ring Imaging CHerenkov detector (RICH) for lepton-hadron discrimination, four planes of tracking detectors, the Multiwire Drift Chambers (MDC), the inner and outer time of flight detectors iTOF and TOF plus the Resistive Plate Chamber detector (RPC) and ECAL, the Electromagnetic CALorimeter. A magnet producing a toroidal magnetic field is placed in between the second and third tracking plane to make momentum reconstruction possible. The Forward Detector consists of four double layers of Straw Tube tracking Stations, the STS, originally designed for PANDA and tested in HADES as a Fair Phase-0 project, and the forward Resistive Plate Chambers (fRPC), a time of flight detector.

3. The Standard: Elastic pp Scattering

Every time the experimental setup is changed, the apparatus has to be calibrated again. In addition the luminosity of the beam time needs to be determined. A "standard", or reference, reaction that is well understood is therefore needed to establish those parameters. pp elastic scattering at small scattering angles is ideal for this purpose due to the large cross section and the small energy dependence. It has been measured in detail by other experiments [4] and the kinematic relations of a two-body reaction are well defined. At small scattering angles, one proton is detected in the Forward Detector while the other one is reconstructed in main HADES. Elastic scattering is used for

- **Monitoring the beam quality** already during the beam time. Many elastic scattering counts suggest a large amount of proton-proton interactions.
- **Alignment and calibration of subdetectors** can be tested thanks to the strict kinematic relations of the protons. Systematic deviations of the reconstructed track parameters from those can reveal misalignment. The recently added parts of the Forward Detector are calibrated using the tight relations of the track measured in main HADES with the forward track.
- **Normalization** of the data. By counting the number of elastic events within the acceptance of the forward detector and correcting it for the efficiency estimated from simulations, the luminosity is determined using the integrated elastic cross section from existing data.

In addition the new data from HADES offer a **measurement of the differential elastic scattering cross section** at large scattering angles where both scattered protons are reconstructed in the main spectrometer. The existing data are of lower quality here and show stronger energy dependence. HADES will complement the data base with a more precise and accurate measurement at 4.5 GeV.

The scattering angles of the two elastic protons are directly related by Equations (1) and (2),

$$\tan\vartheta_1 \cdot \tan\vartheta_2 = \frac{1}{\gamma_{\mathrm{CM}}^2} = 0.29429 \qquad (1)$$

$$\varphi_2 = |180^\circ - \varphi_1| \qquad (2)$$

where ϑ_1, ϑ_2 and φ_1, φ_2 are the polar and azimuthal angles of the scattered protons in the laboratory reference frame and γ_{CM} is the Lorentz factor of the center of mass (CM) system. Each proton momentum p is given by its scattering angle and the beam momentum p_{beam} as

$$p = \frac{p_{\mathrm{beam}}}{\cos\vartheta \cdot (1 + \tan^2\vartheta\gamma_{\mathrm{CM}}^2)}. \qquad (3)$$

By selecting events that contain two protons that fulfill Equations (1), (2) and (3), a very clean sample of elastic scattering events can be extracted from data.

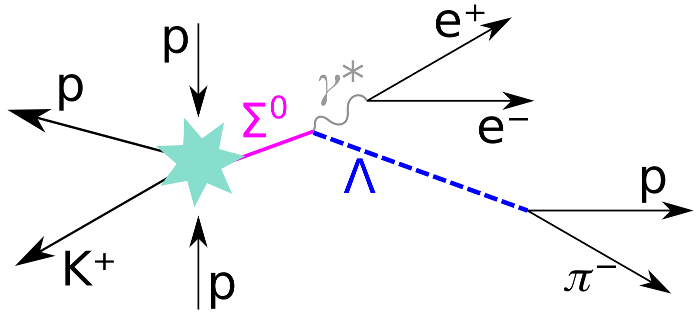

Figure 2: Illustration of Σ^0 produced in pp reactions, decaying via electromagnetic Dalitz decay.

4. The Unknown: Hyperon Form Factors

Once the experiment parameters are understood, unknown physics can be explored. Of special interest for hyperon transition form factor (TFF) measurements is the Σ^0 hyperon. Being the second heaviest hyperon with a mass of 1192.642 MeV, it is only 77 MeV heavier than the Λ. The mean life of the Σ^0 is $7.4 \cdot 10^{-20}\,s$ since it is decaying electromagnetically into $\Lambda\gamma$ with a branching fraction of almost 100% [5]. The Dalitz decay of the Σ^0 is predicted to have a branching fraction of $5 \cdot 10^{-3}$ and is expected to provide valuable information needed for the determination of $\Sigma^0 - \Lambda$ magnetic TFFs [1] but has never been measured before. HADES has already proven its power for reconstructing Dalitz decays in case of the Δ [6] and now a feasibility study has been performed to evaluate the possibilities of measuríng the Σ^0 Dalitz decay with the recently collected data. Challenges are expected to be the low mass difference of Λ and Σ^0, leading to low lepton momenta and a large background from the radiative decay when the photon converts in the detector material. In order to study these effects, one million events for the reaction $pp \to pK\Sigma^0[\Lambda e^+ e^-]$ illustrated in Figure 2 were simulated at $T = 4.5\,\text{GeV}$ with a uniform phase space distribution. Only the charged decay $\Lambda \to p\pi^-$ with BR = 0.639 [5] is considered. Particle identification is performed based on velocity, momentum and charge of the particles. The first step in the selection procedure is to reconstruct the Λ. The decay vertex of this weak decay is located at a distance in the order of a few centimeters ($c_\tau(\Lambda) = 7.98\,\text{cm}$) away from the interaction point [5] which is not ideal for regular track reconstruction algorithms. To improve efficiency and resolution, a kinematic fit is applied. The measured and unmeasured track parameters are adjusted within their uncertainties to fulfill a given constraint. First the Λ decay vertex is reconstructed from a p and a π^- track. The production vertex by at least two other tracks originating from the interaction point which yields the Λ direction [7]. The Λ momentum is then determined by a kinematic fit securing four momentum conservation in the Λ decay. The Λ mass is fixed to its PDG mass and its momentum obtained by the fit. Λ candidates with a fit probability of more than 1% are accepted, in case of several candidates in the same event the one with better fit probability is retained.

Two strategies to reconstruct the Σ^0 have been developed to tackle the challenges that arose.

1. **Inclusive Σ^0 reconstruction:** The interaction point is defined by the e^+ and e^- track, p and K^+ from the interaction point are not considered. Figure 3 shows the invariant mass of the Σ^0, reconstructed from Λ, e^+ and e^-. Testing the same reconstruction strategy on a simulated sample of the same reaction where the Σ^0 decays into $\Lambda\gamma$ shows very good background suppression power with a signal (S) over background (B) ratio of 92. However the expected count rate is very low since it turned out that many of the low momentum positrons are not detected, leading to a maximum expected significance of $\frac{S}{\sqrt{S+B}} = 9.1$.

2. **Σ^0 with missing e^+:** All tracks except the e^+ are required, giving the possibility to reconstruct the e^+ four-momentum by missing kinematics using a fit in the interaction point, constraining the four momenta of all final state particles to that of the initial pp system. Candidates with fit probabilities larger than 1% are accepted. This procedure leads to an invariant mass distribution of the Σ^0 as shown in Figure 3. It is somewhat broader compared to the first strategy but the count rate is improved by a factor of 10. The Forward Detector contributes to a larger acceptance for these events. This strategy needs additional requirements that secure that the electron comes from the interaction point. It has a lower background suppression power, $\frac{S}{B} = 0.48$, and a maximum significance of $\frac{S}{\sqrt{S+B}} = 17$.

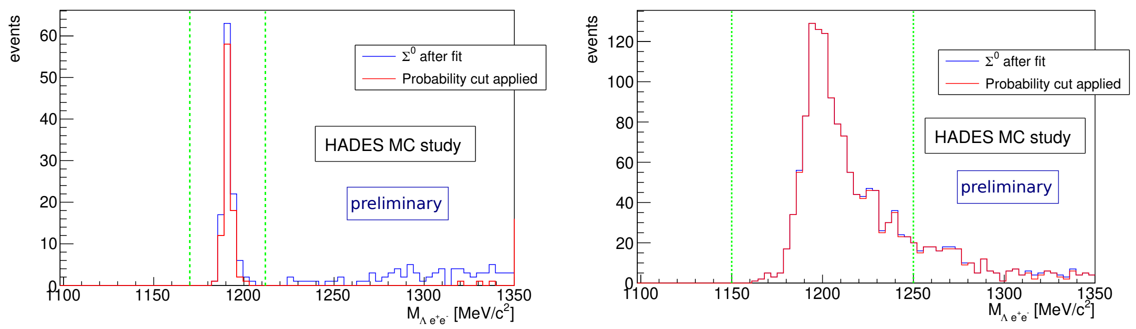

Figure 3: Λe^+e^- invariant mass. The effect of the $P > 1\%$ selection is shown and selected mass window marked in green. Left: Σ^0 from strategy 1, inclusive. Right: Σ^0 from strategy 2, missing e^+.

5. Conclusions

The HADES experiment has had a promising pp@4.5 GeV beam time. The powerful and versatile possibilities of using elastic scattering as a tool for data preparation in terms of quality assurance, calibration and normalization have been presented. Suiting the theme of electromagnetic hyperon decays, a feasibility study for a measurement of the Σ^0 Dalitz decay has been performed. Two complementary analysis strategies have been developed that show promising results for the measurement of the Dalitz decay's branching ratio.

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