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Investigating Proton-Proton Elastic Scattering with the Upgraded HADES Spectrometer

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An experiment focused on hyperon production was carried out with the upgraded HADES spectrometer. The upgrade includes a new Forward Detector system (FD) consisting of two PANDA-type Straw Tracking Stations, and an RPC. The measurements were performed with a proton beam of p_{beam} = 5.3 GeV/c impinging onto an LH_2 target. Proton-proton elastic scattering events were selected based on kinematic observables, and demanding that one proton was detected in the FD ($\theta_{FD} < 6\,°$), and the other proton was measured in the HADES acceptance ($18° < \theta_H < 85°$). The number of elastic events, corrected for acceptance and reconstruction efficiency, is used to determine the time-integrated luminosity recorded during this experiment. The measured differential cross-section $d\sigma$ as a function of the square of the 4-momentum transfer t is well described by a function of the form $\mathrm{d}\sigma/\mathrm{d}t = Ae^{-B|t|}$, from which the optical point $A = \mathrm{d}\sigma/\mathrm{d}t\big|_{t=0}$ and the nuclear slope parameter B are obtained. Here the proton-proton elastic scattering event selection will be explained, and preliminary results of A and B will be presented and compared with existing data from other experiments.

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1. Introduction

Measurements of total and elastic cross-sections across a wide range of energies and angles are needed to achieve a detailed study of proton-proton hadronic interactions. The differential elastic scattering cross-section is commonly expressed as [1]:

$$\frac{d\sigma_{el}}{dt} = |f_C(t)e^{i\alpha\phi(t)} + f_n(t)|, \tag{1}$$

where t is the square of the four-momentum transfer, and f_C and f_n are the Coulomb and nuclear amplitudes, respectively. Eq. 1 can be decomposed into a Coulomb contribution C, a nuclear contribution n and an interference contribution int as [1]:

$$\frac{d\sigma_{el}}{dt} = \frac{d\sigma_C}{dt} + \frac{d\sigma_n}{dt} + \frac{d\sigma_{int}}{dt}. \tag{2}$$

The t region in which the elastic scattering reaction is measured defines which of the contributions in Eq. 2 dominates. At the energies of the HADES measurements, the dominant region is the nuclear (hadronic), defined as:

$$\frac{d\sigma_n}{dt} = \frac{\sigma_{TOT}^2(1+\rho^2)e^{-B|t|}}{16\pi(\hbar c)^2}, \tag{3}$$

where B is the nuclear slope parameter, ρ is defined as $\rho \equiv Ref_n(0)/Imf_n(0)$ and σ_{TOT} is the total elastic scattering cross-section [1]. These parameters have to be experimentally determined. Measurements at different regions of t are needed to have access to all parameters that characterize $d\sigma_{el}/dt$. For instance, measurements above the Coulomb-nuclear interference region provide access to B, whereas the ρ parameter can only be determined within the interference region. Given the well-defined kinematic constraints of proton-proton elastic scattering [3], specific event selection criteria can be applied to identify these events. For HADES, a subset of these events referred to as HF are defined by one proton detected in the main HADES acceptance ($18° < \theta < 85°$) and the other in the Forward Detector (FD) system ($1° < \theta < 6°$). These are used to assess the newly implemented FD's performance and determine the integrated luminosity $\mathcal{L}$ during the February 2022 production run. In addition, in this nuclear-dominated t-region the differential cross-section is well described by an exponential function of the form $d\sigma_{el}/dt = Ae^{-B|t|}$ [1], giving access to the optical point $A = d\sigma/dt\big|_{t=0}$ and to the nuclear slope parameter B.

2. The Forward Detector

The Forward Detector (FD) system was installed in HADES in 2020. It consists of two Straw Tracking Stations (STS) for charged particle track reconstruction and a Forward Resistive Plate Chamber (FRPC) used for time of flight measurements. The FD system increases the polar angle acceptance of the HADES spectrometer to the region $1° < \theta < 6°$. Detailed feasibility studies of hyperon channel measurements showed that the FD system is crucial for hyperon reconstruction [2]. A diagram of HADES, including the FD system is shown in Figure 1.

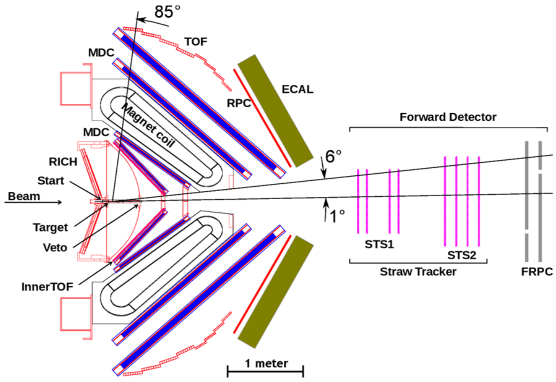

Figure 1: HADES cross-sectional diagram. The components of the FD: STS in magenta and FRPC in gray.

Straw Tracking Stations

The Straw Tracking Stations (STS1 & STS2), based on the PANDA Forward Tracker design, each consist of four double layers of gas-filled straws. Each straw, made of a thin Al-Mylar film cathode and a gold-plated W/Re anode wire, has an inner diameter of 10 mm. They operate with an Ar/CO_2 (90:10) gas mixture at 2 bar absolute pressure. The straw orientations differ between STS1 (ϕ = 0°, 90°, 90°, 0°) and STS2 (ϕ = 0°, 90°, ±45°, 0°), enabling precise 3D track reconstruction and ambiguity resolution in multi-track events. Ionization electrons, separated by an electric field, drift toward the anode wire where they are multiplied and the induced current is measured. The drift time of the first electrons to arrive is used to determine the shortest track-wire distance, used then for the track reconstruction. An average spatial resolution of $\sigma = 0.13$ mm for minimum ionizing particles (MIPs) has been achieved [4].

Forward Resistive Plate Chambers

The Forward Resistive Plate Chamber (FRPC) consists of four sectors, each containing two layers of 16 individually shielded hybrid (metal-glass) strip-like RPCs. Each counter is 750 mm long, with two different widths (22 mm and 42 mm) to handle the increased particle flux near the beam axis [5]. A high voltage is applied to the central aluminum electrode, where the signals are registered. Time-of-flight and Time-over-Threshold measurements are recorded and analyzed to extract timing information. The FRPC is designed to sustain particle rates of up to 320 Hz/cm^2, while maintaining an efficiency of at least 90%. Preliminary evaluations show an efficiency of approximately 85–90% and a time resolution of <100–120 ps at this rate density [5].

3. Event Selection

The selection of HF events starts with a particle identification (PID) graphical cut on β(p) for protons in the HADES acceptance. Selected protons are then paired with proton candidates from the FD system, and selection cuts based on the kinematics of p-p elastic scattering are applied: i) $|\phi_H - \phi_{FD} - 180°| < 7°$, ii) $|tan\theta_H \times tan\theta_{FD} - 0.29429| < 0.1$ and iii) $\Delta p = |p_{reco,H} - p_{el}| <$ 200 MeV/c, where p_{el} is the theoretical momentum calculated for an elastically scattered proton, emitted at θ_H [3]. In addition, specific calibrations account for small deviations in a) the lateral position of the beam-target overlap, b) misalignment of the beam axis with the z-axis, c) provided beam momentum, and d) energy loss for slow hadrons. The distributions of $tan\theta_H \times tan\theta_{FD}$, $\Delta\phi$, and Δp before (blue) and after (black) selection are shown in Figure 2, along with the selection ranges and a fit to the signal distribution. The final distributions show negligible background and are centered around the expected nominal values, indicating good alignment between the FD system and the HADES detector. Based on the kinematics of the elastic scattering process and the overall detector acceptance, the HF event reconstruction is restricted to the polar angle range $70^\circ < \theta_H < 79^\circ$, corresponding to -0.318 < t < -0.093 (GeV/c)^2. This region is used to determine $\mathcal{L}$.

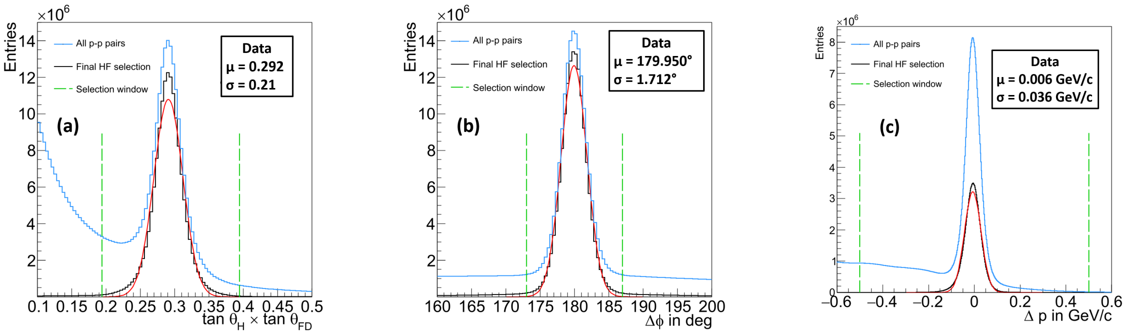

Figure 2: Distributions of (a) $tan\theta_H \times tan\theta_{FD}$, (b) $\Delta\phi$, and (c) Δp before (blue) and after (black) the selection cuts were applied to the other two variables. The green dashed lines show the selection window.

4. Luminosity Determination

The integrated luminosity $\mathcal{L}$ is needed to convert the number of detected events, such as hyperon decays, into a cross-section over a given data-taking period. $\mathcal{L}$ is defined as:

$$\mathcal{L} = \frac{1}{\sigma_{el}} \int \frac{\mathrm{d}N_{el} \times DS \times \mathrm{d}\eta}{\mathrm{d}\epsilon} \mathrm{d}t, \tag{4}$$

where N_{el} is the total number of elastic pairs reconstructed in the HF selection, σ_{el} is the elastic scattering cross-section at p_{beam} = 5.3 GeV/c and DS = 64 is a downscaling factor due to trigger settings. ε is the reconstruction efficiency from simulation and η is the FD efficiency correction. A brief overview of these parameters is provided below, with further details in [3].

Since the $\Delta\phi$ distribution has minimal background after selection cuts, the yield N_{el} is extracted by subdividing the data into narrow bins in t (0.01 GeV^2) and then fitting a Gaussian function to the $\Delta\phi$ distribution for each t-bin within the normalization window. The yield for each t-bin is then obtained by integrating within a $\pm 3\sigma$ window.

As no data exist for p_{beam} = 5.3 GeV/c, σ_{el} was determined by linearly interpolating measurements from [6] at 5.0 and 6.0 GeV/c. An exponential function was fit to the interpolated points and integrated over the normalization range, yielding σ_{el} = (4.69 ± 0.04) mb/GeV^2.

The reconstruction efficiency defined as $\varepsilon = (N_{el,reco}/N_{el,total})_{sim}$ is determined by comparing the number of Monte Carlo generated protons $N_{el,total}$ with the yield of reconstructed protons in the simulation after applying the same HF-selection criteria and method as for the data. The ε for t-intervals of 0.01 GeV/c^2 is shown in Fig. 3 panel (a). It shows a plateau region where it remains stable and it decreases outside of this region. For smaller θ_H ($|t|$ >0.25 (GeV/c)^2), the drop in ε is attributed to the FD acceptance limit at $\theta_{FD} \sim 6°$ ($|t|$ = 0.32 (GeV/c)^2). At larger θ_H ($|t|$ < 0.19 (GeV/c)^2), the drop is caused by decreasing momentum and geometrical acceptance in HADES. The correction factor η is defined as $\eta = (HF/SingleH)_{sim}/(HF/SingleH)_{data}$, where $SingleH$

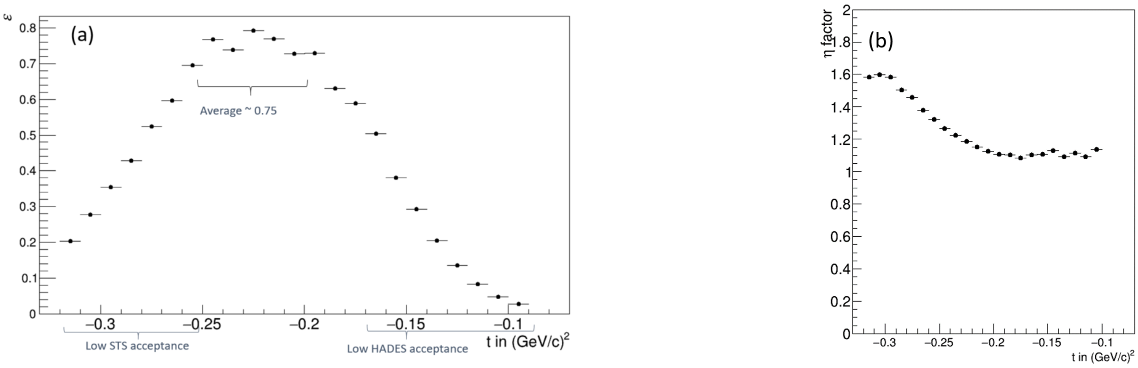

Figure 3: ε and (b) η as a function of t.

is the elastic scattering yield when requiring only the detection of the proton reaching the HADES, and HF is the yield after additionally requiring a coincident track in the FD. Therefore, the ratio $(HF/SingleH)$ represents the FD efficiency. This ratio is expected to improve with an enhanced FD tracking algorithm. η then compares the FD efficiency between simulation and data, where values closer to 1 indicate similar efficiency in both cases. Figure 3 (b) shows the η factor which starts at around η = 1.6 for the most negative t value (θ_H = 70°) and then drops until it stabilizes to a value of $\eta \sim 1.11$ in the interval -0.22 < t < -0.13 (GeV/c)^2 corresponding to 73.0° < θ_H < 77.5°. Further investigations are underway to improve the characterization of background fluctuations in future iterations of the η correction factor determination. Equation 4 yields a preliminary value of $\mathcal{L}$ = (5.86 ± 0.09) pb^{-1}, where the uncertainty is purely statistical. The luminosity as a function of the data-taking day is shown in Figure 4 (a).

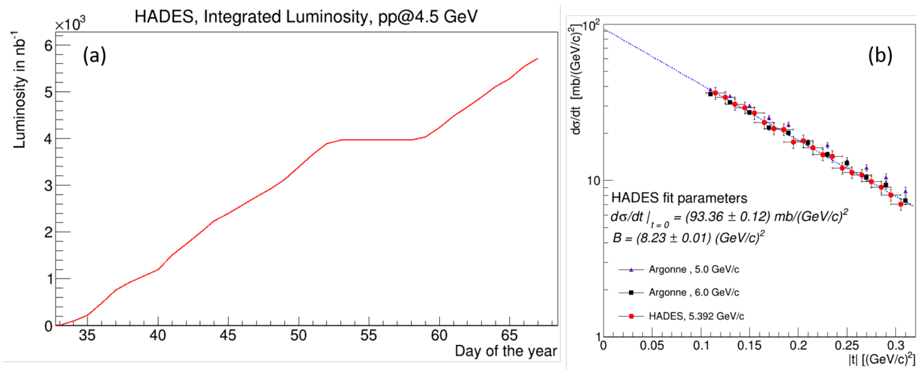

Figure 4: (a) Luminosity as a function of the day of the year and (b) Proton-proton elastic scattering differential cross-section measured by HADES (red) together with the data from [6].

5. P-p Elastic Scattering Differential Cross-Section

The differential cross-section of p-p elastic scattering dσ_{el}/dt is obtained by normalizing the efficiency-corrected number of reconstructed elastic-scattering events dN by the integrated Luminosity $\mathcal{L}$. The $d\sigma_{el}/dt$ is shown in Fig. 4 (b) as a function of $|t|$. The data in this figure are well described by an exponential function of the form $d\sigma_{el}/dt = Ae^{-B|t|}$ [1], from which the preliminary parameters are determined to be: optical point A = (93.36 ± 0.12) mb/(GeV/c)^2 and nuclear slope parameter B = (8.23 ± 0.01) (GeV/c)$^{-2}$. These preliminary results for A and B show good agreement with existing data for p_{beam} = 5.0 GeV/c and 6.0 GeV/c, as shown in the same figure. Additionally, Fig. 5 presents a compilation of the (a) nuclear slope parameter values and (b) optical points obtained by various experiments at different beam momenta, demonstrating that the HADES results agree well with existing world data.

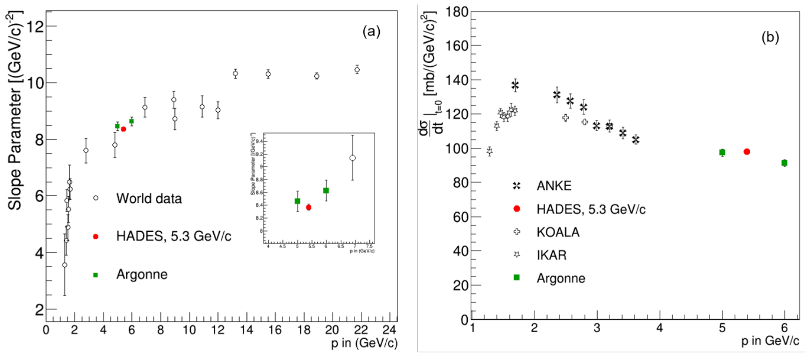

Figure 5: (a) Overview of the nuclear slope parameter and (b) optical point from different experiments, including the preliminary results from HADES.

6. Conclusions

The HF reconstruction of proton-proton elastic scattering in the February 2022 HADES run was used to evaluate the FD system performance and determine the time-integrated luminosity. Kinematic distributions confirm good FD alignment with the HADES and proper calibration. Additionally, the differential cross-section and nuclear slope parameter at 5.392 GeV/c show good agreement with existing world data.

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