Production and decays of hyperons in p+p reactions measured with HADES

Konrad Sumara[1,*] for the HADES collaboration

[1]Faculty of Physics, Astronomy and Applied Computer Science, Jagiellonian University, Łojasiewicza 11, Kraków, Poland

Abstract. Preliminary results of inclusive $\Sigma^+(1385)$ production in $p + p$ reactions at $E_{beam} = 4.5$ GeV and $\Lambda(1520)$ in $p + p$ and $p + Nb$ at $E_{beam} = 3.5$ GeV are presented. Both measurements were performed by the HADES ("High Acceptance Di-Electron Spectrometer") experiment at FAIR/GSI. The analysis consisted of multiple steps including track reconstruction, particle identification and the reconstruction of the hyperon signal from their hadronic decays $\Lambda(1520) \rightarrow \Lambda\pi^+\pi^-$ and $\Sigma^+(1385) \rightarrow \Lambda\pi^+$. The main part of the analysis, which is signal/background classification, was performed utilizing Machine Learning methods. The employed method relied on a data-driven approach called "Classification Without Labels" and the Multilayer Perceptron style Artificial Neural Networks. The analysis resulted in reconstruction of the resonance distributions for both $\Sigma^+(1385)$ and $\Lambda(1520)$, and allowed for the extraction of parameters of the relativistic Breit-Wigner distributions.

1 Introduction

The structure and spectrum of hadrons have been a matter of ongoing debate since the existence of quarks was postulated. The currently used quark models describe hadrons as combinations of quark-antiquark (mesons), three quarks (baryons) or more complex objects [2][3]. On the other hand, a great deal of experimental evidence has accumulated that indicates that nucleons and their excited states are not simple static quark states, but are significantly influenced by the dynamics of baryon-meson interactions [4][5][6]. In this context, it is interesting to extend the study to hyperons, such as Σ or Λ, and in particular their excited states (e.g. $\Lambda(1520)$, $\Lambda(1405)$). Within the framework of the quark model, the ground states of hyperons are described as composed of "u" (up), "d" (down) and "s" (strange) quarks. The spectra of excited hyperons have been predicted by various quark models (see for example [7]), but there are also competing models that describe these hyperons as molecular-like objects emerging from baryon-meson interactions [4]. An example here is $\Lambda(1520)$ that, in this picture, is explained as a state generated by $\Sigma^+(1385)\,\pi^-$ interaction [5][6]. Measurements of hadronic e.g. $\Lambda(1520) \rightarrow \Sigma^+(1385)\,\pi^-$, $\Lambda(1405) \rightarrow \Sigma\,\pi$, and radiative, with photon or e^+e^- pair emission, decays were suggested to discriminate between these models (see for example [8]).

The scope of this work is a study of the production and decays of $\Sigma^+(1385)$ and $\Lambda(1520)$ hyperons in proton-proton collisions. The first goal is to establish the inclusive hyperon

*e-mail: konrad.sumara@doctoral.uj.edu.pl

production cross section as a function of the kinematic variables (transverse mass, rapidity, emission angles) as well as the integrated total cross sections. The second goal is to study the sequential decay of $\Lambda(1520) \rightarrow \Sigma^{*+}(1385)\,\pi^- \rightarrow \Lambda\pi^+\pi^-$, to learn about the role of $\Sigma^*(1385)$ π interaction in $\Lambda(1520)$ structure. This can be achieved by reconstructing the Dalitz plots of the three body decay $\Lambda(1520) \rightarrow \Lambda + \pi^+ + \pi^-$ to understand the role of $\Sigma^*(1385) + \pi$ interactions. The final state interaction of $\Sigma^*(1385) + \pi$ is expected to show as enhancement in the Dalitz that is expected to be flat if the $\Lambda(1520) \rightarrow \Lambda + \pi^+ + \pi^-$ is governed by the phase space only. The utilized data were produced in proton-proton scattering at energies of 4,5 GeV ($\Sigma^+(1385)$) and 3,5 GeV ($\Lambda(1520)$) measurements performed with the HADES detector operating at FAIR/GSI [1].

2 Analysis procedure

The analysis of experimental data from the measurements and the Monte Carlo simulations consists of: track reconstruction, particle identification and preselection, separation of the signal from the background and reconstruction of hyperon distributions. The reconstructed signal distributions of the hyperons are corrected for losses due to the HADES acceptance and the reconstruction efficiencies to estimate cross-section for their production.

2.1 Hyperon reconstruction

The first stage of the analysis is a pre-processing of the experimental data involving particle track reconstruction and identification, followed by selection of events containing p, π^+, π^- tracks. Particle identification has been achieved via graphic cuts defined on two-dimensional distributions of relativistic particle velocity as a function of momentum. These distributions have been reconstructed from particle tracks and change of direction in magnetic field measurements provided by the MDC (Multiwire Drift Chamber) detectors, as well as Time of Flight measurements provided by the ToF (Time of Flight) and RPC (Resistive Plate Chamber) detectors. Additional loose conditions were imposed on relative positions of primary and lambda candidate vertices, missing mass of $\Lambda(1115)$ and $\Sigma(1385)$ candidates as well as a relevancy window cut on $\Lambda(1115)$ invariant mass distribution.

The second stage of this analysis is focused on separating the events containing $\Lambda(1115)$ hyperon from background events, mainly originating from multipion production. For this purpose, Machine Learning methods, in particular the Multilayer Perceptron architecture of Artificial Neural Networks [9], have been utilized. In most cases, training neural networks for event classification requires labeled datasets (supervised learning methods), usually produced in simulations. However, in order to avoid systematic errors introduced by the use of imperfect detector model, an alternate training approach has been applied. The utilized method is called "Classification Without Labels" ("CWoLa") [10] and operates by training a classifier on two data samples consisting of a mix of signal and background in different ratios, which according to Neyman-Pearson Lemma, can be shown to also distinguish between signal and background.

2.2 Reconstruction of $\Sigma^+(1385)$

$\Lambda(1115)$ candidates ($p\pi^-$ pairs) invariant mass distribution obtained after CWoLa is shown in Fig. 1 (left). The $\Sigma(1385)^+$ signal has been identified using sideband subtraction procedure. The two sideband regions, defined on the Λ invariant mass distribution shown in Fig. 1 (left), approximate the background underneath the $\Lambda(1115)$ signal peak. As shown in Fig. 1 (right)

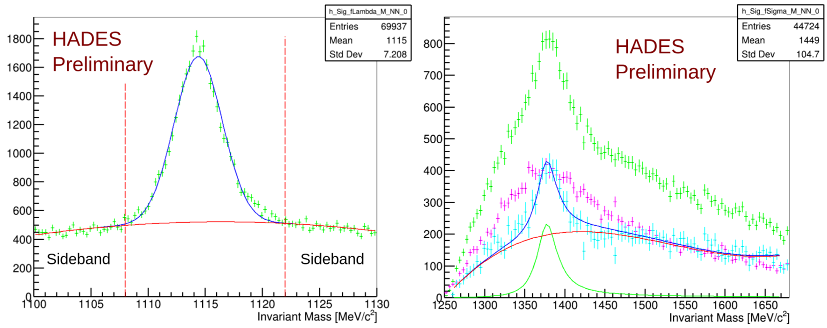

Figure 1. Left: $\Lambda(1115)$ candidates ($p\pi^-$ pairs) invariant mass distribution with Gaussian peak on top of polynomial background fit. Ranges for sideband and background underneath the peak marked with red dashed lines. **Right:** $\Sigma^+(1385)$ candidates ($\Lambda(1115)\ \pi^+$) invariant mass with fitted functions. Points: Green - all events from $\Lambda(1115)$ peak area, Magenta - rescaled sideband, Cyan - distribution after sideband subtraction. Lines: Breit-Wigner + polynomial fit, Green - Breit-Wigner distribution extracted from fit, Red - polynomial backgroudn extracted from fit.

the resulting sideband (rescaled to the same integral as background underneath the Λ peak - magenta distribution) has been subtracted from the $\Lambda\pi^+$ invariant mass distribution from $\Lambda(1115)$ peak area (green). After the background subtraction, s a clear peak located around the expected $\Sigma^+(1385)$ position is visible on top of the background in the resulting distribution (cyan). The distribution has been fitted with the relativistic Breit-Wigner function (green line) on top of a fifth degree polynomial background (red line) (combined functions fit shown as blue line). The parameters of the fitted Breit-Wigner function are:

$$\mathbf{M_0} = 1378.7 \pm 1.4 \text{ MeV/c}^2 \text{ and } \mathbf{\Gamma_0} = 32.2 \pm 4.1 \text{ MeV/c}^2 \tag{1}$$

Obtained results are quite close to the Particle Data Group data ($M_0 = 1382.80 \pm 0.35$ MeV/c^2 and $\Gamma_0 = 36.0 \pm 0.7$ MeV/c^2) and the results from earlier exclusive channel analysis ($M_0 = 1383.2 \pm 0.9$ MeV/c^2 and $\Gamma_0 = 40.2 \pm 2.1$ MeV/c^2) but the peak position is notably shifted towards lower mass. This is most likely caused by energy loss in the detector. Implementation of the respective correction and the other corrections related to the acceptance and reconstruction efficiency are on the way.

2.3 Reconstruction of $\Lambda(1520)$

The reconstruction of the $\Lambda(1520)$ in former experiment performed with proton beams and proton and niobium targets with $E_{beam} = 3.5$ GeV was already completed [11]. The analysis procedure was analogous to the one described for $\Sigma^+(1385)$. The resulting invariant mass distributions of $\Lambda\pi^+\pi^-$ for $p+p$ and $p+Nb$ collisions are shown in Fig. 2. The distributions are compared to the simulated signal (green) and non-resonant background contributions (red). The yield of the latter ones were fixed for $p+p$ by the known cross sections of exclusive channels, while for $p+Nb$ by UrQMD simulations.

The parameters of the $\Lambda(1520)$ distributions were determined from fits using a Voigt-function (not shown) and are as follows for respective collision systems:

$$\begin{aligned} p+Nb \rightarrow \mathbf{M_0} &= 1519 \pm 4.2 \text{ MeV/c}^2, \sigma = 14.7 \text{ MeV/c}^2, \mathbf{\Gamma_0} = 24 \pm 10 \text{ MeV/c}^2 \\ p+p \rightarrow \mathbf{M_0} &= 1509 \pm 4.7 \text{ MeV/c}^2, \sigma = 14.7 \text{ MeV/c}^2, \mathbf{\Gamma_0} = 15.6 \pm 1 \text{ MeV/c}^2 \end{aligned} \tag{2}$$

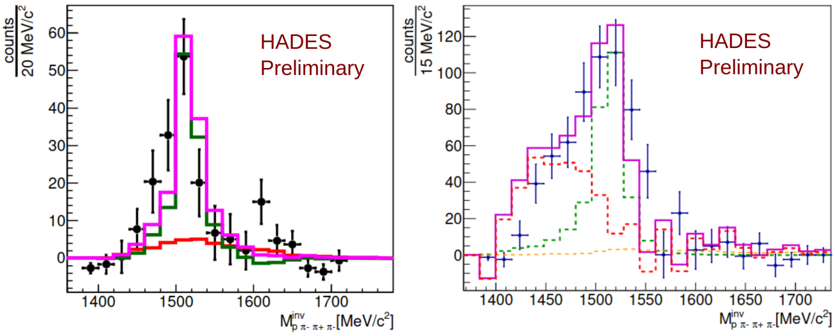

Figure 2. Histograms showing Λ(1520) invariant mass in p+p (**left**) and p+Nb (**right**) data. Points - experimental data, Green - simulated Λ(1520) signal, Red - simulated non-resonant background (UrQMD for pNb), Magenta - sum of simulated channels (fit) [11].

While the Λ(1520) line shape in $p + Nb$ system are consistent with the PDG, the peak position in $p + p$ is found to be lower. This might be caused by the interference between signal and non-resonant background or systematic effects, and will be investigated further in the new data from $p + p$ collisions with E_{beam} = 4.5 GeV data.

3 Conclusion

The inclusive production of Σ^+(1385) hyperon has been identified utilizing data from p + p measurements at 4.5 GeV in HADES experiment in GSI Darmstadt. The analysis was carried out using Machine Learning methods for Λ(1115) hyperon reconstruction and background identification. Specifically, the Classification without Labels method was employed, using Multilayer Perceptron neural networks. Using these methods and, at a later stage, the side-band analysis, it was possible to reconstruct the invariant mass distribution of the Σ^+(1385) hyperon and examine its parameters in comparison with results from earlier exclusive analysis studies.

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