PROCEEDINGS OF SCIENCE

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

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The internal structure of nucleons and interactions between their components have been debated ever since the existence of quarks was postulated. A lot of experimental evidence has been gathered, indicating that nucleons and their excited states are not simple static quark states but are significantly influenced by the dynamics of baryon-meson interactions. In this context it is interesting to extend internal structure studies to hyperons, particles where one light quark of a nucleon is replaced by a heavier strange quark, e.g. Λ, Σ or $\Sigma^{+}(1385)$, or excited states such as: $\Lambda(1520)$ or $\Lambda(1405)$. Many competing models, including also those based on the dynamical state generation, try to describe the internal structure of these hyperons. The predictions are sensitive to e.g. relative widths of radiative decays of hyperons. In order to discriminate between models, it is helpful to measure radiative decays (with emission of a γ or $e^{+}e^{-}$ pairs) and hadronic decays, e.g. $\Lambda(1520) \rightarrow \Sigma^{+}(1385)\,\pi^{-}$, $\Lambda(1405) \rightarrow \Sigma\,\pi$. These decays are largely unexplored at present and are the motivation for the project presented in this talk.

The goal of this project is to study the production of $\Sigma^{+}(1385)$, $\Lambda(1520)$ and $\Lambda(1405)$ hyperons produced in proton-proton at beam energies ranging from 3.5 GeV to 4.5 GeV with HADES detector at FAIR. The analysis described in this work is a first step in this direction and presents results of $\Sigma^{+}(1385)$ production in p + p at 3.5 GeV.

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1. The goal of the project

The aim of the project is to study the inclusive production of the $\Sigma^+(1385)$ hyperon - produced in the p + p $\rightarrow$ $\Sigma^+(1385)$ + K + X(additional particles) reaction at beam energy of 3.5 GeV, and its decay channel into $\Lambda(1115)\ \pi^+$ (see figure 1). The invariant mass distribution of $\Sigma^+(1385)$ and the differential cross section for $\Sigma^+(1385)$ hyperon production. The data used in the analysis came from the measurements made in previous years with the HADES detector at the GSI facility in Darmstadt, Germany [1].

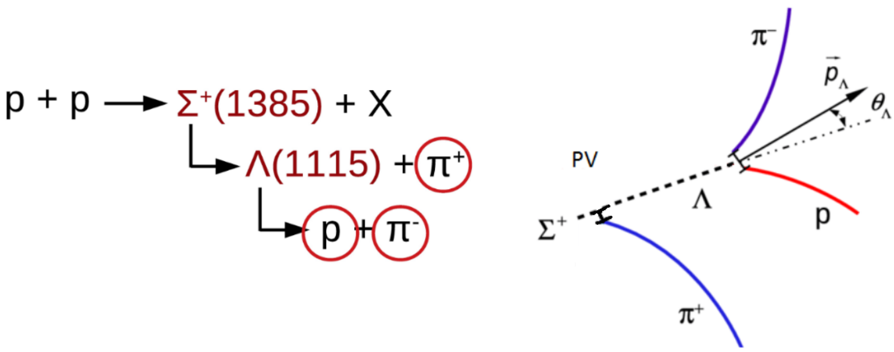

Figure 1: Analyzed production and decay channel of $\Sigma^+(1385)$.

The aim of the project is to establish a general reconstruction method for higher mass hyperons decaying into final states including lambda. Especially interesting are Dalitz decays which give insight into the Vector Meson Dominance model [2]. Dalitz decays of $\Lambda(1520)/\Sigma^+(1385) \rightarrow \Lambda e^+e^-$, which would allow for first measurement of hyperon Form Factors in time-like region. Moreover ,the production cross sections for $\Lambda(1520)/\Sigma^+(1385)$ decays are yet unmeasured. Study of hadronic decays $\Lambda(1520) \rightarrow \Lambda\pi^+\pi^-$ and $\Sigma^+(1385) \rightarrow \Lambda\pi^+$ (characterized by large branching ratios) can be used for normalization for Dalitz decay studies.

2. Data preprocessing

The first stage of the analysis was the preprocessing of the experimental data. It consisted of the identification of the recorded particles (using graphic cuts on dE/dx for identification of p, π^-, π^+) and the initial selection of relevant data. In order to select relevant data for the analysis, additional conditions were imposed on the following variables:

- Σ Decay Vertex Z coordinate $\in$ (-90; 0) mm - Production in target region (Z coordinate along beam axis)
- Σ Decay Vertex R coordinate < 10 mm - Production in target region (R coordinate perpendicular beam axis)
- Σ Decay Vertex Z coordinate < Λ Decay Vertex Z coordinate
- Λ Invariant Mass $\in$ (1137; 1096) MeV/c^2
- Σ Missing Mass > Invariant Mass (K + p) = 1350 MeV/c^2

3. Separation of decay channel from the background

3.1 Reconstruction of $\Lambda(1115)$ utilizing neural networks

The purpose of this step of the analysis was to separate the decay channel under study (signal) from the background and to reconstruct the distributions of invariant mass, rapidity and transverse momentum of the $\Sigma^+(1385)$ hyperon. The first step was the reconstruction of the $\Lambda(1115)$ particle and the separation of the background. Note that this part is common for all decays involving Λ in the final state. To do this, machine learning methods (specifically neural networks [3]) were used to separate the signal from the background. Due to the lack of a known classification for the signal and the background, it was not possible to use supervised learning methods. For this reason, a machine learning method of "Classification Without Labels" ("CWoLa") [4] was applied, which relies on the Neymann-Pearson Lemma and allows the classifier to be trained to distinguish the signal from the background by training on two data samples containing both signal and background events in different proportions.

Multilayer Perceptron neural networks [5] were trained using this method to separate the signal from the background. The procedure of training the neural network and subtracting the background was carried out four times, each time reducing the amount of background in the data and thus increasing the signal-to-background ratio, which enhanced the performance of the machine learning algorithm in the next iteration. The $p\pi^-$ invariant mass distribution after selection of lambda candidates by the neural network is shown in figure 2.

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

In this stage of the study, a ”sideband” analysis has been performed, rescaling the background outside the signal peak area (figure 2 left) to the same integral value as the background under the signal peak. The background rescaled in this way was then subtracted when reconstructing the invariant mass distribution of $\Sigma^+(1385)$ (cyan points in figure 2 right).

After this procedure, a clear signal peak was visible on the distribution of the $\Sigma^+(1385)$ invariant mass. The mass distribution was fitted with the relativistic Breit-Wigner function on top of fifth degree polynomial background (see figure 2). Parameters of $\Sigma^+(1385)$ extracted from the fit are as follows (M_0 - the center of the distribution and Γ_0 - the width of the invariant mass distribution):

$$\begin{aligned} M_0 &= 1382.96 \pm 0.59\ MeV/c^2 \\ \Gamma_0 &= 32.7 \pm 1.9\ MeV/c^2 \end{aligned} \tag{1}$$

The obtained parameters agree well with the data from the Particle Data Group ($M_0 = 1382.80 \pm 0.35\ MeV/c^2$ and $\Gamma_0 = 36.0 \pm 0.7\ MeV/c^2$) and the exclusive analysis of this channel ($M_0 = 1383.2 \pm 0.9\ MeV/c^2$ and $\Gamma_0 = 40.2 \pm 2.1\ MeV/c^2$), as described in the publication [6].

The distributions of rapidity and transverse momentum (see figure 3) have been reconstructed, bin by bin using background siubtraction method described above.

The plan for further analysis involves:

- Finalizing the rapidity and transverse momentum distributions analysis, including incorporating acceptance and efficiency correction

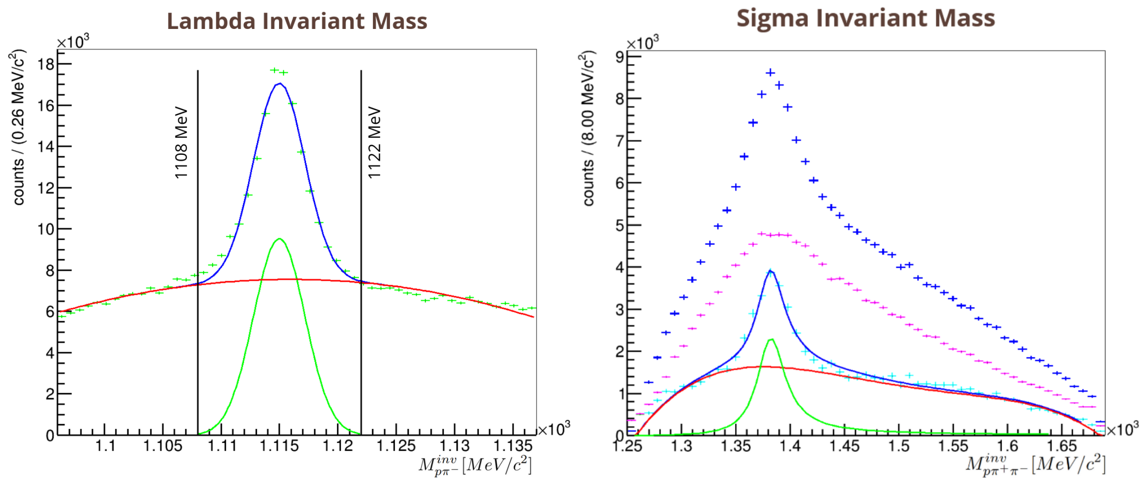

Figure 2: Left: Histogram of Λ candidates invariant mass distribution after neural network cut, with Gaussian signal on polynomial background fit. Vertical black lines denote positions of cuts for sideband subtraction procedure.
Right: Histograms illustrating the stages of reconstruction of the invariant mass distribution of $\Sigma^+(1385)$. Dark blue - total data after selection by neural networks, magenta points - scaled sideband (approximation of the background under the Λ peak), light blue points - data after sideband subtraction, blue line - fit of the relativistic Breit-Wigner function (signal) on a polynomial background (background), green line - fitted signal, red line - fitted background.

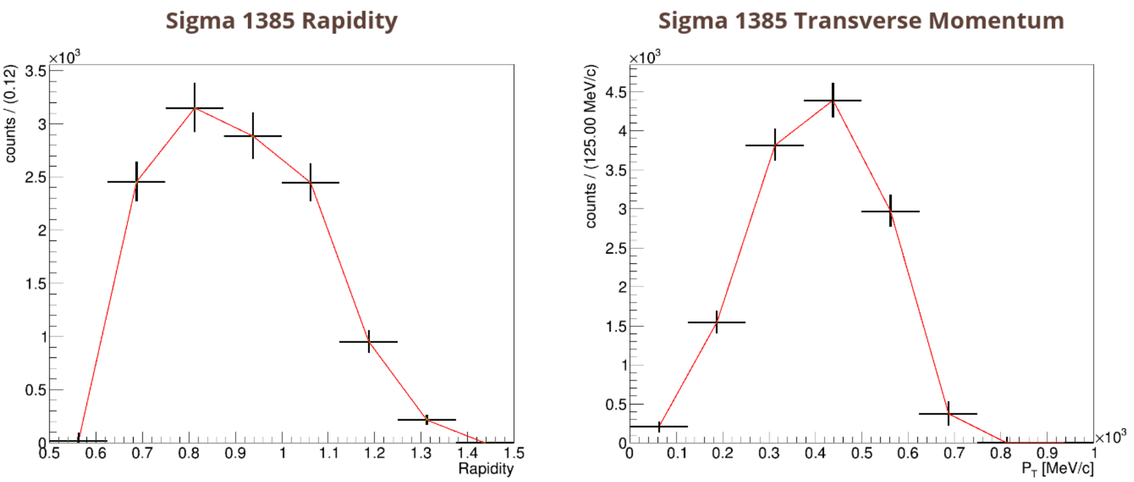

Figure 3: Histograms of reconstructed rapidity (left) and transverse momentum (right) distributions for $\Sigma^+(1385)$.

- Preparing a simulation of the analyzed decay channel
- Comparison of simulated and experimental data
- Utilizing the simulated data for calculation of cross-section for the analyzed decay channel
- Performing analogous analysis for $\Sigma^+(1385)$ and $\Lambda(1520)$ channel reconstruction in proton-proton 4.5 GeV scattering

PoS(FAIRness2022)059

4. Conclusion

As described above, the inclusive analysis of $\Sigma^+(1385)$ hyperon production and decay has been performed utilizing data from p + p $\rightarrow$ $\Sigma^+(1385)$ + K + X(additional particles) reaction at beam energy of 3.5 GeV measured in HADES experiment in GSI Darmstadt.

The analysis was carried out using Machine Learning methods for $\Lambda(1115)$ hyperon reconstruction and background subtraction. Specifically, the "Classification without Labels" ("CWoLa") method was employed, using Multilayer Perceptron neural networks. Using these methods, as well as, at a later stage, sideband analysis, it was possible to reconstruct the invariant mass distribution of the $\Sigma^+(1385)$ hyperon and examine its parameters in comparison with results from earlier exclusive analysis.

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