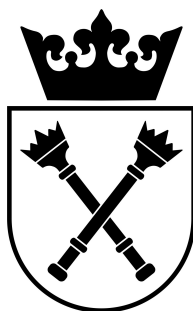


DOCTORAL DISSERTATION
PREPARED IN THE INSTITUTE OF PHYSICS
OF THE JAGIELLONIAN UNIVERSITY
SUBMITTED TO THE FACULTY OF PHYSICS,
ASTRONOMY AND APPLIED COMPUTER SCIENCE
OF THE JAGIELLONIAN UNIVERSITY



Hyperons @ HADES

Supervised by:
prof. dr hab. Piotr Salabura

Cracow, 2020

Wydział Fizyki, Astronomii i Informatyki Stosowanej
Uniwersytet Jagielloński

Oświadczenie

Ja niżej podpisany Krzysztof Nowakowski (nr indeksu: 1078309), doktorant Wydziału Fizyki Astronomii i Informatyki Stosowanej Uniwersytetu Jagiellońskiego, oświadczam, że przedłożona przeze mnie rozprawa doktorska pt. „Hyperons by HADES” jest oryginalna i przedstawia wyniki badań wykonanych przeze mnie osobiście, pod kierunkiem prof. dr. hab. Piotra Salabury. Pracę napisałem samodzielnie.

Oświadczam, że moja rozprawa doktorska została opracowana zgodnie z Ustawą o prawie autorskim i prawach pokrewnych z dnia 4 lutego 1994 r. (Dziennik Ustaw 1994 nr 24 poz. 83 wraz z późniejszymi zmianami).

Jestem świadom, że niezgodność niniejszego oświadczenia z prawdą ujawniona w dowolnym czasie, niezależnie od skutków prawnych wynikających z ww. ustawy, może spowodować unieważnienie stopnia nabytego na podstawie tej rozprawy.

Kraków, dnia

.....

Jakis mądry cytat

Autor „Zrodlo”

Ten sam cytat po angielsku

Autor, “Zrodlo”
Translation by Tlumacz

Abstract

sOME ABSTRACT

Streszczenie

Jakies streszczenie

Contents

Abstract	vii
1 Introduction	1
1.1 Hyperons	2
1.2 Form factors	2
1.3 Dalitz decays	4
2 HADES detector	5
2.1 Tracking system	5
2.2 RICH detector	6
2.3 Start detector and a trigger system	6
2.4 HADES upgrades	6
2.4.1 The Forward Detector	6
2.4.2 RICH update	6
2.4.3 Electromagnetic calorimeter	6
3 Data analysis	7
3.1 Particles identification	7
3.2 Event selection	8
3.3 Reaction kinematics	8
3.4 The Λ^0 Reconstruction	8
3.5 The $\Lambda^0 K^0$ reconstruction	9
3.6 Absolute normalization	11
3.7 The $\Lambda(1520)$ Reconstruction	11
3.7.1 Side-band analysis	12
3.7.2 Cross-section extraction differential analysis	12
3.7.3 Analysis of a $\pi^+\pi^-$ spectrum	13
3.8 results from p Nb experiment	14
4 Neural networks	15
4.1 The ROC curve and the optimal classifier	15
4.2 The data-driven approach	16
4.3 Application for analysis	16
5 Simulations of a new experiment	19
5.1 An estimation of cross-sections	19
5.1.1 Λ^0 inclusive cross section	19

5.1.2	Σ^0 inclusive cross section	20
5.1.3	$\Lambda(1520)$, $\Lambda(1405)$ and $\Sigma(1385)^0$ production cross sections	20
5.1.4	$\Xi^-(1322)$	21
5.2	Decay branching ratios	21
5.3	Background channels selection	22
5.4	Simulations results	24
5.4.1	Particles identification	24
5.4.2	Hyperons Dalitz decays	24
5.4.3	Cascade decay	24
6	Conclusions	25
	Appendices	27
	Bibliography	27

Chapter 1

Introduction

The history of a particle physics is a fascinating journey towards the smallest, the most principle elements of the Universe. Starting from memorable Rutheford experiment in 1909 [1] up to Higgs boson discovery [2, 3], and misterous states X,Y,Z [ref] oserved at the begining of XXIth century. Throughout this entire journey there were many attemps to point out which particles are realy elementary, and classify them. Nowadays the knowledge about elementary particles is collected in theory colled the standart model (SM) which describes almost all known particles and interaction between them.

According to the Standard Model we can divide elementary particles into three groups: leptons and quarks, basic bricks of the universe and elementary bosons a force-carryng particles. In contrary to leptons bosons can not exist in the nature in free states. This phenomena called “a confiment” is still not fully understood. Nonetheless, as a result ot the confiment, we can observe quarks in bound states: mesons and baryons. Mesons have a baryonic number equal 0 and mostly consist of two quarks. However such an exotic object like glueball are also classyified as mesons. Baryons are characterized by barionic number different than 0. Commonly obsered in nature consist of three quarks, but rare objects, like pentaquark, also belong to baryons.

A quark model proposed by Gell-Mann and Zweig in 1964 [4, 5] describes well a hierarchy of ground barionic nad masonic states. However to discribe origin of paricles properties like mass or spin, and predict excited states, a theory of quarks dynamics is required. Interaction between quarks are dominated by the strong force. Its general description, given by quantum chromodynamisc is very demanding in sspecific problems. For high energy regime an asymptotic freedom allows to solve equation by a series expansion. For low energys two approaches are possible: a phenomenological models, or a lattice calculations. Especially a barionic spectrum is poorly known and requires further investigations.

1.1 Hyperons

Assuming that energy available in the system is below a J/ψ meson mass (3.1 GeV/c) we can acknowledge that all the matter is built of three types of quarks: up, down and strange. These quarks are treated in quark model as an irreducible representation of a SU3 symmetry group. The possible ground states for a three-quarks systems have been predicted by quark model and described by the baryon octet and the baryon decuplet. All baryons consisting a strange quark are called hyperons.

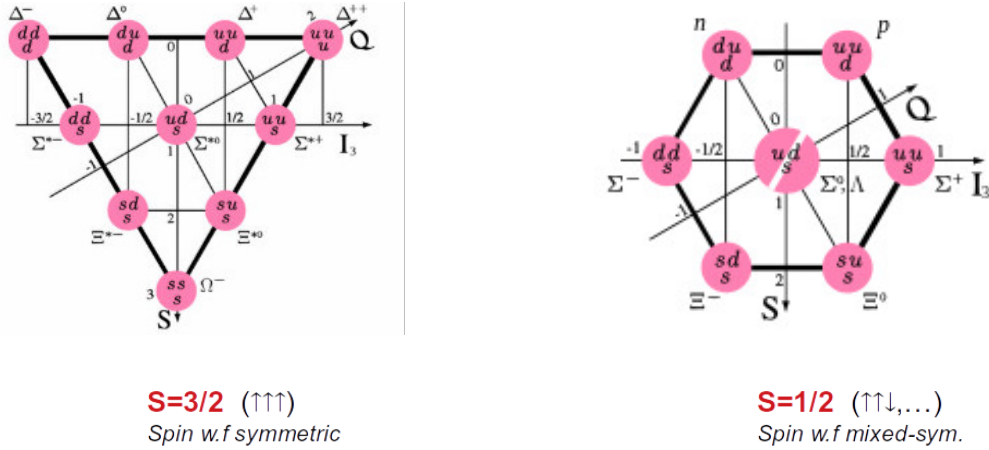


FIGURE 1.1: The eightfolds proposed by Gell-Mann and Ne'eman in 1961 to classify baryonic states. At a publication moment they classify all known baryons except the Ω^- . Its discovery in 1964 [6] was a great success of the quark model.

The quark model is very successful in a description of the baryonic ground states. However it gives no clue about excited states and quarks dynamics inside a particle. Because lattice QCD is still not able to reproduce even ground states masses the hyperons spectrum is calculated using effective theories [ref]. Despite a huge theoretical and experimental effort a theoretical predictions and experimental data are still far away from agreement, especially in high mass range. The example of such is presented in fig. 1.2.

1.2 Form factors

Any kind of a scattering experiment performed to examine physics inside baryons faces a fundamental problem of a rich internal structure of them. An complicated interactions inside the baryon can be treated together and their impact on a scattering could be taken into consideration by one scalar function called a form factor $F(q)$,

$$\frac{d\sigma}{d\Omega} = \left(\frac{d\sigma}{d\Omega} \right)_{point-like} |F(\vec{q})|^2. \quad (1.1)$$

As long as a target is static and spin-less the form factor is a the Fourier Transform of the charge deccity in target,

$$F(\vec{q}) = \int \rho(\vec{x}) e^{i\vec{q}\cdot\vec{x}} d^3x. \quad (1.2)$$

Practically this relation occures whent a target is much heavier than a projectle, like in Rutheford experiment [1]. In case of electron on proton scattering situation is more complicated because both particles has a spin and a proton gets recoil after scattering. A solution for this problem is called the Rosenbluth formula and looks as follows

$$\left. \frac{d\sigma}{d\Omega} \right|_{lab} = \left(\frac{\alpha^2}{4E^2 \sin^4 \frac{\theta}{2}} \right) \frac{E'}{E} \left[\left(F_1(q^2)^2 - \frac{\kappa^2 q^2}{4M^2} F_2(q^2)^2 \right) \cos^2 \frac{\theta}{2} - \frac{q^2}{2M^2} (F_1(q^2) + \kappa F_2(q^2))^2 \sin^2 \frac{\theta}{2} \right], \quad (1.3)$$

where $F_1(q^2)$ and $F_2(q^2)$ are two independent form factors, κ anomalus magnetic moment, q a four-momentum transfer. Factor

$$\frac{E'}{E} = \frac{1}{1 + \frac{2E}{M} \sin^2 \frac{\theta}{2}} \quad (1.4)$$

is conected with the proton recoil. Because functions F_1 and F_2 form an interference term it is convinient to express them as a linear combination of G_e and G_M .

$$G_e = F_1 + \frac{\kappa q^2}{4M^2} F_2 \quad (1.5)$$

$$G_M = F_1 + \kappa F_2 \quad (1.6)$$

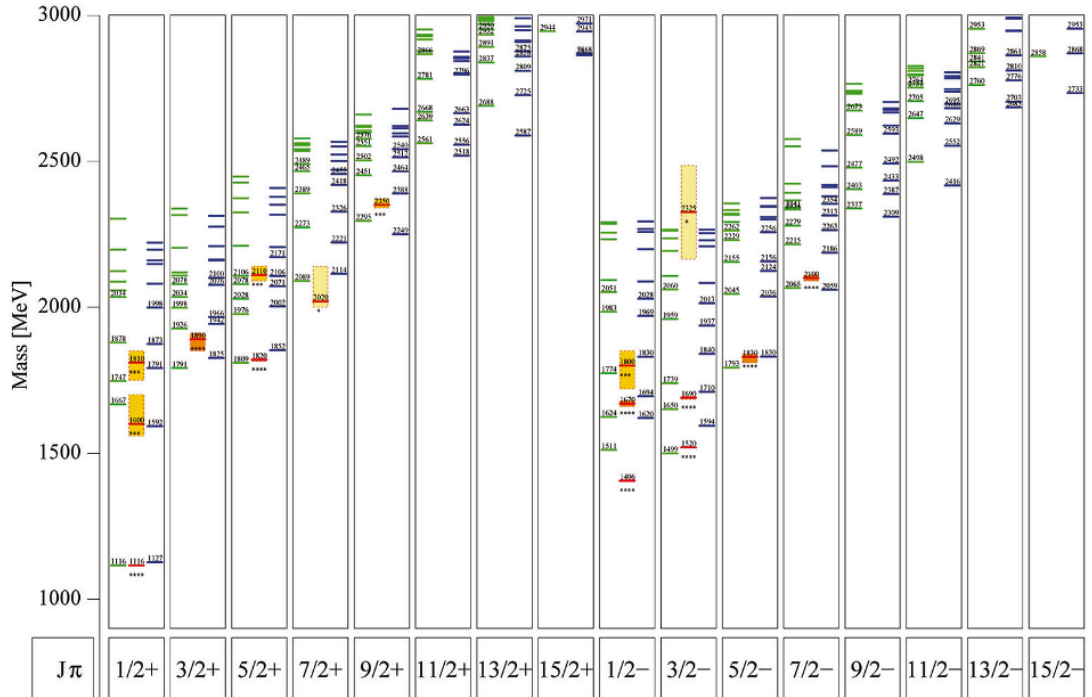


FIGURE 1.2: The comparison of experimental data (middle column) and theoretical predictions (left, and right column) of relativistically covariant constituent quark models for Λ hyperons. The picture shows how limited is our experimental knowledge compare to theroetical predictions. The picture is taken from [7]

1.3 Dalitz decays

The idea of form-factors was introduced first time in context of scattering experiments. A Feynmann diagram for such phenomena is shown in fig. 1.3 a). Due to kinematic constraints for the scattering a four-momentum q^2 is always negative - a projectile transfers part of its four-momentum into target. However an idea of the form factor can be extended to annihilation experiments, where $q^2 > 0$ (fig.1.3 b)). Unfortunately, to produce a baryon-antibaryon pair energy equal at least their masses is required. It means that q^2 can not be smaller than $4M_b^2$. This gap in q^2 can be explored in a range $0 < q^2 < 4M_b^2$ by process called a Dalitz decay.

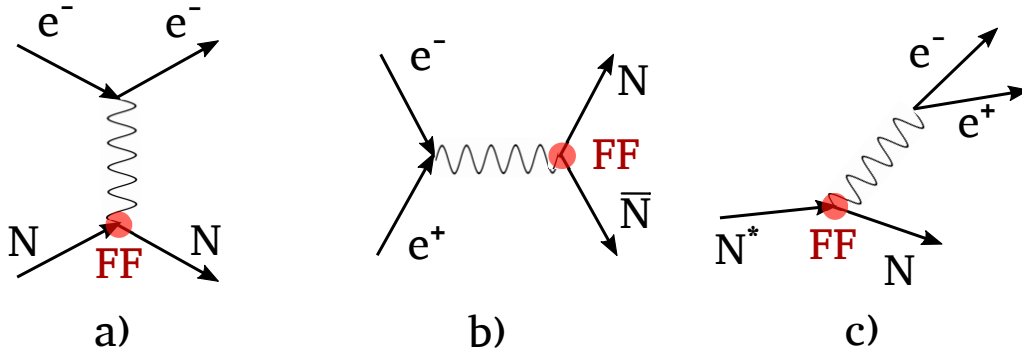


FIGURE 1.3: Three processes involving a nucleon electromagnetic form factors: a) an electron-nucleon scattering, b) an electron-positron annihilation, c) a nucleon Dalitz decay.

The Dalitz decay of a nucleon (is fig.1.3 c)) is a reaction

Chapter 2

HADES detector

The **H**igh **A**ccceptance **D**i-**E**lectron Spectrometer (HADES) [8] is a detector located at the GSI Helmholtzzentrum für Schwerionenforschung. The HADES detector was designed for various measurements with the especial emphasis on di-electron spectroscopy. Thanks to versatility of the SIS18 (German: **S**chwer**I**onen**S**ynchrotron) accelerator and a secondary pion beam facility, various kind of experiments can be conducted: starting from pion scattering on proton or nucleus targets, through proton-proton and proton-nucleus reactions, up to the heavy ion collisions.

The detector provides almost full azimuthal angular coverage, whereas the acceptance in the polar angle used to range from 18° to 80° . A current upgrade extends the detector acceptance for forwards angles, for more details see 2.4.1. Two sets of **M**ulti-**w**ire **D**rift **C**hambers (MDC) together with a superconducting toroid magnet allow for momentum measurements with $\frac{dp}{p} \approx 2 - 3\%$ and particle identification (PID) via energy loss measurement. The PID is further enhanced by high resolution **T**ime **O**f **F**light (TOF) detectors ($\sigma \approx 80$ ps) and a hadron-blind **R**ing **I**maging **C**herenkov (RICH) detector. A combined information from the detectors allow for efficient $p/\pi/K/e$ separation over broad momentum range.

2.1 Tracking system

The HADES tracking system bases on four sets of a drift chambers. Two before and two after a magnetic field. First one are called inner MDC, the second outer MDC. Each single drift chamber has a trapezoidal shape and consist of 13 layers of wires. They create 6 layers of a drift cells. A shape of the cells and the wires density was optimized to get the best momentum resolutions. Tracks reconstructed in inner and outer MDCs are matched together during a track reconstruction process, performed offline.

2.2 RICH detector

2.3 Start detector and a trigger system

2.4 HADES upgrades

2.4.1 The Forward Detector

2.4.2 RICH update

2.4.3 Electromagnetic calorimeter

Chapter 3

Data analysis

The HADES experiment has performed a proton-proton experiment with protons kinetic energy 3.5 GeV in September 2018. Data collected during this experiment allowed to conduct a series of analysis devoted to hyperons studies [9–13]. In the following thesis the next step of hyperon studies is presented. The four particles $p\pi^-\pi^+\pi^-$ final state was analyzed. It allows to reconstruct the inclusive signals of a $\Lambda(1520)$ and a $\Lambda^0 K^0$ production. The obtained results were compared with previous, exclusive measurements and used to constrain simulation of a new experiment devoted to hyperon studies 5.

All methods developed for $pp@3.5$ GeV experiment were also used for data deriving from $pNb@3.5$ GeV experiment. In result an inclusive cross section for $\Lambda(1520)$ together with the reference state $\Lambda^0 K^0$ were measured. Compare to previous HADES studies [14–17] it allows to extend knowledge about hyperons in pNb reactions. Additionally to obtain a background description an event mixing method was used.

3.1 Particles identification

The HADES detector allows for two complementary methods of particles analysis. The first, bases on particles' time of flight measured in the ToF detectors and particle's momentum measured in the MDC. The second method, bases on the MDC exclusively and uses combined information about particles' momentum and energy losses. The first one is favoured due to better precision, however a limited geometrical acceptance of the TOF detectors reduces detection efficiency by a factor 0.8 for each particle. In case of four particles final state, discussed in this thesis, a total loss caused by the TOF detectors can reach 60% of all detected particles. For that reason the $\frac{dE}{dx}$ vs. p identification method was used. The identification cuts were optimized for previous analysis conducted by the HADES experiment and described in [9, 18]. Cuts used for π^- and π^+ are the same and differ only by electric charge.

3.2 Event selection

Among all registered events only these containing at least four charged particles (two positive and two negative) was considered in analysis. They were observed events with more than four particles detected. They produces kombinatorics which are very difficult to control during further analysis. Because of that only one four-particle combination from every event was taken. The combinations were ordered according to track reconstruction quality and the best one was chosen.

3.3 Reaction kinematics

For pp@3.5 GeV collisions the production threshold for $\Lambda(1520)$ ($E_{pK+\Lambda^0}^{\text{thr}} =$) lies just below available energy ($\sqrt{S} =$). Using the rule of a energy-momentum conservation is possible to calculate missing mass for observed particles. Because the analyzed final state is produced via reaction

$$pp \rightarrow pK^+\Lambda(1520)[\Lambda^0\pi^+\pi^-], \quad (3.1)$$

the smallest missing mass for the signal channel is $\sqrt{S} - \Lambda(1520)_{\text{mass}} = 1432$ MeV. It is a very strong kinematical constrain which separates well the signal from most of background channels. The missing mass spectrum is presented in fig. 3.1. There is visible a resonance behaviour around 1200 MeV. Due to a charge conservation rule missing particles have to have a total charge +2. It leads to the conclusion that the missing mass spectrum is dominated by a Δ^{++} production.

Because in HADES energy regime almost all pions are produced via barionic resonances, and Δ^{++} s tend to be produced in pairs, it was expected that an invariant mass of $p\pi^+$ detected in experiment would also contain a Δ^{++} component. Indeed, as it is shown in fig. 3.2 most of the background comes from correlated source with mass maximum around double Δ^{++} production. The figure shows also that a cut on missing mass > 1432 MeV removes a significant part of a background events. In case of $\Lambda^0 K^0$ channel (see. 3.5) the missing mass cut was put on a lower mass ??.

3.4 The Λ^0 Reconstruction

The next step of the analysis after a missing mass cut was an inclusive Λ^0 reconstruction. In previous HADES experiments the reconstruction had based on a set of geometrical cuts. Their role was to increase signal-to-background ratio utilizing a Lz decay geometry. Because the Λ^0 decays via weak interactions its lifetime is relatively long: $c\tau = 7.89\text{cm}$ [19]. That may be used to discriminate an out of target vertex from a background originates from a target.

As it was shown in 3.3 an available phase-space for $\Lambda(1520)$ production for a $E_k = 3.5$ GeV is very limited. An inclusive analysis performed in [11] has measured ?? events of Ls after all

cuts. To improve statistics, and also examine new reconstruction methods in following analysis a neural network was used as a replacement of the geometrical cuts. Details about used methods are explained in chapter 4.

The optimized neural network enhanced a signal to background ratio from ??? without any cuts to ???. A Λ^0 signal obtained in this way was used for next steps of analysis: the $\Lambda(1520)$ analysis (chapter 3.7) and associated $\Lambda^0 K^0$ production (chapter 3.5);

3.5 The $\Lambda^0 K^0$ reconstruction

Because of a strangeness conservation law a Λ^0 has to be produced with some anti-strange particle. The lightest candidate is a K^0 meson, which decays in 69.2% into $p\bar{p}$ pair [19]. For that reason a $\Lambda^0 K^0$ signal is expected to be a significant part of the $\Lambda^0 \pi^+ \pi^-$ final state.

After the Λ^0 reconstruction two spectra were drawn: a) a $\pi^+ \pi^-$ invariant mass spectrum for events $1006 < M_{p\pi^-}^{inv} < 1026$ and b) a $p\bar{p}$ invariant mass for $480 \text{ MeV} < M_{\pi^+ \pi^-}^{inv} < 500 \text{ MeV}$. The same analysis chain was used to analyze all channels listed in 3.1 which contains Λ^0 and K^0 . In

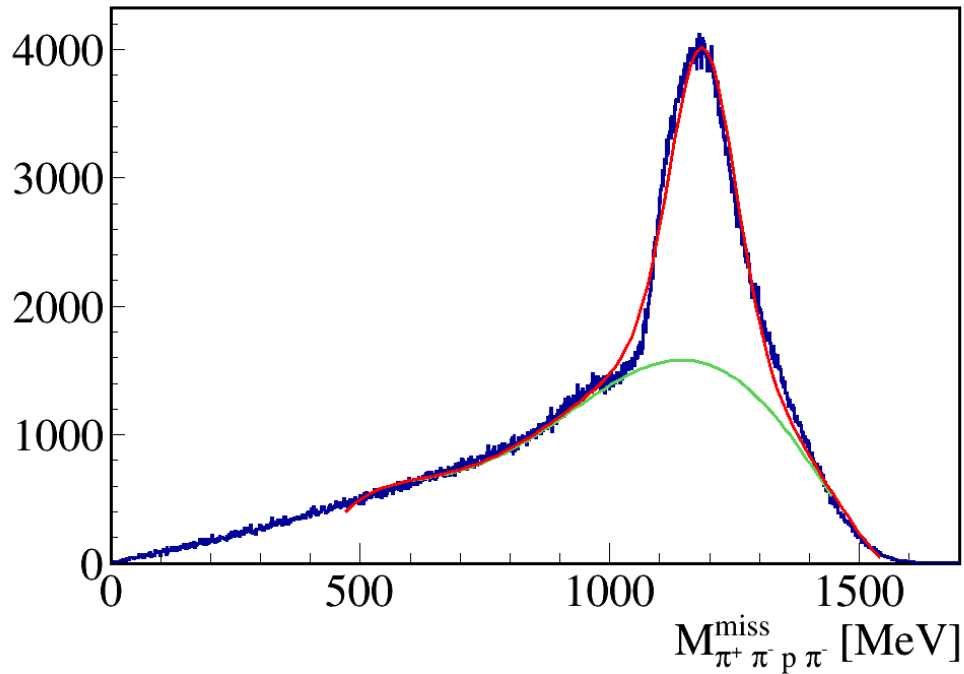


FIGURE 3.1: The missing mass of $p\pi^-\pi^+\pi^-$ system. The resonance behaviour around 1200 MeV is clearly visible. The red line represents sum of signal (a Voigt function) and a background (5-th order polynomial) fit. Fitted Voigt function gives following parameters: $\bar{M} = 1186 \text{ MeV}$, $\sigma = 61 \text{ MeV}$, $\Gamma = 20 \text{ MeV}$.

FIGURE 3.2: The missing mass of $p\pi^-\pi^+\pi^-$ system vs. invariant mass of a $p\pi^-$ system. It is clearly visible that most of the background comes from correlated source of two Δ^{++} production. Such situation helps to easily discriminate most of the background.

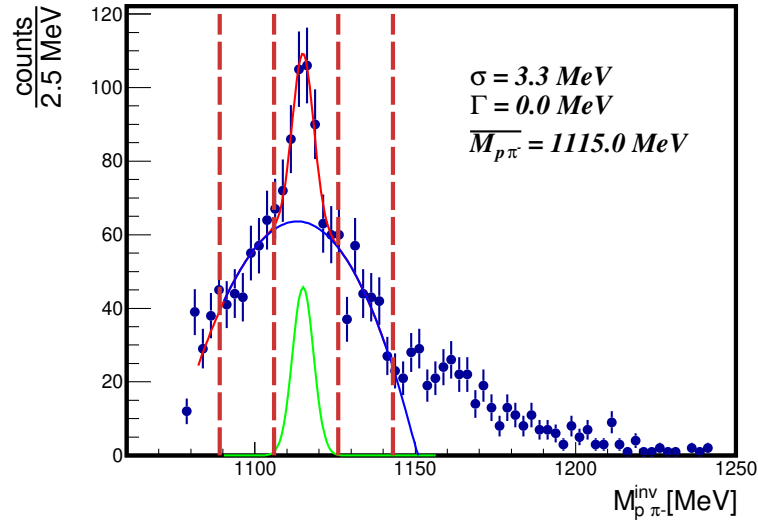


FIGURE 3.3: The Λ^0 spectrum after a neural network analysis. The vertical lines denotes regions of a side-band analysis described in 3.7.1. The data was fitted by a sum of 4-th order polynomial (blue line) and a Voigt function (green line). A very small value for Γ parameter is caused by the Λ^0 long live-time. Obtained σ value describe an apparatus energy resolution.

case of the reference channel the missing mass cut was lowered to ???, what is a minimall missing mass expected for $pp \rightarrow pK^0\Lambda^0\pi^+$ reaction.

Using a procedure described in 3.6 the simulation was compared with experimental data (see 3.4). The simulation describes well a yield of K^0 and Λ^0 produced in experiment, although it does not describe the background shape. This is mostly caused by lack of realable model for a double Δ^{++} production.

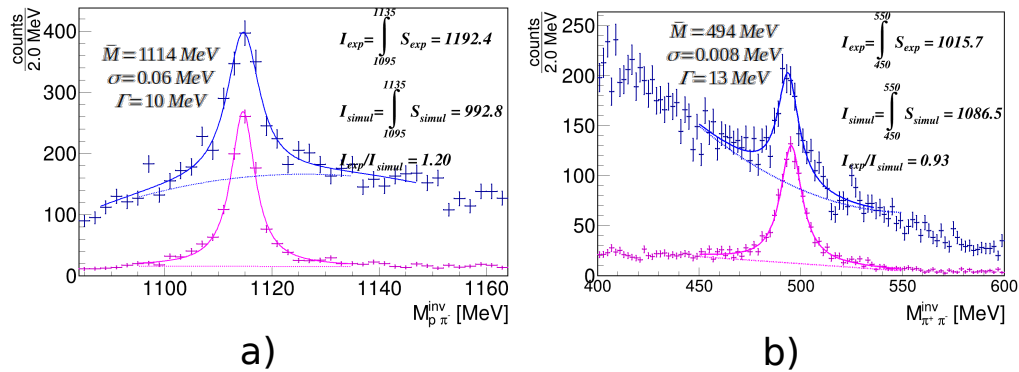


FIGURE 3.4: The results for $\Lambda^0 K^0$ asocieted production. Blue point reprezents experimental data, magenta a sum simulated channels. For both: the simulation and the experimental data a Voigt function was fitted. Than, a total signal yield between simulation and experiment was calculated.

TABLE 3.1: List of the channels considered in following chapter. Numbers from 3 up to 10 indicates reactions containing $p\pi^-\pi^+\pi^-$ in a final state. They are treated as a possible background channels. All values taken from [9].

no.	Channel	$\sigma [\mu\text{b}]$
3-body reactions		
1	$\Lambda^0 p K^+$	$35.26 \pm 0.43^{+3.55}_{-2.83}$
2	$\Sigma^0 p K^+$	$16.5 \pm 20\%$
3	$\Lambda^0 \Delta^{++} K^0$	$29.45 \pm 0.08^{+1.67}_{-1.46} \pm 2.06$
4	$\Sigma^0 \Delta^{++} K^0$	$9.26 \pm 0.05^{+1.41}_{-0.31} \pm 0.65$
5	$\Sigma(1385)^+ p K^0$	$14.05 \pm 0.05^{+1.79}_{-2.14} \pm 1.00$
6	$\Delta^{++} \Lambda(1405) K^0$	$5.0 \pm 20\%$
7	$\Delta^{++} \Sigma(1385)^0 K^0$	$3.5 \pm 20\%$
8	$\Delta^+ \Sigma(1358)^+ K^0$	$2.3 \pm 20\%$
4-body reactions		
9	$\Lambda p \pi^+ K^0$	$2.57 \pm 0.02^{+0.21}_{-1.98} \pm 0.18$
10	$\Sigma^0 p \pi^+ K^0$	$1.35 \pm 0.02^{+0.10}_{-1.35} \pm 0.09$

3.6 Absolute normalization

An integrated luminosity for the pp experiment was calculated using a pp elastic scattering, it was

$$L^{int} = 3.13 \cdot 10^8 \text{mb}^{-1}. \quad (3.2)$$

Thanks to a full scale simulation performed in HYDRA framework (for more details see chapter 5) it is possible to get a total detection efficiency for given reaction. The efficiency, together with known luminosity and a cross section allows for an expected count rate estimation, for any reaction.

$$N_{pp \rightarrow X}^{\text{expected}} = \frac{N_{\text{detected}}}{N_{\text{Simulated in } 4\pi} \cdot 3} \cdot \sigma_{pp \rightarrow X} \cdot L. \quad (3.3)$$

The factor 3 in denominator is connected with a trigger down-scaling. Due to limited read-out capabilities For a hadronic channels each 3th triggered event was saved on tapes. A list of the reactions used in following analysis are in 3.1.

3.7 The $\Lambda(1520)$ Reconstruction

The neural network analysis gives a data sample with good S/B ratio for Λ^0 signal. However set of additional cuts has to be applied to extract a $\Lambda(1520)$ signal from the data. Using the signal channel's simulation a set of hard cuts was optimized: i) a distance between a secondary vertex (SV) and a primary vertex (PV) has to be larger than 5 mm, ii) an opening angle (OA_{Λ^0}) between a reconstructed Λ^0 momentum direction and line connecting the primary and secondary vertices has to be smaller than ?? . The cuts are illustrated in fig. 3.5. A $p\pi^-\pi^+\pi^-$ spectrum obtained after the hard cuts contains both: a $\Lambda(1520)$ signal and background originated from background under a Λ^0 peak. To remove that contamination additional steps were necessary. One of them was a

side-band analysis which allowed to remove uncorelated combinatorial background from $\Lambda(1520)$ spectrum.

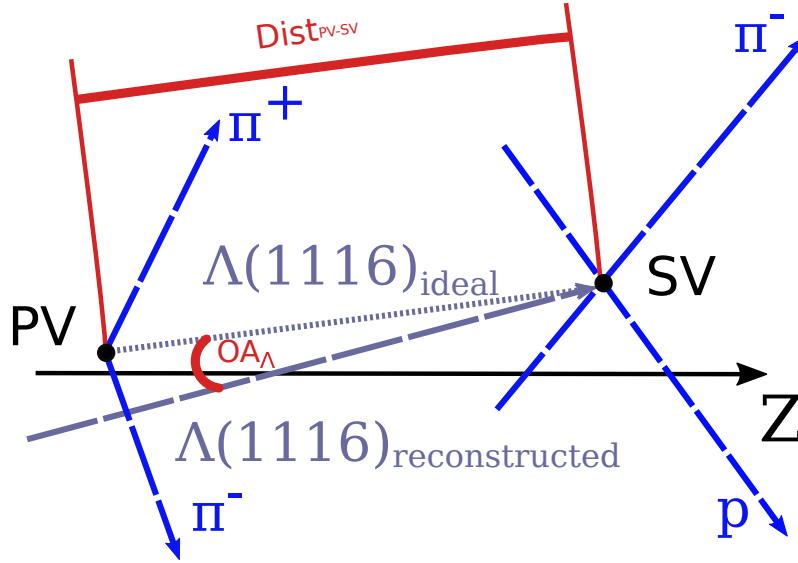


FIGURE 3.5: Cuts used for a $\Lambda(1520)$ reconstruction. They were optimized using simulation.

3.7.1 Side-band analysis

A side-band analysis bases on assumption that a background kinematic changes slowly through a spectrum. Thanks to this, kinematics of the background events from signal region can be well described by background outside the signal region. In case of described analysis the side-band method was used to estimate an impact of non-perfect Λ^0 reconstruction for the $\Lambda(1520)$ spectrum. The fig. 3.3 shows input for the side-band. The $p\pi^-\pi^+\pi^-$ spectra for the signal and SB region after all the cuts are shown in 3.6. The side-band describes very well both wings of the data distribution. A difference between signal and the side-band spectrum can be interpreted as $p\pi^-\pi^+\pi^-$ signal associated with the Λ^0 signal.

3.7.2 Cross-section extraction differential analysis

Despite the side-band spectrum describes a background shape very well, there is still some signal contamination in a mass region over 1540 MeV, see fig. ???. It may be caused by correlated combinatorial background, when a fake $\pi^+\pi^-$ pair is combined with real Λ^0 signal. The main source of di-pion pairs, a K^0 decay, is suppressed by a cut $M_{\pi^+\pi^-}^{inv} < 410 \text{ MeV}$. However there are reactions which allow for mixing pions from two different sources. Three of them were chosen as the most important ones. They are presented in tab. 3.1 with numbers 3-5. the final state for each of them contains Λ^0 and two different sources of pions. A combination of a π^- from a K^0 decay and a π^+ from a Δ^{++} or a Σ^+ creates a correlated combinatorial background.

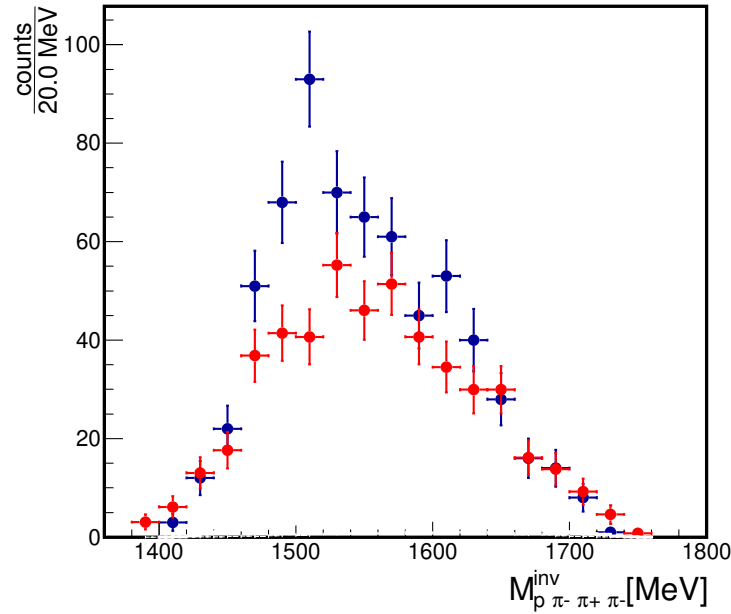


FIGURE 3.6: The $p\pi^-\pi^+\pi^-$ spectrum for events from signal region ($M_{p\pi^-}^{inv} \in (1106, 1126)$) - blue points, and from SB regions ($M_{p\pi^-}^{inv} \in (1089, 1106] \cup [1126, 1143)$) - red points. Error bars show a statistical uncertainty

An identification of the background channels allows to simulate them and, together with a simulation of the signal channel estimate an inclusive cross section for $pp \rightarrow \Lambda(1520)X$ reaction. The signal channel was simulated according to exclusive cross section measured by HADES $\sigma_{pp \rightarrow pK^+\Lambda(1520)} = 6.5 \mu\text{b}$ [11]. Next the simulated signal spectrum was scaled up to get the same area under a simulation and experimental histogram. Finally, according to the obtained scaling an inclusive cross section is equal $\sigma_{pp \rightarrow \Lambda(1520)X} = 7.1 \pm 1.5 \mu\text{b}$. A uncertainty comes from a statistical error.

The total yield of detected decays allows to conduct a simple differential analysis. A transverse momentum (p_t) and rapidity (Y) was calculated for each reconstructed $\Lambda(1520)$. Obtained spectra are presented in fig ???

3.7.3 Analysis of a $\pi^+\pi^-$ spectrum

In simulation model used for the cross section extraction pions were emitted according to available phase-space. However it is possible that pion production occurs through a virtual ρ meson. A possible ρ contribution would manifest by a distortion of a $\pi^+\pi^-$ spectrum compared to direct production. An alternative simulation with the rho decay was also prepared and both of them compared with experimental data. By naked eye an only-phase-space distribution describes data better. That was proven quantitatively making a linear combination of the two available spectra

$$sum = N \cdot M_{\pi^+\pi^-_{w/o\rho}}^{inv} + (N - 1)M_{\pi^+\pi^-_{\rho}}^{inv}, \quad (3.4)$$

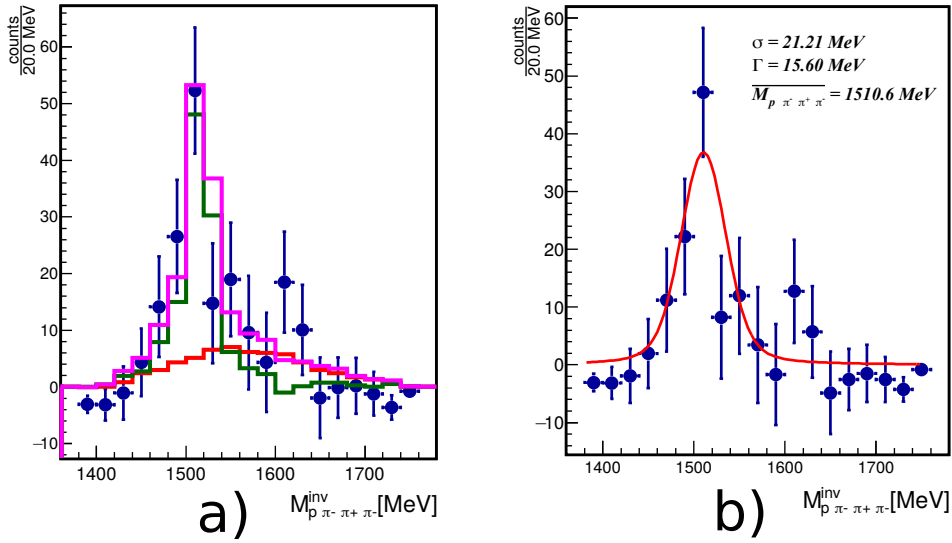


FIGURE 3.7: The $\Lambda(1520)$ signal obtained in experiment. A) The experimental spectrum after a side-band subtraction (blue points) together with the signal and the background simulation (green and red line respectively). The magenta line shows the sum of all simulated channels. B) Signal after the simulated background subtraction. The Voigt functions used to describe the data points was constrained by a known $\Lambda(1520)$ decay width $\Gamma = 15.6 \text{ MeV}$ [19]. Obtained σ value can be treated as a measure of energy resolution obtained in the experiment.

where $N \in [0, 1]$. An agreement between data and simulation was tested by χ^2 test. It proved that within available errors the best data description is given by only-phase-space distribution of pions.

3.8 results from p Nb experiment

Chapter 4

Neural networks

4.1 The ROC curve and the optimal classifier

One of the most common problem in machine learning is a binary classification, when a data set has to be divided into two subsets, fulfilling serian requirements. A simple example of such a problem is distinction between signal and bacground events in deta collected by experiment. We would like to have a function which takes as agruments set of physical observables (eg. particles' energy, momentum, coordinates of vertexes), represents by \vec{x} and returns sigle number. More formally, a clasyfier can be call any function $h : \vec{x} \rightarrow \mathbb{R}$ designed in such a way, that high $h(\vec{x})$ values correspond signal events and low $h(\vec{x})$ values correspond background event. A threshold value $h(\vec{x})=c$, which is the value separating signal and backgrond events is called a working point, and has to be set by a user. The signal efficiency will be defined as $\epsilon_S = \int d\vec{x} \rho_S(\vec{x}) \Theta(h(\vec{x}) - c)$ and respectively a background efficiency $\epsilon_B = \int d\vec{x} \rho_B(\vec{x}) \Theta(h(\vec{x}) - c)$.

The problems how to represent a clasyfier performance, how to compare different clasyfiers and how to choose proper working point have been discused since many years. During World War II engeneners faced a probelm of a radar detection efficiency. With an increasing radar sensitivity a chance to detect an enemy aircraft increses. However, the chanse that signal is a fake caused by birds or other circumstances also increases. To represent this relation a so-colled ROC (**R**eceiver **O**perating **C**haracteristic curve) curve was invited. One axis represents a true positive rate or a detection efficiency, second axis shows a background reduction. Each point on the curve represents working-point for the clasyfier. Comparing two different classyfiers someone can not compare performance for one working point, but has to compare all.

FIGURE 4.1: The ROC curve, it represents a clasyfier performance. In case of the ideal clasyfier area under the curve is equal 1, what means that for each working point all background events are rejected and non of singal is lost.

4.2 The data-driven approach

The original paper by Metodiev, Nachman and Thaler [20] the others show the idea of a data-driven analysis in details. In this chapter I want to introduce main concepts, necessary to understand how the proposed metode helps in week decays reconstrution.

In a classical approach to supervised machine learning, a model learns its properties usign sets of labeled data. Of course providing good training sets is always a problem. To do this, someone can use either experimental data, labeled by a user, or simulation. In first case a user uses his external knowledge about the data to describe it. In second case the user fully rely on simulation. First case is quite often impossible to perform, but even when a user is able to label data a labeling could be systematicly biased by user lack of knowlage or missunderstand of detector. In second case they are two main threats: either a simulation does not describe data well, or creates some artificial structures in data, which can lead into sistematic errors in network performance.

The data-data driven analysis avoids inconveniences of two mentioned methodes. It requires neither labeling nor simulation and it bases only on statistical properties of a collected deta set. According to Neyman-Pearson lemma [21] the optimal clasyfier for two sets, A and B is a function given by a dencity ratio

$$h_{opt}^{A/B}(\vec{x}) = \frac{\rho_A}{\rho_B} \quad (4.1)$$

or any monotonous function of $\frac{\rho_A}{\rho_B}$. Assuming that both sets A and B contains signal (s) and bacground (b) events and a statistical distribution of s and b is the same in A and B, we can write (4.1) in the following way

$$h_{opt}^{A/B} = \frac{f_1 \rho_s + (1 - f_1) \rho_b}{f_2 \rho_s + (1 - f_2) \rho_b} = \frac{f_1 \rho_s / \rho_b + 1 - f_1}{f_2 \rho_s / \rho_b + 1 - f_2} = \frac{f_1 h_{opt}^{s/b} + 1 - f_1}{f_2 h_{opt}^{s/b} + 1 - f_2}. \quad (4.2)$$

It can be proven that $\partial_{h_{opt}^{s/b}} h_{opt}^{A/B} > 0$, what means that optimal clasyfier for both cases is the same. It is important to underline that the reasoning gives no clue about the working points for both cases.

4.3 Application for analysis

In case of $\Lambda(1520)$ reconstruction the data driven approach was used to replace set of geometrical cuts and enchace a Λ^0 signal to background ratio. So for the neural network all events with Λ^0 were treated as a signal and without like a background. For all events an invariant mas of $p\pi^-$ pair was ploted (fig. 4.3). Using this spectrun the dataset was divided in two subsets: for $M_{p\pi^-}^{inv} \in (1015, 1125)$ and $M_{p\pi^-}^{inv} \notin (1015, 1125)$. In the first of them a ratio between Λ^0 and background is clearly different than in the second, what fulfil the requariments for the data-driven approach. Hence, a numerous networka architecture were tested to check which deals the best with Λ^0 reconstruction.

A learning and testing proces was done within scope of TMVA framework [22]. Using TMVA a user has to provide list of input variables and a network architecture, than the framework automatically preperes learning and testing sets and performs whole learning process together with testing the final classifier. As an input variables the set of geometrical properties was used.

- Distance between $p\pi^-$
- Λ^0 vertex cooridanenes, reconstructed as a point of the closest aproach of p and π^- tracks
- $\Lambda(1520)$ vertex coordinates, rseconstructed as a point of the closest approach of π^+ and π^- tracks
- $\Lambda(1520)$ vertex coordinates, reconstructed by tracking algorithm as a primary vertex
- Opaning angle between reconstructed Λ^0 vector and a line conecting primary and secondary verteces

Using any combination of input variables it is impossible to reconstruct $p\pi^-$ invariant mass. It is important feature wich allows to use mesioned invariant mass spectrum as a cross-check for all procedure, and a network will not collapse into trivial solution.

During treaning the network is optymalized to sepearate sets A and B. Its performance for Λ^0 reconstruction has to be investigated in a different way. After the traning the network was used to evaluate each event collected during the experiment. It means, that network output - a number in range from 0 to 1 - is assigned to each reconstructed event. Fitting a Λ^0 peak (see 4.4 a)) it was possible to check how signal efficiency and signal to background ratio changes with cut on the network output.

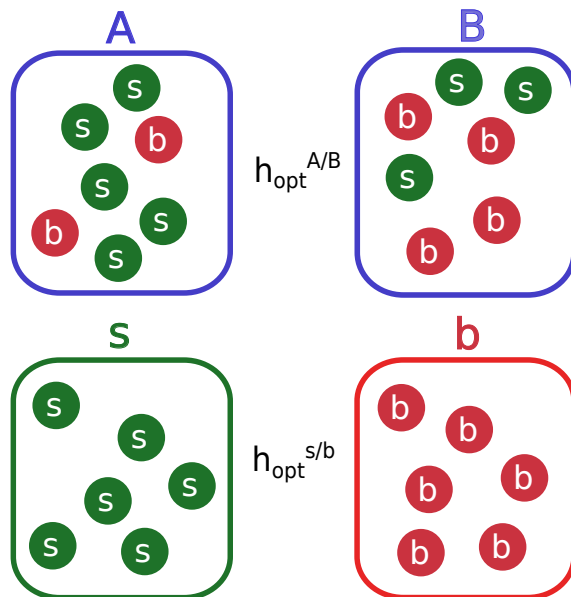


FIGURE 4.2: A data-driven approach visualisation. According to [20] the optimal clasifier for sets A and B is equivalent to optimal clasifier for sets s and b.

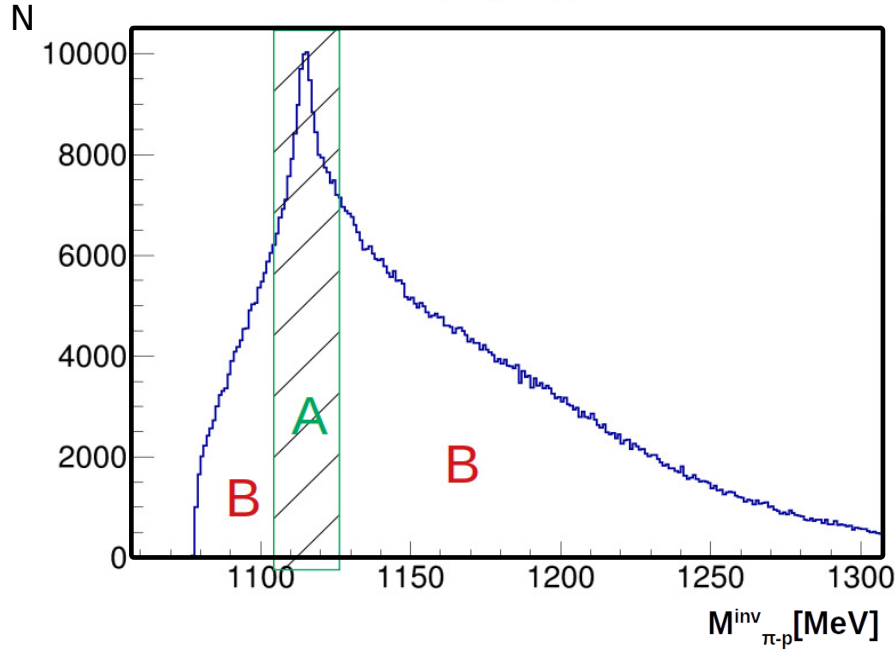


FIGURE 4.3: A $p\pi^-$ invariant mass spectrum. Whole data set was divided into two subsets, A and B, each of them is characterized by different signal to background ratio. All tested models were trained to distinguish between sets A and B and later use to separate events containing Λ^0 .

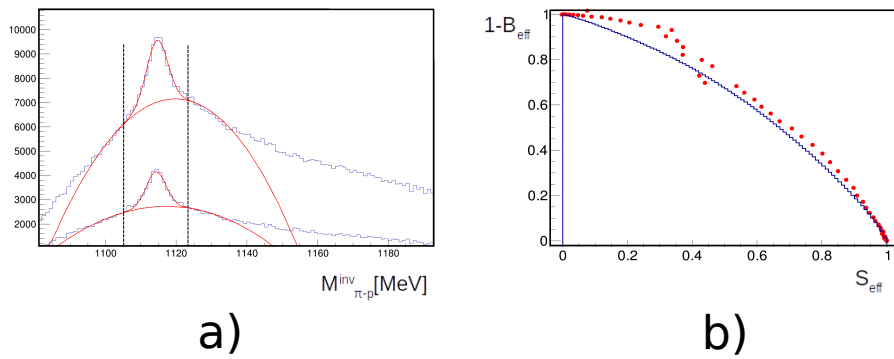


FIGURE 4.4: Results of a neural network training. a) Example of two spectra after a cut on the network output. For each of the the signal (gaussian function) and background (4-th order polynomial) were fitted. Such fits allows to calculate a signal efficiency $\frac{S}{S_0}$ and a background rejection $1 - \frac{B}{B_0}$, where S_0 and B_0 are yields of signal and background without any cut on a neural network output.

Chapter 5

Simulations of a new experiment

The HADES collaboration is one of the leading forces of a FAIR Phase-0 project. Within the scope of FAIR project a $pp@4.5\text{GeV}$ experiment is going to be performed. It gives a great opportunity to measure hyperons' Dalitz decays (see Chapter 1). One of the goals of my work was to carry out a simulation of such an experiment.

5.1 An estimation of cross-sections

In energy range of $1\text{GeV} < \sqrt{S} < 6\text{GeV}$ an inclusive cross section for Λ^0 and Σ^0 were measured for many different energies [9, 23, 24]. Also an inclusive cross section for $\Lambda(1405)$ production was measured for two different energies [10, 25], and for $\Lambda(1520)$ is known for one energy [9] in this range. In contrast to the exclusive production cross section, inclusive cross sections for hyperons' production are poorly known. First step to perform a simulation was to estimate possible cross sections based on available knowledge.

5.1.1 Λ^0 inclusive cross section

The first step for all estimations is a parametrization of a Λ^0 inclusive production. In a given energy range there are four measured values. Moreover I made two additional assumptions i) the inclusive cross section is equal 0 for threshold energy, ii) for energy below one pion mass (140MeV) the inclusive and the exclusive cross sections are the same. For the parametrization I can use cross section measured for $pp \rightarrow pK^+\Lambda^0$ for \sqrt{S} below ???. To all available data points meeting my requirements I fitted a 3th order polynomial

$$\sigma_{pp \rightarrow \Lambda^0 X}(\sqrt{S}) = 48 \cdot (\sqrt{S} - 2.55) + 292.6 \cdot (\sqrt{S} - 2.55)^2 - 45.4 \cdot (\sqrt{S} - 2.55)^3. \quad (5.1)$$

Fit result, together with residual plot is shown in 5.1 by a blue dotted line. This parametrization forms the basis for all inclusive cross sections estimated in my work.

5.1.2 Σ^0 inclusive cross section

According to PDG [19] almost all Σ^0 s decay into Λ^0 . It means that the inclusive Λ^0 signal contains a fraction deriving from Σ^0 decays. However knowing a relation between Λ^0 and Σ^0 it is possible to disentangle both contributions.

A Σ^0/Λ^0 ratio was measured by COSY and others [23]. Additionally the COSY collaboration proposed a parametrization of the ratio for excess energy $\epsilon < 200\text{MeV}$. Above this energy ($\epsilon > 200\text{MeV}$) a linear parametrization

$$\frac{\Lambda^0}{\Sigma^0}(\epsilon) = 2.215 - 2.7 \cdot 10^{-5} \epsilon \quad (5.2)$$

describes data quite well ($\chi^2 = 0.89$). In fact for $\epsilon > 200\text{MeV}$ the ratio is almost constant and does not depend on energy.

Knowing the Λ^0/Σ^0 I was able to disentangle a Λ^0 and Σ^0 production. Using determined ratio and the Λ^0 production (let me call it P_1) parametrization given by eq. 5.1 (called P_2) I created following set of equations,

$$P_1(\epsilon) = \frac{L(\epsilon)}{S(\epsilon)} = \frac{L(\sqrt{S} - \Lambda_{thr}^0)}{S(\sqrt{S} - \Sigma_{thr}^0)} = P_1(\sqrt{S}), \quad (5.3)$$

$$P_2(\sqrt{S}) = \Lambda(\sqrt{S}) + \Sigma(\sqrt{S}), \quad (5.4)$$

Where Σ represents the inclusive Σ^0 production cross section and Λ the Lz cross section accordingly. Solving the first equation and shifting an argument by $\Sigma(1385)_{thr}^0$ I obtained an equation,

$$\Sigma(\sqrt{S}) \cdot P_1(\sqrt{S} + \Sigma_{thr}^0) = \Lambda(\sqrt{S} - \Lambda_{thr}^0 + \Sigma_{thr}^0). \quad (5.5)$$

Now, using eq. 5.5 and 5.4 I got a recurrence relation

$$\Lambda(\sqrt{S} - \Lambda_{thr}^0 + \Sigma_{thr}^0) = P_1(\sqrt{S} + \Sigma_{thr}^0) \left(P_2(\sqrt{S}) - \Lambda(S_{qs}) \right). \quad (5.6)$$

Assuming that $\Lambda(\Lambda_{thr}^0) = 0$ and $\Sigma(\Sigma_{thr}^0) = 0$, the above equation can be solved with any given precision. For the purpose of cross sections estimation a single step was set $\Delta M = \frac{\Sigma_{thr}^0 - \Lambda_{thr}^0}{10}$, obtained decomposition is shown in 5.1 by dashed lines. A characteristic “kick” on the green line corresponds to energy when two parametrizations of $\frac{\Lambda^0}{\Sigma^0}$ ratio are glued (see fig ??).

5.1.3 $\Lambda(1520)$, $\Lambda(1405)$ and $\Sigma(1385)^0$ production cross sections

A knowledge about cross sections for Λ and Σ in function of \sqrt{S} or energy over the threshold ϵ gives a possibility to estimate cross section for excited hyperon states. As a first approximation I have assumed that a production matrix element for ground and excited states is the same. It means that only factor cases the difference in cross section is available energy over the threshold. It can be

expressed by an equation

$$\sigma_{\Lambda^*X}(\Lambda_{thr}^* + \epsilon) = \sigma_{\Lambda X}(\Lambda_{thr} + \epsilon), \quad (5.7)$$

or in terms of \sqrt{S}

$$\sigma_{\Lambda^*X}(\sqrt{S}) = \sigma_{\Lambda X}(\sqrt{S} - \Lambda_{thr}^* + \Lambda_{thr}). \quad (5.8)$$

Using the equation 5.7 I have calculated expected cross sections for the excited hyperons states $\Lambda(1520)$ and $\Sigma(1385)^0$. They are shown in 5.1 as blue and green star.

A $\Lambda(1405)$ exclusive cross section was measured for two different energies by HADES [10] and COSY-tof [25] experiment. In [10] authors proposed a phenomenological parametrization of $\Lambda(1405)$ exclusive cross section ,

$$\sigma_{\Lambda(1405)pK^+}^{excl}(\epsilon) = \frac{1}{3}\sigma_{\Lambda^0 pK^+}^{excl}(\epsilon). \quad (5.9)$$

I have followed the same relation for inclusive reactions multiplying the inclusive Λ^0 cross section by factor 1/3. Result is shown in 5.1 by a magenta line. A magenta star shows point corresponding to $E_k = 4.5\text{GeV}$ proton beam. Numerical values of the estimated cross sections are in tab. 5.1.

5.1.4 $\Xi^-(1322)$

Knowledge about a double-strange hyperon $\Xi^-(1322)$ is extremely limited.

5.2 Decay branching ratios

Because Dalitz decays of hyperons were never measured a decay branching ratio have to be estimated considering available data. A first approximation may be obtained using result for a

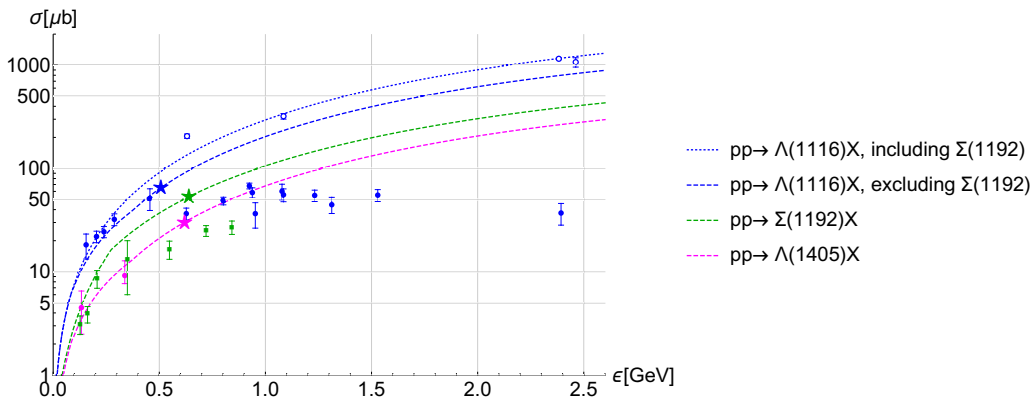


FIGURE 5.1: An estimated cross sections for Hyperons production. Blue dotted line shows an inclusive Λ^0 production. It was decomposed into two components: i) Λ^0 - blue dashed line and ii) Σ^0 green dashed line. Magenta dashed line represents a parametrization of $\Lambda(1405)$ cross section. All points refer to experimental data measured by different experiments [9, 10, 23–25]. Color code is the same like for lines. Full points represent an exclusive cross section, empty points an inclusive one.

non-strange sector. For a reaction $\Delta^+ \rightarrow p e^+ e^-$ the HADES reported [26] $\text{BR}_{\Delta \rightarrow p e^+ e^-} = (4.19 \pm 0.62 \text{ syst.} \pm 0.34 \text{ stat.}) \times 10^{-5}$. More precise estimation bases on, measured by CLAS collaboration [27], hyperons' radiative decays. A relation between radiative decays and Dalitz decays is given by the formula derived in F. Scozzi PhD thesis [28],

$$\Gamma^{N^* \rightarrow N e^+ e^-} = 1.35 \cdot \alpha \Gamma^{N^* \rightarrow N \gamma}. \quad (5.10)$$

For $\Lambda(1520)$ and $\Sigma(1385)^0$ decay with for real photon decay are known. For Lss the branchin ratio have to be astimted using other decay channels [ref]. Obtanied results (tab. 5.1 are located in range of measured BR for Δ^+ dalitz decay.

5.3 Background channels selection

To obtain a relaiablble simulation a cocktail of background channels shoud be considered and tested. In case of hadronic physic, for low and medium enrgys, due to lack of approximation theorem, get a realistic background is a very challenging task. For a $\sqrt{S} = 3.46$ GeV a hadronic matter tends to form resonances. It means that almost all hadrons in final states originate from decays of high-mass resonances. Because knowledge about porperities of such a resonances is limited I made a simplified assumption that all pions are produced directly, without any intermediate state and with angular distribution defined jus by a reaction phase-space. List of all bacground channels considered during studies is presented in tab. 5.1.

All channels considered as a $\Xi^-(1322)$ background have to constist $p\pi^-\pi^-$ in final state. A dominant one is a multi-pion production, however thanks to topological cuts (see chapter 5.4.3) this kind of the background is relatively easy to filter out. Second kind of the background considered in simulation is a Λ^0 production associated with π^- . Reactions much more challenging because the Λ^0 decay vertex is displaced from a target, the same like in signal reaction. Cross sections for channels numer 2-7 are taken from [24]. When data in a proper energy range is missing, the value for the lowest avaiable enegy above $\sqrt{S} = 3.46$ GeV is taken. that conservative assumption gives me a save margin.

For all channels consisting of the hyperons' Dalitz decays a final state is the same: $p\pi^-e^+e^-$. That allows me to use the same background cocktail for all three chanel. I divided possible bacground sources into three main grops. Firstly I considered a multi-pion production in a target area, channels: 14, 16 and 18. A di-lepton pair originates from a π^0 Dalitz decay and combination of p and π^- creates false Λ^0 signal. These channels differ from singal one mainly by a decay geometry. The Λ^0 decays via weak interaction with long lifetime $c\tau = 7.89$ cm [19], so its decay vertex is expected to be observed outside the target. A second group, channels 19, 21, 23, 24, 25, contains Λ^0 production associated with a di-lepton source. In this case I have a real Λ^0 and a e^+e^- pair coming from decay of different particles, mainly π^0 . The cross section are taken from [24]. The third source of background are Dalitz decays of non-strange baryons associated with Λ^0 production. The braching ratio was mesured only for Δ^+ Dalitz [26], for Δ^0 Dalitz I have

TABLE 5.1: List of signal (S) and background (B) channels for simulated reactions. Each channel containing Δ Dalitz decay is listed below reference channel, used for cross section estimation.

no.	Channel	$\sigma [\mu\text{b}]$	Type
$\Xi^-(1322)$ production			
1	$pK^+K^+\Xi^-(1322)$	3.6/0.35	S
2	$pp\pi^+\pi^+\pi^-\pi^-$	227	B
3	$p\Lambda^0K_S^0\pi^+$	30	B
4	$p\Lambda^0K^+\pi^+\pi^-$	21	B
5	$n\Lambda^0K_S^0\pi^+\pi^+$	10	B
6	$p\Sigma^0K_S^0\pi^+$	9	B
7	$ppK_S^0K_S^0$	1.6	B
Dalitz decays of hyperons			
8	$pK^+\Lambda(1520)[\Lambda^0e^+e^-]$	69.6, BR = 8.4×10^{-5}	S
9	$pK^+\Lambda(1405)[\Lambda^0e^+e^-]$	32.2, BR = 5.3×10^{-6}	S
10	$pK^+\Sigma(1385)^0[\Lambda^0e^+e^-]$	56.24, BR = 1.1×10^{-4}	S
11	$pK^+\Lambda(1520)[X]$	69.6	B
12	$pK^+\Lambda(1405)[X]$	32.2	B
13	$pK^+\Sigma(1385)^0[X]$	56.24	B
14	$pp\pi^+\pi^-\pi^0$	1840	B
15	$p\pi^+\pi^-\Delta^+[pe^+e^-]$	2760, BR = 4.5×10^{-5}	B
16	$pn\pi^+\pi^+\pi^-\pi^0$	300	B
17	$p\pi^+\pi^+\pi^-\Delta^0[ne^+e^-]$	450, BR = 4.5×10^{-5}	B
18	$pp\pi^+\pi^-\pi^0\pi^0$	300	B
19	$p\Lambda^0K^+\pi^0$	43	B
20	$K^+\Lambda^0\Delta^+[pe^+e^-]$	64, BR = 4.5×10^{-5}	B
21	$n\Lambda^0K^+\pi^+\pi^0$	20	B
22	$\pi^+K^+\Lambda^0\Delta^0[ne^+e^-]$	30, BR = 4.5×10^{-5}	B
23	$p\Lambda^0K^+\pi^0\pi^0$	10	B
24	$p\Sigma^0K_S^0\pi^+$	9	B
25	$p\Lambda^0K^+\pi^0\pi^0\pi^0$	7	B

assumed the same value. A production cross section for the channels containing Δ has been calculated assuming that all pions comes from the resonances decays. For example, channel 14 is the final state for reaction $pp \rightarrow p\Delta^+[p\pi^0]\pi^+\pi^-$. Assuming that the Δ decay into pions conserves an isospin symmetry I used Clebsch-Gordan coefficients to calculate a ratio

$$\frac{\Delta^+ \rightarrow p\pi^0}{\Delta^+ \rightarrow n\pi^+} = \frac{2}{1}. \quad (5.11)$$

Hence, a total cross section for the reaction $pp \rightarrow p\Delta^+\pi^+\pi^-$ is $\frac{3}{2} \cdot \sigma_{pp \rightarrow pp\pi^+\pi^-\pi^0}$. The cross sections for other channels containing Δ dalitz decay were calculated in a similar way. Each Δ channel is listed below a reference multi-pion production channel.

5.4 Simulations results

The simulation has been performed using following frameworks. The PLUTO event generator [29, 30] to simulate reactions in the target, the GEANT3 [31] software to simulate particles propagation through the detector and to simulate decay of unstable reaction's products like Λ^0 or K_S^0 . After all physics simulations, the detector answer and a full reconstruction chain was done in the HYDRA framework. All together gives me a realistic simulation of an examined physics, and the HADES behaviour. The new HADES upgrades: new RICH, and the FwDet (see chapter 2.4.3) were included.

5.4.1 Particles identification

The particle identifications algorithms used for simulation are, in principle, the same as for data collected during experiment. In first step all particle candidates are filtered to find events in which track reconstructed in the MDC is fitted with the RICH rings. Additionally a Time-Of-Flight and Beta for leptonic track has to lay within a graphical cut. If both criteria were fulfilled they are treated as lepton candidates. In next step for all non-leptonic candidates the mass is calculated according to the formula

$$m = \frac{pc}{\beta\gamma}. \quad (5.12)$$

For protons and pions the mass cuts are 650-1127 MeV and 40-240 MeV respectively.

5.4.2 Hyperons Dalitz decays

5.4.3 Cascade decay

Chapter 6

Conclusions

Bibliography

- [1] H. Geiger, “On the scattering of α -particles by matter,” *Proceedings of the Royal Society of London A* **81** (Jul, 1908) 174–177.
- [2] S. Chatrchyan, V. Khachatryan, A. M. Sirunyan, A. Tumasyan, W. Adam, and et. al. [CMS Collaboration], “Observation of a new boson at a mass of 125 GeV with the CMS experiment at the LHC,” *Physics Letters B* **716** no. 1, (Sept., 2012) 30–61, [arXiv:1207.7235 \[hep-ex\]](#).
- [3] G. Aad, T. Abajyan, B. Abbott, J. Abdallah, S. Khalek, A. Abdelalim, O. Abdinov, R. Aben, M. Abolins, O. Abouzeid, H. Abramowicz, H. Abreu, B. Acharya, L. Adamczyk, D. Adams, T. Addy, J. Adelman, S. Adomeit, and L. Zwalinsk, “Observation of a new particle in the search for the standard model higgs boson with the atlas detector at the lhc,” *Physics Letters B* **716** (09, 2012) 1–29.
- [4] M. Gell-Mann, “A schematic model of baryons and mesons,” *Physics Letters* **8** (Feb, 1964) 214–215.
- [5] G. Zweig, “An $su(3)$ model for strong interaction symmetry and its breaking,” *CERN Report* **8182/TH.401** (Jen, 1964) .
- [6] V. E. Barnes, P. L. Connolly, D. J. Crennell, B. B. Culwick, W. C. Delaney, W. B. Fowler, P. E. Hagerty, E. L. Hart, N. Horwitz, P. V. C. Hough, J. E. Jensen, J. K. Kopp, K. W. Lai, J. Leitner, J. L. Lloyd, G. W. London, T. W. Morris, Y. Oren, R. B. Palmer, A. G. Prodel, D. Radojićić, D. C. Rahm, C. R. Richardson, N. P. Samios, J. R. Sanford, R. P. Shutt, J. R. Smith, D. L. Stonehill, R. C. Strand, A. M. Thorndike, M. S. Webster, W. J. Willis, and S. S. Yamamoto, “Observation of a hyperon with strangeness minus three,” *Phys. Rev. Lett.* **12** (Feb, 1964) 204–206.
<https://link.aps.org/doi/10.1103/PhysRevLett.12.204>.
- [7] M. Ronniger and B. Metsch, “Effects of a spin-flavour dependent interaction on light-flavoured baryon helicity amplitudes,” *The European Physical Journal A* **49** (07, 2012) .
- [8] G. Agakishiev *et al.* [HADES collaboration Collaboration], “The High-Acceptance Dielectron Spectrometer HADES,” *EPJ A* **41** (2009) 243–277, [arXiv:0902.3478 \[nucl-ex\]](#) . %%CITATION = ARXIV:0902.3478;%%.
- [9] J. Adamczewski-Musch, G. Agakishiev, O. Arnold, E. T. Atomssa, C. Behnke, J. C. Berger-Chen, J. Biernat, A. Blanco, C. Blume, M. Böhmer, P. Bordalo, S. Chernenko,

- C. Deveaux, J. Dreyer, A. Dybczak, E. Epple, L. Fabbietti, O. Fateev, P. Fonte, C. Franco, J. Friese, I. Fröhlich, T. Galatyuk, J. A. Garzón, K. Gill, M. Golubeva, F. Guber, M. Gumberidze, S. Harabasz, T. Hennino, S. Hlavac, C. Höhne, R. Holzmann, A. Ierusalimov, A. Ivashkin, M. Jurkovic, B. Kämpfer, T. Karavicheva, B. Kardan, I. Koenig, W. Koenig, B. W. Kolb, G. Korcyl, G. Kornakov, R. Kotte, A. Krása, E. Krebs, H. Kuc, A. Kugler, T. Kunz, A. Kurepin, A. Kurilkin, P. Kurilkin, V. Ladygin, R. Lalik, K. Lapidus, A. Lebedev, L. Lopes, M. Lorenz, T. Mahmoud, L. Maier, S. Maurus, A. Mangiarotti, J. Markert, V. Metag, J. Michel, S. Morozov, C. Müntz, R. Münzer, L. Naumann, M. Palka, Y. Parpottas, V. Pechenov, O. Pechenova, V. Petousis, J. Pietraszko, W. Przygoda, S. Ramos, B. Ramstein, L. Rehnisch, A. Reshetin, A. Rost, A. Rustamov, A. Sadosky, P. Salabura, T. Scheib, K. Schmidt-Sommerfeld, H. Schuldes, P. Sellheim, J. Siebenson, L. Silva, Y. G. Sobolev, S. Spataro, H. Ströbele, J. Stroth, P. Strzempek, C. Sturm, O. Svoboda, A. Tarantola, K. Teilab, P. Tlusty, M. Traxler, H. Tsertos, T. Vasiliev, V. Wagner, C. Wendisch, J. Wirth, Y. Zanevsky, and P. Zumbach [HADES Collaboration Collaboration], “Inclusive Λ production in proton-proton collisions at 3.5 gev,” *Phys. Rev. C* **95** (Jan, 2017) 015207.
<https://link.aps.org/doi/10.1103/PhysRevC.95.015207>.
- [10] G. Agakishiev *et al.* [HADES Collaboration], “Baryonic resonances close to the $\bar{K}N$ threshold: the case of $\Lambda(1405)$ in pp collisions,” *Phys. Rev. C* **87** (2013) 025201, [arXiv:1208.0205](https://arxiv.org/abs/1208.0205) [nucl-ex].
- [11] G. Agakishiev *et al.*, “Production of $\Sigma^\pm \pi^\mp p K^+$ in p+p reactions at 3.5 GeV beam energy,” *Nucl. Phys. A* **881** (2012) 178–186, [arXiv:1202.2734](https://arxiv.org/abs/1202.2734) [nucl-ex].
- [12] G. Agakishiev, O. Arnold, D. Belver, A. Belyaev, J. C. Berger-Chen, A. Blanco, M. Böhmer, J. L. Boyard, P. Cabanelas, S. Chernenko, A. Dybczak, E. Epple, L. Fabbietti, O. Fateev, P. Finocchiaro, P. Fonte, J. Friese, I. Fröhlich, T. Galatyuk, J. A. Garzón, R. Gernhäuser, K. Göbel, M. Golubeva, D. González-Díaz, F. Guber, M. Gumberidze, T. Heinz, T. Hennino, R. Holzmann, A. Ierusalimov, I. Iori, A. Ivashkin, M. Jurkovic, B. Kämpfer, T. Karavicheva, I. Koenig, W. Koenig, B. W. Kolb, G. Kornakov, R. Kotte, A. Krása, F. Krizek, R. Krücken, H. Kuc, W. Kühn, A. Kugler, T. Kunz, A. Kurepin, V. Ladygin, R. Lalik, K. Lapidus, A. Lebedev, L. Lopes, M. Lorenz, L. Maier, A. Mangiarotti, J. Markert, V. Metag, J. Michel, C. Müntz, R. Münzer, L. Naumann, Y. C. Pachmayer, M. Palka, Y. Parpottas, V. Pechenov, O. Pechenova, J. Pietraszko, W. Przygoda, B. Ramstein, A. Reshetin, A. Rustamov, A. Sadosky, P. Salabura, A. Schmah, E. Schwab, J. Siebenson, Y. G. Sobolev, S. Spataro, B. Spruck, H. Ströbele, J. Stroth, C. Sturm, A. Tarantola, K. Teilab, P. Tlusty, M. Traxler, H. Tsertos, T. Vasiliev, V. Wagner, M. Weber, C. Wendisch, J. Wüstenfeld, S. Yurevich, Y. Zanevsky, and A. V. Sarantsev, “Partial wave analysis of the reaction $p(3.5 \text{ gev}) + p \rightarrow pK^+ \Lambda$ to search for the “ ppK^- ” bound state,” *Physics Letters B* **742** (1, 2015) .
- [13] G. Agakishiev, A. Balanda, D. Belver, A. Belyaev, A. Blanco, M. Boehmer, P. Cabanelas, E. Castro, J. Chen, S. Chernenko, T. Christ, M. Destefanis, F. Dohrmann, A. Dybczak, E. Epple, T. Eberl, L. Fabbietti, O. Fateev, and Y. Zanevsky, “Baryonic resonances close to the $kbar$ -n threshold: the case of $\sigma(1385)^+$ in pp collisions,” *Physical Review C* (09, 2011) .
- [14] J. Adamczewski-Musch, G. Agakishiev, O. Arnold, E. Atomssa, C. Behnke, J. Berger-Chen, J. Biernat, A. Blanco, C. Blume, M. Böhmer, P. Bordalo, S. Chernenko, C. Deveaux,

- A. Dybczak, E. Eppe, L. Fabbietti, O. Fateev, P. Fonte, C. Franco, J. Friese, I. Fröhlich, T. Galatyuk, J. Garzón, R. Gernhäuser, K. Gill, M. Golubeva, F. Guber, M. Gumberidze, S. Harabasz, T. Hennino, S. Hlavac, C. Höhne, R. Holzmann, A. Ierusalimov, A. Ivashkin, M. Jurkovic, B. Kämpfer, T. Karavicheva, B. Kardan, I. Koenig, W. Koenig, B. Kolb, G. Korcyl, G. Kornakov, R. Kotte, A. Krása, E. Krebs, H. Kuc, A. Kugler, T. Kunz, A. Kurepin, A. Kurilkin, P. Kurilkin, V. Ladygin, R. Lalik, K. Lapidus, A. Lebedev, L. Lopes, M. Lorenz, T. Mahmoud, L. Maier, S. Maurus, A. Mangiarotti, J. Markert, V. Metag, J. Michel, C. Müntz, R. Münzer, L. Naumann, M. Palka, Y. Parpottas, V. Pechenov, O. Pechenova, V. Petousis, J. Pietraszko, W. Przygoda, S. Ramos, B. Ramstein, L. Rehnisch, A. Reshetin, A. Rost, A. Rustamov, A. Sadovsky, P. Salabura, T. Scheib, K. Schmidt-Sommerfeld, H. Schuldes, P. Sellheim, J. Siebenson, L. Silva, Y. Sobolev, S. Spataro, H. Ströbele, J. Stroth, P. Strzempek, C. Sturm, O. Svoboda, A. Tarantola, K. Teilab, P. Tlusty, M. Traxler, H. Tsertos, T. Vasiliev, V. Wagner, C. Wendisch, J. Wirth, J. Wüstenfeld, Y. Zanevsky, and P. Zumbach, “ Σ^0 production in proton nucleus collisions near threshold,” *Physics Letters B* **781** (2018) 735 – 740. <http://www.sciencedirect.com/science/article/pii/S0370269318301539>.
- [15] J. Adamczewski-Musch *et al.* [HADES Collaboration], “The Λp interaction studied via femtoscopy in p + Nb reactions at $\sqrt{s_{NN}} = 3.18$ GeV,” *Phys. Rev. C* **94** no. 2, (2016) 025201, [arXiv:1602.08880](https://arxiv.org/abs/1602.08880) [nucl-ex].
- [16] O. Arnold, “Two-particle correlation measurements in p+nb reactions $\sqrt{s_{NN}} = 3.18$ GeV,” *Journal of Physics: Conference Series* **668** (Jan, 2016) 012037. <https://doi.org/10.1088%2F1742-6596%2F668%2F1%2F012037>.
- [17] G. Agakishiev, O. Arnold, A. Balanda, D. Beyer, A. Belyaev, J.-C. Berger-Chen, A. Blanco, M. Boehmer, P. Cabanelas, S. Chernenko, A. Dybczak, E. Eppe, L. Fabbietti, O. Fateev, P. Finocchiaro, P. Fonte, J. Friese, I. Fröhlich, and Y. Zanevsky, “Subthreshold Ξ^- production in collisions of p (3.5 gev) + nb,” *Physical review letters* **114** (01, 2015) .
- [18] R. Lalik, “A beam detector for pion experiments and analysis of the inclusive λ production in proton-proton reactions with hades,” PhD thesis (2016). https://www.das.ktas.ph.tum.de/DasDocs/Public/PhD_Theses/Rafal_Lalik_PhD_Thesis.pdf.
- [19] M. Tanabashi, P. Grp, K. Hagiwara, K. Hikasa, K. Nakamura, Y. Sumino, F. Takahashi, J. Tanaka, K. Agashe, G. Aielli, C. Amsler, M. Antonelli, D. Asner, H. Baer, S. Banerjee, R. Barnett, T. Basaglia, C. Bauer, and J. Beatty, “Review of particle physics: Particle data group,” *Physical Review D* **98** (08, 2018) .
- [20] E. M. Metodiev, B. Nachman, and J. Thaler, “Classification without labels: learning from mixed samples in high energy physics,” *Journal of High Energy Physics* **2017** no. 10, (Oct, 2017) . [http://dx.doi.org/10.1007/JHEP10\(2017\)174](http://dx.doi.org/10.1007/JHEP10(2017)174).
- [21] J. Neyman and E. S. Pearson, “On the problem of the most efficient tests of statistical hypotheses,” *Philosophical Transactions of the Royal Society of London* **231** (Feb, 1933) . <https://doi.org/10.1098/rsta.1933.0009>.

- [22] A. Hoecker, P. Speckmayer, J. Stelzer, J. Therhaag, E. von Toerne, H. Voss, M. Backes, T. Carli, O. Cohen, A. Christov, D. Dannheim, K. Danielowski, S. Henrot-Versille, M. Jachowski, K. Kraszewski, A. K. Jr., M. Kruk, Y. Mahalalel, R. Ospanov, X. Prudent, A. Robert, D. Schouten, F. Tegenfeldt, A. Voigt, K. Voss, M. Wolter, and A. Zemla, “Tmva - toolkit for multivariate data analysis,” (2007).
- [23] T. COSY-TOF Collaboration, M. Abdel-Bary, S. Abdel-Samad, K.-T. Brinkmann, H. Clement, J. Dietrich, E. Doroshkevich, S. Dshemuchadse, K. Ehrhardt, A. Erhardt, W. Eyrich, D. Filges, A. Filippi, H. Freiesleben, M. Fritsch, W. Gast, J. Georgi, A. Gillitzer, J. Gottwald, and P. Żuprański, “Production of λ^0 and σ^0 hyperons in proton-proton collisions,” *European Physical Journal A* **46** (10, 2010) 27–44.
- [24] G. Höhler, “Landolt-börnstein - group i elementary particles, nuclei and atoms,” 7–8. 01, 1983.
- [25] I. Zychor, M. Büscher, M. B. A. C, I. Keshelashvili, A. Khoukaz, V. F. V. G, Y. H, T. E, S. G, R. B, H. B, Y. Valdau, and C. I, “Lineshape of the $\lambda(1405)$ hyperon measured through its $\sigma^0 \pi^0$ decay,” *Physics Letters B* **660** (02, 2008) 167–171.
- [26] J. Adamczewski-Musch, O. Arnold, E. T. Atomssa, C. Behnke, A. Belounnas, A. Belyaev, J. C. Berger-Chen, J. Biernat, A. Blanco, C. Blume, M. Böhmer, P. Bordalo, S. Chernenko, L. Chlad, C. Deveau, J. Dreyer, A. Dybczak, E. Eppe, L. Fabbietti, O. Fateev, P. Filip, P. Finocchiaro, P. Fonte, C. Franco, J. Friese, I. Fröhlich, T. Galatyuk, J. A. Garzón, R. Gernhäuser, M. Golubeva, F. Guber, M. Gumberidze, S. Harabasz, T. Heinz, T. Hennino, S. Hlavac, C. Höhne, R. Holzmann, A. Ierusalimov, A. Ivashkin, B. Kämpfer, T. Karavicheva, B. Kardan, I. Koenig, W. Koenig, B. W. Kolb, G. Korcyl, G. Kornakov, R. Kotte, W. Kühn, A. Kugler, T. Kunz, A. Kurepin, A. Kurilkin, P. Kurilkin, V. Ladygin, R. Lalik, K. Lapidus, A. Lebedev, T. Liu, L. Lopes, M. Lorenz, T. Mahmoud, L. Maier, A. Mangiarotti, J. Markert, S. Maurus, V. Metag, J. Michel, E. Morinière, D. M. Mihaylov, S. Morozov, C. Müntz, R. Münzer, L. Naumann, K. Nowakowski, M. Palka, Y. Pappotas, V. Pechenov, O. Pechenova, V. Petousis, O. Petukhov, J. Pietraszko, W. Przygoda, S. Ramos, B. Ramstein, A. Reshetin, P. Rodriguez-Ramos, P. Rosier, A. Rost, A. Sadovsky, P. Salabura, T. Scheib, H. Schuldes, E. Schwab, F. Scozzi, F. Seck, P. Sellheim, J. Siebenson, L. Silva, Y. G. Sobolev, S. Spataro, H. Ströbele, J. Stroth, P. Strzempek, C. Sturm, O. Svoboda, P. Tlusty, M. Traxler, H. Tsertos, E. Usenko, V. Wagner, C. Wendisch, M. G. Wiebusch, J. Wirth, Y. Zanevsky, P. Zumbach, and A. V. Sarantsev [HADES Collaboration Collaboration], “ $\Delta(1232)$ Dalitz decay in proton-proton collisions at $T = 1.25$ GeV measured with HADES at GSI,” *Phys. Rev.* **C95** (6, 2017) 065205. <https://link.aps.org/doi/10.1103/PhysRevC.95.065205>.
- [27] S. Taylor, G. S. Mutchler, G. Adams, P. Ambrozewicz, E. Anciant, M. Anghinolfi, B. Asavapibhop, G. Asryan, G. Audit, H. Avakian, H. Bagdasaryan, J. P. Ball, S. Barrow, V. Batourine, M. Battaglieri, K. Beard, M. Bektasoglu, M. Bellis, N. Benmouna, B. L. Berman, N. Bianchi, A. S. Biselli, S. Boiarinov, B. E. Bonner, S. Bouchigny, R. Bradford, D. Branford, W. J. Briscoe, W. K. Brooks, S. Bültmann, V. D. Burkert, C. Butuceanu, J. R. Calarco, D. S. Carman, B. Carnahan, S. Chen, P. L. Cole, D. Cords, P. Corvisiero, D. Crabb, H. Crannell, J. P. Cummings, E. D. Sanctis, R. DeVita, P. V. Degtyarenko, H. Denizli, L. Dennis, A. Deur, K. V. Dharmawardane, C. Djalali, G. E. Dodge, D. Doughty,

- P. Dragovitsch, M. Dugger, S. Dytman, O. P. Dzyubak, H. Egiyan, K. S. Egiyan, L. Elouadrhiri, A. Empl, P. Eugenio, R. Fatemi, G. Feldman, R. G. Fersch, R. J. Feuerbach, T. A. Forest, H. Funsten, M. Garçon, G. Gavalian, G. P. Gilfoyle, K. L. Giovanetti, E. Golovatch, C. I. O. Gordon, R. W. Gothe, K. A. Griffioen, M. Guidal, M. Guillo, N. Guler, L. Guo, V. Gyurjyan, C. Hadjidakis, R. S. Hakobyan, J. Hardie, D. Heddle, F. W. Hersman, K. Hicks, I. Hleiqawi, M. Holtrop, J. Hu, M. Huertas, C. E. Hyde-Wright, Y. Ilieva, D. G. Ireland, M. M. Ito, D. Jenkins, K. Joo, H. G. Juengst, J. D. Kellie, M. Khandaker, K. Y. Kim, K. Kim, W. Kim, A. Klein, F. J. Klein, A. V. Klimenko, M. Klusman, M. Kossov, V. Koubarovski, L. H. Kramer, S. E. Kuhn, J. Kuhn, J. Lachniet, J. M. Laget, J. Langheinrich, D. Lawrence, T. Lee, J. Li, A. C. S. Lima, K. Livingston, K. Lukashin, J. J. Manak, C. Marchand, S. McAleer, J. W. C. McNabb, B. A. Mecking, J. J. Melone, M. D. Mestayer, C. A. Meyer, K. Mikhailov, M. Mirazita, R. Miskimen, V. Mokeev, L. Morand, S. A. Morrow, V. Muccifora, J. Mueller, J. Napolitano, R. Nasseripour, S. Niccolai, G. Niculescu, I. Niculescu, B. B. Niczyporuk, R. A. Niyazov, M. Nozar, G. V. O’Rielly, M. Osipenko, A. I. Ostrovidov, K. Park, E. Pasyuk, S. A. Philips, N. Pivnyuk, D. Pocanic, O. Pogorelko, E. Polli, S. Pozdniakov, B. M. Preedom, J. W. Price, Y. Prok, D. Protopopescu, L. M. Qin, B. S. Raue, G. Riccardi, G. Ricco, M. Ripani, B. G. Ritchie, F. Ronchetti, G. Rosner, P. Rossi, D. Rowntree, P. D. Rubin, F. Sabatié, C. Salgado, J. P. Santoro, V. Sapunenko, R. A. Schumacher, V. S. Serov, A. Shafi, Y. G. Sharabian, J. Shaw, S. Simionatto, A. V. Skabelin, E. S. Smith, L. C. Smith, D. I. Sober, M. Spraker, A. Stavinsky, S. Stepanyan, S. S. Stepanyan, B. E. Stokes, P. Stoler, I. I. Strakovsky, S. Strauch, R. Suleiman, M. Taiuti, D. J. Tedeschi, U. Thoma, R. Thompson, A. Tkabladze, L. Todor, C. Tur, M. Ungaro, M. F. Vineyard, A. V. Vlassov, K. Wang, L. B. Weinstein, H. Weller, D. P. Weygand, C. S. Whisnant, M. Williams, E. Wolin, M. H. Wood, A. Yegneswaran, J. Yun, and L. Zana [CLAS Collaboration Collaboration], “Radiative decays of the $\Sigma^0(1385)$ and $\Lambda(1520)$ hyperons,” *Phys. Rev.* **C71** (5, 2005) 054609. <https://link.aps.org/doi/10.1103/PhysRevC.71.054609>.
- [28] F. Scozzi, “Studying excited states of the nucleon with the hades detector at gsi,” PhD thesis, Technische Universitat Darmstadt, Darmstadt (2018).
- [29] I. Fröhlich *et al.*, “Pluto: A Monte Carlo Simulation Tool for Hadronic Physics,” *PoS ACAT* (2007) 076, [arXiv:0708.2382](https://arxiv.org/abs/0708.2382) [nucl-ex].
- [30] I. Frohlich *et al.*, “A versatile method for simulating $pp \rightarrow pp\,e^+e^-$ and $dp \rightarrow pn\,e^+e^-$ p(spec) reactions,” *Eur. Phys. J. A* **45** (2010) 401–411, [arXiv:0909.5373](https://arxiv.org/abs/0909.5373) [nucl-ex].
- [31] R. Brun, F. Bruyant, M. Maire, A. McPherson, and P. Zancarini, “GEANT3,”.