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Hyperons @ HADES

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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

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Chapter 1

Introduction

The history of a particle physics is a fascinating jurney towards the smallest, the most principle elements of the Universe. Starting from memorable Rutheford experiment in 1909 [1] up to Higss boson discovery [2, 3], and misterous states X,Y,Z [ref] oserved at the begining of XXIth century. Throughout this entire jurney there were many attemps to point out which particles are realy elementery, 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 baryions. Mesons have a baryonic number equal 0 and mostly consist of two quarks. However such an exotic object like glueball are also classyfied 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 baryions.

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 descripction, given by quantum chromodynamisc is very demanding in scpecific 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 avaliable in the system is below a J/ψ messon 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 irreduciable representation of a SU3 symmetry group

1.2 Form factors

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

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

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

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

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

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

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

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

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.

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

$$G_M = F_1 + \kappa F_2 \tag{1.6}$$

1.3 Dalitz decays

Chapter 2

The HADES detector

Chapter 3

Deta analysis

Chapter 4

Neural networks

4.1 Introduction into artificial neural networks

4.2 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, fulfiling 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 $h : \vec{x} \to \mathbb{R}$ 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 performence, how to compare different clasyfiers and how to choose proper working point have been discused since many years.

4.3 The data-driven approach

The original paper by Metodiev, Nachman and Thaler [6] the othors show the idea of a data-driven analysis in details. In this chapter I want to introduce main concepts, necessery to understand how the proposed metode helps in week decays recosntruction.

In a classical approach to supervized machine learning, a model learns its properties usign sets of labeled data. Of courese 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 necond case the user fully rely on simulation. (opisz zagrożenia)

The data-data driven analysis avoids inconveniencees of two mentioned methodes. It requires neither labeling nor simulation. According to Neyman-Pearson lemma [7] the optimal clasyfier for two sets, A and B is a function given by a dencity ratio

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

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

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

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.

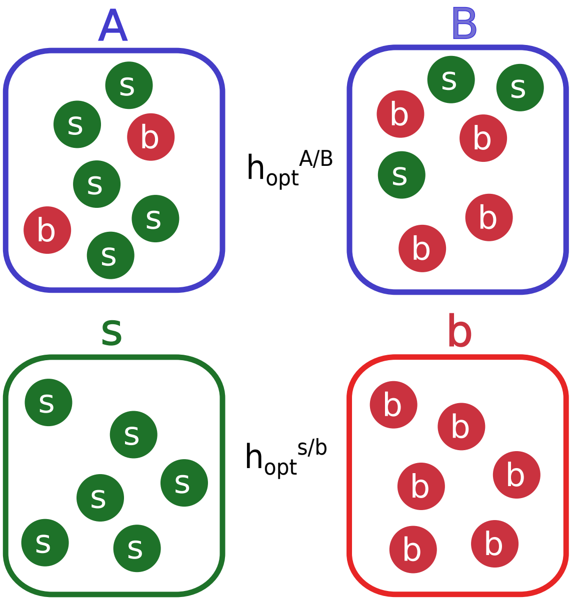

FIGURE 4.1: A data-driven approach visualisation. According to [6] the opitimal clasyfier for sets A and B is equivalent to optimal clasyfier for sets s and b.

4.4 Application for analysis

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@4.5GeV experiment is going to be pervormed. 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 $1GeV < \sqrt{S} < 6GeV$ an inclusive cross section for $\Lambda(1116)$ and $\Sigma(1193)$ were measured for many different enegys [8–10]. Also an inclusive cross section for $\Lambda(1405)$ production was measured for two different energys [11, 12], and for $\Lambda(1520)$ in known for one energy [8] in this range. In contrast to the exclusive production cross section , inclusive cross sections for hyperons' production are poorly known. Ferst step to perform a simulation was to estimate possible cross sections based on avaliable knowledge.

5.1.1 $\Lambda(1116)$ inclusive cross section

The first step for all estimations is a parametrization of a $\Lambda(1116)$ inclusive prodaction. In a given energy range there are four measured values. More over I made two additional assumptions i) the inclusive cross section is equal 0 for threshold enegy, ii) for energy below one pion mass (140MeV) the inclusive and the exclusive cross sections are the same. For the parametrization I can used cross section measured for $\mathrm{pp} \rightarrow \mathrm{pK}^{+}\Lambda(1116)$ for $\sqrt{S}$ below ??. To the all avaliable data points meeting my requirements I fitted a 3th order polynomial

$$\sigma_{\mathrm{pp}\rightarrow\Lambda(1116)X}(\sqrt{S}) = 48 \cdot (\sqrt{S} - 2.55) + 292.6 \cdot (\sqrt{S} - 2.55)^2 - 45.4 \cdot (\sqrt{S} - 2.55)^3. \quad (5.1)$$

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

5.1.2 $\Sigma(1193)$ inclusive cross section

According to PDG [13] almost all $\Sigma(1193)$s decay into $\Lambda(1116)$. I means that the inclususive $\Lambda(1116)$ signal contains a fraction deriving from $\Sigma(1193)$ decays. However knowing a relation between $\Lambda(1116)$ and $\Sigma(1193)$ it is possible to disantanle both contributions.

A $\Sigma(1193)/\Lambda(1116)$ ratio was measured by COSY and others [9]. Additionally the COSY collaboration proposed a parametrization of the ratio for eccess energy $\epsilon < 200MeV$. Above this energy ($\epsilon > 200MeV$) a linear parametziation

$$\frac{\Lambda(1116)}{\Sigma(1193)}(\epsilon) = 2.215 - 2.7 \cdot 10^{-5}\epsilon \tag{5.2}$$

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

Knowing the $\Lambda(1116)/\Sigma(1193)$ I was able to disantagle a $\Lambda(1116)$ and $\Sigma(1193)$ production. Using determinated ratio and the $\Lambda(1116)$ production (let me call it P_1) parametrization given by eq. 5.1(called P_2) I created following set of equations,

$$P_1(\epsilon) = \frac{L(\epsilon)}{S(\epsilon)} = \frac{L(\sqrt{S} - \Lambda(1116)_{thr})}{S(\sqrt{S} - \Sigma(1193)_{thr})} = P_1(\sqrt{S}), \tag{5.3}$$

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

Where Σ represents the inclusive $\Sigma(1193)$ production cross section and Λ the Lz cross section accordingly. Solving the first equation and shifting an argument by $\Sigma(1385)_{thr}$ I obtained an equation,

$$\Sigma(\sqrt{S}) \cdot P_1(\sqrt{S} + \Sigma(1193)_{thr}) = \Lambda(\sqrt{S} - \Lambda(1116)_{thr} + \Sigma(1193)_{thr}). \tag{5.5}$$

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

$$\Lambda(\sqrt{S} - \Lambda(1116)_{thr} + \Sigma(1193)_{thr}) = P_1(\sqrt{S} + \Sigma(1193)_{thr}) \left(P_2(\sqrt{S}) - \Lambda(Sqs)\right). \tag{5.6}$$

Assuming that $\Lambda(\Lambda(1116)_{thr}) = 0$ and $\Sigma(\Sigma(1193)_{thr}) = 0$, the above equation can be solved with any given precision. For the purpuse of cross sections estimation a single step was set $\Delta M = \frac{\Sigma(1193)_{thr} - \Lambda(1116)_{thr}}{10}$, obtained decomposition is shown in 5.1 by dashed lines. A characteristic "kick" on

[8–12]

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

A knowledge about cross sections for Λ and Σ in function of $\sqrt{S}$ or energy over the freshold ϵ gives a possibility to estimate cross section for excided hyperon states. As a first approximation

I have assumed that a production matrix element for graound and excited states is the same. It means that only factor cases the difference in cross section ia avaliable energy over the treshold.

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

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

The results of this approximations are shown in ref. ??

A $\Lambda(1405)$ exclusive cross section was mesured for two different energys [ref], what allows to estimate the cross section more precise. The phenomenological parametrization uses additional factor 1/3

$$\sigma_{\Lambda(1405)X}(\Lambda^*_{thr} + \epsilon) = \frac{1}{3}\sigma_{\Lambda(1116)}(\Lambda_{thr} + \epsilon). \quad (5.9)$$

5.1.4 $\Xi^-(1322)$

5.2 Background channels selection

5.3 Simulations results

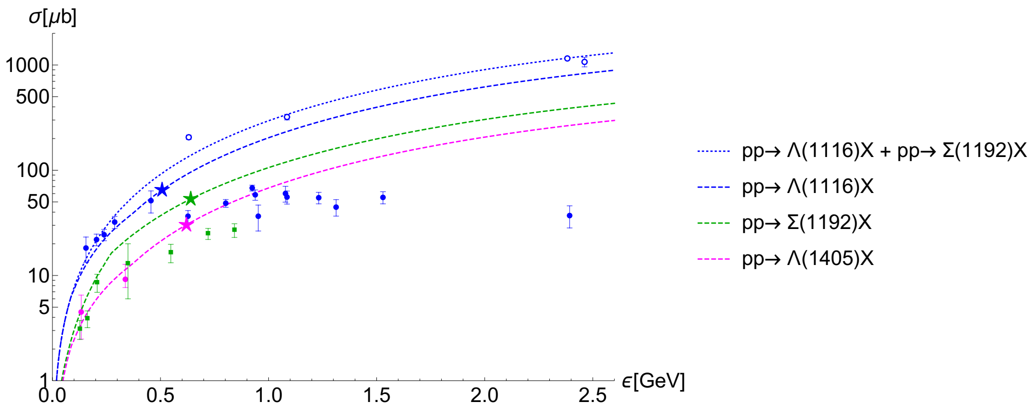

FIGURE 5.1: An estimeted cross sections for Hyperons production. Blue dotted line shows an inclusive $\Lambda(1116)$ producton. It was decomposed into dwo componets:i) $\Lambda(1116)$ - blue dashed line and ii) Sz green dashed line. Magenta dashed line reprezents a parametrization of $\Lambda(1405)$ cross section . All points refer to experimental data measured by different experiments . Color code is the same like for lines. Full points represent an exclusive cross section , empty points an inclusive one.

TABLE 5.1: List of signal (S) and background (B) channels for simulated benchmark reactions. Channels marked with * have estimated cross-sections, as described in Chapter ??. Each channel containing Δ Dalitz decay is listed below reference channel, used for cross section estimation.

Channel	σ (μb)	Type
$\Xi^-(1322)$ production		
$\mathrm{pK^+K^+\Xi^-(1322)}$	$3.6/0.35$	S*
$\mathrm{pp}\pi^+\pi^+\pi^-\pi^-$	600	B†
$\mathrm{p\Lambda(1116)K^0_S}\pi^+$	100	B†
$\mathrm{p\Lambda(1116)K^+}\pi^+\pi^-$	30	B†
$\mathrm{n\Lambda(1116)K^0_S}\pi^+\pi^+$	30	B†
$\mathrm{p\Sigma(1193)K^0_S}\pi^+$	20	B†
$\mathrm{ppK^0_SK^0_S}$	20	B†
background channels the same like for $\Xi^-(1322)$ plus below		
$\mathrm{ppK^+K^-}$	20	B†
Dalitz decays of hyperons		
$\mathrm{pK^+\Lambda(1405)[\Lambda(1116)e^+e^-]}$	69.6, BR = 8.4×10^{-5}	S*
$\mathrm{pK^+\Lambda(1520)[\Lambda(1116)e^+e^-]}$	32.2, BR = 5.3×10^{-6}	S*
$\mathrm{pK^+\Sigma(1385)[\Lambda(1116)e^+e^-]}$	56.24, BR = 1.1×10^{-4}	S*
$\mathrm{pK^+\Lambda(1405)}[X]$	69.6	B†
$\mathrm{pK^+\Lambda(1520)}[X]$	32.2	B†
$\mathrm{pK^+\Sigma(1385)}[X]$	56.24	B†
$\mathrm{pp}\pi^+\pi^-\pi^0$	1840	B
$\mathrm{p}\pi^+\pi^-\Delta^+\mathrm{[pe^+e^-]}$	2760, BR = 4.5×10^{-5}	B†
$\mathrm{pn}\pi^+\pi^+\pi^-\pi^0$	300	B†
$\mathrm{p}\pi^+\pi^+\pi^-\Delta^0[n\mathrm{e^+e^-}]$	450, BR = 4.5×10^{-5}	B†
$\mathrm{pp}\pi^+\pi^-\pi^0\pi^0$	300	B†
$\mathrm{p\Lambda(1116)K^+}\pi^0$	43	B†
$\mathrm{K^+\Lambda(1116)\Delta^+[pe^+e^-]}$	64, BR = 4.5×10^{-5}	B
$\mathrm{n\Lambda(1116)K^+}\pi^+\pi^0$	20	B†
$\pi^+\mathrm{K^+\Lambda(1116)\Delta^0[ne^+e^-]}$	30, BR = 4.5×10^{-5}	B
$\mathrm{p\Lambda(1116)K^+}\pi^0\pi^0$	10	B†
$\mathrm{p\Sigma(1193)K^0_S}\pi^+$	18	B†
$\mathrm{p\Lambda(1116)K^+}\pi^0\pi^0\pi^0$	7	B†
Real photon decays of hyperons		
$\mathrm{pK^+\Lambda(1405)[\Lambda(1116)}\gamma]$	69.6, BR = 1.3×10^{-2}	S*
$\mathrm{pK^+\Lambda(1520)[\Lambda(1116)}\gamma]$	32.2, BR = 5.0×10^{-4}	S*
$\mathrm{pK^+\Sigma(1385)[\Lambda(1116)}\gamma]$	56.24, BR = 1.1×10^{-2}	S*
$\mathrm{pp}\pi^+\pi^-\pi^0$	1840	B†
$\mathrm{p\Lambda(1116)K^+}$	54.5	B‡
$\mathrm{p\Lambda(1116)K^+}\pi^0$	35	B†
$\mathrm{p\Lambda(1116)K^+}\pi^+\pi^-$	20	B†
$\mathrm{p\Sigma(1193)K^+}$	23.5	B‡
$\mathrm{p\Sigma(1193)K^+}\pi^0$	20	B‡
$\mathrm{p\Sigma(1193)K^+}\pi^+\pi^-$	2	B‡

Chapter 6

Conclusions

Appendix A

The data-driven approach for a neural network training

The original paper by Metodiev, Nachman and Thaler [6] shows the idea of a data-driven analysis in details. In this chapter I want to introduce main concepts, necessery to understand how the proposed metode helps in week decays recosntruction.

In a classical approach to supervized machine learning, a model learns its properties usign sets of labeled data.

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