Simulation study of the $\bar{p}p \rightarrow \bar{\Sigma}^0\Lambda$ reaction with PANDA at FAIR

G. Perez-Andrade[1], Karin Schönning[1], WI Andersson[1],
Jenny Regina[1], Michael Papenbrock[1]
[1]Dept. of Physics and Astronomy, Uppsala University, Uppsala, Sweden
gabipa_28@hotmail.com

February 2019

Abstract

The PANDA experiment will be one of the pillars of the new Facility for Antiproton and Ion Research (FAIR), which is currently under construction in Darmstadt, Germany. PANDA will be a fixed-target experiment which will allow the study of non-perturbative phenomena of the strong interaction. These will be probed in antiproton-proton collisions in the momentum range of 1.5 - 15 GeV/c. Within the PANDA physics program, strangeness production will be addressed through $\bar{p}p \rightarrow \bar{Y}Y$ processes. Measurements of the $\bar{p}p \rightarrow \bar{\Sigma}^0\Lambda$ channel for its comparison with the existing data of the $\bar{\Lambda}\Lambda$ channel are highly encouraged to study the role of isospin symmetry in hadron production dynamics. This work consists on a simulation study focusing on the feasibility of measuring the $\bar{p}p \rightarrow \bar{\Sigma}^0\Lambda$ channel at PANDA.

Keywords: Hyperons, non-perturbative QCD, PANDA

1 Introduction

Within the Standard Model (SM), a coherent understanding of the strong interaction at low energies is still missing. This represents a challenge given the striking nature of the strong coupling α_s: while being weaker at small distances, it becomes stronger at large distances. In Figure 1, a summary of α_s predictions together with experimental measurements is displayed. A good agreement between theory and experiments is seen at large momentum transfers [1], and in this region perturbative Quantum Chromodynamics (pQCD) succeeds in describing α_s. However, as one goes down in energy α_s diverges and pQCD breaks down. The fact that different strategies have to be used to describe strong interactions at different energies calls for new investigations. One of the challenges are the different degrees of freedom that have to be taken into account at the different energy ranges: quarks and gluons are the relevant the degrees of freedom at high energies, whereas the hadrons are at low energies. At the intermediate energy scale it remains unclear which are the proper degrees of freedom to take into account. The lack of understanding of the strong interaction reflects in the poorly understood nucleons: their mass [2], spin [3], radius [4] and structure [5] are still unsolved puzzles. For instance, only about 2% of their mass is generated by the Higgs mechanism, while the rest is generated dynamically by the strong interaction. However, the exact mechanism is one of the open questions in modern physics.

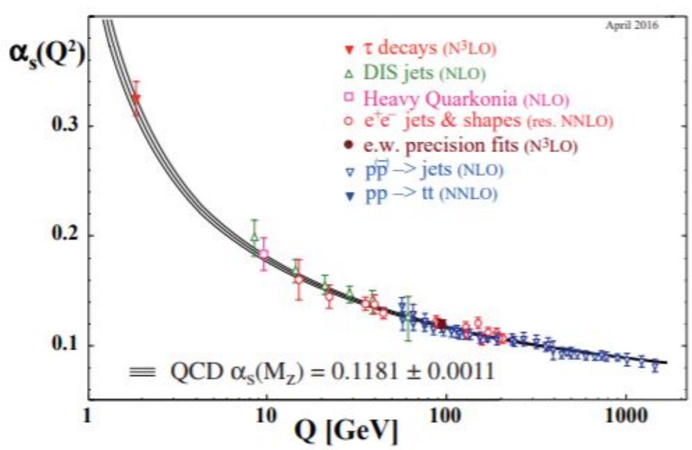

Figure 1: Summary of measurements of as a function of the respective energy scale Q. Image extracted from [1].

1.1 Hyperons

Hyperons (antihyperons), denoted as $Y(\bar{Y})$ are baryons which contain one or several $s(\bar{s})$ quarks, *e.g.* the Λ (uds) or $\bar{\Sigma}^0$ $(\bar{u}\bar{d}\bar{s})$. One of the main motivations of studying these particles is that their production is set by the mass of the s quark, m_s $\sim$ 100 MeV, which is close to the QCD cut-off or hadronization scale $\Lambda_{QCD} \sim 200$ MeV/c^2. Therefore, to study reactions containing strange hyperons at different energies, provide tools to address the question of how are quarks bounded into hadrons in the region where perturbative QCD is not valid anymore.

Hyperons have larger masses than the nucleons and are unstable. Except for the Σ^0 which decays electromagnetically, all other ground-state hyperons decay weakly. Weak decays are self-analyzing *i.e.* there is a parity violating part in the decay amplitude which causes the daughter particles to be emitted according to the initial hyperon spin vector. By measuring such asymmetry, the hyperon polarization can be reconstructed [6]. In processes such as $\bar{p}p \to \bar{Y}Y$ when the decay products of the hyperon are detected, one can in addition access to some spin correlations [7]. Spin observables such as the polarization are model dependent and therefore, constitute an important testing tool for theoretical models.

2 The $\bar{p}p \to \bar{\Sigma}^0\Lambda$ channel

Several reactions containing hyperons have been studied at previous experiments (Figure 2). From such measurements, the total and differential cross sections, polarization of outgoing hyperons and spin correlations have been obtained at several beam momenta. However the focus has remained on single-strange hyperon production *e.g.* the $\bar{p}p \to \bar{\Lambda}\Lambda$, at low energies.

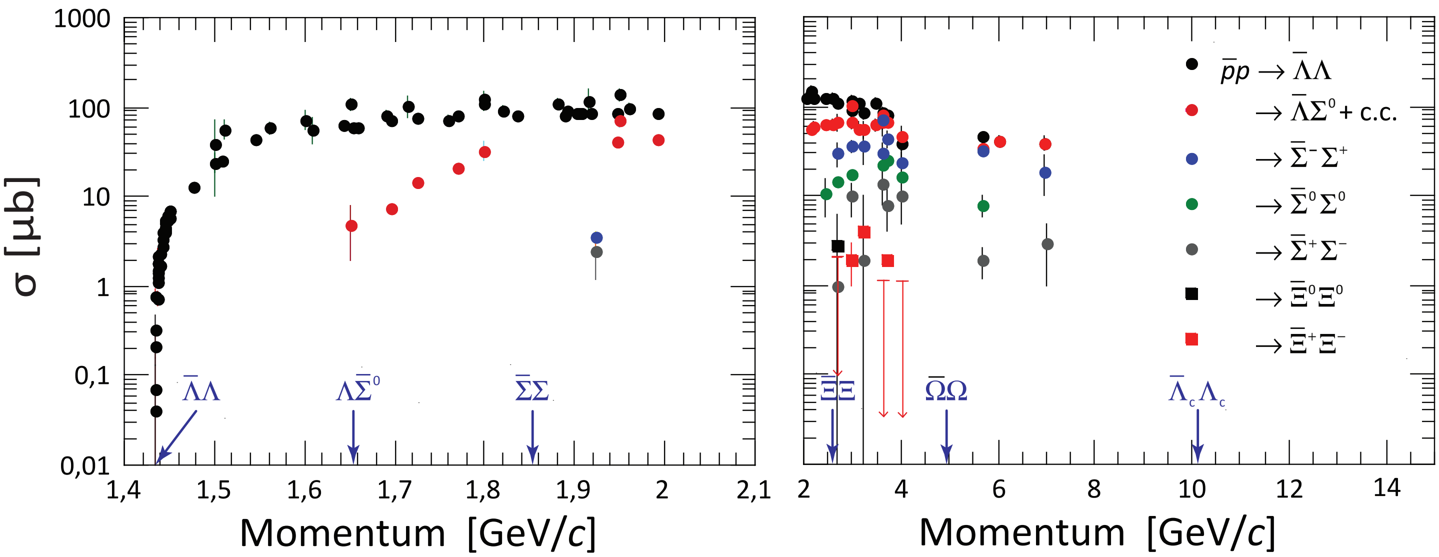

Figure 2: Hyperon production in $\bar{p}p$ annihilations [7]. Thresholds of various reactions are marked in blue.

The attempts of explaining strangeness production in $\bar{p}p \to \bar{Y}Y$ reactions have motivated the development of theoretical descriptions: i) a meson exchange model (MEX) [8], ii) a quark-gluon model (QG) [9] and iii) the combination of the two afore-mentioned approaches [10]. These models describe to some extent what has been observed in the experiments. However, fail to describe the complete spin dynamics, and there are few predictions and data about other hyperons different from Λ.

Providing information about hyperons such as the $\bar{\Sigma}^0$, could give important clues to the underlying physics of the strong interaction mechanism. For this reason, measurements of the $\bar{\Sigma}^0\Lambda$ reaction for its comparison with the existing $\bar{\Lambda}\Lambda$ data has been motivated. The similarities in quark content between Λ and Σ^0, lead to think that these reactions dynamics can be similar. On the other hand, the isospin and spin structure should be different in the two cases. For instance, predictions given by the MEX model establish that the strength of the coupling in the $\bar{\Sigma}^0$ case is stronger than the Λ case. While, the comparison between the channels in the QG picture provides information about the isospin dependence of the production mechanism.

From previous measurements reported by the PS185 collaboration at CERN, it was concluded that the angular distributions of both the $\bar{\Lambda}$ and the $\bar{\Sigma}^0$ in all measurements of the $\bar{p}p \to \bar{\Lambda}\Lambda$ and $\bar{p}p \to \bar{\Sigma}^0\Lambda + c.c.$ reactions respectively, show a forwardly peaked behavior and that the strength of the peak depends on the beam momentum [11],[12],[13]. The existing measurements of such reactions are limited to p_{beam} up to $\sim$ 6 GeV. At higher energies, the data bank is scarce. Therefore, if one wants to get more information about strangeness production and explore the multi-strange sector, more data are needed.

3 The PANDA experiment

The antiProton ANnihilations at DArmstadt (PANDA) experiment, is one of the pillars within the Facility for Antiproton and Ions Research (FAIR) currently under construction in Germany. The PANDA experiment has a broad physics program focused on strong interaction studies. At the first stage, strangeness production will be addressed through $\bar{p}p \to \bar{Y}Y$ processes [14]. With a *Target spectrometer* and a *Forward* Spectrometer, the PANDA detector will offer a nearly 4π-solid angle coverage. Each spectrometer will contain devices to perform tasks such as particle tracking and identification, vertex detection and calorimetry. The PANDA detector will be hosted within the High Energy Storage Ring (HESR) antiproton ring. At its first stage, the HESR will provide a luminosity of 10^{31} cm^{-2}s^{-1} until the design luminosity of 1.5×10^{32} cm^{-2}s^{-1} is achieved. As part of the PANDA experiment preparations, it is of major importance to understand such reactions and study their measurement feasibility. From some simulation studies so far completed for PANDA ([6],[15]), it has been concluded that it will be possible to start collecting large and clean samples of strange hyperons from the first phase of operation. Therefore, a high strange hyperon production rate is expected when the full luminosity is achieved.

4 Software tools

To perform the simulation studies, the *PandaRoot* framework is used. PandaRoot is based on ROOT [16] and Virtual MonteCarlo [17] for the detector implementation and simulation. It is specific for PANDA and has been developed to simulate the full experiment chain: from the particles generation in the $\bar{p}p$ annihilation, to the physics analysis. Several particle generators are included within PandaRoot. The most relevant for this particular study are EvtGen and Dual Parton Model (DPM) [18]. EvtGen is used to generate the signal events, including complex sequential decay channels taking into account known decay properties, such as angular distributions or polarization [14]. The DPM is a background generator in which all possible hadronic reactions are simulated at a given beam momentum and takes into account differential cross-sections parametrized from existing experimental data [19],[20]. After the event generation, the particles get transported through the PANDA detector material using GEANT [21]. Interactions such as multiple scattering and energy loss by *e.g.* ionization, [18] as well as effects from traversing magnetic fields are accounted for. After the transport, the detector responses to the particle passage are digitized. Different algorithms are used for the track reconstruction and the particle identification. These two tasks are carried out in two steps: first locally at each detector and then globally when all the single detector information are collected [22]. From the obtained information the physics analysis can be performed. With the current analysis tools implemented in PandaRoot, it is possible to obtain reconstruction efficiencies and rates for several channels containing hyperons. However, it is important to mention that PandaRoot is still under development.

5 Analysis

A previous simulation study of the reaction $\bar{p}p \to \bar{\Lambda}\Sigma^0 + c.c.$ was performed by Sophie Grape [6]. However, given that her simulations were using a Software framework based on the Babar experiment [23] and with isotropic distribution for the scattering angle of the $\bar{\Sigma}^0(\Sigma^0)$ as input, it called for an update. This work is currently under an internal review process, therefore a general explanation of the analysis strategy will be given without showing any result. Preliminary results are presented in [24].

In this work, two samples of 10k events of the reaction $\bar{p}p \to \bar{\Sigma}^0\Lambda$ were simulated: one at $p_{beam} = 1.771$ GeV/c and one at $p_{beam} = 6$ GeV/c. Both simulations were performed using a decay model based on the results obtained by the different experiments at CERN (Refs. [11] and [13]). The $\bar{\Sigma}^0$ baryon decays into a $\bar{\Lambda}$ almost at the interaction point ($\tau_{\bar{\Sigma}^0} \approx 7.4\times10^{-20}$s [1]). The $\bar{\Lambda}$ and Λ decay after traveling a few centimeters ($\tau_{\Lambda/\bar{\Lambda}} \approx 2.632\times10^{-10}$s [1]) and thus their decay products are the particles reaching the detectors. After the generation, five final state particles per event are expected:

$$\bar{p}p \to \bar{\Sigma}^0\Lambda \to \bar{\Lambda}\gamma p\pi^- \to \bar{p}\pi^+\gamma p\pi^- \quad (1)$$

However, after the generated particles are propagated through the detector material, more particles are created. These can be of the same or different particle species than the final state particles. The focus of this analysis is to test how well the $\bar{\Sigma}^0$ and Λ corresponding to the generated channel can be reconstructed and identified. This is achieved by selecting and combining their final state particles measured in the detectors. The analysis strategy is divided in a *pre-selection* and a *final selection* stage. At both stages, *kinematic fitting* procedures are used: these are statistical methods which improve the measurements of processes such as particle interaction or decay, by utilizing known information *e.g.* particle masses, energy and momentum conservation [25].

The pre-selection is divided in three steps: i) the final state particles identification, ii) a photon selection based on the reaction kinematics and iii) the $\bar{\Lambda}/\Lambda$ reconstruction through the combination of the charged candidates $p\pi^-/\bar{p}\pi^+$ respectively.

Since the main goal of the analysis is to obtain a sample where false particle candidates are as few as possible, two types of event selection methods were tested: *inclusive* or single-tag and *exclusive* or double-tag.

5.1 Inclusive selection

In this case, not all final state particles are detected and thus only one part of the system can be reconstructed. In this specific case, only the $\bar{p}\pi^{+}\gamma$ particles are detected and hence only the $\bar{\Sigma}^0$ can be directly reconstructed. The reaction is of the form $\bar{p}p \rightarrow \bar{\Sigma}^0 X$ where X denotes the undetected particle. The identity of X can be obtained from missing kinematics. Usually, a good efficiency is achieved with this type of selection since less particles have to be reconstructed and thus, the probability of not detecting them is lower. On the other hand, fewer kinematic constraints can be imposed, meaning that the background cannot be suppressed to the same extent as if the complete system was reconstructed.

5.2 Exclusive selection

In this case all five final state particles are reconstructed so the complete $\bar{\Sigma}^0\Lambda$ system can be reconstructed. As a consequence, more information is available and the kinematic properties given by the initial state, *i.e.* the $\bar{p}p$ system, constrain the final state. The latter can be used to improve the momentum or energy resolution of the reconstructed particles. The disadvantage in this type of event selection is that the probability of particles escaping the detector is higher and thus the reconstruction efficiency is usually lower than the case of inclusive selection. In addition, since the approach implies selection of a specific decay channel, the selected sample size is reduced with the corresponding branching fraction [24].

With this analysis strategy, signal and background reconstruction efficiencies for the $\bar{\Sigma}^0\Lambda$ channel were obtain at the two p_{beam} chosen, as well as their reconstruction rates **??**.

6 Summary

A complete model to explain the strong interaction at all relevant energy ranges is needed. Currently, there are many open questions about the principal characteristics of the nucleon. Reactions involving hyperons are a powerful tool probe the strong interaction at the intermediate energy region and therefore at the experiment we will seek to increase the database on hyperon reactions: exploring a wider range of p_{beam} and the multi-strange region. So far, various simulation studies have shown tht the PANDA experiment is very promising for the production of several hyperon channels from already the starting phase. An updated simulation study on the reconstruction feasibility of the $\bar{p}p \rightarrow \bar{\Sigma}^0\Lambda$ channel with a realistic angular distribution has been performed.

References

[1] M. Tanabashi *et al.* [Particle Data Group], *Review of Particle Physics*, Phys. Rev. D **98** (2018) no.3, 030001.

[2] S. Scherer and M. R. Schindler, *Quantum chromodynamics and chiral symmetry*, Lect. Notes Phys. **830** (2012) 1.

[3] C. A. Aidala *et al.*, *The Spin Structure of the Nucleon*, Rev. Mod. Phys. **85** (2013) 655

[4] S. Scherer, and M. R. Schindler, *Quantum chromodynamics and chiral symmetry. In A Primer for Chiral Perturbation Theory*, Springer, Berlin, Heidelberg. (2011) 1-48.

[5] R. Pohl, *et al.*, *The size of the proton*, Nature, **466**(7303), (2010) 213.

[6] Grape, S., *Studies of PWO Crystals and Simulations of the $\bar{p}p \rightarrow \bar{\Lambda}\Lambda, \bar{\Lambda}\Sigma^0$ Reactions for the Experiment.* PhD thesis, Uppsala University (2009).

[7] Johansson T, *AIP Conf. Proc. 8th Int. Conf. on Low Energy Antiproton Physics*, 95 (2003)

[8] F. Tabakin and R. A. Eisenstein, *Meson Exchange Calculation of the $\bar{p}p \rightarrow \bar{\Lambda}\Lambda$ Reaction*, Phys. Rev. C **31** (1985) 1857.

[9] H. R. Rubinstein and H. Snellman, *Dynamics of QCD in the Nonperturbative Low-energy Region*, Phys. Lett. B**165** (1985) 187.

[10] P. G. Ortega, D. R. Entem and F. Fernandez, *p anti-p —¿ Lambda anti-Lambda depolarization and spin transfer in a constituent quark model*, Phys. Lett. B **696** (2011) 352.

[11] P. D. Barnes *et al.*, *Measurement of the anti-p p —¿ anti-lambda Lambda and anti-p p —¿ Antisigma0 Lambda + c.c. reactions at 1.726-GeV/c and 1.771-GeV/c*, Phys. Rev. C **54** (1996) 2831.

[12] P. D. Barnes *et al.*, *Measurement of the Reaction $\bar{p}p \rightarrow \bar{l}$ambda Sigma0 + c.c. At 1.695-GeV/c*, Phys. Lett. B **246** (1990) 273.

[13] H. Becker *et al.* [CERN-Munich Collaboration], *Measurement of the Reactions $\bar{P}P \rightarrow \bar{\Lambda}\Lambda$, $\bar{p}p \rightarrow \bar{\Lambda}\Sigma^0$ and $\bar{P}P \rightarrow \bar{\Lambda}$ (Missing Mass) at 6-GeV*, Nucl. Phys. B **141** (1978) 48.

[14] M. F. M. Lutz *et al.* [PANDA Collaboration], *Physics Performance Report for PANDA: Strong Interaction Studies with Antiprotons*,

[15] I. Andersson, W., *Measurement of Spin Observables in the* $\bar{p}p \rightarrow \bar{\Lambda}\Lambda$ *reaction at* RN-NOP-2018-003 (2018)

[16] Brun, R. *et al*, *ROOT-an object oriented data analysis framework.* Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment *389*(1-2), (1997), 81-86

[17] Virtual Monte Carlo, https://root.cern.ch/root/vmc/

[18] S. Spataro [PANDA Collaboration], *The PandaRoot framework for simulation, reconstruction and analysis*, J. Phys. Conf. Ser. **331** (2011) 032031.

[19] K. Götzen, $\bar{p}p$ *Cross-section estimator* https://panda.gsi.de/pbarx/index.php?&mode=1 (2014)

[20] V. Flaminio *et al.*, *Compilation of cross-sections: p and p bar induced reactions* (1984) CERN/HERA 84-01

[21] M. Asai, *Geant4-a simulation toolkit*, Trans. Amer. Nucl. Soc. **95** (2006) 757.

[22] S. Spataro [PANDA Collaboration], *Simulation and event reconstruction inside the PandaRoot framework*, J. Phys. Conf. Ser. **119** (2008) 032035.

[23] Hamel de Monchenault, G., *The BaBar Computing Model.* Stanford Linear Accelerator Center, Menlo Park, CA (US), No. SLAC-PUB-9964 (2003).

[24] G. Pérez Andrade, *Production of the* $\bar{\Sigma}^0$ *hyperon in the PANDA experiment at FAIR*, Master thesis, Uppsala University (2019)

[25] P. Avery, *Applied Fitting Theory VI: Formulas for Kinematic Fitting.* CBX (1999) 98-37

[26] S. Spataro, *Event Reconstruction in the PandaRoot framework.* Journal of Physics: Conference Series. Vol. **396.** No. 2. IOP Publishing, (2012).