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

G. Perez-Andrade, Karin Schönning, W.I. Andersson, Jenny Regina and Michael Papenbrock on behalf of the PANDA Collaboration

Dept. of Physics and Astronomy, Uppsala University, Uppsala, Sweden
E-mail: gabipa28@hotmail.com

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 $\bar{p}p \rightarrow \bar{\Sigma}^0\Lambda$ 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.

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 $\alpha_s$: while being weaker at small distances, it becomes stronger at large distances. In Figure 1, a summary of $\alpha_s$ 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 $\alpha_s$. However, as one goes down in energy the strong coupling grows and pQCD predicts an unphysical divergent value for $\alpha_s$ [2].

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 [3], spin [4], radius [5] and structure [6] 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.
Hyperons (antihyperons), denoted as $Y(\bar{Y})$ are baryons which contain one or several $s(\bar{s})$ quarks, e.g. the $\Lambda (uds)$ or $\Sigma^0 (\bar{u}\bar{d}\bar{s})$. 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 $\Sigma^0$ 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 [7]. In processes such as $\bar{p}p \rightarrow \bar{Y}Y$ when the decay products of the hyperon are detected, one can in addition access to some spin correlations [8]. Spin observables such as the polarization are model dependent and therefore, constitute an important testing tool for theoretical models.

2. The $\bar{p}p \rightarrow \Sigma^0\Lambda$ 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 $\bar{p}p \rightarrow \bar{\Lambda}\Lambda$, at low energies.

The attempts of explaining strangeness production in $\bar{p}p \rightarrow YY$ reactions have motivated the development of theoretical descriptions: i) a meson exchange model (MEX) [9], ii) a quark-gluon model (QG) [10] and iii) the combination of the two afore-mentioned approaches [11]. 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 $\Lambda$.

Figure 1. Summary of measurements of $\alpha_s$ 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 $\Lambda (uds)$ or $\Sigma^0 (\bar{u}\bar{d}\bar{s})$. 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 $\Sigma^0$ 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 [7]. In processes such as $\bar{p}p \rightarrow \bar{Y}Y$ when the decay products of the hyperon are detected, one can in addition access to some spin correlations [8]. Spin observables such as the polarization are model dependent and therefore, constitute an important testing tool for theoretical models.
Figure 2. Hyperon production in $\bar{p}p$ annihilations [8]. Thresholds of various reactions are marked in blue.

Providing information about hyperons such as the $\Sigma^0$, 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 $\Lambda$ and $\Sigma^0$, 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 $\Lambda$ 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 $\bar{p}p \rightarrow \bar{\Lambda}\Lambda$ and $\bar{p}p \rightarrow \bar{\Sigma}^0\Lambda + \text{c.c.}$ reactions respectively, show a forwardly peaked behavior and that the strength of the peak depends on the beam momentum [12],[13],[14]. The existing measurements of such reactions are limited to $p_{\text{beam}}$ 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 $\bar{p}p \rightarrow \bar{\Lambda}\Lambda$ and $\bar{p}p \rightarrow \bar{\Sigma}^0\Lambda + \text{c.c.}$ processes [15].

With a Target spectrometer and a Forward Spectrometer, the PANDA detector will offer a nearly $4\pi$-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 $1.5 \times 10^{32}$ 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. For instance, a recent simulation study of double-strange excited $\Xi^*$ shows that it will be possible to start collecting large and clean exclusive samples from already the first phase of operation [16]. 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 [17] and Virtual MonteCarlo [18] 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) [19]. 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 [15]. 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 [20],[21]. After the event generation, the particles get transported through the PANDA detector material using GEANT [22]. Interactions such as multiple scattering and energy loss by e.g. ionization, [19] 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 [23]. 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 study of the reaction $\bar{p}p \rightarrow \Lambda\Sigma^0 + c.c.$ has been already performed for PANDA and it is shown in Ref. [7]. In the latter, a Software framework based on the Babar experiment [24] and an isotropic distribution for the scattering angle of the $\Sigma^0$ were used. Since the PandaRoot framework is now in an advanced stage of development, the reaction under study called for update. The present work is currently under an internal review process and therefore, a general explanation of the analysis strategy will be given without showing any result. Preliminary results are presented in [25].

In this work, two samples of 10k events of the reaction $\bar{p}p \rightarrow \Sigma^0\Lambda$ were simulated: one at $p_{beam} = 1.771$ GeV/c and one at $p_{beam} = 6$ GeV/c. These two beam momenta were chosen for easier comparison to previous measurements. Both simulations were performed using a decay model based on the results obtained by the different experiments at CERN (Refs. [12] and [14]). The $\Sigma^0$ baryon decays into a $\Lambda$ almost at the interaction point ($\tau_{\Sigma^0} \approx 7.4 \times 10^{-20}$s [1]). The $\Lambda$ and $\Lambda$ decay after traveling a few centimeters ($\tau_{\Lambda}/\bar{\Lambda} \approx 2.632 \times 10^{-10}$s [1]) and thus their decay products are the particles reaching the detectors. After the generation, five final state particles per event are expected:

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

However, after the generated particles are propagated through the detector material, a non-negligible background originates and must be considered. The latter can contain the same or different particle species than the final state particles. The focus of this analysis is to test how well the $\Sigma^0$ and $\Lambda$ 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 [26].
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 \( \Sigma^0 \) can be directly reconstructed. The reaction is of the form \( \bar{p} p \rightarrow \Sigma^0 X \) where \( X \) denotes the undetected particle. The identity of \( X \) can be obtained from missing kinematics. Since the capability to detect a limited number of particles per event is higher, usually the inclusive selection features a good efficiency. 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 considered, so the complete \( \Sigma^0 \Lambda \) 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 [25].

With this analysis strategy, signal and background reconstruction efficiencies for the \( \Sigma^0 \Lambda \) channel were obtained at the two \( p_{beam} \) chosen, as well as their reconstruction rates shown at [25].

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 PANDA 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 that 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 \( \bar{p} p \rightarrow \Sigma^0 \Lambda \) channel with a realistic angular distribution has been performed.

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