SIMULATION STUDY OF THE $\bar{p}p \to \Sigma^0 \Lambda$ REACTION AT PANDA AT FAIR

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ON BEHALF OF THE PANDA COLLABORATION

FORSCHUNZENTRUM JÜLICH
UPPSALA UNIVERSITY

HADRON 2019
OVERVIEW

• Introduction

• The PANDA experiment at FAIR

• Analysis strategy

• Results

• Conclusions
INTRODUCTION

Open question in QCD:

a comprehensive understanding of the strong interaction.

At high energies:
• $\alpha_s$ is weak
• pQCD is successful

At low and intermediate energies:
• $\alpha_s$ grows
• pQCD fails

To provide the effective degrees of freedom in the confinement domain is one of the challenges in modern physics
Non-perturbative QCD phenomena are connected to some of the **nucleons puzzles** *e.g.*:

- Mass
- Spin *
- Inner structure**

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* C. A. Aidala et al., RMP 85 (2013) 655-691.
Non-perturbative QCD phenomena are connected to some of the *nucleons puzzles* e.g.:

- Mass
- Spin *
- Inner structure**

To learn more about a system, one can ***:

- Excite it
- Scatter on it
- **Replace one of its building blocks:**

**HYPERONS**

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* C. A. Aidala et al., RMP 85 (2013) 655-691.
*** C. Granados et al., EPJA 53 (2017) 117

Figure extracted from *Hyperon Physics with PANDA at FAIR* Karin Schönnning, The 12th International Workshop on Excited Nucleons,
HYPERONS

- Strange hyperon production is governed by $m_s \sim 100\text{ MeV}$, probing confinement domain.
- Spin observables are experimentally accessible and distinguish between different production models.
- $\bar{p}p \rightarrow \bar{Y}Y$ production models:
  - Occur through different kinematic channels
  - Have different degrees of freedom

Which are the relevant degrees of freedom? What is the role of spin?
PREVIOUS $\bar{p}p \rightarrow \bar{Y}Y$ MEASUREMENTS

- Performed mainly at PS185 experiment at LEAR
- $\bar{p}p \rightarrow \Xi^+\Xi$ measurements were performed with bubble chambers
- Cross sections and spin observables obtained for mainly single-strange $\bar{p}p \rightarrow \bar{Y}Y$ channels
- Little data at $\bar{p}_{beam} > 4$ GeV/c
- No data on $\Omega$

**Figure.** Johansson T 2003 Proceedings of 8th Int. Conf. on Low Energy Antiproton Physics 95
THE $\bar{p}p \rightarrow \Sigma^0\Lambda$ CHANNEL

- Comparisons between channels containing isospin partners such as $\bar{p}p \rightarrow \Lambda\Lambda$, $\Sigma^0\Lambda$ and $\Sigma^0\Sigma$, provides information about the role of the isospin in strangeness production.

- Data from PS185 shows a strongly forward peaked differential cross section down to the reaction threshold*:

![Graph showing cross section parametrization for different energies](image)

*Figure. Cross section parametrization, $p_{\text{beam}} = 1.771$ GeV/c **


**H. Becker Nuclear Physics B141 (1978) 48-64
The High Energy Storage Ring (HESR)

• Anti-proton beam within $1.5 < p < 15$ GeV/c

• High resolution mode (Day One)
  \[ L \sim 10^{31}\text{cm}^{-2}\text{s}^{-1}, \text{dp/p} = 4 \times 10^{-5} \]

• High luminosity mode (Design)
  \[ L \sim 2 \times 10^{32}\text{cm}^{-2}\text{s}^{-1}, \text{dp/p} = 2 \times 10^{-4} \]
• Fixed target experiment.

• Target and Forward spectrometers for $4\pi$ coverage with:
  • PID
  • Tracking
  • Calorimetry
  • Muon detection

$p, pbar, Hi (from CR)$

$panda = \text{antiProton ANihilations at Darmstadt.}$
THE PANDA PHYSICS PROGRAM

- Nucleon structure
- Strangeness physics
- Charm and exotics
- Hadrons in nuclei

*Karin Schoenning talk at The 12th International Workshop on Excited Nucleons
FEASIBILITY STUDIES OF $\bar{p}p \rightarrow \bar{\Upsilon}\Upsilon$ RECONSTRUCTION AT PANDA

- Single and double strange channels (so far)
- Exclusive event reconstruction (so far)
- Ideal pattern recognition and PID
- Cross section distribution based on data for $\bar{\Lambda}\Lambda$, $\Sigma^0\Lambda$ and $\Xi\Xi$ at 4.6 GeV/c
- Model prediction for $\bar{p}p \rightarrow \Xi\Xi$ cross-section at 7 GeV/c

<table>
<thead>
<tr>
<th>$p_{\text{beam}}$</th>
<th>Reaction</th>
<th>$\sigma[\mu\text{b}]$</th>
<th>Efficiency (%)</th>
<th>$^2$Rate [min$^{-1}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.64</td>
<td>$^1\bar{p}p \rightarrow \bar{\Lambda}\Lambda$</td>
<td>64.0</td>
<td>16</td>
<td>600</td>
</tr>
<tr>
<td>1.77</td>
<td>$\bar{p}p \rightarrow \bar{\Sigma}^0\Lambda$</td>
<td>10.9</td>
<td>?</td>
<td>?</td>
</tr>
<tr>
<td>6.0</td>
<td>$\bar{p}p \rightarrow \bar{\Sigma}^0\Lambda$</td>
<td>20</td>
<td>?</td>
<td>?</td>
</tr>
<tr>
<td>4.6</td>
<td>$^1\bar{p}p \rightarrow \bar{\Xi}^+\Xi^-$</td>
<td>$\sim 1$</td>
<td>8.2</td>
<td>6.4</td>
</tr>
<tr>
<td>7</td>
<td>$^1\bar{p}p \rightarrow \bar{\Xi}^+\Xi^-$</td>
<td>$\sim 0.3$</td>
<td>7.9</td>
<td>2.0</td>
</tr>
</tbody>
</table>

1 W. Ikegami-Andersson (talk at FAIRNESS 2019)
2 At Day One Luminosity mode: $10^{31}\text{cm}^{-2}\text{s}^{-1}$
ANALYSIS STRATEGY: $\bar{p}p \rightarrow \bar{\Sigma}^0 \Lambda$

Two cases studied for $\bar{p}p \rightarrow \bar{\Sigma}^0 \Lambda$:
- 10k events at $p_{\text{beam}} = 1.771$ GeV/c
- 10k events at $p_{\text{beam}} = 6$ GeV/c

- **Pre-selection**
  - Final state particles identification
  - Photon energy selection
  - $\Lambda/\bar{\Lambda}$ reconstruction
    - Combine all $\pi^+ \bar{p} / \pi^- p$ respectively.
    - Kinematic fit on vertices
ANALYSIS STRATEGY: $\bar{p}p \rightarrow \Sigma^0 \Lambda$, $p_{beam} = 1.771$ GeV/c

- **Final selection**
  - Pre-selected $\bar{\Lambda}$ and $\gamma$ combined.
  - $\Sigma^0$ and $\Lambda$ candidates combined.
  - 4-C fit on all the $\Sigma^0 \Lambda$ pairs.
BACKGROUND GENERATION

- Generic hadronic background by DPM generator ($\bar{p}p \rightarrow$ anything).
- Independent $\Lambda\Lambda$ sample used as background.
- $\Sigma^0$ $\Lambda$ and $\bar{\Lambda}\Lambda$ channels were removed from DPM sample.
- Additional cut: $3\sigma$ around $m(\bar{\Lambda})$ and $m(\Sigma^0)$. 

![Graphs showing invariant mass distributions for $\Lambda$ and $\Sigma^0$ candidates with and without cuts.](image-url)
FINAL RESULTS, $p_{\text{beam}} = 1.771$ GeV/c

![Graphs showing $\Sigma^0$ and $\Lambda$ candidates invariant mass distributions with m$_{\Sigma^0}$ and m$_{\Lambda}$ cuts.]

**Figure**: Signal and background reconstruction. Simulation at $p_{\text{beam}} = 1.771$ GeV/c

<table>
<thead>
<tr>
<th>Channel</th>
<th>$\Sigma^0 \Lambda$</th>
<th>Combinatorial</th>
<th>DPM (90% C.L.)</th>
<th>$\bar{\Lambda}\Lambda$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total</td>
<td>526 ± 23</td>
<td>38</td>
<td>&lt;50.6</td>
<td>4</td>
</tr>
<tr>
<td>S/B</td>
<td>--------</td>
<td>14</td>
<td>&gt;11</td>
<td>120</td>
</tr>
<tr>
<td>$\varepsilon$ (%)</td>
<td>5.3 ± 0.2</td>
<td>0.38</td>
<td>&lt;5.1 ×10$^{-4}$</td>
<td>4.0×10$^{-5}$</td>
</tr>
</tbody>
</table>

**Table**: Final efficiencies for the signal and background samples at $p_{\text{beam}} = 1.771$ GeV/c
ANALYSIS STRATEGY, $p_{\text{beam}} = 6$ GeV/c

- Final selection
  - Pre-selected $\bar{\Lambda}$ and $\gamma$ combined
  - Cut in the photon energy boosted to its $\bar{\Sigma}^0$ rest frame.
  - $\bar{\Sigma}^0$ and $\Lambda$ candidates combined.
  - 4-C fit on all the $\bar{\Sigma}^0 \Lambda$ pairs

![Diagram showing reaction $pp \rightarrow \bar{\Sigma}^0 \Lambda \pi^+ \pi^-$]
BACKGROUND GENERATION

- DPM sample
- DPM sample filtered from all channels containing $\Lambda$ and $\bar{\Lambda}$ hyperons
- Additional cuts:
  - $3\sigma$ and $5\sigma$ around $m(\bar{\Lambda})$ and $5\sigma \, m(\Sigma^0)$ respectively
  - $\bar{\Lambda}$ decay vertex $> 6$ cm
**FINAL RESULTS, $p_{\text{beam}} = 6$ GeV/c**

**Figure**: Signal and background reconstruction. Simulation at $p_{\text{beam}} = 6$ GeV/c

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<tr>
<td>Total</td>
<td>614 ± 25</td>
<td>111</td>
<td>30</td>
<td>&lt; 18</td>
</tr>
<tr>
<td>S/B</td>
<td>--------</td>
<td>5.5</td>
<td>20.7</td>
<td>&gt; 34.7</td>
</tr>
<tr>
<td>$\varepsilon$(%)</td>
<td>6.1 ± 0.3</td>
<td>1.1</td>
<td>3.0 ×10^{-6}</td>
<td>&lt; 3.9 × 10^{-6}</td>
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**Table**: Final efficiencies for the signal and background samples at $p_{\text{beam}} = 6$ GeV/c
FEASIBILITY STUDIES OF $\bar{p}p \rightarrow \bar{Y}Y$ RECONSTRUCTION AT PANDA

- Single and double strange channels (so far)
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<td>10.9</td>
<td>5.3</td>
<td>32</td>
</tr>
<tr>
<td>6.0</td>
<td>$\bar{p}p \rightarrow \bar{\Sigma}^0\Lambda$</td>
<td>20</td>
<td>6.1</td>
<td>96</td>
</tr>
<tr>
<td>4.6</td>
<td>$\bar{p}p \rightarrow \bar{\Xi}^+\Xi^-$</td>
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1 W. Ikegami-Andersson (talk at FAIRNESS 2019)
2 At Day One Luminosity mode: $10^{31}$ cm$^{-2}$s$^{-1}$
CONCLUSIONS

- Hyperons studies can provide valuable information to complement our knowledge of the strong interaction.

- The PANDA experiment aims to increase the available data on single and multi-strange $\bar{p}p \rightarrow \bar{Y}Y$ processes.

- Feasibility studies of event reconstruction have been performed showing that high exclusive reconstruction efficiencies will be achievable at PANDA starting from Day One.
Thank you!
Back-up
Previous measurements: $\bar{p}p \rightarrow \Sigma^0 \Lambda$

The cross-section was parametrization in terms of the reduced four-momentum transfer

$$t' = 2pq(\cos \vartheta^* - 1)$$

$\vartheta^* = \text{c.m. scattering angle of the antihyperon}$

$p = \text{incoming } \bar{p} \text{ c.m. momentum}$

$q = \text{outgoing } \Sigma^0 \text{ c.m. momentum}$

*H. Becker Nuclear Physics B141 (1978) 48-64

Figure. Cross section parametrization, $p_{\text{beam}} = 1.771$ GeV/c *(top) and $p_{\text{beam}} = 6$ GeV/c (bottom)**
Why hyperons?

- Strange hyperon production is governed by $m_s \sim 100$ MeV, probing confinement domain.
- Spin observables are model dependent and experimentally accessible e.g. polarization:

All ground state hyperons ($Y$) decay weakly* $\rightarrow$ Parity is violated. Consider:

$$Y \left( \frac{1}{2} \right) \rightarrow B \left( \frac{1}{2} \right) + M(0)$$

- Decay angular distribution given by

$$I(\cos \theta_B) \propto (1 + \alpha P_Y \cos \theta_B)$$

- Where:
  - $\alpha$: Asymmetry parameter (known)
  - $\cos \theta_B$: Baryon emission angle (measured)
  - $P_Y$: Hyperon polarization (extracted!)

*Except for the $\Sigma^0$, which decays electromagnetically
Exclusive event selection

\[ p_{\text{beam}} = 6 \text{ GeV/c} \]

- Pre-selected \( \bar{\Lambda} \) and \( \Upsilon \) combined.
- Cut in the photon energy boosted to its \( \bar{\Sigma}^0 \) rest frame.
- \( \bar{\Sigma}^0 \) and \( \Lambda \) candidates combined.
- 4-C fit on all the \( \bar{\Sigma}^0 \) \( \Lambda \) pairs,
- Reject \( p < 0.01 \).
- Best pair selection according to \( \chi^2 \) value.
Figure 4.18: Probability distribution corresponding to the vertex fit performed on the (a) $\Lambda$ and (b) $\bar{\Lambda}$ respectively. Beam momenta $p_{beam} = 1.771$ GeV/c.
Figure 4.20: Probability distribution corresponding to the vertex fit performed on the (a) $\Lambda$ and (b) $\bar{\Lambda}$ respectively. Beam momenta $p_{\text{beam}} = 6$ GeV/c.
<table>
<thead>
<tr>
<th>Channel</th>
<th>$\hat{\Sigma}^0\Lambda$</th>
<th>DPM</th>
<th>$\bar{\Lambda}\Lambda$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size</td>
<td>$10^4$</td>
<td>$10^7$</td>
<td>$10^5$</td>
</tr>
<tr>
<td>$\sigma[\mu b]$</td>
<td>11</td>
<td>95,000</td>
<td>80</td>
</tr>
<tr>
<td>$w$</td>
<td>1</td>
<td>22</td>
<td>0.73</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Channel</th>
<th>$\hat{\Sigma}^0\Lambda$</th>
<th>DPM</th>
<th>DPM filtered</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size</td>
<td>$10^4$</td>
<td>$10^7$</td>
<td>$9 \times 10^6$</td>
</tr>
<tr>
<td>$\sigma[\mu b]$</td>
<td>20.0</td>
<td>59,000</td>
<td>57,690</td>
</tr>
<tr>
<td>$w$</td>
<td>1</td>
<td>7.4</td>
<td>7.7</td>
</tr>
</tbody>
</table>

$$
\epsilon = \frac{N_{\text{reconstructed}}}{N_{\text{simulated}}} \times 100\%
$$

$$
\bar{w}_{\text{anything}} = \frac{N_{\text{signal}}}{N_{\text{anything}}} \frac{\sigma(\bar{p}p \to \text{anything})}{\sigma(\bar{p}p \to \hat{\Sigma}^0\Lambda)BR(\hat{\Sigma}^0 \to \bar{\Lambda}\gamma)BR(\bar{\Lambda} \to \bar{p}\pi^+)^2}
$$

$$
\bar{w}_{\bar{\Lambda}\Lambda} = \frac{N_{\text{signal}}}{N_{\bar{\Lambda}\Lambda}} \frac{\sigma(\bar{p}p \to \bar{\Lambda}\Lambda)BR(\bar{\Lambda} \to \bar{p}\pi^+)^2}{\sigma(\bar{p}p \to \hat{\Sigma}^0\Lambda)BR(\hat{\Sigma}^0 \to \bar{\Lambda}\gamma)BR(\bar{\Lambda} \to \bar{p}\pi^+)^2}
$$

$$
\hat{N}_{\text{rec}} = \sigma(\bar{p}p \to \hat{\Sigma}^0\Lambda) \times BR(\hat{\Sigma}^0 \to \bar{\Lambda}\gamma) \times BR(\bar{\Lambda} \to \bar{p}\pi^-)^2 \times \mathcal{L} \times \epsilon
$$
<table>
<thead>
<tr>
<th>Device</th>
<th>Polar angle coverage</th>
</tr>
</thead>
<tbody>
<tr>
<td>MVD (Discs)</td>
<td>3° - 40°</td>
</tr>
<tr>
<td>MVD (Half-shells)</td>
<td>40° - 150°</td>
</tr>
<tr>
<td>STT</td>
<td>22° - 140°</td>
</tr>
<tr>
<td>GEM</td>
<td>0° - 22°</td>
</tr>
<tr>
<td>FT</td>
<td>0° - 10°</td>
</tr>
</tbody>
</table>

Table 4.4: Angular coverage of the principal tracking devices at the Target and Forward spectrometer at PANDA.

<table>
<thead>
<tr>
<th>Device</th>
<th>Polar angle coverage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Barrel DIRC</td>
<td>22° - 140°</td>
</tr>
<tr>
<td>Forward endcap DIRC</td>
<td>5° - 22°</td>
</tr>
<tr>
<td>Barrel TOF</td>
<td>22° - 140°</td>
</tr>
<tr>
<td>RICH</td>
<td>5° - 22°</td>
</tr>
</tbody>
</table>

Table 4.5: Angular coverage of the principal PID devices in the Target and Forward spectrometers at PANDA.

<table>
<thead>
<tr>
<th>Device</th>
<th>Polar angular coverage</th>
<th>Energy coverage (GeV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Backward</td>
<td>151.4° - 169.7°</td>
<td>0.01 - 0.7</td>
</tr>
<tr>
<td>Barrel</td>
<td>22° - 140°</td>
<td>0.01 - 7.3</td>
</tr>
<tr>
<td>Forward</td>
<td>5° - 23.6°</td>
<td>0.01 - 14.6</td>
</tr>
</tbody>
</table>

Table 4.6: Angular acceptance and energy ranges at which each part of the calorimeter are used as PID device.