New boundaries for the "ppK-" production in p+p collisions

Eliane Epple
for the HADES collaboration

Mo., 2.6.2014

- Introduction
- Data
- Hypothesis Tests
- Conclusions
Bound Objects
Bound Objects

Lambda Hypernuclei

Attractive ΛN interaction
Bound Objects

Lambda Hypernuclei

Attractive $\Lambda N$ interaction

Kaonic Nuclear Cluster

Attractive $\bar{K}N$ interaction
### The Smallest Cluster

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>charge</td>
<td>+1</td>
</tr>
<tr>
<td>strangeness</td>
<td>-1</td>
</tr>
<tr>
<td>participants</td>
<td>$ppK^-, pn\bar{K}^0$</td>
</tr>
<tr>
<td>$I_{NN}$</td>
<td>1</td>
</tr>
</tbody>
</table>

$N\bar{K}

Table 0.1: Selected $N^*$-resonances with their properties.
The Smallest Cluster

Table 1.3: The resulting wave function $\Psi$ for the different particle combinations of the two nucleons and one anti-kaon.

\[
\begin{array}{c}
\text{Property} & \text{Value} \\
\text{charge} & +1 \\
\text{strangeness} & -1 \\
\text{participants} & ppK^-, pn\bar{K}^0 \\
\text{$J^P$} & 0^- \\
\end{array}
\]

$\bar{K}NN$

\[
\begin{align*}
\rightarrow & \Sigma + N + \pi \} \Gamma_m \\
\rightarrow & \Lambda + N + \pi \} \Gamma_{nm} \\
\rightarrow & \Sigma + N \\
\rightarrow & \Lambda + N \\
\end{align*}
\]
The Smallest Cluster

- Chiral, energy dependent
  - BE: 17–23, 26–35, 16, 9–16, 32
  - $\Gamma_m$: 40–70, 50, 41, 34–46, 49
  - $\Gamma_{nm}$: 4–12, 30

- Non-chiral, static calculations
  - BE: 48, 50–70, 60–95, 40–80, 40
  - $\Gamma_m$: 61, 90–110, 45–80, 40–85, 64–86
  - $\Gamma_{nm}$: 12, ~20, ~21

Binding Energy (BE): 10-100 MeV
Mesonic Decay ($\Gamma_m$): 30-110 MeV
Non-Mesonic Decay ($\Gamma_{nm}$): 4-30 MeV
Is there a $\bar{K}NN$?

Hints?

$K^+\{(^6\text{Li},^7\text{Li},^{12}\text{C})\}$


$p+^4\text{He}$


$p+p$

Is there a $\bar{K}NN$?

**Hints?**

<table>
<thead>
<tr>
<th>$K^+$(6Li,7Li,12C)</th>
<th>$\bar{p}+^4$He</th>
<th>p+p</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Measured</th>
<th>acc. corr.</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_{ppK} = 2.267\text{ GeV/c}^2$</td>
<td>$\Gamma_{ppK} = 118\text{ MeV/c}^2$</td>
<td>$M_{ppK} = 2.255\text{ GeV/c}^2$</td>
</tr>
<tr>
<td>$B_{ppK} = 103\text{ MeV}$</td>
<td></td>
<td>$B_{ppK} = 115\text{ MeV}$</td>
</tr>
<tr>
<td>$\Gamma_{ppK} = &lt;24.4\text{ MeV/c}^2$</td>
<td></td>
<td>$\Gamma_{ppK} = 67\text{ MeV/c}^2$</td>
</tr>
</tbody>
</table>

Is there a $\overline{K}\Lambda N$?

Hints?

$K^{+}(^{6}\text{Li},^{7}\text{Li},^{12}\text{C})$

- Measured
- Acc. corr.


Exclusions

$\gamma + d \rightarrow X + K^+ + \pi^0$


0.5-5% of the cross section of typical hadron photo-production
The HADES experiment

High Acceptance Di-electron Spectrometer
GSI, Darmstadt

Accelerator
SIS18 at GSI
Colliding system
p+p at 3.5GeV

- Fixed-target experiment
- Full azimuthal coverage, 15° - 85° in polar angle
- Momentum resolution ≈ 1% - 5%
The Data
**Data Sample**

**HADES data**
- 13,000 events of pK⁺Λ
- Background from wrong PID ≈6%
- Background from pK⁺Σ⁰ ≈1%

**WALL data**
- 8000 events of pK⁺Λ
- Background from wrong PID ≈11.7%
- Background from pK⁺Σ⁰ ≈3%
A Model for the Process
What we included to model the PK⁺Λ process:

N* Resonances in the PDG with measured decay into K⁺Λ

N(1650), N(1710), N(1720), N(1875), N(1880), N(1895), N(1900)

Non-resonant PK⁺Λ production waves
Interferences
The best solution

included resonances:
N(1650), N(1710), N(1720), N(1900), N(1895)

Non-resonant waves:
(pL)(1S0) – K  (pL)(3S1) – K  (pL)(1P1) – K
(pL)(3P0) – K  (pL)(3P2) – K  (pL)(3P1) – K
(pL)(3D1) – K  (pL)(1D2) – K  (pL)(3D2) – K

HADES acceptance
WALL acceptance
Four Best PWA Solutions

Inside HADES acceptance

Measured data
PWA solutions

<table>
<thead>
<tr>
<th>Name</th>
<th>N* combination</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/8</td>
<td>N(1650), N(1710), N(1720), N(1900)</td>
</tr>
<tr>
<td>3/8</td>
<td>N(1650), N(1710), N(1720), N(1880)</td>
</tr>
<tr>
<td>6/9</td>
<td>N(1650), N(1710), N(1720), N(1900), N(1895)</td>
</tr>
<tr>
<td>8/8</td>
<td>N(1650), N(1710), N(1720), N(1895), N(1880)</td>
</tr>
</tbody>
</table>
Four Best PWA Solutions

Inside HADES acceptance

mass of $\Lambda+p = 2053.96\text{ MeV}/c^2$

mass of $\Sigma^0+p = 2130.82\text{ MeV}/c^2$

mass of $p+p+K^- = 2370.22\text{ MeV}/c^2$
Four Best PWA Solutions

CM Angle

Measured Data
PWA solutions
Inside HADES acceptance

E. Epple
MESON 2014 - Kraków
Phase Space Model

Inside HADES acceptance

CM Angle

Jackson Angle

Helicity Angle

Figure 4.8: Angular correlations of the three particles for the HADES data set (black points) shown with phase space simulations of $pK^+\Lambda$ (blue dots). The upper index at the angle indicates the rest frame (RF) in which the angle is investigated. The lower index names the two particles between which the angle is evaluated. CM stands for the center of mass system. B and T denotes the beam and target vector, respectively.
Test of the Null Hypothesis
Test of the Null Hypothesis

\[ \chi^2_P = \frac{(m - \lambda)^2}{\lambda} \]

\[ p-value = \int_{\chi^2_{P,d}}^{\infty} P(\chi^2, Ndf) d\chi^2 \]

\( m_i \) measured events in bin \( i \)

\( \lambda_i \) expected events in bin \( i \) according to the model
Test of the Null Hypothesis

Figure 2.1: The upper figures compare the four best PWA solutions of a fit to both data sets HADES and WALL. Shown is the invariant mass of $p\Lambda$ of the HADES data set compared to the solutions. The lower figures contain the local $p_0$ distributions for the four PWA solutions compared to the measured data.

Figure 2.2: The range of p-values from the four best solutions is displayed here as a gray band.

Figure 2.3: The figure shows the local $p_0$ distribution for a combined analysis of HADES and WALL data. The differences between the four best solutions are summarized by a gray band.

Is There a New Signal? - A Statistical Analysis

Combined result
Test of the Null Hypothesis

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We found no new signal in the data.

$\sigma$
Test of the Signal Hypothesis
Inclusion of a new State

Data Points
Null Hypothesis
Hypothesis with ppK-

E. Epple
Feature of a PWA...

... Interferences

The minimum has to be found by the fit
Upper limit at CL$_s$ 95%

These waves are included into the four best solutions of the PWA

\[ ^{2S+1}L_J \]

WaveA: ‘p + p’ $^1S_0 \rightarrow \ 'ppK(2250) − K'$ $^1S_0$

WaveB: ‘p + p’ $^3P_1 \rightarrow \ 'ppK(2250) − K'$ $^1P_1$

WaveC: ‘p + p’ $^1D_2 \rightarrow \ 'ppK(2250) − K'$ $^1D_2$

Scanned masses:
2220 – 2370 MeV/c$^2$ (in steps of 10 MeV/c$^2$)

Scanned widths:
30 MeV, 50 MeV, and 70 MeV
Upper Limit

Figure 2.9: The upper accepted percentage of total cross section at a CL limit of 95%. The three figures show the limit for all three transition amplitudes. The different colors represent the upper limit for the four best solutions. This is obtained from the HADES dataset for a simulated width of 50 MeV/c².

Figure 2.10: The upper accepted percentage of total cross section at a CL limit of 95%. The three figures show the limit for all three transition amplitudes. The different colors represent the upper limit for the four best solutions. This is obtained from the HADES dataset for a simulated width of 30 MeV/c².

Γ(ppK⁻)=50 MeV
Upper Limit

\[ \Gamma(pp^-) = 50 \text{ MeV} \]
Upper Limit

$\Gamma(ppK^-)=50 \text{ MeV}$
Upper Limit

\[ \Gamma(pp^-) = 50 \text{ MeV} \]

Mass:
2310 MeV/c\(^2\)
Upper Limit

\[ \Gamma(ppK^-) = 50 \text{ MeV} \]

Figure 2.9: The upper accepted percentage of total cross section at a CLs limit of 95%. The three figures show the limit for all three transition amplitudes. The different colors represent the upper limit for the four best solutions. This is obtained from the HADES dataset for a simulated width of 50 MeV/c^2.

Figure 2.10: The upper accepted percentage of total cross section at a CLs limit of 95%. The three figures show the limit for all three transition amplitudes. The different colors represent the upper limit for the four best solutions. This is obtained from the HADES dataset for a simulated width of 30 MeV/c^2.

\[ \Gamma(ppK^-) = 50 \text{ MeV} \]
Upper Limit

Exclusion of a ‘ppK’ at a sensitivity level of 95% (CL$_s$)
This means in 95% of the experiments we would be sensitive to a kaonic cluster of that strength

$$\sigma_{pK^+\Lambda} = 38.12 \pm 0.43^{+3.55}_{-2.83} \pm 2.67(p+p\text{-error})-2.9(\text{background}) \ \mu\text{b}. $$

$\rightarrow 12\% \approx 4\mu\text{b}$
Summary and Outlook

First PWA of pK⁺Λ production with Bonn-Gatchina-PWA
First coherent description of a “ppK⁻” production

The PWA fit yields an excellent description of the data
→ no new signal needed

The Upper limit for a broad KNN is in the order of <12% (Γ = 70 MeV) of the total pK⁺Λ cross section ≈ 4 μb

Outlook:
More experimental data at J-Parc, KLOE, LEPS and BELLEII coming up
A combined PWA of several pK⁺Λ data is currently prepared
(different energies, Experiments, polarization)

DFG Proposal: "Partialwellenanalyse von Ereignissen in Proton-Proton Reaktionen für Energien zwischen 1.9 und 3.5 GeV." FA 898/2-1
Thanks to the HADES Collaboration

Backup
References for the Calculations


[RS14] J. Revai and N.V. Shevchenko. Faddeev calculations of the $\bar{K}NN$ system with chirally-motivated $\bar{K}N$ interaction. II. The $K^-pp$ quasi-bound state. 2014.


N* resonances

Figure 6.10: a) IM$_{K^+\Lambda}$, b) IM$_{p\Lambda}$, c) MM$_{K^+}$ and d) MM$_{\Lambda}$ fitted with the sum of the four N*-resonances from table 6.2 and the simulation of a direct $pK^+\Lambda$ production.

Master Thesis A. Solaguren-Beascoa Negre
Bonn-Gatchina PWA

Cross Section for the production of three particles out of a collision of two particles

\[ d\sigma = \frac{(2\pi)^4|A|^2}{4|k|\sqrt{s}} \ d\Phi_3(P, q_1, q_2, q_3), \quad P = k_1 + k_2 \]

A - reaction amplitude
\( k \) – 3-momentum of the initial particle in the CM
\( s = P^2 = (k_1 + k_2)^2 \)
\( d\Phi_3(P, q_1, q_2, q_3) \) – invariant three-particles phase space

The decomposition of the scattering amplitude into partial waves can be written as follows:

\[ A = \sum \alpha A_{tr}^\alpha(s)Q^{in}_{\mu_1...\mu_J}(S L J) A_{2b}^\alpha(i, S_2 L_2 J_2)(s_i) \times Q^{fin}_{\mu_1...\mu_J}(i, S_2 L_2 J_2 S' L' J). \quad (2) \]

\( S, L, J \) – spin, orbital mom. and total angular momentum of the pp system
\( S_2, L_2, J_2 \) – spin, orbital mom. and total angular momentum of the two particle system in fin. state
\( S', L' \) – spin, orbital mom. between the two particle system and the third particle with four mom. \( q_i \)
multiindex \( \alpha \) – possible combinations of the \( S, L, J, S_2, L_2, J_2, S', L' \) and \( i \)
\( A_{tr}^\alpha(s) \) - transition Amplitude
\( A_{2b}^\alpha(i, S_2 L_2 J_2) \) – rescattering process in the final two-particle channel (e.g. production of \( \Delta \))

http://pwa.hiskp.uni-bonn.de/
A.V. Anisovich, V.V. Anisovich, E. Klempt, V.A. Nikonov and A.V. Sarantsev
Fitting Procedure

The transition Amplitude is parameterized as follows

$$A_{tr}^\alpha(s) = (a_1^\alpha + a_3^\alpha \sqrt{s}) e^{ia_2^\alpha}$$

This is a log-likelihood minimization on an event-by-event base

**What we included to model the PK⁺Λ process:**

N* Resonances in the PDG with measured decay into K⁺Λ

<table>
<thead>
<tr>
<th>Notation in PDG</th>
<th>Old notation</th>
<th>Mass [GeV/c²]</th>
<th>Width [GeV/c²]</th>
<th>$\Gamma_{KK}/\Gamma_{All}$</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>N(1650) 1/2⁻</td>
<td>N(1650)S₁₁</td>
<td>1.655</td>
<td>0.150</td>
<td>3-11</td>
<td></td>
</tr>
<tr>
<td>N(1710) 1/2⁻</td>
<td>N(1710)P₁₁</td>
<td>1.710</td>
<td>0.200</td>
<td>5-25</td>
<td></td>
</tr>
<tr>
<td>N(1720) 3/2⁺</td>
<td>N(1720)D₁₃</td>
<td>1.720</td>
<td>0.250</td>
<td>1-15</td>
<td></td>
</tr>
<tr>
<td>N(1875) 3/2⁻</td>
<td>N(1875)D₁₃</td>
<td>1.875</td>
<td>0.220</td>
<td>4±2</td>
<td></td>
</tr>
<tr>
<td>N(1880) 1/2⁺</td>
<td>N(1880)P₁₁</td>
<td>1.870</td>
<td>0.235</td>
<td>2±1</td>
<td></td>
</tr>
<tr>
<td>N(1895) 1/2⁻</td>
<td>N(1895)S₁₁</td>
<td>1.895</td>
<td>0.090</td>
<td>18±5</td>
<td></td>
</tr>
<tr>
<td>N(1900) 3/2⁺</td>
<td>N(1900)P₁₃</td>
<td>1.900</td>
<td>0.250</td>
<td>0-10</td>
<td></td>
</tr>
</tbody>
</table>

And the production of pK⁺Λ via non resonant waves
## Systematic

### N* content

<table>
<thead>
<tr>
<th>No.</th>
<th>Combination</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>N(1650), N(1710), N(1720)</td>
</tr>
<tr>
<td>1</td>
<td>N(1650), N(1710), N(1720), N(1900)</td>
</tr>
<tr>
<td>2</td>
<td>N(1650), N(1710), N(1720), N(1895)</td>
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<tr>
<td>3</td>
<td>N(1650), N(1710), N(1720), N(1880)</td>
</tr>
<tr>
<td>4</td>
<td>N(1650), N(1710), N(1720), N(1875)</td>
</tr>
<tr>
<td>5</td>
<td>N(1650), N(1710), N(1720), N(1900), N(1880)</td>
</tr>
<tr>
<td>6</td>
<td>N(1650), N(1710), N(1720), N(1900), N(1895)</td>
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<tr>
<td>7</td>
<td>N(1650), N(1710), N(1720), N(1900), N(1875)</td>
</tr>
<tr>
<td>8</td>
<td>N(1650), N(1710), N(1720), N(1895), N(1880)</td>
</tr>
<tr>
<td>9</td>
<td>N(1650), N(1710), N(1720), N(1895), N(1875)</td>
</tr>
<tr>
<td>10</td>
<td>N(1650), N(1710), N(1720), N(1880), N(1875)</td>
</tr>
</tbody>
</table>

### non-resonant content

<table>
<thead>
<tr>
<th>No.</th>
<th>Combination</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>no non-resonant waves</td>
</tr>
<tr>
<td>1</td>
<td>(pL)(1S₀) – K</td>
</tr>
<tr>
<td>2</td>
<td>previous wave + (pL)(3S₁) – K</td>
</tr>
<tr>
<td>3</td>
<td>previous waves + (pL)(1P₁) – K</td>
</tr>
<tr>
<td>4</td>
<td>previous waves + (pL)(3P₀) – K</td>
</tr>
<tr>
<td>5</td>
<td>previous waves + (pL)(3P₁) – K</td>
</tr>
<tr>
<td>6</td>
<td>previous waves + (pL)(3P₂) – K</td>
</tr>
<tr>
<td>7</td>
<td>previous waves + (pL)(3D₂) – K</td>
</tr>
<tr>
<td>8</td>
<td>previous waves + (pL)(3D₁) – K</td>
</tr>
<tr>
<td>9</td>
<td>previous waves + (pL)(3D₂) – K</td>
</tr>
</tbody>
</table>

### Table 4.3: Best solutions

<table>
<thead>
<tr>
<th>No. of N* combination</th>
<th>No. of non-res. waves</th>
<th>Log-likelihood</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>7</td>
<td>-2415.74</td>
</tr>
<tr>
<td>1</td>
<td>8</td>
<td><strong>-2708.49</strong></td>
</tr>
<tr>
<td>2</td>
<td>8</td>
<td>-2524.59</td>
</tr>
<tr>
<td>3</td>
<td>8</td>
<td><strong>-2712.49</strong></td>
</tr>
<tr>
<td>4</td>
<td>4</td>
<td>-2671.05</td>
</tr>
<tr>
<td>5</td>
<td>8</td>
<td>-2310.4</td>
</tr>
<tr>
<td>6</td>
<td>9</td>
<td><strong>-2754.37</strong></td>
</tr>
<tr>
<td>7</td>
<td>8</td>
<td>-2657.77</td>
</tr>
<tr>
<td>8</td>
<td>8</td>
<td><strong>-2734.97</strong></td>
</tr>
<tr>
<td>9</td>
<td>6</td>
<td>-2698.86</td>
</tr>
<tr>
<td>10</td>
<td>4</td>
<td>-2642.58</td>
</tr>
</tbody>
</table>

**Table 4.5:** Different versions of N* combinations in the PWA input.

**Table 4.6:** Different sets of non-resonant waves in the PWA input.

**Figure 4.16 and 4.17:** Exclusive Event Selection and Model Description.
Solution inside WALL acceptance

Figure 2.18: Two-particle masses for the HADES data set (black points) shown with the four best PWA solutions (gray band), obtained by a fit to the HADES and WALL data.

Figure 2.19: Two-particle masses for the WALL data set (black points) shown with the four best PWA solutions (gray band), obtained by a fit to the HADES and WALL data.
Solution inside WALL acceptance

Figure 2.21: Angular correlations of the three particles for the WALL data set (black points) shown with the four best PWA solutions (gray band), obtained by a fit to the HADES and WALL data.
Cross Check

Figure 4.14: Invariant masses of two particles for the three particles for the selected HADES data set (black points) shown with the best PWA solution (blue dots), obtained by a fit to the HADES data, excluding a $M_{p\Lambda}$ mass range of 2200-2300 MeV/c$^2$ (upper row) and excluding a $M_{p\Lambda}$ mass range of 2300-2400 MeV/c$^2$ (lower row).

The PWA fits also well to the selected data sample. These two solutions, obtained from the selected samples, can be drawn in the complete mass range as well. This way one can determine how much the fit changes its prediction for certain mass ranges when events with that range are excluded. Figure 4.15 shows the $M_{p\Lambda}$ for the three different solutions for the HADES and WALL data sets. Specifically, the upper right panel reveals that including mass ranges that could contain a small amount of signal seems not to be the fit. For the WALL data set, more differences between the three cases are visible. This is, however, not surprising as none of the WALL data were used for this test and the lower panels reveal, thus, the changes in the extrapolation.
Cross Check

Figure 4.15: Invariant Mass of $p\Lambda$ for the HADES data set (upper panels) and WALL data set (lower panels) (both black points), presented together with the best PWA solution (blue dots), fitted to the HADES statistic only. Compared to these results are the two cross checks, where once events were rejected from the fit with a mass range of 2200-2300 MeV/c$^2$ (violet points) and once within a mass range of 2300-2400 MeV/c$^2$ (green points). The left panels show the full mass range and the right panels show a zoom into the excluded mass regions.

Good consistency among the results. The solution is not biased by a possible signal in the excluded mass range.
Result

\[ \text{pull} = \sum_{i=1}^{N_b} \frac{(m_i - \lambda_i)}{\lambda_i} \]

- \( m_i \) are the number of measured events in the bin \( i \)
- \( \lambda_i \) number of expected events in the bin according to the model
- \( N_b \) is the number of bins
Test of the Null Hypothesis

$\chi^2_P = \frac{(m - \lambda)^2}{\lambda}$

$p$-value $= \int_{\chi^2_{P,d}}^{\infty} P(\chi^2, Ndf) d\chi^2$

$m_i$ measured events in bin $i$

$\lambda_i$ expected events in bin $i$

according to the model
$\chi^2_P = \frac{(m - \lambda)^2}{\lambda} \quad \Rightarrow \quad \chi^2_P = \sum_{i=1}^{N_b} \frac{(m_i - \lambda_i)^2}{\lambda_i}$

Combined result
Values are rejected in a test if \( CL_S \leq \alpha \).

\[
CL_S = \frac{p_\mu}{1 - p_0}.
\]

\( p_\mu \leq \alpha \cdot (1 - p_0). \)
Figure 6.12: The two columns show two Dalitz plots. Once for the measured data (Exp Acc), once for the data which were corrected for the losses of efficiency (Exp $4\pi$), and once for the PWA model No. 6/9 in $4\pi$ (Sim $4\pi$).
Cross Section

Figure 6.8: Acceptance functions of the two-particle masses for the four best PWA solutions of the PWA (different colors). Sol. No. 6/9 (green), Sol. No. 8/8 (cyan), Sol. No. 1/8 (blue) and Sol. No. 3/8 (red).

Events due to the decay of the $\Lambda$ into $p\pi^-$ (64%) is taken into account as the $4\pi$ distribution contains the full set of all $\Lambda$s.

To obtain the experimental distribution in $4\pi$ the experimental spectra inside the acceptance were divided by the corresponding acceptance function. This was done for each acceptance function of the four best PWA solutions. The single $4\pi$ spectra of all solutions and observables are shown in Appendix G.3.

The combined results are shown in Figures 6.10 and 6.9. The bine ntryc correction corresponds to the value obtained from the correction function of Sol. No. 6/9. The displayed errors account for the statistical error of the experimental data. The gray boxes show the systematic error of the acceptance correction. This error was obtained by the maximum deviation of any of the three other corrections to the one of sol. No. 6/9. As expected, the experimental data in $4\pi$ are consistent with the predictions of the PWA solution.

The CM distributions are symmetric with respect to the CM axes. The IM $K^+\Lambda$ shows the event distributions as predicted by the PWA. Single peaks due to $N^*$ resonances are not visible due to the large widths of the states. The small peak at around 1900 MeV/c$^2$, presenting some of the solutions, seems to appear also in the experimental data but is slightly shifted to lower masses.

The $K^{-}\Lambda$ helicity angle (panel i) Figure 6.9) shows a relatively flat behavior. Within the large spread of the data points it is consistent with the PWA model that predicts a slight modulation as a function of the angle. In Ref. [165,166] this observable was proposed to study the $p\Lambda$ final state interaction. As expressed by Eq. 6.9 the helicity angle is tightly correlated with the invariant mass of two particles. An angle of $\cos \theta = 1$ is related to small invariant masses.

Figure 6.10: Experimental distributions for the two-particle invariant masses corrected for acceptance and efficiency.

For the investigation of the kaonic nuclear bound state $KNN$, the invariant mass of $p$ and $\Lambda$ is the most relevant observable. The acceptance corrected spectrum of the IM $p\Lambda$ of Figure 6.10 shows a smooth increase of the measured yield with increasing mass of the system. There is no broad structure at $M=2267$ MeV/c$^2$ and $\Gamma = 118$ MeV/c$^2$ visible, as reported by the DISTO collaboration [125, 126].

Two bins stick out from the smooth trend of this observable. The near 2130 MeV/c$^2$ can be assigned to the $\Sigma N$-cusp, a well known phenomena in the invariant mass of $p\Lambda$. This behavior is assigned to a coupled channel of $\Sigma^-N \leftrightarrow \Lambda - p$ which opens at about 2130 MeV/c$^2$. To investigate at 2270 MeV/c$^2$ the four IM $p\Lambda$ spectra of Appendix G.3 are shown with a zoom into the relevant mass region. Figure 6.11 presents four times the IM $p\Lambda$ distribution each figure for acceptance and efficiency with another model.

Figure 6.11: IM $p\Lambda$ for the four different correction functions. Points show the experimental values and the lines the PWA-model that was used for the correction.
Figure 6.9: Experimental distributions of the three particle angular correlations, corrected for acceptance and efficiency. Insets show bins that are far out as compared to the other values. See Figure 2.6 for further explanations on the observables.

The final state interaction should be the strongest. In Ref. [155] an enhancement of statistics at very small $p_\Lambda$ opening angles was observed for $E_k = 2.16, 2.26, \text{ and } 2.4 \text{ GeV}$, respectively. This was interpreted as a result of final state interaction. The K- $\Lambda$ helicity angle at 3.5 GeV does not show such behavior at $\cos \theta = 1$. The reason for this is that at higher energies only a small portion of the phase space is influenced by final state interaction [166, 198]. Hence, these effects are less pronounced at the here investigated energy.

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Definition of Angles

I) CM Angle

II) Jackson Angle

III) Helicity Angle

\[ \theta_{CM}^{\Lambda} \]

\[ \theta_{CM}^{N} \]

\[ \theta_{RF, N(\Lambda) - K}^{K, P_t / P_t} \]

\[ \theta_{RF, N(\Lambda) - K}^{K, \Lambda(N)} \]
Is there a $\bar{K}NN$?

Hints?

$K^+({}^6\text{Li}, {}^7\text{Li}, {}^{12}\text{C})$

Measured: $M(pp\bar{K}) = 2.255 \text{ GeV}/c^2$
$B(pp\bar{K}) = 115 \text{ MeV}$
$\Gamma(pp\bar{K}) = 67 \text{ MeV}/c^2$

Acc. corr.: $M(pp\bar{K}) = 2.267 \text{ GeV}/c^2$
$B(pp\bar{K}) = 103 \text{ MeV}$
$\Gamma(pp\bar{K}) = 118 \text{ MeV}/c^2$

$^p_p + ^6\text{Li}, {}^7\text{Li}, {}^{12}\text{C}$


Is there a $\bar{K}NN$?

**Hints?**

$K^+ (^6\text{Li}, ^7\text{Li}, ^{12}\text{C})$


**Exclusions**

$\gamma + d \rightarrow X + K^+ + \pi$


0.5-5% of the cross section of typical hadron photo-production

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**Is there $\bar{K}NN?$**

**Hints?**

$K^+ (^6\text{Li}, ^7\text{Li}, ^{12}\text{C})$


**Exclusions**

$\gamma + d \rightarrow X + K^+ + \pi$


0.5-5% of the cross section of typical hadron photo-production