Properties of the $\Lambda(1405)$
Measured at CLAS

Kei Moriya (Indiana University)
advisor: Reinhard Schumacher
(Carnegie Mellon University)

May 19, 2011
Outline

1. **Introduction**
   - What is the $\Lambda(1405)$?
   - Chiral Unitary Theory of the $\Lambda(1405)$

2. **CLAS Analysis**
   - Introduction to JLab and CLAS
   - Decay Channels of Interest
   - $\Sigma^0(1385)$ and $K^*$ Background
   - Fit to Extract $\Lambda(1405)$ Lineshape

3. **Results**
   - $\Lambda(1405)$ Lineshape Results
   - $\Lambda(1405)$ Cross Section Results
   - $\Lambda(1520)$ Cross Section Results
   - Cross Section Comparison

4. **Conclusion**
What is the $\Lambda(1405)$?

- **** resonance just below $N\bar{K}$ threshold ($\sim 1435$ MeV)
- $I(J^P) = 0(1^-)$ [experimentally unconfirmed until now]
- Decays exclusively to $(\Sigma\pi)^0$
- Past experiments have found the line shape (= invariant $\Sigma\pi$ mass distribution) is distorted from a simple Breit-Wigner form

**Main Question:**

What is the nature of this distorted line shape?
The $\Lambda(1405)$ in Hadron Spectroscopy

<table>
<thead>
<tr>
<th>Mass (MeV)</th>
<th>$I = 0$</th>
<th>$I = 1$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1116</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1190</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1385</td>
<td>$\Lambda(1405)$</td>
<td>$\Sigma(1385)$</td>
</tr>
<tr>
<td>1405</td>
<td>$\Lambda(1405)$</td>
<td></td>
</tr>
<tr>
<td>1435</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1520</td>
<td>$\Lambda(1520)$</td>
<td></td>
</tr>
<tr>
<td>1670</td>
<td>$\Sigma(1670)$</td>
<td>$\Sigma(1660)$</td>
</tr>
</tbody>
</table>

The $\Lambda(1405)$ cannot decay to $N\bar{K}$.

$N\bar{K}$ threshold

May 2011
The $\Lambda(1405)$ in Hadron Spectroscopy

- **Strong $N\bar{K}$ attraction**
- $\Lambda(1405)$ cannot decay to $N\bar{K}$
- $\Sigma(1385)$
- $\Sigma(1670)$
- $\Sigma(1670)$
- $\Sigma(1660)$
- $\Sigma$ threshold
- $N\bar{K}$ threshold
- $I = 0$
- $I = 1$
The $\Lambda(1405)$ in Hadron Spectroscopy

- $\Lambda(1405)$
- $\Sigma(1385)$

Mass (MeV):
- 1116
- 1190
- 1405
- 1435
- 1520
- 1670

$I = 0$
$I = 1$

Strong $N\bar{K}$ attraction

Cannot decay to $N\bar{K}$

Strong dynamics due to $\Sigma\pi$ and $N\bar{K}$ interaction

$N\bar{K}$ threshold
The Lineshape of the $\Lambda(1405)$

• Several theories exist on the nature of the distorted lineshape

• **All** theories agree that there is a strong coupling between the
  - $\Sigma\pi$ channel (below $N\bar{K}$ threshold)
  - $N\bar{K}$ channel (above $N\bar{K}$ threshold)

• Various theories:
  - “normal” $qqq$-baryon resonance
    (the constituent quark model has difficulty with $\Lambda(1405)$ mass)
  - unstable bound state of $N\bar{K}$ (promoted by Dalitz and others)
  - deeply bound state of $N\bar{K}$
  - $qqqq\bar{q}$
  - **dynamically generated resonance** in
    unitary coupled channel approach
**Chiral Theory**

Effective chiral Lagrangian describes the interactions of the ground state baryons and mesons.


**Coupled Channels**

Exact unitarity is enforced amongst the coupled channels

- Many predictions on hadrons have been given by E. Oset and others
Chiral Unitary Coupled Channel Approach

dynamically generate $\Lambda(1405)$ based on chiral unitary model

\[ \gamma p \to K^+\pi \Sigma \]
\[ E_\gamma = 1.7 \text{ GeV} \]

Difference in Lineshape

\[ \frac{d\sigma(\pi^+\Sigma^-)}{dM_I} \propto \frac{1}{2} |T^{(1)}|^2 + \frac{1}{3} |T^{(0)}|^2 + \frac{2}{\sqrt{6}} \text{Re}(T^{(0)}T^{(1)*}) + O(T^{(2)}) \]

\[ \frac{d\sigma(\pi^-\Sigma^+)}{dM_I} \propto \frac{1}{2} |T^{(1)}|^2 + \frac{1}{3} |T^{(0)}|^2 - \frac{2}{\sqrt{6}} \text{Re}(T^{(0)}T^{(1)*}) + O(T^{(2)}) \]

\[ \frac{d\sigma(\pi^0\Sigma^0)}{dM_I} \propto \frac{1}{3} |T^{(0)}|^2 + O(T^{(2)}) \]

J. C. Nacher et al., Nucl. Phys. B455, 55

- Difference in lineshapes is due to interference of isospin terms in calculation ($T^{(1)}$ represents amplitude of isospin I term)
- Distortion of the lineshape is connected to underlying QCD amplitudes that generate the $\Lambda(1405)$
- This analysis will measure all three $\Sigma\pi$ channels
Summary of Current Experimental Status

- Data is sparse
- All experiments show a distortion from a Breit-Wigner
- more data is needed

Summary of Current Experimental Status

- Data is sparse
- All experiments show a distortion from a Breit-Wigner
- **more data is needed**
Summary of Current Experimental Status

- Data is sparse
- All experiments show a distortion from a Breit-Wigner
- more data is needed

Outline

1. Introduction
   - What is the $\Lambda(1405)$?
   - Chiral Unitary Theory of the $\Lambda(1405)$

2. CLAS Analysis
   - Introduction to JLab and CLAS
   - Decay Channels of Interest
   - $\Sigma^0(1385)$ and $K^*$ Background
   - Fit to Extract $\Lambda(1405)$ Lineshape

3. Results
   - $\Lambda(1405)$ Lineshape Results
   - $\Lambda(1405)$ Cross Section Results
   - $\Lambda(1520)$ Cross Section Results
   - Cross Section Comparison

4. Conclusion
JLab and CLAS

- Jefferson Lab (JLab) located in Newport News, VA
- CEBAF (Continuous Electron Beam Accelerator Facility) gives 2 ns timing electron beam up to 6 GeV
- Halls A, B, C (+ D: upcoming)
- Hall B = CLAS (CEBAF Large Acceptance Spectrometer) collaboration
• CLAS@Jefferson Lab
• liquid LH$_2$ target
• $\gamma + p \rightarrow K^+ + \Lambda(1405)$
• CLAS@Jefferson Lab
• liquid LH$_2$ target
• $\gamma + p \rightarrow K^+ + \Lambda(1405)$
• real unpolarized photon beam
• $E_\gamma < 3.84$ GeV
• $\sim 20$B total triggers
• CLAS@Jefferson Lab
• liquid LH$_2$ target
• $\gamma + p \rightarrow K^+ + \Lambda(1405)$
• real unpolarized photon beam
• $E_\gamma < 3.84$ GeV
• $\sim 20B$ total triggers
• measure charged particle
  ▶ $\vec{p}$ with drift chambers
Data From CLAS@JLab

- CLAS@Jefferson Lab
- liquid LH$_2$ target
- $\gamma + p \rightarrow K^+ + \Lambda(1405)$
- real unpolarized photon beam
- $E_\gamma < 3.84$ GeV
- $\sim 20B$ total triggers
- measure charged particle
  - $\vec{p}$ with drift chambers
  - timing with TOF walls

May 2011 12 / 24
**Reaction of Interest**

\[ \gamma + p \rightarrow K^+ + \Lambda(1405) \rightarrow K^+ + \Sigma + \pi \]

- Final state of interest is \( K^+, \Sigma, \pi \)
- \( \Sigma \pi \) resonances: \( \Sigma(1385), \Lambda(1405), \Lambda(1520) \)
- \( K^+ \pi \) resonance: \( K^* \) when \( \pi = \pi^+ \) or \( \pi^0 \)
- besides the \( K^+ \Sigma \pi \) state, we will also detect the \( K^+ \Lambda \pi \) state
  - Resonance of \( \Lambda \pi \) will be \( \Sigma(1385) \)
  - Resonance of \( K^+ \pi \) will be \( K^* \)
- Background channels:
  - \( \Sigma(1385) \) – close in mass, large width (\( \sim 35 \) MeV)
  - \( K^* \) – overlap in 3-body phase space plot of \( K^+, \Sigma, \pi \)
Background Channels

- $\Sigma^0(1385) \rightarrow \Sigma\pi$
  - $BR(\Lambda\pi^0) = 87\% \gg BR(\Sigma^{\pm}\pi^{\mp}) = 6\%$ each
    - $\Rightarrow$ measure in $\Lambda\pi^0$, scale down to each $\Sigma\pi$ channel
  - influence should be small due to branching ratio

- $K^*\Sigma$
  - broad width – will overlap with signal
  - subtract off incoherently

low energy bin
Background Channels

- $\Sigma^0(1385) \rightarrow \Sigma\pi$
  - $BR(\Lambda\pi^0) = 87\% \gg BR(\Sigma^{\pm}\pi^{\mp}) = 6\%$ each
  - $\Rightarrow$ measure in $\Lambda\pi^0$, scale down to each $\Sigma\pi$ channel
  - influence should be small due to branching ratio

- $K^*\Sigma$
  - broad width – will overlap with signal
  - subtract off incoherently

high energy bin
\( \Sigma(1385) \) is Fit in \( \Lambda\pi^0 \) Channel \( (\gamma + p \rightarrow K^+ + p + \pi^- + \pi^0) \)

- \( \Sigma(1385) \) is fit with templates of MC of
  - \( \Sigma(1385) \) (non-relativistic Breit-Wigner)
  - \( K^{*+} \Lambda \) MC
- very good fit results

Example:
1 energy and angle bin out of \( \sim 150 \)
$\Sigma(1385)$ is fit in $\Lambda\pi^0$ Channel ($\gamma + p \rightarrow K^+ + p + \pi^- + \pi^0$)

- $\Sigma(1385)$ is fit with templates of MC of
  - $\Sigma(1385)$ (non-relativistic Breit-Wigner)
  - $K^{*+}\Lambda$ MC
- very good fit results
$\Sigma(1385)$ is Fit in $\Lambda\pi^0$ Channel $(\gamma + p \rightarrow K^+ + p + \pi^- + \pi^0)$

- $\Sigma(1385)$ is fit with templates of MC of
  - $\Sigma(1385)$ (non-relativistic Breit-Wigner)
  - $K^{*+}\Lambda$ MC

very good fit results

example:
1 energy and angle bin out of $\sim 150$
\( \Sigma(1385) \) is Fit in \( \Lambda\pi^0 \) Channel \((\gamma + p \rightarrow K^+ + p + \pi^- + \pi^0)\)

- \( \Sigma(1385) \) is fit with templates of MC of
  - \( \Sigma(1385) \) (non-relativistic Breit-Wigner)
  - \( K^{*+} \Lambda \) MC
- very good fit results

\[
\begin{align*}
\text{Wbin: 2 anglebin: 17} \\
2.050 < W < 2.150 \\
0.700 < \cos \theta_{K^+}^{\text{CM}} < 0.800
\end{align*}
\]

data
\( \Sigma(1385) \) MC
\( K^{*+} \Lambda \) MC
sum of MC
\( \chi^2/\text{ndf}: 1.60 \)

example:
1 energy and angle bin out of \( \sim 150 \)
Fit to Lineshape With MC Templates

\[ \Sigma^+ \rightarrow p \pi^0 \]

Wbin: 3  anglebin: 17
2.150 <W< 2.250
0.700<\cos\theta_{K+}^\text{CM}<0.800
data

\begin{itemize}
  \item subtract off \( \Sigma(1385) \), \( \Lambda(1520) \), \( K^*0 \)
  \item assigned the remaining contribution to the \( \Lambda(1405) \)
\end{itemize}

example:
1 energy and angle bin out of \( \sim 150 \)
Fit to Lineshape With MC Templates

\[ \Sigma^+ \rightarrow p \pi^0 \]

- subtract off \( \Sigma(1385) \), \( \Lambda(1520) \), \( K^{*0} \)
- assigned the remaining contribution to the \( \Lambda(1405) \)

example:
1 energy and angle bin out of \( \sim 150 \)
Fit to Lineshape With MC Templates

\[ \Sigma^+ \rightarrow p \pi^0 \]

Example:
1 energy and angle bin out of \( \sim 150 \)

- subtract off \( \Sigma(1385), \Lambda(1520), K^*0 \)
- assigned the remaining contribution to the \( \Lambda(1405) \)
Fit to Lineshape With MC Templates

\[ \Sigma^+ \rightarrow p \pi^0 \]

- subtract off \( \Sigma(1385), \Lambda(1520), K^*0 \)
- assigned the remaining contribution to the \( \Lambda(1405) \)
Fit to Lineshape With MC Templates

\[ \Sigma^+ \rightarrow p \pi^0 \]

- subtract off $\Sigma(1385)$, $\Lambda(1520)$, $K^{*0}$
- assigned the remaining contribution to the $\Lambda(1405)$

example:
1 energy and angle bin out of $\sim 150$
**Fit to Lineshape With MC Templates**

\[ \Sigma^+ \rightarrow p \pi^0 \]

\[ \Sigma(1385) \text{ MC} \]
\[ \Lambda(1405) \text{ MC ver.1} \]
\[ \Lambda(1520) \text{ MC} \]
\[ K^{*0} \Sigma^+ \text{ sum of MC} \]

\[ \chi^2/\text{ndf}: 4.16 \]

- subtract off \( \Sigma(1385), \Lambda(1520), K^{*0} \)
- assigned the remaining contribution to the \( \Lambda(1405) \)

\[ \text{example: 1 energy and angle bin out of } \sim 150 \]
Fit to Lineshape With MC Templates

\[ \Sigma^+ \rightarrow p \pi^0 \]

\[ \Lambda(1405) \text{ MC ver.2} \]

\[ \Sigma(1385) \text{ MC} \]
\[ \Lambda(1520) \text{ MC} \]
\[ K^{*0} \Sigma^+ \]

sum of MC
\[ \chi^2/\text{ndf}: 2.09 \]

Wbin: 3 anglebin: 17
\[ 2.150 < W < 2.250 \]
\[ 0.700 < \cos \theta_{K^+}^{CM} < 0.800 \]

counts

example:
1 energy and angle bin out of \( \sim 150 \)

- subtract off \( \Sigma(1385) \), \( \Lambda(1520) \), \( K^{*0} \)
- assigned the remaining contribution to the \( \Lambda(1405) \)
Fit to Lineshape With MC Templates

\[
\Sigma^+ \rightarrow p \pi^0
\]

Wbin: 3  anglebin: 17
2.150 <W< 2.250
0.700 < \cos \theta_{K^+}^{CM} < 0.800
data
residual

example:
1 energy and angle bin out of \( \sim 150 \)

- subtract off \( \Sigma(1385), \Lambda(1520), K^{*0} \)
- assigned the remaining contribution to the \( \Lambda(1405) \)
1 Introduction
   - What is the $\Lambda(1405)$?
   - Chiral Unitary Theory of the $\Lambda(1405)$

2 CLAS Analysis
   - Introduction to JLab and CLAS
   - Decay Channels of Interest
   - $\Sigma^0(1385)$ and $K^*$ Background
   - Fit to Extract $\Lambda(1405)$ Lineshape

3 Results
   - $\Lambda(1405)$ Lineshape Results
   - $\Lambda(1405)$ Cross Section Results
   - $\Lambda(1520)$ Cross Section Results
   - Cross Section Comparison

4 Conclusion
Results of Lineshape

- Lineshapes do appear different for each $\Sigma\pi$ decay mode
- $\Sigma^+\pi^-$ decay mode has peak at highest mass, narrow than $\Sigma^-\pi^+$
- Lineshapes are summed over acceptance region of CLAS
- Difference is less prominent at higher energies
• lineshapes do appear different for each $\Sigma\pi$ decay mode
• $\Sigma^+\pi^-$ decay mode has peak at highest mass, narrow than $\Sigma^-\pi^+$
• lineshapes are summed over acceptance region of CLAS
• difference is less prominent at higher energies
Results of Lineshape

- Lineshapes do appear different for each $\Sigma\pi$ decay mode.
- $\Sigma^+\pi^-$ decay mode has peak at highest mass, narrow than $\Sigma^-\pi^+$.
- Lineshapes are summed over acceptance region of CLAS.
- Difference is less prominent at higher energies.

Invariant Mass [GeV]

$\pi$ $\Sigma$

1.3 1.4 1.5

$\mu/dM$ $[\sigma d]

0 0.1 0.2 0.3 0.4 0.5 0.6 0.7

$<3.27 \gamma 3.00 < E < 2.55 < W < 2.65$ thresholds

Weighted average

$-\pi + \Sigma$

$0\pi 0\Sigma

$+\pi -\Sigma$

PDG Breit-Wigner

• preliminary
Theory Prediction From Chiral Unitary Approach

\[ \gamma p \rightarrow K^+ \pi \Sigma \]
\[ E_\gamma = 1.7 \text{ GeV} \]

- $\Sigma^- \pi^+$ decay mode peaks at highest mass, most narrow
- difference in lineshapes is due to interference of isospin terms in calculation ($T^{(1)}$ represents amplitude of isospin I term)
- we have started trying fits to the resonance amplitudes

J. C. Nacher et al., Nucl. Phys. B455, 55
Λ(1405) Differential Cross Section Results

- lines are fits with 6th order Legendre polynomials
- clear turnover of $\Sigma^+\pi^-$ channel at forward angles
- theory: contact term only, no angular dependence for interference
- experiment: able to see strong **isospin** AND **angular** interference effect

---

**Legend**
- Wbin: 3
- $2.150 < W < 2.250$
- $(1.994 < E_\gamma < 2.229)$
- $\Sigma^+\pi^-$ weighted
- $\Sigma^0\pi^0$
- $\Sigma^-\pi^+$
- total/3

---

**Graph Details**
- $\frac{d\sigma}{d\cos\theta_{c.m.}} [\mu b]$ vs. $\cos\theta_{c.m.}$
- Preliminary results

---

**Notes**
- K. Moriya (IU)
- Lambda (1405) lineshape
- May 2011 20 / 24
• lines are fits with 6\textsuperscript{rd} order Legendre polynomials

• clear turnover of $\Sigma^+\pi^-$ channel at forward angles

• theory: contact term only, no angular dependence for interference

• experiment: able to see strong isospin AND angular interference effect
• lines are fits with 6\textsuperscript{rd} order Legendre polynomials
• clear turnover of $\Sigma^+\pi^-$ channel at forward angles
• theory: contact term only, no angular dependence for interference
• experiment: able to see strong isospin AND angular interference effect
• binning is in $t - t_{\text{min}}$

• good agreement with $pK^-$ channel from CLAS (unpublished) — data provided by R. de Vita et al. (INFN Genova)
Extrapolation of Cross Sections

- Ad hoc functions were chosen to fit the measured cross sections
- total cross section $\sigma_{\text{tot}}$ depends strongly on how cross section is extrapolated
- final result is a statistical mean of the various fit functions used

$\Sigma(1385)$
Extrapolation of Cross Sections

- Ad hoc functions were chosen to fit the measured cross sections
- total cross section $\sigma_{\text{tot}}$ depends strongly on how cross section is extrapolated
- final result is a statistical mean of the various fit functions used

$\Lambda(1405)$

$p_{\text{c.m.}} + K \theta \cos^{-1} -0.5 0 0.5 1$

$|2^\text{nd order Legendre}|$

$|3^\text{rd order Legendre}|$

$\exp+|1^\text{st order Legendre}|$

$\exp+|2^\text{nd order Legendre}|$

$\exp+|3^\text{rd order Legendre}|$

$\exp \times |1^\text{st order Legendre}|$

$\exp \times |2^\text{nd order Legendre}|$

$\exp \times |3^\text{rd order Legendre}|$

$\exp+|1^\text{st order Legendre}|$

$\text{preliminary}$
Extrapolation of Cross Sections

- Ad hoc functions were chosen to fit the measured cross sections
- total cross section $\sigma_{\text{tot}}$ depends strongly on how cross section is extrapolated
- final result is a statistical mean of the various fit functions used
- $\Lambda(1520)$
Extrapolated Total Cross Sections

- final result is a statistical mean of the various fit functions used
- $\Sigma(1385)$
Extrapolated Total Cross Sections

- final result is a statistical mean of the various fit functions used
- $\Lambda(1405)$
Extrapolated Total Cross Sections

- final result is a statistical mean of the various fit functions used
- $\Lambda(1520)$
• final result is a statistical mean of the various fit functions used

• comparison of $\Sigma(1385)$, $\Lambda(1405)$, $\Lambda(1520)$
• Most precise measurement of $\Lambda(1405)$ for any reaction
• Strong hints of “dynamical” nature
• **Difference in lineshapes** observed
  ▶ Strong effects of both isospin $I = 0$ and $I = 1$
  ▶ Hints of dynamical nature of $\Lambda(1405)$?
  ▶ Shifts in opposite direction compared to theory
• **Difference in $d\sigma/d\cos\theta_{K^+}^c.m.$ behavior** observed
  ▶ Again, effects of both isospin $I = 0$ and $I = 1$
  ▶ Cross sections for $\Sigma(1385)$ and $\Lambda(1520)$ also measured
• **Spin and parity experimentally determined** for first time
  ▶ $J^P = \frac{1}{2}^-$
  ▶ Polarization at forward $K^+$ angles, higher energies $W \sim 2.5$-2.8 GeV is $\sim 40\%$
  ▶ Falloff of lineshape at $N\overline{K}$ threshold also supports $J^P = \frac{1}{2}^-$
\[ \Sigma^- \rightarrow n \pi^- \]

**Example:**

- subtract off \( \Sigma(1385), \Lambda(1520), K^+\Sigma^-\pi^+ \) phase space
- assigned the remaining contribution to the \( \Lambda(1405) \)
\[ M(\Sigma^-\pi^+) \text{ vs } M(K^+\pi^+) \] Plots

- Kinematic boundary
- Wbin: 3
- \(2.150 < W < 2.250\)
- Data kfit \(\Sigma\) only, 43108
- Low energy bin
- Acceptance is good over entire area
$M(\Sigma^-\pi^+) \text{ vs } M(K^+\pi^+) \text{ Plots}$

- High energy bin
- Acceptance is good over entire area

$2.650 < W < 2.750$
- Data kfit $\Sigma$ only: 35855

$\Lambda(1520)$
$\Lambda(1405)$
Effect of $K^*$ on Lineshape

$1.950 < W \text{ [GeV]} < 2.050$ (below $K^*$ threshold)

$K^*$ vs $Y^*$ mass plot for $\Sigma^+$ channel
Effect of $K^*$ on Lineshape

$1.950 < W [\text{GeV}] < 2.050$ (below $K^*$ threshold)

![Graph showing extracted lineshape](image)

$1.56 < E_\gamma < 1.77$

$1.95 < W < 2.05$

$\Sigma \pi$ thresholds

$\Sigma^+ \pi^0$ weighted average

$\Sigma^0 \pi^0$

$\Sigma^+ \pi^+$

PDG Breit-Wigner

Preliminary
Comparison of Lineshapes for Two $\Sigma^+$ Channels

Invariant Mass [GeV]

$\pi$  $\Sigma$

$1.3$  $1.4$  $1.5$

$\mu$/dM [$\sigma$ d]

$0$  $0.5$  $1$  $1.5$  $2$  $2.5$  $<1.99$

$\gamma$

$1.77 < E^\gamma < 1.99$

$2.05 < W < 2.15$

$\pi^- p \rightarrow \pi^0 \pi^-$

$\Sigma^+ n \rightarrow \pi^+ \pi^-$

weighted average

PDG Breit-Wigner

Preliminary

K. Moriya (IU)
Comparison of Lineshapes for Two $\Sigma^+$ Channels
Comparison of Lineshapes for Two $\Sigma^+$ Channels

![Graph showing the comparison of lineshapes for two $\Sigma^+$ channels. The graph plots the differential cross section $d\sigma/dM$ in units of $\text{mb/GeV}$ against the invariant mass of the $\Sigma\pi$ system. The graph includes data points and three curves: one for $\Sigma^+ \pi^- \rightarrow p \pi^0 \pi^-$, another for $\Sigma^+ \pi^- \rightarrow n \pi^+ \pi^-$, and a weighted average curve. The PDG Breit-Wigner shape is also shown. The graph covers the invariant mass range from 1.3 to 1.5 GeV with $E_\gamma$ and $W$ ranges from 3.27 to 3.56 GeV and 2.65 to 2.75 GeV, respectively. The graph is preliminary in nature.]
Comparison of Two $\Sigma^+$ Channels

$\Lambda(1405)$ lineshape

May 2011
Comparison of Two $\Sigma^+$ Channels

$\Lambda (1405)$ Comparison of Two $\Sigma^+$ Channels

$\Sigma^+ \pi^- \rightarrow p \pi^- \pi^0$

$\Sigma^+ \pi^- \rightarrow n \pi^+ \pi^-$

weighted $\Sigma^+ \pi^-$

Wbin: 5

$2.350 < W < 2.450$

$(2.474 < E_\gamma < 2.730)$

$K. Moriya (IU)$
Λ(1405) Comparison of Two Σ⁺ Channels

Wbin: 8
2.650 < W < 2.750
(3.273 < Eγ < 3.561)

\[
\frac{d\sigma}{d\cos\theta_{K^+}} [\mu b] = \begin{cases} 
\Sigma^+ \pi^- \rightarrow p \pi^- \pi^0 \\
\Sigma^+ \pi^- \rightarrow n \pi^+ \pi^- \\
\text{weighted } \Sigma^+ \pi^-
\end{cases}
\]
**Λ(1520) Comparison of Two Σ⁺ Channels**

- **1.77 < E_γ < 1.99**
- **2.05 < W < 2.15**

Graph showing the differential cross section $\frac{d\sigma}{d\cos\theta}$ in the CMS frame for the reactions $\Sigma^+ \pi^- \rightarrow p \pi^- \pi^0$ and $\Sigma^+ \pi^- \rightarrow n \pi^+ \pi^-$. The graph also includes data points for a weighted $\Sigma^+ \pi^-$ channel.
$\Lambda(1520)$ Comparison of Two $\Sigma^+$ Channels

$2.47 < E_\gamma < 2.73$

$2.35 < W < 2.45$

$\Sigma^+ \pi^- \rightarrow p \pi^- \pi^0$

$\Sigma^+ \pi^- \rightarrow n \pi^+ \pi^-$

weighted $\Sigma^+ \pi^-$

Preliminary
Λ(1520) Comparison of Two Σ⁺ Channels

$3.27 < E_\gamma < 3.56$

$2.65 < W < 2.75$

$\Sigma^+ \pi^- \rightarrow p \pi^- \pi^0$

$\Sigma^+ \pi^- \rightarrow n \pi^+ \pi^-$

weighted $\Sigma^+ \pi^-$

Preliminary
Backup Slides

Spin and Parity
no previous direct experimental evidence for the spin and parity
(PDG assumes $1/2^-$)

“Note on the $\Lambda(1405)$” 1998 PDG, R.H. Dalitz

How do we measure these quantities?

- **spin** – measure distribution into $\Sigma\pi$
  - flat distribution is best evidence possible for $J = 1/2$
- **parity** – measure polarization of $\Sigma$ from $\Lambda(1405)$
  - Polarization direction as a function of $\Sigma$ decay angle will be determined by $J^P$ of $\Lambda(1405)$
Determination of Spin

Fit to $\Sigma \pi$ distribution is FLAT

\[ \chi^2/\text{ndf from average: 1.02} \]

- consistent with $J = 1/2$
- fits to higher moments may be necessary
**s-wave, p-wave Scenario**

\[
\begin{align*}
L = 0 \text{ (s-wave)} & \quad \bar{P}_{\Sigma^+} = \bar{P}_{\Lambda^*} \\
L = 1 \text{ (p-wave)} & \quad \bar{P}_{\Sigma^+} = |\bar{P}_{\Lambda^*}|\hat{n}(2\theta_{\Sigma^+})
\end{align*}
\]

\( \Lambda(1405) \rightarrow \Sigma\pi \) is s-wave
\( \iff J^P = 1/2^- \)

\( \Lambda(1405) \rightarrow \Sigma\pi \) is p-wave
\( \iff J^P = 1/2^+ \)
Determination of Parity

polarization of $\Lambda(1405)$ in direction $\perp$ to production plane is measured

- $W = 2.6$ GeV
- forward $K^+$ angles
- use reaction:
  $\Lambda(1405) \to \Sigma^+\pi^-$,
  $\Sigma^+ \to p\pi^0$
- very large hyperon decay parameter $\alpha = -0.98$
- background is $\sim 10\%$ $\Sigma(1385)$

\[ \begin{align*}
  & 2.550 < W < 2.650 \\
  & 0.60 < \cos\theta_{K^+} < 0.70 \\
  & 0.60 < \cos\theta_{\Sigma^+} < 1
\end{align*} \]

$P_z$ vs $\cos\theta_{\Sigma^+}$

$\Lambda(1405)$ lineshape

K. Moriya (IU)  May 2011
Determination of Parity

polarization of $\Lambda(1405)$ in direction $\perp$ to production plane is measured

- $W = 2.6$ GeV
- forward $K^+$ angles
- use reaction:
  $\Lambda(1405) \rightarrow \Sigma^+ \pi^-$,
  $\Sigma^+ \rightarrow p\pi^0$
- very large hyperon decay parameter $\alpha = -0.98$
- background is $\sim 10\%$ $\Sigma(1385)$
Determination of Parity

polarization of $\Lambda(1405)$ in direction $\perp$ to production plane is measured

- $W = 2.6$ GeV
- forward $K^+$ angles
- use reaction:
  $\Lambda(1405) \rightarrow \Sigma^+\pi^-$,
  $\Sigma^+ \rightarrow p\pi^0$
- very large hyperon decay parameter $\alpha = -0.98$
- background is $\sim 10\%$ $\Sigma(1385)$
Determination of Parity

polarization of $\Lambda(1405)$ in direction $\perp$ to production plane is measured

- $W = 2.6$ GeV
- forward $K^+$ angles
- use reaction: $\Lambda(1405) \to \Sigma^+ \pi^-$, $\Sigma^+ \to p\pi^0$
- very large hyperon decay parameter $\alpha = -0.98$
- background is $\sim 10\%$ $\Sigma(1385)$

polarization does not change with $\Sigma^+$ angle ($\theta_{\Sigma^+}$)
Determination of Parity

polarization of $\Lambda(1405)$ in direction $\perp$ to production plane is measured

- $W = 2.6$ GeV
- forward $K^+$ angles
- use reaction:
  $\Lambda(1405) \rightarrow \Sigma^+ \pi^-$,  
  $\Sigma^+ \rightarrow p\pi^0$
- very large hyperon decay parameter $\alpha = -0.98$
- background is $\sim 10\%$ $\Sigma(1385)$

polarization does not change with $\Sigma^+$ angle ($\theta_{\Sigma^+}$)

$\Rightarrow J^P = 1/2^-$ is confirmed
Determination of Parity

polarization of $\Lambda(1405)$ in direction $\perp$ to production plane is measured

- $W = 2.6$ GeV
- forward $K^+$ angles
- use reaction: $\Lambda(1405) \rightarrow \Sigma^+ \pi^-$, $\Sigma^+ \rightarrow p\pi^0$
- very large hyperon decay parameter $\alpha = -0.98$
- background is $\sim 10\%$ $\Sigma(1385)$

polarization does not change with $\Sigma^+$ angle ($\theta_{\Sigma^+}$)

$\Rightarrow J^P = 1/2^-$ is confirmed

furthermore, this measured $\Sigma^+$ polarization is the $\Lambda(1405)$ polarization
Determination of Parity

polarization of $\Lambda(1405)$ in direction $\perp$ to production plane is measured

- $W = 2.6$ GeV
- forward $K^+$ angles
- use reaction:
  $\Lambda(1405) \rightarrow \Sigma^+ \pi^-$,
  $\Sigma^+ \rightarrow p \pi^0$
- very large hyperon decay parameter $\alpha = -0.98$
- background is $\sim 10\%$ $\Sigma(1385)$

polarization does not change with $\Sigma^+$ angle ($\theta_{\Sigma^+}$)

$\Rightarrow J^P = 1/2^-$ is confirmed

furthermore, this measured $\Sigma^+$ polarization is the $\Lambda(1405)$ polarization

$\Rightarrow \Lambda(1405)$ is produced with $\sim +40\%$ polarization