A Study of 3π production in $\gamma p \rightarrow n\pi^+\pi^+\pi^-$ and $\gamma p \rightarrow \Delta^{++}\pi^+\pi^-\pi^-$ with CLAS at Jefferson Lab

Aristeidis Tsaris
Florida State University

CLAS Collaboration Meeting
Newport News, VA
October 21-23, 2015
Using the CLAS-g12 dataset we selected events with three charge pions, measured by the CLAS spectrometer and identified a neutron by energy and momentum conservation.

- Analysis is being redone in preparation of publication
  - Error was found in the parametrization of the partial waves
  - New data selection and new Monte Carlo with analysis in line with g12 analysis note procedures
Error Found in the Parametrization of the Partial Waves

- helicity amplitudes are not parity eigenstates

- reflectivity amplitudes are linear combinations of helicity amps which are parity eigenstates.

\[
|\epsilon m\rangle = \left[|am\rangle - \epsilon P(-1)^J m|a - m\rangle\right]\theta(m)
\]  

(38)

where \(P\) is the parity of the state ‘a’ and

\[
\theta(m) = \begin{cases} 
\frac{1}{\sqrt{2}}, & m > 0 \\
\frac{1}{2}, & m = 0 \\
0, & m < 0 
\end{cases}
\]  

(39)

The reflectivity \(\epsilon\) is here defined such that it coincides with the naturality of exchanged Regge trajectories. Note that

\[
|\epsilon m\rangle = 0 \text{ for } m = 0, \quad \text{if } \epsilon = P(-1)^J
\]  

(40)

--------- Chung ---------
Enhance Peripheral Production

$\gamma p \rightarrow n \pi^+ \pi^+ \pi^-$

$\text{Mass}(\pi^+ \pi^+ \pi^-)$ (GeV/$c^2$)

$\text{Mass}(n, \pi_{fast}^+)$ (GeV/$c^2$)

$\text{Mass}(n, \pi^-)$ (GeV/$c^2$)
Further Reducing the Baryon Background

\[ \gamma p \rightarrow n \pi^+ \pi^+ \pi^- \]

\[ \theta_{lab}[\pi_{slow}] < 25^o \]
Features of the $3\pi$ sample

\[ \gamma p \rightarrow n \pi^+ \pi^+ \pi^- \]

\[ M_{3\pi} < 1.5 \text{GeV} \]

\[ M_{3\pi} > 1.5 \text{GeV} \]

\[ M^2(\pi^-, \pi_{\text{fast}}) \]

\[ M^2(\pi^-, \pi_{\text{slow}}) \]

\[ M^2(\pi^+, \pi_{\text{slow}}) \]

\[ M^2(\pi^+, \pi_{\text{fast}}) \]

\[ (\text{GeV}/c^2)^2 \]

\[ \text{Entries 328323} \]

\[ \text{Entries 184774} \]

\[ \text{Entries 528898} \]

\[ \text{Events/14 MeV/c}^2 \]

\[ \text{Events/14 GeV/c}^2 \]

\[ \text{Events/14 (GeV/c) }^2 \]

\[ \text{Events/14 (GeV/c) }^3 \]

Aristeidis Tsaris

Florida State University
Partial Wave Analysis

- A mass independent pwa is performed using an event based likelihood fit
- To calculate the amplitudes we used helicity formalism in the reflectivity basis using the isobar model

\[ I(\tau) = \sum_{\kappa \epsilon} \left| \sum_{\alpha} \epsilon^\kappa V_{\alpha} \epsilon^\alpha A_\alpha(\tau) \right|^2 \]

- For the current fit a total of 17 partial waves were used in the high mass region and 13 partial waves in the low mass region
Features of the partial waves of the $3\pi$ System for the $\gamma p \rightarrow n \pi^+ \pi^+ \pi^-$

- **Intensity of 2++ D waves**
  
  \[ M = 1.318 \text{ GeV} \]
  \[ \Gamma = 0.130 \text{ GeV} \]

  - Curve is with Craig's fitting parameters

- **Intensity of 1++ S waves**
  
  \[ M = 1.200 \text{ GeV} \]
  \[ \Gamma = 0.380 \text{ GeV} \]

- **Phase difference between 1++1-S and 2++1-D waves**

- **Phase difference between 1++1+S and 2++1+D waves**

  Curve is with Craig's fitting parameters
Features of the partial waves of the $3\pi$ System for the $\gamma p \rightarrow n\pi^+\pi^+\pi^-$

- **Intensity of 2++ D waves**
  - $M = 1.318$ GeV
  - $\Gamma = 0.130$ GeV
  - Curve is with Craig's fitting parameters

- **Mass ($\pi^+\pi^+\pi^-$)**
  - $M = 1.200$ GeV
  - $\Gamma = 0.380$ GeV

- **Phase difference between 1++1-S and 2++1-D waves**

- **Phase difference between 1++1+S and 2++1+D waves**

- **Fitting simultaneously intensities of 1++, 2++ and their phase difference**
  - $M = 1.319 \pm 0.001$
  - $\Gamma = 0.099 \pm 0.002$

- **Curve is with Craig's fitting parameters**

- **$X^2$/DoF $\approx 3$**

Aristeidis Tsaris
Florida State University
Features of the partial waves of the $3\pi$ System for the $\gamma p \rightarrow n\pi^+\pi^+\pi^-$

- $M = 1.640 \text{ GeV}$
- $\Gamma = 0.260 \text{ GeV}$

### Intensity of 2-+ S waves

Curve is a non-resonant 1-+ and 2-+ wave

$M = 1.640 \text{ GeV}$
$\Gamma = 0.260 \text{ GeV}$

### Intensity of 1-+ P waves

Curve is with Craig's fitting parameters

$M = 1.640 \text{ GeV}$
$\Gamma = 0.260 \text{ GeV}$
Features of the partial waves of the $3\pi$ System for the $\gamma p \to n \pi^+ \pi^+ \pi^-$

Fitting simultaneously intensities of 2-, 1-+ and their phase difference

**Fitting with 1-+ resonance results a non-resonant solution**

- **Intensity of 2-+1-S wave**
  - $M = 1.636 \pm 0.002$
  - $\Gamma = 0.251 \pm 0.006$

- **Intensity of 1-+1-P wave**
  - $M = 2.036 \pm 0.047$
  - $\Gamma = 0.000002 \pm 0.000001$

- **Phase 2-+1-S, 1-+1-P wave**
  - $\chi^2/\text{DoF} \approx 4$

- **Intensity of 2-+1+S wave**
  - $M = 0.947 \pm 0.439$
  - $\Gamma = 3.000 \pm 0.001$

- **Intensity of 1-+1+P wave**
  - $M = 1.634 \pm 0.002$
  - $\Gamma = 0.246 \pm 0.007$

- **Phase 2-+1+S, 1-+1+P wave**
  - $\chi^2/\text{DoF} \approx 5$
Using the CLAS-g12 dataset we selected events with four charge pions, measured by the CLAS spectrometer and identified a proton by energy and momentum conservation.
Kinematic Separation of the $\Delta^{++}$

$\gamma p \rightarrow \Delta^{++} \pi^+ \pi^- \pi^-$

Momentum Difference:

$|\vec{p}_{\pi_1} - |\vec{p}_{\pi_2}| > 0.35$ (GeV/c)

Background $\Delta^{++}$

Signal $\Delta^{++}$

Mass($p, \pi_{fast}^+$) (GeV/c$^2$)

Mass($p, \pi_{slow}^+$) (GeV/c$^2$)

Aristeidis Tsaris

Florida State University
Data Selection and Background Reduction

\[ \gamma p \rightarrow \Delta^{++} \pi^+ \pi^- \pi^- \]

\[ + M_{p \pi^+_\text{slow}} < 1.35 \]

- Black → Data
- Red → Data with Cuts
- Blue → MC with Cuts
Features of the $3\pi$ sample

$\gamma p \rightarrow \Delta^{++} \pi^+ \pi^- \pi^-$

$M_{3\pi} < 1.5 \text{GeV}$

$M_{3\pi} > 1.5 \text{GeV}$
Partial Wave Analysis

\[ \gamma p \rightarrow \Delta^{++} \pi^+ \pi^- \pi^- \]

- A mass independent pwa is performed using an event based likelihood fit
- To calculate the amplitudes we used helicity formalism in the reflectivity basis using the isobar model

�(τ) = \[ \sum_{\kappa \epsilon} \left| \sum_{\alpha} \epsilon_\kappa V_\alpha \epsilon A_\alpha (\tau) \right|^2 \]

- For the current fit a total of 13 partial waves were used in the high mass region and 9 partial waves in the low mass region
Features of the partial waves of the $3\pi$ System for the $\gamma p \rightarrow \Delta^{++} \pi^+ \pi^- \pi^-$ reaction:

- **Intensity of 2++ D waves**
  - Mass $M = 1.318$ GeV
  - Width $\Gamma = 0.105$ GeV
  - Curve is just to guide the eye

- **Intensity of 1++ S waves**
  - Mass $M = 1.260$ GeV
  - Width $\Gamma = 0.367$ GeV

- **Phase difference between 1++1-S and 2++1-D waves**

- **Intensity of 1++ D waves**
  - Mass $M = 1.307 \pm 0.003$ GeV
  - Width $\Gamma = 0.100 \pm 0.006$ GeV

Fitting simultaneously intensities of 1++, 2++ and their phase difference gives:

- 2++1-D
  - Mass $M = 1.280 \pm 0.005$ GeV
  - Width $\Gamma = 0.244 \pm 0.017$ GeV
- 1++1-S
- 1++1-S - 2++1-D
  - $X^2/DoF \approx 1.8$
Features of the partial waves of the $3\pi$ System for the $\gamma p \rightarrow \Delta^{++} \pi^+ \pi^- \pi^-$

leakage of $a_2(1320)$ into the P-wave

Total Intensity of 2-+ waves

Intensity of 2-+ S waves

Intensity of 2-+ D waves

Aristeidis Tsaris
Florida State University
Summary

- $\gamma p \rightarrow n \pi^+ \pi^+ \pi^-$:
  - The $a_2(1320)$ and the $a_1(1260)$ are observed
  - The $\pi_2(1670)$ is observed
  - The $J^{PC} = 1^{--}$ appears to have no phase motion relative to the $\pi_2(1670)$

- $\gamma p \rightarrow \Delta^{++} \pi^+ \pi^- \pi^-$:
  - A first time PWA of the $\Delta^{++} 3\pi$ system
  - The $a_2(1320)$ and the $a_1(1260)$ are observed
  - The $\pi_2(1670)$ is observed
Back up slides
List of Waves used for the current Fit $\gamma p \rightarrow n \pi^+ \pi^+ \pi^-$

### $M_{3\pi} < 1.4 \text{ GeV}$

<table>
<thead>
<tr>
<th>$J^{PC}$</th>
<th>$M^\epsilon$</th>
<th>$L$</th>
<th>$Y$</th>
<th>Number of waves</th>
</tr>
</thead>
<tbody>
<tr>
<td>$1^{++}$</td>
<td>$1^{-/+}$</td>
<td>$S, P, D$</td>
<td>$\rho(770), \sigma$</td>
<td>6</td>
</tr>
<tr>
<td>$1^{-+}$</td>
<td>$1^{-/+}$</td>
<td>$P$</td>
<td>$\rho(770)$</td>
<td>2</td>
</tr>
<tr>
<td>$2^{++}$</td>
<td>$1^{-/+}$</td>
<td>$D$</td>
<td>$\rho(770)$</td>
<td>2</td>
</tr>
<tr>
<td>$2^{-+}$</td>
<td>$1^{-/+}$</td>
<td>$P$</td>
<td>$\rho(770)$</td>
<td>2</td>
</tr>
</tbody>
</table>

Isotropic background wave

### $M_{3\pi} > 1.4 \text{ GeV}$

<table>
<thead>
<tr>
<th>$J^{PC}$</th>
<th>$M^\epsilon$</th>
<th>$L$</th>
<th>$Y$</th>
<th>Number of waves</th>
</tr>
</thead>
<tbody>
<tr>
<td>$1^{++}$</td>
<td>$1^{-/+}$</td>
<td>$S, P, D$</td>
<td>$\rho(770), \sigma$</td>
<td>6</td>
</tr>
<tr>
<td>$1^{-+}$</td>
<td>$1^{-/+}$</td>
<td>$P$</td>
<td>$\rho(770)$</td>
<td>2</td>
</tr>
<tr>
<td>$2^{++}$</td>
<td>$1^{-/+}$</td>
<td>$D$</td>
<td>$\rho(770)$</td>
<td>2</td>
</tr>
<tr>
<td>$2^{-+}$</td>
<td>$1^{-/+}$</td>
<td>$S, P, D$</td>
<td>$\rho(770), f_2(1270)$</td>
<td>6</td>
</tr>
</tbody>
</table>

Isotropic background wave
List of Waves used for the current Fit $\gamma p \rightarrow \Delta^{++} \pi^+ \pi^- \pi^-$

<table>
<thead>
<tr>
<th>$J^{PC}$</th>
<th>$M^\epsilon$</th>
<th>$L$</th>
<th>$Y$</th>
<th>Number of waves</th>
</tr>
</thead>
<tbody>
<tr>
<td>$1^{++}$</td>
<td>1$^{-/+}$</td>
<td>$S, D$</td>
<td>$\rho(770)$</td>
<td>4</td>
</tr>
<tr>
<td>$2^{++}$</td>
<td>1$^{-/+}$</td>
<td>$D$</td>
<td>$\rho(770)$</td>
<td>2</td>
</tr>
<tr>
<td>$2^{-+}$</td>
<td>1$^{-/+}$</td>
<td>$P$</td>
<td>$\rho(770)$</td>
<td>2</td>
</tr>
</tbody>
</table>

Isotropic Background Wave

$M_{3\pi} < 1.4 \text{ GeV}$

<table>
<thead>
<tr>
<th>$J^{PC}$</th>
<th>$M^\epsilon$</th>
<th>$L$</th>
<th>$Y$</th>
<th>Number of waves</th>
</tr>
</thead>
<tbody>
<tr>
<td>$1^{++}$</td>
<td>1$^{-/+}$</td>
<td>$S, D$</td>
<td>$\rho(770)$</td>
<td>4</td>
</tr>
<tr>
<td>$2^{++}$</td>
<td>1$^{-/+}$</td>
<td>$D$</td>
<td>$\rho(770)$</td>
<td>2</td>
</tr>
<tr>
<td>$2^{-+}$</td>
<td>1$^{-/+}$</td>
<td>$S, P, D$</td>
<td>$\rho(770), f_2(1270)$</td>
<td>6</td>
</tr>
</tbody>
</table>

Isotropic Background Wave

$M_{3\pi} > 1.4 \text{ GeV}$