Photoproduction of $3\pi$ with CLAS

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CLAS g12 Analysis

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

Form CLAS-g12 dataset (~25B events):

- **Three** charged pions selected
- **Neutron** is identified by energy and momentum conservation

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

Form CLAS-g12 dataset (~25B events):

- **Four** charged pions selected
- **Proton** is identified by energy and momentum conservation

Partial Wave Analysis in the \(3\pi\) sample

A. Tsaris (2016 FSU Dissertation)
Selection Criteria

<table>
<thead>
<tr>
<th>Description</th>
<th>Interval</th>
<th>Events In</th>
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</tr>
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<tbody>
<tr>
<td>Vertex within $z$-extent of target</td>
<td>$-110 &lt; z &lt; -70$ cm</td>
<td>707,329,219</td>
<td>658,403,589</td>
</tr>
<tr>
<td>Vertex within target radius</td>
<td>$r &lt; 10.0$ cm</td>
<td>658,403,589</td>
<td>587,508,335</td>
</tr>
<tr>
<td>Event vertex timing cut</td>
<td>$</td>
<td>t_{vtx}(TAG) - t_{vtx}(ST)</td>
<td>&lt; 1.002$ ns</td>
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<td>Beta selection for particle tracks</td>
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<td>\beta_{TOF} - \beta_{p/m}</td>
<td>&lt; 0.03$</td>
</tr>
<tr>
<td>Photon Energy</td>
<td>$E_\gamma \geq 4.4 GeV$</td>
<td>382,907,980</td>
<td>118,656,025</td>
</tr>
<tr>
<td>Confidence level cut</td>
<td>$FOMkinFit &gt; 1%$</td>
<td>118,656,025</td>
<td>7,424,941</td>
</tr>
</tbody>
</table>

\[ \gamma p \rightarrow n \pi^- \pi^+ \pi^+ X \]
Features of the Data

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

**Features for \( M_{3\pi} < 1.5 \text{GeV} \):**

- **Histogram:** Mass distribution of \( \pi^+ \pi^+ \pi^- \)
- **Scatter Plot:** \( M^2(\pi^- , \pi_{\text{fast}}^-) \)

**Features for \( M_{3\pi} > 1.5 \text{GeV} \):**

- **Histogram:** Mass distribution of \( \pi^- \pi_{\text{slow}}^- \) and \( \pi^- \pi_{\text{fast}}^- \)
- **Scatter Plot:** \( M^2(\pi^- , \pi_{\text{fast}}^-) \)
**Partial Wave Analysis**

**Step 1: Decompose to Partial Waves**

\[
X \rightarrow p_1 + p_2 + p_3 + \ldots
\]

Bin by bin event based likelihood analysis

<table>
<thead>
<tr>
<th>Mass [X]</th>
<th>Total Intensity</th>
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<tbody>
<tr>
<td></td>
<td>(\beta) Intensity</td>
</tr>
<tr>
<td></td>
<td>Relative Phase ([\alpha, \beta])</td>
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</tbody>
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<table>
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<tr>
<th>Mass [X]</th>
<th>Wave((\alpha)) Intensity</th>
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<td>Wave((\beta)) Intensity</td>
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</table>

\[\text{Mass}[X] \rightarrow p_1 + p_2 + p_3 + \ldots\]
Partial Wave Analysis

Step 1: Decompose to Partial Waves

\[ X \rightarrow p_1 + p_2 + p_3 + \ldots \]

Bin by bin
event based
likelihood analysis
Partial Wave Analysis

Step 2: Extract Resonance Parameters

- Mass\[X\]
- Total Intensity
- Relative Phase\[\alpha, \beta\]
- Wave(\alpha) Intensity
- Wave(\beta) Intensity

Mass Dependent Analysis
Using PWA to Identify $J^{PC}$ States

Helicity Decay Amplitudes

$A_{\alpha, M}(\tau) = A^{\lambda_1 \lambda_2; M}_{\alpha X} A^{\nu_1 \nu_2; \lambda_1}_{iso}$

Mass Dynamic Factor

(like Breit-Wigner, K-matrix, ...)
Helicity Decay Amplitudes in the Reflectivity Basis

For unpolarized beam & target:

\[ I(\tau) = \frac{1}{2} \sum_{k} \left| \sum_{\alpha}^{k\epsilon} V_{\alpha} \epsilon A_{\alpha}(\tau) \right|^2 \]

\[ \tau = \{ \theta, \phi, m_{iso}, \theta', \phi', ... \} \]

Helicity amplitudes are not eigenstates of Parity

Reflectivity basis takes Parity into account

\[ A_{\alpha,\epsilon M}^*(\tau) = \Delta(m) [ A_{\alpha, m}^*(\tau) - \epsilon P (-1)^{J-m} A_{\alpha, -m}^*(\tau) ] \]

- Unpolarized photon beam results in equal mixture of \( M^\epsilon = 1^+ \) & \( 1^- \)

- \( \pi \) exchange photoproduction forbids \( M=0 \)

\[ \Delta(m) = \begin{cases} 1/\sqrt{2} & m > 0 \\ 1/2 & m = 0 \\ 0 & m < 0 \end{cases} \]
Earlier FSU Results*

\[ 2^{-+} \left[ f_2(1270) \pi \right]_S \text{ Intensity} \]

\[ \times 10^5 \]

\[ \pi_2(1670) \]

Equal yields for \( M^e = 1^+ \) & \( 1^- \)

* Large signal in M=0 wave

Did not expect M=0 waves to contribute

*C. Bookwalter (FSU Dissertation)
# Minimum List of Partial Waves

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

<table>
<thead>
<tr>
<th>$J^{PC}$</th>
<th>$M^c$</th>
<th>$L$</th>
<th>$Y$</th>
<th>Number of waves</th>
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</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>
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Isotropic background wave

## $M_{3\pi} > 1.38\,\text{GeV}$

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<td>$\rho(770), f_2(1270)$</td>
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Isotropic background wave
PWA Results: $n\pi^+ \pi^+ \pi^-$

First observation of the $a_1(1260)$ in photoproduction

- Equal population of both parity eigenstates
- No observation in $M=0$ wave

$\Delta \phi$

A. Tsaris (2016 FSU Dissertation)
\( \pi_2(1670) \) & Non-resonant 1\(^{-+} \) wave

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

\( \pi_2(1670) \)

Intensity of 2\(^{-+} \) S waves

\( M = 1.634 \pm 0.002 \)

\( \Gamma = 0.252 \pm 0.005 \)

\( \chi^2/\text{DoF} = 6 \)

Intensity of 1\(^{-+} \) P waves

\( M(3\pi) \) (GeV/c\(^2\))

Phase difference between 1\(^{-+} \) P and 2\(^{-+} \) S waves

Phase difference between 2\(^{-+} \) S and a resonating 1\(^{-+} \) P wave

Pure 2\(^{-+} \) S phase motion

The exotic 1\(^{-+} \) partial wave does not show resonant behavior
\( \pi_2(1670) \) D-wave decay

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

![Graphs showing intensity and phase differences between different wave states](image)

- Graph (a) shows the intensity of 2-+ D waves as a function of mass.
- Graphs (b) and (c) show the phase difference between 1-+1-P and 2-+1-D waves.

- Phase motion was not stable in earlier FSU results.

Also a falling phase motion consistent with a non-resonant 1-+
\[ \gamma p \rightarrow \Delta^{++} \pi^+ \pi^- \pi^- \]

**Event Selection**

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<td>Vertex within ( z )-extent of target</td>
<td>(-110 &lt; z &lt; -70 ) cm</td>
<td>105,863,100</td>
<td>100,840,300</td>
</tr>
<tr>
<td>Vertex within target radius</td>
<td>( r &lt; 10.0 ) cm</td>
<td>100,840,300</td>
<td>93,575,180</td>
</tr>
<tr>
<td>Event vertex timing cut</td>
<td>(</td>
<td>t_{vtx}(TAG) - t_{vtx}(ST)</td>
<td>&lt; 1.002 ) ns</td>
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<td>Beta selection for particle tracks</td>
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<td>\beta_{TOF} - \beta_{p/m}</td>
<td>&lt; 0.03)</td>
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<tr>
<td>Photon Energy</td>
<td>Beam - Photon ( \geq 4.4 GeV)</td>
<td>75,917,040</td>
<td>31,874,591</td>
</tr>
<tr>
<td>Confidence level cut</td>
<td>(FOM - kinFit &gt; 1%)</td>
<td>31,874,591</td>
<td>3,750,040</td>
</tr>
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![Graphs showing event selection criteria](image_url)
**Kinematic Separation of the Δ⁺⁺**

Momentum Difference between fast and slow $\pi^+$

Background $\Delta^{++}$

Signal $\Delta^{++}$

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

\[ \Delta^{++} \]

\[ M(p, \pi^+) \quad (GeV/c^2) \]

\[ M(p, \pi^{slow}) \quad (GeV/c^2) \]
Data Selection & Background Reduction

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

+ \( M_{p \pi_{\text{slow}}^+} < 1.35 \)

\( t' \) (GeV/c\(^2\))^2

Events/40 (MeV/c\(^2\))^2

- 45000
- 40000
- 35000
- 30000
- 25000
- 20000
- 15000
- 10000
- 5000
- 0

< 0.4

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

Events/18 (MeV/c\(^2\))

- 50000
- 40000
- 30000
- 20000
- 10000
- 0

Black → Data
Red → Data with Cuts
Blue → MC with Cuts

Mass(\( p \pi_{\text{slow}}^+ \pi_{\text{slow}}^- \)) (GeV/c\(^2\))

Events/12 (MeV/c\(^2\))

- 45000
- 40000
- 35000
- 30000
- 25000
- 20000
- 15000
- 10000
- 5000
- 0

Mass(\( p, \pi_{\text{fast}}^- \)) (GeV/c\(^2\))

Events/12 (MeV/c\(^2\))

- 45000
- 40000
- 35000
- 30000
- 25000
- 20000
- 15000
- 10000
- 5000
- 0

Mass(\( \pi_{\text{slow}}^- \pi_{\text{slow}}^- \)) (GeV/c\(^2\))

Events/12 (MeV/c\(^2\))

- 45000
- 40000
- 35000
- 30000
- 25000
- 20000
- 15000
- 10000
- 5000
- 0
The $\Delta^{++}$ Recoil Baryon

Fitted with a mass dependent Breit-Wigner function convoluted with a Gaussian along with a first degree polynomial function.

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

$\cos \theta$ in the $\Delta^{++}$ rest frame for data and accepted MC weighted by $\Delta^{++}$ amplitudes.
Features of the $3\pi$ sample

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

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

$M_{3\pi} > 1.5 \text{ GeV}$
**PWA Results:** \( \Delta^{++} \pi^+ \pi^- \pi^- \)

Confirmation of the \( a_1(1260) \) in photoproduction

- PWA results:
  - \( a_2(1320) \)
  - \( a_1(1260) \)

1\(^+\) exotic wave was not required

Deck free background
Features of the PWA

PWA in the high mass region:
- was more challenging
- results were less stable here
- further investigation in this region shows that this channel suffers from background

\( \gamma p \rightarrow \Delta^{++} \pi^+ \pi^- \pi^- \)
Investigating the high $3\pi$ mass region
Summary & Plans

- \( \gamma p \rightarrow n \pi^+ \pi^+ \pi^- : \)
  - The \( a_2(1320) \) and the \( a_1(1260) \) are observed
  - The \( \pi_2(1670) \) is observed
  - The \( J^{PC} = 1^{++} \) does not show resonant behavior and it is strongly consistent with a non-resonant non-interfering wave relative to a resonant \( \pi_2(1670) \)

- \( \gamma p \rightarrow \Delta^{++} \pi^+ \pi^- \pi^- : \)
  - 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

- Analysis Review is underway:
  - written draft PRL for \( n3\pi \)
  - writing longer paper to include details of \( n3p \) and \( \Delta^{++}3\pi \)
PWA Predicted Distributions

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

**GJ $\cos \theta$ (fast Y)**

**GJ $\phi$ (fast Y) (deg)**

**GJ $\cos \theta$ (slow Y)**

**GJ $\phi$ (slow Y) (deg)**
Minimum List of Waves Required for the $\gamma p \rightarrow \Delta^{++} \pi^+ \pi^- \pi^-$

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<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>
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<tr>
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<td>1$^{-/-}$</td>
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Isotropic Background Wave

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

$M_{3\pi} > 1.375\text{ GeV}$

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Isotropic Background Wave
Enhance Peripheral Production

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

\[ t = (P_\gamma^\mu - P_X^\mu)^2 \]
\[ t' = t - t_{\min} \]

\(< 0.1\)
Further Reducing the Baryon Background

\[ \theta_{lab}[\pi_{\text{slow}}] < 25^\circ \]