Measurement of beam and target polarization observables in $\vec{\gamma}\vec{p} \rightarrow p\pi^+\pi^-$ using the CLAS spectrometer at Jefferson Lab.

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on the behalf of CLAS Collaboration

Florida State University

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Outline

1 Introduction
   - Why is $\pi^+\pi^-$ photoproduction needed?

2 FROST Experiment
   - The Frozen-Spin Target (FroST)

3 Data Analysis
   - Kinematic variables
   - Previous measurements
   - Basic event selection

4 The Preliminary Results
   - Polarization Observable $I$
   - Q-factor method: Event-based background subtraction
   - Polarization Observable $P_z$
   - Polarization Observable $P_z^{\circ}$
Why is $\pi^+\pi^-$ photoproduction needed?

- Total cross section for the photoproduction off the proton
- Total cross section of $\pi\pi$ production off the proton

- Search for new baryon states that are predicted by quark models to decay strongly to $\Delta\pi$ and $p\rho$.
- The most biggest cross section contribution is from double pion production, especially $(\gamma, \pi^+\pi^-)$, in the second resonance region.
- Polarization observables are important in the resonance extraction from data.
The Frozen-Spin Target (FroST)

1. High magnetic field (5 T)
   - (a) The longitudinal holding magnet. (0.56 T)
     - Average target polarization
       - \( \sim 82\%\) (+Pol) and 85\% (-Pol)
   - (b) The transversal holding magnet. (0.50 T)
     - (g9b: March 2010 - August 2010)
   - (c) The polarizing magnet. (5 T)

2. Low temperature
   - 28 mK (w/o beam) and 30 mK (w/ beam)
The $\pi^+ \pi^-$ photoproduction requires 5 independent variables.

ex: $E_\gamma$, $\theta_{c.m.}$, $\phi_{\pi^+}$, $\theta_{\pi^+}$, $M_{\pi^+ \pi^-}$

- Other variables are integrated over in this presentation.
The differential cross section for $\gamma p \rightarrow p\pi^+\pi^-$

(without measuring the polarization of the recoiling nucleon)

$$\frac{d\sigma}{d\chi_i} = \sigma_0 \left\{ (1 + \vec{\Lambda}_i \cdot \vec{P}) + \delta_\odot (I^\odot + \vec{\Lambda}_i \cdot \vec{P}^\odot) \right\}$$

$$+ \delta_\perp \left[ \sin 2\beta (I^s + \vec{\Lambda}_i \cdot \vec{P}^s) + \cos 2\beta (I^c + \vec{\Lambda}_i \cdot \vec{P}^c) \right] \}$$

- $\sigma_0$: The unpolarized cross section
- $\beta$: The angle between the direction of polarization and the x-axis
- $\chi_i$: The kinematic variables
- $\delta_\odot, \perp$: The degree of polarization of the photon beam \(\Rightarrow\) $\delta_\odot$, and $\delta_\perp$
- $\vec{\Lambda}_i$: The polarization of the initial nucleon \(\Rightarrow\) $(\Lambda_x, \Lambda_y, \Lambda_z)$
- $I^\odot, I^s, I^c$: The observable arising from use of polarized photons \(\Rightarrow\) $I^\odot, I^s, I^c$
- $\vec{P}$: The polarization observable \(\Rightarrow\) $(P_x, P_y, P_z)$ $(P_x^\odot, P_y^\odot, P_z^\odot)$ $(P_x^s, P_y^s, P_z^s)$ $(P_x^c, P_y^c, P_z^c)$

15 Observables
The data used for this analysis:

1. circularly-polarized beam
2. longitudinally-polarized target

\[
\frac{d \sigma}{d x_i} = \sigma_0 \left\{ (1 + \Lambda_z \cdot P_z) + \delta^\circ (I^\circ + \Lambda_z \cdot P_z^\circ) \right\}
\]

$I^\circ$ : Phys.Rev.Lett. 95, 162003 (2005, CLAS Collaboration)

$I^\circ$ : Phys.Rev.Lett. 103, 052002 (2009, Crystal Ball at MAMI, TAPS, and A2 Collaboration)


- The helicity-dependent total cross-section difference

\[
\Delta \sigma = (\sigma_{3/2} - \sigma_{1/2})
\]
Basic event selection

**Photon selection**

- Photon selection: $|\Delta t| < 1.2$ ns

**Proton and pion selection**

- Proton selection: $|\Delta \beta| < 0.032$
- Pion selection: $|\Delta \beta| < 0.044$

**Vertex cut (Butanol)**

- Vertex cut: $|Z_{vertex}| < 3$ cm

**Accidental cut**

- Accidental cut: one photon selection

**Confidence-level cut**

- Confidence-level cut: CL-cut $> 5\%$

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**Basic Cuts**

- Photon selection: $|\Delta t| < 1.2$ ns
- Proton selection: $|\Delta \beta| < 0.032$
- Pion selection: $|\Delta \beta| < 0.044$
- Vertex cut (Butanol): $|Z_{vertex}| < 3$ cm
- Accidental cut: one photon selection
- Confidence-level cut: CL-cut $> 5\%$
**Basic event selection**

- **The kinematic fitting**

<table>
<thead>
<tr>
<th>Proton (mom)</th>
<th>Mean -0.012</th>
<th>Sigma 1.029</th>
</tr>
</thead>
<tbody>
<tr>
<td>Proton (λ)</td>
<td>Mean 0.205</td>
<td>Sigma 0.983</td>
</tr>
<tr>
<td>Proton (φ)</td>
<td>Mean -0.050</td>
<td>Sigma 0.991</td>
</tr>
<tr>
<td>π⁻ (mom)</td>
<td>Mean -0.086</td>
<td>Sigma 1.002</td>
</tr>
<tr>
<td>π⁺ (λ)</td>
<td>Mean 0.099</td>
<td>Sigma 1.004</td>
</tr>
<tr>
<td>π⁻ (φ)</td>
<td>Mean -0.098</td>
<td>Sigma 0.990</td>
</tr>
<tr>
<td>π⁻ (mom)</td>
<td>Mean -0.090</td>
<td>Sigma 1.023</td>
</tr>
<tr>
<td>π⁺ (λ)</td>
<td>Mean -0.371</td>
<td>Sigma 0.976</td>
</tr>
<tr>
<td>π⁻ (φ)</td>
<td>Mean -0.085</td>
<td>Sigma 0.987</td>
</tr>
<tr>
<td>Photon (mom)</td>
<td>Mean 0.088</td>
<td>Sigma 1.035</td>
</tr>
</tbody>
</table>

- **Basic Cuts**
  -Photon selection: $| \Delta t | < 1.2 \text{ ns}$
  -Proton selection: $| \Delta \beta | < 0.032$
  -Pion selection: $| \Delta \beta | < 0.044$
  -Vertex cut (Butanol): $| Z_{vertex} | < 3 \text{ cm}$
  -Accidental cut: one photon selection
  -Confidence-level cut: CL-cut $> 5 \%$

- **Corrections**
  -Energy-loss correction
  -Photon-energy correction
  -Momentum correction
Polarization observable
The Preliminary Results

Polarization Observable \( I \odot \)

\[
I^\odot(W, \phi_{\pi^+}) = \frac{1}{\overline{\delta}^\odot(W)} \frac{N(\rightarrow; W, \phi_{\pi^+})_{\text{beam}} - N(\leftarrow; W, \phi_{\pi^+})_{\text{beam}}}{N(\rightarrow; W, \phi_{\pi^+})_{\text{beam}} + N(\leftarrow; W, \phi_{\pi^+})_{\text{beam}}}
\]

- \( \overline{\delta}^\odot(W) \) : The average degree of the photon beam polarizations
- \( \rightarrow (\leftarrow) \) : the direction of the beam polarization is parallel (anti-parallel) to the beam.
- Beam-helicity asymmetry for the unpolarized target and circularly-polarized photon beam

\begin{itemize}
  \item Example:
    \begin{itemize}
      \item Topology: \( \gamma p \rightarrow p\pi^+(\pi^-) \)
      \item \( W : 1.60 \text{ GeV} \)
      \item \( \theta_{\text{c.m.}}, \phi_{\pi^+}, \theta_{\pi^+}, M_{\pi^+\pi^-} \) are integrated over.
      \item Using the 5\% Confidence Level Cut
    \end{itemize}
  \end{itemize}

There are still an effect of background events
Butanol data are composed of
- free-proton data
- bound-nucleon data & background data

After applying CL-cut, there are still bound-nucleon and background events. These bound-nucleon and background events have a small influence on the beam asymmetry.
Check the symmetry of polarization observable \( I^{\circ} \)

- Kinematic variables \( \theta_{\text{c.m.}}, \theta_{\pi^+}, M_{\pi^+\pi^-} \) are integrated over.
- \( \text{Butanol}(2\pi - \phi) : -I^{\circ}(2\pi - \phi) \)
The Preliminary Results

Beam-Helicity Asymmetry $I^\circ$ with the published data

$I^\circ$ : Phys.Rev.Lett. 95, 162003 (2005, CLAS Collaboration)

$W = 1.40$ GeV
$W = 1.45$ GeV
$W = 1.50$ GeV
$W = 1.55$ GeV
$W = 1.60$ GeV
$W = 1.65$ GeV
$W = 1.70$ GeV
$W = 1.75$ GeV
$W = 1.80$ GeV
$W = 1.85$ GeV
$W = 1.90$ GeV
$W = 1.95$ GeV
$W = 2.00$ GeV
$W = 2.05$ GeV
$W = 2.10$ GeV

Butanol
Q-factor method

The Q-factor method is used to subtract background (developed at CMU, arXiv:0804.3382v1):

- The Q-factor is an event-based quality factor which describes the ratio of hydrogen signal to butanol signal, i.e. an event-based dilution factor.

From the butanol ($C_4H_9OH$) data, the free proton data is extracted on an event-by-event basis. No overall dilution factor is necessary.

A comparison between an event-based method and the method for overall background subtraction.
The Preliminary Results

Q-factor method: Event-based background subtraction

Beam-Helicity Asymmetry with models

- FSU-model calculated by Winston Roberts

Graphs showing polarization observable $I^\circ$ for different $W$ values:
- $W = 1.40$ GeV
- $W = 1.45$ GeV
- $W = 1.50$ GeV
- $W = 1.55$ GeV
- $W = 1.60$ GeV
- $W = 1.65$ GeV
- $W = 1.70$ GeV
- $W = 1.75$ GeV
- $W = 1.80$ GeV
- $W = 1.85$ GeV
- $W = 1.90$ GeV
- $W = 1.95$ GeV
- $W = 2.00$ GeV
- $W = 2.05$ GeV
- $W = 2.10$ GeV

Lines represent:
- Butanol (wQ)
- Butanol
- FSU-Model
- A.Fix-Model

Polarization Observable $I^\circ$ vs. $\phi_{\pi^+}$ for each $W$ value.
Polarization observable $P_z$
Polarization observable $P_z$

\[ P_z(W, \phi_{\pi^+}) = \frac{1}{\bar{\Lambda}_z(W)} \left\{ \frac{N(\Rightarrow; W, \phi_{\pi^+})_{\text{target}} - N(\Leftarrow; W, \phi_{\pi^+})_{\text{target}}}{N(\Rightarrow; W, \phi_{\pi^+})_{\text{target}} + N(\Leftarrow; W, \phi_{\pi^+})_{\text{target}}} \right\} \]

- $\bar{\Lambda}_z(W)$: The average of the degree of the target polarizations
- $\Rightarrow (\Leftarrow)$: the direction of the target polarization is parallel (anti-parallel) to the beam.
- Target asymmetry for the linearly-polarized target and unpolarized photon beam

**Example:**
- Topology: $\gamma p \rightarrow p\pi^+(\pi^-)$
- $W$: 1.60 GeV
- $\theta_{\text{c.m.}}, \phi_{\pi^+}, \theta_{\pi^+}, M_{\pi^+\pi^-}$ are integrated over.
- Using the 5% Confidence Level Cut & Q-factor method
Check the symmetry of polarization observable $P_z$

- Kinematic variables $\theta_{\text{c.m.}}$, $\theta_{\pi^+}$, $M_{\pi^+ \pi^-}$ are integrated over.
- $\text{Butanol}(wQ) \left(2\pi - \phi\right) : -P_z \left(2\pi - \phi\right)$
The Preliminary Results  

**Target Asymmetry $P_z$ with models**

- FSU-model calculated by Winston Roberts

![Graphs showing polarization observable $P_z$ at different $W$ values from 1.40 GeV to 2.10 GeV.](image-url)
Polarization observable $P_z$
The Preliminary Results

Polarization Observable $P_z^\circ$

$P_z^\circ(W, \phi_{\pi^+}) = \frac{1}{\bar{\Lambda}_z(W) \cdot \bar{\delta}^\circ} \left\{ \frac{N(W, \phi_{\pi^+})^{3/2} - N(W, \phi_{\pi^+})^{1/2}}{N(W, \phi_{\pi^+})^{3/2} + N(W, \phi_{\pi^+})^{1/2}} \right\}$

- $\bar{\Lambda}_z(W)$: The average of the degree of the target polarizations
- $\bar{\delta}^\circ(W)$: The average of the degree of the photon beam polarizations
- Helicity Difference for the linearly-polarized target and circularly-polarized photon beam

Example:
- Topology: $\gamma p \rightarrow p\pi^+(\pi^-)$
- $W$: 1.60 GeV
- $\theta_{c.m.}, \phi_{\pi^+}, \theta_{\pi^+}, M_{\pi^+\pi^-}$ are integrated over.
- Using the 5% Confidence Level Cut & Q-factor method
Check the symmetry of polarization observable $P_z$

- Kinematic variables $\theta_{c.m.}, \theta_{\pi^+}, M_{\pi^+\pi^-}$ are integrated over.
- Butanol(wQ)$(2\pi - \phi) : P_z(2\pi - \phi)$
The Preliminary Results

Polarization Observable $P_z$

Helicity Difference $P_z$

- FSU-model calculated by Winston Roberts

Butanol(wQ)

FSU-model calculated by Winston Roberts

Summary

- Polarization Observable $I^\circ$ using the FROST data is in good agreement with the previously published CLAS data.
  - The CLAS-analysis note for Observable $I^\circ$ will be prepared (95 %)
  - The systematic errors used for Observable $I^\circ$

<table>
<thead>
<tr>
<th>Contribution</th>
<th>$\Delta I^\circ$</th>
<th>$\Delta I^\circ/I^\circ$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Circular polarization of photon beam</td>
<td>&lt; 1.8 %</td>
<td></td>
</tr>
<tr>
<td>Target polarization</td>
<td>&lt; 4.33 %</td>
<td></td>
</tr>
<tr>
<td>Electron beam-charge asymmetry</td>
<td>&lt; 0.004</td>
<td></td>
</tr>
</tbody>
</table>

- Polarization Observables $P_z$ and $P_z^\circ$ will be first-time measurements for double-pion photoproduction.
- The event-based dilution factor can separate the background from the butanol data efficiently.
The Preliminary Results
Polarization Observable $P_z$

Back up

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NStar 2013 at Peniscola
May 27, 2013
Polarization observable $I^\odot$

$$I^\odot(W, \phi_{\pi^+}) = \frac{1}{\bar{\delta}(W)} \frac{1}{2} \left\{ \frac{N(\rightarrow; W, \phi_{\pi^+})_{\text{beam}} - N(\leftarrow; W, \phi_{\pi^+})_{\text{beam}}}{N(\rightarrow; W, \phi_{\pi^+})_{\text{beam}} + N(\leftarrow; W, \phi_{\pi^+})_{\text{beam}}} \right\}$$

- $\bar{\delta}(W)$: The average of the degree of the photon beam polarizations
- $\Lambda_{\pi}$: The degree of the target polarizations
- $F$: The photon flux (Normalization factor between periods)
- $\rightarrow$ (←): the direction of the beam polarization is parallel (anti-parallel) to the beam.
- $\Rightarrow$ (⇐): the direction of the target polarization is parallel (anti-parallel) to the beam.

Using the dataset with the unpolarized target and circularly-polarized beam

$$N(\rightarrow; W, \phi_{\pi^+})_{\text{beam}} = \frac{N(\rightarrow\Rightarrow; W, \phi_{\pi^+})_{\text{butanol}}}{\Lambda_{\pi}(\Rightarrow) \cdot F(\Rightarrow)} + \frac{N(\rightarrow\leftarrow; W, \phi_{\pi^+})_{\text{butanol}}}{\Lambda_{\pi}(\leftarrow) \cdot F(\leftarrow)}$$

$$N(\leftarrow; W, \phi_{\pi^+})_{\text{beam}} = \frac{N(\leftarrow\Rightarrow; W, \phi_{\pi^+})_{\text{butanol}}}{\Lambda_{\pi}(\Rightarrow) \cdot F(\Rightarrow)} + \frac{N(\leftarrow\leftarrow; W, \phi_{\pi^+})_{\text{butanol}}}{\Lambda_{\pi}(\leftarrow) \cdot F(\leftarrow)}$$
The Preliminary Results

Missing mass distribution in several CL-cuts.

- **1% CL-Cut**
  - Butanol-Data
  - CL-cut > 0.01
  - CL-cut < 0.01

- **5% CL-Cut**
  - Butanol-Data
  - CL-cut > 0.05
  - CL-cut < 0.05

- **10% CL-Cut**
  - Butanol-Data
  - CL-cut > 0.10
  - CL-cut < 0.10

- **15% CL-Cut**
  - Butanol-Data
  - CL-cut > 0.15
  - CL-cut < 0.15
The different CL-cuts have the different background effect. However, they have the similar values in the observable $I^\circ$. 

- g9a dataset is not sensitive to distinguish between the beam asymmetry from free-proton, bound-nucleon and background data.