Helicity Asymmetry $E$ for $\gamma p \rightarrow \pi^0 p$ from JLAB CLAS g9a/FROST dataset with application of Machine Learning

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Overview

1 Motivation

2 Event Selection

3 ML: Target Classification

4 ML: Hydrogen Contamination on Carbon

5 Helicity Asymmetry E

6 Next Steps
Baryon Spectroscopy is the study of excited nucleon states.

Different quark models have different degrees of freedom, causing different predictions of resonance states & parameters of resonances (mass, width, etc).
Motivation

Thomas Jefferson National Accelerator Facility (JLab)

JLab Continuous $e^-$ Beam Accelerator (6 Gev, before upgrade to 12 GeV)

<table>
<thead>
<tr>
<th>Electron Beam Energy (GeV)</th>
<th>Photon Beam Polarization</th>
<th># of Events (M)</th>
<th>Observable</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.645</td>
<td>Circular</td>
<td>$\sim$1000</td>
<td>E</td>
</tr>
<tr>
<td>2.478</td>
<td>Circular</td>
<td>$\sim$2000</td>
<td>E</td>
</tr>
<tr>
<td>2.751</td>
<td>Linear</td>
<td>$\sim$1000</td>
<td>G</td>
</tr>
<tr>
<td>3.538</td>
<td>Linear</td>
<td>$\sim$2000</td>
<td>G</td>
</tr>
<tr>
<td>4.599</td>
<td>Linear</td>
<td>$\sim$3000</td>
<td>G</td>
</tr>
</tbody>
</table>

Hall B g9a/FROST run from 12/2007 $\sim$ 2/2008
**CLAS g9a/FROST Experiment**

- Bremsstrahlung radiation (gold foil or thin diamond) → real polarized photon
- Dynamic Nuclear Polarization → polarized targets
- g9a/FROST - Circularly polarized photons with $E_\gamma \approx 0.4 - 2.4$ GeV and longitudinally polarized proton target
- 8 observables at fixed $(E_\gamma, \theta) \rightarrow 4$ helicity amplitudes → Resonances (PWA)

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$UP, P, LP, CP, B, T, R$ denote unpolarized, polarized, linearly polarized, circularly polarized, beam, target, and recoil, respectively.
Helicity Asymmetry $E$

- Double polarization observable $E$ is the helicity asymmetry of the cross section:

$$E = \frac{\sigma_{3/2} - \sigma_{1/2}}{\sigma_{3/2} + \sigma_{1/2}}$$

for $\frac{3}{2}$ & $\frac{1}{2}$ are total helicity states

- $\frac{d\sigma}{d\Omega}$ of polarized beam & polarized target for $E$ (theo. & exp.):

$$\left( \frac{d\sigma}{d\Omega} \right)_{\frac{1}{2}, \frac{3}{2}} = \frac{d\sigma_0}{d\Omega} (1 \mp (P_zP_\lambda)_{\frac{1}{2}, \frac{3}{2}} E)$$

$$\left( \frac{d\sigma}{d\Omega} \right)_{\frac{1}{2}, \frac{3}{2}} = \frac{N_{\frac{1}{2}, \frac{3}{2}}}{A \cdot F \cdot \rho \cdot \Delta \chi_i}$$

- $E$ is measured via:

$$E = \left[ \frac{1}{D_f} \right] \left[ \frac{1}{P_zP_\lambda} \right] \left[ \frac{N_{\frac{3}{2}} - N_{\frac{1}{2}}}{N_{\frac{3}{2}} + N_{\frac{1}{2}}} \right]$$

$D_f$ = dilution factor

$P_z$ = Polarization of target in $\hat{z}$

$P_\lambda$ = Polarization of beam

$N_{\frac{3}{2}, \frac{1}{2}}$ = # of events
Motivation

Butanol & Carbon Targets

- Butanol target ($C_4H_9OH$) consists of polarized hydrogen (free-nucleons) & unpolarized carbon and oxygen (bound-nucleons)
- Fermi motion of bound-nucleons $\rightarrow$ negative missing mass $M_{\pi^0}$
- Carbon target consists of unpolarized bound-nucleon
- Scale carbon target events & subtract from butanol target events
ML Objectives: Target Selection & Ice on Carbon

- Target Selection
  - Events with z-vertex \( \in [2, 5] \text{cm} \), uncertain whether \( \gamma \) hit Butanol or Carbon

- Ice on Carbon
  - Carbon events (bound-nucleon) expected to have broader \( m_{\pi^0}^2 \) peak due to Fermi motion.
  - Sharp peak (free-nucleon) observed in the Carbon target region.
Event Selections

(a) Proton selection

(b) Radial vertex selection

(c) Z-vertex selection

(d) Fiducial selection

(e) TOF paddles

(f) $M_X^2(E_\gamma, m_{p_1}, E_{p_f}, p_\gamma, p_{p_2})$
Neural Network Training Flowchart

Event → \( m \) → \( \phi_1 \) → \( \phi_2 \) → \( \phi_3 \) → \( \phi_4 \) → \( \phi_5 \) → \( \phi_6 \) → Weight update → Optimizer

→ \( E \) → \( \beta \) → \( m_{\pi_0}^2 \) → \( \vec{p} \) → \( \ldots \) → \( \phi_6 \) → \( W^{(2)} \) → Loss score → Loss fn

\( W^{(1)} \) → \( \phi_6 \) → \( W^{(2)} \) → Loss score → Loss fn

\( T \) → \( T' \) → Weight update → Optimizer
Training Data Selection

- Randomly select events with z-vertex position in close proximity of each targets
  - Butanol $\in [-3.3, 3.3]$cm
  - Carbon $\in [5.5, 7.0]$cm
  - Polythene $\in [15.5, 17.0]$cm
ML: Target Classification

Result on Target Selection

- Classified Carbon events from Butanol in $z$-vertex $\in [2.5, 4.5]$cm
- Some Carbon events in Polythene regions & Polythene events in Butanol region.
Training Data for Hydrogen Contamination

- Tight cut on the $m^2_{\pi_0}$ peak on g9a-Carbon data (or MC sim) as ice
  - Bound-nucleon (fermi p) → broader $m^2$ distribution
  - Sharper peaks from free-nucleon (ice) & Broad background from bound-nucleon (carbon)

- Randomly select events within three criterion:
  - Classified as carbon events in previous target classification distribution
  - Missing mass squared $\notin [-\sigma, \sigma]$  
  - Z-vertex position $\in [5.5, 6.5]$
Final Result of ML: ICE vs CARBON

- Classified ice events from Carbon target in z-vertex $\in [6.0, 7.5]$cm
- It is likely that ice was formed in 20 K heat shield in between Carbon and Polythene targets.

[Result from USC for $\gamma p \rightarrow \pi^+ n$]
Scale Factor \( \left( \frac{N_{C4H9OH}}{N_{C}} \right) \) & Dilution Factor

- Sector dependence only evident in low Energy: \( E_{\gamma} \sim [0, 0.45] \text{GeV} \)
- As \( E_{\gamma} \uparrow \), more interactions in butanol target than carbon
- \( D_f \bigg|_{\text{low lim}} = \frac{\text{free H in butanol}}{\text{total nucleon in butanol}} = \frac{10}{74} \approx 0.135 \)
- \( D_f(E_{\gamma}, \theta_{cm}) = \frac{N_{B,f}}{N_{B,tot}} \approx 1 - \frac{s(E_{\gamma}) \times N_{C}(E_{\gamma}, \theta_{cm})}{N_{B,tot}(E_{\gamma}, \theta_{cm})} \)
\[
E = \left[ \frac{1}{D_f} \right] \left[ \frac{1}{P_\gamma P_T} \right] \left[ \frac{N_3}{2} - \frac{N_1}{2} \right] \left[ \frac{N_3}{2} + \frac{N_1}{2} \right]
\]

- Result of \( \sim 30\% \) of JLab CLAS g9a experiment data
- Measured \( E \) comparison to SAID Partial Wave Analysis predictions
Next Steps

- Process all g9a data for full statistics
- Quantify uncertainties in neural network training
  - Bayesian Neural Network - probability distribution to weights and biases while training
  - Compute purity of the training data used for uncertainty
- Energy loss correction
- Systematic Error studies
- Measured E into world database \(\rightarrow\) more constrains on reaction amplitude

Acknowledgements

This work was performed with support from US DOE DE-SC001658, The George Washington University.
Backup Slides
Backup: Constituent Quark Models & LQCD Predictions of Non-Strange Baryon Resonances

Constituent Quark Model
- Constituent Quark Models predicted states: 64 \( N^* \) & 22 \( \Delta^* \)
- Experimentally confirmed state: 26 \( N^* \) & 22 \( \Delta^* \)
Backup: Hall B Photon Tagger

- Bremsstrahlung radiation due to slowing of electrons by EM field of radiator (gold foil or thinyo diamond)
- Determine incoming photon energy of $\gamma p \rightarrow \pi^0 p$ by $E_\gamma = E_0 - E_e$
- g9a/FROST - circularly polarized photons with $E_\gamma \approx 0.4 \sim 2.4$ GeV
- Tagger was built by the GWU, CUA, & ASU nuclear physics group
Polarization transfer:

\[ P(\gamma) = P(e) \frac{4x - x^2}{4 - 4x + 3x^2} \]

\[ x = \frac{k}{E_0} = \frac{\text{photon energy}}{\text{incident electron energy}} \]

Backup: Frozen Spin Target

The FroST target and its components:
A: Primary heat exchanger
B: 1 K heat shield
C: Holding coil
D: 20 K heat shield
E: Outer vacuum can (Rohacell extension)
F: CH2 target
G: Carbon target
H: Butanol target
J: Target insert
K: Mixing chamber
L: Microwave waveguide
M: Kapton coldseal

Performance Specs:
Base Temp: 28 mK w/o beam, 30 mK with
Cooling Power: 800 μW @ 50 mK, 10 mW @ 100 mK, and 60 mW @ 300 mK
Polarization: +82%, -90%
1/e Relaxation Time: 2800 hours (+Pol), 1600 hours (-Pol)
Roughly 1% polarization loss per day.

Backup: CLAS g9a/FROST Data

- Select only $\gamma \vec{p} \rightarrow \pi^0 p$ events
- $\gamma \vec{p} \rightarrow \pi^0 p$ resonance channels
- Appropriate energy bins - include all resonances ($\leq 1500$ MeV)
$\pi^0$ photoproduction

From $T$ Matrix to Helicity Amplitudes of $\gamma p \rightarrow \pi^0 p$:

\[
\langle q \ m_{s'} \ | \ T \ | \ k \ m_s \ \lambda \rangle = \langle m_{s'} \ | \ J \ | \ m_s \rangle \cdot \epsilon^\lambda(k) \quad \Rightarrow \quad H_i(\theta) \equiv \langle \lambda_2 | \ J | \lambda_1 \rangle
\]

4 Complex Helicity Amplitudes:

\[
H_1(\theta) = \langle +\frac{3}{2} \ | \ J \ | \ +\frac{1}{2} \rangle \\
H_2(\theta) = \langle +\frac{1}{2} \ | \ J \ | \ +\frac{1}{2} \rangle \\
H_3(\theta) = \langle +\frac{3}{2} \ | \ J \ | \ -\frac{1}{2} \rangle \\
H_4(\theta) = \langle +\frac{1}{2} \ | \ J \ | \ -\frac{1}{2} \rangle
\]
Backup: Complete Experiment - 8 Polarization Observables

- Polarizable: incoming photons, target & recoiling nucleons
- 8 well chosen observables at fixed $E_\gamma$ & angle → 4 helicity amplitudes

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- Helicity asymmetry $E$ related to other observables via Fierz identities:

\[
E^2 + F^2 + G^2 + H^2 = 1 + P^2 - \Sigma^2 - T^2 \\
FG - EH = P - \Sigma T \\
\vdots
\]
Overtraining Limits

- Overtraining:

  Excess training with only specific training data

  \[ L_D(h) \leq L_S(h) + \sqrt{\frac{(n+1)\log_2(d+3) + \log(2/\delta)}{2m}} \]

  \( L_D(h) \) = Error of classification on actual data set
  \( h \) = Error of classification on a training data set
  \( \delta \) = Confidence level of randomly selected training data points
  \( n \) = Number of nodes
  \( L_S(h) \) = Error of classification on a training data set
  \( d \) = Number of variables
  \( m \) = Size of training data sets
  • n & d inversely proportional to \( L_s \)
Proton Selection: $\Delta \beta$ Selection

- $\Delta \beta = \beta_{\text{measured}} - \beta_p = \beta_{\text{measured}} - \frac{p}{\sqrt{m_p^2 + p^2}}$
- Select events with only 1 positive outgoing particle (for $\gamma \vec{p} \rightarrow \pi^0 \vec{p}$)
- Measure $p$ (via curvature) and $\beta$ (via SC & TOF) of positive particles
- Select events with $\Delta \beta \approx 0$
Result on Hydrogen Contamination of Carbon Target

- Classified ice events from Carbon target in z-vertex $\in [6.0, 7.5]$ cm
- It is likely that ice was formed in 20 K heat shield in between Carbon and Polythene targets.
Final Result Target Classification
g9a/FROST Target setup

Side view of FROST target with beam entering from the right. (A) Primary head exchanger, (B) 1 K heat shield, (C) Holding coil, (D) 20 K heat shield, (E) Outer vacuum can, (F) Polyethylene target, (G) Carbon target, (H) Butanol target, (J) Target insert, (K) Mixing chamber, (L) Microwave waveguide, and (M) Kapton cold seal.
JLab Hall B Photon Tagger

- Bremsstrahlung radiation due to slowing of electrons by EM field of radiator (gold foil or thinyo diamond)
- Determine incoming photon energy of $\vec{\gamma}p \rightarrow \pi^0 p$ by $E_\gamma = E_0 - E_e$
- g9a/FROST - circularly polarized photons with $E_\gamma \approx 0.4 \sim 2.4$ GeV
- Tagger was built by the GWU, CUA, & ASU nuclear physics group
CEBAF Large Acceptance Spectrometer
Evidence of Hydrogen Contamination on Carbon

- Sharp peak at downstream end of Carbon foil → ice built up while cooling the target
- Ice formed on the right side of Carbon target: $Z$-vertex $\in [6, 7] \text{cm}$
- Plots from [Steffen Strauch]'s Analysis page of FROST Wikipage
Proton Selection: GPID bank

- $\Delta \beta = \beta_{\text{measured}} - \beta_p = \beta_{\text{measured}} - \frac{p}{\sqrt{m_p^2 + p^2}}$

- Select events with only 1 positive outgoing particle (for $\gamma p \rightarrow \pi^0 p$)

- Measure $p$ (via curvature) and $\beta$ (via SC & TOF) of positive particles

- Select events with $\Delta \beta \approx 0$
Photon Beam Selection

\[ \Delta t = t_{pv} - t_{\gamma v} \]

- time when \( p \) was at event vertex
- time when \( \gamma \) was at event vertex

- Readings from SC, DC & TOF system to determine \( t_{pv} \) & \( t_{\gamma v} \)
- JLab \( e^- \) beam sent in bunches separated by 2 ns
- Neglect events caused by photons emitted from different \( e^- \) bunches
- Select out events with \( \Delta t \approx 0 \)
Radial Vertex Selection - Target Cup

- Removed events outside of target cup ($d = 1.5\, cm$)
- He-Bath outer region
Inefficient Time-Of-Flight system paddles

- Events from inefficient scintillator paddles removed
- Sector2 - 25, Sector3 - 23, 35, Sector4 - 23 and etc
Fiducial Selection - Inactive CLAS regions

- Inactive regions of detector - coil of torus magnet, beamline holes, etc
- \( \theta < 7, -180 < \phi < -175, -125 < \phi < -115, -65 < \phi < -55 \)
- \(-5 < \phi < 5, 55 < \phi < 65, 115 < \phi < 125, 175 < \phi < 180 \)
Neural Network Model Setup

- Two fully-connected (dense) neural layers
  
  1. Dense layer with 15 nodes - 15 parameters:
     - $E, \beta, \beta_{diff}, \beta_m E_\gamma, m, m^2_{\pi 0}, \text{pid}, |p|, p_x, p_y, p_z, x, y, \text{and } z$.
     - Too many parameters + insufficient train data → Too specific training → Overfitting (fail)
  
  2. Dense layer with 3 nodes - one for each target
     - For each event, this layer returns an array of 3 probability scores (butanol, carbon, or polythene) that sum to 1

- Optimizer used: AdamOptimizer
- Loss function used - Sparse categorical cross entropy:
  
  \[ H_{y'}(y) = - \sum_i y'_i \log(y_i) \]
  , where $y_i$ is the predicted target and $y'_i$ is the true target

- Python and Tensorflow
Choosing Classifying Parameters

- Choose 10 ~ 15 adequately correlated parameters to avoid overfitting and underfitting

- Higher correlation $\rightarrow$ lesser contribution to classification

- Lower correlation $\rightarrow$ biased training $\rightarrow$ overfitting
Training Data for Carbon from g9b experiment

- g9b-carbon $m_{\pi^0}^2$ peak broader than g9a/Carbon $\rightarrow$ No ice on g9b
- During g9b, Carbon target was moved further in downstream.
- Shifted Z-vertex of g9b-Carbon events to use as training events for g9a [F. Klein].
- Failed (under investigation) $\rightarrow$ Different training data for carbon used
Neural Network Training Flowchart: ICE vs CARBON

Event → $m$ → $\phi_1$ → Ice → T
Event → $E$ → $\phi_2$ → $\phi_3$ → $\phi_4$ → $\phi_5$ → C12
Event → $\beta$ → $\phi_2$ → $\phi_3$ → $\phi_4$ → $\phi_5$ → C12
Event → $m_{\pi_0}^2$ → $\phi_3$ → $\phi_4$ → $\phi_5$ → C12
Event → $\vec{p}$ → $\phi_4$ → $\phi_5$ → C12
Event → $z$ → $\phi_6$ → $W^{(2)}$ → Loss score

Weight update → Optimizer → Loss fn → Loss score

$W^{(1)}$ → $W^{(2)}$
Dilution Factor

\[ D_f(E_\gamma, \theta_{cm}) = \frac{N_{B,f}}{N_{B,tot}} = \frac{N_{B,tot} - N_{B,b}}{N_{B,tot}} \approx 1 - \frac{s(E_\gamma) \times N_C(E_\gamma, \theta_{cm})}{N_{B,tot}(E_\gamma, \theta_{cm})} \]

\[ D_f \bigg|_{\text{low lim}} = \frac{\text{free H in butanol}}{\text{total nucleon in butanol}} = \frac{10}{74} \approx 0.135 \]