



Helicity Asymmetry E for $\gamma p \rightarrow \pi^0 p$ from FROST

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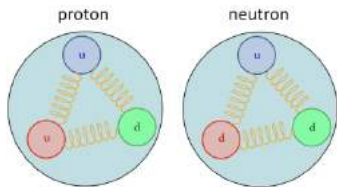
The George Washington University

CLAS Collaboration Meeting (HSWG)

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Baryon Spectroscopy

- Baryon Spectroscopy is the study of excited nucleon states.

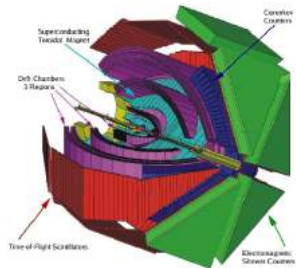
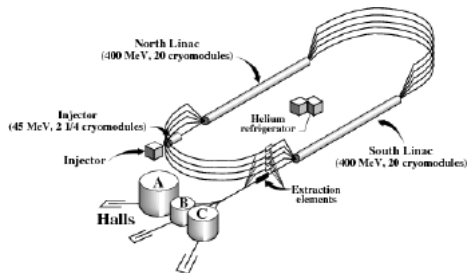


Excitation

Baryon											Meson													
Baryon											Meson													
Particle	J ^P	uud	udd	uuu	ddd	uus	uds	uds	dds	ddd	Particle	J ^P	quark	antiquark	u	d	s	c	b	Particle	J ^P	quark	antiquark	
...

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

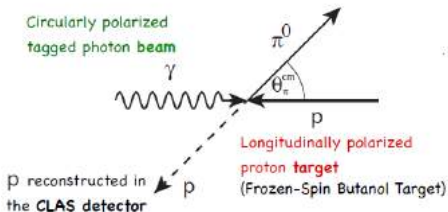


JLab Continuous e^- Beam Accelerator (6 GeV, before upgrade to 12 GeV)

Electron Beam Energy (GeV)	Photon Beam Polarization	# of Events (M)	Observable
1.645	Circular	~1000	E
2.478	Circular	~2000	E
2.751	Linear	~1000	G
3.538	Linear	~2000	G
4.599	Linear	~3000	G

Hall B g9a/FROST run from 12/2007 ~ 2/2008

CLAS g9a/FROST Experiment



- Bremsstrahlung radiation (gold foil or thin diamond) \rightarrow real polarized photon
- Dynamic Nuclear Polarization \rightarrow 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 \rightarrow Resonances (PWA)

	UP_T and UP_R	UP_T and P_R	P_T and UP_R	P_T and P_R
UP_B	$\frac{d\sigma}{d\Omega}$	P	T	$T_{x'}, T_{z'}, L_{x'}, L_{z'}$
LP_B	$-\Sigma$	$O_{x'}, (-T), O_{z'}$	$H, (-P), -G$	
CP_B		$-C_{x'}, -C_{z'}$	$F, -E$	

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:

$$E = \frac{\sigma_{3/2} - \sigma_{1/2}}{\sigma_{3/2} + \sigma_{1/2}} \quad \text{for } \frac{3}{2} \text{ \& } \frac{1}{2} \text{ are total helicity states}$$

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

$$\left(\frac{d\sigma}{d\Omega}\right)_{\frac{1}{2}, \frac{3}{2}} = \frac{d\sigma_0}{d\Omega} (1 \mp (P_z P_\lambda)_{\frac{1}{2}, \frac{3}{2}} E) \quad \left(\frac{d\sigma}{d\Omega}\right)_{\frac{1}{2}, \frac{3}{2}} = \frac{N_{\frac{1}{2}, \frac{3}{2}}}{A \cdot F \cdot \rho \cdot \Delta x_i}$$

- E is measured via:

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

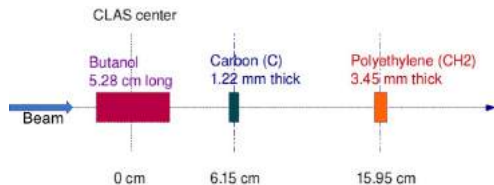
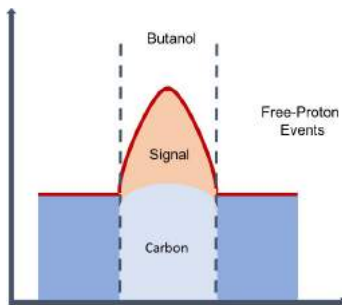
D_f = dilution factor

P_z = Polarization of target in \hat{z}

P_λ = Polarization of beam

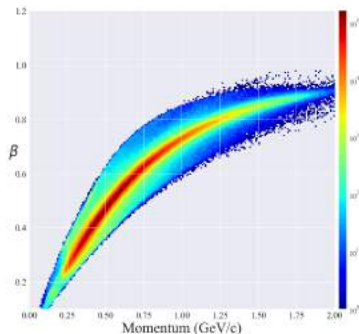
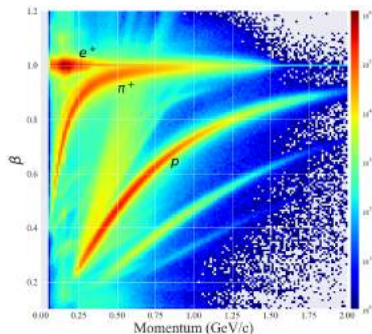
$N_{\frac{3}{2}, \frac{1}{2}}$ = # of events

Butanol & Carbon Targets



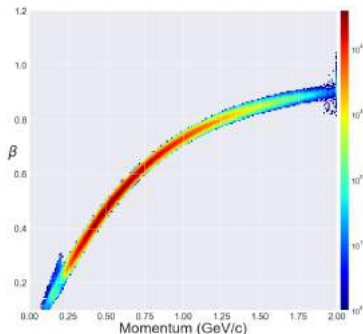
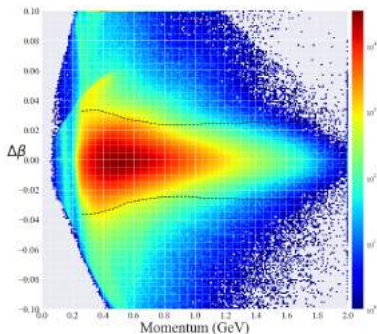
- Butanol target (C_4H_9OH) consists of polarized hydrogen (free-nucleons) & unpolarized carbon and oxygen (bound-nucleons)
- Fermi motion of bound-nucleons \rightarrow negative missing mass M_{π^0}
- Carbon target consists of unpolarized bound-nucleon
- Scale carbon target events & subtract from butanol target events

GPID for pid & MVRT for vertex positions



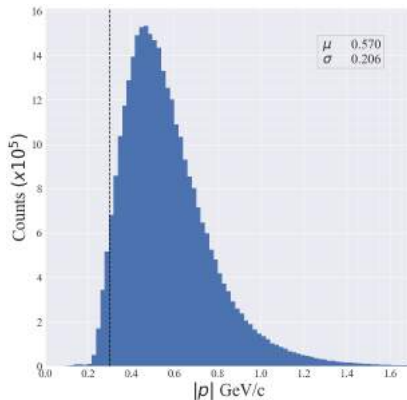
- Select events with only 1 positive outgoing particle (for $\vec{\gamma}\vec{p} \rightarrow \pi^0 p$)
- GPID matches photons in the tagging system for every charged particle.
- MVRT for single track vertex position - Closest distance to measured center of the beam

Proton Selection: $\Delta\beta$ Selection



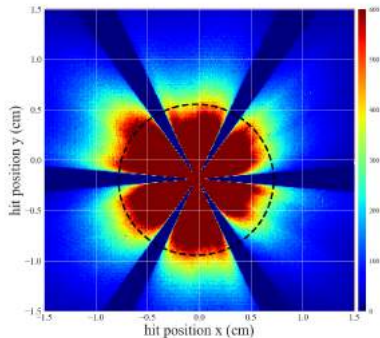
- $\Delta\beta = \beta_{\text{measured}} - \beta_p = \beta_{\text{measured}} - \frac{p}{\sqrt{m_p^2 + p^2}}$
- Measure p (via curvature) and β (via SC & TOF) of positive particles
- 2D $\Delta\beta$ distribution \rightarrow 1D in bins of 100 MeV momentum \rightarrow Gaussian fit
 \rightarrow Find μ, σ in each momentum bins
- Select events within $\Delta\beta < \mu \pm 3\sigma$

Low Momentum Removal



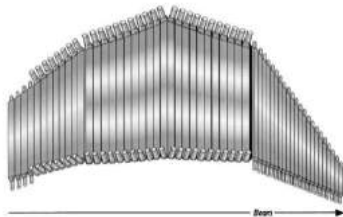
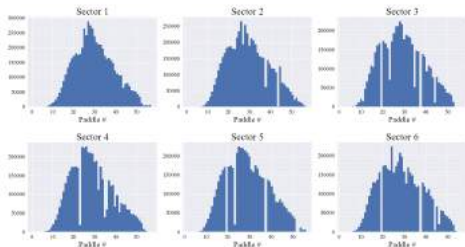
- Removal of particles with $|p| < 300$ MeV
- Low momentum \rightarrow cannot reach drift chambers
- Low momentum particles \rightarrow more energy loss in materials \rightarrow larger errors

Radial Vertex Selection - Target Cup



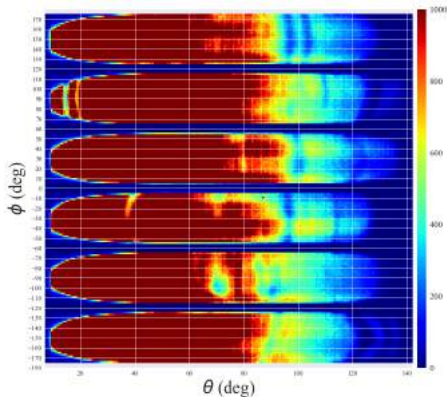
- Removed events outside of target cup ($d = 1.5 \text{ cm}$)
- He-Bath outer region

Inefficient Time-Of-Flight system paddles



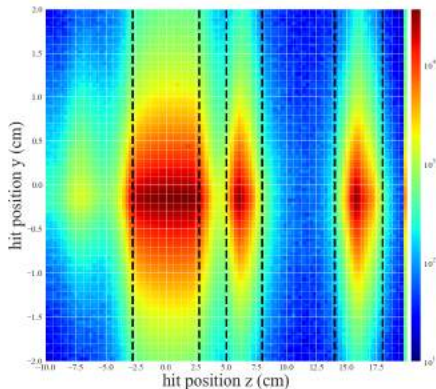
- Events from inefficient scintillator paddles removed
- Sector1 - 17, 24, Sector2 - 45, Sector3 - 23, 35
Sector4 - 23, 49, Sector5 - 23, 55, Sector6 - 54

Inactive CLAS regions



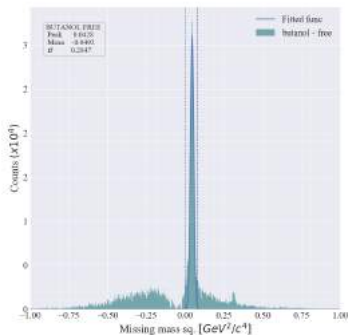
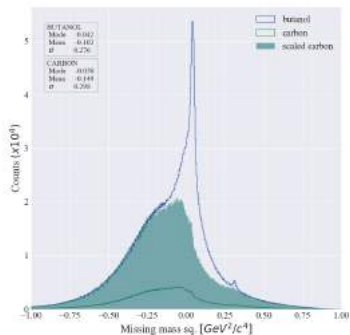
- Inactive regions of detector - coil of torus magnet, beamline holes, etc
- $\theta < 7$, $-180 < \phi < -175$, $-125 < \phi < -115$, $-65 < \phi < -55$ $-5 < \phi < 5$, $55 < \phi < 65$, $115 < \phi < 125$, $175 < \phi < 180$

Z-Vertex selection



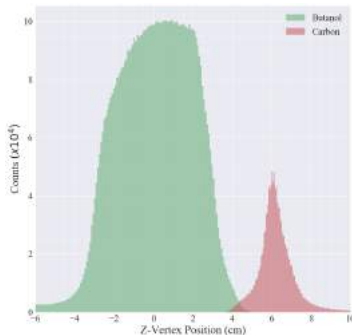
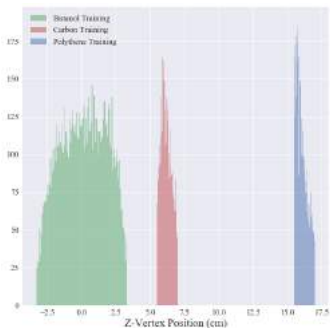
- Butanol - $[-2.75, 2.75]$ cm
- Carbon - $[5, 8]$ cm
- Polythene - $[14, 18]$ cm

Missing Mass Sq. Selection



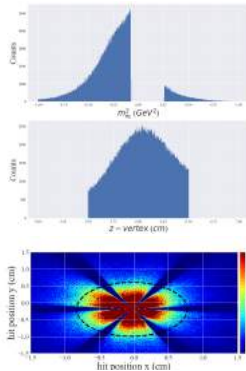
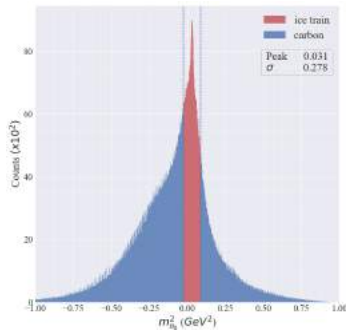
- $M_X^2 = (E_\gamma + m_{p_i} - E_{p_f})^2 - (\mathbf{p}_\gamma - \mathbf{p}_{p_2})^2$
- Butanol free-nucleon region by subtracting scaled carbon from total butanol events
- Select events within $M_X \leq M_{\pi^0} \pm 3\sigma$

Initial Target Classification



- 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
- 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 $m_{\pi_0}^2$ 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 carbon from initial target classification
 - Missing mass squared $\notin [-\sigma, \sigma]$
 - Z-vertex position $\in [5.5, 6.5]$
 - Events within target cup (r=7.5mm)

Final Result of ML: ICE vs CARBON

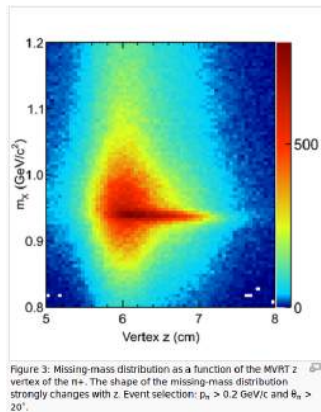
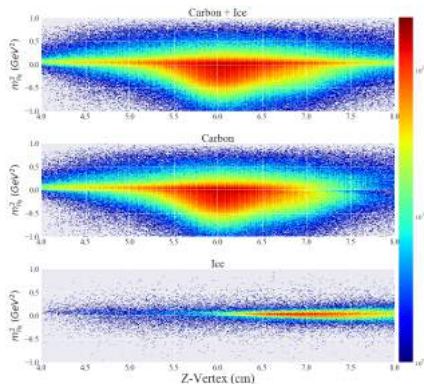
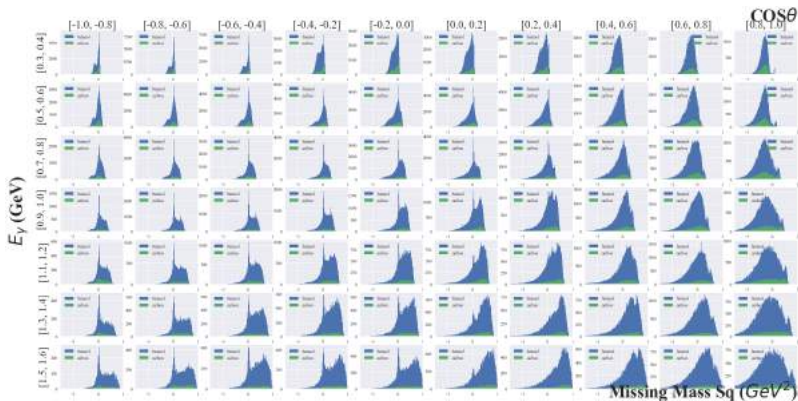


Figure 3: Missing-mass distribution as a function of the MVRT z-vertex of the n^+ . The shape of the missing-mass distribution strongly changes with z. Event selection: $p_n > 0.2$ GeV/c and $\theta_n > 20^\circ$.

[Result from USC for $\gamma p \rightarrow \pi^+ n$]

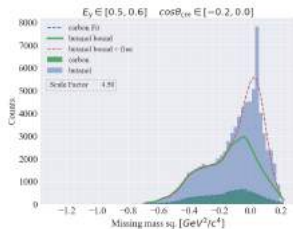
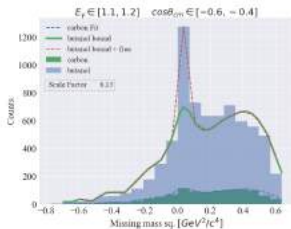
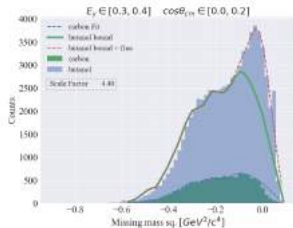
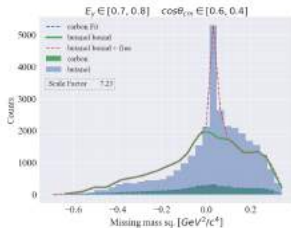
- Classified ice events from Carbon target in z-vertex $\in [6.0, 7.5]$ cm
- It is likely that ice was formed in 20 K heat shield in between Carbon and Polythene targets.

Scale Factor ($\frac{N_{C_4H_9OH}}{N_C}$) & Dilution Factor



- As $E_\gamma \uparrow$, more interactions in butanol target than carbon
- $D_f \Big|_{\text{low lim}} = \frac{\text{free H in butanol}}{\text{total nucleon in butanol}} = \frac{10}{74} \approx 0.135$
- $D_f(E_\gamma, \theta_{cm}) = \frac{N_{B,f}}{N_{B,tot}} \approx 1 - \frac{s(E_\gamma) \times N_C(E_\gamma, \theta_{cm})}{N_{B,tot}(E_\gamma, \theta_{cm})}$

Scale Factor $\left(\frac{N_{C_4H_9OH}}{N_C}\right)$



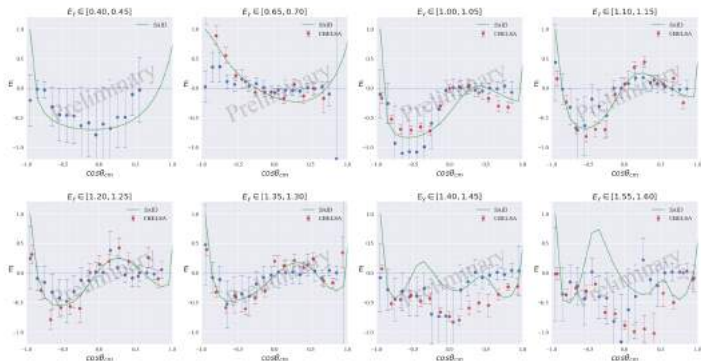
- Fit carbon with splines polynomials
- Splines + Gaussian to fit butanol
- Extract scale factor

$$B(x) = \alpha C(x) + S(x)$$

$$C(x) = p_2(x_0, \dots, x_i)$$

$$S(x) = A \exp\left[-\frac{(x - m_0^2)^2}{2\sigma^2}\right]$$

Preliminary: Helicity Asymmetry E



- $$E = \left[\frac{1}{D_f} \right] \left[\frac{1}{P_\gamma P_T} \right] \left[\begin{array}{c} N_{3/2} - N_{1/2} \\ N_{3/2} + N_{1/2} \end{array} \right]$$
- Measured E comparison to SAID Partial Wave Analysis predictions & CBELSA measurements
- Large error from low photon polarization (20% - 83%) & incomplete scale factor calculation

Next Steps

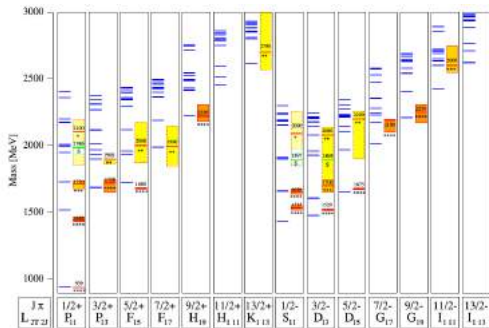
- Compute scale factor for all energy and $\cos\theta_{cm}$ bins
- Add 2.4 GeV dataset
- Energy loss correction
- Systematic Error studies
- Compute E without Machine learning to see effects of ML
- Quantify uncertainties in neural network training
 - Bayesian Neural Network - probability distribution to weights and biases while training
 - Compute purity of the training data used for uncertainty
- Measured E into world database \rightarrow more constrains on reaction amplitude

Acknowledgements

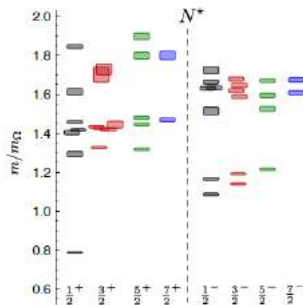
This work was performed with support from US DOE DE-SC001658, The George Washington University.

Backup Slides

Backup: Constituent Quark Models & LQCD Predictions of Non-Strange Baryon Resonances



Constituent Quark Model

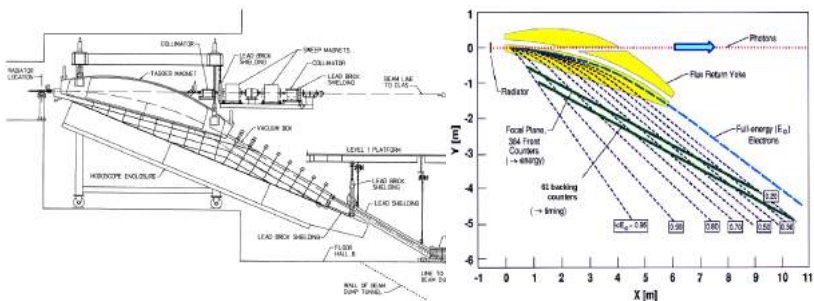


Lattice QCD

- Constituent Quark Models predicted states: 64 N^* & 22 Δ^*
- Experimentally confirmed state: 26 N^* & 22 Δ^*

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 $\vec{\gamma}\vec{p} \rightarrow \pi^0 p$ 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



Backup: Circularly Polarized Photon Beam

Linearly
Polarized
Electron Beam

Bremsstrahlung



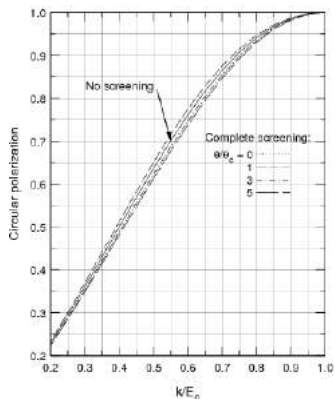
Circularly
Polarized
Photon Beam

- Polarization transfer:

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

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

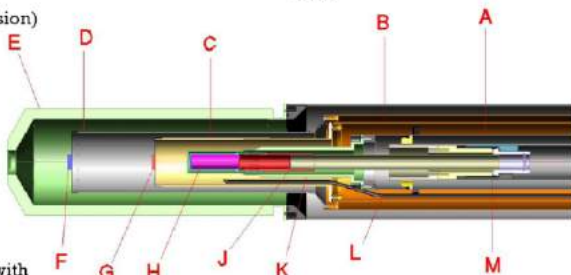
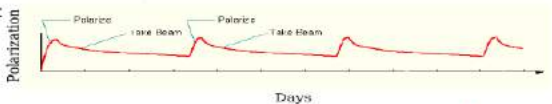
H. Olsen and L.C. Maximon, Phys. Rev. 114, 887 (1959)



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

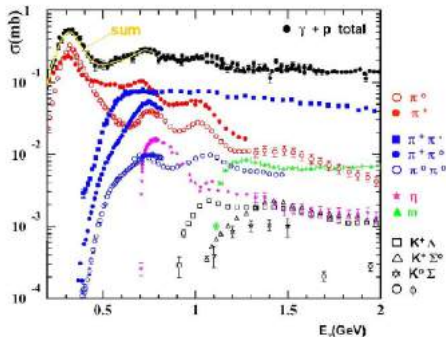
Cooling Power: 800 μ W @ 80 mK, 10 mW @ 100 mK, and 60 mW @ 300 mK

Polarization: +82%, -90%

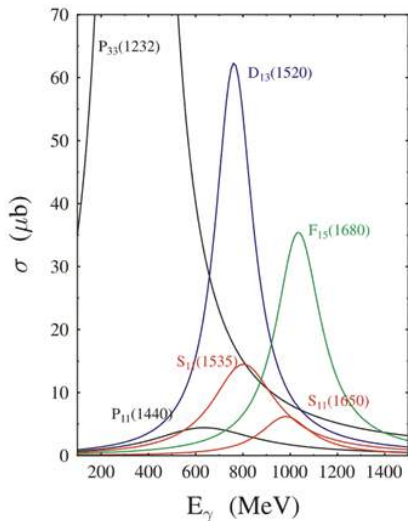
1/e Relaxation Time: 2800 hours (+Pol), 1600 hours (-Pol)

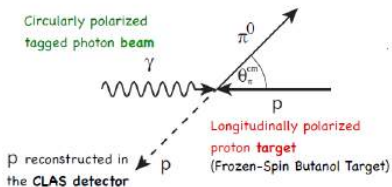
Roughly 1% polarization loss per day.

Backup: CLAS g9a/FROST Data



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



π^0 photoproduction

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

$$\langle \mathbf{q} m_{s'} | T | \mathbf{k} m_s \lambda \rangle = \langle m_{s'} | \mathbf{J} | m_s \rangle \cdot \epsilon_{\lambda}(\mathbf{k}) \quad \longrightarrow \quad H_i(\theta) \equiv \langle \lambda_2 | \mathbf{J} | \lambda_1 \rangle$$

- 4 Complex Helicity Amplitudes:

$$H_1(\theta) = \left\langle +\frac{3}{2} \left| \mathbf{J} \right| +\frac{1}{2} \right\rangle$$

$$H_2(\theta) = \left\langle +\frac{1}{2} \left| \mathbf{J} \right| +\frac{1}{2} \right\rangle$$

$$H_3(\theta) = \left\langle +\frac{3}{2} \left| \mathbf{J} \right| -\frac{1}{2} \right\rangle$$

$$H_4(\theta) = \left\langle +\frac{1}{2} \left| \mathbf{J} \right| -\frac{1}{2} \right\rangle$$

Evidence of Hydrogen Contamination on Carbon

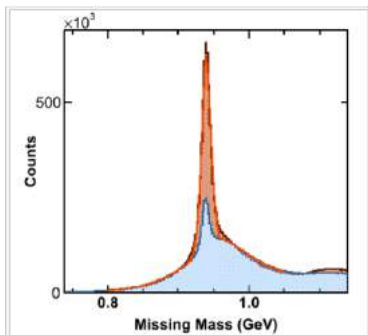


Figure 2: Missing-mass distribution for the $n+n$ channel from FROST g9a data, $W = 1.25 - 1.50$ GeV, integrated over all angles. Events in the red histogram are from the butanol target and events in the blue histogram are from the ^{12}C target with z -vertex larger 5.0 cm and smaller than 7.5 cm. The blue histogram is scaled by 5.26. The FROST distribution from the ^{12}C target region show a **narrow peak** at the mass of then neutron.

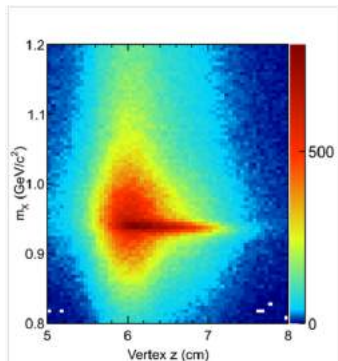
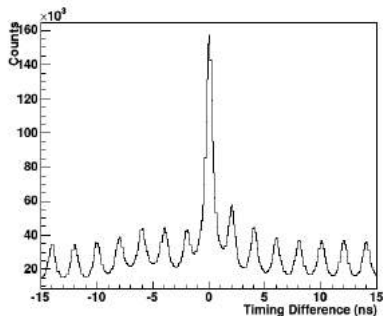


Figure 3: Missing-mass distribution as a function of the MVRT z vertex of the $n+$. The shape of the missing-mass distribution strongly changes with z . Event selection: $p_x > 0.2$ GeV/c and $\theta_n > 20^\circ$.

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

Photon Beam Selection



$$\Delta t = t_{pV} - t_{\gamma V}$$

= time when p was at event vertex

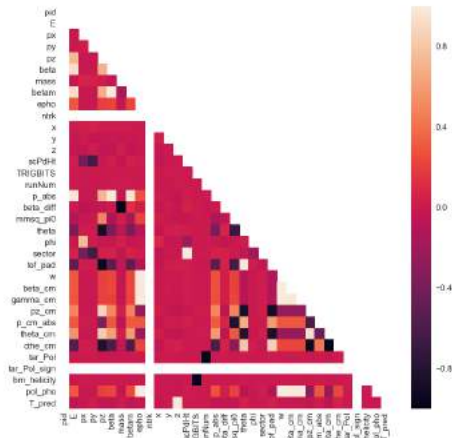
– time when γ was at event vertex

- 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 $\Delta t \approx 0$

Neural Network Model Setup

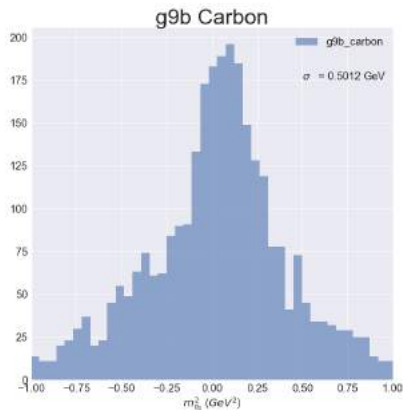
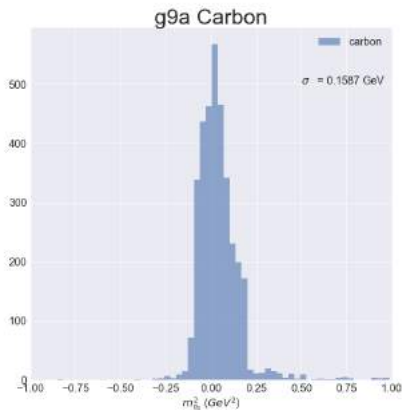
- Two fully-connected (dense) neural layers
 - 1 Dense layer with 15 nodes - 15 parameters:
 - $E, \beta, \beta_{diff}, \beta_m, E_\gamma, m, m_{\pi_0}^2, pid, |p|, p_x, p_y, p_z, x, y,$ and z .
 - Too many parameters + insufficient train data \rightarrow Too specific training \rightarrow Overfitting (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 → lesser contribution to classification
- Lower correlation → biased training → overfitting

Training Data for Carbon from g9b experiment



- g9b-carbon $m_{\pi_0}^2$ peak broader than g9a/Carbon → 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) → Different training data for carbon used

Neural Network Training Flowchart: ICE vs CARBON

