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

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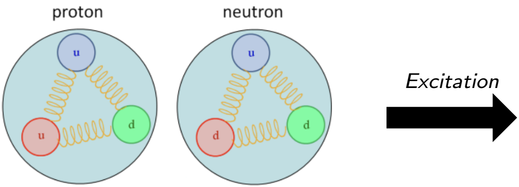
APS Division of Nuclear Physics
October 15, 2019

Overview

Baryon Spectroscopy

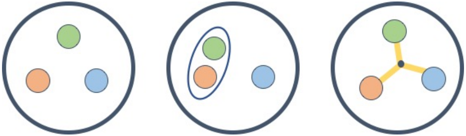
- Baryon Spectroscopy is the study of excited nucleon states.



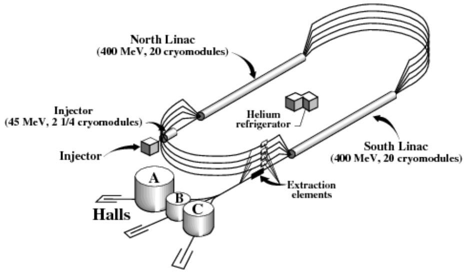
Particle	J^P	Status overall	πN	γN	$N\eta$	$N\sigma$	$N\omega$	ΛK	ΣK	$N\rho$	$\Delta\pi$
N	$1/2^+$	****									
$N(1440)$	$1/2^+$	****	****	****		***				*	***
$N(1520)$	$3/2^-$	****	****	****	***					***	***
$N(1535)$	$1/2^-$	****	****	****	****					**	*
$N(1650)$	$1/2^-$	****	****	***	***			***	**	**	***
$N(1675)$	$5/2^-$	****	****	***	*			*		*	***
$N(1680)$	$5/2^+$	****	****	****	*	**				***	***
$N(1685)$	??	*									
$N(1700)$	$3/2^-$	***	***	**	*			*	*	*	***
$N(1710)$	$1/2^+$	***	***	***	***		**	***	**	*	**
$N(1720)$	$3/2^+$	****	****	***	***			**	**	**	*
$N(1860)$	$5/2^+$	**	**							*	*
$N(1875)$	$3/2^-$	***	*	***			**	***	**		***
$N(1880)$	$1/2^+$	**	*	*		**		*			
$N(1895)$	$1/2^-$	**	*	**	**			**	*		
$N(1900)$	$3/2^+$	***	**	***	**		**	***	**	*	**
$N(1990)$	$7/2^+$	**	**	**					*		
$N(2000)$	$5/2^+$	**	*	**	**			**	*	**	
$N(2040)$	$3/2^+$	*									
$N(2060)$	$5/2^-$	**	**	**	*				**		
$N(2100)$	$1/2^+$	*									
$N(2150)$	$3/2^-$	**	**	**				**			**
$N(2190)$	$7/2^-$	****	****	***			*	**		*	
$N(2220)$	$9/2^+$	****	****								
$N(2250)$	$9/2^-$	****	****								
$N(2600)$	$11/2^-$	***	***								
$N(2700)$	$13/2^+$	**	**								

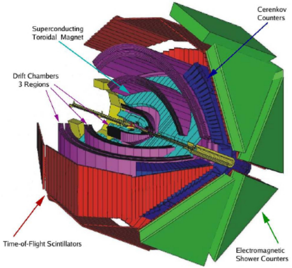
Particle	J^P	Status overall	πN	γN	$N\eta$	$N\sigma$	$N\omega$	ΛK	ΣK	$N\rho$	$\Delta\pi$
$\Delta(1232)$	$3/2^+$	****	****	****	F						
$\Delta(1600)$	$3/2^+$	***	***	***	o					*	***
$\Delta(1620)$	$1/2^-$	****	****	***		r				***	***
$\Delta(1700)$	$3/2^-$	****	****	****		b				**	***
$\Delta(1750)$	$1/2^+$	*	*				i				
$\Delta(1900)$	$1/2^-$	**	**	**			d		**	**	**
$\Delta(1905)$	$5/2^+$	****	****	****			d		***	**	**
$\Delta(1910)$	$1/2^+$	****	****	**				e	*	*	**
$\Delta(1920)$	$3/2^+$	***	***	**				n	***		**
$\Delta(1930)$	$5/2^-$	***	***								
$\Delta(1940)$	$3/2^-$	**	*	**	F				(seen	in	$\Delta\eta$)
$\Delta(1950)$	$7/2^+$	****	****	****	o				***	*	***
$\Delta(2000)$	$5/2^+$	**				r					**
$\Delta(2150)$	$1/2^-$	*	*			b					
$\Delta(2200)$	$7/2^-$	*	*				i				
$\Delta(2300)$	$9/2^+$	**	**				d				
$\Delta(2350)$	$5/2^-$	*	*				d				
$\Delta(2390)$	$7/2^+$	*	*					e			
$\Delta(2400)$	$9/2^-$	**	**					n			
$\Delta(2420)$	$11/2^+$	****	****	*							
$\Delta(2750)$	$13/2^-$	**	**								
$\Delta(2950)$	$15/2^+$	**	**								

- 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)

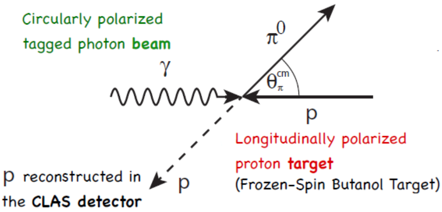




Electron Beam Energy (GeV)	Photon Beam Polarization	# of Events (M)	Observable
1.645	Circular	∼1000	E
2.478	Circular	∼2000	E
2.751	Linear	∼1000	G
3.538	Linear	∼2000	G
4.599	Linear	∼3000	G

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

CLAS g9a/FROST Experiment



- Bremsstrahlung radiation (gold foil or thin diamond) → real polarized photon
- Dynamic Nulcear 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_γ, θ) → 4 helicity amplitudes → 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:

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

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

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

- E is measured via:

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

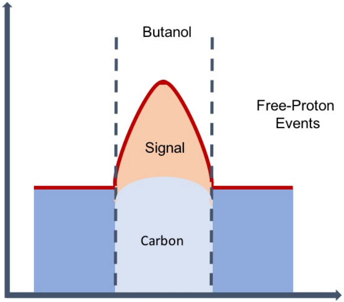
D_f = dilution factor

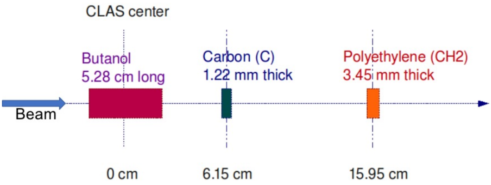
P_z = Polarization of target in $\hat{z}$

P_λ = Polarization of beam

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

Butanol & Carbon Targets

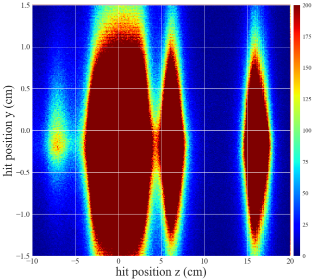




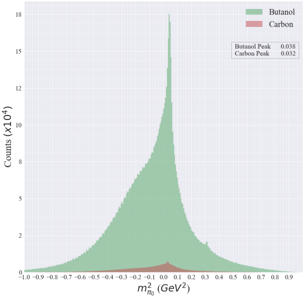
- Butanol target (C_4H_9OH) consists of polarized hydrogen (free-nucleons) & unpolarized carbon and oxygen (bound-nucleons)
- Fermi motion of bound-nucleons $\rightarrow$ negative missing mass M_{π^0}
- Carbon target consists of unpolarized bound-nucleon
- Scale carbon target events & subtract from butanol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

ML Objectives: Target Selection & Ice on Carbon

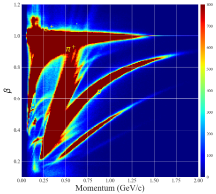
- Target Selection
  - Events with z-vertex $\in [2, 5]$cm, uncertain whether γ hit Butanol or Carbon



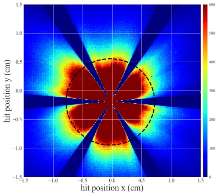
- Ice on Carbon
  - Carbon events (bound-nucleon) expected to have broader $m^2_{\pi_0}$ peak due to Fermi motion.
  - Sharp peak (free-nucleon) observed in the Carbon target region.



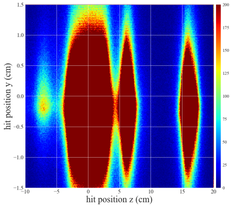
Event Selections



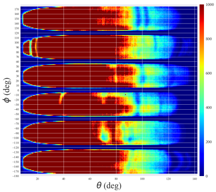
(a) Proton selection



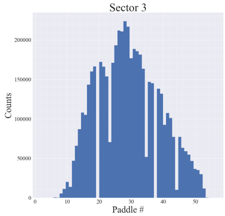
(b) Radial vertex selection



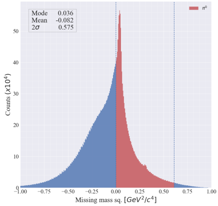
(c) Z-vertex selection



(d) Fiducial selection

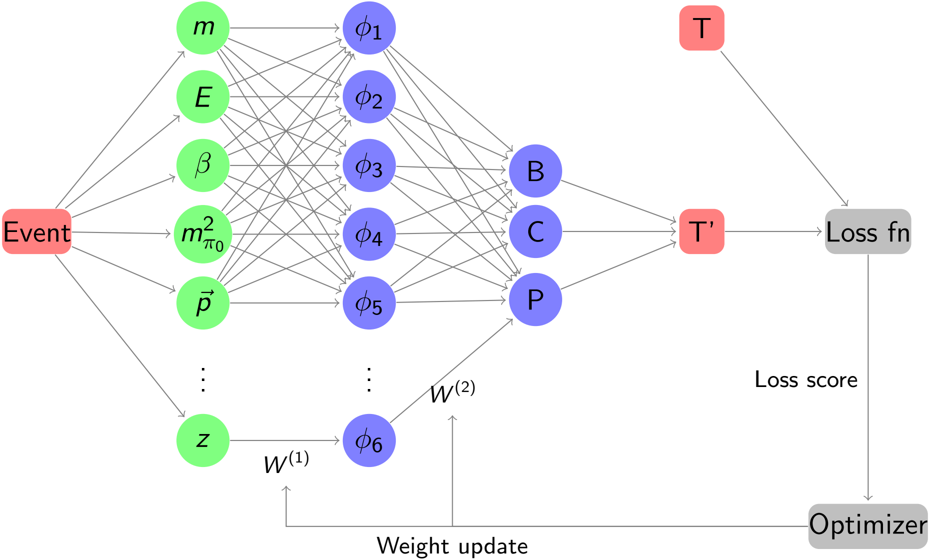


(e) TOF paddles

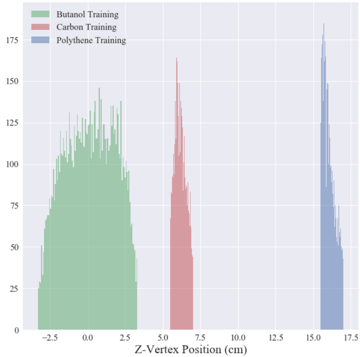


(f) $M_X^2(E_\gamma, m_{p_i}, E_{p_f}, \mathbf{p}_\gamma, \mathbf{p}_{p_2})$

Neural Network Training Flowchart

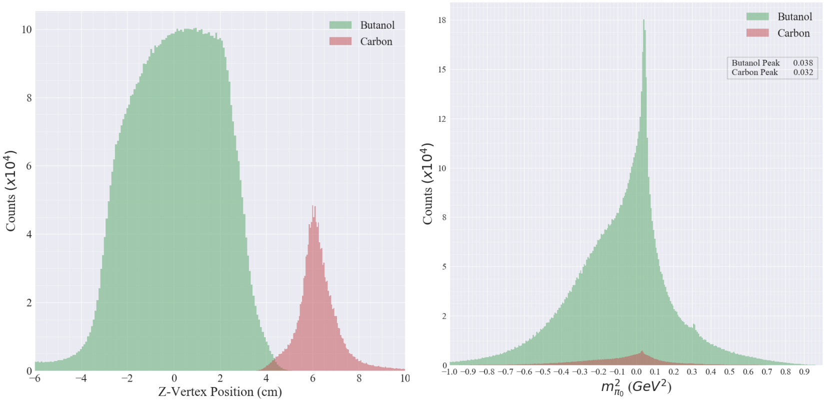


Training Data Selection



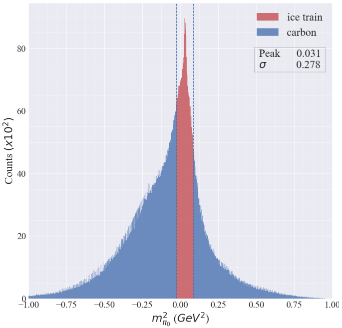
- Randomly select events with z-vertex position in close proximity of each targets
  - Butanol $\in$ [-3.3, 3.3]cm
  - Carbon $\in$ [5.5, 7.0]cm
  - Polythene $\in$ [15.5, 17.0]cm

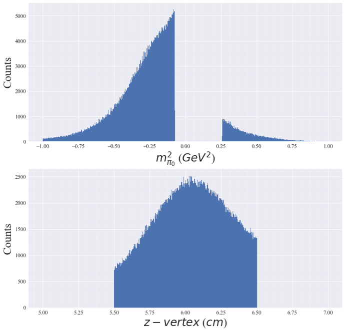
Result on Target Selection



- Classified Carbon events from Butanol in z-vertex ∈ [2.5, 4.5]cm
- Some Carbon events in Polythene regions & Polythene events in Butanol region.

Training Data for Hydrogen Contamination

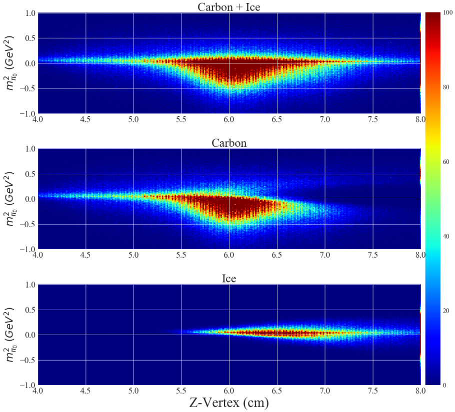




- Tight cut on the $m^2_{\pi_0}$ peak on g9a-Carbon data (or MC sim) as ice
  - Bound-nucleon (fermi p) $\rightarrow$ broader m^2 distribution
  - Sharper peaks from free-nucleon (ice) & Broad background from bound-nucleon (carbon)

- 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



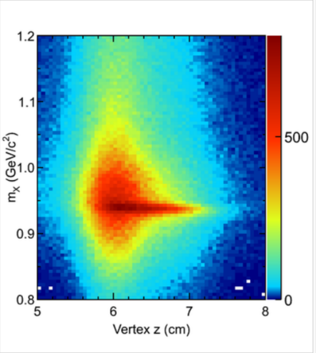
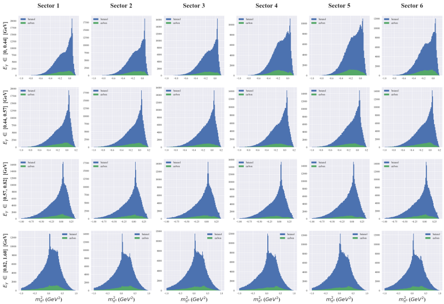


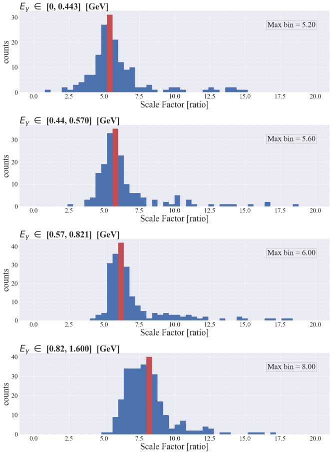
Figure 3: Missing-mass distribution as a function of the MVRT z vertex of the π+. The shape of the missing-mass distribution strongly changes with z. Event selection: $p_\pi > 0.2$ GeV/c and $\theta_\pi > 20^\circ$.

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

- 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.

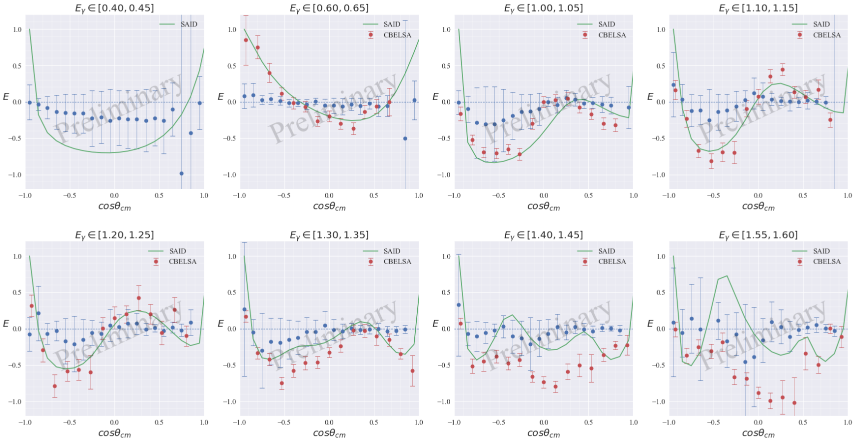
Scale Factor ($\frac{N_{C_4H_9OH}}{N_C}$) & Dilution Factor





- Sector dependence only evident in low Energy: $E_\gamma \sim [0, 0.45] GeV$
- As $E_\gamma \uparrow$, more interactions in butanol target than carbon
- $D_f\big|_{\text{low lim}} = \frac{\text{free H in butanol}}{\text{total nucleon in butanol}} = \frac{10}{74} \cong 0.135$
- $D_f(E_\gamma, \theta_{cm}) = \frac{N_{B,f}}{N_{B,tot}} \cong 1 - \frac{s(E_\gamma) \times N_C(E_\gamma, \theta_{cm})}{N_{B,tot}(E_\gamma, \theta_{cm})}$

Preliminary: Helicity Asymmetry E



- $E = \left[\frac{1}{D_f}\right]\left[\frac{1}{P_\gamma P_T}\right]\left[\frac{N_{\frac{3}{2}} - N_{\frac{1}{2}}}{N_{\frac{3}{2}} + N_{\frac{1}{2}}}\right]$
- Result of $\sim 30\%$ of JLab CLAS g9a experiment data
- Measured E comparison to SAID Partial Wave Analysis predictions

Next Steps

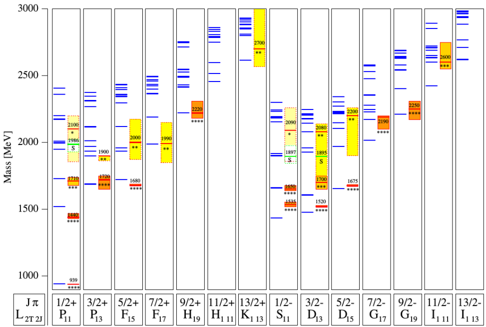
- Process all g9a data for full statistics
- Quantify uncertainties in neural network training
  - Bayesian Neural Network - probability distribution to weights and biases while training
  - Compute purity of the training data used for uncertainty
- Energy loss correction
- Systematic Error studies
-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

Acknowledgements

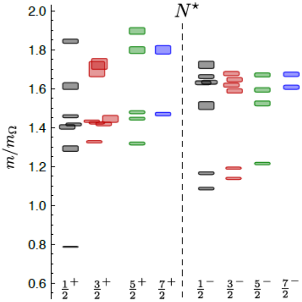
This work was performed with support from US DOE DE-SC001658, The George Washington University.

Backup Slides

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



Constituent Quark Model

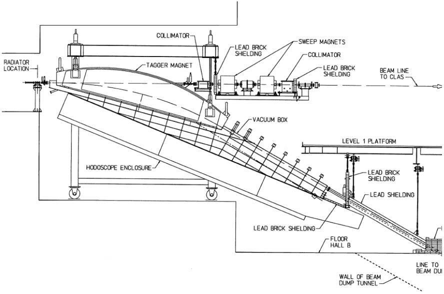


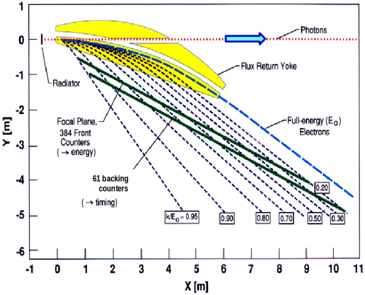
Lattice QCD

- 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

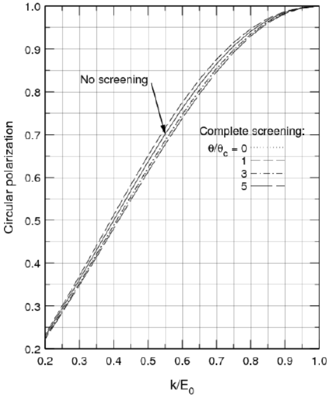
Linearly Polarized Electron Beam → *Bremsstrahlung* → Circularly Polarized Photon Beam

- Polarization transfer:

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

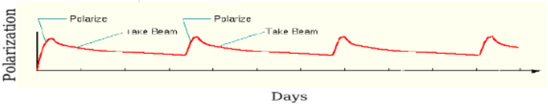
$$x = \frac{k}{E_0} = \frac{\text{photon energy}}{\text{incident electron energy}}$$

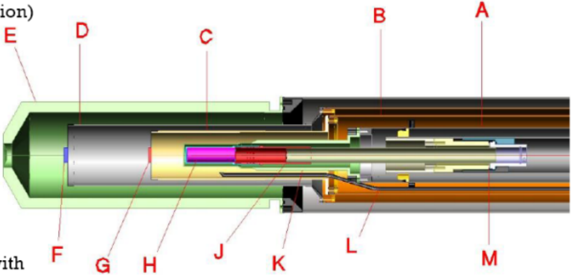
H. Olsen and L.C. Maximon, Phys. Rev. 114, 887 (1959)



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

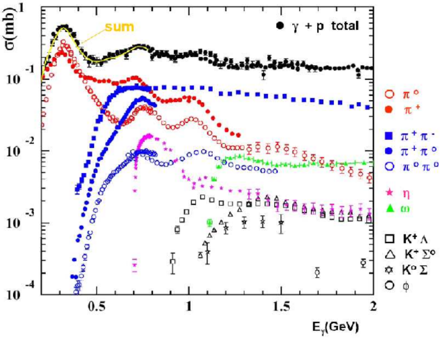




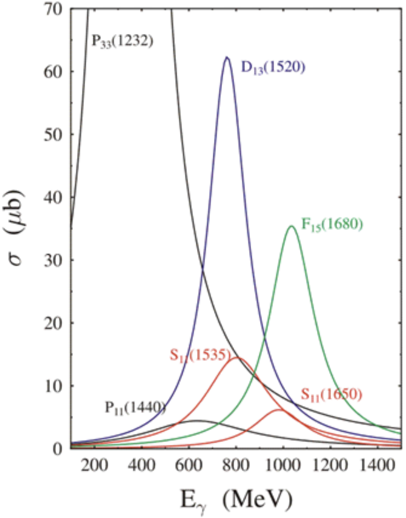
Performance Specs:
Base Temp: 28 mK w/o beam, 30 mK with
Cooling Power: 800 μW @ 50 mK, 10 mW @ 100 mK, and 60 mW @ 300 mK
Polarization: +82%, -90%
1/e Relaxation Time: 2800 hours (+Pol), 1600 hours (-Pol)
Roughly 1% polarization loss per day.

C. Keith et al. Nucl Instrum Meth A 684, 27 (2012)

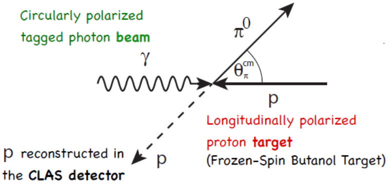
Backup: CLAS g9a/FROST Data



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



π^0 photoproduction



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

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

- 4 Complex Helicity Amplitudes:

$$H_1(\theta) = \left\langle +\frac{3}{2} \middle| \mathbf{J} \middle| +\frac{1}{2} \right\rangle \qquad H_2(\theta) = \left\langle +\frac{1}{2} \middle| \mathbf{J} \middle| +\frac{1}{2} \right\rangle$$

$$H_3(\theta) = \left\langle +\frac{3}{2} \middle| \mathbf{J} \middle| -\frac{1}{2} \right\rangle \qquad H_4(\theta) = \left\langle +\frac{1}{2} \middle| \mathbf{J} \middle| -\frac{1}{2} \right\rangle$$

Backup: Complete Experiment - 8 Polarization Observables

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

	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 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

$\downarrow$

Classification succeeds on training data, but fails on actual data

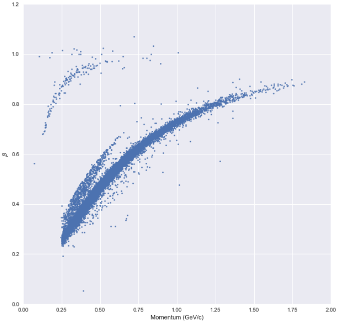
- Must determine adequate classifying variables & size of training data
- Rule of thumb for Decision Tree algorithm:

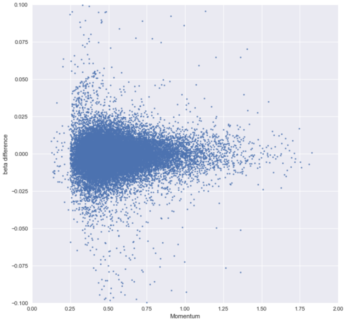
$$L_D(h) \quad \leq \quad L_S(h) + \sqrt{\frac{(n+1)\log_2(d+3) + \log(2/\delta)}{2m}}$$

$L_D(h)$ = Error of classification on actual data set
h = Error of classification on a training data set
δ = 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

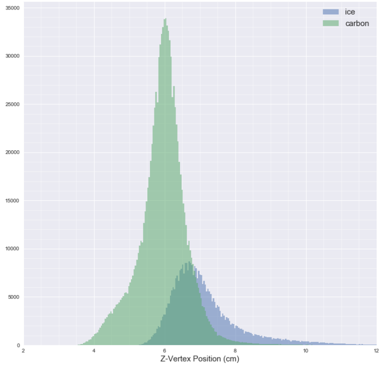
Proton Selection: $\Delta\beta$ Selection

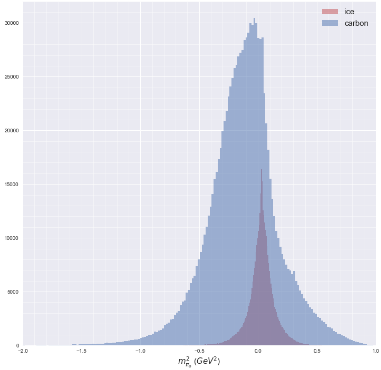




- $\Delta\beta = \beta_{\text{measured}} - \beta_{p} = \beta_{\text{measured}} - \frac{p}{\sqrt{m_p^2 + p^2}}$
- Select events with only 1 positive outgoing particle (for $\vec{\gamma}\vec{p} \to \pi^0 p$)
- Measure p (via curvature) and β (via SC & TOF) of positive particles
- Select events with $\Delta\beta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

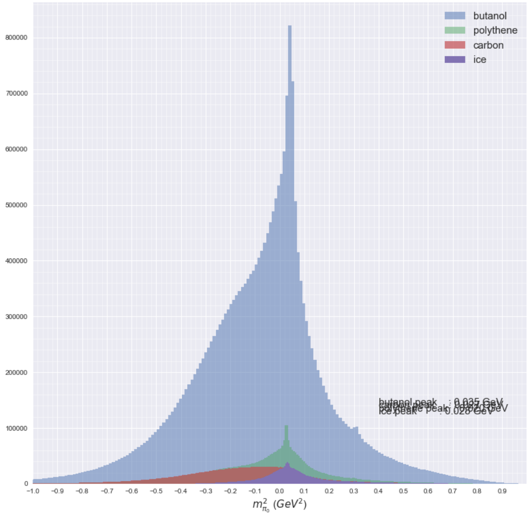
Result on Hydrogen Contamination of Carbon Target



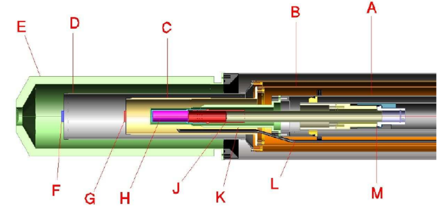


- Classified ice events from Carbon target in z-vertex $\in$ [6.0, 7.5]cm
- It is likely that ice was formed in 20 K heat shield in between Carbon and Polythene targets.

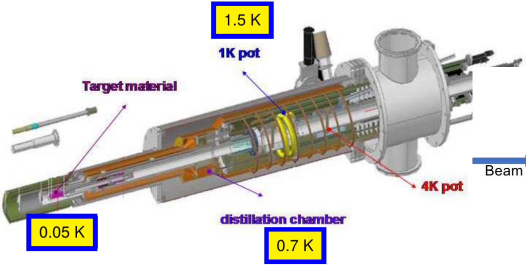
Final Result Target Classification

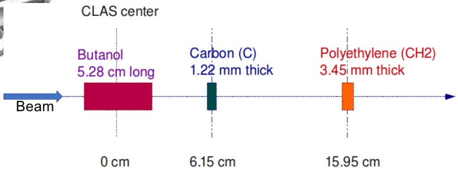


g9a/FROST Target setup



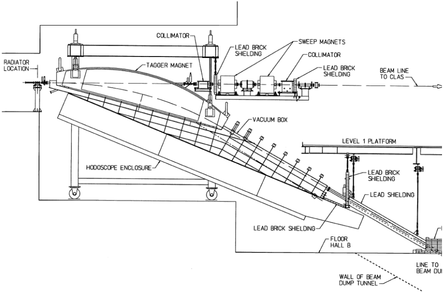
Side view of FROST target with beam entering from the right. (A) Primary head exchanger, (B) 1 K heat shield, (C) Holding coil, (D) 20 K heat shild,(E) Outer vacuum can , (F) Polyethylene target,(G) Carbon target,(H) Butanol target ,(J) Target insert, (K) Mixing chamber, (L) Microwave waveguide, and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

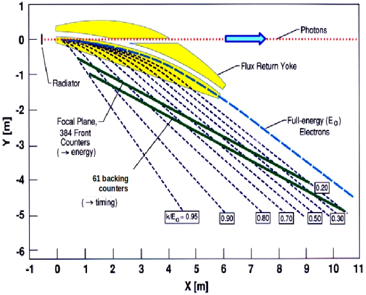




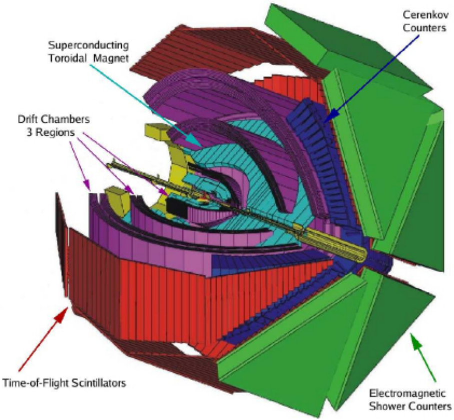
JLab Hall B Photon Tagger

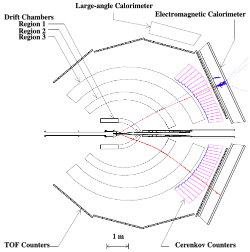
- Bremsstrahlung radiation due to slowing of electrons by EM field of radiator (gold foil or thinyo diamond)
- Determine incoming photon energy of $\vec{\gamma}\vec{p} \to \pi^0 p$ by $E_\gamma = E_0 - E_e$
- g9a/FROST - circularly polarized photons with $E_\gamma \approx 0.4 \sim 2.4\ GeV$
- Tagger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

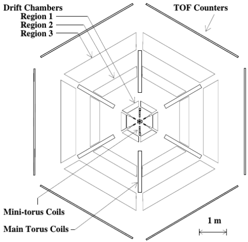




CEBAF Large Acceptance Spectrometer







Evidence of Hydrogen Contamination on Carbon

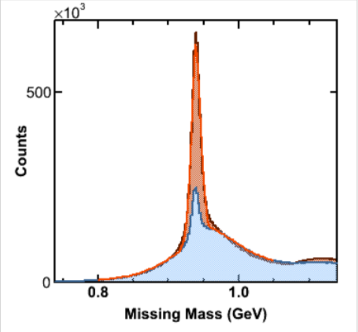


Figure 2: Missing-mass distribution for the π+n channel from FROST g9a data. W = 1.25 - 1.50 GeV, integrated over all angles. Events in the red histogram are from the butanol target and events in the blue histogram are from the 12C target with z-vertex larger 5.0 cm and smaller than 7.5 cm. The blue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

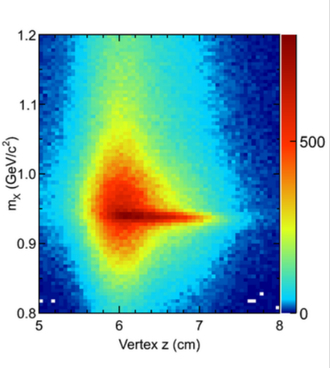
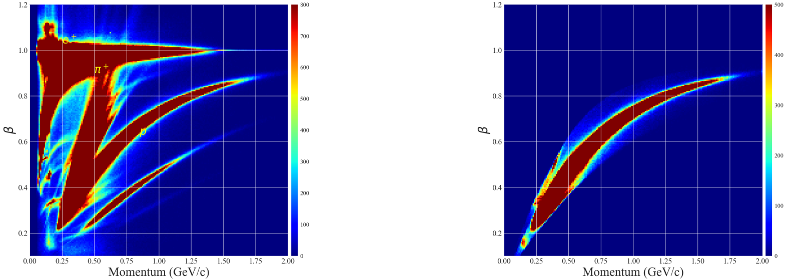


Figure 3: Missing-mass distribution as a function of the MVRT z vertex of the π+. The shape of the missing-mass distribution strongly changes with z. Event selection: $p_\pi > 0.2$ GeV/c and $\theta_\pi > 20^\circ$.

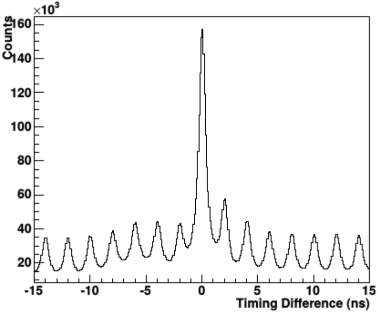
- Sharp peak at downstream end of Carbon foil → ice built up while cooling the target
- Ice formed on the right side of Carbon target: Z-vertex ∈ [6, 7]cm
- Plots from [Steffen Strauch]'s Analysis page of FROST Wikipage

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 $\vec{\gamma}\vec{p} \rightarrow \pi^0 p$)
- Measure p (via curvature) and β (via SC & TOF) of positive particles
- Select events with $\Delta\beta \approx 0$

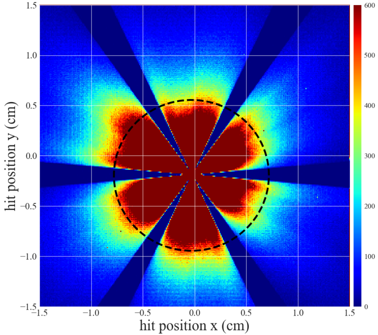
Photon Beam Selection



$$\Delta t = t_{pv} - t_{\gamma v}$$
$$= \text{time when } p \text{ was at event vertex}$$
$$- \text{time when } \gamma \text{ was at event vertex}$$

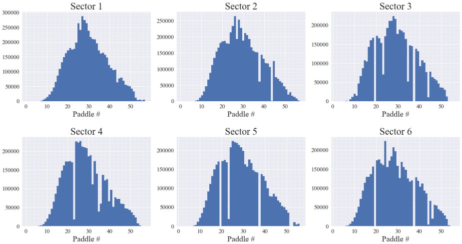
- Readings from SC, DC & TOF system to determine t_{pv} & $t_{\gamma v}$
- JLab e^- beam sent in bunches separated by 2 ns
- Neglect events caused by photons emitted from different e^- bunches
- Select out events with $\Delta t \approx 0$

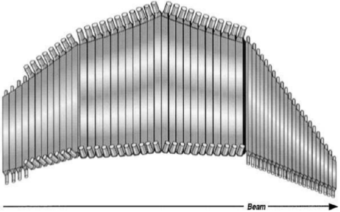
Radial Vertex Selection - Target Cup



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

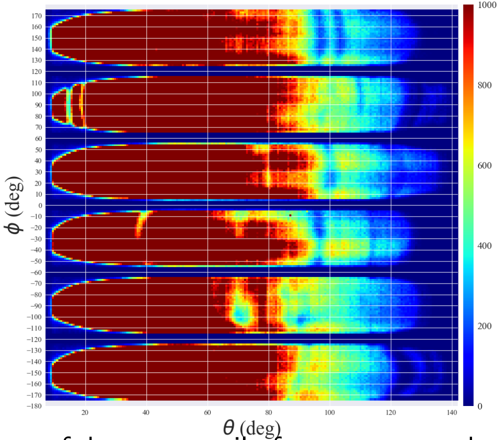
Inefficient Time-Of-Flight system paddles





- 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
- $\theta < 7$, $-180 < \phi < -175$, $-125 < \phi < -115$, $-65 < \phi < -55$ $-5 < \phi < 5$, $55 < \phi < 65$, $115 < \phi < 125$, $175 < \phi < 180$

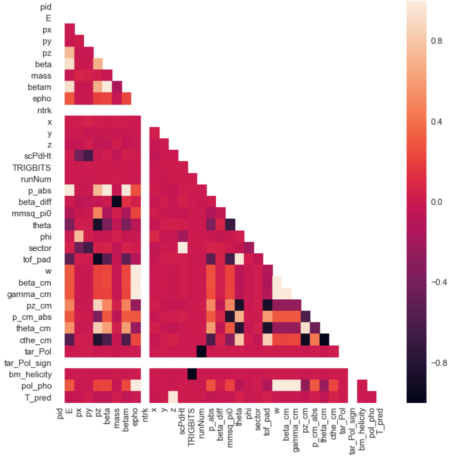
Neural Network Model Setup

- Two fully-connected (dense) neural layers

  1. Dense layer with 15 nodes - 15 parameters:
     - E, β, β_{diff}, β_m E_γ, m, $m^2_{\pi_0}$, 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

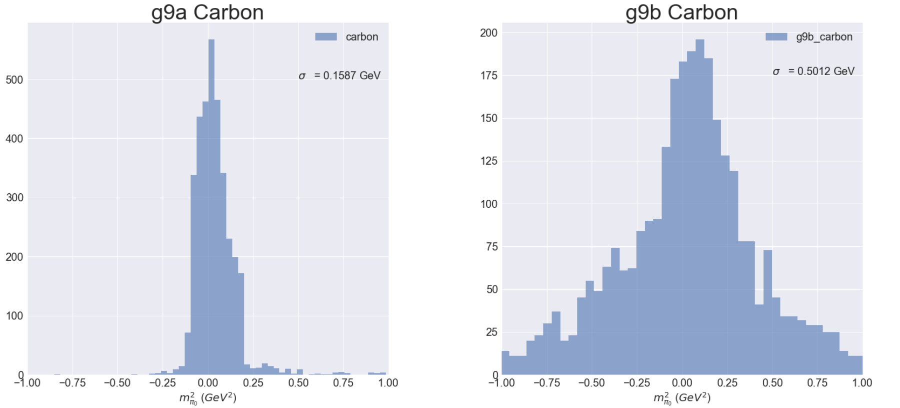
- Optimizer used: AdamOptimizer
- Loss function used - Sparse categorical cross entropy:
  - $H_{y'}(y) = -\sum_i y'_i \log(y_i)$,where y_i is the predicted target and y'_i is the true target
- Python and Tensorflow

Choosing Classifying Parameters



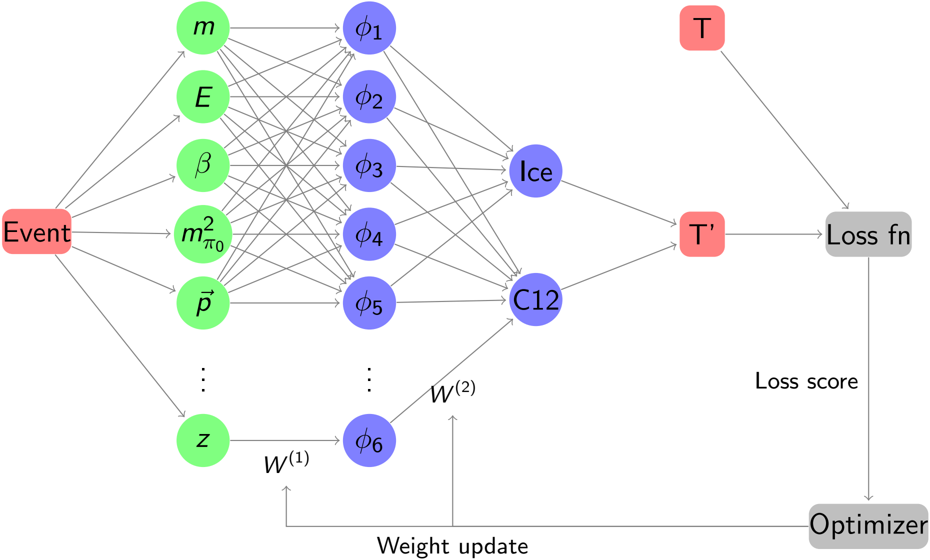
- Choose 10 $\sim$ 15 adequately correlated parameters to avoid overfitting and underfitting
- Higher correlation $\rightarrow$ lesser contribution to classification
- Lower correlation $\rightarrow$ biased training $\rightarrow$ overfitting

Training Data for Carbon from g9b experiment

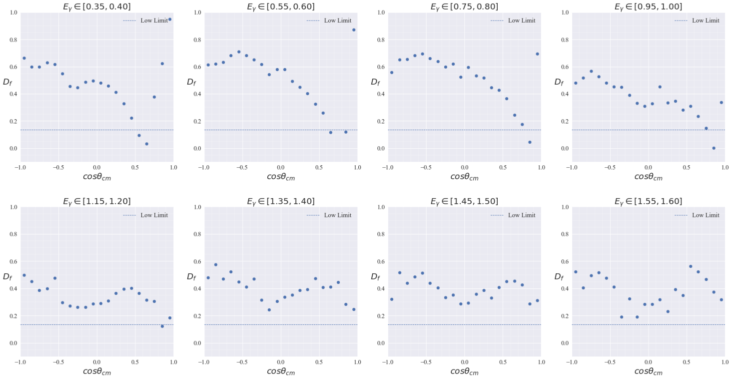


- g9b-carbon $m^2_{\pi_0}$ peak broader than g9a/Carbon → No ice on g9b
- During g9b, Carbon target was moved further in downstream.
- Shifted Z-vertex of g9b-Carbon events to use as training events for g9a [F. Klein].
- Failed (under investigation)→ Different training data for carbon used

Neural Network Training Flowchart: ICE vs CARBON



Dilution Factor



- $D_f(E_\gamma, \theta_{cm}) = \frac{N_{B,f}}{N_{B,tot}} = \frac{N_{B,tot} - N_{B,b}}{N_{B,tot}} \cong 1 - \frac{s(E_\gamma) \times N_C(E_\gamma, \theta_{cm})}{N_{B,tot}(E_\gamma, \theta_{cm})}$
- $D_f\Big|_{\text{low lim}} = \frac{\text{free H in butanol}}{\text{total nucleon in butanol}} = \frac{10}{74} \cong 0.135$