Determination of the Polarization Observables C_x, C_z, and P for $\vec{\gamma}\mathrm{d} \to K^0\vec{\Lambda}(p)$ From g13a Data

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Overview

- Motivation for studying $K^0\Lambda$ photoproduction.
- Identification of the reaction of $\vec{\gamma}\mathrm{d} \rightarrow K^0\vec{\Lambda}(p) \rightarrow p\pi^+\pi^-\pi^-(p)$
- Background subtraction and observable calculation.
- Preliminary results
  - Comparison with current Bonn–Gatchina projections
  - Comparison with $K^+\Lambda$
  - Dependence on neutron virtuality
- Summary

Motivation: Nucleon Spectroscopy

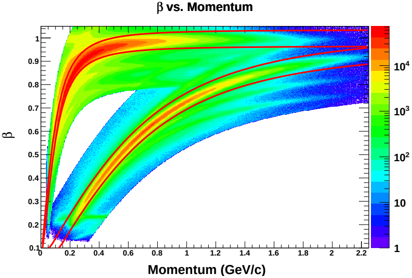
g13 run group aims to provide a nearly complete experiment on $K^0\Lambda$ photoproduction off the bound neutron ($\frac{d\sigma}{d\Omega}, P, \Sigma, C_x, C_z, O_x, O_z, T$).

- Majority of strangeness data are from experiments involving a free proton target.
  - $\gamma p \to K^+\Lambda$ moving $N(1900)\frac{3}{2}^+$ from $\star\star$ to $\star\star\star$, $N(1710)\frac{1}{2}^+$ from $\star\star\star$ to $\star\star\star\star$
  - $\gamma n \to K^0\Lambda$ sensitive to $\star$ $N(2120)\frac{3}{2}^-$ and $\star\star\star$ $N(1875)\frac{3}{2}^-$
- Recent paper from N. Compton et al. on $\frac{d\sigma}{d\Omega}$ of $\gamma(n) \to K^0\Lambda$ has 2 PWA solutions from Bonn–Gatchina.
  - A new fit with polarization observables in this channel could have an impact on the fits.
- How do data off the free proton and the bound neutron compare to each other?

$\gamma d \to K^0 \Lambda(p)$

Topology of interest: $\gamma d \to K^0 \Lambda(p) \to \pi^+ \pi^- p \pi^- (p)$

- Particles identified based off their β and momentum



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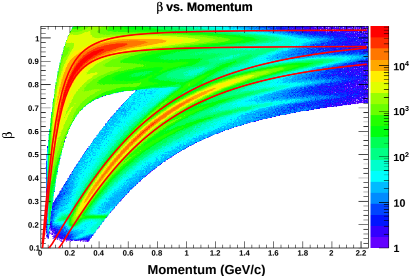
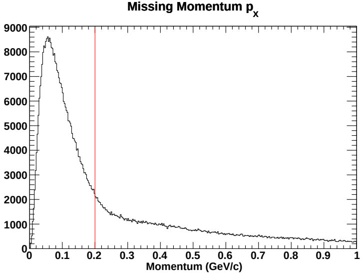
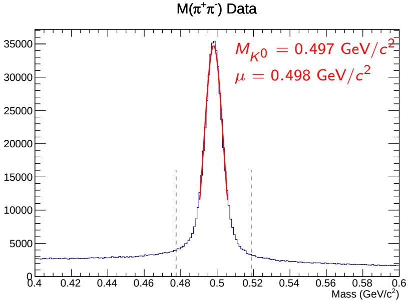


- Quasi–free events selected with $p_n < 0.2$ GeV/c



Identification of K^0 and Λ: $M(\pi^+\pi^-)$ and $M(p\pi^-)$

- $M(\pi^+\pi^-) = \sqrt{(\tilde{p}_{\pi^+} + \tilde{p}_{\pi^-})^2}$
- Fit peak with Gaussian, $\pm 4\sigma$ cut



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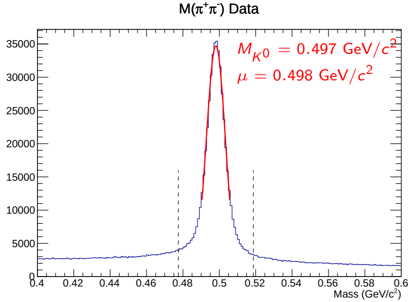

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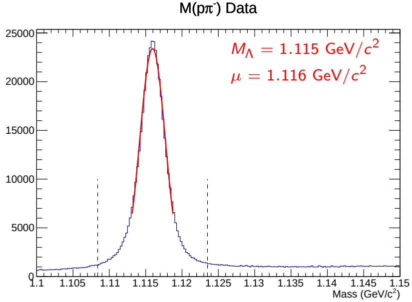
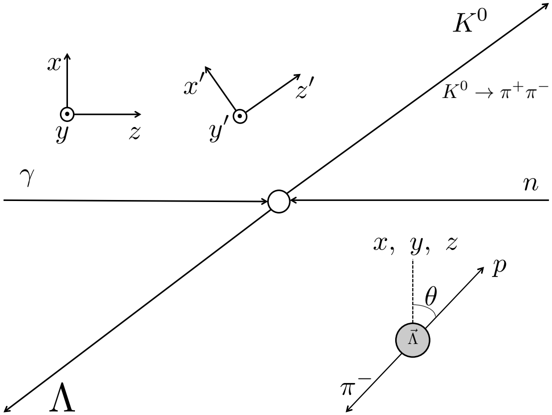


Axis Conventions for $\gamma(n) \to K^0\Lambda$



$$\frac{d\sigma}{d\Omega} = \sigma_0[1 - \alpha\cos\theta_x P_{circ} C_x - \alpha\cos\theta_z P_{circ} C_z + \alpha\cos\theta_y P]$$

$C_{x,z}$ measure polarization transfer from γ to Λ w.r.t. x/z axis, P is the Λ recoil polarization

Maximum Likelihood Method

Once cosθ_x, cosθ_y, and cosθ_z are calculated, we can extract the observables.

- C_x, C_z, P are simultaneously extracted using an unnormalized maximum likelihood function

$$f_i^{\pm}(x, y, z) = 1 \pm x\cos\theta_{x,i} \pm z\cos\theta_{z,i} + y\cos\theta_{y,i} \tag{1}$$

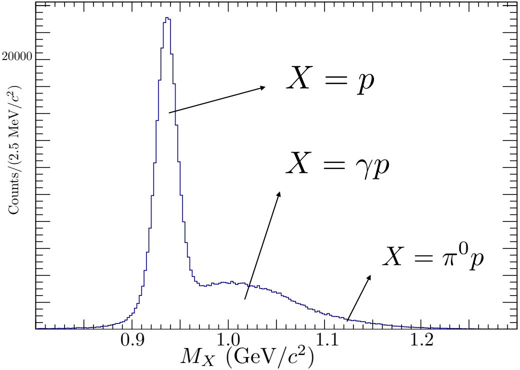
$$log\ f = \sum_{i=1}^{N^+} log(f_i^+) + \sum_{i=1}^{N^-} log(f_i^-) \tag{2}$$

$$C_x = \frac{x}{\alpha P_{circ}},\ C_z = \frac{z}{\alpha P_{circ}},\ P = \frac{y}{\alpha} \tag{3}$$

- Ideally, would have some normalization constant that takes care of normalization and Acceptance effects.
- Systematic studies using generated data are ongoing to test this method.

Background Channels: $\gamma d \to K^0\Lambda(X)$

- Non–resonant, unpolarized $\gamma d \to \pi^+\pi^- p\pi^-(p)$
- Higher mass channels:
  - $\gamma d \to K^0\Sigma^0(p) \to K^0\Lambda(\gamma p) \to \pi^+\pi^- p\pi^-(\gamma p)$
  - $\gamma d \to K^0\Sigma^{\star 0}(p) \to K^0\Lambda(\pi^0 p) \to \pi^+\pi^- p\pi^-(\pi^0 p)$
  - $\gamma d \to K^\star(892)\Lambda(p) \to K^0\Lambda(\pi^0 p) \to \pi^+\pi^- p\pi^-(\pi^0 p)$



- $\gamma d \to K^0\Lambda(X)$
- Simulations are used to separate $K^0\Lambda(p)$ events from higher mass channels
- Non–resonant background has a peak at $X = p$ and is accounted for using $M(p\pi^-)$

Observable Extraction and Background Subtraction

- This method is based off the 2016 analysis note by N. Zachariou for studying FSI on $\vec{\gamma} d \rightarrow K^+ \vec{\Lambda}(n)$
- Extract the total observable $(C_x^T,\ C_z^T,\ P^T)$ that includes background then *correct* it using background–to–total ratios to get a signal observable $(C_x^S,\ C_z^S,\ P^S)$.
- Choose this method because it integrates over $\cos\theta_{x,z}$ allowing for finer kinematic binning.

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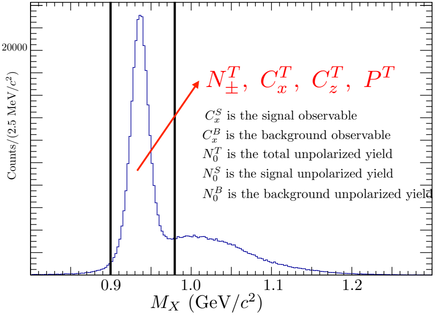
From the cross–section, we can write down the total polarized yield, $N_\pm^T$, as

$$N_\pm^T \approx N_0^T [1 \pm \alpha P_{circ} \cos\theta_x C_x^T \pm \alpha P_{circ} \cos\theta_z C_z^T + \alpha \cos\theta_y P^T]$$



$$N_0^T = N_0^S + N_0^B + N_0^{unpol} \quad (4)$$

$$N_0^T C_x^T = N^S C_x^S + N^B C_x^B \quad (5)$$

$$C_X^S = \frac{C_X^T - r^B C_X^B}{1 - r^B - r^{unpol}} \quad (6)$$

where $r^B = \frac{N_0^B}{N_0^T}$ and $r^{unpol} = \frac{N_0^{unpol}}{N_0^T}$

Observable Extraction and Background Subtraction

To find signal observables, need to eliminate the background observable. This is done by determining the total observables (C_x^T, C_z^T, P^T) and ratios in two regions of M_X.

- Region 1 corresponds to a signal–dominated region: $0.9 < M_X < 0.98$ GeV/c^2
- Region 2 corresponds to a background dominated region $0.98 < M_X < 1.05$ GeV/c^2

$$C_x^S = \frac{C_{x,1}^T - r_1^B C_x^B}{1 - r_1^B - r_1^{unpol}}, \quad C_x^S = \frac{C_{x,2}^T - r_2^B C_x^B}{1 - r_2^B - r_2^{unpol}} \tag{7}$$

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We can extract $C_{x,i}^T$ and calculate r_i^B and r_i^{unpol}. Solve for C_x^S:

$$C_x^S = \frac{r_1^B C_{x,2}^T - r_2^B C_{x,1}^T}{r_1^B - r_2^B - r_1^B r_2^{unpol} + r_1^{unpol} r_2^B} \tag{8}$$

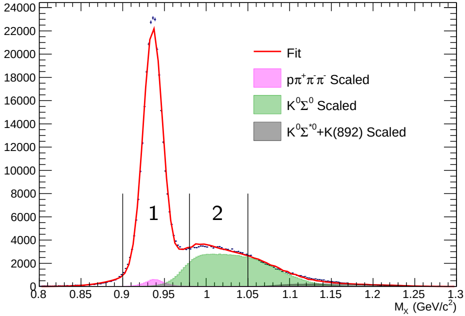
r's determined by fitting simulations to the data

Observable Calculation and Background Subtraction

$$C_x^S = \frac{r_1^B C_{x,2}^T - r_2^B C_{x,1}^T}{r_1^B - r_2^B - r_1^B r_2^{unpol} + r_1^{unpol} r_2^B}$$

- $C_{x,i}^T$ is the total observable in Region $i = 1, 2$,
- r_i^B are the ratios of polarized background to signal
- r_i^{unpol} are the ratios of unpolarized background to signal
    - Scaling done by fitting $p\pi^+\pi^-\pi^-$ to $M(p\pi^-)$

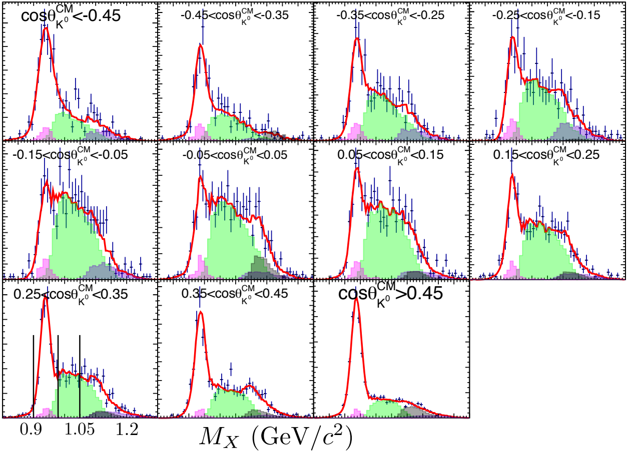
1. Fit Double Gaus+background histograms to data
2. Use fit parameters to scale background
3. Calculate r_i^B and r_i^A



1: signal dominated, 2: $K^0\Sigma^0$ dominated

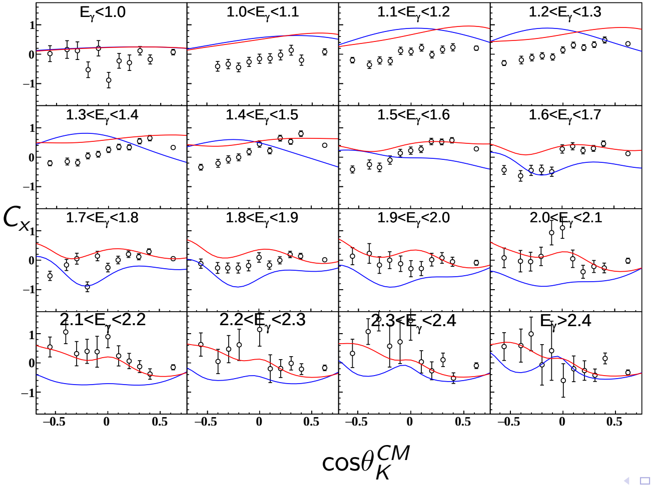
M_X Fits Example: $2.2 < E_\gamma < 2.3$ GeV

$$\gamma d \to K^0 \Lambda (X),\ X = p, \gamma p, \pi^0 p$$



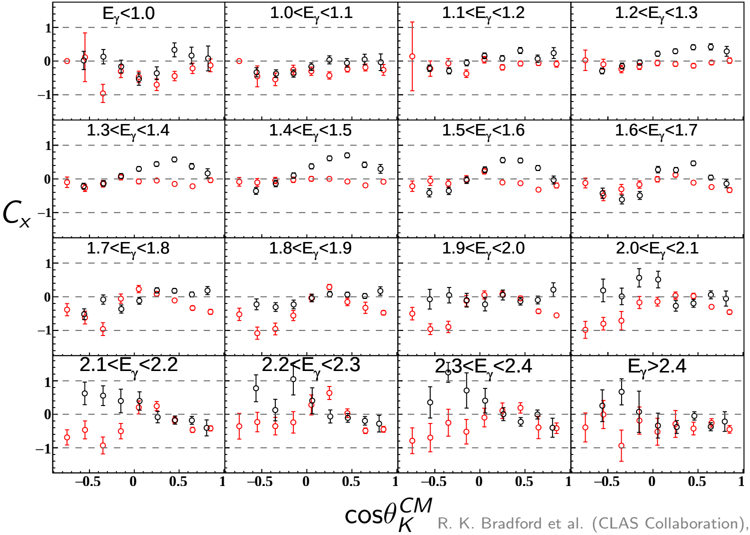
- Colored histograms scaled using the corresponding fit parameter.
- Higher mass states included to get fit correct.
  - Excluded from observable extraction by cut at 1.05 GeV/c^2
- Simultaneously extract C_x, C_z, P for each region using an unnormalized maximum likelihood method

C_x–Polarization Transfer from $\vec{\gamma}$ to $\vec{\Lambda}$ Along x–axis



- Two BonnGa solutions from fits to $K^0\Lambda$ cross–sections
- Same resonances included, two sets of parameters give reasonable fit to $\gamma d \to K^+\Sigma^-(p)$ and $K^0\Lambda(p)$
- BonnGa provided me with the two solution's projected onto C_x, C_z, P
- **No $K^0\Lambda$ polarization observables included in fits**
- Potential impact: resolution of current ambiguity, or lead to new results

C_x: Comparison of $\vec{\gamma} d \to K^0 \vec{\Lambda}(p)$ to $\vec{\gamma} p \to K^+ \vec{\Lambda}$

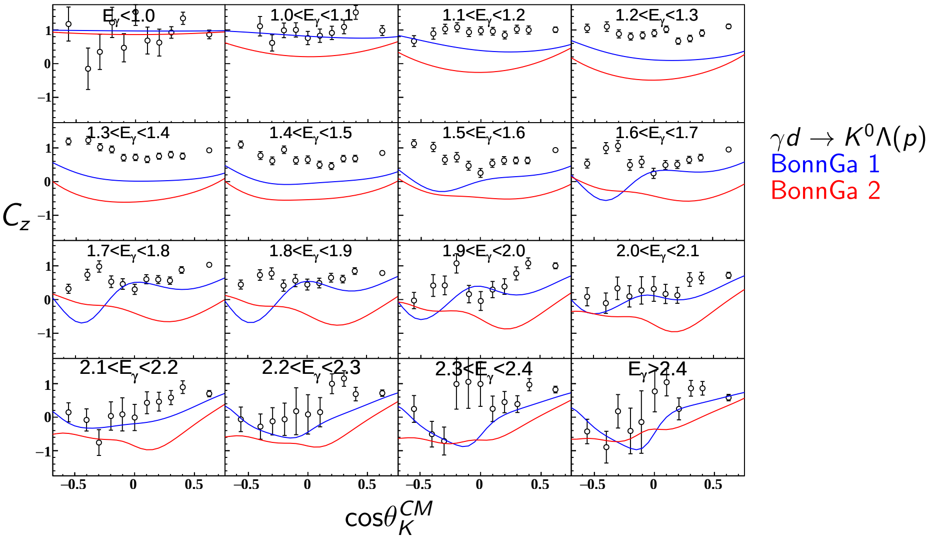


$\gamma d \to K^0 \Lambda(p)$

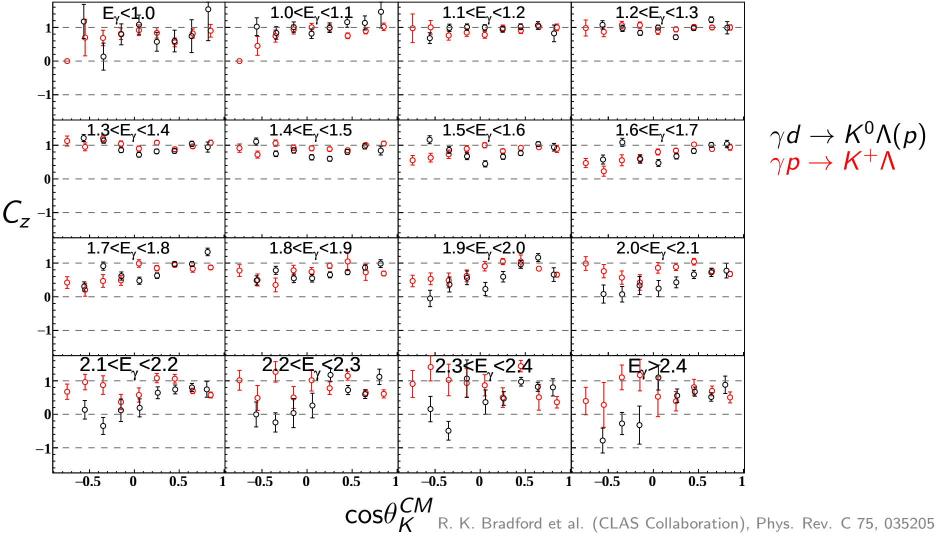
$\gamma p \to K^+ \Lambda$

R. K. Bradford et al. (CLAS Collaboration), Phys. Rev. C 75, 035205

C_z–Polarization Transfer from $\vec{\gamma}$ to $\vec{\Lambda}$ Along z–axis



C_z: Comparison of $\gamma d \to K^0\Lambda(p)$ to $\gamma p \to K^+\Lambda$



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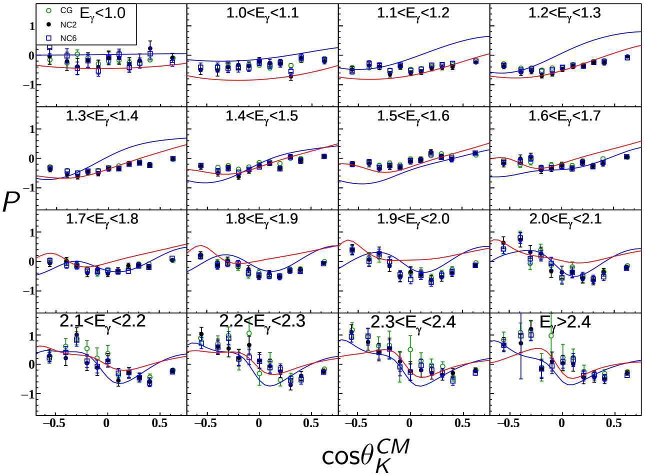
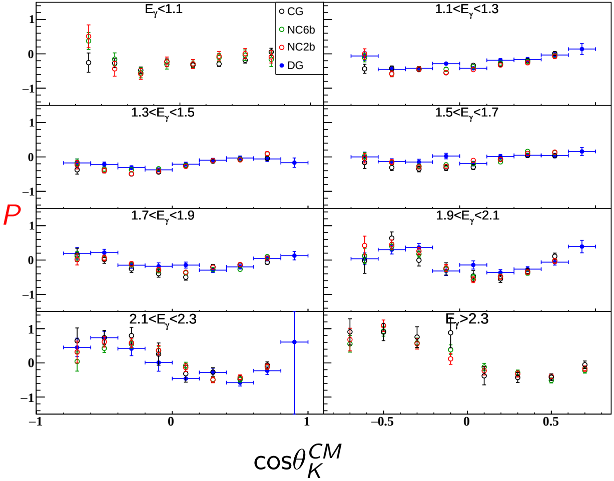
P Comparison with Different Extraction Methods



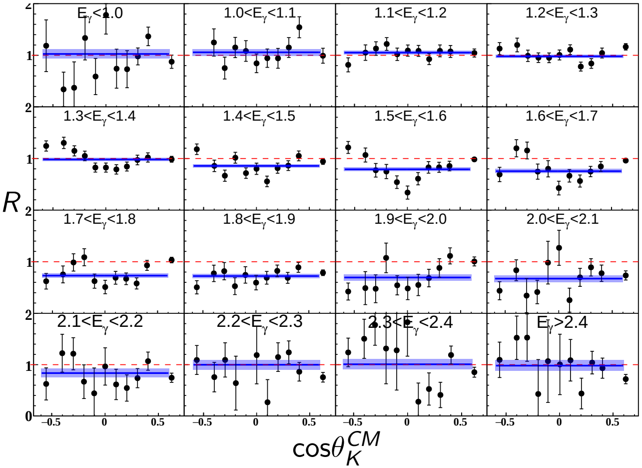
- Systematic test for extracting P
- Different extraction and background subtraction methods
- Same cuts on $M(p\pi^-)$, $M(\pi^+\pi^-)$, and $p_X < 0.2$ GeV/c
- Me, NC6, NC2
- All points have good visual agreement and calculations show no significant biases

P Comparison with g13b

- Derek Glazier extracting P from g13b data (linearally polarized γ)
- Different background subtraction and extraction method (Extended Maximum Likelihood)
- Different cuts from me and Nick Compton
- Derek has no cut on neutron momentum
- All points in good visual agreement, early calculations show good agreement statistically (pull distributions, correlations)

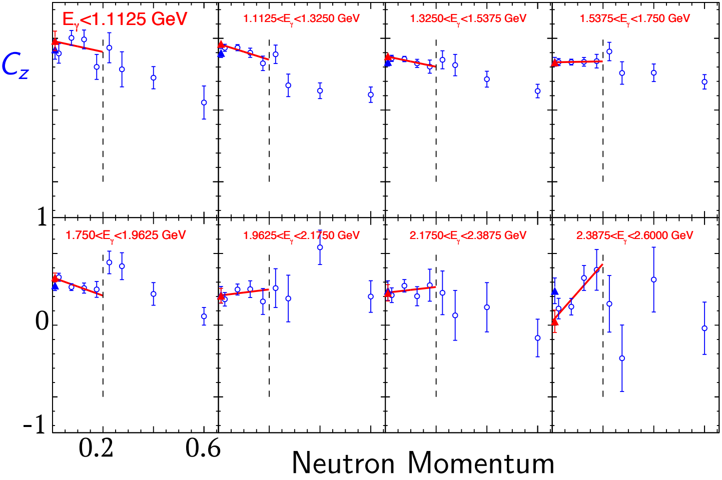


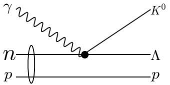
$R = \sqrt{C_x^2 + C_z^2 + P^2}$: Total Polarization Transfer



- Low E_γ – Λ fully polarized
- Mid E_γ – Λ fully polarized at forward and backward angles
- High E_γ – large uncertainties, but Λ near full polarizations within uncertainties

Dependence on Neutron Momentum





- Neutron is not free
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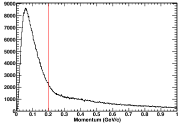
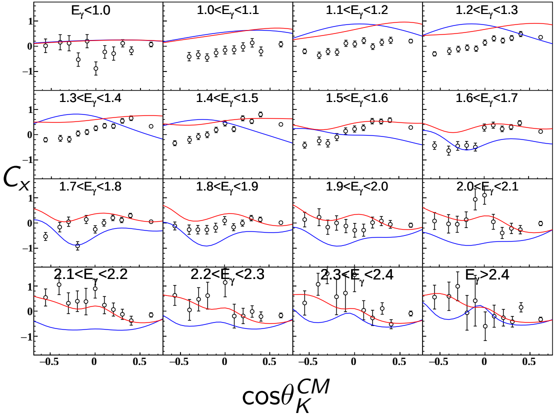


Conclusion and Outlook

- First estimates of the polarization transfers from circularly–polarized photons to the Λ and the Λ recoil polarizations in the reaction $\gamma d \to K^0 \Lambda (p)$ have been obtainted
- A maximum log likelihood method was used to extract the observables
  - Background subtraction method is promising– work still being done to improve fits and determine optimal binning in M_X, E_γ, and $\cos\theta^{CM}_{K^0}$.
- Similarities and differences are observed in data from free proton (different isopsin, reaction dynamics, resonances).
- Very good agreement in extracting P between 3 different methods for g13a data.
  - Potential for very good agreement in P over g13a and g13b.
- Timeline: thesis for the summer and analysis note to follow.
- Major work left (and in progress) is to quantify systematics.

Summary for Friday Report

C_x for $\gamma d \to K^0\Lambda(p)$



- $K^0\Lambda$ cross–sections resulted in two reasonable solutions from BonnGa PWA.
- BonnGa provided me with the two solutions projected onto C_x, C_z, P
- Same resonances included, two sets of parameters give reasonable fit to $\gamma d \to K^+\Sigma^-(p)$ and $K^0\Lambda(p)$
- **No $K^0\Lambda$ polarization observables included in fits**
- Potential impact: resolution of current ambiguity, or lead to new results

Backup

Background Subtraction

Method from 2016 analysis note by N. Zachariou for extracting observables on $\vec{\gamma} d \rightarrow K^+ \vec{\Lambda}(n)$. The goal is to remove background channels by fitting M_X with simulated background channels.

$$N^T = N^S + N^B + N^{unpol} \quad (9)$$

$$N^T C_x^T = N^S C_X + N^B C_X^B \quad (10)$$

$$C_X^S = \frac{C_X^T - r^B C_X^B}{1 - r^B - r^{unpol}} \quad (11)$$

- C^S is the signal observable
- C^B is the background observable
- $C^T = \frac{N^S C^S + N^B C^B}{N}$ is the total value of the observble
- r^B is the ratio of polarized background to data
- r^{unpol} is the ratio of unpolarized background to data

Determine the effective observables and ratios in two regions, $C^T_{X,1}$, $C^T_{X,2}$, r^B_1, r^B_2, r^{unpol}_1, and r^{unpol}_2

$$C_X^S = \frac{C^T_{X,1} - r^B_1 C^B_X}{1 - r^B_1 - r^{unpol}_1} \quad (12)$$

$$C_X^S = \frac{C^T_{X,2} - r^B_2 C^B_X}{1 - r^B_2 - r^{unpol}_2} \quad (13)$$

Two equations, two unknowns C^S_X and C^B_X. Can solve:

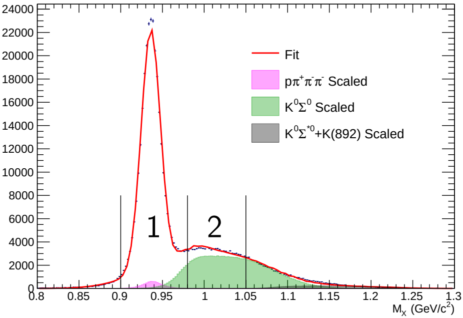
$$C_x^S = \frac{r^B_1 C^T_{x,2} - r^B_2 C^T_{x,1}}{r^B_1 - r^B_2 - r^B_1 r^{unpol}_2 + r^{unpol}_1 r^B_2} \quad (14)$$

Background Subtraction and Observable Extraction

$f(x) =$

$$A_1 \exp \frac{(x-\mu)^2}{2\sigma_1^2} + A_2 \exp \frac{(x-\mu)^2}{2\sigma_2^2} + SF^{un} H^{sim}_{p\pi^+\pi^-\pi^-} + SF^{\Sigma^0} H^{sim}_{\Sigma^0} + SF^{\Sigma^\star} H^{sim}_{\Sigma^\star} + SF^{K^\star(892)} H^{sim}_{K^\star(892)}$$

- $SF^{un} H^{sim}_{p\pi^+\pi^-\pi^-}$ is fixed.
- All other parameters (SF, A's, μ, σ's) allowed to vary.
- $r^B = \frac{SF^{\Sigma^0} H^{sim}_{\Sigma^0}}{H^{data}}$
- $r^{unpol} = \frac{SF^{un} H^{sim}_{p\pi^+\pi^-\pi^-}}{H^{data}}$
- 1 and 2 represent Regions 1 and 2



Calculation of $r_i^{unpol} = \frac{N_0^{unpol}}{N_0^T}$

- Can not distinguish signal from background using M_X for non–resonant $p\pi^+\pi^-\pi^-$
- The final yield is calculated using M_X, but the proper scaling is determined from $M(p\pi^-)$
- Scaling done by fitting $M(p\pi^-)$ with a Double Gaussian$+p\pi^+\pi^-\pi^-$ simulation

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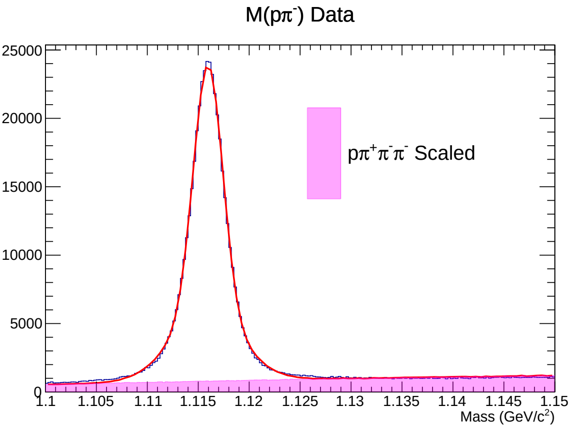
- The scale factor, SF, is determined from the fit for each $[E_\gamma, \cos\theta_{K^0}]$ bin.
- SF is fixed when performing the fit to M_X



P Comparison with Nick Compton

- Nick Compton extracted cross-sections for $\gamma d \rightarrow K^0 \Lambda(p)$ for g13 data
    - Two methods to extract P: 2–bin (NC2) and a multi–bin (NC6)
- NC2: $P = \frac{N^+ - N^-}{\frac{\alpha}{2}(N^+ + N^-)}$
- $N^{+/-}$ is corrected yield above or below cosθ_y=0
- NC6: get yield in 6 cosθ_y bins, fit acceptance corrected yield to straight line
- $N(\cos\theta_y) = \frac{N}{2}(1 + P_\Lambda \alpha \cos\theta_y)$

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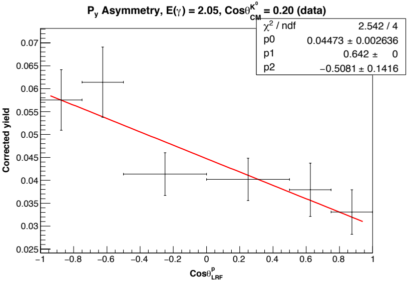
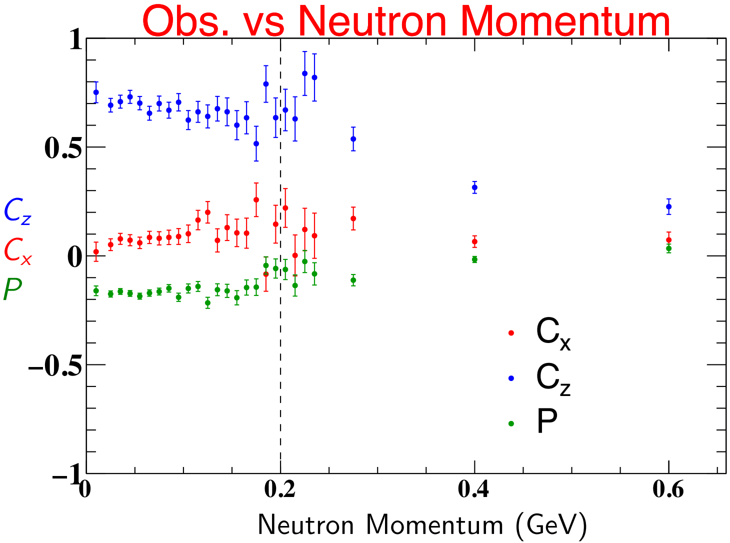
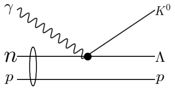
- $N(\cos\theta_y) = \frac{N}{2}(1 + P_\Lambda \alpha \cos\theta_y)$

- $y = [0] + [1][2]x$
- Fix $[0] = \frac{N}{2}\frac{2}{PYBINS}$ and $[1] = \frac{N}{2}\alpha\frac{2}{PYBINS}$, $PYBINS = 6$
- $[2] = P_\Lambda$



Dependence on Neutron Momentum





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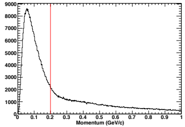
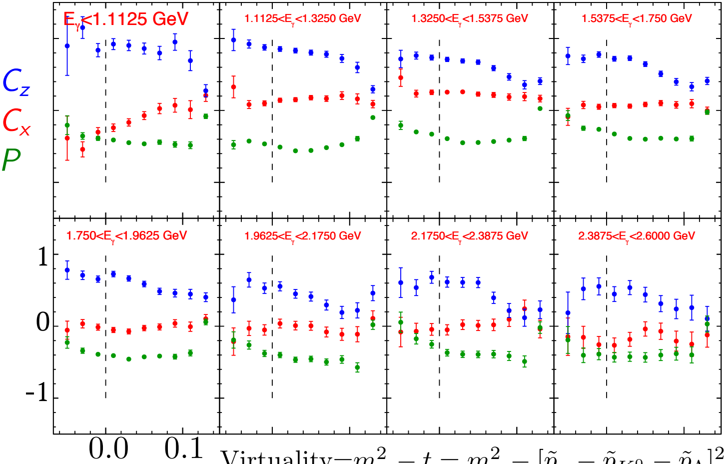
- How well do the observables represent the free neutron?

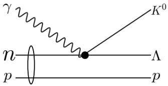
Neutron Momentum



Dependence on Neutron Virtuality

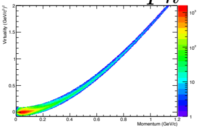


$$\text{Virtuality}=m_n^2 - t = m_n^2 - [\tilde{p}_\gamma - \tilde{p}_{K^0} - \tilde{p}_\Lambda]^2$$

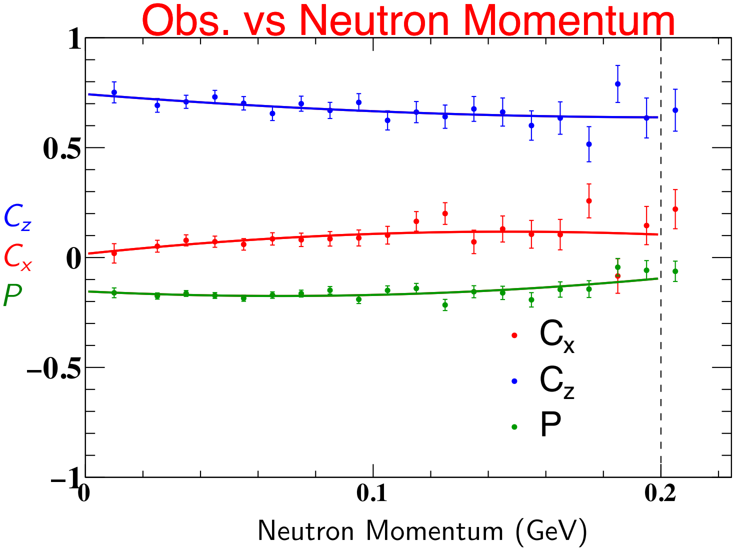


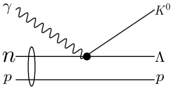
- Neutron is not free
- Virtuality describes the off-shellness of the neutron
- How well do the observables represent the free neutron?

Virt. vs. $\vec{p}_n$



Dependence on Neutron Momentum





- Neutron is not free
- Need free neutron for CCA
- How well do the observables represent the free neutron?

Neutron Momentum