Determination of the Hyperon Induced Polarization and Polarization–Transfer Coefficients for Quasi-Free Hyperon Photoproduction off the Bound Neutron

NSTAR 2017

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Overview

- Motivation for studying $K\Lambda$ photoproduction
- Identification of the reaction of $\vec{\gamma}\mathrm{d} \rightarrow K^0\vec{\Lambda}(p) \rightarrow p\pi^+\pi^-\pi^-(p)$
- Background subtraction
- Preliminary results
  - Comparison of C_x and P with current Bonn–Gatchina projections
  - Comparison of C_z with $K^+\Lambda$
  - Dependence on neutron momentum
  - First interpretations with Legendre polynomial fits
- Summary

Motivation for $\vec{\gamma} d \rightarrow K^0 \vec{\Lambda}(p)$

- Majority of data is πN scattering or final states with π's
  - Some resonances couple weakly to these channels while having significant branching ratios to $K\Lambda$
- Most strangeness data from free proton
  - $\gamma p \rightarrow K^+\Lambda$ moving $N(1900)\frac{3}{2}^+$ from $**$ to $***$
  - $\gamma n \rightarrow K^0\Lambda$ sensitive to $**N(2120)\frac{3}{2}^-$ and $***N(1875)\frac{3}{2}^-$
- How do data from the proton and bound neutron compare to each other?

Particle	J^P	overall	Status as seen in								
			$N\gamma$	$N\pi$	$N\eta$	$N\sigma$	$N\omega$	ΛK	ΣK	$N\rho$	$\Delta\pi$
N	$1/2^+$	****									
$N(1440)$	$1/2^+$	****	****	****		***				*	***
$N(1520)$	$3/2^-$	****	****	****	***					***	***
$N(1535)$	$1/2^-$	****	****	****	****					**	*
$N(1650)$	$1/2^-$	****	****	****	***			***	**	**	***
$N(1675)$	$5/2^-$	****	****	****	*			*		*	***
$N(1680)$	$5/2^+$	****	****	****	*	**				***	***
$N(1700)$	$3/2^-$	***	**	***	*			*	*	*	***
★$N(1710)$	$1/2^+$	****	****	****	***		**	****	**	*	**
$N(1720)$	$3/2^+$	****	****	****	***			**	**	**	*
$N(1860)$	$5/2^+$	**		**						*	*
★$N(1875)$	$3/2^-$	***	***	*			**	***	**		***
$N(1880)$	$1/2^+$	**	*	*		**		*			
$N(1895)$	$1/2^-$	**	**	*	**			**	*		
★$N(1900)$	$3/2^+$	***	***	**	**		**	***	**	*	**
$N(1990)$	$7/2^+$	**	**	**					*		
$N(2000)$	$5/2^+$	**	**	*	**			**	*	**	
$N(2040)$	$3/2^+$	*		*							
$N(2060)$	$5/2^-$	**	**	**	*				**		
$N(2100)$	$1/2^+$	*		*							
★$N(2120)$	$3/2^-$	**	**	**				*	*		
$N(2190)$	$7/2^-$	****	***	****			*	**		*	
$N(2220)$	$9/2^+$	****		****							
$N(2250)$	$9/2^-$	****		****							
$N(2300)$	$1/2^+$	**		**							
$N(2570)$	$5/2^-$	**		**							
$N(2600)$	$11/2^-$	***		***							
$N(2700)$	$13/2^+$	**		**							

C. Patrignani et al. (Particle Data Group), Chin. Phys. C, 40, 100001 (2016).

Polarization Observables in $K\Lambda$ Photoproduction

- The 4 complex scattering amplitudes can define 16 polarization observables

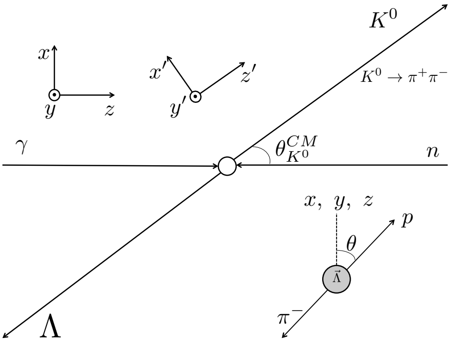
Unpolarized Cross Section	σ_0			
Single		P	Σ	T
Beam-Recoil	C_x	C_z	O_x	O_z
Target-Recoil	T_x	T_z	L_x	L_z
Beam-Target	E	F	G	H

- The full scattering amplitude can be determined by carefully choosing 8 observables.

$$\frac{d\sigma}{d\Omega} = \sigma_0[1 - P_{lin}\Sigma\cos 2\phi - \alpha\cos\theta_x(P_{lin}O_x\sin 2\phi + P_{circ}C_x) - \alpha\cos\theta_y(-P + P_{lin}T\cos 2\phi) - \alpha\cos\theta_z(P_{lin}O_z\sin 2\phi + P_{circ}C_z)]$$

Defining Kinematics: $\vec{\gamma}N \to K\vec{\Lambda}$

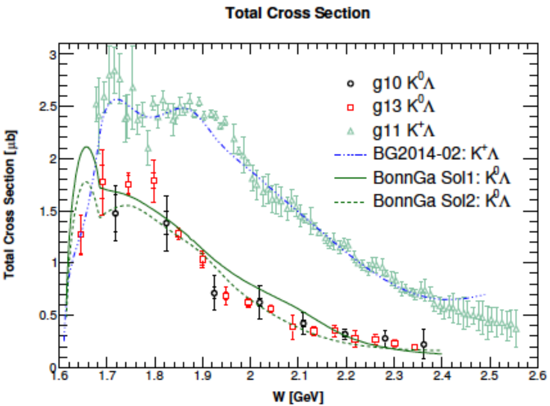
Two different coordinate systems for KY photoproduction:



- Observables are dependent on E_γ and θ_K^{CM}
- The coordinate systems define $\theta_x, \theta_y, \theta_z$
- Polarization of Λ depends on choice of axes

Previous Studies of $K^0\Lambda$ Photoproduction

Compton $\frac{d\sigma}{d\Omega}$ for $\vec{\gamma}d \to K^0\vec{\Lambda}(p)$ (under review 2017)



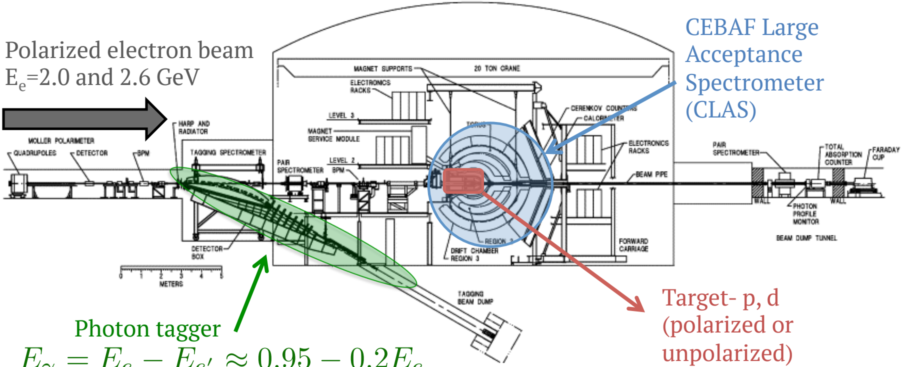
- Bonn–Gatchina multi–channel fit for $\gamma d \to \pi^- p(p)$, $\pi^- p \to \gamma n$, $\gamma d \to \pi^0 n(p)$, $\gamma d \to \eta n(p)$, $\gamma d \to K^+\Sigma^-$
- "Both solutions seem to describe $\gamma d \to K^+\Sigma^-(p)$ and $\gamma d \to K^0\Lambda(p)$ reasonable well."

Need to include polarization observables in the fits to (a) resolve this ambiguity or (b) provide a new solution!

arXiv:1706.04748 [nucl-ex]

Hall–B (1997-2012) at Thomas Jefferson National Accelerator Facility (JLab)

Polarized electron beam
E_e=2.0 and 2.6 GeV



CEBAF Large Acceptance Spectrometer (CLAS)

Target- p, d (polarized or unpolarized)

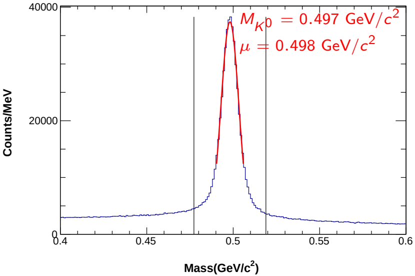
Photon tagger

$$E_\gamma = E_e - E_{e'} \approx 0.95 - 0.2E_e$$

B.A. Mecking et al., Nucl. Instr. and Meth. A 503, 513 (2003)

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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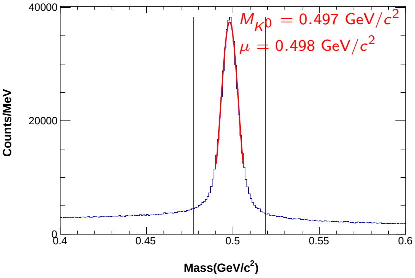

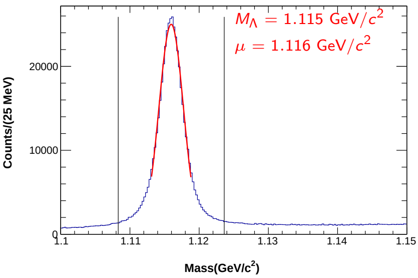

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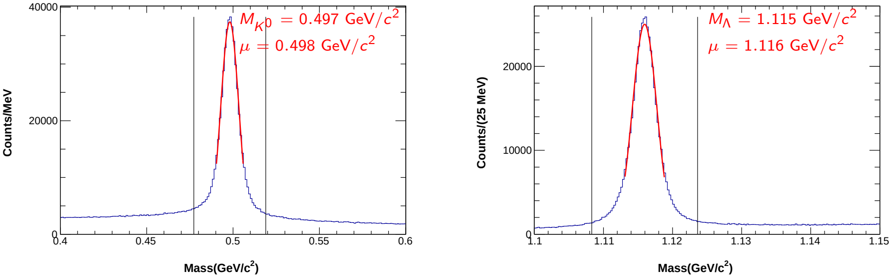
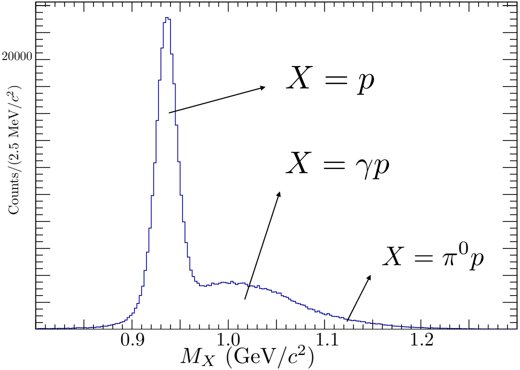


$p_X < 0.2$ GeV/c cut used to select the quasi–free events

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

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



- $M_X = \sqrt{(\tilde{p}_\gamma + \tilde{p}_d - \tilde{p}_{K^0} - \tilde{p}_\Lambda)^2}$

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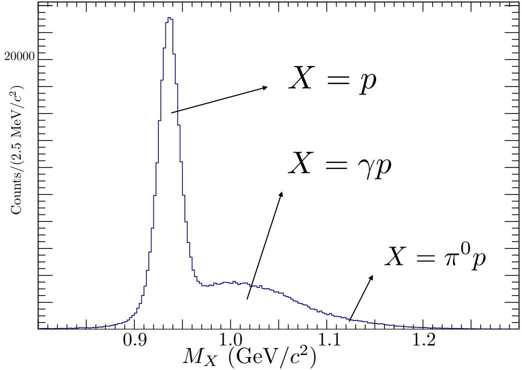

- $M_X = \sqrt{(\tilde{p}_\gamma + \tilde{p}_d - \tilde{p}_{K^0} - \tilde{p}_\Lambda)^2}$
- Need a realistic event generator and simulations to separate signal from background

Background Subtraction

- Determine background free observable from ratios of background to signal events
- Done by fitting M_X with the simulated background channels

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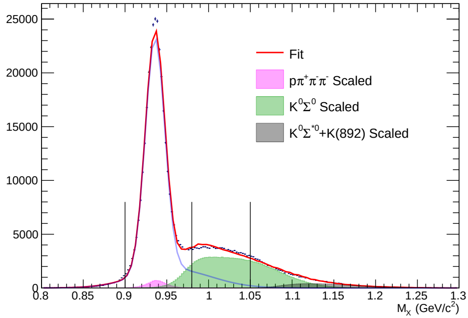
1. Fit Double Gaus+background histograms to data
2. Use fit parameters to normalize background
3. Calculate background to total ratios: r^B and r^{unpol}



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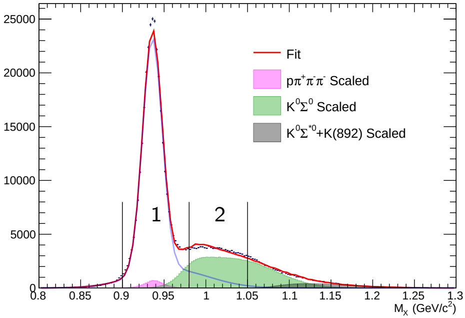
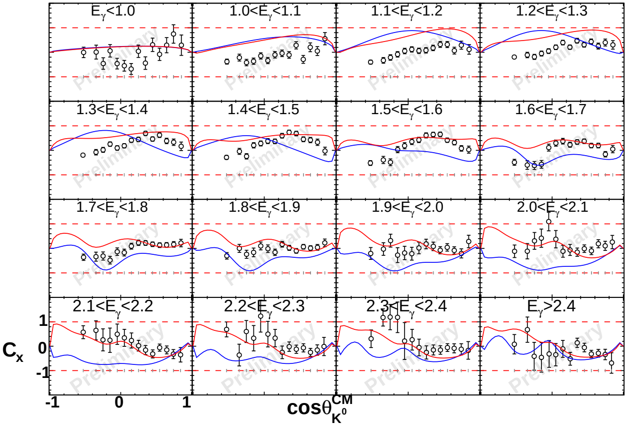


1: signal dominated, 2: $K^0\Sigma^0$ dominated

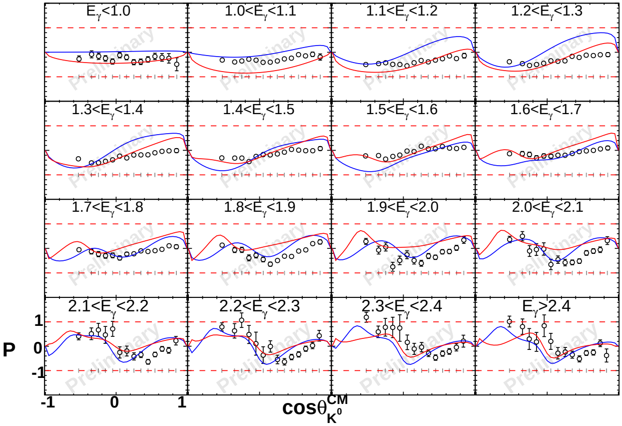
- A "total" observable can be extracted for regions 1 and 2
- The total observable is *corrected* using the background to total ratios (r_i^B, r_i^{unpol}) to get a "signal" (background free) observable
- $C_x^S = \dfrac{r_1^B C_{x,2}^T - r_2^B C_{x,1}^T}{r_1^B - r_2^B - r_1^B r_2^{unpol} + r_1^{unpol} r_2^B}$

C_x–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

P–Λ Recoil Polarization



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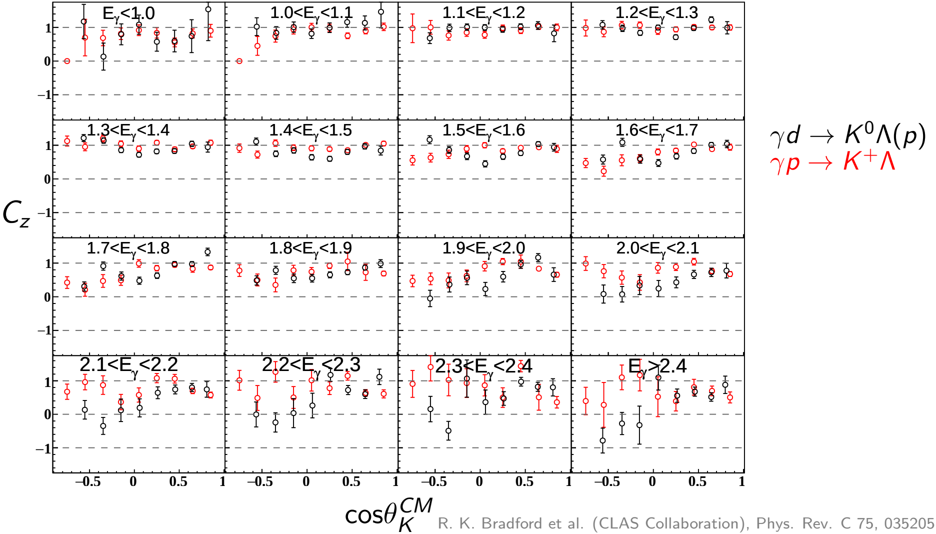
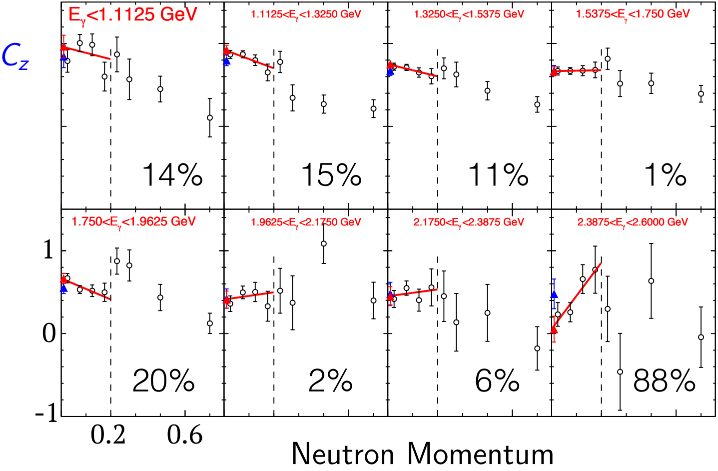
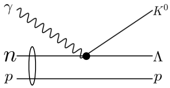
C_z: Comparison of $\gamma d \to K^0\Lambda(p)$ to $\gamma p \to K^+\Lambda$



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

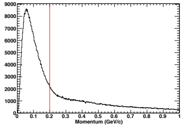
Dependence on Neutron Momentum





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

Neutron Momentum



First Interpretation: Legendre Polynomial Fits

- The goal is to determine the dominant partial wave contribution to the observables, $\mathcal{O} = O\frac{d\sigma}{d\Omega}$, using an expansion of Legendre polynomials

$$\mathcal{C}_x = \rho \sum_{k=1}^{2L_{max}+1} (a_L)_k^{\mathcal{C}_x} P_k^1(\cos\theta), \quad (1)$$

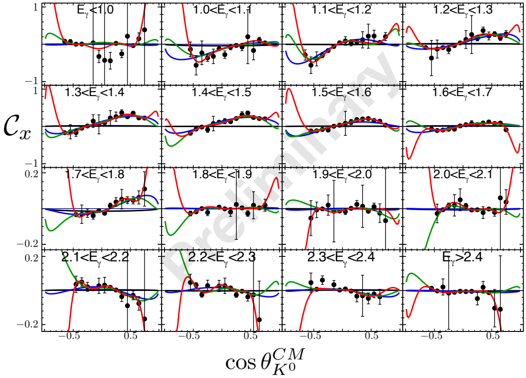
$$\mathcal{C}_z = \rho \sum_{k=0}^{2L_{max}+1} (a_L)_k^{\mathcal{C}_z} P_k^0(\cos\theta), \quad (2)$$

$$\mathcal{P} = \rho \sum_{k=1}^{2L_{max}} (a_L)_k^{\mathcal{P}} P_k^1(\cos\theta). \quad (3)$$

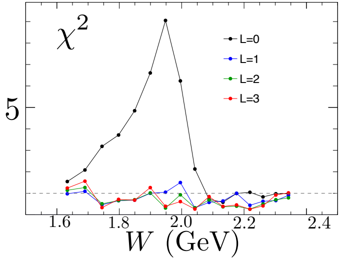
- The procedure is to fit $\mathcal{O}$ and determine the L_{max} where the $\chi^2 \to 1$.
- This is not to replace PWA, but is instead a complimentary tool.

Y. Wunderlich, F. Afzal, A. Thiel and R. Beck, *Eur. Phys. J.* A**53**, no. 5, 86 (2017)

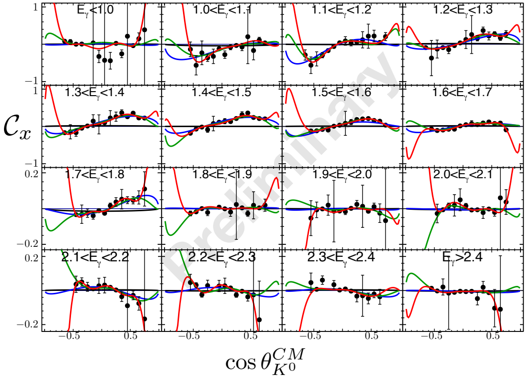
First Interpretation: Legendre Polynomial Fits to $\mathcal{C}_x$



$L_{max} = 0$: S–wave
$L_{max} = 1$: P–wave
$L_{max} = 2$: D–wave
$L_{max} = 3$: F–wave



First Interpretation: Legendre Polynomial Fits to $\mathcal{C}_x$



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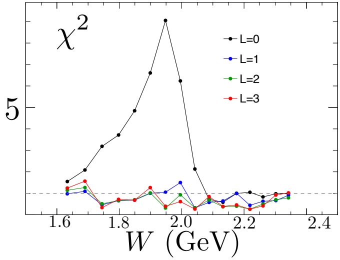
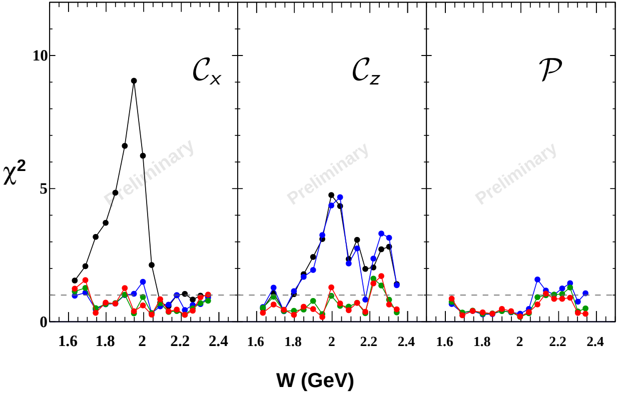


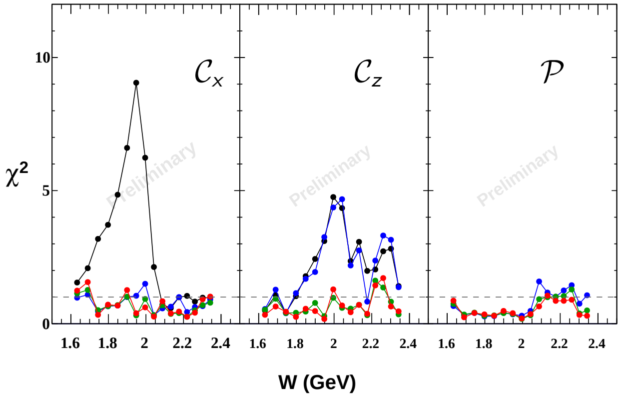
- $L_{max} = 0$: $****\ N(1650)\frac{1}{2}^-$, $**N(1895)\frac{1}{2}^-$
- $L_{max} = 1$: $****\ N(1710)\frac{1}{2}^+$, $****N(1720)\frac{3}{2}^-$, $**N(1880)\frac{1}{2}^+$, $***\ N(1900)\frac{3}{2}^+$
- $L_{max} = 2$: $****\ N(1675)\frac{5}{2}^-$, $***\ N(1700)\frac{3}{2}^-$, $***\ N(1875)\frac{3}{2}^-$, $**N(2120)\frac{3}{2}^-$
- $L_{max} = 3$: $**\ N(2000)\frac{5}{2}^+$

First Interpretation: Legendre Polynomial χ^2



- $\mathcal{C}_x$: $L_{max} = 1$ below $W = 2.1$ GeV, $L_{max} = 0$ above 2.1 GeV
- $\mathcal{C}_z$: $L_{max} = 2$ for most bins
- $\mathcal{P}$: $L_{max} = 1$

First Interpretation: Legendre Polynomial χ^2



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- $L_{max} = 1$: $****N(1710)\frac{1}{2}^+$, $****N(1720)\frac{3}{2}^-$, $**N(1880)\frac{1}{2}^+$, $***N(1900)\frac{3}{2}^+$
- $L_{max} = 2$: $****N(1675)\frac{5}{2}^-$, $***N(1700)\frac{3}{2}^-$, $***N(1875)\frac{3}{2}^-$, $**N(2120)\frac{3}{2}^-$
- $L_{max} = 3$: $**N(2000)\frac{5}{2}^+$

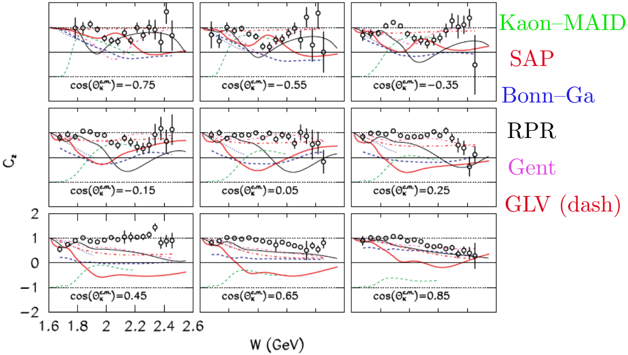
Conclusions and Outlook

- Studying $K\Lambda$ photoproduction is needed in the search for $N^* > 1800$ MeV
  - Significant work has been done to study $K^+\Lambda$, but more data is needed on this and other channels, like $K^0\Lambda$
- I have extracted the first estimates for C_x, C_z, and P for $\vec{\gamma}d \rightarrow K^0\vec{\Lambda}(p)$.
- There are similarities and differences observed in data from free proton (isopsin, reaction dynamics, other resonances).
- Disagreement between current Bonn–Gatchina “predictions” and my results
  - My results should have an impact on new fits (resolve fit ambiguity, new N^*?)
- Legendre fits: $L_{max} = 2$ (D–wave) dominance in $\mathcal{C}_z$ suggesting presence of $N(1875)\frac{3}{2}^-$ and/or $N(2120)\frac{3}{2}^-$?

Backup

Previous Studies of $K\Lambda$ Photoproduction

Bradford $\vec{\gamma}p \to K^+\vec{\Lambda}$ (2006) CLAS Collaboration

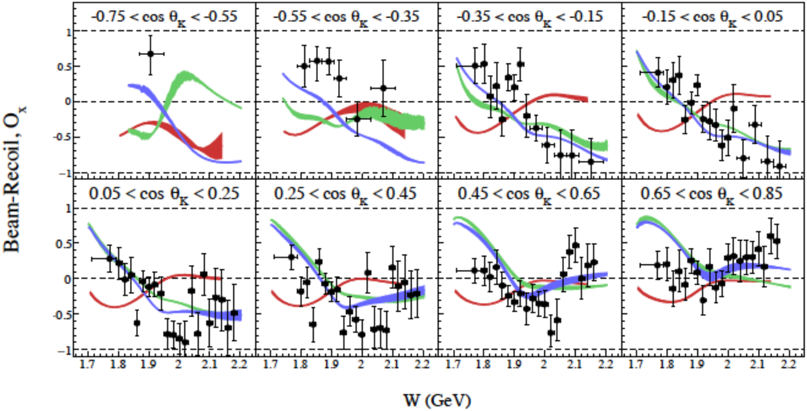


R. K. Bradford et al. (CLAS Collaboration), Phys. Rev. C 75, 035205

- C_z is the polarization transfer from the circularly polarized beam to the Λ along the z–axis
- Hadronic model predictions are in poor agreement with these results
- This work, in combination with other $K^+\Lambda$ observables led to the promotion of $N(1900)\frac{3}{2}^+$ from ** to ***

Previous Studies of $K\Lambda$ Photoproduction

Paterson $\vec{\gamma}p \rightarrow K^+\vec{\Lambda}$ (2016) CLAS

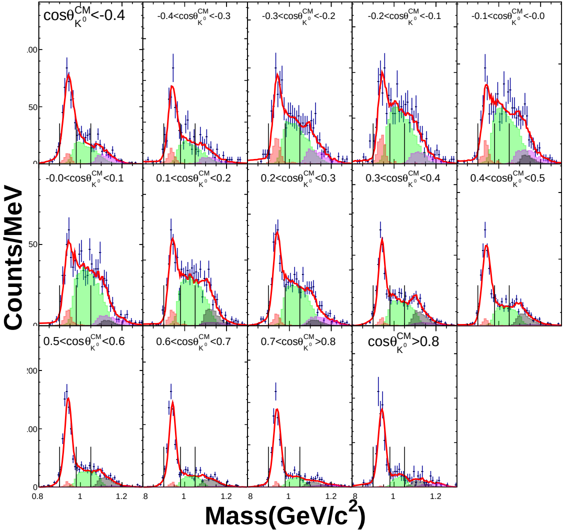


- Osaka group fit ($N^* < 2GeV$), 2014 BG fit, new BG fit to all observables
- "... data set shows some evidence of resonances beyond the 2014 solution, but that it is not strong enough to deduce the quantum numbers or masses of these states or indeed conclusively support their existence."

C.A. Paterson et al. (CLAS Collaboration) Phys. Rev. C 93, 065201 (2016)

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

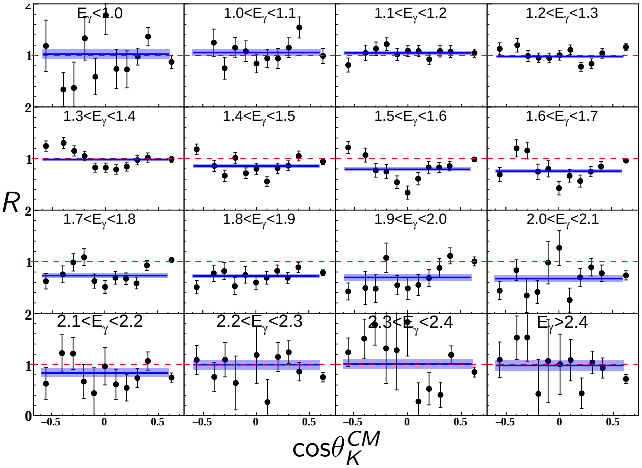
$$\gamma d \to K^0 \Lambda(X),\ X = p, \gamma p, \pi^0 p$$



- Colored histograms scaled using the corresponding fit parameter.
- Higher mass states

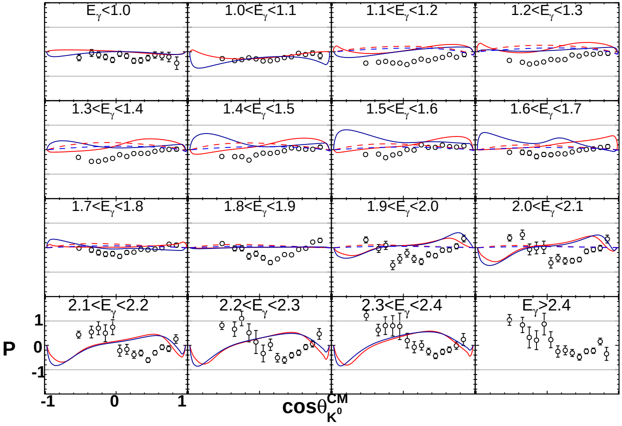
  included to get fit correct.
  - Excluded from observable extraction by cut at 1.05 GeV$/c^2$

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



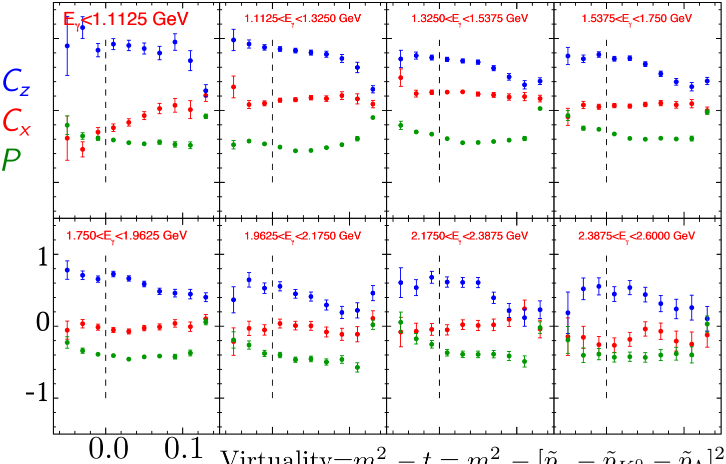
- Low E_γ– Λ fully polarized
- Mid E_γ– Λ fully polarized at forward and backward angles
- High E_γ– large uncertainties, but Λ near full polarizations within uncertainties

P Comparison with Different Predictions

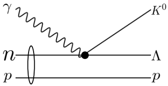


- Comparison of P to Kaon–MAID (soild) and Waluyo Ph.D. thesis (dashed)
- With $N(1900)\frac{3}{2}$
- Without $N(1900)\frac{3}{2}$
- A new fit to $K^0\Lambda$ with inclusion of all channels would help constrain amplitudes for $N(1900)\frac{3}{2}$, and maybe provide information about other states like $N(2120)$

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. $\vec{p}_n$