Polarization Observables in Vector-Meson Photoproduction off Transversely-Polarized Protons at CLAS

Priyashree Roy
(for the CLAS collaboration)

Florida State University

Baryons 2016

05/16/2016

Outline

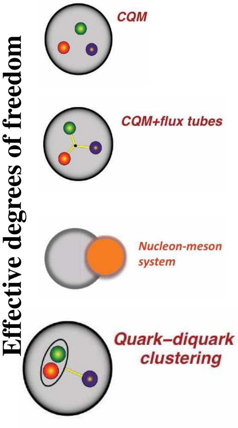
1. Introduction
   - Motivation
   - Polarization Observables
   - The FROST Experiment using CLAS
2. Data Analysis and Results
   - $p\omega$ Reaction
   - $p\pi^+\pi^-$ Reaction
3. Summary and Outlook

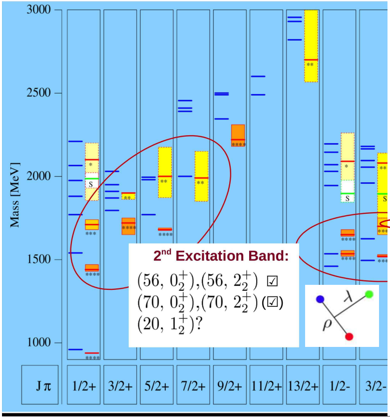
Outline

1. Introduction
   - Motivation
   - Polarization Observables
   - The FROST Experiment using CLAS
2. Data Analysis and Results
   - $p\omega$ Reaction
   - $p\pi^+\pi^-$ Reaction
3. Summary and Outlook

Why Baryon Spectroscopy?

[1] R. Bradford *et al.* (CLAS), PRC **75**, 035205 (2007), Observables C_x, C_z from $\vec{\gamma} p \rightarrow K^+ \vec{\Lambda}$
[2] Fits: BnGa Model, V.A. Nikonov *et al.*, Phy. Lett. B **662**, 245 (2008)

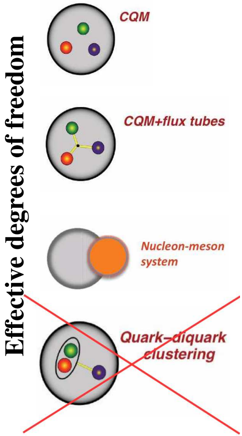


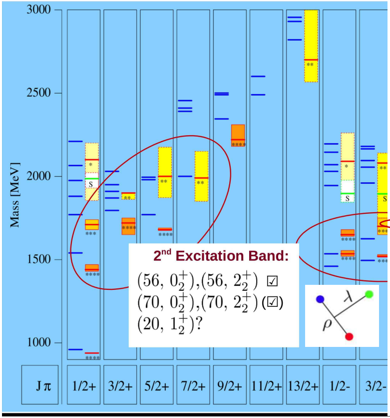


N^*	J^P $(L_{2I,2J})$	2010	2012
$N(1440)$	$1/2^+$ (P_{11})	****	****
$N(1520)$	$3/2^-$ (D_{13})	****	****
$N(1535)$	$1/2^-$ (S_{11})	****	****
$N(1650)$	$1/2^-$ (S_{11})	****	****
$N(1675)$	$5/2^-$ (D_{15})	****	****
$N(1680)$	$5/2^+$ (F_{15})	****	****
$N(1685)$			*
$N(1700)$	$3/2^-$ (D_{13})	***	***
$N(1710)$	$1/2^+$ (P_{11})	***	***
$N(1720)$	$3/2^+$ (P_{13})	****	****
$N(1860)$	$5/2^+$		**
$N(1875)$	$3/2^-$		***
$N(1880)$	$1/2^+$		**
$N(1895)$	$1/2^-$		**
$N(1900)$	$3/2^+$ (P_{13})	**	***
$N(1990)$	$7/2^+$ (F_{17})	**	**
$N(2000)$	$5/2^+$ (F_{15})	**	**
~~$N(2080)$~~	D_{13}	**	
~~$N(2090)$~~	S_{11}	*	
$N(2040)$	$3/2^+$		*
$N(2060)$	$5/2^-$		**
$N(2100)$	$1/2^+$ (P_{11})	*	*
$N(2120)$	$3/2^-$		**
$N(2190)$	$7/2^-$ (G_{17})	****	****
~~$N(2200)$~~	D_{15}	**	
$N(2220)$	$9/2^+$ (H_{19})	****	****

Why Baryon Spectroscopy?

[1] R. Bradford *et al.* (CLAS), PRC **75**, 035205 (2007), Observables C_x, C_z from $\vec{\gamma} p \rightarrow K^+ \vec{\Lambda}$
[2] Fits: BnGa Model, V.A. Nikonov *et al.*, Phy. Lett. B **662**, 245 (2008)



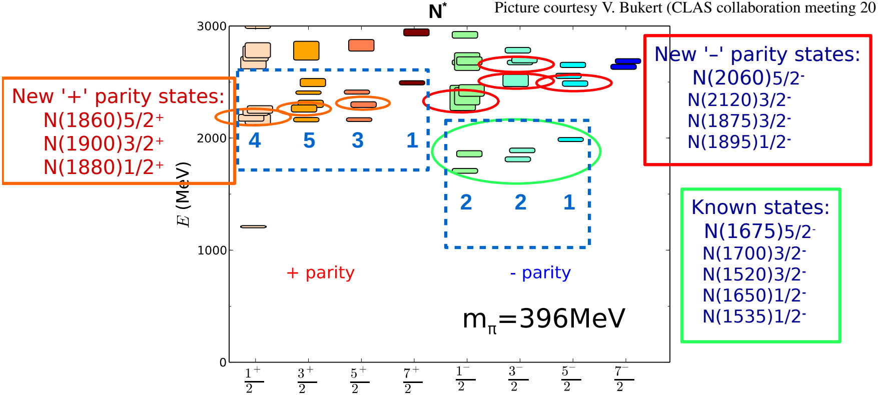


N^*	J^P $(L_{2I,2J})$	2010	2012
$N(1440)$	$1/2^+$ (P_{11})	∗∗∗∗	∗∗∗∗
$N(1520)$	$3/2^-$ (D_{13})	∗∗∗∗	∗∗∗∗
$N(1535)$	$1/2^-$ (S_{11})	∗∗∗∗	∗∗∗∗
$N(1650)$	$1/2^-$ (S_{11})	∗∗∗∗	∗∗∗∗
$N(1675)$	$5/2^-$ (D_{15})	∗∗∗∗	∗∗∗∗
$N(1680)$	$5/2^+$ (F_{15})	∗∗∗∗	∗∗∗∗
$N(1685)$			∗
$N(1700)$	$3/2^-$ (D_{13})	∗∗∗	∗∗∗
$N(1710)$	$1/2^+$ (P_{11})	∗∗∗	∗∗∗
$N(1720)$	$3/2^+$ (P_{13})	∗∗∗∗	∗∗∗∗
$N(1860)$	$5/2^+$		∗∗
$N(1875)$	$3/2^-$		∗∗∗
$N(1880)$	$1/2^+$		∗∗
$N(1895)$	$1/2^-$		∗∗
$N(1900)$	$3/2^+$ (P_{13})	∗∗	∗∗∗
$N(1990)$	$7/2^+$ (F_{17})	∗∗	∗∗
$N(2000)$	$5/2^+$ (F_{15})	∗∗	∗∗
~~$N(2080)$~~	D_{13}	∗∗	
~~$N(2090)$~~	S_{11}	∗	
$N(2040)$	$3/2^+$		∗
$N(2060)$	$5/2^-$		∗∗
$N(2100)$	$1/2^+$ (P_{11})	∗	∗
$N(2120)$	$3/2^-$		∗∗
$N(2190)$	$7/2^-$ (G_{17})	∗∗∗∗	∗∗∗∗
~~$N(2200)$~~	D_{15}	∗∗	
$N(2220)$	$9/2^+$ (H_{19})	∗∗∗∗	∗∗∗∗

N(1900)3/2$^+$ (which can be assigned as a member of the quartet of (**70**, 2_2^+)) cannot be accommodated in the naive quark-diquark picture, both oscillators need to be excited.[1],[2]

Baryon Spectrum with LQCD

R. Edwards *et al.* Phys. Rev. D **84** 074508 (2011)
Picture courtesy V. Bukert (CLAS collaboration meeting 2015)

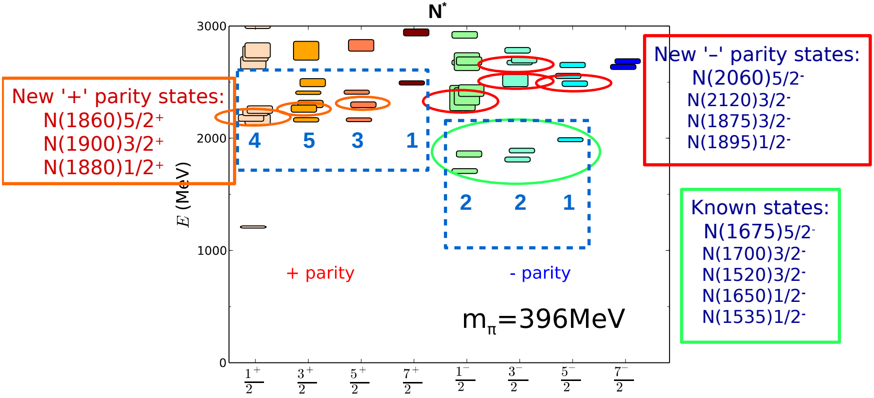


- - - LQCD manifests broad features of $SU(6) \otimes O(3)$ symmetry.

New states accommodated in LQCD calculations (ignoring mass scale) with J^P values consistent with CQM.

Baryon Spectrum with LQCD

More predicted states than experimentally observed. Lot more yet to be learnt!



- - - LQCD manifests broad features of $SU(6) \otimes O(3)$ symmetry.

New states accommodated in LQCD calculations (ignoring mass scale) with J^P values consistent with CQM.

Study of N^* to Vector Meson Decay Modes

Vector meson (ω, ρ, ϕ) decay modes have mostly remained unexplored. Vast pool of information yet to be unearthed:

- For a better understanding of known resonances, it is essential to study their vector meson decay modes.
- They carry the same J^{PC} as the photon so it is highly expected that they play an important role in the baryon spectrum.
- This talk will focus on $\gamma p \to p\pi^+\pi^-$ and $\gamma p \to p\omega \to p\pi^+\pi^-(\pi^0)$ reactions. The former gives information on $N^* \to p\rho$ which is difficult to study directly due to the broad nature of ρ.
- Ongoing analysis on $\gamma p \to p\phi$ cross section from CLAS-g12 (A. Hurley, Z. Akbar (FSU)).

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

Particle Data Group 2014

Study of N^* to Vector Meson Decay Modes

Vector meson (ω, ρ, ϕ) decay modes have mostly remained unexplored. Vast pool of information yet to be unearthed:

- For a better understanding of known resonances, it is essential to study their vector meson decay modes.
- They carry the same J^{PC} as the photon so it is highly expected that they play an important role in the baryon spectrum.
- This talk will focus on $\gamma p \to p\pi^+\pi^-$ and $\gamma p \to p\omega \to p\pi^+\pi^-(\pi^0)$ reactions. The former gives information on $N^* \to p\rho$ which is difficult to study directly due to the broad nature of ρ.
- Ongoing analysis on $\gamma p \to p\phi$ cross section from CLAS-g12 (A. Hurley, Z. Akbar (FSU)).

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

Particle Data Group 2014

Study of N^* to Vector Meson Decay Modes

Vector meson (ω, ρ, ϕ) decay modes have mostly remained unexplored. Vast pool of information yet to be unearthed:

- For a better understanding of known resonances, it is essential to study their vector meson decay modes.
- They carry the same J^{PC} as the photon so it is highly expected that they play an important role in the baryon spectrum.
- This talk will focus on $\gamma p \to p\pi^+\pi^-$ and $\gamma p \to p\omega \to p\pi^+\pi^-(\pi^0)$ reactions. The former gives information on $N^* \to p\rho$ which is difficult to study directly due to the broad nature of ρ.
- Ongoing analysis on $\gamma p \to p\phi$ cross section from CLAS-g12 (A. Hurley, Z. Akbar (FSU)).

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

Particle Data Group 2014

Study of N^* to Vector Meson Decay Modes

Vector meson (ω, ρ, ϕ) decay modes have mostly remained unexplored. Vast pool of information yet to be unearthed:

- For a better understanding of known resonances, it is essential to study their vector meson decay modes.
- They carry the same J^{PC} as the photon so it is highly expected that they play an important role in the baryon spectrum.
- This talk will focus on $\gamma p \to p\pi^+\pi^-$ and $\gamma p \to p\omega \to p\pi^+\pi^-(\pi^0)$ reactions. The former gives information on $N^* \to p\rho$ which is difficult to study directly due to the broad nature of ρ.
- Ongoing analysis on $\gamma p \to p\phi$ cross section from CLAS-g12 (A. Hurley, Z. Akbar (FSU)).

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

Particle Data Group 2014

Study of N^* to Vector Meson Decay Modes

Vector meson (ω, ρ, ϕ) decay modes have mostly remained unexplored. Vast pool of information yet to be unearthed:

- For a better understanding of known resonances, it is essential to study their vector meson decay modes.
- They carry the same J^{PC} as the photon so it is highly expected that they play an important role in the baryon spectrum.
- This talk will focus on $\gamma p \to p\pi^+\pi^-$ and $\gamma p \to p\omega \to p\pi^+\pi^-(\pi^0)$ reactions. The former gives information on $N^* \to p\rho$ which is difficult to study directly due to the broad nature of ρ.
- Ongoing analysis on $\gamma p \to p\phi$ cross section from CLAS-g12 (A. Hurley, Z. Akbar (FSU)).

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

Particle Data Group 2014

Why are Spin Observables Important?

- Most of the identified baryon resonances came from πN scattering. Many missing resonances may couple to photoproduction reactions.
- Baryon resonances are broad and overlapping so peak hunting is difficult. Need more observables in addition to cross sections to disentangle the resonances.

Why are Spin Observables Important?

Polarization observables are essential for the determination of the scattering amplitudes with minimal ambiguities $\rightarrow$ 'reveal' the baryon resonances.

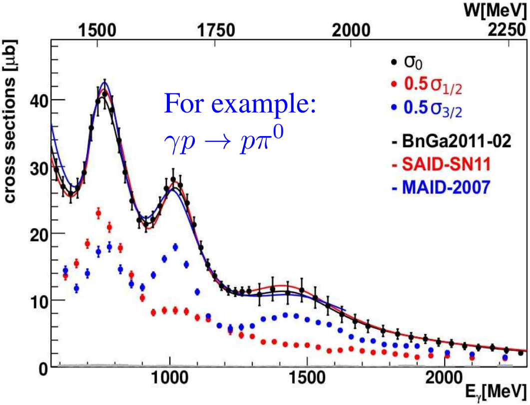
E.g., in single meson photoproduction:

$$\sigma_{\text{total}} = \sigma_{\text{unpol.}}[1 - \delta_l\, \Sigma \cos(2\phi)$$
$$+\Lambda_x\,(-\delta_l\, \mathbf{H} \sin(2\phi)\, +\, \delta_\odot\, \mathbf{F})$$
$$-\Lambda_y\,(-\mathbf{T}\, +\, \delta_l\, \mathbf{P} \cos2\phi)$$
$$-\Lambda_z\,(-\delta_l\, \mathbf{G} \sin(2\phi)\, +\, \delta_\odot\, \mathbf{E}\,)\, +\, ...]$$

$\delta_\odot(\delta_l)$: degree of beam pol.
Λ : degree of target pol.

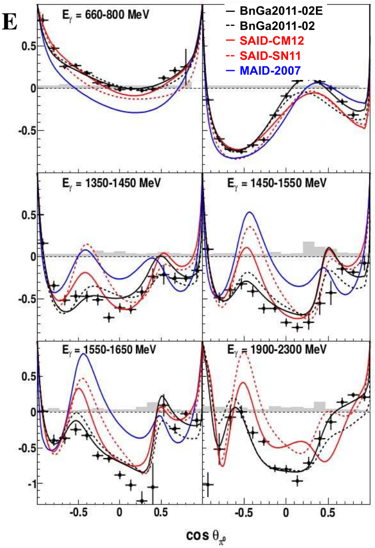
Why are Spin Observables Important?

M. Gottschall *et al.* PRL 112 (2014)

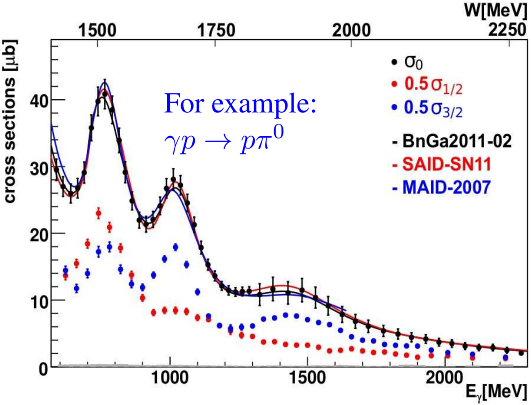


All 3 model predictions agree with experimental results for the unpolarized cross section → leads to ambiguous solutions for the set of contributing resonances!

Why are Spin Observables Important?



M. Gottschall *et al.* PRL 112 (2014)



For example:
$\gamma p \to p\pi^0$

Spin observables sensitive to the interference between resonances. Reveal discrepancies between model predictions and experimental data.

Spin Observables for $\vec{\gamma}\vec{p} \to p\pi^+\pi^-$ & $p\omega$ @ CLAS

FROST experiment using CLAS, JLab

- World-wide effort to extract polarization observables in photoproduction reactions: CLAS @ JLab (U.S.), ELSA, MAMI (Germany), SPring-8 (Japan), GRAAL (France)
- Getting close to completing the set of accessible polarization observables. 'Complete experiment in pseudoscalar meson production': next talk

$p\omega$:

Beam \ Target	Transversely Pol.	Longitudinally Pol.
Linearly Pol.	Σ, T, H, P	Σ, G
Circularly Pol.	F, T	E

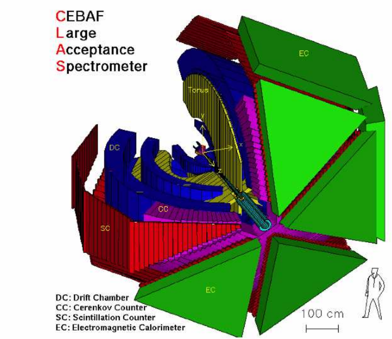
Prelim. results (Priyashree, FSU)
(Analysis Note under review)

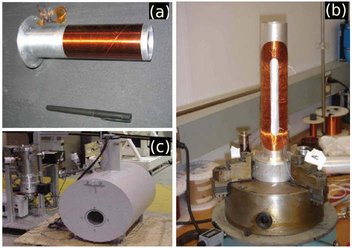
Data acquired
Prelim. results available
(Talk by L. Net: today, 16:55)
(Talk by Z. Akbar: today, 15:45)

$p\pi^+\pi^-$:

Beam \ Target	Transversely Pol.	Longitudinally Pol.
Linearly Pol.	$P^{s,c}_{x,y}$, $P_{x,y}$, $I^{s,c}$	$P^{s,c}_{z}$, P_z, $I^{s,c}$
Circularly Pol.	$P^{\odot}_{x,y}$, $P_{x,y}$, $I^{\odot}$	$P^{\odot}_{z}$, P_z, $I^{\odot}$

The FROST Experiment using CLAS at JLab





W range covered $\sim$ 1.5 to 2.3 GeV

g9a run (Oct 2007 to Jan 2008)
Photon pol.: Linear/Circular
Target: Frozen Spin Butanol
Target pol.: Longitudinal

g9b run (Mar to Aug, 2010)
Photon pol.: Linear/Circular
Target: Frozen Spin Butanol
Target pol.: Transverse

Outline

1. Introduction
   - Motivation
   - Polarization Observables
   - The FROST Experiment using CLAS
2. Data Analysis and Results
   - $p\omega$ Reaction
   - $p\pi^+\pi^-$ Reaction
3. Summary and Outlook

Data Selection and Analysis

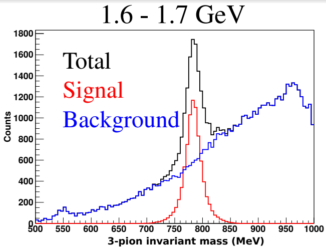
- **Topologies for** $\mathrm{p}\pi^+\pi^-$**:**
  $\vec{\gamma}\vec{p} \to p\pi^+$ (missing π^-)
  $\vec{\gamma}\vec{p} \to p\pi^-$ (missing π^+)
  $\vec{\gamma}\vec{p} \to p\pi^+\pi^-$ (no missing particle)
  The observables are weighted avg. over topologies.
- **Topology for** $\mathrm{p}\omega$ **(89% branching fraction):**
  $\vec{\gamma}\vec{p} \to p\pi^+\pi^-$(missing π^0)
  Topology identified using Kinematic fitting.
- **Standard cuts & corrections:** vertex cut, photon selection, β cuts, E-p corrections.
- **Event-based method**[1] for signal-background separation.
- **Event-based maximum likelihood method**[2] for extracting polarization observables.

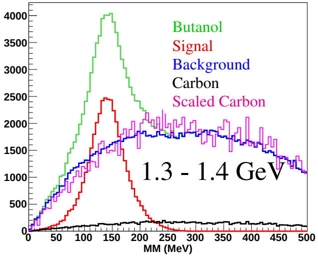
Data Selection and Analysis

- **Topologies for** $\mathrm{p}\pi^+\pi^-$:
  $\vec{\gamma}\vec{p} \to p\pi^+$ (missing π^-)
  $\vec{\gamma}\vec{p} \to p\pi^-$ (missing π^+)
  $\vec{\gamma}\vec{p} \to p\pi^+\pi^-$ (no missing particle)
  The observables are weighted avg. over topologies.
- **Topology for** $\mathrm{p}\omega$ **(89% branching fraction):**
  $\vec{\gamma}\vec{p} \to p\pi^+\pi^-$(missing π^0)
  Topology identified using Kinematic fitting.
- **Standard cuts & corrections:** vertex cut, photon selection, β cuts, E-p corrections.
- **Event-based method**[1] for signal-background separation.
- **Event-based maximum likelihood method**[2] for extracting polarization observables.

Data Selection and Analysis

- **Topologies for $p\pi^+\pi^-$:**
  $\vec{\gamma}\vec{p} \to p\pi^+$ (missing π^-)
  $\vec{\gamma}\vec{p} \to p\pi^-$ (missing π^+)
  $\vec{\gamma}\vec{p} \to p\pi^+\pi^-$ (no missing particle)
  The observables are weighted avg. over topologies.
- **Topology for $p\omega$ (89% branching fraction):**
  $\vec{\gamma}\vec{p} \to p\pi^+\pi^-$(missing π^0)
  Topology identified using Kinematic fitting.
- **Standard cuts & corrections:** vertex cut, photon selection, β cuts, E-p corrections.
- **Event-based method**[1] for signal-background separation.
- **Event-based maximum likelihood method**[2] for extracting polarization observables.



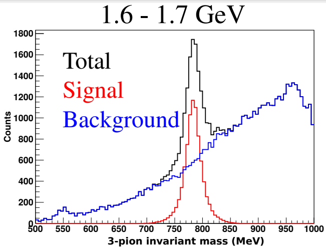


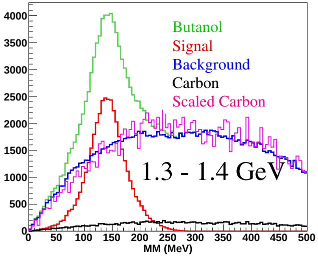
[1] M. Williams *et al.*, JINST 4 (2009) P10003

Data Selection and Analysis

- **Topologies for $p\pi^+\pi^-$:**
  $\vec{\gamma}\vec{p} \to p\pi^+$ (missing π^-)
  $\vec{\gamma}\vec{p} \to p\pi^-$ (missing π^+)
  $\vec{\gamma}\vec{p} \to p\pi^+\pi^-$ (no missing particle)
  The observables are weighted avg. over topologies.
- **Topology for $p\omega$ (89% branching fraction):**
  $\vec{\gamma}\vec{p} \to p\pi^+\pi^-$(missing π^0)
  Topology identified using Kinematic fitting.
- **Standard cuts & corrections:** vertex cut, photon selection, β cuts, E-p corrections.
- **Event-based method**[1] for signal-background separation.
- **Event-based maximum likelihood method**[2] for extracting polarization observables.

[1] M. Williams *et al.*, JINST 4 (2009) P10003
[2] D G Ireland, CLAS Note 2011-010



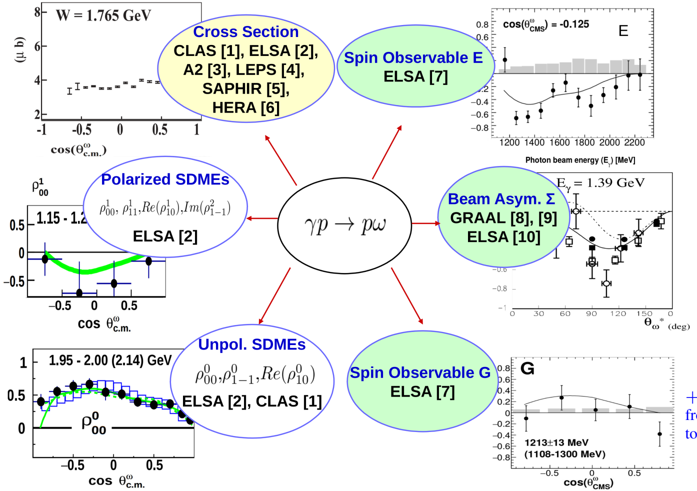


Results

Results in $\vec{\gamma}\vec{p} \rightarrow p\omega$

Published Results in $\gamma p \to p\omega$

Isospin filter (sensitive to N^* only), reduces complexity



[1] Williams *et al.*, PRC **80**, 065208 (2009)
[2] Wilson *et al.*, Phys. Lett. B **749** (2015)
[3] Strakovsky *et al.*, PRC **91** (2015)
[4] Sumihama *et al.*, PRC **80**, 052201 (2009)
[5] Barth *et al.*, EPJ A **18**, 117 (2003)
[6] Wolf, Rept. Prog. Phys. **73**, 116202 (2010)
[7] Eberhardt *et al.*, Phy. Lett. B **750** (2015)
[8] Vegna *et al.*, PRC **91**, 065207 (2015)
[9] Ajaka *et al.*, PRL **96**, 132003 (2006)
[10] F. Klein *et al.*, PRD **78**, 117101 (2008)

+ High quality polarized SDMEs from CLAS, Brian Vernarsky (CMU), to be published soon.

Partial Wave Analysis of $\gamma p \to p\omega$ Observables

Pol. SDMEs and Σ were crucial to understand the t-channel background: Major contribution from pomeron exchange mechanism.

BnGa PWA 2016 (coupled-channel) using ELSA data

Notable contribution — Suggestive evidence

CLAS PWA 2009

Notable contribution — Suggestive evidence

I. Denisenko *et al.*, Phys. Lett. B (2016)
M. Williams *et al.*, PRC **80**, 065208 (2009)

* rating in PDG 2014

Particle J^P	overall	$N\omega$
$N(1680)\ 5/2^+$	****	
$N(1685)\ ?^?$	*	
$N(1700)\ 3/2^-$	***	
$N(1710)\ 1/2^+$	***	**
$N(1720)\ 3/2^+$	****	
$N(1860)\ 5/2^+$	**	
$N(1875)\ 3/2^-$	***	**
$N(1880)\ 1/2^+$	**	
$N(1895)\ 1/2^-$	**	
$N(1900)\ 3/2^+$	***	**
$N(1990)\ 7/2^+$	**	
$N(2000)\ 5/2^+$	**	
$N(2040)\ 3/2^+$	*	
$N(2060)\ 5/2^-$	**	
$N(2100)\ 1/2^+$	*	
$N(2150)\ 3/2^-$	**	
$N(2190)\ 7/2^-$	****	*
$N(2220)\ 9/2^+$	****	
$N(2250)\ 9/2^-$	****	

Partial Wave Analysis of $\gamma p \to p\omega$ Observables

Pol. SDMEs and Σ were crucial to understand the t-channel background: Major contribution from pomeron exchange mechanism.

Need more polarization observables, in particular to understand W$>$ 2 GeV region:

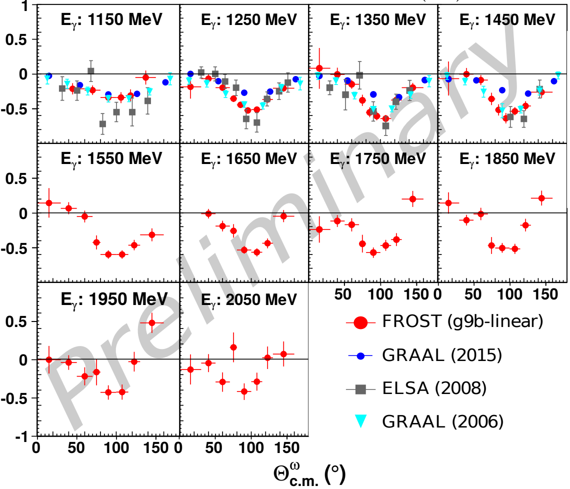
- N($\sim$ 2.2 GeV) Uncertain J^P: $1/2^-, 3/2^+, 3/2^-$ or $5/2^+$?[?]
- N($>$ 2.1 GeV) $7/2^-$?

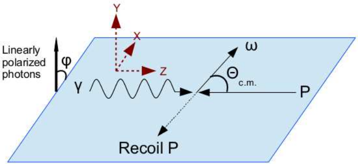
* rating in PDG 2014

Particle J^P	overall	$N\omega$
$N(1680)\ 5/2^+$	****	
$N(1685)\ ?^?$	*	
$\boxed{N(1700)\ 3/2^-}$	***	
$N(1710)\ 1/2^+$	***	**
$\boxed{N(1720)\ 3/2^+}$	****	
$N(1860)\ 5/2^+$	**	
$\boxed{N(1875)\ 3/2^-}$	***	**
$N(1880)\ 1/2^+$	**	
$\boxed{N(1895)\ 1/2^-}$	**	
$N(1900)\ 3/2^+$	***	**
$N(1990)\ 7/2^+$	**	
$\boxed{N(2000)\ 5/2^+}$	**	
$N(2040)\ 3/2^+$	*	
$N(2060)\ 5/2^-$	**	
$N(2100)\ 1/2^+$	*	
$N(2150)\ 3/2^-$	**	
$\boxed{N(2190)\ 7/2^-}$	****	*
$N(2220)\ 9/2^+$	****	
$N(2250)\ 9/2^-$	****	

Beam Asymmetry Σ in $\vec{\gamma}p \to p\omega$

ω reconstructed from $\pi^+\pi^-(\pi^0)$



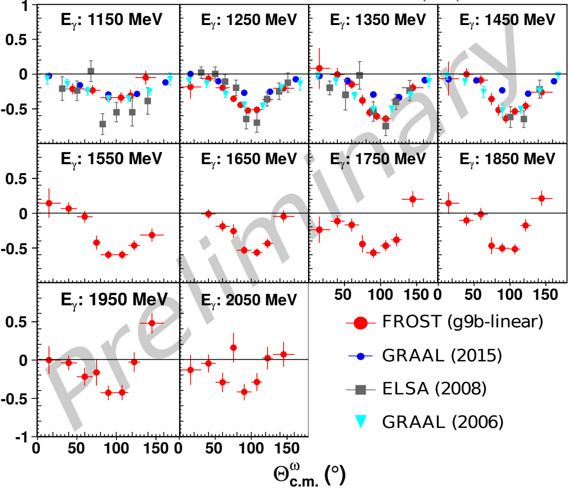


$$\sigma = \sigma_0[1 - \boldsymbol{\Sigma}\ \delta_l\cos(2\phi) + \Lambda\cos(\alpha)(-\delta_l\mathbf{H}\sin(2\phi) + \delta_\odot\mathbf{F}) - \Lambda\sin(\alpha)(-\mathbf{T} + \delta_l\mathbf{P}\cos(2\phi)) - \Lambda_z(-\delta_l\mathbf{G}\sin(2\phi) + \delta_\odot\mathbf{E})]$$

$\delta_\odot(\delta_l)$: degree of beam pol.
Λ : degree of target pol.

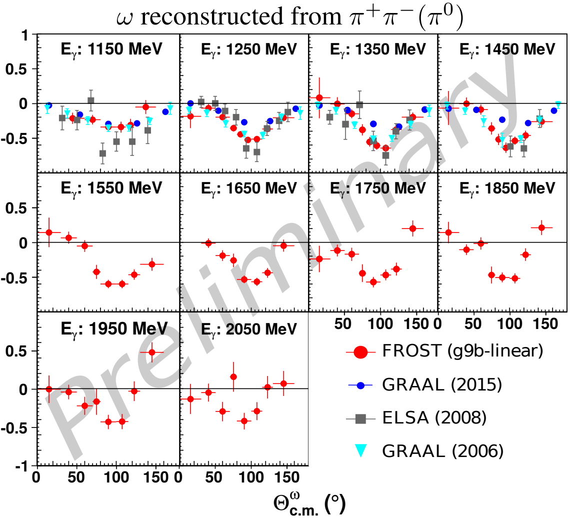
Beam Asymmetry Σ in $\vec{\gamma}p \to p\omega$

ω reconstructed from $\pi^+\pi^-(\pi^0)$



- **FROST**: transversely pol. target (more complex analysis)
  Others: unpolarized H_2 target

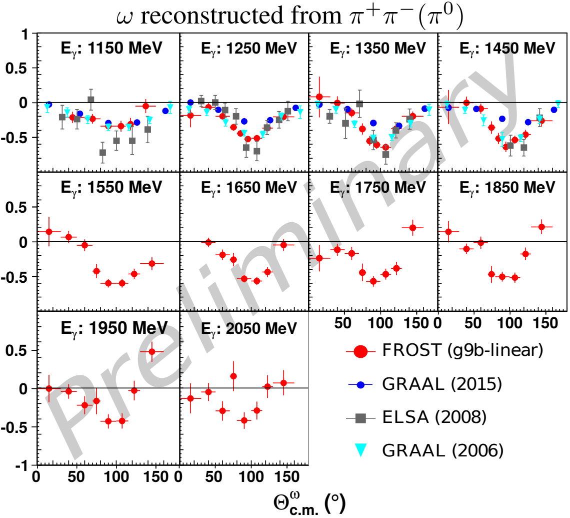
Beam Asymmetry Σ in $\vec{\gamma}p \to p\omega$



- **FROST**: transversely pol. target (more complex analysis) **Others**: unpolarized H_2 target
- **GRAAL 2006**: 3-pion decay mode **ELSA 2008**: radiative decay mode

FROST results fall nicely in-between GRAAL 06 & ELSA above 1.2 GeV. This provides good support for the FROST results.

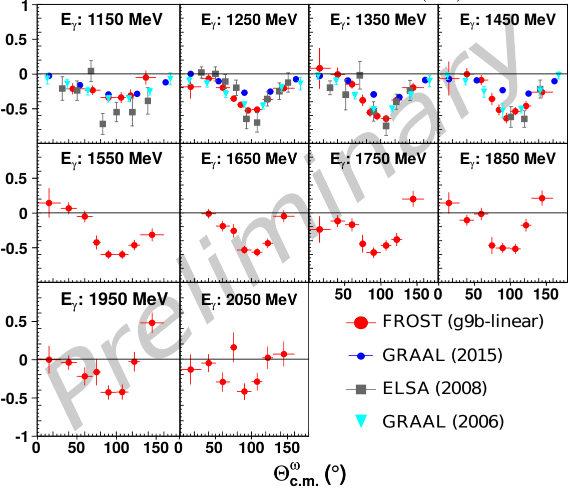
Beam Asymmetry Σ in $\vec{\gamma}p \to p\omega$



- **GRAAL 2015** inconsistent with other published results and FROST results. The disagreement is currently unresolved.

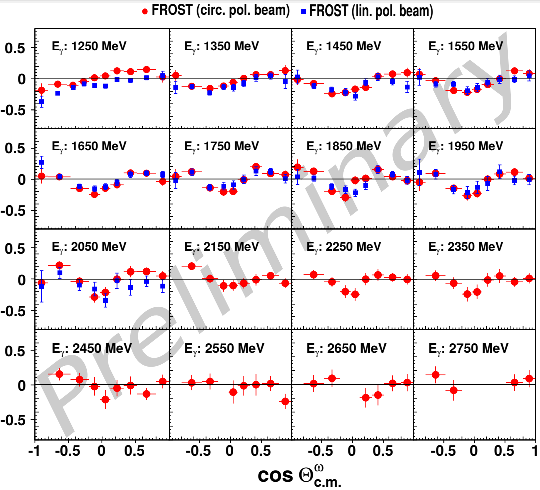
Beam Asymmetry Σ in $\vec{\gamma}p \rightarrow p\omega$

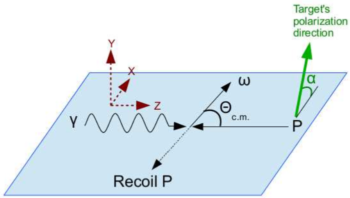
ω reconstructed from $\pi^+\pi^-(\pi^0)$



- **GRAAL 2015** inconsistent with other published results and FROST results. The disagreement is currently unresolved.
- **First high-quality measurements** at $E_\gamma \in [1.5, 2.1]$ GeV. Large Σ indicate significant s- and/or u-contributions at these energies.

First Measurements of Target Asymmetry T in $\gamma\vec{p} \to p\omega$



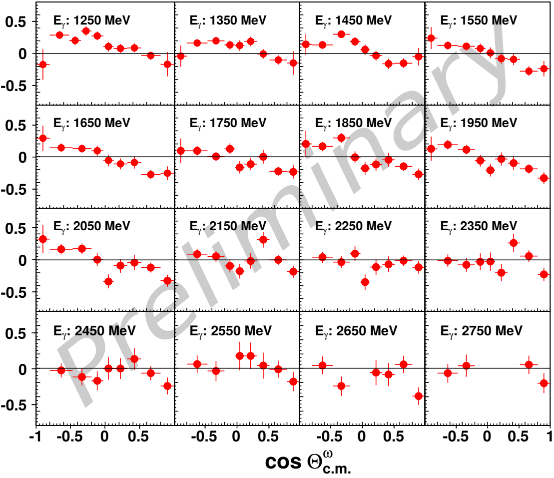


$$\begin{aligned}\sigma &= \sigma_0[1 - \Sigma\, \delta_l \cos(2\phi) \\ &+ \Lambda\cos(\alpha)(-\delta_l \mathbf{H}\sin(2\phi) + \delta_\odot \mathbf{F}) \\ &- \Lambda\sin(\alpha)(-\mathbf{T} + \delta_l \mathbf{P}\cos(2\phi))] \\ &- \Lambda_z(-\delta_l \mathbf{G}\sin(2\phi) \quad + \quad \delta_\odot \mathbf{E})]\end{aligned}$$

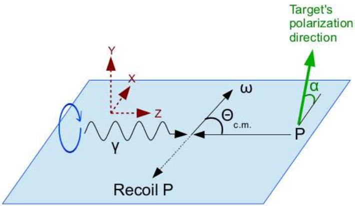
$\delta_\odot(\delta_l)$: degree of beam pol.
Λ : degree of target pol.

The two experimental results on target asym. **T** from FROST agree well.

First Measurements of F in $\vec{\gamma}\vec{p} \to p\omega$



Double-polarization observable F

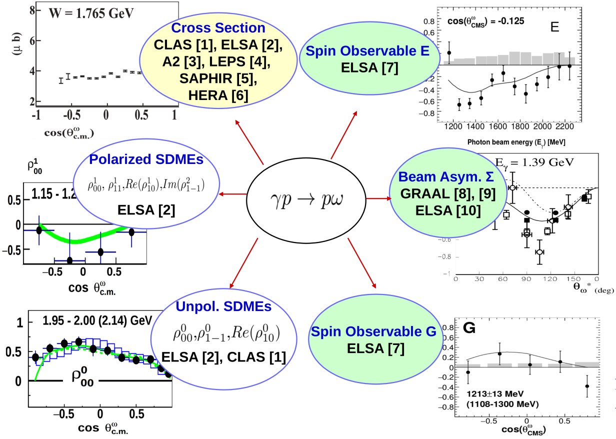


$$\sigma = \sigma_0[1 - \mathbf{\Sigma}\ \delta_l \cos(2\phi) + \Lambda\cos(\alpha)(-\delta_l \mathbf{H}\sin(2\phi) + \delta_\odot \mathbf{F}) - \Lambda\sin(\alpha)(-\mathbf{T} + \delta_l \mathbf{P}\cos(2\phi))] - \Lambda_z(-\delta_l \mathbf{G}\sin(2\phi) + \delta_\odot \mathbf{E})]$$

$\delta_\odot(\delta_l)$: degree of beam pol.

Λ : degree of target pol.

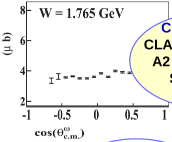
Published Results + New Results in $\gamma p \to p\omega$



+ High quality pol. SDMEs from CLAS, B. Vernarsky (CMU), to be published soon.

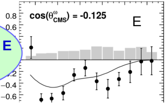
Published Results + New Results in $\gamma p \to p\omega$

Getting close to completing the set of observables!

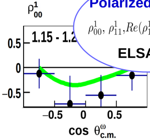


Cross Section
CLAS [1], ELSA [2], A2 [3], LEPS [4], SAPHIR [5], HERA [6]

Spin Observable E
ELSA [7]

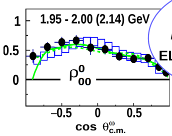


Polarized SDMEs
ρ^1_{00}, ρ^1_{11}, $Re(\rho^1_{10})$, $Im(\rho^2_{1-1})$
ELSA [2]

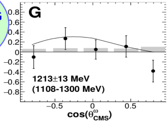


$\gamma p \to p\omega$

Unpol. SDMEs
ρ^0_{00}, ρ^0_{1-1}, $Re(\rho^0_{10})$
ELSA [2], CLAS [1]



Spin Observable G
ELSA [7]



+ FROST (Prelim.) Results

Beam \ Target	Transversely Pol.	Longitudinally Pol.
Linearly Pol.	Σ, T, H, P	Σ, G
Circularly Pol.	F, T	E

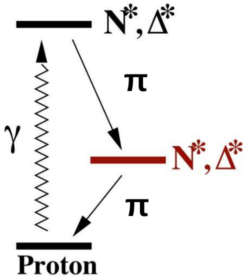
+ High quality pol. SDMEs from CLAS, B. Vernarsky (CMU), to be published soon.

Results

Results in $\vec{\gamma}\vec{p} \to p\pi^+\pi^-$

Results in $\vec{\gamma}\vec{p} \to p\pi^+\pi^-$

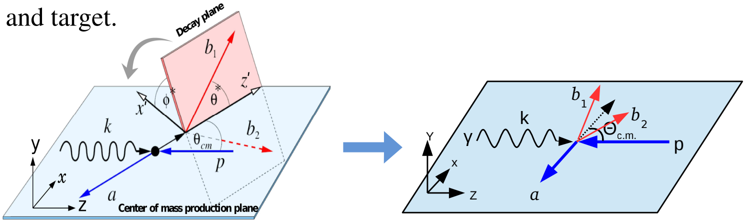
- Allow the study of sequential decays of intermediate N^* and also $N^* \to p\rho$ decay but the large hadronic background makes it challenging.



Sequential decay of N^*, Δ^* to the ground state.

Results in $\vec{\gamma}\vec{p} \to p\pi^+\pi^-$

- Allow the study of sequential decays of intermediate N^* and also $N^* \to p\rho$ decay but the large hadronic background makes it challenging.
- Reaction described using 2 planes (5 kinematic variables) $\to$ more spin observables than in single-meson photoproduction using polarized beam and target.



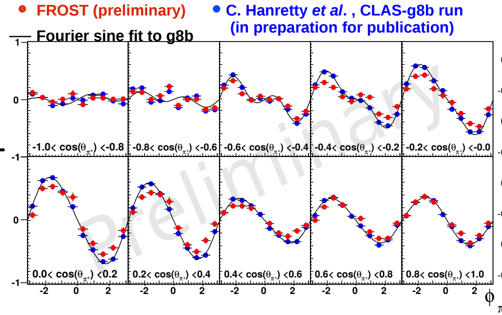
2 beam-pol. observables: I^s, I^c
Unlike only one (Σ observable) in single-meson photoproduction.

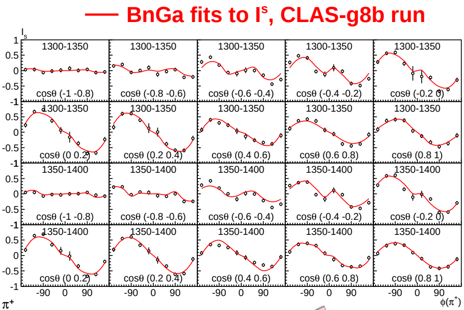
I^s vanishes, I^c survives.

W. Roberts *et al.*, Phys. Rev. C **71**, 055201 (2005)

Beam Asymmetry I^s in $\vec{\gamma}p \to p\pi^+\pi^-$

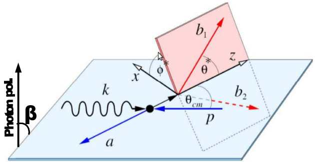
Example: $1.30 < E_\gamma < 1.40$ GeV (Total E_γ range covered: 0.7 - 2.1 GeV)





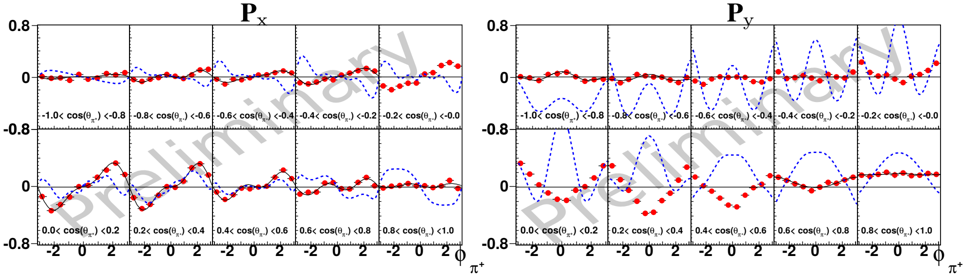
Good agreement between experiments

$$I = I_0\{\delta_l[I^s \sin(2\beta) + I^c \cos(2\beta)]\}$$



First Measurements of Target Asym. $\mathrm{P_{x,y}}$ in $\gamma\vec{p} \rightarrow p\pi^+\pi^-$

Example: $0.8 < \mathrm{E}_\gamma < 0.9$ GeV (Total E_γ range covered: 0.7 - 2.1 GeV)



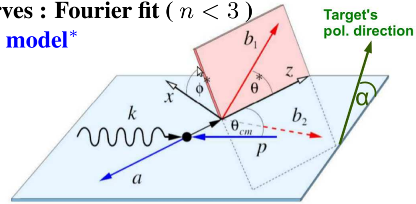
FROST g9b (lin. pol. beam) **Solid curves : Fourier fit ($n < 3$)**

Dashed curves : A. Fix and H. Arenhovel model*

3-dim. phase space: $(\mathrm{E}_\gamma, \phi^*_{\pi^+}, \cos\theta^*_{\pi^+})$

$$\mathrm{I} = \mathrm{I}_0[1 + \Lambda\cos(\alpha)\mathbf{P_x} + \Lambda\sin(\alpha)\mathbf{P_y}]$$

Λ : degree of target pol.

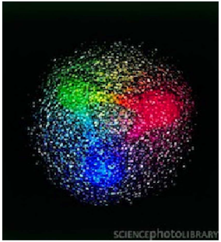


Eur. Phys. J. A **25**, 115 (2005)

Outline

1. Introduction
   - Motivation
   - Polarization Observables
   - The FROST Experiment using CLAS
2. Data Analysis and Results
   - $p\omega$ Reaction
   - $p\pi^+\pi^-$ Reaction
3. Summary and Outlook

Summary and Outlook



- **Photoproduction of vector mesons and multi-pion final states**: essential to **discover new resonances** and better understand the known resonances.
- **Many first-time measurements from CLAS-FROST for $\vec{\gamma}\vec{p} \to p\omega$ and $\vec{\gamma}\vec{p} \to p\pi^+\pi^-$**: they will **significantly augment the world database** of polarization observables in photoproduction.
- **The high-quality FROST results are expected to put tight constraints on data interpretation tools**, immensely aiding in determining contributing N^* with minimal ambiguities.
- The findings in the light baryon sector together with the findings in strange and heavy flavor sectors (GlueX, LHCb, BES III etc.), will help us **understand the evolution of bound states of QCD from light to heavy-quark regime.**

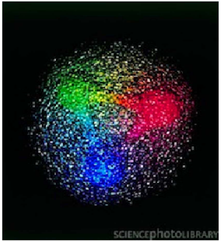
Summary and Outlook

- **Photoproduction of vector mesons and multi-pion final states**: essential to **discover new resonances** and better understand the known resonances.
- **Many first-time measurements from CLAS-FROST for $\vec{\gamma}\vec{p} \to p\omega$ and $\vec{\gamma}\vec{p} \to p\pi^+\pi^-$**: they will **significantly augment the world database** of polarization observables in photoproduction.
- **The high-quality FROST results are expected to put tight constraints on data interpretation tools**, immensely aiding in determining contributing N^* with minimal ambiguities.
- The findings in the light baryon sector together with the findings in strange and heavy flavor sectors (GlueX, LHCb, BES III etc.), will help us **understand the evolution of bound states of QCD from light to heavy-quark regime.**

Summary and Outlook

- **Photoproduction of vector mesons and multi-pion final states**: essential to **discover new resonances** and better understand the known resonances.
- **Many first-time measurements from CLAS-FROST for $\vec{\gamma}\vec{p} \to p\omega$ and $\vec{\gamma}\vec{p} \to p\pi^+\pi^-$**: they will **significantly augment the world database** of polarization observables in photoproduction.
- **The high-quality FROST results are expected to put tight constraints on data interpretation tools**, immensely aiding in determining contributing N^* with minimal ambiguities.
- The findings in the light baryon sector together with the findings in strange and heavy flavor sectors (GlueX, LHCb, BES III etc.), will help us **understand the evolution of bound states of QCD from light to heavy-quark regime.**

Summary and Outlook



- **Photoproduction of vector mesons and multi-pion final states**: essential to **discover new resonances** and better understand the known resonances.
- **Many first-time measurements from CLAS-FROST for $\vec{\gamma}\vec{p} \to p\omega$ and $\vec{\gamma}\vec{p} \to p\pi^+\pi^-$**: they will **significantly augment the world database** of polarization observables in photoproduction.
- **The high-quality FROST results are expected to put tight constraints on data interpretation tools**, immensely aiding in determining contributing N^* with minimal ambiguities.
- The findings in the light baryon sector together with the findings in strange and heavy flavor sectors (GlueX, LHCb, BES III etc.), will help us **understand the evolution of bound states of QCD from light to heavy-quark regime.**

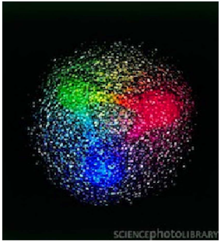
Summary and Outlook

- **Photoproduction of vector mesons and multi-pion final states**: essential to **discover new resonances** and better understand the known resonances.
- **Many first-time measurements from CLAS-FROST for $\vec{\gamma}\vec{p} \to p\omega$ and $\vec{\gamma}\vec{p} \to p\pi^+\pi^-$**: they will **significantly augment the world database** of polarization observables in photoproduction.
- **The high-quality FROST results are expected to put tight constraints on data interpretation tools**, immensely aiding in determining contributing N^* with minimal ambiguities.
- The findings in the light baryon sector together with the findings in strange and heavy flavor sectors (GlueX, LHCb, BES III etc.), will help us **understand the evolution of bound states of QCD from light to heavy-quark regime.**

Summary and Outlook

- **Photoproduction of vector mesons and multi-pion final states**: essential to **discover new resonances** and better understand the known resonances.
- **Many first-time measurements from CLAS-FROST for $\vec{\gamma}\vec{p} \to p\omega$ and $\vec{\gamma}\vec{p} \to p\pi^+\pi^-$**: they will **significantly augment the world database** of polarization observables in photoproduction.
- **The high-quality FROST results are expected to put tight constraints on data interpretation tools**, immensely aiding in determining contributing N^* with minimal ambiguities.
- The findings in the light baryon sector together with the findings in strange and heavy flavor sectors (GlueX, LHCb, BES III etc.), will help us **understand the evolution of bound states of QCD from light to heavy-quark regime.**

Summary and Outlook



- **Photoproduction of vector mesons and multi-pion final states**: essential to **discover new resonances** and better understand the known resonances.
- **Many first-time measurements from CLAS-FROST for $\vec{\gamma}\vec{p} \to p\omega$ and $\vec{\gamma}\vec{p} \to p\pi^+\pi^-$**: they will **significantly augment the world database** of polarization observables in photoproduction.
- **The high-quality FROST results are expected to put tight constraints on data interpretation tools**, immensely aiding in determining contributing N^* with minimal ambiguities.
- The findings in the light baryon sector together with the findings in strange and heavy flavor sectors (GlueX, LHCb, BES III etc.), will help us **understand the evolution of bound states of QCD from light to heavy-quark regime.**

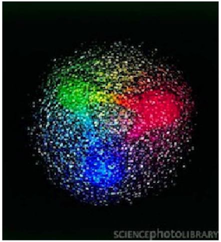
Summary and Outlook

- **Photoproduction of vector mesons and multi-pion final states**: essential to **discover new resonances** and better understand the known resonances.
- **Many first-time measurements from CLAS-FROST for** $\vec{\gamma}\vec{p} \to p\omega$ **and** $\vec{\gamma}\vec{p} \to p\pi^+\pi^-$: they will **significantly augment the world database** of polarization observables in photoproduction.
- **The high-quality FROST results are expected to put tight constraints on data interpretation tools**, immensely aiding in determining contributing N^* with minimal ambiguities.
- The findings in the light baryon sector together with the findings in strange and heavy flavor sectors (GlueX, LHCb, BES III etc.), will help us **understand the evolution of bound states of QCD from light to heavy-quark regime.**

Summary and Outlook

- **Photoproduction of vector mesons and multi-pion final states**: essential to **discover new resonances** and better understand the known resonances.
- **Many first-time measurements from CLAS-FROST for $\vec{\gamma}\vec{p} \to p\omega$ and $\vec{\gamma}\vec{p} \to p\pi^+\pi^-$**: they will **significantly augment the world database** of polarization observables in photoproduction.
- **The high-quality FROST results are expected to put tight constraints on data interpretation tools**, immensely aiding in determining contributing N^* with minimal ambiguities.
- The findings in the light baryon sector together with the findings in strange and heavy flavor sectors (GlueX, LHCb, BES III etc.), will help us **understand the evolution of bound states of QCD from light to heavy-quark regime.**

Summary and Outlook



- **Photoproduction of vector mesons and multi-pion final states**: essential to **discover new resonances** and better understand the known resonances.
- **Many first-time measurements from CLAS-FROST for $\vec{\gamma}\vec{p} \to p\omega$ and $\vec{\gamma}\vec{p} \to p\pi^+\pi^-$**: they will **significantly augment the world database** of polarization observables in photoproduction.
- **The high-quality FROST results are expected to put tight constraints on data interpretation tools**, immensely aiding in determining contributing N^* with minimal ambiguities.
- The findings in the light baryon sector together with the findings in strange and heavy flavor sectors (GlueX, LHCb, BES III etc.), will help us **understand the evolution of bound states of QCD from light to heavy-quark regime.**

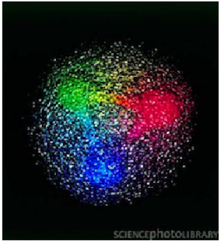
Summary and Outlook

- **Photoproduction of vector mesons and multi-pion final states**: essential to **discover new resonances** and better understand the known resonances.
- **Many first-time measurements from CLAS-FROST for $\vec{\gamma}\vec{p} \to p\omega$ and $\vec{\gamma}\vec{p} \to p\pi^+\pi^-$**: they will **significantly augment the world database** of polarization observables in photoproduction.
- **The high-quality FROST results are expected to put tight constraints on data interpretation tools**, immensely aiding in determining contributing N^* with minimal ambiguities.
- The findings in the light baryon sector together with the findings in strange and heavy flavor sectors (GlueX, LHCb, BES III etc.), will help us **understand the evolution of bound states of QCD from light to heavy-quark regime.**

Summary and Outlook

- **Photoproduction of vector mesons and multi-pion final states**: essential to **discover new resonances** and better understand the known resonances.
- **Many first-time measurements from CLAS-FROST for $\vec{\gamma}\vec{p} \to p\omega$ and $\vec{\gamma}\vec{p} \to p\pi^+\pi^-$**: they will **significantly augment the world database** of polarization observables in photoproduction.
- **The high-quality FROST results are expected to put tight constraints on data interpretation tools**, immensely aiding in determining contributing N^* with minimal ambiguities.
- The findings in the light baryon sector together with the findings in strange and heavy flavor sectors (GlueX, LHCb, BES III etc.), will help us **understand the evolution of bound states of QCD from light to heavy-quark regime.**

Summary and Outlook



- **Photoproduction of vector mesons and multi-pion final states**: essential to **discover new resonances** and better understand the known resonances.
- **Many first-time measurements from CLAS-FROST for $\vec{\gamma}\vec{p} \to p\omega$ and $\vec{\gamma}\vec{p} \to p\pi^+\pi^-$**: they will **significantly augment the world database** of polarization observables in photoproduction.
- **The high-quality FROST results are expected to put tight constraints on data interpretation tools**, immensely aiding in determining contributing N^* with minimal ambiguities.
- The findings in the light baryon sector together with the findings in strange and heavy flavor sectors (GlueX, LHCb, BES III etc.), will help us **understand the evolution of bound states of QCD from light to heavy-quark regime.**

Summary and Outlook

- **Photoproduction of vector mesons and multi-pion final states**: essential to **discover new resonances** and better understand the known resonances.
- **Many first-time measurements from CLAS-FROST for $\vec{\gamma}\vec{p} \rightarrow p\omega$ and $\vec{\gamma}\vec{p} \rightarrow p\pi^+\pi^-$**: they will **significantly augment the world database** of polarization observables in photoproduction.

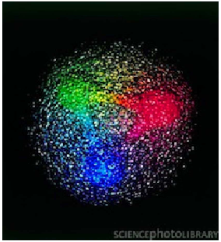
- **The high-quality FROST results are expected to put tight constraints on data interpretation tools**, immensely aiding in determining contributing N^* with minimal ambiguities.
- The findings in the light baryon sector together with the findings in strange and heavy flavor sectors (GlueX, LHCb, BES III etc.), will help us **understand the evolution of bound states of QCD from light to heavy-quark regime.**

Summary and Outlook

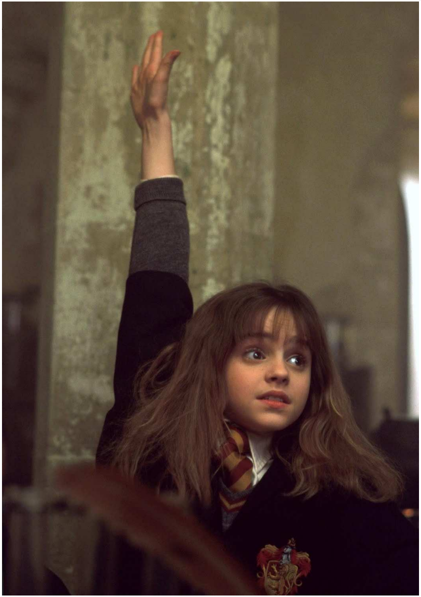
- **Photoproduction of vector mesons and multi-pion final states**: essential to **discover new resonances** and better understand the known resonances.
- **Many first-time measurements from CLAS-FROST for $\vec{\gamma}\vec{p} \to p\omega$ and $\vec{\gamma}\vec{p} \to p\pi^+\pi^-$**: they will **significantly augment the world database** of polarization observables in photoproduction.
- **The high-quality FROST results are expected to put tight constraints on data interpretation tools**, immensely aiding in determining contributing N^* with minimal ambiguities.
- The findings in the light baryon sector together with the findings in strange and heavy flavor sectors (GlueX, LHCb, BES III etc.), will help us **understand the evolution of bound states of QCD from light to heavy-quark regime.**

Summary and Outlook

- **Photoproduction of vector mesons and multi-pion final states**: essential to **discover new resonances** and better understand the known resonances.
- **Many first-time measurements from CLAS-FROST for $\vec{\gamma}\vec{p} \to p\omega$ and $\vec{\gamma}\vec{p} \to p\pi^+\pi^-$**: they will **significantly augment the world database** of polarization observables in photoproduction.



- **The high-quality FROST results are expected to put tight constraints on data interpretation tools**, immensely aiding in determining contributing N^* with minimal ambiguities.
- The findings in the light baryon sector together with the findings in strange and heavy flavor sectors (GlueX, LHCb, BES III etc.), will help us **understand the evolution of bound states of QCD from light to heavy-quark regime.**



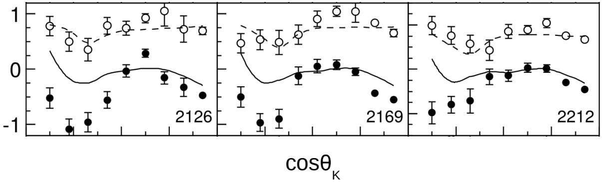
This work is supported by DOE# DE-FG02-92ER40735

Thank You !
Any Questions ?

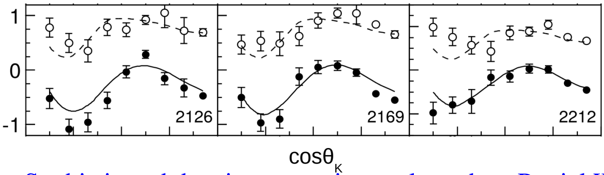
Why are Spin Observables Important?

[1] R. Bradford *et al.* (CLAS), PRC **75**, 035205 (2007), Observables C_x, C_z from $\vec{\gamma} p \to K^+ \vec{\Lambda}$
[2] Fits: BnGa Model, V.A. Nikonov *et al.*, Phy. Lett. B **662**, 245 (2008)

C_x, C_z Fits without N(1900)3/2$^+$ resonance



C_x, C_z Better Fit Results with N(1900)3/2$^+$!

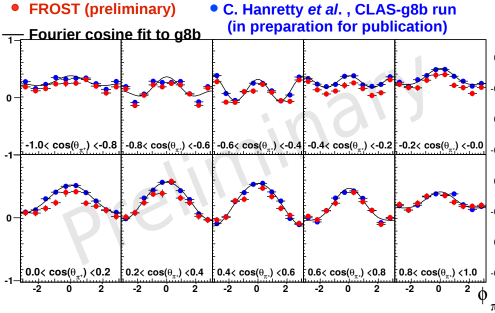


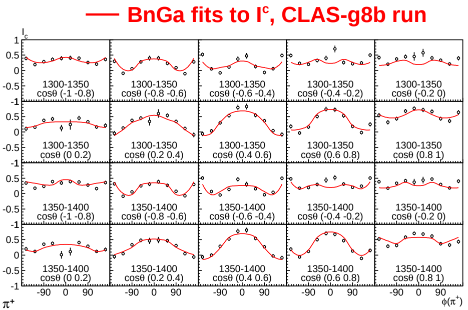
N^*	J^P ($L_{2I,2J}$)	2010	2012
$N(1440)$	$1/2^+$ (P_{11})	****	****
$N(1520)$	$3/2^-$ (D_{13})	****	****
$N(1535)$	$1/2^-$ (S_{11})	****	****
$N(1650)$	$1/2^-$ (S_{11})	****	****
$N(1675)$	$5/2^-$ (D_{15})	****	****
$N(1680)$	$5/2^+$ (F_{15})	****	****
$N(1685)$			*
$N(1700)$	$3/2^-$ (D_{13})	***	***
$N(1710)$	$1/2^+$ (P_{11})	***	***
$N(1720)$	$3/2^+$ (P_{13})	****	****
$N(1860)$	$5/2^+$		**
$N(1875)$	$3/2^-$		***
$N(1880)$	$1/2^+$		**
$N(1895)$	$1/2^-$		**
$N(1900)$	$3/2^+$ (P_{13})	**	***
$N(1990)$	$7/2^+$ (F_{17})	**	**
$N(2000)$	$5/2^+$ (F_{15})	**	**
~~$N(2080)$~~	D_{13}	**	
~~$N(2090)$~~	S_{11}	*	
$N(2040)$	$3/2^+$		*
$N(2060)$	$5/2^-$		**
$N(2100)$	$1/2^+$ (P_{11})	*	*
$N(2120)$	$3/2^-$		**
$N(2190)$	$7/2^-$ (G_{17})	****	****
~~$N(2200)$~~	D_{15}	**	
$N(2220)$	$9/2^+$ (H_{19})	****	****

Sophisticated data interpretation tools such as Partial Wave Analysis and Phenomenological models are required to identify the contributing resonances.

Beam Asymmetry I^c in $\vec{\gamma} p \to p \pi^+ \pi^-$

Example: $1.30 < E_\gamma < 1.40$ GeV

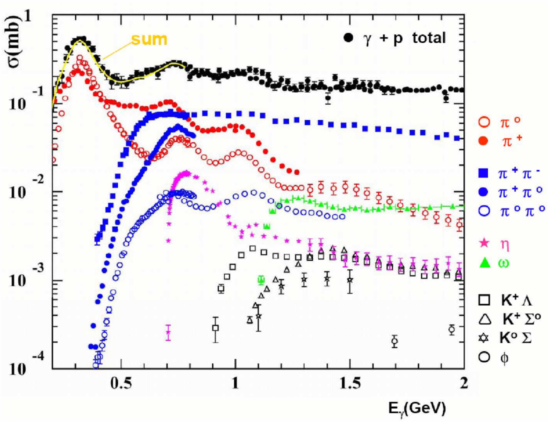




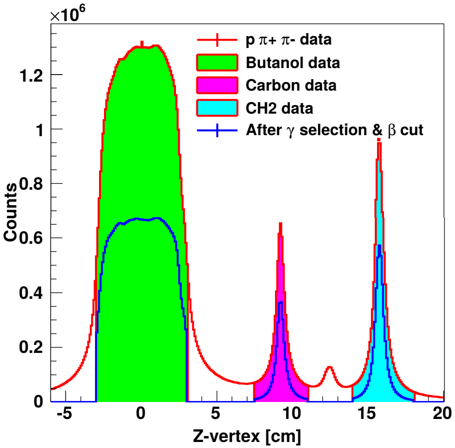
Good agreement between experiments

$$I = I_0\{\delta_l[I^s \sin(2\beta) + I^c \cos(2\beta)]\}$$

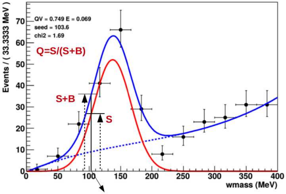
Photoproduction Cross Section



Vertex cut


×10^6
p π+ π- data
Butanol data
Carbon data
CH2 data
After γ selection & β cut
Counts
0
0.2
0.4
0.6
0.8
1
1.2
-5
0
5
10
15
20
Z-vertex [cm]

Event-Based Qfactor Method with Likelihood Fits



- **A multivariate analysis -** For each event ("seed event"), find N nearest neighbors in 4-D kinematic phase space $(E_\gamma, \theta^*, \phi^*, cos(\theta_p)^{c.m.})$. Plot mass distribution of the $N+1$ events and fit.
- Since N is small (300), use ML method to fit the mass distribution.
  $L = \prod_i [f^{Signal}(m_i, \alpha) + f^{Bkg}(m_i, \beta)]$
  $\mathbf{Q}_{\mathbf{seed-event}} = \frac{f^{Signal}(m_0, \alpha^{best})}{[f^{Signal}(m_0, \alpha^{best}) + f^{Bkg}(m_0, \beta^{best})]}$,
  m_0- seed event's mass.
- **Computation time reasonably minimized-** fits 10,000 events in 30 min.