Baryon Spectroscopy: Polarization Observables in Vector-Meson Photoproduction at JLab

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Florida State University

Nuclear Physics Seminar

11/20/2015

Outline

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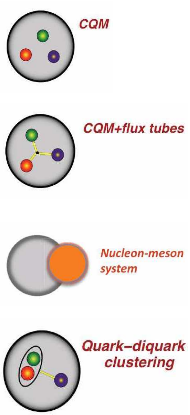
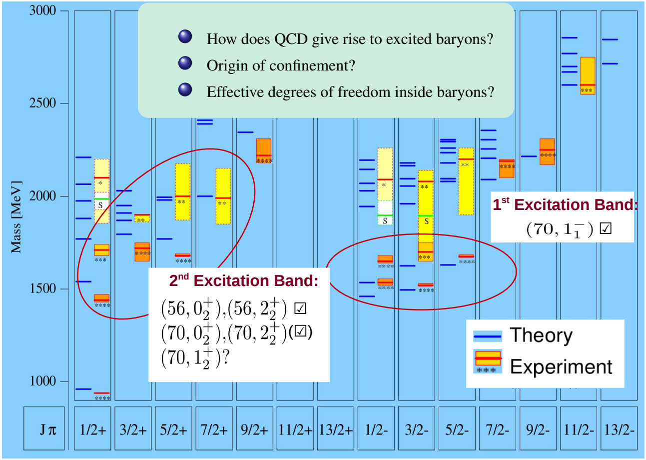
1. Introduction
   - Motivation
   - Polarization Observables
   - The FROST Experiment using CLAS
2. Data Selection and Analysis
   - Results
   - $p\omega$ Reaction, Single Polarization Observables
   - $p\pi^+\pi^-$ Reaction, Single Polarization Observables
3. Summary and Outlook

Why Baryon Spectroscopy?

Effective degrees of freedom





- How does QCD give rise to excited baryons?
- Origin of confinement?
- Effective degrees of freedom inside baryons?

1st Excitation Band:
$(70, 1_1^-)$ ☑

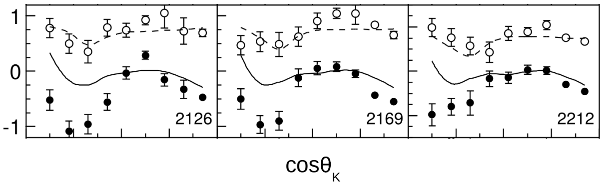
2nd Excitation Band:
$(56, 0_2^+), (56, 2_2^+)$ ☑
$(70, 0_2^+), (70, 2_2^+)$ (☑)
$(70, 1_2^+)$?

S. Capstick and N. Isgur, Phys. Rev. D **34** (1986) 2809

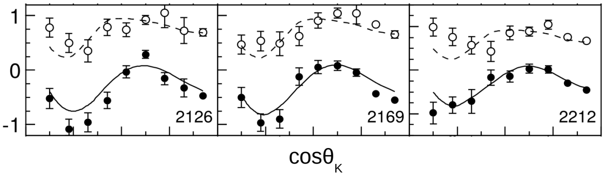
Why Baryon Spectroscopy?

[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)

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



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})	* * **	* * **
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$N(1900)$	$3/2^+$ (P_{13})	**	* * *
$N(1990)$	$7/2^+$ (F_{17})	**	**
$N(2000)$	$5/2^+$ (F_{15})	**	**
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$N(2120)$	$3/2^-$		**
$N(2190)$	$7/2^-$ (G_{17})	* * **	* * **
~~$N(2200)$~~	D_{15}	**	
$N(2220)$	$9/2^+$ (H_{19})	* * **	* * **

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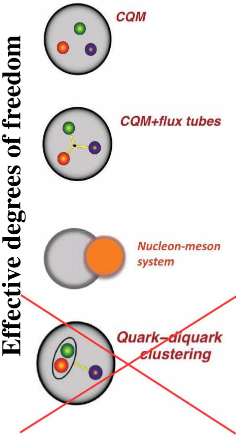
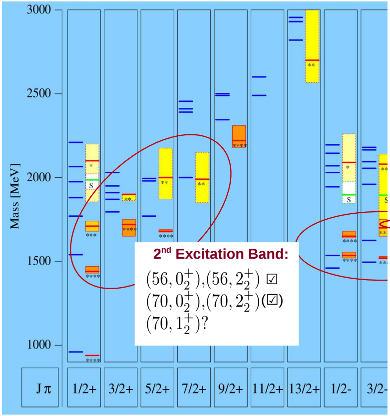
Effective degrees of freedom





2nd Excitation Band:
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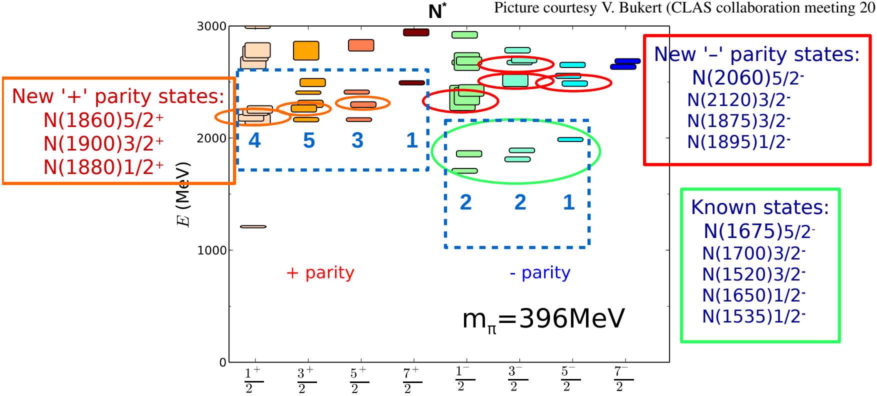
$N(1900)3/2^+$ cannot be accommodated in the naive quark-diquark picture, both oscillators need to be excited.[1],[2]

Baryon Spectrum with LQCD


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

New '+' parity states:
N(1860)$5/2^+$
N(1900)$3/2^+$
N(1880)$1/2^+$

New '–' parity states:
N(2060)$5/2^-$
N(2120)$3/2^-$
N(1875)$3/2^-$
N(1895)$1/2^-$

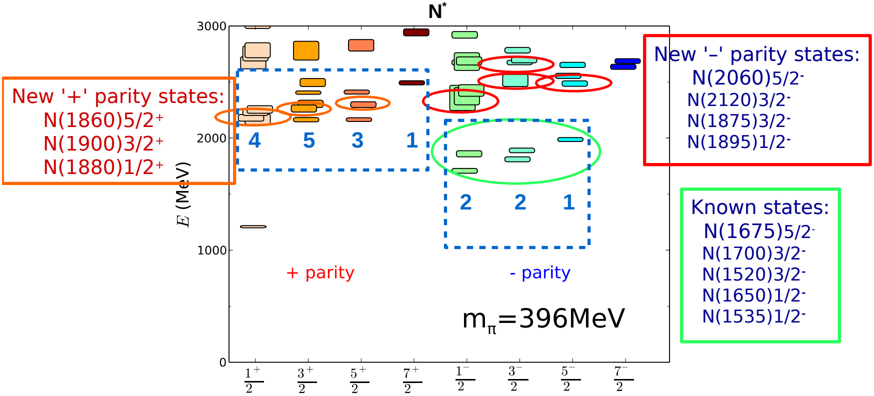
Known states:
N(1675)$5/2^-$
N(1700)$3/2^-$
N(1520)$3/2^-$
N(1650)$1/2^-$
N(1535)$1/2^-$

- - - 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!



New '+' parity states:
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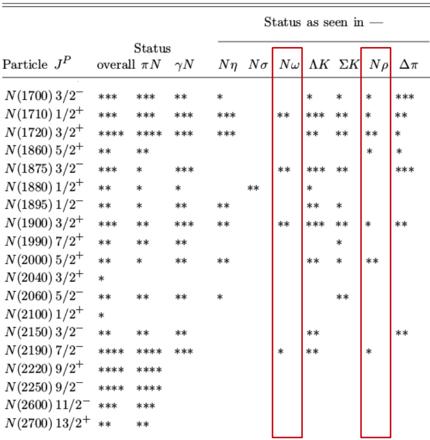
Study of N^* to Vector Meson Decay Modes

Vector meson decay modes have mostly remained unexplored. Vast pool of information yet to be unearthed:

- Baryon spectrum is inadequately understood particularly at W > 1.7 GeV where vector mesons and multi-pion final states are the **dominant contributors to the photoproduction cross section.**
- For a better understanding of known resonances, it is essential to study their vector meson decay modes.
- This talk will focus on $\gamma p \to p\omega \to p\pi^+\pi^-(\pi^0)$ and $\gamma p \to p\pi^+\pi^-$ reactions. The latter will give information on $N^* \to p\rho$ decay mode.



	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

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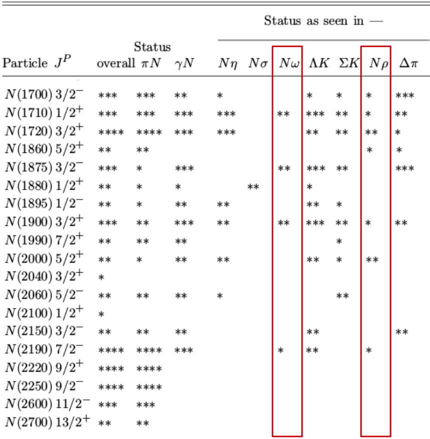

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$N(1720)\,3/2^+$	****	****	***	***			**	**	**	*
$N(1860)\,5/2^+$	**	**							*	*
$N(1875)\,3/2^-$	***	*	***			**	***	**		***
$N(1880)\,1/2^+$	**	*	*		**		*			
$N(1895)\,1/2^-$	**	*	**	**			**	*		
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$N(2190)\,7/2^-$	****	****	***			*	**		*	
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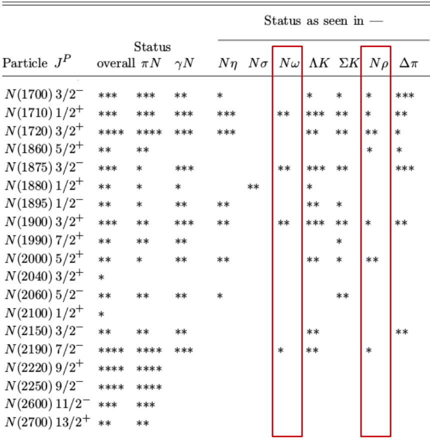

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$N(1875)\,3/2^-$	***	*	***			**	***	**		***
$N(1880)\,1/2^+$	**	*	*		**		*			
$N(1895)\,1/2^-$	**	*	**	**			**	*		
$N(1900)\,3/2^+$	***	**	***	**		**	***	**	*	**
$N(1990)\,7/2^+$	**	**	**					*		
$N(2000)\,5/2^+$	**	*	**	**			**	*	**	
$N(2040)\,3/2^+$	*									
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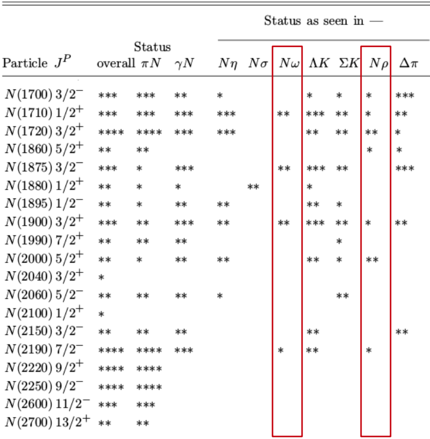

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Why are Spin Observables Important?

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Polarization observables essential for determination of scattering amplitudes with minimal ambiguities → reveal 'hidden' baryon resonances.

Why are Spin Observables Important?

E.g.,

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

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

Λ : degree of target pol.

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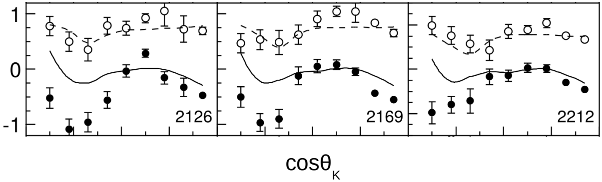
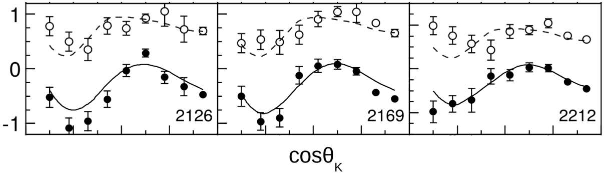
C_x, C_z Fits without N(1900)3/2$^+$ resonance



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



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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)

$p\omega$:

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

Prelim. results (Priyashree, FSU)

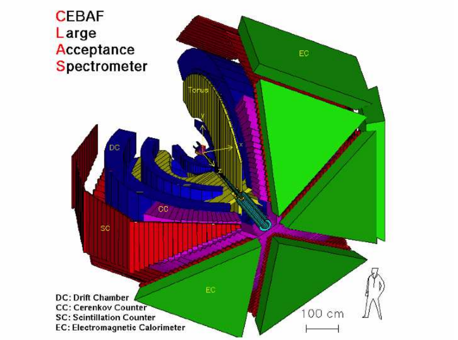
Prelim. results available

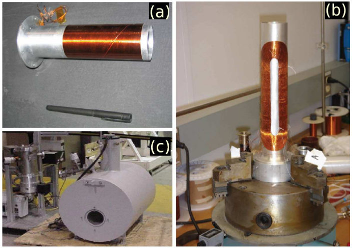
Data acquired

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

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

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

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3. Summary and Outlook

Data Selection and Analysis

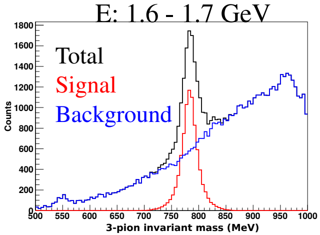
- Topologies for p$\pi^+\pi^-$:
  $\vec{\gamma}\vec{p} \to p\pi^+$ (missing π^-)
  $\vec{\gamma}\vec{p} \to p\pi^-$ (missing π^+)
  $\vec{\gamma}\vec{p} \to p\pi^+\pi^-$
  The observables are weighted avg. over topologies.
- Topology for pω:
  $\vec{\gamma}\vec{p} \to p\pi^+\pi^-$(missing π^0)
  Kinematic fitting was utilized to identify this topology.

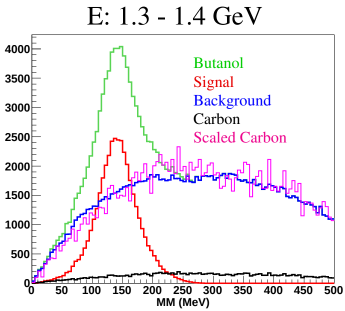
Cuts and corrections:

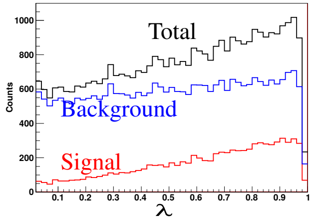
- Vertex cut
- Particle id.: β cut
- Photon selection: cuts on accidentals and timing cut
- Eloss[1] & momentum corrections[2].

[1] E. Pasyuk, CLAS-NOTE 2007-016
[2] M. Dugger *et. al.* CLAS-NOTE 2013-011

Data Selection and Analysis







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

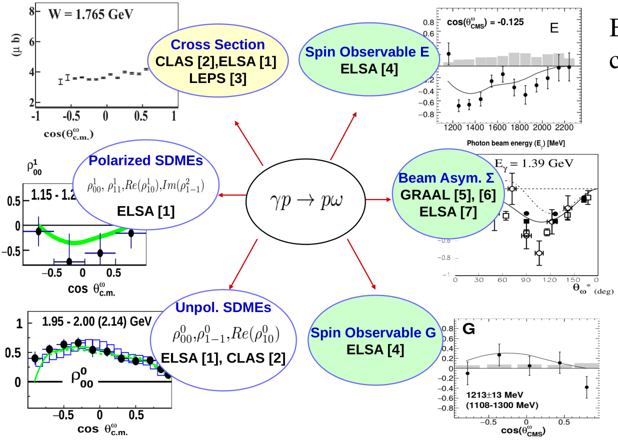
- **Event-based method**[1] for signal-background separation.
- **Event-based Maximum Likelihood Method** for extracting polarization observables[2].

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



$\gamma p \to p\omega$

Cross Section
CLAS [2],ELSA [1]
LEPS [3]

Spin Observable E
ELSA [4]

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

Beam Asym. Σ
GRAAL [5], [6]
ELSA [7]

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

Spin Observable G
ELSA [4]

PWA solution:

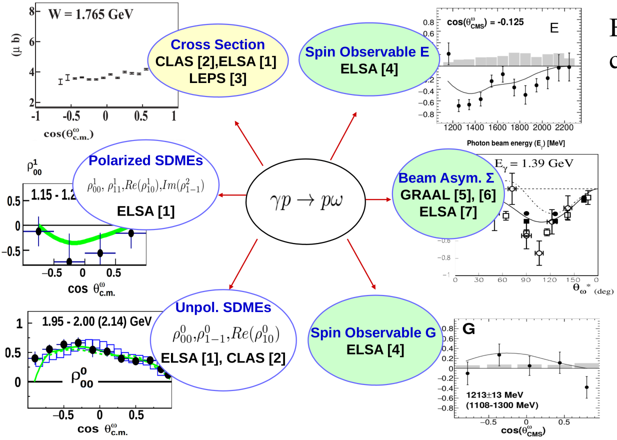
BnGa PWA results from ELSA[1] consistent with CLAS[2].

$N(1720)3/2^+$,
$N(2120)3/2^-$,
$N(1875)3/2^-$,
$N(2000)5/2^+$,
$N(>2.1\text{GeV})7/2^-$?

[1] Wilson *et al.*, arXiv:1508.01483 (2015)
[2] Williams *et al.*, PRC **80**, 065208 (2009)
[3] Sumihama *et al.*, PRC **80**, 052201 (2009)
[4] Eberhardt *et al.*, arXiv:1504.02221 (2015)
[5] Vegna *et al.*, PRC **91**, 065207 (2015)
[6] Ajaka *et al.*, PRL **96**, 132003 (2006)
[7] F. Klein *et al.*, PRD **78**, 117101 (2008)

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

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



$\gamma p \to p\omega$

Cross Section
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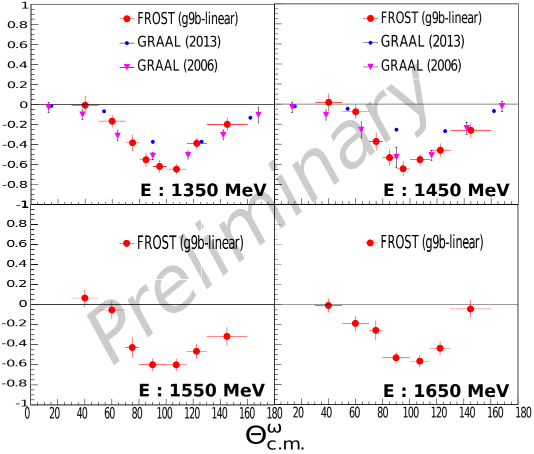
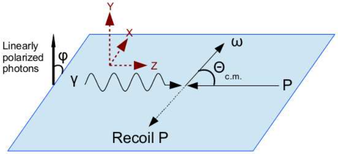
Ambiguity in $J^P \sim$ 2.2 GeV

$1/2^-$, $1/2^+$, $3/2^+$ or $5/2^+$ give comparable data descriptions. **Polarization observables required !**

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



FROST: transversely polarized target
GRAAL: unpolarized target.
Good agreement between FROST and GRAAL (2006) results.

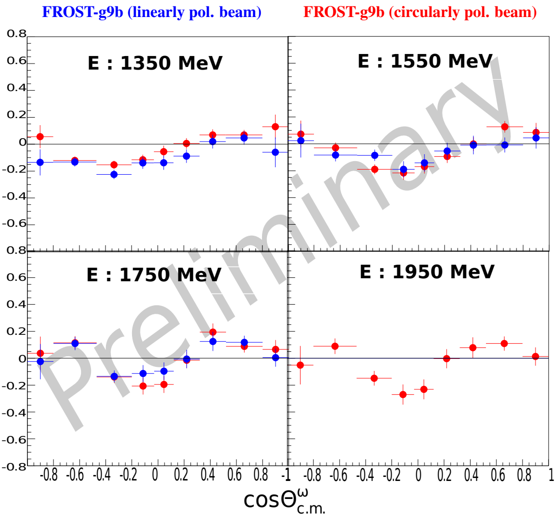


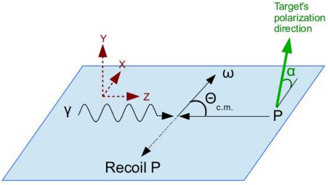
ω reconstructed from $\pi^+\pi^-(\pi^0)$

$$\begin{aligned} I = I_0[1 - \Sigma\ \delta_l \cos(2\phi) \\ + \Lambda\cos(\alpha)(-\delta_l \mathbf{H}\sin(2\phi) + \delta_\odot \mathbf{F}) \\ - \Lambda\sin(\alpha)(-\mathbf{T} + \delta_l \mathbf{P}\cos 2\phi)] \end{aligned}$$

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

First Measurement of Target Asymmetry T in $\gamma\vec{p} \rightarrow p\omega$





The two experimental results agree well.

$$\mathbf{I} = \mathbf{I}_0[1 - \mathbf{\Sigma}\ \delta_l\cos(2\phi) + \Lambda\cos(\alpha)(-\delta_l\mathbf{H}\sin(2\phi) + \delta_\odot\mathbf{F}) - \Lambda\sin(\alpha)(-\mathbf{T} + \delta_l\mathbf{P}\cos2\phi)]$$

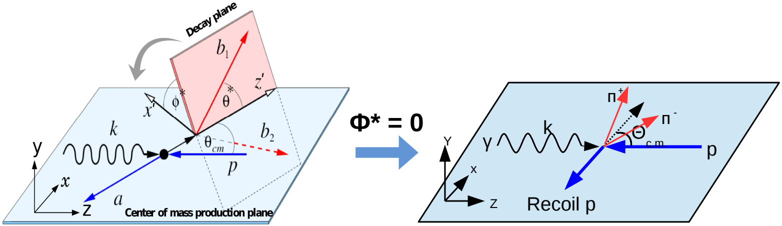
$\delta_\odot(\delta_l)$: degree of beam pol.
Λ : degree of target pol.

Results

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

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

$$\mathrm{I} = \mathrm{I}_0\{\delta_l[\mathrm{I}^s \sin(2\beta) + \mathrm{I}^c \cos(2\beta)]\}$$



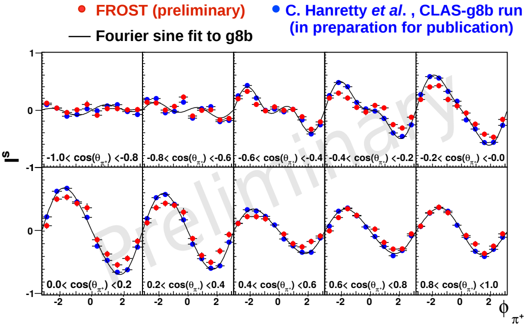
2 beam asymmetry observables: I^s, I^c

I^s vanishes, I^c survives.

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

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

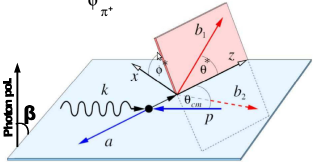
Example: 1.30 $<$ E$_\gamma$ $<$ 1.40 GeV (Total E$_\gamma$ range covered: 0.7 - 2.1 GeV)



odd parity w.r.t ϕ^*,
vanishes at $\phi^* = 0$.

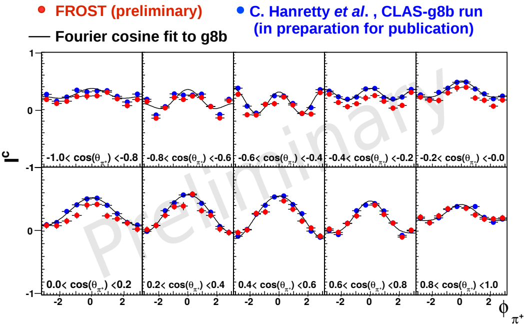
Good agreement between experiments

$$\mathrm{I} = \mathrm{I}_0\{\delta_l[\mathrm{I}^s\sin(2\beta) + \mathrm{I}^c\cos(2\beta)]\}$$



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

Example: $1.30 < \mathrm{E}_\gamma < 1.40$ GeV



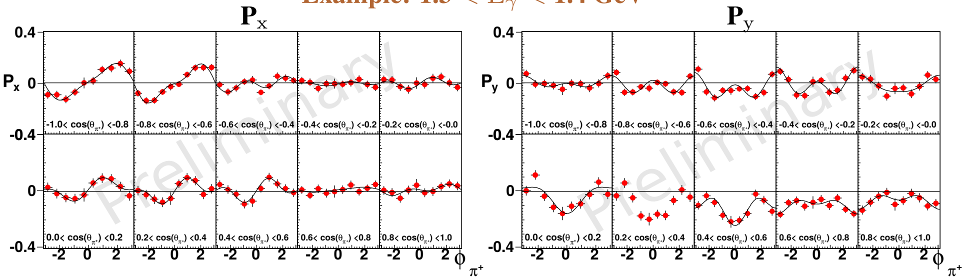
even parity w.r.t ϕ^*

Good agreement between experiments

$$\mathrm{I} = \mathrm{I}_0\{\delta_l[\mathrm{I^s}\sin(2\beta) + \mathrm{I^c}\cos(2\beta)]\}$$

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

Example: $1.3 < E_\gamma < 1.4$ GeV

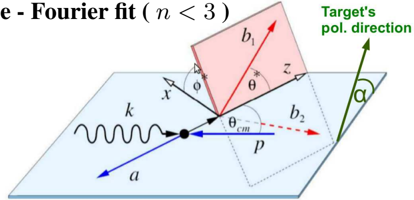


FROST g9b (lin. pol. beam) **Solid Line - Fourier fit ($n < 3$)**

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

$$I = I_0[1 + \Lambda\cos(\alpha)P_x + \Lambda\sin(\alpha)P_y]$$

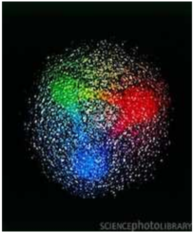
Λ : degree of target pol.



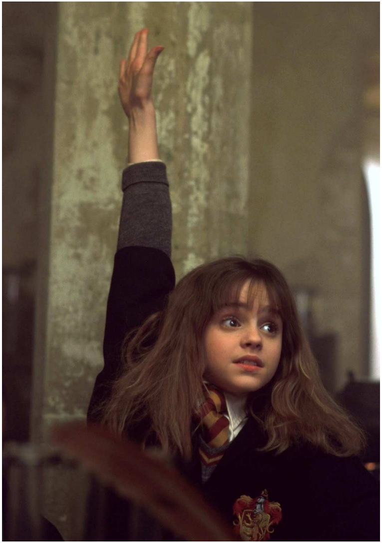
Outline

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

Summary and Outlook



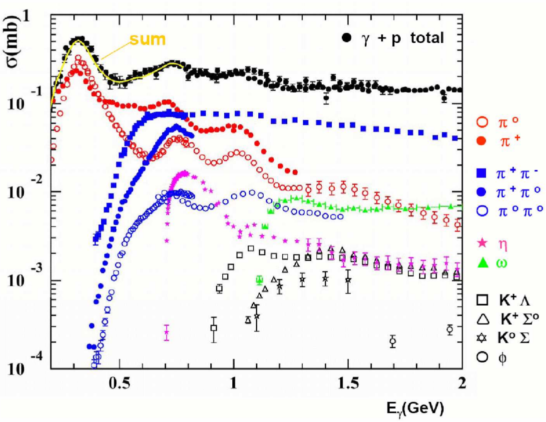
- **Photoproduction of vector mesons and multi-pion final states**: essential to **discover new resonances** and better understand the known resonances. These decay modes have mostly remained unexplored in the past.
- **Many first time measurements of single- and double-polarization observables from CLAS 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 new high quality CLAS results are expected to put tight constraints on data interpretation tools**, immensely aiding in determining contributing N^* with minimal ambiguities.
  - Advancement in our understanding of the systematics of the baryon spectrum, together with the findings from meson spectroscopy experiments (GlueX, PANDA, BES III etc.), will help us **understand QCD and confinement.**



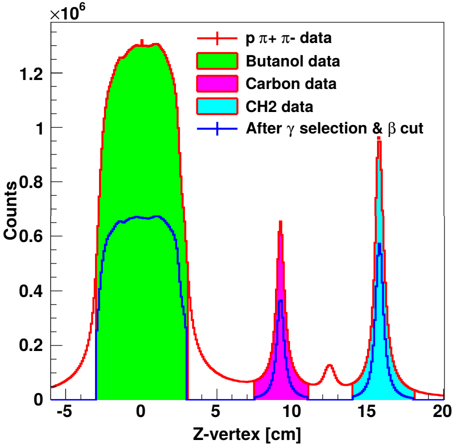
This work is supported by
DOE# DE-FG02-92ER40735

Thank You !
Any Questions ?

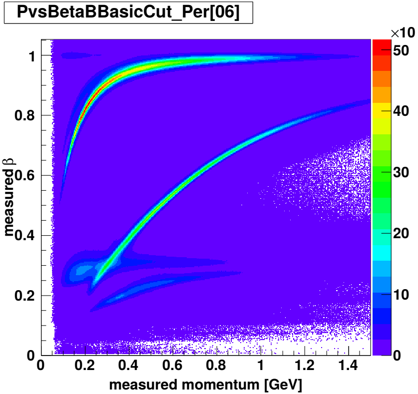
Photoproduction Cross Section

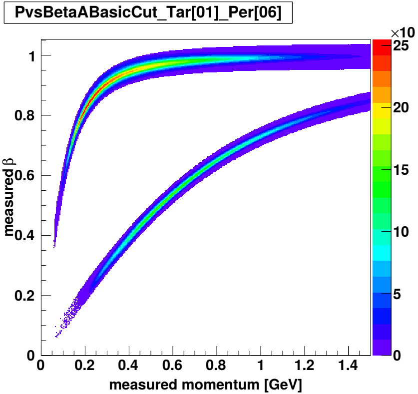


Vertex cut

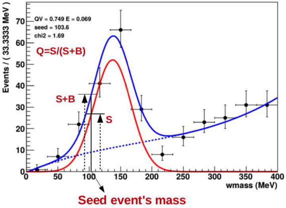

×10^6
p π+ π- data
Butanol data
Carbon data
CH2 data
After γ selection & β cut
Counts
0
0.2
0.4
0.6
0.8
1
1.2
-5
0
5
10
15
20
Z-vertex [cm]

β cut


PvsBetaBBasicCut_Per[06]
measured β
measured momentum [GeV]
0
0.2
0.4
0.6
0.8
1
1.2
1.4
0
0.2
0.4
0.6
0.8
1
×10
0
10
20
30
40
50


PvsBetaABasicCut_Tar[01]_Per[06]
measured β
measured momentum [GeV]
0
0.2
0.4
0.6
0.8
1
1.2
1.4
0
0.2
0.4
0.6
0.8
1
×10
0
5
10
15
20
25

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.
$$L = \prod_i [f^{Signal}(m_i, \alpha) + f^{Bkg}(m_i, \beta)]$$
$$\mathbf{Q_{seed-event}} = \frac{f^{Signal}(m_0, \alpha^{best})}{[f^{Signal}(m_0, \alpha^{best}) + f^{Bkg}(m_0, \beta^{best})]},$$
m_0- seed event's mass.
- **Computation time reasonably minimized-** fits 10,000 events in 30 min.