Recent Progress in the Understanding of the Baryon Spectrum

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Excited QCD Workshop

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Outline

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1. Introduction
   - Motivation
   - CLAS and ELSA Collaborations
2. Results
   - Observables in $\gamma p \to p\omega$ Reaction
   - Observables in $\gamma p \to p\pi\pi$ Reaction
3. Summary and Outlook

Why Baryon Spectroscopy?

[1] R. Bradford *et al.* (CLAS), PRC **75**, 035205 (2007), Observables C_x, C_z from $\vec{\gamma}p \rightarrow K^+\vec{\Lambda}$
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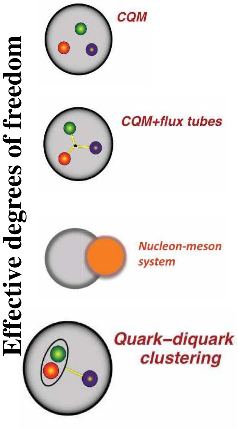

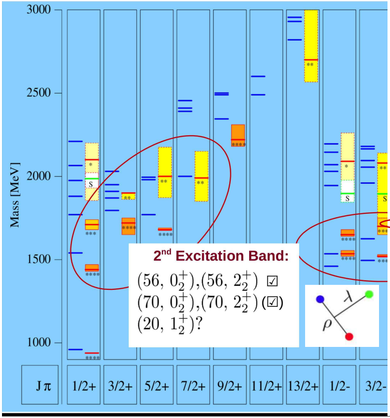

N^*	J^P $(L_{2I,2J})$	2010	2012
$N(1440)$	$1/2^+$ (P_{11})	****	****
$N(1520)$	$3/2^-$ (D_{13})	****	****
$N(1535)$	$1/2^-$ (S_{11})	****	****
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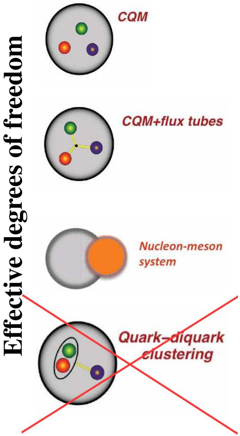

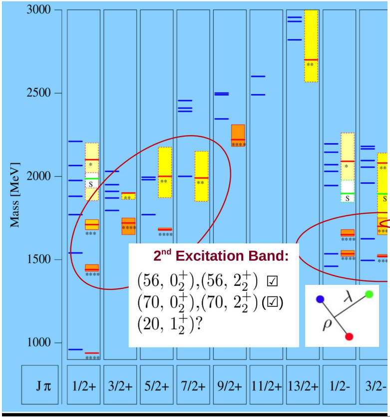

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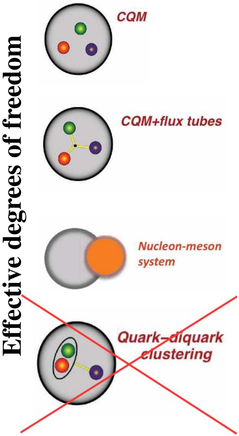

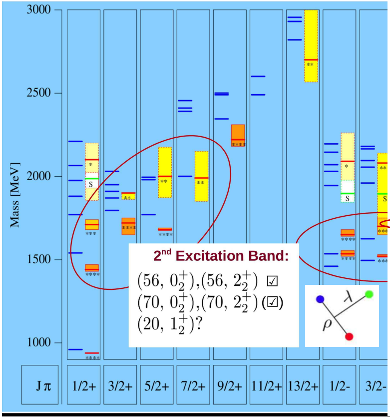

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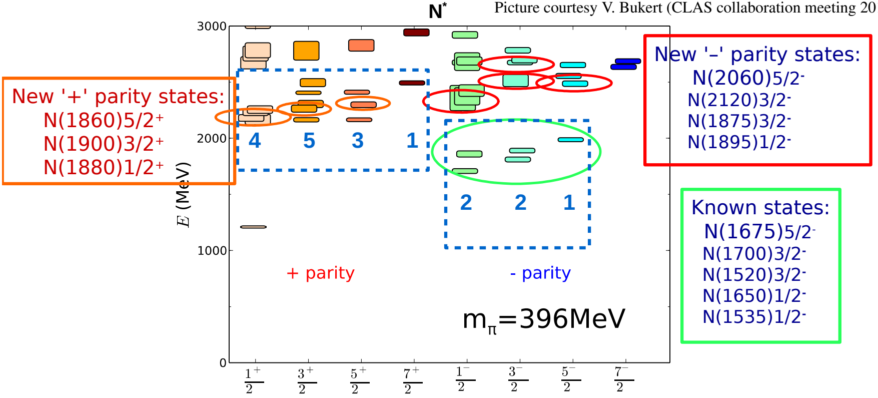
Baryon Spectrum with LQCD

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

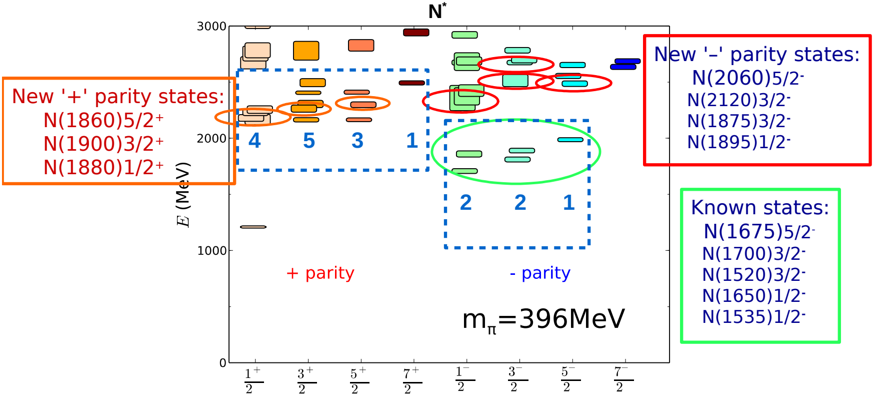


- - - LQCD manifests broad features of $SU(6) \otimes O(3)$ symmetry.

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!



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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:

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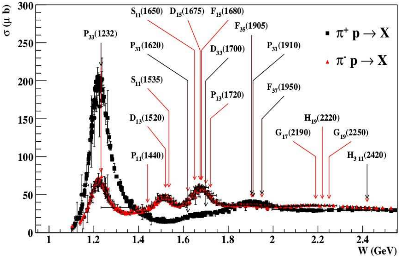
Resonance Hunting is Not Easy!

- 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.



Picture courtesy: M. Williams

Resonance Hunting is Not Easy!

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

E.g., in single meson photoproduction:

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

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

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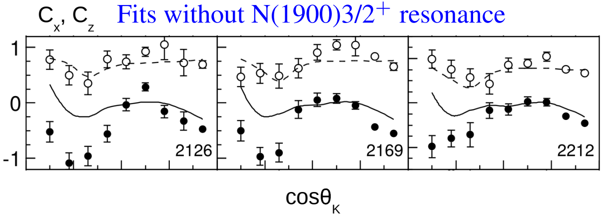
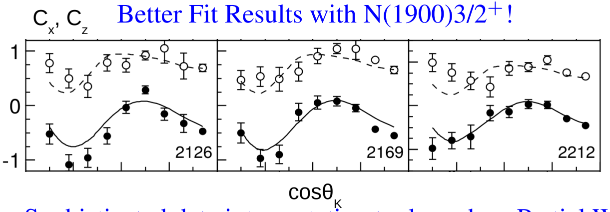
Fits without N(1900)3/2$^+$ resonance



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



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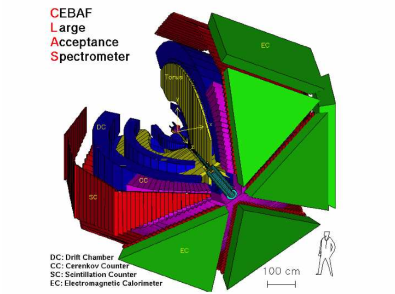
Sophisticated data interpretation tools such as Partial Wave Analysis and Phenomenological models are required to identify the contributing resonances.

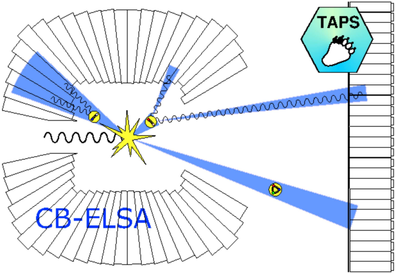
Photoproduction @ JLAB and CBELSA/TAPS

- Two major collaborations in photoproduction experiments.
- Complimentary detectors: charged tracks at CLAS (JLab, U.S.), neutral tracks at CBELSA/TAPS (Germany).

CLAS: almost 4π acceptance.

Crystal Barrel calorimeter: coverage 30°-168°.
TAPS calorimeter: coverage 5.8°-30°.





Picture courtesy: A. Wilson

Status of N^* Program in Photoproduction at CLAS

Observables	σ	Σ	T	P	E	F	G	H	T_x	T_z	L_x	L_z	O_x	O_z	C_x	C_z
✔ published	✓ acquired or under analysis															
$p\pi^0$	✔	✔	✓	(✓)	✓	✓	✓	✓								
$n\pi^+$	✔	✔	✓	(✓)	✓	✓	✓	✓								
$p\eta$	✔	✓	✓	(✓)	✓	✓	✓	✓	Proton targets							
$p\eta'$	✔	✓	✓	(✓)	✓	✓	✓	✓								
$p\omega/\phi$	✔	✓	✓	(✓)	✓	✓	✓	✓	Tensor polarization, SDME							
$K^+\Lambda$	✔	✓	✓	✔	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✔	✔
$K^+\Sigma^0$	✔	✓	✓	✔	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✔	✔
$K^{0*}\Sigma^+$	✔	✓									✓	✓				
$p\pi^-$	✔	✓		(✓)	✓	✓	✓									
$p\rho^-$	✓	✓		(✓)	✓	✓	✓		Neutron targets							
$K^-\Sigma^+$	✓	✓		(✓)	✓	✓	✓									
$K^0\Lambda$	✓	✓		✓	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓	✓
$K^0\Sigma^0$	✓	✓		✓	✓	✓	✓		✓	✓	✓	✓	✓	✓	✓	✓
$K^{0*}\Sigma^0$	✓	✓									✓	✓				

Status of multi-meson channels not shown here.

Wide range of targets used: H_2, deuterium, FROST, HDIce

Understanding the systematics of the baryon spectrum requires a combined effort by different collaborations to extract and analyse results from many relevant channels.

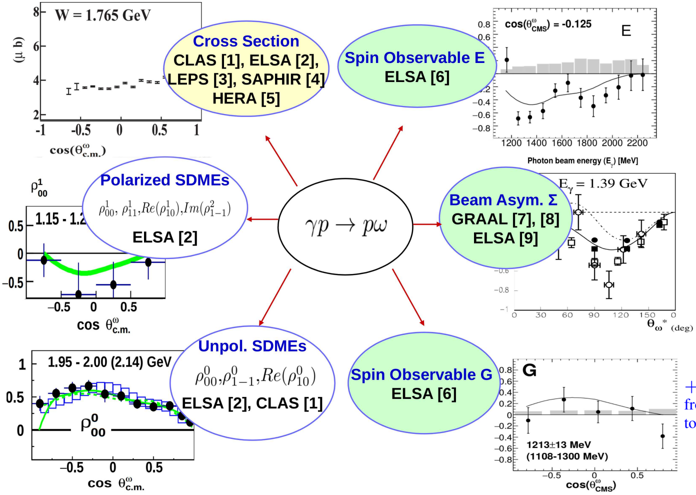
Outline

Results

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

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

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



[1] Williams *et al.*, PRC **80**, 065208 (2009)
[2] Wilson *et al.*, arXiv:1508.01483 (2015)
[3] Sumihama *et al.*, PRC **80**, 052201 (2009)
[4] Barth *et al.*, EPJ A **18**, 117 (2003)
[5] Wolf, Rept. Prog. Phys. **73**, 116202 (2010)
[6] Eberhardt *et al.*, arXiv:1504.02221 (2015)
[7] Vegna *et al.*, PRC **91**, 065207 (2015)
[8] Ajaka *et al.*, PRL **96**, 132003 (2006)
[9] 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 (solid blue box) — Suggestive evidence (dashed blue box)

CLAS PWA 2009

Notable contribution (solid red line) — Suggestive evidence (dashed red line)

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.

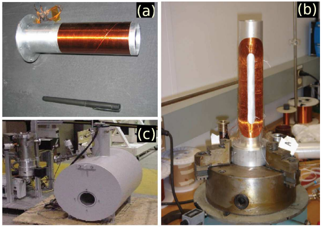
Need more polarization observables, in particular to understand W$>$ 2 GeV region:

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

Spin Observables in $\vec{\gamma}\vec{p} \to p\omega$ from FROST using CLAS



JLab aerial view

Data taking: Oct 2007 - Jan 2008 (g9a)
Mar. - Aug 2010 (g9b)
W range covered: ~ 1.5 - 2.3 GeV
Target: **FRO**zen **S**pin butanol **T**arget
Target pol.: Longitudinal (g9a run)/
Transverse (g9b run)
Photon pol.: Linear/Circular

Prelim. results (Priyashree, FSU)
(Almost final results)

Data acquired

$p\omega$:

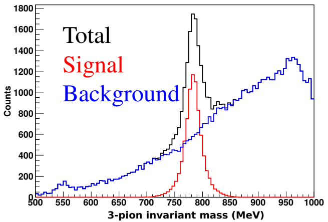
Beam \ Target	Transversely Pol.	Longitudinally Pol.
Linearly Pol.	Σ, T, H, P	Σ, G
Circularly Pol.	F, T	E

Getting close to a 'complete experiment'!

Highlights of the CLAS-FROST Data Analysis

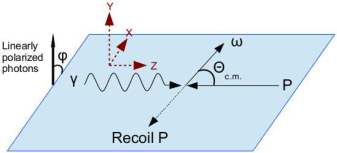
- **Topology for pω (89% branching fraction):** $\vec{\gamma}\vec{p} \to p\pi^+\pi^-$(missing π^0) Topology identified using Kinematic fitting.
- **Standard cuts & corrections:** vertex cut, photon selection, β cuts, E-p corrections.
- **Event-based method**[1] for signal-background separation.
- **Event-based maximum likelihood method**[2] for extracting polarization observables.

1.6 - 1.7 GeV



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

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

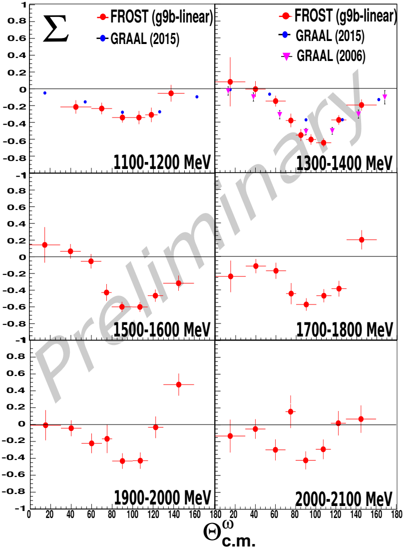


ω reconstructed from $\pi^+\pi^-(\pi^0)$

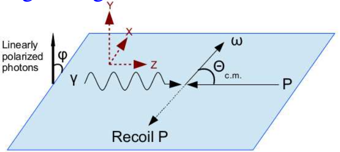
$$\sigma = \sigma_0[1 - \boldsymbol{\Sigma}\ \delta_l \cos(2\phi)$$
$$+\Lambda\cos(\alpha)(-\delta_l \mathbf{H}\sin(2\phi) + \delta_\odot \mathbf{F})$$
$$-\Lambda\sin(\alpha)(-\mathbf{T} + \delta_l \mathbf{P}\cos(2\phi))]$$
$$-\Lambda_z(-\delta_l \mathbf{G}\sin(2\phi) + \delta_\odot \mathbf{E})]$$

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

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



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

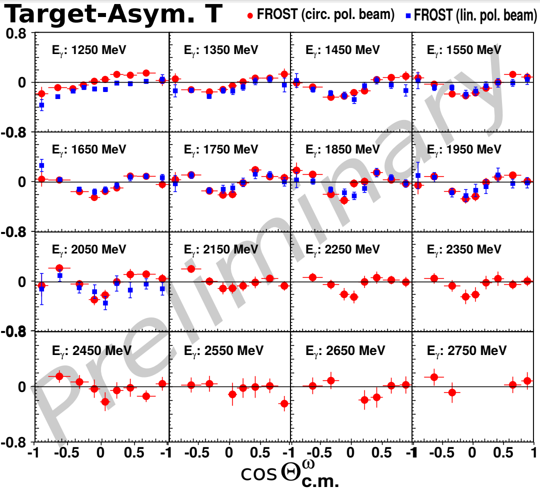


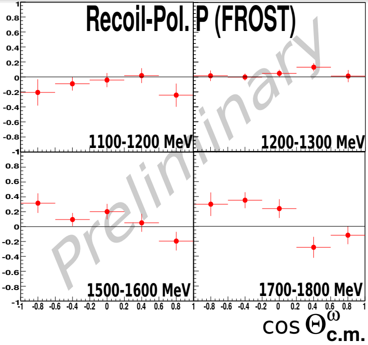
ω reconstructed from $\pi^+\pi^-(\pi^0)$

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

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

First Measurements of T, P in $\vec{\gamma}\vec{p} \rightarrow p\omega$ from FROST



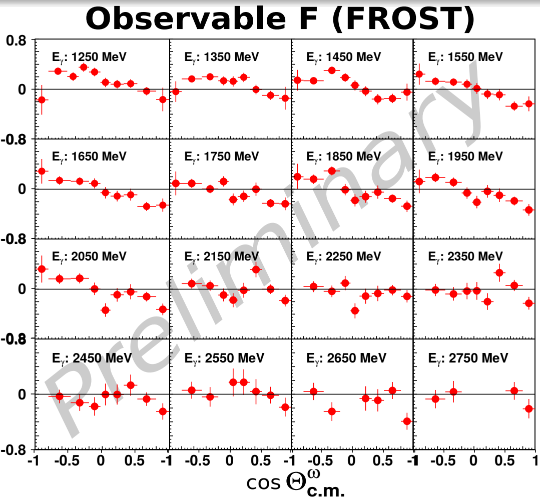


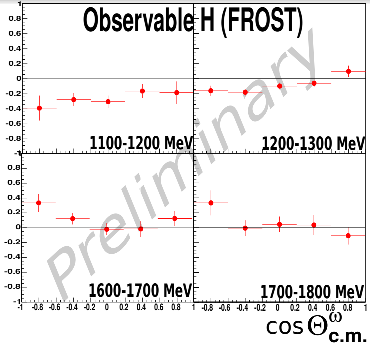
The two experimental results on target asym. **T** from FROST agree well.

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

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

First Measurements of F, H in $\vec{\gamma}\vec{p} \to p\omega$ from FROST





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

F and **H** are double-polarization observables.

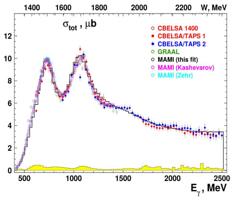
$\delta_\odot(\delta_l)$: degree of beam pol.
Λ : degree of target pol.

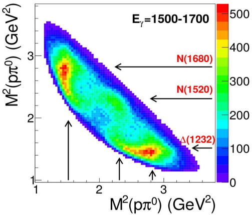
Results

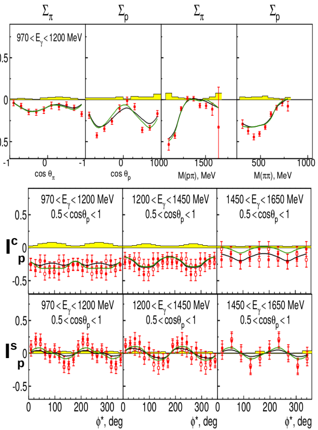
Results in $\vec{\gamma}\vec{p} \to p\pi\pi$

Results in $\vec{\gamma} p \to p\pi^0\pi^0$ from ELSA

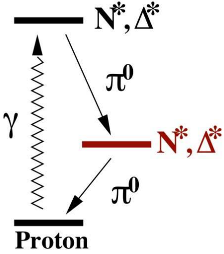
V. Sokhoyan *et al.*, EPJ A **51**, no. 8, 95 (2015)







- Allow the study of sequential decays of intermediate N^*.
- Not sensitive to $N^* \to p\rho$.

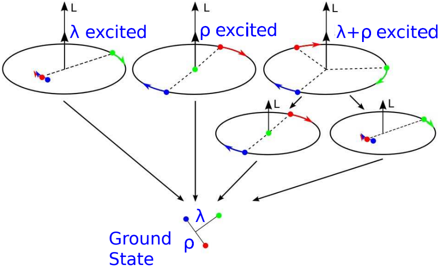


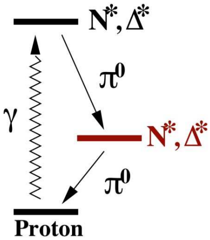
Sequential Decay of N* to Multi-pion Final States

V. Sokhoyan *et al.*, EPJ A **51**, no. 8, 95 (2015)

Sequential decay of N^* to multi-pion final state via intermediate excited baryon states.

BnGa PWA observed new decay modes in the decay of N^* resonances.

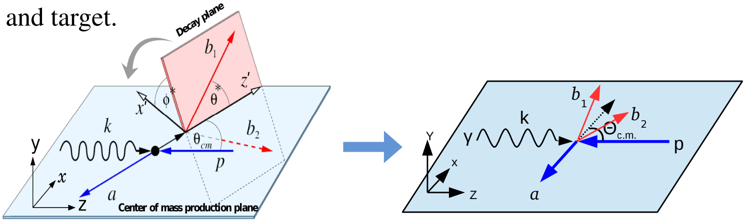




N* ($\lambda + \rho$ excited)	**N* ($L = 1$) π**
$N(1880)1/2^+$ $N(1900)3/2^+$ $N(2000)5/2^+$ $N(1990)7/2^+$	$N(1520)3/2^-$ $N(1535)1/2^-$

Results in $\vec{\gamma}\vec{p} \to p\pi^+\pi^-$ from FROST @ CLAS

- 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.

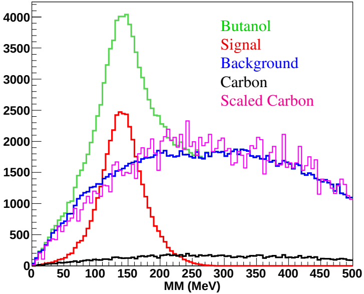


2 beam-pol. observables: I^s, I^c
Unlike only one (Σ observable) in single-meson photoproduction.

I^s vanishes, I^c survives.

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

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



- **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.
- **Event-based method** for signal-background separation.
- **Event-based maximum likelihood method** for extracting polarization observables.

Prelim. results (Priyashree, FSU) (Almost final results)
Prelim. results available (FSU, USC)
Data acquired

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

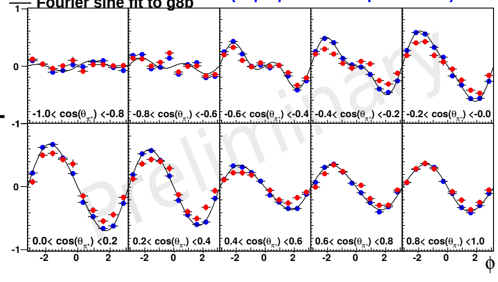
Beam \ Target	Transversely Pol.	Longitudinally Pol.
Linearly Pol.	$P^{s,c}_{x,y}$, $P_{x,y}$, $I^{s,c}$	$P^{s,c}_z$, P_z, $I^{s,c}$
Circularly Pol.	$P^{\odot}_{x,y}$, $P_{x,y}$, $I^{\odot}$	$P^{\odot}_z$, P_z, $I^{\odot}$

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

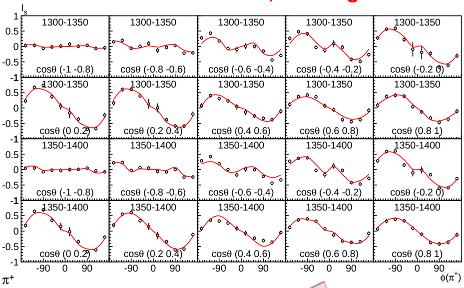
Example: $1.30 < E_\gamma < 1.40$ GeV (Total E_γ range covered: 0.7 - 2.1 GeV)

● FROST (preliminary) ● C. Hanretty *et al.*, CLAS-g8b run (in preparation for publication)

— Fourier sine fit to g8b

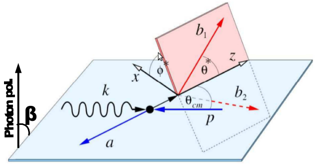


— BnGa fits to I^s, CLAS-g8b run



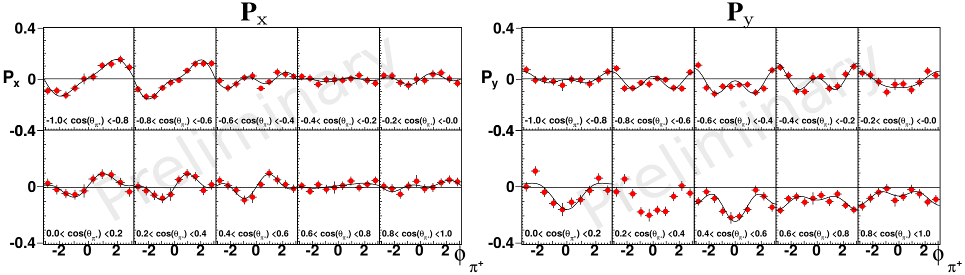
Good agreement between experiments

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



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

Example: $1.3 < E_\gamma < 1.4$ GeV (Total E_γ range covered: 0.7 - 2.1 GeV)

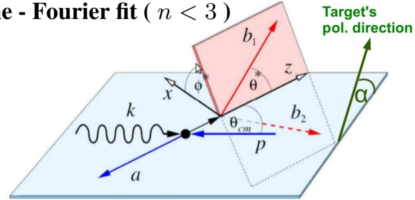


FROST g9b (lin. pol. beam) **Solid Line - Fourier fit ($n < 3$)**

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

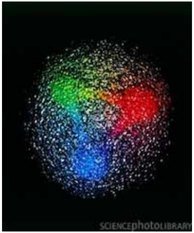
$I = I_0[1 + \Lambda\cos(\alpha)P_x + \Lambda\sin(\alpha)P_y]$

Λ : degree of target pol.



Outline

Summary and Outlook

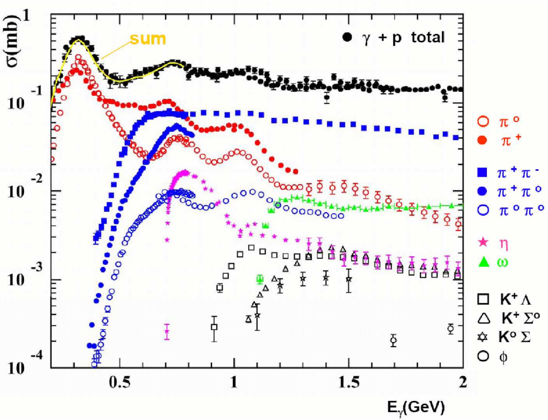


- **Photoproduction of vector mesons and multi-pion final states**: essential to **discover new resonances** and better understand the known resonances. These decay modes have mostly remained unexplored in the past.
- **Many first time measurements of single- and double-polarization observables from CLAS-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 new high quality CLAS 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.**

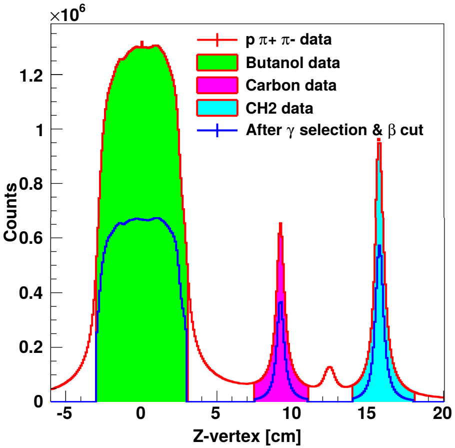
This work is supported by
DOE# DE-FG02-92ER40735

Thank You !

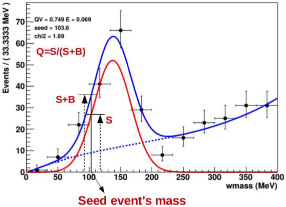
Photoproduction Cross Section



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]

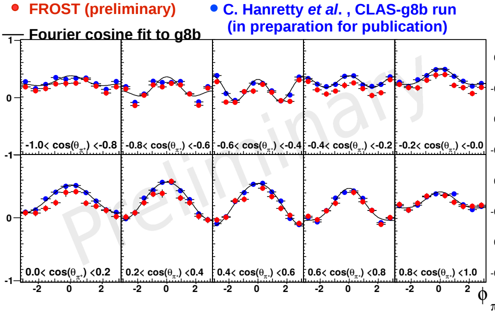
Event-Based Qfactor Method with Likelihood Fits

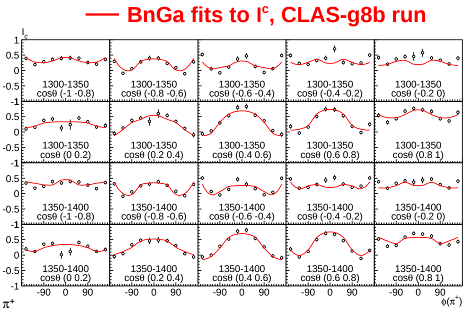


- **A multivariate analysis -** For each event ("seed event"), find N nearest neighbors in 4-D kinematic phase space $(E_\gamma, \theta^*, \phi^*, cos(\theta_p)^{c.m.})$. Plot mass distribution of the $N+1$ events and fit.
- Since N is small (300), use ML method to fit the mass distribution.
  $L = \prod_i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

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

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





Good agreement between experiments

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