Polarization Observables in Vector Meson Photoproduction from the FROST Experiment using CLAS at Jefferson Lab

Priyashree Roy

University of Michigan/Florida State University

HPS Seminar

GSI, Darmstadt

10/05/2017

Outline

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Understanding Baryons

- Matter that we see around us is made up of baryons like protons and neutrons.
- Baryons are fermions. In quark model, they are considered as a system of 3 quarks.
- Six known quarks, each with a unique ‘flavor’ quantum number. Focus on Light Baryons (i.e. made of u and/or d quarks).
- Gluons, the mediators of the strong force, also carry color charge. They participate in the strong interaction in addition to mediating it unlike photons in QED.
- Strong interaction shows Confinement at low energies where matter exists. No free quarks in the non-perturbative regime.

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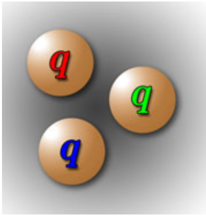

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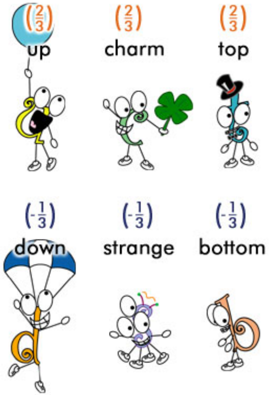

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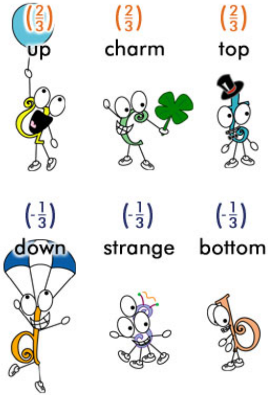

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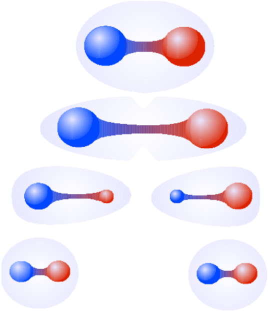

Light Baryon Spectroscopy

Open question in the non-perturbative regime (where QCD is difficult to solve):
How does QCD give rise to excited baryons?

- What is the origin of confinement? How are confinement and chiral symmetry breaking connected?
- What are the relevant degrees of freedom? How do they evolve with energy?

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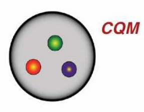
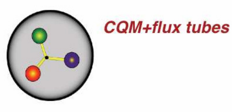
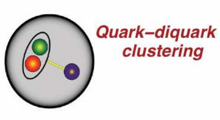
Light Baryon Spectroscopy

Effective degrees of freedom







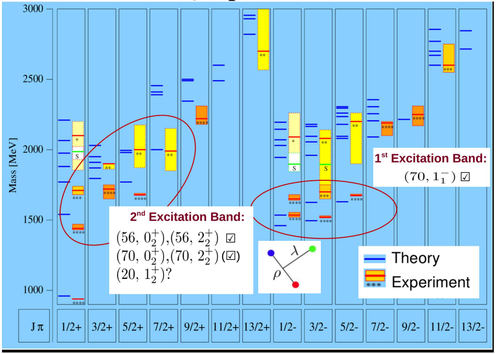
+ Lattice-QCD computations
(complementary to phenomenological models)

Light Baryon Spectroscopy: Map out the excited states of light baryons, identify the underlying multiplets to reveal answers to the open questions.

Understanding the Light Baryon Spectrum

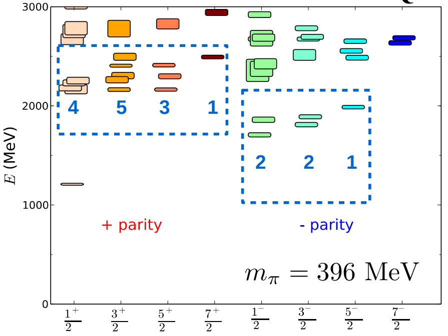
- **Underlying Pattern**: the resonances can be grouped into bands and multiplets.
- The level counting in LQCD for each J^P in each band is **consistent** with CQM.

A CQM prediction for N*



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

N* from Lattice-QCD



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

Understanding the Light Baryon Spectrum

- Many **'missing'** states, particularly above 1.7 GeV in W.
- **A possible explanation**: perhaps the static quark-diquark picture is correct?

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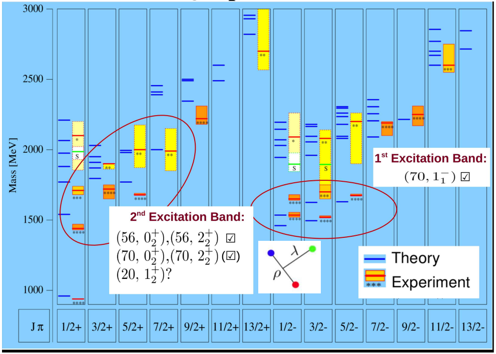

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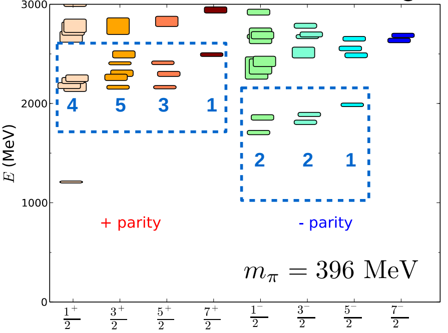

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Understanding the Light Baryon Spectrum

- 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.
- No sign of 'freezing' in LQCD calculations.

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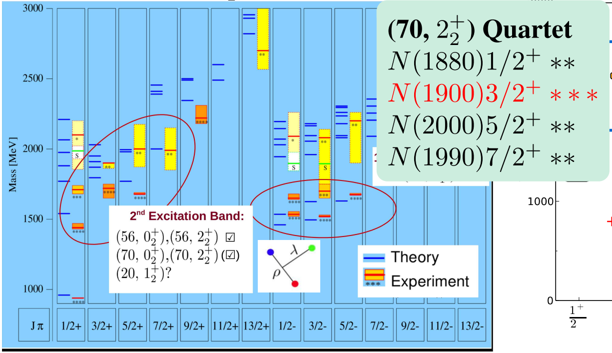

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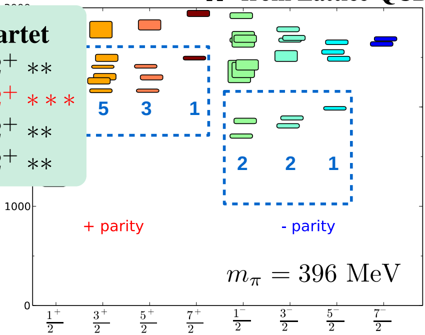

Bradford *et al.* (CLAS), PRC **75**, 035205 (2007), Observables C_x, C_z from $\vec{\gamma}p \to K^+\vec{\Lambda}$
Fits: BnGa Model, V.A. Nikonov *et al.*, Phy. Lett. B **662**, 245 (2008)

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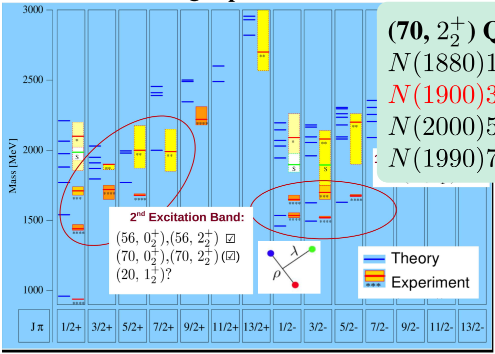

$(70,\ 2_2^+)$ Quartet
$N(1880)1/2^+$ $**$
$N(1900)3/2^+$ $***$
$N(2000)5/2^+$ $**$
$N(1990)7/2^+$ $**$

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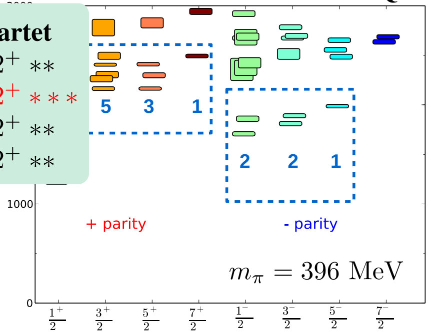

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Vector Meson and Multi-Pion Photoproduction

Alternate explanation suggested from an experimental point-of-view:

- Past measurements were mostly done using π beams. It is predicted that the high-mass resonances predominantly couple to γ beams.
- The high-mass resonances preferably decay to heavier mesons, e.g. vector mesons (e.g. ω, ρ, ϕ), or sequentially decay to multi-particle final states via intermediate resonances.
- The study these reactions also aid in further investigating poorly-understood properties of known resonances. Their contributions to these reactions have mostly remained under-explored.
- These factors motivated the analysis of $\gamma p \to p\omega \to p\pi^+\pi^-(\pi^0)$ and $\gamma p \to p\pi^+\pi^-$ reactions. The latter gives information on $N^* \to p\rho$, and on sequential decays via intermediate resonances.

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Particle J^P	overall	$N\gamma$	$N\pi$	$N\eta$	$N\sigma$	$N\omega$	ΛK	ΣK	$N\rho$	$\Delta\pi$
$N(1700)\ 3/2^-$	***	**	***	*			*	*	*	***
$N(1710)\ 1/2^+$	****	****	****	***		**	****	**	*	**
$N(1720)\ 3/2^+$	****	****	****	***			**	**	**	*
$N(1860)\ 5/2^+$	**		**						*	*
$N(1875)\ 3/2^-$	***	***	*			**	***	**		***
$N(1880)\ 1/2^+$	**	*	*		**		*			
$N(1895)\ 1/2^-$	**	**	*	**			**	*		
$N(1900)\ 3/2^+$	***	***	**	**		**	***	**	*	**
$N(1990)\ 7/2^+$	**	**	**					*		
$N(2000)\ 5/2^+$	**	**	*	**			**	*	**	
$N(2040)\ 3/2^+$	*		*							
$N(2060)\ 5/2^-$	**	**	**	*				**		
$N(2100)\ 1/2^+$	*		*							
$N(2120)\ 3/2^-$	**	**	**				*	*		
$N(2190)\ 7/2^-$	****	***	****			*	**		*	
$N(2220)\ 9/2^+$	****		****							
$N(2250)\ 9/2^-$	****		****							
$N(2300)\ 1/2^+$	**		**							
$N(2570)\ 5/2^-$	**		**							

Particle Data Group 2016

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$N(1875)\,3/2^-$	***	***	*			**	***	**		***
$N(1880)\,1/2^+$	**	*	*		**		*			
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$N(2300)\,1/2^+$	**		**							
$N(2570)\,5/2^-$	**		**							

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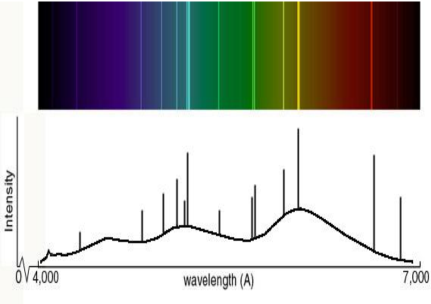
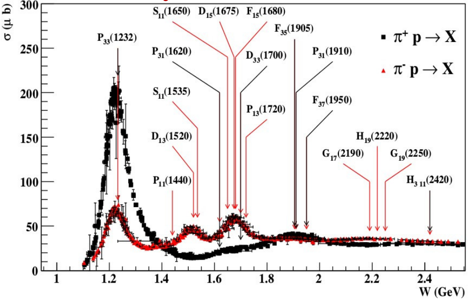
Why are Spin Observables Important?

Atomic Cross Section



Baryon Cross Section



(Courtesy of Michael Williams)

- Baryon resonances are broad and overlapping so ‘peak-hunting’ is not a good way to look for resonances.
- Significant background from non-resonant processes which are entangled with resonant processes.

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Polarized measurements in addition to the unpolarized cross section measurements necessary to disentangle and reveal the resonances with minimum ambiguities.

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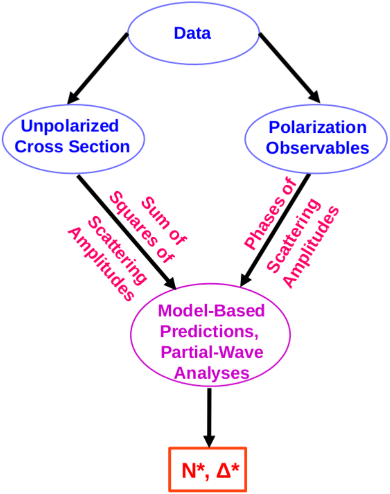
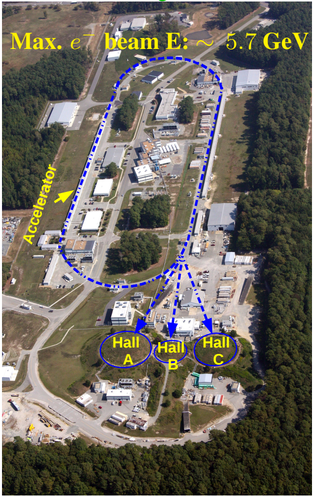


w/o polarizer w/ polarizer

Polarized measurements in addition to the unpolarized cross section measurements necessary to disentangle and reveal the resonances with minimum ambiguities.

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

The FROST N^* Program in Hall B, JLab



$\vec{\gamma}\vec{p} \to p\omega$

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

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

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

13 spin observables extracted in my analysis

Data acquired

Final or prelim. results available

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

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

$\delta_\odot(\delta_l)$: degree of beam polarization

Λ : degree of target polarization

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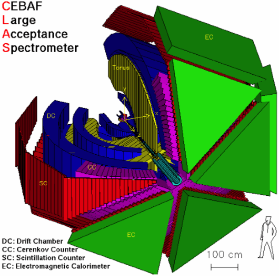
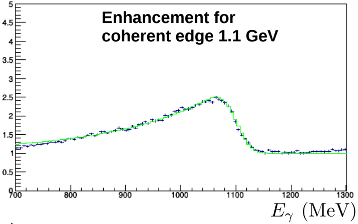
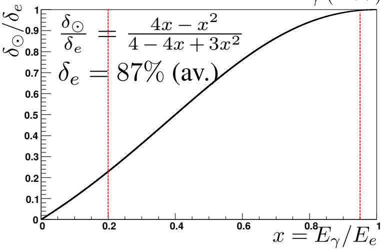


$\sim$ 4π acceptance of charged particles, well-suited for spectroscopy.

Coherent edges: 0.9-2.1 GeV (0.2 GeV wide)
Deg. of linear beam pol., δ_γ: $40 - 60\%$

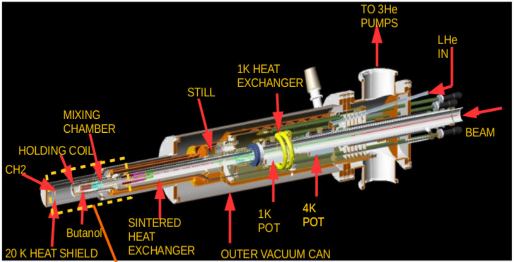


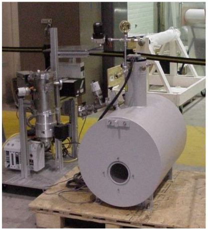


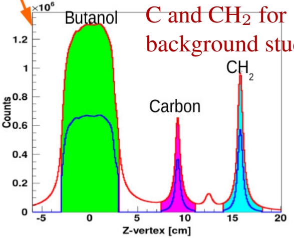
g9b run (Mar to Aug, 2010)

Photon Pol.: Linear/Circular
Target: (Nitroxyl) Doped Butanol (C_4H_9OH)
Target Pol.: Transverse
W **range:** 1.4-2.1 GeV (Lin. Data)
1.5-2.5 GeV (Circ. Data)

The FROzen Spin Target (FROST) Apparatus







- Polarizing field = 5 T, T$\sim$ 0.3 K
- Dipole holding field = 0.5 T, T$\sim$ 50 mK
- Offset angle = 116.1 $\pm$ 0.4° from x_{lab}
- Av. target pol. = 81.0 $\pm$ 1.7%
- Relaxation time: 3400 hrs w/ beam, 4000 hrs w/o beam

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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] to fit angular distributions in ϕ_{lab}^{recoil} and extract the polarization observables.

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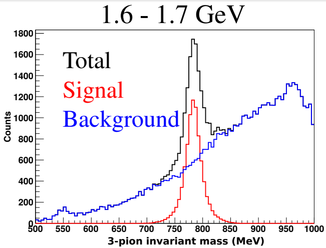
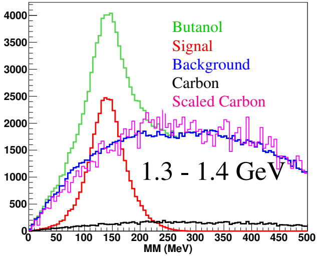
- **Event-based maximum likelihood method**[2] to fit angular distributions in $\phi_{\rm lab}^{\rm recoil}$ and extract the polarization observables.

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

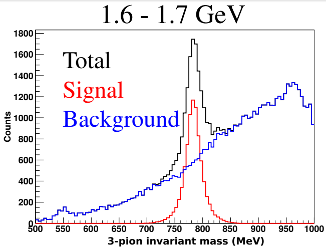


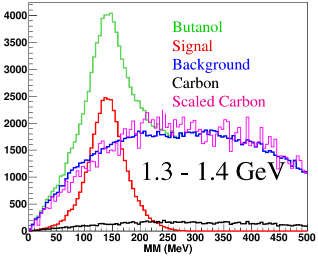


Data Selection and Analysis

- **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] to fit angular distributions in $\phi_{\text{lab}}^{\text{recoil}}$ and extract the polarization observables.

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



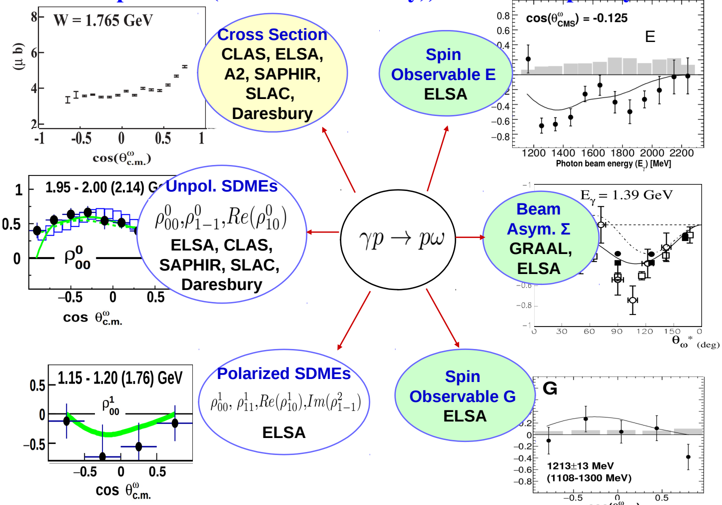


Results

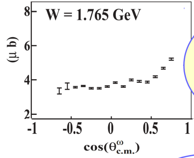
Results in $\vec{\gamma}\vec{p} \to p\omega$

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

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

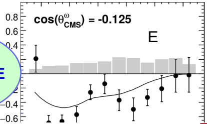


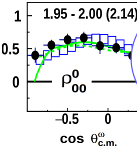
Published Results + New Spin Observables from FROST



Cross Section
CLAS, ELSA, A2, SAPHIR, SLAC, Daresbury

Spin Observable E
ELSA

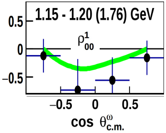




Unpol. SDMEs
$\rho^0_{00}, \rho^0_{1-1}, Re(\rho^0_{10})$
ELSA, CLAS, SAPHIR, SLAC, Daresbury

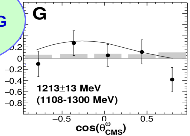
+ FROST (Prelim.) Results

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

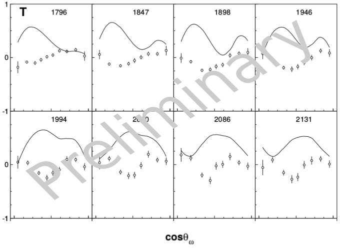


Polarized SDMEs
$\rho^1_{00}, \rho^1_{11}, Re(\rho^1_{10}), Im(\rho^2_{1-1})$
ELSA

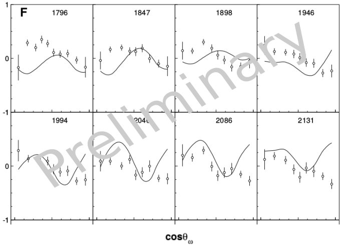
Spin Observable G
ELSA

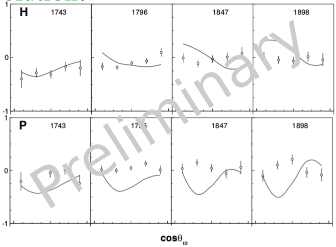


Importance of the Spin Observables from FROST



- BnGa-2016 solution, based on fits to ELSA data + new high statistics Σ from CLAS-g8b, was not entirely unique. Other acceptable solutions existed.
- BnGa-2016 predictions did NOT describe the new FROST observables well.
- Adding the new FROST observables to BnGa database has reduced ambiguities : BnGa-2017 PWA solution!

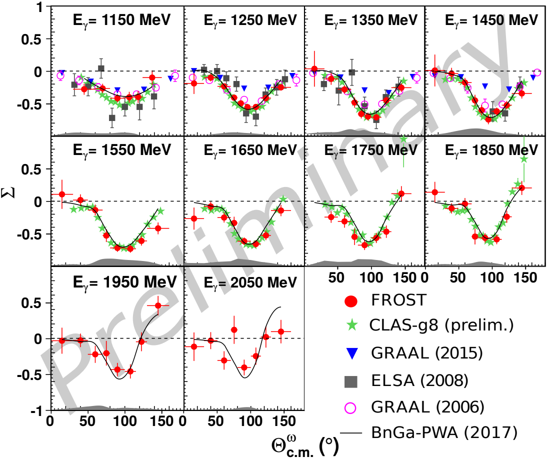


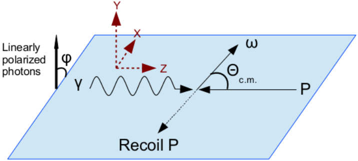


Beam Asymmetry Σ in $\vec{\gamma}p \to p\omega$

P. Roy *et al.* (CLAS-FROST), paper under collaboration review

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





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

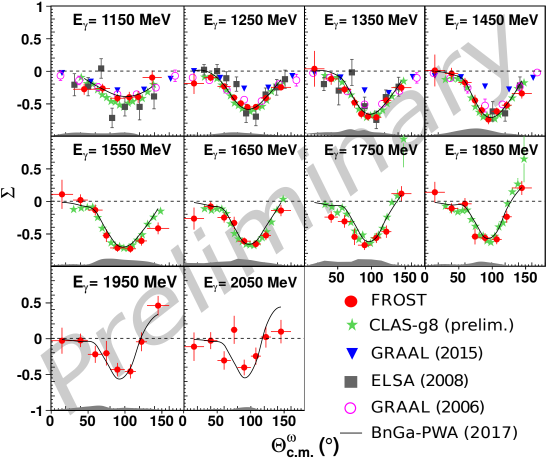
$\delta_\odot(\delta_l)$: degree of beam pol.

Λ : degree of target pol.

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

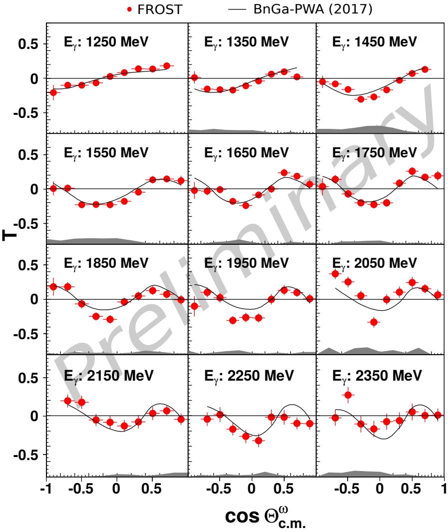
P. Roy *et al.* (CLAS-FROST), paper under collaboration review

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

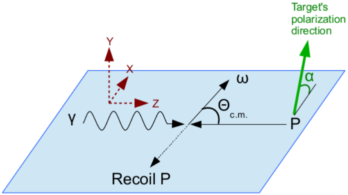


- **FROST**: transversely pol. target (more complex analysis) **Others**: unpolarized H_2 target
- **FROST results** in excellent agreement with CLAS-g8 and fair agreement with other published results except for GRAAL 15.

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



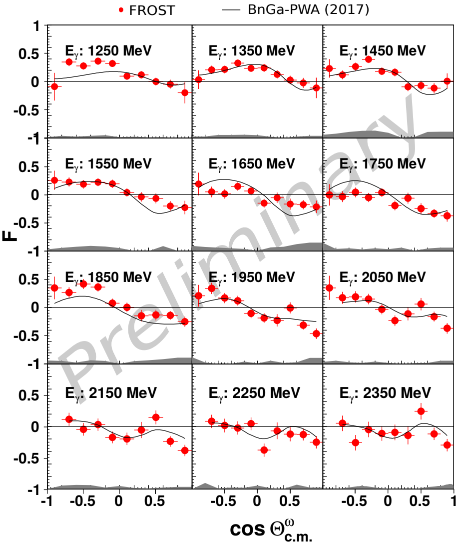
P. Roy *et al.* (CLAS-FROST), paper under collaboration review



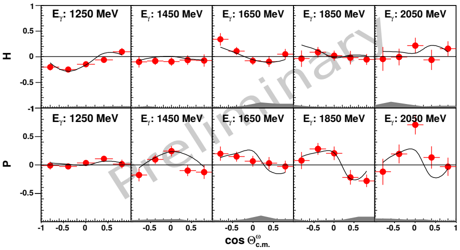
$$\sigma = \sigma_0[1 - \mathbf{\Sigma}\,\delta_l\cos(2\phi)$$
$$+\Lambda\cos(\alpha)(-\delta_l\mathbf{H}\sin(2\phi) + \delta_\odot\mathbf{F})$$
$$-\Lambda\sin(\alpha)(-\mathbf{T} + \delta_l\mathbf{P}\cos(2\phi))$$
$$-\Lambda_z(-\delta_l\mathbf{G}\sin(2\phi) + \delta_\odot\mathbf{E})]$$

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

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



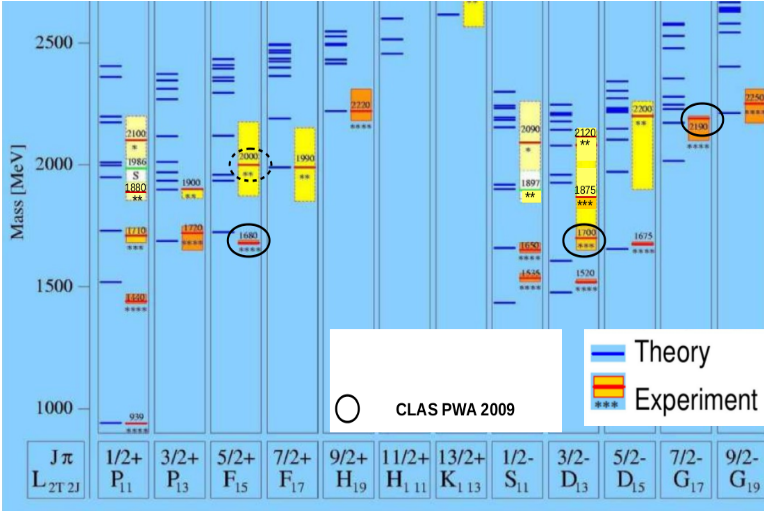
P. Roy *et al.* (CLAS-FROST), paper under preparation



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

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

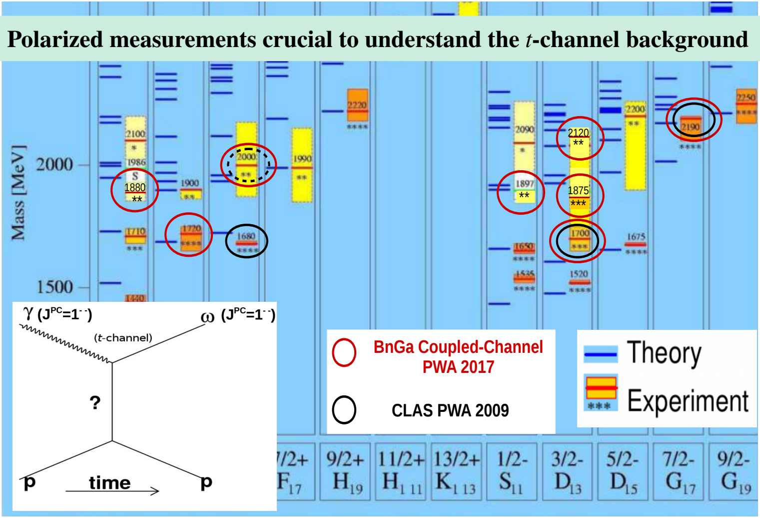
Partial Wave Analysis of $\gamma p \to p\omega$ Observables



Williams *et al.*, PRC **80**, 065208 (2009)

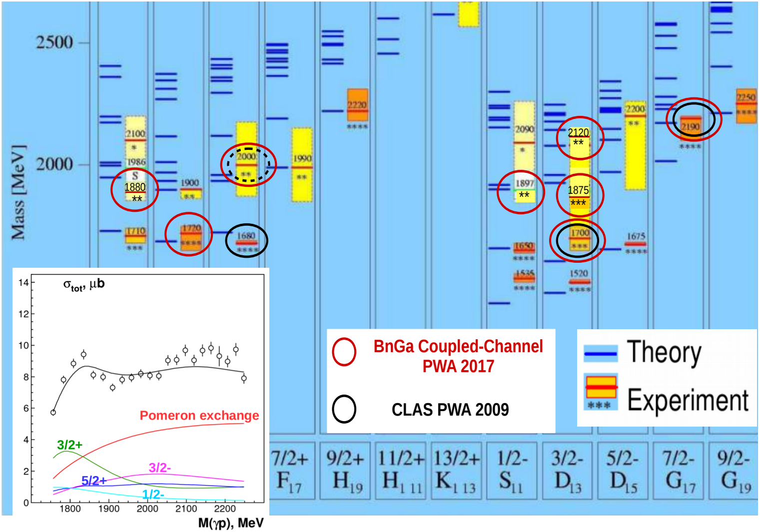
Partial Wave Analysis of $\gamma p \to p\omega$ Observables

Polarized measurements crucial to understand the *t*-channel background



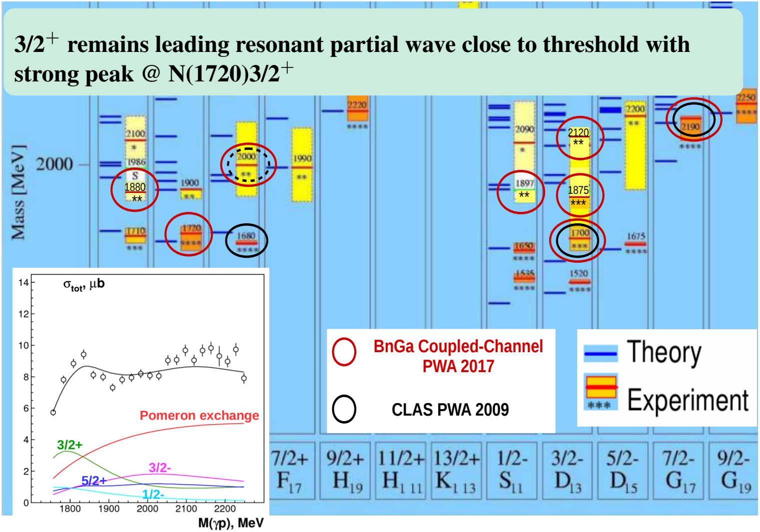
Williams *et al.*, PRC **80** (2009)
Denisenko *et al.*, Phys. Lett. B **755** (2016)

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



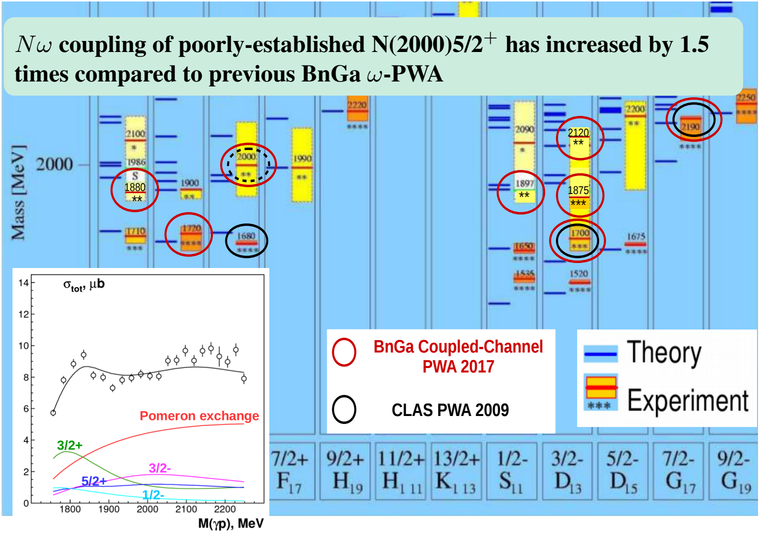
Partial Wave Analysis of $\gamma p \to p\omega$ Observables

3/2$^+$ remains leading resonant partial wave close to threshold with strong peak @ N(1720)3/2$^+$



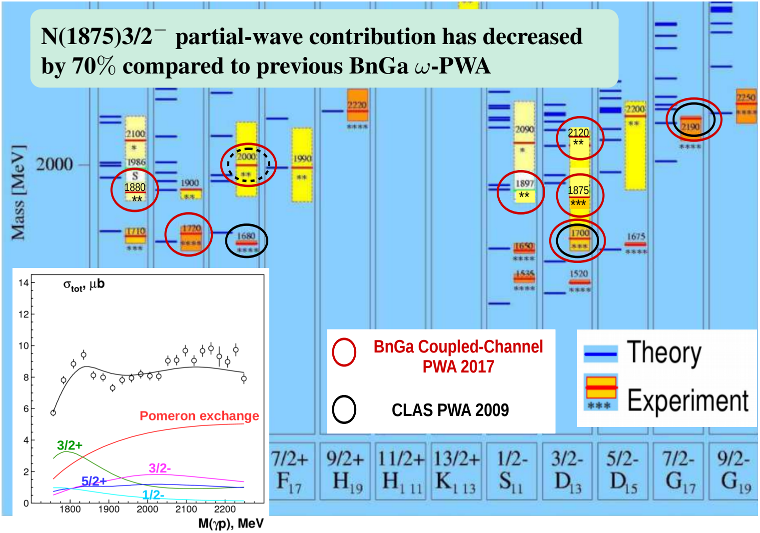
Partial Wave Analysis of $\gamma p \to p\omega$ Observables

$N\omega$ **coupling of poorly-established N(2000)5/2$^+$ has increased by 1.5 times compared to previous BnGa ω-PWA**

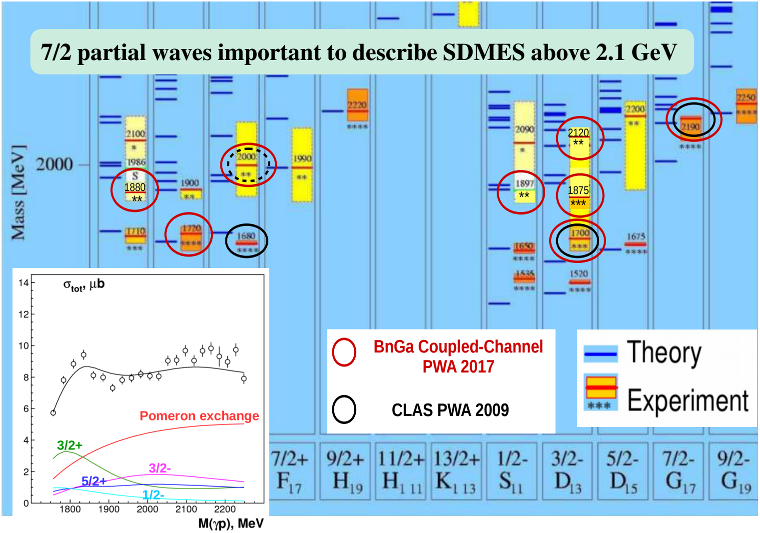


Partial Wave Analysis of $\gamma p \to p\omega$ Observables

N(1875)3/2$^-$ partial-wave contribution has decreased by 70% compared to previous BnGa ω-PWA



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

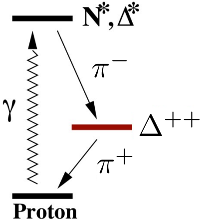


Results

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

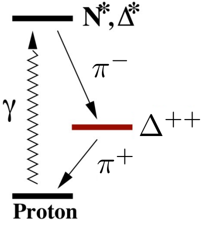
Published Results in $\vec{\gamma}\vec{p} \rightarrow p\pi^+\pi^-$

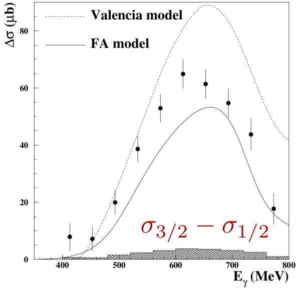
Allow the study of sequential decays of intermediate N^* and also $N^* \rightarrow p\rho$ decay but the large hadronic background makes it challenging.

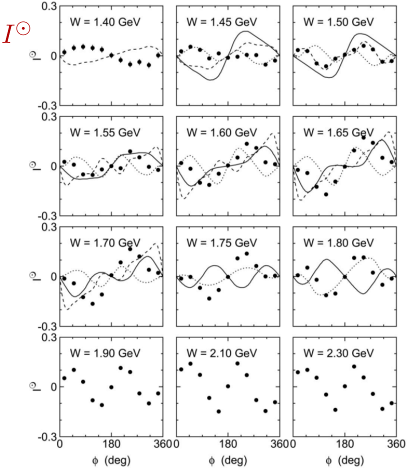


Published Results in $\vec{\gamma}\vec{p} \to p\pi^+\pi^-$

Polarization observables database rather sparse in the past. Moreover, existing models do not describe the data well.





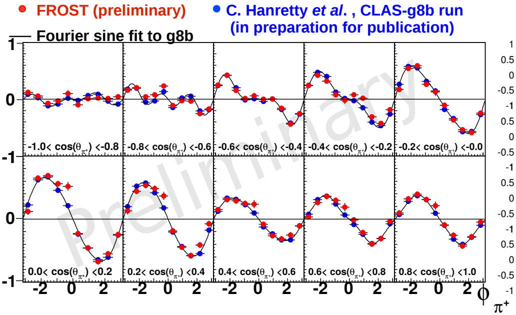


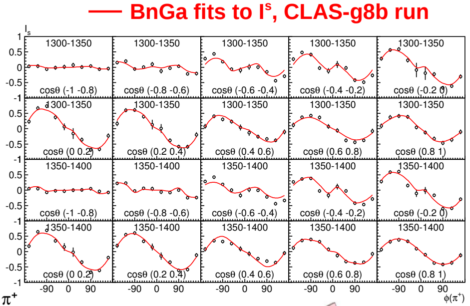
Beam \ Target	Transversely Pol.	Longitudinally Pol.
Linearly Pol.	$P^{s,c}_{x,y}$, $P_{x,y}$, $I^{s,c}$	$P^{s,c}_{z}$, P_{z}, $I^{s,c}$
Circularly Pol.	$P^{\odot}_{x,y}$, $P_{x,y}$, $I^{\odot}$	$P^{\odot}_{z}$, P_{z}, $I^{\odot}$

Strauch *et al.*, PRL **95**, 162003 (2005); Krambrich *et al.*, PRL **103**, 052002 (2009)
Ahrens *et al.*, EPJ A **34**, 11 (2007)

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)

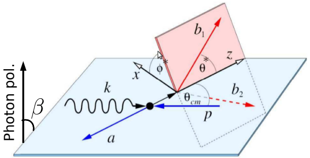




P. Roy *et al.* (CLAS-FROST), paper under preparation

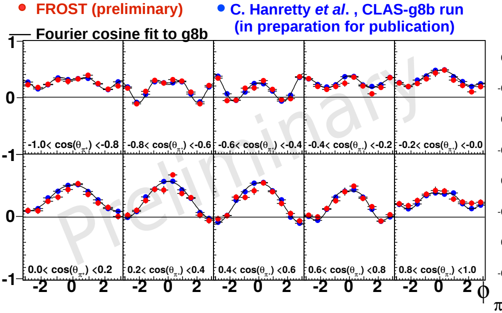
Good agreement between experiments

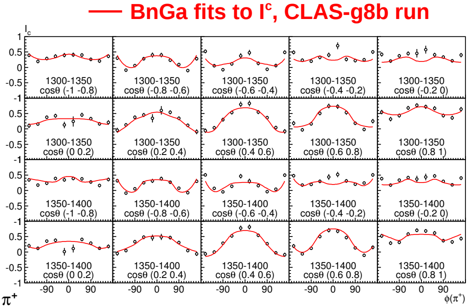
$$I = I_0\{\delta_l[I^s\sin(2\beta) + I^c\cos(2\beta)]\}$$



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

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





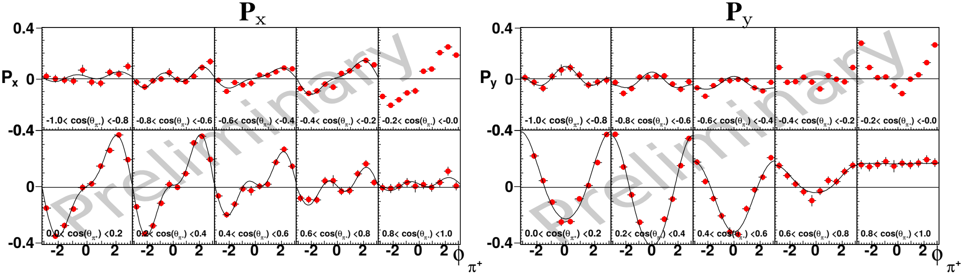
P. Roy *et al.* (CLAS-FROST), paper under preparation

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

Example: $0.8 < E_\gamma < 0.9$ GeV (Total E_γ range covered: 0.7 - 2.1 GeV)

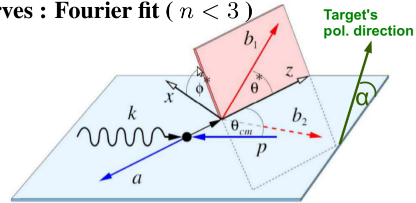


FROST g9b (lin. pol. beam) **Solid curves : Fourier fit ($n < 3$)**

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.



W. Roberts and T. Oed, PRC **71**, 055201 (2005)

Outline

1. Introduction
   - Why Baryon Spectroscopy?
   - Polarization Observables
   - The FROST Experiment using CLAS
2. Data Analysis and Results
   - $\vec{\gamma}\vec{p} \to p\omega$ Reaction
   - $\vec{\gamma}\vec{p} \to p\pi^+\pi^-$ Reaction
3. Outlook

Summary

- **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 $\vec{\gamma}\vec{p} \to p\omega$ (Σ (for $E_\gamma > 1.7$ GeV), T, H, P, F) and $\vec{\gamma}\vec{p} \to p\pi^+\pi^-$ ($I^{s,c}$, $P_{x,y}$, $P^{s,c}_{x,y}$): 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.
- Our findings from FROST on the N^* members, together with the findings on the strange members (e.g. from PANDA at GSI, BES at Beijing, GlueX at JLab) of the multiplets will complete the study of the light baryon spectrum. This will give more insight into the phenomenon of color confinement in the system of light quarks.

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

Thank You !
Any Questions ?