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

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Florida State University

Jefferson Lab Seminar

07/28/2016

Outline

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Understanding Hadrons

- Matter that we see around us is made up of hadrons like protons and neutrons. Hadrons are made of quarks and gluons which interact via the strong force.
- Broad classification of hadrons:
  Baryons: 3 quarks, **Mesons**: quark-antiquark pairs.
- 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.

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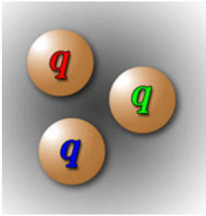
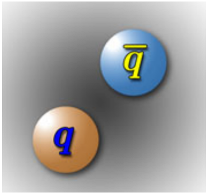


Mesons



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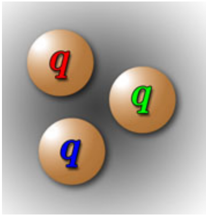

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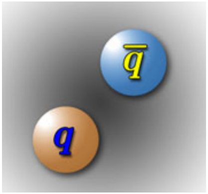
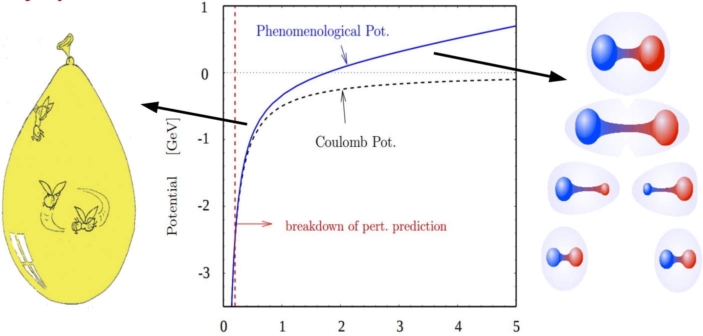


Understanding Hadrons

Quantum Chromodynamics (QCD) is the theory of the strong force which describes quark-gluon interactions. Two peculiar features of the strong force are:

Asymptotic freedom ..

Confinement ..



.. at short distances, as if the quarks were free.

.. at large distances. No free quarks! Non-perturbative regime.

Hadron Spectroscopy

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

- How are confinement and chiral symmetry breaking connected?
- What are the relevant degrees of freedom? How do they evolve with energy?
- Do states beyond the conventional $|qqq\rangle$ and $|q\bar{q}\rangle$ exist? E.g. tetraquarks, gluonic excitations, glueballs ..

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Hadron spectroscopy is essential to answer these questions: map out the spectrum and study the underlying pattern.

- Baryon spectroscopy: a tool to understand the effective degrees of freedom in excited nucleons.
- Meson spectroscopy: a tool to search for gluonic excitations. Unlike hybrid baryons, hybrid mesons $(q\bar{q}g)$ can carry exotic J^{PC}. E.g. 0^{--}, 0^{+-}, 1^{-+} ..

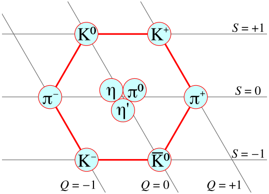
Hadron Spectroscopy

The **ground state** of light hadrons can be grouped in SU(6) multiplets.

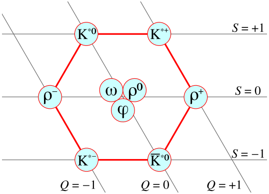
- Pseudoscalar mesons ($J^P = 0^-$) in a nonet.
- Vector mesons ($J^P = 1^-$) in a nonet.
- Baryons with $J^P = \frac{1}{2}^+$ in an octet.
- Baryons with $J^P = \frac{3}{2}^+$ in a decuplet.

All of them have been experimentally observed.

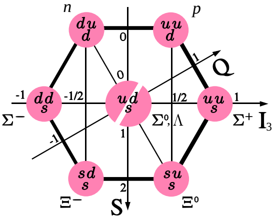
Pseudoscalar mesons nonet



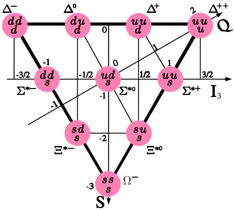
Vector mesons nonet



Baryon octet

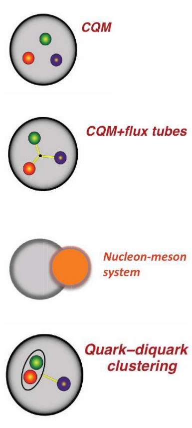


Baryon decuplet



Light Baryon Spectroscopy

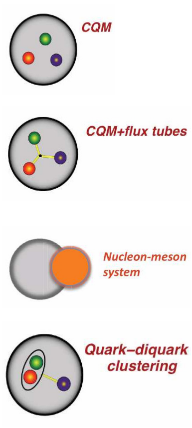
Effective degrees of freedom

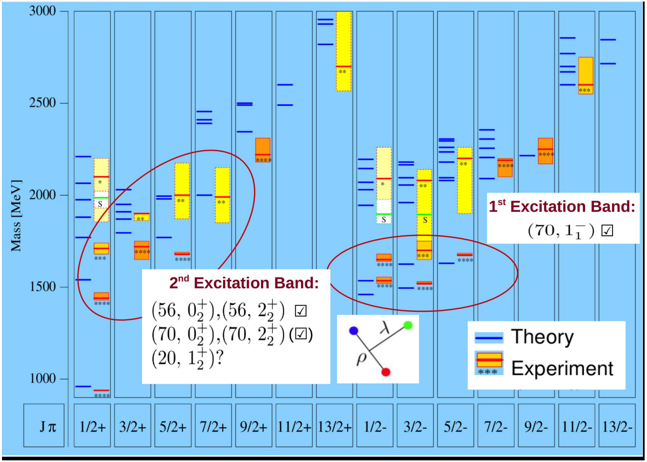


Map out the excited states of (light) baryons, identify the underlying multiplets to understand how QCD gives rise to excited baryons.

Light Baryon Spectroscopy

Effective degrees of freedom





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

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[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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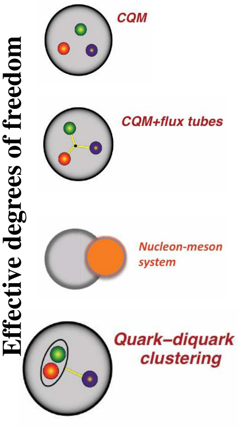

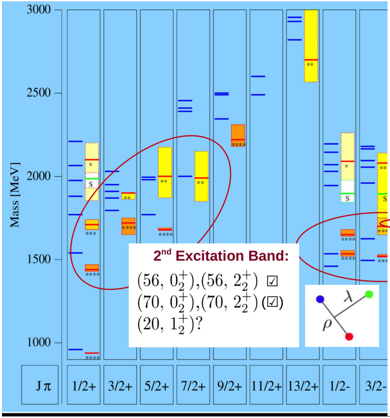

N^*	J^P $(L_{2I,2J})$	2010	2012
$N(1440)$	$1/2^+$ (P_{11})	****	****
$N(1520)$	$3/2^-$ (D_{13})	****	****
$N(1535)$	$1/2^-$ (S_{11})	****	****
$N(1650)$	$1/2^-$ (S_{11})	****	****
$N(1675)$	$5/2^-$ (D_{15})	****	****
$N(1680)$	$5/2^+$ (F_{15})	****	****
$N(1685)$			*
$N(1700)$	$3/2^-$ (D_{13})	***	***
$N(1710)$	$1/2^+$ (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})	****	****

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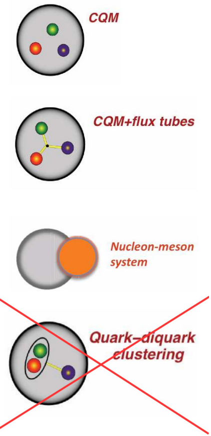
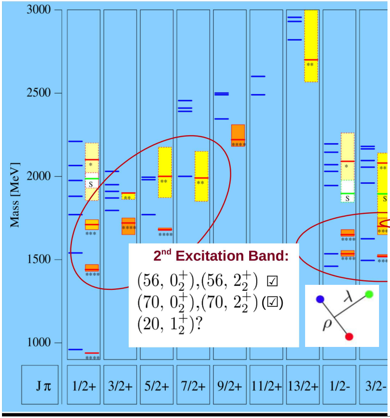
Effective degrees of freedom





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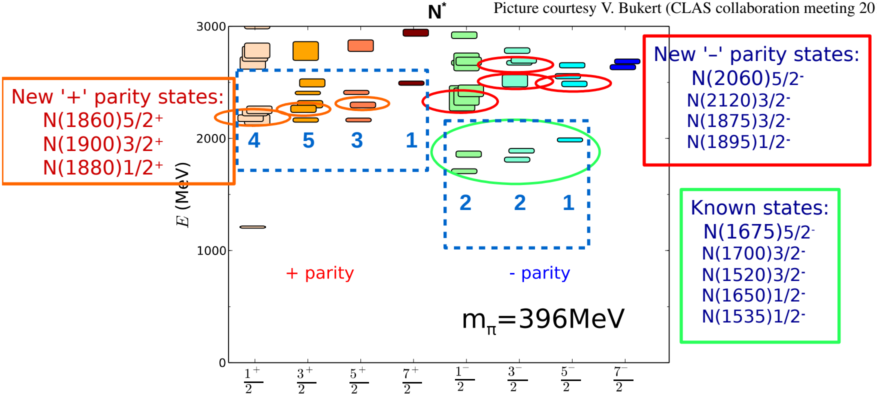
N(1900)$3/2^+$ (which can be assigned as a member of the quartet of (**70**, 2^+_2)) cannot be accommodated in the naive quark-diquark picture, both oscillators need to be excited.[1],[2]

Baryon Spectrum with LQCD

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



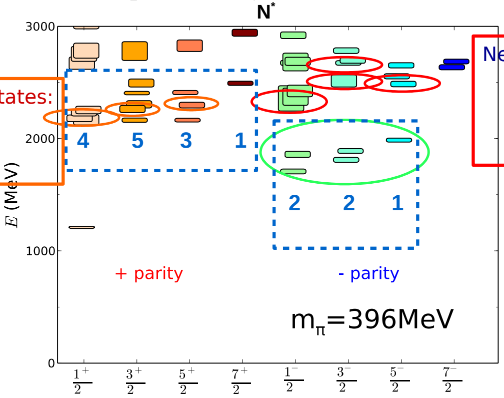
- - - LQCD manifests broad features of $SU(6) \otimes O(3)$ symmetry.

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 There is a lot more to learn!

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:
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N(1700)3/2-
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Vector meson (ω, ρ, ϕ) photoproduction have mostly remained unexplored. Vast pool of information yet to be unearthed:

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$N(1880)\ 1/2^+$	**	*	*		**		*			
$N(1895)\ 1/2^-$	**	**	*	**			**	*		
$N(1900)\ 3/2^+$	***	***	**	**		**	***	**	*	**
$N(1990)\ 7/2^+$	**	**	**					*		
$N(2000)\ 5/2^+$	**	**	*	**			**	*	**	
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$N(2190)\ 7/2^-$	****	***	****			*	**		*	
$N(2220)\ 9/2^+$	****		****							
$N(2250)\ 9/2^-$	****		****							
$N(2300)\ 1/2^+$	**		**							
$N(2570)\ 5/2^-$	**		**							

Particle Data Group 2015

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$N(1880)\,1/2^+$	**	*	*		**		*			
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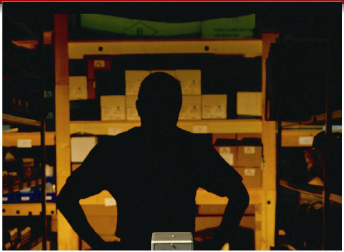
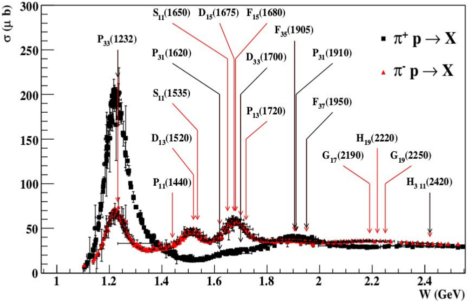
Why are Spin Observables Important?



Courtesy of Michael Williams



Baryon resonances are broad and overlapping so it is not possible to identify all contributing resonances by just looking for peaks in the unpolarized cross section.

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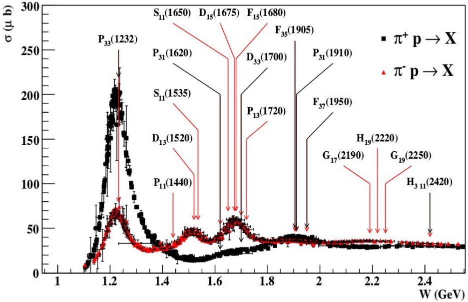


Need polarization observables in addition to the cross section to disentangle and reveal the resonances.

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

FROST experiment using CLAS, JLab

Prelim. results on 13 observables from this analysis (Analysis Note approved)

Data acquired

Prelim. results available

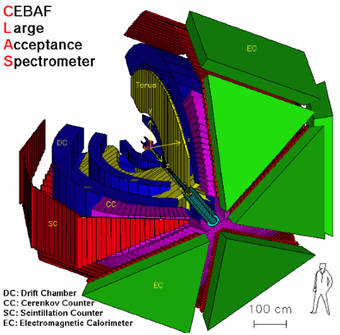
$\vec{\gamma}\vec{p} \to p\omega$

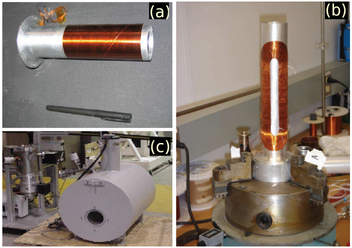
Beam \ Target	Transversely Pol.	Longitudinally Pol.
Linearly Pol.	Σ, T, H, P	Σ, G
Circularly Pol.	F, T	E

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

Beam \ Target	Transversely Pol.	Longitudinally Pol.
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 ∼ 1.5 to 2.3 GeV

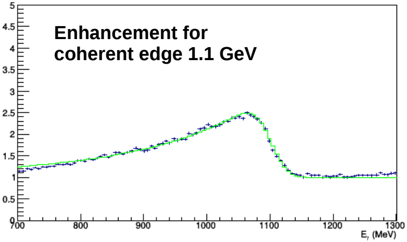
g9b run (Mar to Aug, 2010)
Photon pol.: Linear/Circular
Target: Frozen Spin Butanol
Target pol.: Transverse

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

The FROST Experiment using CLAS at JLab

Coherent edges: 0.9 – 2.1 GeV (0.2 GeV wide)

Deg. of linear beam pol.: 40 – 60%

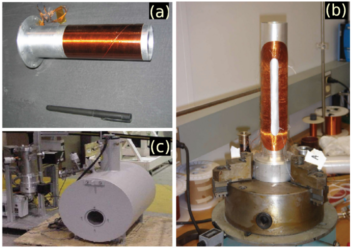


g9b run (Mar to Aug, 2010)

Photon pol.: Linear/Circular

Target: Frozen Spin Butanol

Target pol.: Transverse



- Polarizing field = 5 T, T$\sim$ 0.5 K
- Dipole holding field = 0.5 T, T$\sim$ 30 mK
- Offset angle = 116.1 ± 0.4° from x_{lab}
- Av. target pol. = 81.0 ± 1.7%
- Relaxation time: 3400 hrs w/ beam, 4000 hrs w/o beam

Outline

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.

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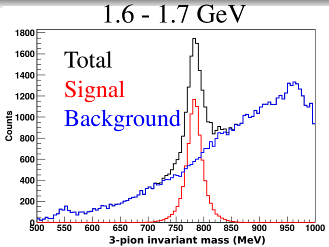

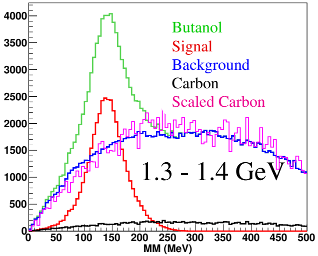

[1] M. Williams *et al.*, JINST 4 (2009) P10003

Data Selection and Analysis

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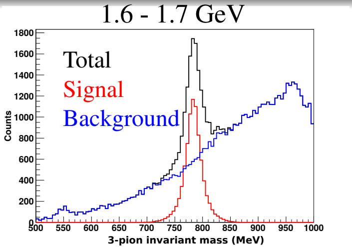

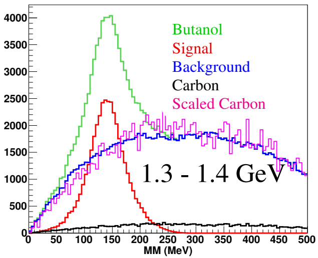

[1] M. Williams *et al.*, JINST 4 (2009) P10003
[2] D G Ireland, CLAS Note 2011-010

The Unbinned Maximum Likelihood Method (MLM)

- The ϕ asymmetry was manifested as modulations.
- Polarization observables were extracted by fitting the modulations using unbinned MLM. **Advantage**: no loss of information due to binning.
- Expressed the likelihood L in terms of the asymmetry $A = (n_{\text{pol1}} - n_{\text{pol2}})/(n_{\text{pol1}} + n_{\text{pol2}})$ in any kinematic bin with N_{total} events (with each event having a weight w_i) as:

$$-\ln L = - \sum_{i=1}^{N_{\text{total}}} w_i \ln\left(P\left(\text{event}_i\right)\right),$$

$$\text{where } P\left(\text{event}_i\right) = \begin{cases} \frac{1}{2}\,(1 + A), & \text{for pol1}, \\ \frac{1}{2}\,(1 - A), & \text{for pol2 (orthogonal to pol1).} \end{cases}$$

- A is a function of the polarization observable. Minimizing $-\ln L$ gave the most likely value of the observable.

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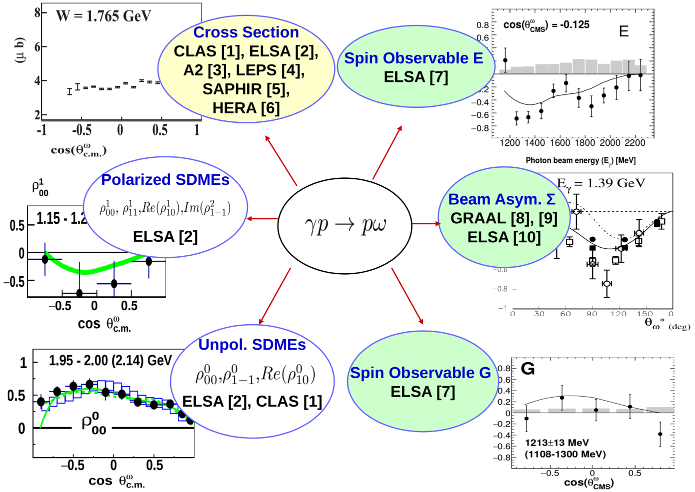
Results

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



[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)

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

Pol. SDMEs and polarization observables 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

* rating in PDG 2014

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

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

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

Pol. SDMEs and polarization observables 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:

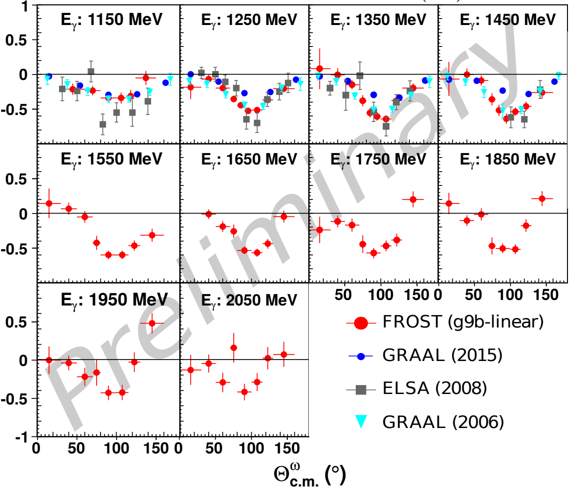
- N($\sim$ 2.2 GeV) Uncertain J^P: $1/2^-, 3/2^+, 3/2^-$ or $5/2^+$??
- N(> 2.1 GeV) $7/2^-$?

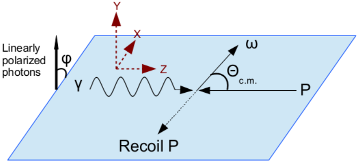
* rating in PDG 2014

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

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

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

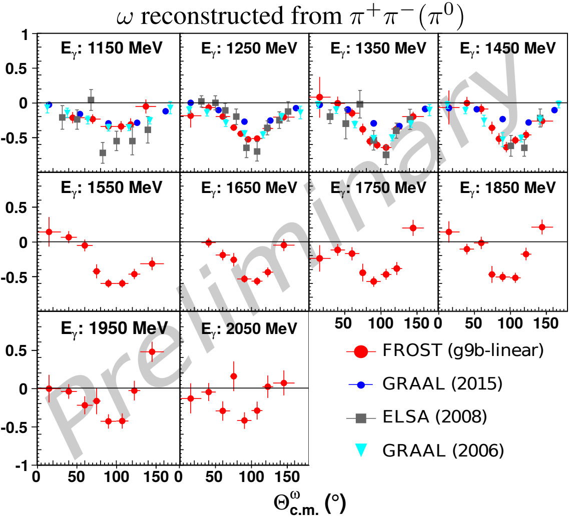




$$\sigma = \sigma_0[1 - \boldsymbol{\Sigma}\ \delta_l \cos(2\phi)$$
$$+\Lambda\cos(\alpha)(-\delta_l \mathbf{H}\sin(2\phi) + \delta_\odot \mathbf{F})$$
$$-\Lambda\sin(\alpha)(-\mathbf{T} + \delta_l \mathbf{P}\cos(2\phi))]$$
$$-\Lambda_z(-\delta_l \mathbf{G}\sin(2\phi) \quad + \quad \delta_\odot \mathbf{E})]$$

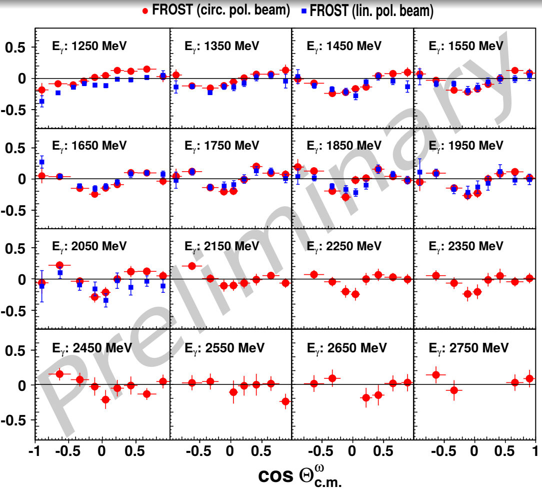
$\delta_\odot(\delta_l)$: degree of beam pol.
Λ : degree of target pol.

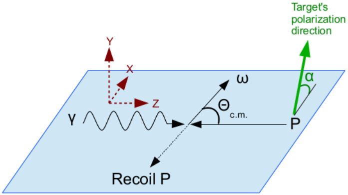
Beam Asymmetry Σ in $\vec{\gamma}p \to p\omega$



- **FROST**: transversely pol. target (more complex analysis) **Others**: unpolarized H_2 target
- **FROST results** agree well with previously published results except for GRAAL 15.
- First-time 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 $\gamma\vec{p} \to p\omega$





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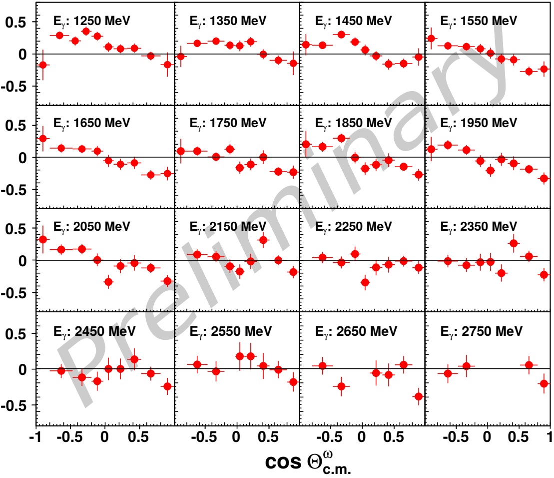
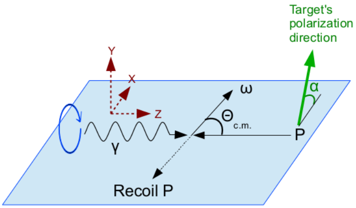
$\delta_\odot(\delta_l)$: degree of beam pol.
Λ : degree of target pol.

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

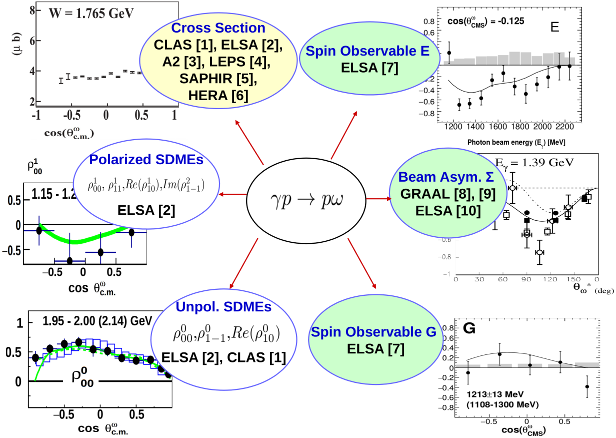


$$\begin{aligned}\sigma &= \sigma_0[1 - \mathbf{\Sigma}\,\delta_l\cos(2\phi)\\ &+\Lambda\cos(\alpha)(-\delta_l\mathbf{H}\sin(2\phi) + \delta_\odot\mathbf{F})\\ &-\Lambda\sin(\alpha)(-\mathbf{T} + \delta_l\mathbf{P}\cos(2\phi))]\\ &-\Lambda_z(-\delta_l\mathbf{G}\sin(2\phi) + \delta_\odot\mathbf{E})]\end{aligned}$$

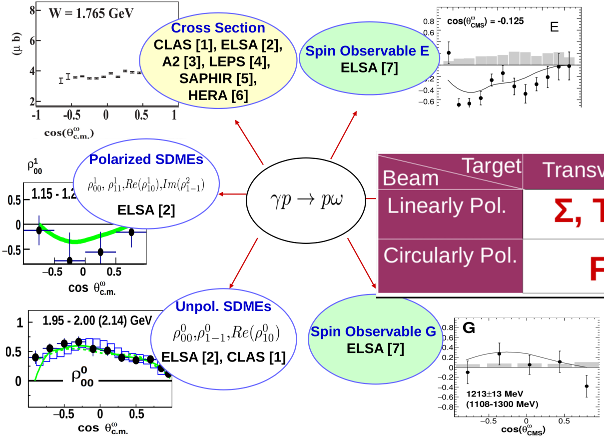
$\delta_\odot(\delta_l)$: degree of beam pol.

Λ : degree of target pol.

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



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



+ FROST (Prelim.) Results

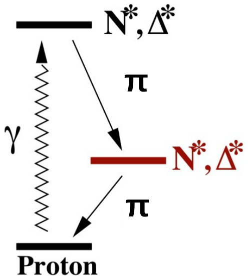
Beam \ Target	Transversely Pol.	Longitudinally Pol.
Linearly Pol.	Σ, T, H, P	Σ, G
Circularly Pol.	F, T	E

Results

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

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

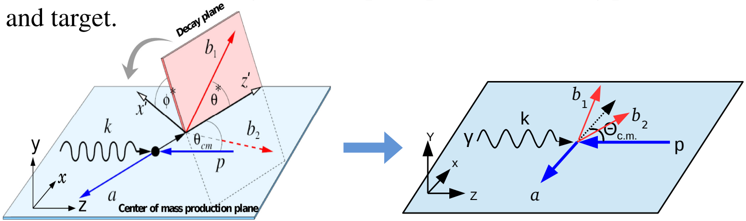
- Allow the study of sequential decays of intermediate N^* and also $N^* \to p\rho$ decay but the large hadronic background makes it challenging.



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

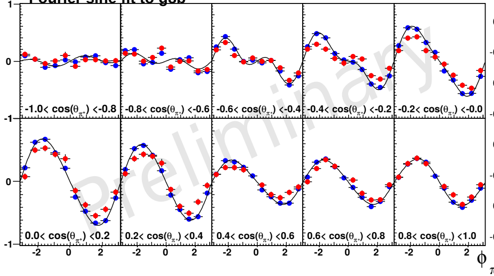
Example: $1.30 < E_\gamma < 1.40$ GeV (Total E_γ range covered: 0.7 - 2.1 GeV)

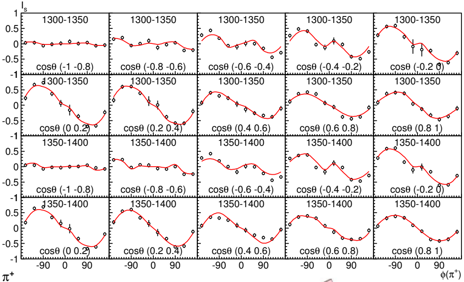
● FROST (preliminary)

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

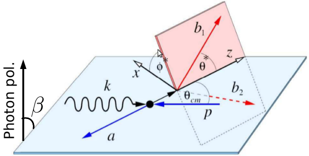
— Fourier sine fit to g8b

— BnGa fits to I^s, CLAS-g8b run





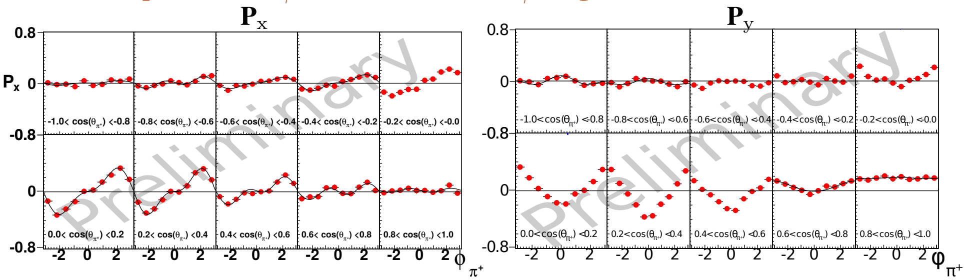
Good agreement between experiments



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

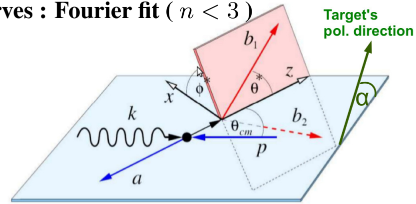
First Measurements of Target Asym. $P_{x,y}$ in $\gamma\vec{p} \to p\pi^+\pi^-$

Example: 0.8 < E_γ < 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: $(E_\gamma, \phi^*_{\pi^+}, \cos\theta^*_{\pi^+})$

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

Λ : degree of target pol.

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

Outline

1. Introduction
   - Strong Interaction
   - 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

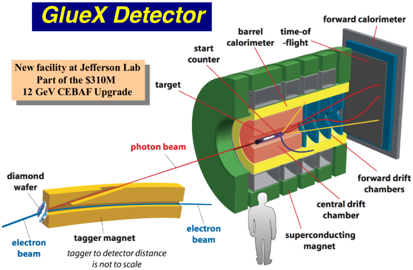
Summary

- **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 $\vec{\gamma}\vec{p} \to p\pi^+\pi^-$ ($P_{x,y}$, $P^{s,c}_{x,y}$): 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.
- 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 confinement and the evolution of bound states of QCD from light to heavy-quark regime.**

Opportunities at GlueX

The GlueX experiment at JLab Hall D offers many exciting opportunities.

- **Flagship physics progam**: Search for exotic mesons and study of their production mechanism using linearly-polarized photons (E_γ up to 9 GeV).
  In addition, spectroscopy of strange baryon resonances. E.g. Σ and cascades.
- Primakoff experiment to determine the η radiative decay width.
- Pion polarisability measurements.
- Photoproduction of ω on nuclei.



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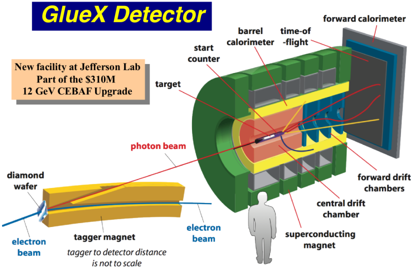

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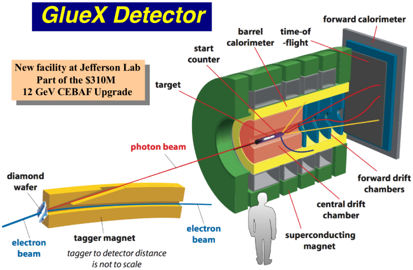

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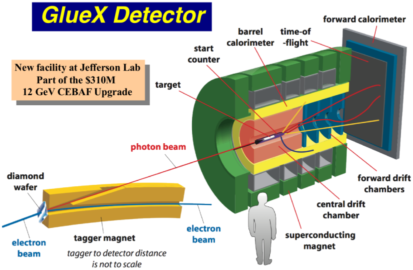

Cascade (S=-2) Spectroscopy at GlueX

Only 6 Ξ states have been observed with 3 or 4 star rating:
$\Xi(1320)\frac{1}{2}^{+}, \Xi(1530)\frac{3}{2}^{+}, \Xi(1690)?^{?}, \Xi(1820)\frac{3}{2}^{-}, \Xi(1950)?^{?}, \Xi(2030)(\geq \frac{5}{2})^{?}$.
Instanton Model[1] and LQCD calculations[2] predict many more states.

[1] U. Loering, B. Ch. Metsch, H. R. Petry, Eur. Phys. J. **A 10** 447 (2001).
[2] R. Edwards *et al.*, Phys. Rev. D **87**, no. 5, 054506 (2013).

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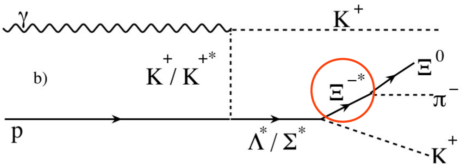
A possible production mechanism for Ξ^{-*}



To produce excited Ξ states in photo-production experiments, we need to invest energy in creating kaons so that the total strangeness $= 0$.

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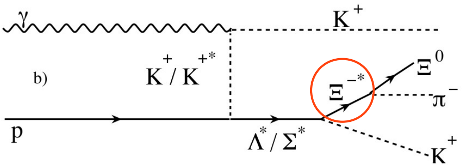


To produce excited Ξ states in photo-production experiments, we need to invest energy in creating kaons so that the total strangeness = 0.
$\Rightarrow$ need high photon energies and good kaon identification!

GlueX, covering photon energies up to 9 GeV and with an enhanced kaon identification using DIRC, will offer a good opportunity to study the excited Ξ states.

[1] U. Loering, B. Ch. Metsch, H. R. Petry, Eur. Phys. J. **A 10** 447 (2001).
[2] R. Edwards *et al.*, Phys. Rev. D **87**, no. 5, 054506 (2013).

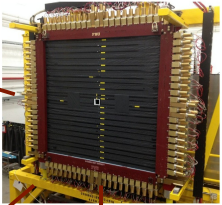
The GlueX Time-Of-Flight Spectrometer

Constructed at Florida State University. My contributions to the team effort were:

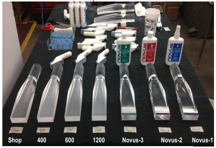
- Polishing lightguides (optical coupling between scintillators & PMTs) to prevent loss of photons.
- Wrapping scintillators with Enhanced Specular Reflector to facilitate internal reflection of photons.
- Wrapping tedlar to provide a light-tight enclosure.

Wrapping tedlar

FSU TOF



Wrapping ESR



Polishing lightguides

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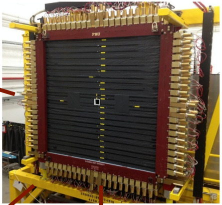
These steps were necessary to minimize the loss of light and improve the resolution. TOF resolution achieved: $\sim$ 100 ps.
Particle id $\pi/K/p$ up to $\sim$ 2 GeV/c at 4σ.

Wrapping tedlar

FSU TOF



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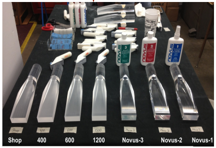
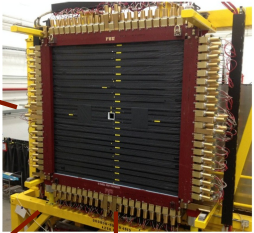
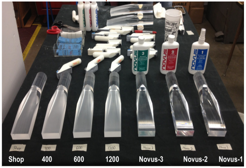


Polishing lightguides

The GlueX Time-Of-Flight Spectrometer

It was a fun experience!





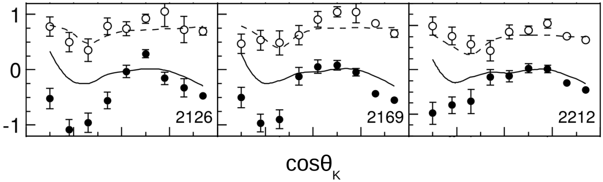
Thank you!

Backup slides

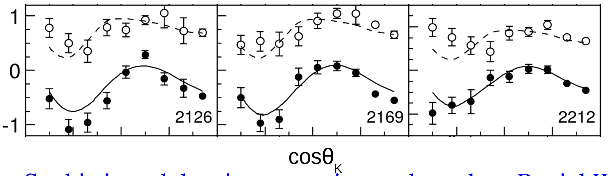
Why are Spin Observables Important?

[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})	****	****

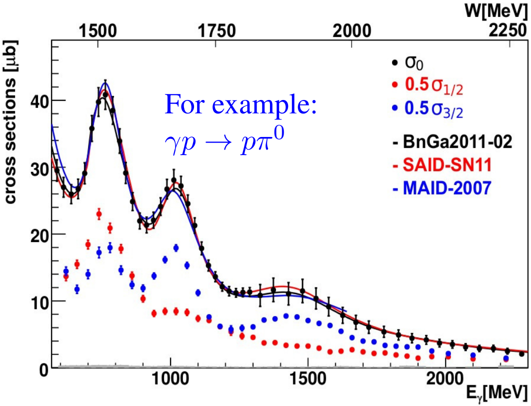
Sophisticated data interpretation tools such as Partial Wave Analysis and Phenomenological models are required to identify the contributing resonances.

Why are Spin Observables Important?

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

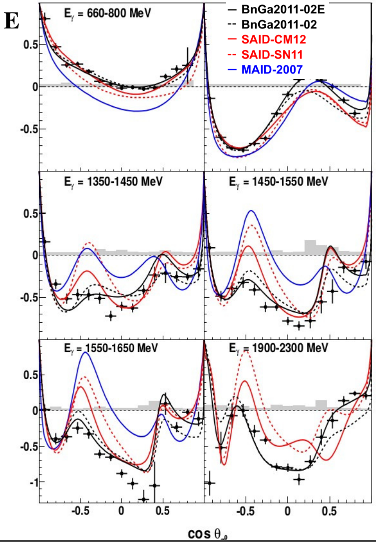
$\delta_\odot (\delta_l)$: degree of beam pol.
Λ : degree of target pol.

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?



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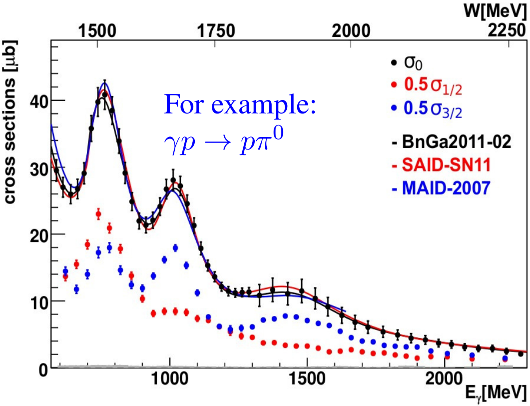
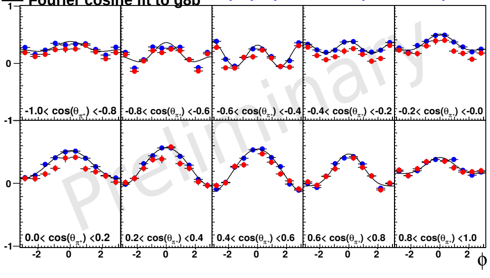


Spin observables sensitive to the interference between resonances. Reveal discrepancies between model predictions and experimental data.

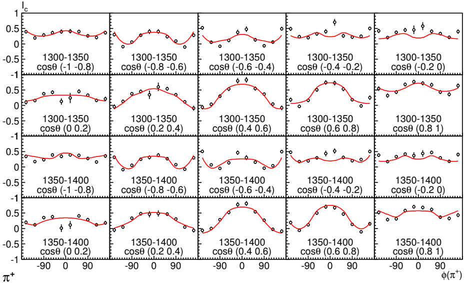
Beam Asymmetry I^c in $\vec{\gamma} p \to p\pi^+\pi^-$

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

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



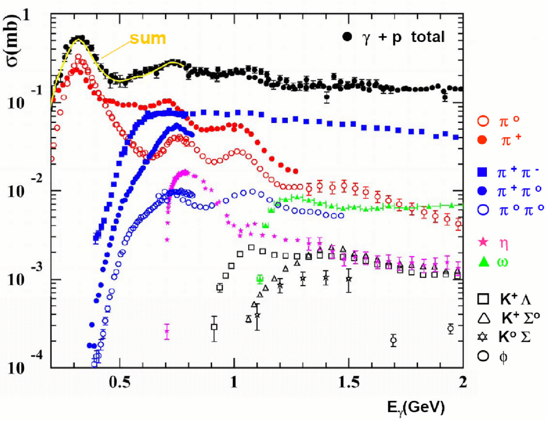
— BnGa fits to I^c, CLAS-g8b run



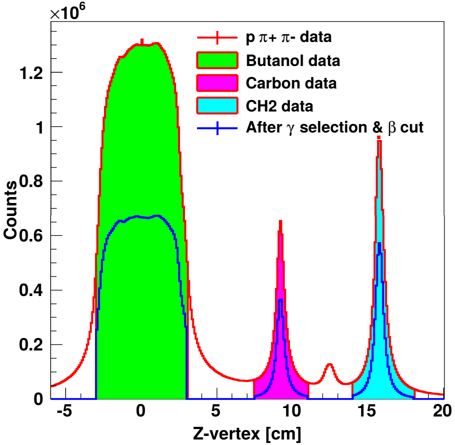
Good agreement between experiments

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

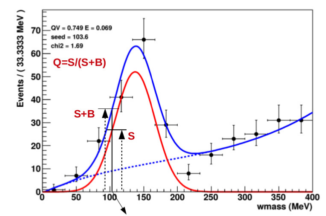
Photoproduction Cross Section



Vertex cut


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

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.

Scattering Amplitudes in $\gamma p \rightarrow p\pi^+\pi^-$ and $\gamma p \rightarrow p\omega$

$\gamma p \rightarrow p\pi^+\pi^-$ reaction: Roberts and Oed, PRC **71**, 055201 (2015)

- 8 independent helicity amplitudes after parity invariance operation.
- Need 15 carefully selected observables at each kinematic bin for fully determining the helicity amplitudes.
- A complete measurement will require certain single, double and triple polarization observables in addition to the differential cross section.

$\gamma p \rightarrow p\omega$ reaction: Pichowsky *et al.*, PRC **53** (1996)

- 12 independent helicity amplitudes after parity invariance.
- 8 single spin, 51 double spin, 123 triple spin and 108 quadrupole spin (γ, p, p', vector and tensor pol. of ω) observables after parity conservation.
- Need 23 carefully selected observables for determining the helicity amplitudes.
- A complete experiment doesn't seem plausible, but it is useful to extract experimental observables to extract useful dynamical information.

CLAS experiment details

Capability	Quantity	Range
Coverage	Charged-particle angle	$8^\circ \leqslant \theta \leqslant 140^\circ$
	Charged-particle momentum	$p \geqslant 0.2$ GeV/c
	Photon angle (4 sectors)	$8^\circ \leqslant \theta \leqslant 45^\circ$
	Photon angle (2 sectors)	$8^\circ \leqslant \theta \leqslant 75^\circ$
	Photon energy	$E_\gamma \geqslant 0.1$ GeV
Resolution	Momentum ($\theta \lesssim 30^\circ$)	$\sigma_p/p \approx 0.5\%$
	Momentum ($\theta \gtrsim 30^\circ$)	$\sigma_p/p \approx$ (1–2)%
	Polar angle	$\sigma_\theta \approx 1$ mrad
	Azimuthal angle	$\sigma_\phi \approx 4$ mrad
	Time (charged particles)	$\sigma_t \approx$ (100–250) ps
	Photon energy	$\sigma_E/E \approx 10\%/\sqrt{E}$
Particle ID	π/K separation	$p \leqslant 2$ GeV/c
	π/p separation	$p \leqslant 3.5$ GeV/c
	π^- misidentified as e^-	$\leqslant 10^{-3}$
Luminosity	Electron beam	$L \approx 10^{34}$ nucleon cm^{-2} s^{-1}
	Photon beam	$L \approx 5 \times 10^{31}$ nucleon cm^{-2} s^{-1}
Data acquisition	Event rate	4 kHz
	Data rate	25 MB/s
Polarized target	Magnetic field	$B_{max} = 5$ T

Multiplets in the 2^{nd} excitation band of N^*

V. Crede and W. Roberts, Rept.Prog.Phys. **76** (2013)

$SU(6)$ (flavor + spin), $O(3)$: orthogonal group of rotations
$6 \otimes 6 \otimes 6 = 56_S \oplus 70_M \oplus 70_M \oplus 20_A$
$56 = 10^4 \oplus 8^2$, $(4 = 2(\frac{3}{2}) + 1)$
$70 = 10^2 \oplus 8^4 \oplus 8^2 \oplus 1^2$
$20 = 8^2 \oplus 1^4$

Why is 20plet inconsistent with the static quark-diquark picture?
The static diquark: $6 \otimes 6 = 21 \oplus 15$
The symmetry of diquark requires it to be 21 since the color $\Psi$is antisymmetric.
The static diquark +the third quark: $21 \otimes 6 = 56 \oplus 70$, i.e. no 20plet!

Only two N^*states with 1-star rating have been assigned to the 20plet.

FROST Target and Detector Information

Polarizing field: 5 T, Temperature $\sim$ 0.5 K
Holding field: 0.5 T, Temperature $\sim$ 30 mK
Average target polarization: $80 - 86\%$
Typical relaxation times for '$+'$ target pol.:
2800 hrs with beam, 3600 hrs without (g9a)
3400 hrs with beam, 4000 hrs without (g9b)

E-T plane resolution: 110 ps
Average time resolution for reconstructed electrons in CLAS: 150 ps
Momentum resolution varied with angle,
average fractional momentum resolution: $0.5 - 1\%$

Measuring $\Gamma(\eta \to \gamma\gamma)$ at GlueX

Gluonic Excitations: Physics beyond the Quark Model

- Hybrid baryons do not have exotic quantum numbers, hence they are very difficult to identify.
- Hybrid mesons can have exotic J^{PC}. From conventional $q\bar{q}$ picture:
  - $S = 0$ (anti-aligned) or 1 (aligned).
  - $P = (-1)^{L+1}$
  - $C = (-1)^{L+S}$
  - $\vec{J} = \vec{L} + \vec{S}$
  - Not all quantum numbers allowed in $q\bar{q}$!
    E.g. $J^{PC} = 0^{--}, 0^{+-}, 1^{-+}, 2^{+-}$