Hadron Spectroscopy at Jefferson Lab: Search for new States of Hadronic Matter

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Outline

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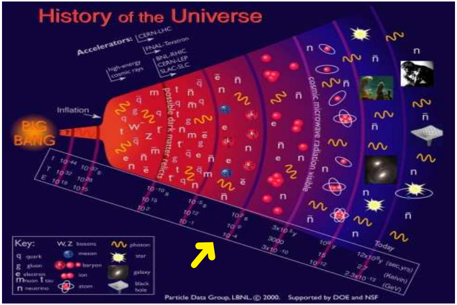
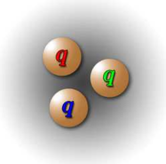
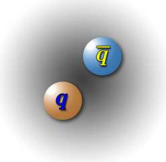
QCD and Confinement



From about 10^{-6} s on, all quark and anti-quarks became confined inside of hadronic matter. Only protons and neutrons remained after about 1 s.

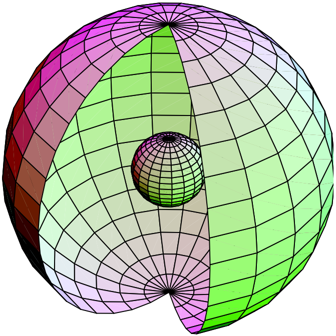




1. What is the origin of confinement?
2. How are confinement and chiral symmetry breaking connected?
3. Would the answers to these questions explain the origin of $\sim$ 99 % of observed matter?

Non-Perturbative QCD

Courtesy of Craig Roberts, Argonne



How does QCD give rise to hadrons?

Interaction between quarks unknown throughout > 98 % of a hadron's volume.

➜

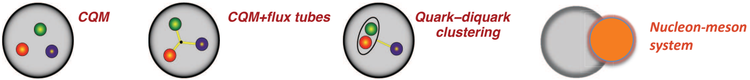
Explaining the excitation spectrum of hadrons is central to our understanding of QCD in the low-energy regime (Hadron Models, Lattice QCD, etc.)

➜ Complementary to Deep Inelastic Scattering (DIS) where information on collective degrees of freedom is lost.

The (Experimental) Issues with Hadrons

1. **Baryons**

   What are the fundamental degrees of freedom inside a proton or a neutron? How do they change with varying quark masses?



2. **Mesons**

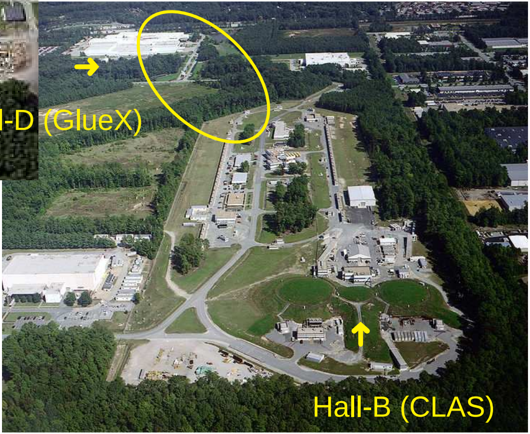
   What is the role of glue in a quark-antiquark system and how is this related to the confinement of QCD?

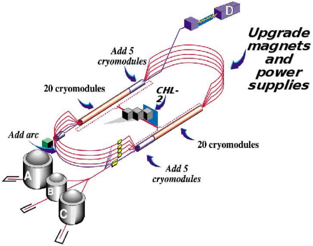
   What are the properties of predicted states beyond simple quark-antiquark systems (hybrids, glueballs, multi-quark states, ...)?

   ➜ **Need to map out new states:**
   BES III, BELLE, COMPASS, Panda@GSI, GlueX@Jefferson Lab, ...

Aerial View of Jefferson Laboratory

July 7, 2011





One of the Goals of the Excited N^* Program ...

... is the search for *missing* or yet unobserved baryon resonances.

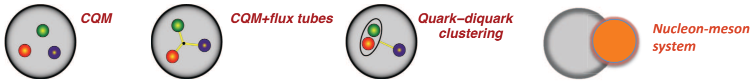
Quark models predict many more baryons than have been observed.

	$****$	$***$	$**$	$*$
N Spectrum	11	3	6	2
Δ Spectrum	7	3	6	6

→ Particle Data Group
(J. Phys. G **37**, 075021 (2010))

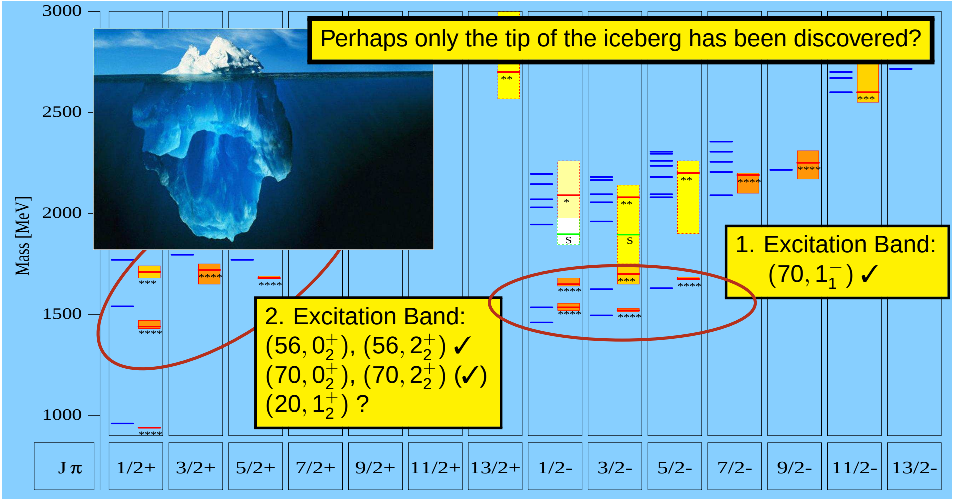
→ little known
(many open questions left)

→ Are the states missing because our models do not capture the correct degrees of freedom? Or have the resonances simply escaped detection?



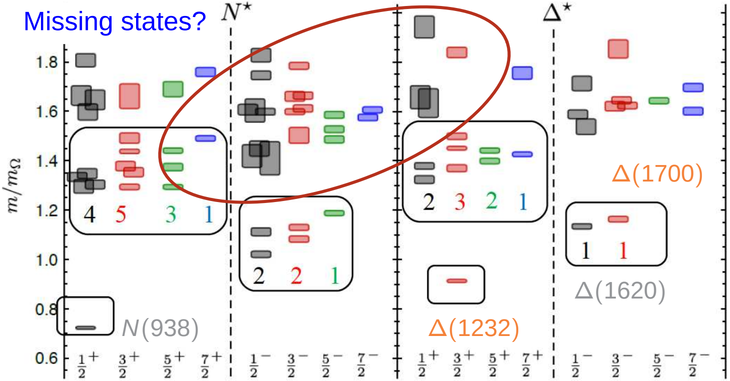
Spectrum of Nucleon Resonances

—— S. Capstick and N. Isgur, Phys. Rev. **D34** (1986) 2809



Excited-State Baryon Spectroscopy from Lattice QCD

R. Edwards *et al.*, arXiv:1104.5152 [hep-ph]



$m_\pi = 400$ MeV

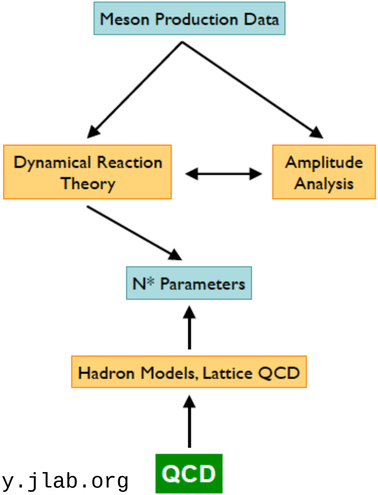
Exhibits broad features expected of $SU(6) \otimes O(3)$ symmetry

➜ Counting of levels consistent with non-rel. quark model, no parity doubling

Extraction of Resonance Parameters

- Double-polarization measurements
- Measurements off neutron and proton to resolve isospin contributions:
  1. $\mathcal{A}(\gamma N \to \pi,\ \eta,\ K)^{I=3/2} \quad \Longleftrightarrow \quad \Delta^*$
  2. $\mathcal{A}(\gamma N \to \pi,\ \eta,\ K)^{I=1/2} \quad \Longleftrightarrow \quad N^*$
- Re-scattering effects: Large number of measurements (and reaction channels) needed to define full scattering amplitude.

Coupled Channels



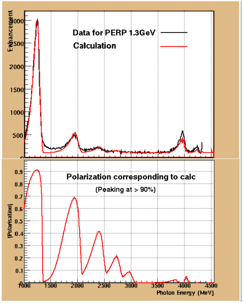
http://ebac-theory.jlab.org

Outline

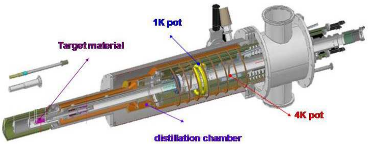
CLAS (Polarization) Run Periods: Photoproduction

- g1c: C_x and C_z, $I^{\odot}$ for $\gamma p \to p\pi^+\pi^-$ (circ.-pol. beam, mostly published)
- g8b: Σ, I^s and I^c (lin.-pol. beam, H_2)
- FROST (g9a, g9b) (double pol., C_4H_9OH)
- g13 (lin.-pol. beam, D_2)
- HD-ICE
  ➜ future measurements (Fall 2011)

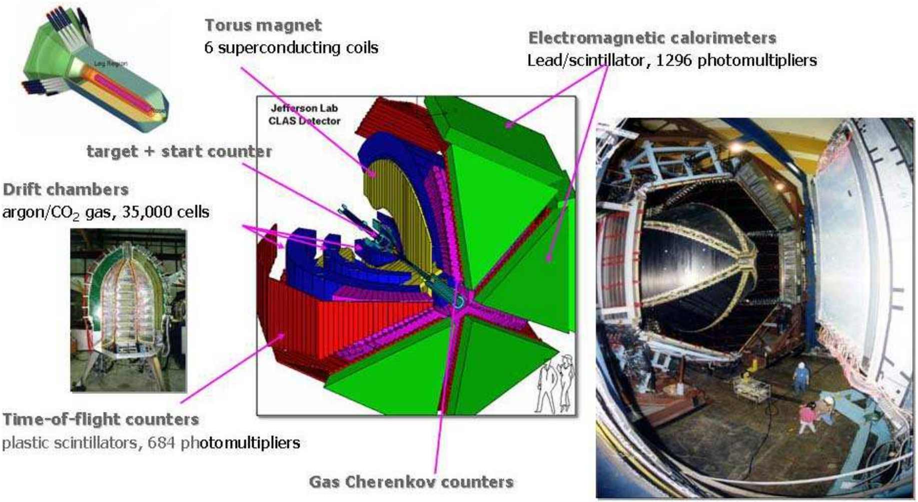
➜ g8b



FROST ➜

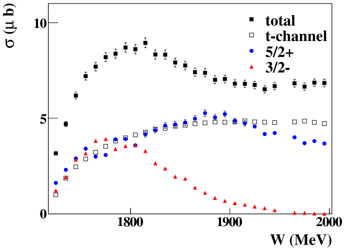


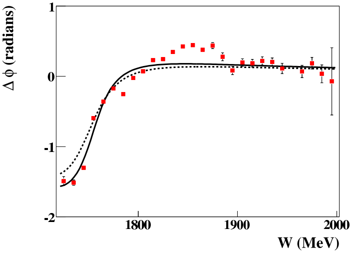
CEBAF Large Acceptance Spectrometer (CLAS)



Isospin Filter: $\gamma p \to N^* \; (I = 1/2) \; \to p\,\omega$

M. Williams *et al.* [CLAS Collaboration], Phys. Rev. C **80**, 065209 (2009)





PWA fit includes resonances + t-channel amplitudes.

Strong evidence for ($W < 2$ GeV):

$(3/2)-$ N(1700) $***$

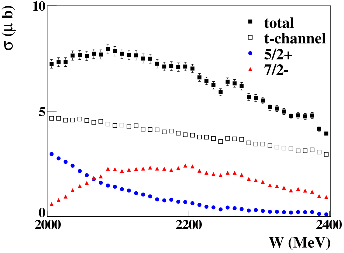
$(5/2)+$ N(1680) $****$

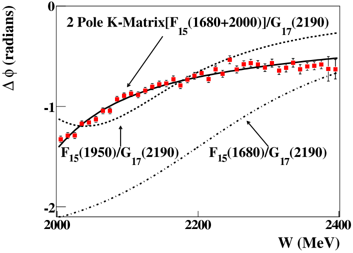
Only nucleon resonances can contribute (isospin filter)

- First-time PWA of ω photoproduction channel
- High statistics data sets are key to pull out signals.
  - ➜ CLAS at JLab can provide statistics, but there are also limitations in the acceptance.

Isospin Filter: $\gamma p \rightarrow N^* \ (I = 1/2) \ \rightarrow p\,\omega$

M. Williams *et al.* [CLAS Collaboration], Phys. Rev. C **80**, 065209 (2009)





PWA fit includes resonances + *t*-channel amplitudes.

Strong evidence for $(W > 2$ GeV$)$:

$(5/2)+$ N(1680) $****$

$(5/2)+$ N(1950) $**$

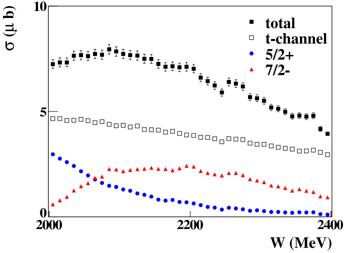
$(7/2)-$ N(2190) $****$

Only nucleon resonances can contribute (isospin filter)

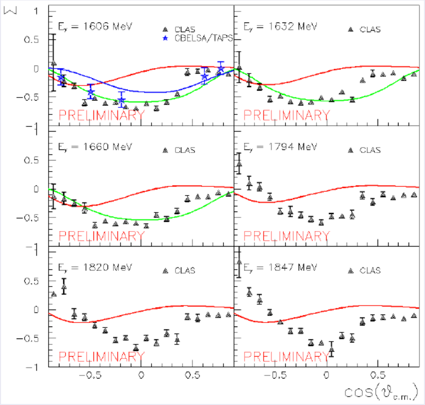
- First-time PWA of ω photoproduction channel
- High statistics data sets are key to pull out signals.
  - ➜ CLAS at JLab can provide statistics, but there are also limitations in the acceptance.
- Hints for a missing state!

Isospin Filter: $\gamma p \to N^* \ (I = 1/2) \ \to p\,\omega$

M. Williams *et al.* [CLAS Collaboration], Phys. Rev. C **80**, 065209 (2009)



Asymmetry Σ for $\vec{\gamma} p \to p\,\omega$ (P. Collins *et al.*, CUA)



Strong evidence for $(W > 2$ GeV$)$:

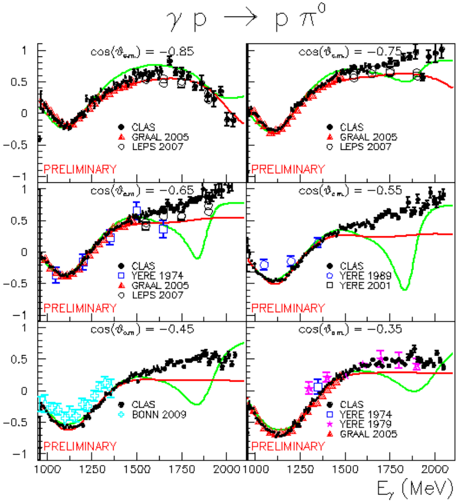
- $(5/2)+$ N(1680) $****$
- $(5/2)+$ N(1950) $**$
- $(7/2)-$ N(2190) $****$

— Oh *et al.*
— Paris *et al.*
— Sarantsev *et al.*

Beam Asymmetry Measurements: CLAS g8b

- $\gamma p \to p\,\pi^0,\, n\,\pi^+$ (M. Dugger *et al.*)
  Arizona State University
- $\gamma p \to p\,\eta,\ \eta'$ (P. Collins *et al.*)
  Arizona State University
- $\gamma p \to p\,\omega$ (P. Collins *et al.*)
  Catholic University
- $\gamma p \to p\,\pi^+\pi^-$ (C. Hanretty *et al.*)
  Florida State University
- $\gamma p \to p\,\phi$ (J. Salamanca *et al.*)
  Idaho State University
- $\gamma p \to K^+Y$ (C. Paterson *et al.*)
  University of Edinburgh, Glasgow

Beam Asymmetry Σ in $\vec{\gamma} p \to p\,\pi^0$



$$\frac{d\sigma}{d\Omega} = \sigma_0 \{ 1 - \delta_l\, \Sigma \cos 2\phi + \Lambda_x (-\delta_l\, \mathbf{H} \sin 2\phi + \delta_\odot\, \mathbf{F}) - \Lambda_y (-\mathbf{T} + \delta_l\, \mathbf{P} \cos 2\phi) - \Lambda_z (-\delta_l\, \mathbf{G} \sin 2\phi + \delta_\odot\, \mathbf{E}) \}$$

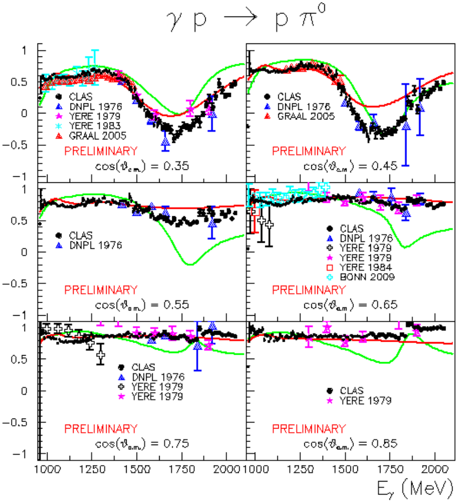
— SAID — MAID • CLAS

($E_\gamma < 2$ GeV, $-0.85 < \cos\theta_\pi < -0.35$)

➜ Serious discrepancies between models and data above 1.4 GeV.

M. Dugger (ASU), CLAS g8b run group, to be published

Beam Asymmetry Σ in $\vec{\gamma} p \to p\,\pi^0$



M. Dugger (ASU), CLAS g8b run group, to be published

— SAID — MAID • CLAS

($E_\gamma < 2$ GeV, $0.35 < \cos\theta_\pi < 0.85$)

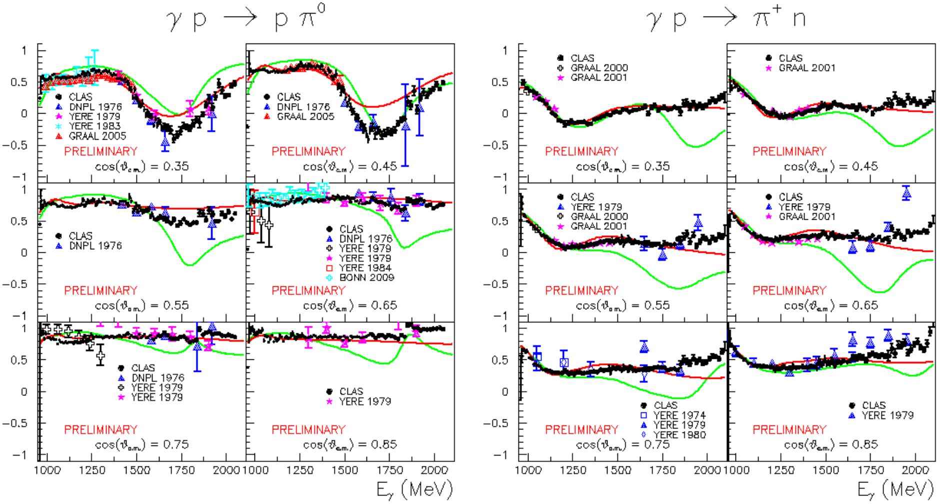
Combination of $p\,\pi^0$ and $n\,\pi^+$ final states can help distinguish between Δ and N^* resonances:

Δ^+ ↓ $\quad N^*$ ↓

$$\pi^0 + p : \sqrt{2/3}\left|I=\tfrac{3}{2}, I_3=\tfrac{1}{2}\right\rangle - \sqrt{1/3}\left|I=\tfrac{1}{2}, I_3=\tfrac{1}{2}\right\rangle$$

$$\pi^+ + n : \sqrt{1/3}\left|I=\tfrac{3}{2}, I_3=\tfrac{1}{2}\right\rangle + \sqrt{2/3}\left|I=\tfrac{1}{2}, I_3=\tfrac{1}{2}\right\rangle$$

Beam Asymmetry Σ in $\gamma p \to p\,\pi^0$ and $\gamma p \to n\,\pi^+$



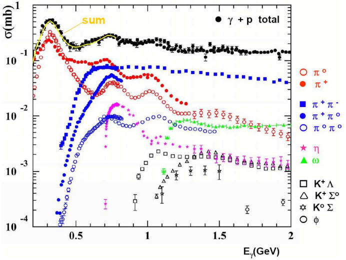
M. Dugger (ASU), CLAS g8b run group, to be published

Beam-Target Polarization Observables

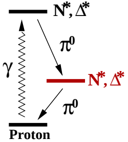
W. Roberts *et al.*, Phys. Rev. C **71**, 055201 (2005)

$$I = I_0 \{ (1 + \vec{\Lambda}_i \cdot \vec{\mathbf{P}}) + \delta_\odot (\mathbf{I}^\odot + \vec{\Lambda}_i \cdot \vec{\mathbf{P}}^\odot) + \delta_l [\sin 2\beta (\mathbf{I}^s + \vec{\Lambda}_i \cdot \vec{\mathbf{P}}^s) + \cos 2\beta (\mathbf{I}^c + \vec{\Lambda}_i \cdot \vec{\mathbf{P}}^c)] \}$$

$\Leftarrow$ Double-Meson Final States (15 Observables)



At higher excitation energies:
Multi-meson final states play an increasingly important role.



➜ Search for states in cascades!

Photoproduction of $\pi^+\pi^-$ off the Proton: Kinematics

Two mesons in the final state require 5 independent variables!

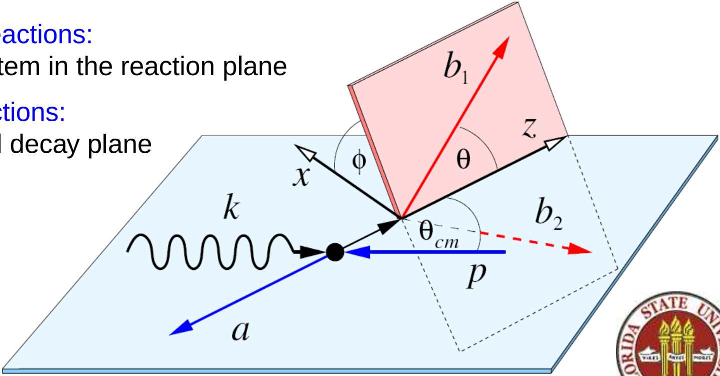
For example: E_γ, $\Theta_{\text{c.m.}}$, ϕ^*, θ^*, $M_{p\,+\,meson\,1}$

Single-meson reactions:

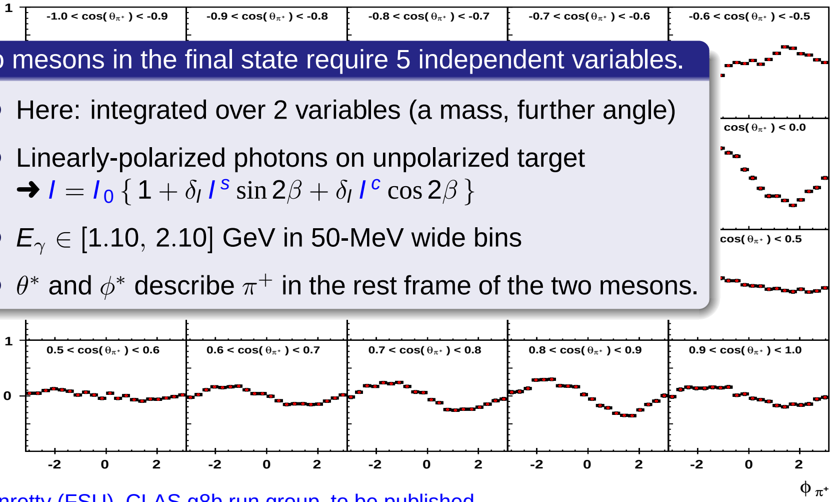
➜ p-meson system in the reaction plane

Two-meson reactions:

➜ Reaction and decay plane form angle ϕ



I^s in $\gamma p \to p\,\pi^+\pi^-$ $1100 < E_\gamma < 1150$ MeV

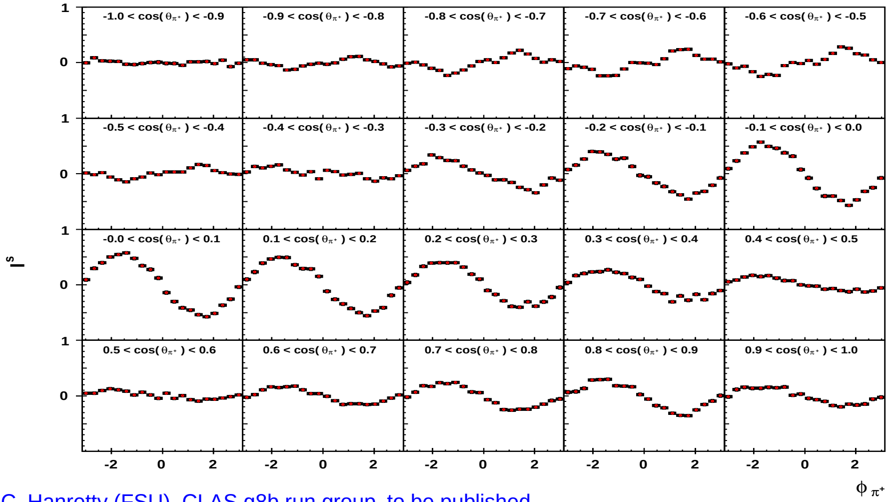


Two mesons in the final state require 5 independent variables.

- Here: integrated over 2 variables (a mass, further angle)
- Linearly-polarized photons on unpolarized target
  ➜ $I = I_0 \{ 1 + \delta_l I^s \sin 2\beta + \delta_l I^c \cos 2\beta \}$
- $E_\gamma \in [1.10,\ 2.10]$ GeV in 50-MeV wide bins
- θ^* and ϕ^* describe π^+ in the rest frame of the two mesons.

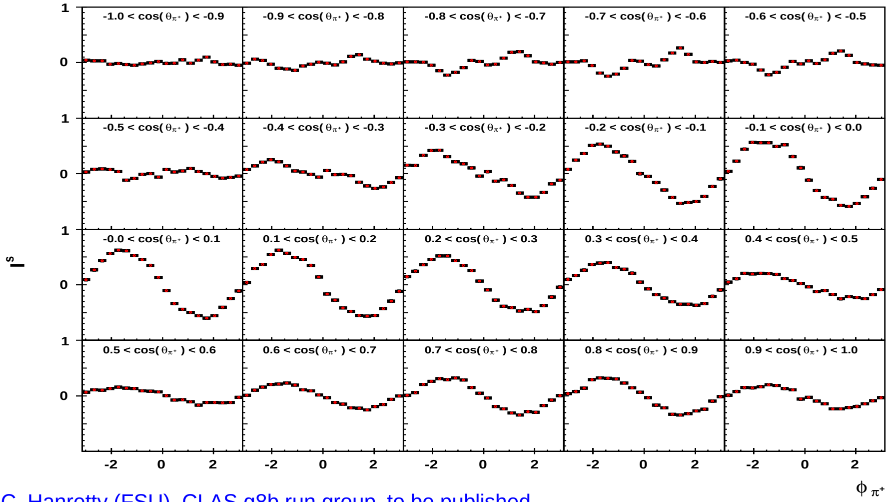
C. Hanretty (FSU), CLAS g8b run group, to be published

I^s in $\gamma p \rightarrow p\,\pi^+\pi^-$ $1100 < E_\gamma < 1150$ MeV



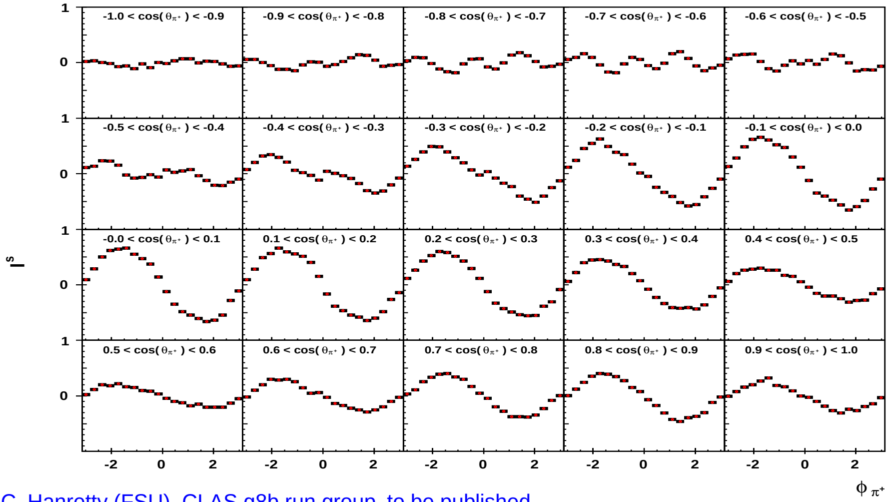
C. Hanretty (FSU), CLAS g8b run group, to be published

I^s in $\gamma p \to p\,\pi^+\pi^-$ $1150 < E_\gamma < 1200$ MeV



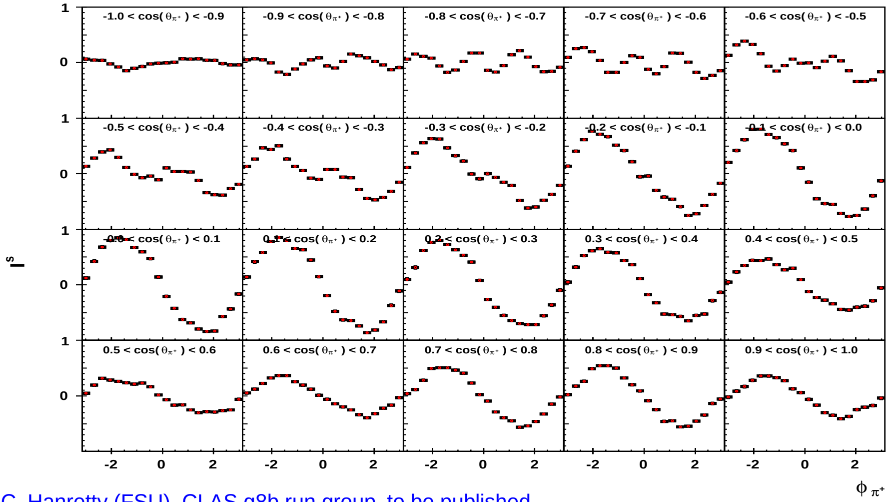
C. Hanretty (FSU), CLAS g8b run group, to be published

I^s in $\gamma p \to p\,\pi^+\pi^-$ $1200 < E_\gamma < 1250$ MeV



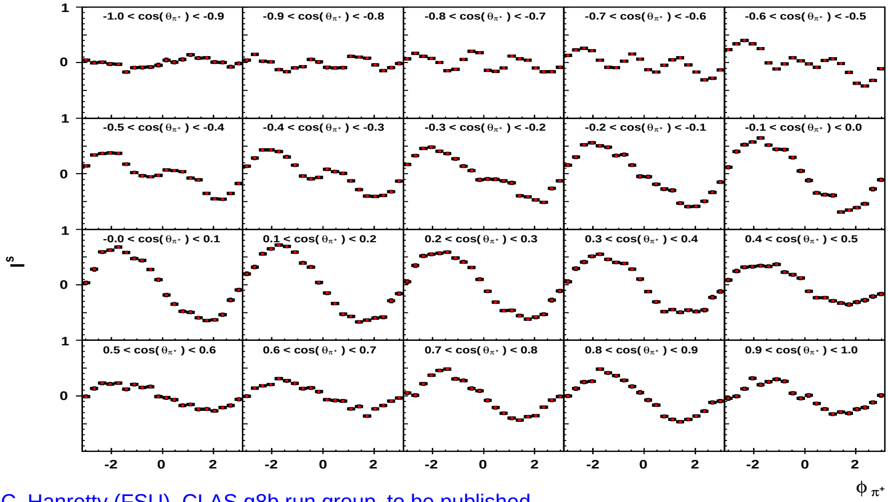
C. Hanretty (FSU), CLAS g8b run group, to be published

I^s in $\gamma p \to p\,\pi^+\pi^-$ $\quad 1250 < E_\gamma < 1300$ MeV



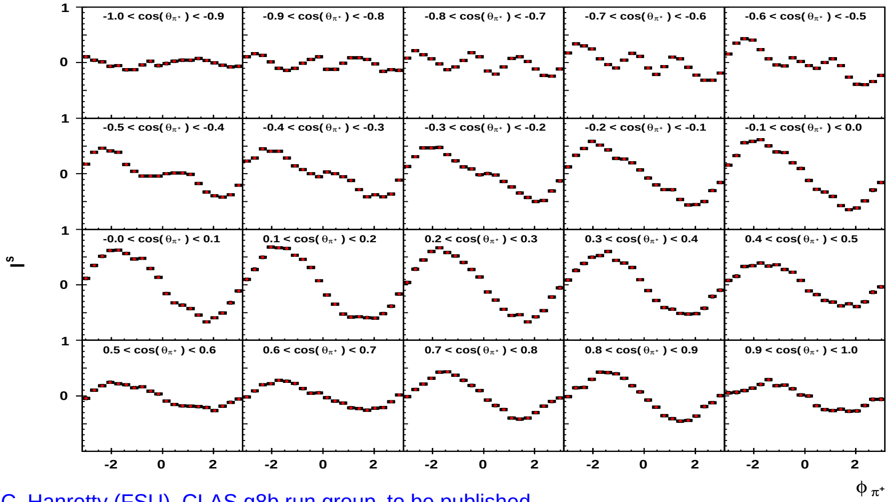
C. Hanretty (FSU), CLAS g8b run group, to be published

I^s in $\gamma p \to p\,\pi^+\pi^-$ $\quad 1300 < E_\gamma < 1350$ MeV



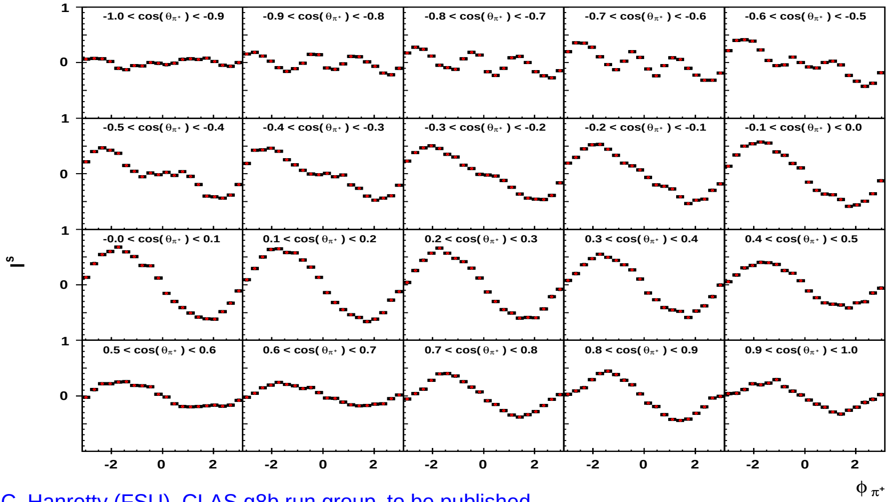
C. Hanretty (FSU), CLAS g8b run group, to be published

I^s in $\gamma p \to p\,\pi^+\pi^-$ $\quad 1350 < E_\gamma < 1400$ MeV



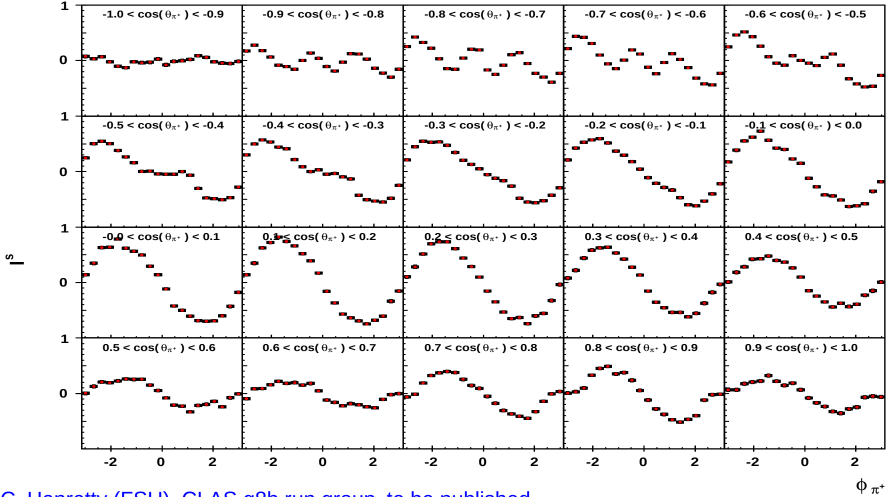
C. Hanretty (FSU), CLAS g8b run group, to be published

I^s in $\gamma p \to p\,\pi^+\pi^-$ $\quad 1400 < E_\gamma < 1450$ MeV



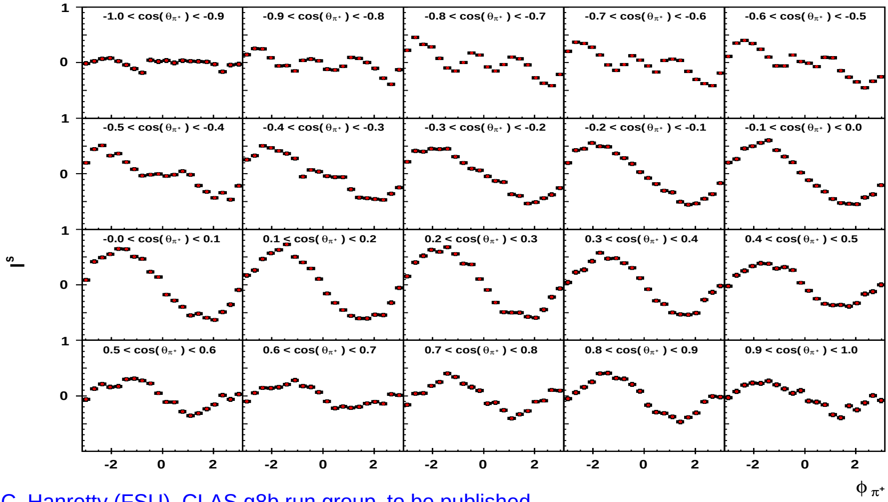
C. Hanretty (FSU), CLAS g8b run group, to be published

I^s in $\gamma p \to p \pi^+ \pi^-$ $1450 < E_\gamma < 1500$ MeV



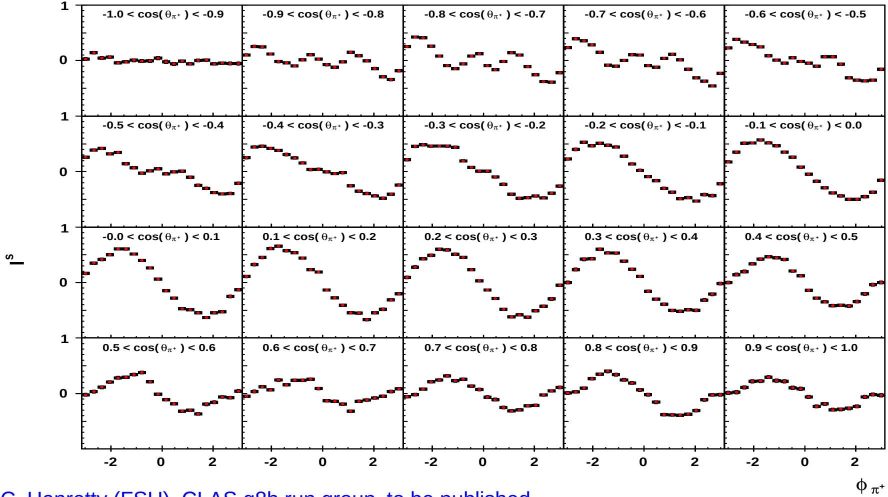
C. Hanretty (FSU), CLAS g8b run group, to be published

I^s in $\gamma p \to p\,\pi^+\pi^-$ $\quad 1500 < E_\gamma < 1550$ MeV



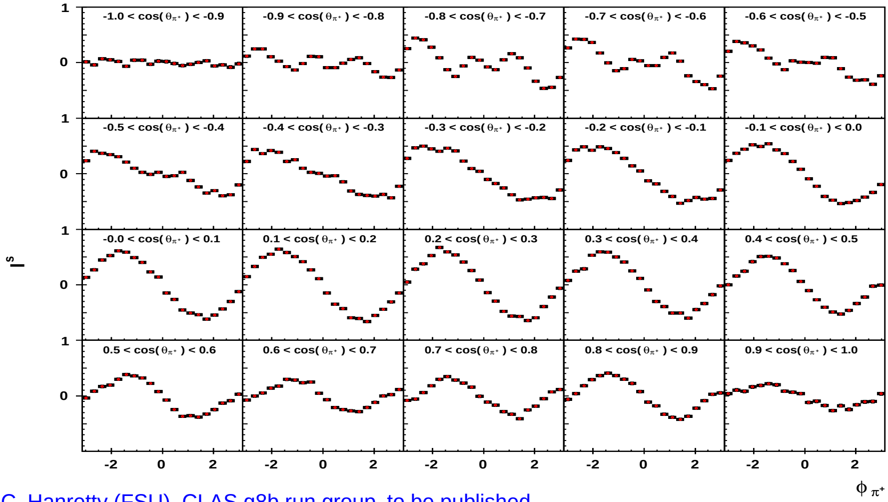
C. Hanretty (FSU), CLAS g8b run group, to be published

I^s in $\gamma p \to p\,\pi^+\pi^-$ $1550 < E_\gamma < 1600$ MeV



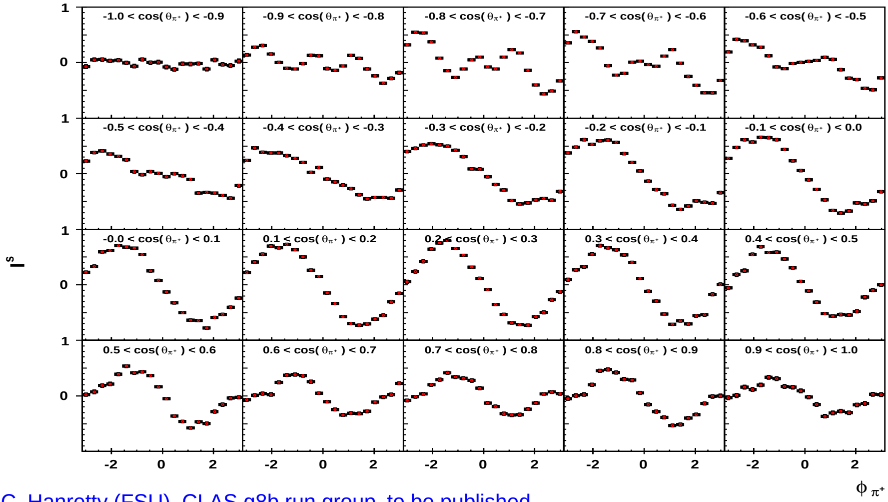
C. Hanretty (FSU), CLAS g8b run group, to be published

I^s in $\gamma p \to p\,\pi^+\pi^-$ $\quad 1600 < E_\gamma < 1650$ MeV



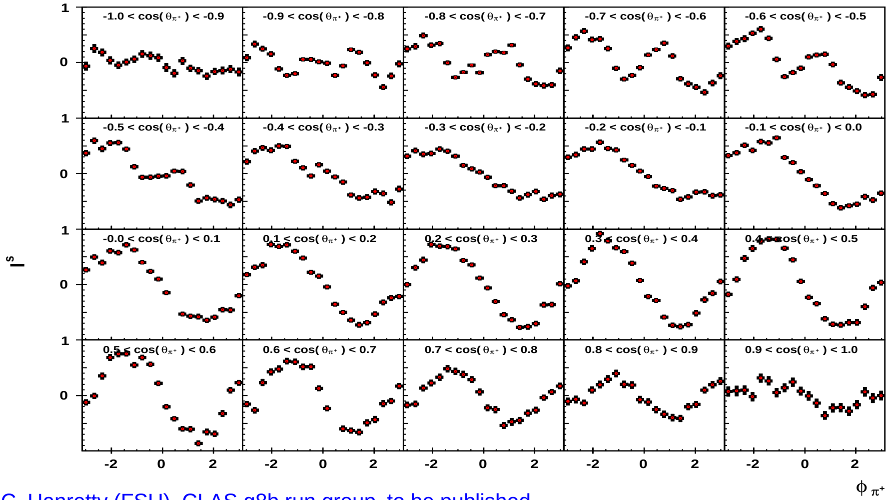
C. Hanretty (FSU), CLAS g8b run group, to be published

I^s in $\gamma p \to p\,\pi^+\pi^-$ $\quad 1650 < E_\gamma < 1700$ MeV



C. Hanretty (FSU), CLAS g8b run group, to be published

I^s in $\gamma p \to p\,\pi^+\pi^-$ 2050 < E_γ < 2100 MeV



C. Hanretty (FSU), CLAS g8b run group, to be published

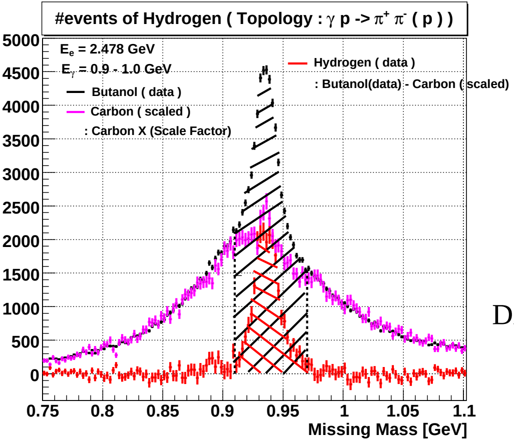
Double-Polarization at JLab: CLAS-FROST

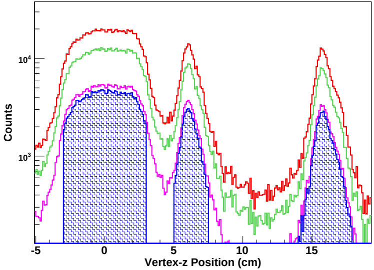
FRozen-Spin Target (FROST)

- $P_z \approx 80\,\%$
- Relaxation time $\sim$ 2,000 h
- Holding mode (B = 0.5 T, T $\approx$ 28 mK)

- $\gamma p \to p\,\eta$ (Dugger, Morrison *et al.*)
  Arizona State University
- $\gamma p \to p\,\omega$ (Collins, Vernarsky *et al.*)
  Catholic University, Carnegie Mellon
- $\gamma p \to n\,\pi^+\;(E)$ (S. Strauch *et al.*)
  University of South Carolina
- $\gamma p \to n\,\pi^+\;(G)$ (J. McAndrew *et al.*)
  University of Edinburgh
- $\gamma p \to p\,\pi^0$ (H. Iwamoto *et al.*)
  George Washington University
- $\gamma p \to p\,\pi^+\pi^-$ (S. Park *et al.*)
  Florida State University
- $\gamma p \to K^+ Y$ (S. Fegan *et al.*)
  University of Glasgow

Dilution Factor



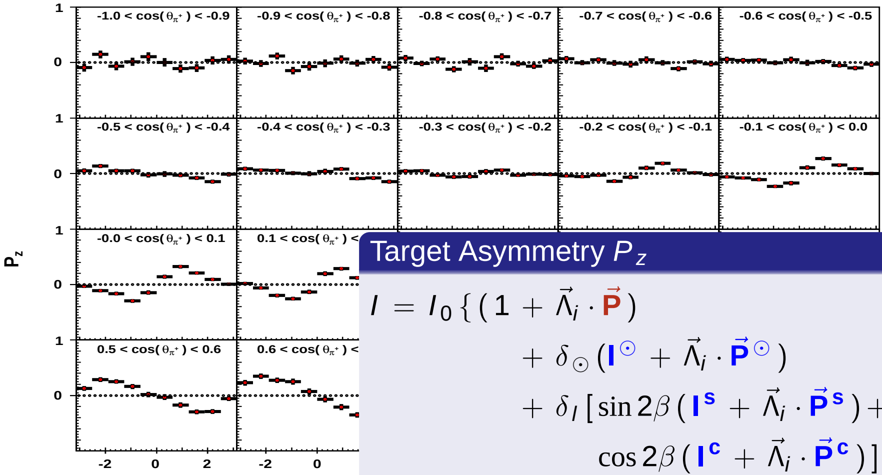


C_4H_9OH $\quad$ ^{12}C $\quad$ CH_2

$$\text{Dilution factor} = \frac{N_{\text{hydrogen}}}{N_{\text{butanol}}}$$

$$= \frac{N_{C_4H_9OH} - N_C\, S}{N_{C_4H_9OH}}$$

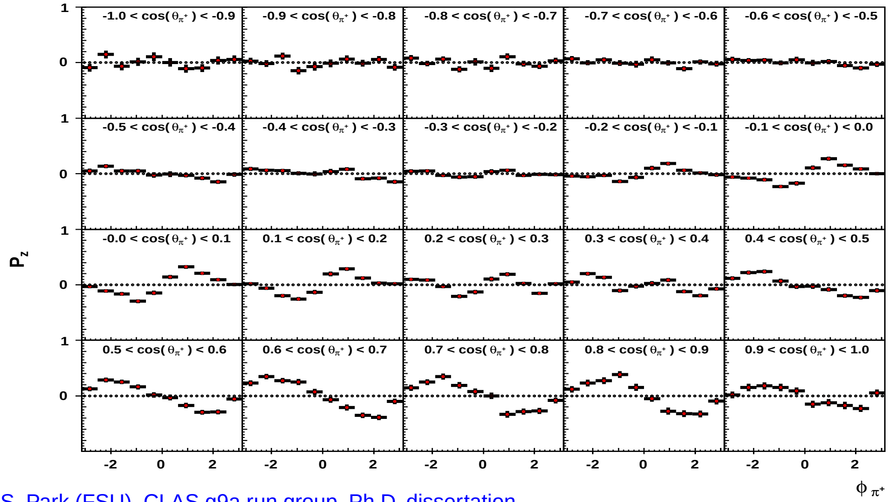
P_z in $\gamma p \to p\,\pi^+\pi^-$ $\quad 700 < E_\gamma < 800$ MeV



Target Asymmetry P_z

$$I = I_0 \{ (1 + \vec{\Lambda}_i \cdot \vec{\mathbf{P}}) + \delta_\odot (\mathbf{I}^\odot + \vec{\Lambda}_i \cdot \vec{\mathbf{P}}^\odot) + \delta_l [\sin 2\beta (\mathbf{I}^s + \vec{\Lambda}_i \cdot \vec{\mathbf{P}}^s) + \cos 2\beta (\mathbf{I}^c + \vec{\Lambda}_i \cdot \vec{\mathbf{P}}^c)] \}$$

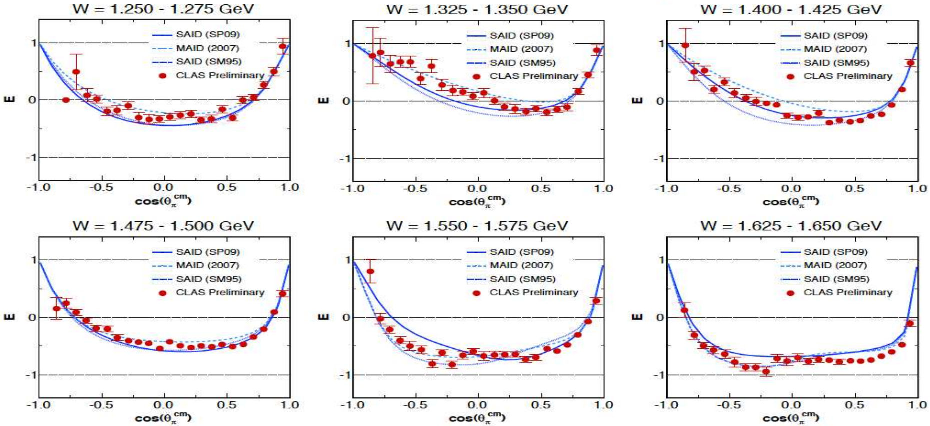
P_z in $\gamma p \to p \pi^+ \pi^-$ $700 < E_\gamma < 800$ MeV



S. Park (FSU), CLAS g9a run group, Ph.D. dissertation

Helicity Difference in $\gamma p \to n\pi^+$

$\gamma(p,\pi^+)n$ – Selected Preliminary Results (1)

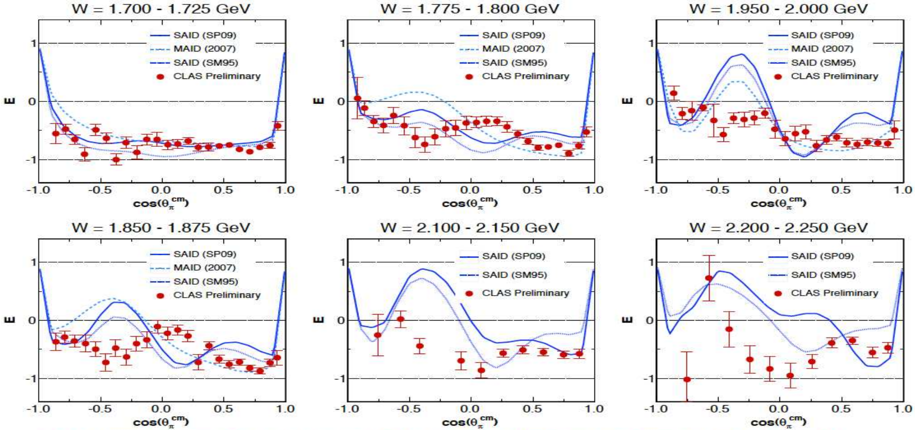


SP09: M. Dugger, et al., Phys. Rev. C **79**, 065206 (2009); SM95: R. A. Arndt, I. I. Strakovsky, R. L. Workman, Phys. Rev. C **53**, 430 (1996);
MAID: D. Drechsel, S.S. Kamalov, L. Tiator Nucl. Phys. **A645**, 145 (1999)

S. Strauch (University of South Carolina)

Helicity Difference E in $\gamma p \to n\pi^+$

$\gamma(p,\pi^+)n$ – Selected Preliminary Results (2)



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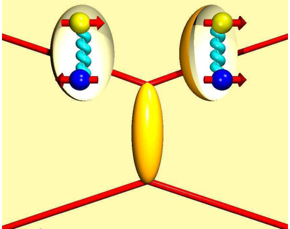
Outline

Meson Spectroscopy in Photoinduced Reactions

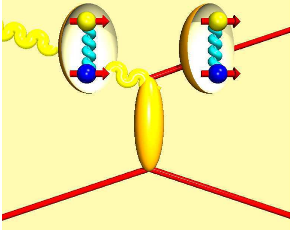
Results on light mesons from CLAS at Jefferson Lab

➜ Search for the photo-excitation of exotic mesons in the $\pi^+\pi^+\pi^-$ system
(M. Nozar *et al.*, Phys. Rev. Lett. **102**, 102002 (2009))



Pion Beam

- π with $S = 0$, $L = 0$ and $m = 1$
  ➜ $J^{PC} = 1^{++}, 1^{--}$
- Spin flip required for exotic QNs



Photon Beam

- γ with $S = 1$, $L = 0$ and $m = 1$
  ➜ $J^{PC} = 0^{-+}, 0^{+-}, 1^{-+}, 1^{+-}, \ldots$
- No spin flip needed for exotic QN's

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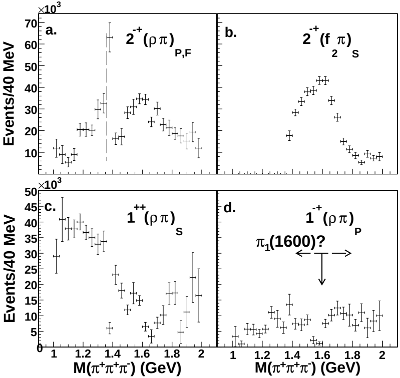

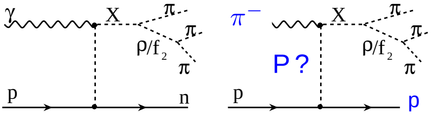

charge exchange
CLAS

neutral exchange
E852

The authors do not observe a resonant structure in the 1^{-+} $(\rho\pi)_P$ partial wave.

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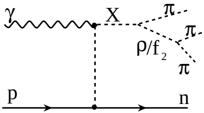
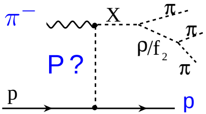
A $J^{PC} = 1^{-+}$ gluonic hybrid should be photo-produced at the same rate as the $a_2(1320)$, whereas in pion production it should be suppressed by a factor of 10.
(Close & Page, Phys. Rev. D **52**, 1706 (1995))



charge exchange
CLAS



neutral exchange
E852

- Upper limit for the $\pi_1(1600)$ of 13.5 nb, less than 2 % of the $a_2(1320)$.

- New HyCLAS (g12) data have an order of magnitude more statistics.
  ➜ e.g. $\gamma p \to n\pi^+\pi^+\pi^-$, $\gamma p \to p\pi^+\pi^-\pi^0$ ($J^{PC} = 1^{-+}$ isoscalar production?)
- GlueX proposed to map out the light exotic spectrum.

Meson Spectroscopy in Photoinduced Reactions

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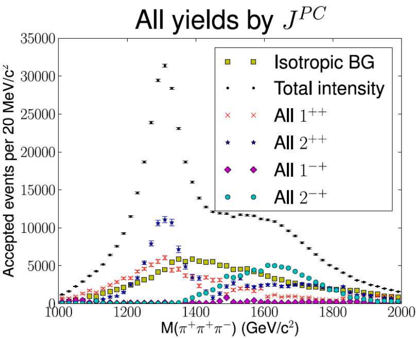
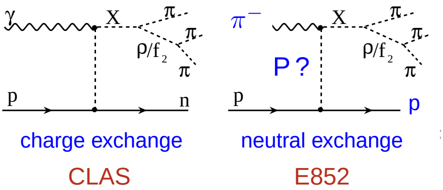


C. Bookwalter (FSU), CLAS g12 run group, HADRON 2011



Preliminary HyCLAS (g12) results at 5.75 GeV

- No evidence for a $J^{PC} = 1^{-+}$ wave
- Strong evidence for well-known $a_1(1260)$, $a_2(1320)$, and $\pi_2(1670)$

The GlueX Experiment

2009

2010

Delivery now - 2013

2011

2014 beam & engineering runs

2015 first physics

Outline

Summary and Outlook

The quest to understand confinement and the strong force is about to make great leaps forward:

- Progress in theory and computing will allow us to solve QCD and understand the baryon spectrum and the role of glue.
- New results from the current polarization programs worldwide will (soon) give us new insight on the observed and *missing* baryons.
  ➜ New candidates for baryon resonances have been proposed.
- The definitive experiments to confirm or refute current expectations on the role of glue are being built, e.g. GlueX@Jefferson Lab.

Conclusions

Advances in both areas will allow us to finally understand QCD and confinement.