The Fascinating Structure of Hadrons: What have we learned about excited protons?

Volker Credé

Florida State University, Tallahassee, FL

Physics Colloquium

University of Georgia, 04/04/2013

Outline

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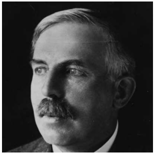
The Early Particle Zoo and the Quark Model



Name "proton" given to hydrogen nucleus by Rutherford in 1920:

- He had discovered earlier that the proton was a candidate to be a fundamental particle and building block of nitrogen, and all other heavier atomic nuclei.

1932 Neutron

1947 First Mesons: π^+, π^-, K^+, K^-

1951 Strange baryons: Λ with $|uds\rangle$

1964 Ω^- with $|sss\rangle$

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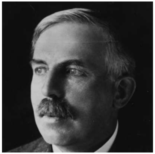

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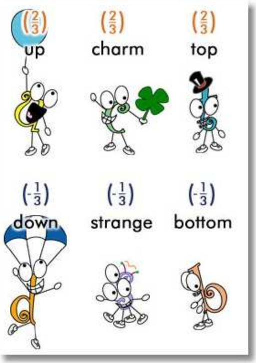
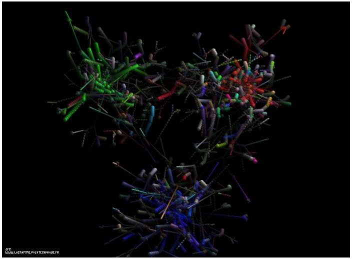
1964 Quark model (based on Flavor $SU(3)$)

1968 Discovery of “partons” at SLAC
after 1970: Quantum Chromodynamics (QCD)



Non-Perturbative Quantum Chromodynamics (QCD)

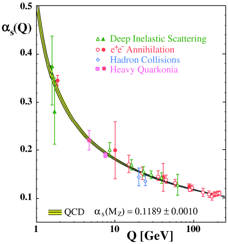


QCD is the theory of the strong nuclear force which describes the interactions of quarks and gluons making up hadrons.

Strong processes at larger distances and at small (soft) momentum transfers belong to the realm of non-perturbative QCD.

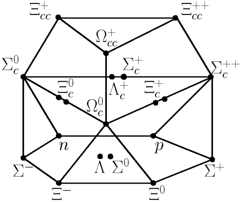
Simple ansatz for the quark-antiquark potential:

$$V = -\frac{4}{3}\frac{\alpha_S(r)\,\hbar c}{r} + k\cdot r$$

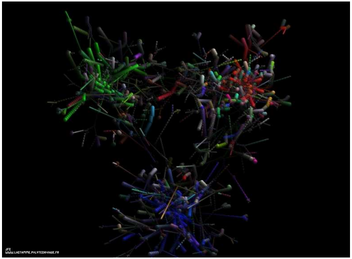


arXiv:hep-ex/0606035

Hadron multiplets, e.g.



Non-Perturbative Quantum Chromodynamics (QCD)



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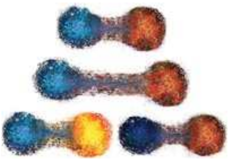
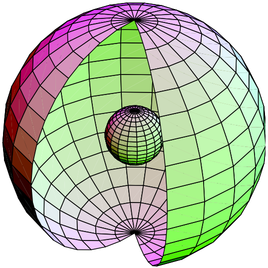
Quarks are confined within hadrons.

Confinement of quarks and gluons within nucleons is a non-perturbative phenomenon, and QCD is extremely hard to solve in non-perturbative regimes: Knowledge of internal structure of nucleons is still limited.

This is particularly true for excited nucleons.



Non-Perturbative QCD



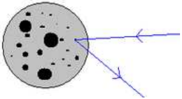
How does QCD give rise to excited hadrons?

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

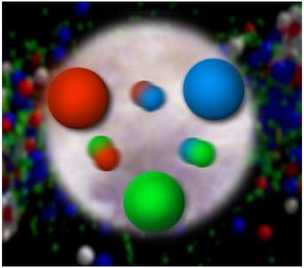
➜

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.



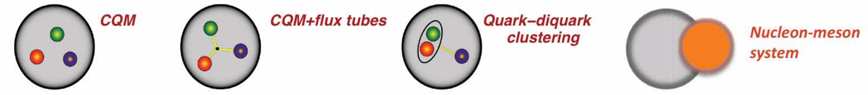
Non-Perturbative QCD



How does QCD give rise to excited hadrons?

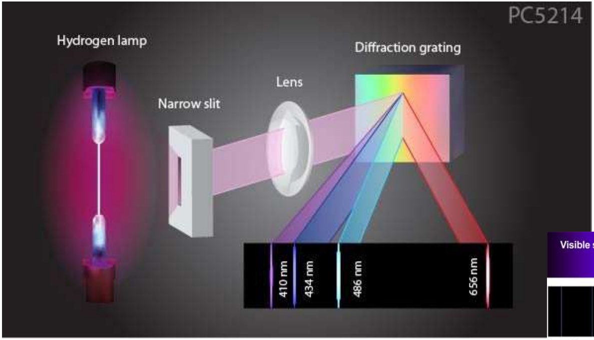
1. What is the origin of confinement?
2. How are confinement and chiral symmetry breaking connected?
3. Would the answers to these questions explain the origin of $\sim 98\,\%$ of observed matter in the universe?

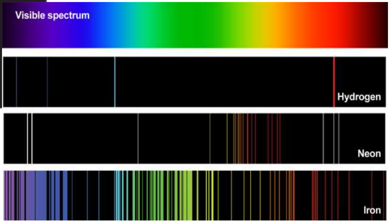
Excited Baryons: What are the fundamental degrees of freedom inside a proton or a neutron? How do they change with varying quark masses?



Understanding Excited Baryons

The excitation spectrum of the hydrogen atom:



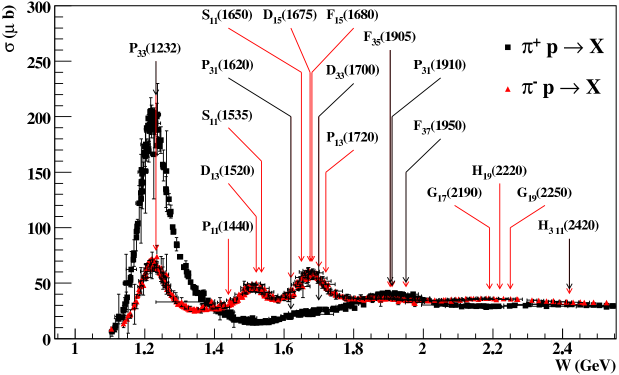


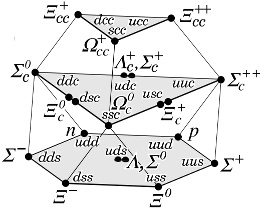
Study of the hydrogen spectrum has shown that the understanding of the structure of a bound state and of its excitation spectrum go hand in hand.

Understanding Excited Baryons

	∗∗∗∗	∗∗∗	∗∗	∗
N^*	11	3 → 5	6 → 8	2 → 3
Δ^*	7	3	6 → 7	6 → 5

PDG 2012





Nomenclature:

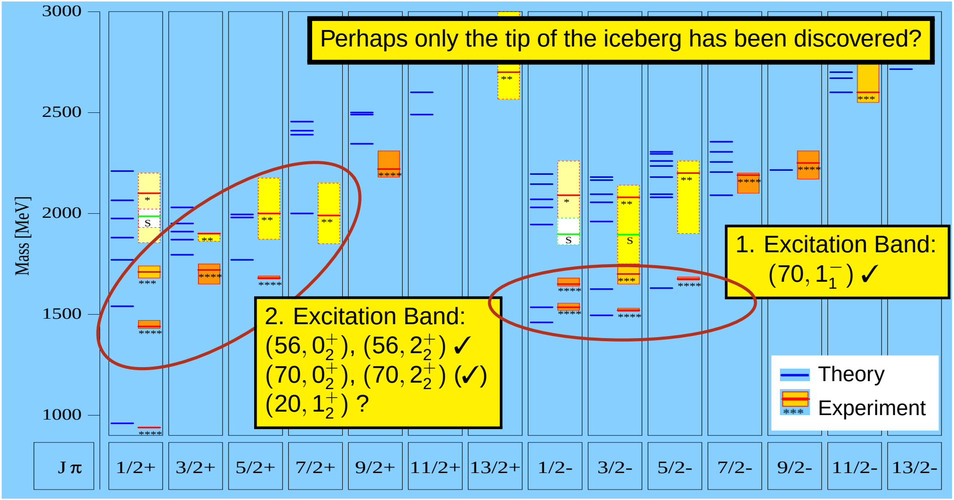
$P_{33}(1232)$ (old)

↓

$\Delta(1232)\,\frac{3}{2}^{+}$ (new)

Spectrum of Nucleon Resonances

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



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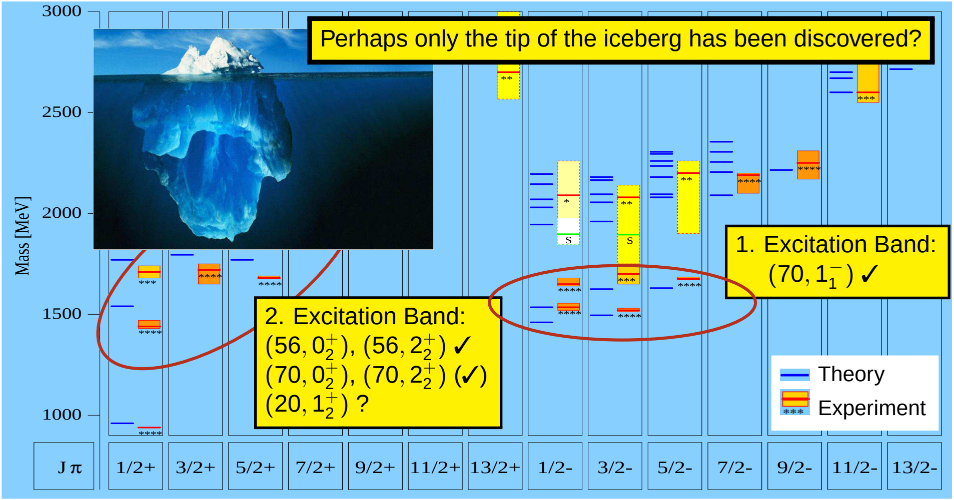
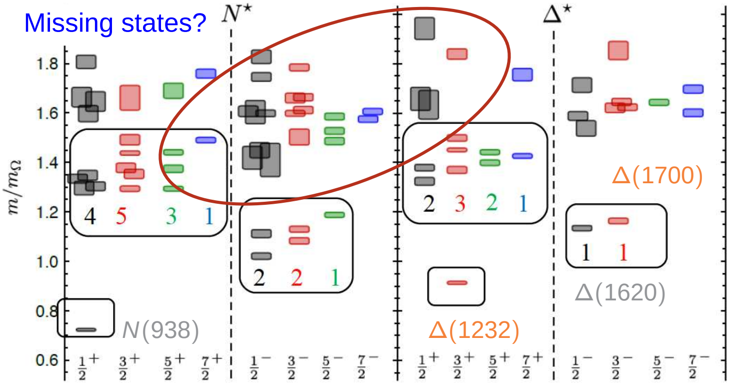


Excited-State Baryon Spectroscopy from Lattice QCD

R. Edwards *et al.*, Phys. Rev. D **84**, 074508 (2011)



$m_\pi = 400$ MeV

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

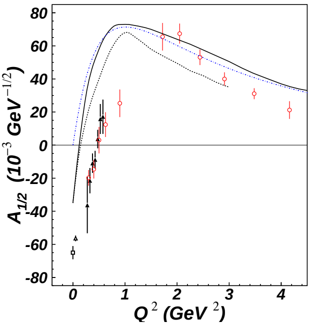
➜ Counting of levels consistent with non-rel. quark model, no parity doubling

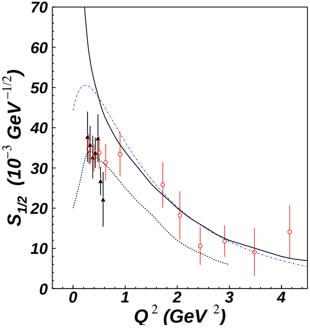
Components of the Experimental N^* Program

The excited baryon program has two main components:

- Probe resonance transitions at different distance scales
  Electron beams are ideal to measure resonance form factors and their corresponding Q^2 dependence.
  ➜ Provides information on the structure of excited nucleons and on the confining (effective) forces of the 3-quark system.
- Establish the systematics of the spectrum
  Current medium-energy experiments use photon beams to map out the baryon spectrum (JLab, ELSA, MAMI, SPring-8, etc.).
  ➜ Provides information on the nature of the effective degrees of freedom in strong QCD and also addresses the issue of previously unobserved or so-called *missing resonances.*

Helicity Amplitudes for the “Roper” Resonance





Data from CLAS

$A_{1/2}$ and $S_{1/2}$ amplitudes:

e.g. V. Mokeev *et al.*,
PRC **86**, 035203 (2012);
PRC **80**, 045212 (2009).

Quark-model calculations:

—- q^3 radial excitation
- - - q^3G hybrid state

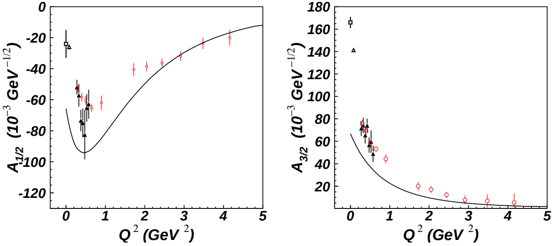
Consistency between both channels ($N\pi\pi$, $N\pi$): sign change, magnitude, ...

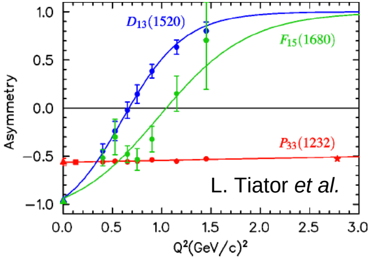
- At short distances (high Q^2), Roper behaves like radial excitation.
- Low Q^2 behavior not well described by LF quark models: e.g. meson-baryon interactions missing

➜ Gluonic excitation likely ruled out!

Helicity Amplitudes for $\gamma^* p \to N(1520)D_{13}$ Transition

V. Mokeev *et al.*, PRC bf 86, 035203 (2012).



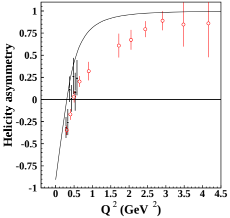


There is clear evidence for helicity switch from $\lambda = 3/2$ (at photon point) to $\lambda = 1/2$ at high Q^2:

- Rapid change in helicity structure when going from photo- to electroproduction of a nucleon resonance

➜ Stringent prediction of the CQM!

$$\mathcal{A}_{\text{hel}} = \frac{|A_{1/2}|^2 - |A_{3/2}|^2}{|A_{1/2}|^2 + |A_{3/2}|^2} \rightarrow$$



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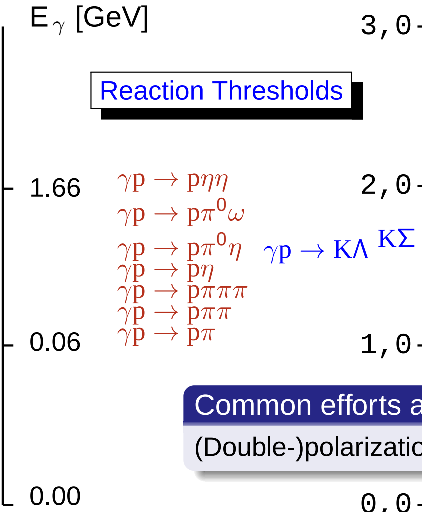
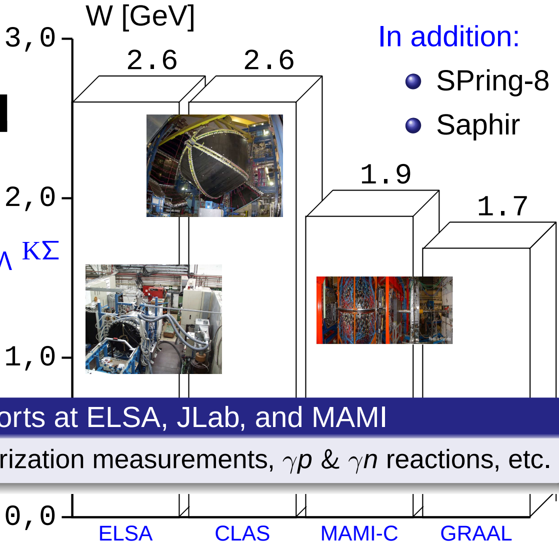




In addition:

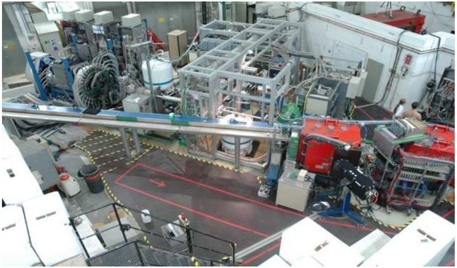
- SPring-8
- Saphir

Common efforts at ELSA, JLab, and MAMI

(Double-)polarization measurements, γp & γn reactions, etc.

Experimental Facilities

CBELSA/TAPS at ELSA



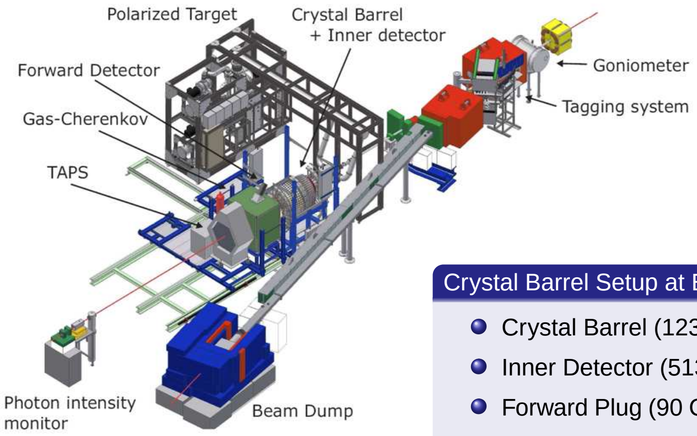
Jefferson Laboratory

Meson photoproduction:

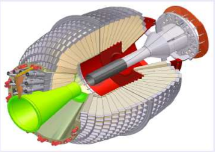
- $\gamma p \to p\,\pi^0 \to p\,\gamma\gamma$
- $\gamma p \to p\,\eta \to p\,\gamma\gamma,\ p\,3\pi^0,\ p\,\pi^+\pi^-\pi^0$
- $\gamma p \to p\,\omega \to p\,\pi^0\gamma,\ \pi^+\pi^-\pi^0$

Double-Polarization: Toward Complete Experiments

Calorimeter system at ELSA is optimized for neutral particles.



Crystal Barrel



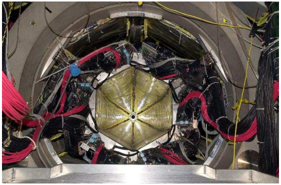
Close to 4π coverage

Frozen-Spin Target: Butanol (C_4H_9OH).

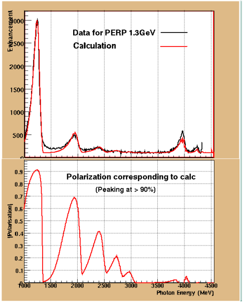
Crystal Barrel Setup at ELSA

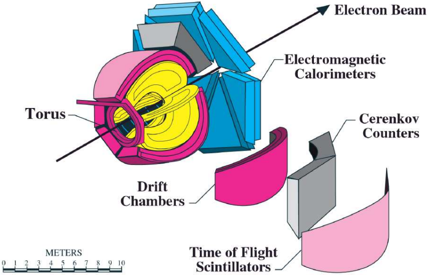
- Crystal Barrel (1230 CsI crystals)
- Inner Detector (513 scintillating fibers)
- Forward Plug (90 CsI crystals with PM's)
- MiniTAPS (216 BaF_2, 1° - 12°)

The CLAS Spectrometer at Jefferson Laboratory

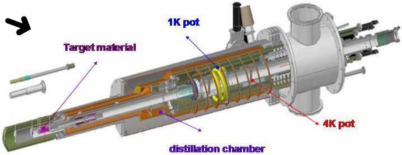


g8b
linear beam
polarization





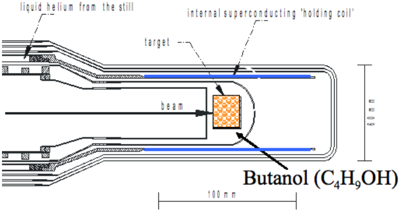
FROST
double polarization

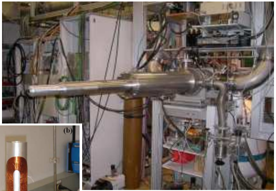


Double-Polarization: Frozen Spin Targets

Horizontal cryostat with integrated solenoid to freeze the proton spin.

- DNP at high B-field (2.5 T), holding mode at 0.4 T
- Relaxation time at ELSA $\sim$ 500 h

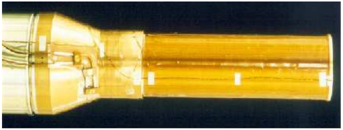




“ELSA”

“CLAS”

Transverse Target Polarization
(race-track coil - Dipole Magnet)



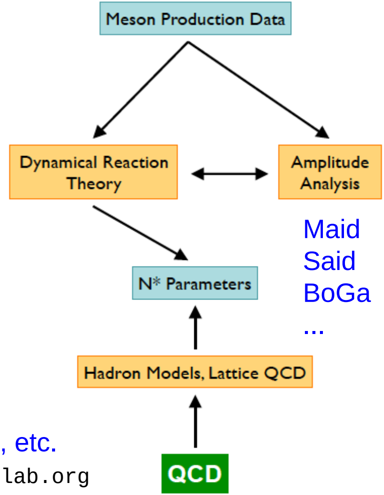
Longitudinally-Polarized Target ($P_z \approx 80$ %)

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 extract full scattering amplitude.

Coupled Channels

Jülich, Gießen, EBAC, etc.
`http://ebac-theory.jlab.org`



Why are Polarization Observables Important?

1. From π threshold up to $\Delta(1232)$ region
   - s- & p-wave approximation
   - Fermi-Watson Theorem

   ➜ Two observables sufficient, e.g. $d\sigma/d\Omega$, Σ.
2. Above the $\pi\pi$ threshold

   ➜ More observables needed.

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

Chiang & Tabakin, Phys. Rev. C55, 2054 (1997)

In order to determine the full scattering amplitude without ambiguities, one has to carry out eight carefully selected measurements: <u>four</u> double-spin observables along with <u>four</u> single-spin observables.

Eight well-chosen measurements are needed to fully determine production amplitudes F_1, F_2, F_3, and F_4.

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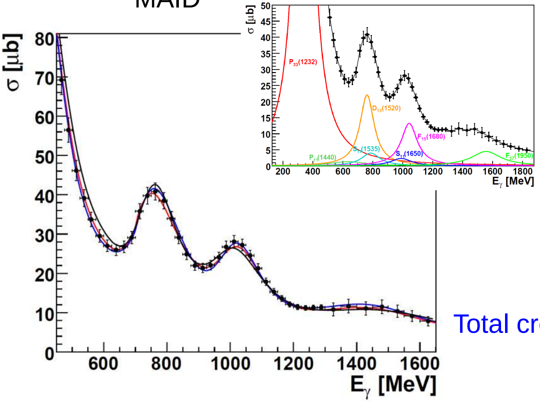
Example: Ambiguities in $\gamma p \to p \pi^0$

— Bonn-Gatchina (BnGa)

— SAID

— MAID



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Example:

$$E = -\frac{1}{2\Lambda_z \delta_\odot} \frac{N^{\rightarrow\Rightarrow} - N^{\rightarrow\Leftarrow}}{N^{\rightarrow\Rightarrow} + N^{\rightarrow\Leftarrow}}$$

Total cross section: $\gamma p \to p \pi^0$

Example: Ambiguities in $\gamma p \rightarrow p \pi^0$

—— Bonn-Gatchina (BnGa) PWA

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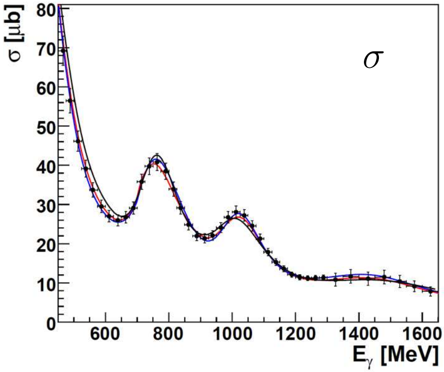
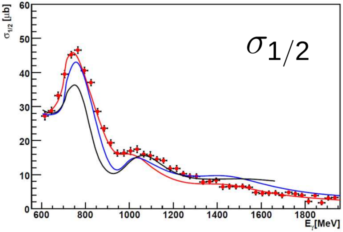
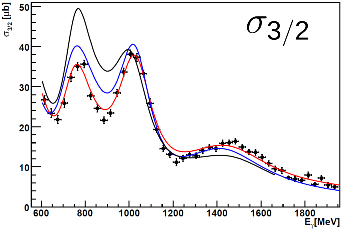
—— MAID

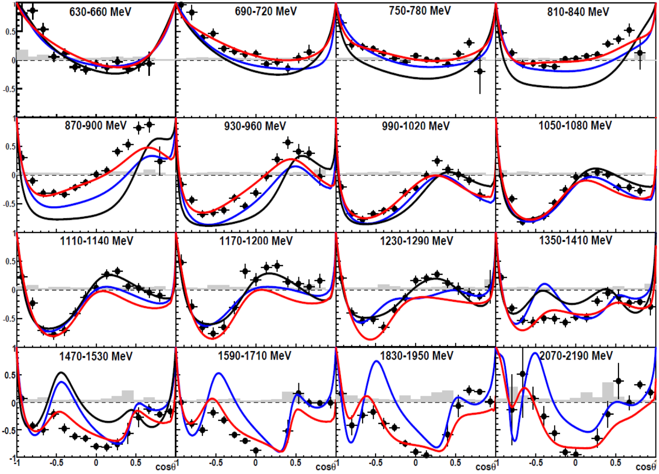






Helicity Asymmetry E in $\vec{\gamma}\vec{p} \to p\,\pi^0$ (Data from ELSA)

E



$\cos\theta_{\pi^0}$

$$E = \frac{\sigma_{1/2} - \sigma_{3/2}}{\sigma_{1/2} + \sigma_{3/2}}$$

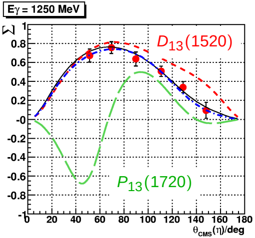
$E_\gamma \in [0.6, 2.2]$ GeV

- • CBELSA/TAPS
- — Maid
- — Said
- — BoGa

Angular distributions sensitive to interference between resonances.

M. Gottschall *et al.* [CBELSA/TAPS]

Example: Ambiguities in $\gamma p \to p \eta$

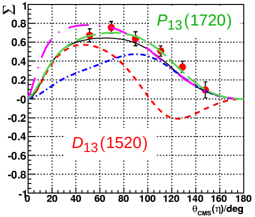


$$\frac{d\sigma}{d\Omega} = \sigma_0 \{ 1 - \delta_l \Sigma \cos 2\phi \}$$

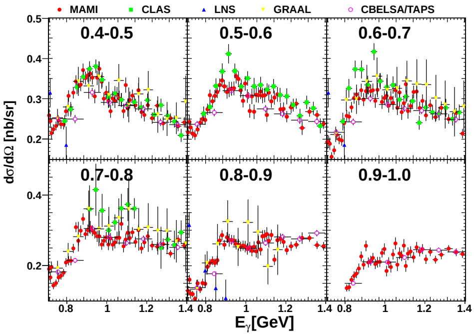
CLAS g11a ■
CBELSA/TAPS ○
MAMI ●
GRAAL ▼

BoGa-PWA

$E_\gamma = 1250$ MeV

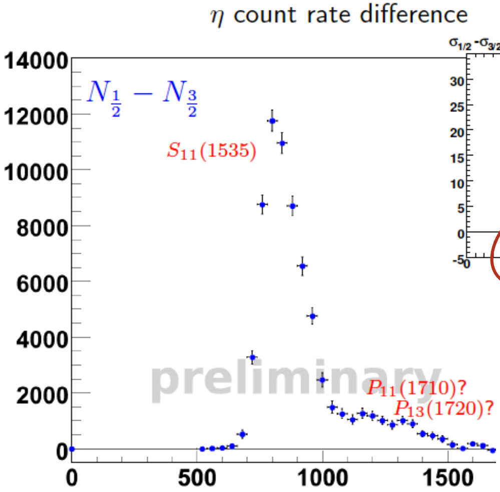


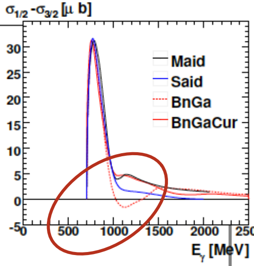
η-MAID



D. Elsner *et al.* [CBELSA/TAPS], EPJ A **33**, 147 (2007)

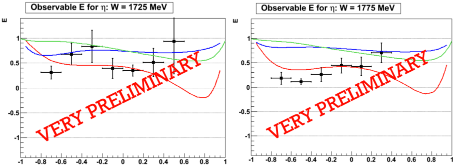
Helicity-Dependent Cross Section for $\vec{\gamma}\,\vec{p} \to p\,\eta$





$$E = \frac{\sigma_{1/2} - \sigma_{3/2}}{\sigma_{1/2} + \sigma_{3/2}}$$

➜ Very preliminary: Data are positive

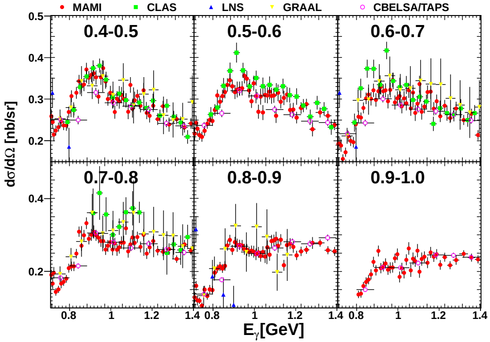


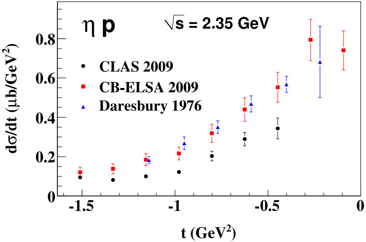
B. Morrison *et al.* [CLAS Collaboration]

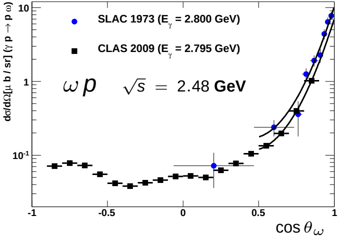
M. Gottschall *et al.* [CBELSA/TAPS]

Systematics in Photoproduction (Normalization)

$$\frac{d\sigma}{d\Omega} = \frac{N_{\text{events}}}{\Phi_\gamma \, \epsilon_{MC} \, \rho_t \, \Gamma \, \Delta\Omega}$$



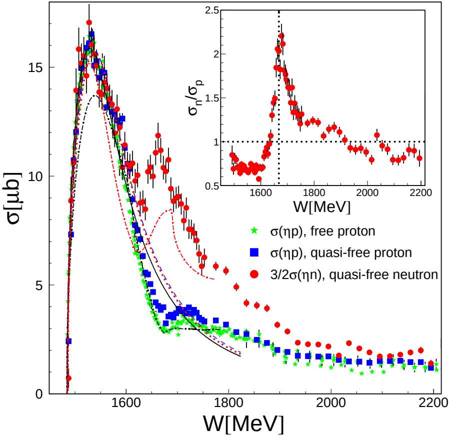




$\gamma p \to p\eta$: O. Bartholomy, V. C. *et al.* [ELSA]

PRL **94** (2005), EPJ A **33** (2007), PRC **80** (2009).

Fascinating Discovery in Reactions off the Neutron



Neutron measurements important:

- Different resonance contributions
- Study of isospin composition of el.-magn. couplings

Narrow structure in $\gamma d \to n\,\eta + p$ with $M \approx$ 1670 MeV and $\sigma =$ 25 MeV:

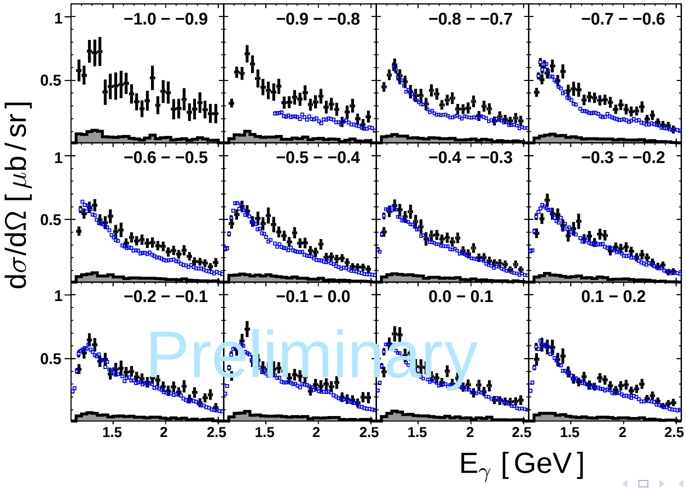
- Interference effect of the $S_{11}(1535)$ and $S_{11}(1535)$ resonances
- Coupled channel effect of $S_{11}(1535)$ and $P_{11}(1710)$
- New narrow state?

I. Jaegle *et al.* [CBELSA/TAPS], Eur. Phys. J. A **47**, 89 (2011)

Outline

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

A. Wilson *et al.* [CBELSA/TAPS], Ph.D. thesis (Florida State)



— — CBELSA/TAPS

— — CLAS (2009)

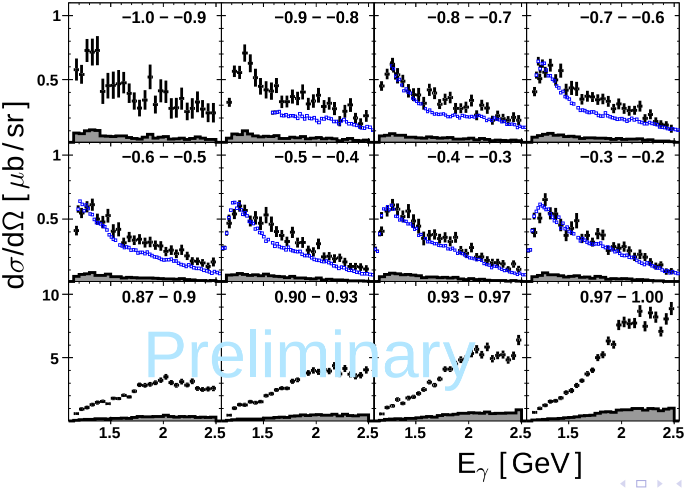
Good agreement between experiments

Excellent statistics

Great progress in our understanding of the differences between experiments.

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

A. Wilson *et al.* [CBELSA/TAPS], Ph.D. thesis (Florida State)



— — CBELSA/TAPS

— — CLAS (2009)

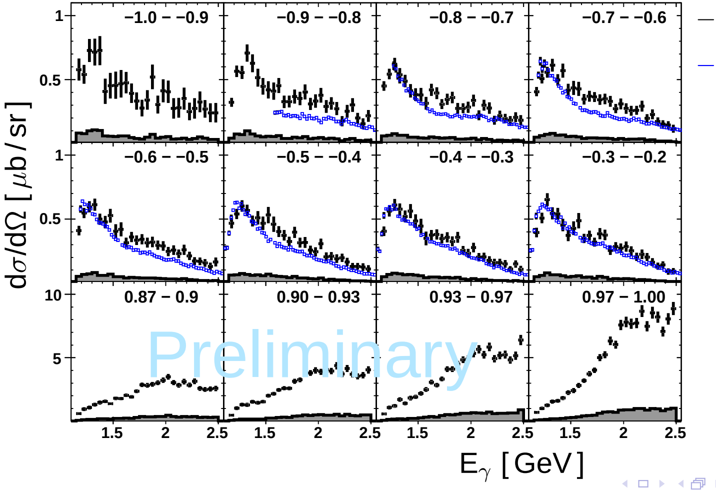
Good agreement between experiments

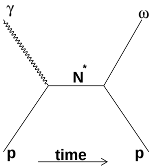
Excellent statistics

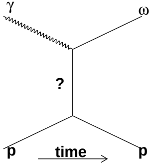
New CBELSA/TAPS data extend the world database in the most forward direction.

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

A. Wilson *et al.* [CBELSA/TAPS], Ph.D. thesis (Florida State)

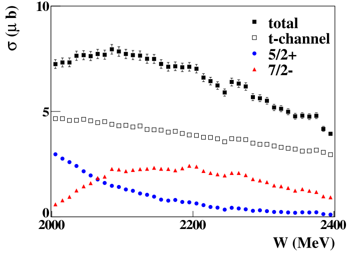


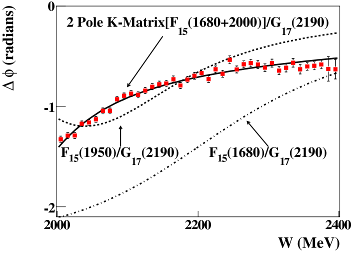




Baryon Resonances in the Reaction $\gamma p \to p \omega$

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

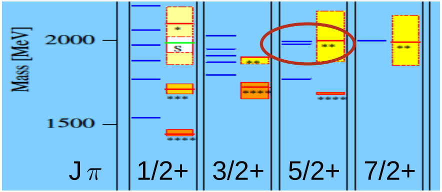




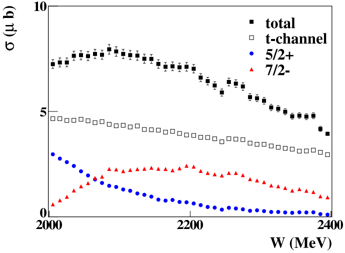
PWA fit includes resonances + t-channel amplitudes.

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

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



Polarization Observables in $\gamma\, p \to p\, \omega$



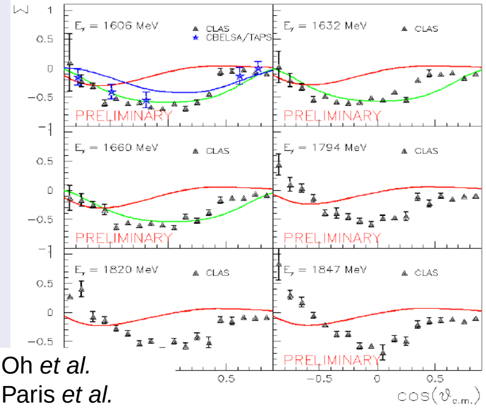
Strong evidence for $(W > 2$ GeV$)$:

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

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

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

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



— Oh *et al.*

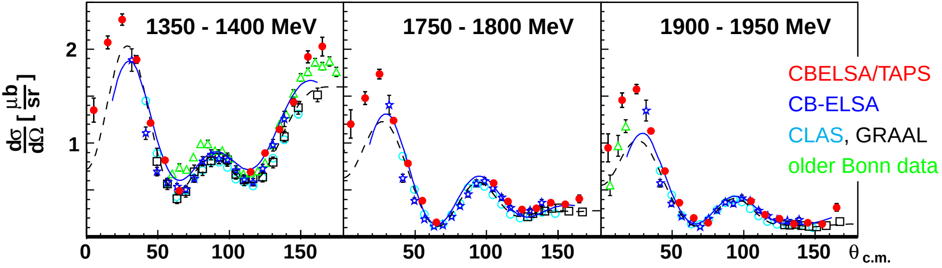
— Paris *et al.*

— Sarantsev *et al.*

Photoproduction of π^0 Mesons from the Proton

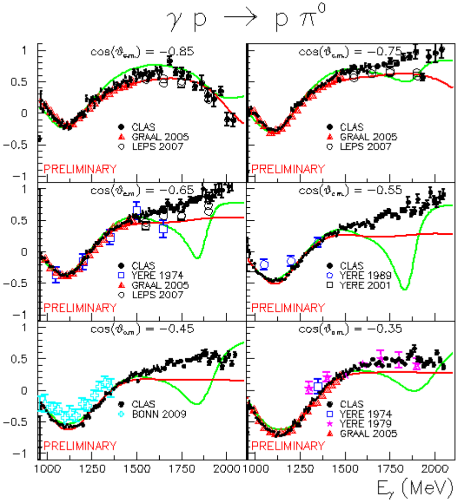
Reaction $\gamma p \to p\,\pi^0$ remains important for our understanding of baryons.

- At ELSA, excellent data with good statistics in the forward direction.
- Forward region is very sensitive to higher-spin resonances:
  ➜ Observation of $N(2190)G_{17}$ within the Bonn-Gatchina PWA framework
  (Important to confirm high-mass states first observed in πN scattering)



V. C. *et al.* [CBELSA/TAPS], Phys. Rev. C **84**, 055203 (2011)

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



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

— SAID — MAID • CLAS

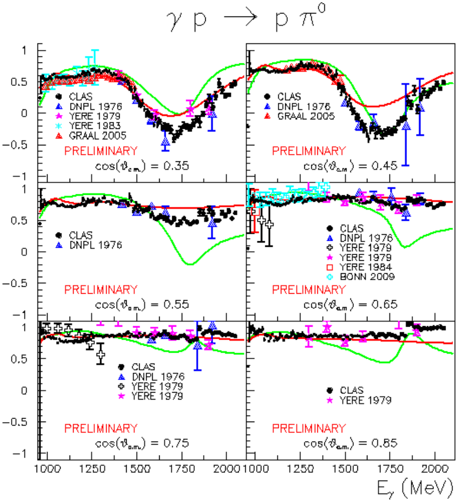
($E_\gamma < 2$ GeV, $-0.85 < \cos\theta_\pi < -0.35$)

➜ Serious discrepancies between models and data above 1.4 GeV.

Photoproduction of π mesons still not very well understood.

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

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



— 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:

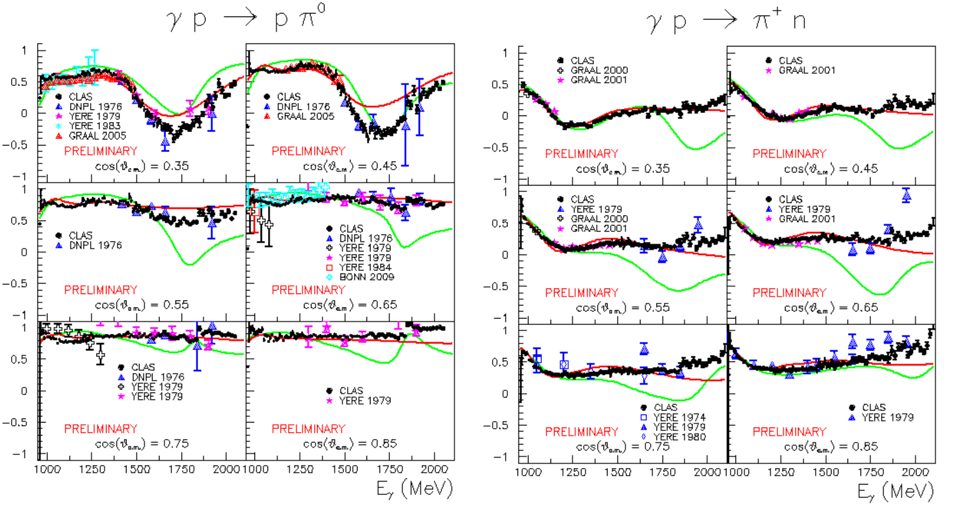
Δ^+ $\quad$ N^*

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

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

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

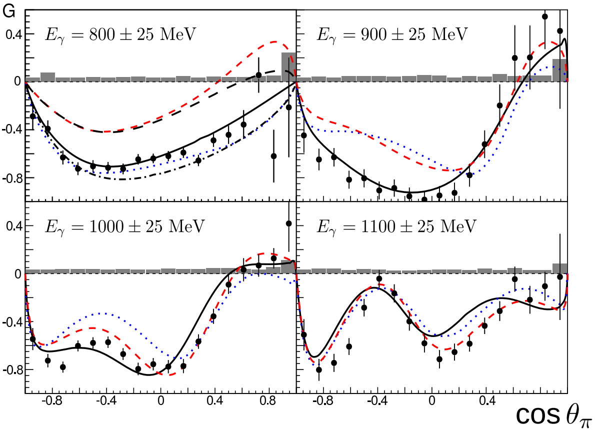
Beam Asymmetry Σ in $\vec{\gamma} p \to p\,\pi^0$ and $\vec{\gamma} p \to n\,\pi^+$



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

Asymmetry G in $\vec{\gamma}\vec{p} \to p\,\pi^0$ (Results from ELSA)

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

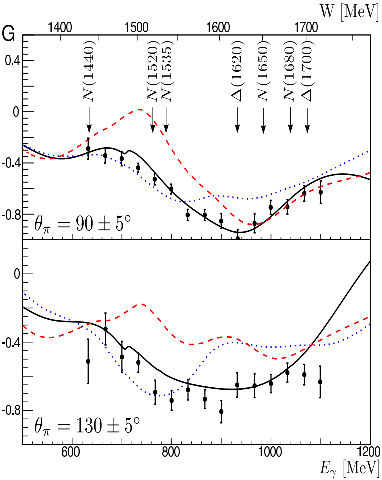


Surprisingly, π production also not well understood at lower energies:

- — BoGa
- - - SAID
- ···· MAID

A. Thiel *et al.* [CBELSA/TAPS], PRL **109**, 102001 (2012)

Asymmetry G in $\vec{\gamma}\vec{p} \to p\,\pi^0$ (Results from ELSA)



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

$\theta_\pi = 90 \pm 5°$

$\theta_\pi = 130 \pm 5°$

Surprisingly, π production also not well understood at lower energies.

Below 1 GeV, discrepancies can be traced to the E_{0+} and E_{2-} multipoles, which are related to certain resonances:

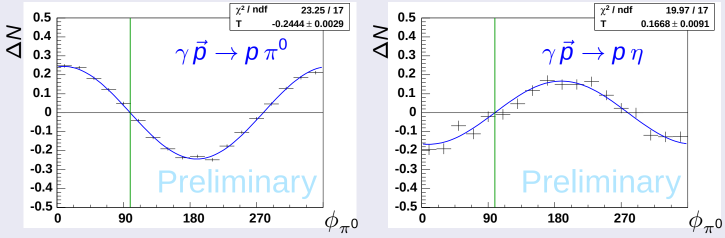
E_{0+}: $N(1535)\,\frac{1}{2}^-$, $N(1650)\,\frac{1}{2}^-$, $\Delta(1620)\,\frac{1}{2}^-$

E_{2-}: $N(1520)\,\frac{3}{2}^-$, $\Delta(1700)\,\frac{3}{2}^-$

A. Thiel *et al.* [CBELSA/TAPS], PRL **109**, 102001 (2012)

Transverse Target Polarization: Target Asymmetry T

$700 < E_\gamma < 800$ MeV　　$800 < E_\gamma < 900$ MeV



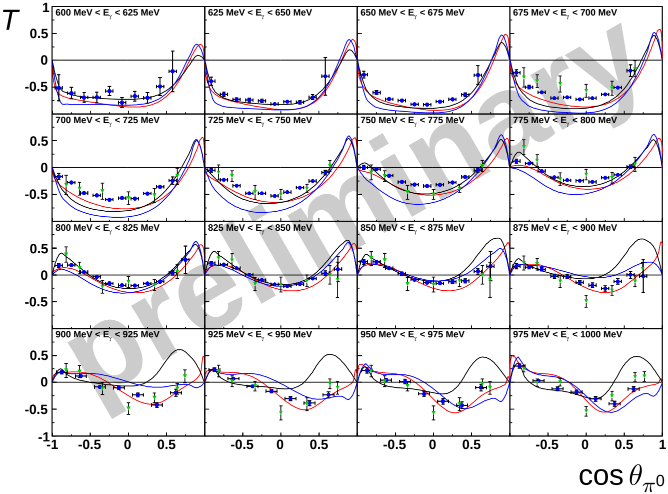
direction of target pol.: $\beta = 99^\circ$

$$\Delta N(\phi) = \frac{1}{f\, P_{\text{target}}} \cdot \frac{N_\uparrow - N_\downarrow}{N_\uparrow + N_\downarrow} = T \cdot \sin(\phi - \beta)$$

➜ Unprecedented statistical quality.

photon pol.		target pol. axis x	y	z
unpolarized	σ		T	
linear	$-\Sigma$	H	$-P$	$-G$
circular		F		$-E$

Target Asymmetry T in $\gamma \vec{p} \to p\, \pi^0$ (Data from ELSA)



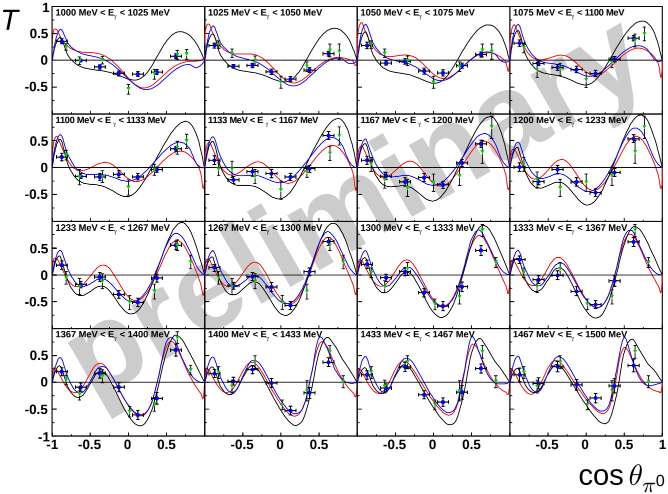
$600 < E_\gamma < 1000$ MeV
in bins of $\Delta E = 25$ MeV

- ● CBELSA/TAPS
- ▼ Daresbury (1977)
  Nucl. Phys. B **121** (1977), 45
- — Maid
- — Said
- — Bonn Gatchina

➜ Good agreement of experimental data. (improved statistics)

J. Hartmann *et al.* [CBELSA/TAPS]

Target Asymmetry T in $\gamma \vec{p} \to p\, \pi^0$ (Data from ELSA)



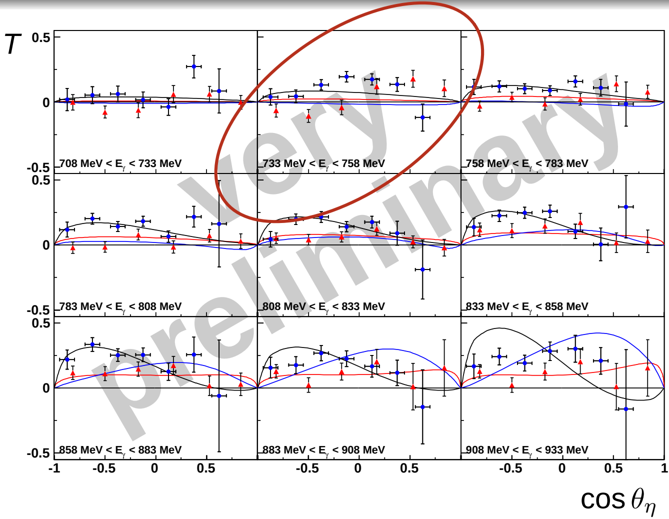
$1000 < E_\gamma < 1500$ MeV

- CBELSA/TAPS
- Daresbury (1977)
  Nucl. Phys. B **121** (1977), 45
- Maid
- Said
- Bonn Gatchina

➜ Good agreement of experimental data.

Model disagreement toward 3rd resonance region: $W > 1.6$ GeV (E_{0+}, E_{2-} multipoles?)

Target Asymmetry T in $\gamma \vec{p} \to p\, \eta$ (Data from ELSA)



$708 < E_\gamma < 933$ MeV

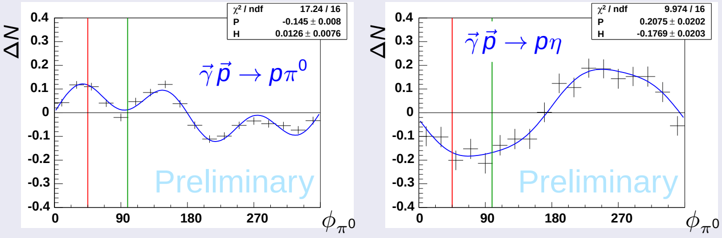
in bins of $\Delta E = 25$ MeV

- CBELSA/TAPS
- PHOENICS (1998)
  Phys. Rev. Lett. **81** (1998), 534
- Maid
- Said
- Bonn Gatchina

J. Hartmann *et al.* [CBELSA/TAPS]

Observables P, H (Results from CBELSA/TAPS)

$800 < E_\gamma < 900$ MeV



angle of lin. pol. plane:

$\alpha = 45°$

direction of target pol.:

$\beta = 99°$

$$\Delta N(\phi) = C \cdot \frac{(N_{\perp\uparrow} - N_{\perp\downarrow}) - (N_{\parallel\uparrow} - N_{\parallel\downarrow})}{(N_{\perp\uparrow} + N_{\perp\downarrow}) + (N_{\parallel\uparrow} + N_{\parallel\downarrow})}$$

$$= P\,(\sin(\phi - \beta)\cos(2(\phi - \alpha)) + H\,(\cos(\phi - \beta)\sin(2(\phi - \alpha))$$

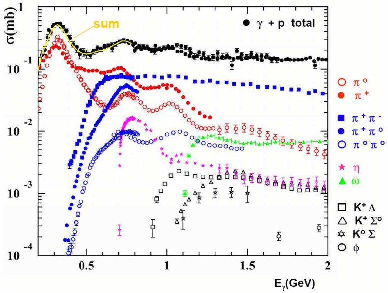
photon pol.		target pol. axis x	y	z
unpolarized	σ		T	
linear	$-\Sigma$	H	$-P$	$-G$
circular		F		$-E$

Beam-Target Polarization Observables in $\gamma p \to p \pi\pi$

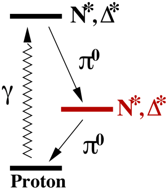
W. Roberts *et al.*, Phys. Rev. C **71**, 055201 (2005)

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

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



At higher excitation energies:
Multi-meson final states important.



➜ Search for states in decay cascades!

Photoproduction of $\pi\pi$ Pairs off the Proton: Kinematics

Two mesons in the final state require 5 independent variables!

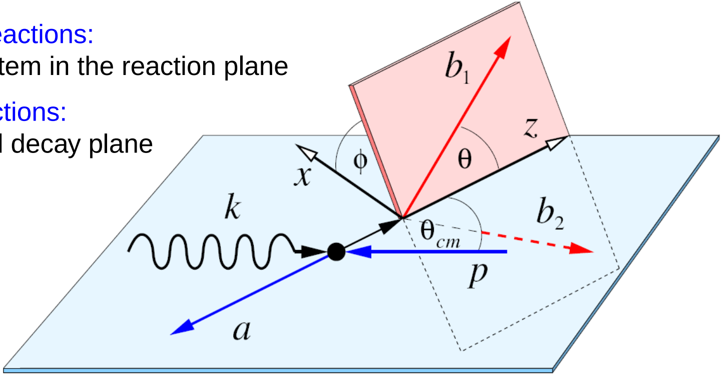
For example: E_γ, $\Theta_{\text{c.m.}}$, ϕ^*, θ^*, $M_{p\,+\,meson\,1}$

Single-meson reactions:

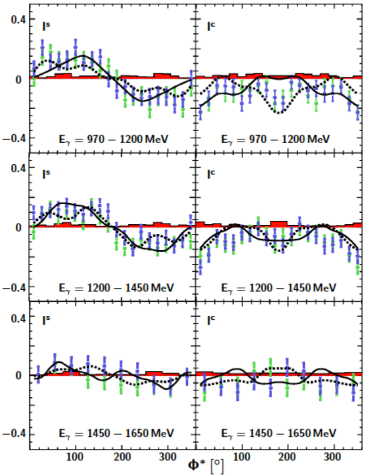
➜ p-meson system in the reaction plane

Two-meson reactions:

➜ Reaction and decay plane form angle ϕ



Beam Asymmetries I^s, I^c in $\vec{\gamma} p \to p\,\pi^0\pi^0$



First measurements of beam asymmetries I^s and I^c using linearly-polarized photons in the reaction $\gamma p \to p\,\pi^0\pi^0$.

Among other things, study of decays into $\Delta\pi$:

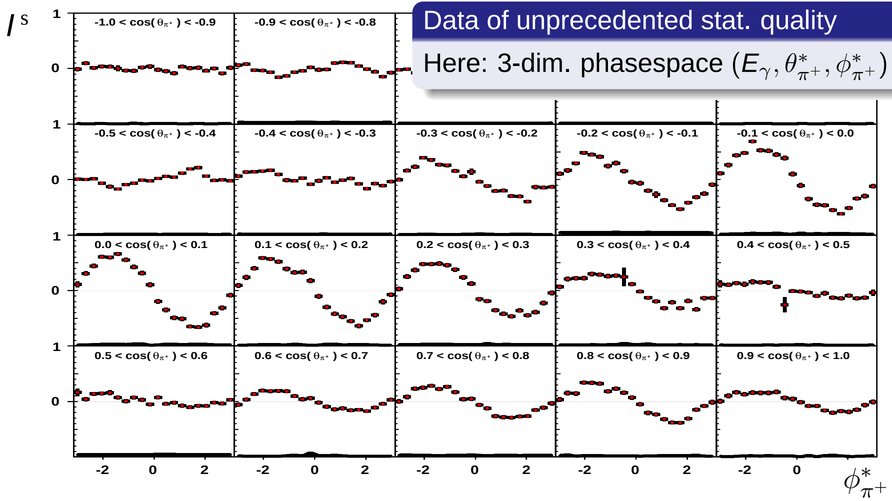
– – BoGa-PWA solution with a dominant $\Delta(1700)D_{33} \to \Delta\pi$ D-wave

······ BoGa-PWA solution with a dominant $\Delta(1700)D_{33} \to \Delta\pi$ S-wave

- Direct measurements
- From mirror operation $I^s(\Phi^*) \to I^s(2\pi - \Phi^*)$

V. Sokhoyan *et al.* [CBELSA/TAPS], to be published

I^{s} in $\vec{\gamma} p \to p \pi^+ \pi^-$ from JLab: $1100 < E_\gamma < 1150$ MeV



Data of unprecedented stat. quality

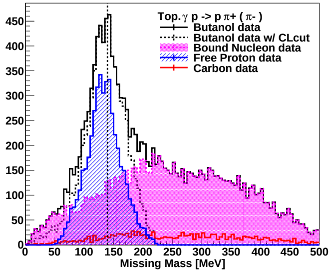
Here: 3-dim. phasespace $(E_\gamma, \theta^*_{\pi^+}, \phi^*_{\pi^+})$

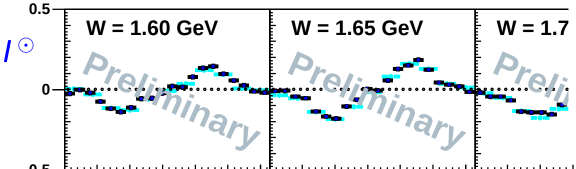
C. Hanretty *et al.*, CLAS-g8b run group, under review

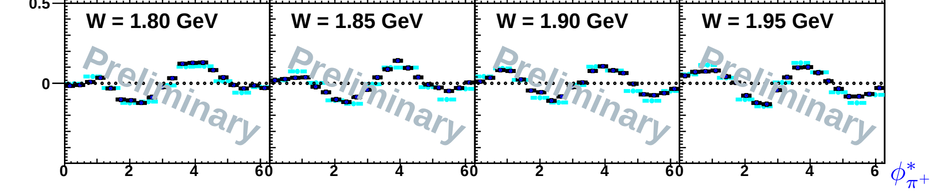
Beam Asymmetry $I^{\odot}$ in $\vec{\gamma} p \to p\, \pi^+ \pi^-$ from JLab

Analysis of butanol target challenging:

- Determination of dilution factor ➜ (event-based dilution factors possible)







S. Park *et al.*, CLAS (FROST); CLAS (g1c) PRL **95** (2005)

Outline

Summary and Outlook

Our understanding of baryon resonances has made great leaps forward. There is good evidence that most of the known states (listed in the PDG) will be confirmed in photoproduction and that new states will be revealed:

- Goal of performing (almost) complete experiments has been (almost) achieved; program on neutron ongoing.
- Advances in both theory and experiment will allow us to finally understand QCD and confinement.

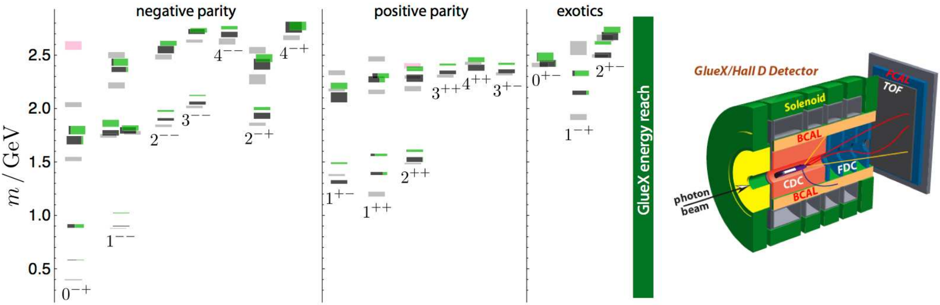
$N(1860)\,\frac{5}{2}^+$	$**$	πN	γN					
$N(1875)\,\frac{3}{2}^-$	$***$	πN	γN		ΛK	ΣK		$N\sigma$
$N(1880)\,\frac{1}{2}^+$	$**$	πN	γN		ΛK	ΣK		
$N(1895)\,\frac{1}{2}^-$	$**$	πN	γN	ηN	ΛK	ΣK		
$N(1900)\,\frac{3}{2}^+$	$***$	πN	γN	ηN	ΛK	ΣK	$\Delta\pi$	
$N(2060)\,\frac{5}{2}^-$	$**$	πN	γN	ηN		ΣK		
$\Delta(1940)\,\frac{3}{2}^-$	$* \rightarrow **$	πN	γN				$\Delta\eta$ (!)	

New States in PDG 2012.

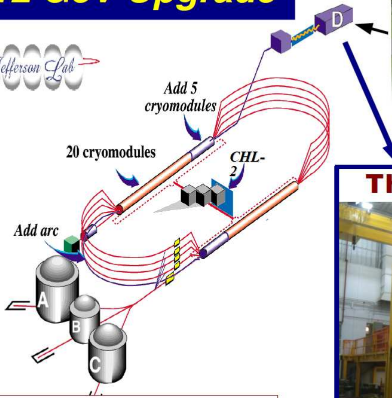
Summary and Outlook

Our understanding of baryon resonances has made great leaps forward. There is good evidence that most of the known states (listed in the PDG) will be confirmed in photoproduction and that new states will be revealed:

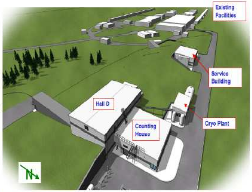
- Hadron spectroscopy (e.g. search for exotic mesons) will continue at Jefferson Lab in the 12 GeV era with the GlueX experiment in Hall D:



Jefferson Lab 12 GeV Upgrade



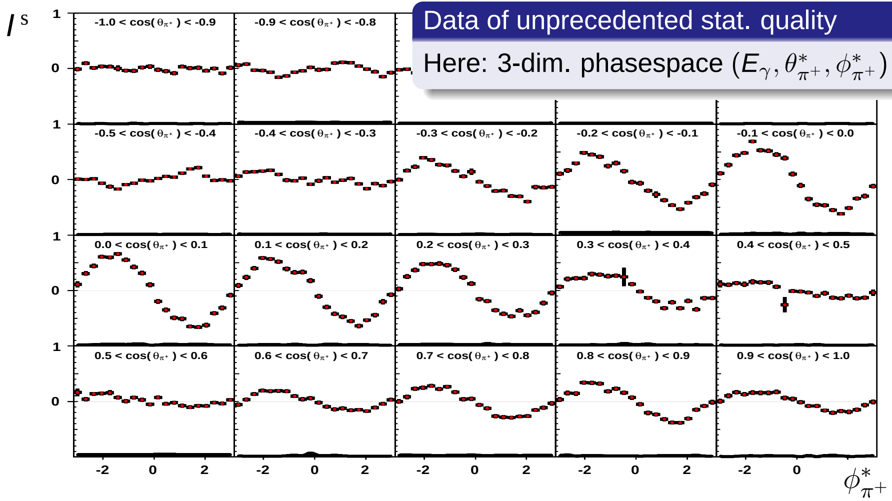
~~April~~ Fall 2014 Beam Commissioning



The Hall D

Thank you.

I^s in $\vec{\gamma} p \to p \pi^+ \pi^-$ from JLab: $1100 < E_\gamma < 1150$ MeV

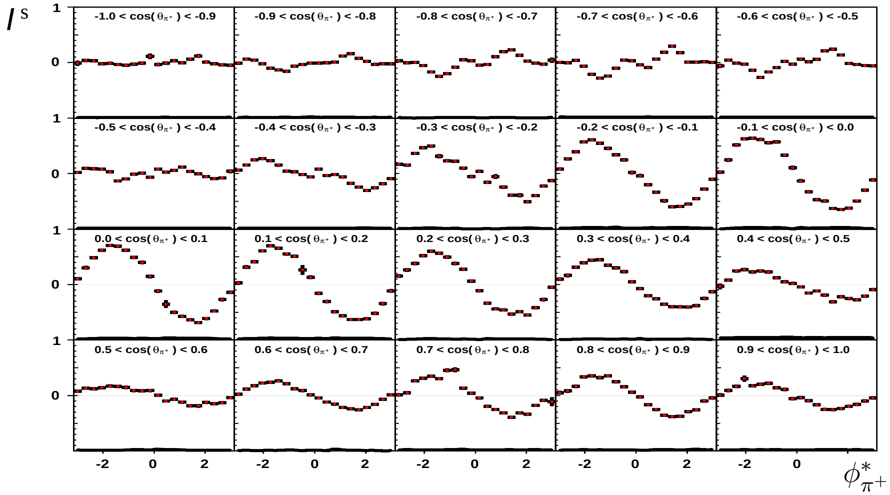


Data of unprecedented stat. quality

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

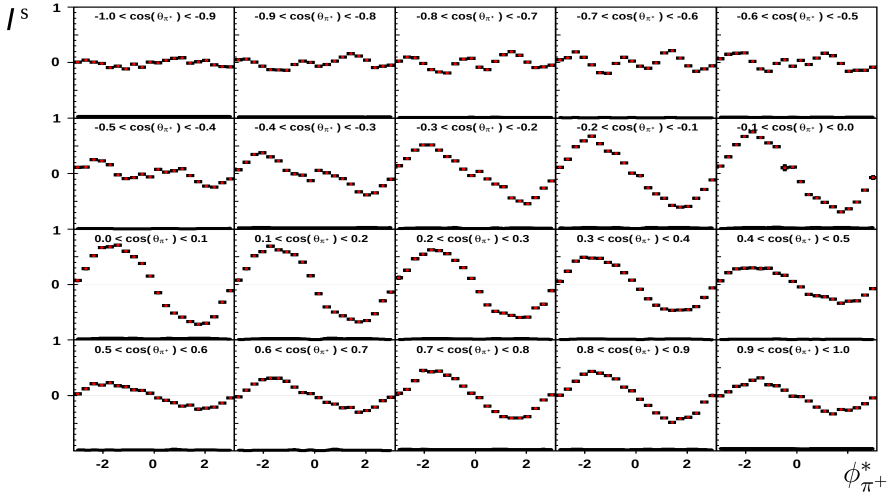
C. Hanretty *et al.*, CLAS-g8b run group, under review

I^s in $\vec{\gamma} p \to p \pi^+ \pi^-$ from JLab: $1150 < E_\gamma < 1200$ MeV



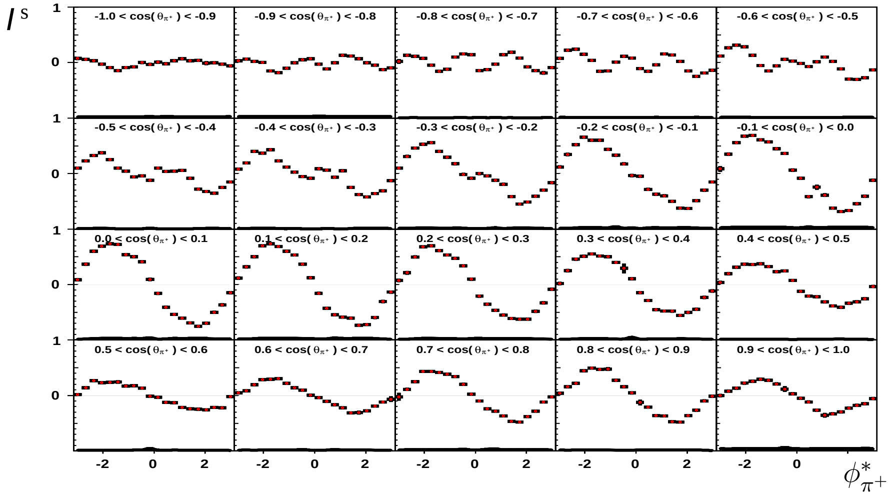
C. Hanretty *et al.*, CLAS-g8b run group, under review

I^s in $\vec{\gamma} p \to p \pi^+ \pi^-$ from JLab: $1200 < E_\gamma < 1250$ MeV



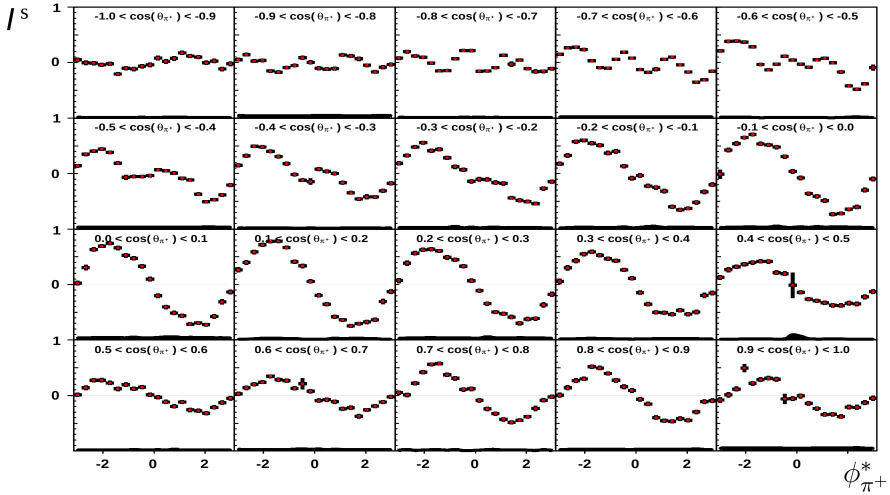
C. Hanretty *et al.*, CLAS-g8b run group, under review

I^s in $\vec{\gamma} p \to p \pi^+ \pi^-$ from JLab: $1250 < E_\gamma < 1300$ MeV



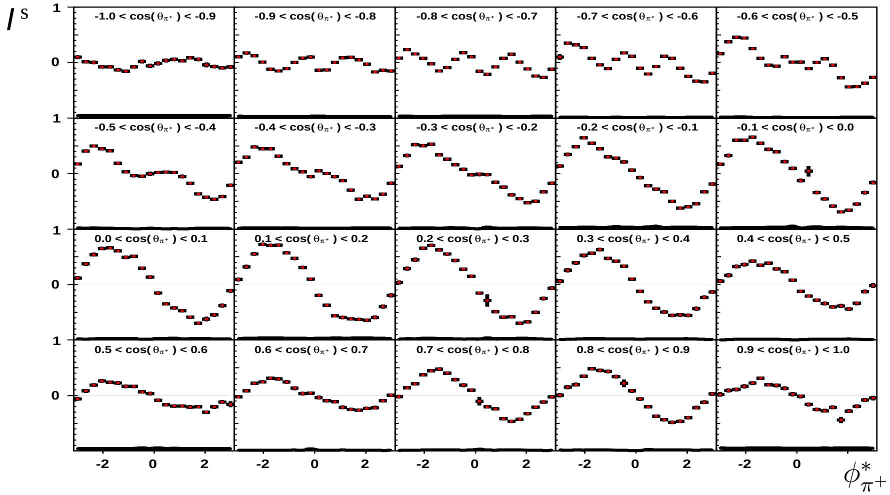
C. Hanretty *et al.*, CLAS-g8b run group, under review

I^s in $\vec{\gamma} p \to p\,\pi^+\pi^-$ from JLab: $1300 < E_\gamma < 1350$ MeV



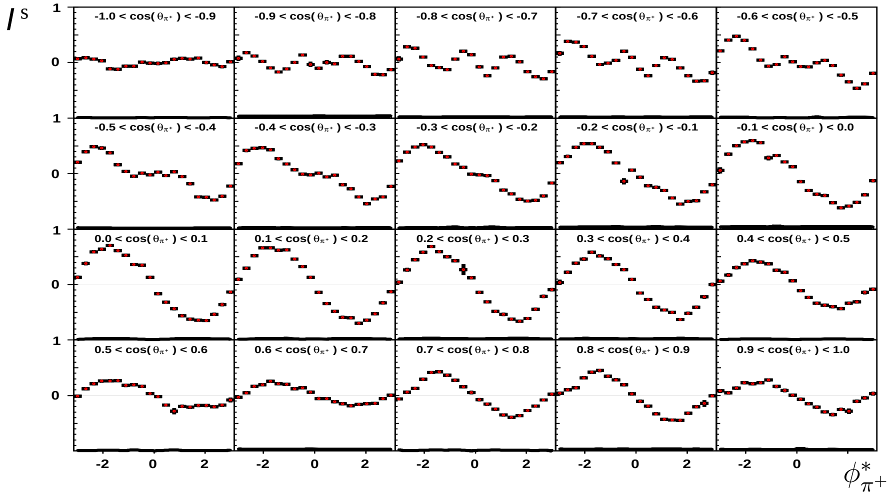
C. Hanretty *et al.*, CLAS-g8b run group, under review

I^s in $\vec{\gamma} p \to p \pi^+ \pi^-$ from JLab: $1350 < E_\gamma < 1400$ MeV



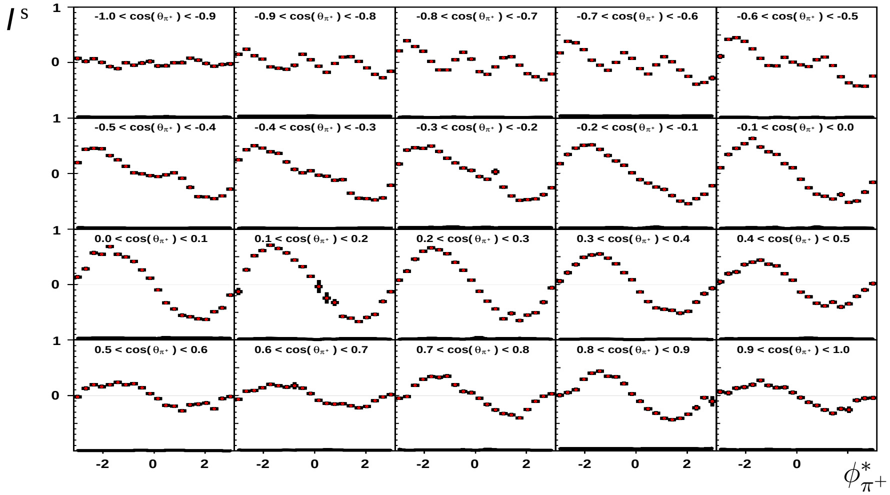
C. Hanretty *et al.*, CLAS-g8b run group, under review

I^s in $\vec{\gamma} p \to p \pi^+ \pi^-$ from JLab: $1400 < E_\gamma < 1450$ MeV



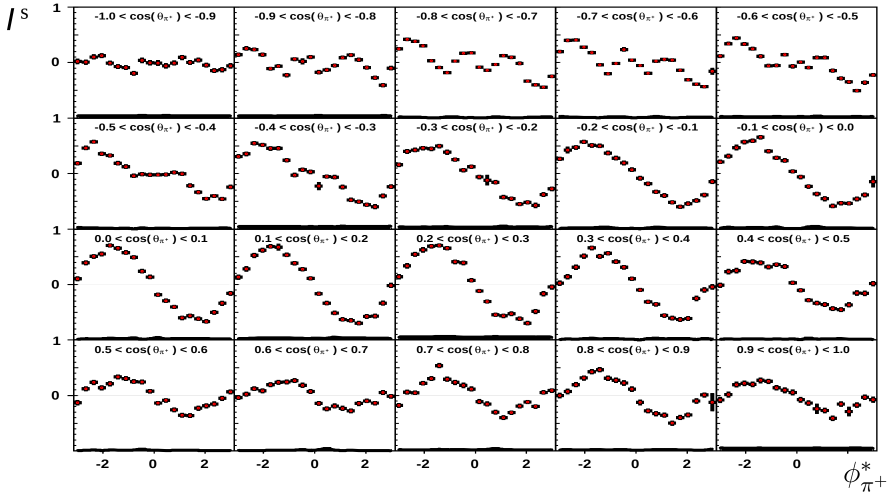
C. Hanretty *et al.*, CLAS-g8b run group, under review

I^s in $\vec{\gamma} p \to p \pi^+ \pi^-$ from JLab: $1450 < E_\gamma < 1500$ MeV



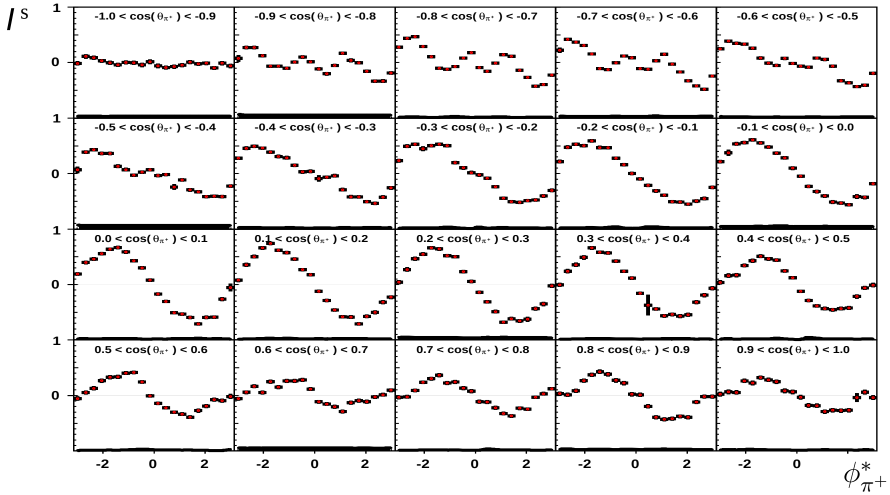
C. Hanretty *et al.*, CLAS-g8b run group, under review

I^s in $\vec{\gamma} p \to p \pi^+ \pi^-$ from JLab: $1500 < E_\gamma < 1550$ MeV



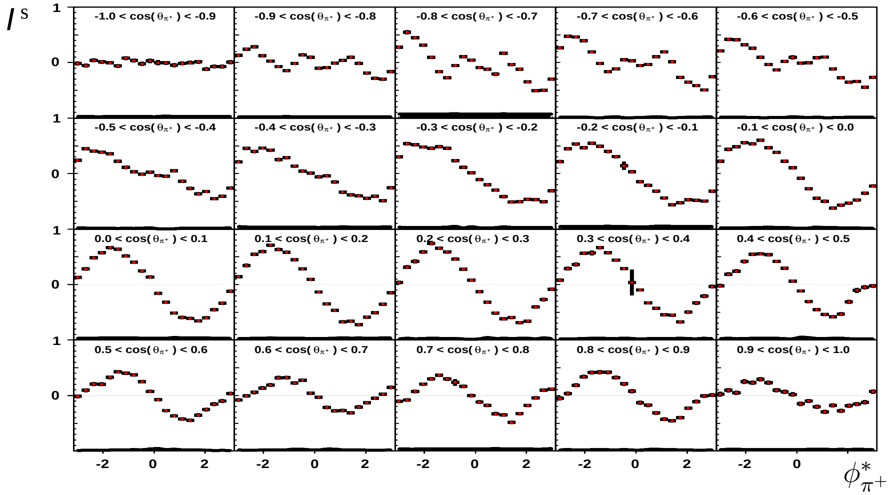
C. Hanretty *et al.*, CLAS-g8b run group, under review

I^s in $\vec{\gamma} p \to p \pi^+ \pi^-$ from JLab: $1550 < E_\gamma < 1600$ MeV



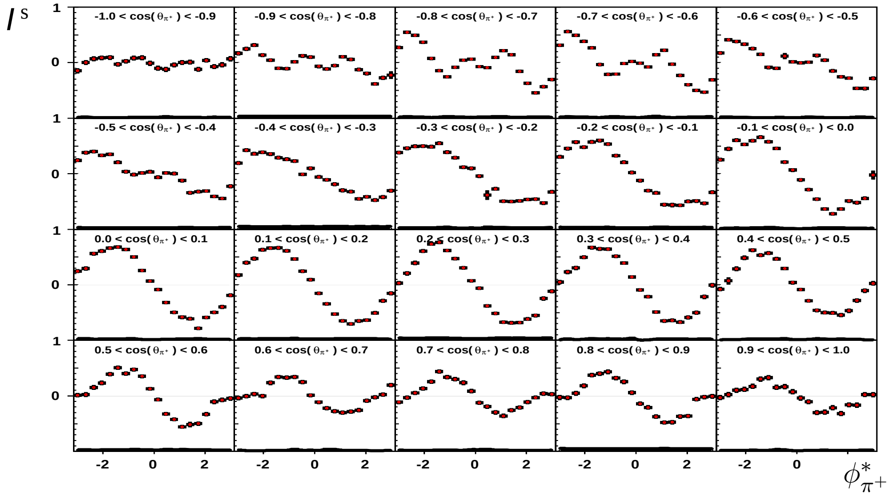
C. Hanretty *et al.*, CLAS-g8b run group, under review

I^s in $\vec{\gamma} p \to p \pi^+ \pi^-$ from JLab: $1600 < E_\gamma < 1650$ MeV



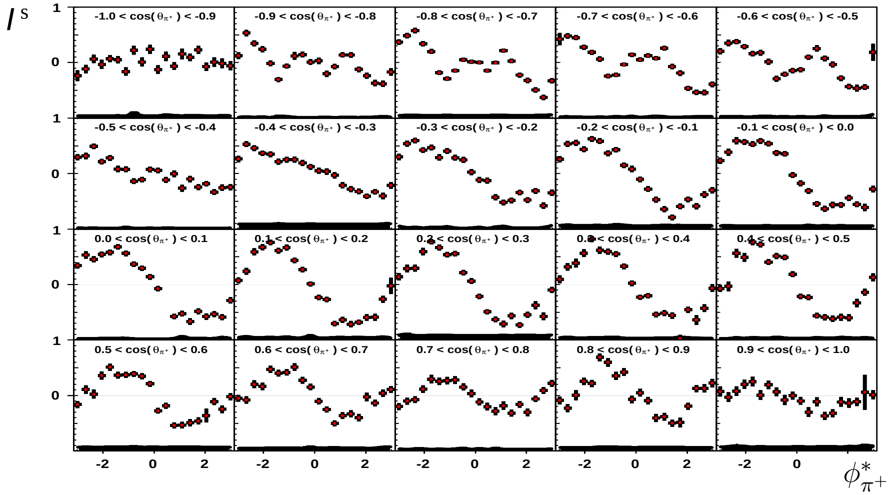
C. Hanretty *et al.*, CLAS-g8b run group, under review

I^s in $\vec{\gamma} p \to p \pi^+ \pi^-$ from JLab: $1650 < E_\gamma < 1700$ MeV



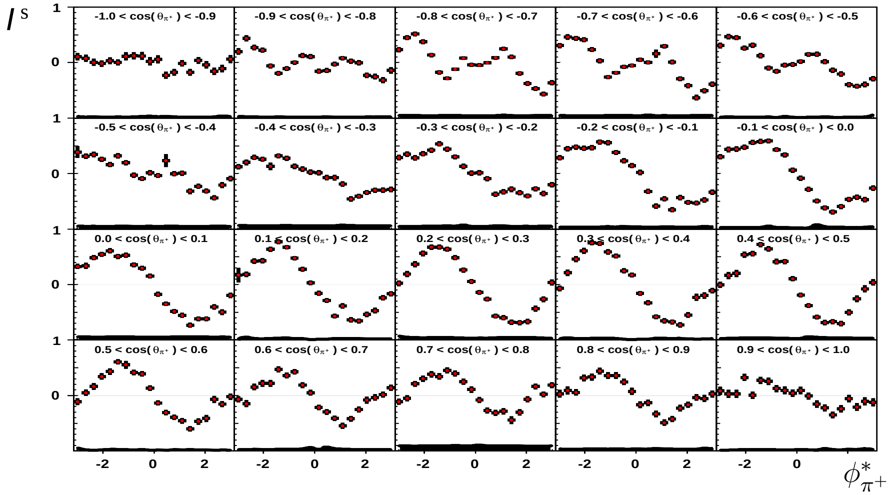
C. Hanretty *et al.*, CLAS-g8b run group, under review

I^s in $\vec{\gamma} p \to p \pi^+ \pi^-$ from JLab: $1700 < E_\gamma < 1750$ MeV



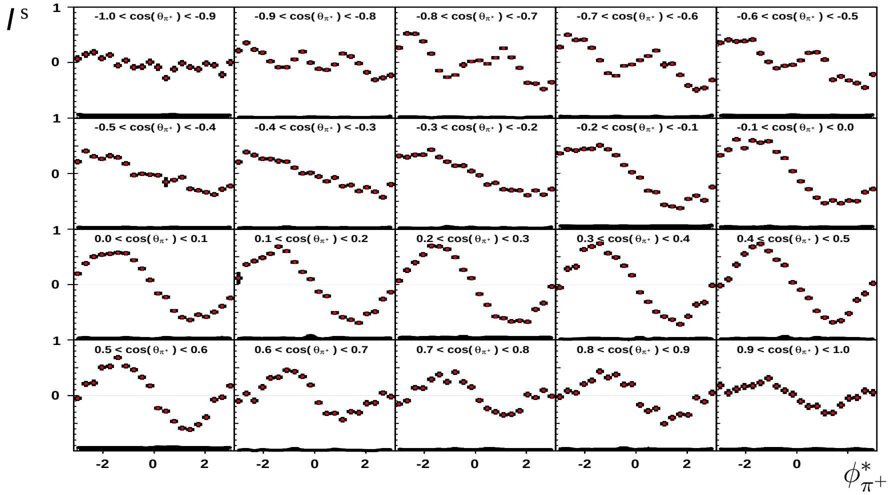
C. Hanretty *et al.*, CLAS-g8b run group, under review

I^s in $\vec{\gamma} p \to p \pi^+ \pi^-$ from JLab: $1750 < E_\gamma < 1800$ MeV



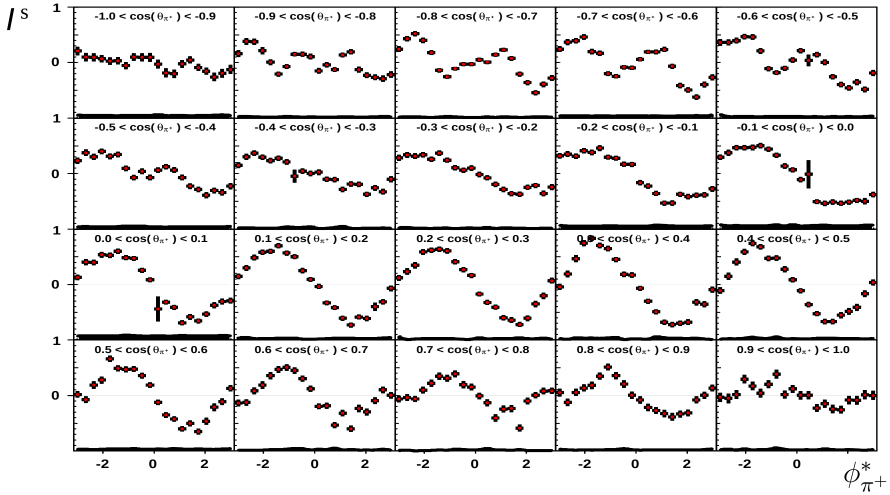
C. Hanretty *et al.*, CLAS-g8b run group, under review

I^s in $\vec{\gamma} p \to p \pi^+ \pi^-$ from JLab: $1800 < E_\gamma < 1850$ MeV



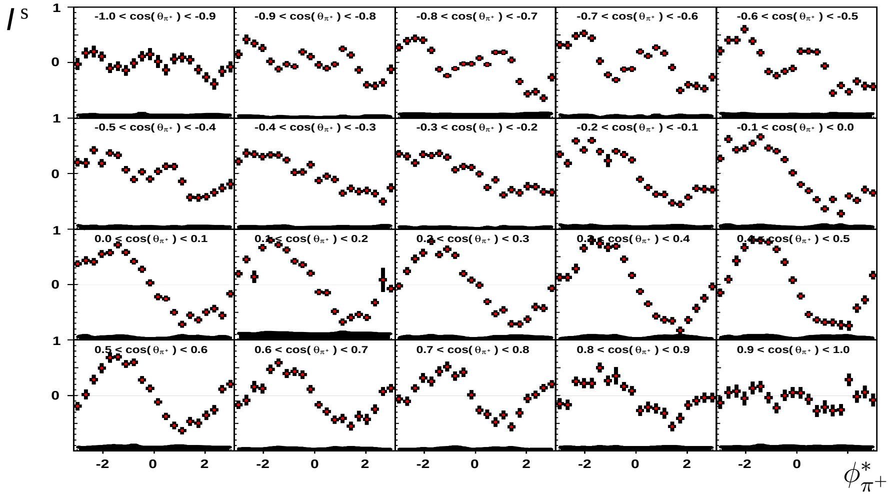
C. Hanretty *et al.*, CLAS-g8b run group, under review

I^s in $\vec{\gamma} p \to p \pi^+ \pi^-$ from JLab: $1850 < E_\gamma < 1900$ MeV



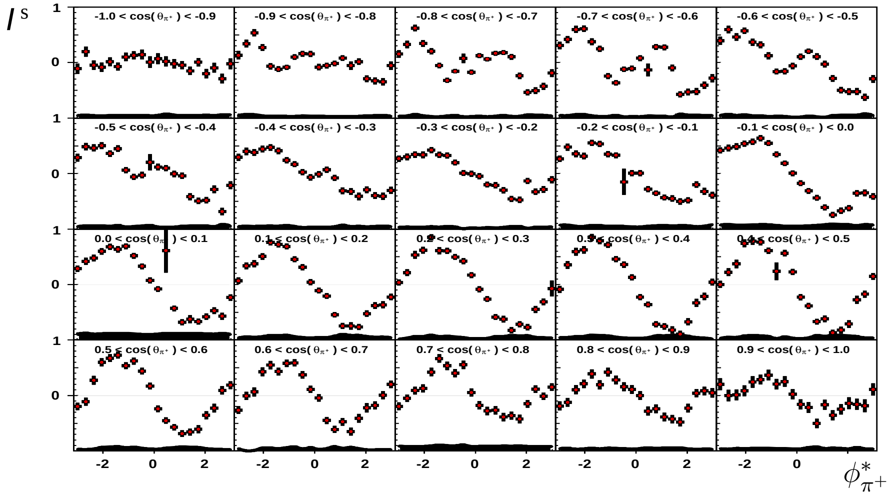
C. Hanretty *et al.*, CLAS-g8b run group, under review

I^s in $\vec{\gamma} p \to p\,\pi^+\pi^-$ from JLab: $1900 < E_\gamma < 1950$ MeV



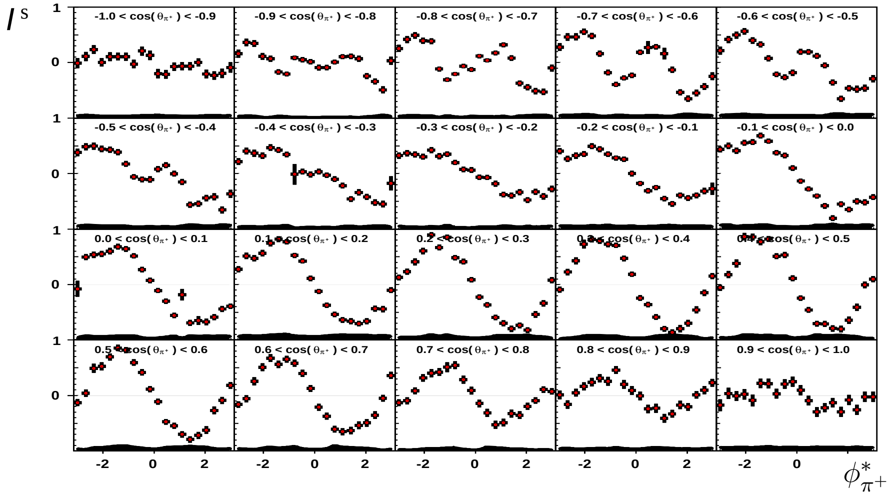
C. Hanretty *et al.*, CLAS-g8b run group, under review

I^s in $\vec{\gamma} p \to p \pi^+ \pi^-$ from JLab: $1950 < E_\gamma < 2000$ MeV



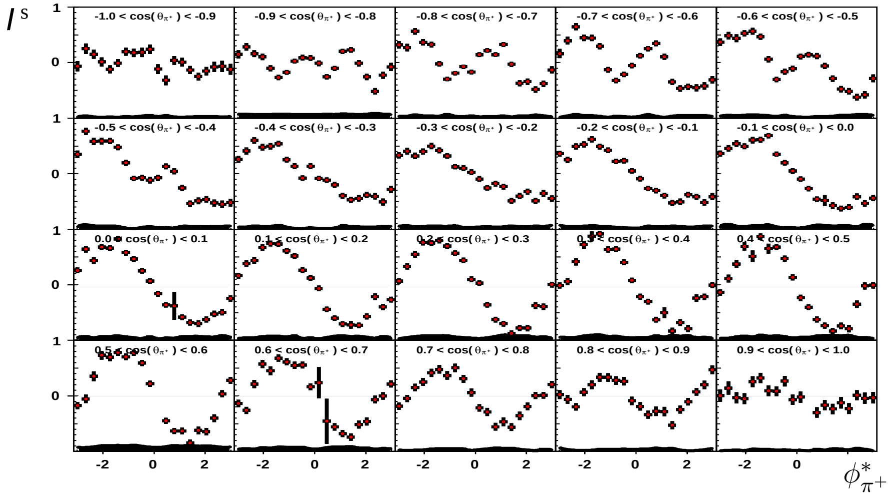
C. Hanretty *et al.*, CLAS-g8b run group, under review

I^s in $\vec{\gamma} p \to p \pi^+ \pi^-$ from JLab: $2000 < E_\gamma < 2050$ MeV



C. Hanretty *et al.*, CLAS-g8b run group, under review

I^s in $\vec{\gamma} p \to p \pi^+ \pi^-$ from JLab: $2050 < E_\gamma < 2100$ MeV



C. Hanretty *et al.*, CLAS-g8b run group, under review