Baryon Spectroscopy at Jefferson Lab
What have we learned about excited baryons?

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Florida State University, Tallahassee, FL

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American Physical Society

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Jefferson Lab

Outline

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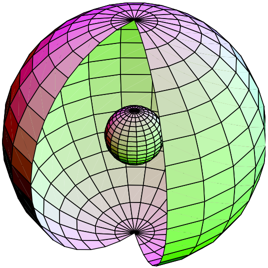
1. Introduction
   - Quarks, QCD, and Confinement
   - Structure of Baryon Resonances
2. The Search for Undiscovered States
   - Electromagnetic Probes
   - Mission Goal: Complete Experiments
3. Results from Photoproduction Experiments
   - Photoproduction of π, η, and ω Mesons
   - Observables in the Photoproduction of Two Pions
4. Summary and Outlook

Non-Perturbative QCD

Courtesy of Craig Roberts, Argonne



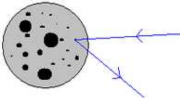
How does QCD give rise to hadrons?

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

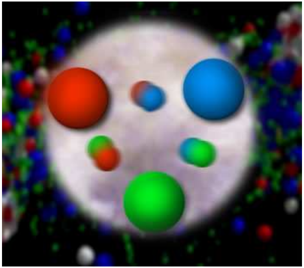
➜

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.



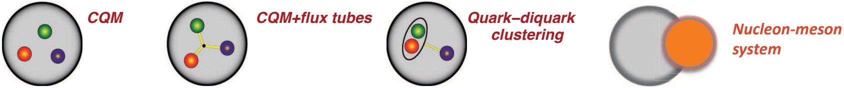
Non-Perturbative QCD



How does QCD give rise to 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 $\sim 99\,\%$ of observed matter in the universe?

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

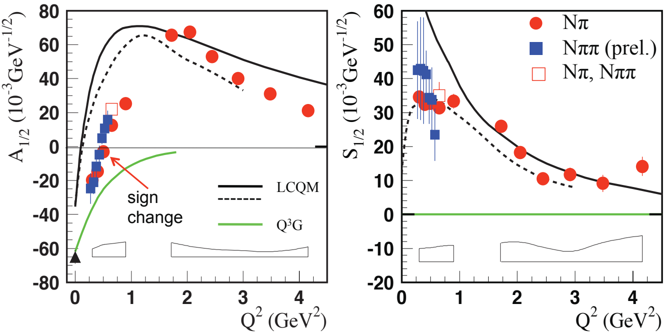


Components of the Experimental N^* Program

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. I. Aznauryan *et al.*, PRC **78**, 045209 (2008); PRC **80**, 055203 (2009).

Quark-model calculations:

— q^3G hybrid state

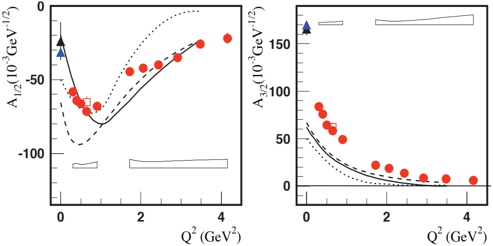
— - - q^3 radial excitation

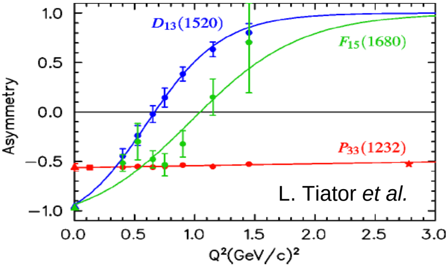
Consistency between both channels ($N\pi\pi$, $N\pi$): sign change, magnitude, ...

- 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

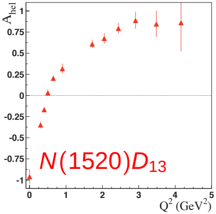




There is clear evidence for helicity switch from $\lambda = 3/2$ (at photon point) to $\lambda = 1/2$ at high Q^2:

- Rapid change in helicity structure when going from photo- to electroproduction of a nucleon resonance
  ➜ Stringent prediction of the CQM!

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



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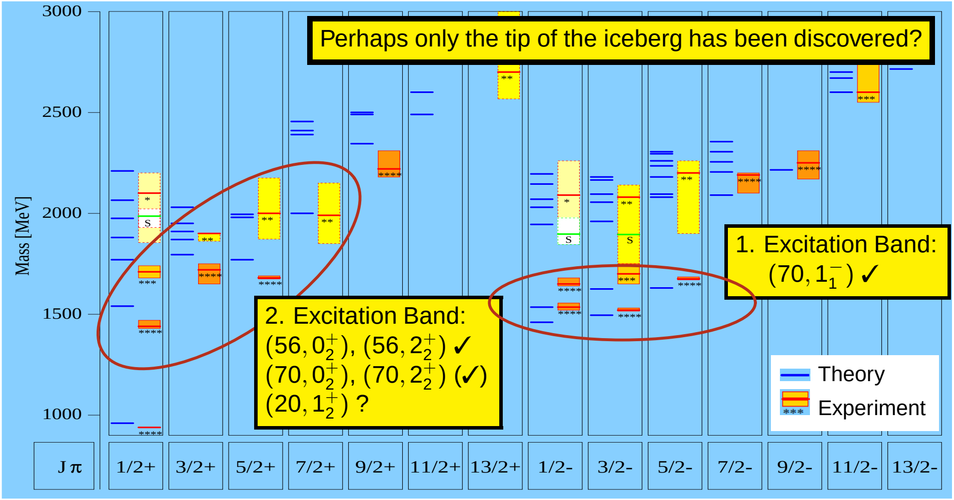
Spectrum of Nucleon Resonances

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



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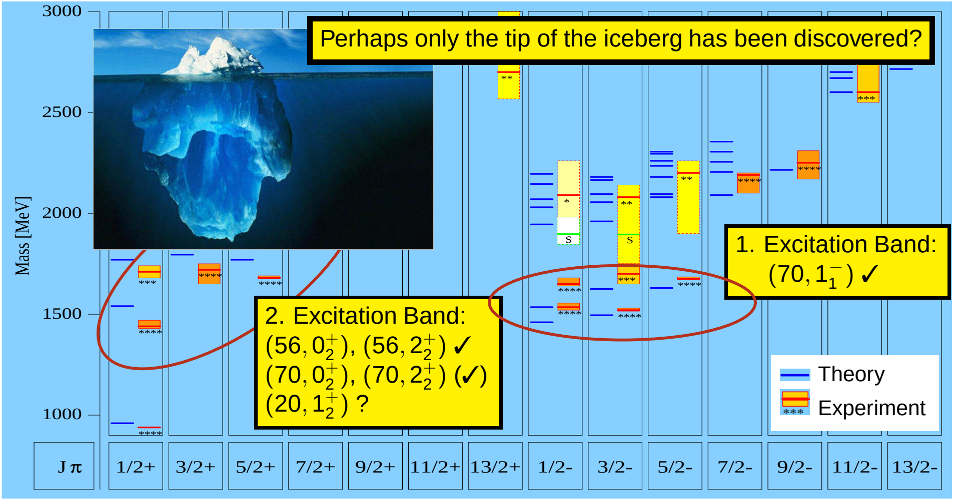
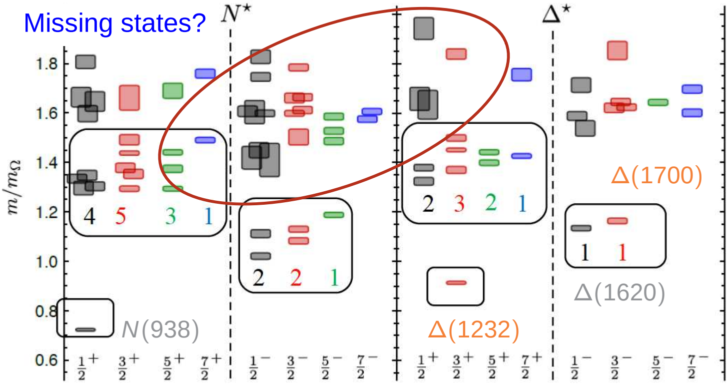


Excited-State Baryon Spectroscopy from Lattice QCD

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

Outline

E_γ [GeV]

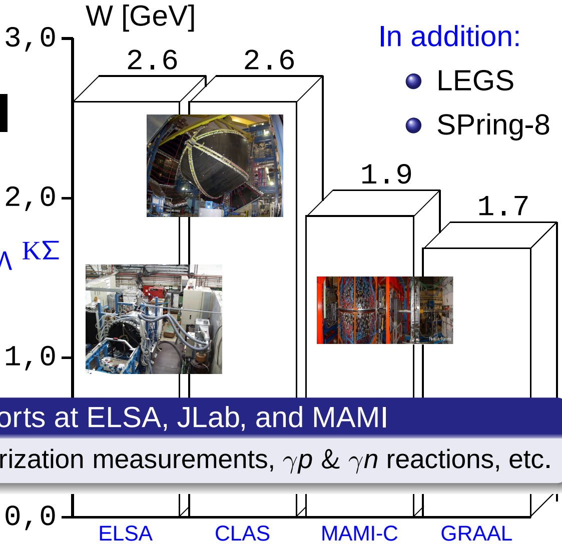
Reaction Thresholds

1.66 — $\gamma p \to p\eta\eta$, $\gamma p \to p\pi^0\omega$, $\gamma p \to p\pi^0\eta$, $\gamma p \to p\eta$, $\gamma p \to p\pi\pi\pi$, $\gamma p \to p\pi\pi$, $\gamma p \to p\pi$

$\gamma p \to K\Lambda$ $K\Sigma$

0.06

0.00



In addition:

- LEGS
- SPring-8

Common efforts at ELSA, JLab, and MAMI

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

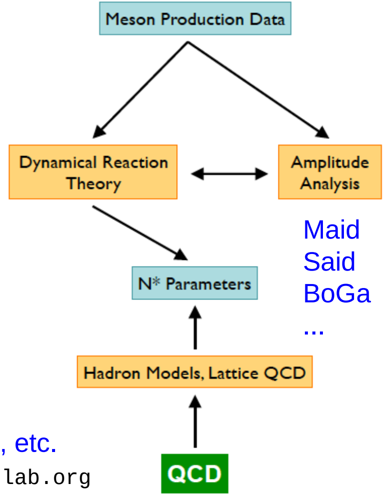
Extraction of Resonance Parameters

- 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.

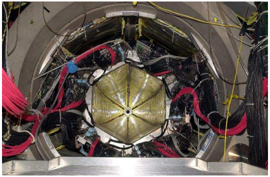
http://ebac-theory.jlab.org

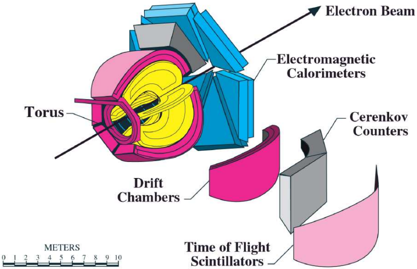


Maid
Said
BoGa
...

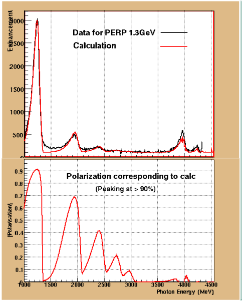
The CLAS Spectrometer at Jefferson Laboratory

➜ More talks on CLAS results in Session Q 11

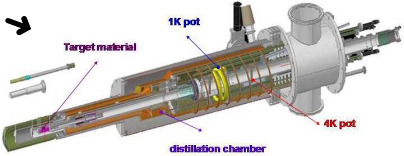




g8b
linear beam polarization



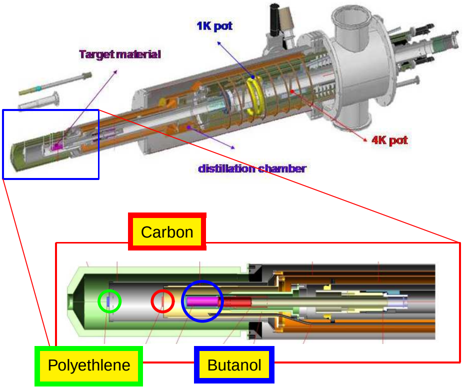
FROST
double polarization

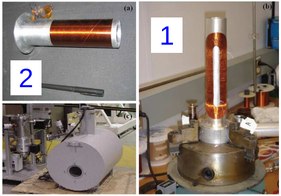


Double-Polarization: Frozen Spin Targets

Horizontal cryostat with integrated solenoid to freeze the proton spin.

- DNP at high B-field of 5 T
- Holding Mode: $B \approx 0.5$ T, $T \approx 30$ mK, $\tau \approx 2000$ h





Target Holding Magnets ($P_z \approx 80$ %)

1. Race-track coil - Dipole Magnet
2. Solenoid

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: four double-spin observables along with four 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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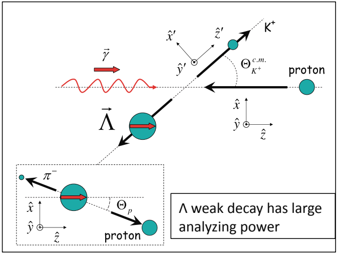
“Complete Experiment” in $K\Lambda$ Photoproduction

Photon beam		*Target*			*Recoil*			*Target - Recoil*								
					x'	y'	z'	x'	x'	x'	y'	y'	y'	z'	z'	z'
		x	y	z				x	y	z	x	y	z	x	y	z
unpolarized	σ_0		T			P		$T_{x'}$		$L_{x'}$		Σ		$T_{z'}$		$L_{z'}$
linearly P_γ	Σ	H	P	G	$O_{x'}$	T	$O_{z'}$	$L_{z'}$	$C_{z'}$	$T_{z'}$	E		F	$L_{x'}$	$C_{x'}$	$T_{x'}$
circular P_γ		F		E	$C_{x'}$		$C_{z'}$		$O_{z'}$		G		H		$O_{x'}$	

CLAS:
16 observables



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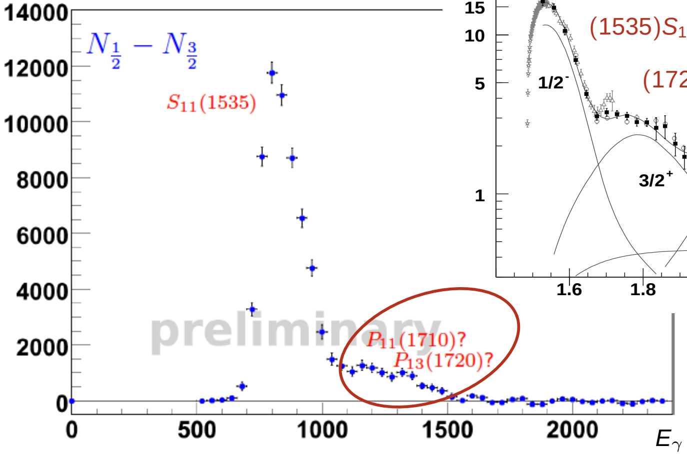
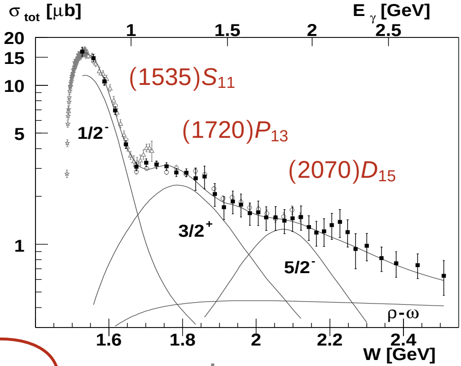
Helicity-Dependent Cross Section for $\vec{\gamma}\,\vec{p} \to p\,\eta$

η count rate difference

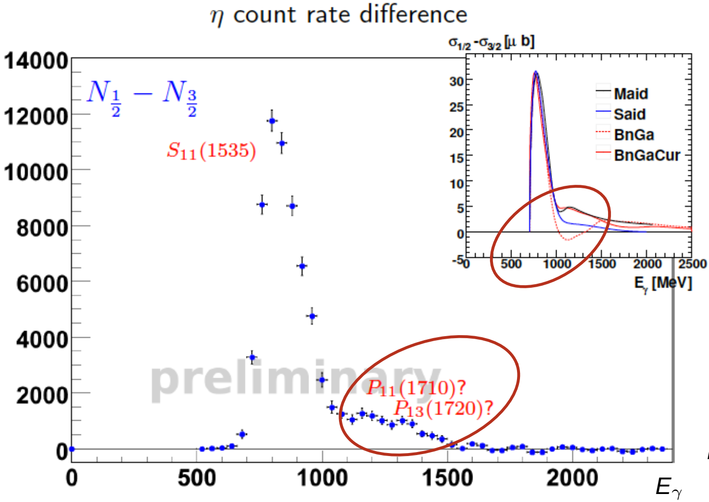


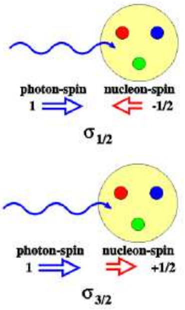


$$E = \frac{\sigma_{1/2} - \sigma_{3/2}}{\sigma_{1/2} + \sigma_{3/2}}$$

CBELSA/TAPS Collaboration

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





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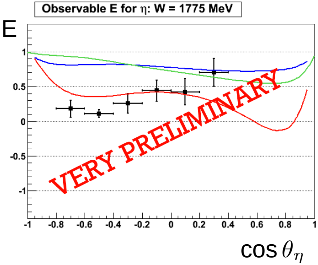
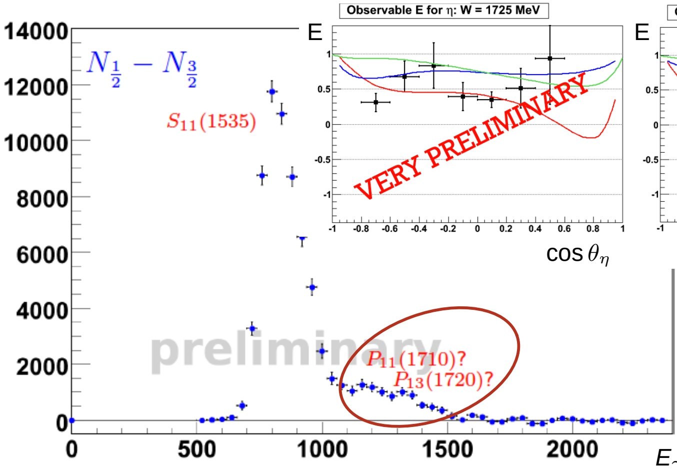
CBELSA/TAPS Collaboration

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

η count rate difference

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





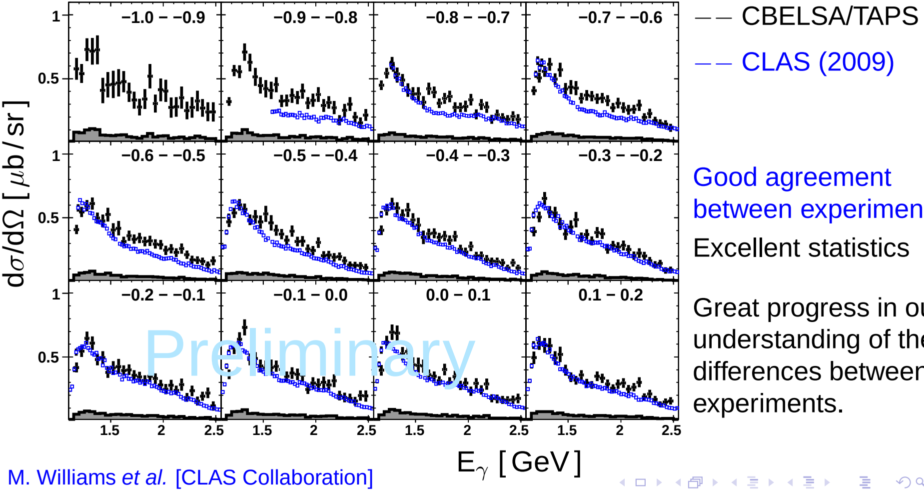
➜ Very preliminary:
Data are positive

CBELSA/TAPS Collaboration

Outline

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

A. Wilson *et al.* [CBELSA/TAPS], Ph.D. thesis



Good agreement between experiments

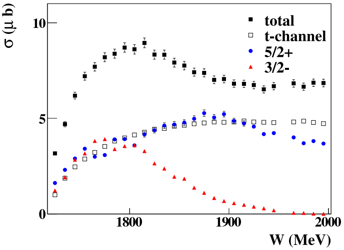
Excellent statistics

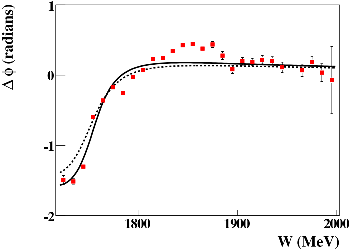
Great progress in our understanding of the differences between experiments.

M. Williams *et al.* [CLAS Collaboration]

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):

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

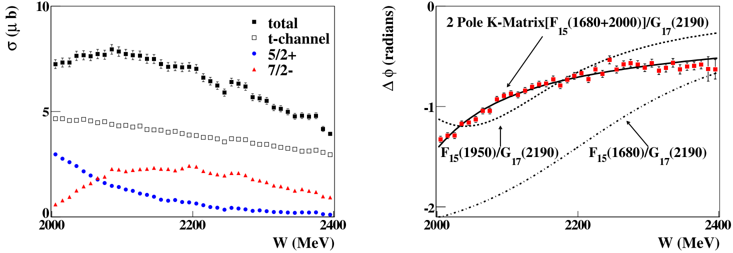
$(5/2)+$ N(1680) $****$

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.

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

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



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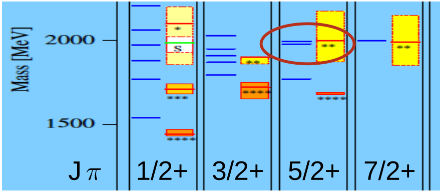
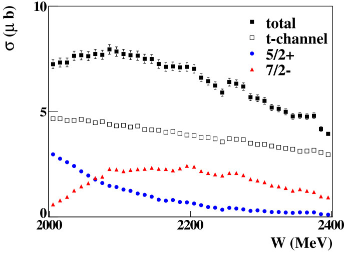
Strong evidence for ($W > 2$ GeV):

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



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



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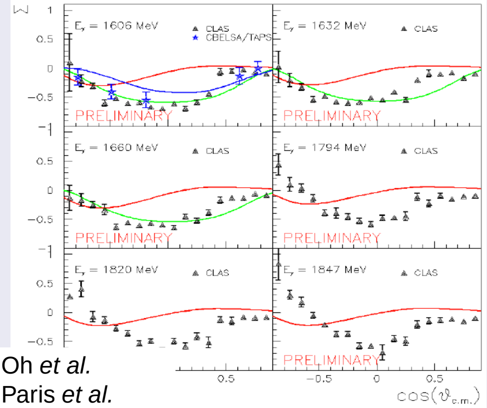
Asymmetry Σ for $\vec{\gamma} p \to p \omega$ (P. Collins *et al.*, CUA)

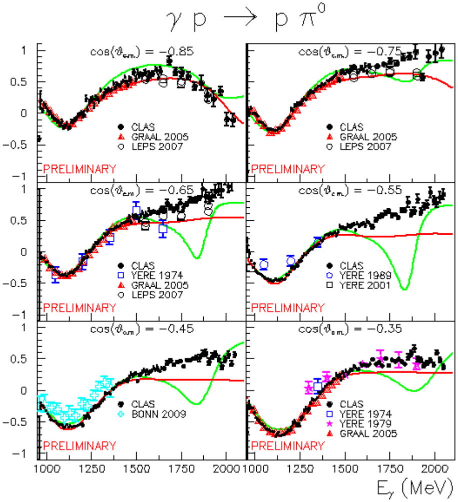


— Oh *et al.*

— Paris *et al.*

— Sarantsev *et al.*

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



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

— SAID — MAID • CLAS

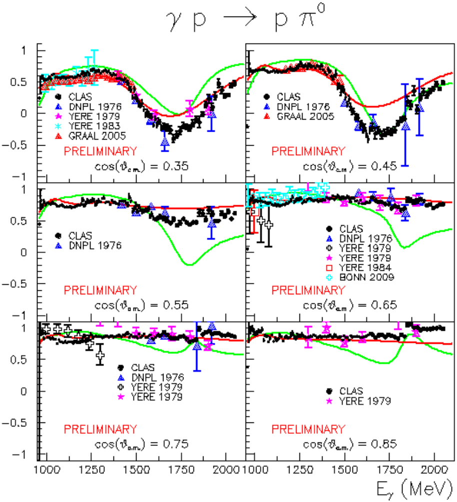
($E_\gamma < 2$ GeV, $-0.85 < \cos\theta_\pi < -0.35$)

➜ 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, $0.35 < \cos\theta_\pi < 0.85$)

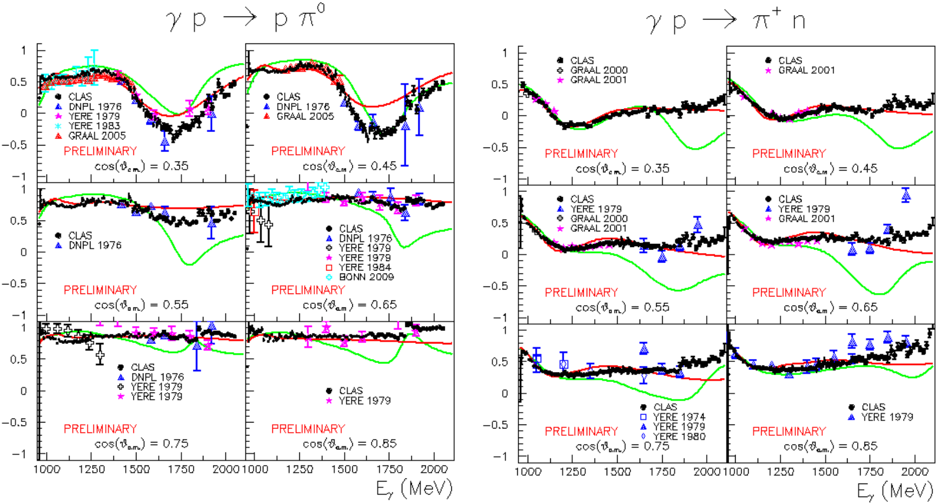
Combination of $p\,\pi^0$ and $n\,\pi^+$ final states can help distinguish between Δ and N^* resonances:

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

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

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

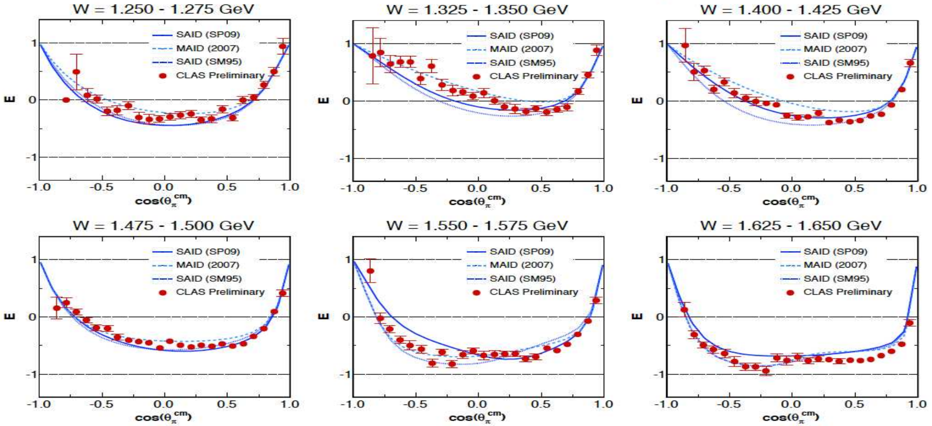
Beam Asymmetry Σ in $\vec{\gamma} p \to p\,\pi^0$ and $\vec{\gamma} p \to n\,\pi^+$



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

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

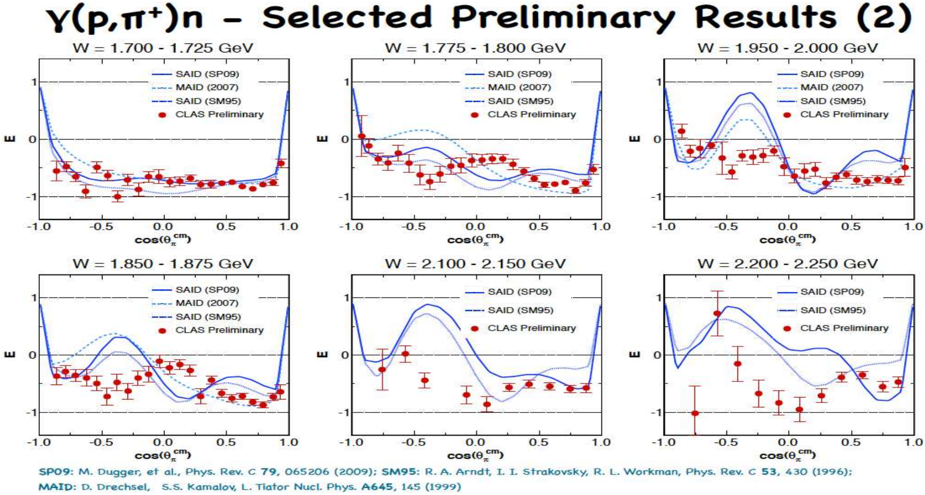
$\gamma(p,\pi^+)n$ – Selected Preliminary Results (1)



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 et *al.*, CLAS (FROST)

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



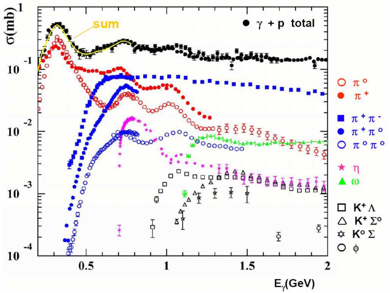
S. Strauch et *al.*, CLAS (FROST)

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

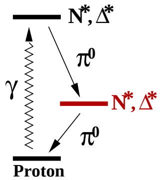
W. Roberts *et al.*, Phys. Rev. C **71**, 055201 (2005)

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

$\Leftarrow$ 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!

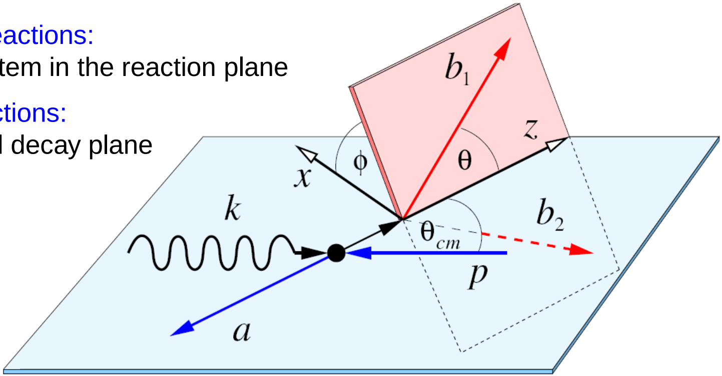
For example: E_γ, $\Theta_{\text{c.m.}}$, ϕ^*, θ^*, $M_{p\,+\,meson\,1}$

Single-meson reactions:

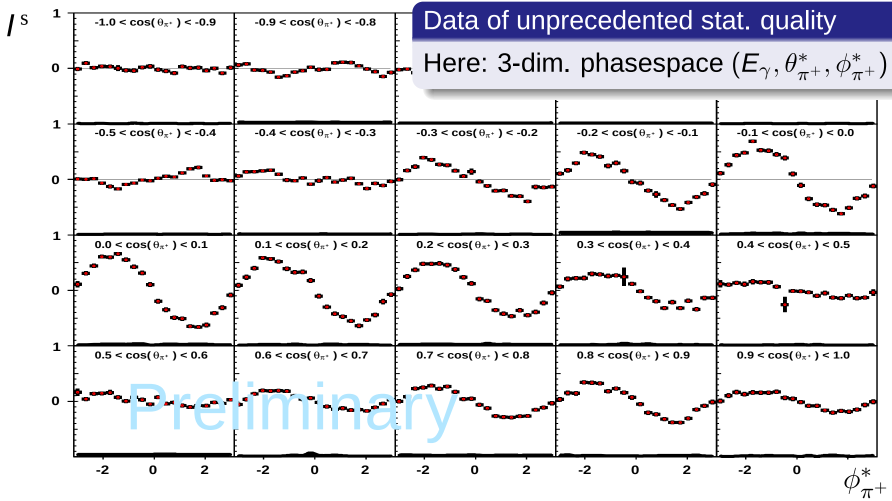
➜ p-meson system in the reaction plane

Two-meson reactions:

➜ Reaction and decay plane form angle ϕ



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



Data of unprecedented stat. quality

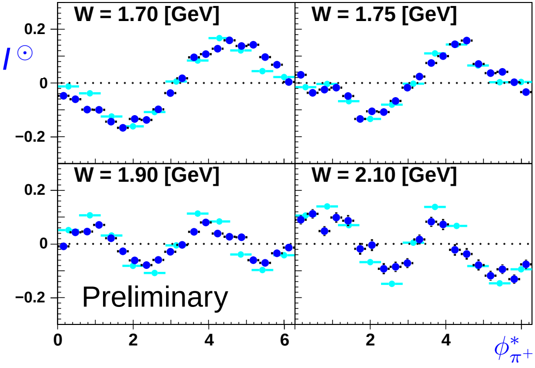
Here: 3-dim. phasespace ($E_\gamma, \theta^*_{\pi^+}, \phi^*_{\pi^+}$)

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

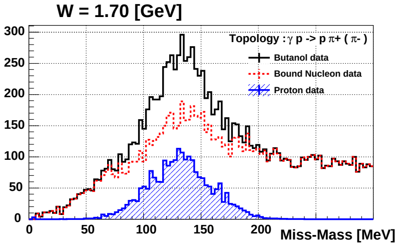
Beam Asymmetry $I^{\odot}$ in $\vec{\gamma} p \to p \pi^+\pi^-$ from JLab

Analysis of butanol target challenging:

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



S. Park *et al.*, CLAS (FROST), to be published



- CLAS-FROST (butanol) data
- Phys. Rev. Lett. **95**, 162003 (2005) (CLAS Collaboration)

The interpretation of these $\pi\pi$ data has only just begun.

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:

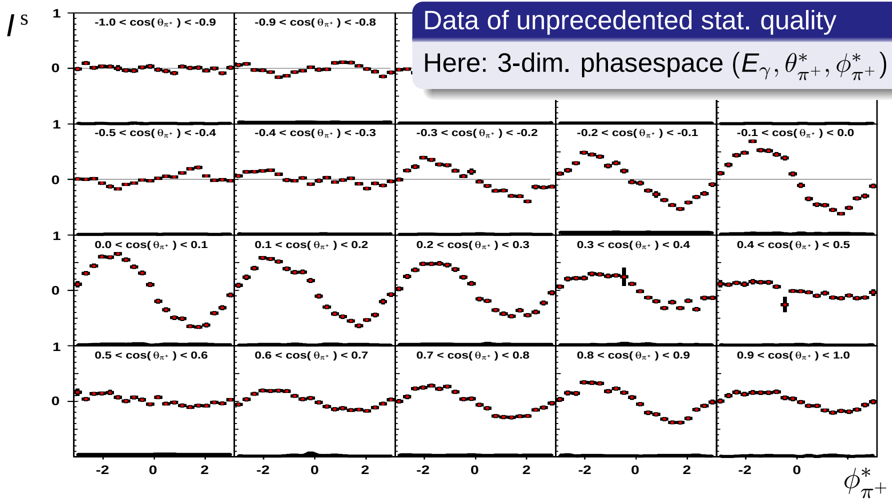
- The current (6 GeV) N^* program at Jefferson Laboratory is almost complete, but the data need to be analyzed in the coming years.
- Goal of performing (almost) complete experiments has been (almost) achieved; program on neutron ongoing.
- Baryon spectroscopy at Jefferson Lab will continue in the 12 GeV era (e.g. Ξ, Ω states): GlueX and CLAS12

Conclusions

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

U.S. DEPARTMENT OF ENERGY

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



Data of unprecedented stat. quality

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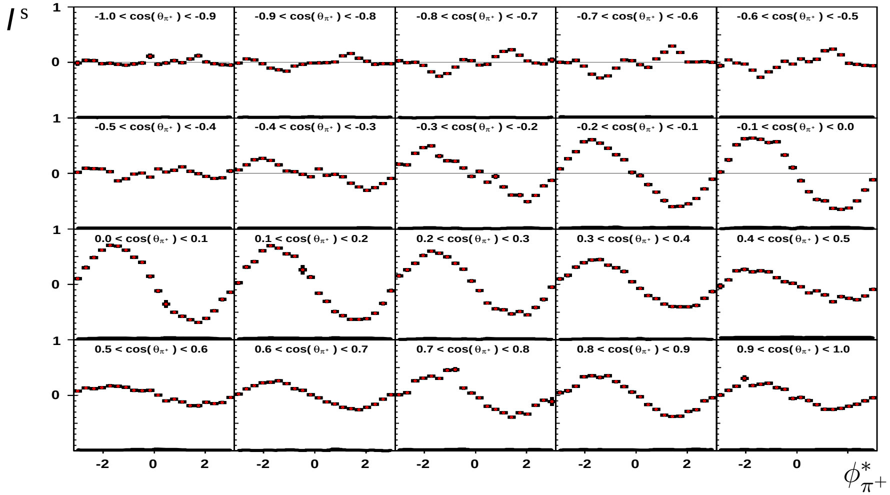
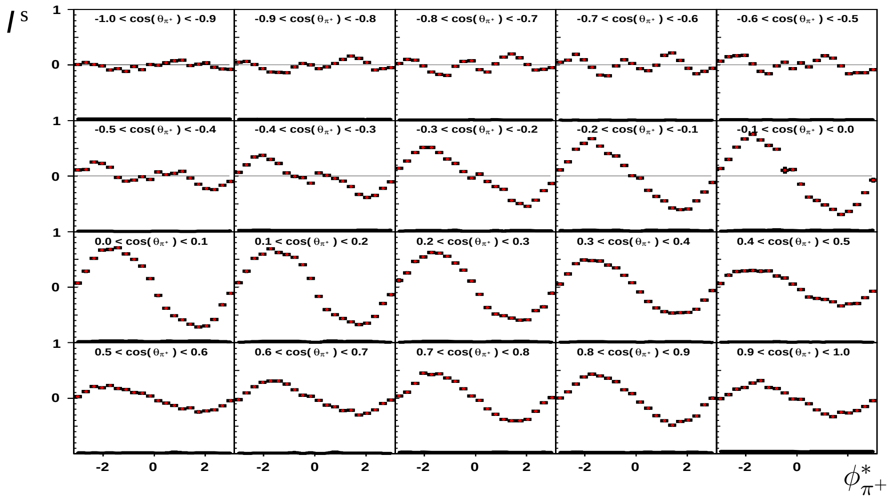
C. Hanretty *et al.*, CLAS-g8b run group, under review

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



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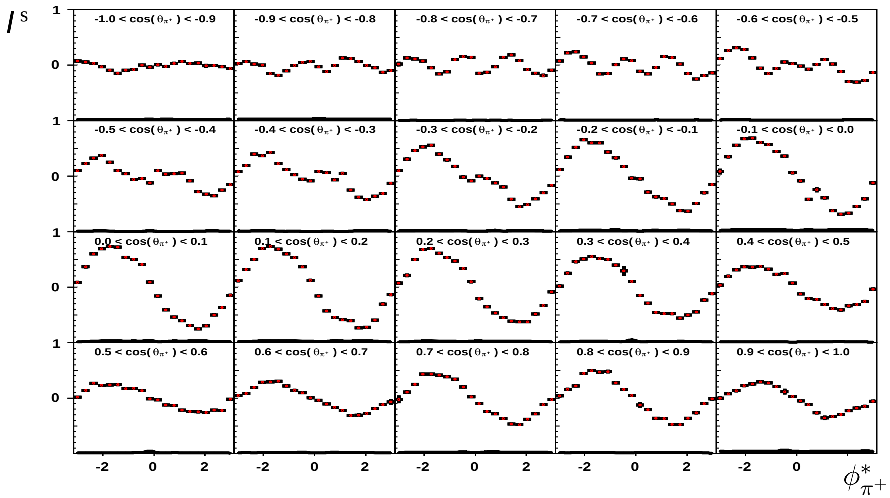
I^s in $\vec{\gamma} p \to p \pi^+ \pi^-$ from JLab: $1250 < E_\gamma < 1300$ MeV



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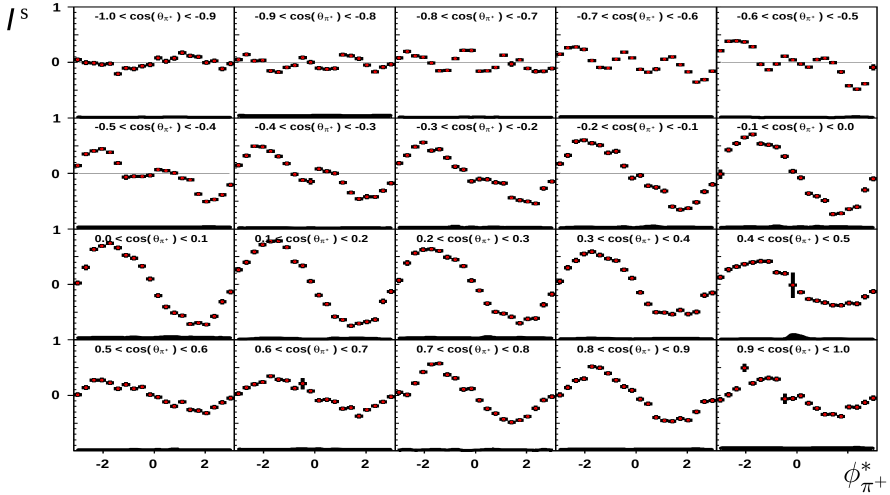
I^s in $\vec{\gamma} p \to p \pi^+ \pi^-$ from JLab: $1300 < E_\gamma < 1350$ MeV



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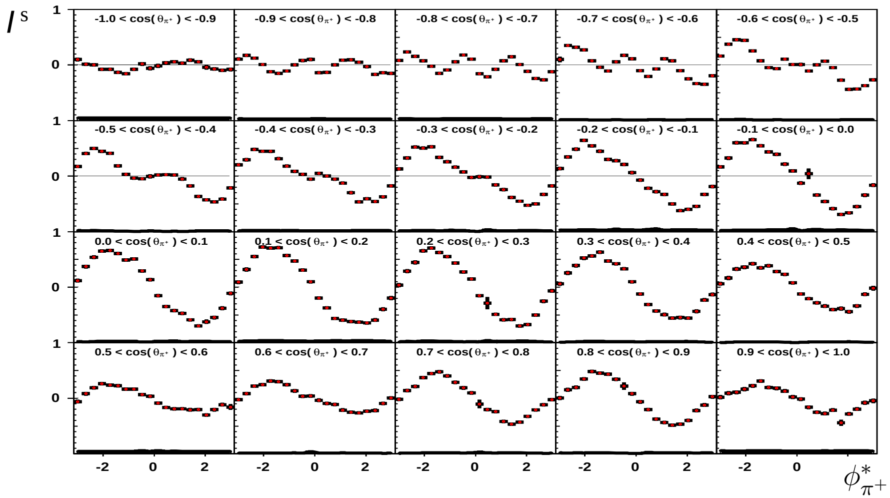
I^s in $\vec{\gamma} p \rightarrow p\,\pi^+\pi^-$ from JLab: $1350 < E_\gamma < 1400$ MeV



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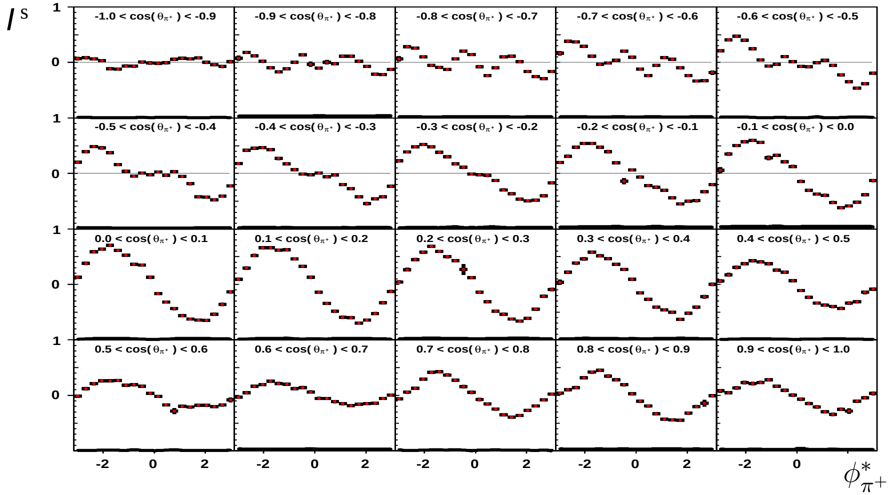
I^s in $\vec{\gamma} p \rightarrow p \pi^+ \pi^-$ from JLab: $1400 < E_\gamma < 1450$ MeV



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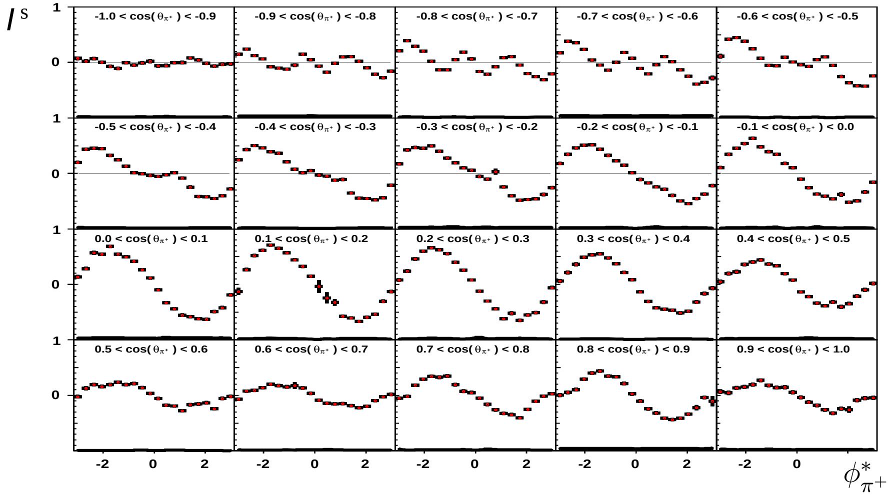
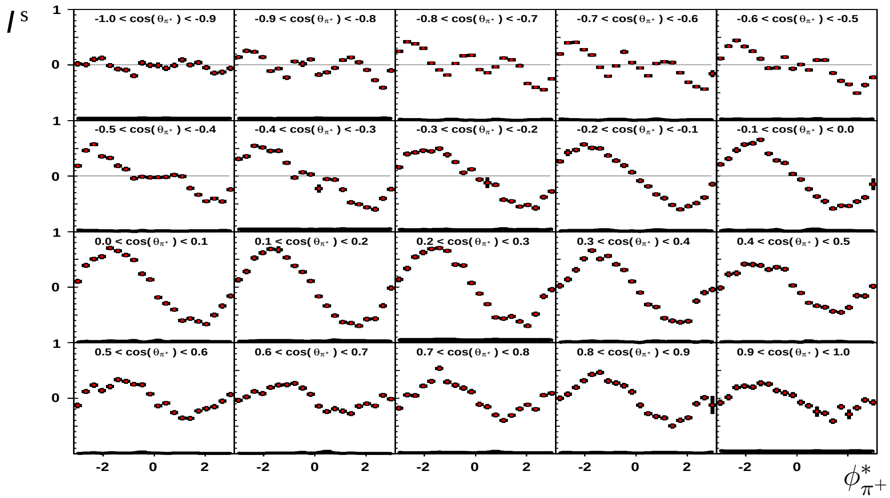
I^s in $\vec{\gamma} p \to p \pi^+ \pi^-$ from JLab: $1450 < E_\gamma < 1500$ MeV



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

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



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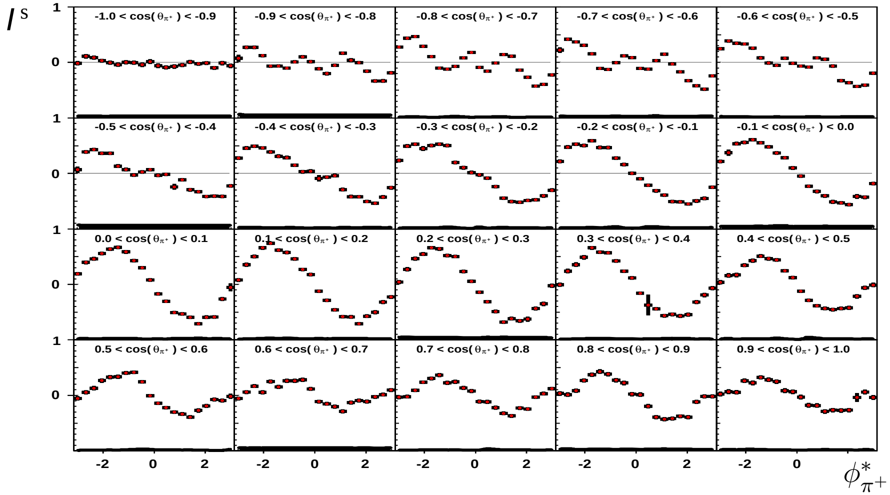
I^s in $\vec{\gamma} p \rightarrow p \pi^+ \pi^-$ from JLab: $1550 < E_\gamma < 1600$ MeV



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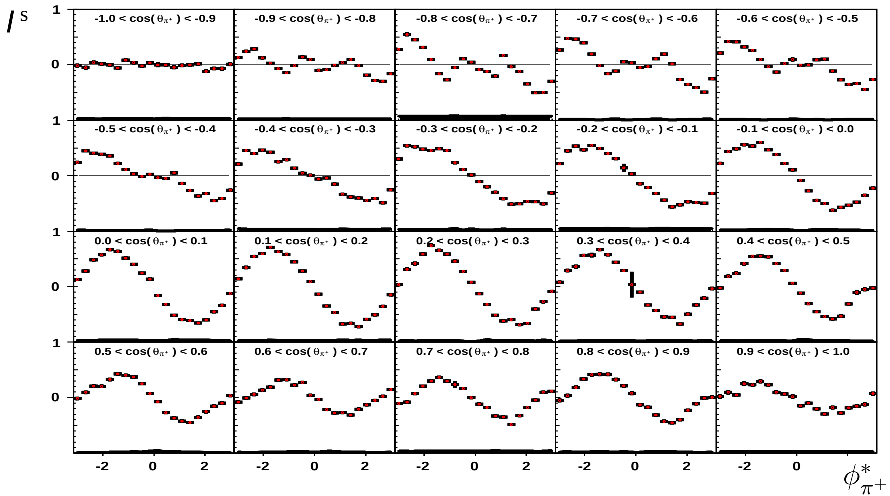
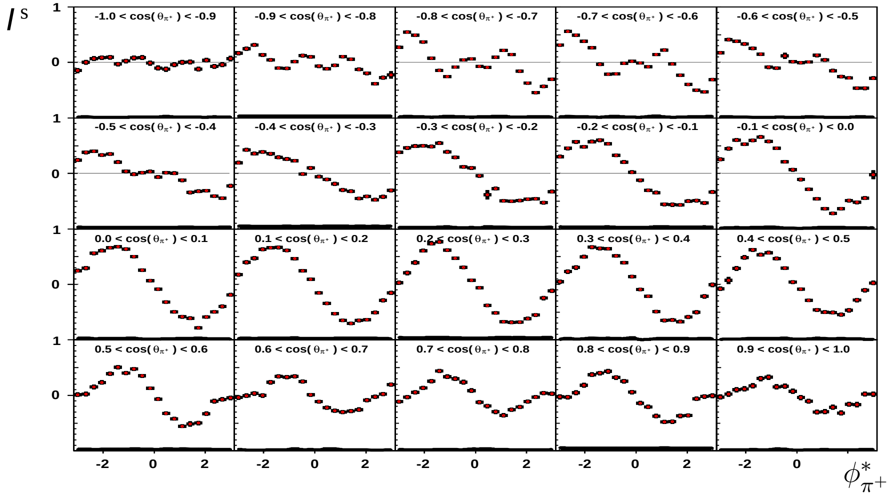
I^s in $\vec{\gamma} p \to p \pi^+ \pi^-$ from JLab: $1600 < E_\gamma < 1650$ MeV



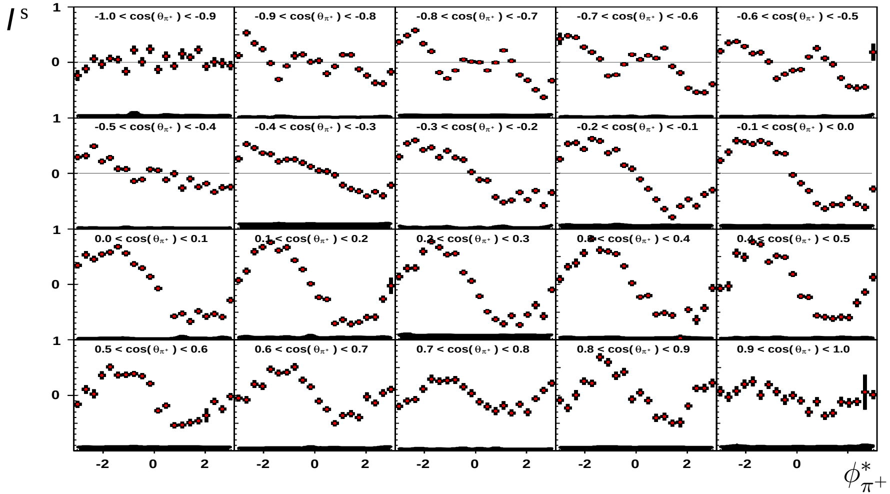
C. Hanretty *et al.*, CLAS-g8b run group, under review

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



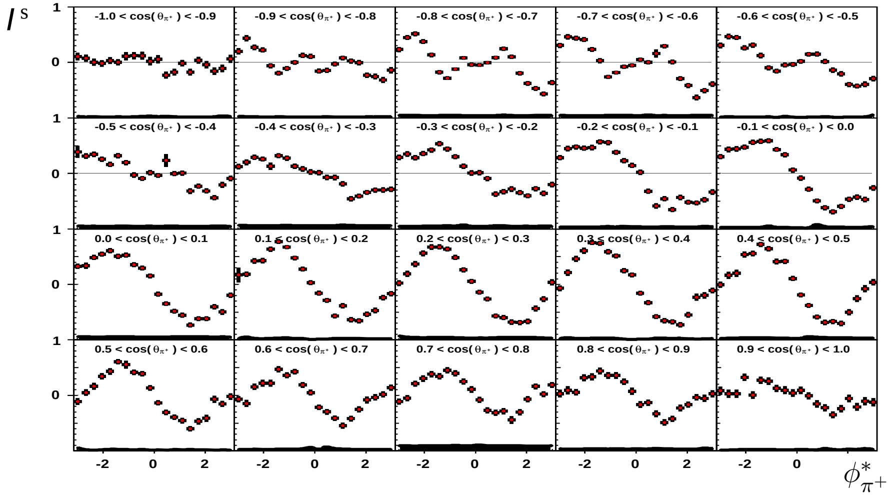
C. Hanretty *et al.*, CLAS-g8b run group, under review

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



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

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



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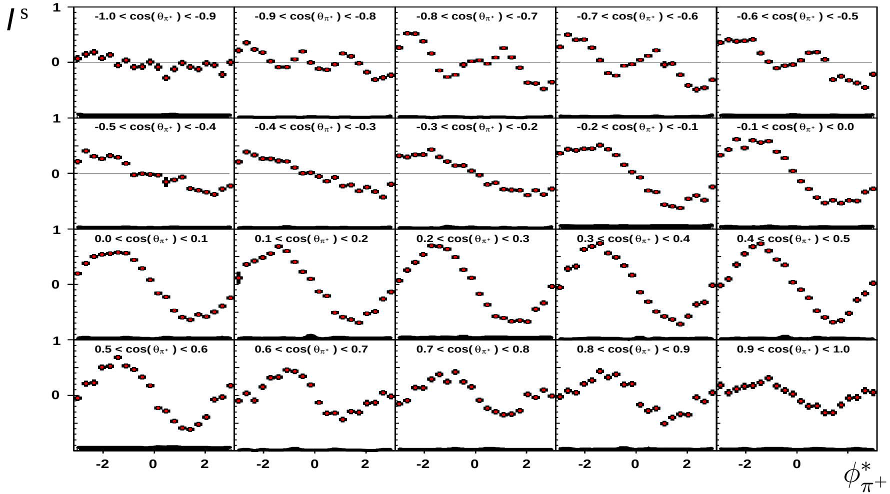
I^{s} in $\vec{\gamma} p \to p \pi^+ \pi^-$ from JLab: $1800 < E_\gamma < 1850$ MeV



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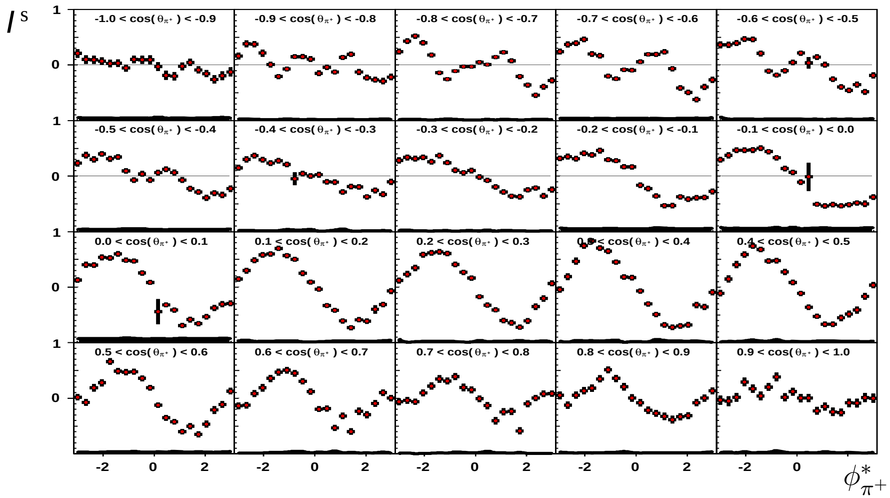
I^s in $\vec{\gamma} p \rightarrow p \pi^+ \pi^-$ from JLab: $1850 < E_\gamma < 1900$ MeV



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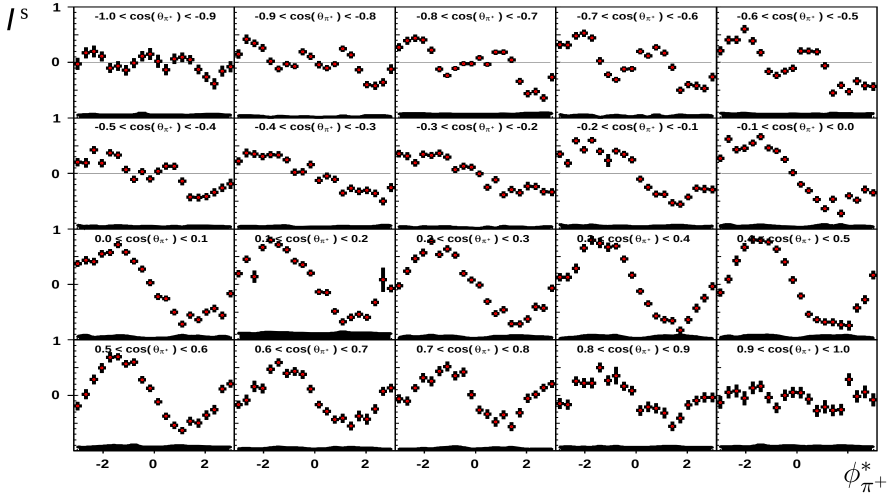
I^s in $\vec{\gamma} p \to p \pi^+ \pi^-$ from JLab: $1900 < E_\gamma < 1950$ MeV



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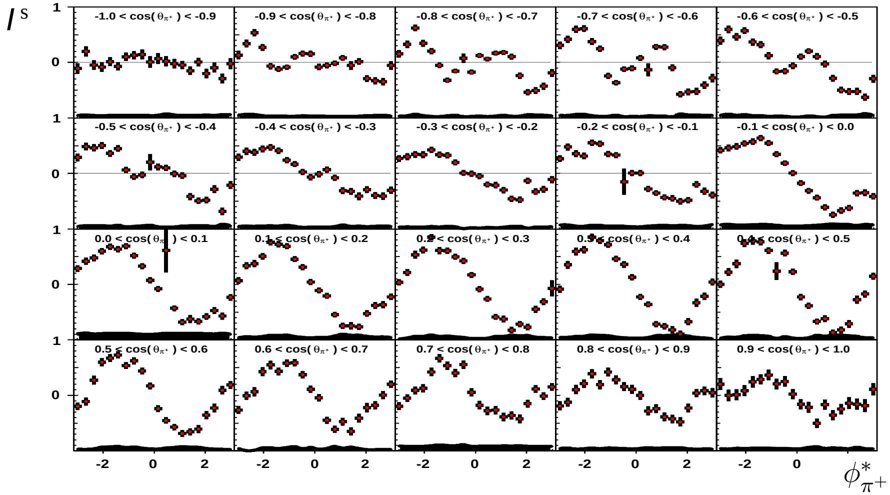
I^s in $\vec{\gamma} p \rightarrow p \pi^+ \pi^-$ from JLab: $1950 < E_\gamma < 2000$ MeV



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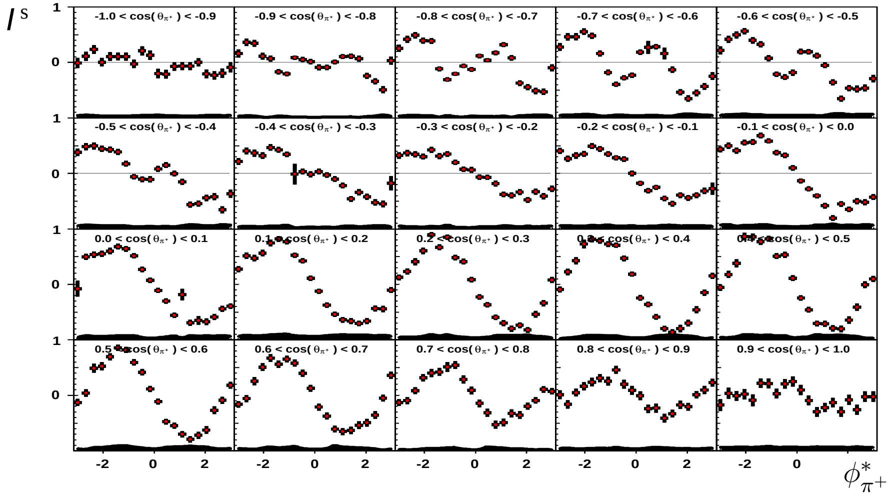
I^s in $\vec{\gamma} p \to p \pi^+ \pi^-$ from JLab: $2000 < E_\gamma < 2050$ MeV



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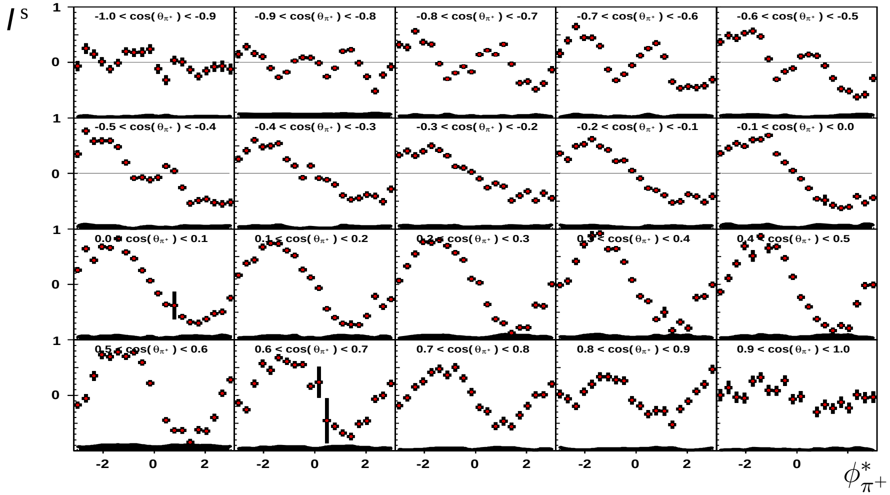
I^s in $\vec{\gamma} p \to p \pi^+ \pi^-$ from JLab: $2050 < E_\gamma < 2100$ MeV



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