Baryon Spectroscopy in Photoproduction: What have we learned about excited baryons?

Volker Credé

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X$_{\text{th}}$ Quark Confinement
and the Hadron Spectrum

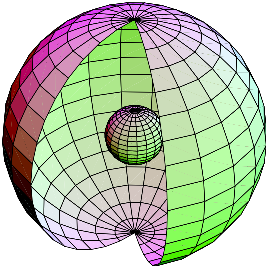
Munich, Germany, 10/08/2012

Outline

Outline

Non-Perturbative QCD

Courtesy of Craig Roberts, Argonne



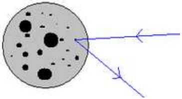
How does QCD give rise to hadrons?

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

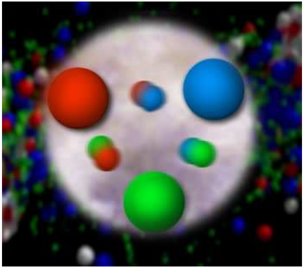
➜

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.



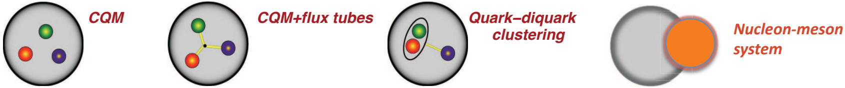
Non-Perturbative QCD



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?



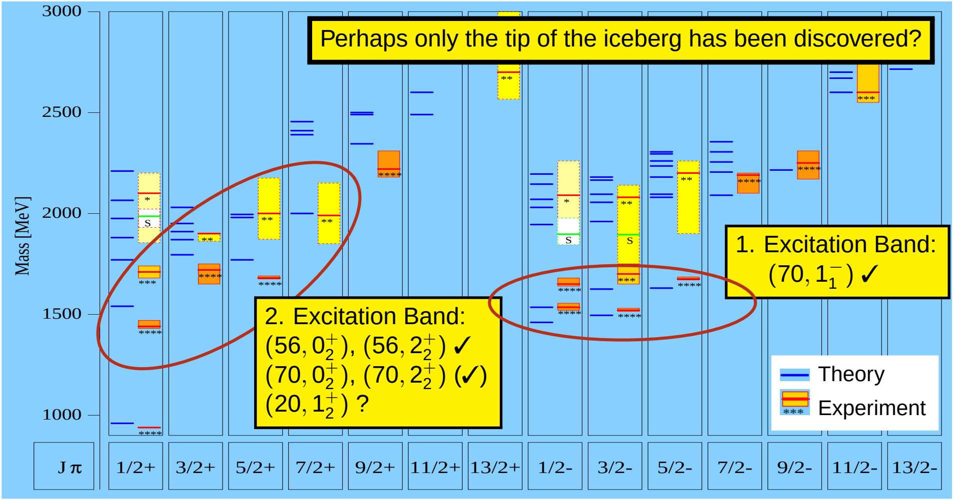
Components of the Experimental N^* Program

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.*

Spectrum of Nucleon Resonances

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



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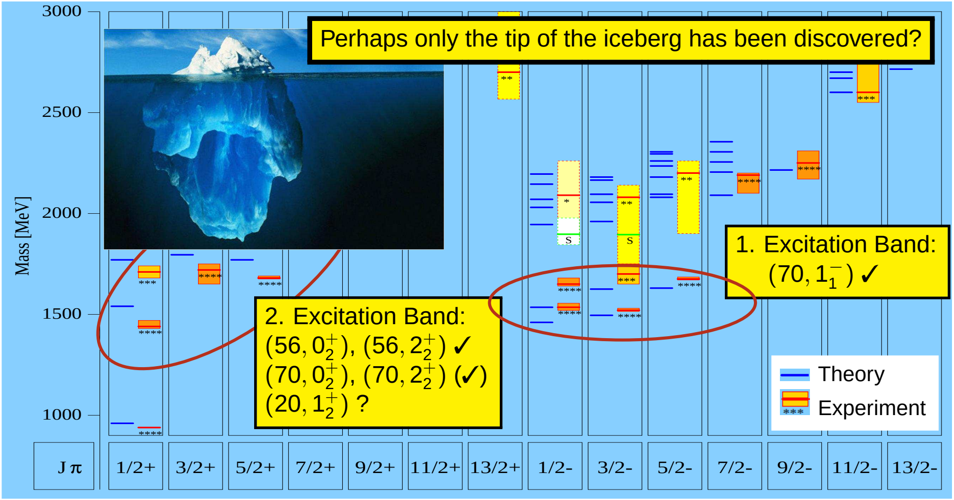
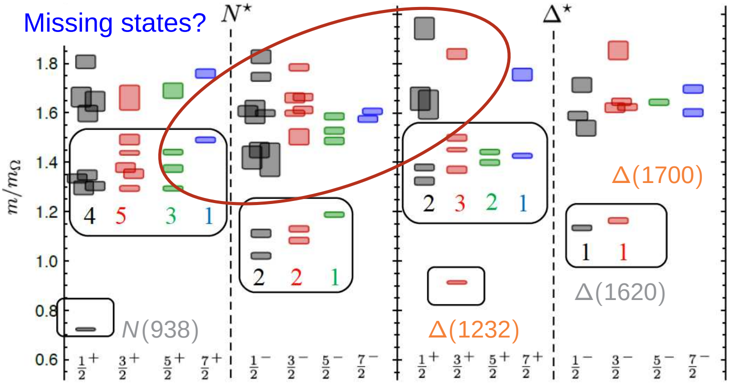


Excited-State Baryon Spectroscopy from Lattice QCD

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

Missing states?

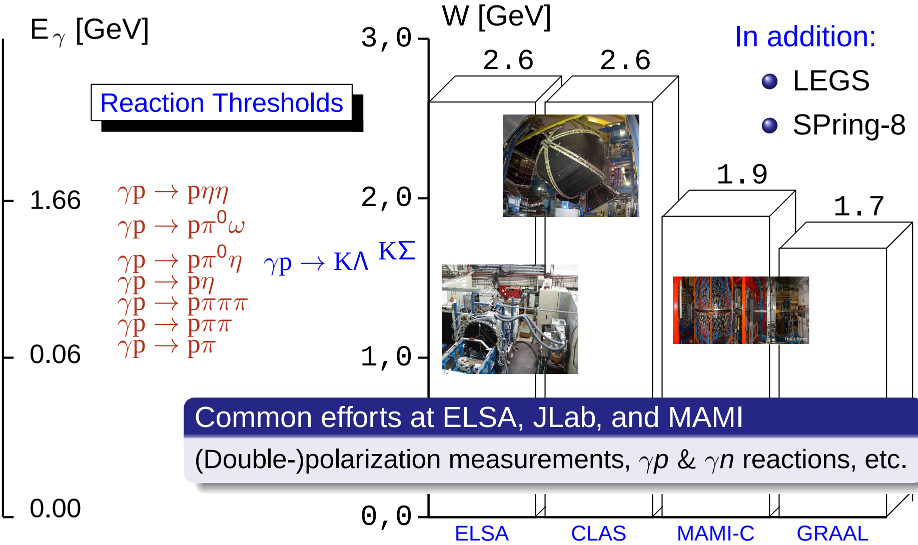


$m_\pi = 400$ MeV

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

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

Outline



In addition:

- LEGS
- SPring-8

Common efforts at ELSA, JLab, and MAMI

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

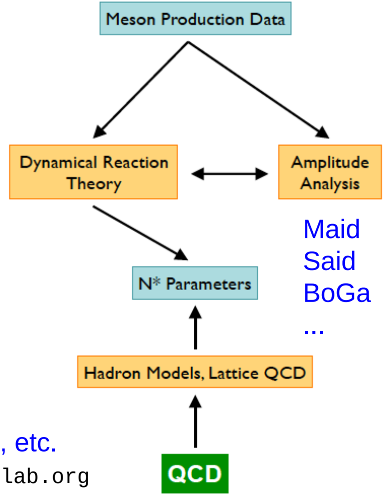
Extraction of Resonance Parameters

- 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.

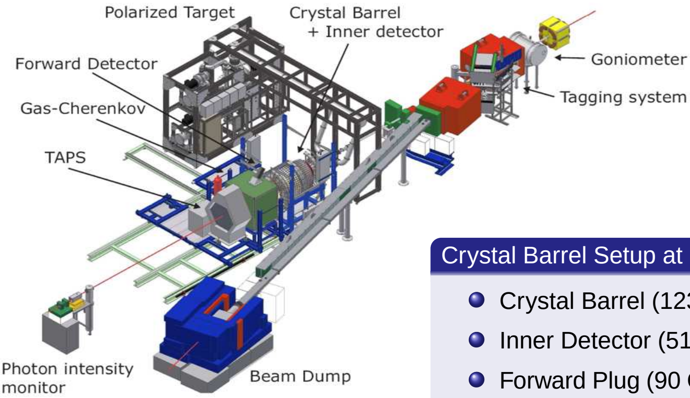
`http://ebac-theory.jlab.org`



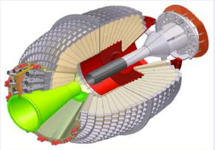
Maid
Said
BoGa
...

Double-Polarization: Toward Complete Experiments

Calorimeter system at ELSA is optimized for neutral particles.



Crystal Barrel



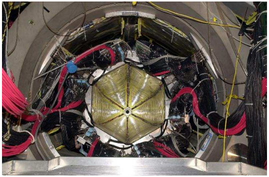
Close to 4π coverage

Frozen-Spin Target: Butanol (C_4H_9OH).

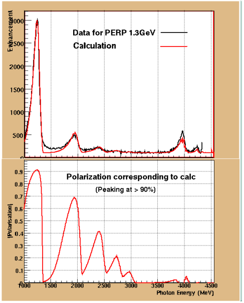
Crystal Barrel Setup at ELSA

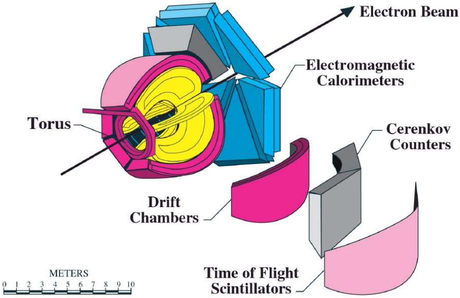
- Crystal Barrel (1230 CsI crystals)
- Inner Detector (513 scintillating fibers)
- Forward Plug (90 CsI crystals with PM's)
- MiniTAPS (216 BaF_2, 1° - 12°)

The CLAS Spectrometer at Jefferson Laboratory

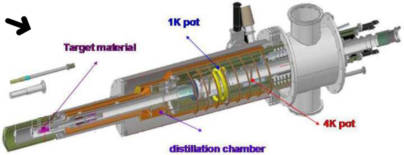


g8b
linear beam
polarization





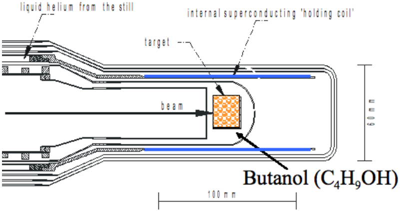
FROST
double polarization

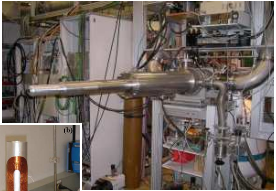


Double-Polarization: Frozen Spin Targets

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

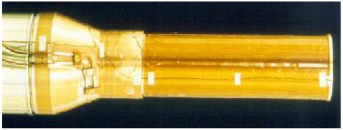




"ELSA"

"CLAS"

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



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

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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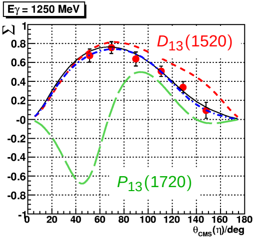
Example: Beam Asymmetry Σ in $\vec{\gamma}\, p \to p\, \eta$



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

CLAS g11a ■

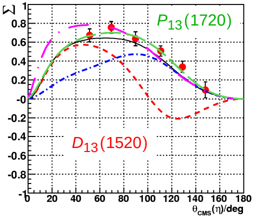
CBELSA/TAPS ○

MAMI ●

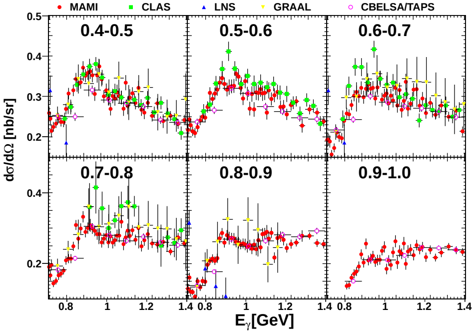
GRAAL ▼

BoGa-PWA

$E_\gamma = 1250$ MeV



η-MAID



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

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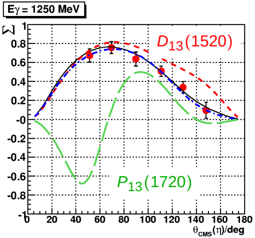

$$\frac{d\sigma}{d\Omega} = \sigma_0 \{ 1 - \delta_l \, \Sigma \cos 2\phi \}$$

BoGa-PWA

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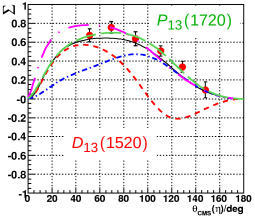
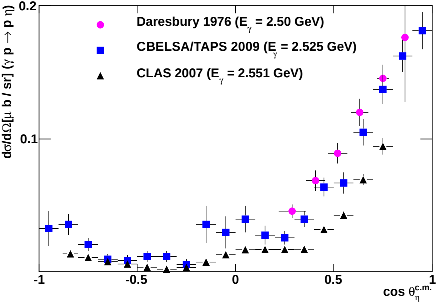


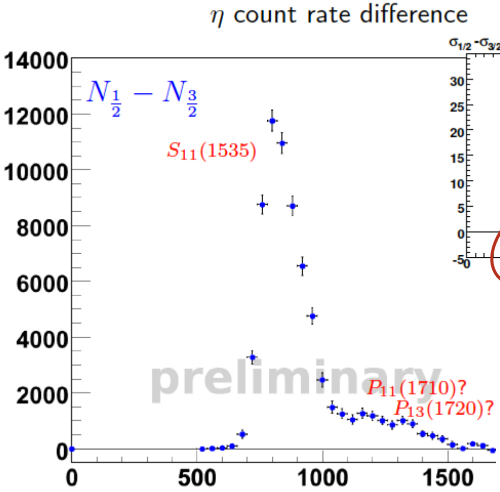
η-MAID

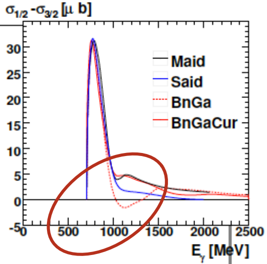
Normalization Discrepancy



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

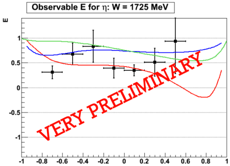
Helicity-Dependent Cross Section for $\vec{\gamma}\,\vec{p} \to p\,\eta$

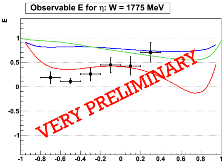




$$E = \frac{\sigma_{1/2} - \sigma_{3/2}}{\sigma_{1/2} + \sigma_{3/2}}$$

➜ Very preliminary: Data are positive





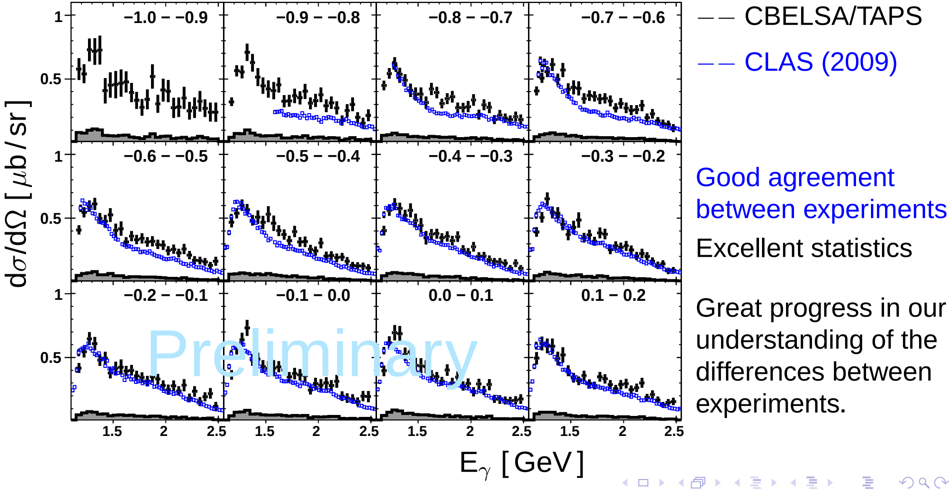
B. Morrison *et al.* [CLAS Collaboration]

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

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.

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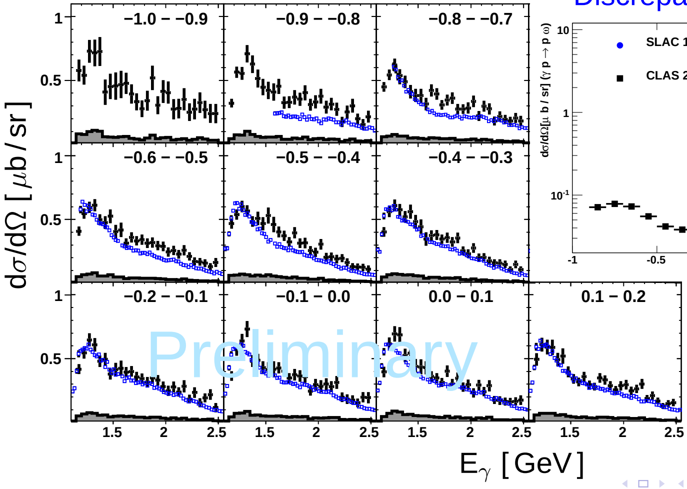
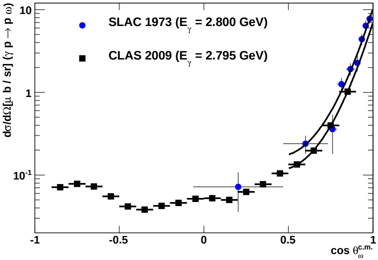


Discrepancy similar to $p\eta$



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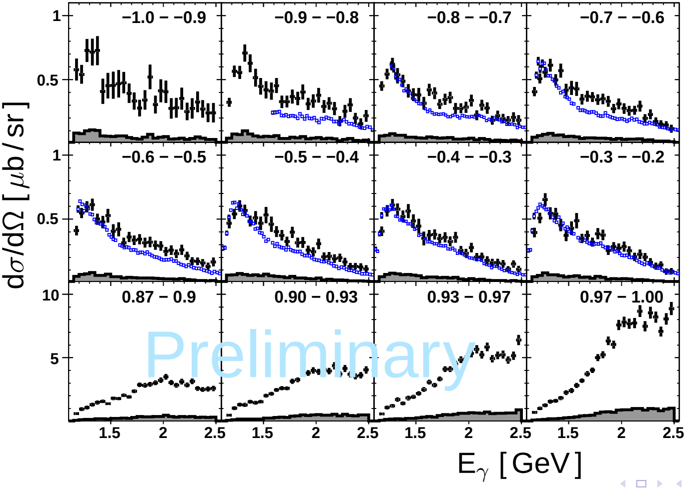


— — CBELSA/TAPS

— — CLAS (2009)

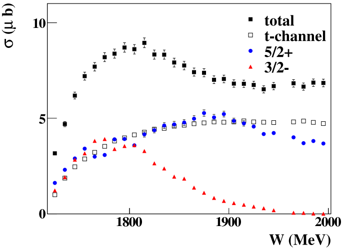
Good agreement between experiments

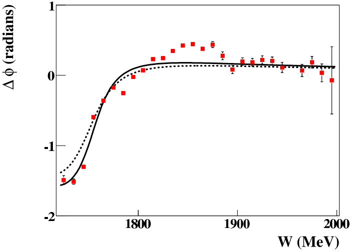
Excellent statistics

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

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

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):

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

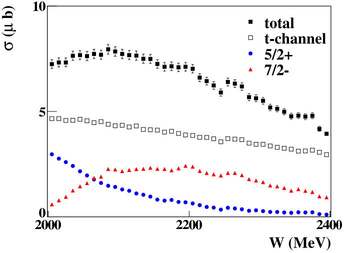
$(5/2)+$ N(1680) $****$

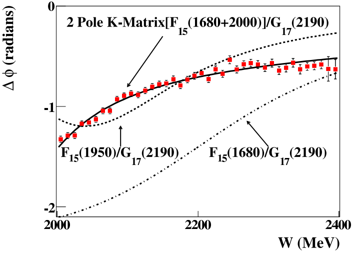
Only nucleon resonances can contribute (isospin filter)

- 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 $\gamma\, p \to p\, \omega$

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





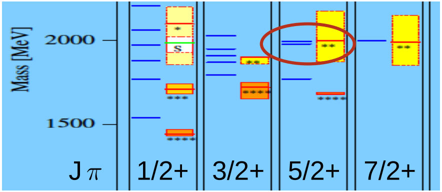
PWA fit includes resonances + *t*-channel amplitudes.

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

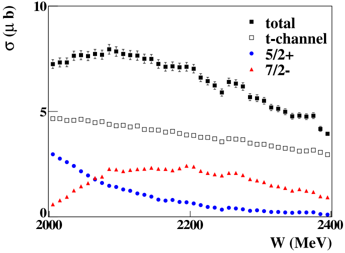
$(5/2)+$ N(1680) $***\,*$

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

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



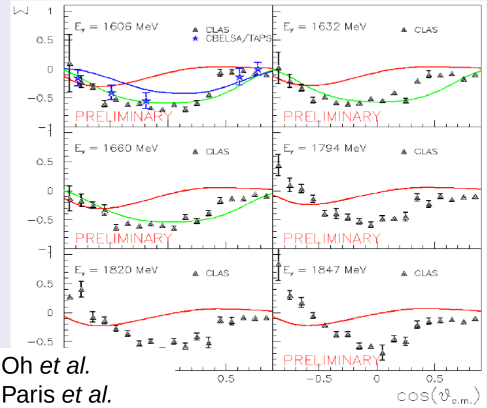
Polarization Observables in $\gamma\, p \to p\, \omega$



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

- $(5/2)+$ N(1680) $****$
- $(5/2)+$ N(1950) $**$
- $\boxed{(7/2)- \text{ N(2190) } ****}$

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

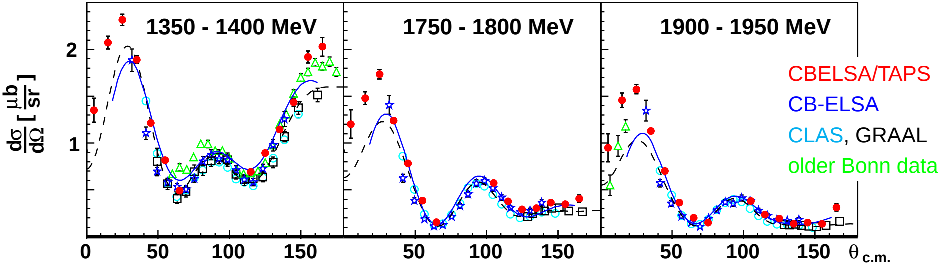


— Oh *et al.*
— Paris *et al.*
— Sarantsev *et al.*

Photoproduction of π^0 Mesons from the Proton

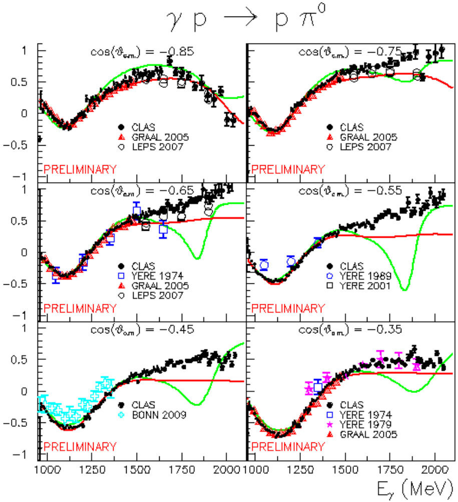
Reaction $\gamma p \to p\,\pi^0$ remains important for our understanding of baryons.

- 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 $\vec{\gamma}\, p \to p\, \pi^0$



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$$+ \Lambda_x \left(-\delta_l\, H \sin 2\phi + \delta_\odot\, F \right)$$
$$- \Lambda_y \left(-T + \delta_l\, P \cos 2\phi \right)$$
$$- \Lambda_z \left(-\delta_l\, G \sin 2\phi + \delta_\odot\, E \right) \}$$

— SAID — MAID • CLAS

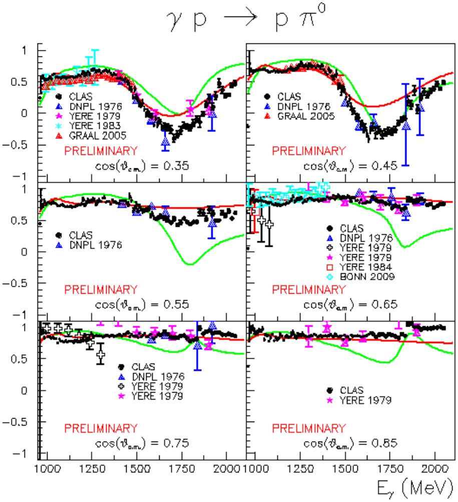
($E_\gamma < 2$ GeV, $-0.85 < \cos\theta_\pi < -0.35$)

➜ 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, $0.35 < \cos\theta_\pi < 0.85$)

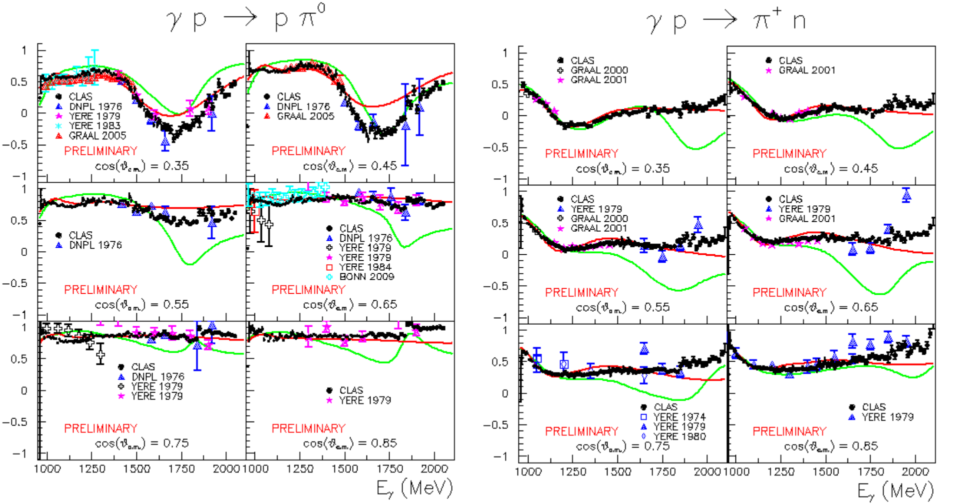
Combination of $p\,\pi^0$ and $n\,\pi^+$ final states can help distinguish between Δ and N^* resonances:

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

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

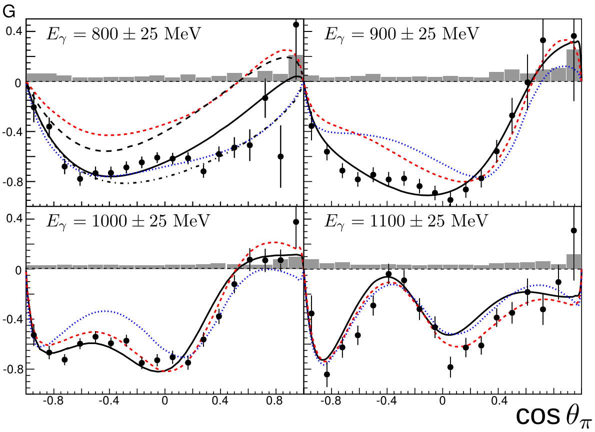
M. Dugger (ASU), CLAS g8b run group, to be published

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

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



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$$+ \Lambda_x \,(-\delta_l\, H \sin 2\phi + \delta_\odot\, F)$$
$$- \Lambda_y \,(-T + \delta_l\, P \cos 2\phi)$$
$$- \Lambda_z \,(-\delta_l\, G \sin 2\phi + \delta_\odot\, E)\}$$

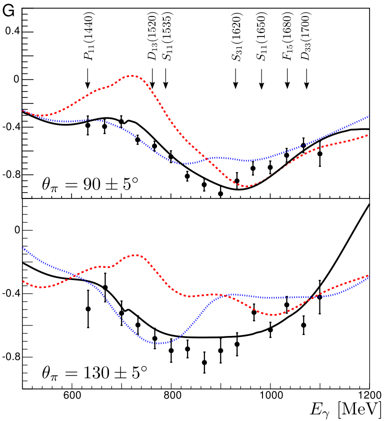
Surprisingly, π production also not well understood at lower energies:

— 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)

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



$\theta_\pi = 90 \pm 5°$

$\theta_\pi = 130 \pm 5°$

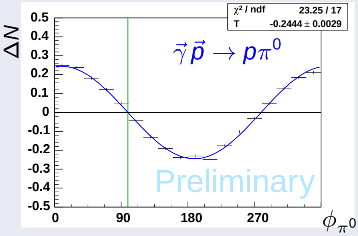
Surprisingly, π production also not well understood at lower energies.

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

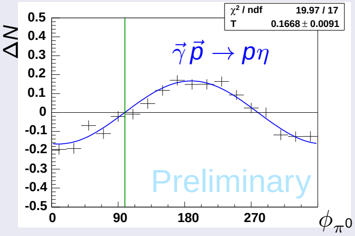
A. Thiel *et al.* [CBELSA/TAPS], PRL **109**, 102001 (2012)

Transverse Target Polarization: Target Asymmetry T

700 < E_γ < 800 MeV



800 < E_γ < 900 MeV



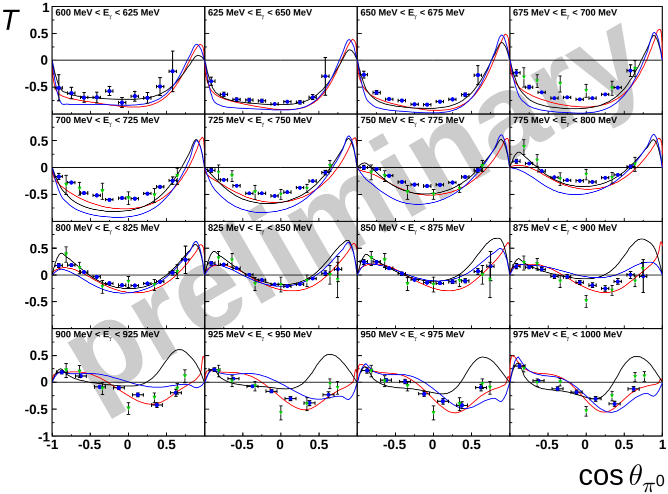
direction of target pol.: $\beta = 99^\circ$

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

➜ 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)



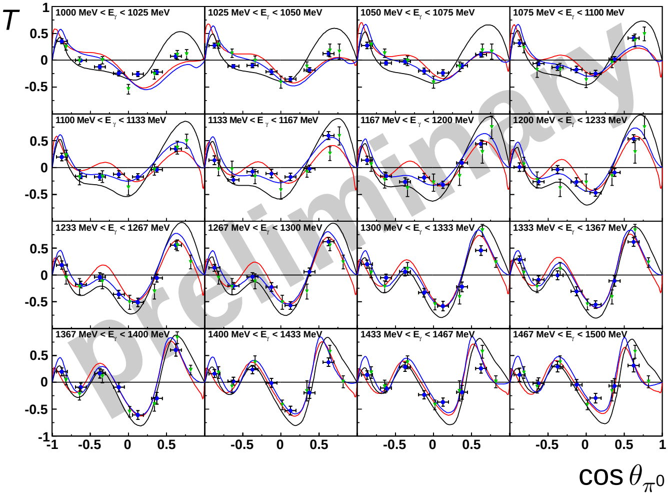
$600 < E_\gamma < 1000$ MeV
in bins of $\Delta E = 25$ MeV

- 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

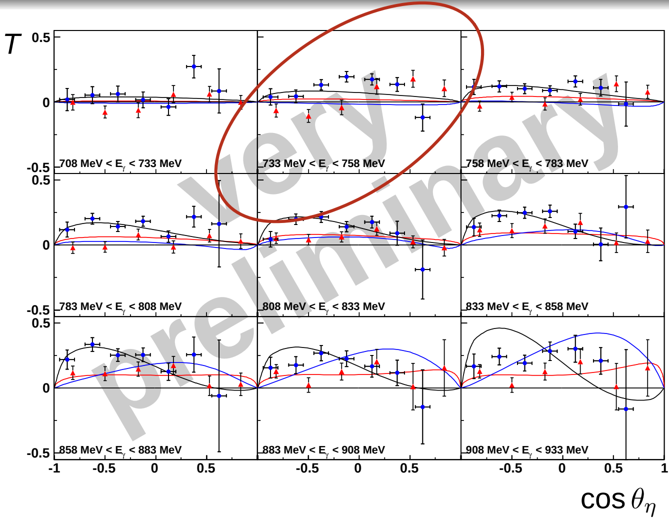
- CBELSA/TAPS
- Daresbury (1977)
  Nucl. Phys. B **121** (1977), 45
- Maid
- Said
- Bonn Gatchina

➜ Good agreement of experimental data.

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

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

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

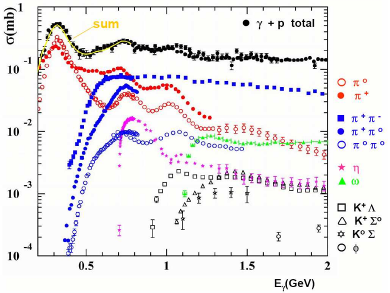
J. Hartmann *et al.* [CBELSA/TAPS]

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

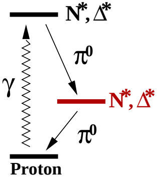
W. Roberts *et al.*, Phys. Rev. C **71**, 055201 (2005)

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

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



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



$\rightarrow$ Search for states in decay cascades!

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.
- Spectroscopy will continue at ELSA, MAMI and JLab in the 12 GeV era (e.g. Ξ, Ω states): GlueX and CLAS12.

$N(1860)\,\frac{5}{2}^+$	$**$	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		
$\Delta(1940)\,\frac{3}{2}^-$	$* \to **$	πN	γN				$\Delta\eta$ (!)	

New States in PDG 2012.

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

Two mesons in the final state require 5 independent variables!

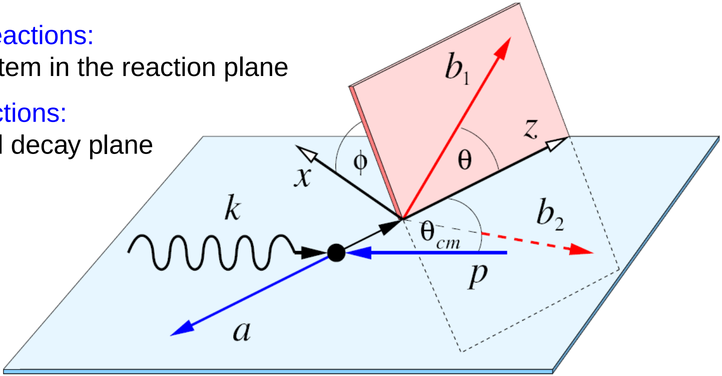
For example: E_γ, $\Theta_{\rm c.m.}$, ϕ^*, θ^*, $M_{p\,+\,meson\,1}$

Single-meson reactions:

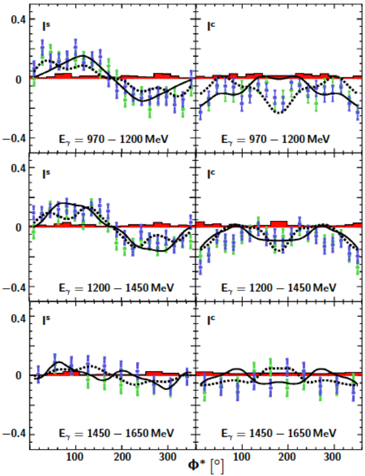
➜ p-meson system in the reaction plane

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 $\Delta\pi$:

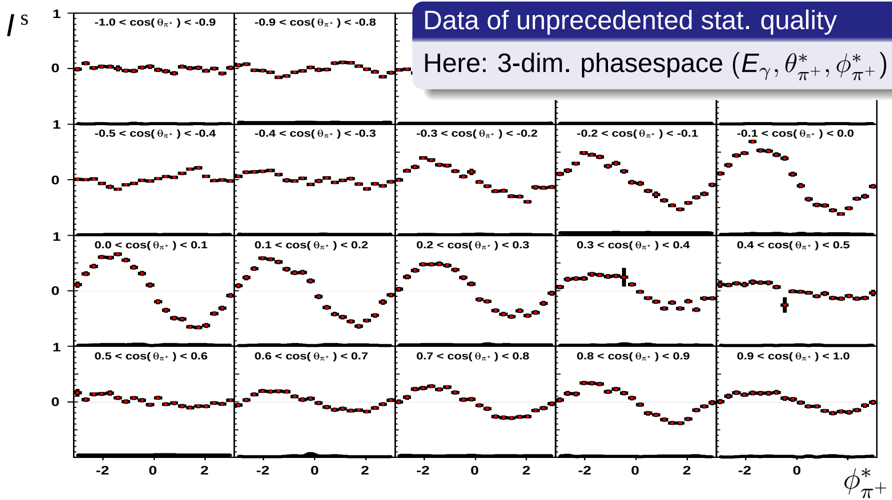
— — BoGa-PWA solution with a dominant $\Delta(1700)D_{33} \to \Delta\pi$ D-wave

…… 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

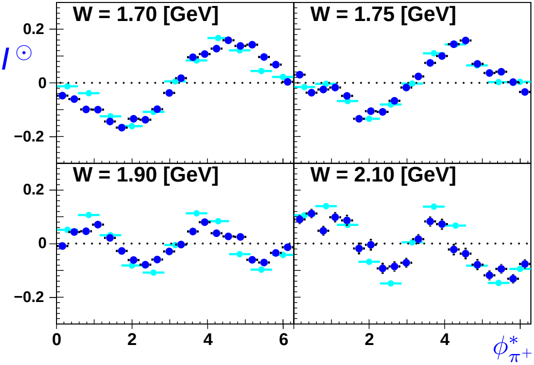
Here: 3-dim. phasespace $(E_\gamma, \theta^*_{\pi^+}, \phi^*_{\pi^+})$

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

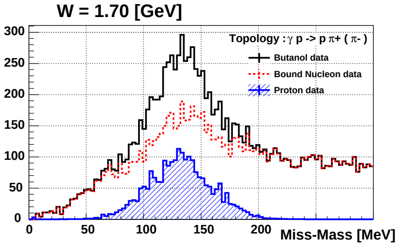
Beam Asymmetry $I^{\odot}$ in $\vec{\gamma} p \to p\,\pi^+\pi^-$ from JLab

Analysis of butanol target challenging:

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



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