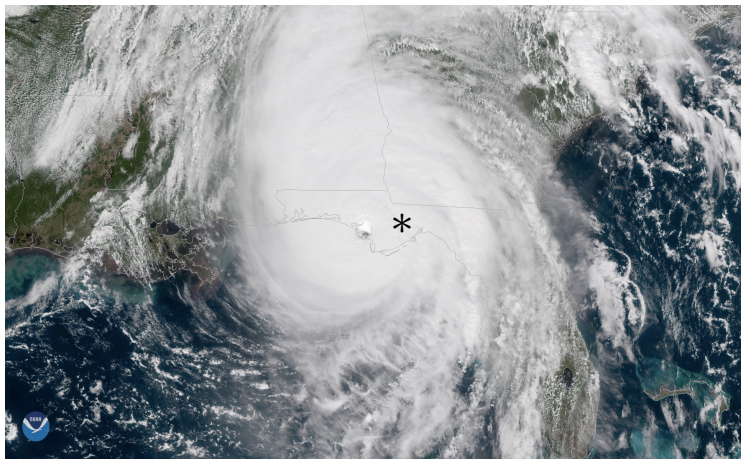
Photoproduction of $p\eta$, $K^0\Sigma^+$, and $p\omega$ using CLAS-g12 $\vec{\gamma}p \to p\pi^+\pi^-\pi^0$ Data

Volker Credé

Florida State University, Tallahassee, FL *



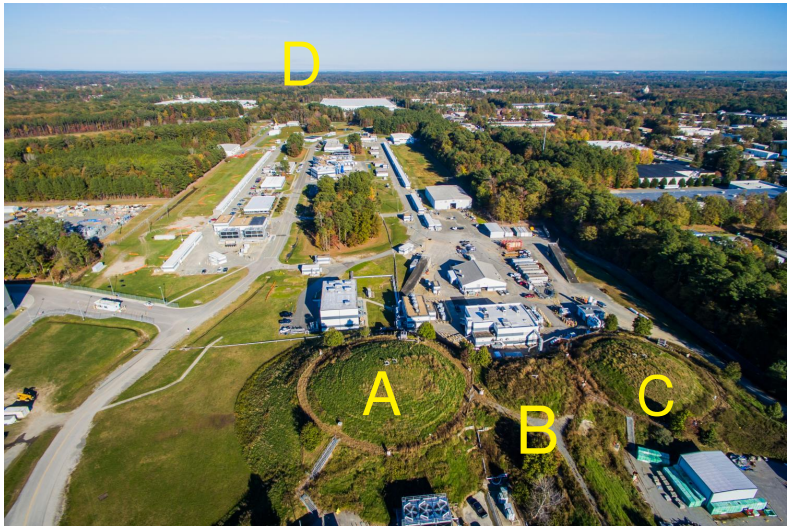
CLAS Collaboration Meeting

Jefferson Lab

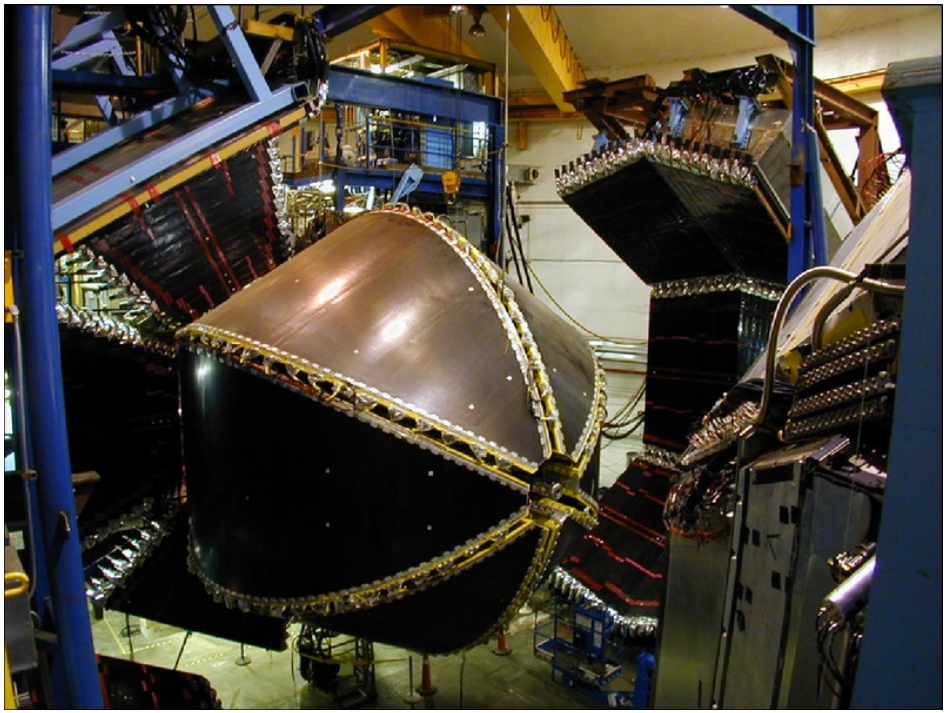
11/15/2019

Outline

Outline



CLAS (6 GeV) at JLab 1998 - 2012



Double-Polarization Experiments

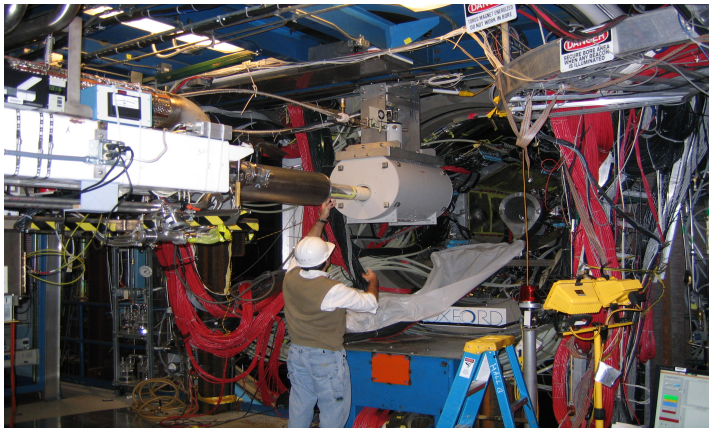


Photo-/electroproduction experiments in search for N^* states and measurement of the transition amplitudes.

← CLAS FROST

Table representing CLAS@JLab measurements

	σ	Σ	T	P	E	F	G	H	$T_{x'}$	$T_{z'}$	$L_{x'}$	$L_{z'}$	$O_{x'}$	$O_{z'}$	$C_{x'}$	$C_{z'}$
							Proton targets									
$p\,\pi^0$	✓	✓	✓	(✓)	✓	✓	✓	✓								
$n\,\pi^+$	✓	✓	✓	(✓)	✓	✓	✓	✓								
$p\,\eta$	✓	✓	✓	(✓)	✓	✓	✓	✓								
$p\,\eta'$	✓	✓	✓	(✓)	✓	✓	✓	✓								
$p\,\omega\,(\phi)$	✓	✓	✓	(✓)	✓	✓	✓	✓								
$K^+\,\Lambda$	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
$K^+\,\Sigma^0$	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
$K^0\,\Sigma^+$	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
							Neutron (deuteron) targets									
$p\,\pi^-$	✓	✓			✓		✓									
$K^+\,\Sigma^-$	✓	✓	✓	✓	✓	✓	✓									
$K^0\,\Lambda$	✓	✓	✓	✓	✓*	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
$K^0\,\Sigma^0$	✓	✓	✓	✓	✓*	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

✓ published
✓ acquired or under analysis
Tensor polarization, SDMEs

Complete Experiments?

* published

"Uncertainty is an uncomfortable position. But Certainty is an absurd one."

Voltaire

Table representing CLAS@JLab measurements

	σ	Σ	T	P	E	F	G	H	$T_{x'}$	$T_{z'}$	$L_{x'}$	$L_{z'}$	$O_{x'}$	$O_{z'}$	$C_{x'}$	$C_{z'}$
						Proton targets										
$p\,\pi^0$	✓	✓	✓	(✓)	✓	✓	✓	✓								
$n\,\pi^+$	✓	✓	✓	(✓)	✓	✓	✓	✓		✓						
$p\,\eta$	✓	✓	✓	(✓)	✓	✓	✓	✓		✓						
$p\,\eta'$	✓	✓	✓	(✓)	✓	✓	✓	✓								
$p\,\omega\,(\phi)$	✓	✓	✓	(✓)	✓	✓	✓	✓								
$K^+\,\Lambda$	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
$K^+\,\Sigma^0$	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
$K^0\,\Sigma^+$	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
						Neutron (deuteron) targets										
$p\,\pi^-$	✓	✓			✓		✓									
$K^+\,\Sigma^-$	✓	✓	✓	✓	✓	✓	✓									
$K^0\,\Lambda$	✓	✓	✓	✓	✓*	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
$K^0\,\Sigma^0$	✓	✓	✓	✓	✓*	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

✓ published

✓ acquired or under analysis

Tensor polarization, SDMEs

Complete Experiments?

* published

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Table representing CLAS@JLab measurements

	σ	Σ	T	P	E	F	G	H	$T_{x'}$	$T_{z'}$	$L_{x'}$	$L_{z'}$	$O_{x'}$	$O_{z'}$	$C_{x'}$	$C_{z'}$
						Proton targets										
$p\,\pi^0$	✓	✓	✓	(✓)	✓	✓	✓	✓								
$n\,\pi^+$	✓	✓	✓	(✓)	✓	✓	✓	✓								
$p\,\eta$	✓	✓	✓	(✓)	✓	✓	✓	✓								
$p\,\eta'$	✓	✓	✓	(✓)	✓	✓	✓	✓								
$p\,\omega\,(\phi)$	✓	✓	✓	(✓)	✓	✓	✓	✓								
$K^+\,\Lambda$	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
$K^+\,\Sigma^0$	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
$K^0\,\Sigma^+$	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
						Neutron (deuteron) targets										
$p\,\pi^-$	✓	✓			✓		✓									
$K^+\,\Sigma^-$	✓	✓	✓	✓	✓	✓	✓									
$K^0\,\Lambda$	✓	✓	✓	✓	✓*	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
$K^0\,\Sigma^0$	✓	✓	✓	✓	✓*	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

✓ published
✓ acquired or under analysis

Tensor polarization, SDMEs

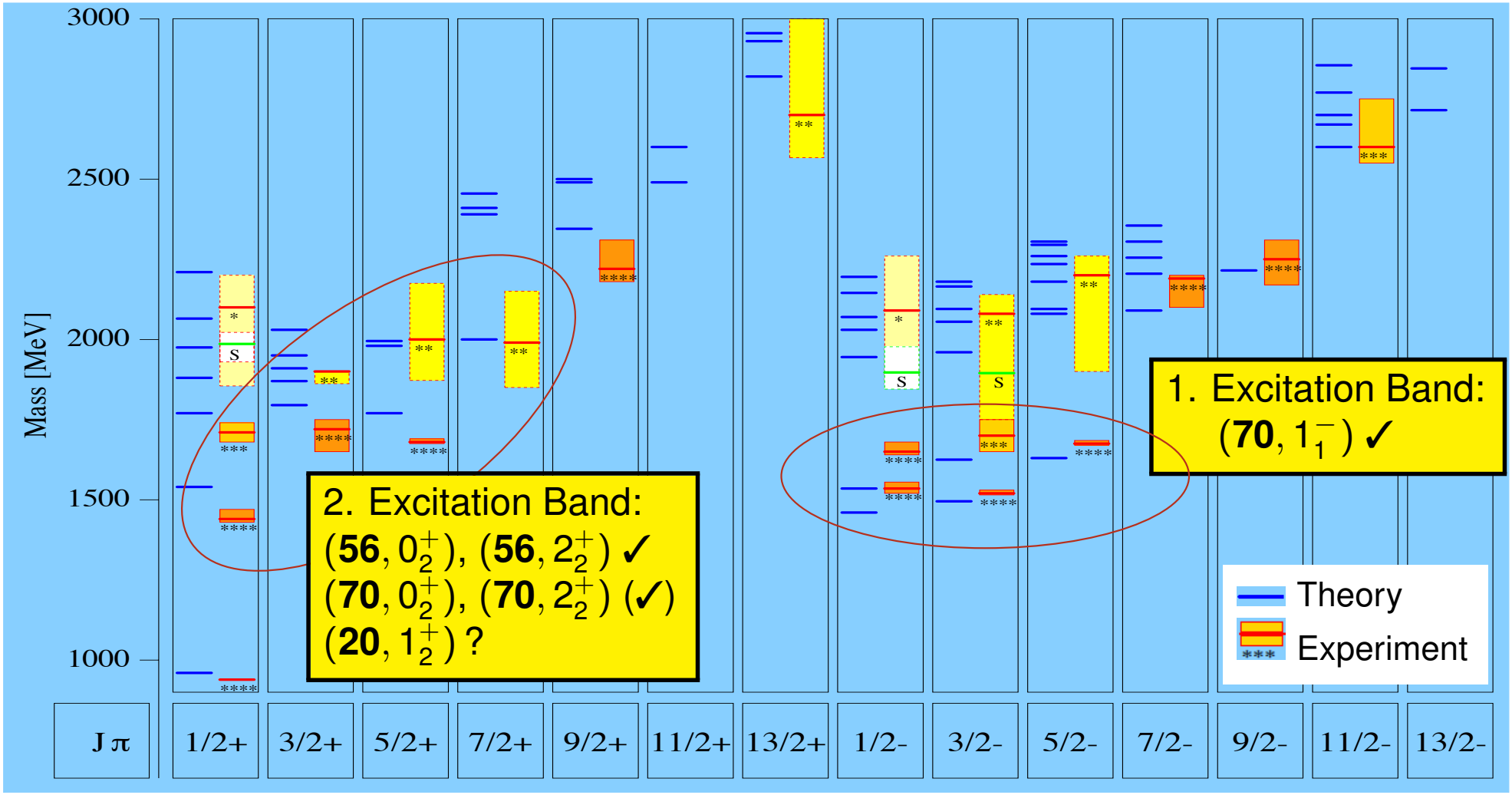
* published

In addition, two-meson reactions are being analyzed:

$\gamma p \to (p\,\rho) \to p\,\pi^+\pi^-$ (CLAS), $\gamma p \to p\,\pi^0\pi^0$, $p\,\pi^0\eta$, $p\,\pi^0\omega$ (ELSA, MAMI, etc.)

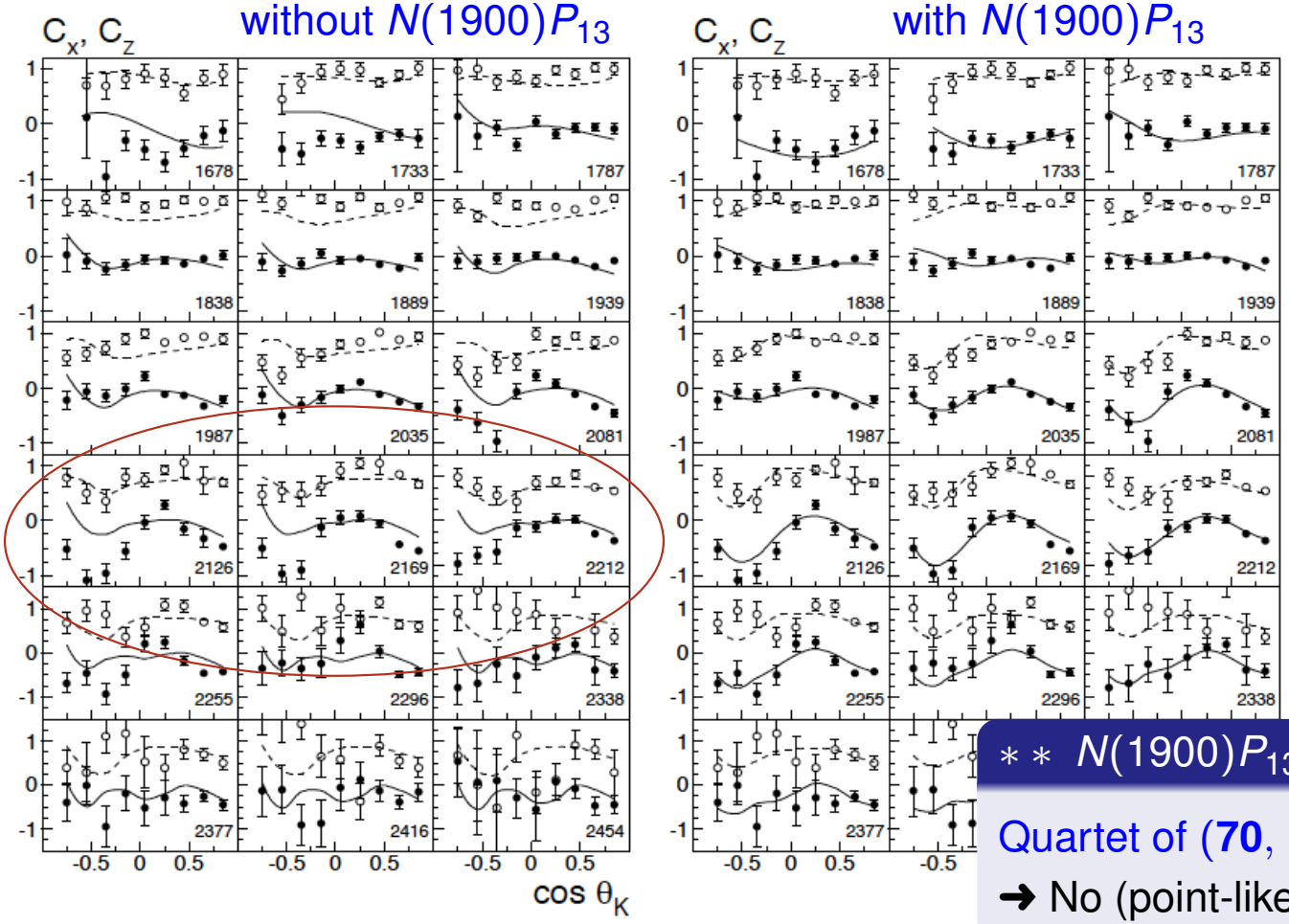
Outline

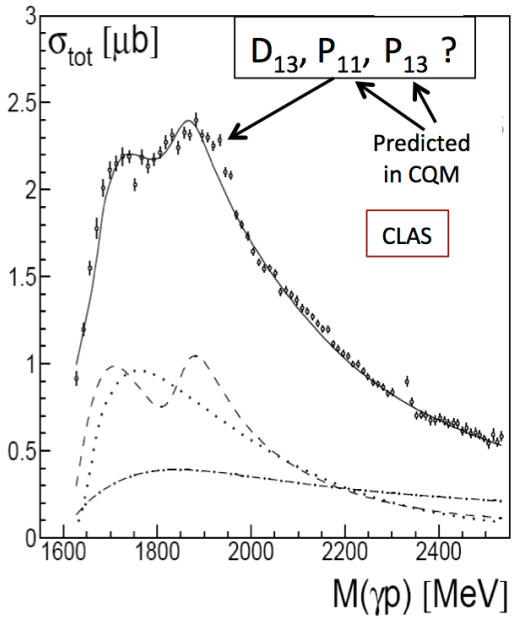
Spectrum of N^* Resonances



V. C. & W. Roberts, Rep. Prog. Phys. **76** (2013)

Polarization Transfer in $\vec{\gamma} p \to K^+ \vec{\Lambda}$: C_x & C_z





* * $N(1900)P_{13}$, $N(2000)F_{15}$, $N(1990)F_{17}$

Quartet of (**70**, 2_2^+) with $S = \frac{3}{2}$

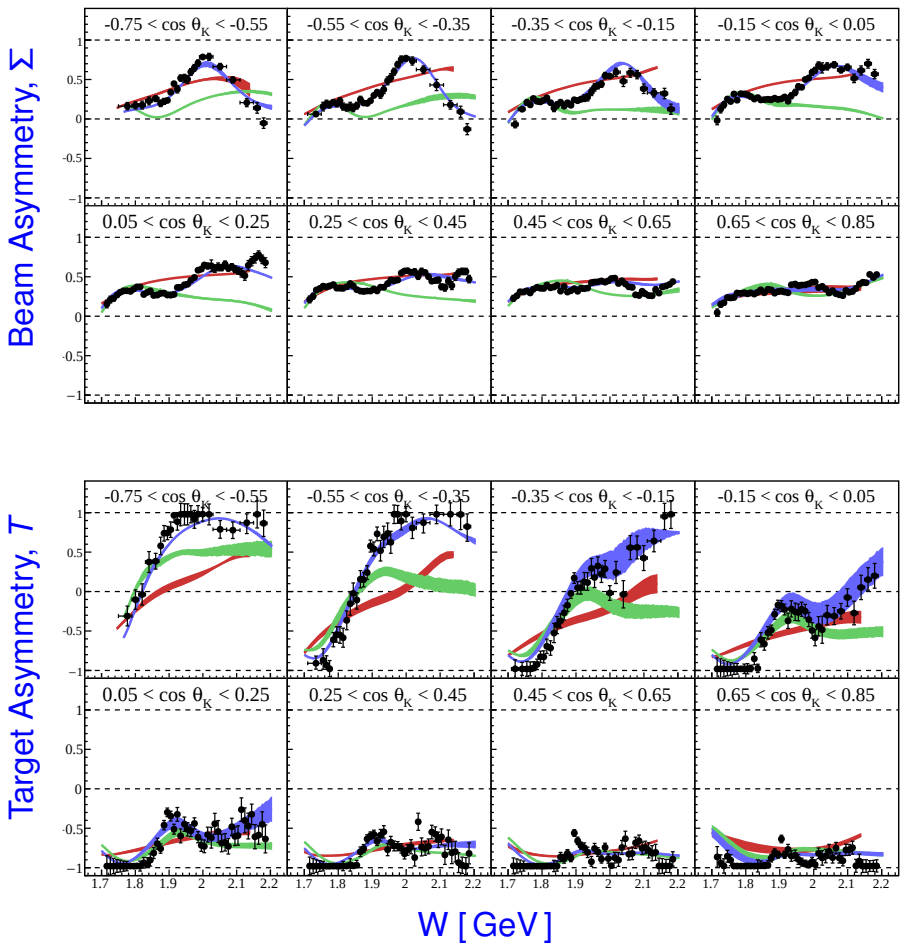
➜ No (point-like) quark-diquark oscillations!

R. Bradford *et al.* [CLAS Collaboration], PRC **75**, 035205 (2007)

Fits: BoGa-Model, V. A. Nikonov *et al.*, Phys. Lett. B **662**, 245 (2008)

Polarization Observables in $\vec{\gamma} p \to K^+ \Lambda$ (g8b)

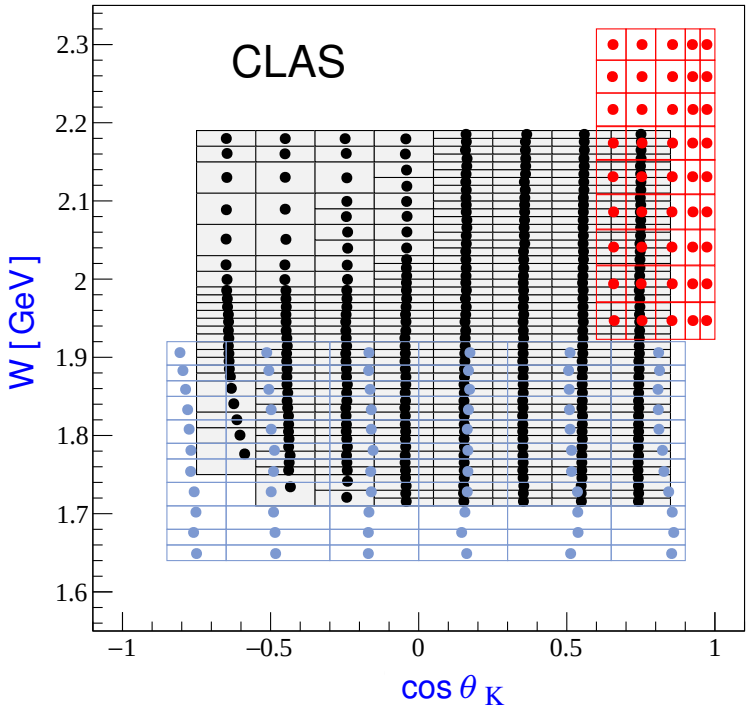
C. A. Paterson *et al.*, Phys. Rev. C **93**, 065201 (2016)



— ANL-Osaka — BnGa '14 — BnGa '14 refit

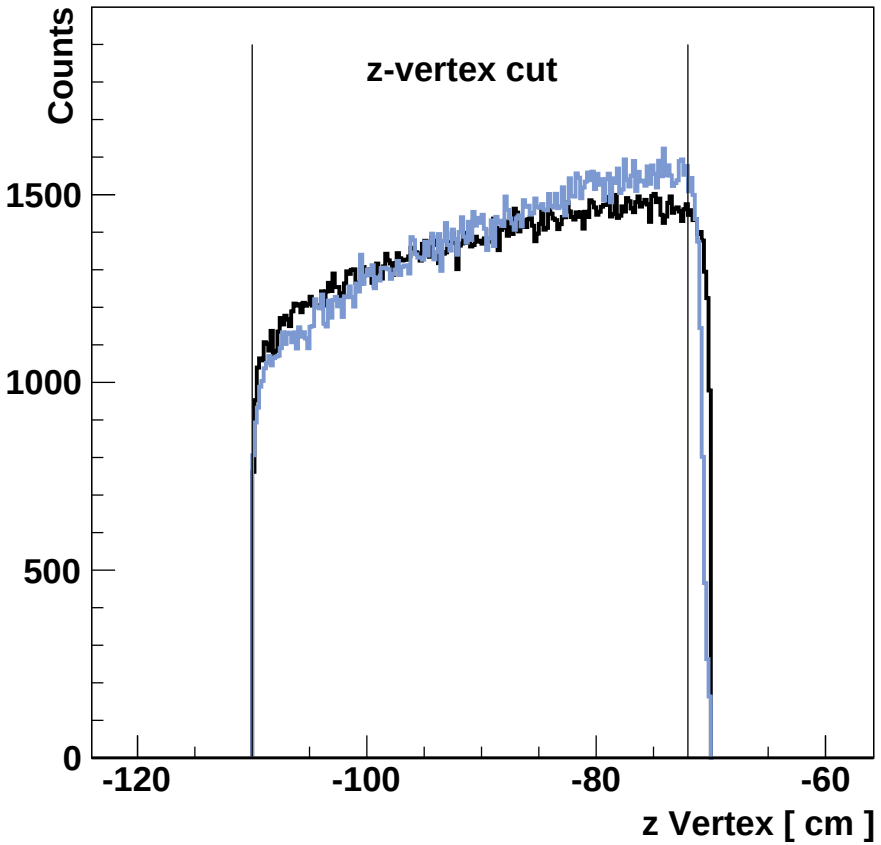
➜ Additional $N^* \frac{3}{2}^+$, $N^* \frac{5}{2}^+$ needed in BnGa refit.

comparison of kinematic coverage



The CLAS-g12 Experiment (for this analysis)

1. **Target position**
   Shifted upstream by 90 cm
2. **Tagging range ($E_{e^-} = 5.715$ GeV)**
   Lowest tagged photon energy
   $$E_\gamma \approx 1150 \text{ MeV}$$
3. **Trigger**
   1. 2 tracks & $E_\gamma > 3.6$ GeV
   2. 3 tracks & no E_γ restrictions
4. **Polarization**
   Circularly-pol. incident photons



Preparation of the $\gamma p \to p\pi^+\pi^-\pi^0$ Final State

The reaction $\gamma p \to p\pi^+\pi^-\pi^0$ is interesting for many reasons:

1. $\gamma p \to p\omega \to p\pi^+\pi^-\pi^0$

   Initial motivation: This high-statistics channel is important to understand cross sections using g12 data.

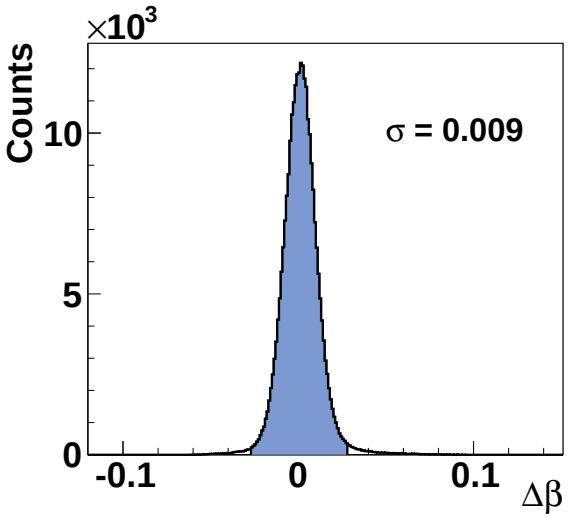
   Moreover: Measurement of g12 SDMEs (combined with SDMEs from g8b) complements FROST results and extends the earlier g11a results into the Regge regime.

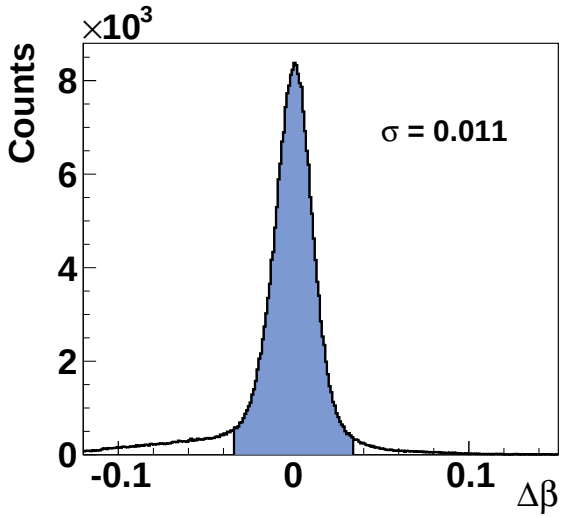
2. Primary motivation: $\gamma p \to K^0 \Sigma^+ \to p\pi^+\pi^-\pi^0$
   (cross sections; polarization observables P, C_x, C_z)

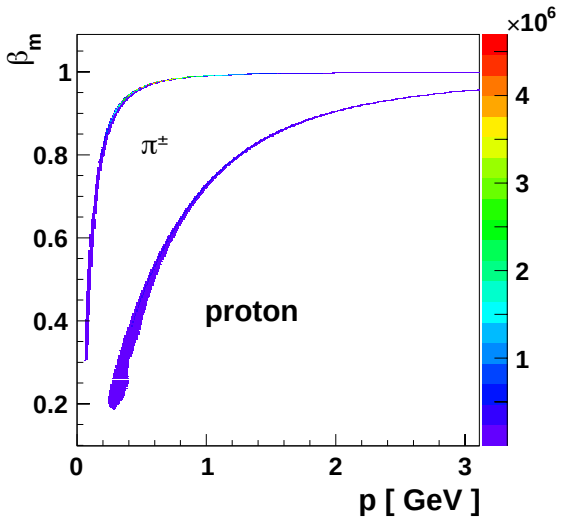
3. Byproduct but first to be published: $\gamma p \to p\eta \to p\pi^+\pi^-\pi^0$

➜ Work by the g12 group; FSU students Z. Akbar, T. Hu, F. Gonzalez

Preparation of the $\gamma p \to p\pi^+\pi^-\pi^0$ Final State





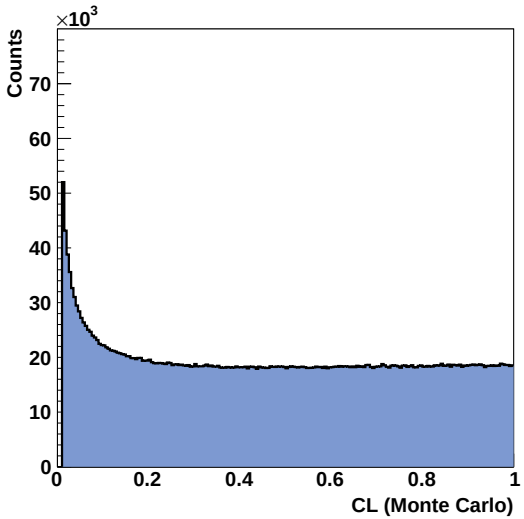


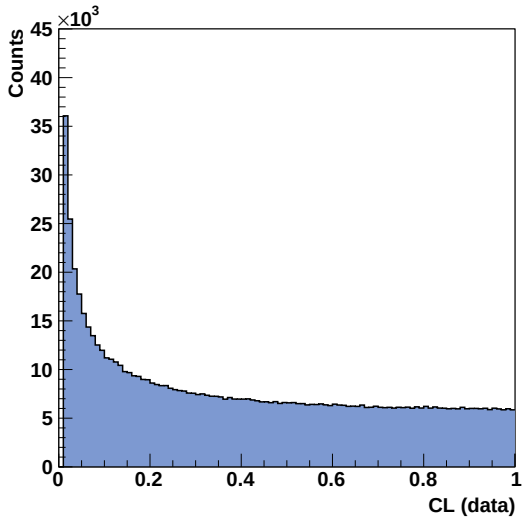
Event reconstruction and selection criteria

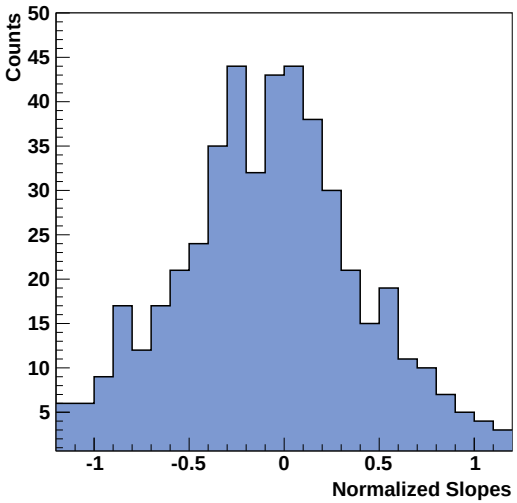
(CLAS-g12 Run Group, CLAS-NOTE 2017-002, 2017)

- Selection of tracks: $\gamma p \to p\pi^+\pi^-$ (π^0)
- Standard g12 fiducial cuts, ELoss & momentum corrections
- z-Vertex cut: $-110\ \text{cm} < z\ \text{vertex} < -72\ \text{cm}$
- PID: 3σ cuts on $\Delta\beta$ distributions for either proton or π^+

Preparation of the $\gamma p \to p\pi^+\pi^-\pi^0$ Final State







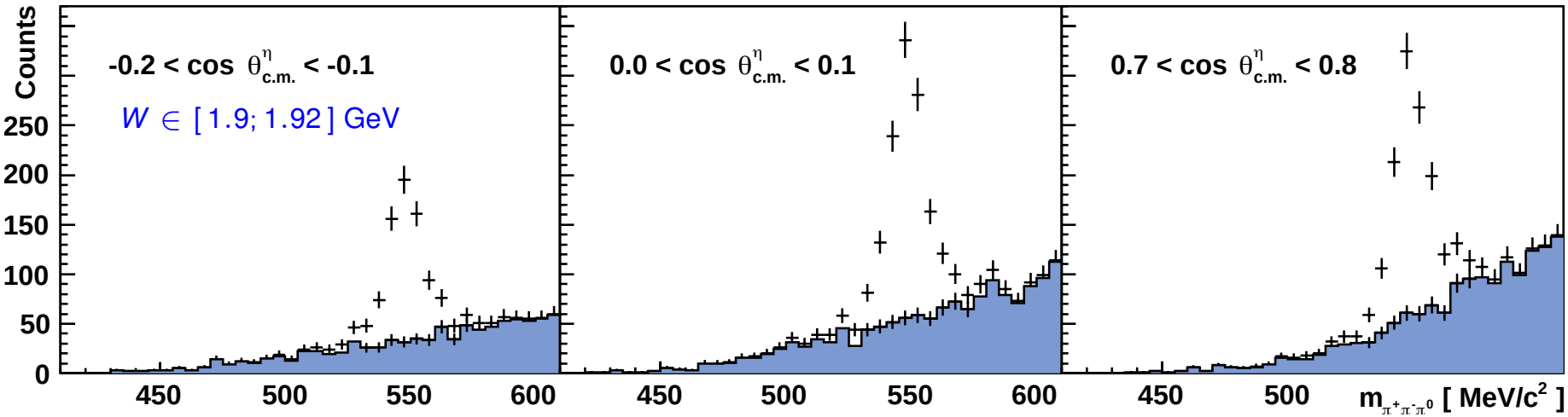
Kinematic fitting and reconstruction of missing π^0:

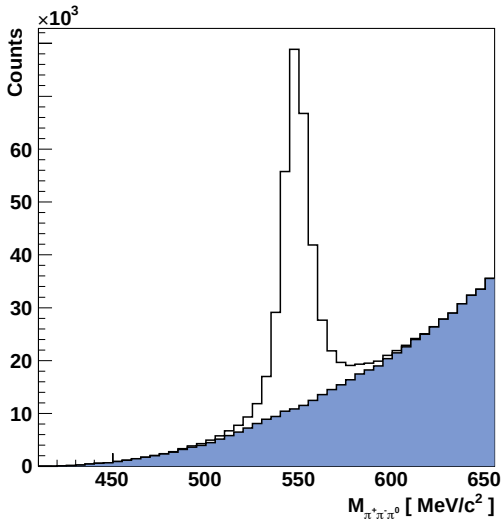
- Covariance matrix tuned to exclusive $\gamma p \to p\pi^+\pi^-$ channel.
- Normalized slopes:

$$\bar{a} = \frac{a}{a/2 + b}$$

- Event selection with $p_{\mathrm{CL}} > 0.01$

Preparation of the $\gamma p \to p\pi^+\pi^-\pi^0$ Final State





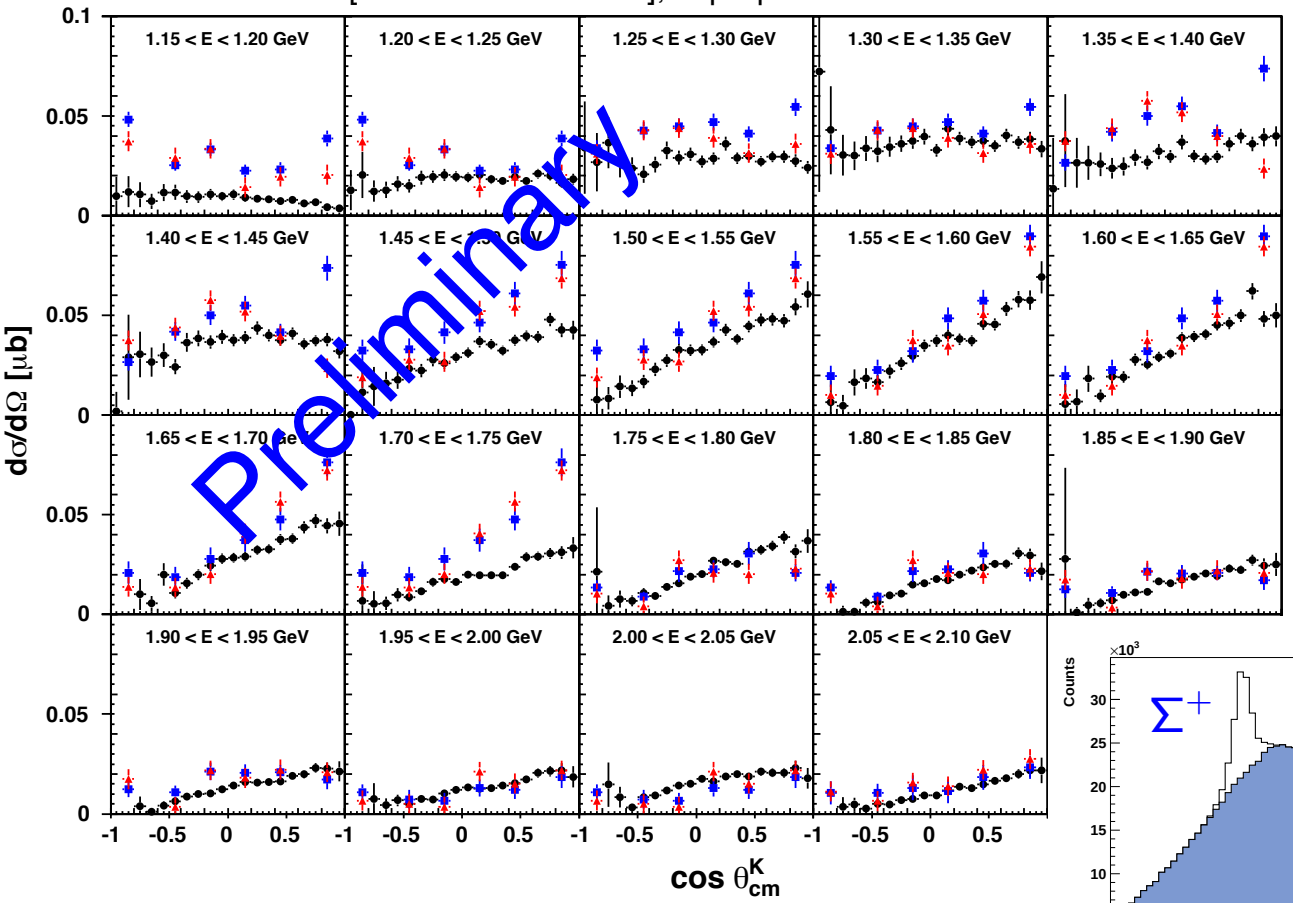
Final background subtraction based on the event-based Q-value method:

$$\cos\theta^{\eta}_{\mathrm{c.m.}},\ \cos\theta_{\mathrm{HEL}},\ \phi_{\mathrm{HEL}},\ \phi^{\eta}_{\mathrm{lab}},\ \lambda$$

➜ Total uncertainty: $\sigma^2 = \sigma^2_{\eta} + \sigma^2_{\mathrm{statistical}}$

Cross Sections for $\gamma p \to K^0 \Sigma^+ \to p\pi^+\pi^-\pi^0$

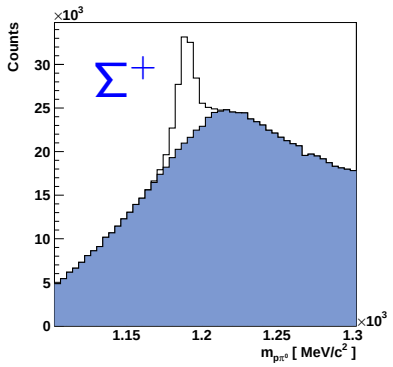
Z. Akbar *et al.* [CLAS Collaboration], in preparation.

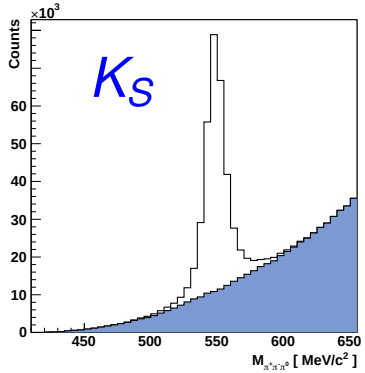


New cross section results in 50-MeV-wide E_γ bins for

$$1.15 < E_\gamma < 3.0 \text{ GeV}$$

➜ Need theory support to understand physics!!



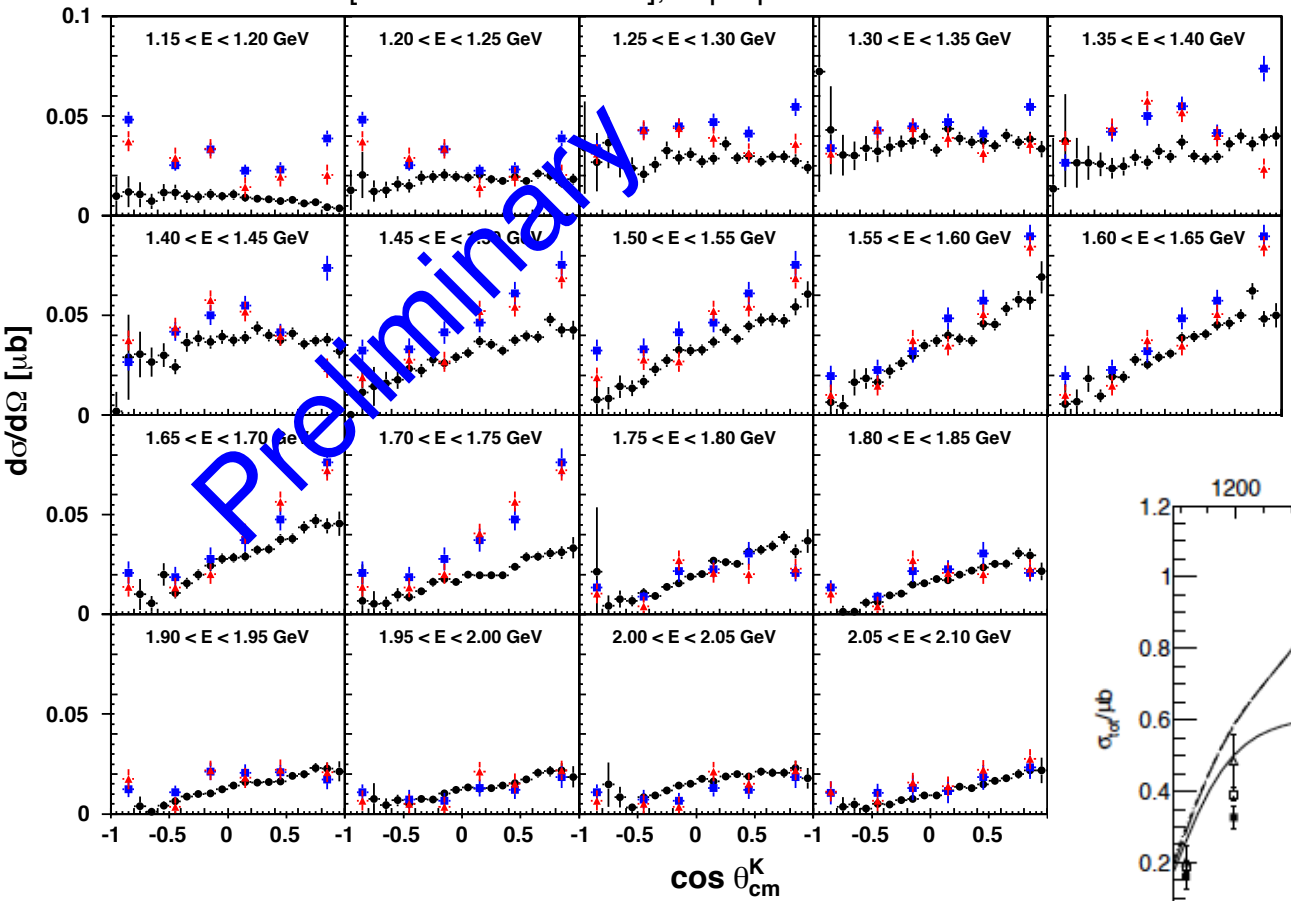


CLAS-g12 • CB-ELSA • CBELSA/TAPS •

Phys. Lett. B **713**, 180 (2012)

Cross Sections for $\gamma p \to K^0 \Sigma^+ \to p \pi^+ \pi^- \pi^0$

Z. Akbar *et al.* [CLAS Collaboration], in preparation.

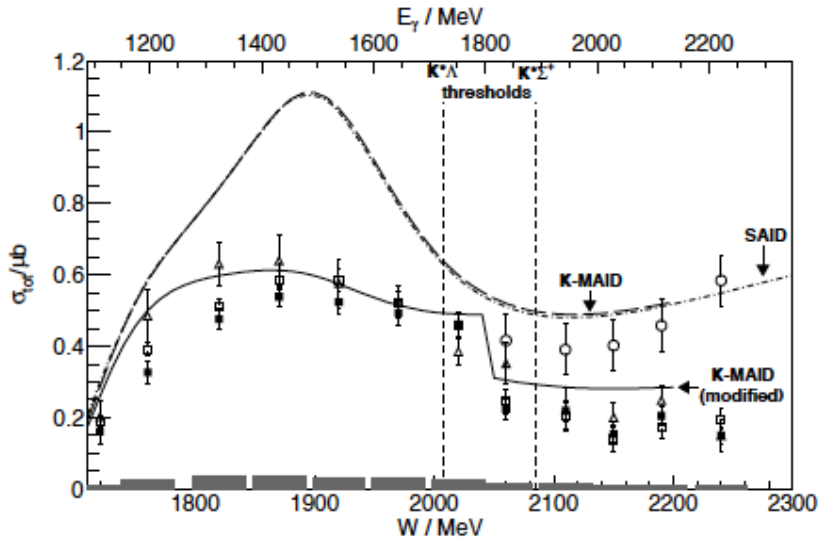


CLAS-g12 • CB-ELSA • CBELSA/TAPS •

New cross section results in 50-MeV-wide E_γ bins for

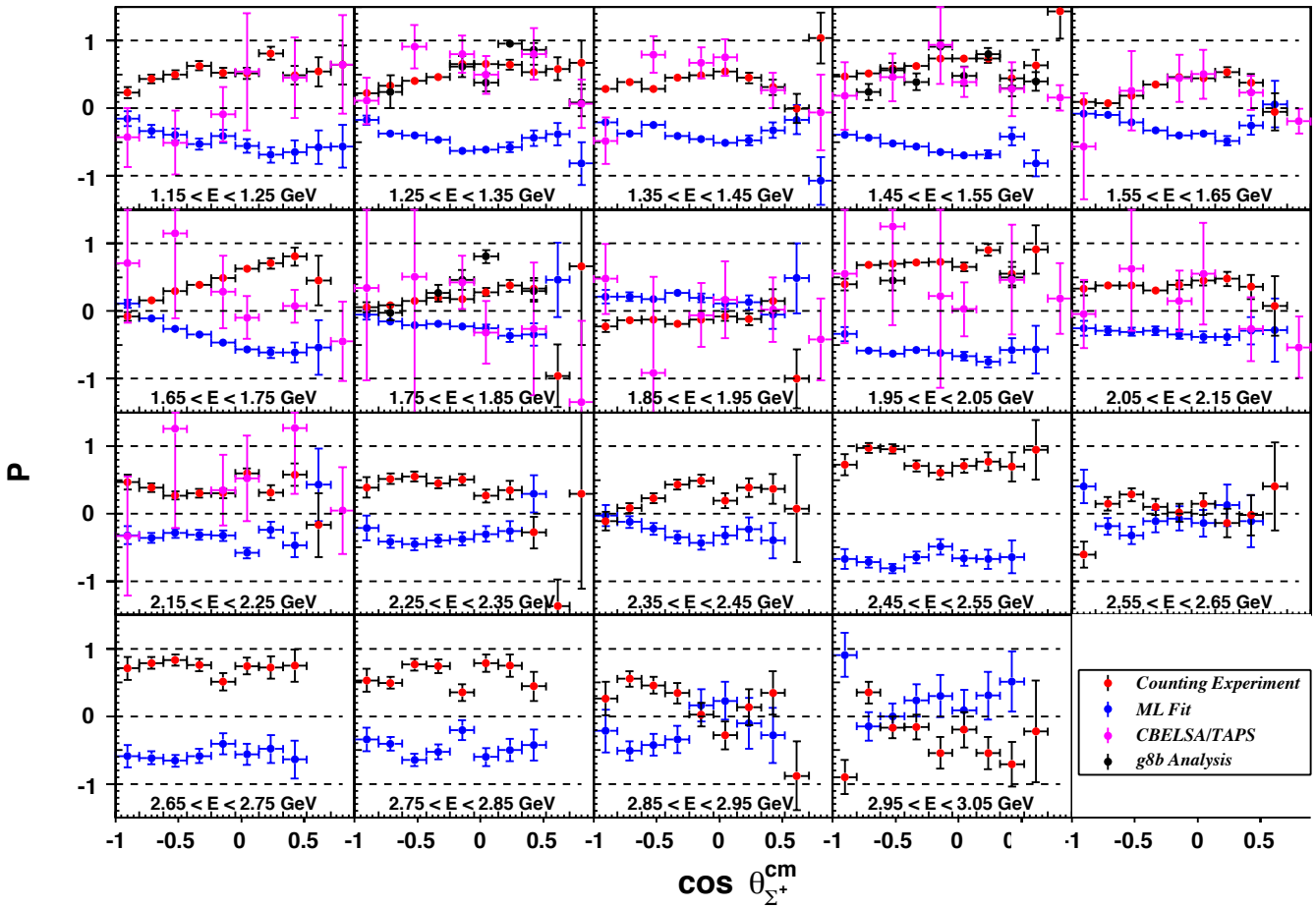
$1.15 < E_\gamma < 3.0$ GeV

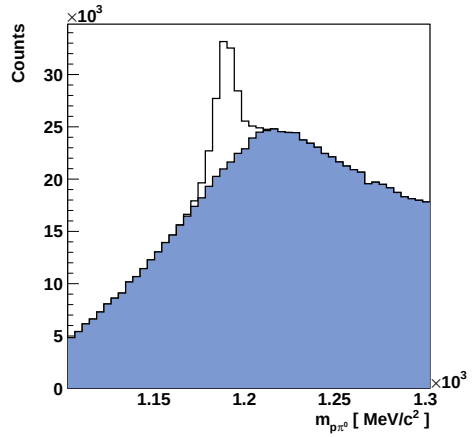
Phys. Lett. B **713**, 180 (2012)



➜ In preparation: $(E), P, C_x, C_z$ & T, Σ, P, O_x, O_z

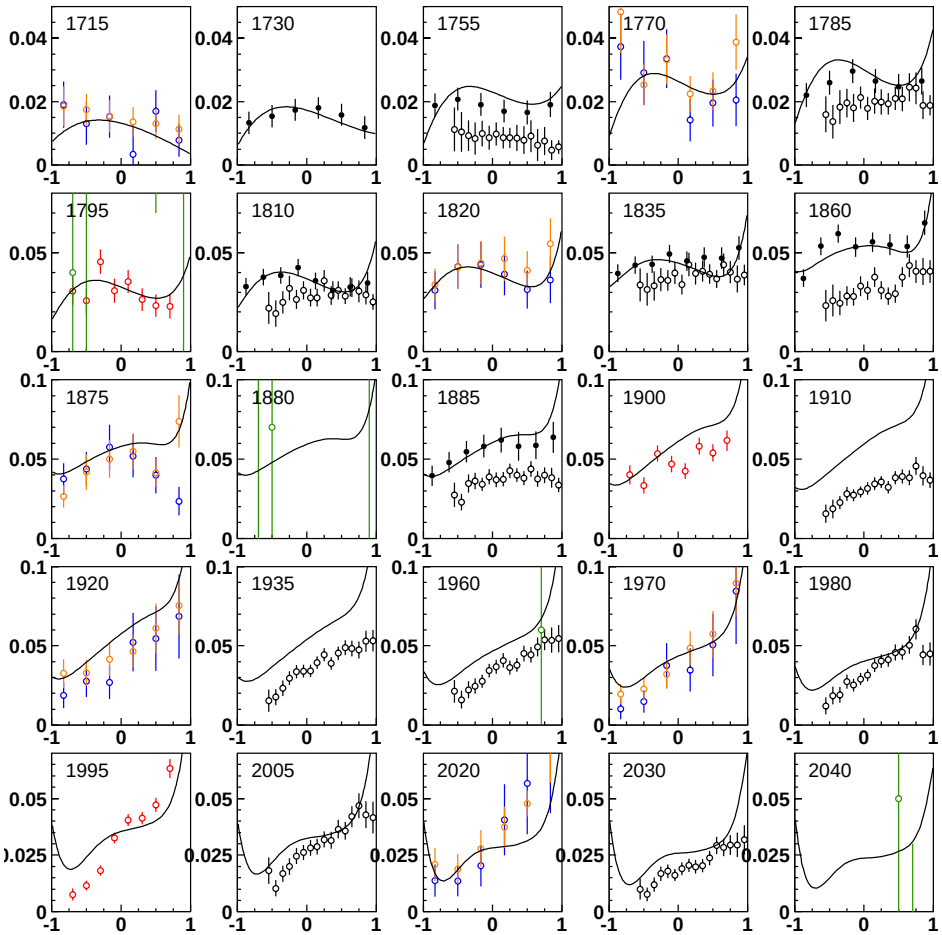
Induced Polarization P in $\gamma p \to K^0 \Sigma^+ \to p \pi^+ \pi^- \pi^0$





g12 • / g12 • g8b • CBELSA/TAPS •

Cross Sections for $\gamma p \to K^0 \Sigma^+ \to p \pi^+ \pi^- \pi^0$

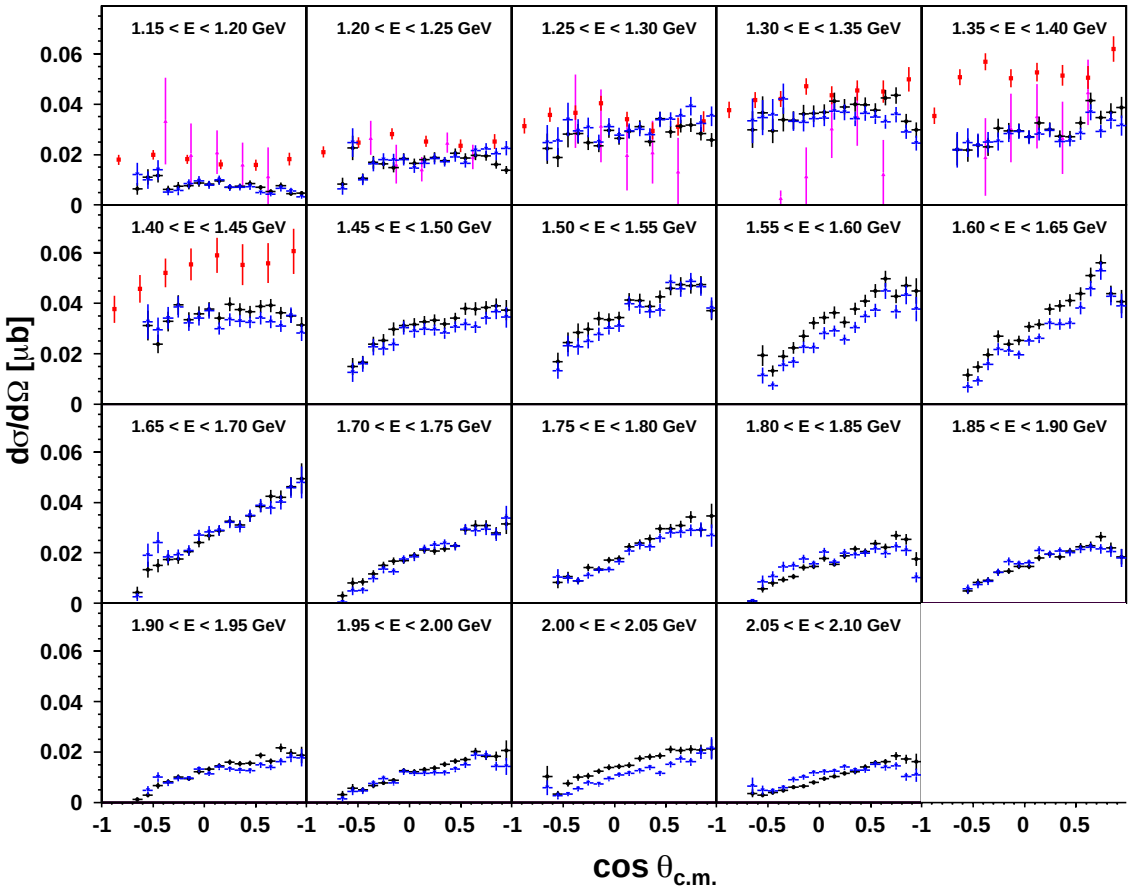


MAMI-A2 • CB-ELSA ○ CBELSA/TAPS ○

Data are presented in W bins
(picture prepared by V. Nikonov)

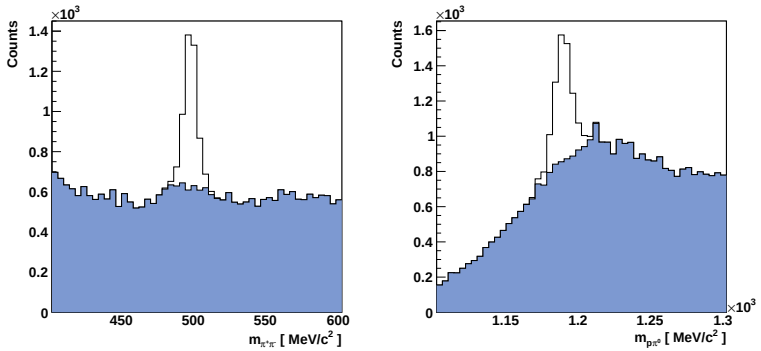
➜ Clear discrepancies visible!

Cross Sections for $\gamma p \to K^0 \Sigma^+ \to p\pi^+\pi^-\pi^0$



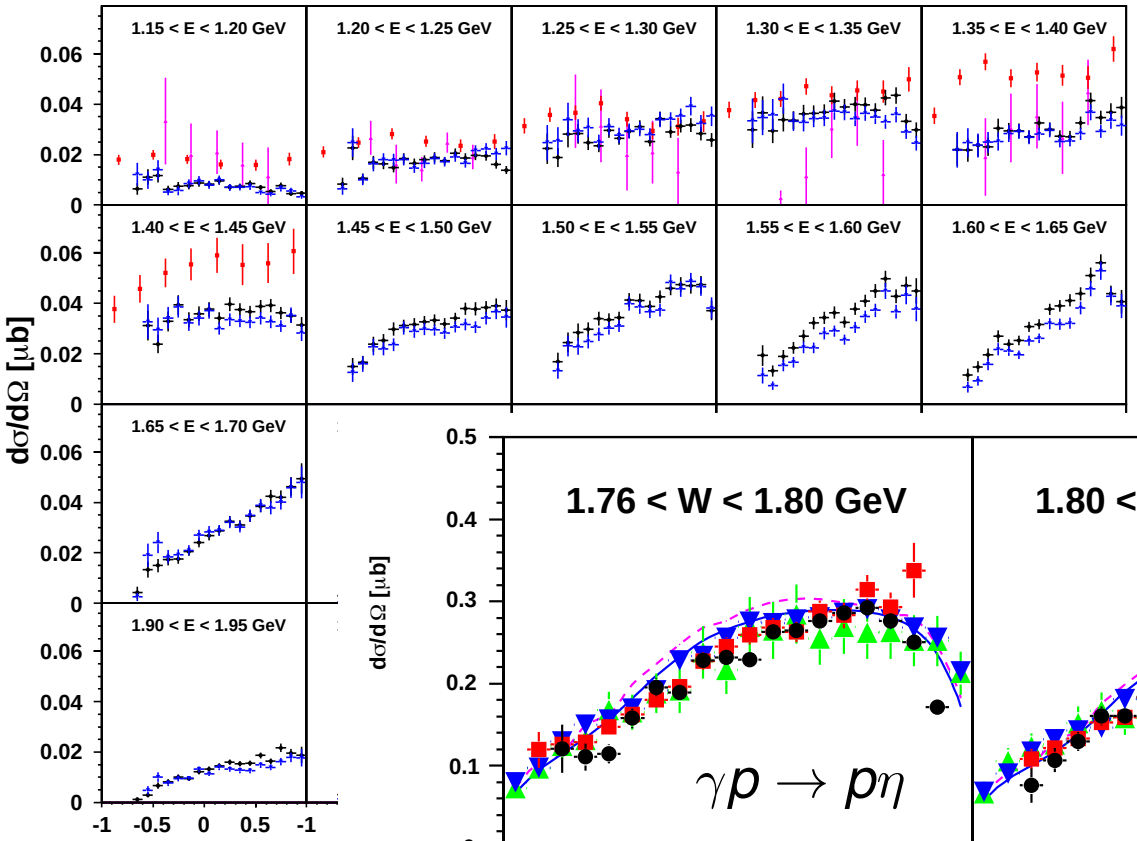
MAMI / CLAS discrepancies for
$1.35 < E_\gamma < 1.45$ GeV
➜ $1.85 < W < 1.90$ GeV

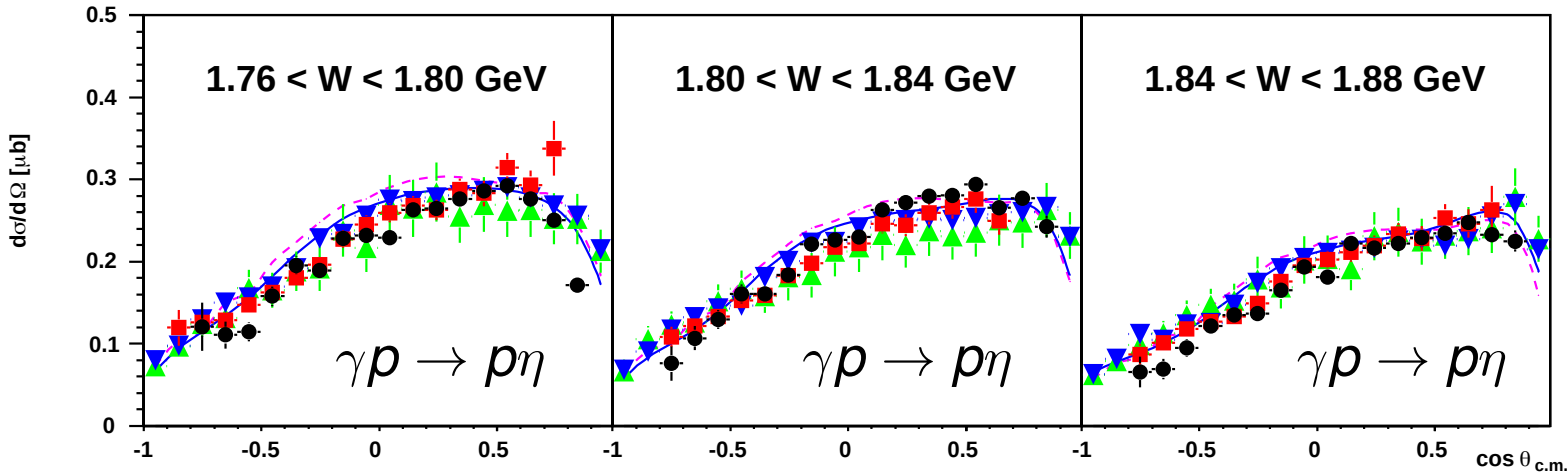
$1.55 < E_\gamma < 1.60$ GeV



MAMI-A2 (2013) ■ MAMI-A2 (2018) • CLAS-g12 K^0 • CLAS-g12 Σ^+ •

Cross Sections for $\gamma p \to K^0 \Sigma^+ \to p \pi^+ \pi^- \pi^0$



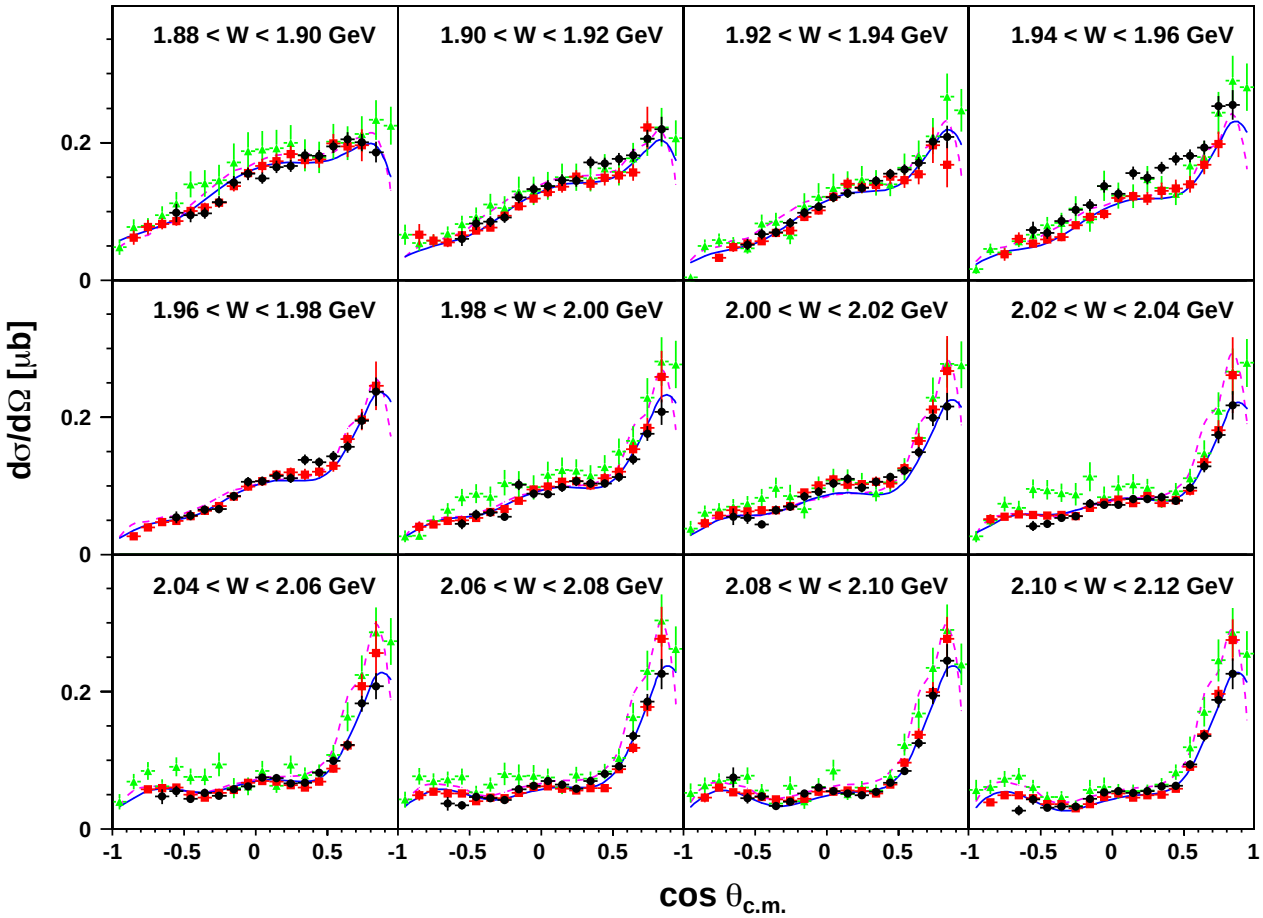


MAMI / CLAS discrepancies for $1.35 < E_\gamma < 1.45$ GeV

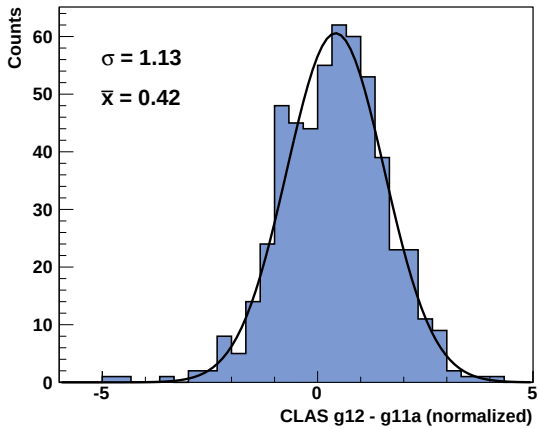
➜ $1.85 < W < 1.90$ GeV

CLAS-g11a (2009) ■ CLAS-g12 ● MAMI-A2 CBELSA/TAPS

Cross Sections for $\gamma p \to p\eta \to p\pi^+\pi^-\pi^0$

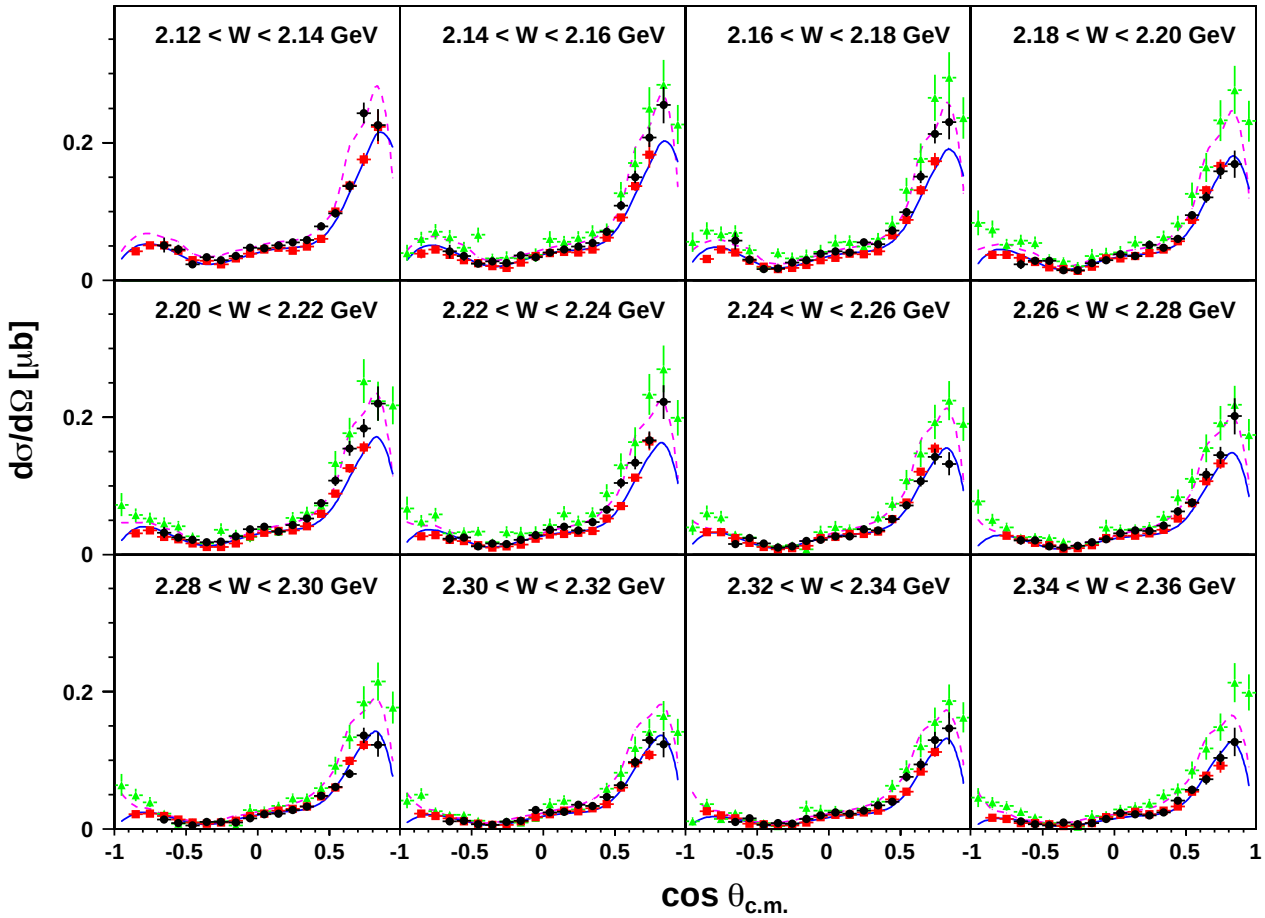


Normalized difference

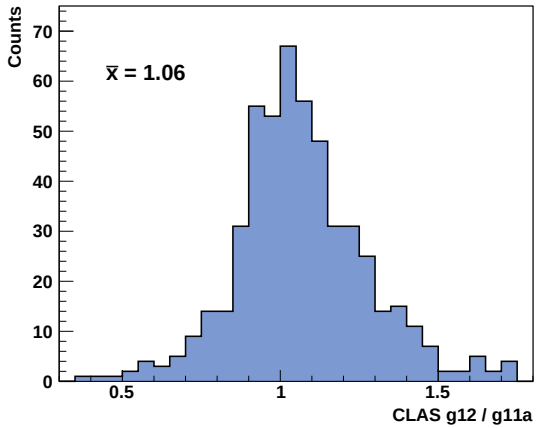


CLAS-g11a (2009) ■ CLAS-g12 ● CBELSA/TAPS (2009)

Cross Sections for $\gamma p \to p\eta \to p\pi^+\pi^-\pi^0$

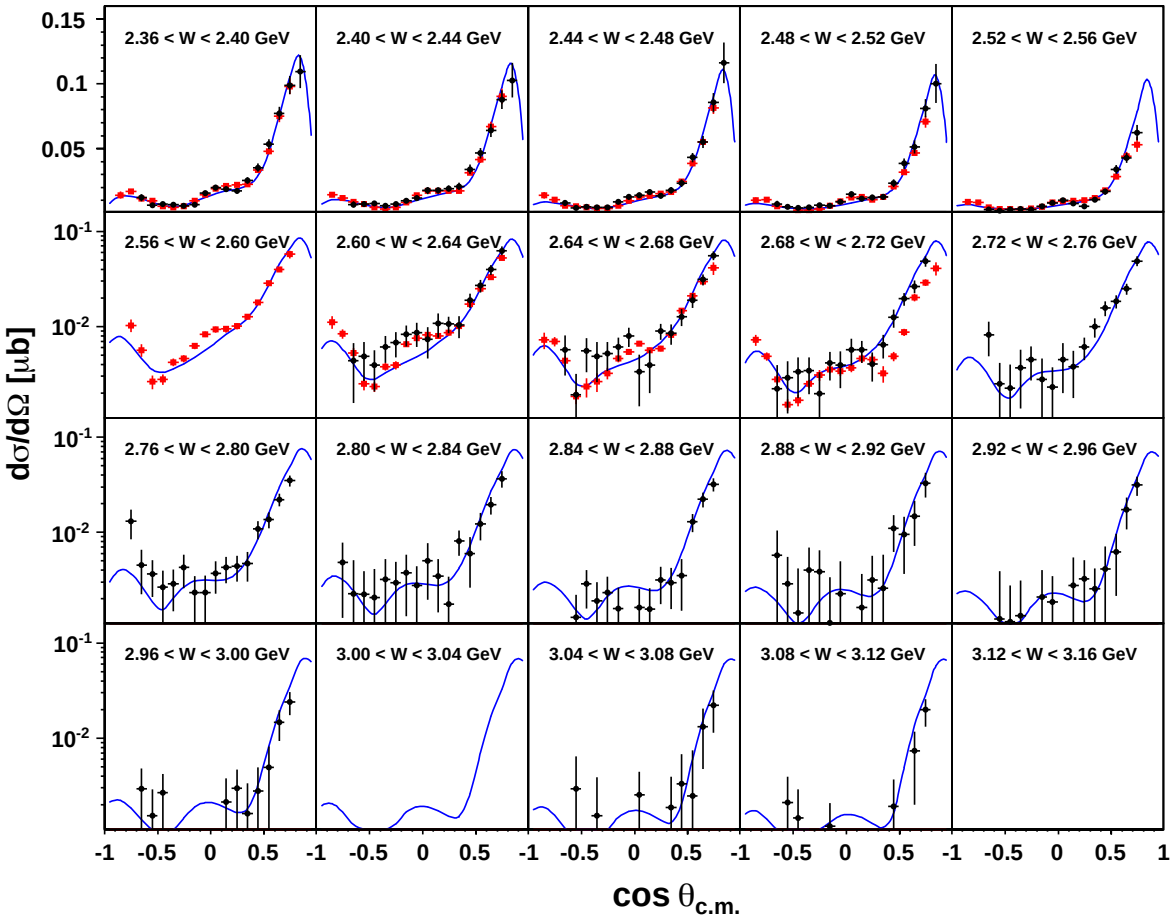


Unweighted ratio



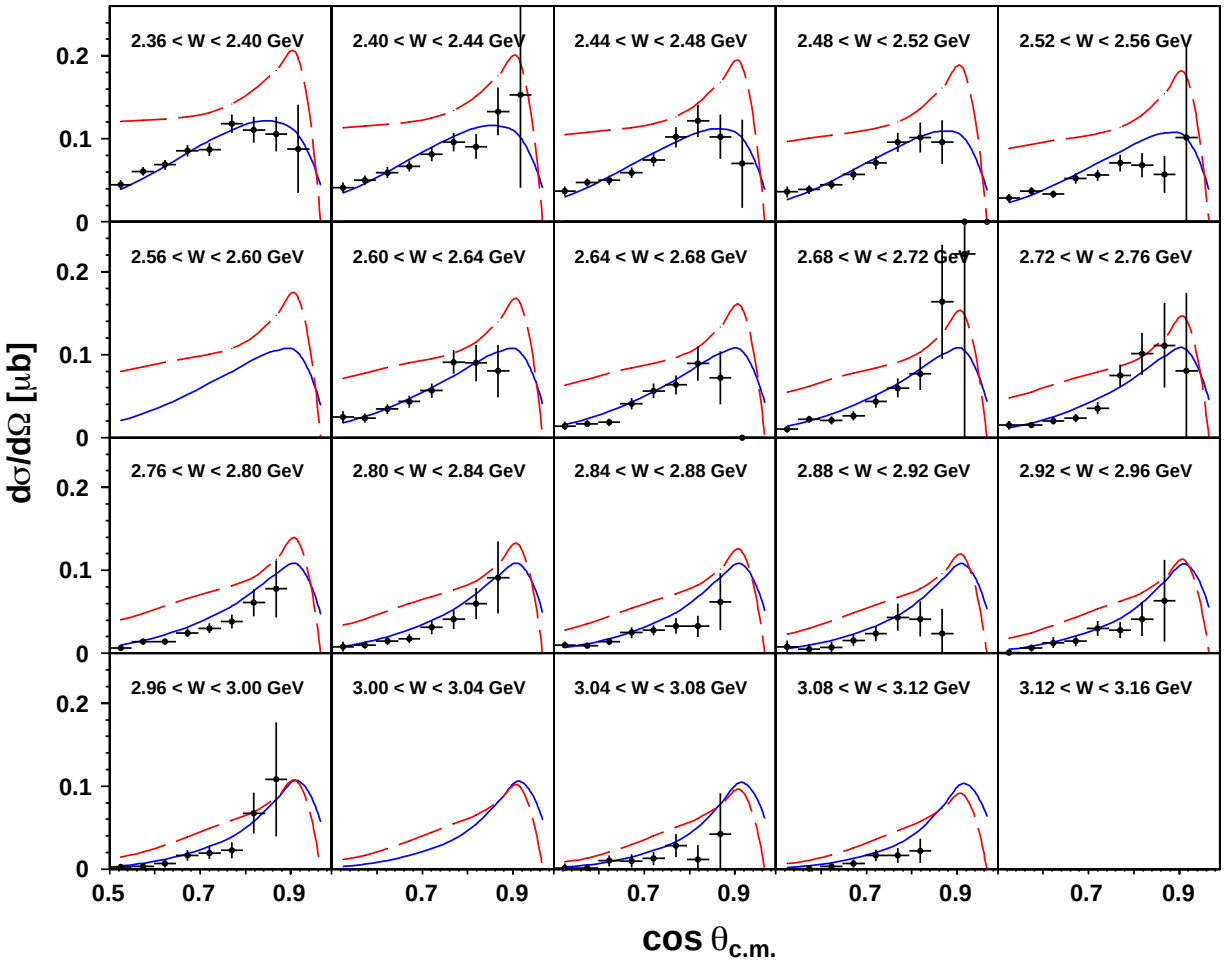
CLAS-g11a (2009) ■ CLAS-g12 ● CBELSA/TAPS (2009)

Cross Sections for $\gamma p \to p\eta \to p\pi^+\pi^-\pi^0$



CLAS-g11a (2009) ■ CLAS-g12 • CBELSA/TAPS (2009)

Cross Sections for the Reaction $\gamma p \to p \eta \to p \pi^+ \pi^- \pi^0$



New cross section results in 40-MeV-wide W bins for

$2.50 < E_\gamma < 4.72$ GeV, or

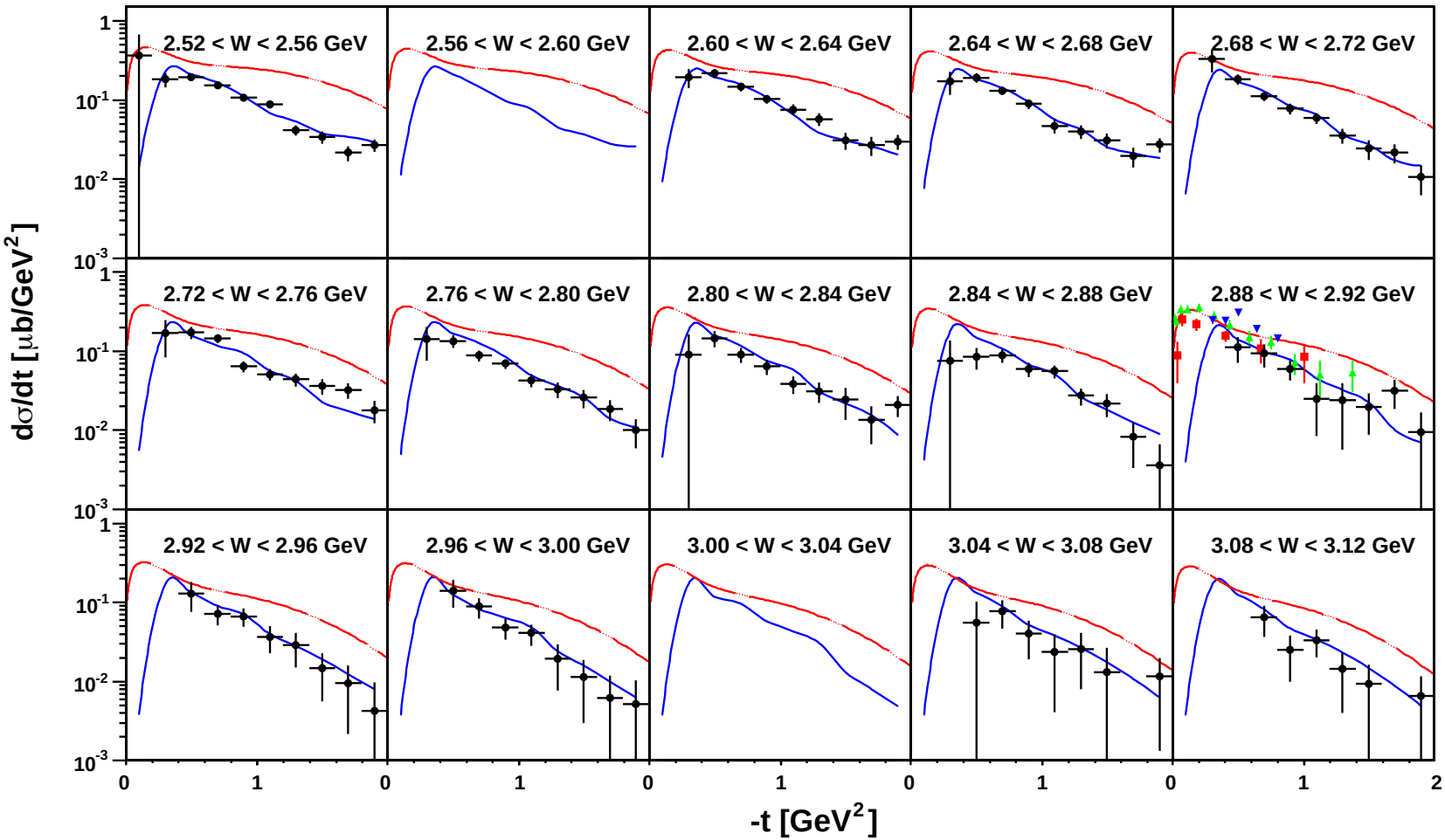
$2.36 < W < 3.12$ GeV

— JPAC, J. Nys *et al.*

— ηMAID 2018

T. Hu *et al.* [CLAS Collaboration], paper under review.

Cross Sections for the Reaction $\gamma p \to p\eta \to p\pi^+\pi^-\pi^0$



T. Hu *et al.* [CLAS Collaboration], paper under review.

(Complete) Experiments in $\gamma p \to p\omega$

- Event-based background subtraction (event-based dilution factors)

  ➜ $\gamma p \to p\pi^+\pi^-$ ✓ $\gamma p \to p\pi^+\pi^-(\pi^0)$ ✓

- In analogy to pseudoscalar mesons:

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

published (+ SDME's)

in progress

$\phi = \Psi \equiv$ Angle between $p\omega$ production plane and the photon polarization plane in the overall CM frame.

$\Phi \equiv$ Azimuthal angle of normal to the ω decay plane in helicity frame - quantization axis in the direction opposite the recoiling proton in the ω rest frame.

The ω is a vector meson (A. I. Titov and B. Kampfer, Phys. Rev. C 78, 038201 (2008))

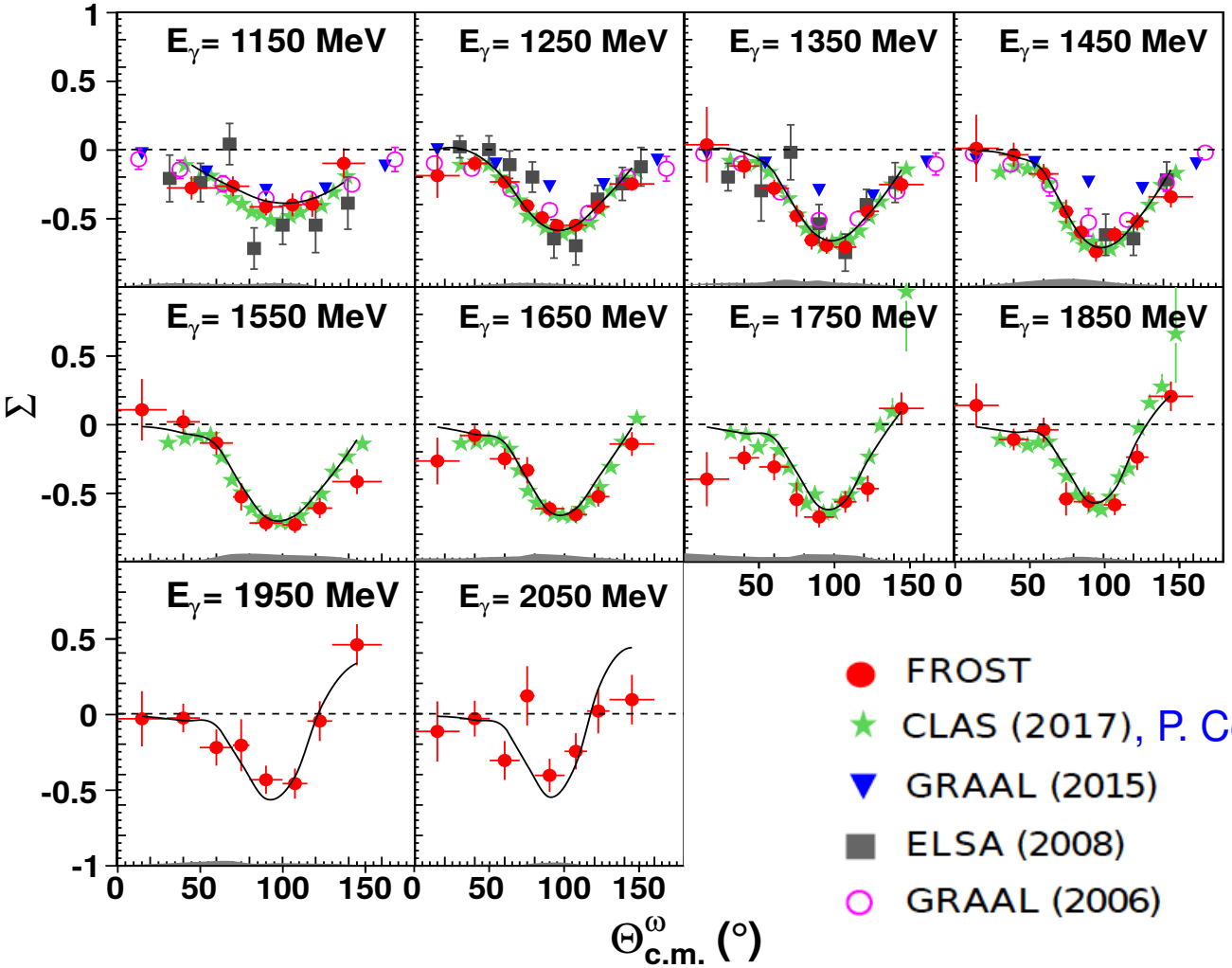
$$2\pi W^f(\Phi,\Psi) = 1 - \Sigma^f_\Phi \cos 2\Phi - P_\gamma \Sigma^f_b \cos 2\Psi + P_\gamma \Sigma^f_d \cos 2(\Phi - \Psi)$$

$$\Sigma^h_b = \Sigma^r_b = 2\rho^1_{11} + \rho^1_{00} \qquad -\tfrac{1}{2}\Sigma^h_d = \Sigma^r_d = \rho^1_{1\,-1} \qquad -\tfrac{1}{2}\Sigma^h_\Phi = \Sigma^r_\Phi = -\rho^0_{1\,-1}$$

Pol. SDMEs: B. Vernarsky (CMU), PhD dissertation

The Beam Asymmetry in $\vec{\gamma} p \to p \omega$ (CLAS-g9b)

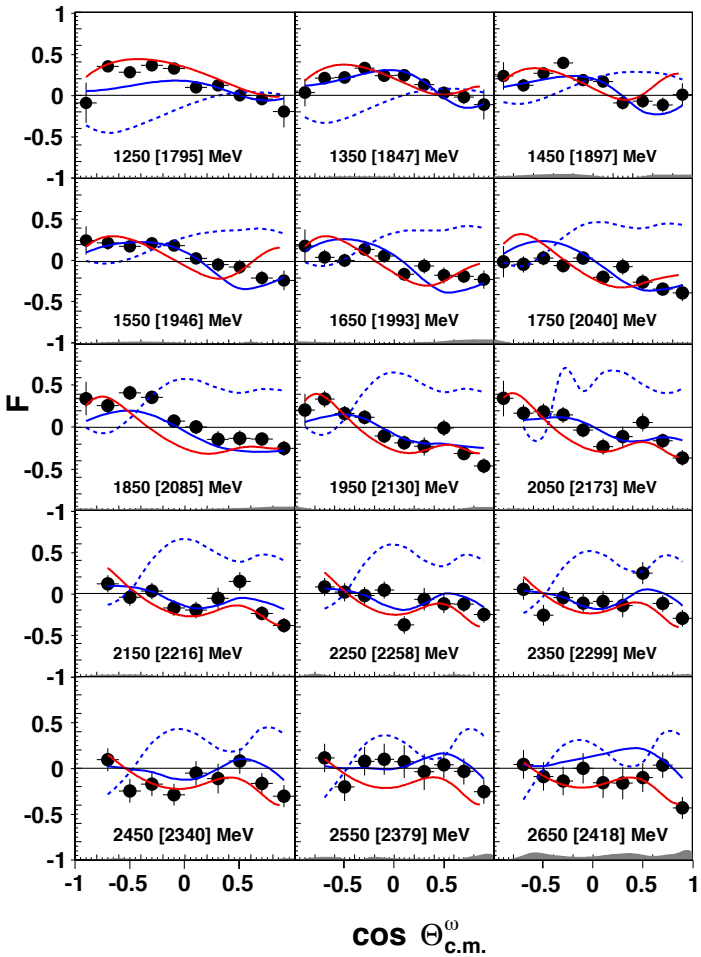
P. Roy *et al.* [CLAS Collaboration], PR C **97**, 055202 (2018)



$$\Sigma^h = \Sigma^r = 2\rho^1_{11} + \rho^1_{00}$$

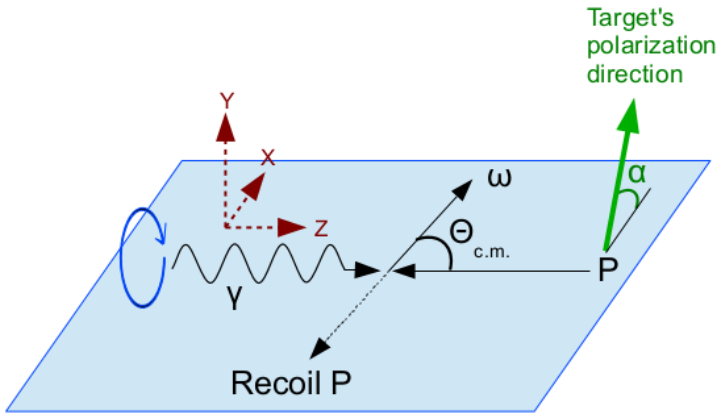
- FROST
- CLAS (2017), P. Collins *et al.* PL B **773**, 112 (2017)
- GRAAL (2015)
- ELSA (2008)
- GRAAL (2006)

F Observable in $\vec{\gamma}\,\vec{p} \to p\,\omega$ (CLAS g9b)



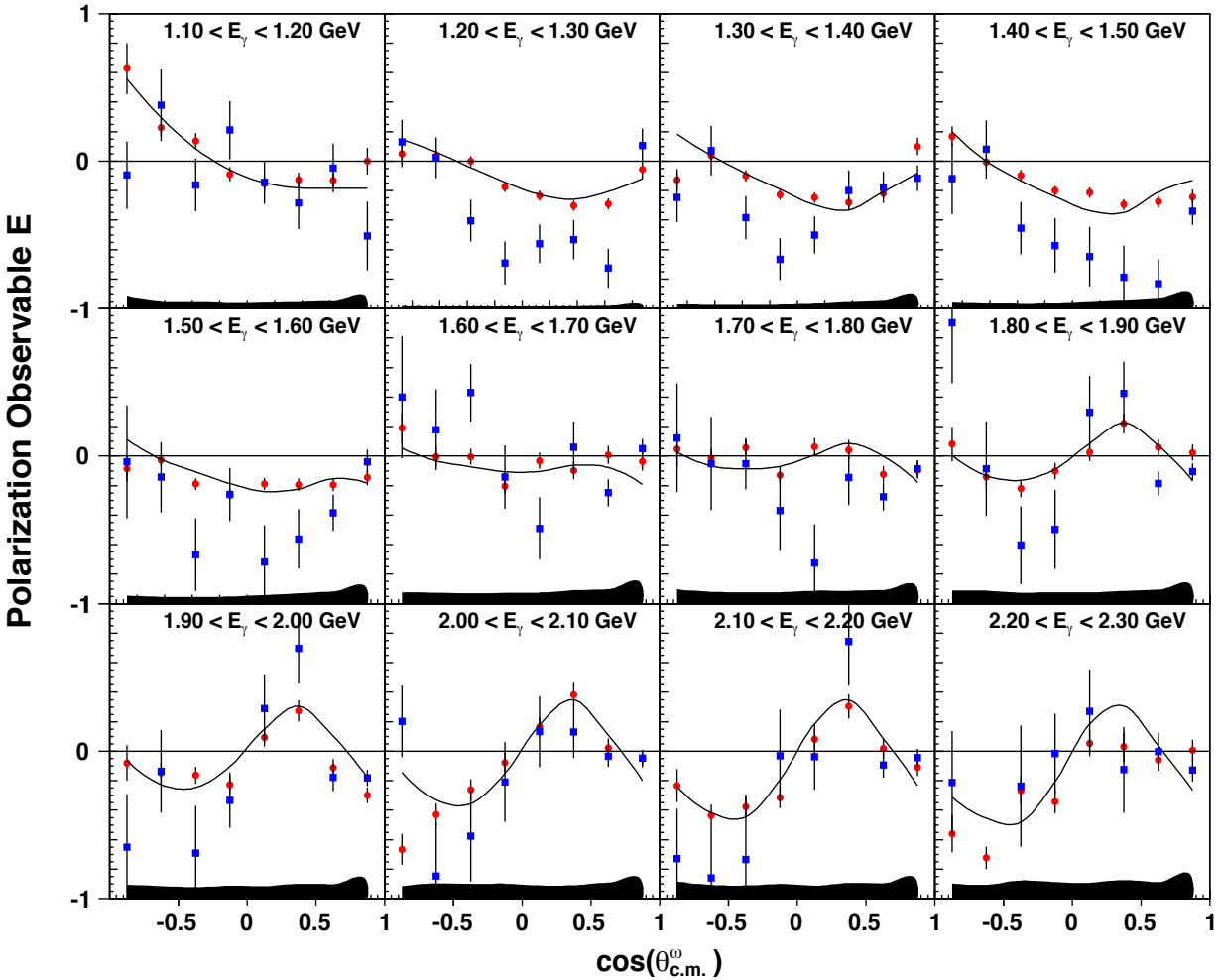
Polarized Cross Section

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



P. Roy *et al.* [CLAS Collaboration], PRL **122**, 162301 (2019)

Helicity Asymmetry in $\vec{\gamma}\vec{p} \to p\omega$ (CLAS g9a)



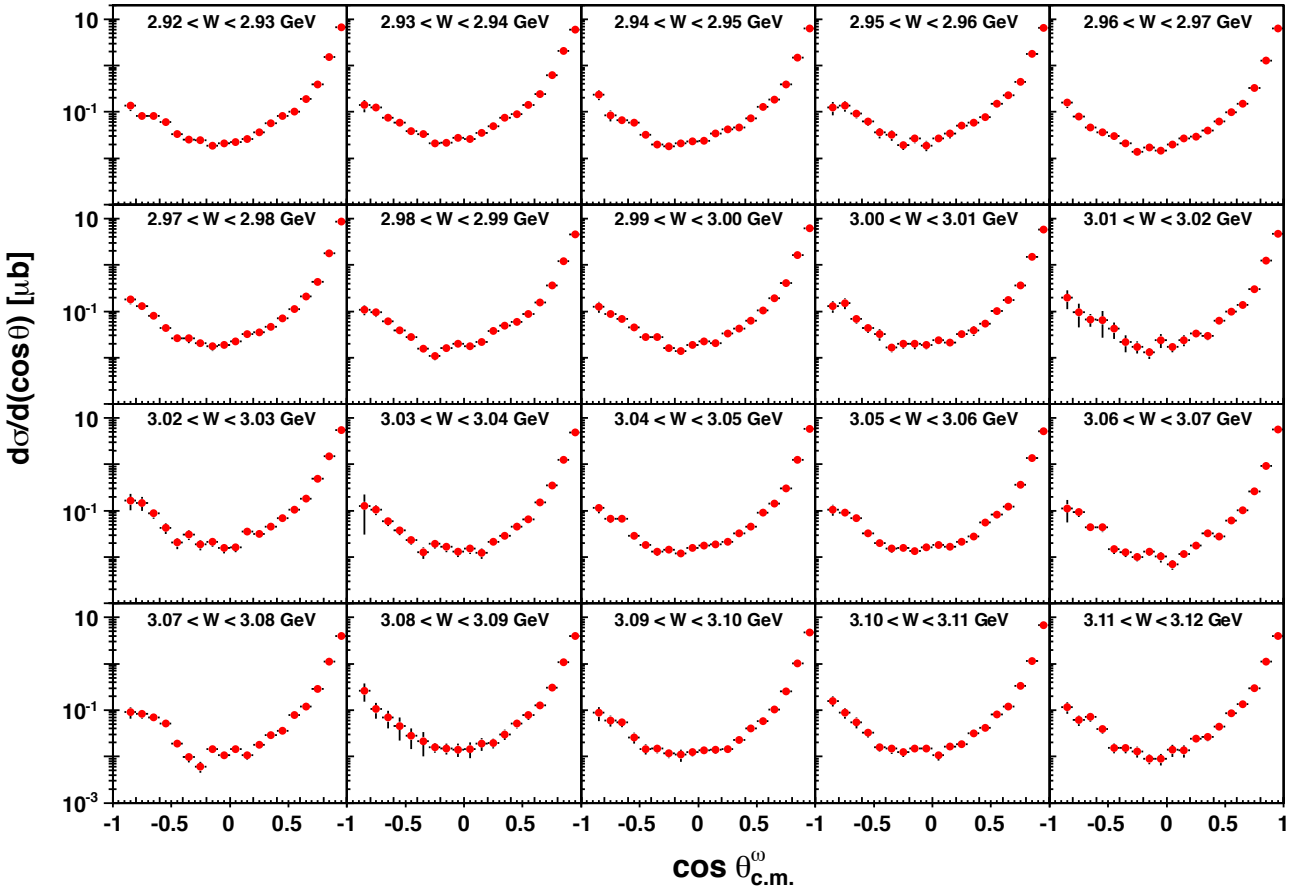
BnGa (coupled-channels) PWA

- Dominant $\mathbb{P}$ exchange
- Complex $3/2^+$ wave
  1. $N(1720)$
  2. $W \approx 1.9$ GeV
- $N(1895)\,1/2^-$ (new state)
- $N(1680), N(2000)\,5/2^+$
- 7/2 wave > 2.1 GeV

- CLAS-g9a
- CBELSA/TAPS
  Phys. Lett. B **750**, 453 (2015)

Z. Akbar *et al.* [CLAS Collaboration], PR C **96**, 065209 (2017)

Cross Sections for the Reaction $\gamma p \to p \omega \to p \pi^+ \pi^- \pi^0$



New cross section results in 10-MeV-wide W bins for

$1.15 < E_\gamma < 5.40$ GeV, or

$1.75 < W < 3.32$ GeV

➜ Need theory support to understand physics at these high energies!!

Working with JPAC.
(JPAC, V. Mathieu *et al.*)

➜ Data of unprecedented quality

Z. Akbar *et al.* [CLAS Collaboration], in preparation.

The impact of photoproduction on baryon resonances

Decay modes of nucleon resonances
black: PDG 2004
red: PDG 2018
blue: BESIII resonances

	Existence
****	Existence is certain.
***	Existence is very likely.
**	Evidence of existence is fair.
*	Evidence of existence is poor.

		overall	$N\gamma$	$N\pi$	$\Delta\pi$	$N\sigma$	$N\eta$	ΛK	ΣK	$N\rho$	$N\omega$	$N\eta'$	$N_{1440}\pi$	$N_{1520}\pi$	$N_{1535}\pi$	$N_{1680}\pi$
N	$1/2^+$	****														
$N(1440)$	$1/2^+$	****	****	****	****	***										
$N(1520)$	$3/2^-$	****	****	****	****	**	****									
$N(1535)$	$1/2^-$	****	****	****	**	*	****									
$N(1650)$	$1/2^-$	****	****	****	***	*	****	**					*			
$N(1675)$	$5/2^-$	****	****	****	****	***	*	*	*	**				*		
$N(1680)$	$5/2^+$	****	****	****	****	***	*			****						
$N(1700)$	$3/2^-$	***	**	***	***	*	*	**	*	*						
$N(1710)$	$1/2^+$	****	****	****	**		***	**	*	*	*				*	
$N(1720)$	$3/2^+$	****	****	****	**	*	*	****	*	**	*					
$N(1860)$	$5/2^+$	**	*	**		*	*									
$N(1875)$	$3/2^-$	***	**	**	*	**	*	*	*	*	*	*	*			
$N(1880)$	$1/2^+$	***	**	*	**	*	*	**	**		**				*	
$N(1895)$	$1/2^-$	****	****	*	*	*	****	**	**	*	*	****	*			
$N(1900)$	$3/2^+$	****	****	**	**	*	*	**	**	*	*	**				
$N(1990)$	$7/2^+$	**	**	**	*	*	*	**	**							
$N(2000)$	$5/2^+$	**	**	**	**	*	*	*	*		*					
$N(2040)$	$3/2^+$	*		*												
$N(2060)$	$5/2^-$	***	***	**	*	*	*	*	*	*	*		*	*		*
$N(2100)$	$1/2^+$	***	**	***	**	**	*	*		*	*	**			***	
$N(2120)$	$3/2^-$	***	***	***	**	**		**	*		*	*	*	*	*	
$N(2190)$	$7/2^-$	****	****	****	****	**	*	**	*	*	*					
$N(2220)$	$9/2^+$	****	**	****			*	*	*							
$N(2250)$	$9/2^-$	****	**	****			*	*	*							
$N(2300)$	$1/2^+$	*		*												
$N(2570)$	$5/2^-$	*		*												
$N(2600)$	$11/2^-$	***		***												
$N(2700)$	$13/2^+$	**		**												

Based on results at Jefferson Lab, ELSA, MAMI, ...

Outline

The CLAS-g12 data set still contains a lot of physics:

- Among other analyses, cross section measurements of
  - $\gamma p \to p\,\eta$ ($E_\gamma < 4.7$ GeV)

    Extending the CLAS-g11a results into the Regge regime; competing with GlueX on this reaction. JPAC is awaiting data ...
  - $\gamma p \to K^0\,\Sigma^+$ ($E_\gamma < 3.0$ GeV)

    Important reaction in the seach for N^* states; no CLAS data published, yet.
  - $\gamma p \to p\,\omega$ ($E_\gamma < 5.4$ GeV)

    Extending the CLAS-g11a results into the Regge regime; JPAC is awaiting data ...
- Determination of ω spin-densitymatrix elements(SDMEs)
- (Double-) polarization observables in $\gamma p \to K^0\,\Sigma^+$

Acknowledgement

This material is based upon work supported in part by the U.S. Department of Energy, Office of Science, Office of Nuclear Physics, under Award Number DE-FG02-92ER40735.