Baryon spectroscopy with polarization observables from CLAS

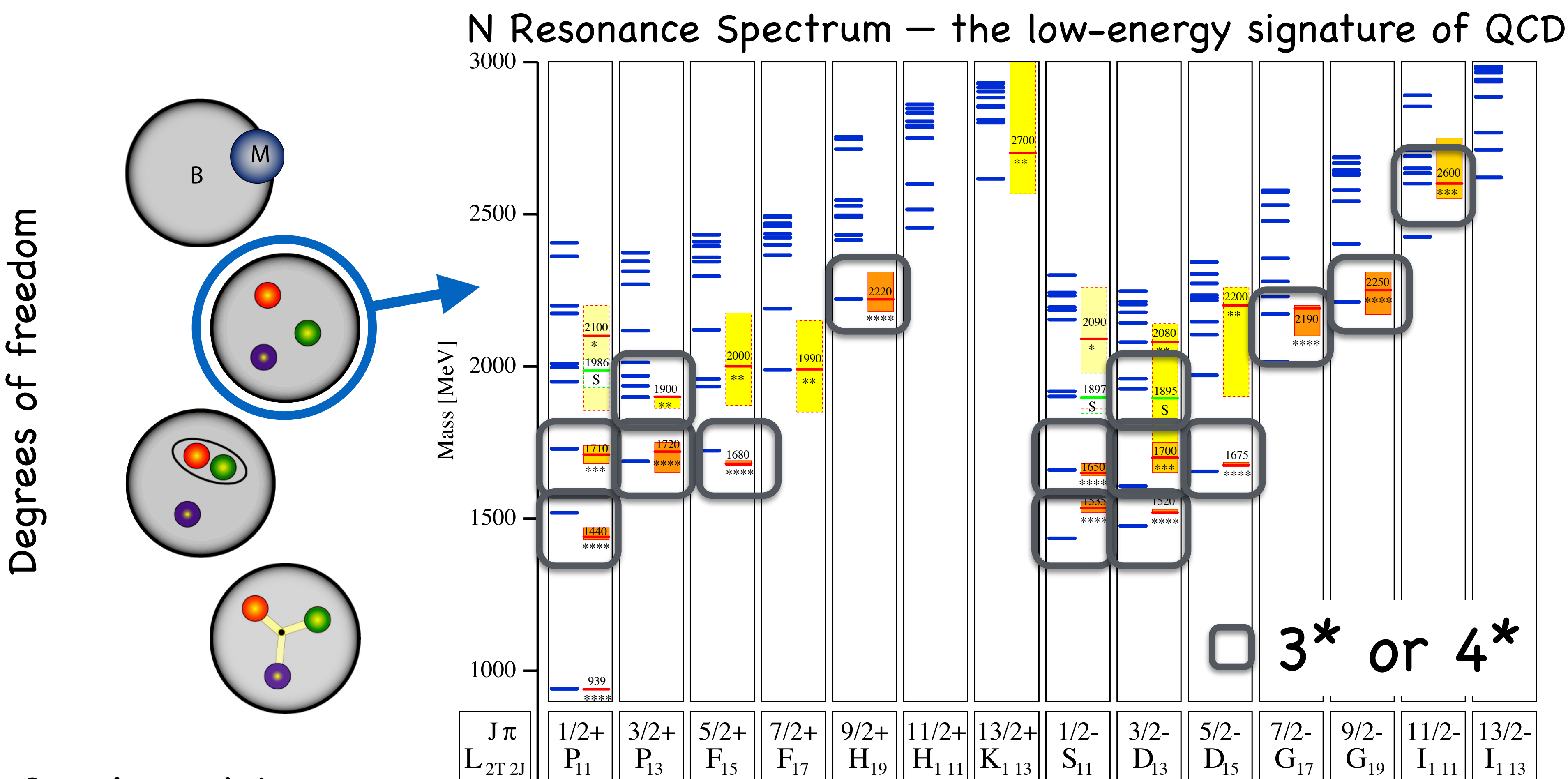
1. Unpolarized target
2. Polarized proton target (FROST)
3. Polarized neutron target (HDice)
4. CLAS 12 Forward Tagger

Steffen Strauch for the CLAS Collaboration
University of South Carolina

Supported in parts by the U.S. National Science Foundation: NSF PHY-1205782

Nucleon Resonances: From Photoproduction to High Photon Virtualities,
ECT*, Trento, Italy, October 12 - 16, 2015

Relevant degrees of freedom and missing resonance problem



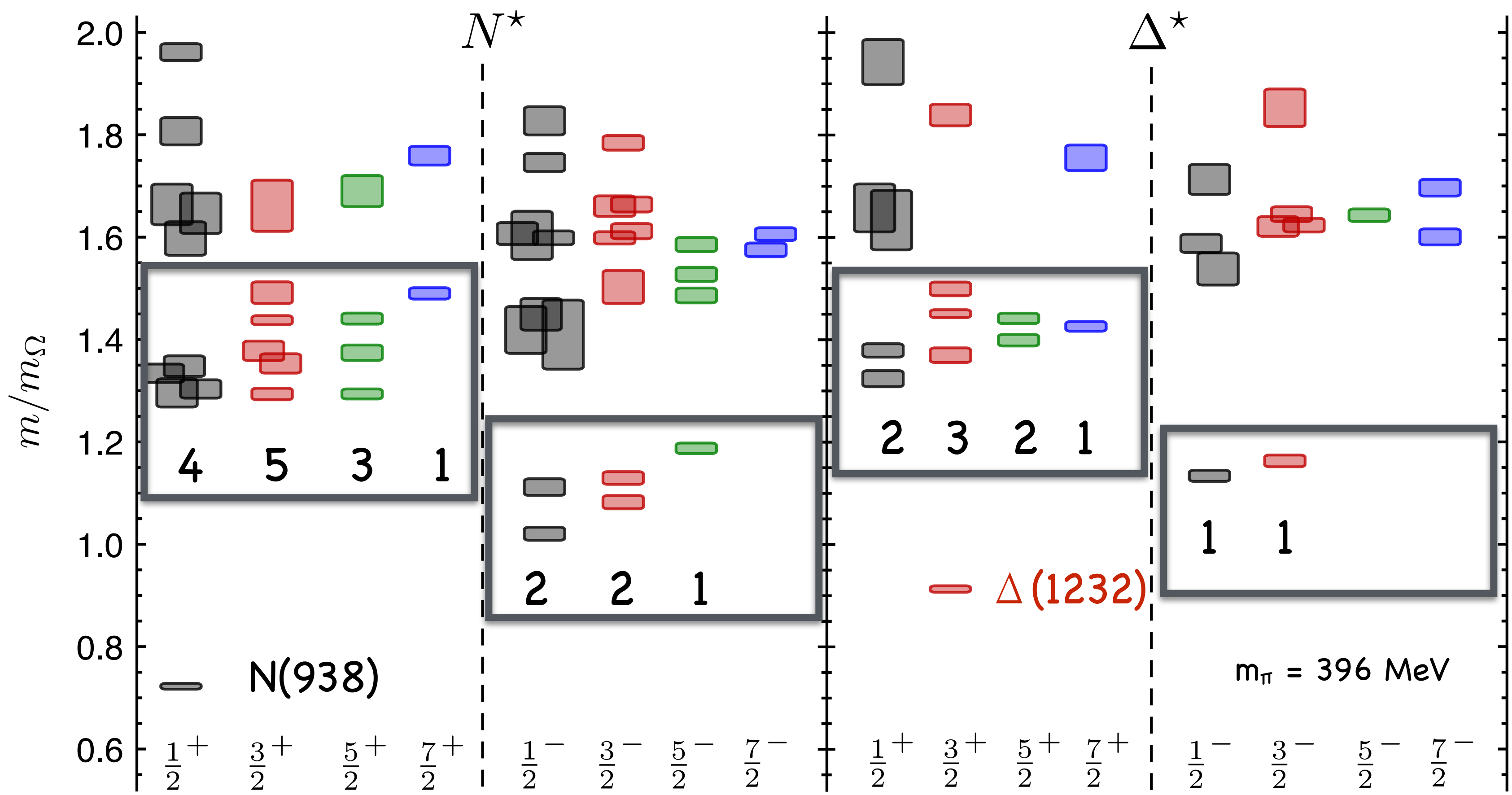
Quark Models

- Constituent Quark Models predict many more of excited states than have been observed; some of the states may only couple weakly to πN.
- Quark-Diquark Models predict fewer states.
- Quark and Flux-Tube Models predict increased number of states.

CQM: U. Löring, B.C. Metsch, and H.R. Petry, Eur. Phys. J. **A10** 395 (2001)

Resonance spectrum in Lattice QCD

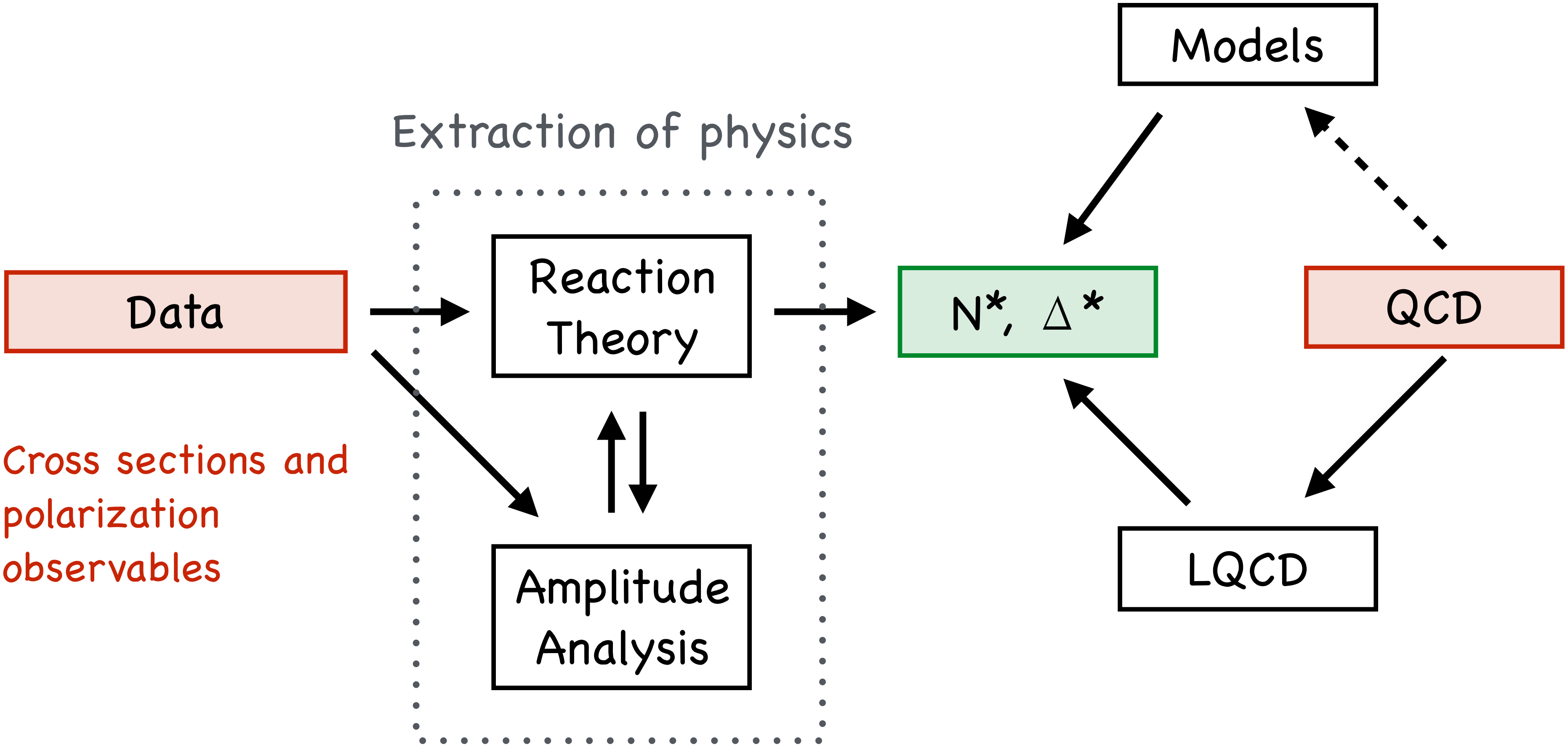
Hadron spectrum collaboration



LQCD predicts states with the same quantum numbers as CQMs with underlying SU(6) x O(3) symmetry; more states than have been identified experimentally.

R.G. Edwards, J.J. Dudek, D.G. Richards, and S.J. Wallace, Phys. Rev. D **84**, 074508 (2011)

Extracting nucleon-resonance information from experimental data



Cross sections and polarization observables

Coupled-channel analysis especially important

Nucleon resonance information:
mass, spin, parity, coupling constants, decay parameters, ...

What we measure with CLAS

Proton target

$$\gamma p \to \pi^0 p, \pi^+ n$$

$$\gamma p \to \eta p, \eta' p$$

$$\gamma p \to KY\ (K^+\Lambda, K^+\Sigma^0, K^0\Sigma^+)$$

$$\gamma p \to \pi^+\pi^- p, \omega p, \rho p, \phi p$$

...

e.g. CLAS frozen spin target (FROST)

Neutron target

$$\gamma n \to \pi^- p$$

$$\gamma n \to \pi^+\pi^- n$$

$$\gamma n \to \Sigma^- K^+, \Lambda K^0$$

...

e.g. unpolarized deuterium target (g13), polarized HD-Ice target (g14)

Cross section and polarization observables

Unpolarized, circularly polarized, linearly polarized beam

Unpolarized, longitudinally polarized, transversally polarized target

Recoil polarization (asymmetry in the weak decay of the hyperon)

Observables in pseudoscalar meson photoproduction

4 complex amplitudes ⇒ 16 possible (not independent) observables

double pion photoproduction fills empty cells in the table

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	$d\sigma_0$		T			P		$T_{x'}$		$L_{x'}$		Σ		$T_{z'}$		$L_{z'}$
$P_L^\gamma \sin(2\varphi_\gamma)$		H		G	$O_{x'}$		$O_{z'}$		$C_{z'}$		E		F		$-C_{x'}$	
$P_L^\gamma \cos(2\varphi_\gamma)$	$-\Sigma$		$-P$			$-T$		$-L_{x'}$		$T_{z'}$		$-d\sigma_0$		$L_{x'}$		$-T_{x'}$
circular P_c^γ		F		$-E$	$C_{x'}$		$C_{z'}$		$-O_{z'}$		G		$-H$		$O_{x'}$	

coherent and incoherent Bremsstrahlung

e.g, FROST and HDice

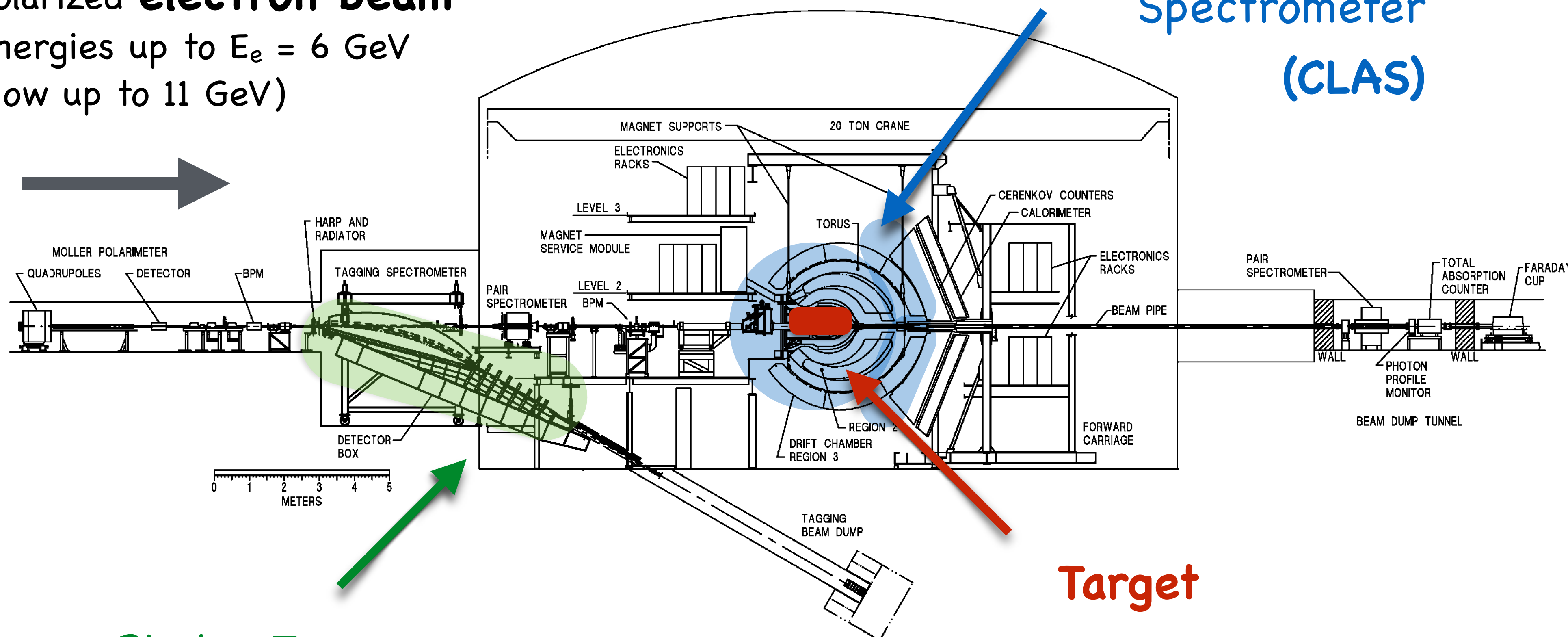
e.g, Hyperon weak decay

A.M. Sandorfi, S. Hoblit, H. Kamano and T.-S.H. Lee, J. Phys. G, Nucl. Part. Phys. **38**, 053001 (2011)

CEBAF Large Acceptance Spectrometer in Hall B (1997 - 2012)

CEBAF Large Acceptance Spectrometer **(CLAS)**

Polarized **electron beam**
Energies up to E_e = 6 GeV
(now up to 11 GeV)



Target

unpolarized p or d, polarized FROST, HDice

Photon Tagger

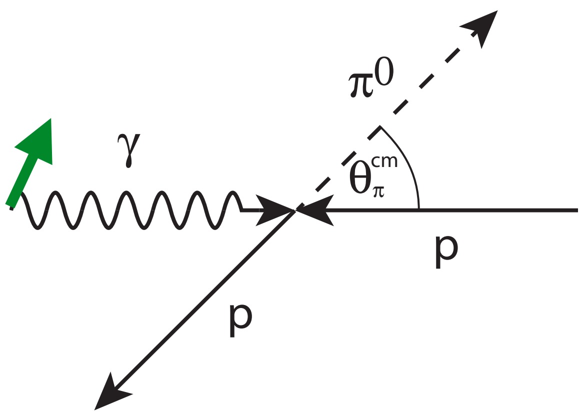
$$E_\gamma = E_e - E_{e'}$$

B.A. Mecking et al., Nucl. Instr. and Meth. A **503**, 513 (2003).

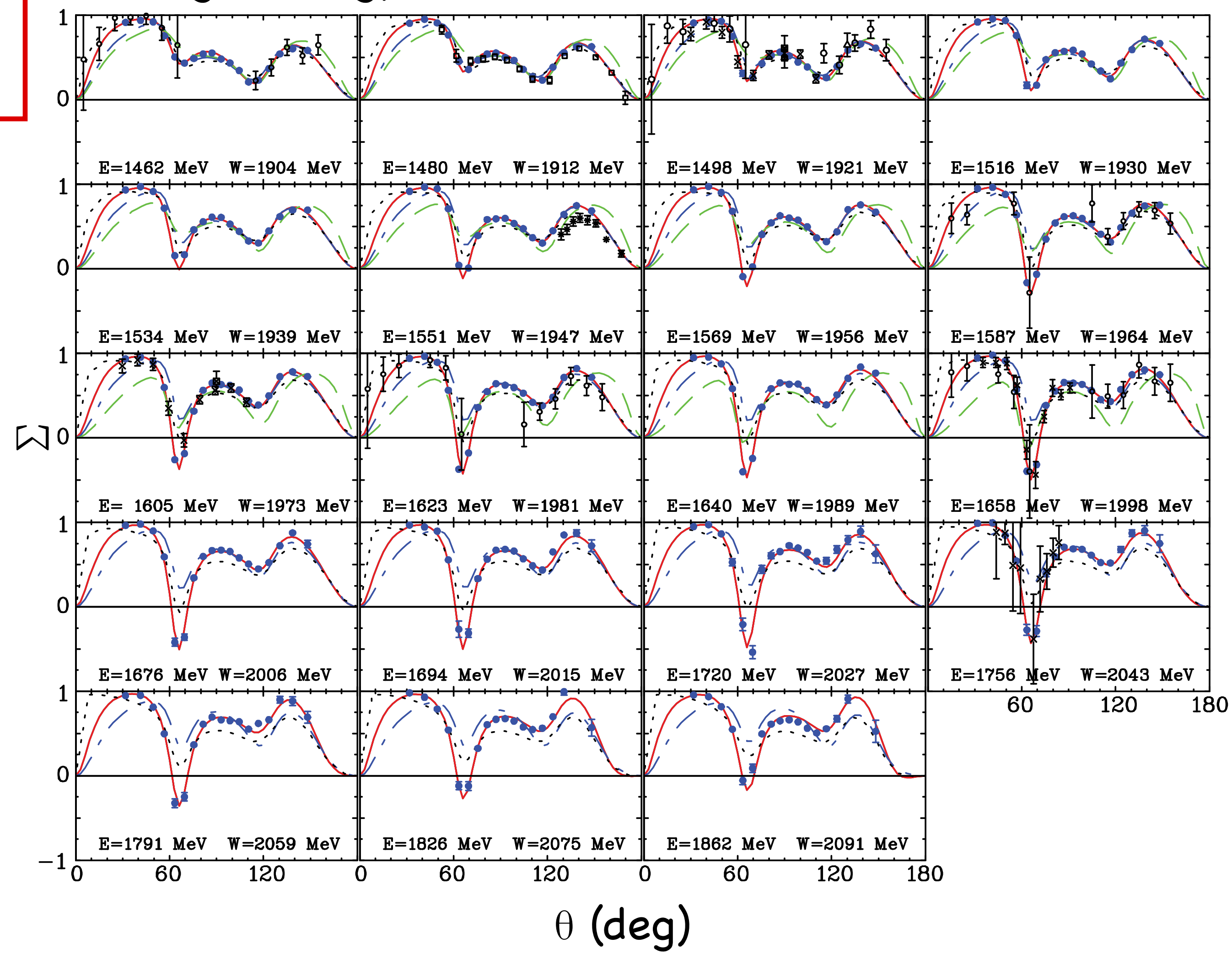
Beam asymmetry Σ for π⁺ and π⁰ photo production on the proton

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

$$\left(\frac{d\sigma}{d\Omega}\right) = \left(\frac{d\sigma}{d\Omega}\right)_0 \left(1 - P_L^\gamma \Sigma \cos(2\varphi_\gamma)\right)$$



high-energy π0 data: 1904 MeV < W < 2091 MeV



Models: SAID DU13 (CM12), MAID07, BG2011-02

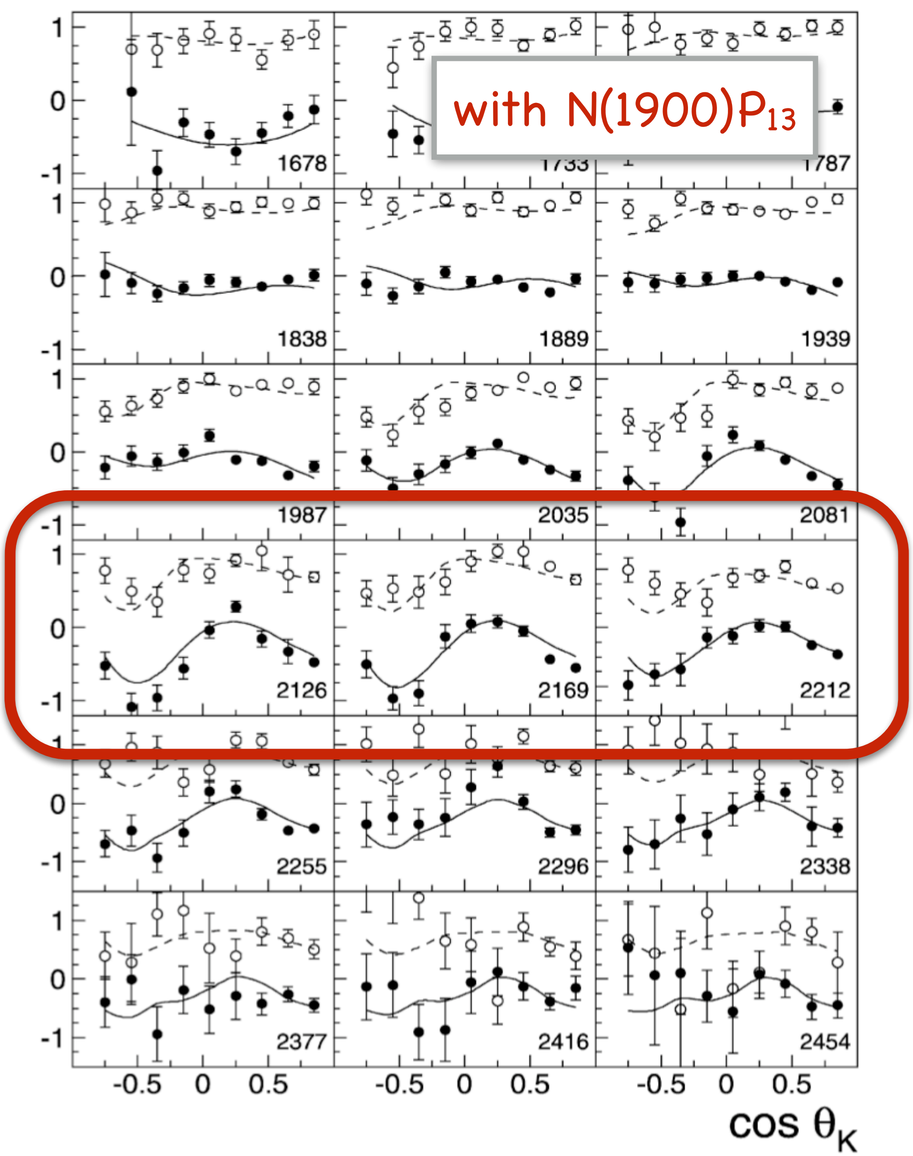
Largest changes from previous fits are for "well known" Δ(1700)3/2⁻ and Δ(1905)5/2⁺ states.

M. Dugger et. al (CLAS Collaboration), Phys. Rev. C**88**, 065203 (2013)

Polarization Transfer Observables C_x, C_z

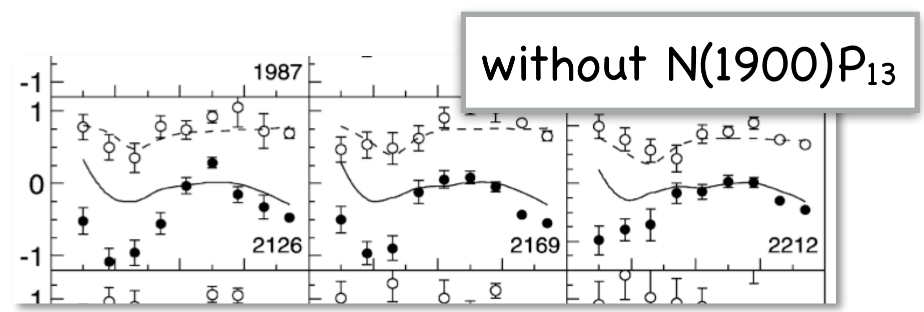
$\vec{\gamma} p \to K^+ \vec{\Lambda}$

C_x (●), C_z (○) for $K^+\Lambda$ channel



Bonn-Gatchina coupled-channel isobar model: $N(1900)P_{13}$ needed in PWA of Nikonov et al.

Strongest contributions to $\gamma p \to K\Lambda$: S_{11}-wave, $P_{13}(1720)$, $P_{13}(1900)$, $P_{11}(1840)$



State confirmed in more recent analyses.

$N(1900)P_{13}$ found in qqq models, not expected in quark-diquark models.

CLAS Data: R. Bradford, et al., Phys. Rev. C 75, 035205 (2007).
Analysis: V.A. Nikonov et al., Phys. Lett. B 662, 245 (2008)

Recoil Polarization P

$\gamma p \to K^+ \vec{\Lambda}$

Kaon-MAID model (green)

Single-channel BW resonance fits

No longer up-to-date

F.X. Lee et al., Nucl. Phys. A695, 237 (2001)

Bonn-Gatchina model (blue)

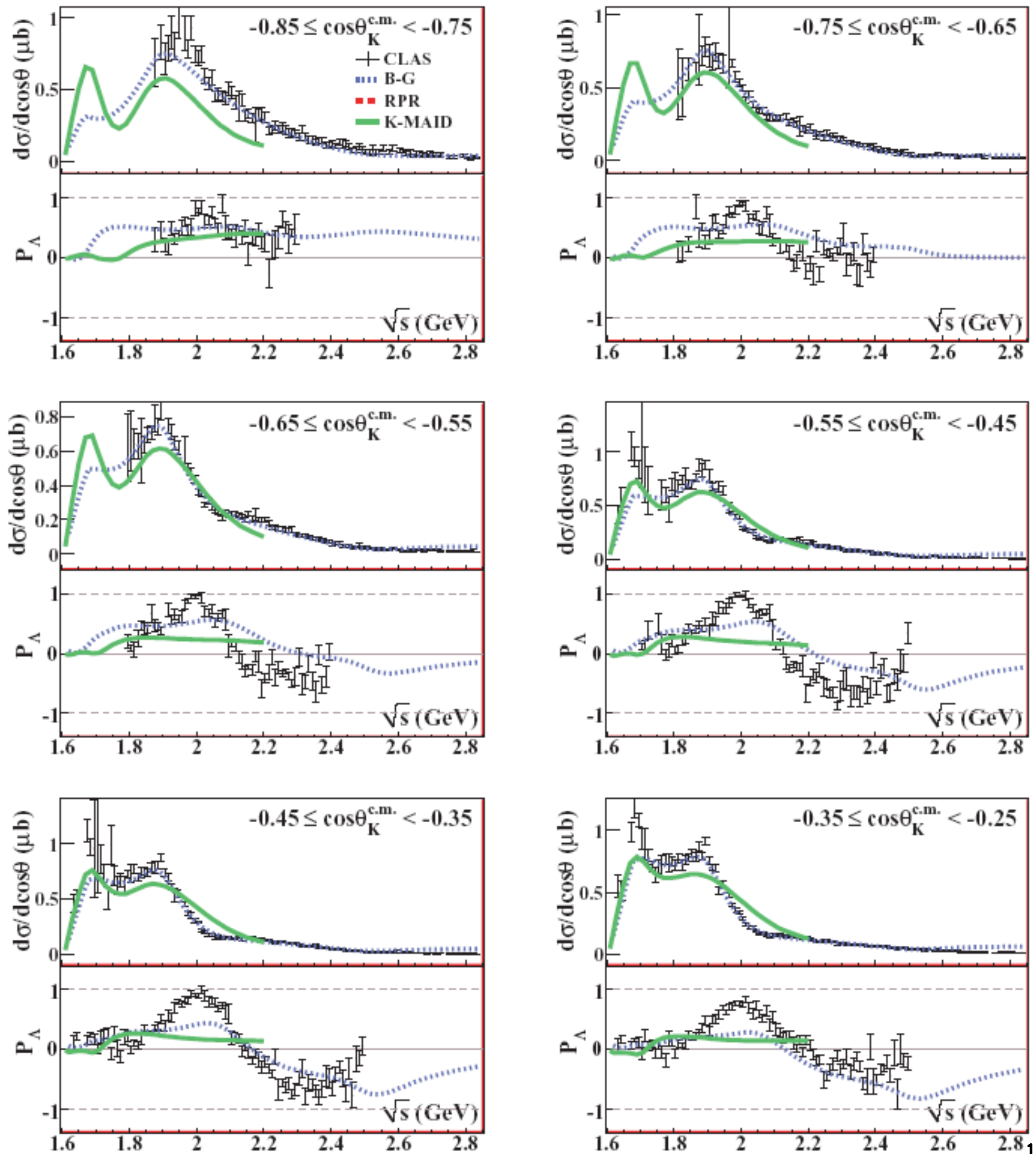
Multi-channel, unitary, BW resonance fit

Large suite of N* contributions

Was not predictive for recoil polarization

BnGa: A.V. Sarantsev et al., Eur. Phys. J., A 25, 441 (2005).

Data: M. McCracken et al, (CLAS) Phys. Rev. C 81, 025201 (2010).



Hyperon photoproduction with linearly polarized photons

1700 MeV < W < 2200 MeV

Self-analyzing weak hyperon decay gives access to recoil polarization.

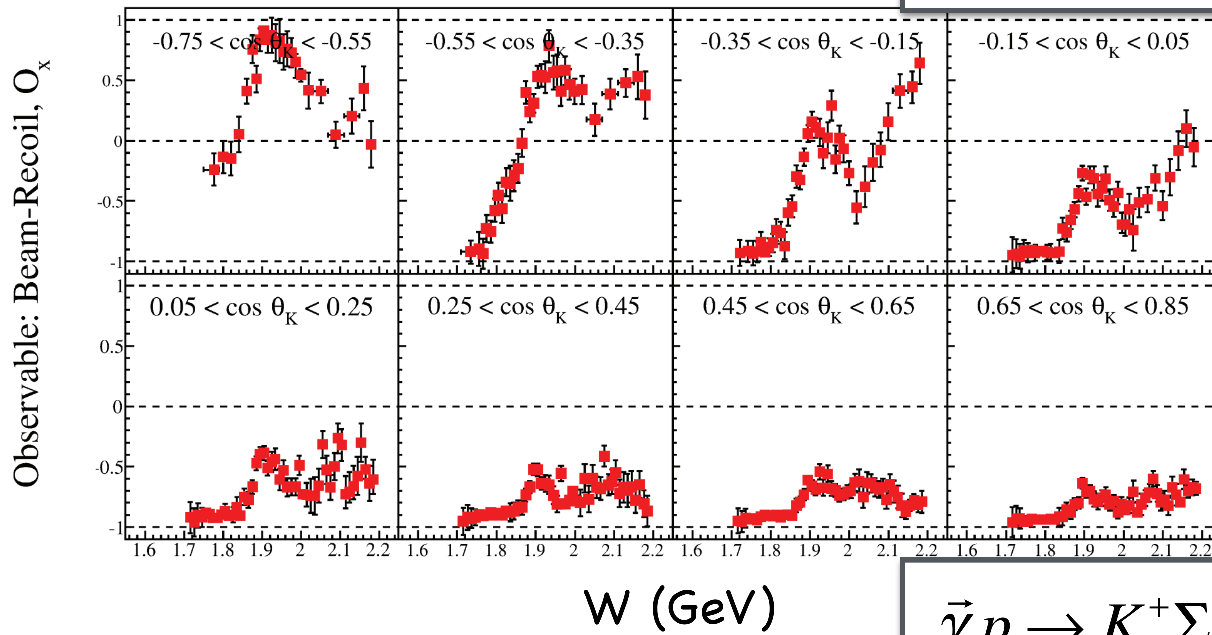
$$\left(\frac{d\sigma}{d\Omega}\right) = \left(\frac{d\sigma}{d\Omega}\right)_{\text{unpol}} \Big(1 - P_L^{\gamma}\Sigma\cos(2\varphi_\gamma)$$
$$+P_{x'}^{R}\left[P_L^{\gamma}O_{x'}\sin(2\varphi_\gamma)\right]$$
$$+P_{y'}^{R}\left[P - P_L^{\gamma}T\cos(2\varphi_\gamma)\right]$$
$$-P_{z'}^{R}\left[P_L^{\gamma}O_{z'}\sin(2\varphi_\gamma)\right]\Big)$$

Simultaneous fit to five polarization observables: Σ, P, T, O_x, and O_z.

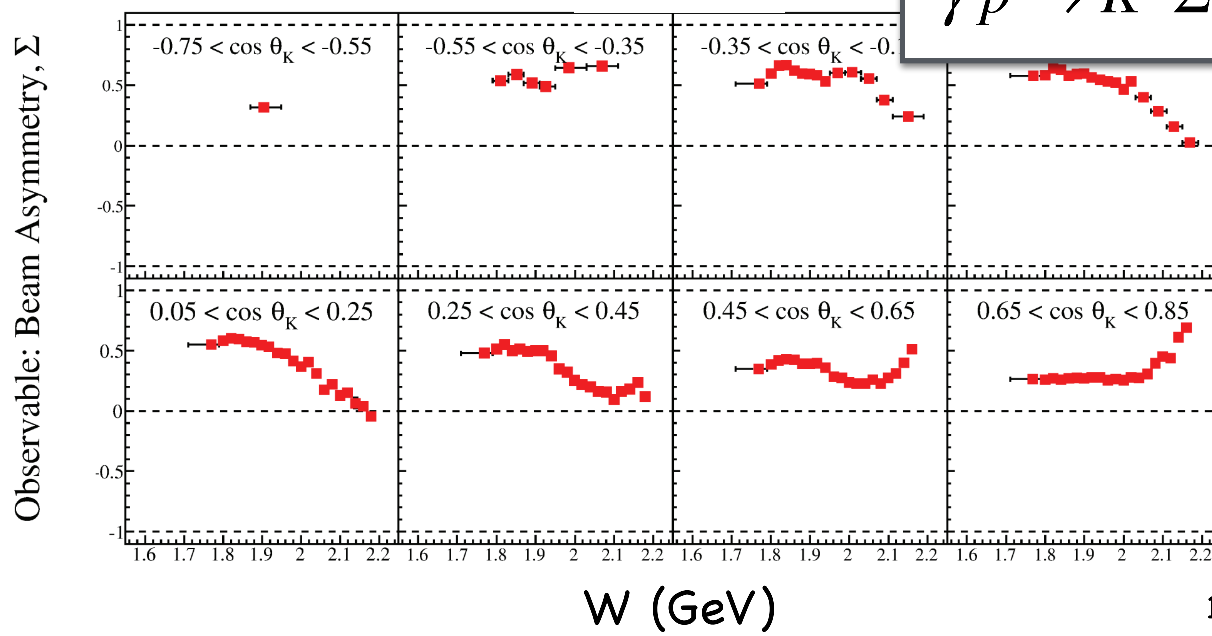
■ prelim. CLAS g8 data

g8 analysis:
Dave Ireland (U. of Glasgow)

$$\vec{\gamma}p \rightarrow K^{+}\vec{\Lambda}$$

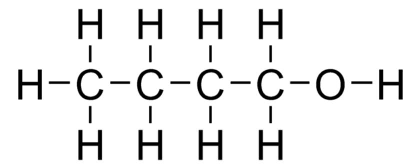


$$\vec{\gamma}p \rightarrow K^{+}\Sigma$$

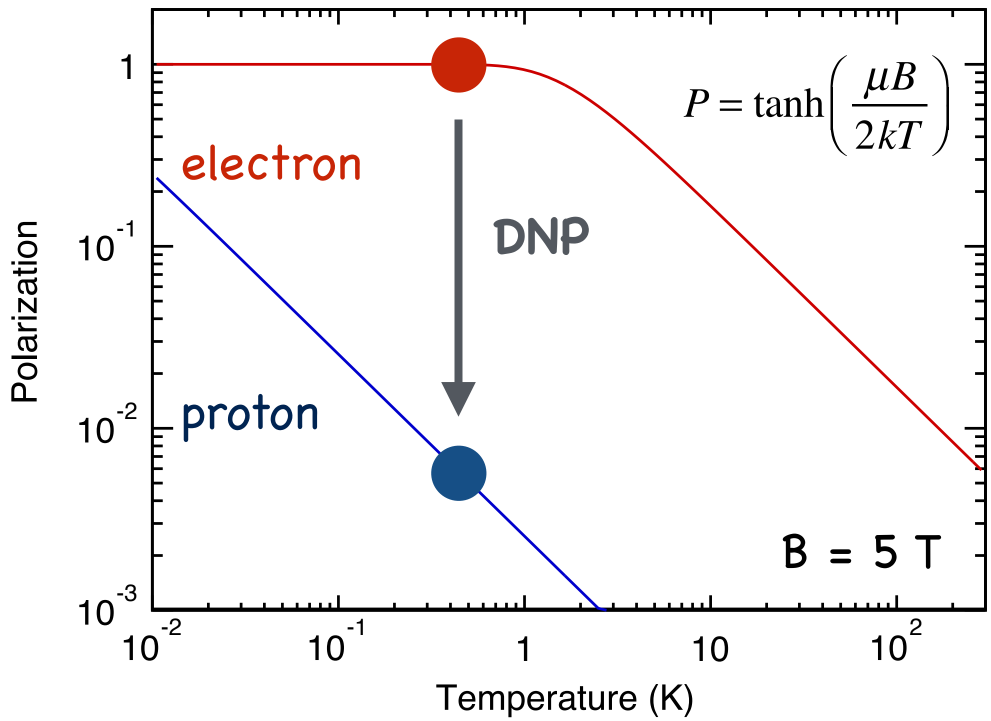


The FROST Target

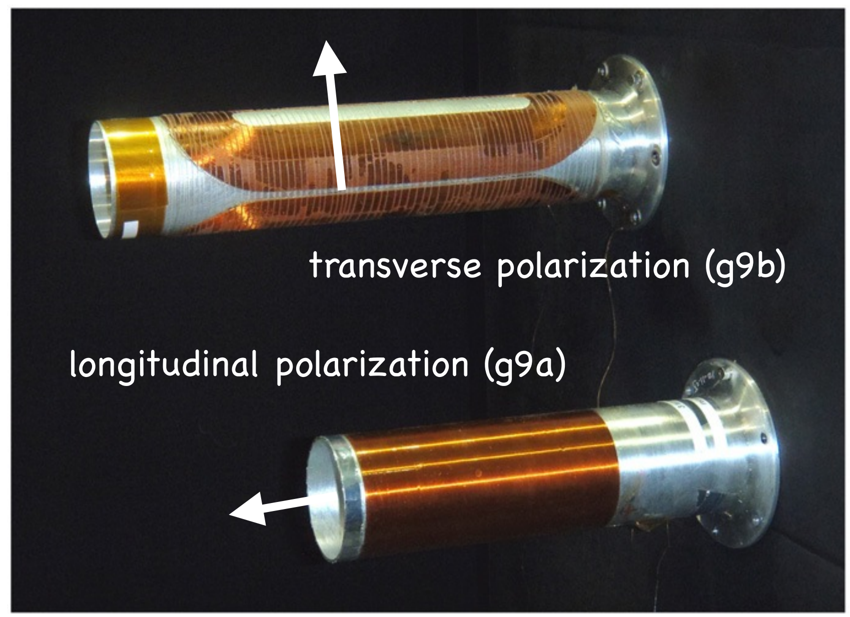
Target: Frozen beads of butanol (C_4H_9OH) at 50 mK



Thermal equilibrium polarization of a spin-1/2 particle



superconducting holding coils (0.5 T)



Through **dynamic nuclear polarization** the high electron polarization is transferred to the proton spin system via microwave induced transitions.

FROST Target: C.D. Keith et al., Nucl. Instrum. and Methods A **684**, 27 (2012)

The simple idea of the experiment

$$\vec{\gamma}\vec{p} \rightarrow \pi^{+} n$$

- Measure polarized free-proton and unpolarized bound-nucleon yield off butanol.
- Measure simultaneously unpolarized bound-nucleon yield off ^{12}C target.
- Determine the polarized proton yield in the difference.

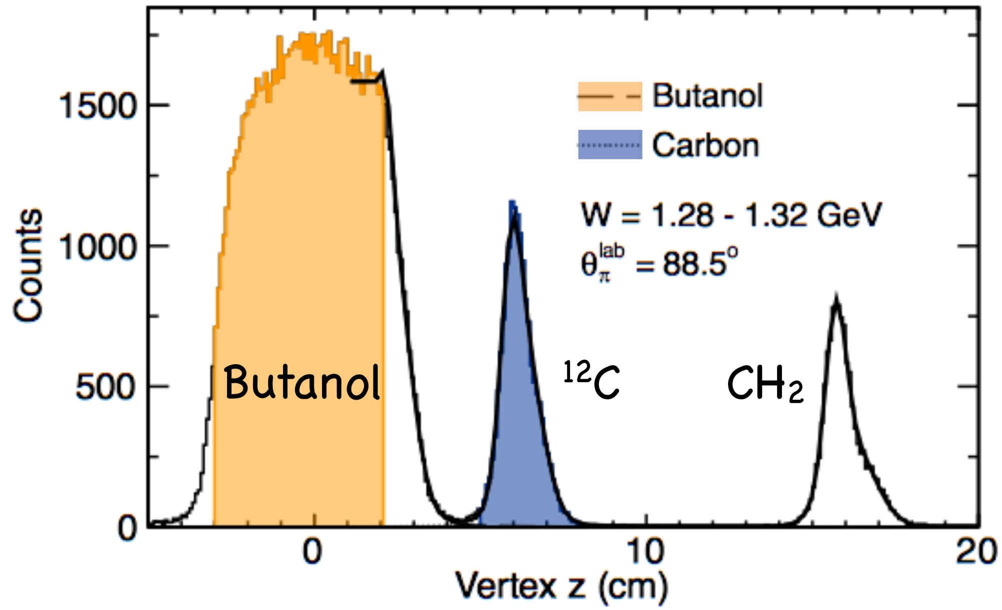
$$N^{p} \approx N^{B} - \alpha N^{C}$$

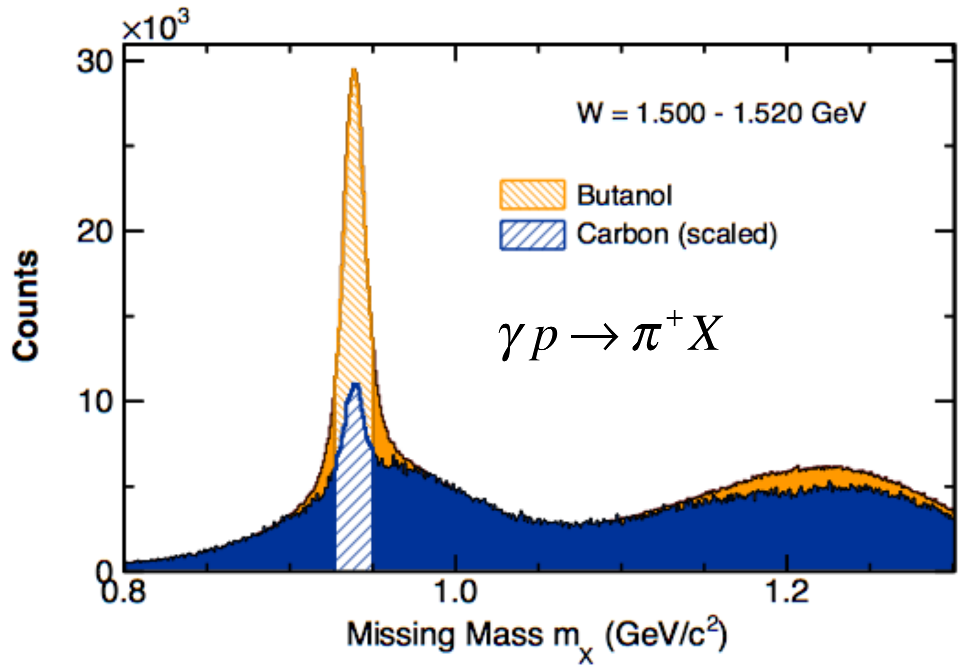
- Data analysis in 900 bins

$$W = 1240 - 2260 \text{ MeV}$$

$$-0.9 \leq \cos(\theta_{\pi}^{cm}) \leq +0.9$$

$$\Delta W = 20 \text{ MeV}, n_{\cos\theta} = 30$$





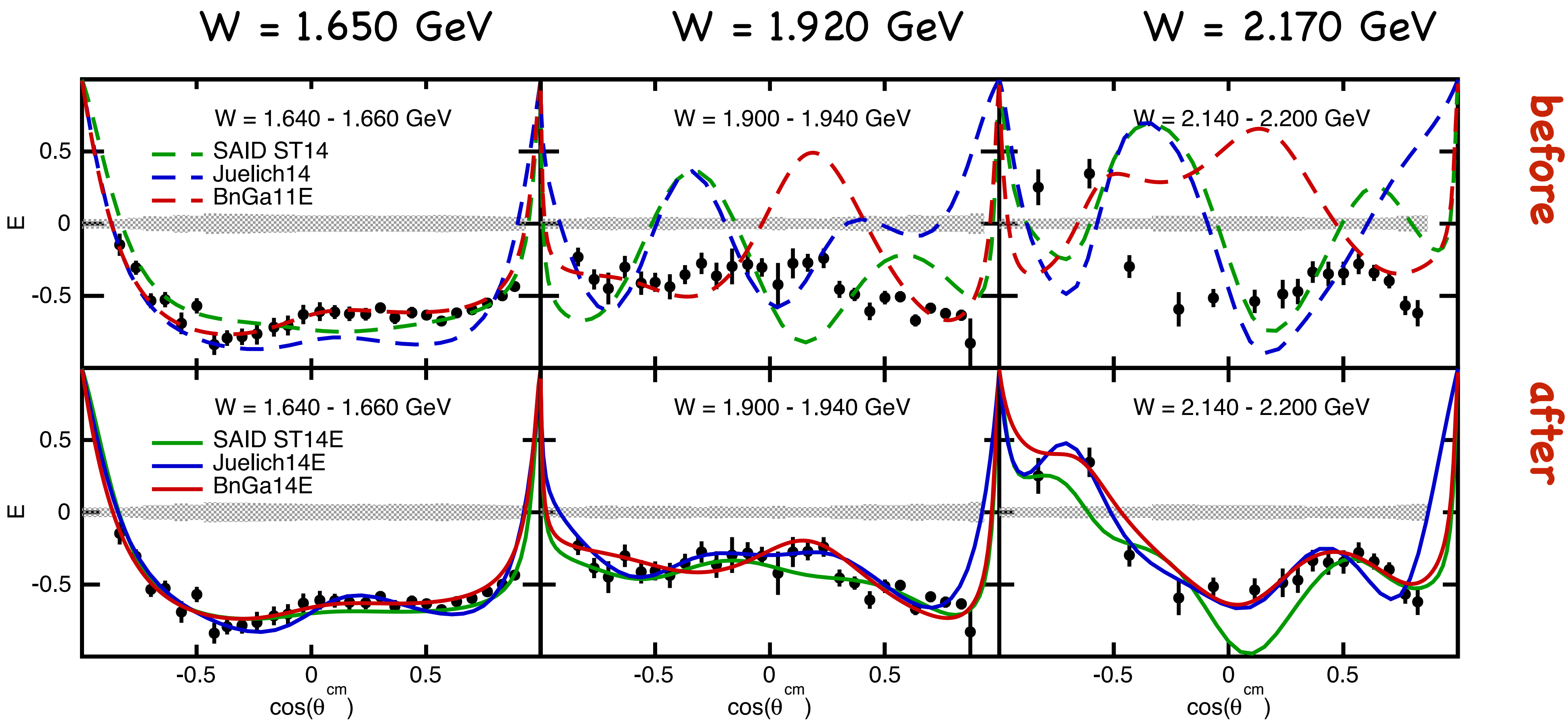
Double Polarization Observable E in π^+n

$$\left(\frac{d\sigma}{d\Omega}\right)=\left(\frac{d\sigma}{d\Omega}\right)_0\left(1-P_zP_\odot E\right)$$

$W = 1240 - 2260$ MeV

$-0.9 \leq \cos(\theta_\pi^{cm}) \leq +0.9$

$$\vec{\gamma}\vec{p} \rightarrow \pi^+ n$$

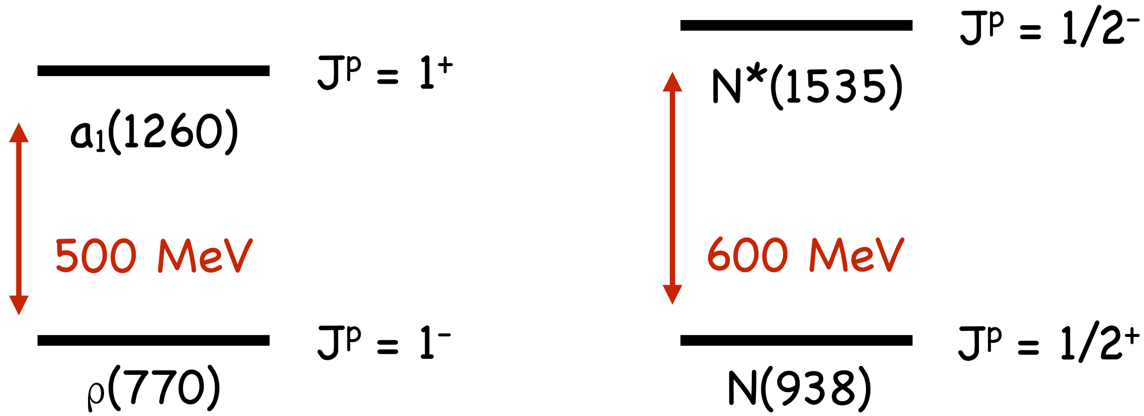


Partial Wave Analyses Good overall description <u>after</u> fit, however, not with identical results.

S.S. et al. (CLAS Collaboration), PLB **750**, 53 (2015)

Is chiral symmetry effectively restored in highly excited mesons and baryons?

An important consequence of the spontaneous breaking of the chiral symmetry is the large mass gap between chiral partners:



Mesons and baryons at higher masses are often observed in parity doublets. Example: four positive-parity and four negative-parity Δ_* resonances at about 1900 MeV

$$\Delta(1910)1/2^+ \quad \Delta(1920)3/2^+ \quad \Delta(1905)5/2^+ \quad \Delta(1950)7/2^+ \;\; (****)$$
$$\Delta(1900)1/2^- \quad \Delta(1940)3/2^- \quad \Delta(1930)5/2^- \quad \Delta(2200)7/2^- \;\; (*)$$

A.V. Anisovich et al., arXiv:1503.05774 [nucl-ex]

New evidence for Δ(2200)7/2$^-$ resonance

BnGa analysis of CLAS and CBELSA/TAPS data

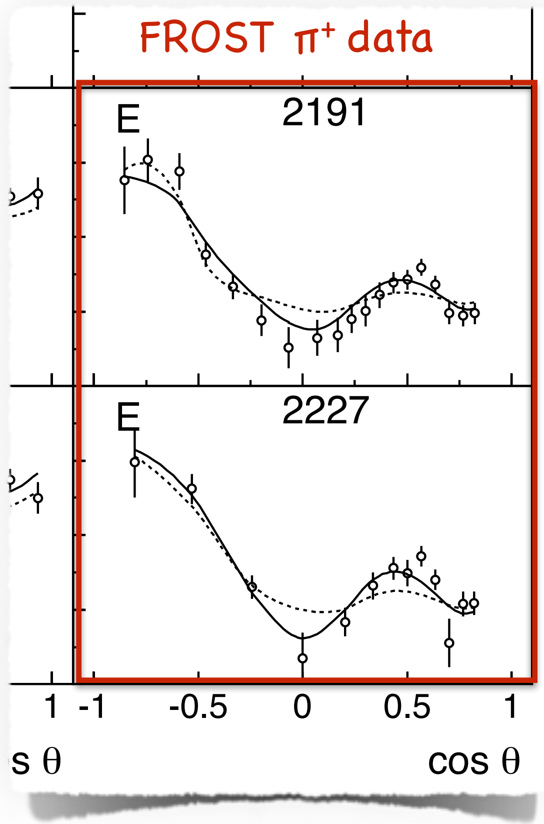
Parity partner of Δ(1950)7/2$^+$ is poorly known.

Δ(1950)7/2+	****
Δ(2200)7/2$^-$	*

Evidence found for Δ(2200)7/2$^-$ in a preliminary analysis of the Bonn/Gatchina group.

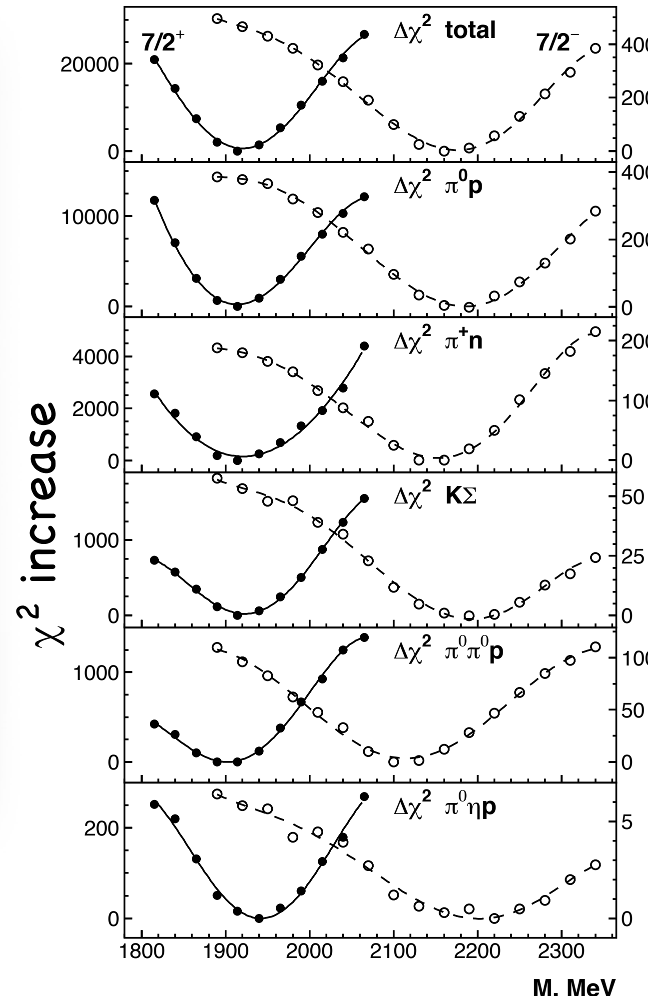
M(Δ7/2$^-$) ≈ 2180 MeV

... and not ≈ 1950 MeV. Chiral symmetry is not restored in high-mass hadrons.



with Δ(2200)7/2$^-$

without



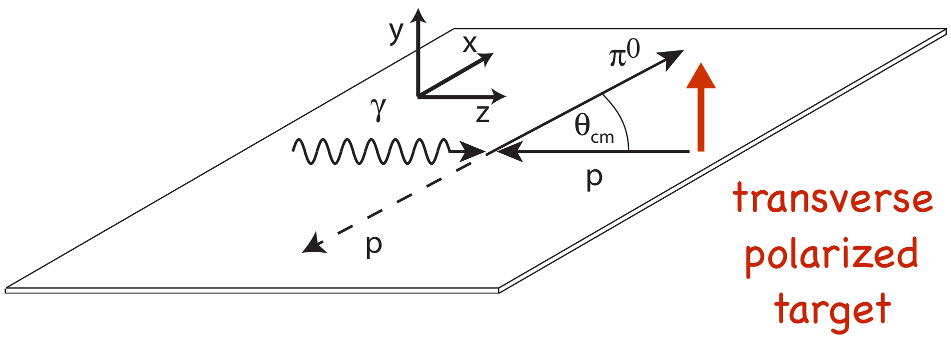
7/2$^+$ 7/2$^-$

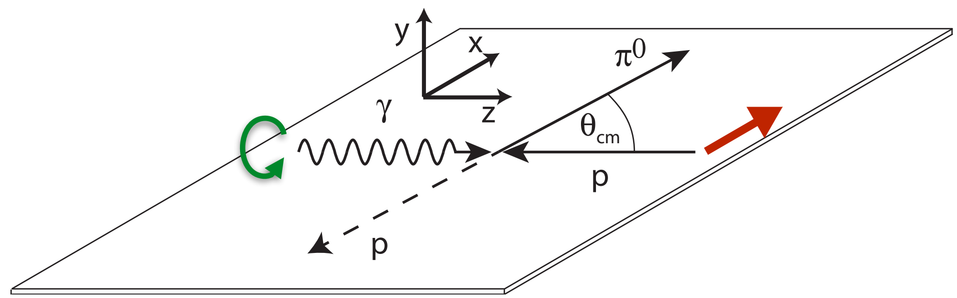
A.V. Anisovich et al., arXiv:1503.05774 [nucl-ex]

All isospin channels are important to constrain coupled-channel analyses: two examples for $\pi^0 p$

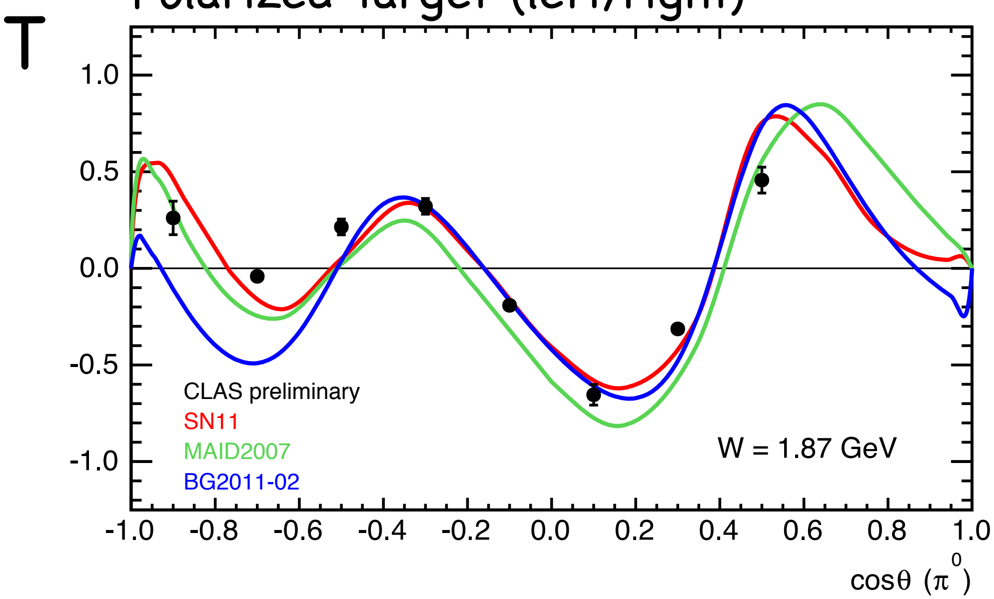
$$\vec{\gamma}\vec{p} \to \pi^0 p$$

$$\left(\frac{d\sigma}{d\Omega}\right) = \left(\frac{d\sigma}{d\Omega}\right)_0 \left\{1 + P_y T + P_x P_\odot F\right\}$$

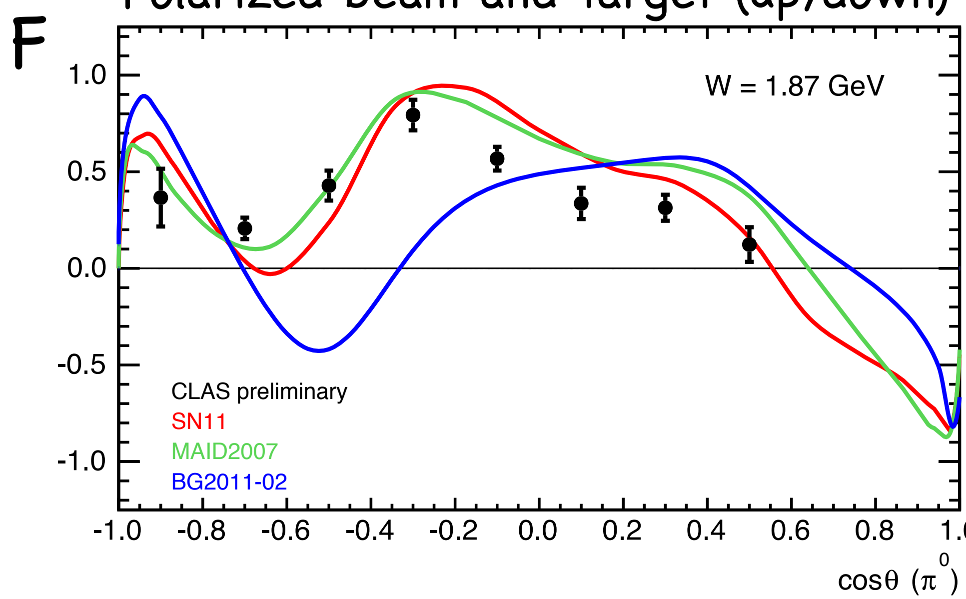




Polarized target (left/right)



Polarized beam and target (up/down)



g9 analysis: Hao Jiang (USC)

Helicity asymmetry E in eta photoproduction on the proton

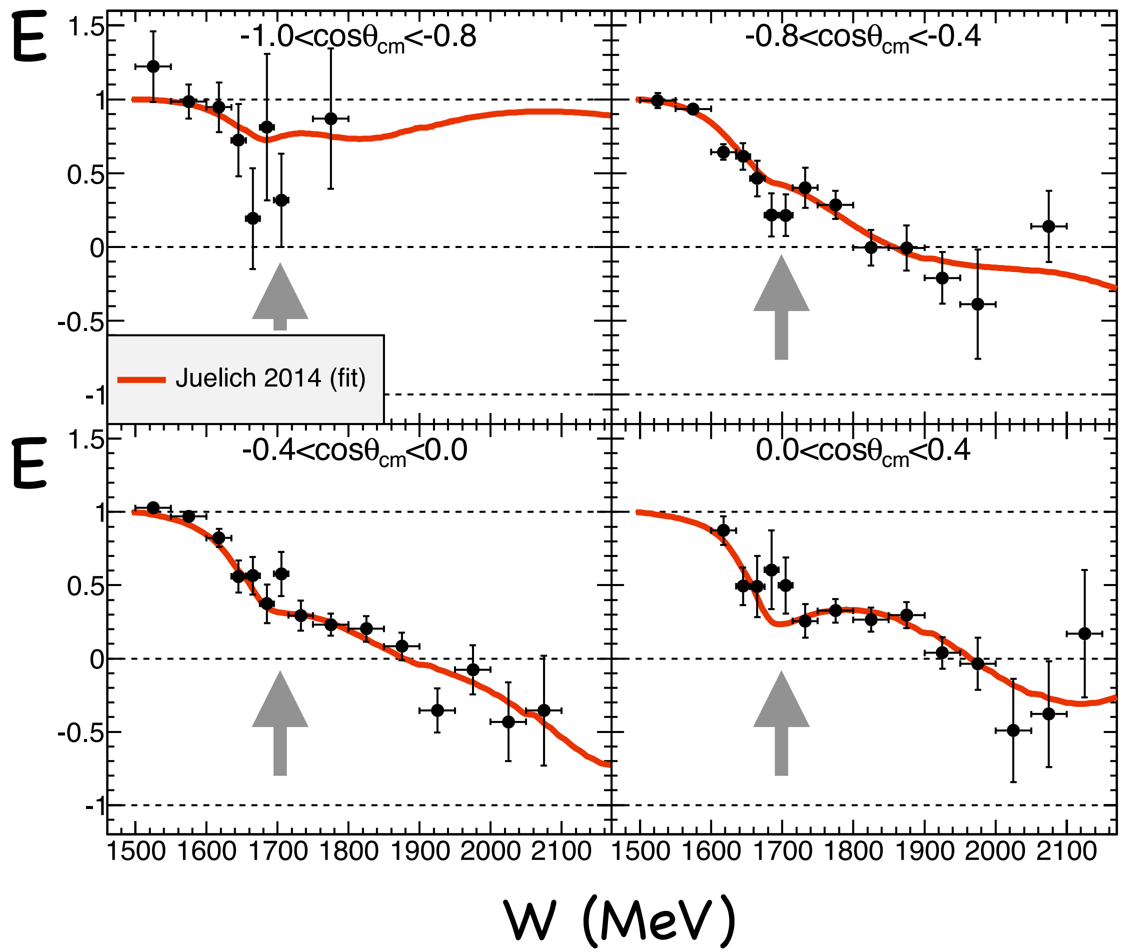
$$\vec{\gamma}\vec{p} \rightarrow \eta p$$

η photoproduction isolates N*(I=1/2) states in the resonance spectrum.

Narrow structure seen in MAMI $\gamma p \rightarrow \eta p$ cross section data.

[predicted in πN PWA: Phys. Rev. C 69, 035208 (2004)]

Present CLAS E data do not demand the presence of a narrow resonance with a width of 40 MeV or less at about 1.7 GeV.



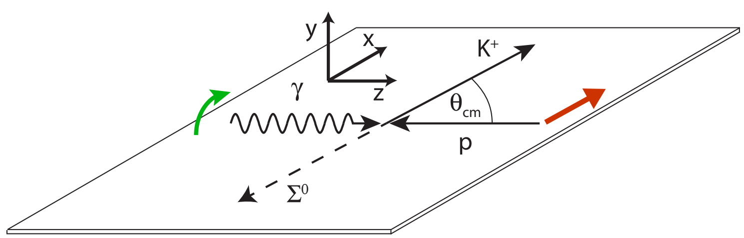
I. Senderovich et al. (CLAS Collaboration), arXiv:1507.00325 [nucl-ex]

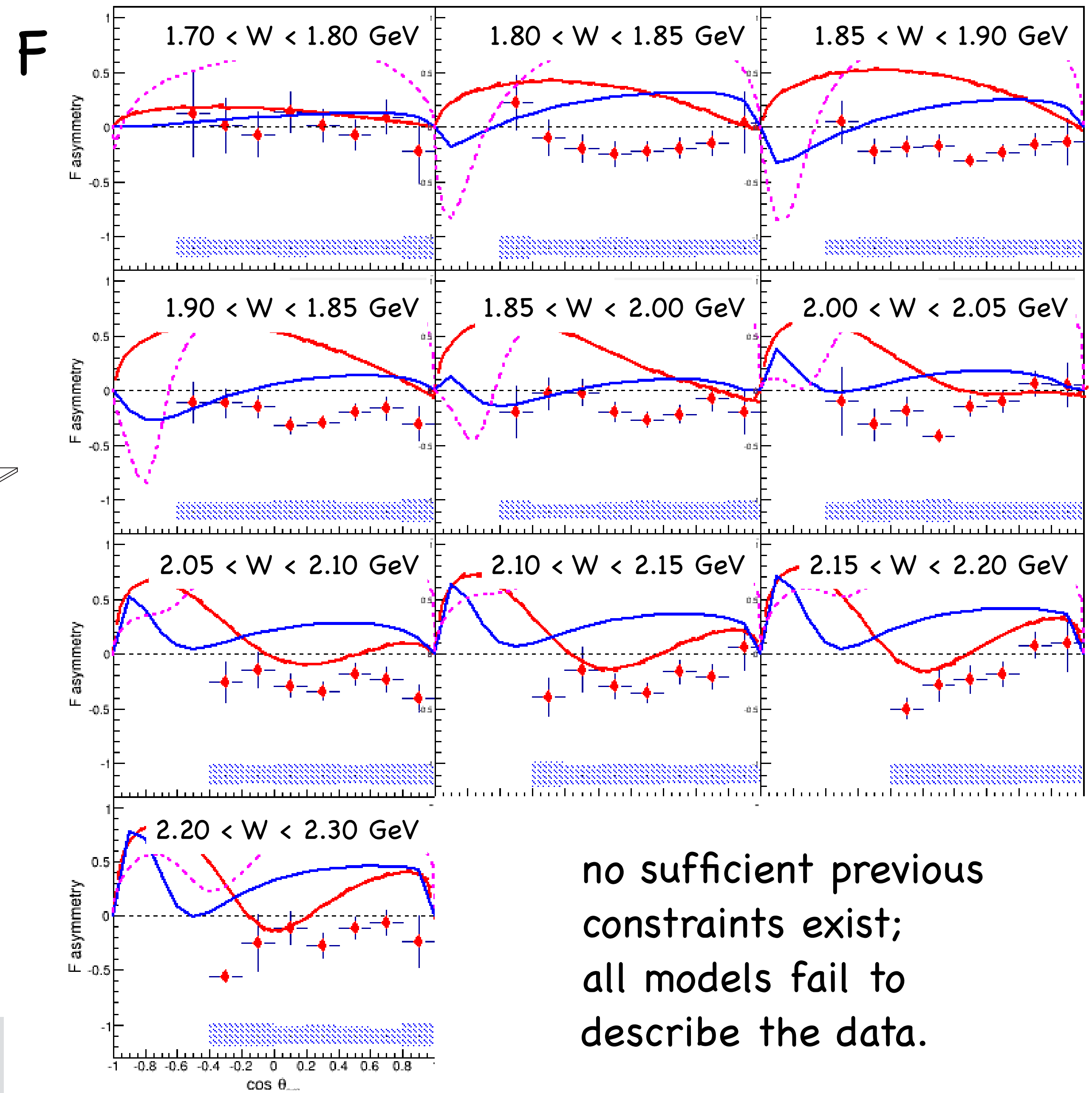
Hyperon photoproduction

$$\vec{\gamma}\vec{p} \rightarrow K^+\Sigma^0$$

FROST data for Λ, Σ photoprouction

First measurement of the polarization observable F up to 2.30 GeV.





◆ CLAS g9b preliminary
— RPR-Ghent
— KAON-MAID
⋯ Bonn-Gatchina

no sufficient previous constraints exist; all models fail to describe the data.

g9 analysis:
Natalie Walford (CUA, now Basel)

Double-pion photoproduction as a tool in the study of excited nucleons

Nππ is a dominant decay channel of highly excited nucleons.

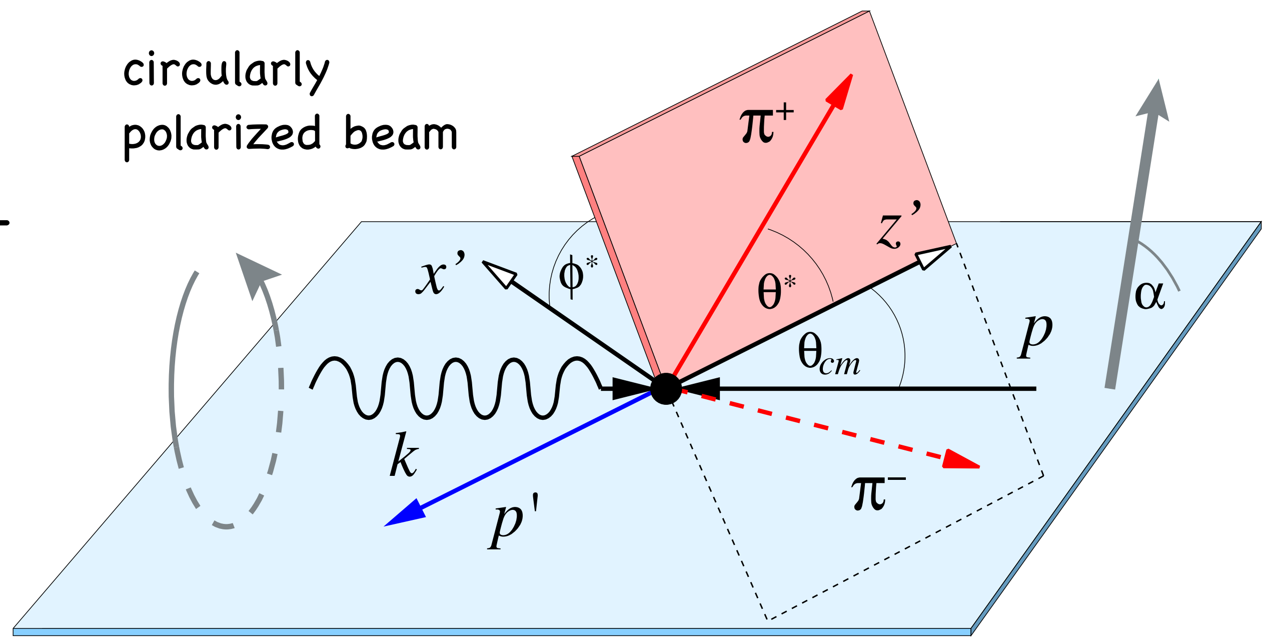
Essential part in coupled-channel calculations.

Allows for the study of sequential decays.

$$\gamma p \rightarrow N^* \rightarrow \pi\Delta$$

$$\gamma p \rightarrow N^* \rightarrow \rho p$$

Example:



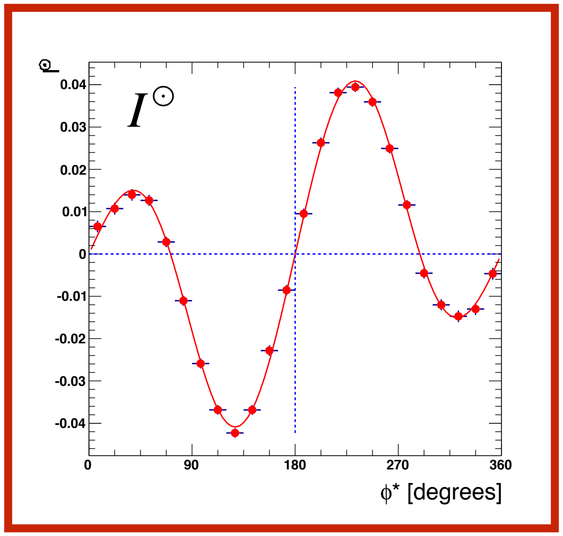
$$\frac{d^5\sigma}{dm(\pi^+\pi^-)\, d\Omega^*_{\pi+}\, d\cos\theta}$$

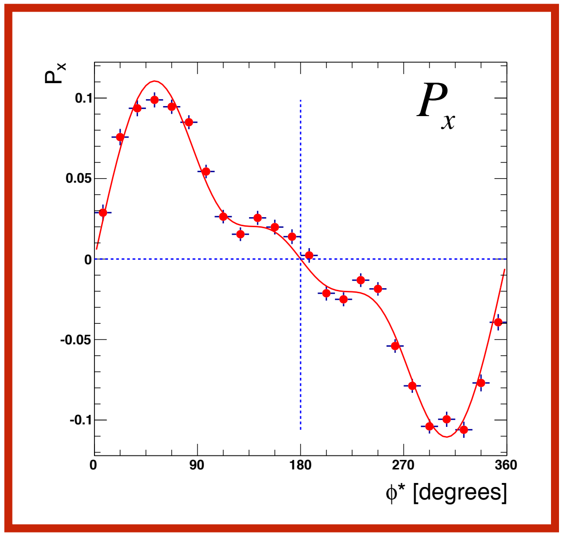
Parity conservation yields to symmetry properties of observables

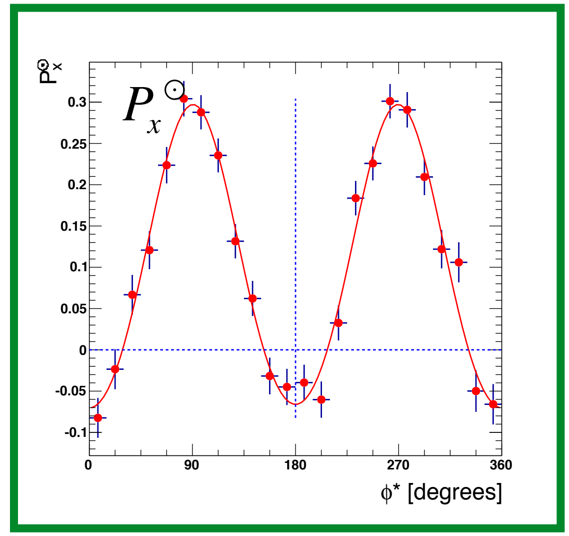
$\gamma p \rightarrow \pi^+ \pi^- p$

$$M^{-\lambda_\gamma}_{-\lambda_N -\lambda'_N}(\theta,\theta_1,\phi_1) = (-1)^{\lambda_\gamma - \lambda_N + \lambda'_N} M^{\lambda_\gamma}_{\lambda_N \lambda'_N}(\theta,\theta_1,2\pi-\phi_1)$$

circularly polarized photons – transversely polarized target

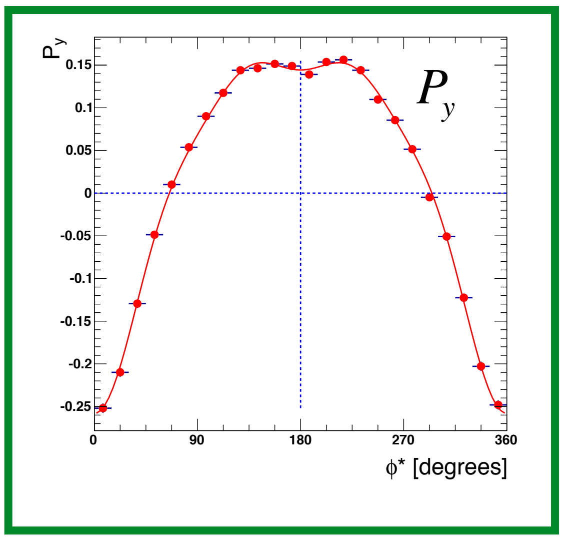


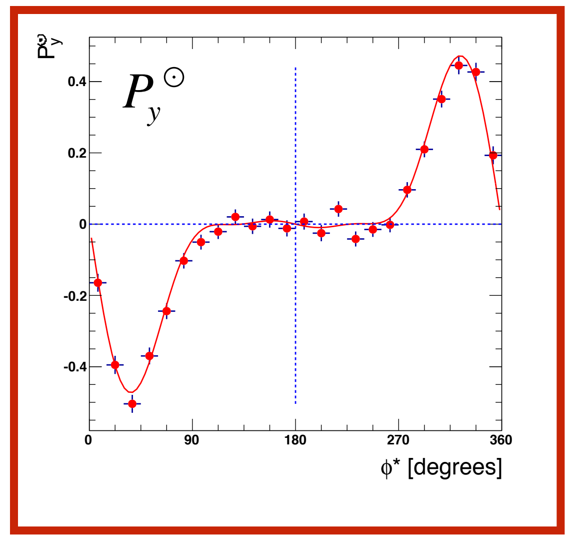




odd observables:
do <u>not</u> exist in single meson final states.

even observables:
P_y and $P_x^{\odot}$ correspond to T and F, respectively.



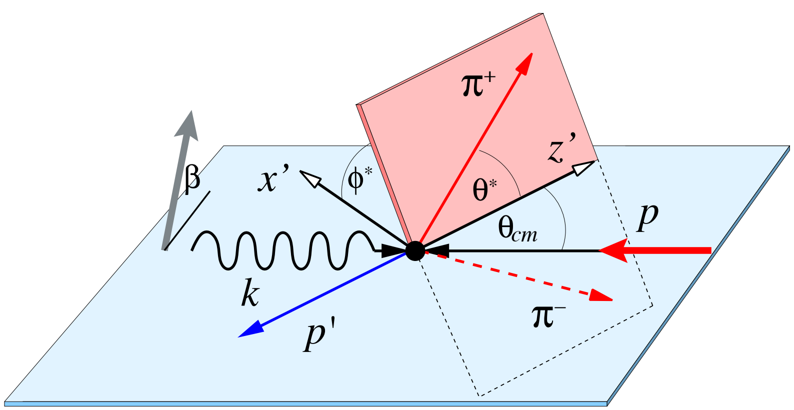


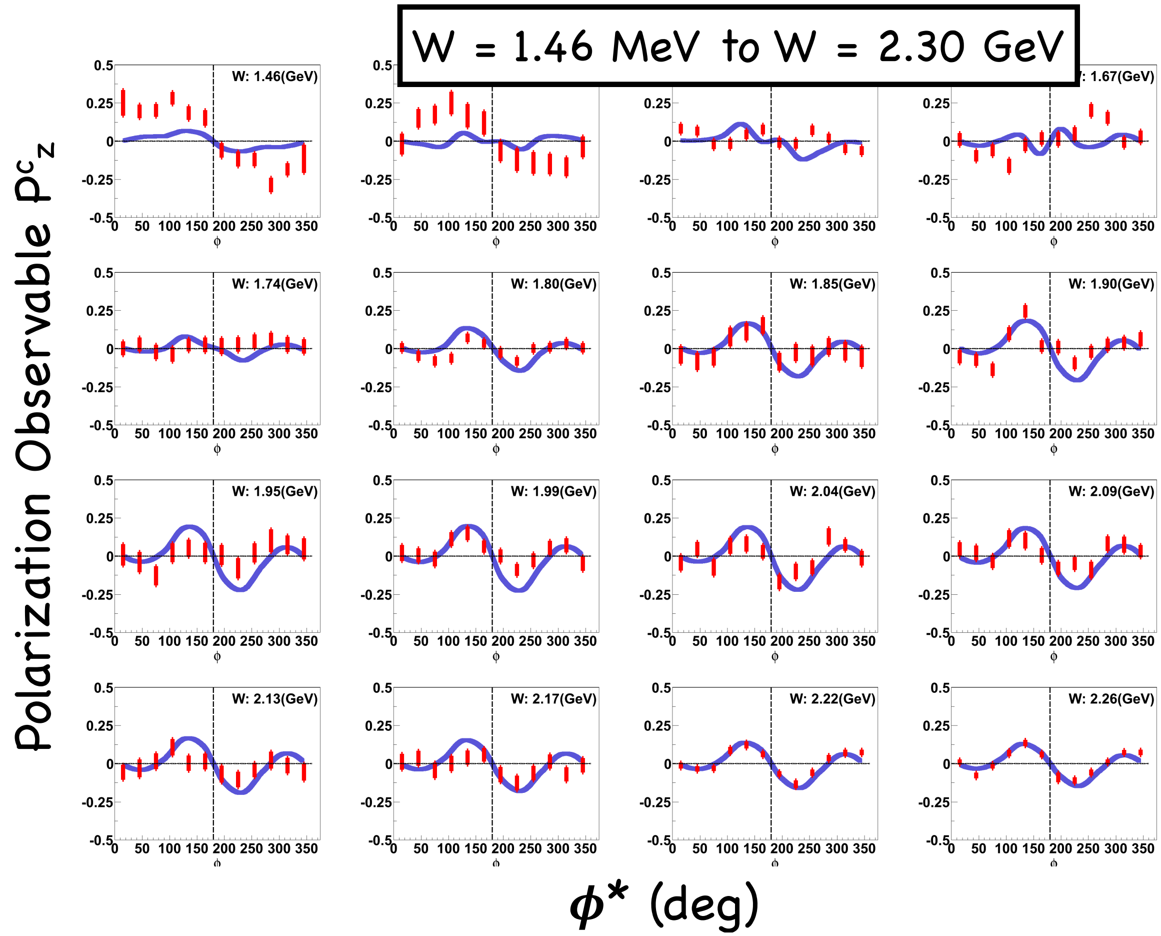
g9 analysis: Aneta Net (USC)

Preliminary results (g9a) for P^c_z

$\gamma p \rightarrow \pi^+ \pi^- p$

$$I = I_0\left\{1+\Lambda_z P_z + \delta_\ell \sin 2\beta\left(I^s+\Lambda_z P_z^s\right) + \delta_\ell \cos 2\beta\left(I^c+\Lambda_z P_z^c\right)\right\}$$

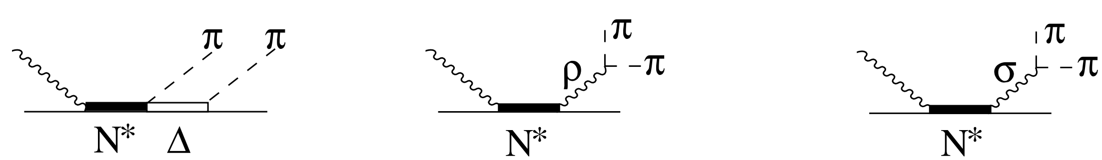




Effective Lagrangian Model (A. Fix)

Exchange mesons, π,ρ,σ, and resonances, Δ(1232), N*(1440), N*(1520), N*(1535), Δ(1620), N*(1675), N*(1680), Δ(1700), N*(1720), Nucleon and Delta Born terms; Resonance terms:

Yuqing Mao (USC)

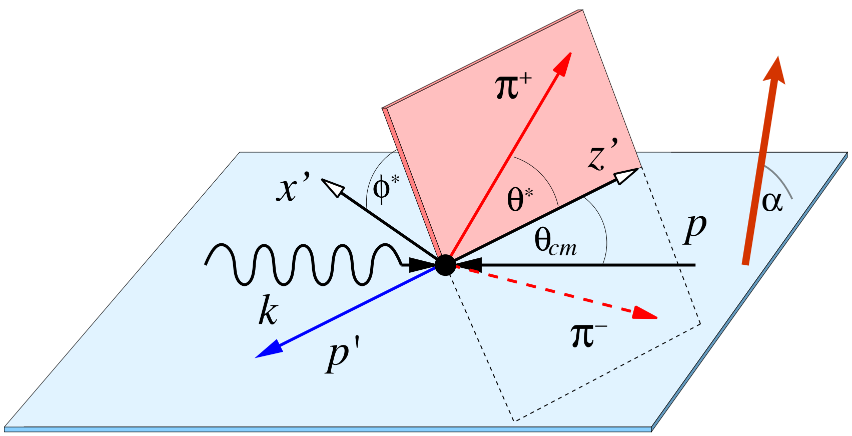


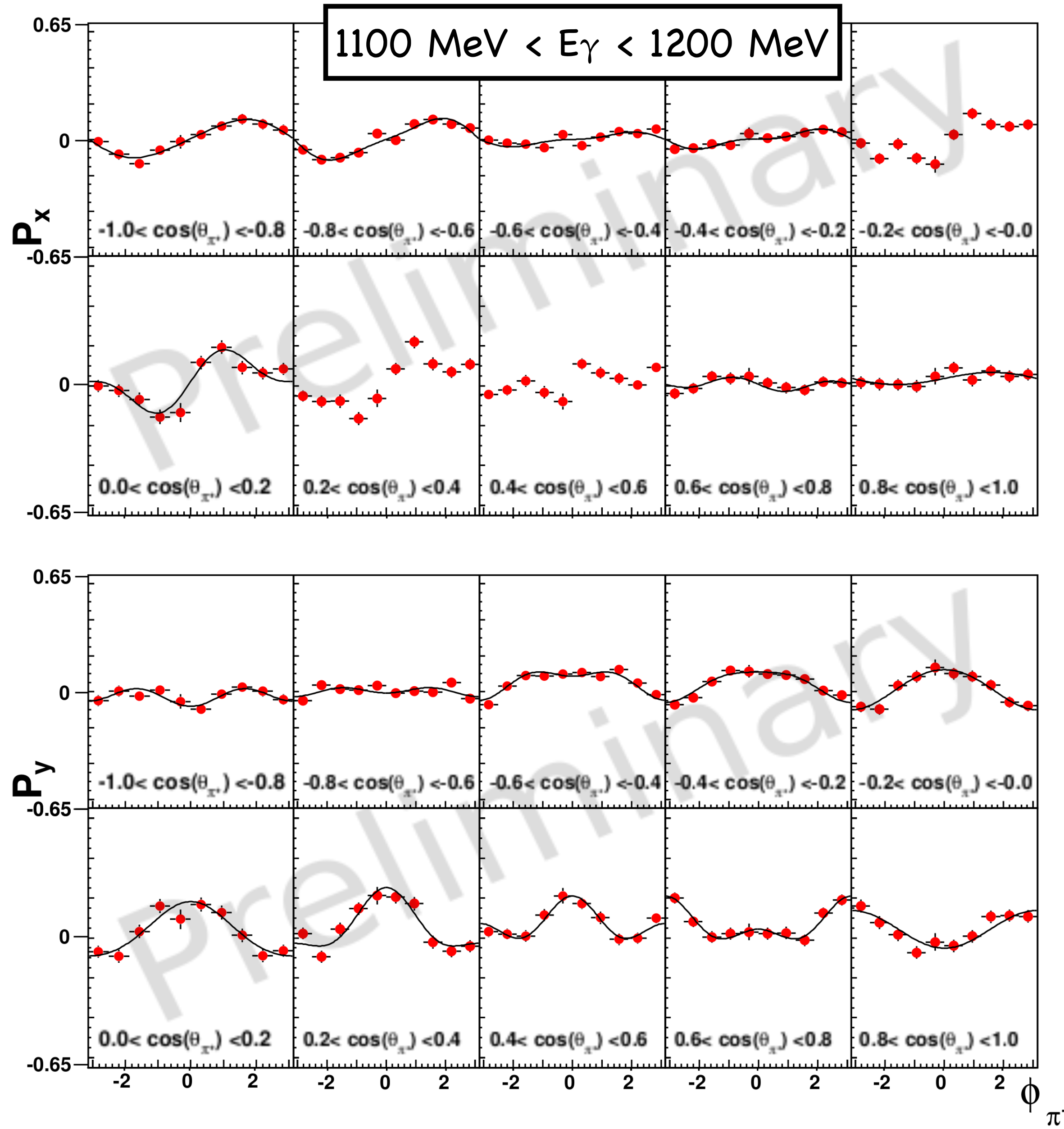
A. Fix and H. Arenhövel, Eur. Phys. J. A **25**, 115 (2005); Preliminary data: Yuqing Mao (USC)

Preliminary results (g9b) for P_x and P_y

$$\gamma p \rightarrow \pi^+ \pi^- p$$

$$I = I_0\left(1 + \Lambda\cos(\alpha) P_x + \Lambda\sin(\alpha) P_y\right)$$





Data binned in E_γ, Φ^*, and cos θ^*,

fit with Fourier series.

g9 analysis:
Priyashree Roy (FSU)

Intermediate $\Delta(1232)$ Resonance

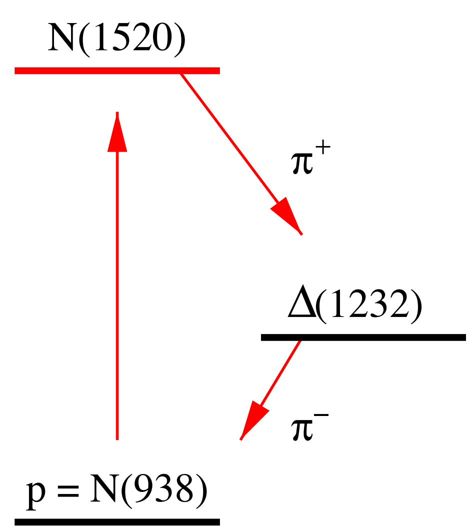
$$\gamma p \to \pi^+ \pi^- p$$

Fourier coefficients of the angular distribution

$$I^{\odot} = \sum a_k \sin(k\phi)$$

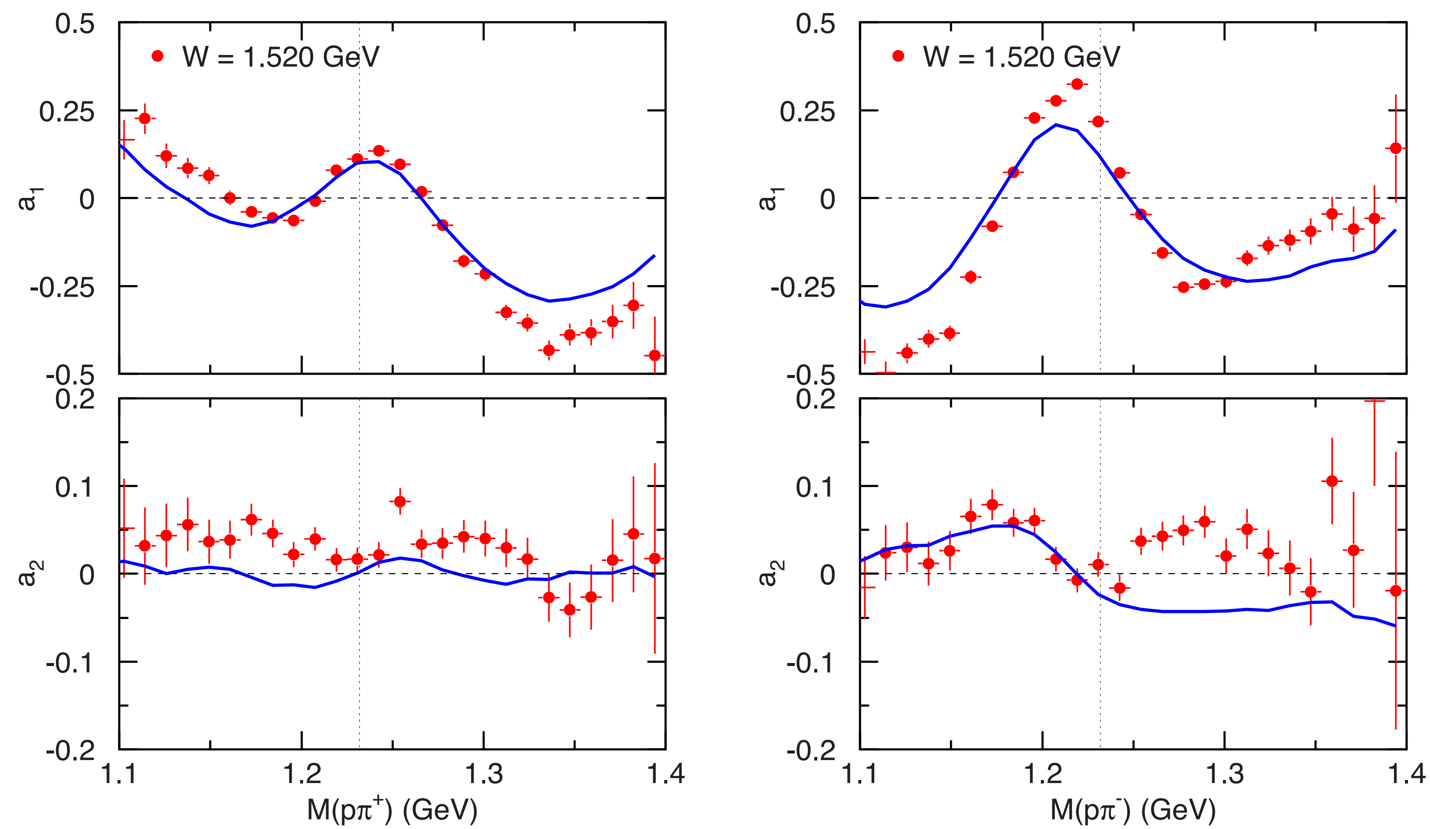
Example of
sequential decays

$$\gamma p \to N^* \to \pi\Delta$$



$N(1520) \to \pi^- \Delta^{++} \to p\pi\pi$

$N(1520) \to \pi^+ \Delta^{0} \to p\pi\pi$

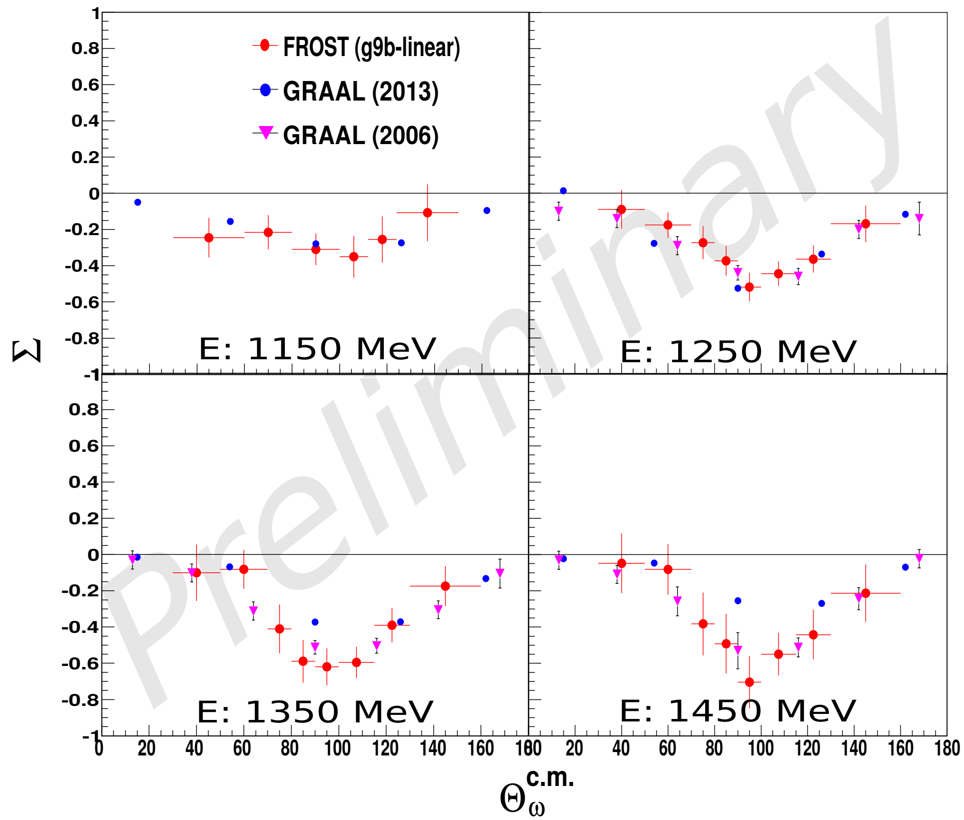


CLAS Data: S.S. et al (CLAS Collaboration), Phys. Rev. Lett 95, 162003 (2005); Model: A. Fix and H. Arenhövel, Eur. Phys. J. A **25**, 115 (2005)

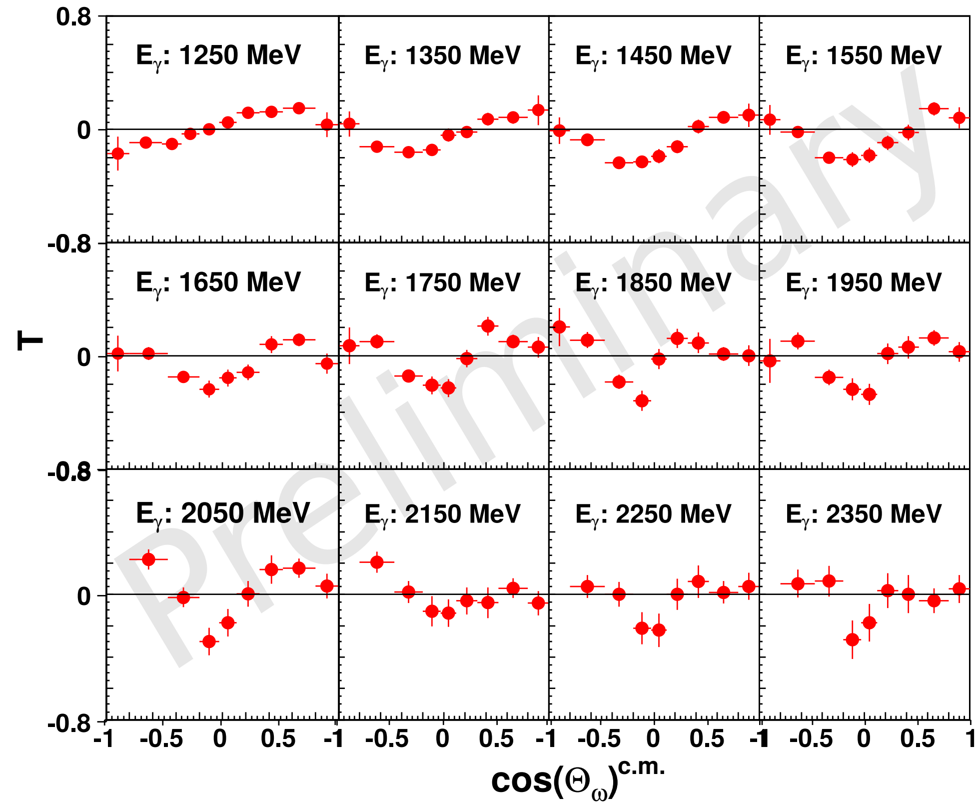
Beam and target asymmetries in omega photoproduction (g9b)

$$\gamma p \rightarrow \omega p$$

Beam asymmetry



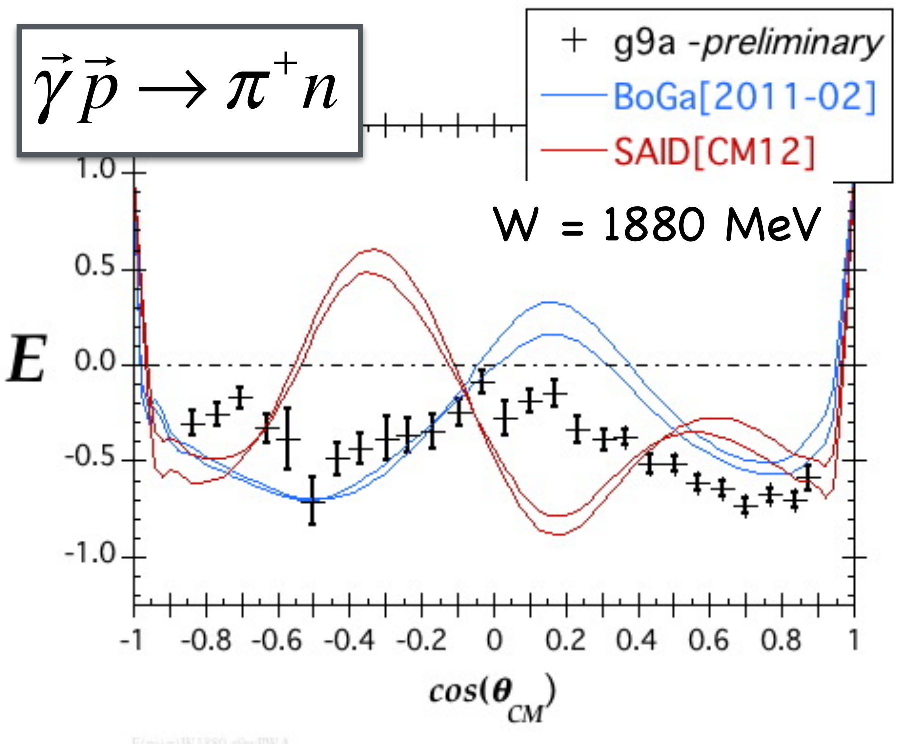
Target asymmetry

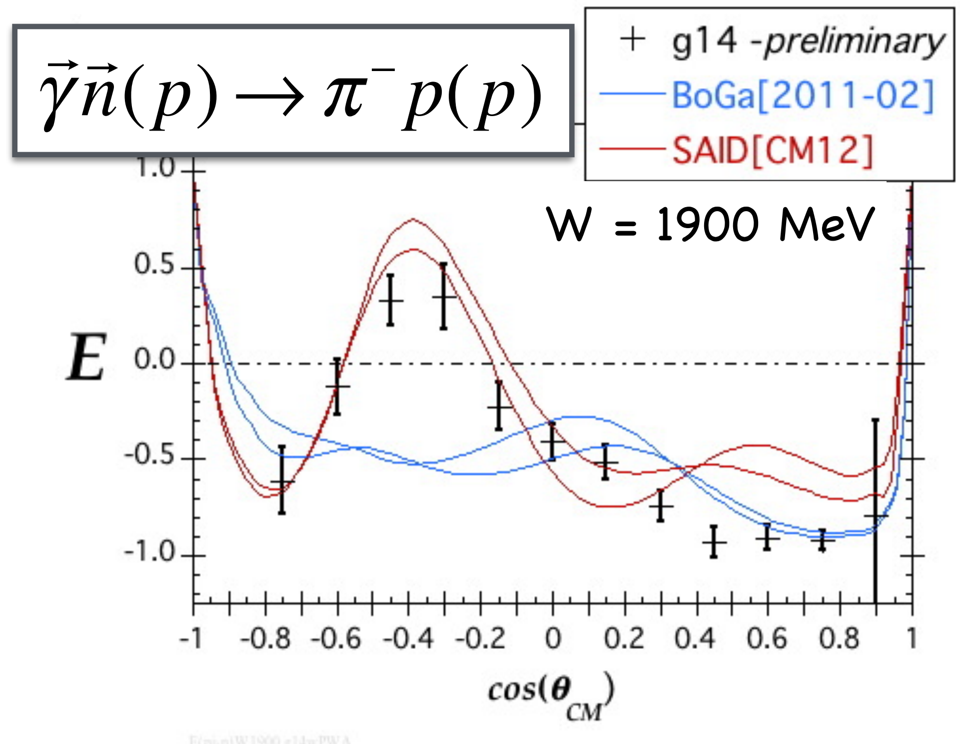


g9 analysis: Priyashree Roy (FSU)

All isospin channels are important to constrain coupled-channel analyses

Beam-Target helicity asymmetry (observable E) for **proton and neutron targets**





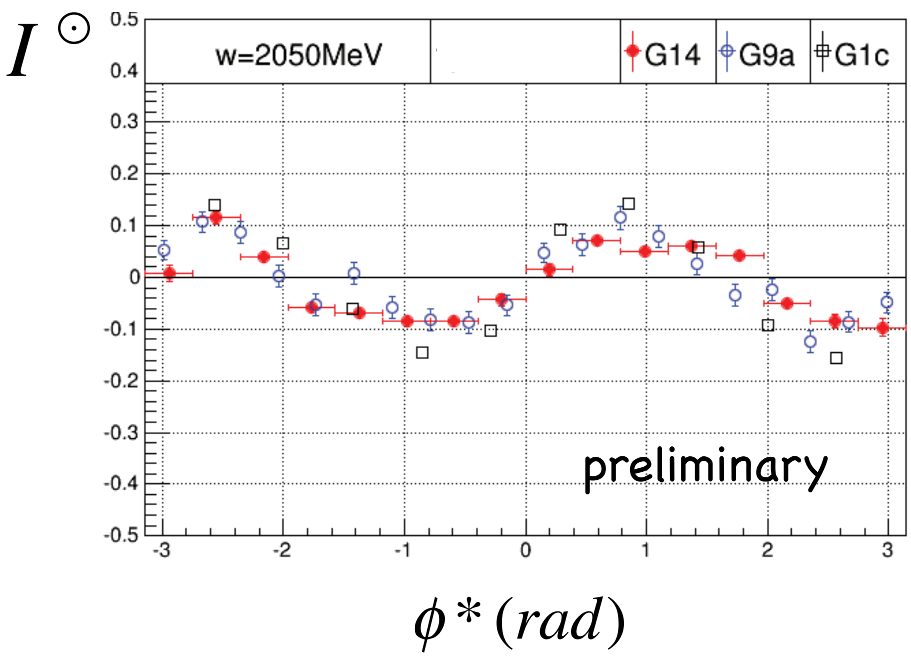
PWA solutions (already outdated) show need to measure all isospin channels.

g14 analysis: Tsuneo Kageya (Jlab)

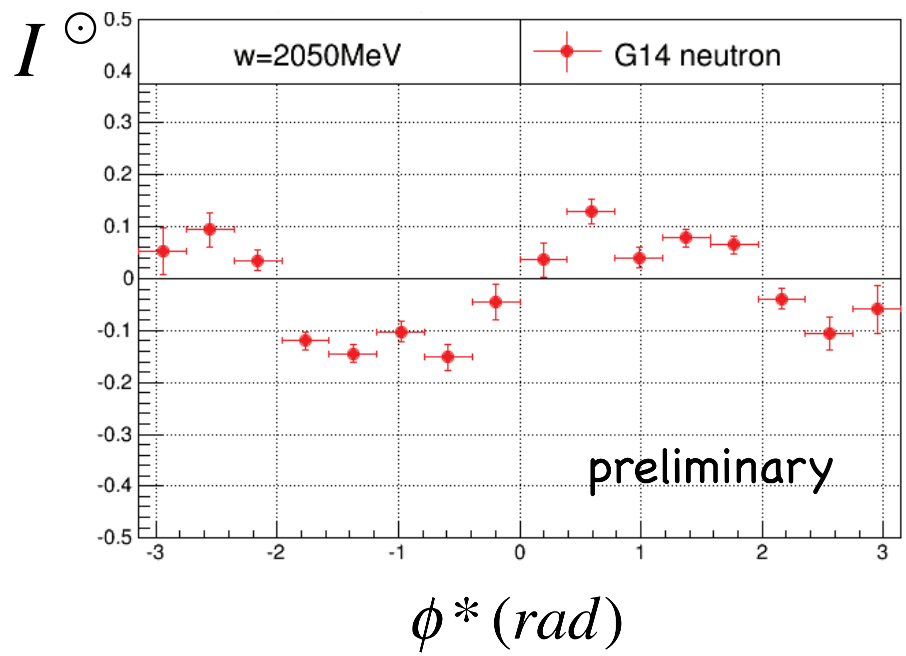
Figs. A.M. Sandorfi, Spin'2014 Symposium

Double pion beam-helicity asymmetry for proton and neutron targets

$$\gamma p \rightarrow \pi^{+}\pi^{-} p$$
$$\gamma p(n) \rightarrow \pi^{+}\pi^{-} p(n)$$



$$\gamma n(p) \rightarrow \pi^{+}\pi^{-} n(p)$$

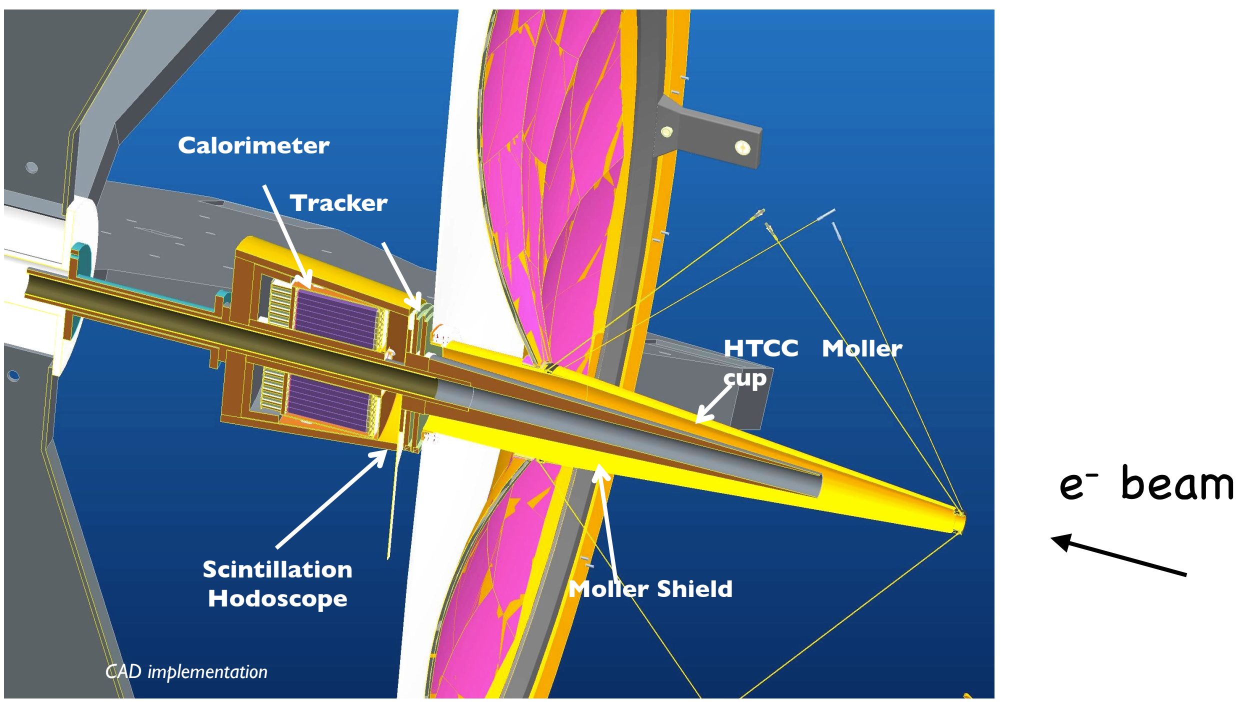


Integrated I° asymmetries off proton and neutron targets are comparable.

g14 analysis: Peng Peng (UVa)

CLAS 12 Forward Tagger

- Small angle e^- scattering (2.5° to 5°)
- $E\gamma$ = 6.5 - 10.5 GeV
- 0.01 $(GeV/c)^2 < Q^2 <$ 0.3 $(GeV/c)^2$ virtual photon, (almost) real photon
- Quasi real photons are linearly polarized wrt to scattering plane
- High luminosity



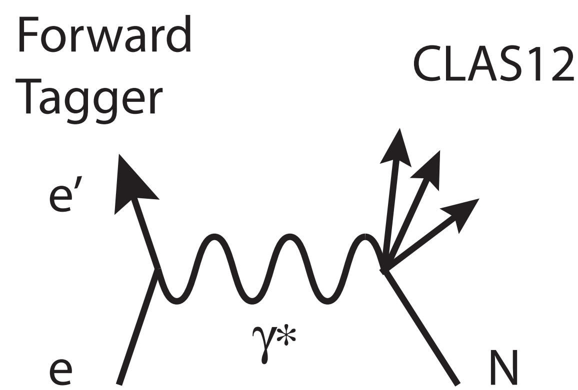
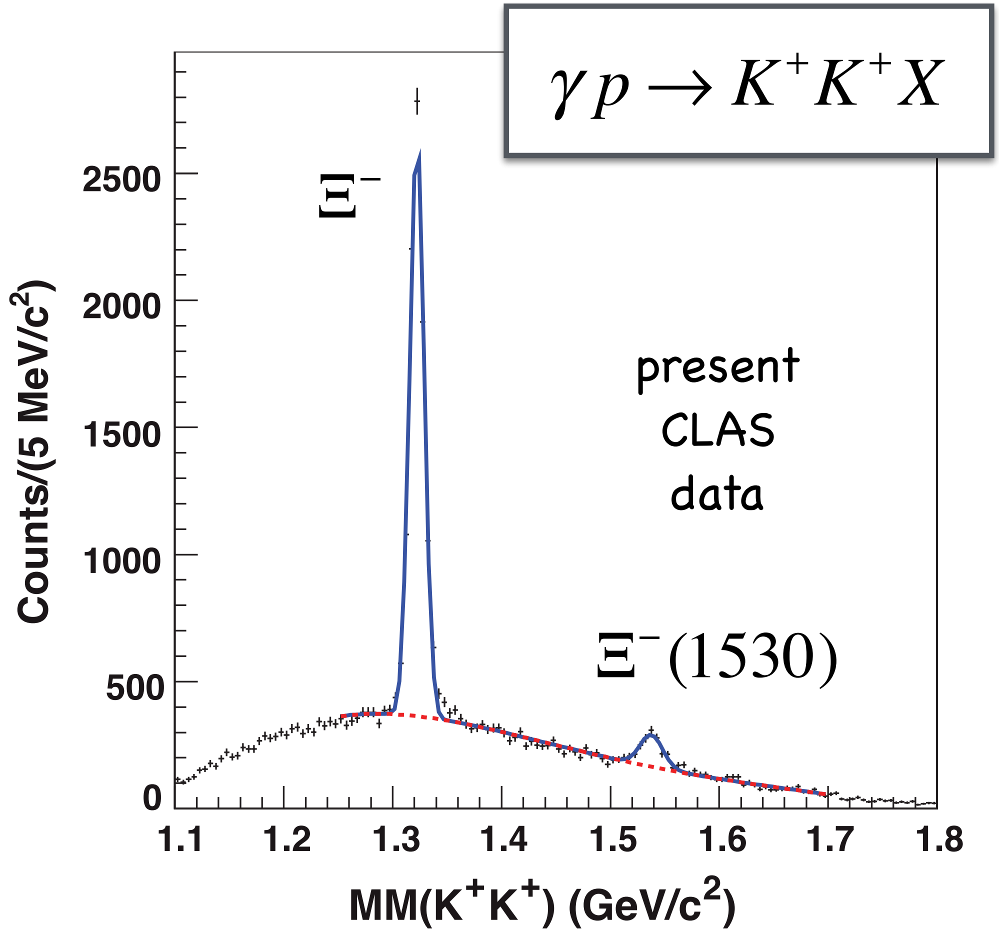


Fig. from M.Battaglieri, ECT* Workshop Lattice QCD and hadronic physics (2014)

Quasi-Real Photoproduction with CLAS12

Baryon Spectroscopy

- E12-11-005A
  - Cascade, $\gamma p \rightarrow K^+K^+\Xi^-$ (millions of reconstructed Ξ)
  - Omega, $\gamma p \rightarrow K^+K^+K^0\Omega^-$ (4,000 reconstructed Ω)
- LOI12-15-004
  - Search for Hybrid Baryons (focus on lowest mass hybrid baryons)



L. Guo et al., Phys. Rev. C **76**, 025208 (2007)

L. Guo et al., Jefferson Lab Experiment E12-11-005A, "Photoproduction of the Very Strangest Baryons on a Proton Target in CLAS12"
V. Burkert et al., Jefferson Lab LOI12-15-004, "Search for Hybrid Baryons with CLAS12 in Hall B"

Summary and outlook

New CLAS polarized photoproduction data off

polarized and unpolarized, proton and neutron targets

contribute to complete or nearly complete experiments.

Evidence of new states found in coupled-channel analyses.

Large impact expected as data analyses are being finalized.

PDG baryon summary table for N* resonances

N^*	J^P $(L_{2I,2J})$	2010	2012	future
p	$1/2^+$ (P_{11})	****	****	
n	$1/2^+$ (P_{11})	****	****	
$N(1440)$	$1/2^+$ (P_{11})	****	****	
$N(1520)$	$3/2^-$ (D_{13})	****	****	
$N(1535)$	$1/2^-$ (S_{11})	****	****	
$N(1650)$	$1/2^-$ (S_{11})	****	****	
$N(1675)$	$5/2^-$ (D_{15})	****	****	
$N(1680)$	$5/2^+$ (F_{15})	****	****	
$N(1685)$			*	
$N(1700)$	$3/2^-$ (D_{13})	***	***	
$N(1710)$	$1/2^+$ (P_{11})	***	***	
$N(1720)$	$3/2^+$ (P_{13})	****	****	
$N(1860)$	$5/2^+$		**	
$N(1875)$	$3/2^-$		***	
$N(1880)$	$1/2^+$		**	
$N(1895)$	$1/2^-$		**	
$N(1900)$	$3/2^+$ (P_{13})	**	***	
$N(1990)$	$7/2^+$ (F_{17})	**	**	
$N(2000)$	$5/2^+$ (F_{15})	**	**	
~~$N(2080)$~~	D_{13}	**		
~~$N(2090)$~~	S_{11}	*		
$N(2040)$	$3/2^+$		*	
$N(2060)$	$5/2^-$		**	
$N(2100)$	$1/2^+$ (P_{11})	*	*	
$N(2120)$	$3/2^-$		**	
$N(2190)$	$7/2^-$ (G_{17})	****	****	
~~$N(2200)$~~	D_{15}	**		
$N(2220)$	$9/2^+$ (H_{19})	****	****	
$N(2250)$	$9/2^-$ (G_{19})	****	****	
$N(2600)$	$11/2^-$ $(I_{1,11})$	***	***	
$N(2700)$	$13/2^+$ $(K_{1,13})$	**	**	

... future updates ...

Table adapted from: V. Crede and W. Roberts, Rep. Prog. Phys. 76 (2013) 076301