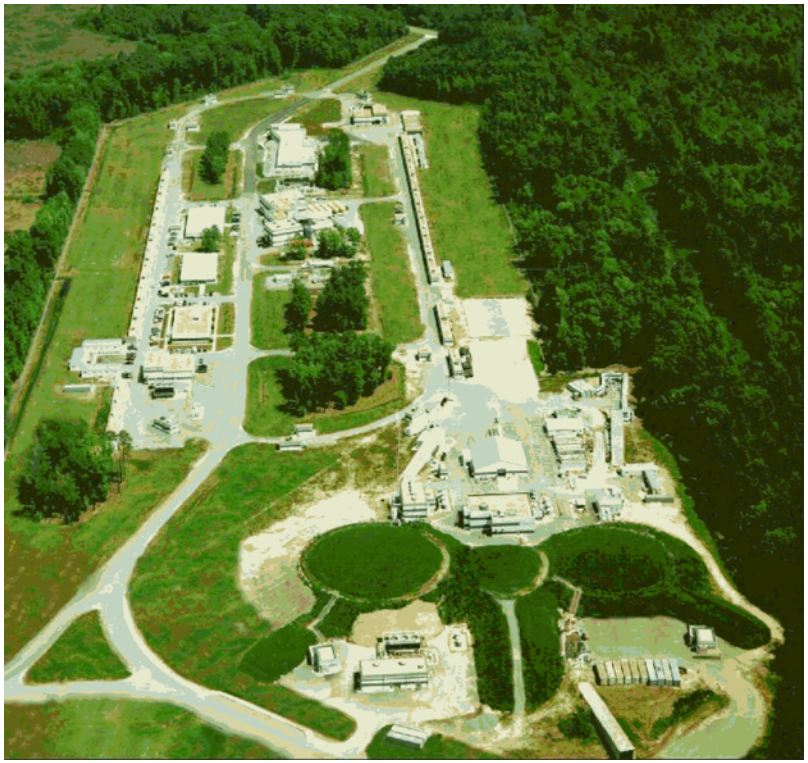
CLAS
Meson Photoproduction Experiments on Protons

- Introduction
- Single meson photoproduction data
- Double pion photoproduction data
- Upcoming frozen-spin target program

Steffen Strauch
University of South Carolina

Workshop on Partial Wave Analysis, Beijing, January 25 - 26, 2007

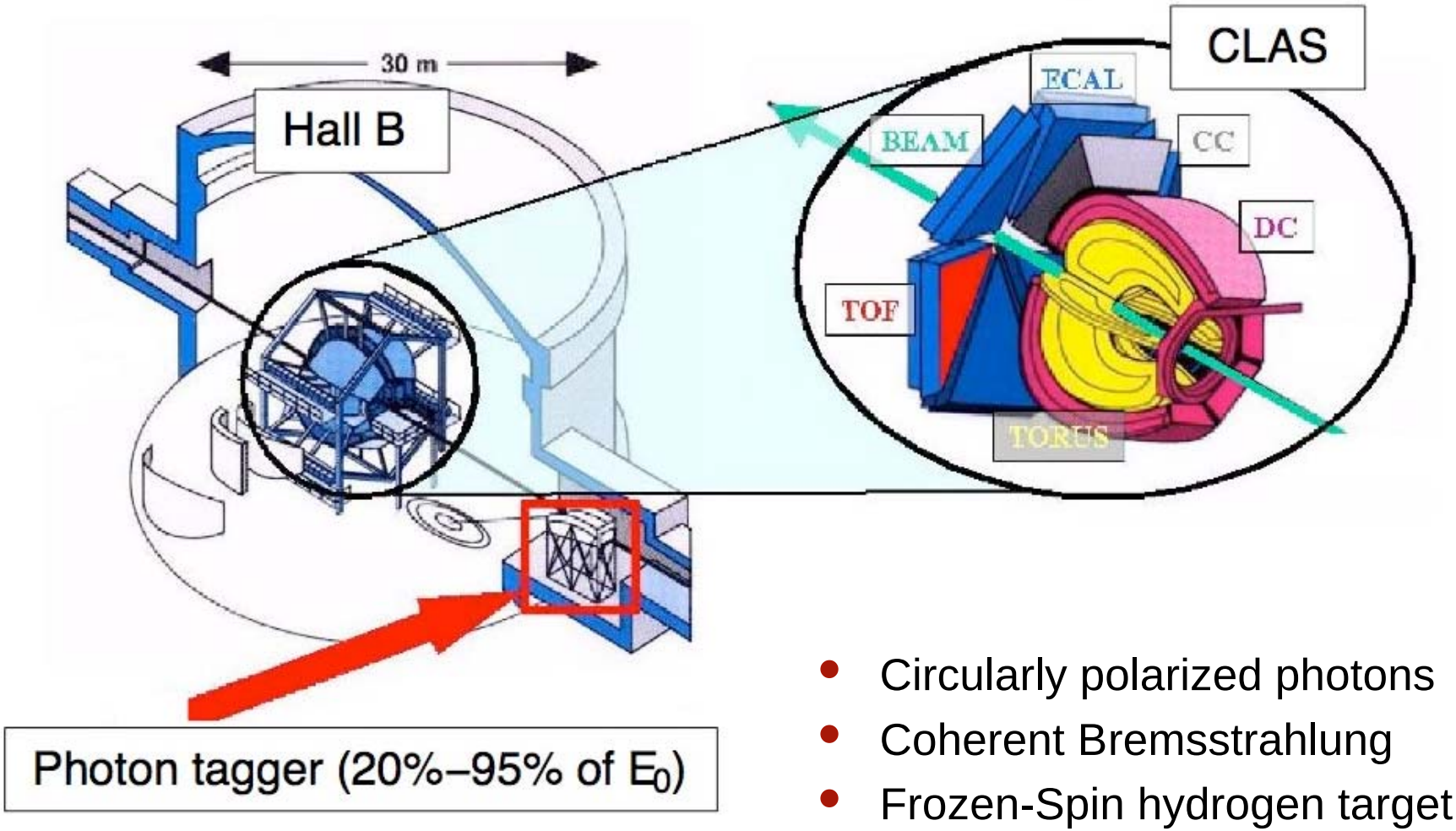
Thomas Jefferson National Accelerator Facility



JLab in Newport News, VA

- Electron-beam accelerator
- Polarized electron beam
- Beam energies up to $E_0 = 6$ GeV
- Three experimental Halls A, B, and C

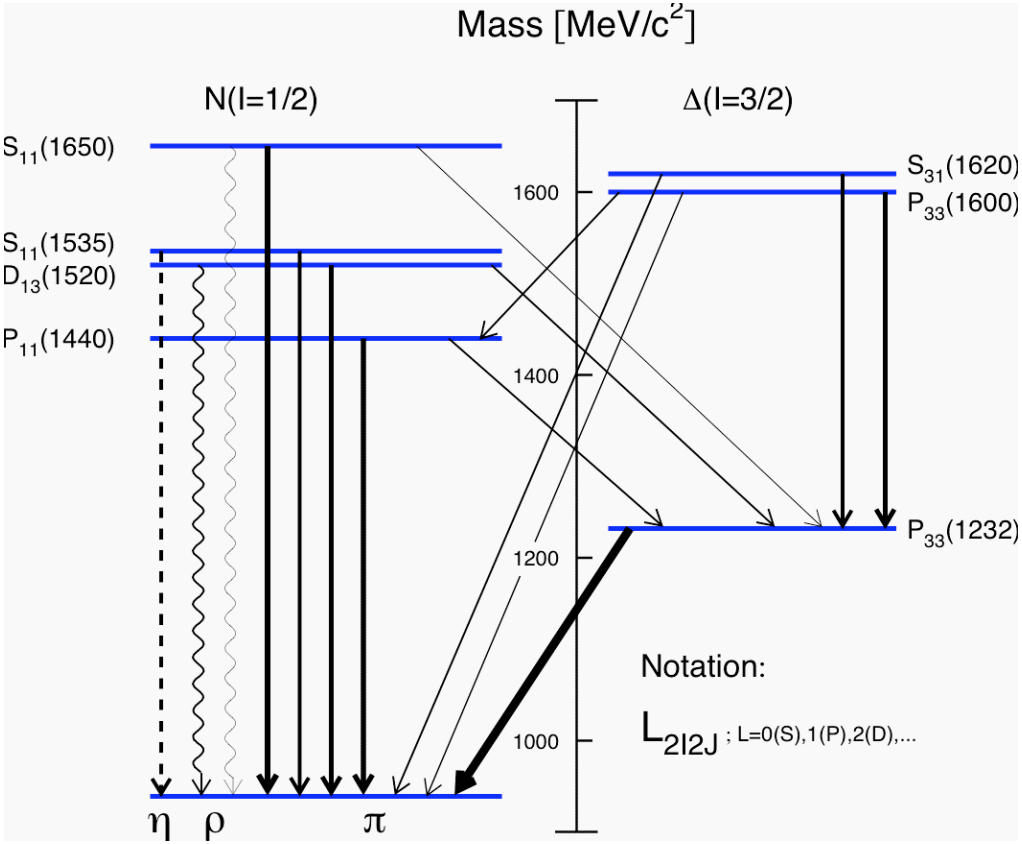
The CEBAF Large Acceptance Spectrometer



- Circularly polarized photons
- Coherent Bremsstrahlung
- Frozen-Spin hydrogen target

B. Mecking, *et al.*, Nucl. Instrum. Methods Phys. Res., Sect. **A 503**, 513 (2003).

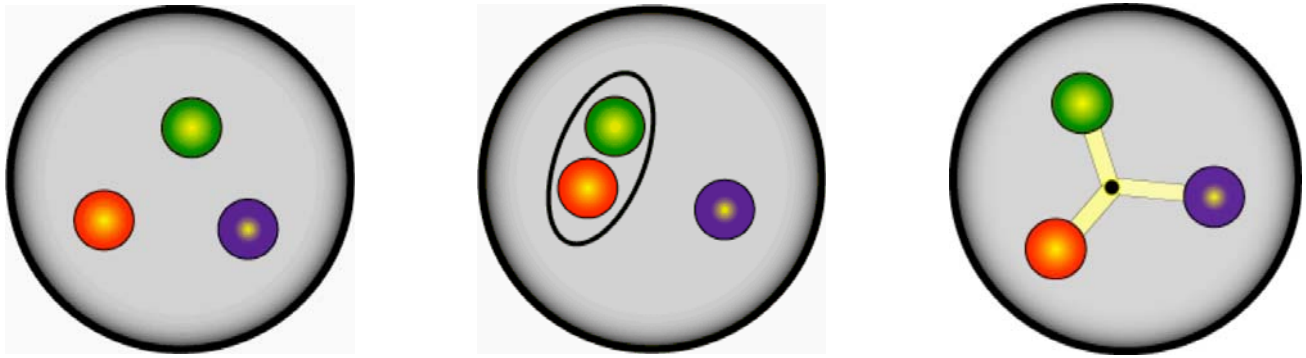
Studying the Excited States of the Nucleon



- The location and properties of excited states reflect the dynamics and relevant degrees-of-freedom within the nucleons.

Figure from: B. Krusche and S. Schadmand, Prog. Nucl. Phys. **51**, 399 (2003)

Effective Degrees Of Freedom

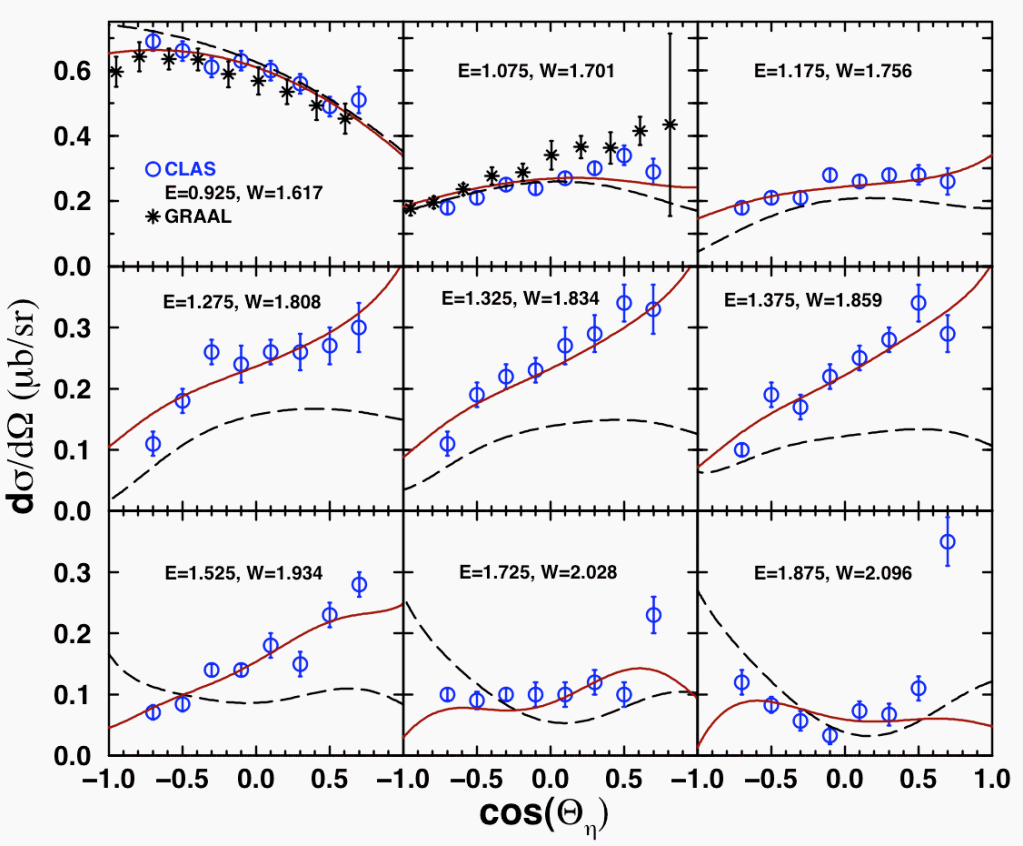


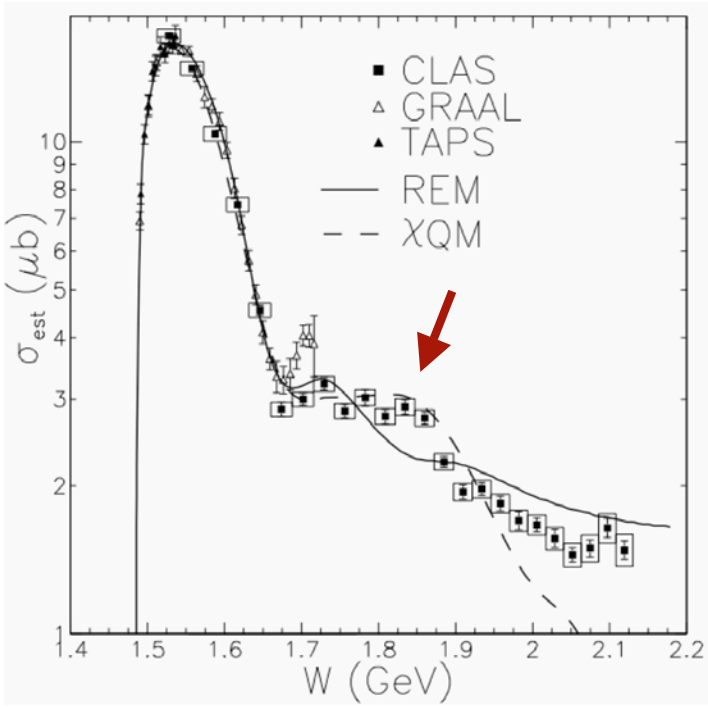
Quark Models

- Symmetric Constituent Quark Models predict overabundance of excited states (“missing” resonance problem)
- Quark-Diquark Models predict fewer states
- Quark and Flux-Tube Models predict increased number of states

S. Capstick and W. Roberts, Prog. Part. Nucl. Phys. **45**, S241 (2000)
Figure from: B. Krusche and S. Schadmand Prog. Part. Nucl. Phys. **51**, 399 (2003)

γp → ηp : Cross Sections





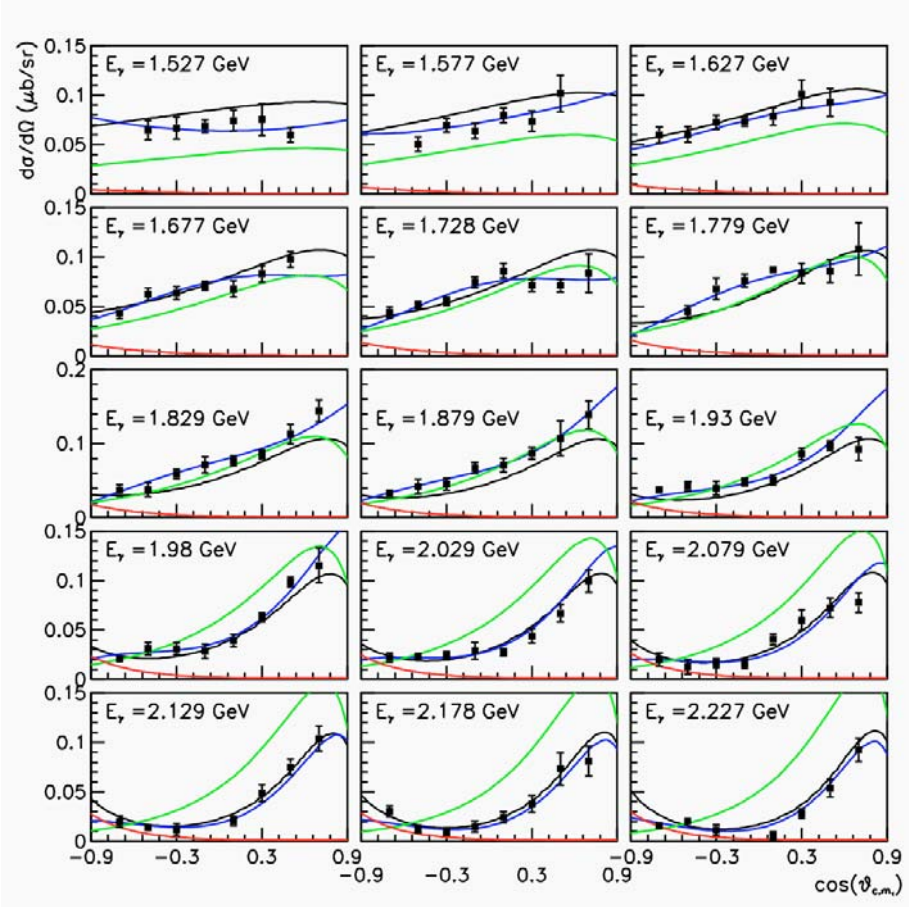
- ηN final states can originate only from isospin I = 1/2 systems (isospin filter)
- Chiral constituent quark formalism [Saghai]: Possible contribution from an additional (3rd) S_{11} resonance with M ≈ 1.8 GeV and Γ ≈ 250 MeV

M. Dugger, B. G. Ritchie *et al.*, Phys. Rev. Lett. **89**, 222002 (2002)
B. Saghai, Proc. of NSTAR 2004 Workshop; nucl-th/0408054

$\gamma p \rightarrow \eta' p$: Differential Cross Sections

- CLAS: first high quality data for the $\gamma p \rightarrow \eta' p$ reaction
- Analysis of data suggests contributions from both the $S_{11}(1535)$ and $P_{11}(1710)$ nucleon resonances to the $\eta' N$ channel in photoproduction.
- η'-nucleon-nucleon coupling constant:

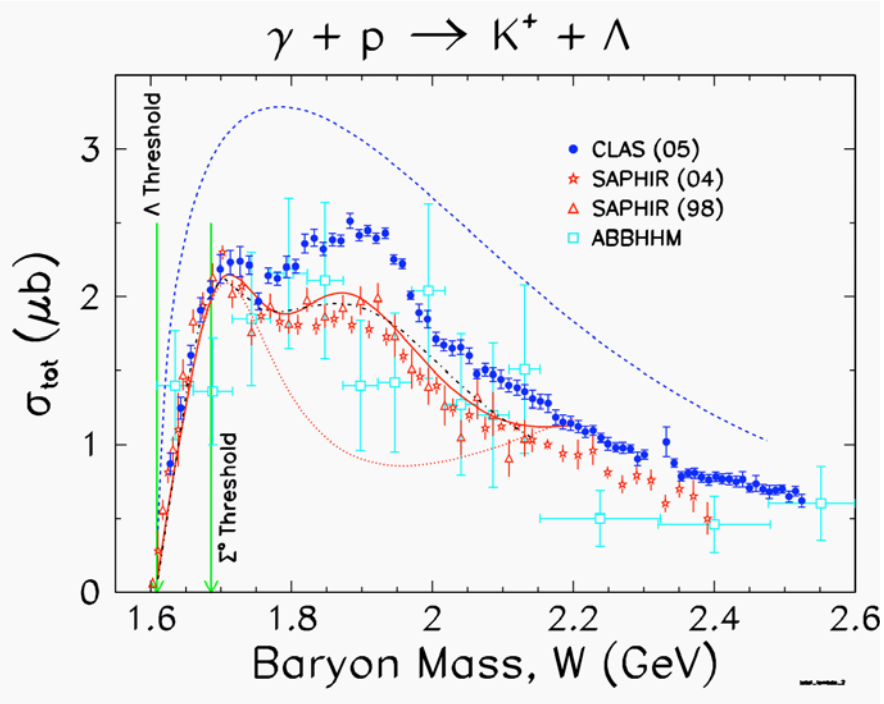
$g_{\eta' NN} = 1.3 - 1.5$

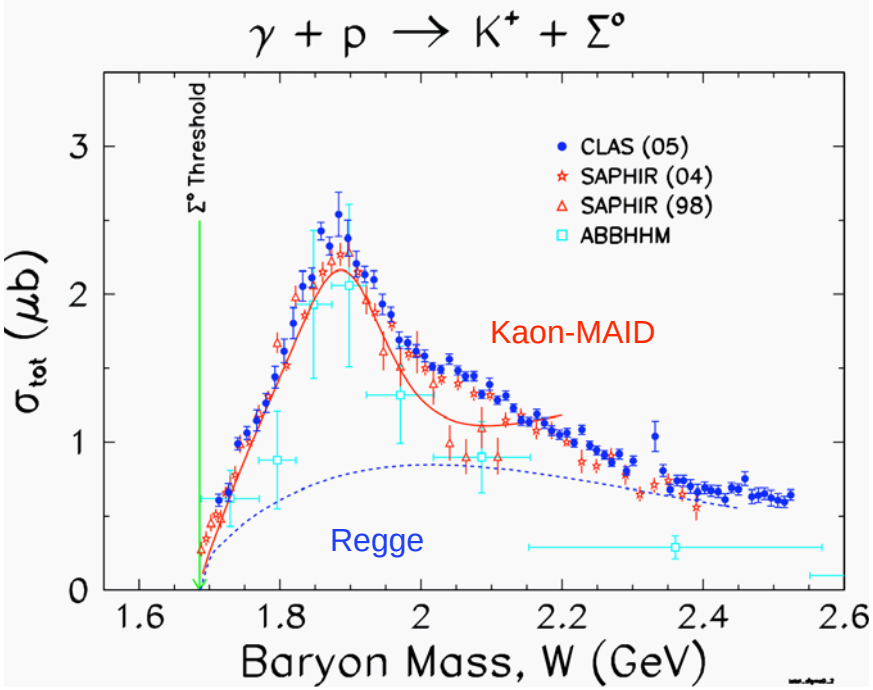


Nakayama & Haberzettl: u-channel, t-channel, full (s,u, & t)
Sibirtsev: full

M. Dugger *et al.*, Phys. Rev. Lett. **96**, 062001 (2006)

$K^+\Lambda$ and $K^+\Sigma^0$: Cross Sections





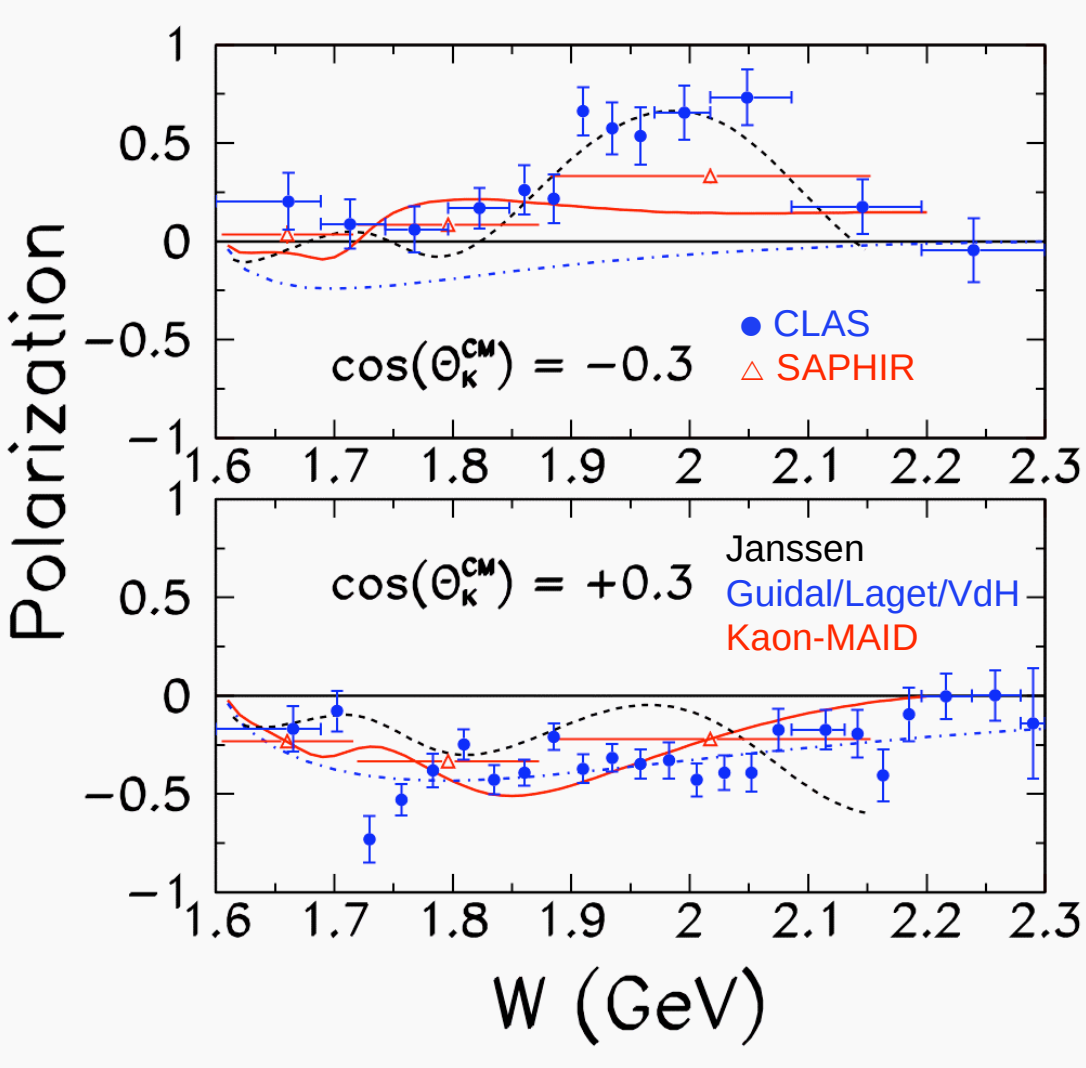
- Peak at W = 1.7 GeV from $P_{11}(1710)$ and $P_{13}(1720)$
- Peak at W = 1.9 GeV shifts with c.m. angle, several resonant structures present

- Peak at W = 1.88 GeV consistent with the mass of several well-established Δ resonances
- Shoulder at W = 2.05 GeV

R. Bradford, R. A. Schumacher *et al.*, Phys. Rev. C **73**, 035202 (2006)

$K^+\Lambda$: Induced Recoil Polarization

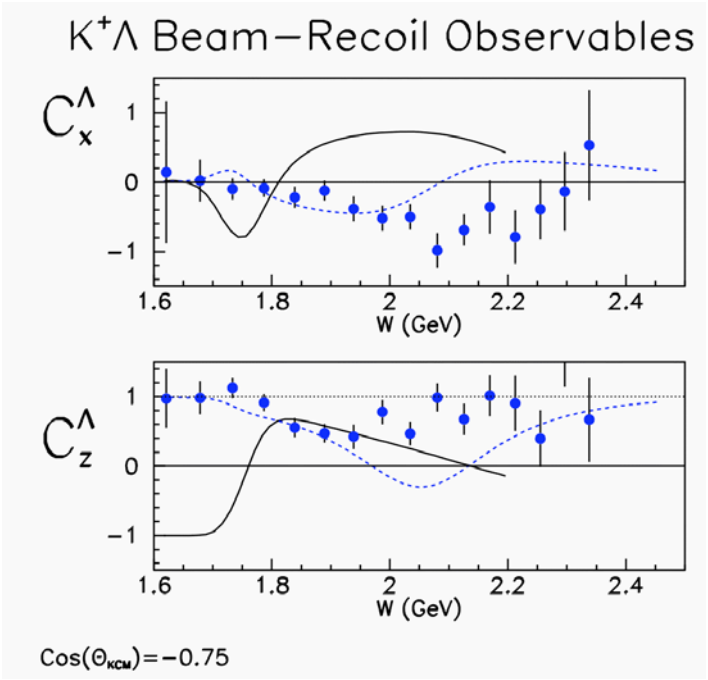
- Janssen *et al.* prediction: *u*-channel Y* contributions added to $D_{13}(1895)$ *s*-channel component.
- P_y sensitive to interference between resonances and background

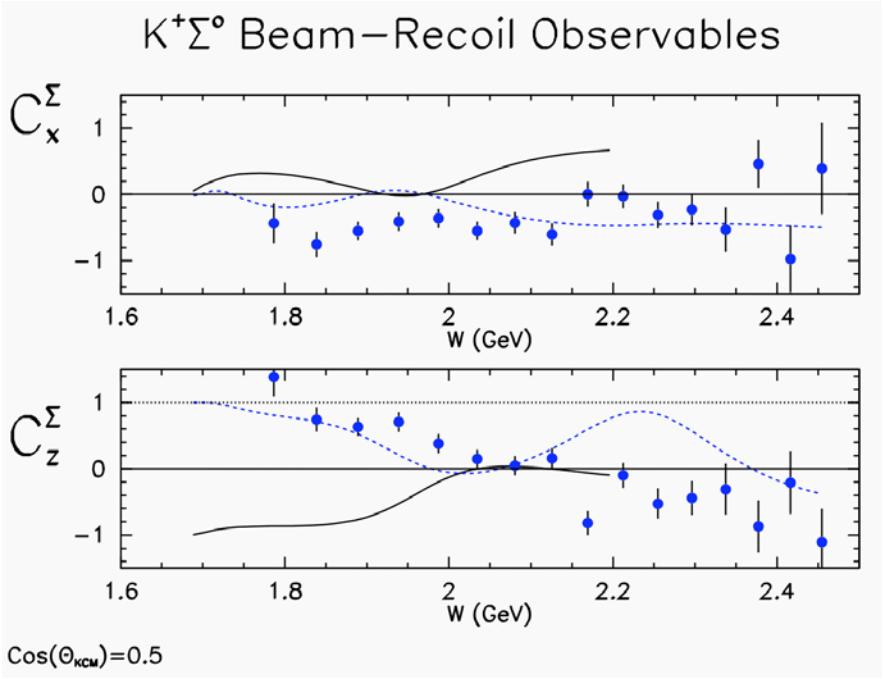


J. W. C. McNabb, R. A. Schumacher et al., Phys. Rev. C **69**, 042201(R) (2004)

$K^+\Lambda$ and $K^+\Sigma^0$: Beam-Recoil Observables

- Nine bins in $\cos(\Theta_{K,cm})$ for $K^+\Lambda$ and six bins for $K^+\Sigma^0$; Examples:





- Λ nearly maximally polarized along the direction of incident photon's polarization for forward-going kaons (not shown)
- Isobar models: Kaon MAID (—), Janssen (…)

R. Bradford and R. A. Schumacher, Proc. of NSTAR 2005 Workshop, nucl-ex/0602004;
R. A. Schumacher, Proc. of HYP 2006, nucl-ex/0611035.

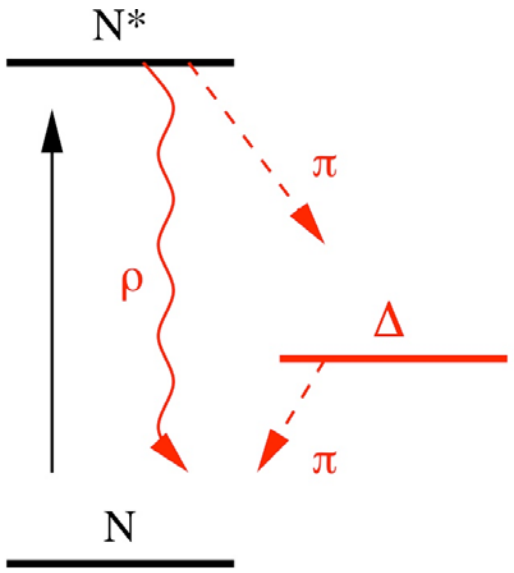
Bonn Partial Wave Analysis

- Combined analysis of σ, Σ, and P_y for $\gamma p \rightarrow K^+\Lambda$, $K^+\Sigma^0$, and $K^0\Sigma^+$ from CLAS, SAPHIR, and LEPS and π and η photoproduction data; energy range: 1.6 GeV to 2.3 GeV
- Evidence for new baryon resonances:
  - new P_{11} state at 1840 MeV with Γ = 140 MeV
  - two D_{13} states at 1870 MeV and 2170 MeV
- S_{11} two lowest mass states observed, no need for additional S_{11} states

V. Sarantsev *et al.*, Eur. Phys. J. A **25**, 441 (2005);
other PWA, *e.g.,* from SAID: R.A. Arndt *et al.*, Phys. Rev. C **74**, 045205 (2006).

Double-Pion Photoproduction: $\gamma N \rightarrow \pi\pi N$

- Dominant nucleon-resonance decay channels above W = 1.6 GeV with $\pi\pi$N final states

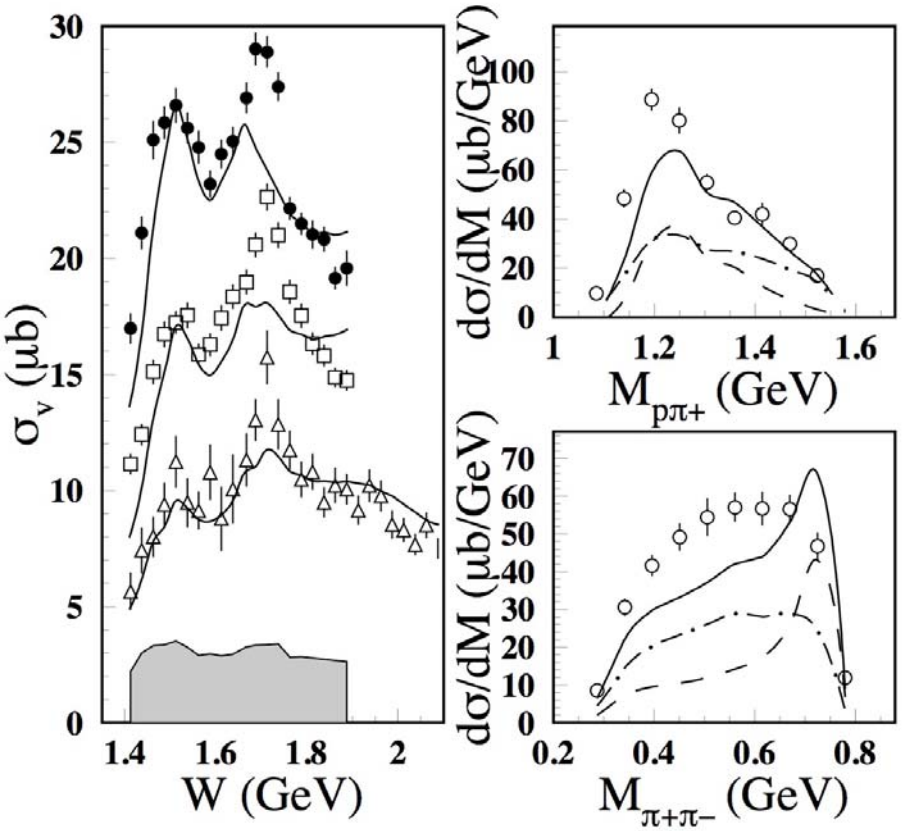


$$N^* \rightarrow \rho N \rightarrow \pi\pi N$$
$$N^* \rightarrow \pi\Delta \rightarrow \pi\pi N$$

- Many “missing” states are predicted to couple strongly to the $\pi\pi$N channels

Particle Data Group Review, S. Eidelman *et al.*, Phys. Lett. B **592**, 1 (2004).
S. Capstick and W. Roberts, Phys. Rev. D **49**, 4570 (1994)

CLAS Measurement of $ep \rightarrow e'\pi^+\pi^- p$



$0.5\ \mathrm{GeV}^2/c^2 < Q^2 < 1.5\ \mathrm{GeV}^2/c^2$

- Comparison of data and phenomenological predictions using available information on *N** and Δ states shows discrepancy.
- Hints for new $3/2^+(1720)$ baryon state from CLAS real- and virtual-photon cross-section data

M. Ripani *et al.*, Phys. Rev. Lett. **91**, 022002 (2003)); V. Mokeev, private communication

Polarization Observables for Two-Pion Production off the Nucleon

- Eight transversity amplitudes for the $\gamma N \rightarrow \pi\pi N$
- Unpolarized cross section

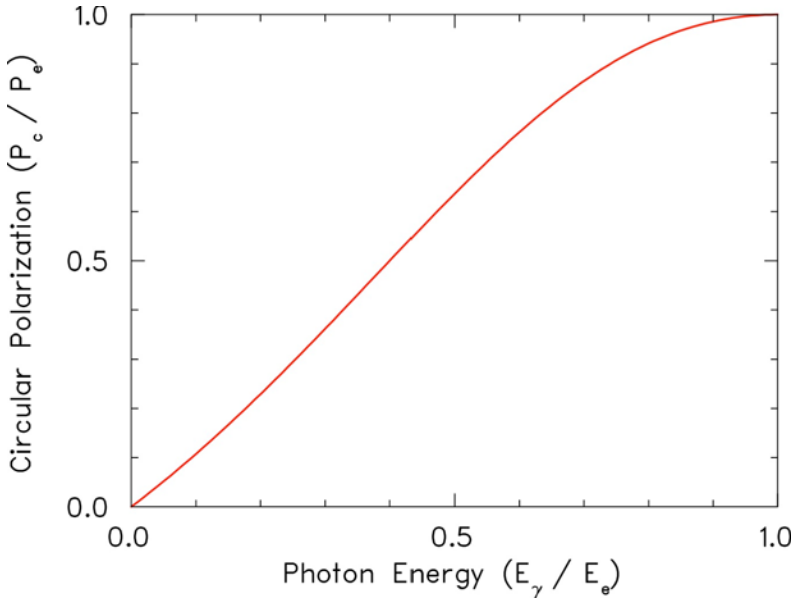
$$I_0 = \sum_{i=1,4} \left| b_i^+ \right|^2 + \sum_{i=1,4} \left| b_i^- \right|^2$$

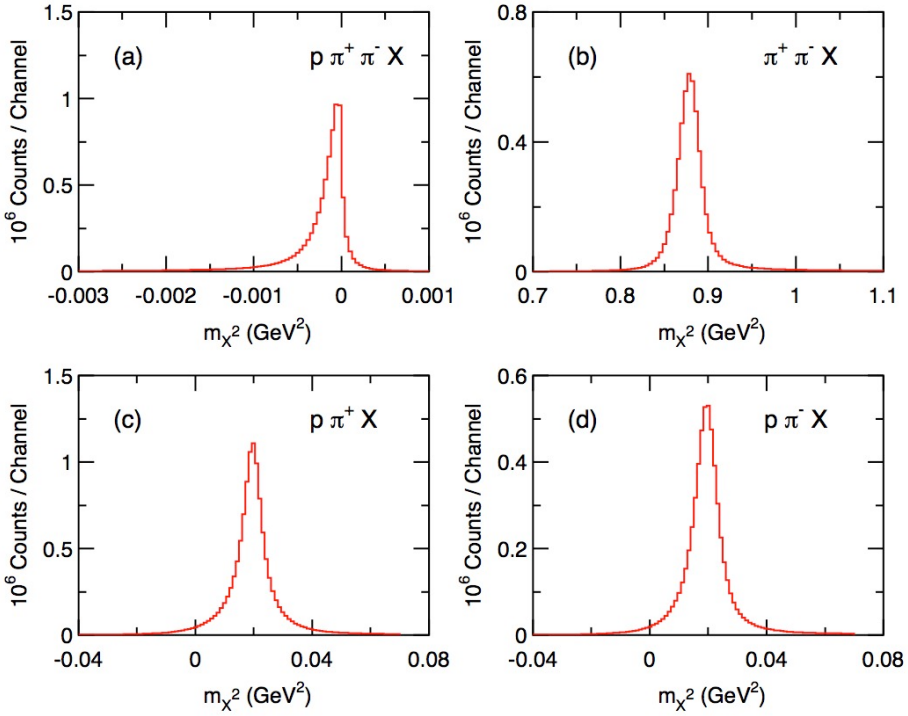
- Polarization observables allow extraction of more information, including phases.
- Complete set requires additional single-, double- and triple- polarization observables
- Photon polarization asymmetry

$$I_0 I^{\otimes} = \sum_{i=1,4} \left| b_i^+ \right|^2 - \sum_{i=1,4} \left| b_i^- \right|^2$$

W. Roberts and T. Oed, Phys. Rev. C **71**, 055201 (2005)

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

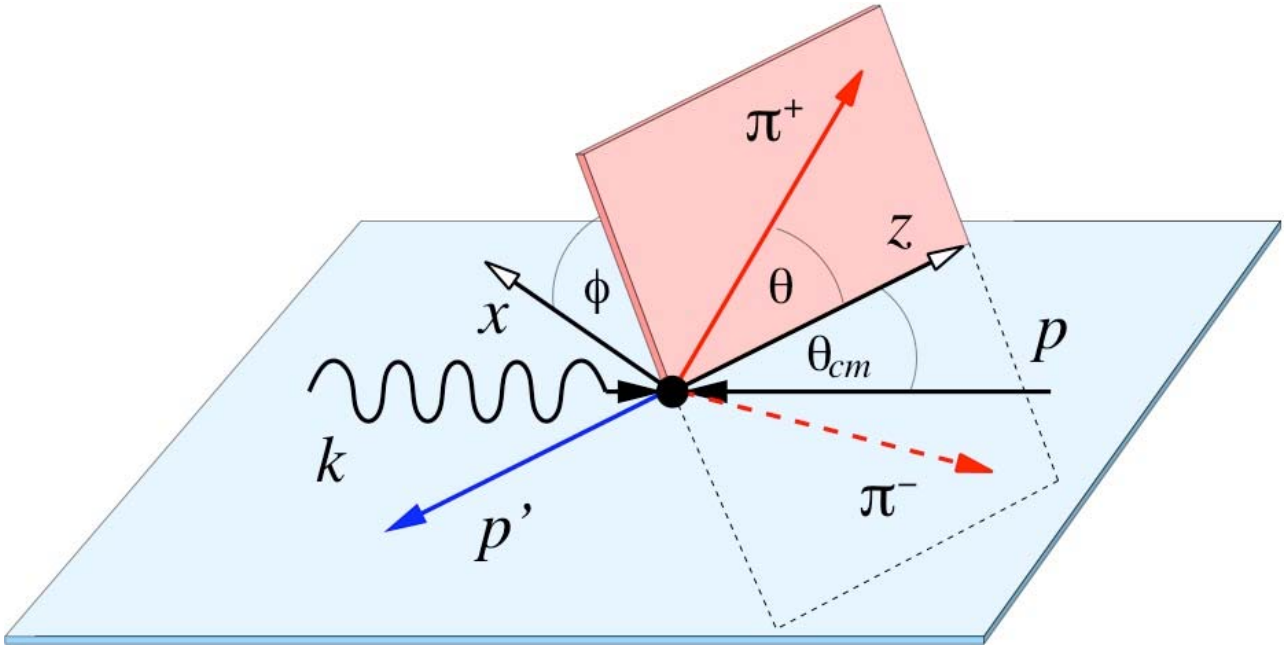




- Circularly polarized photon, E_λ = 0.5 GeV – 2.4 GeV
- Channel identification by missing mass
- 3×10^7 events with W = 1.35 GeV – 2.35 GeV

S. Strauch *et al.*, (CLAS Collaboration), Phys. Rev. Lett. **95**, 162003 (2005)

Experimental Beam-Helicity Asymmetry



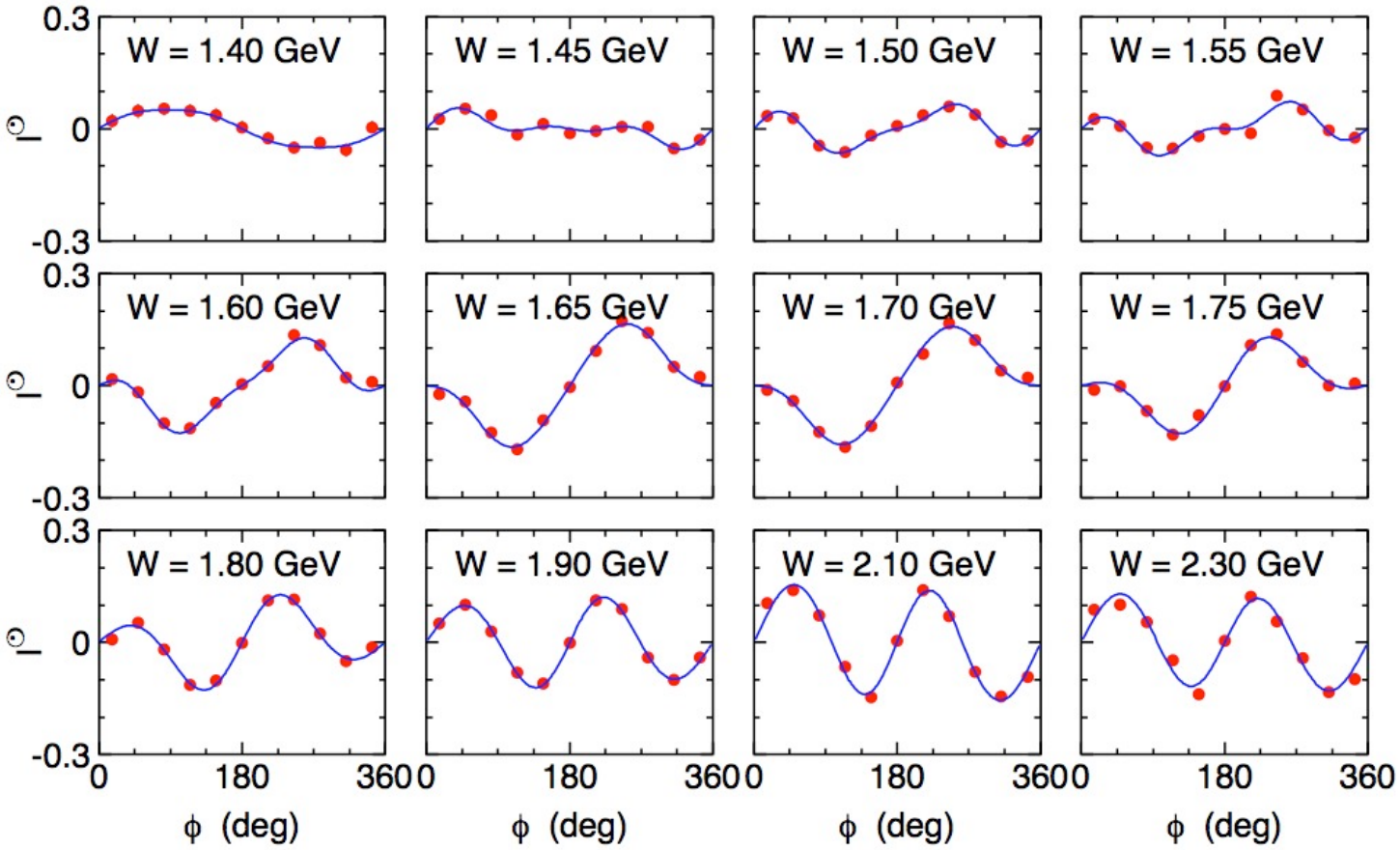
- Asymmetry and Fourier Decomposition

$$I^{\otimes}(\phi) = \frac{1}{P}\frac{N(\lambda=+)-N(\lambda=-)}{N(\lambda=+)+N(\lambda=-)} \approx \sum a_k \sin k\phi$$

- 3×10^7 events with W = 1.35 to 2.35 GeV

W. Roberts and T. Oed, Phys. Rev. Lett. C **71**, 055201 (2005)

Beam-Helicity Asymmetries



- $I^{\otimes}$ observable is odd under ϕ transformation (parity conservation)

$$I^{\otimes}(\phi) = -I^{\otimes}(2\pi - \phi), \quad I^{\otimes}(0) = I^{\otimes}(\pi) = 0$$

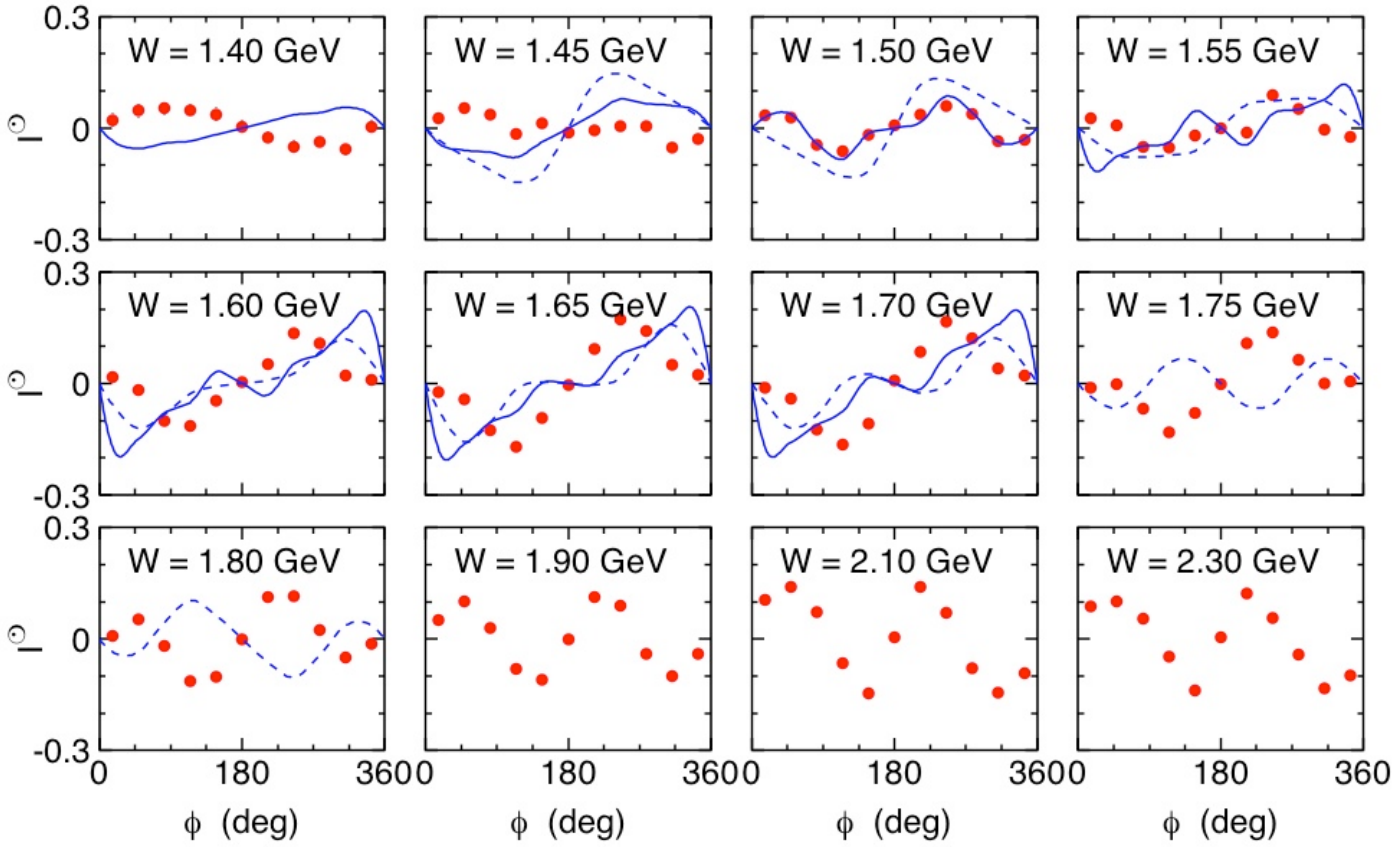
Phenomenological Models

- Groups:
  - W. Roberts and T. Oed, V. Mokeev, L. Roca, and A. Fix and H. Arenhövel
- Models constructed according to the same scheme — effective Lagrangian densities
- Parameters for resonant and background mechanisms taken from experiments or treated as free parameters
- Differences
  - Wide variations in the corresponding coupling constants allowed by the Particle-Data Group listing
  - Treatment of the background, which appears to be very complicated in the effective Lagrangian approach for double-pion photoproduction

W. Roberts and T. Oed, Phys. Rev. C **71**, 055201 (2005); V.I. Mokeev *et al.*, Yad. Fiz. **64**, 1368 (2001); [Phys. At. Nucl. **64**, 1292 (2001)]; L. Roca, Nucl. Phys. A **748**, 192 (2005); A. Fix and H. Arenhövel, Eur. Phys. J. A **25**, 115 (2005)

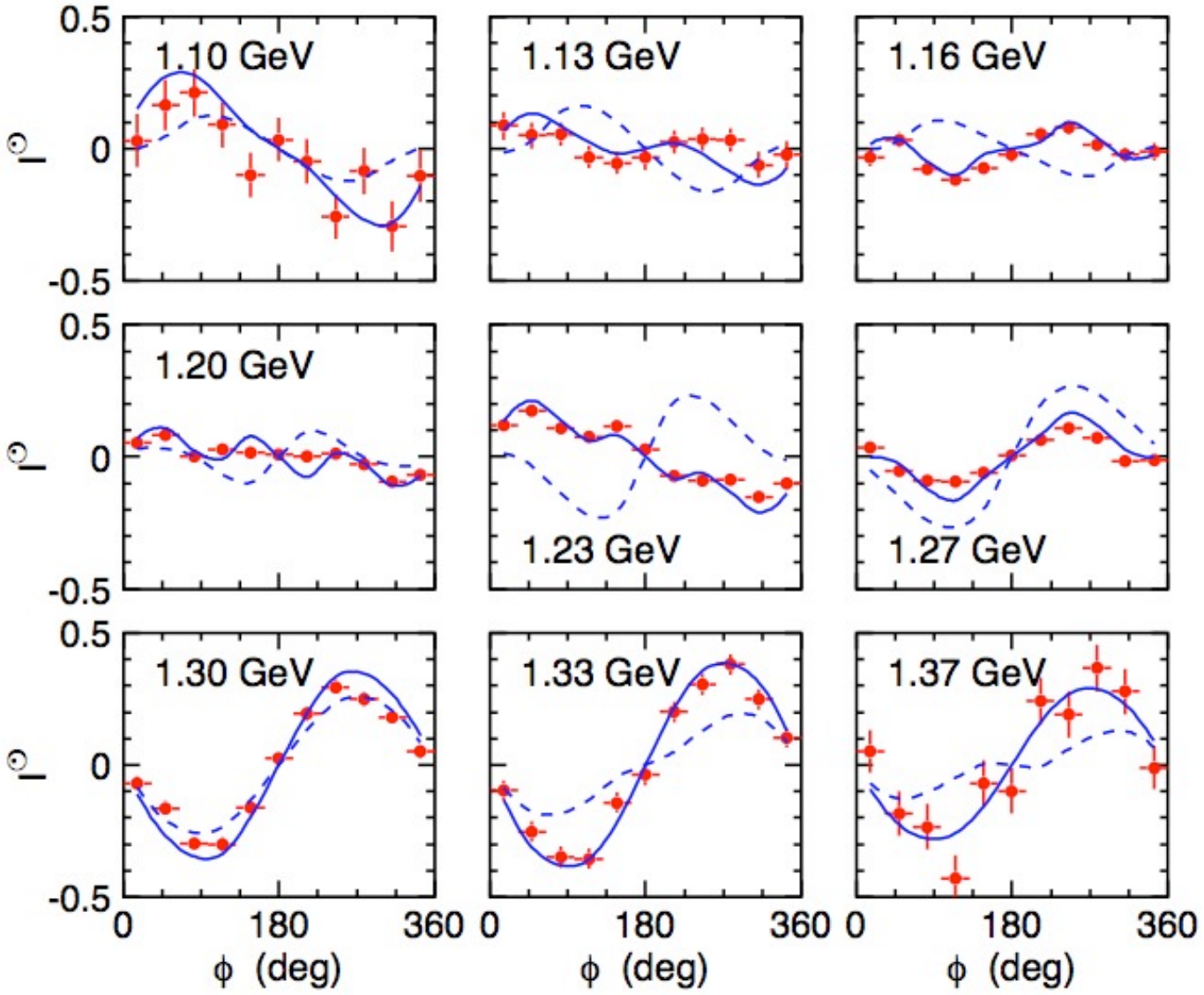
Model Calculations

Calculations from Mokeev (dashed) and Fix (solid)

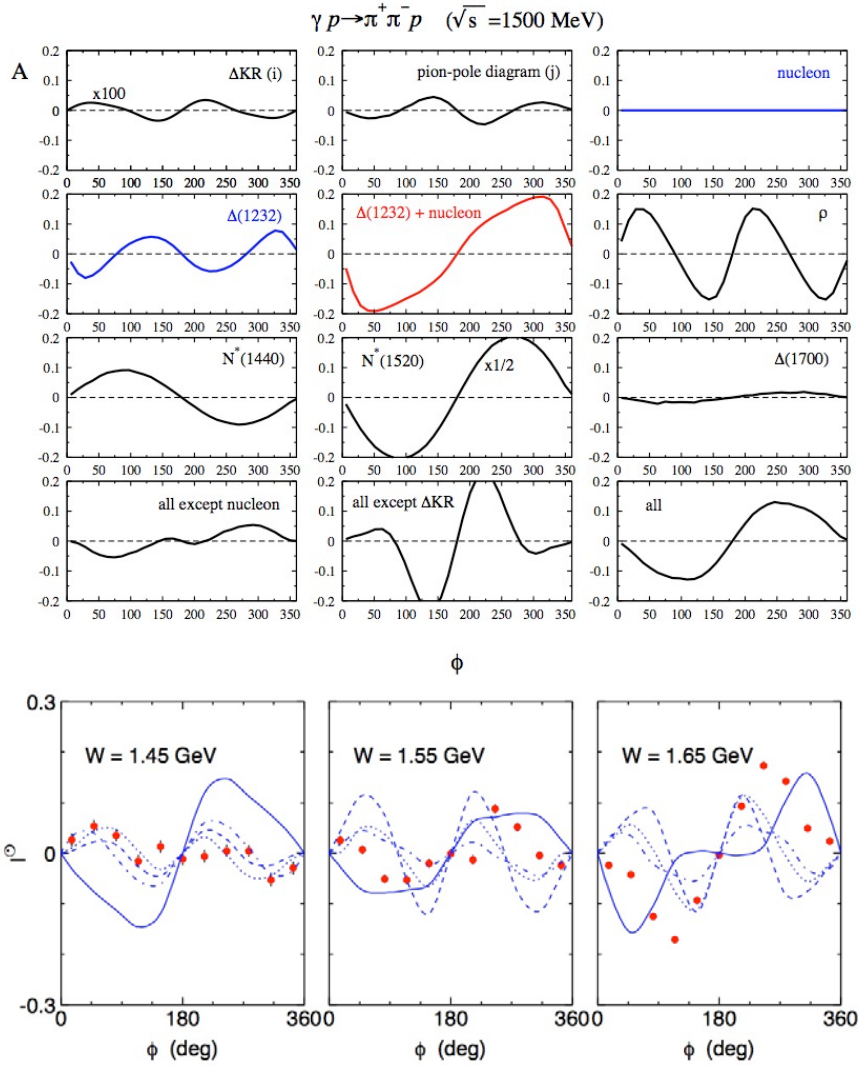


- Model predictions agree remarkably well for certain conditions, for other conditions they are much worse and out of phase entirely.

M(pπ⁺) Distribution at *W* = 1.5 GeV



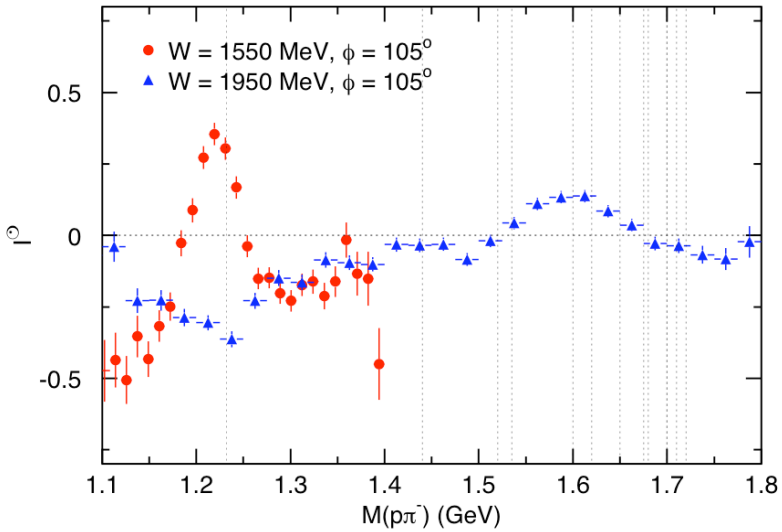
Crucial Role of Interferences

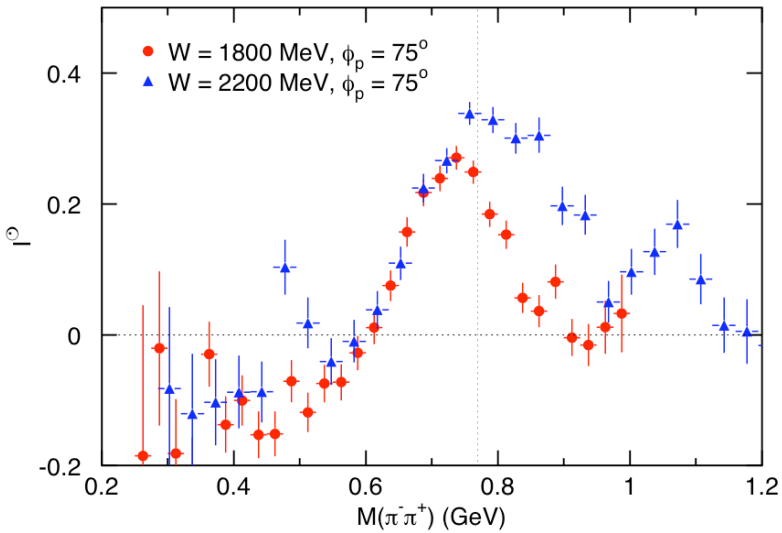


- Intermediate-nucleon mechanisms and Δ(1232) mechanisms, and interference of both.
  L. Roca, Nucl. Phys. A **748**, 192 (2005)

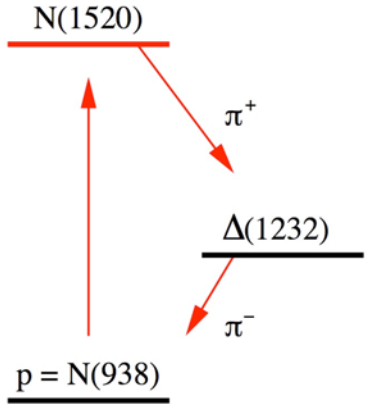
- Calculations with relative phases of 0°, 90°, 180°, and 270° between the background- and πΔ sub-channel amplitudes
  V.Mokeev, private communication

Sequential Decay





- $\gamma N \rightarrow \pi\Delta \rightarrow \pi\pi N$



- $\gamma N \rightarrow \rho N \rightarrow \pi\pi N$
- Helicity asymmetries allow detailed study of the $\gamma N \rightarrow \pi\pi N$ reaction (*e.g.*, sequential decay)

CLAS Polarized-Target Program

E01-104	Helicity Structure of Pion Photoproduction $\vec{\gamma}\vec{p} \rightarrow \pi^0 p,\ \vec{\gamma}\vec{p} \rightarrow \pi^+ n$
E02-112	Search for Missing Nucleon Resonances in Hyperon Photoproduction $\vec{\gamma}\vec{p} \rightarrow K\Lambda,\ \vec{\gamma}\vec{p} \rightarrow K\Sigma$
E03-105	Pion Photoproduction from a Polarized Target $\vec{\gamma}\vec{p} \rightarrow \pi^0 p,\ \vec{\gamma}\vec{p} \rightarrow \pi^+ n$
E05-012	Measurement of Polarization Observables in η Photoproduction with CLAS $\vec{\gamma}\vec{p} \rightarrow \eta p$
E06-013	Measurement of $\pi^+\pi^-$ Photoproduction in Double-Polarization Experiments using CLAS $\vec{\gamma}\vec{p} \rightarrow \pi^+\pi^- p$

scheduled Spring 2007

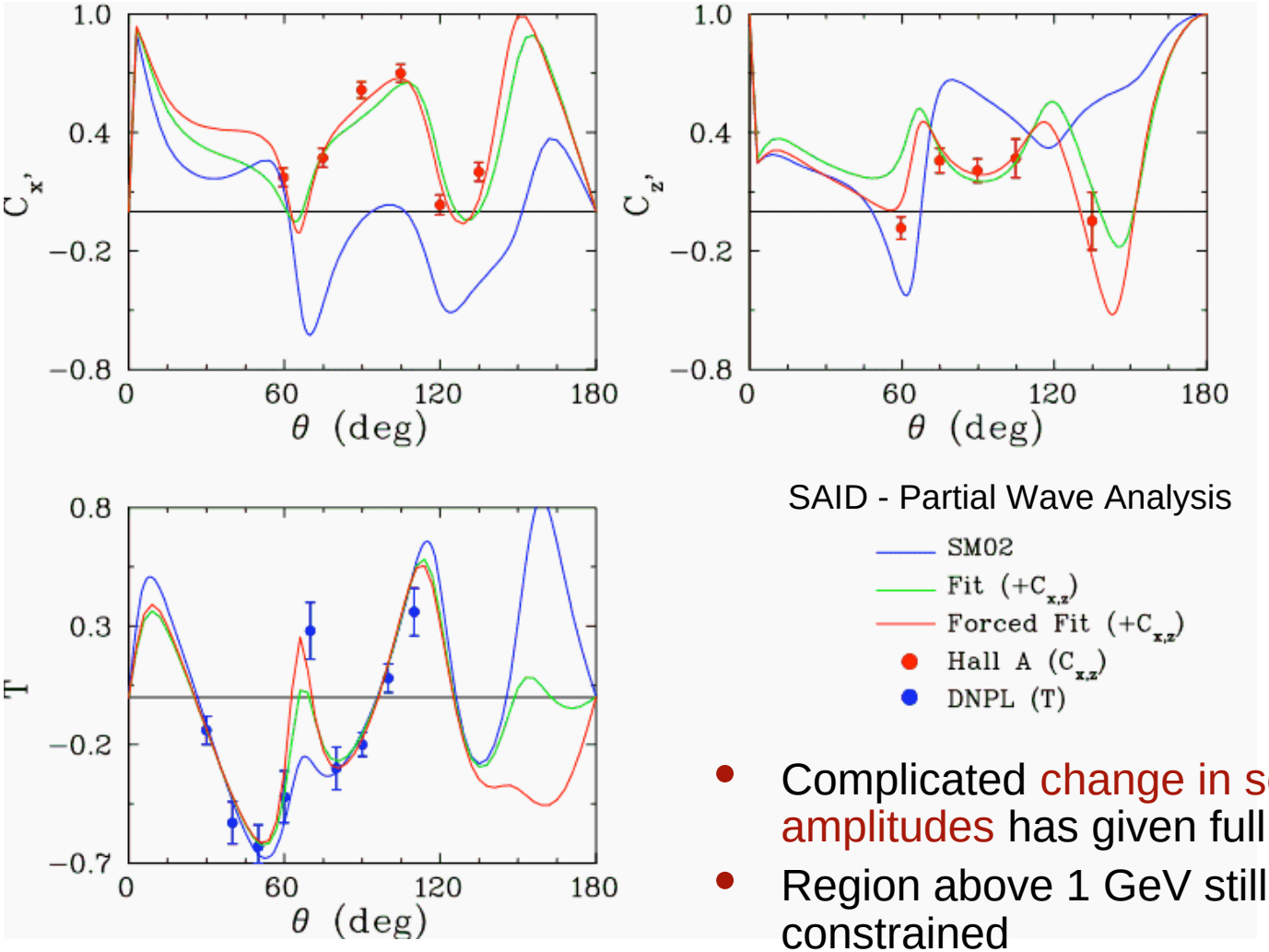
FROST Single-Pion Photoproduction

- Constrain partial-wave analyses and reduce model-dependent uncertainties in the extraction of nucleon resonance properties

	Polarization			
Setting	**Beam**	**Target**	**E_λ (GeV)**	**Observable**
A	circular	longitudinal	0.6 - 2.0	*E*
B	linear	longitudinal	0.4 - 2.0	*G*
C	circular	transverse	0.6 - 2.0	*F*, *T*
D	linear	transverse	0.4 - 2.0	*H*, *P*, *T*

- Four independent complex amplitudes ($\gamma N \rightarrow \pi N$)
- $\theta_{cm} = 15^o - 155^o$; $\Delta E_\lambda \leq 50$ MeV, $\Delta\theta_{cm} = 10^o$
- More than 5000 data points with one detector system; improvements: single-pol. obs. 2×, double-pol. obs. 8×

C_x, and C_z, in $p(\vec{\gamma},\vec{p})\pi^0$ at E_λ = 1900 MeV

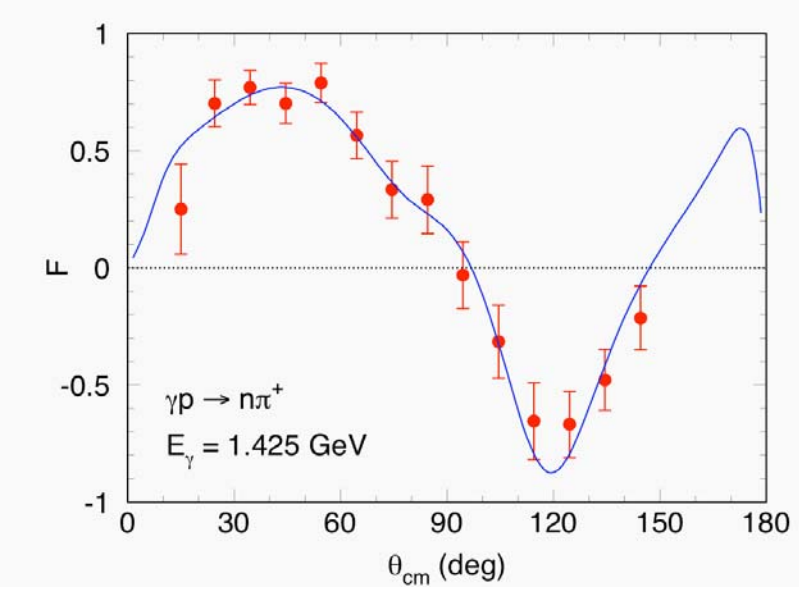


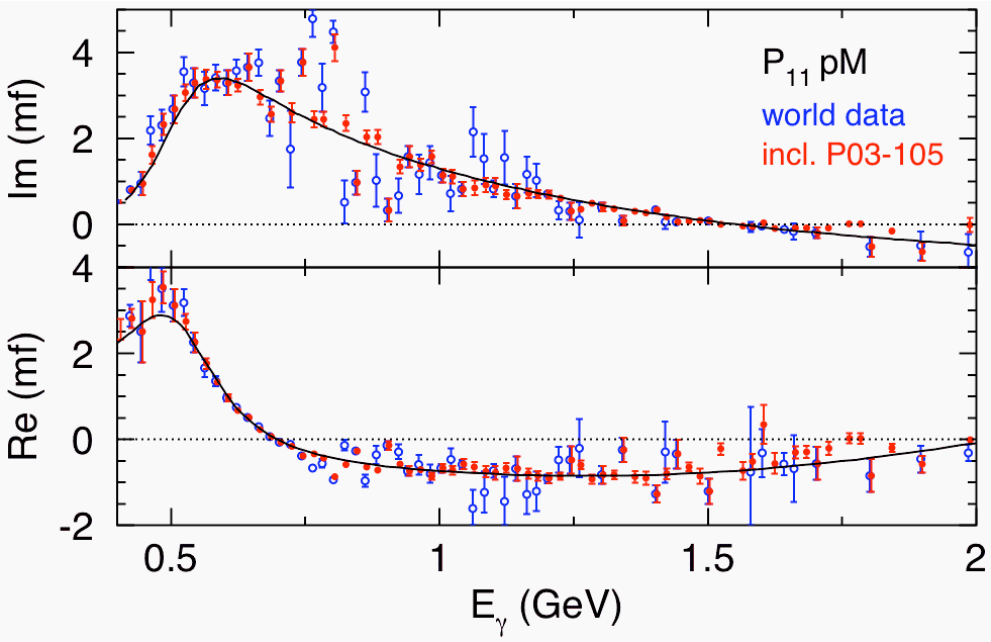
- Complicated change in several amplitudes has given full result
- Region above 1 GeV still under-constrained

R. A. Arndt, I. I. Strakovsky, and R. L. Workman, Phys. Rev. C **67**, 048201 (2003)

SAID Single-Energy Solutions

- Examples: Polarization data and multipole amplitudes (simulated data)





- Reduction of uncertainties in single-energy solutions
- Increase of the number of single-energy solutions

FROST Double-Pion Photoproduction

$$
\begin{aligned}
\rho_f I \;=\; & I_0 \Big\{ \Big(1 + \vec{\Lambda}_i \cdot \vec{P} + \vec{\sigma} \cdot \vec{P}' + \Lambda_i^{\alpha} \sigma^{\beta'} \mathcal{O}_{\alpha\beta'} \Big) \\
& + \delta_{\odot} \Big(I^{\odot} + \vec{\Lambda}_i \cdot \vec{P}^{\odot} + \vec{\sigma} \cdot \vec{P}^{\odot\prime} + \Lambda_i^{\alpha} \sigma^{\beta'} \mathcal{O}^{\odot}_{\alpha\beta'} \Big) \\
& + \delta_{\ell} \Big[\sin 2\beta \Big(I^{s} + \vec{\Lambda}_i \cdot \vec{P}^{s} + \vec{\sigma} \cdot \vec{P}^{s\prime} + \Lambda_i^{\alpha} \sigma^{\beta'} \mathcal{O}^{s}_{\alpha\beta'} \Big) \\
& + \cos 2\beta \Big(I^{c} + \vec{\Lambda}_i \cdot \vec{P}^{c} + \vec{\sigma} \cdot \vec{P}^{c\prime} + \Lambda_i^{\alpha} \sigma^{\beta'} \mathcal{O}^{c}_{\alpha\beta'} \Big) \Big] \Big\}
\end{aligned}
$$

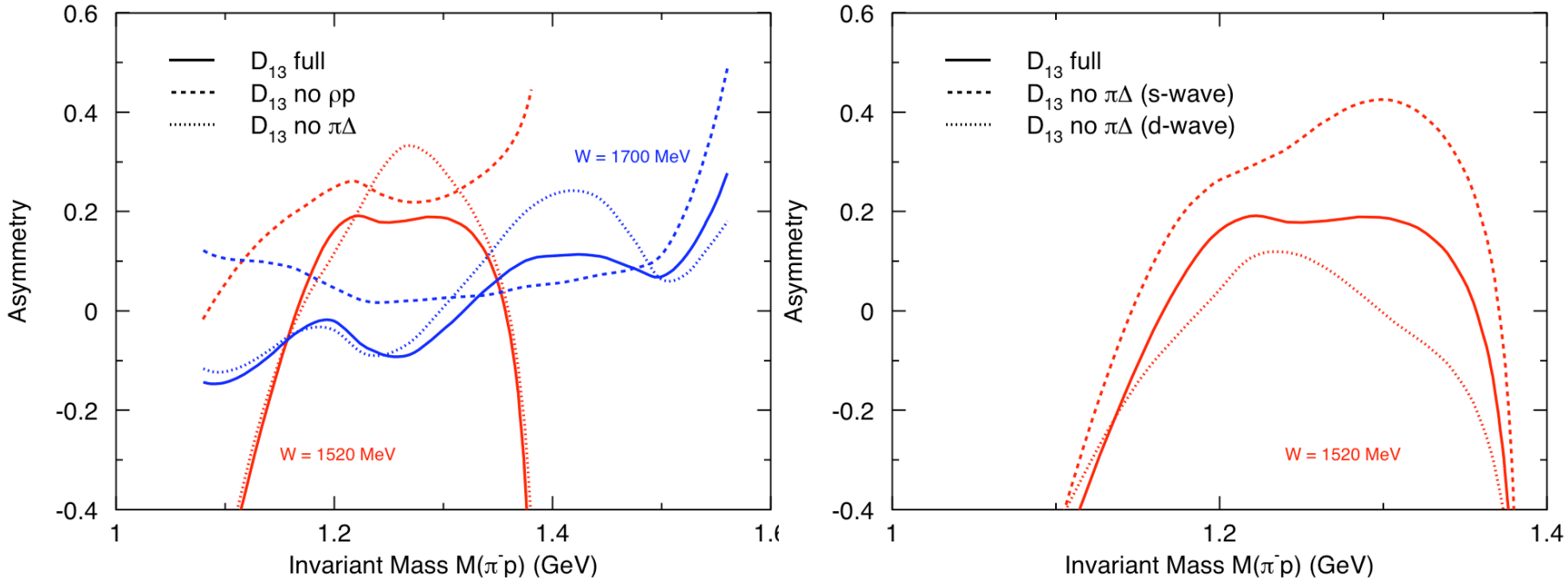
W. Roberts and T. Oed, Phys. Rev. Lett. C **71**, 055201 (2005)

- Known: I_0, $P^{\otimes}_z$ (GDH sum rule); new from CLAS: $I^{\otimes}$
- Polarized beam-target experiments with frozen-spin target at CLAS will make available: $P^{\otimes}_x$, $P^{\otimes}_y$, $P^{\otimes}_z$, I^{s}, P^{s}_x, P^{s}_y, P^{s}_z, I^{c}, P^{c}_x, P^{c}_y, P^{c}_z

Jefferson Lab Experiment E06-013, V. Credé, M. Bellis, S. Strauch, (CLAS Collaboration)

Predictions for $P^{\otimes}_{z}$

Model of A. Fix and H. Arenhövel



- Example of possible studies: $D_{13}(1520)$ decay modes

A. Fix and H. Arenhövel, Eur. Phys. J. A **25**, 115 (2005)

Summary

- CLAS meson photoproduction data:

  $\gamma p \rightarrow \eta p,\ \eta' p,\ K^+\Lambda,\ K^+\Sigma^0,\ K^0\Sigma^+,\ \pi^+\pi^- p$

- New Resonances?
  - third S_{11} state with m ≈ 1800 MeV and Γ = 250 MeV seen in ηN (χQM); not seen in Bonn-PWA
  - new P_{11} state, m = 1840 MeV and Γ = 140 MeV (PWA)
  - two D_{13} states at 1870 MeV and 2170 MeV (PWA)

- Differential cross sections do not provide sufficient constraints for models; spin observables are essential to resolve these issues:

  $\Rightarrow$ helicity asymmetry in $\pi^+\pi^- p$, FROST