Review of Hadron Spectroscopy Expts.

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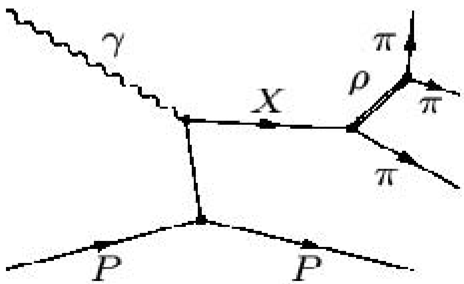
Many thanks to Gary Adams, Inna Aznauryan, Matt Bellis, Bill Briscoe, Raffaella deVita, Mike Dugger, Hovanes Egiyan, Kyungseon Joo, Franz Klein, Harry Lee, Ji Li, Jim Mueller, Marco Ripani, Barry Ritchie, Cole Smith, Paul Stoler, Igor Strakovsky, Dave Tedeschi, Ulrike Thoma, Dennis Weygand

My apologies for not including all your beautiful data

CLAS G6C Group

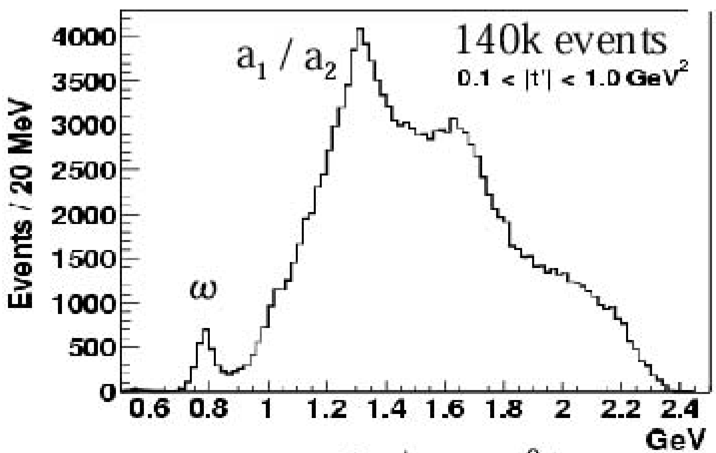


Meson spectroscopy by:

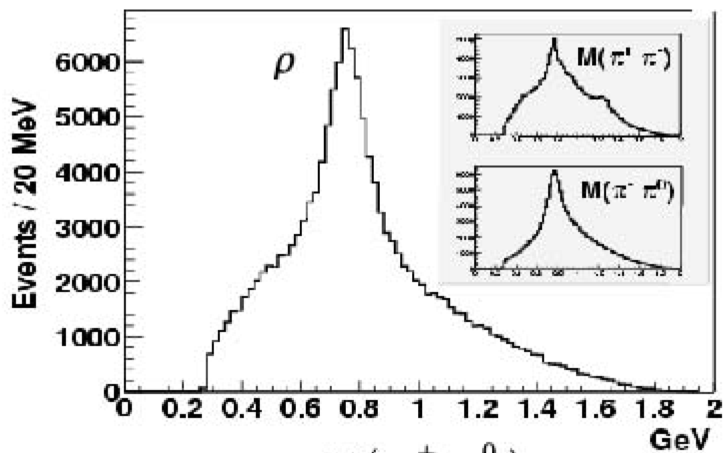
$$\gamma\, p \rightarrow p \pi^+ \pi^- \pi^0$$
$$n \pi^+ \pi^+ \pi^-$$
$$n K^+ K^- \pi^+$$

$E_\gamma \approx 5.2\, GeV$

$Tagged\ photon\ flux \approx 10^7\, s^{-1}$



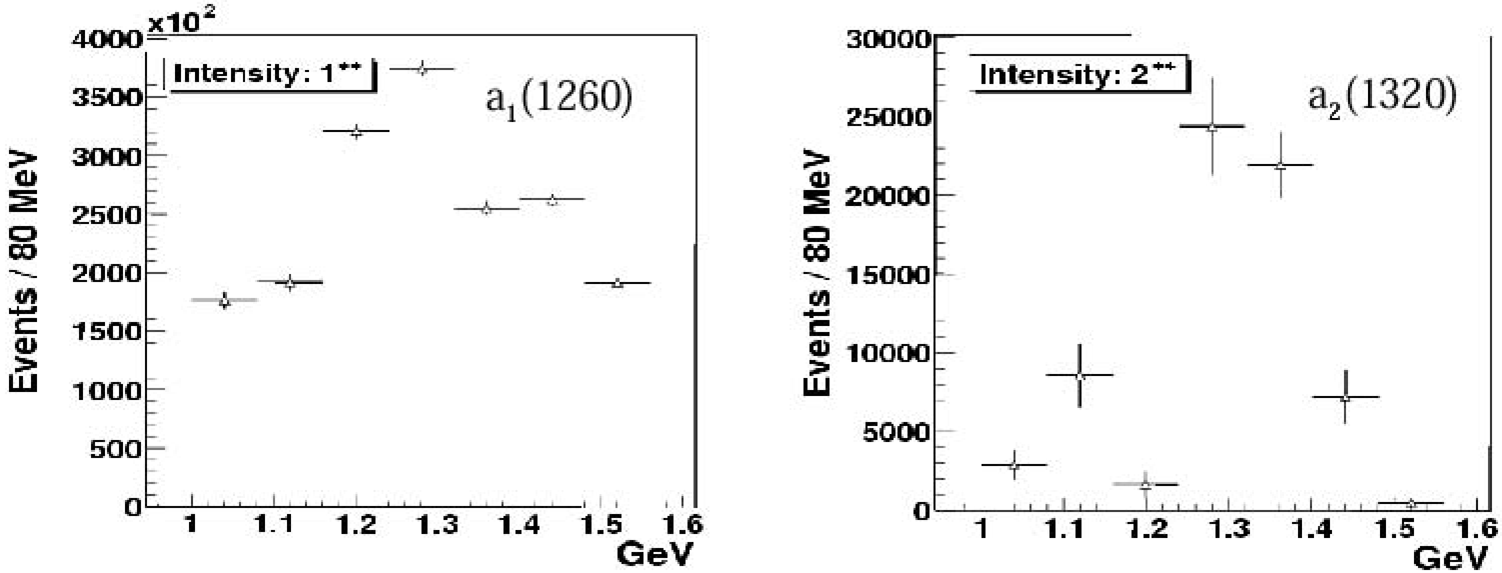
$M(\pi^+ \pi^- \pi^0)$



$M(\pi^+ \pi^0)$

CLAS G6C Group

Preliminary PWA results on the $\pi^+ \pi^- \pi^0$ channel



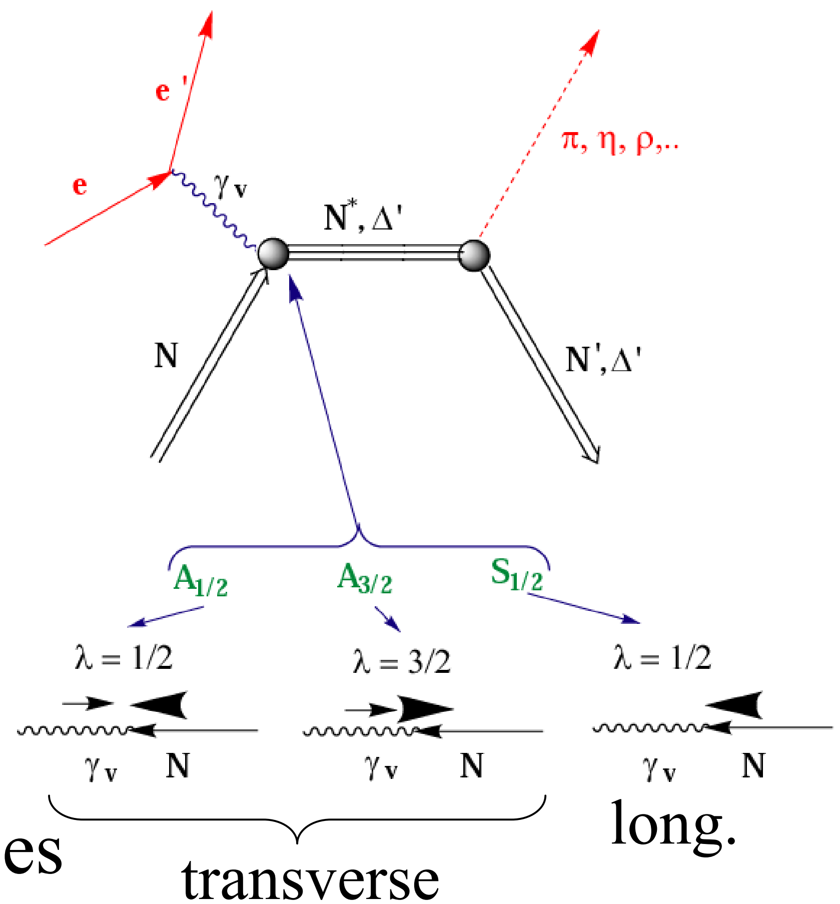
- PWA discriminates small a_2 signal from large a_1
- Recoil baryon waves are important in the PWA
- Sufficient statistics to search for exotic meson signals at higher mass

Interesting Issues - Baryons

- Photocouplings unique to Jlab, window to wave functions of N* states (excitation, not decay)
- Links to quark models, lattice
- Goal to understand effective forces, degrees of freedom
- Nature of threshold states, meson-baryon vs. quarks

  ("It's just a matter of time before all N* are fit with Chiral Pert. Theory" - M. Lutz)

- Missing (extra CQM) states
- New (beyond CQM) resonances



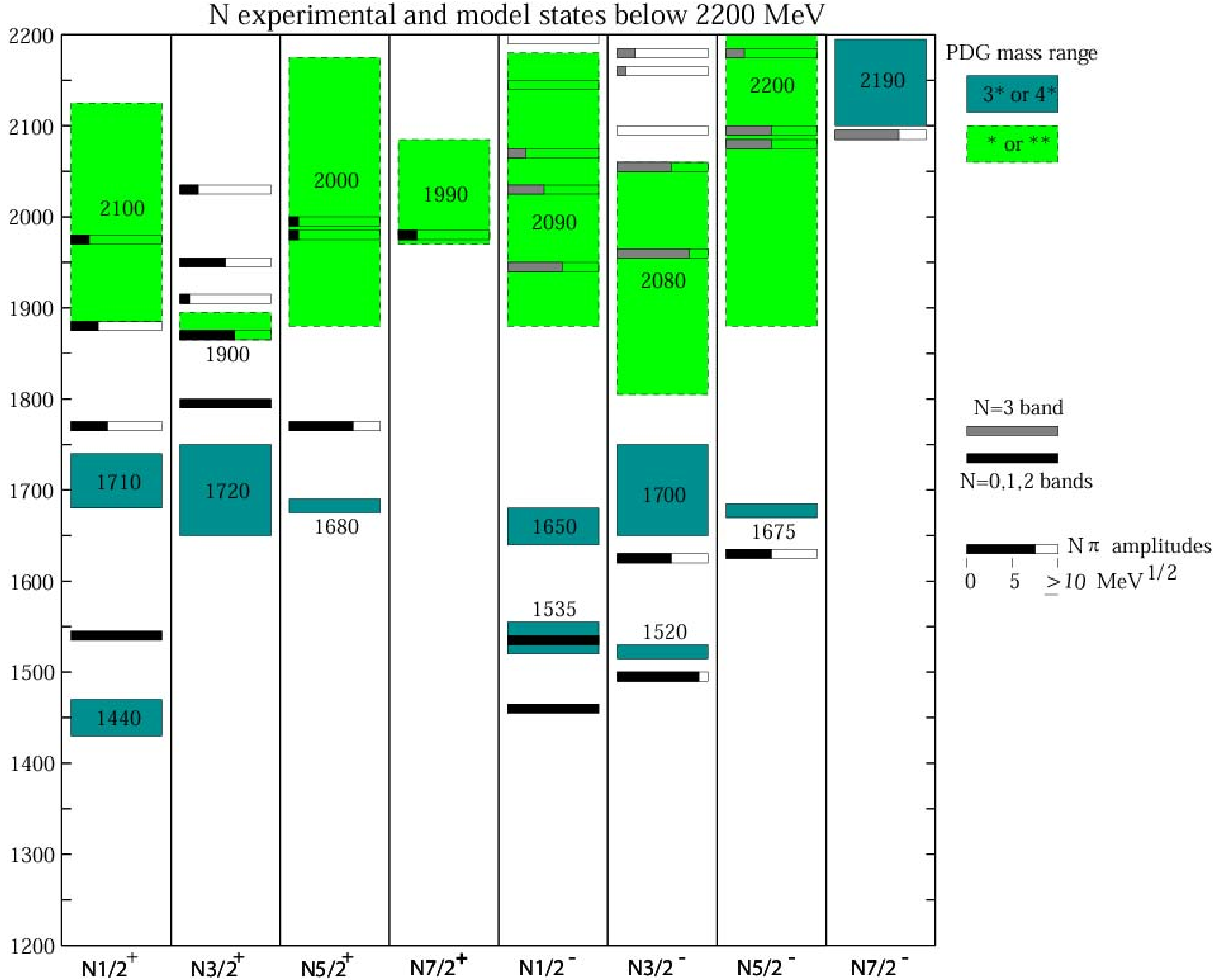
Layout of the spectrum- spin, parity, mass, decays…

CQM Results from Capstick, nucleons

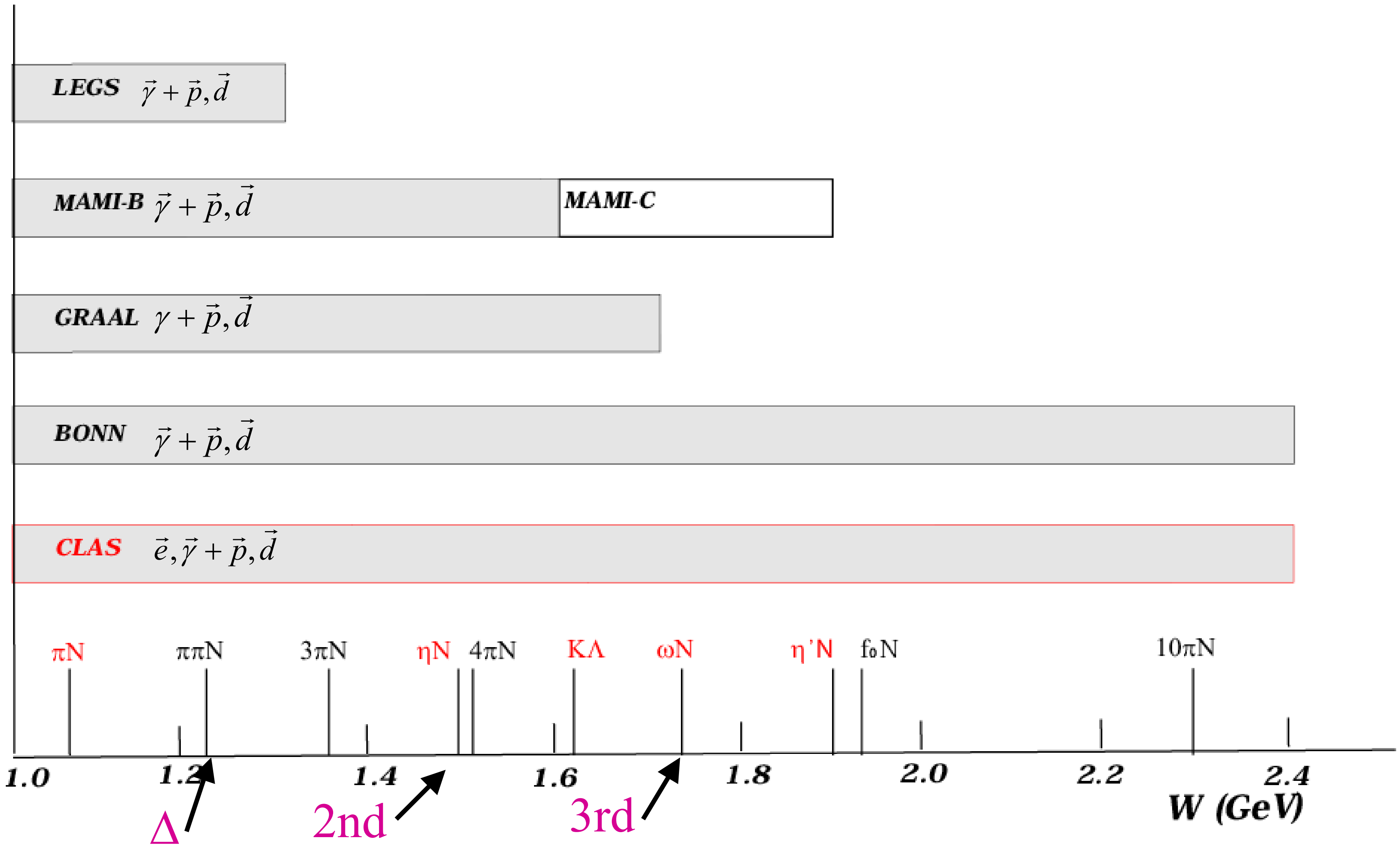
3rd res. region

2nd res. region

1st res. region

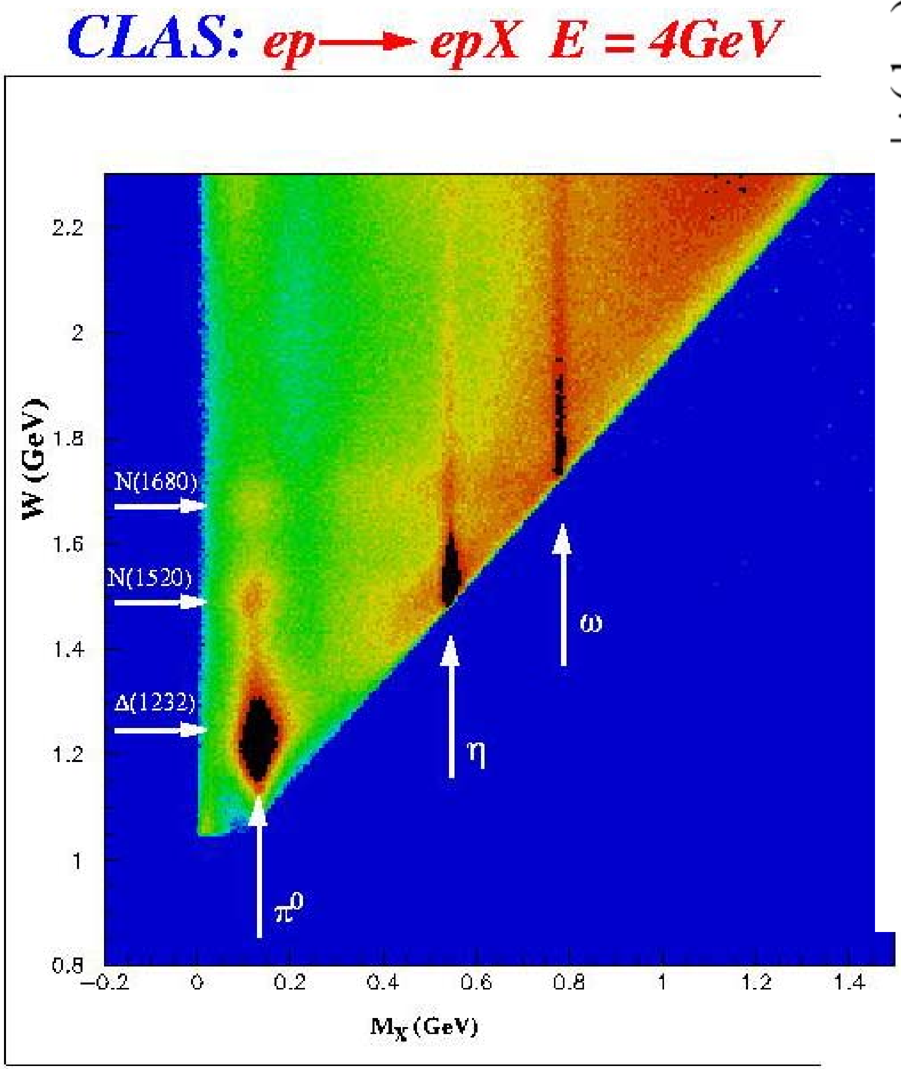


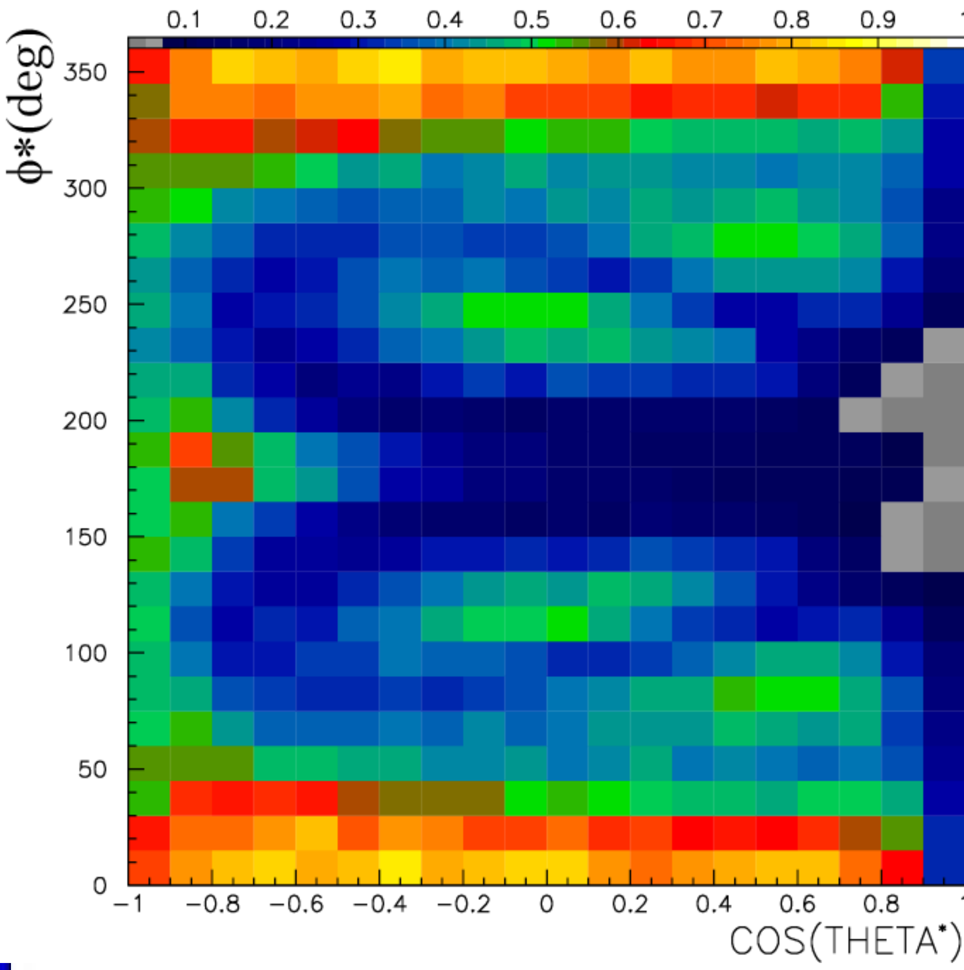
Reach of Existing Accelerators



CLAS was designed for N Studies, other halls can do more precise measurements*

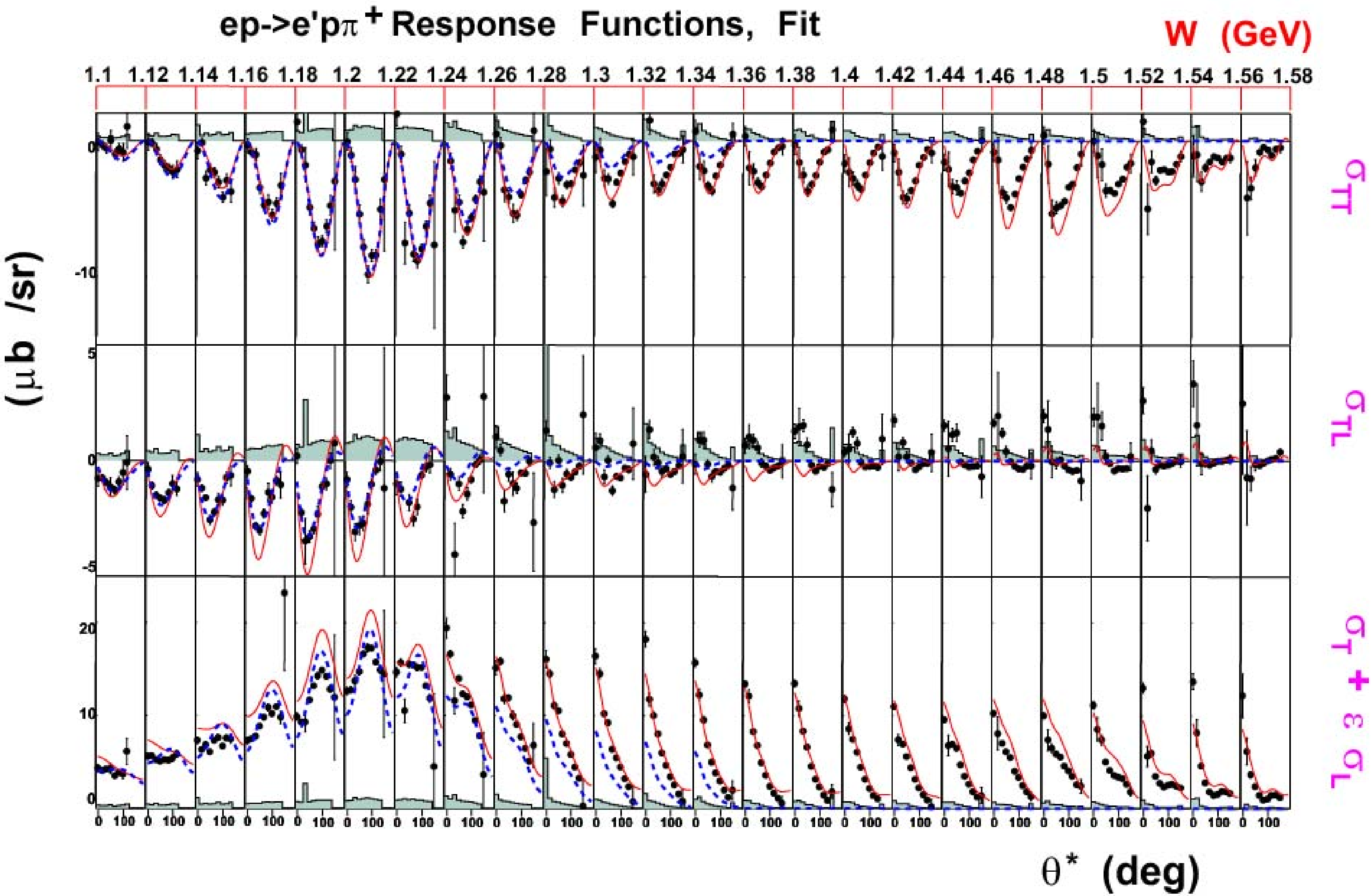
What large solid angle gets you!



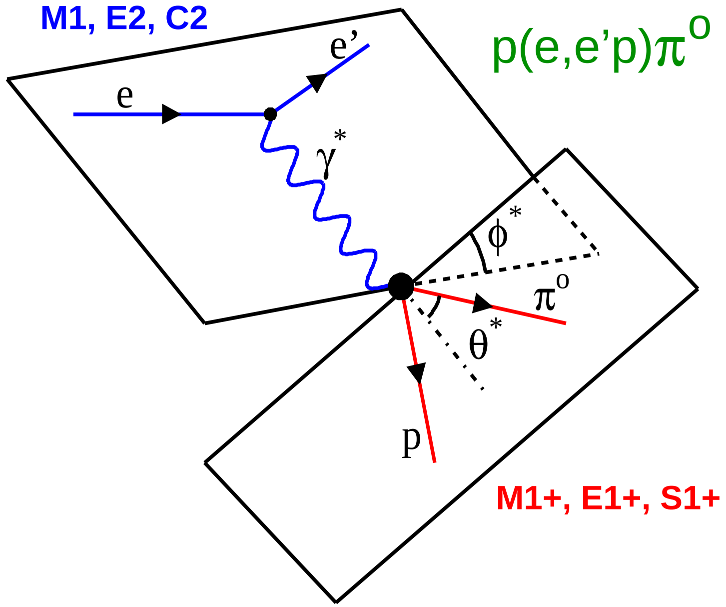


Acceptance for π^0 electroproduction

A hint at the magnitude of data

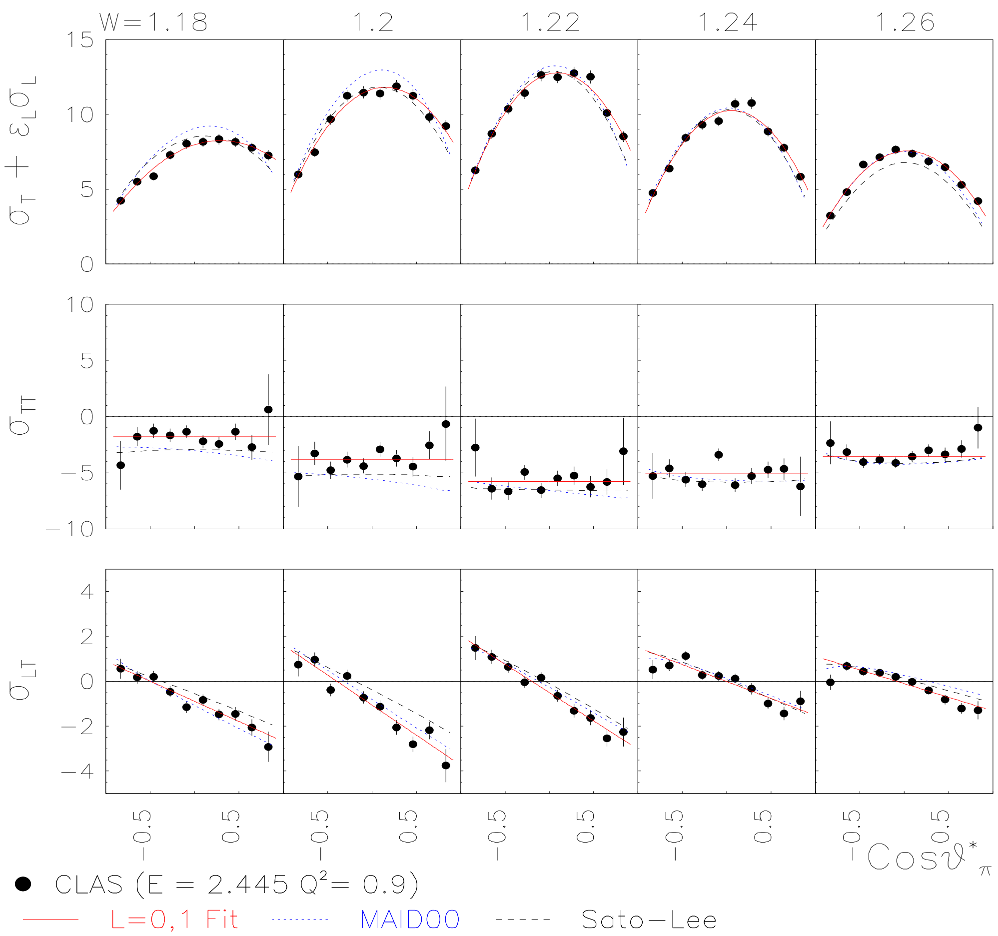


Pion Electroproduction of $\Delta^+(1232)$



M1 M1+ − Magnetic Dipole
E2 E1+ − Electric Quadrupole
C2 S1+ − Coulomb Quadrupole

Joo et al (CLAS collaboration)



Out−of−plane experiment + polarized beam

→ Access 5 **structure functions**

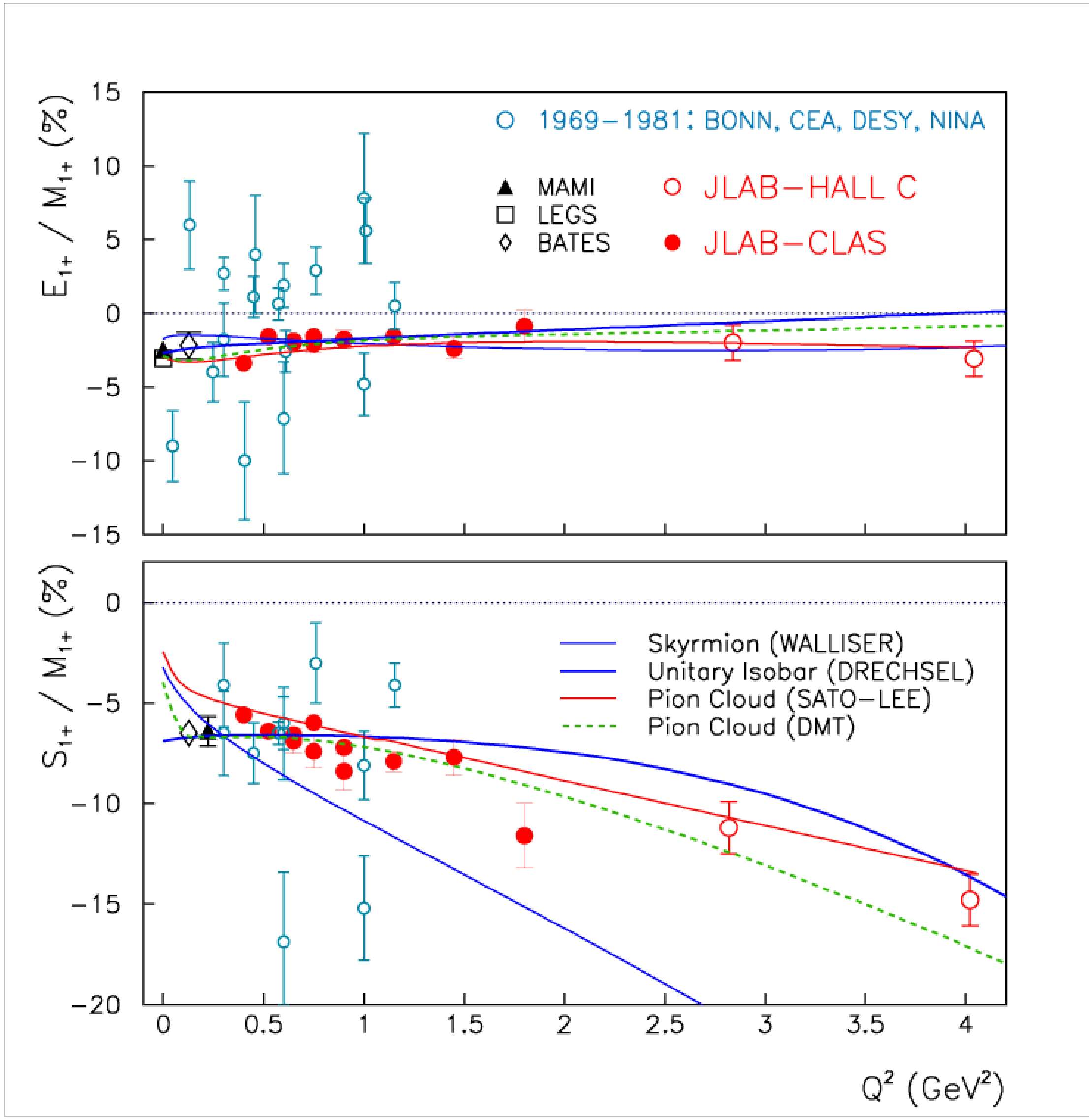
$$\sigma_T + \epsilon_L\,\sigma_L$$
$$+\,\epsilon_T\,\sigma_{TT}\,sin^2\theta^*_\pi\,cos2\phi^*_\pi$$
$$+\,[2\epsilon_L(1+\epsilon_T)]^{1/2}\,\sigma_{LT}\,sin\,\theta^*_\pi\,cos\,\phi^*_\pi$$
$$\pm\,[2\epsilon_L(1-\epsilon_T)]^{1/2}\,\sigma_{LT'}\,sin\,\theta^*_\pi\,sin\,\phi^*_\pi$$

Weak E1+, S1+ quadrupoles detected through interference with dominant M1+

$$\sigma_{TT} = -\frac{3}{2}|M_{1+}|^2 - 3Re(M^*_{1+}E_{1+}) + \ldots$$
$$\sigma_{LT} = 6Re(M^*_{1+}S_{1+})\,cos\,\theta^*_\pi + \ldots$$
$$\sigma_{LT'} = 6Im(M^*_{1+}S_{1+})\,cos\,\theta^*_\pi + \ldots$$

E2/M1, C2/M1

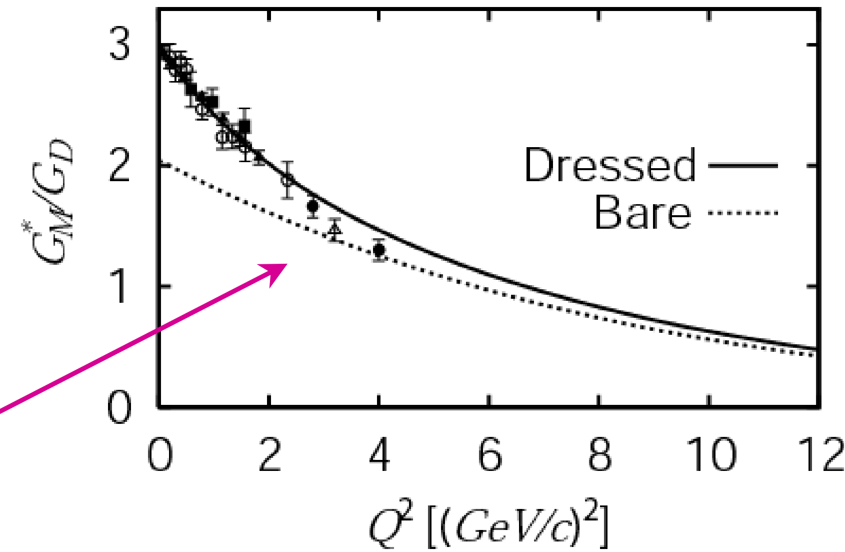
- These are the 2 'other' amplitudes for $\gamma N \rightarrow \Delta$
- They measure the quadrupole deformation of the Δ(,N?)
- Considered to have fundamental importance
- Amplitudes are small, hard to measure
- Many labs, halls build a clean picture
- E2/M1 is a few %, still small at $Q^2 \sim 4$ GeV^2 (no sight of PQCD limit)
- C2/M1 is larger and increasing in magnitude with Q^2.
- First CLAS data published (PRL)



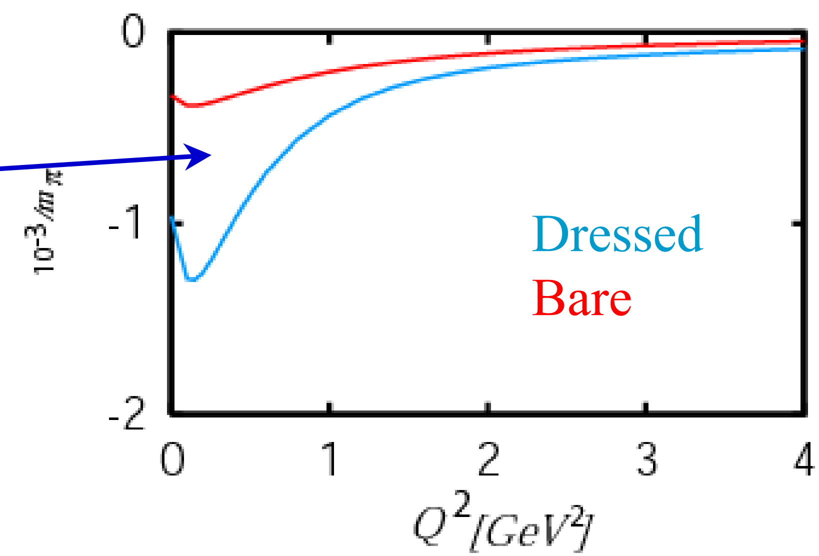
One interpretation of the situation

Determined M1 form factor of $\gamma N \to \Delta$
(By Sato and Lee)

$$G^*_M = G_M + \bar{\Gamma}_{\pi N \to \Delta} G_{\pi N} v_{\gamma\pi}$$
$$\uparrow$$
$$\mathit{Bare}$$



- Dressing=pion cloud=FSI is big effect at low Q^2 for M1.



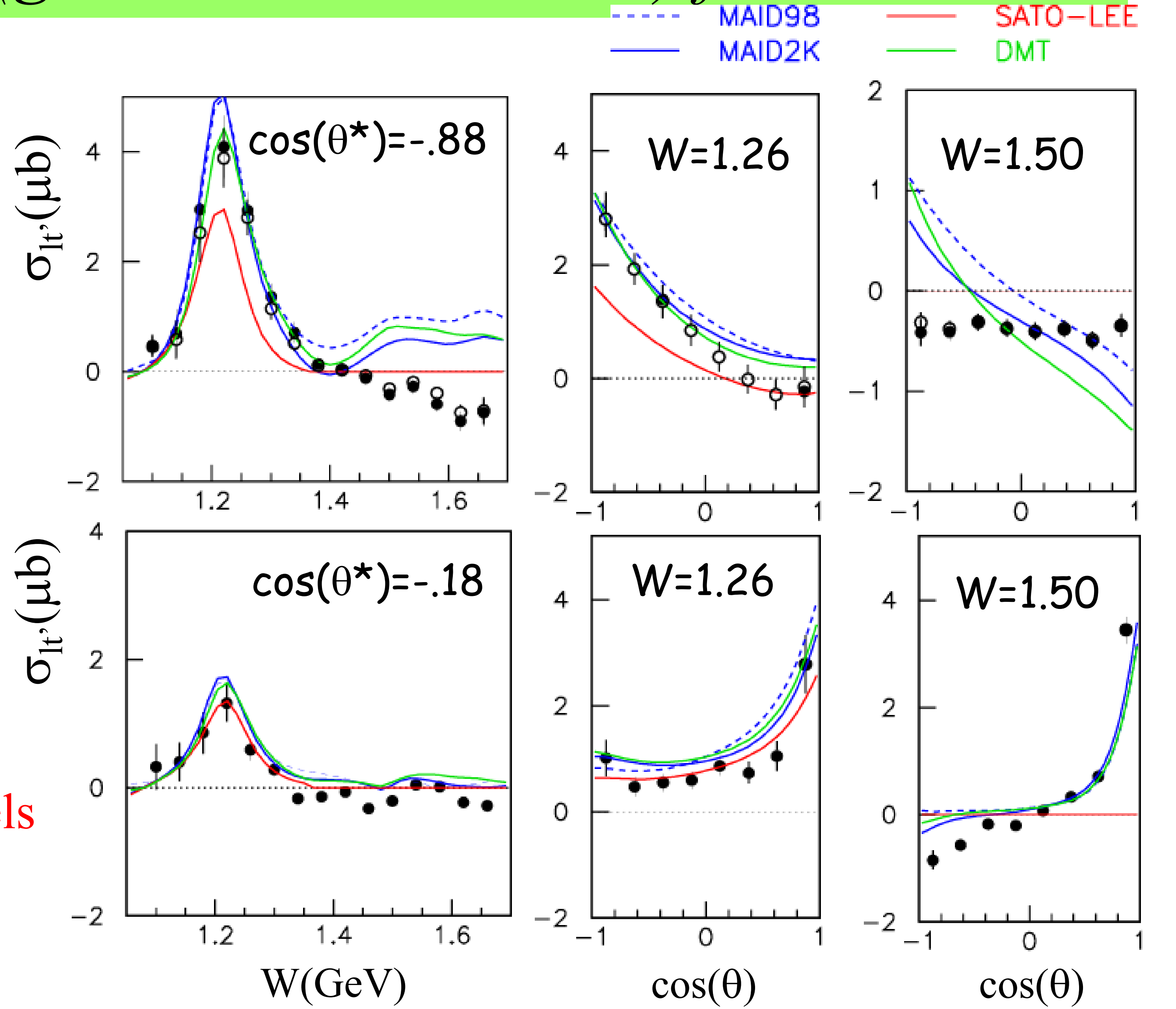
- Even bigger effect for E2
- Agrees well with Joo et al. data!
- Good treatment of dynamics matters!
- Interpretation consistent with DMT

RLT' (good news, bad news) for models

Q^2=0.4 GeV^2

$ep \rightarrow e'p\pi^0$

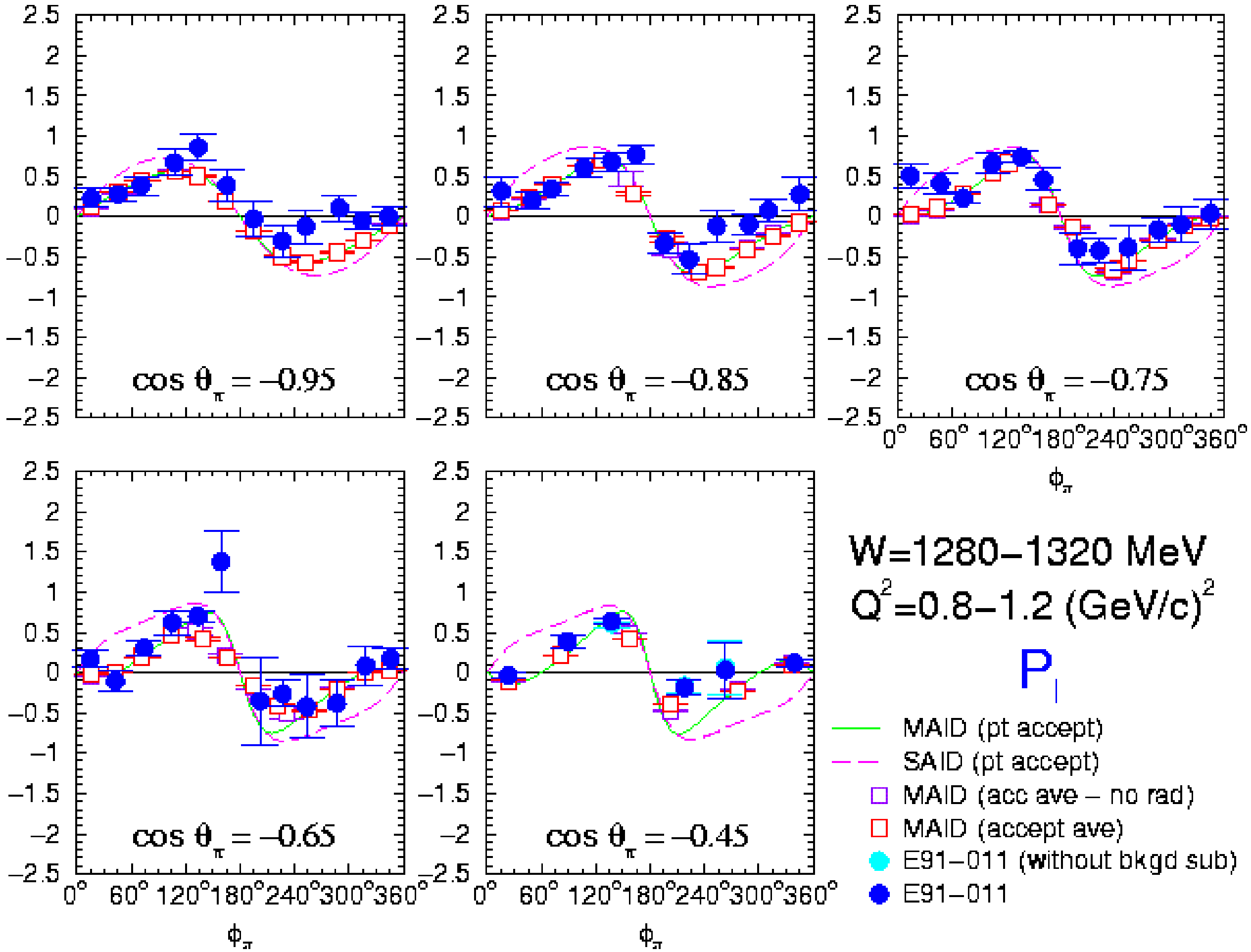
$ep \rightarrow e'n\pi^+$



As the energy increases, models do worse.

Hall A - Recoil Polarization

PRELIMINARY



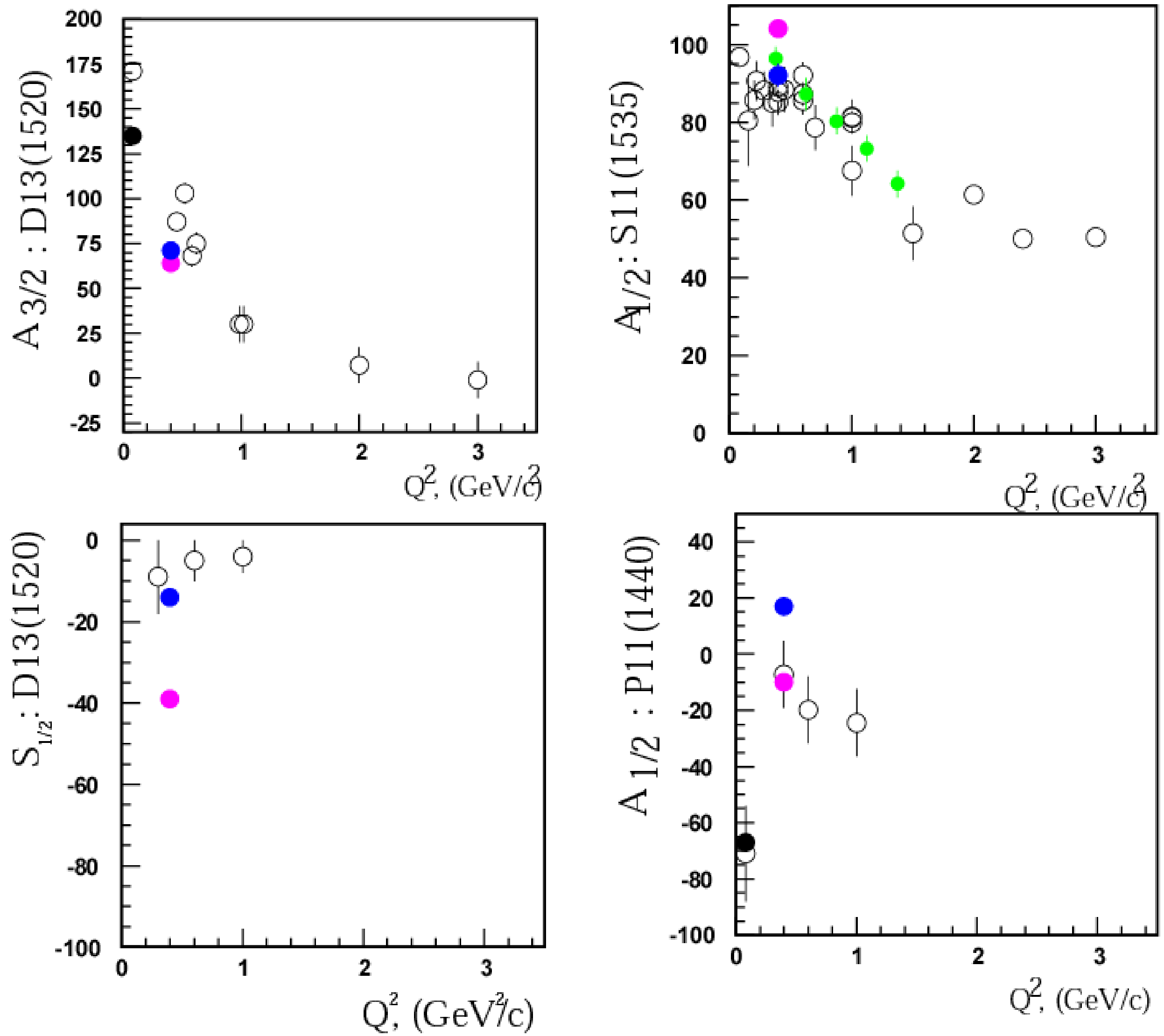
- Complementary to CLAS
- Good agreement with model predictions

Breit-Wigner Models – MAID and UIM

- Excellent way to get a first look at interpretation of data, can go directly from data to basic N* properties.
- Amplitude is sum of Breit-Wigners + Born diagrams
  - At high W, add in Regge t-channel diagrams
- Unitarity ok below 2π threshold, difficult W>1.5 GeV

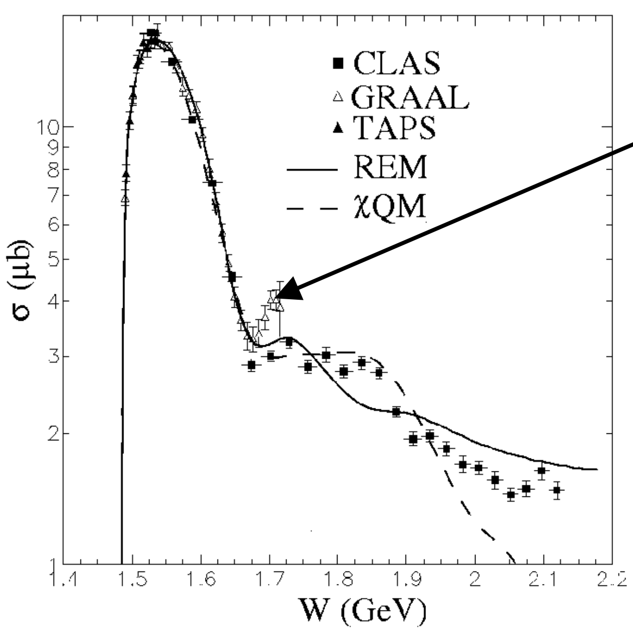
Results of Breit-Wigner fits to all CLAS $ep \to e'N\pi$ data

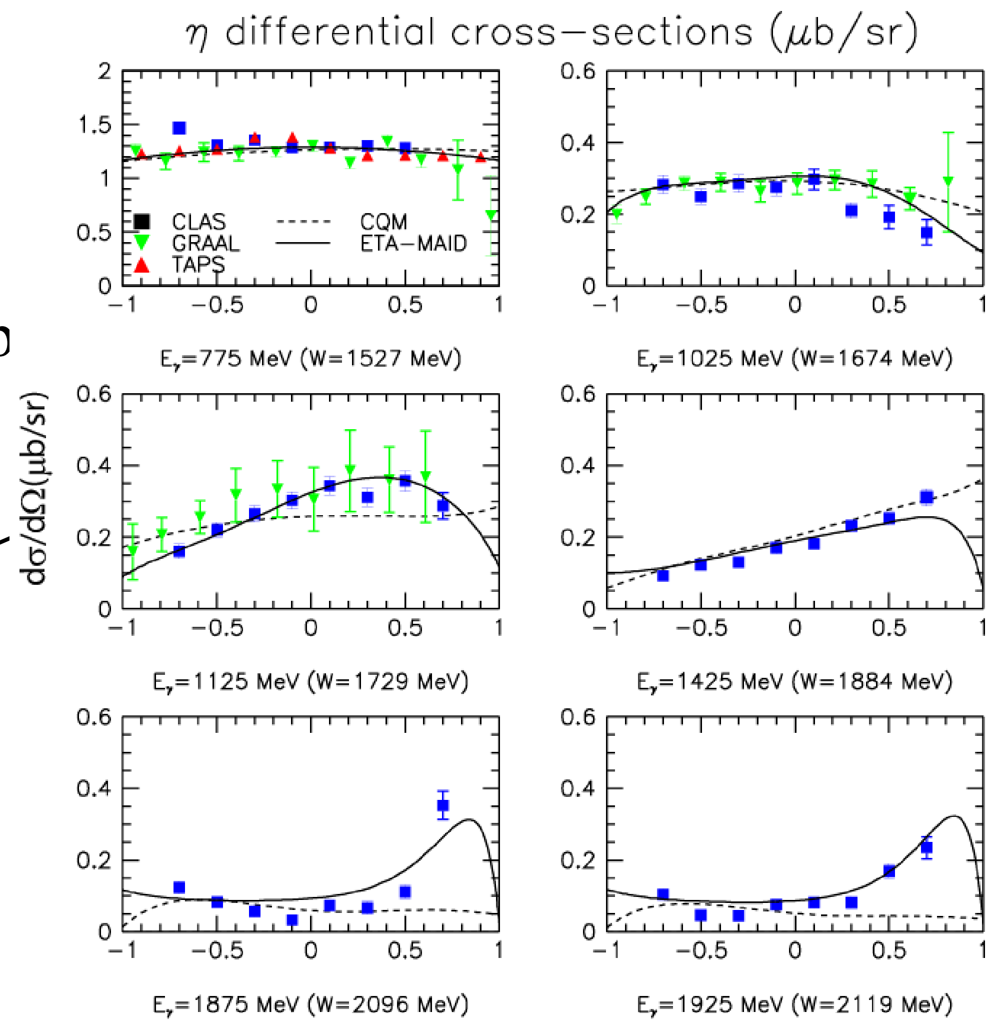
- Uses models (2) of Aznauryan, Egiyan, Stepanyan
- With both π^+ and π^0, isospin can be separated
- No new information in E2/M1, C2/M1
- Weak signals (2 lower plots) still hard to disentangle.



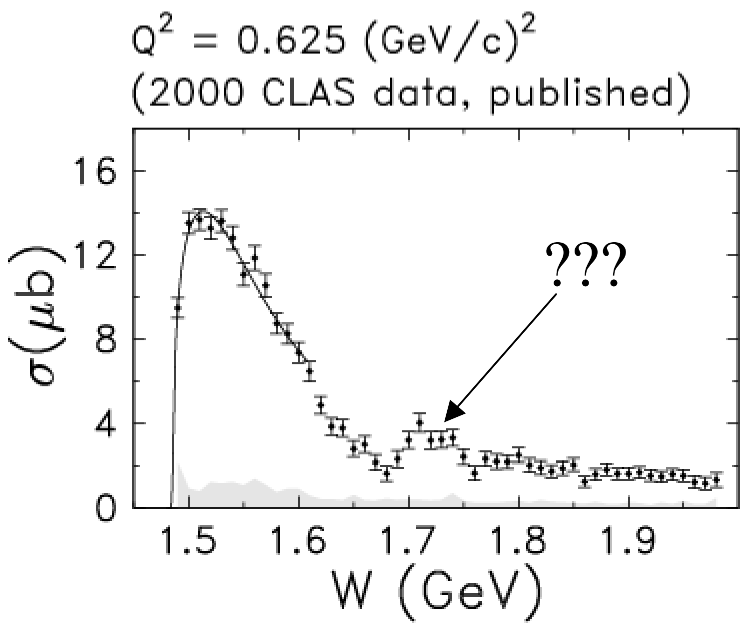
$\gamma p \rightarrow \eta p$

- Vast increase in kinematic range from previous expts.
- Greatly quantifies search for 3rd S_{11} (stay tuned!)
- Published in PRL (2001)
- Limited PDG data for N*→ηp

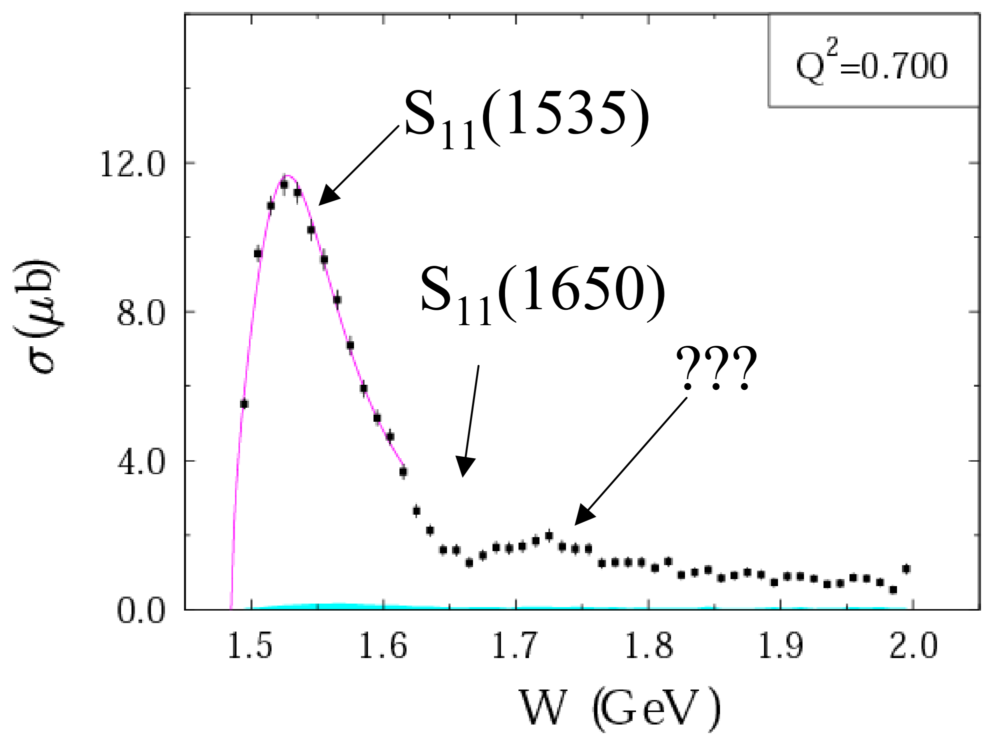




Eta electroproduction more complete
3rd S_{11} (non CQM) awaits solid discovery



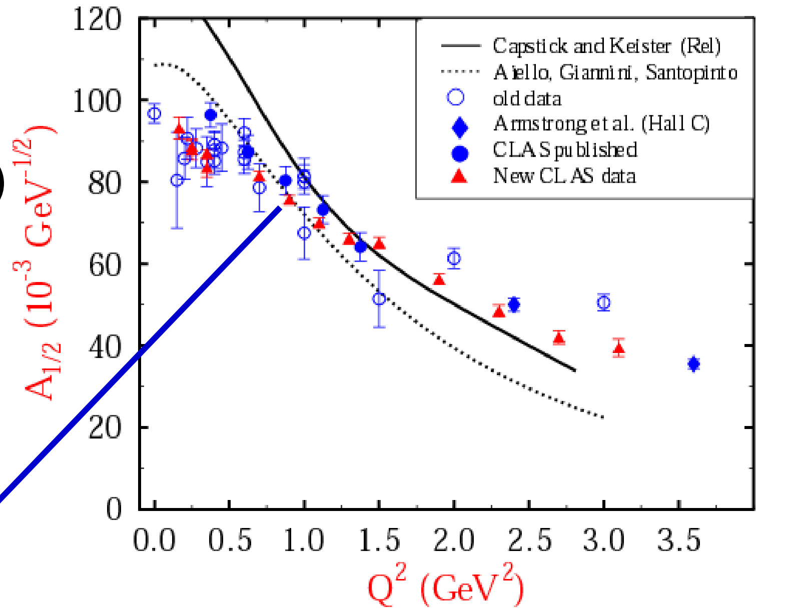
Total cross section from CLAS, old and new

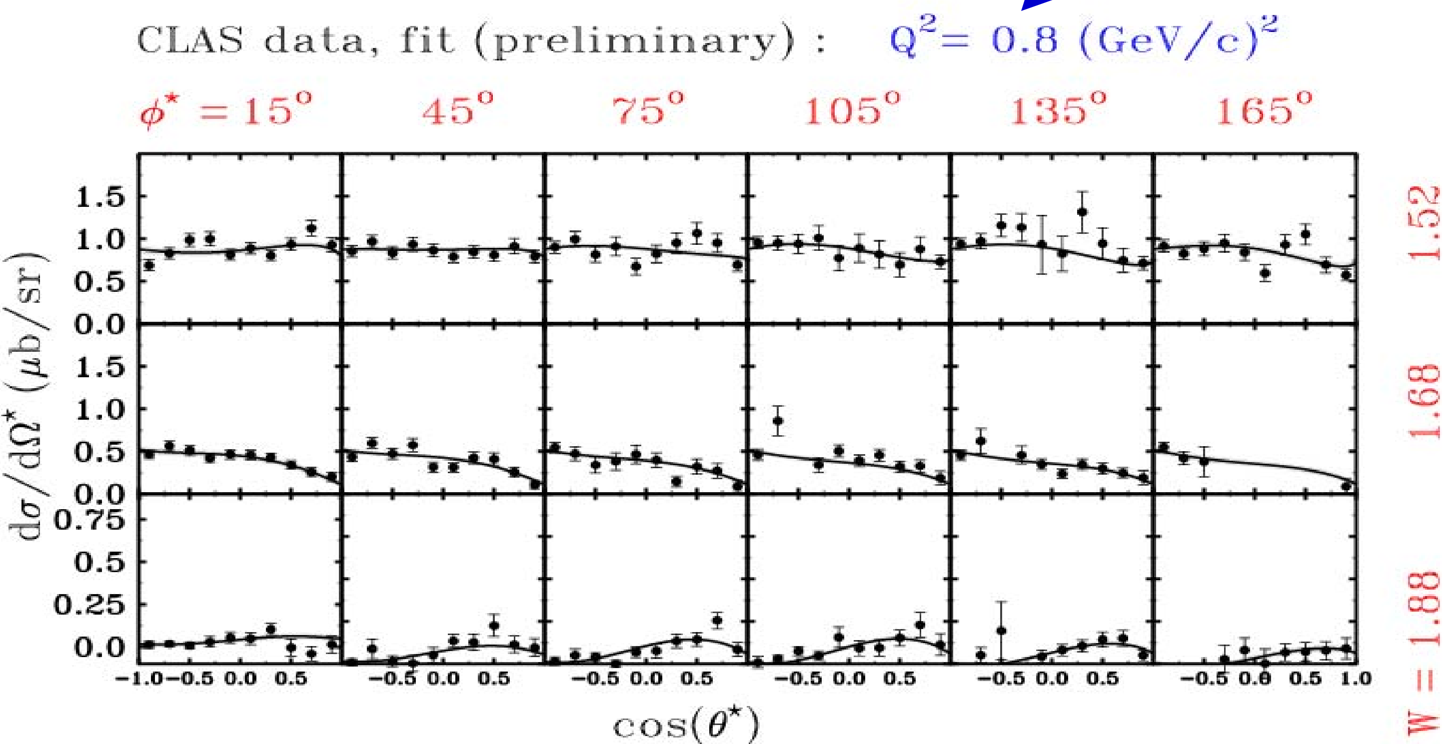


Complete coverage in scattering angle allows much less doubt.

$ep \to e'p\eta$

- First modern results from Hall C (high Q^2)
- Vast improvement from previous data
- $0.2<Q^2<3.1$ GeV^2, W_{max}=2.1 GeV
- Extract $A_{1/2}(Q^2)$ from total cross section with Breit-Wigner model
- Isospin filter (only T=1/2)



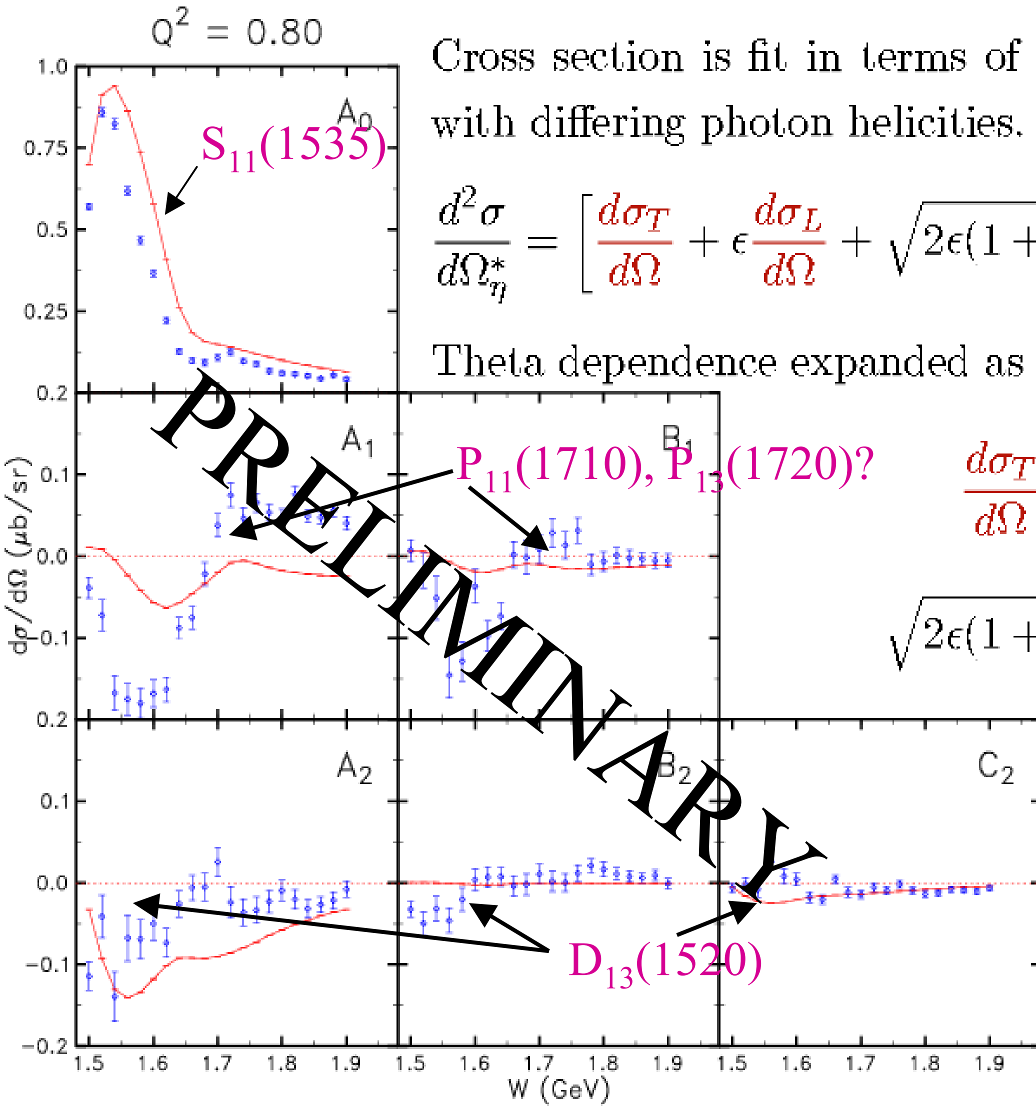


ep →e′pη amplitudes

‘SS’

‘SP’

‘SD’



$R_T+\varepsilon R_L$ R_{LT} R_{TT}

Cross section is fit in terms of contributions from amplitudes with differing photon helicities. Curves from ETAMAID

$$\frac{d^2\sigma}{d\Omega_\eta^*} = \left[\frac{d\sigma_T}{d\Omega} + \epsilon\frac{d\sigma_L}{d\Omega} + \sqrt{2\epsilon(1+\epsilon)}\frac{d\sigma_{LT}}{d\Omega}\cos\phi_\eta^* + \epsilon\frac{d\sigma_{TT}}{d\Omega}\cos 2\phi_\eta^*\right]$$

Theta dependence expanded as series of Legendre Polynomials

$$\frac{d\sigma_T}{d\Omega} + \epsilon\frac{d\sigma_L}{d\Omega} = \sum_{l=0}^{\infty} A_l P_l^0\left(\cos(\theta_\eta^*)\right)$$

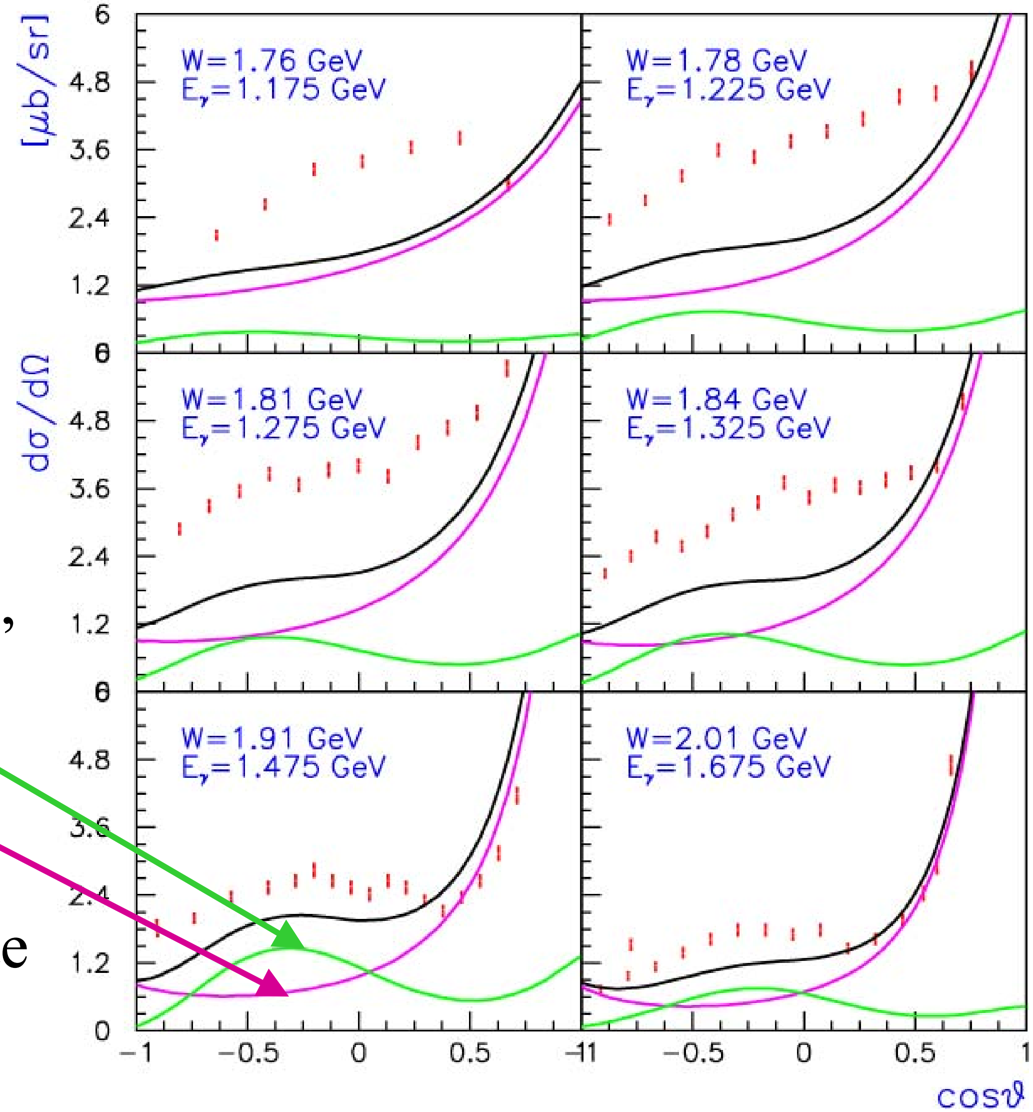
$$\sqrt{2\epsilon(1+\epsilon)}\frac{d\sigma_{LT}}{d\Omega} = \sum_{l=1}^{\infty} B_l P_l^1\left(\cos(\theta_\eta^*)\right)$$

$$\epsilon\frac{d\sigma_{TT}}{d\Omega} = \sum_{l=2}^{\infty} C_l P_l^2\left(\cos(\theta_\eta^*)\right)$$

Interesting structure at W~1.72 GeV → $P_{11}(1710)$, $P_{13}(1720)$? (needs more theory)

γp→ωp

- Old data only showed forward angle peaking (Regge)
- PDG lists no N* →ωp decays
- Strong signal with e,γ beam
- Vector particle provides interesting observables with polarized beam/target
- Calculations from Y. Oh- ‘good’ representation of t-chan+res.
- Results preliminary- strong resonance contribution, but no single signature for a single state



$\gamma p \to \eta' p$

- First SAPHIR data sketchy
- First CLAS data much more expansive and higher quality
- Great way to focus on $W>2$ GeV isospin=1/2 N*
- Calculation of t-chan only fit to SAPHIR data (Elster, et al.)
- To be submitted to PRL
- Only 50% of CLAS data analyzed

PRELIMNARY

$ep \rightarrow e'p\pi^+\pi^-$

accepted for publ., PRL

Comparison with Genova-Moscow phenomenological model for two pion electroproduction

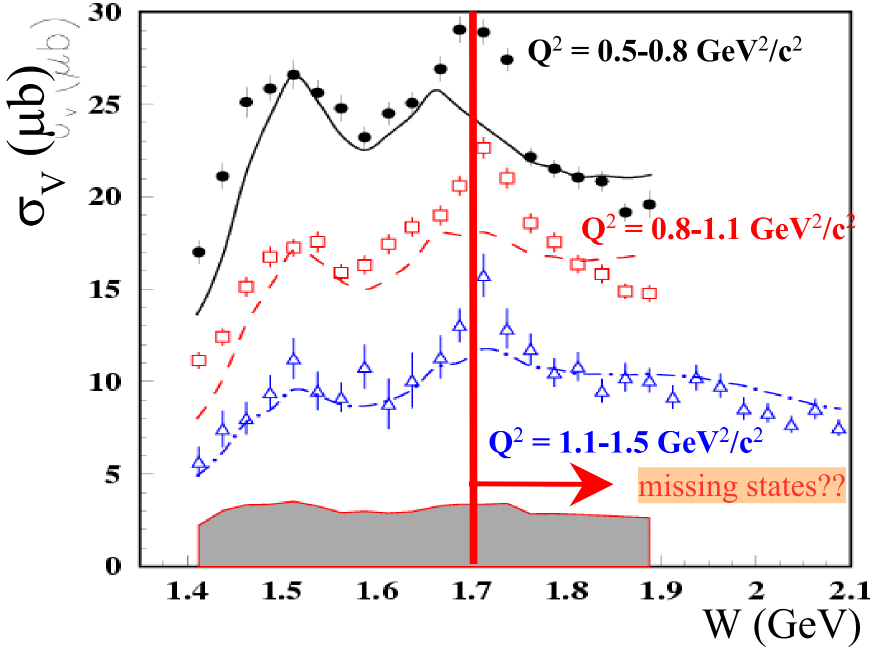
Phys. Atom. Nucl. 64(2001) 1292

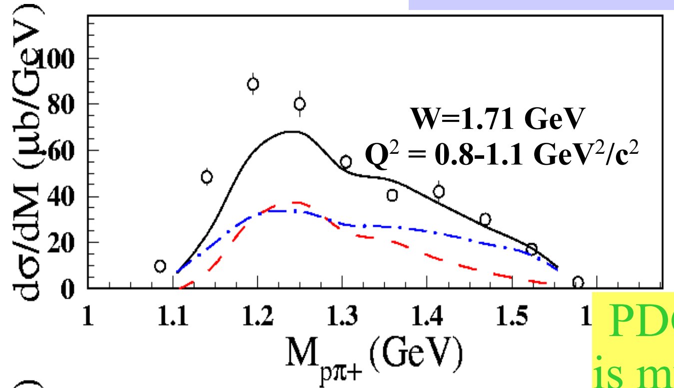
Input for <u>resonance photocouplings</u> $A_{1/2}$, $A_{3/2}$ from global fit based on exptl data + Single Quark Transition Model assumptions

Phys. Rev. C67 (2003) 035204

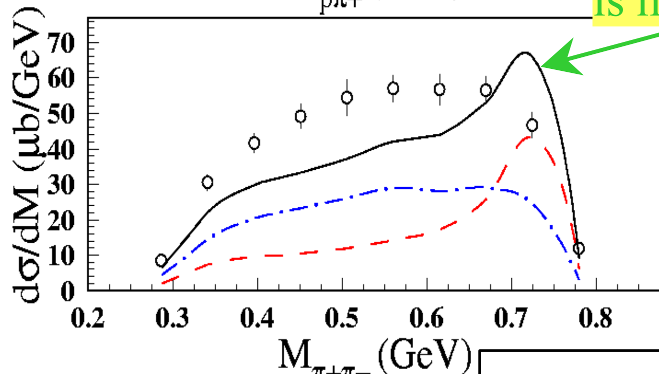
<u>Strong decay couplings</u> from Manley and Saleski hadronic analysis

Phys.Rev.D45 (1992) 4002





PDG $P_{13} \rightarrow \rho N$ is much too large



- blue curve: non- resonant part
- red curve: resonant part
- black curve: full calculation

With this model, there is large Unexplained cross section around 1.7 GeV

<u>Twofold conclusion:</u>

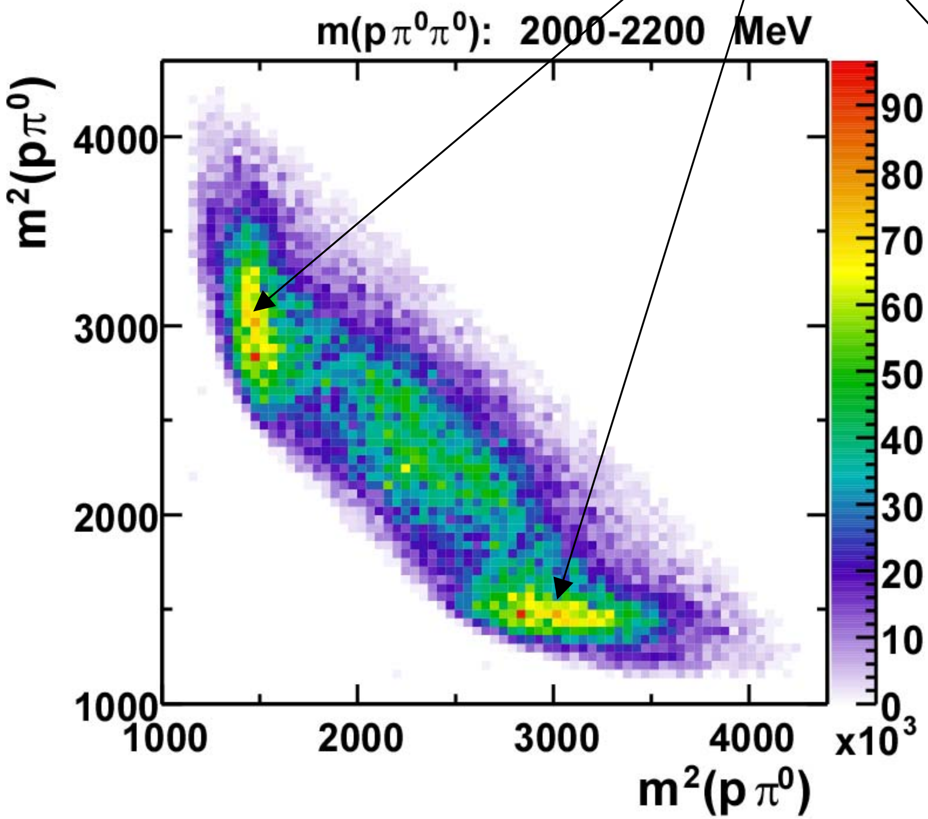
I) <u>Ordinary</u> P_{13}(1720) from PDG can fit the data but with <u>significant strong parameters changes</u>

II) A <u>new</u> (non CQM) P_{13} can equally well fit the data

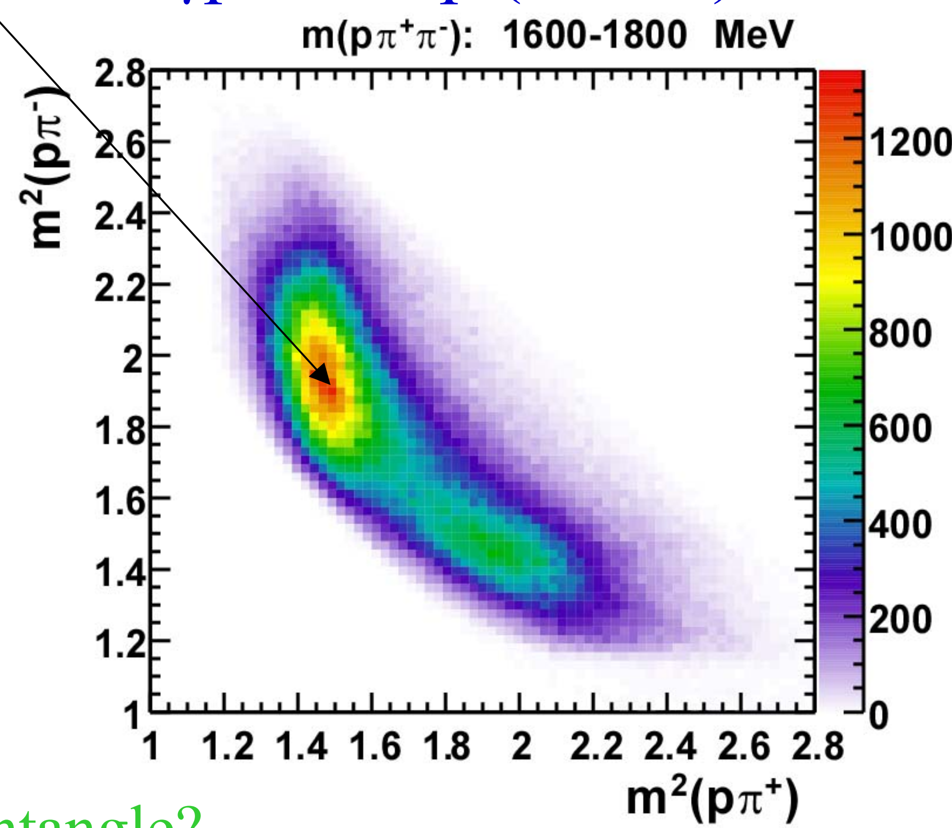
ππ photoproduction- Bonn and CLAS

Δ(1232)π decays dominate despite high W!

$\gamma p \to \pi^0 \pi^0 p$ (Bonn)



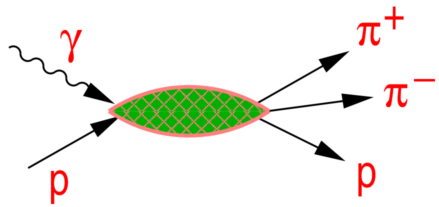
$\gamma p \to \pi^+ \pi^- p$ (CLAS)

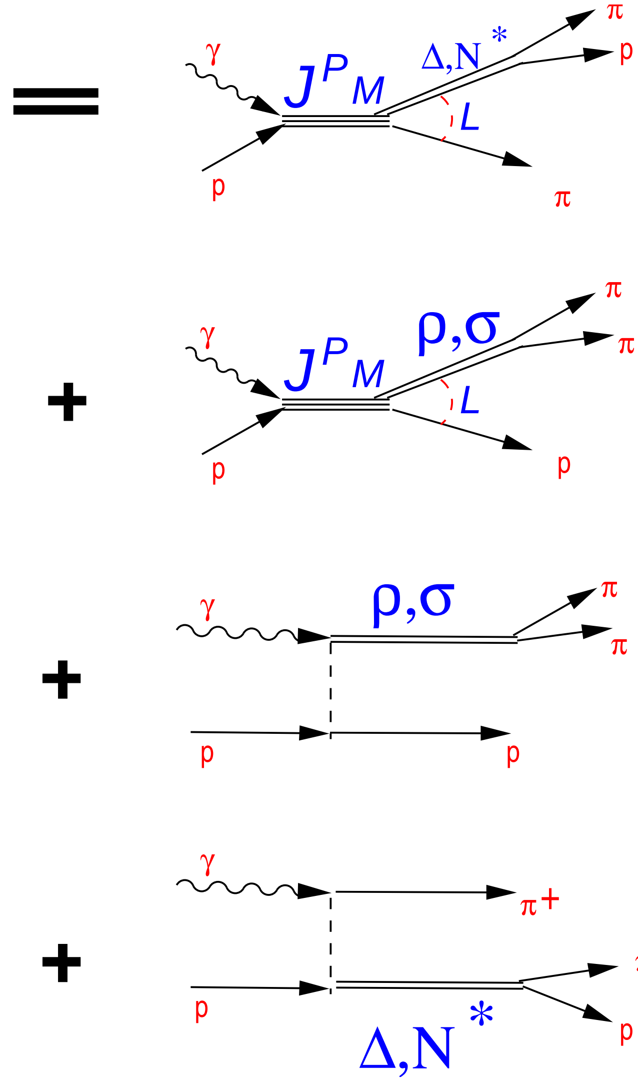


Interesting structure, how to disentangle?

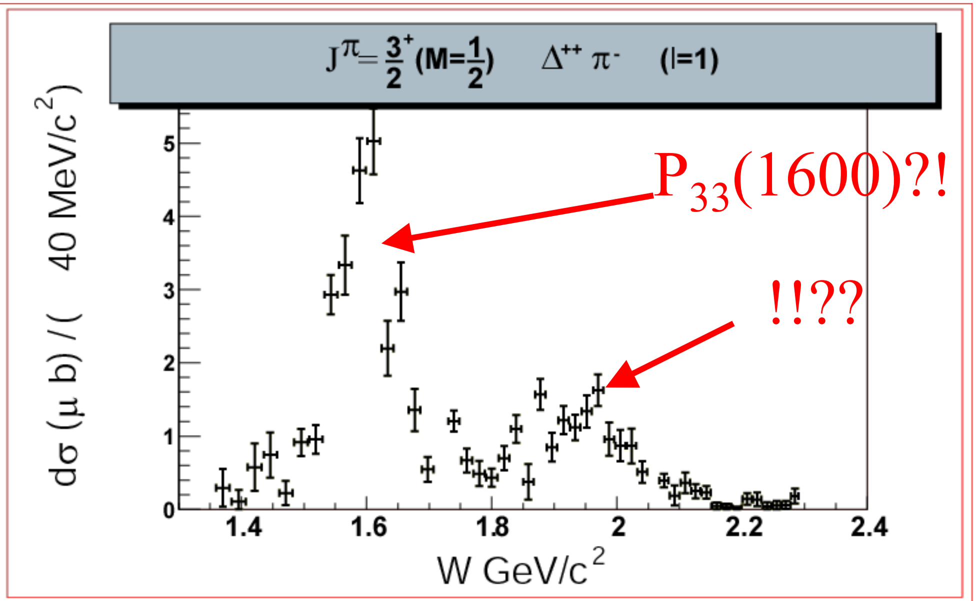
Waves in the fit

- $\frac{1}{2}^+ \longrightarrow \Delta\pi$
- $\frac{1}{2}^- \longrightarrow \Delta\pi, (p\rho)_1$
- $\frac{3}{2}^+ \longrightarrow$ $\Delta\pi_{\ell=1}, (p\rho)_1, (p\rho)_{3(\ell=1,3)}, N^*(1440)\pi$
- $\frac{3}{2}^- \longrightarrow \Delta\pi_{\ell=2,0}$
- $\frac{5}{2}^+ \longrightarrow \Delta\pi_{\ell=1}, p\sigma$
- $\frac{5}{2}^- \longrightarrow \Delta\pi_{\ell=2}$
- t-channel background
- This represents 35 waves

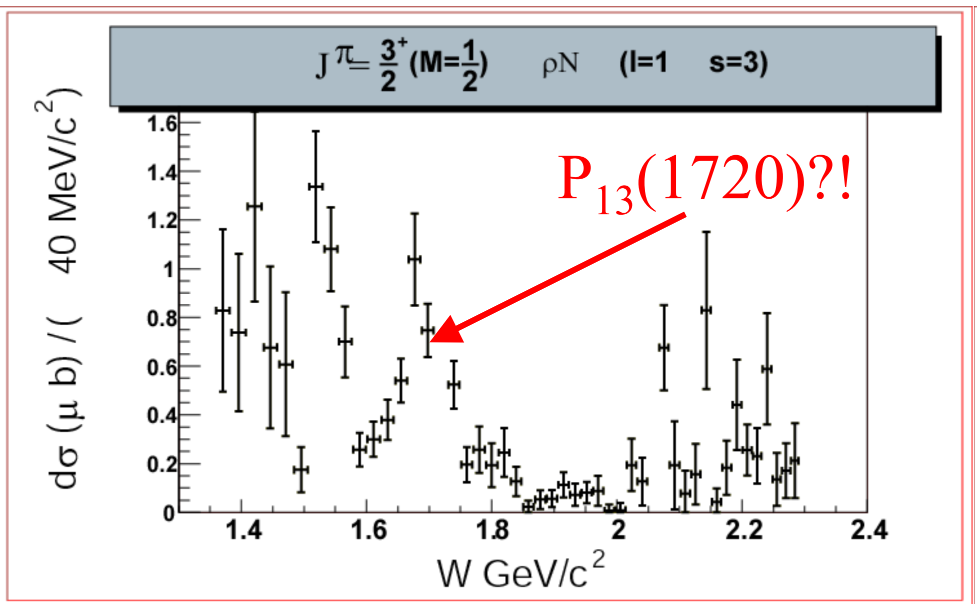


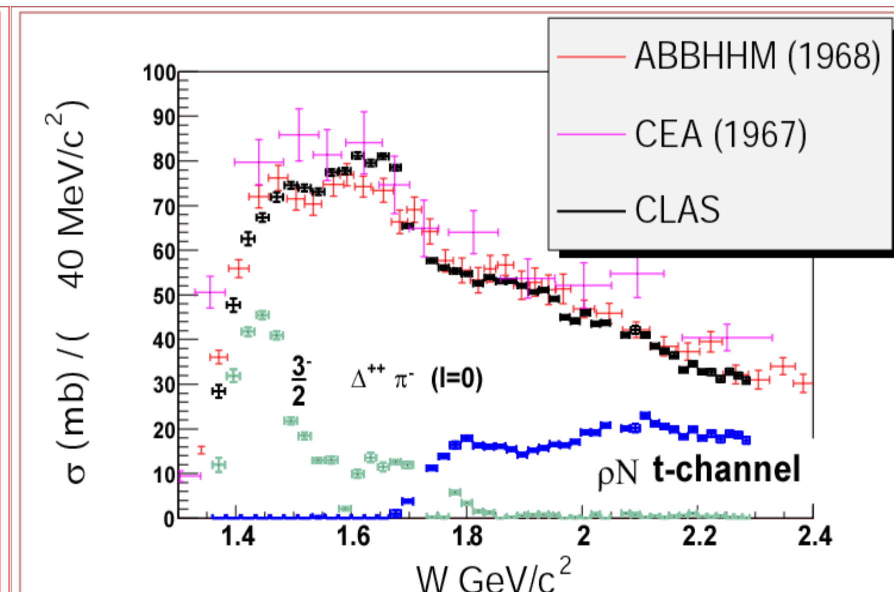


$\gamma p \rightarrow \pi^+ \pi^- p$



- Sample results from RPI-Jlab
- Preliminary (intriguing!) results
  - ✓Peaks clearly seen
  - ✓P_{33} $\Delta\pi$ decays presently
  - ✓ poorly understood
  - ✓P_{13} $\Delta\pi$, ρN decays of great interest
- No isospin separation

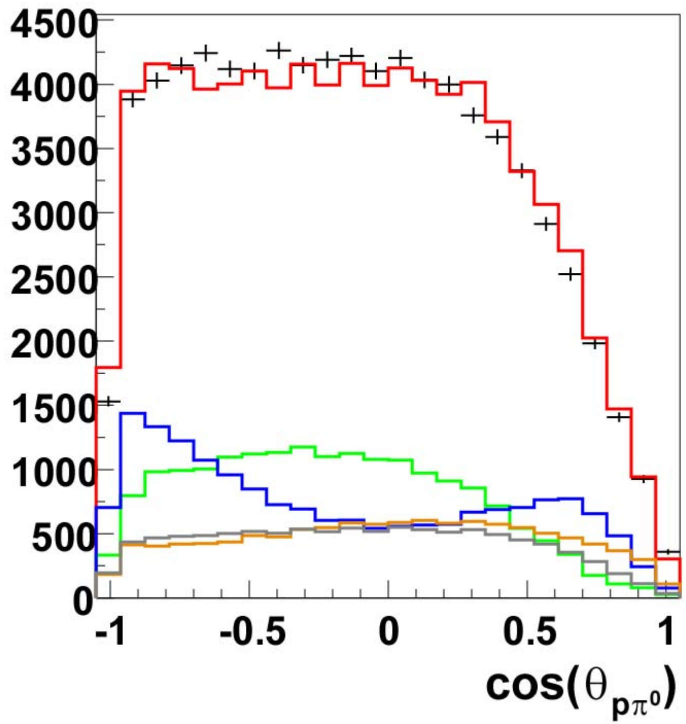




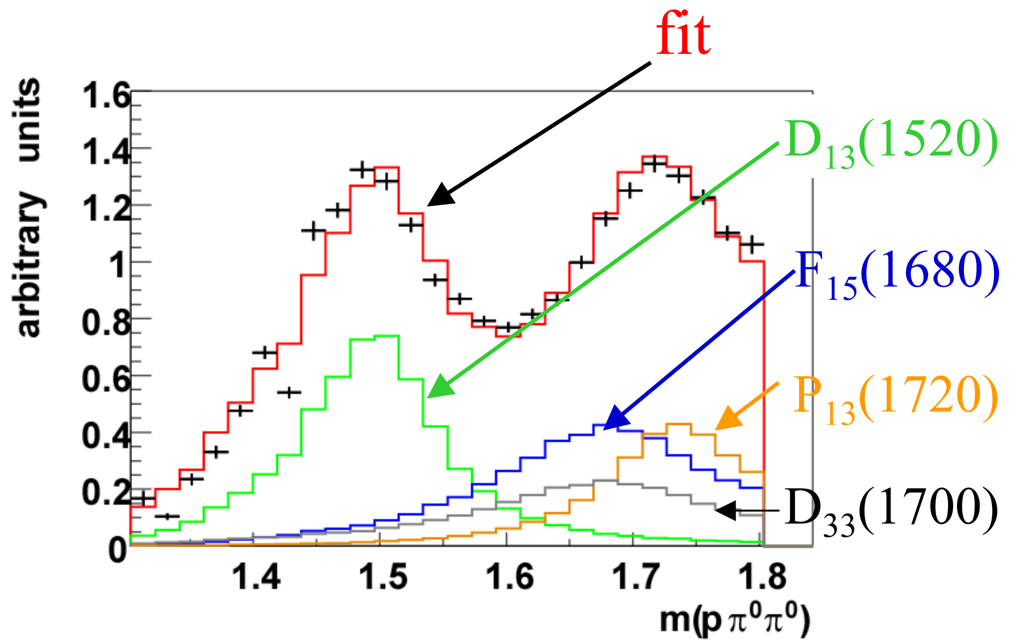
Simultaneous fit to both data sets (U. Thoma)

- 5 independent variables at each W for each reaction
- Keep track of isospin
- Fit Breit-Wigner shapes for various N*
- Results very preliminary

One of many distributions



$\pi^0\pi^0$ Total cross section



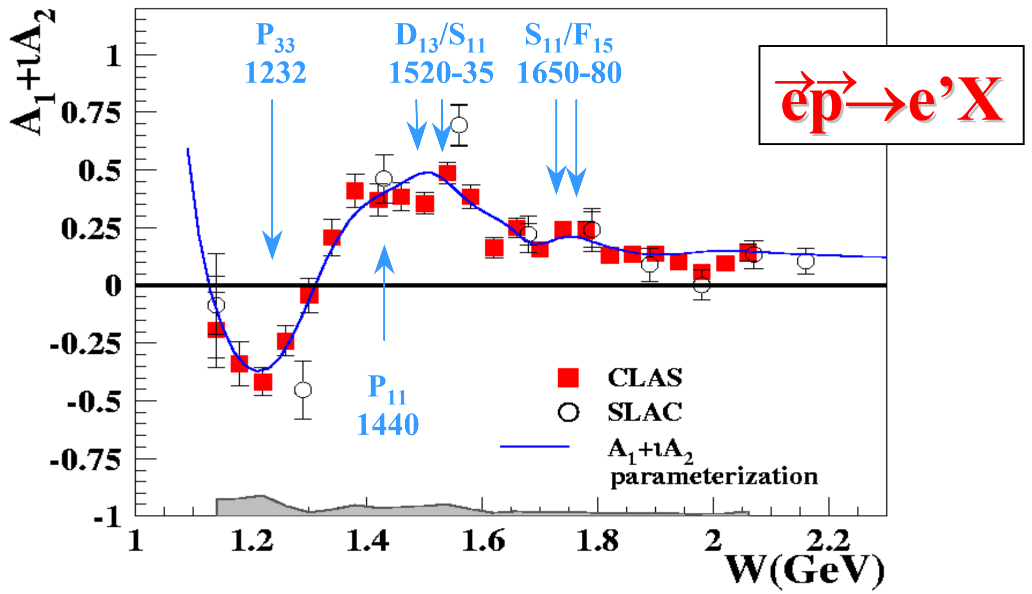
Spin Observables and Resonance Structure

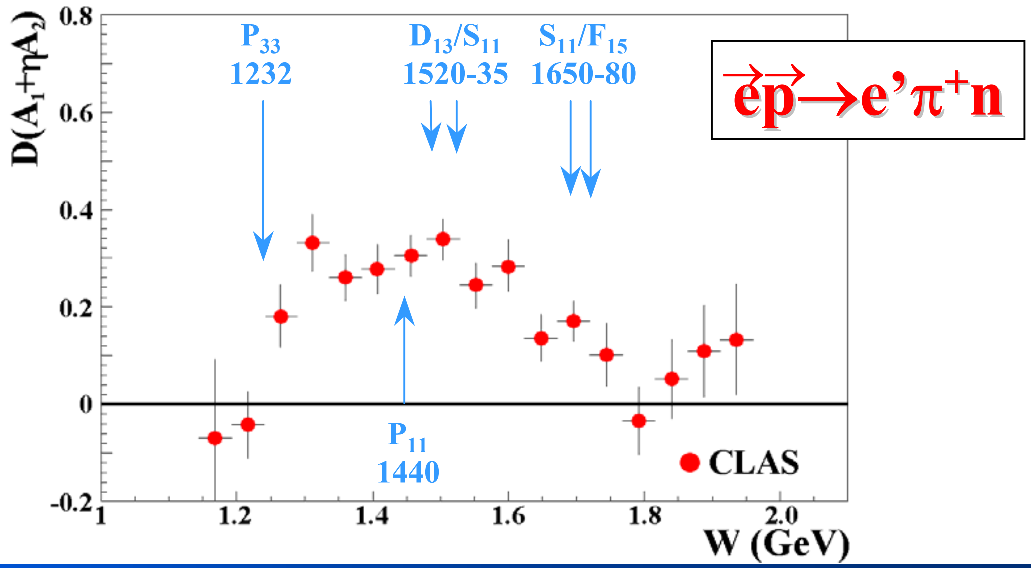
Spin observables are a fundamental tool for the study of baryon resonances

Full extraction of the helicity amplitudes require both cross section and polarization observables

Double spin asymmetry both in inclusive and exclusive channels reflects the helicity structure of resonances

Published (PRL)





$Q^2 \sim 0.5\ GeV^2/c^2$

Other work in progress

- ω electroproduction
- Production of ρ, ω, K, η' with linearly polarized γ's
- Polarization in decays of ρ, ω
- Production of π^0, η, π^+, K with polarized ep collisions

So, you say you're on the way to having ~1 Million data points! How do you get physics results out of all of that stuff?

2 paths to success

Data- cross sections,
polarization observables

SAID
(GWU)

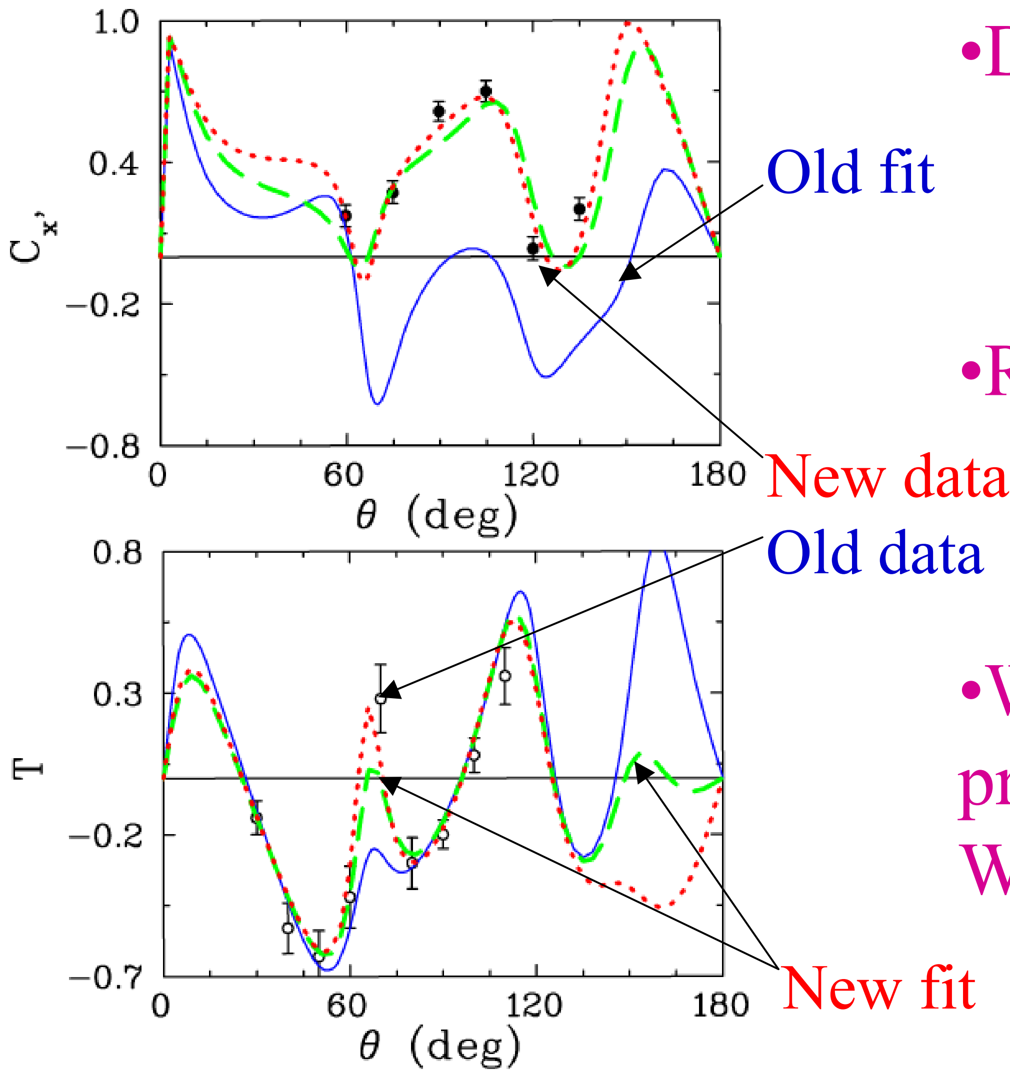
Breit-Wigner

Partial wave amplitudes (PWA)
(complex, specific J^{π})

Multichannel
analyses

PDG- mass, width, decay widths,
photon coupling amplitudes

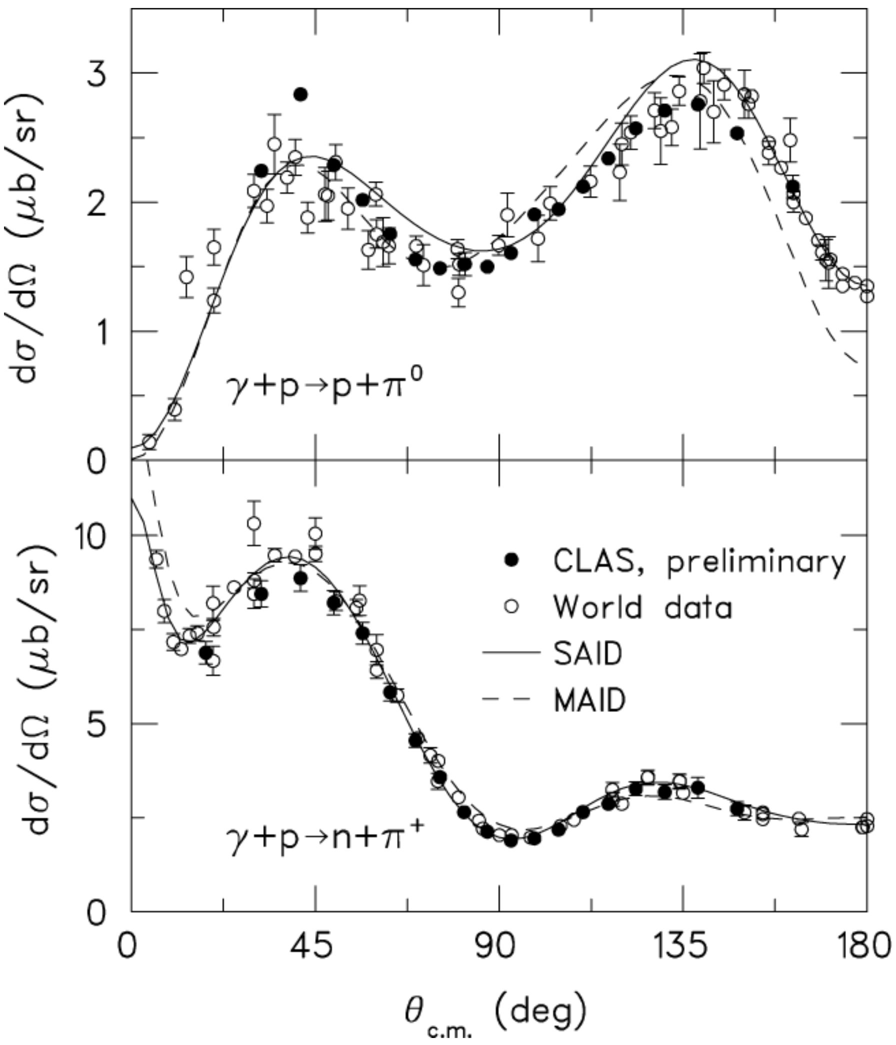
GWU (VPI) Partial Wave Analysis



- Decades-long history
  - ➢Keep track of data
  - ➢Do PWA fits
  - ➢Provide results to all!
- Reactions (past)
  - ➢ $\pi N \rightarrow \pi N$
  - ➢$NN \rightarrow NN$
  - ➢$\gamma N \rightarrow \pi N$
- Wijesooriya et al. (Hall A) presents new challenge at W=2.11 GeV
  - ➢Large impact on amplitudes
  - ➢Impact on N*'s minimal

Ongoing, future projects

- Reactions, present and future, tied strongly to JLab
  - $\gamma N \to \eta N$
  - $eN \to e'\pi N$
  - $\gamma N \to \Lambda K$
- CLAS π photoproduction preliminary results at W=1.65 GeV good match to recent SAID with renormalization.



Summary

- Many interesting physics issues
- The awaited flood of data is here!
- Main results (2-body final states)
  - E2/M1, C2/M1 at broad range of Q^2
  - First estimates of $A_{1/2}$ for $S_{11}(1535)$
  - Apparently excess strength in P wave W~1.7 GeV (η and $\pi^+\pi^-$ electroproduction)
- Very promising progress in $\pi\pi$ production
- Extensive theoretical analysis in progress