Highlights on hadron physics at CLAS

K. Hicks (Ohio U.)

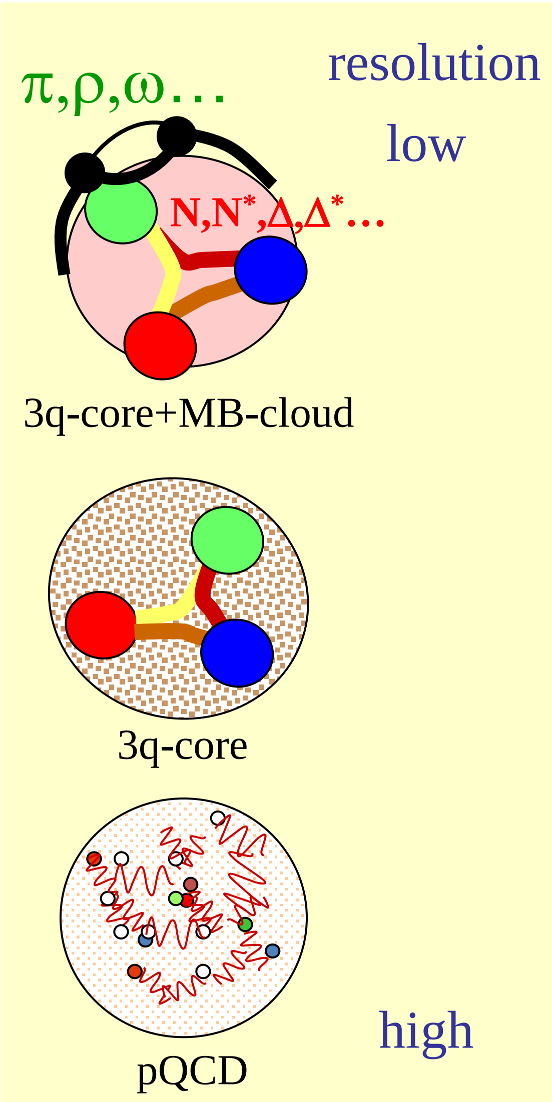
Hadron 2011 Conference

June 16, 2011

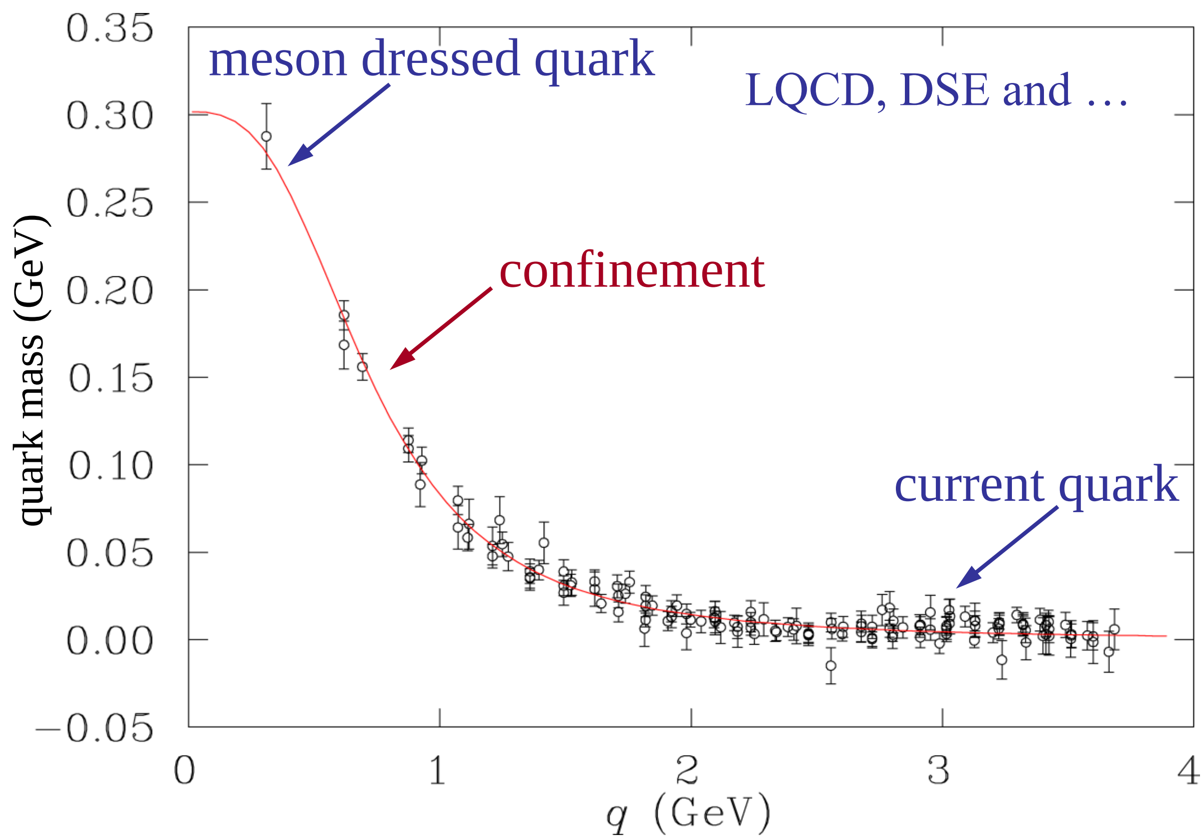
Outline

- Meson-Baryon Cloud (MBC) Effects
  - New results on baryon photocouplings
  - Need for coupled-channels analysis
- Spectroscopy of baryons and mesons
  - New and future analysis of KΛ
  - New data: 2π, K*Y, KY*, etc.
- Future upgrade to CLAS12
  - Probe transition from MBC to quark core.

Hadron Structure with Electromagnetic Probes

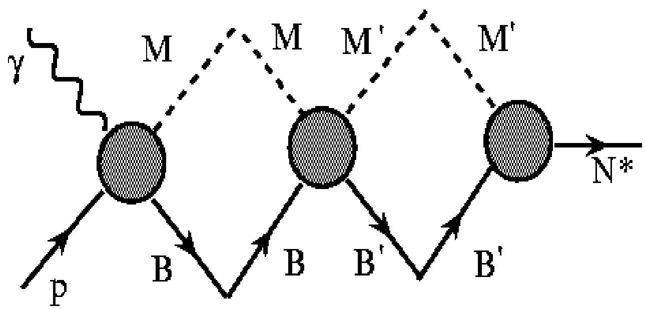


Quark mass extrapolated to the chiral limit, where *q* is the momentum variable of the tree-level quark propagator (curve=DSE, data=LQCD).



NΔ Transition Form Factor (G_M) from EBAC analysis

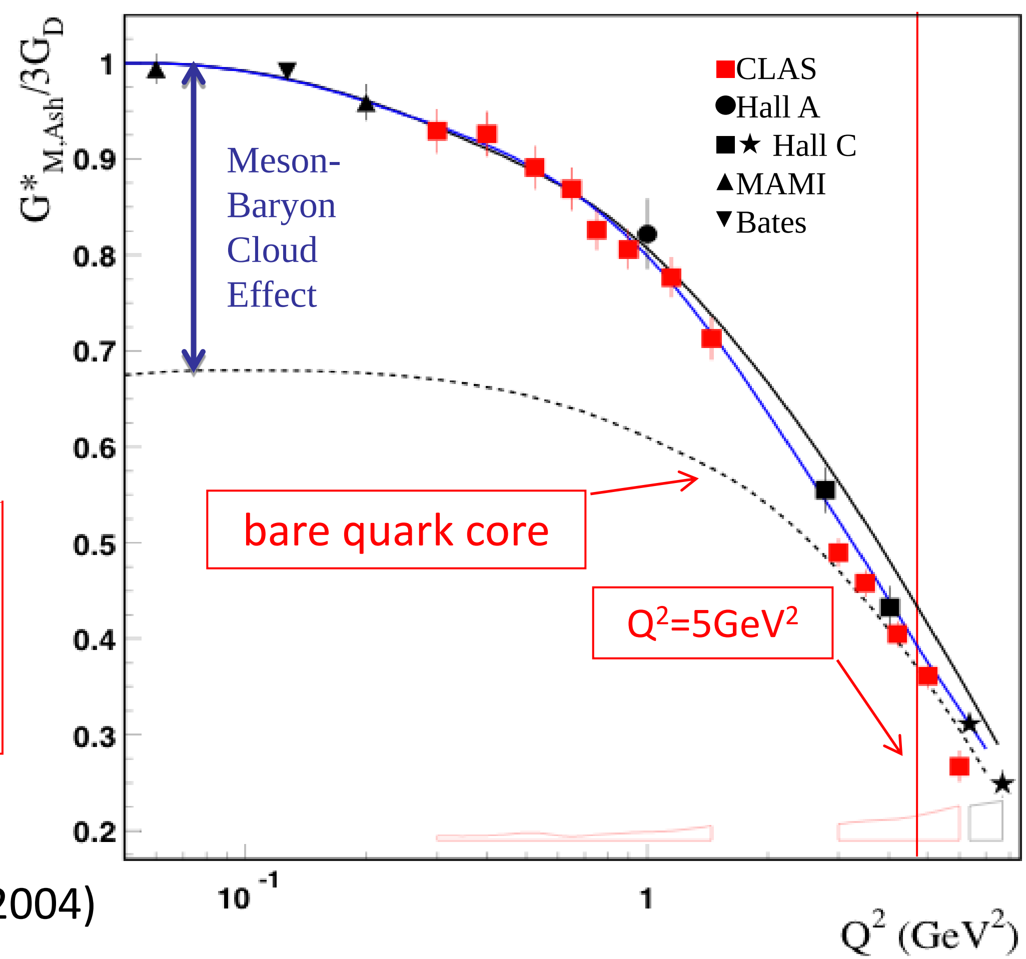
- One third of G^*_M at low Q^2 is due to contributions from meson–baryon (MB) dressing:



In the relativistic QM framework, the bare-core contribution is well described by the three-quark component of the wavefunction.

B.Julia-Diaz *et al.*, PRC 69, 035212 (2004)

The area of Q^2<7.0 GeV^2 is far from pQCD domain



Dynamical coupled-channels model of EBAC

For details see Matsuyama, Sato, Lee, Phys. Rep. 439,193 (2007)

- ✓ Partial wave (LSJ) amplitude of a → b reaction:

$$T^{(LSJ)}_{a,b}(p_a, p_b; E) = V^{(LSJ)}_{a,b}(p_a, p_b) + \underline{\sum_c} \int_0^\infty q^2 dq V^{(LSJ)}_{a,c}(p_a, q) G_c(q; E) T^{(LSJ)}_{c,b}(q, p_b; E)$$

coupled-channels effect

- ✓ Reaction channels:

$$a, b, c = (\gamma^{(*)}N,\ \pi N,\ \eta N,\ \underbrace{\pi\Delta,\ \sigma N,\ \rho N,}_{\pi\pi N}\ K\Lambda,\ K\Sigma, \cdots)$$

- ✓ Transition potentials:

$$V_{a,b} = v_{a,b} + \sum_{N^*} \frac{\Gamma^\dagger_{N^*,a}\Gamma_{N^*,b}}{E - M_{N^*}}$$

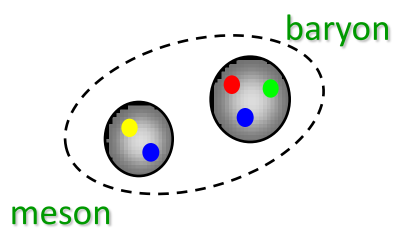
Meson-exchange potentials (Derived from Lagrangians)

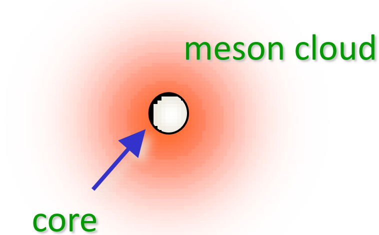
bare N* states

Dynamical coupled-channels model of EBAC

For details see Matsuyama, Sato, Lee, Phys. Rep. 439,193 (2007)

Physical N*s will be a "mixture" of the two pictures:





$$|N^*\rangle = |MB\rangle$$

$$|N^*\rangle = |qqq\rangle + |\mathrm{m.c.}\rangle$$

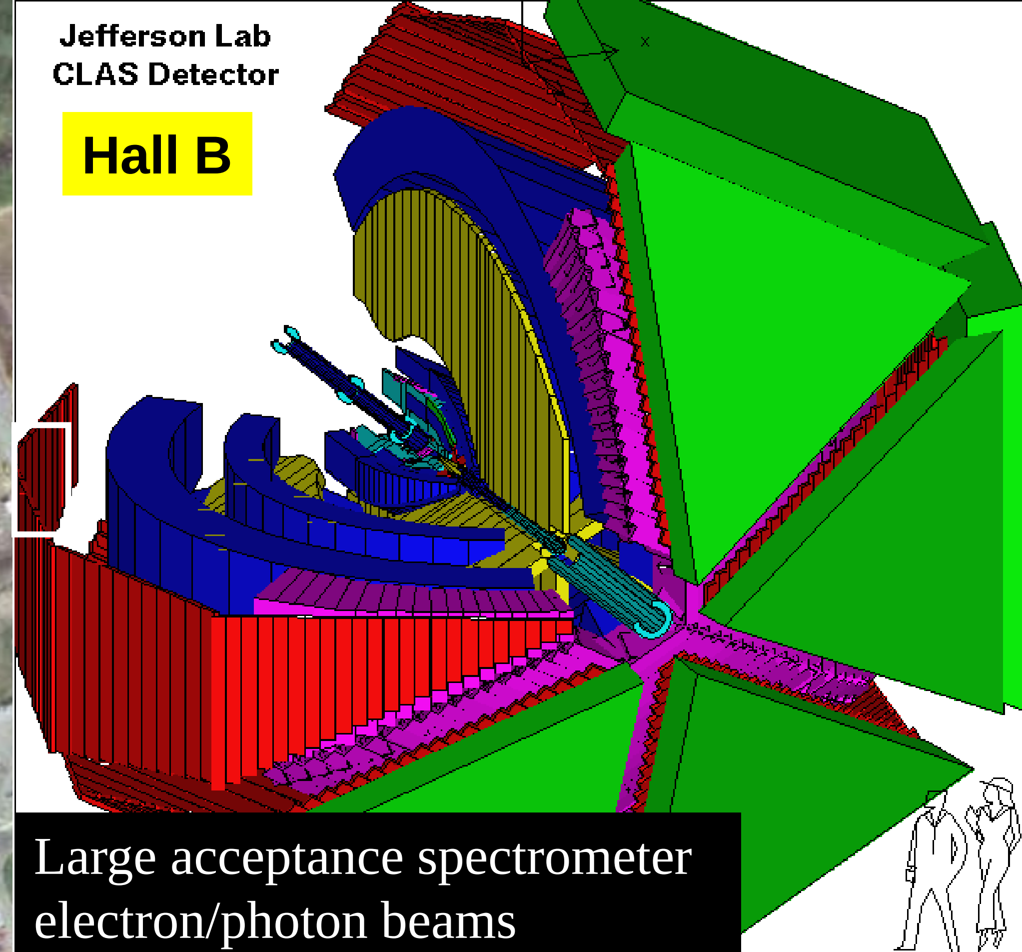
Transition potentials:

$$V_{a,b} = v_{a,b} + \sum_{N^*} \frac{\Gamma^\dagger_{N^*,a} \Gamma_{N^*,b}}{E - M_{N^*}}$$

exchange potentials of ground state mesons and baryons

bare N* states

Jefferson Lab Today



Large acceptance spectrometer
electron/photon beams

Radiative Decay of Strange Baryons

General Motivation

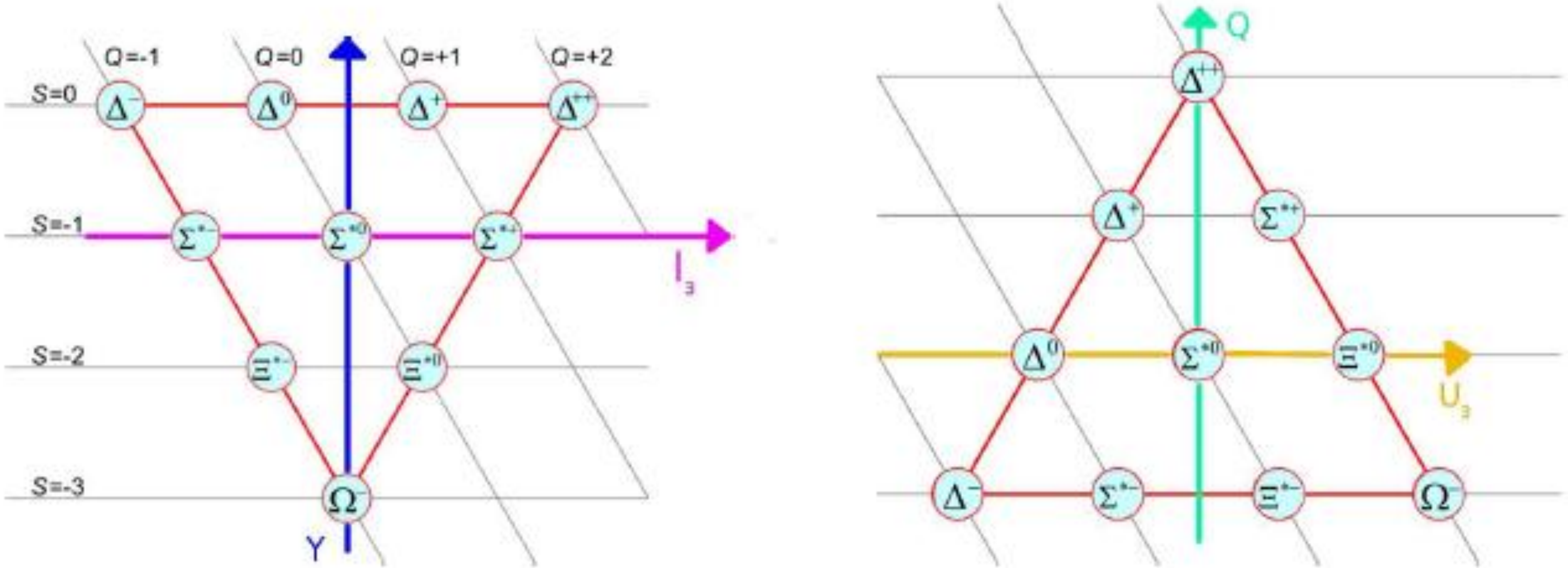
- Electromagnetic interactions are the cleanest way to access information on wavefunctions.
  - For strange baryons, the EM coupling can only be studied by measuring the decay.
- SU(6) wavefunctions provide a zeroth-order prediction for M1 transitions.
  - SU(6) symmetry provides a link between N* and Y* radiative decays: constrain SU(6) symmetries.

U-spin: connects Δ and Σ^* decays

- SU(3) has three equal symmetries:
  - I-spin: exchange of u and d quarks
  - U-spin: exchange of d and s quarks
  - V-spin: exchange of u and s quarks
- With respect to known symmetries:
  - I-spin conserves chiral symmetry (mass)
  - U-spin conserves EM symmetry (charge)
  - V-spin conserves neither chiral nor EM symmetry

Group structure of U-spin:

$$SU(3)_f \supset SU(2)_I \times U(1)_Y \supseteq SU(2)_U \times U(1)_Q$$



How is this useful?

It is possible using the U-spin SU(3) multiplet representation to obtain a prediction for the ratio of the $\Delta^0 \to n\gamma$ partial width to the $\Sigma^{*0} \to \Lambda\gamma$ partial width.

$$\begin{aligned} \langle \Delta^0 | n\gamma \rangle &= \langle 1 -1 | 1 -1\ 0\ \ 0 \rangle = 1 \\ \langle \Sigma^{*0} | \Lambda\gamma \rangle &= -\frac{\sqrt{3}}{2} \langle 1\ \ 0 | 1\ \ 0\ 0\ \ 0 \rangle = -\frac{\sqrt{3}}{2}, \end{aligned}$$

leading to a ratio;

$$\frac{|\langle \Delta^0 | n\gamma \rangle|^2}{|\langle \Sigma^{*0} | \Lambda\gamma \rangle|^2} = \frac{4}{3},$$

including phase space factors (PRD 28 (1983) 1125)

$$\frac{\Gamma(\Delta^0 \to n\gamma)}{\Gamma(\Sigma^{*0} \to \Lambda\gamma)} = \left(\frac{M_n}{M_\Delta}\right) \left(\frac{M_\Lambda}{M_{\Sigma^{*0}}}\right)^{-1} \left(\frac{q_n}{q_\Lambda}\right)^3 \frac{4}{3} = 1.56.$$

CLAS result

~10% uncert.

The final calculated ratio with all uncertainties is

$$R^{\Lambda\gamma}_{\Lambda\pi} = \frac{\Gamma[\Sigma^0(1385) \rightarrow \Lambda\gamma]}{\Gamma[\Sigma^0(1385) \rightarrow \Lambda\pi^0]} = 1.42 \pm 0.12(stat)^{+0.11}_{-0.07}(sys)$$

The electromagnetic decay partial width using the full width $\Gamma = 36 \pm 5$ MeV,

$$\Gamma = 445 \pm 73(stat)^{+71}_{-66}(sys)\text{keV}$$

compared to the previous experimental result by Taylor,

$$\Gamma = 479 \pm 120(stat)^{+81}_{-100}(sys)\text{keV}.$$

PhD thesis, Dustin Keller

Predictions from other models

Model	$\Delta \to N\gamma$	$\Sigma \to \Lambda\gamma$	$\Sigma^{*0} \to \Lambda\gamma$	$\Sigma^{*+} \to \Sigma^{+}\gamma$
NRQM[17, 23, 26]	360	8.6	273	104
RCQM[24]		4.1	267	
χCQM[25]	350		265	105
MIT Bag[26]		4.6	152	117
Soliton[27]			243	91
Skyrme[28, 29]	309-326		157-209	47
Algebraic model[30]	341.5	8.6	221.3	140.7
Experiment:	**660 +/- 60**		**479 +/- 73**	

Interpretation

- Meson-Baryon Cloud effects are substantial for the Y* resonances also.
  - U-spin relation works better than QM, etc.
- We can now make a prediction for Σ^{*+} decay.
  - The Wigner-Eckart theorem requires that the branching ratios $\Delta^+ \rightarrow p\gamma$ and $\Delta^0 \rightarrow n\gamma$ are equal.
  - U-spin predicts a ratio:

$$\frac{\Gamma(\Delta^+ \to p\gamma)}{\Gamma(\Sigma^{*+} \to \Sigma^+\gamma)} = \left(\frac{M_p}{M_\Delta}\right)\left(\frac{M_{\Sigma^+}}{M_{\Sigma^{*+}}}\right)^{-1}\left(\frac{q_p}{q_{\Sigma^+}}\right)^3 = 2.638.$$

New CLAS result

The final results for the ratio of the $\Sigma^{*+} \to \Sigma^+\gamma$ to $\Sigma^{*+} \to \Sigma^+\pi^0$ with systematic uncertainties is

$$R^{\Sigma^{*+}\to\Sigma^+\gamma}_{\Sigma^{*+}\to\Sigma^+\pi^0} = \frac{n_\gamma A_\pi(\Sigma\pi) - n_\pi A_\gamma(\Sigma\pi)}{n_\pi A_\gamma(\Sigma\gamma) - n_\gamma A_\pi(\Sigma\gamma)} = 11.95 \pm 2.21(stat)^{+0.52}_{-1.21}(sys)\%, \quad (27)$$

Preliminary!

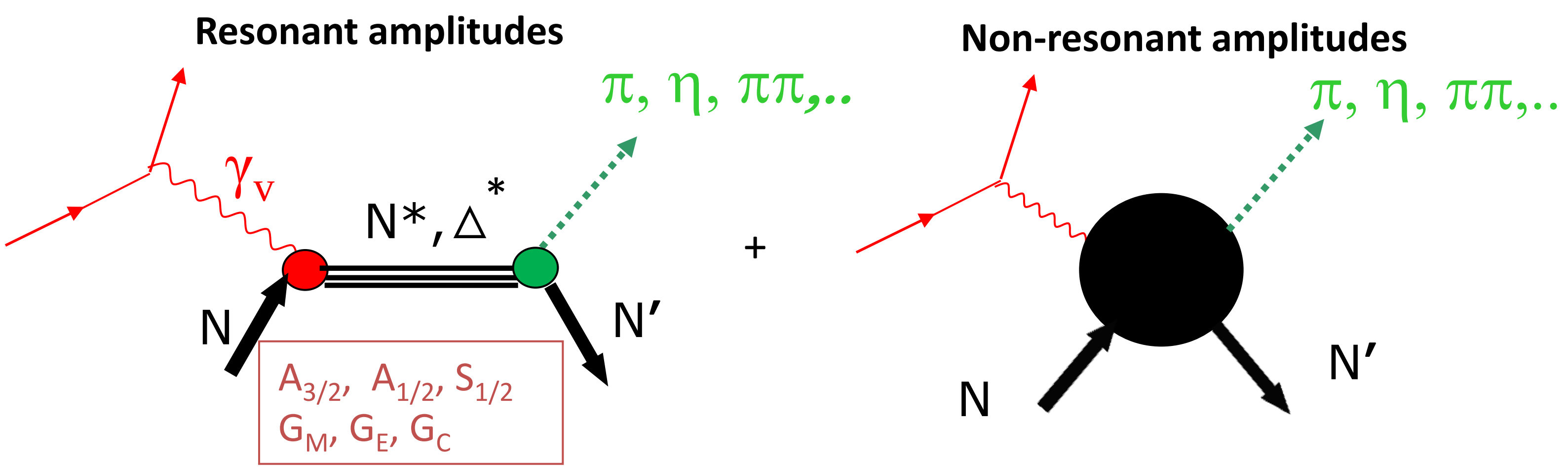
$$\Gamma_{\Sigma^{*+}\to\Sigma^+\gamma} = R^{\Sigma^{*+}\to\Sigma^+\gamma}_{\Sigma^{*+}\to\Sigma^+\pi^0} R(\Sigma^* \to \Sigma^+\pi^0)\Gamma_{Full} = 250 \pm 56.9(stat)^{+34.3}_{-41.2}(sys)\text{keV}.$$

This implies that the U-spin prediction for the partial width of the electromagnetic decay using the width of the $\Delta^+ \to p\gamma$ decay is,

$$2.638^{-1} \times \Gamma(\Delta^+ \to p\gamma) = 2.638^{-1} \times 660 \pm 60 = 250 \pm 23\text{keV}. \qquad (29)$$

The MBC in electroproduction

N* electrocouplings from analyses of exclusive channels



- **Separation of resonant/non-resonant contributions**
- **N* 's can couple to various exclusive channels with entirely different non-resonant amplitudes, while their electrocouplings should remain the same.**
- **Consistent results from the analyses of Nπ and Nππ electroproduction channels show that model uncertainties are under control.**

See the afternoon talk today by Victor Mokeev.

$\gamma_v NN^*$ electrocouplings from $N\pi/N\pi\pi$ production

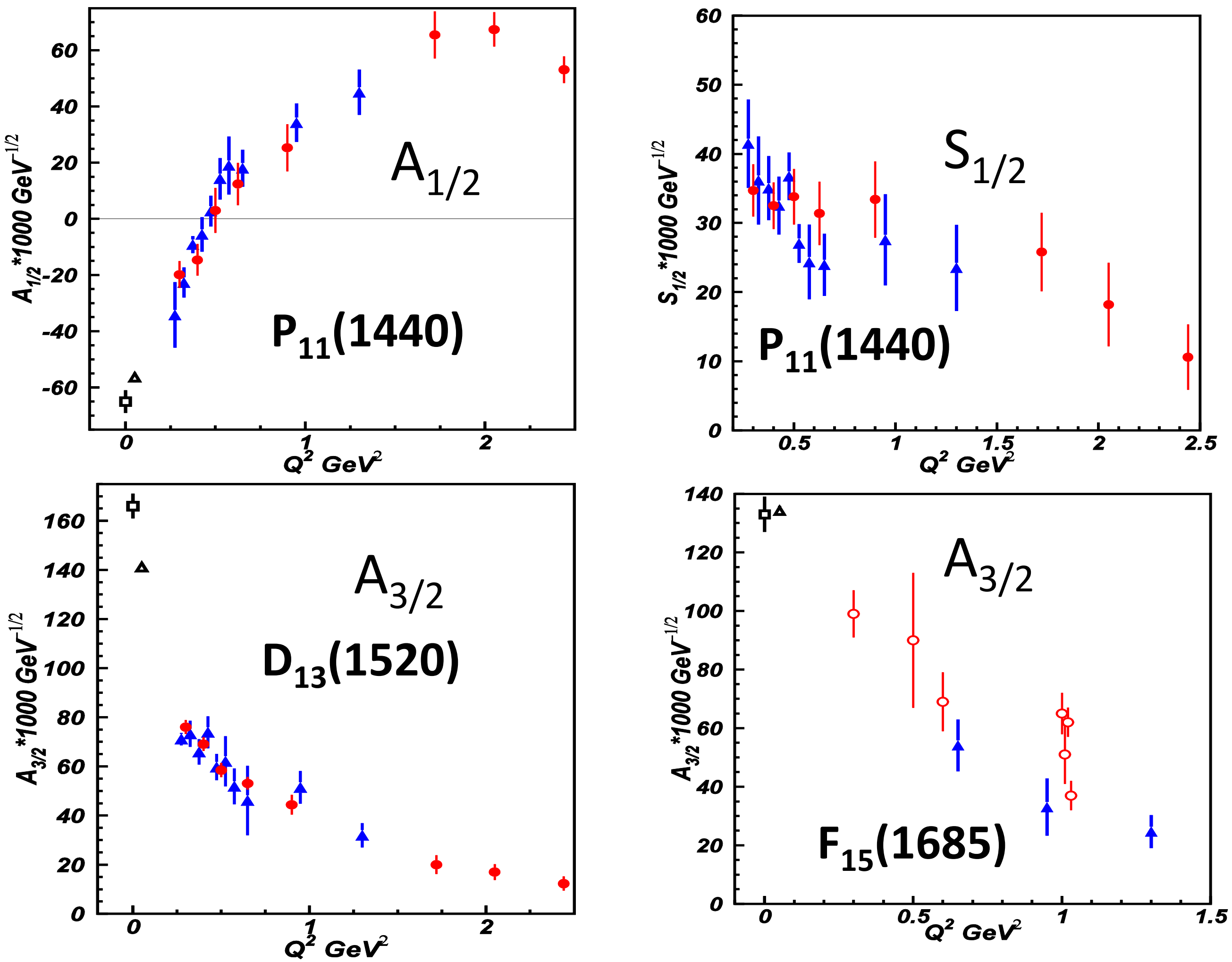
$N\pi\pi$ CLAS (New!) preliminary.

$N\pi$ CLAS
I. Aznauryan,V. Burkert, et al., PRC 80,055203 (2009).

$N\pi$ world
V. Burkert, et al., PRC 67,035204 (2003).

$N\pi$ Q^2=0, PDG.

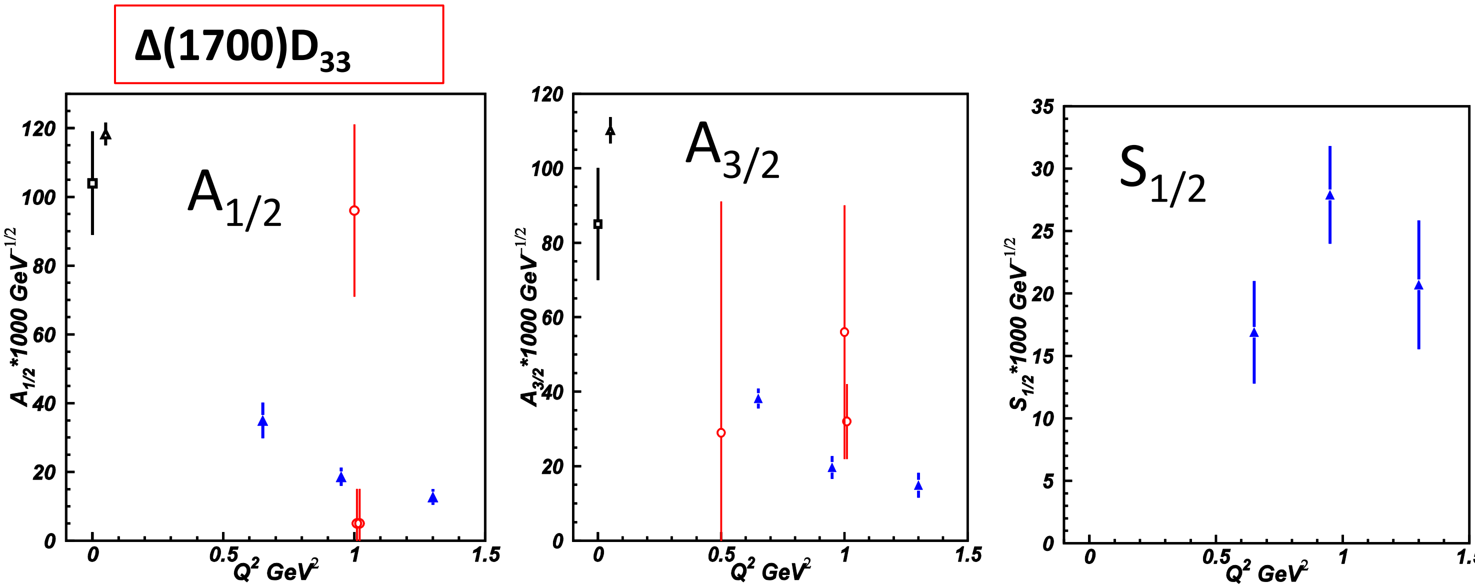
$N\pi$ Q^2=0, CLAS
M. Dugger, et al., PRC 79,065206 (2009).



<u>Good agreement</u> between the <u>*$N\pi$ and $N\pi\pi$*</u> channels.

N^* electrocouplings are <u>measurable</u> and <u>model independent.</u>

High lying resonance electrocouplings from $\pi^+\pi^-p$



Nππ CLAS preliminary.

Nπ world V.D.Burkert, et al., PRC 67, 035204 (2003).

Nπ Q^2=0, PDG.

Nπ Q^2=0, CLAS M.Dugger, et al., PRC 79,065206 (2009).

Electrocouplings of S_{31}(1620), S_{11}(1650), F_{35}(1685), D_{33}(1700) ,and P_{13}(1720) states were obtained for the first time from $\pi^+\pi^-p$ electroproduction data .

Mystery of P_{11}(1440) structure is solved

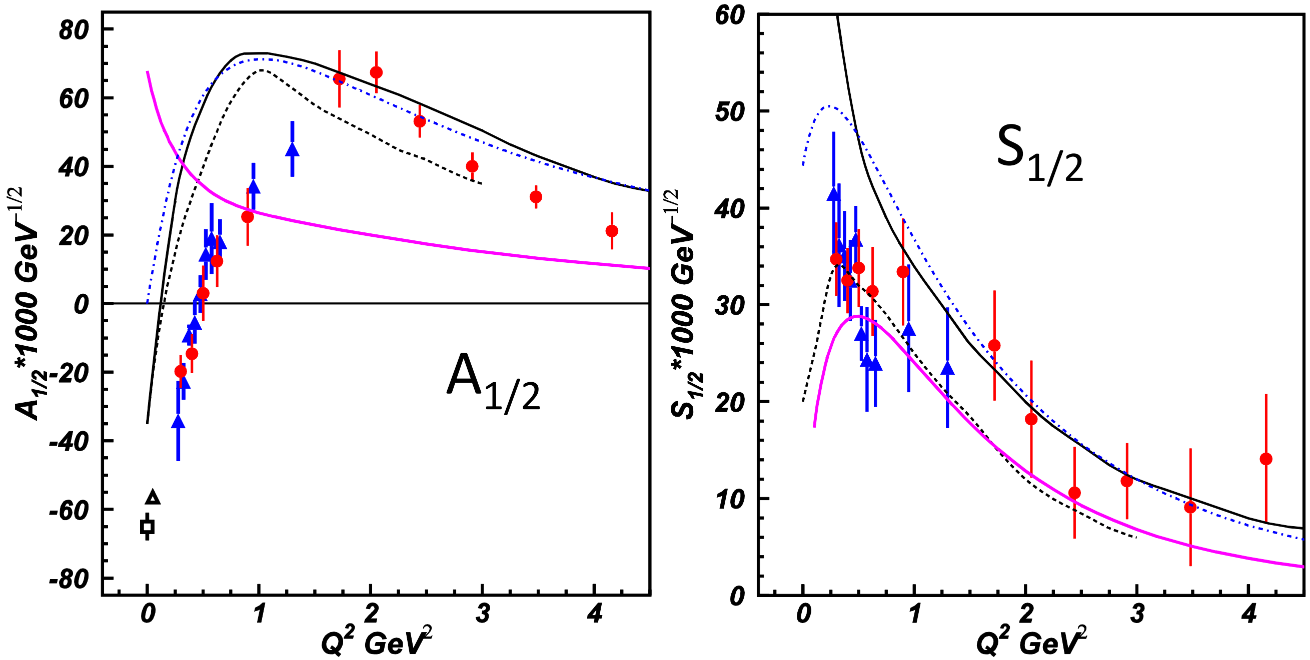
Quark models:

I. Aznauryan LC

S. Capstick LC

Relativistic covariant approach by Ramalho & Gross

EBAC-DCC MB dressing (absolute values).



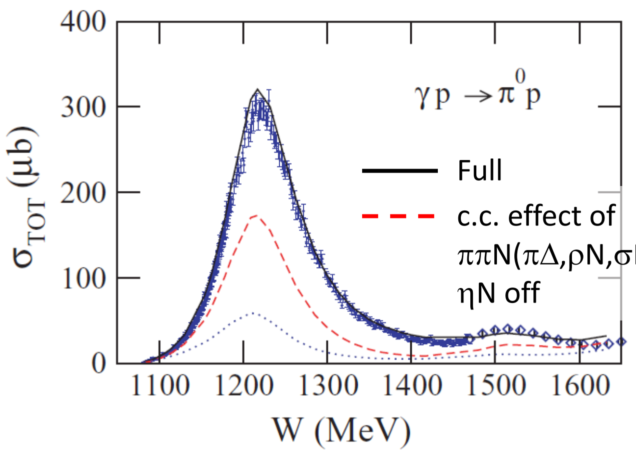
The electrocouplings are consistent with *$\underline{P_{11}(1440)}$* structure as combination:

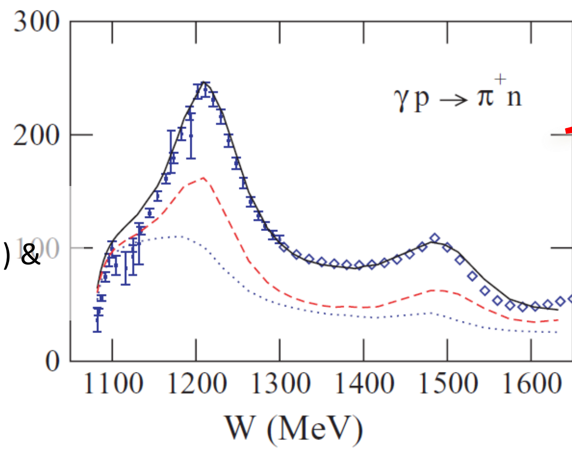
a) quark core as a first *radial excitation of the nucleon, and*

***b) meson-baryon dressing*.**

MBC effects could explain the data at low Q^2.

Coupled-channels effect in various reactions





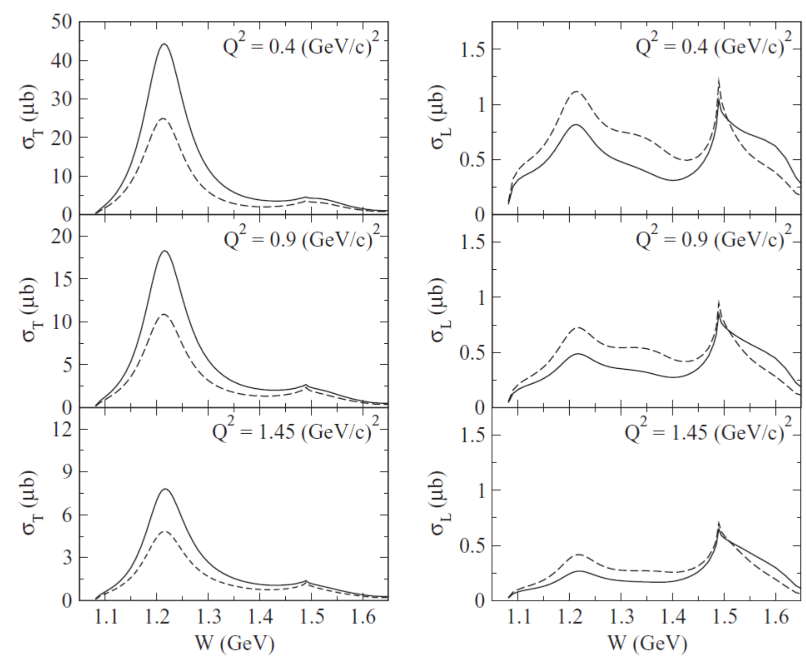
Pion photoproductions

Pion electroproductions

Full

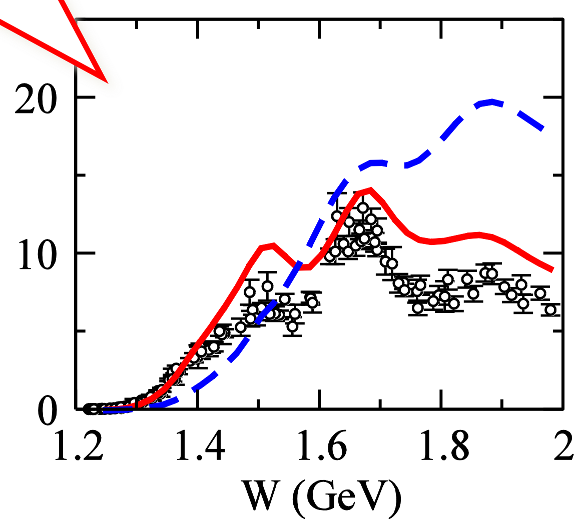
c.c. effect of $\pi\pi N(\pi\Delta,\rho N,\sigma N)$ & ηN off

$p(e, e'\pi^0)p$



Double pion productions

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



Full

c.c effect off

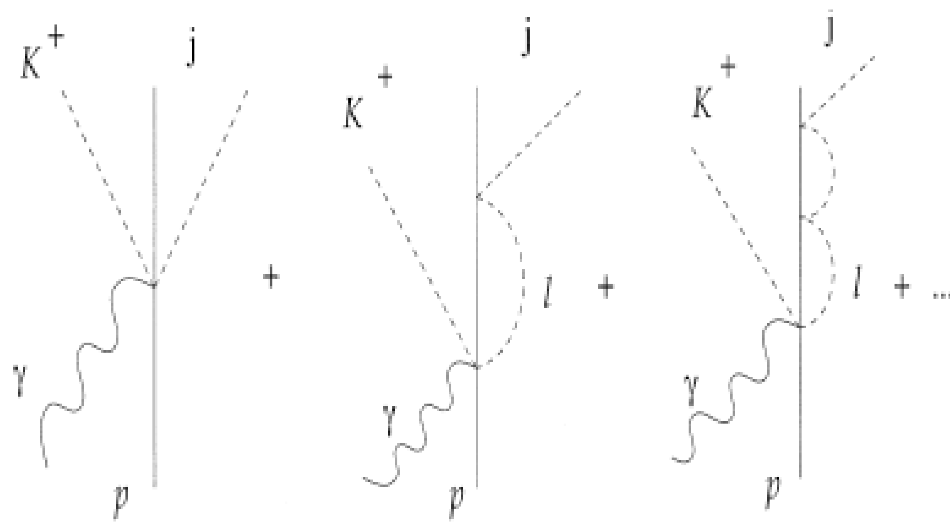
EBAC

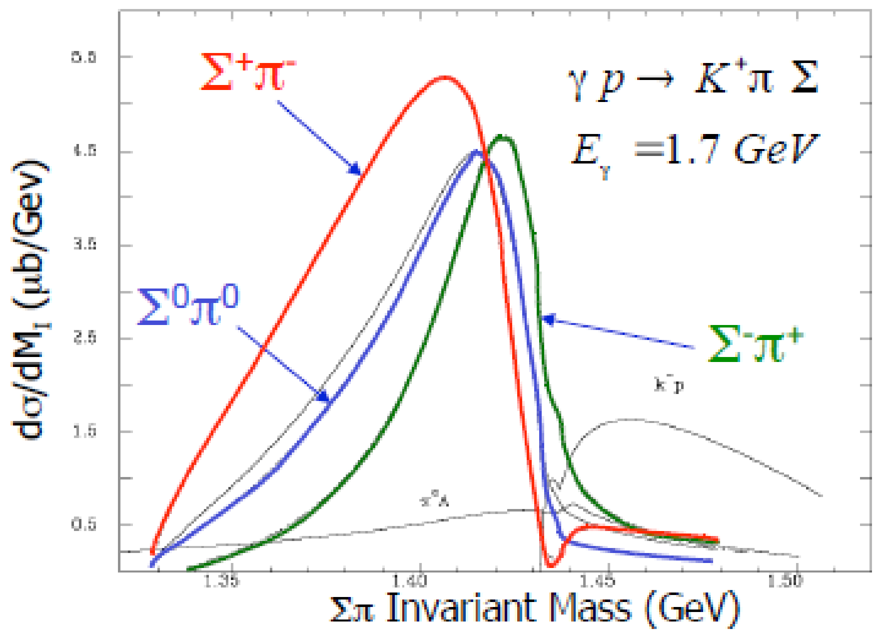
Lineshape of the Λ(1405)

Chiral Unitary Coupled Channel Approach

dynamically generate $\Lambda(1405)$
based on chiral unitary model

⇓





J. C. Nacher et al., Phys. Lett. B455, 55 (1999)

Difference in Lineshape

$$\frac{d\sigma(\pi^+\Sigma^-)}{dM_I} \propto \frac{1}{2}\left|T^{(1)}\right|^2 + \frac{1}{3}\left|T^{(0)}\right|^2 + \frac{2}{\sqrt{6}}\mathrm{Re}\left(T^{(0)}T^{(1)*}\right) + O\left(T^{(2)}\right)$$

$$\frac{d\sigma(\pi^-\Sigma^+)}{dM_I} \propto \frac{1}{2}\left|T^{(1)}\right|^2 + \frac{1}{3}\left|T^{(0)}\right|^2 - \frac{2}{\sqrt{6}}\mathrm{Re}\left(T^{(0)}T^{(1)*}\right) + O\left(T^{(2)}\right)$$

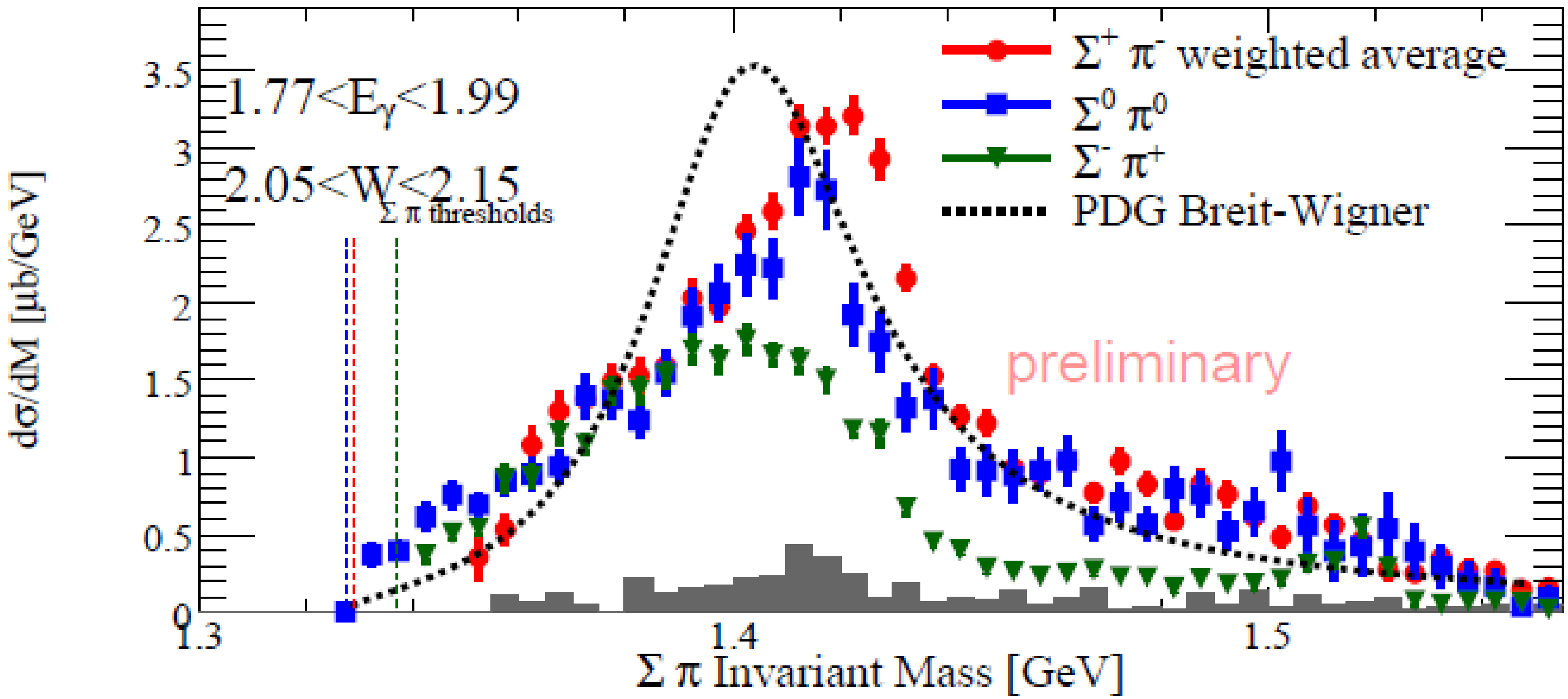
$$\frac{d\sigma(\pi^0\Sigma^0)}{dM_I} \propto \frac{1}{3}\left|T^{(0)}\right|^2 + O\left(T^{(2)}\right)$$

J. C. Nacher et al., Nucl. Phys. B455, 55

- Difference in lineshapes is due to interference of isospin terms in calculation ($T^{(I)}$ represents amplitude of isospin I term)
- Distortion of the lineshape is connected to underlying QCD amplitudes that generate the $\Lambda(1405)$
- This analysis will measure **all three** $\Sigma\pi$ channels

K. Moriya & R. Schumacher
(CMU/IU) (CMU)

Results of Lineshape



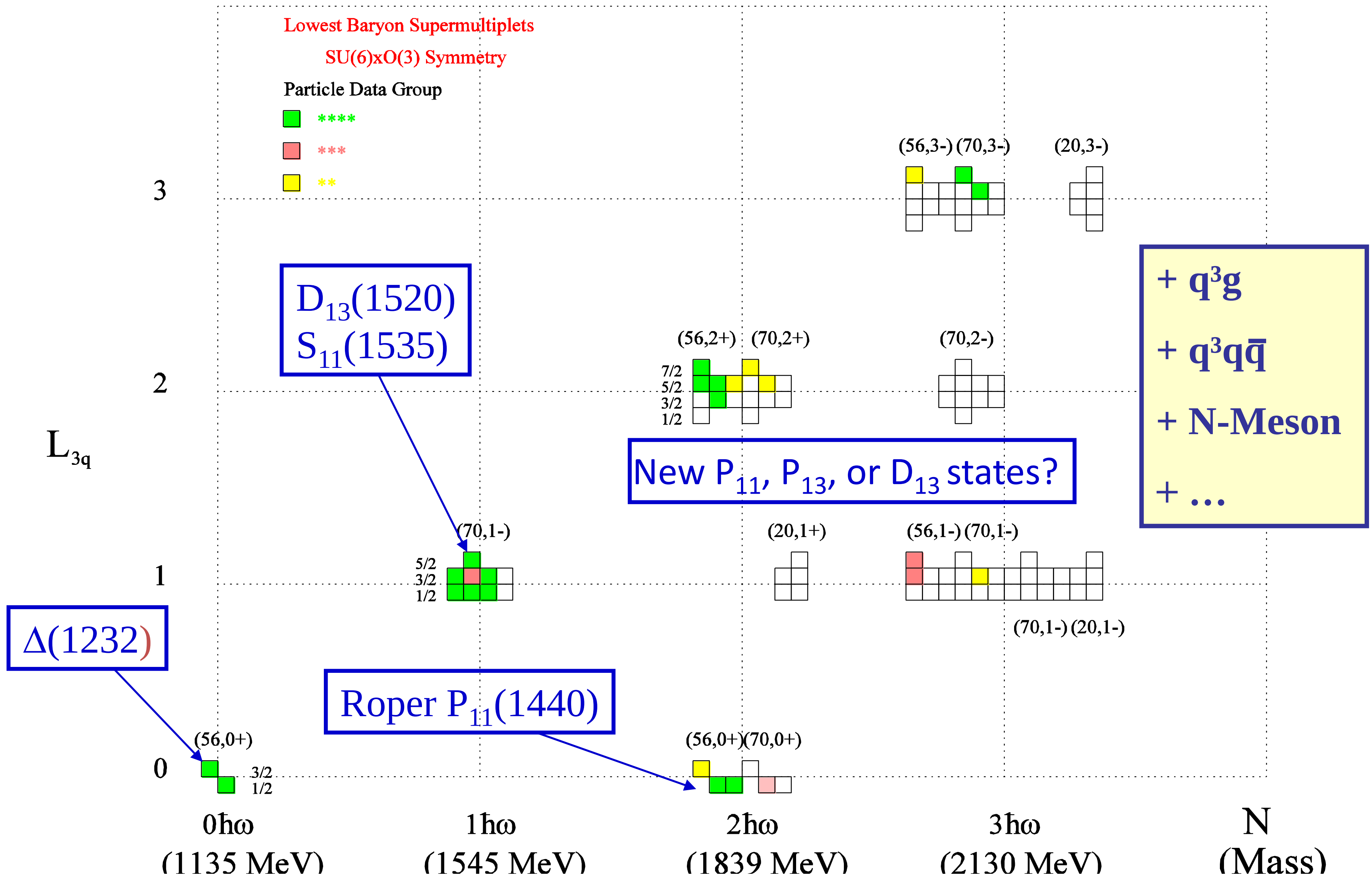
- lineshapes do appear different for each $\Sigma\pi$ decay mode
- $\Sigma^+\pi^-$ decay mode has peak at highest mass, narrow than $\Sigma^-\pi^+$
- lineshapes are summed over acceptance region of CLAS
- difference is less prominent at higher energies

Interpretation

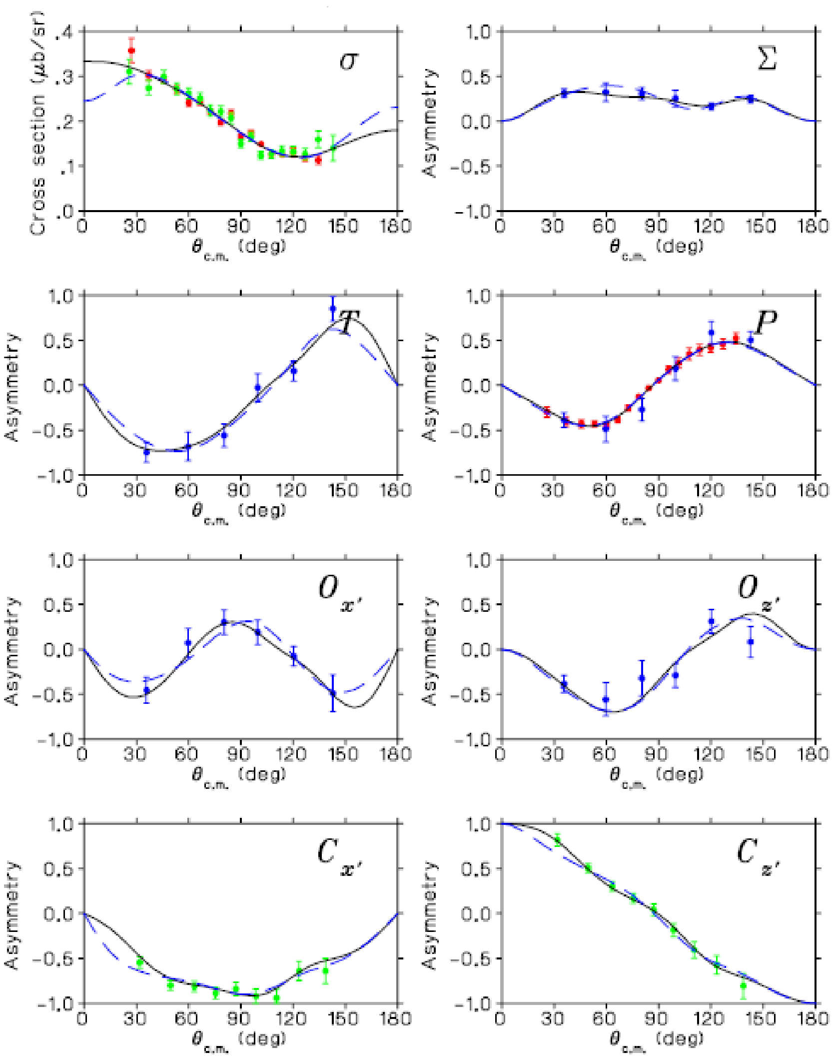
- For a baryon resonance with a single pole, isospin symmetry → $\Sigma^+\pi^- = \Sigma^-\pi^+$.
- The data favor a dynamically-generated resonance (two-pole solution $\Sigma\pi$ and NK).
  - Evidence of MB coupled-channels effects?

Spectroscopy with KY, K*Y and KY*

Quark Model Classification of N*



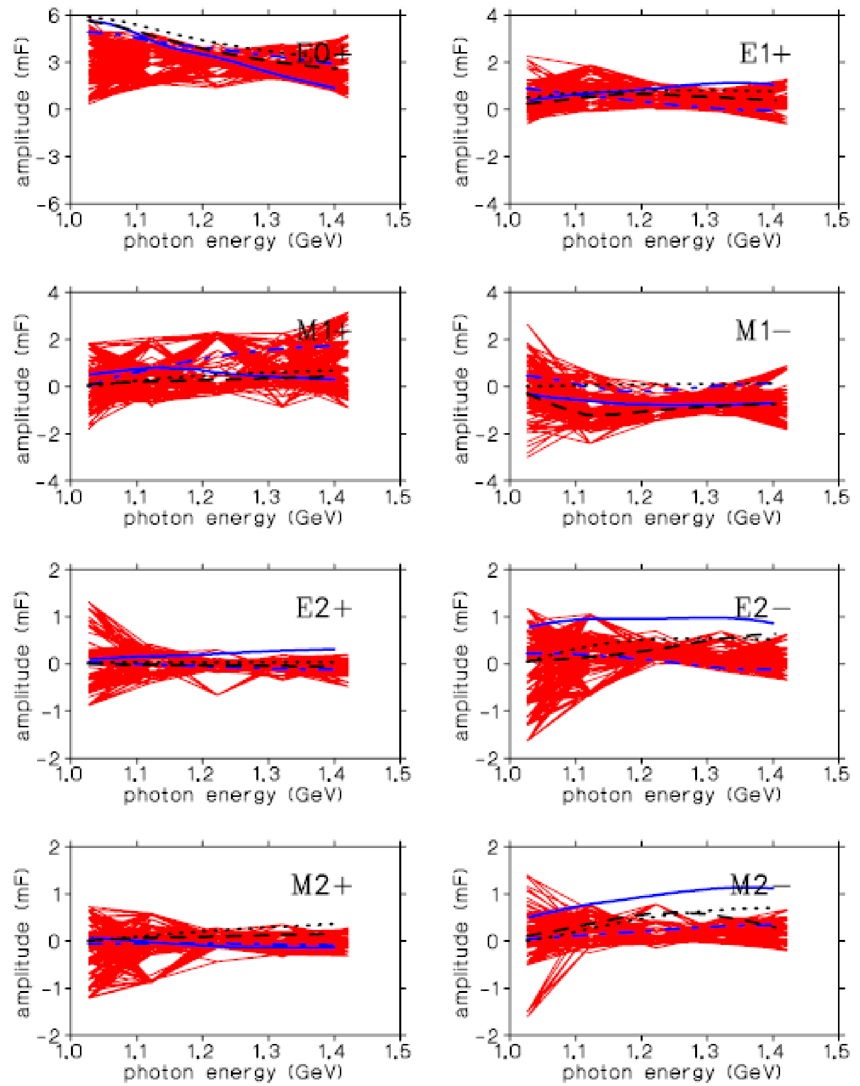
Amplitude Uncertainty in $\vec{\gamma} p \rightarrow K^+ \vec{\Lambda}$



CLAS (g1c, g11a) and GRAAL

σ, $C_{x'}$, $C_{z'}$, σ , P and Σ, T, P, $O_{x'}$, $O_{z'}$

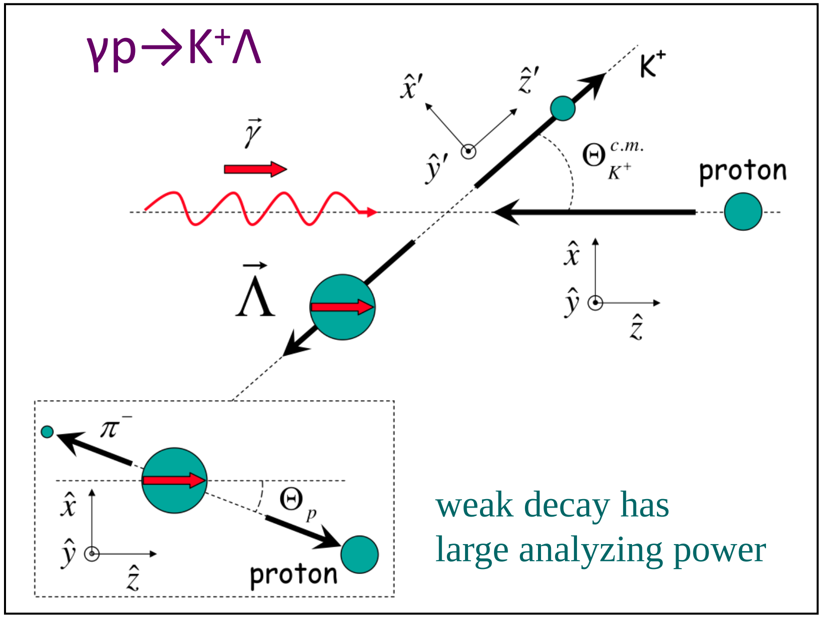
A. Sandorfi et al., J. Phys. G 38 (2011) 053001



Real parts of the PWA multipoles

BoGa (dot-dashed), MAID (dashed), SAID (dotted), JSLT (solid)

FROST/HD $\vec{\gamma}\vec{N} \rightarrow \pi N, \eta N, K\vec{\Lambda}, K\vec{\Sigma}, N\pi\pi$

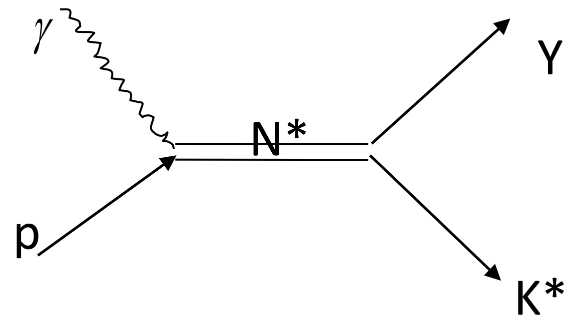


Discussed Monday, talk by V. Cede

- Process is described by 4 complex, parity conserving amplitudes
- 8 well-chosen measurements are needed to determine amplitude
- For hyperon finals state 16 observables will be measured in CLAS ➠ large redundancy in determining the photo-production amplitudes ➠ allows many cross checks
- 8 observables measured in reactions without recoil polarization

Photon 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	σ_0		T			P		$T_{x'}$		$L_{x'}$		Σ		$T_{z'}$		$L_{z'}$
linearly P_γ	Σ	H	P	G	$O_{x'}$	T	$O_{z'}$	$L_{z'}$	$C_{z'}$	$T_{z'}$	E		F	$L_{x'}$	$C_{x'}$	$T_{x'}$
circular P_γ		F		E	$C_{x'}$		$C_{z'}$		$O_{z'}$		G		H		$O_{x'}$	

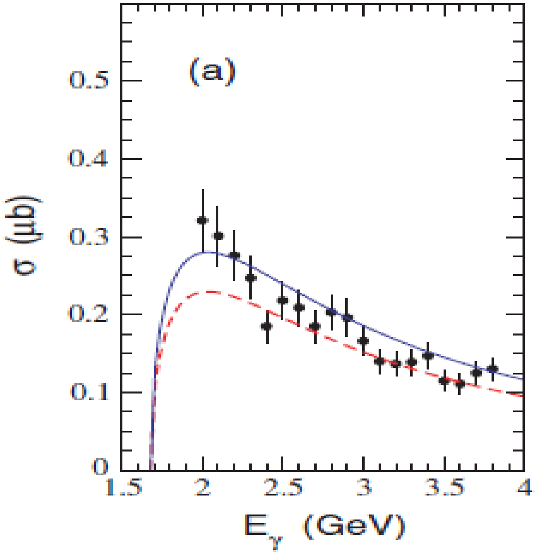
$K^{*+}Y$ Photoproduction



Motivation:

1. Search for higher-mass N* resonances

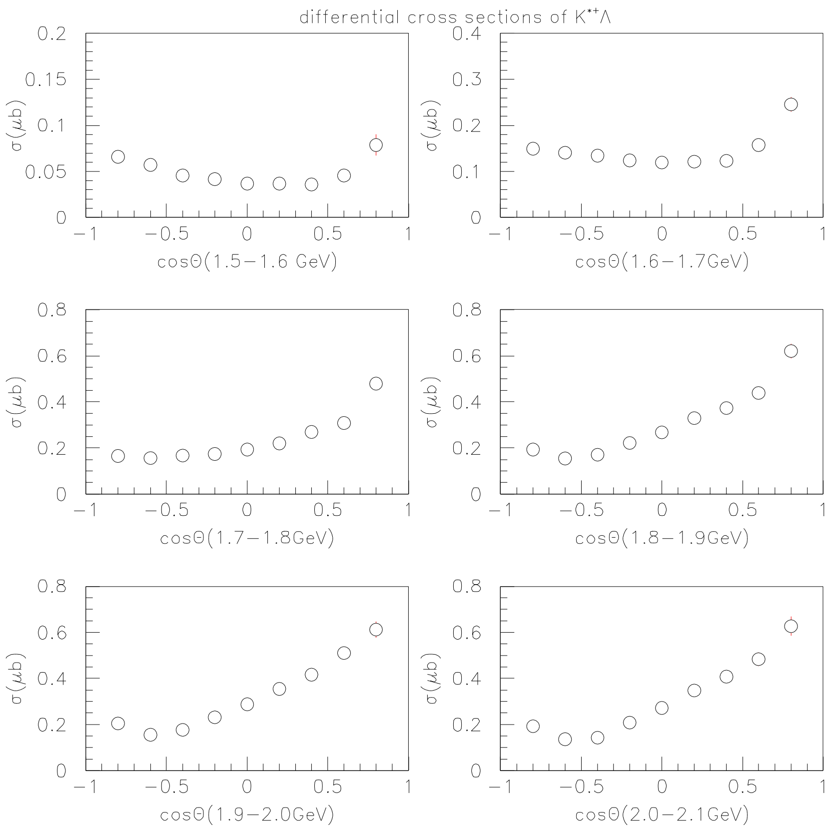
2. Compare with KY and $K^{*0}Y$
   a. $K^{*}Y$ coupling sensitive to $K_0(800)$.
   b. $K_0(800)$ is part of the scalar nonet.
   c. $K_0(800)$ has not been directly observed.



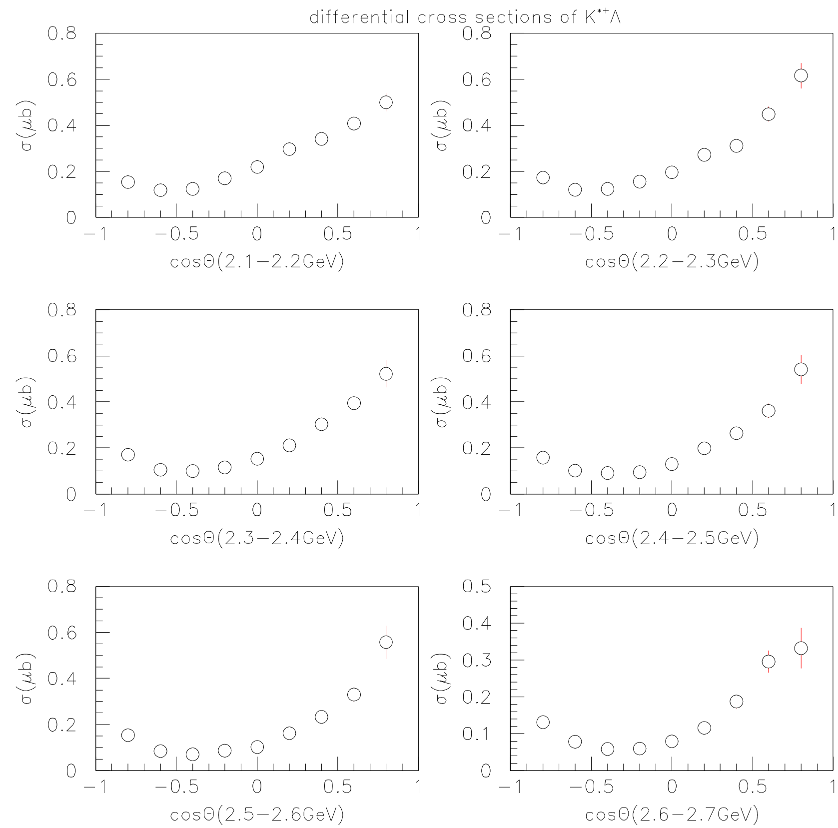
Oh and Kim, Phys Rev C 74, 015208(2006).

Differential cross sections of $K^{*+}\Lambda$:

1.5 --- 2.1 GeV



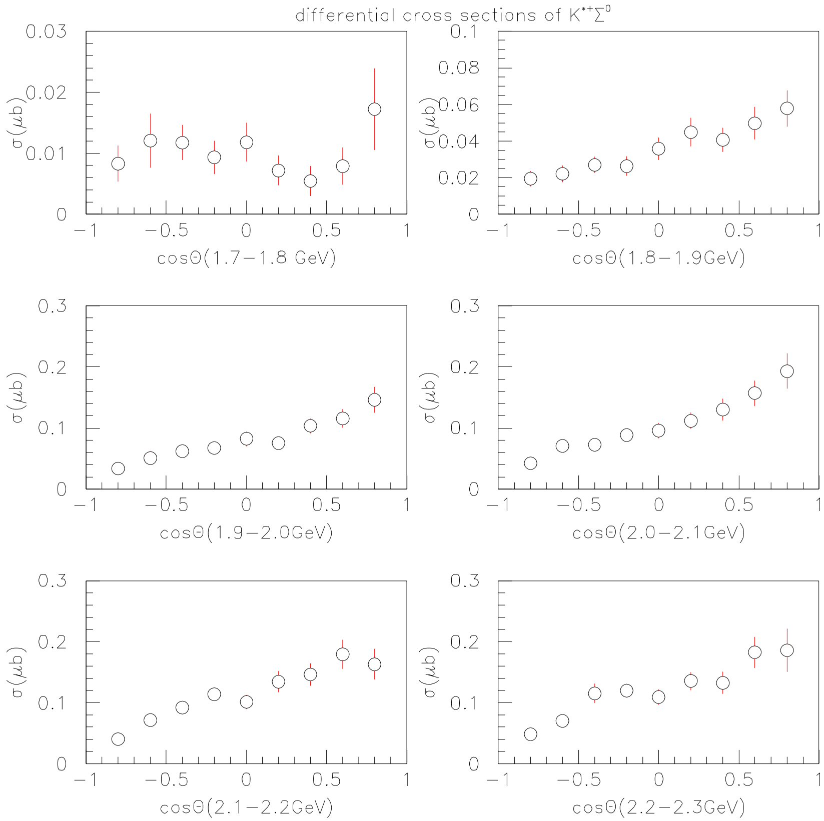
2.1 ---2.7 GeV



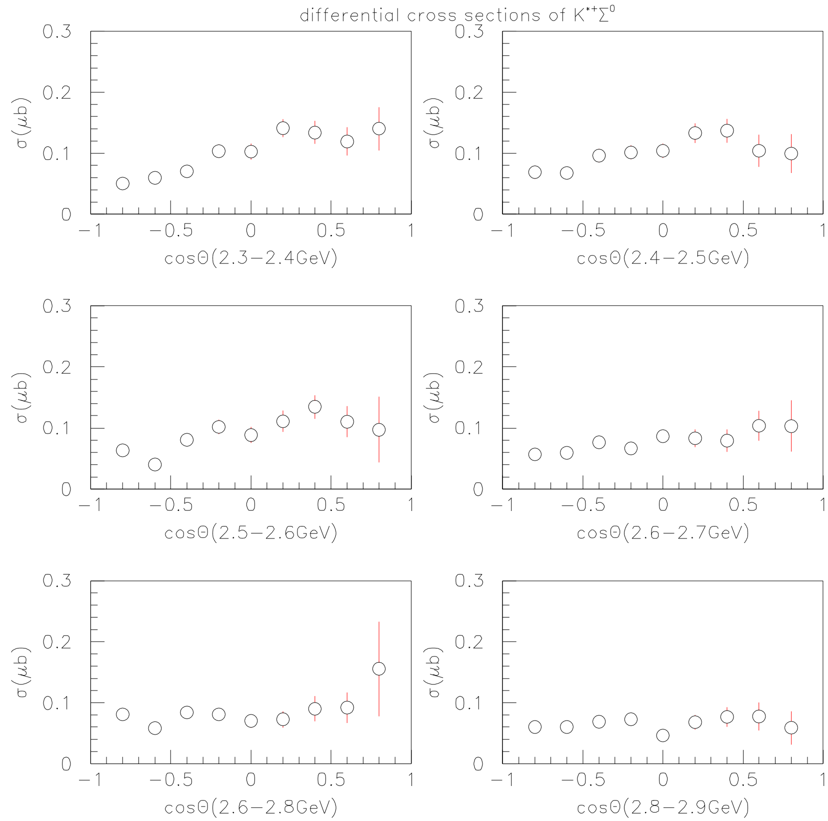
Preliminary result

Differential cross sections of $K^{*+}\Sigma^0$:

1.7 --- 2.3 GeV



2.3 --- 2.9 GeV

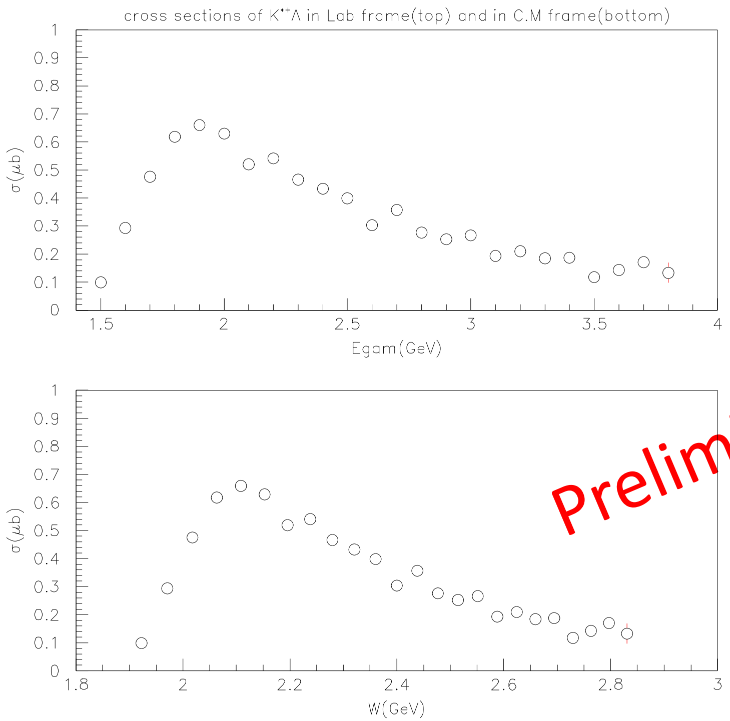


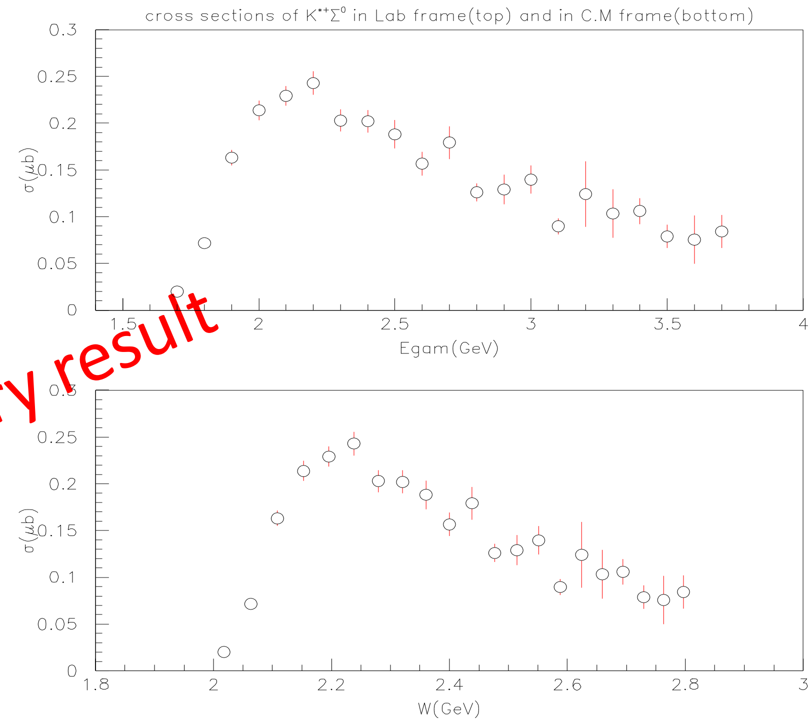
Preliminary result

Total Cross Sections

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

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



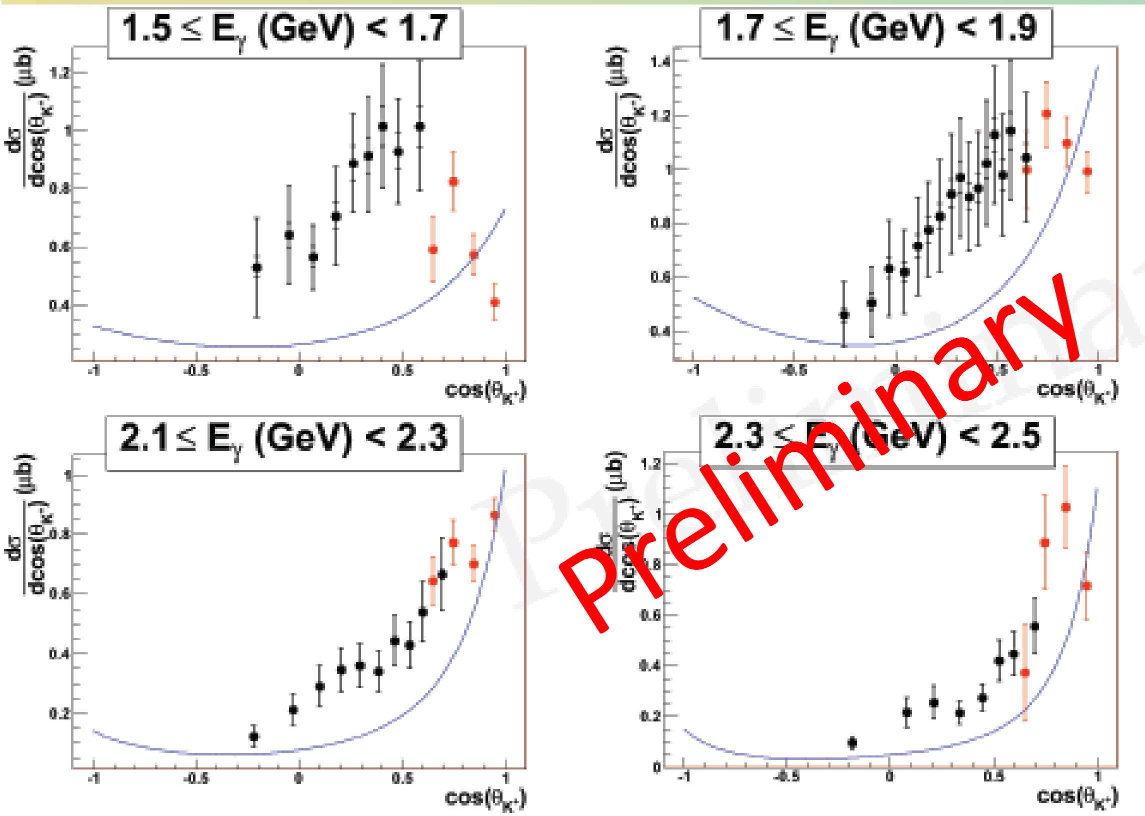


PhD thesis of Wei Tang

γ n→K⁺ Σ *(1385)⁻ Cross Section

15

- Oh, *et. al* model [13]: effective Lagrangians, model $\delta\sigma$'s not quoted
  - Partially constrained by $\gamma p \longrightarrow K^+ \Sigma^{*0}$ preliminary total cross section [11]
  - Dominated by t-channel K^+ and K^{*+}, some N^*'s and Δ^*'s included
    - $N\frac{1}{2}^-(1945), N\frac{3}{2}^-(1960), N\frac{3}{2}^-(2095), N\frac{5}{2}^-(2095), N\frac{5}{2}^+(1980)$



Legend
Black: CLAS g13 (preliminary)
Blue: Oh, *et. al* Model [13]
Red: LEPS [6]

P. Mattione, Rice/CMU

Meson Spectroscopy

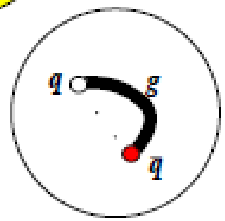
HyCLAS

g12

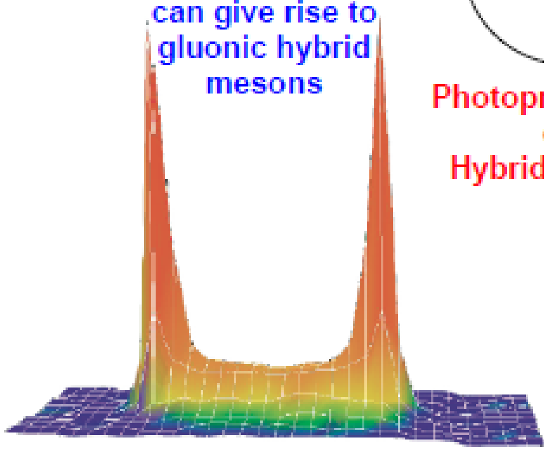
CLAS E04-005

Hybrid Mesons at CLAS

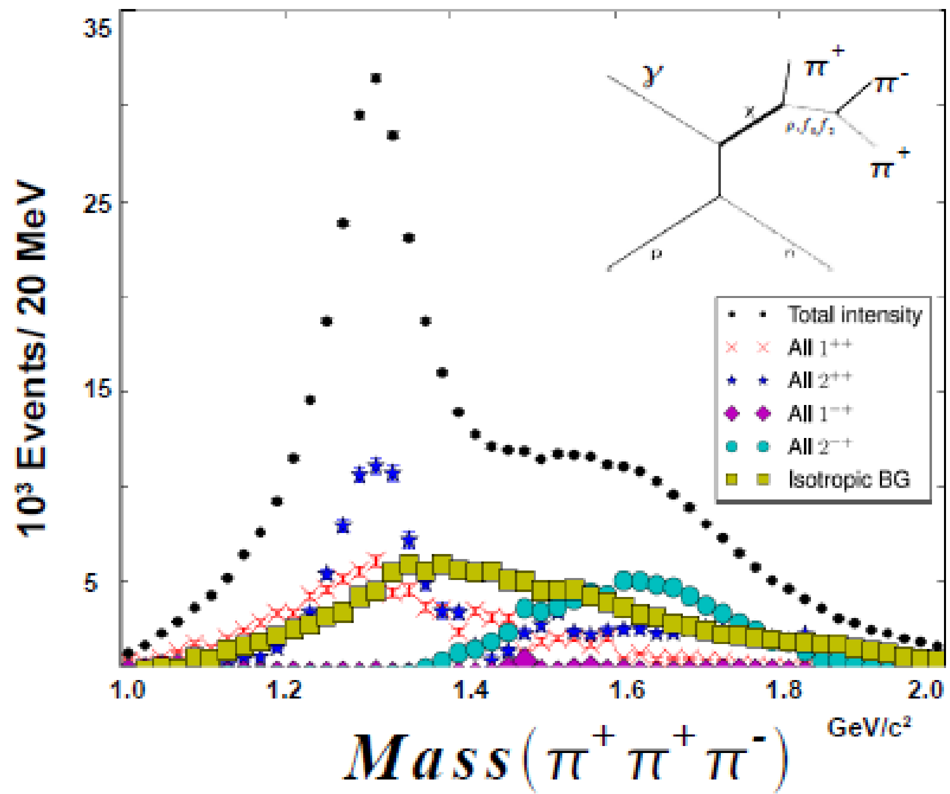
Excitations of the flux tube can give rise to gluonic hybrid mesons



Photoproduction of Hybrid Mesons



Mass Independent Partial Wave Analysis



Reactions of interest

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

See Thursday afternoon talks by D. Weygand, C. Bookwalter

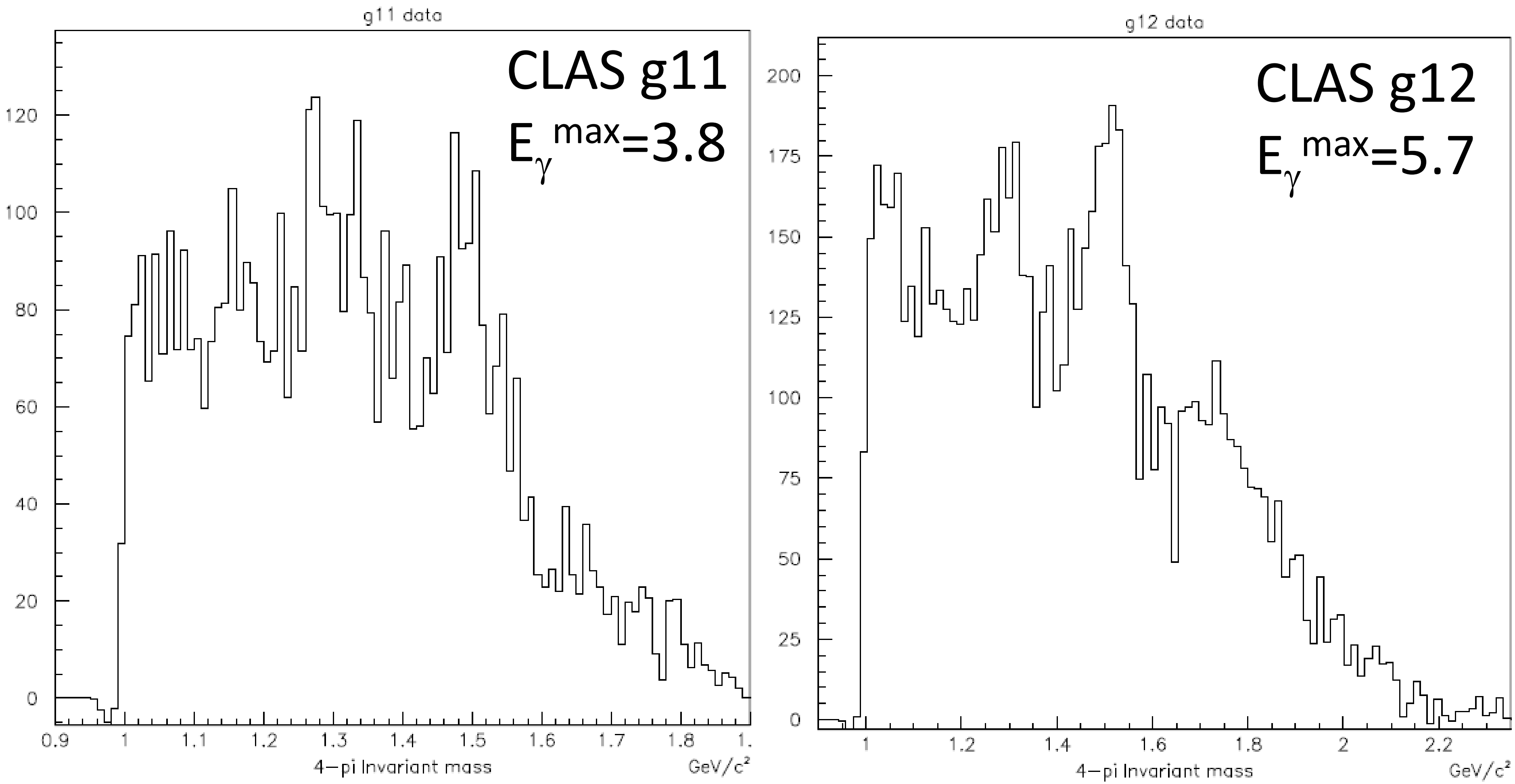
Jefferson Lab

CEBAF @ 6 GeV

Run Conditions

- 5.74 GeV Electron
- 4.4-5.7 GeV tagged photons
- 5x10⁶/sec photon flux
- 30 events/pb sensitivity
- modified CLAS geometry

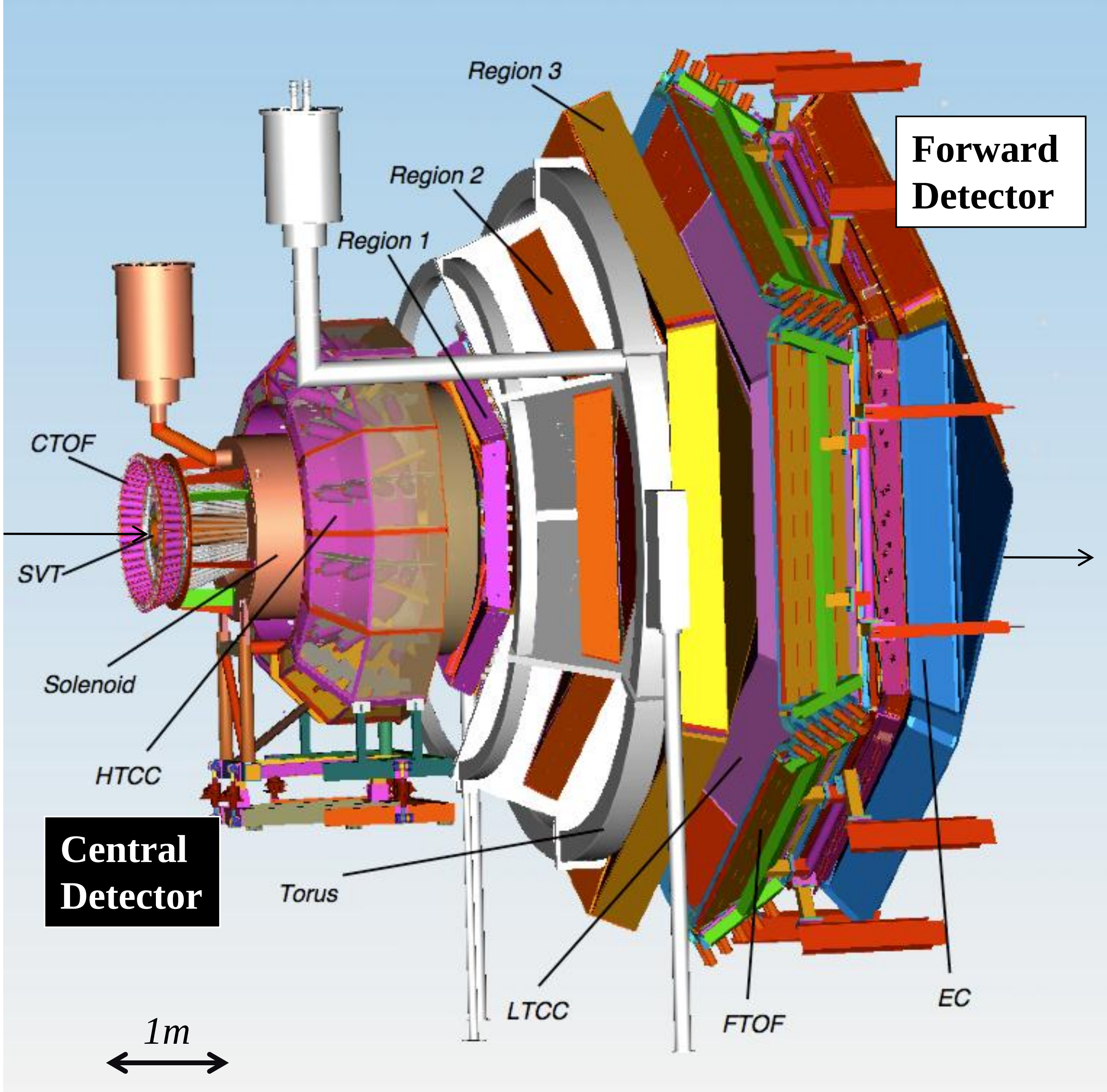
New: Scalar Mesons from $\gamma p \rightarrow K_s K_s p$



4-π Invariant mass (GeV)

The future: CLAS12

CLAS12

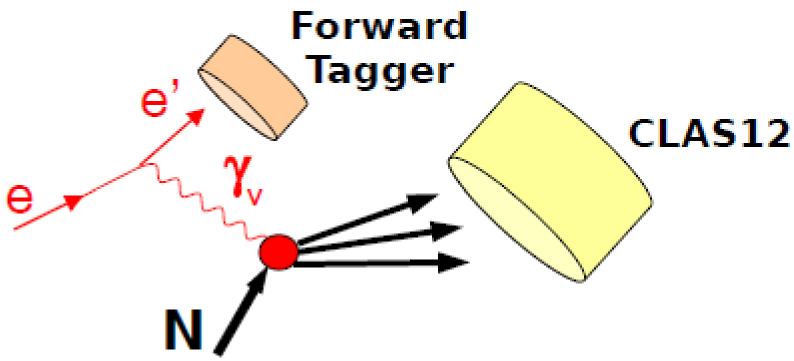


- Luminosity > 10^{35} $cm^{-2}s^{-1}$
- Hermeticity
- Polarization

- Baryon Spectroscopy
- Elastic Form Factors
- N to N* Form Factors
- GPDs and TMDs
- DIS and SIDIS
- Nucleon Spin Structure
- Color Transpareny
- …

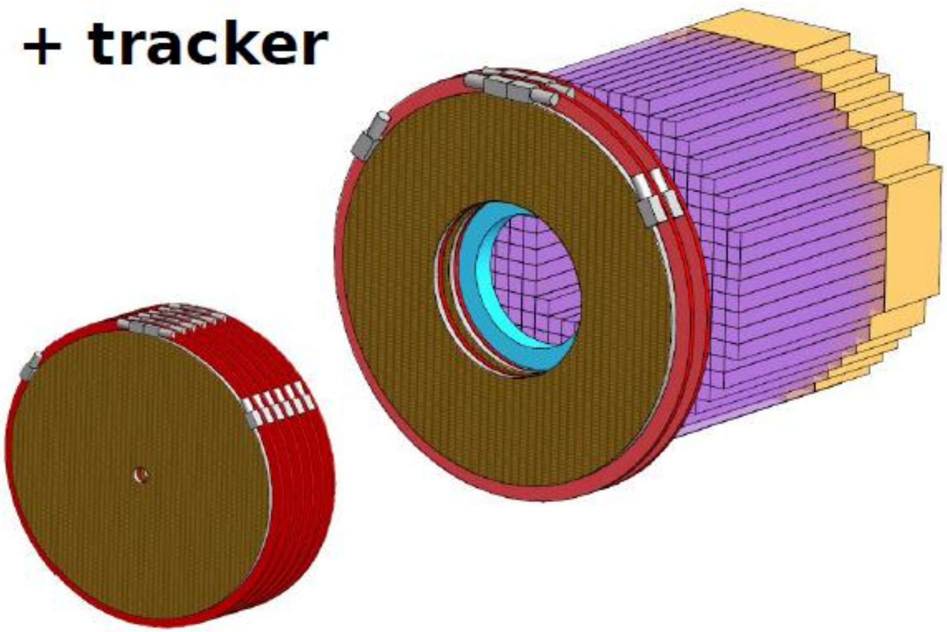
Forward Photon Tagger for Spectroscopy

M. Battaglieri



$E_{scattered}$	0.5 - 4.5 GeV
θ	2.5^o - 4.5^o
ϕ	0^o - 360^o
ν	6.5 - 10.5 GeV
Q^2	0.01 - 0.3 GeV^2 ($< Q^2 >$ 0.1 GeV^2)
W	3.6 - 4.5 GeV

Calorimeter + hodoscope + tracker



Electron energy/momentum

Photon energy (ν=E-E')

Polarization $\varepsilon^{-1} \sim 1 + \nu^2/2EE'$

Veto for photons

Electron angles

$Q^2 = 4\, E\, E' \sin^2 \vartheta/2$

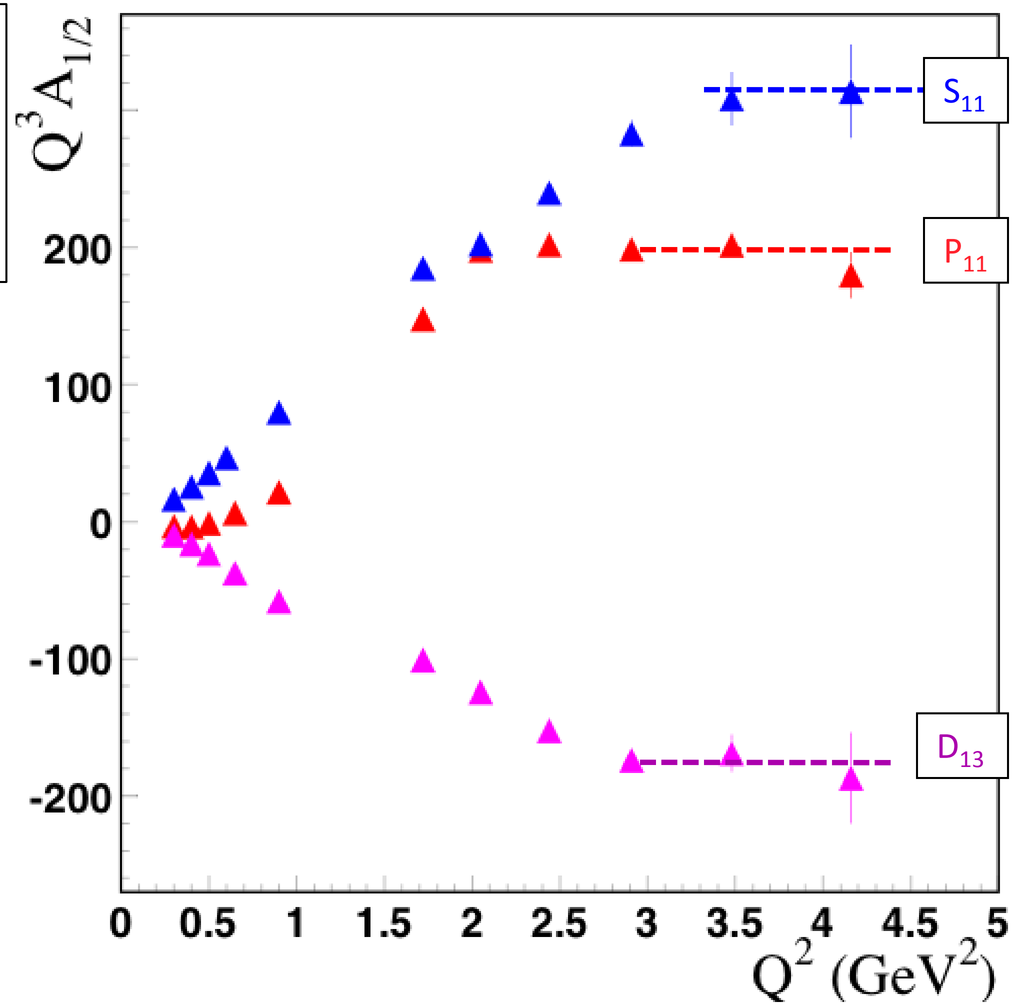
Scattering plane

Rates in the forward tagger

$L_e \sim 10^{35}\ cm^{-2}\ s^{-1}$ ($N_\gamma \sim 5\ 10^8\ \gamma/s$)

A new N* regime at Q^2>3.5 GeV^2?

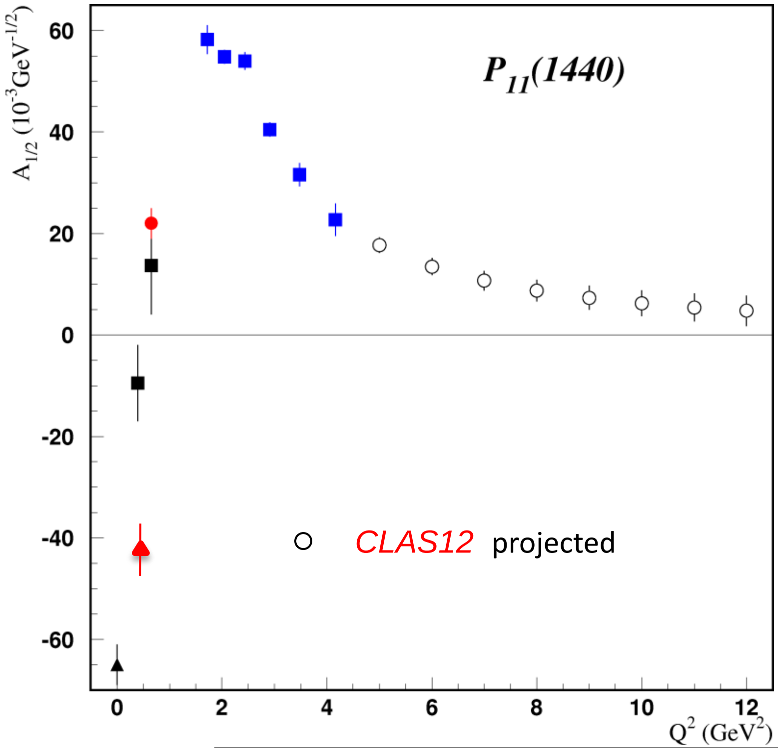
Data appear to reach a plateau at Q^2>3.5 GeV^2, but conclusive tests require higher Q^2



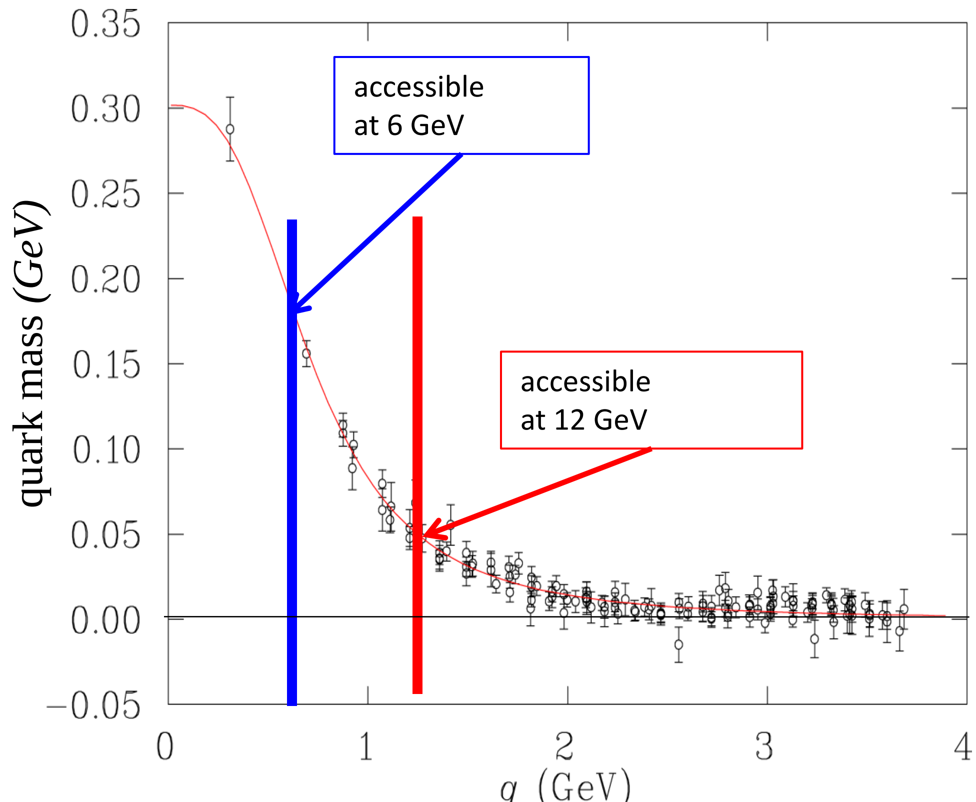
Transition to photon interactions with dressed quarks?

Resonance Transitions at 12 GeV

Experiment E12-09-003 will extend access to transition FF for many prominent states in the range to Q^2=12GeV^2.



Electromagnetic form factors are sensitive to the effective quark mass.



At 12 GeV we probe the transition from "dressed quarks" to elementary quarks.

Summary

- The Meson-Baryon Cloud has significant effects on photon coupling observables
  - We cannot ignore coupled-channel effects!
- There are precise new data on KY, K*Y, KY*
  - This will help the search for missing resonances
  - K* data will determine the role of the $K_0(800)$.
- PWA for mesons: exotics & scalar mixing
- Future: CLAS12: transition to current quarks.

Backup Slides

t-dependence of f(1500)