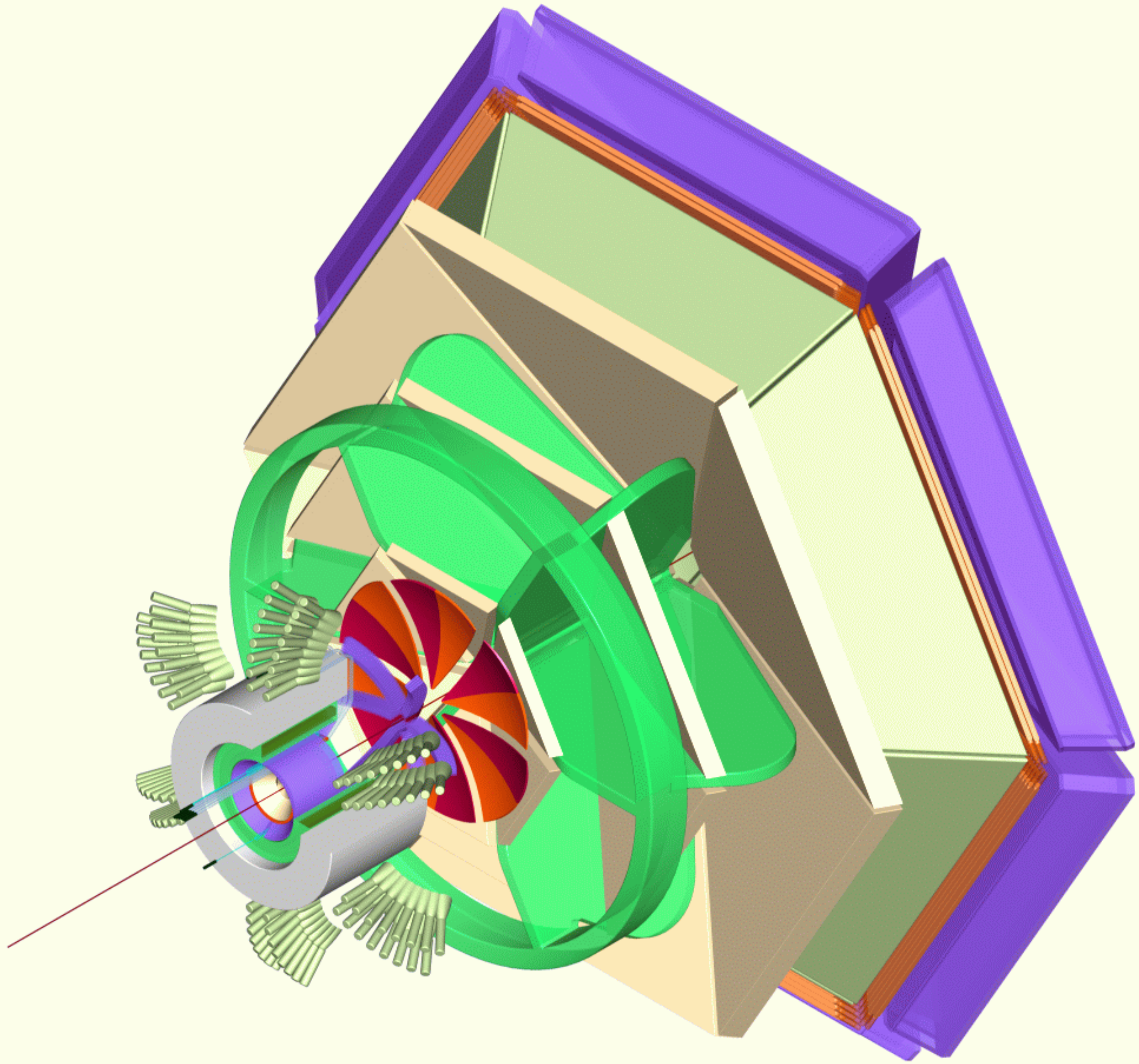
Hadron Spectroscopy with CLAS12: A Window Into Strong QCD

PAC27
Jefferson Lab
Jan 10 2005

Cole Smith

University of Virginia



CLAS @ 12 GeV

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Outline

- Meson Spectroscopy on proton and nuclear targets
  - LOI-03-003 – Search for Exotic Hybrids in the Coherent Production off 4He
  - LOI-03-004 – Meson Spectroscopy Using e- Scattering at Very Small Q^2 in CLAS
- Baryon Spectroscopy in photoproduction
  - Cascades
  - Exotics
- Baryon Spectrocopy in electroproduction
  - Transition form factors
  - Missing resonances

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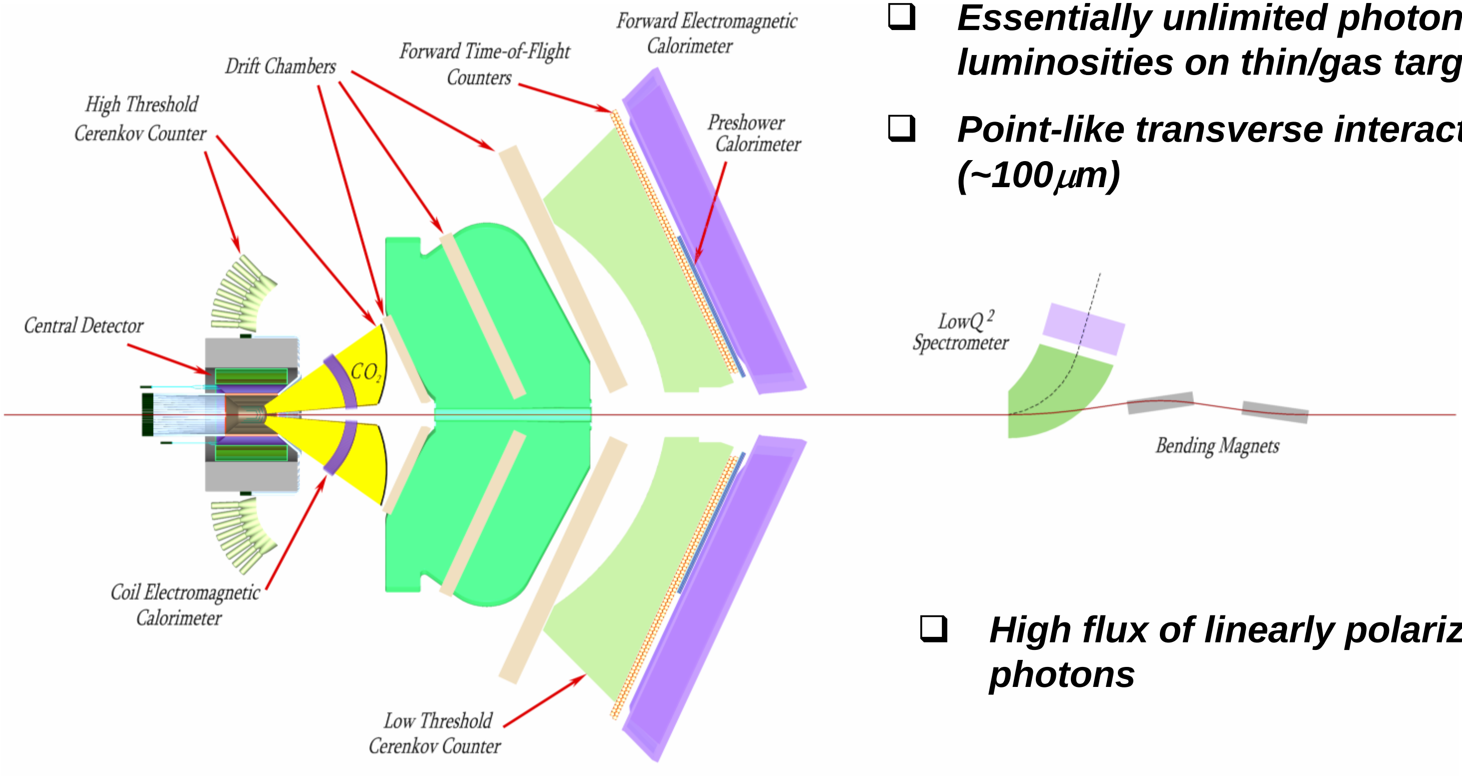
Meson spectroscopy with CLAS12

- Physics goals are similar to GlueX program:
  - Complete mapping of meson resonances in the mass range of 1 to 3 GeV.
  - Search for non $q\bar{q}$ states with exotic quantum numbers.

- A complimentary experimental environment - *electroproduction at very small Q^2 (θ_e<1.5^o)*
  - Experiments with thin gas targets – possibility to detect low energy recoils and spectators.
  - Determination of the linear polarization and the polarization plane of the virtual photon (Q^2~10^{-2}) on event-by-event basis.

CLAS12 and LowQ^2 spectrometer

- ***Detection of hadronic final states in CLAS12. Almost 2π acceptance for θ>35^o, about 50% for forward direction.***



- ***Forward spectrometer (dipole) for electrons scattered at θ_e<1.5^o with E_e=(0.1-0.3)E_0 and $\Delta E/E$~1%***
- ***Essentially unlimited photon flux: high luminosities on thin/gas targets***
- ***Point-like transverse interaction region (~100μm)***
- ***High flux of linearly polarized virtual photons***

Linearly polarized virtual photons

- Electroproduction at very small Q^2 with unpolarized electrons is equivalent to photoproduction with linearly polarized photons.

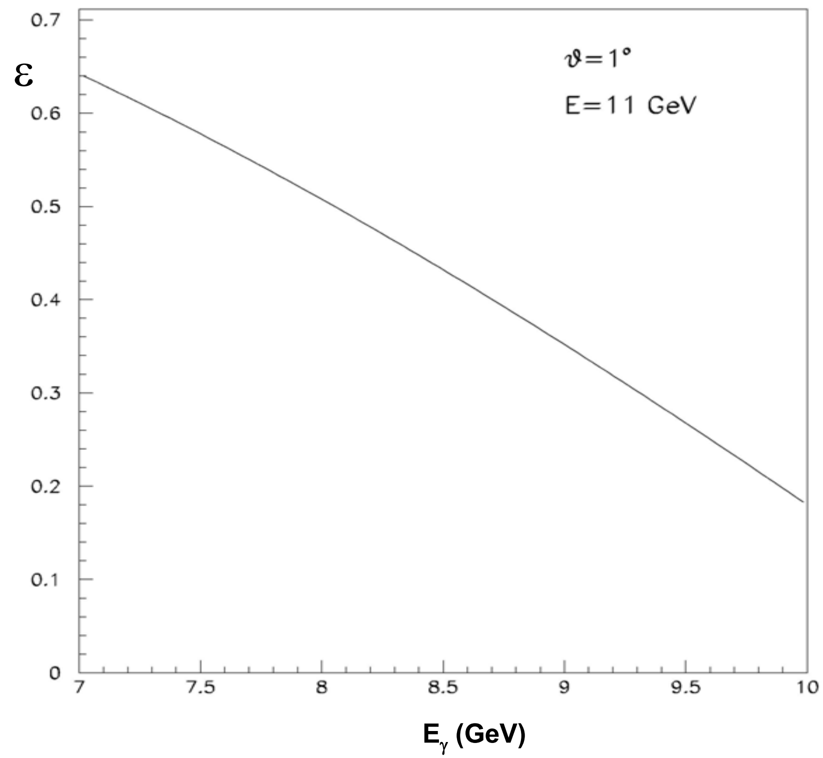
Degree of linear polarization

$$\varepsilon = \left[1 + 2\frac{\left(Q^2 + \nu^2\right)}{Q^2}\tan^2\left(\frac{\theta}{2}\right)\right]^{-1}$$

Spin density matrix

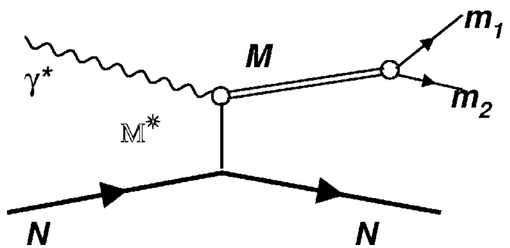
$$\begin{pmatrix} \frac{1}{2}(1+\varepsilon) & 0 & -\left[\frac{1}{2}\varepsilon_L(1+\varepsilon)\right]^{1/2} \\ 0 & \frac{1}{2}(1-\varepsilon) & 0 \\ -\left[\frac{1}{2}\varepsilon_L(1+\varepsilon)\right]^{1/2} & 0 & \varepsilon_L \end{pmatrix}$$

$$\varepsilon_L = \frac{Q^2}{\nu^2}\varepsilon \quad \textbf{\textit{at}} \quad Q^2 \sim 10^{-3} \quad \varepsilon_L \cong 0$$

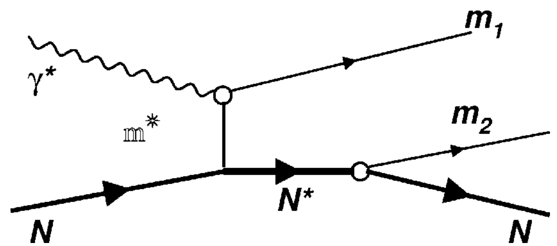


Coherent production on light nuclei

- Clean way to eliminate a background from the S-channel resonances: simplifies significantly analysis and interpretation.



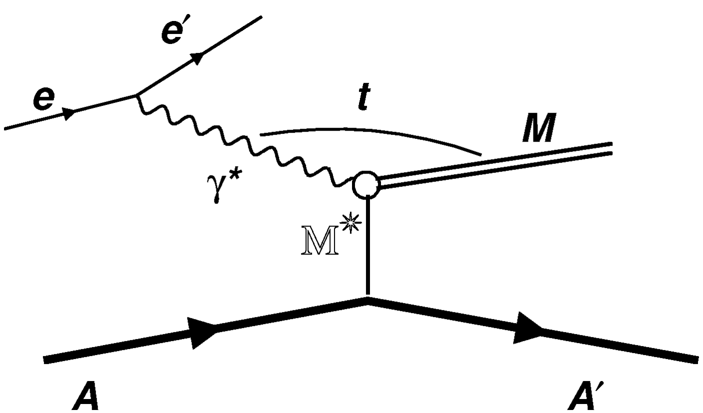
(m_1,m_2) final state from a decay of t-channel meson, **M**



the same (m_1,m_2) via production of **N*** in S-channel

At moderate energies kinematical separation of two processes often impossible.

- Detection of the recoil nuclei will ensure coherence of the process.



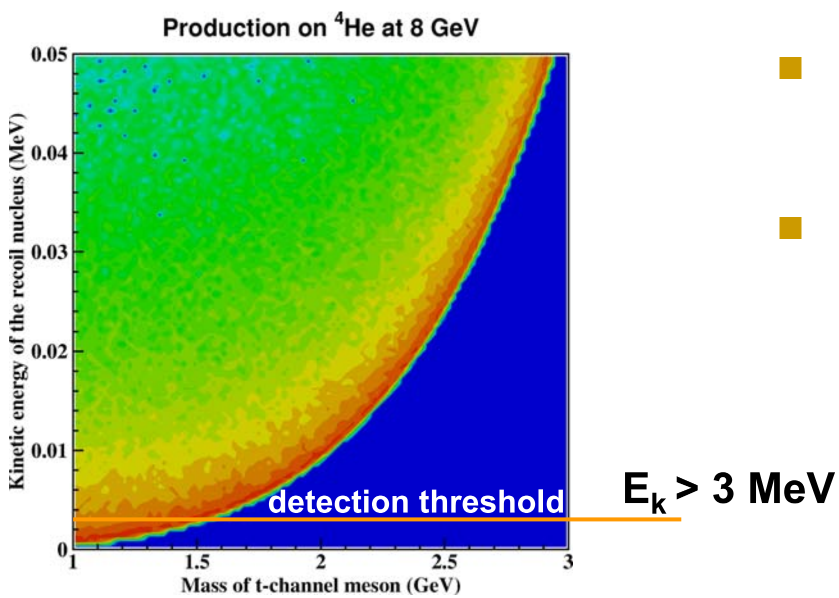
- Requires thin targets (**~10^{-3} g/cm^2**) for detection of **A′** at **$t \to t_{min}$** (**E_k>few MeV,** *BoNus …)*
- Requires high flux of (virtual)photons: Ideal for small angle electroproduction

Proposed measurements

- Combined measurements on light nuclei - ^{4}He, ^{3}He, and ^{3}H, will give access to all isospin combinations of given final state.

$$\gamma * {}^4\boldsymbol{He} \to \boldsymbol{M}^0\, {}^4\boldsymbol{He} \quad (1); \qquad \gamma * {}^3\boldsymbol{He} \to \boldsymbol{M}^+\, {}^3\boldsymbol{H} \quad (2); \qquad \gamma * {}^3\boldsymbol{H} \to \boldsymbol{M}^-\, {}^3\boldsymbol{He} \quad (3);$$

- In some cases coherent production will be also a spin/parity filter.



- Mesons with **m>1.5 GeV** will be studied at **$t \to t_{min}$**
- This will lead to the suppression of the helicity-flip amplitudes

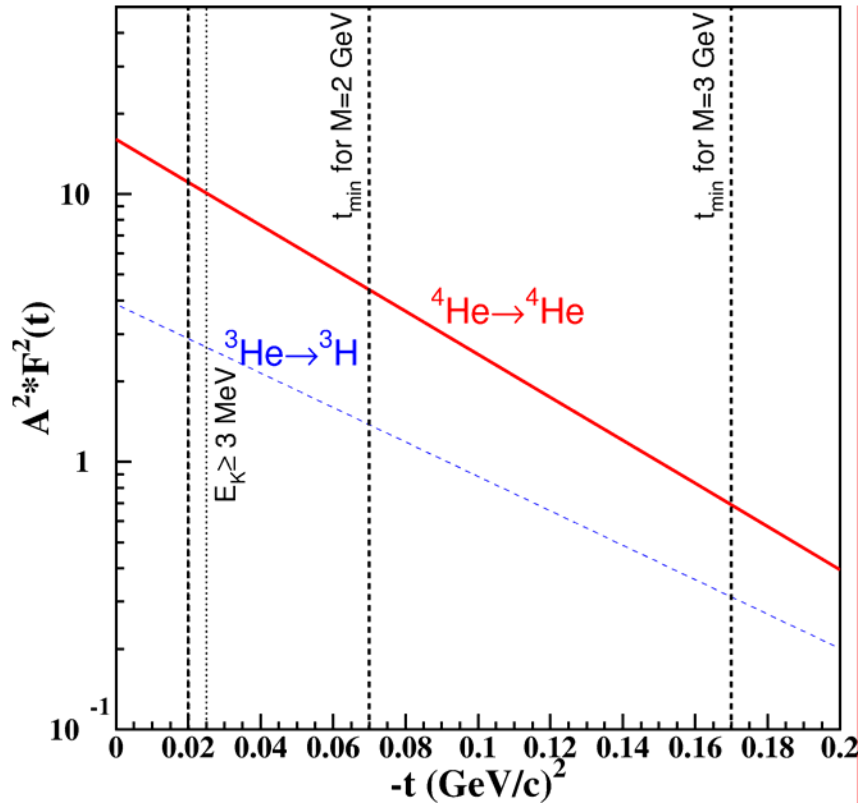
Cross section, rates, background

- Cross section of a coherent production is a square of a sum of scattering amplitudes off of the individual nucleons:

$$\frac{d\sigma}{dE d\Omega dt} = \Gamma_V \left(\frac{d\sigma_\gamma}{dt}\right) A_N^2 F_T^2(t)$$

A_N is **4** for 4He, and **2** for 3H, 3He.

F_T is a transition FF for 3H $\leftrightarrow$ 3He.



- Production rate for a final state with **M=2** GeV at **L=10³³ cm⁻² sec⁻¹** on ⁴He

$$\int_{0.1E}^{0.3E} dE \int_{m/E}^{0.5} \Gamma_V d\Omega \approx 8\times 10^{-2}$$

$$\frac{dn}{dt} = 10^3 \left(\frac{d\sigma_\gamma}{dt}\right) nb^{-1} hour^{-1}$$

PWA: production of $\pi^0\eta$ (0^{-+} 0^{-+}) on ^{4}He

- Can proceed via C-odd exchanges (ρ, ω …).
- $I^{He}=0$: only isosinglet (ω) exchange allowed: natural parity exchange.

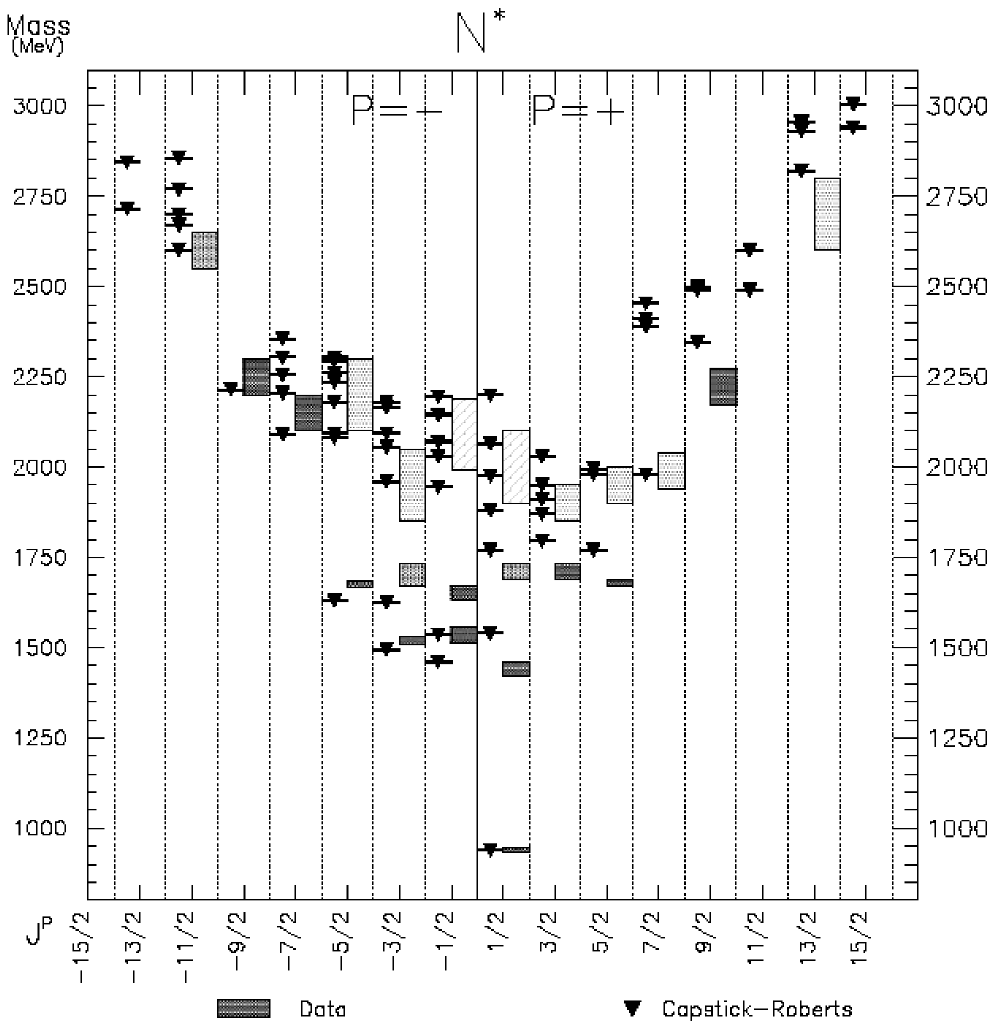
$$\frac{d\sigma}{d\Omega_C} = \left|A_0 + A_-\right|^2 + \left|A_+\right|^2 \Rightarrow \quad A_0 \to 0; A_- \to 0;$$

$$A_+ = \sum_{L=0}^{L\max} \sum_{\lambda=1}^{L} (2L+1)^{1/2} \sqrt{2} L_{\lambda +} \operatorname{Im}\left(D^L_{\lambda 0}(\Theta,\phi)\right)$$

- $S^{He}=0$: At $t \to t_{min}$ $\lambda_M=\lambda_\gamma$ (production of states with L=0 suppressed by $\sin\Theta^* \sim (t-t_{min})/E^2$).

$$A_+ = \sum_{L=1}^{L\max} (2L+1)^{1/2} \sqrt{2} L_{1+} \operatorname{Im}\left(D^L_{10}(\Theta,\phi)\right)$$

New Strategies for Identifying Missing N*s



SU(6) quark models predict more light quark states than observed.

- High lying states are broad and overlapping (W > 1.8 GeV).
- Couple only weakly to single pion channels.

Several CLAS programs are well suited for missing N* studies:

- Cascade photoproduction
- 2π electroproduction

Baryons with Strangeness -2

N* and Ξ* members of same ground state octet. Expect correspondance for spatial w.f., spin, parity.

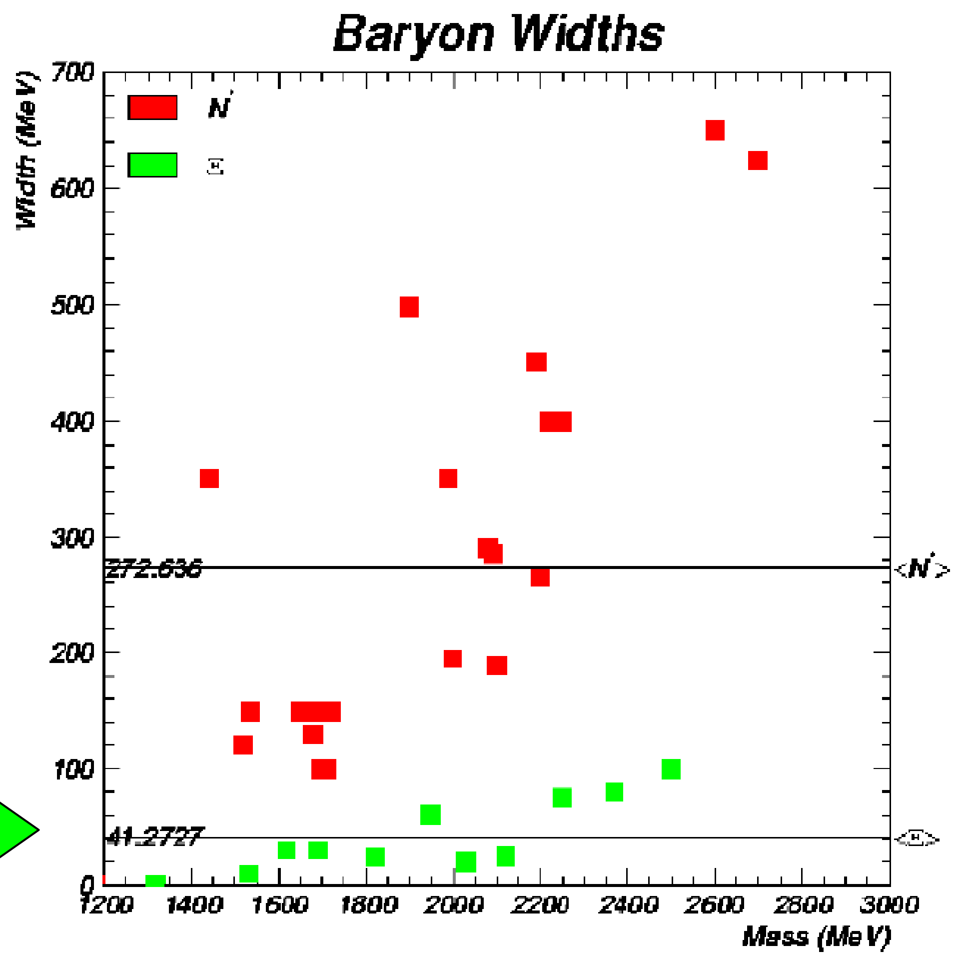
n(939) = *udd* p(938) = *duu*

Ξ^0(1315) = *uss* Ξ^-(1321) = *dss*

- $SU(3)_F$ symmetry requires n(Ξ*) = n(Δ*) + n(N*)
  - 2001 RPP: 22 N*, 22 Δ*, 11 Ξ*
  - Are there 33 missing Ξ* ?
- Study of Ξ* spectrum can shed light on missing N*s.
- Little is known about spectroscopy, decay branching ratios of Ξ*
  - Most cascade data come from bubble chambers and hadron beams
  - Only 3 states have known spin parity assignments
- CLAS12 can make substantial progress here.
  - Feasibility studies underway.
  - Data mining of previous and current running CLAS experiments.

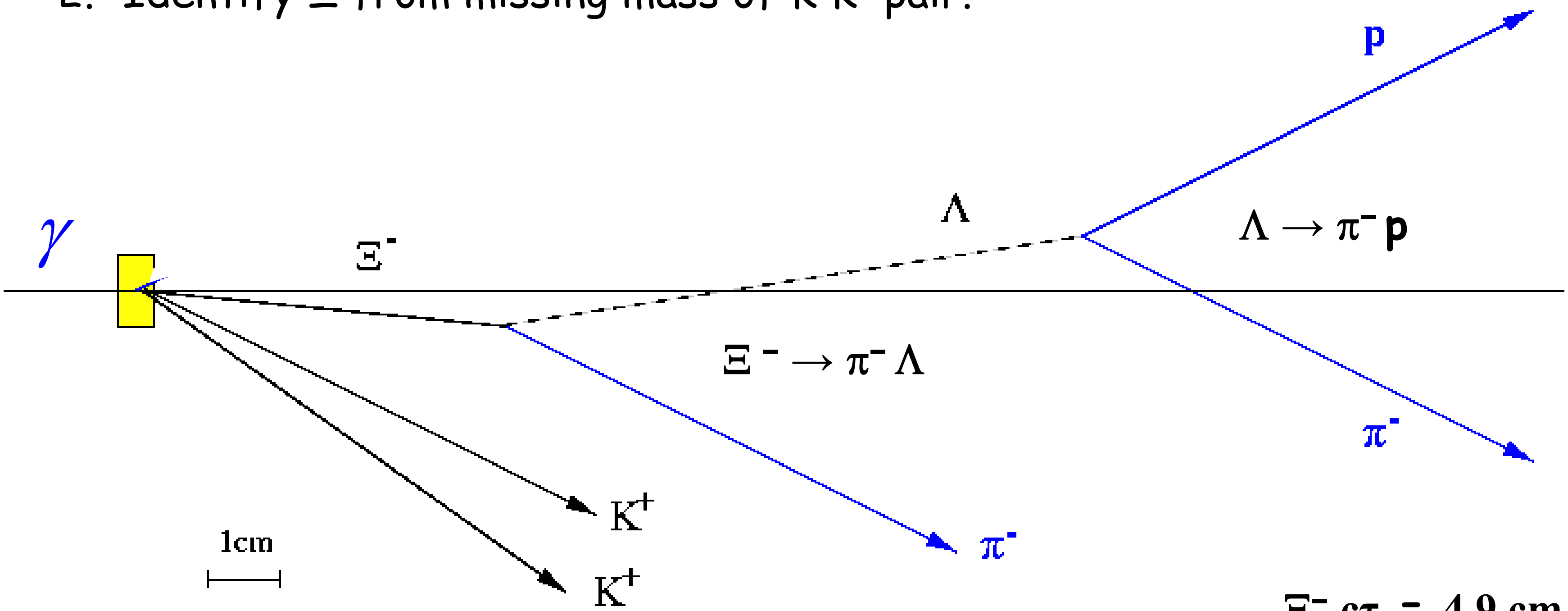
Advantages of Cascade Spectroscopy

- Study dynamics of single light quark in 'heavy' 2q background.
- Two heavier strange quarks reduce uncertainties in lattice calculations of masses.
- Cascade decay widths much narrower compared to N*.
  - Easier to isolate
  - Good test for models of decay dynamics
- Detached vertices of decay products make background suppression easier.



Photoproduction of Cascades: $p(\gamma, K^+K^+)\Xi^-$

1. Reconstruct Ξ from invariant mass of decay products
2. Identify Ξ from missing mass of K^+K^+ pair.



Ξ^- cτ = 4.9 cm
Λ cτ = 7.9 cm

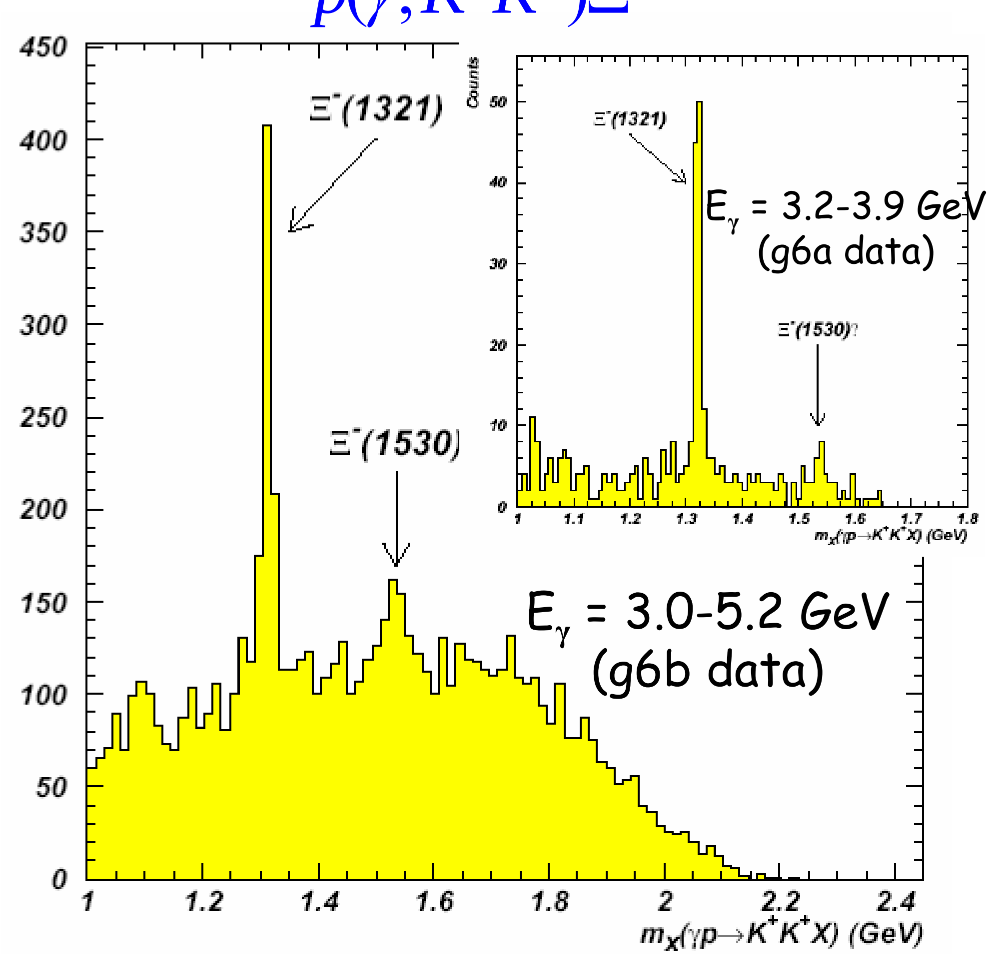
$\langle \gamma\beta \rangle \sim 1.5$

Exploit weak decays to enhance signal to background through reconstruction of detached vertices and cuts on daughter particle masses.

Detection of $\Xi^-(1321)$ in CLAS

J. Price et al., nucl-ex/0409030
submitted to Phys. Rev. C

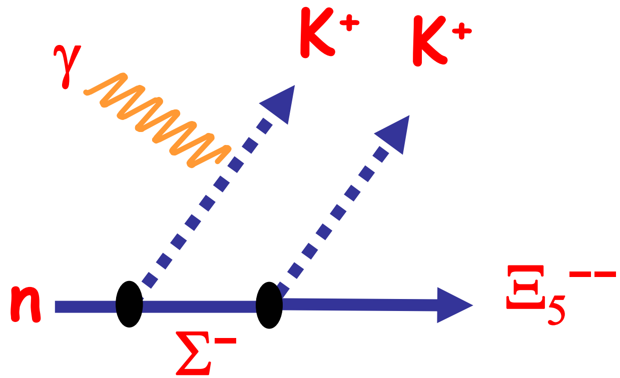
$p(\gamma, K^+K^+)\Xi^-$



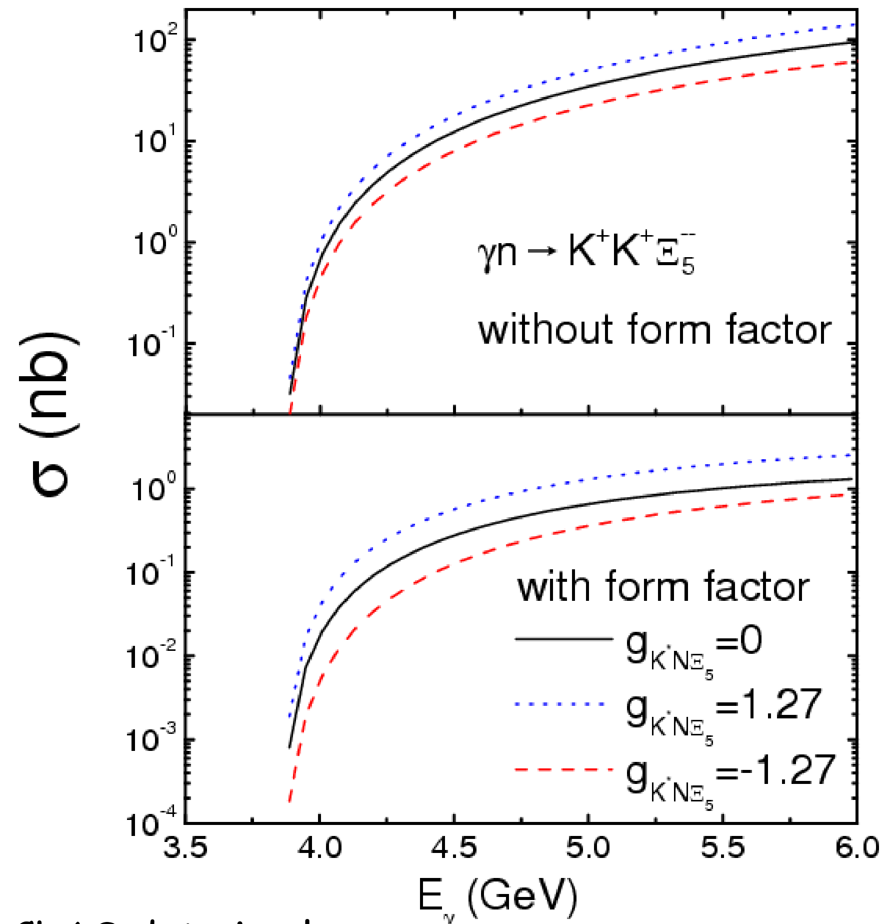
Backgrounds at higher luminosity arise from π/K misidentification and tagged photon accidentals.

New data taken in current eg3 run with improved start counter should greatly reduce combinatorial backgrounds.

Cascade production cross sections: theory



W. Liu C.M. Ko, PRC69 (2004) 045204



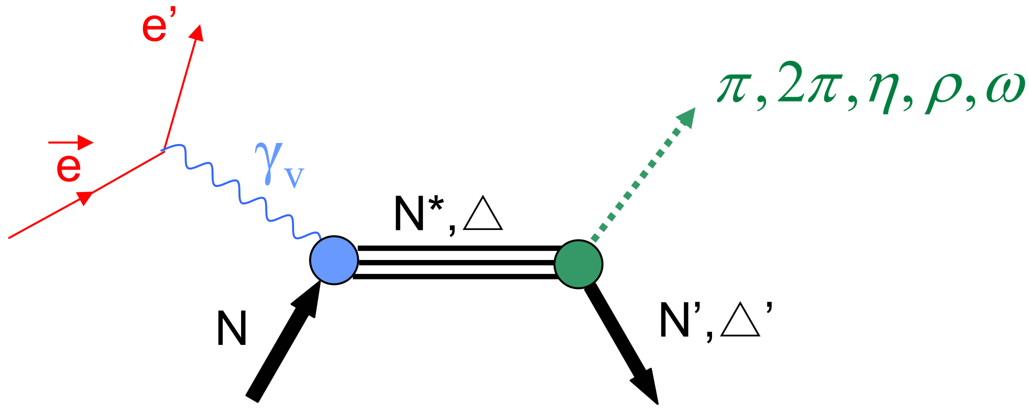
- Calculations exist for production of exotic cascades.
- Can be adapted to production mechanisms of conventional states.

Preliminary estimates from present CLAS data imply ~1000/week ground state cascades possible in dedicated run.

Physics Goals of Cascade Program Summarized

- Search for missing Ξ^*
  - Complementary to N* searches
- Properties of Ξ^0 hyperons
  - $M(\Xi^0) - M(\Xi^-) = m_u - m_d$ (evaluate coulomb corrections)
  - Requires detection of π^-
- Production mechanisms
  - s- vs. t-channel
- New decay modes
  - (mode,threshold): $\Xi\pi\pi(1585)$, $\Lambda\bar{K}(1608)$, $\Sigma\bar{K}(1682)$
- J^P measurements
  - PWA not feasible. Use Dalitz, moments analyses.
- s-d quark mass difference
  - Test octet and decuplet mass relations
- Ξ^-p scattering
- Exotic cascades
  - CLAS experiment (E04-010) in progress (search for Ξ^{--} observed by NA49).
  - Test major refinements in start counter, tagger calibration, background rejection useful for continued exotic searches after 12 GeV upgrade.

N* Program at JLAB



Experimental Goals

- Extract photocoupling amplitudes for known Δ,N* resonances
- Identify missing resonances expected from SU(6)xO(3)

Theoretical Challenges

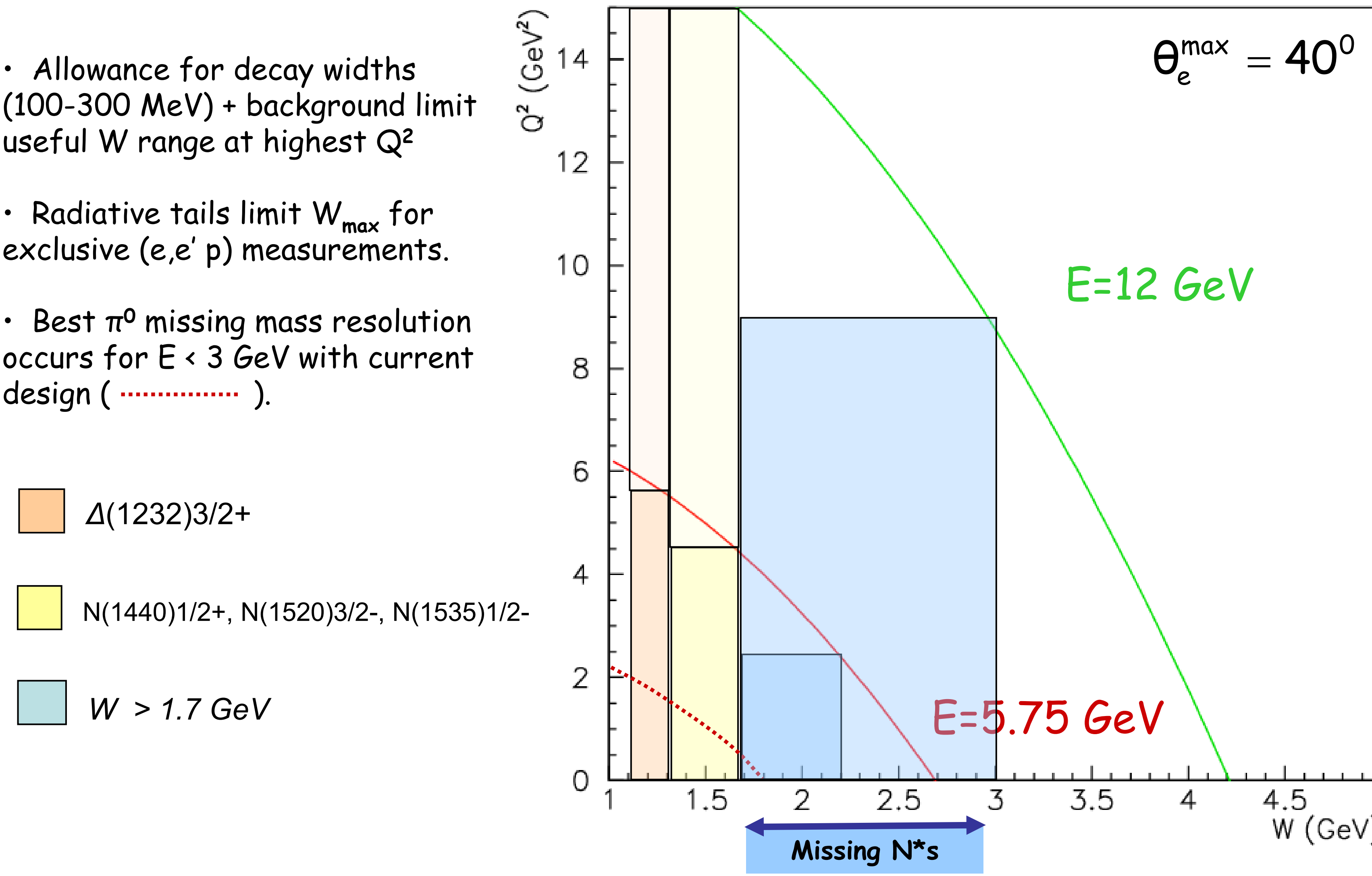
- Partial wave, isospin decomposition and channel coupling of hadronic decay
- Coupling between EM and strong interaction vertices
- Q^2 dependence of photocoupling helicity amplitudes: $A_{3/2}$ $A_{1/2}$ $S_{1/2}$
- Fundamental symmetries of quark wave functions
- Ingredients of quark models: relativity, gluons vs. mesons
- Understand confinement and resonant excitation mechanisms from QCD

Outline of N* program at 12 GeV

- $\gamma^* p \rightarrow \Delta(1232)$
  - Extend transition form factor measurements up to Q^2=10-12 GeV^2
  - Look for onset of pQCD scaling of $A_{1/2}$ and $S_{1/2}$ helicity amplitudes.
- $\gamma^* p \rightarrow P_{11}(1440)$
  - Radial excitation or hybrid?
  - Many models predict Roper dominance above Q^2=3 GeV^2
  - Measure $A_{1/2}$ and $S_{1/2}$ photocouplings on proton and neutron.
- Single Quark Transition Model (SQTM)
  - Test existing SQTM predictions for N* form factors (proton + neutron).
  - Look for Q^2 evolution of resonance parameters:
    - Mixing angles, poles, decay widths.
    - Evidence of chiral restoration (parity doublets) in higher lying states.
  - Eventual goal to fit quark model w/parameterized potential directly to data.
    - Extract mixing angles + photocouplings within generalized SQTM framework.
    - Common analysis of all observables from π and 2π channels to test for consistency.
- Missing N* Resonances
  - Extend search in 2π channel up to W=3 GeV.
  - Exploit possible increase in resonance/background with increasing Q^2 suggested by models.

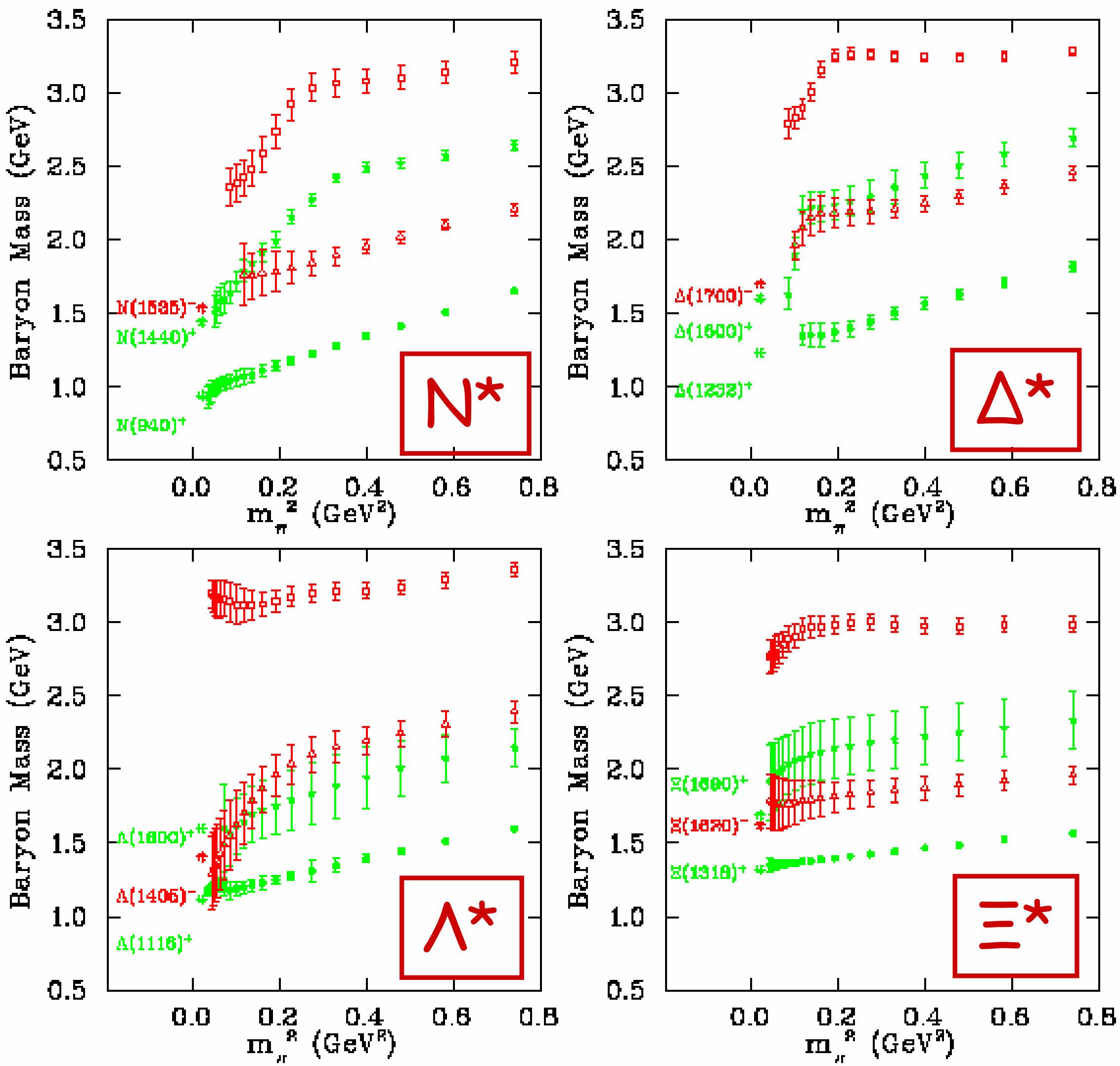
Kinematics for 12 GeV Upgrade

- Allowance for decay widths (100-300 MeV) + background limit useful W range at highest Q^2
- Radiative tails limit W_{max} for exclusive (e,e' p) measurements.
- Best π^0 missing mass resolution occurs for E < 3 GeV with current design (··················).



Baryon Spectroscopy: Masses from Lattice QCD

C. Morningstar, nucl-th/0308026



Mass splitting determined by gluonic interactions. Quark mass sets overall scale.

As chiral limit reached ordering of mass spectrum strongly affected.

Baryon Spectroscopy: Dynamics from Lattice QCD

Quantum Chromodynamics

(Strong) Color Confinement

⇩

(Tightly Stretched) Color Flux-Tube Formation with a Large String Tension $\sigma \simeq 1$ GeV/fm

⇩

Large Excitation Energy of the Flux-Tube Vibration

⇩

Large Gluonic Excitation Energy $\Delta E \simeq 1$ GeV

⇩

Absence of Gluonic Excitation Modes in Low-lying Hadrons

Dynamical Chiral Symmetry Breaking

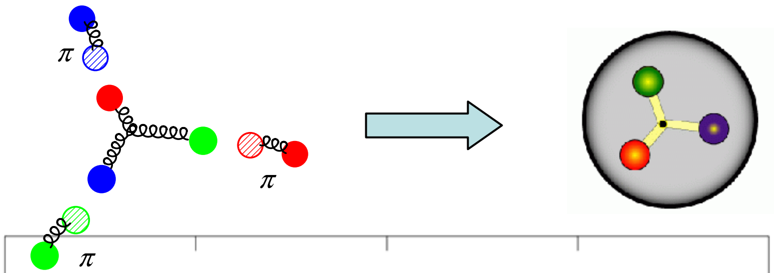
⇩

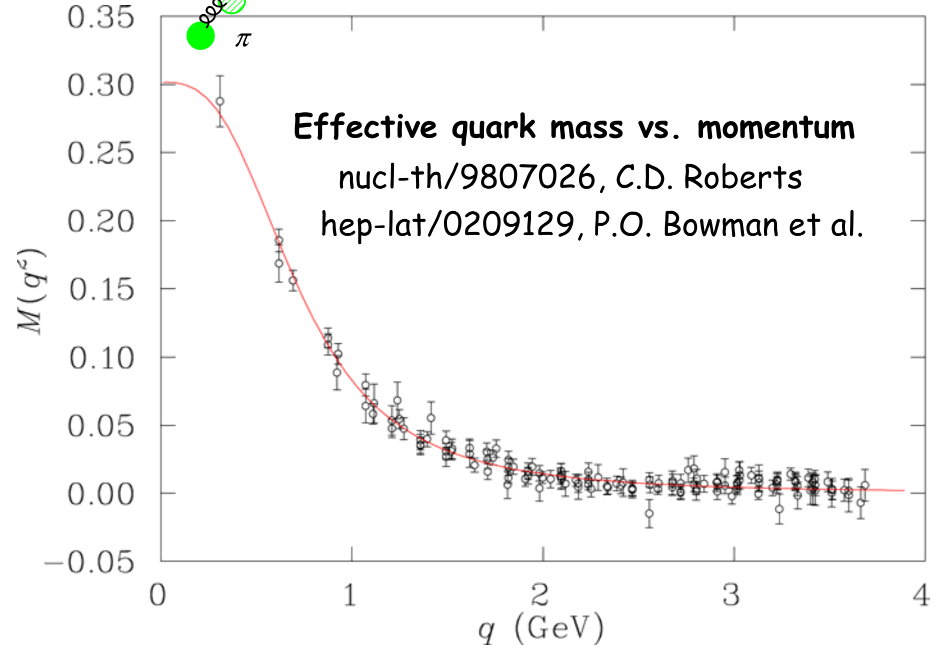
Large Constituent Quark Mass $M_q \simeq 300$ MeV

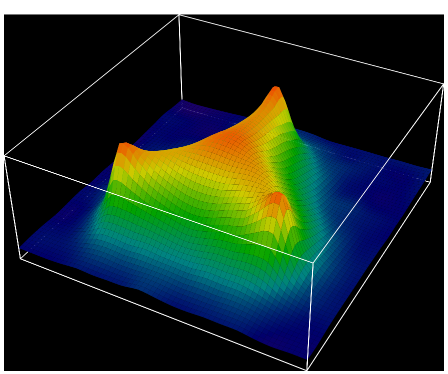
⇩

Non-Relativistic Treatment on Quark Dynamics in Low-lying Hadrons

Massive Quark Model for Low-lying Hadrons







hep-lat/0412026, H.Suganuma et al.

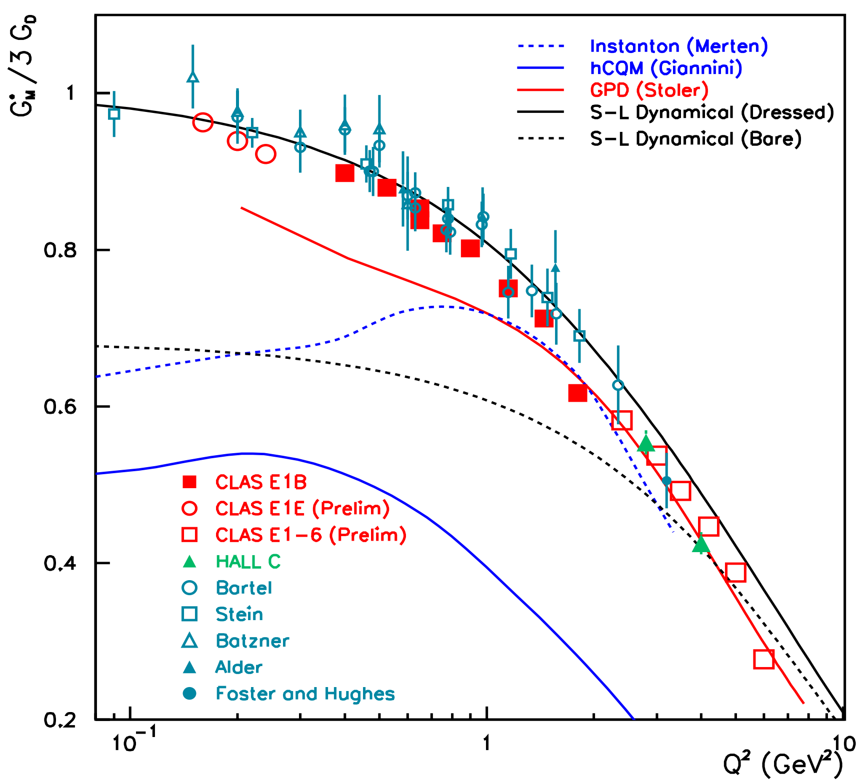
- Confinement scale Λ_{QCD} = 0.2 GeV
- Chiral symmetry breaking scale $\Lambda_{\chi SB}$ = 1 GeV
- Low W,Q^2: flux tube breaking, pion cloud dominance
- High W,Q^2: Resonance structure may reflect gluon d.o.f.

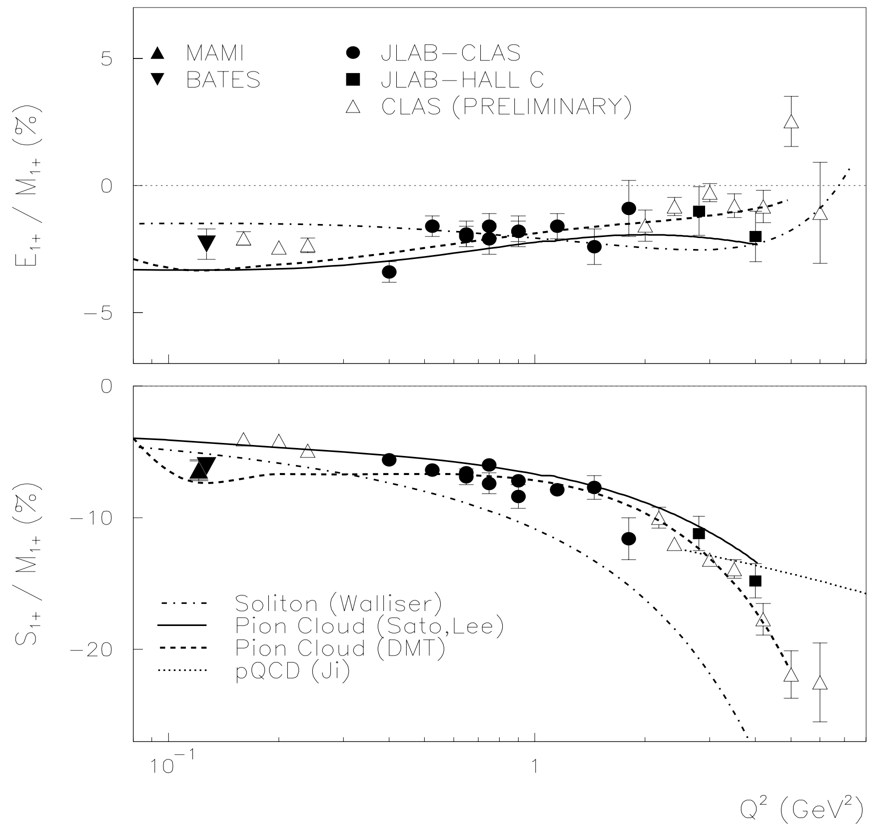
Baryon Spectroscopy: Review of JLAB results

$\gamma^* p \rightarrow \Delta(1232) \rightarrow \pi N$

- M1+, E1+, S1+ transition form factors extracted over range $0.15 < Q^2 < 6$ GeV^2.
- CQM underestimate low Q^2 M1+ strength by 30-50%.
- Dominance of helicity non-conserving $A_{3/2}$ persists at higher Q^2.

Both transverse and longitudinal quadrupole couplings are non-zero and consistent with pion cloud models.

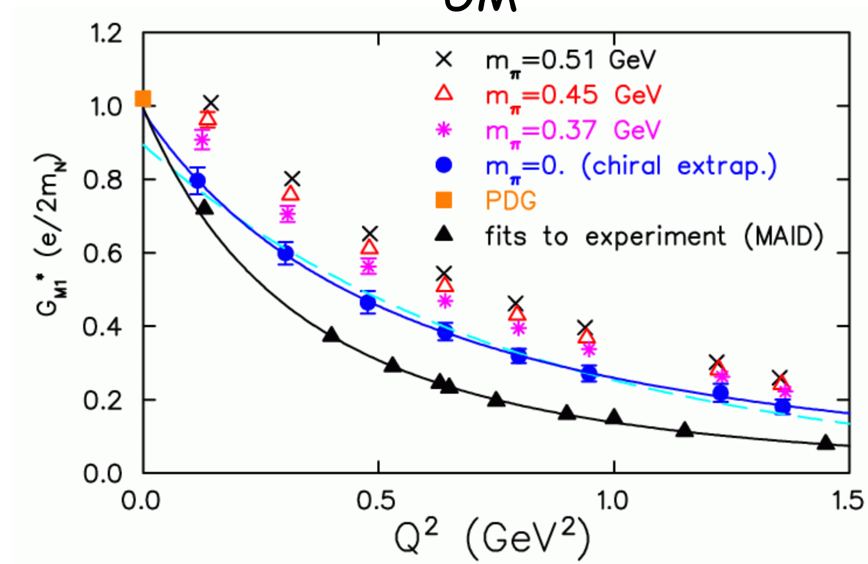




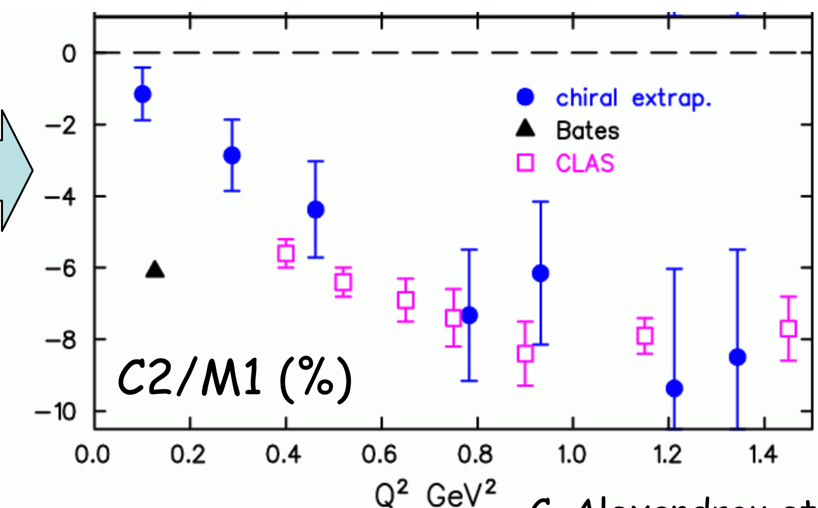
Lattice (quenched) predictions for $\gamma^* p \rightarrow \Delta(1232)$ photocouplings

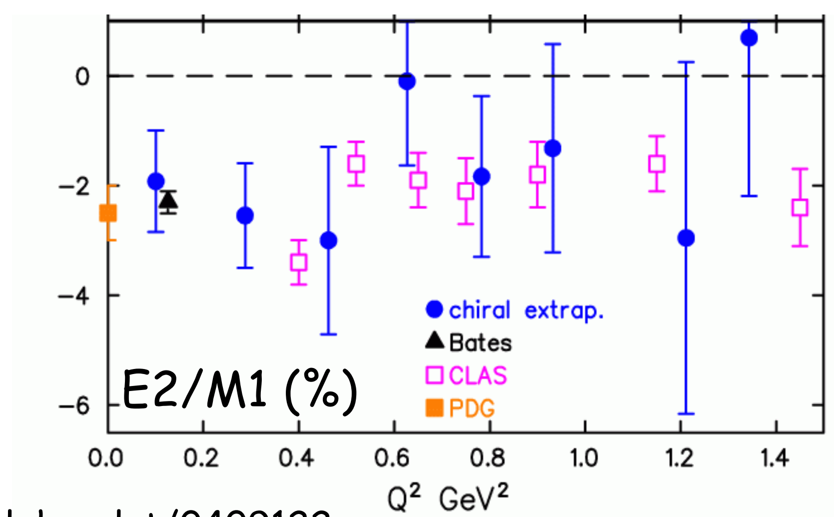
- Agreement with PDG at $Q^2=0$
- Chiral extrapolated f.f. falls with Q^2 more slowly than data.
    - Lattice too small?
    - Chiral extrap. too naïve?
    - Unquenching important?

GM*



Predicted photocoupling ratios in better agreement.



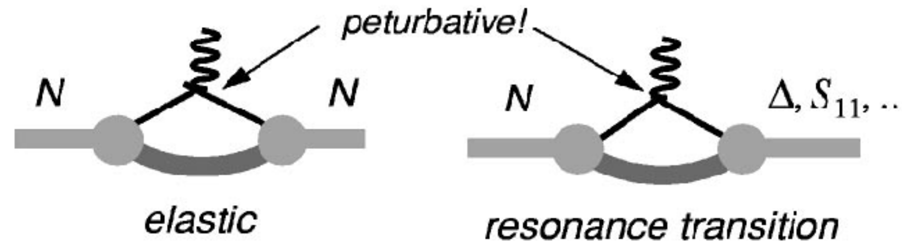


C. Alexandrou et al, hep-lat/0409122

GM* p→Δ and elastic F.F. at large Q^2 – Related via GPD sum rules

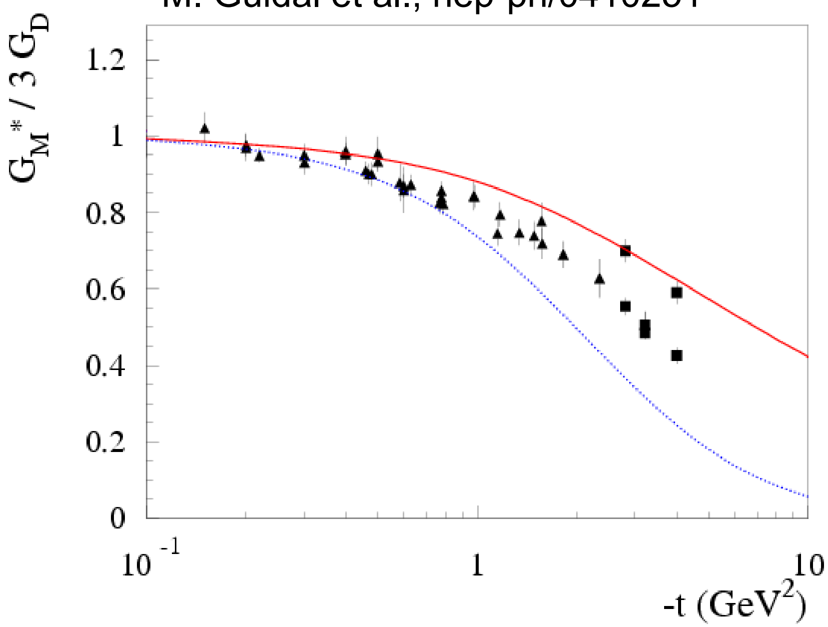
Large N_c limit: p→Δ H_M related to isovector elastic GPDs $E(x,\xi,t)$.

Shapes of GM^*/G_D and G_{EP}/G_{MP} would have similar asymptotic behavior.

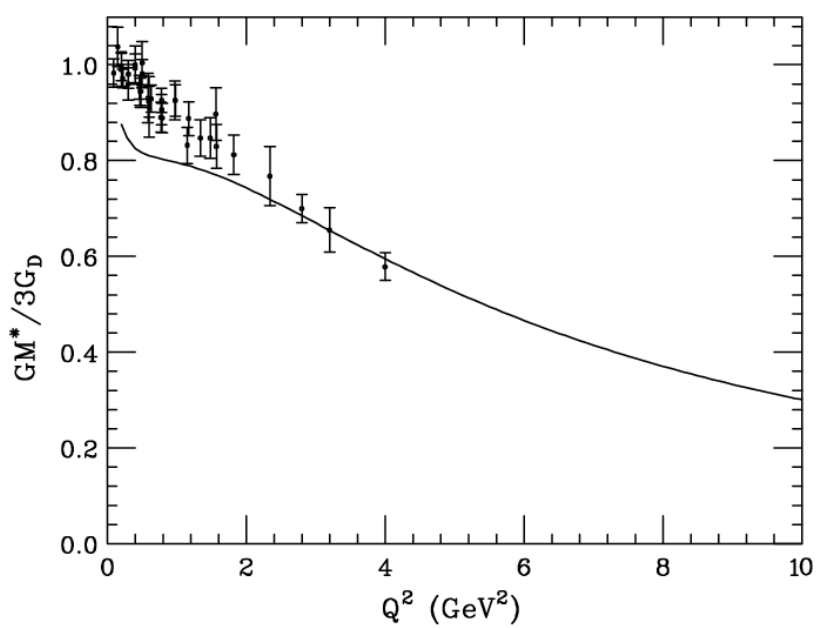


$$G_M^*(t) = \frac{G_M^*(0)}{\kappa_V} \int_{-1}^{+1} dx \left\{ E^u(x,\xi,t) - E^d(x,\xi,t) \right\} = \frac{G_M^*(0)}{\kappa_V} \left\{ F_2^p(t) - F_2^n(t) \right\}$$

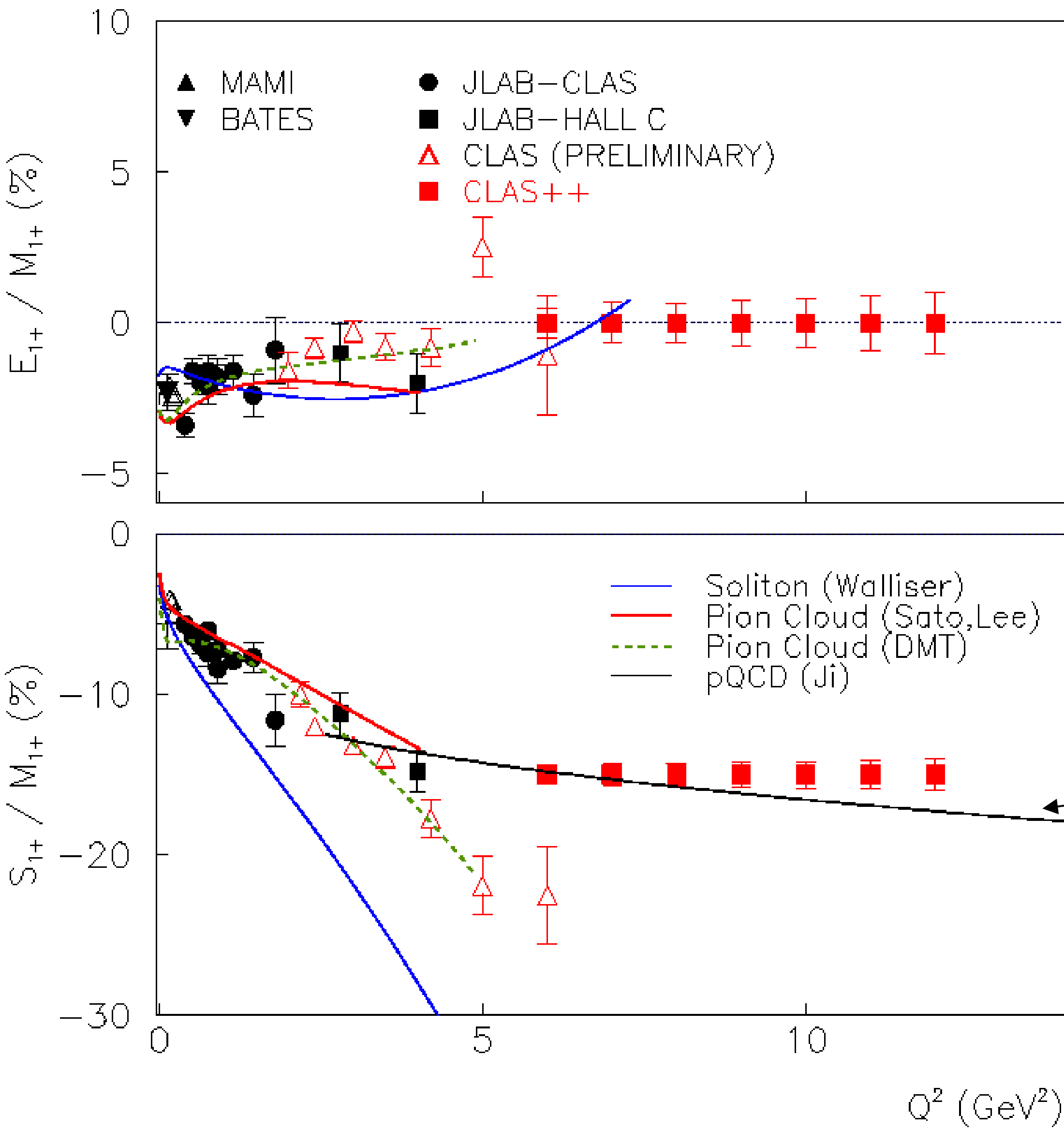
M. Guidal et al., hep-ph/0410251



Stoler, PRL 91,172303 (2003)



Extension of NΔ(1232) Transition F.F. Measurement



$$M1 = -\frac{1}{2}A^{\Delta}_{1/2} - \frac{\sqrt{3}}{2}A^{\Delta}_{3/2}$$

$$E2 = -\frac{1}{2}A^{\Delta}_{1/2} + \frac{1}{2\sqrt{3}}A^{\Delta}_{3/2}$$

pQCD scaling:

$$A^{\Delta}_{1/2} \propto \frac{1}{Q^3} \qquad A^{\Delta}_{3/2} \propto \frac{1}{Q^5}$$

$$\frac{E2}{M1} \xrightarrow{Q^2 \to \infty} 1$$

$$S^{\Delta}_{1/2} \propto \frac{1}{Q^4}\log^2(Q^2/\Lambda^2)$$

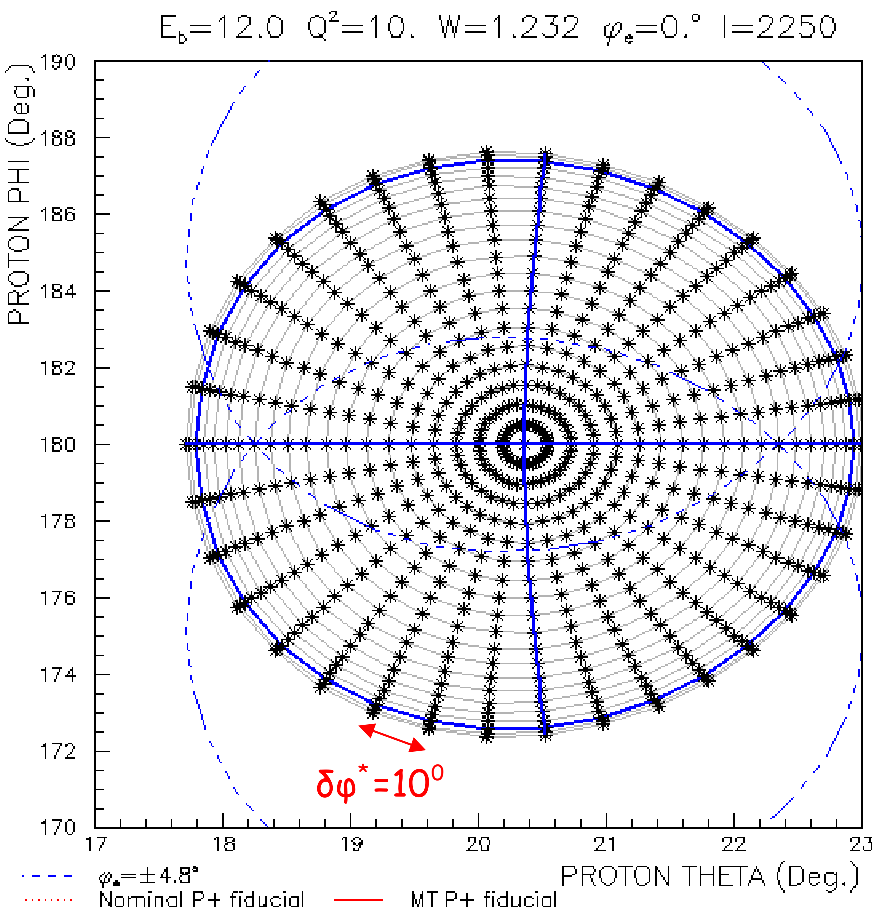
From orbital motion of small-x partons.

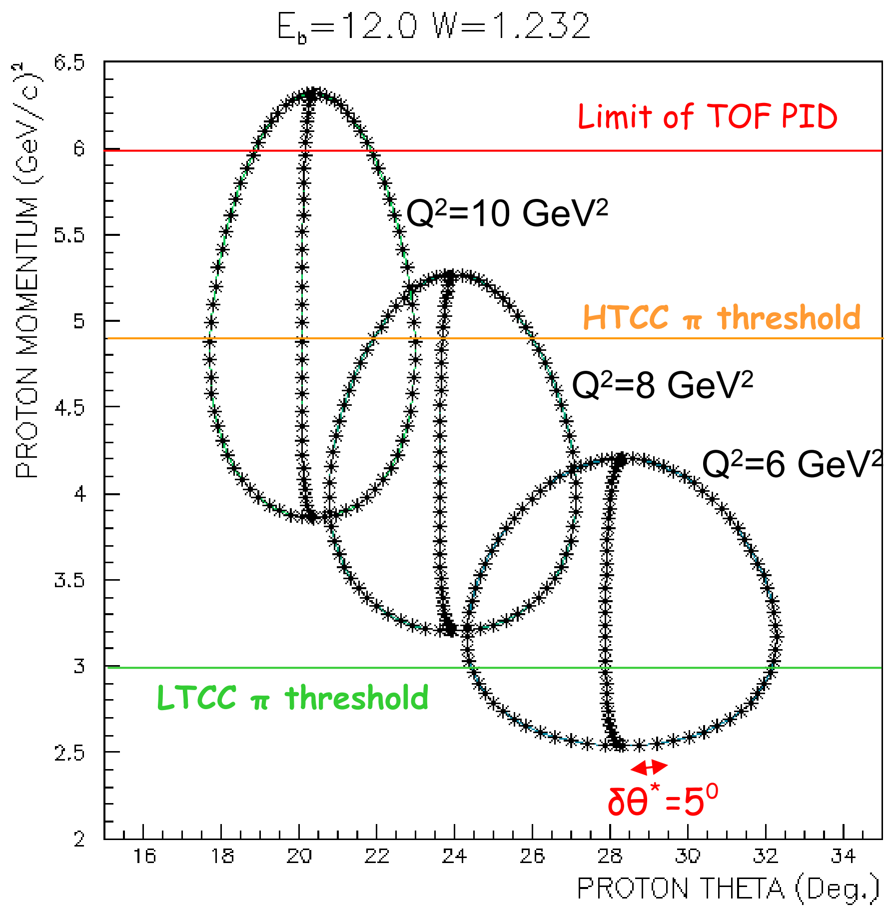
$\Lambda \sim 0.2$ GeV

Errors extrapolated from present measurements assuming $L=10^{35}$ cm^{-2} s^{-1}

Worst case kinematics for p(e,e'p)π^0 at W=1.232 GeV

Lorentz boost of proton kinematics from $p\pi^0$ c.m. to lab





For $\Delta(1232)$ expect $\Delta p/p$~0.35-0.6%

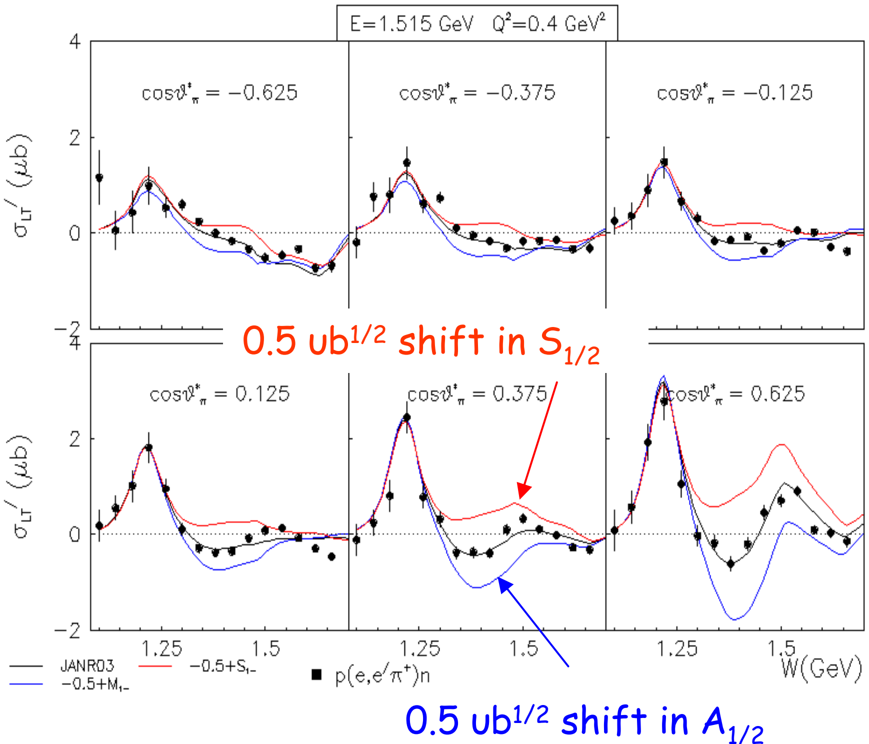
CLAS12: $$\frac{\delta p}{p} = \sqrt{\underbrace{(0.1\% * p)^2}_{\text{spatial}} + \underbrace{(0.2\% / \beta)^2}_{\text{mult. scatt.}}}$$

$\boxed{\delta W \sim 27\,MeV \quad \delta Q^2 \sim 0.1\,GeV^2 \quad \delta\theta_q \sim 0.2^0 \quad \delta\theta^* \sim 5^0}$

Baryon Spectroscopy: Review of JLAB results

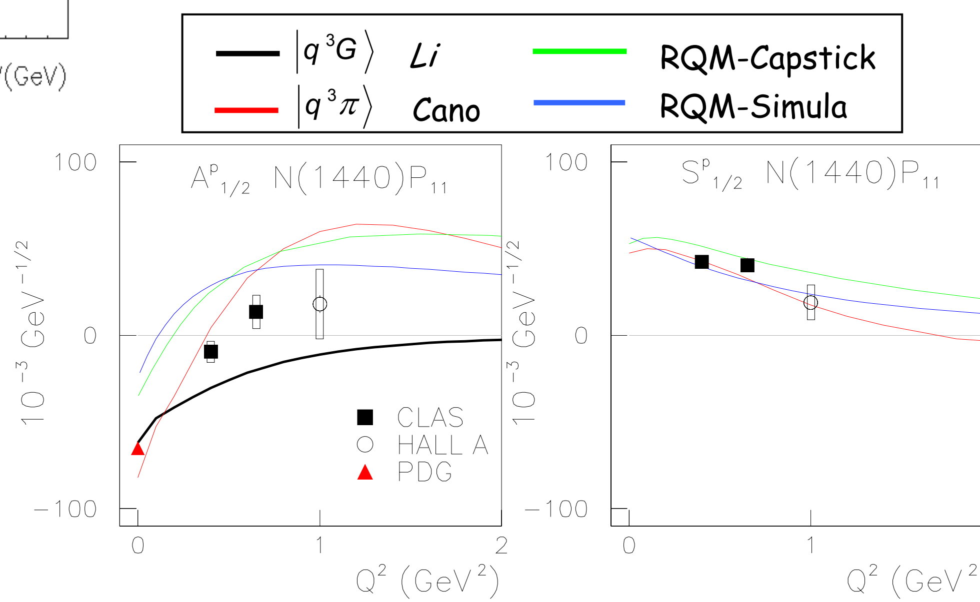
$\gamma^* p \rightarrow N(1440) \rightarrow \pi N$

$$p(\vec{e}, e' \pi^+) n$$



$$\sigma'_{LT} = \mathrm{Im}\,(L^* T)$$

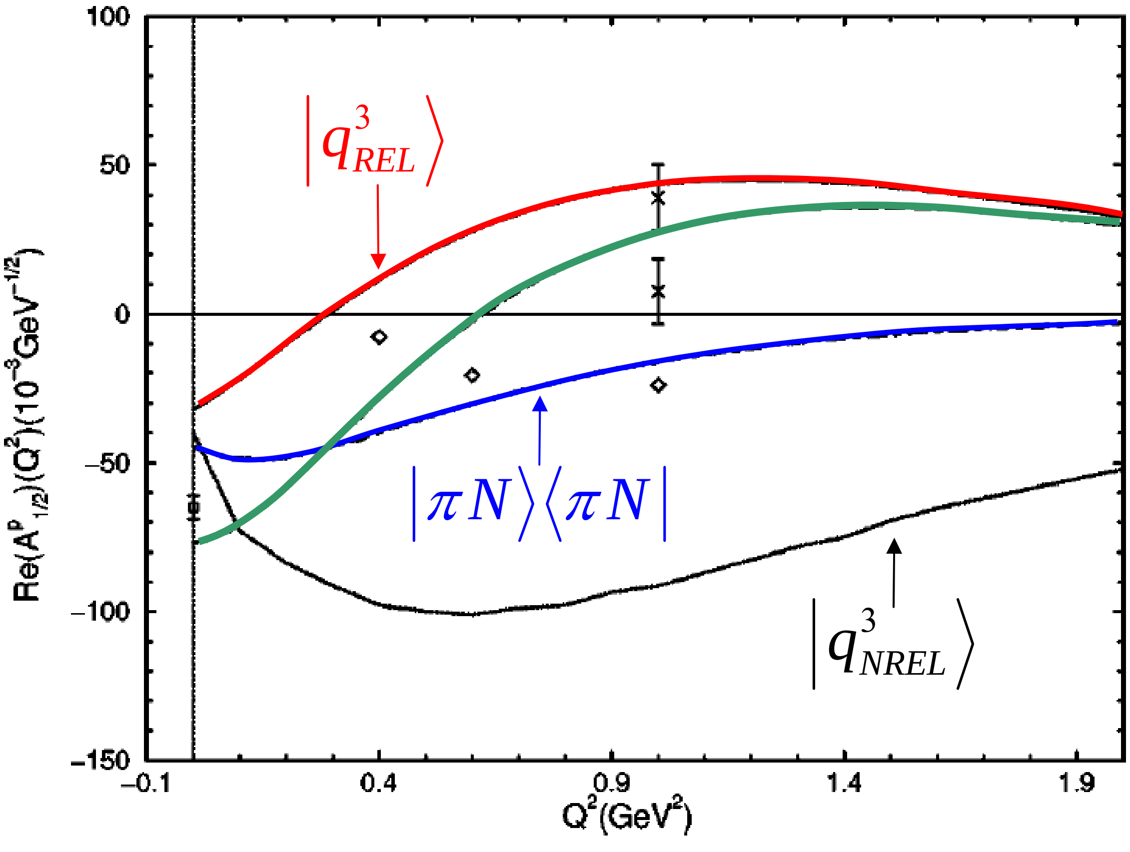
Large sensitivity to imaginary part of $P_{11}(1440)$ through interference with real Born background.



$A_{1/2}$ zero crossing ~ Q^2=0.5 GeV^2 is sensitive to relativistic corrections and meson couplings in models.

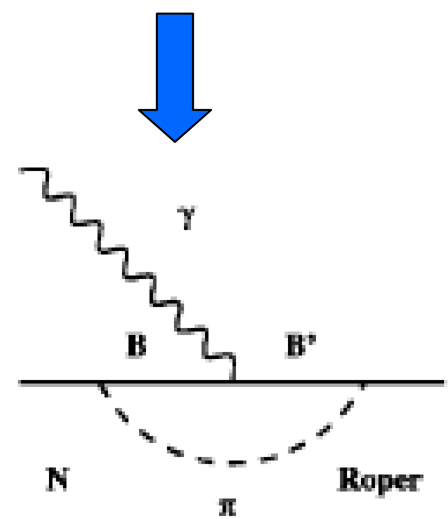
Strong longitudinal strength.
Hybrid (q^3G) model excluded.
Breathing mode + pion coupling?

Models for Roper Electroproduction



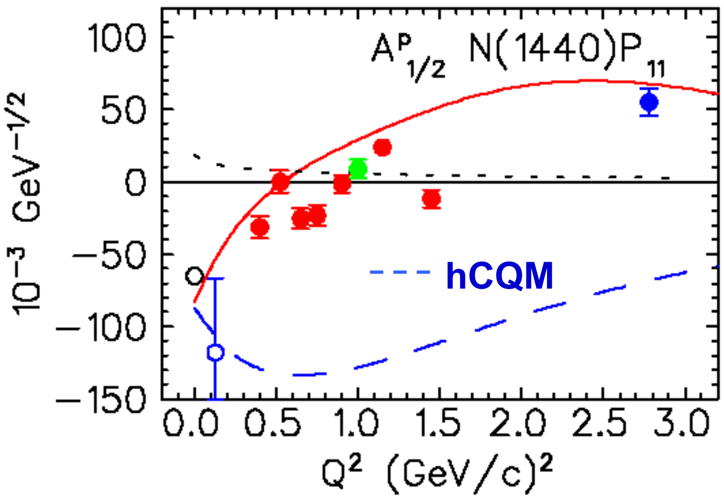
Y.B.Dong, K.Shimuzu, A.Faessler, A.Buchmann PRC, 60, 035203 (1998)

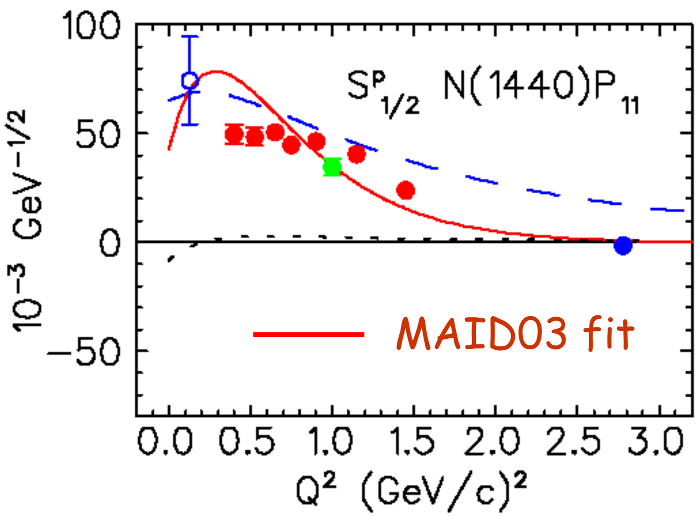
- RQM + meson cloud
- Direct coupling to meson cloud plays small part
- Intermediate πN states important for $A_{1/2}$ zero crossing



Probing the Roper at higher Q^2

Tiator et al. nucl-th/0310041





3-q N=2 radial excitation: slow Q^2 falloff

At Q^2~3, Roper is already comparable in strength to P33, D13 and S11.

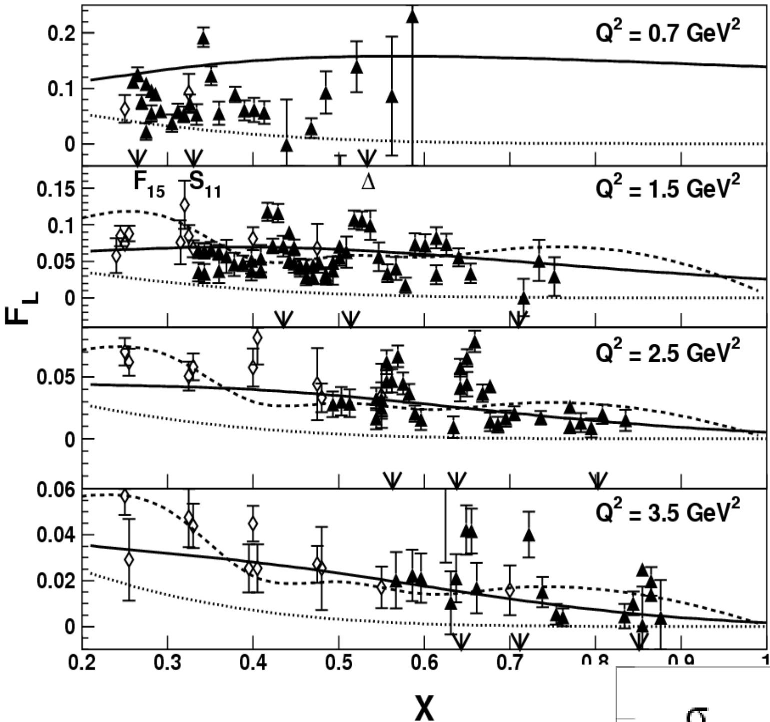
SU(6) limit:

$$A^n_{1/2} / A^p_{1/2} = -2/3$$

$$S^n_{1/2} / S^p_{1/2} = -1$$

SU(6) may be badly broken for this resonance. Data for higher Q^2 and from neutron target may shed light on symmetry breaking mechanisms.

Baryon Spectroscopy: Review of JLAB results



JLAB / Hall C

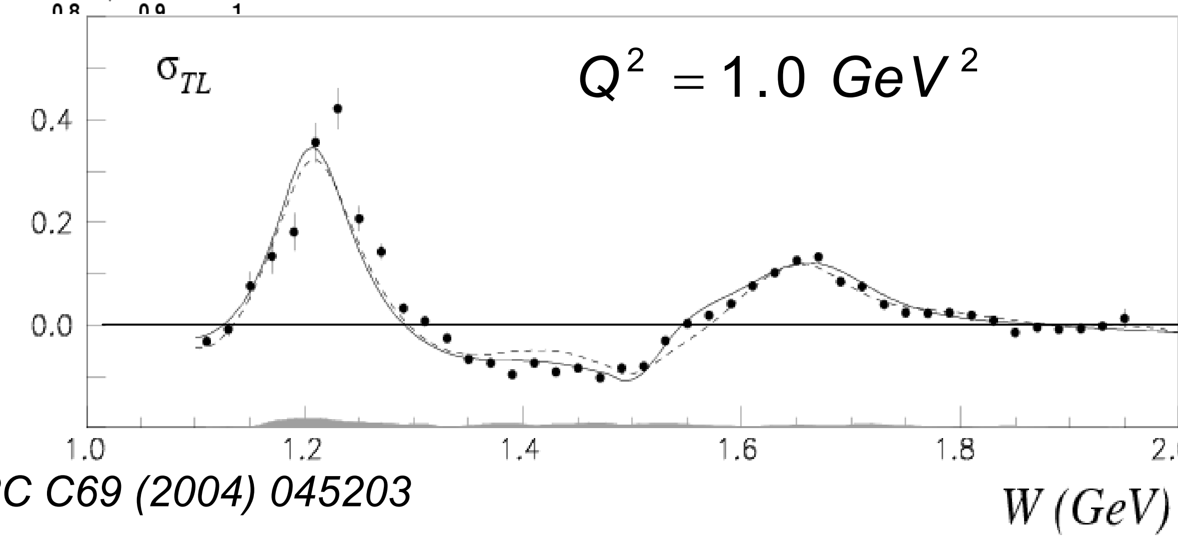
Inclusive Rosenbluth L / T separation

Y. Liang et al., nucl-ex/0410027

Longitudinal resonance couplings should be suppressed for Q^2 and W corresponding to $\Lambda_{\chi SB} > 1$ GeV.

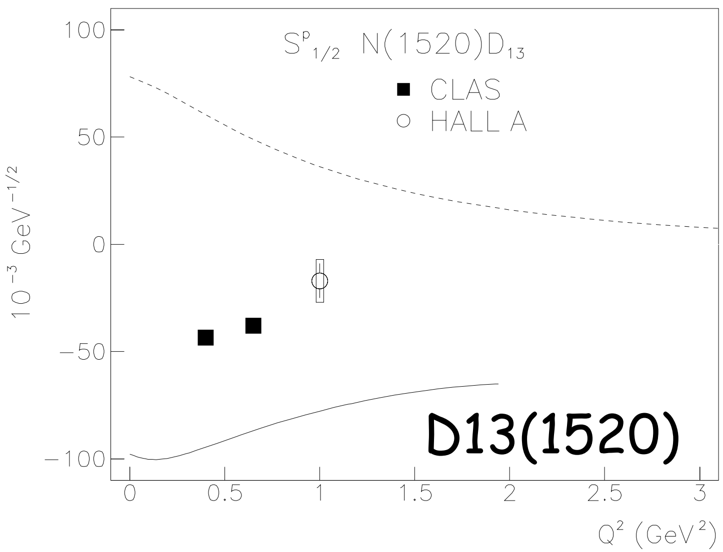
JLAB / Hall A

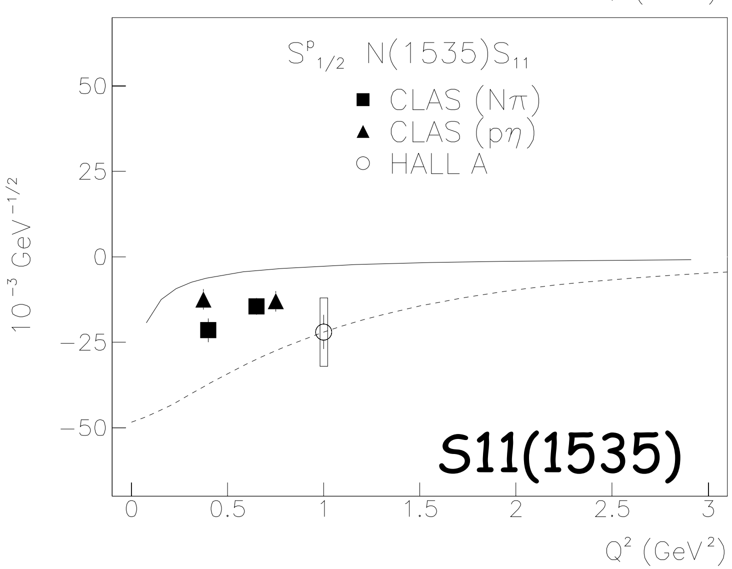
Backward angle π^0 electroproduction



G. Laveissiere et al., PRC C69 (2004) 045203

Global PWA Fit to CLAS Data – Longitudinal Couplings

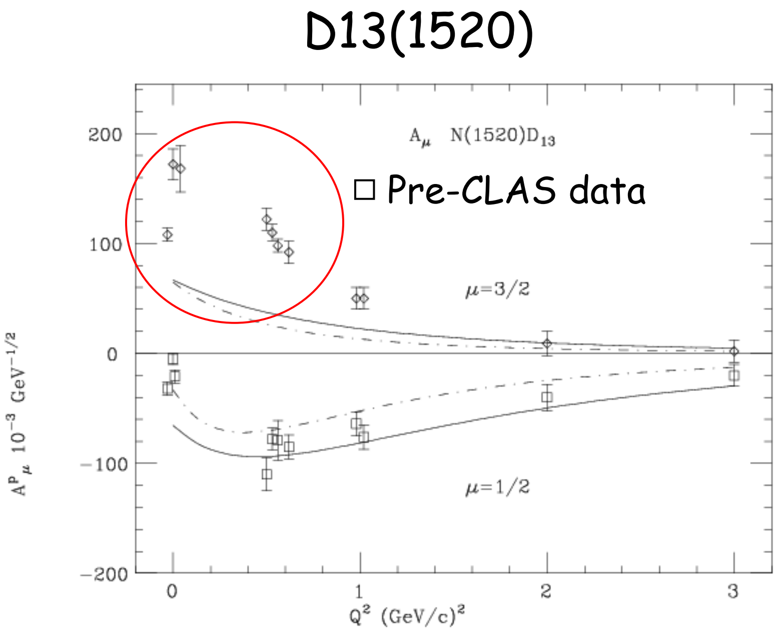


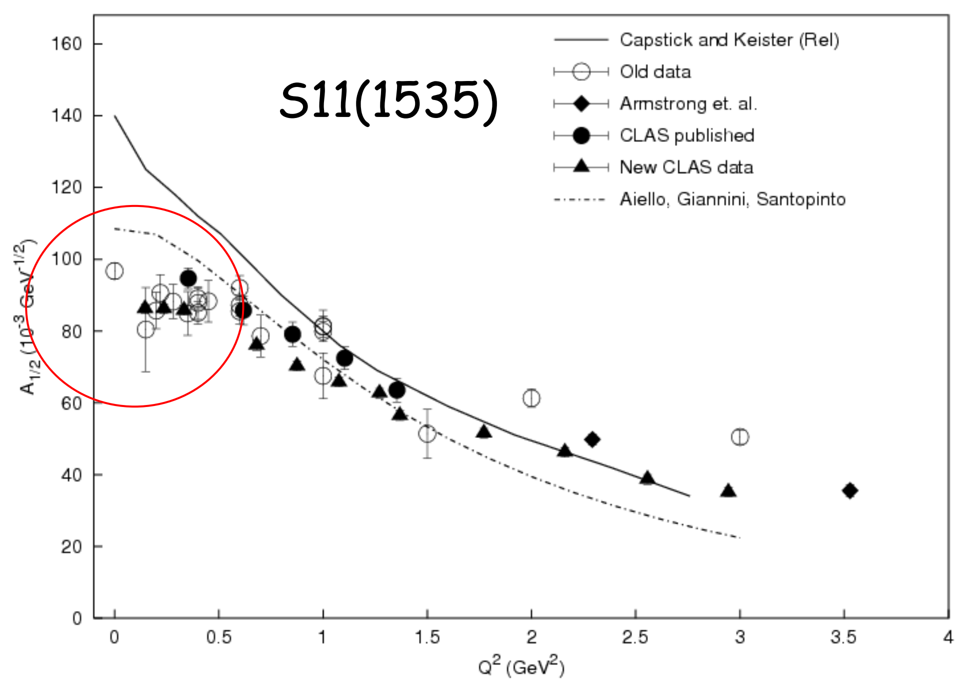


Non-zero longitudinal couplings possible only for massive quarks or spin-0 partons (pion d.o.f).

Baryon Spectroscopy: Review of JLAB results

Second Resonance Region: Transition Form Factors





hCQM model: Underestimates $A_{3/2}$ at low Q^2 (similar to Δ(1232))

Same models *overestimate* S11(1535) strength at low Q^2

Discrepancies at low Q^2 may reflect absence of pion degrees of freedom. Note hCQM uses central confining potential based on flux tube ansatz.

Single Quark Transition Model

EM transitions between all members of two SU(6)xO(3) multiplets expressed as 4 reduced matrix elements A,B,C,D

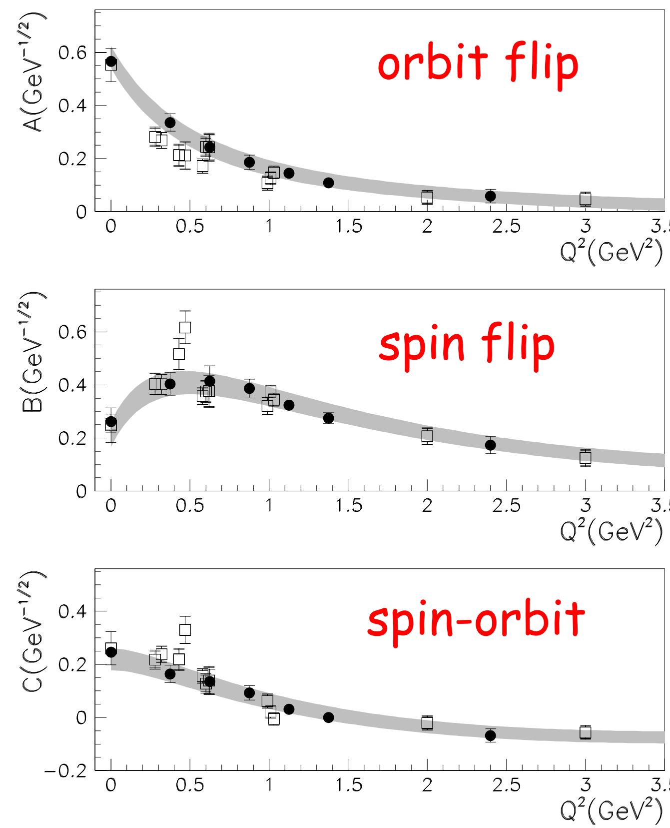
$$J^+ = AL^+ + B\sigma^+L_z + C\sigma_z L^+ + D\sigma^- L^+ L^+$$

$\Delta L_z = 1$ $\quad \Delta S_z = 1$ $\quad \Delta L_z = 1,\ \Delta S_z = 1$ $\quad \Delta L_z = 2,\ \Delta S_z = 1$

$A_{3/2}, A_{1/2}$ ⟵ SU(6) Clebsch-Gordon ⟶ A,B,C,D

Example: $[56, 0^+] \rightarrow [70, 1^-]$ (D=0)

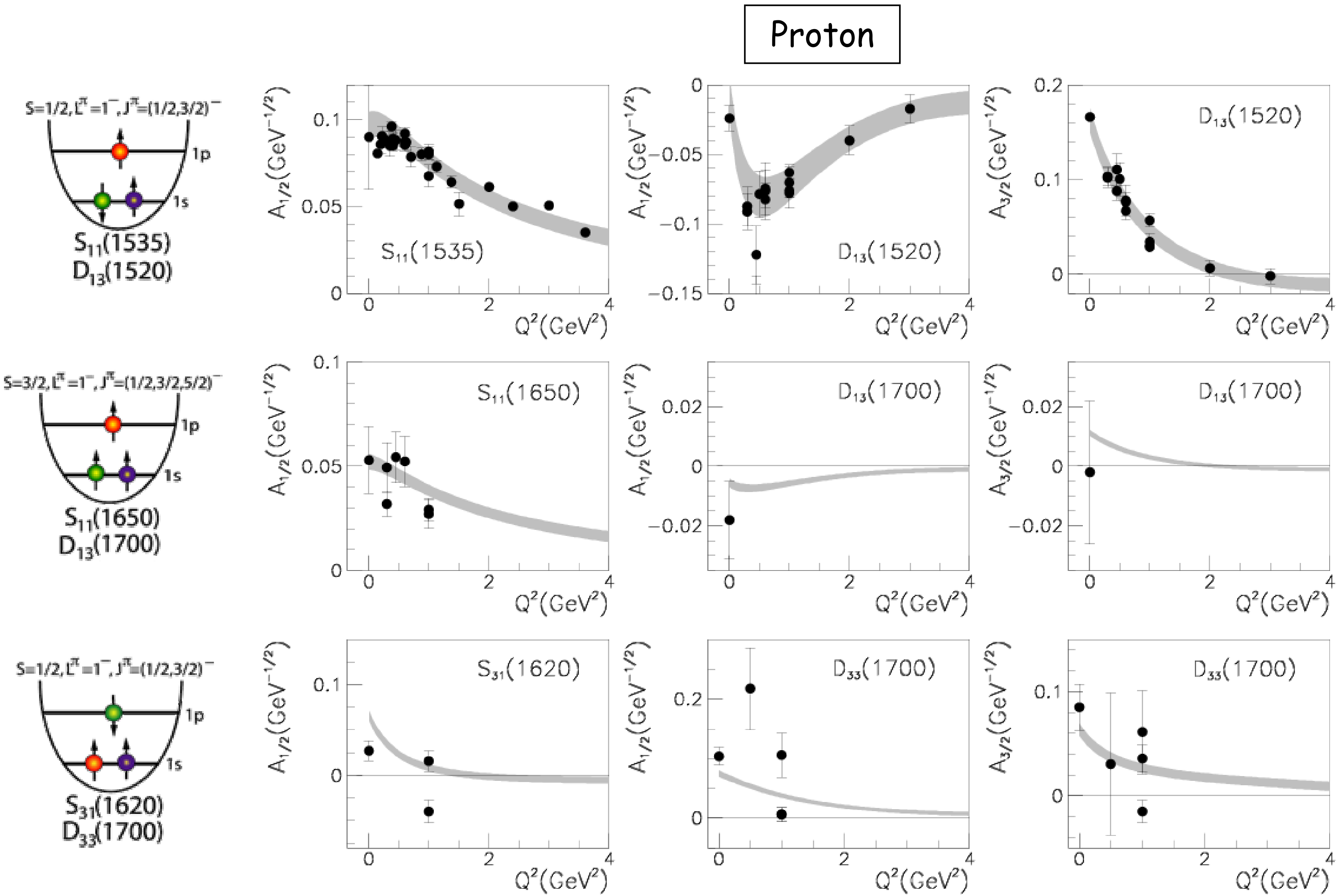
Fit *A,B,C* to $D_{13}(1535)$ and $S_{11}(1520)$



Predicts 16 amplitudes of same supermultiplet

V. Burkert, R. DeVita, M. Battaglieri, M. Ripani, V. Mokeev, PRC67 (2003) 035204

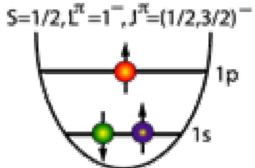
Single Quark Transition Model
Predictions for $[56,0^+] \rightarrow [70,1^-]$ Transitions



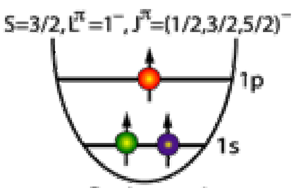
Data of poor quality in 3rd resonance region.

Single Quark Transition Model
Predictions for [56,0⁺]→[70,1⁻] Transitions

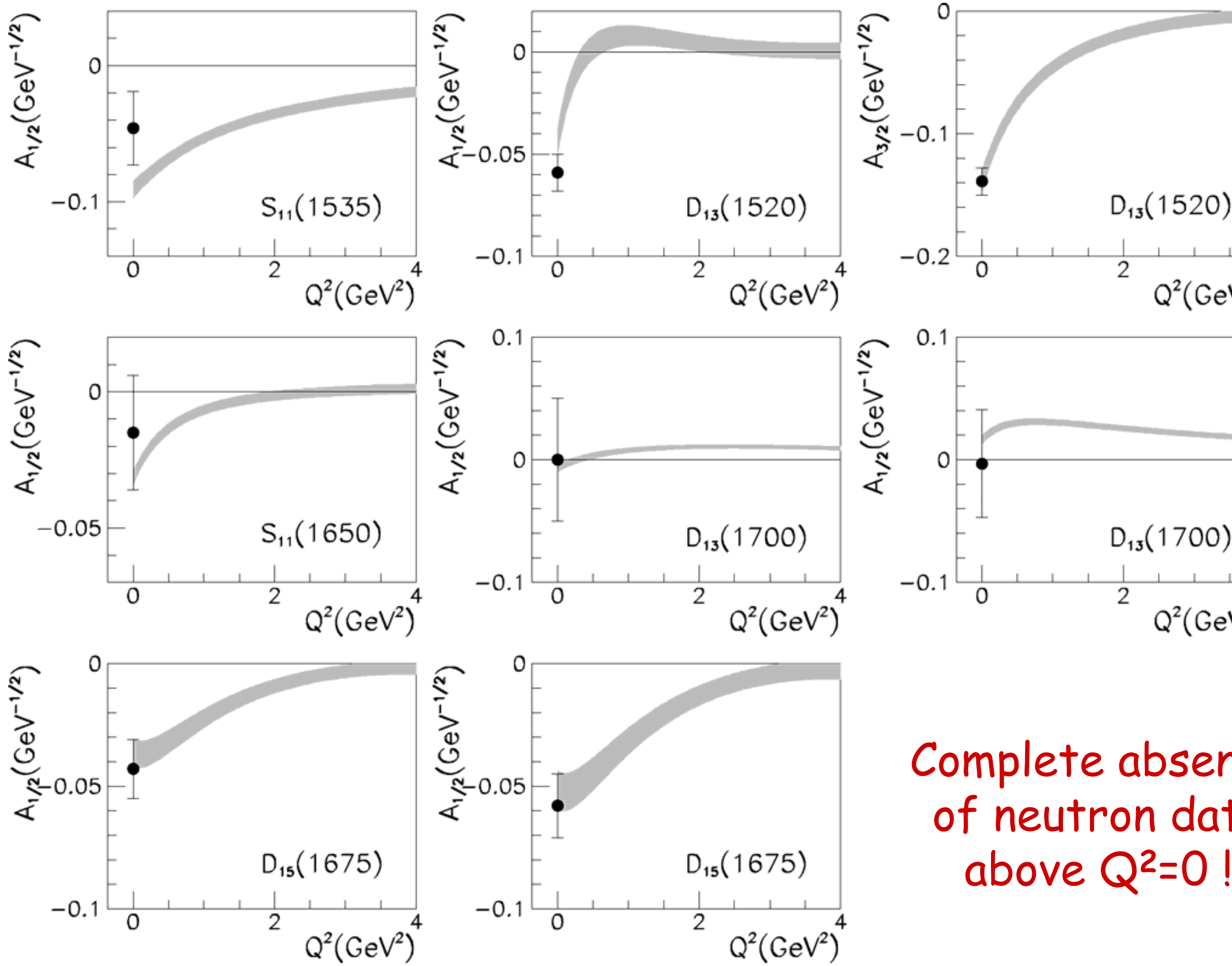
Neutron



$S_{11}(1535)$
$D_{13}(1520)$

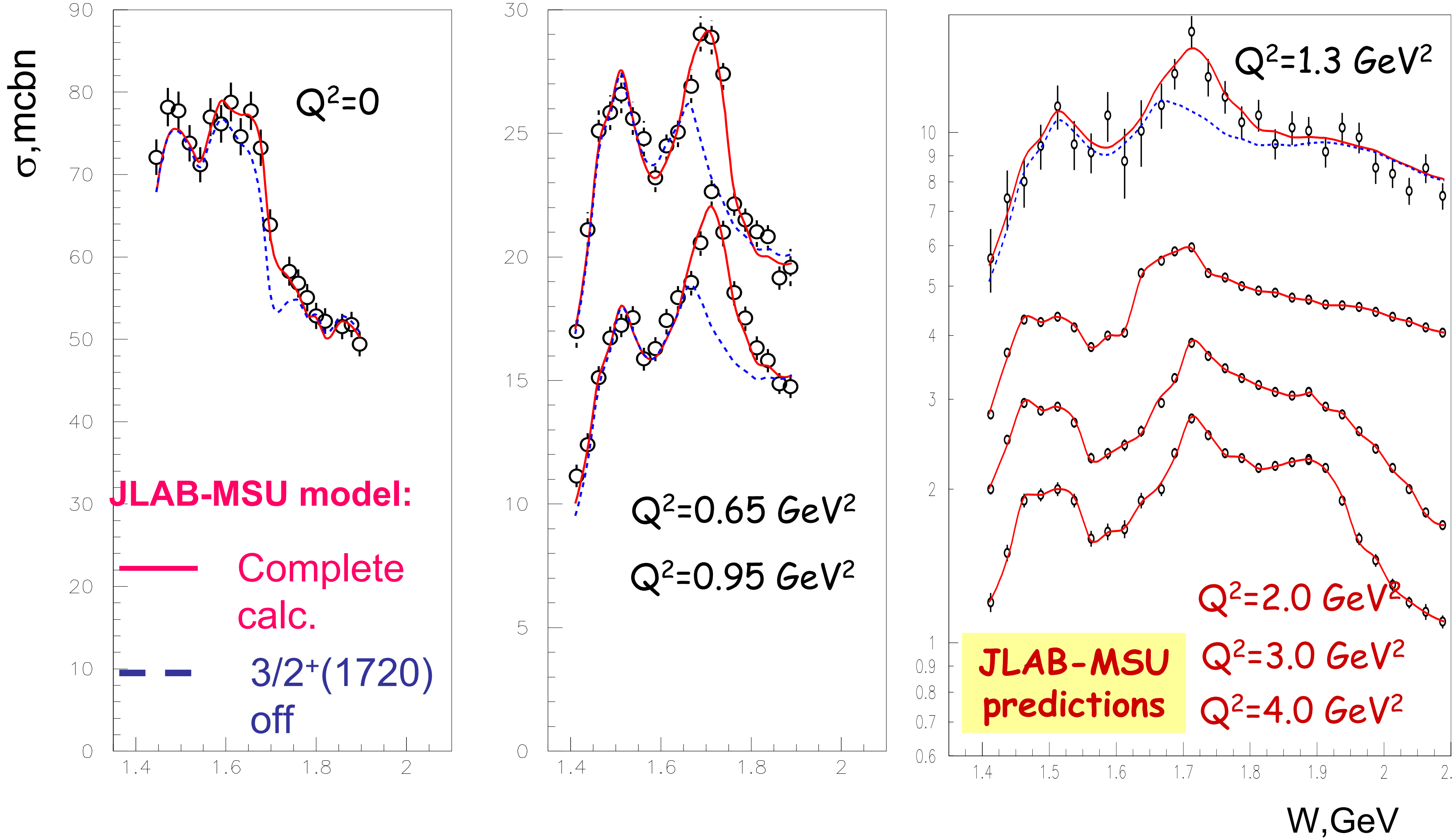


$S_{11}(1650)$
$D_{13}(1700)$
$D_{15}(1675)$



Complete absence of neutron data above $Q^2=0$!

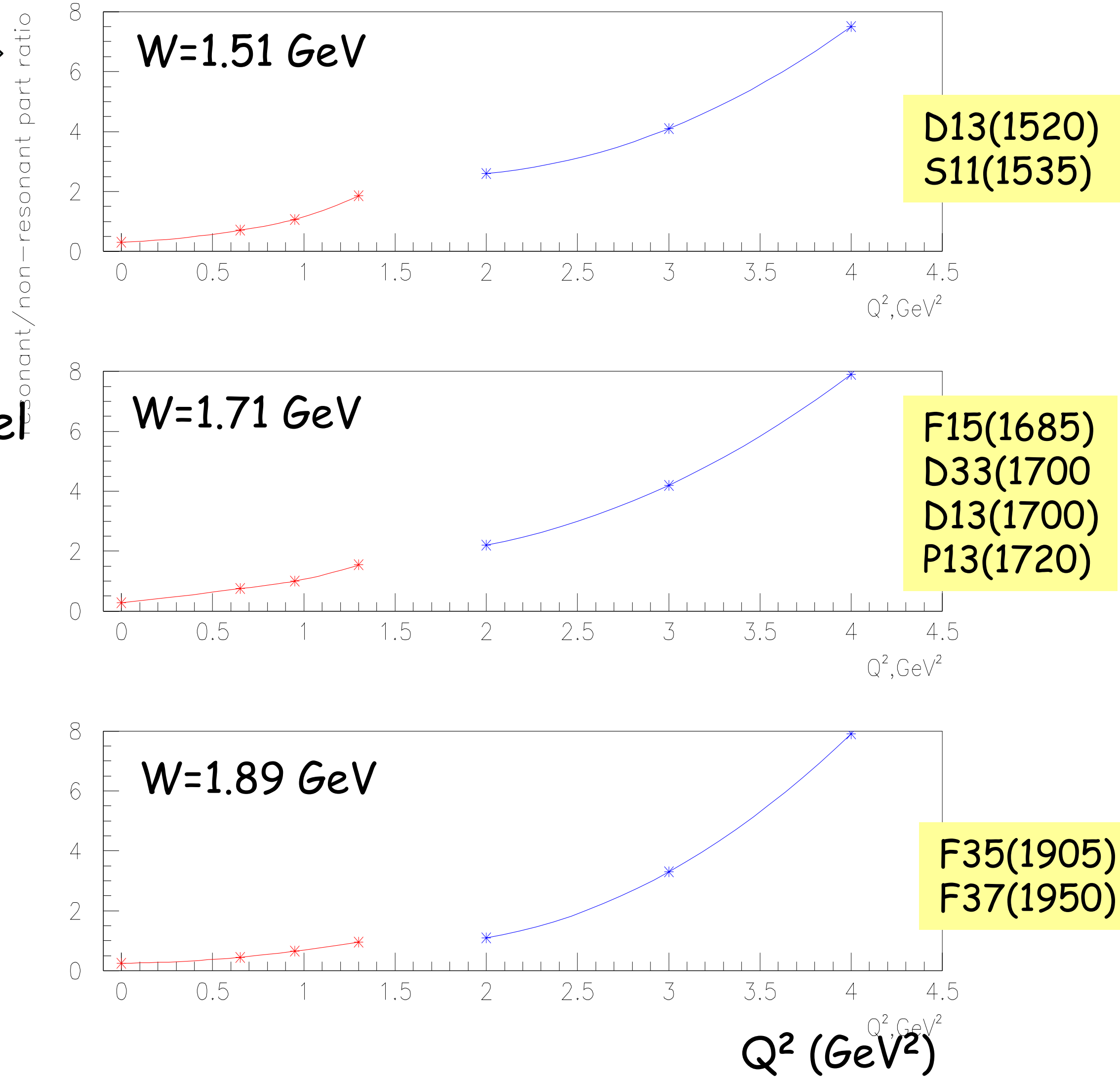
$\gamma\, p \to \pi^+\, \pi^-\, p$: Data from CLAS Experiment E93-006



Two-pion channel promising for missing resonance studies above W=2 GeV and higher Q^2

N* Studies at high Q^2

Resonance/background ratio in 2π photo- and electroproduction



Fits to CLAS 2π Data

JLAB-MSU-INFN model

Resonance contribution *increases* relative to background with Q^2, making high Q^2 preferable for N* studies in 2π electroproduction

$\gamma p \to \pi^+ \pi^- p$: Estimated integrated x-sections for $Q^2 > 4.5$ GeV^2

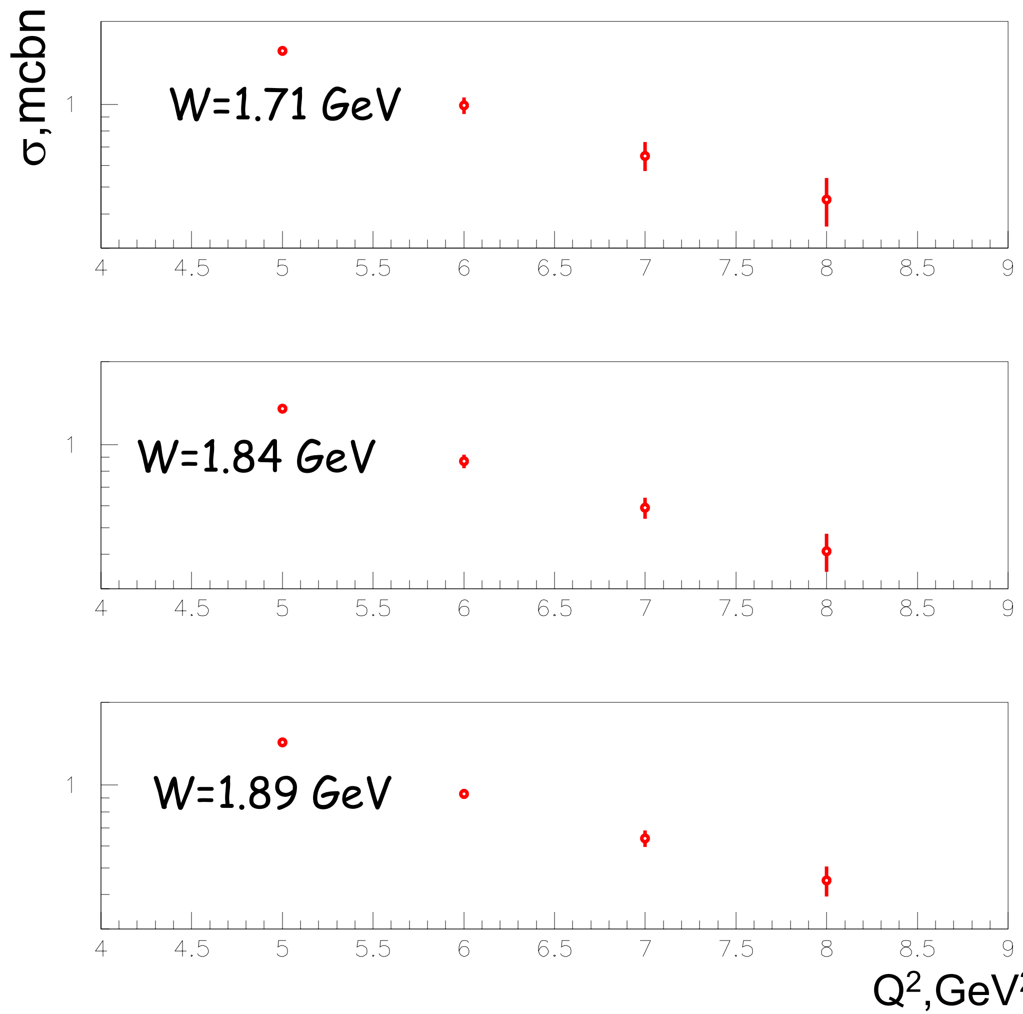
Errors correspond to factor 6 luminosity gain with respect to e1-6 CLAS data

Integrated 2π cross-sections estimated from total inclusive cross-sections σ_{tot} as:

$$\sigma_{2\pi}=\sigma_{tot}*(\sigma_{2\pi}/\sigma_{tot})$$

σ_{tot} obtained from fit of F_2 structure function reported in L.W. Witlow et al., Phys. Lett. B282, 475, (1992)

$\sigma_{2\pi}/\sigma_{tot}$ taken from CLAS data at $0.5 < Q^2 < 1.5$ GeV^2 and extrapolated to high Q^2.



Summary

- Combined program of meson and baryon spectroscopy can usefully exploit upgrade of beam energy, luminosity and detector.
  - Central tracker + BoNuS essential for detection of recoil nuclei and for tagging recoil spectator protons from deuterium (neutron) targets.
  - Central calorimeter will provide wide angle detection of π^0 to assist determination of $\Delta(1232) \rightarrow p\pi^0$ final state.
  - Forward angle tagger will provide high luminosity, linearly polarized tagged photons to enhance production and identification of exotics.
  - Increase in beam energy will open unexplored kinematics.

- Physics program provides novel experiments which utilize unique capabilities of CLAS.
  - Possibility to study excited glue in both mesons and baryons.
  - Search for missing resonances in both heavy and light quark systems.
  - Continue to push current N* program to higher W and Q^2.
  - Strategy for testing fundmental assumptions underlying constituent quark model.