Electromagnetic Transition Form Factors

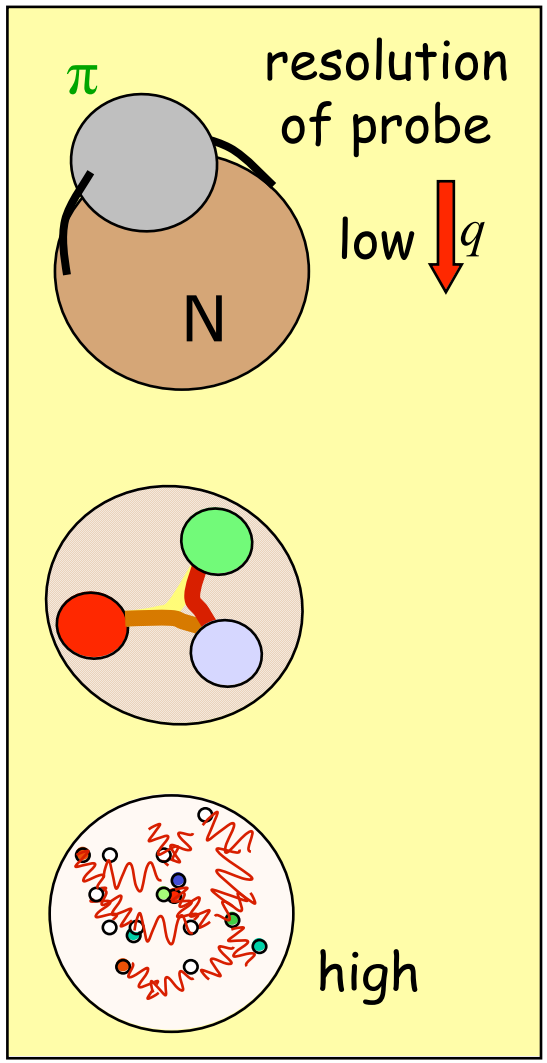
Aznauryan, V. D. Burkert, V. Mokeev

Jefferson Lab

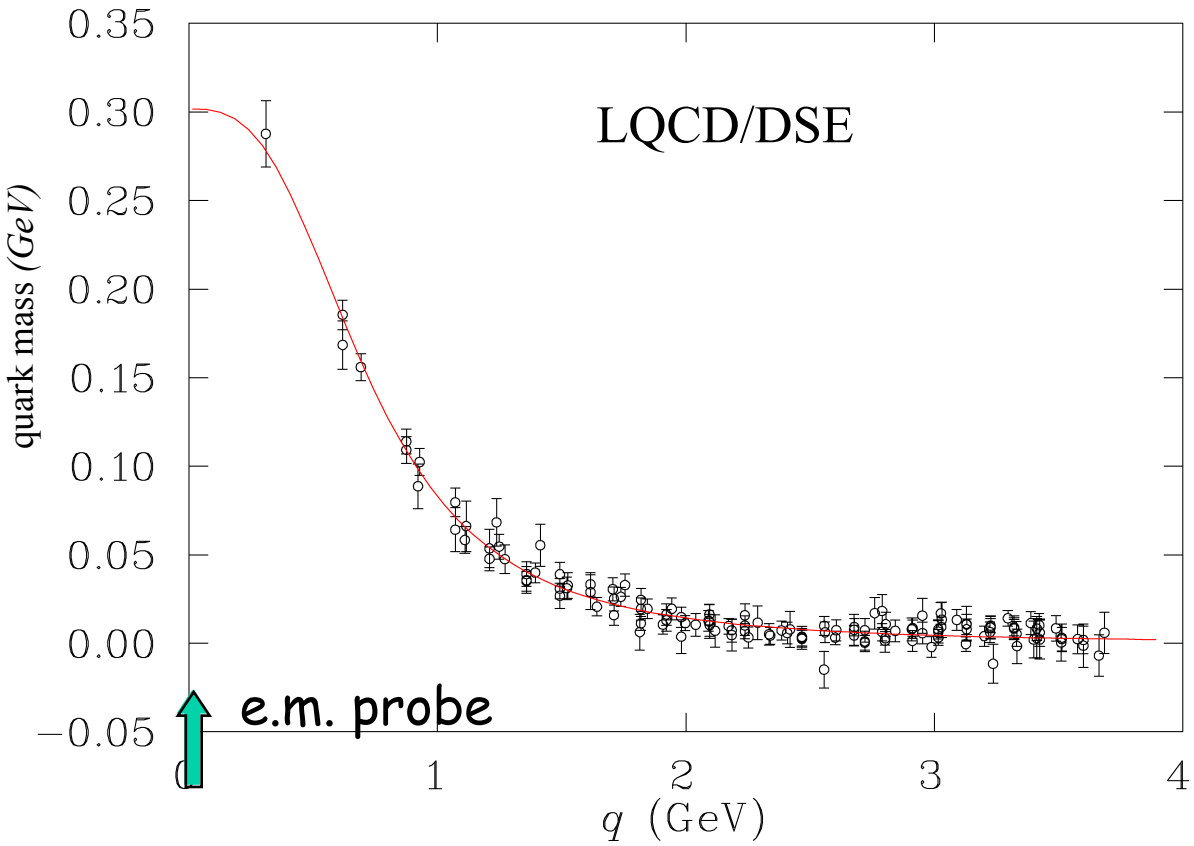
(CLAS Collaboration)

- Motivation
- Baryon resonance transitions in Nπ, Nη
  - NΔ(1232) multipoles
  - Roper $P_{11}(1440)$, $S_{11}(1535)$
  - Helicity structure of $D_{13}(1520)$
- Transition amplitudes in $p\pi^+\pi^-$ channel
  - $P_{11}(1440)$, $D_{13}(1520)$, $D_{33}(1700)$, $P_{13}(1720)$
- Summary & Outlook

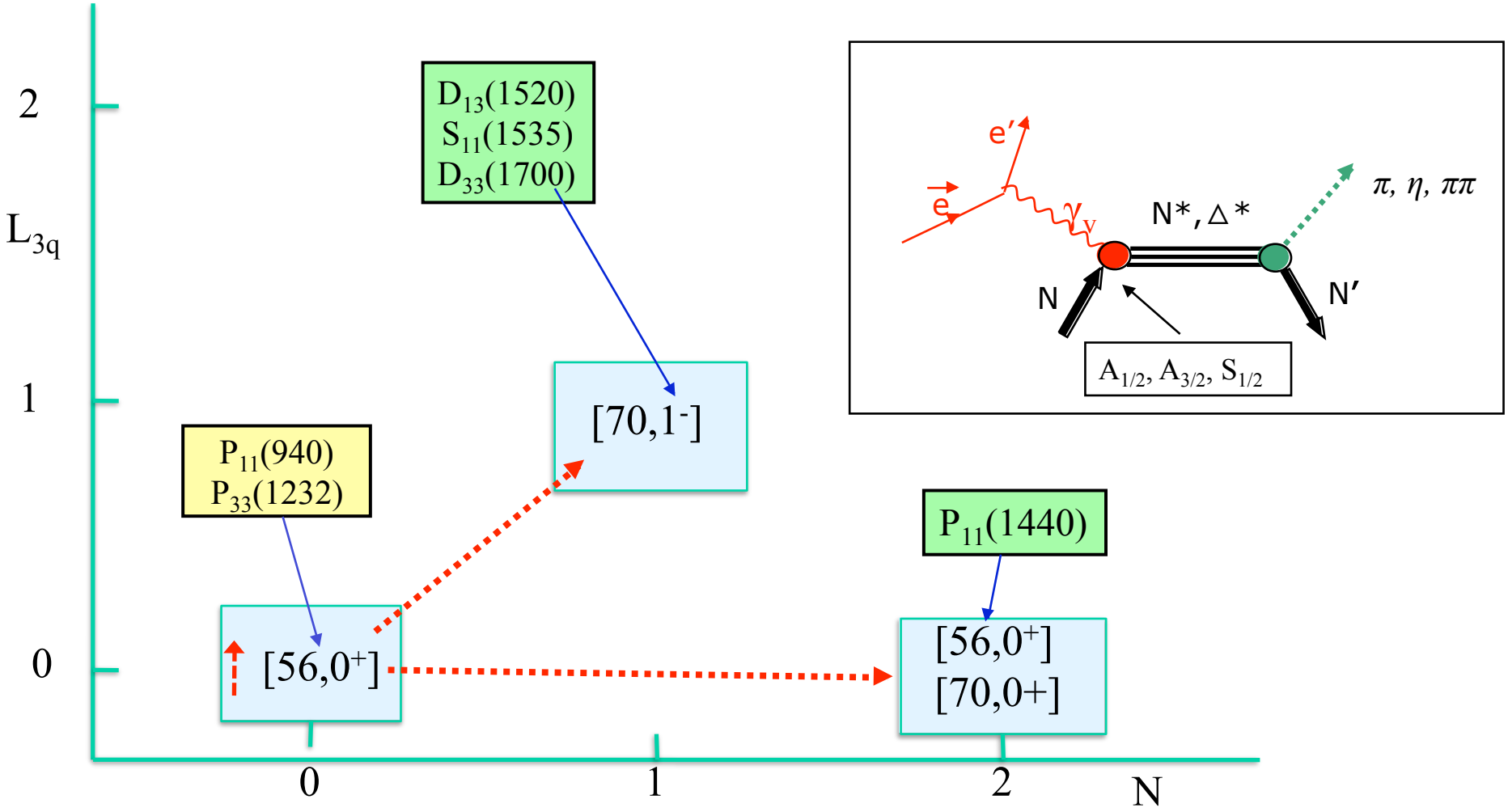
Hadron Structure with e.m. Probes?



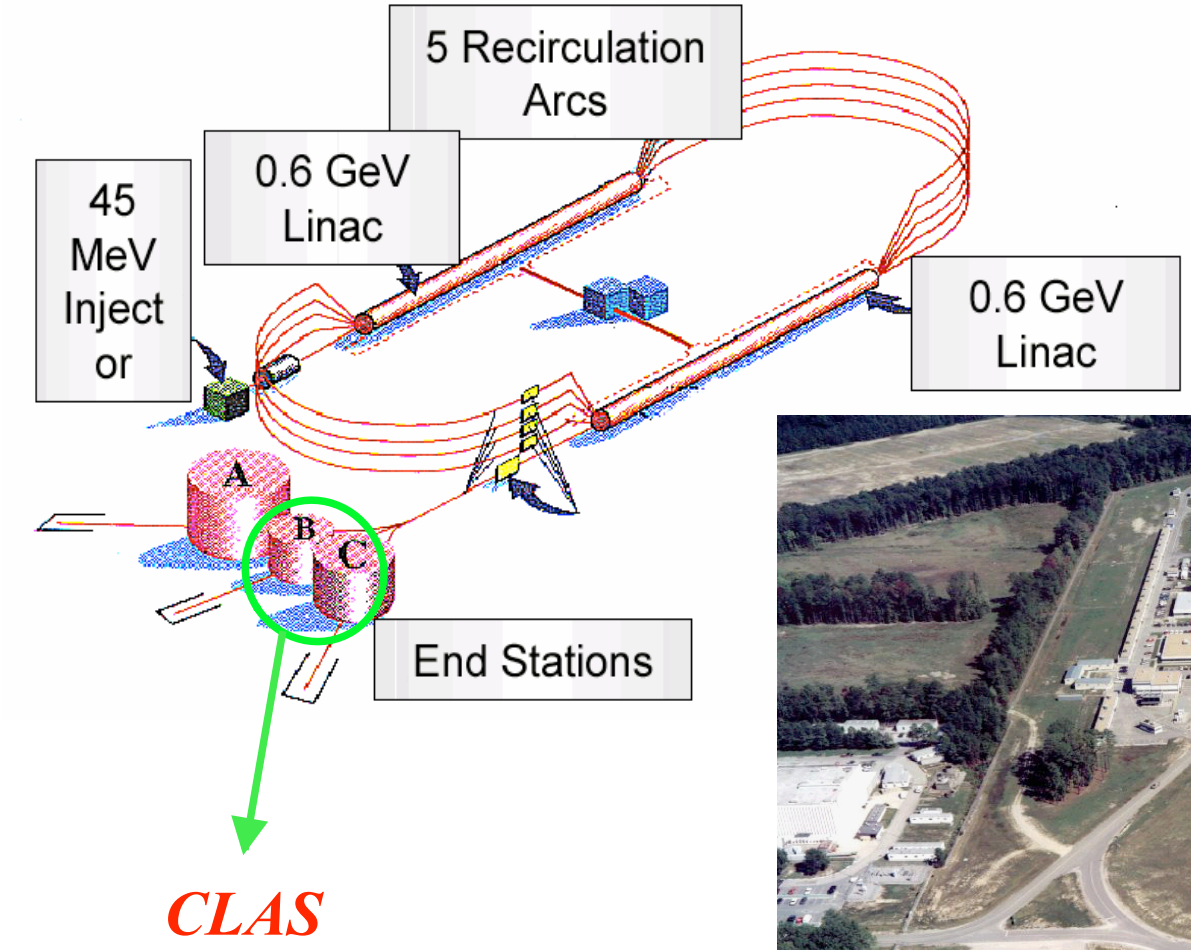
Allows to address central question:
What are the relevant degrees-of-freedom at varying distance scale?



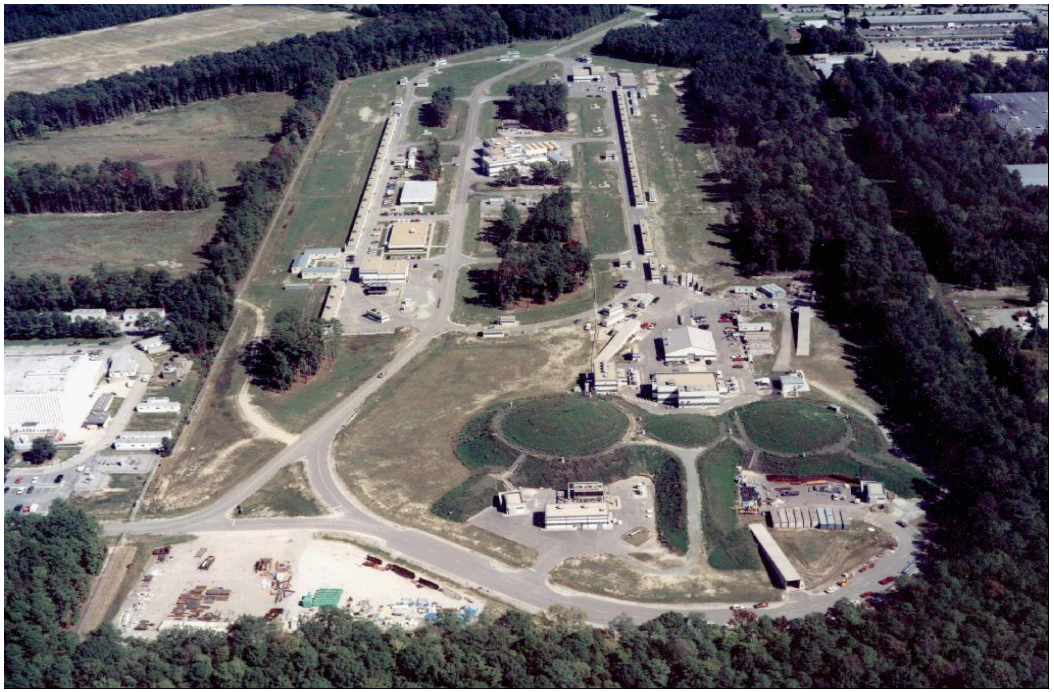
SU(6)xO(3) Classification of lowest lying Baryons

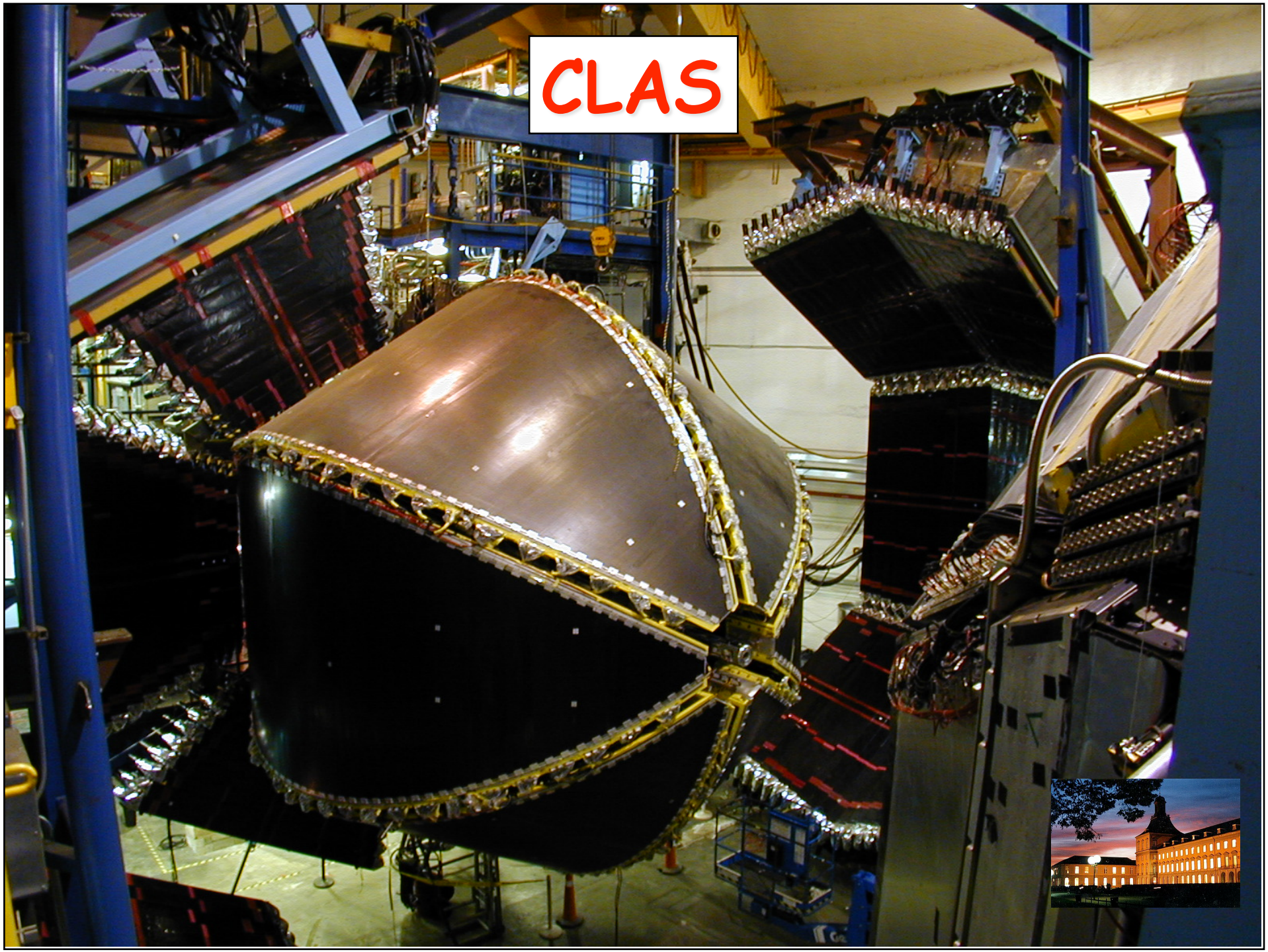


JLab Site: The 6 GeV CW Electron Accelerator

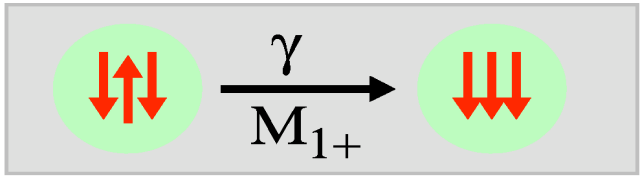


E_{max}	~ 6 GeV
I_{max}	~ 200 μA
Duty Factor	~ 100%
σ_E/E	~ 2.5 10^{-5}
Beam P	~ 85%
$E_{g(tagged)}$	~ 0.8-5.5GeV

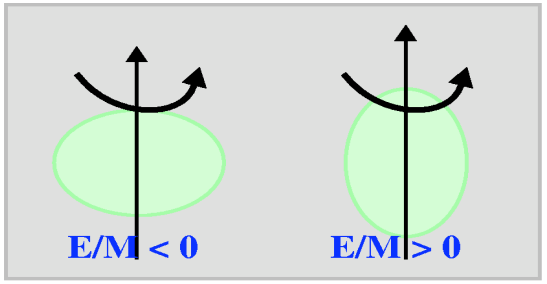



CLAS

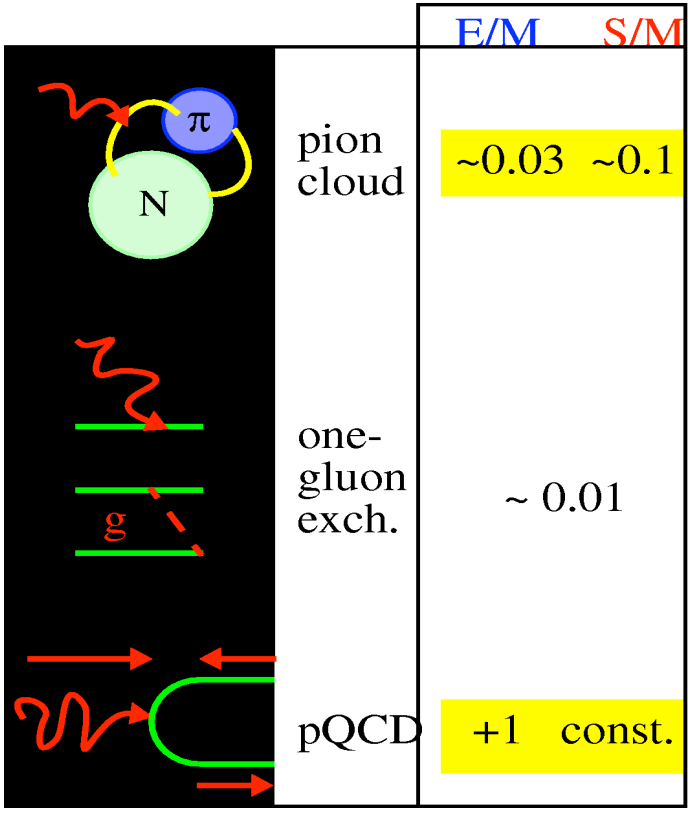
N-Δ(1232) Quadrupole Transition

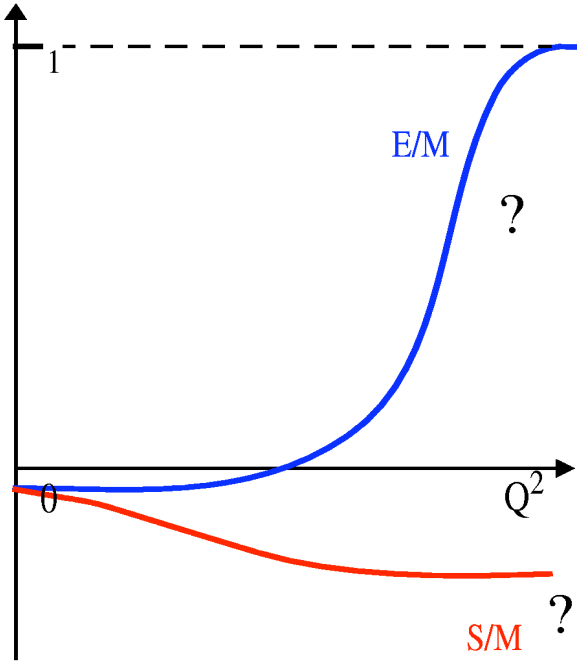


SU(6): $E_{1+}=S_{1+}=0$

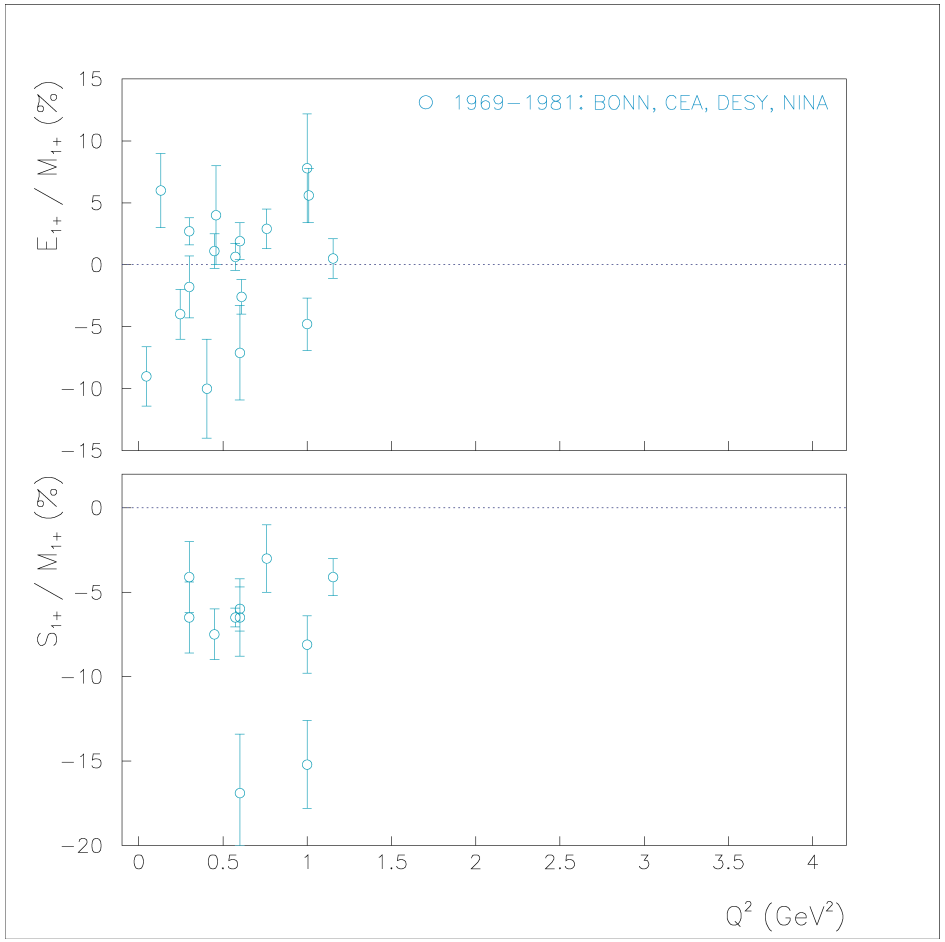


(A. Buchmann, E. Henley, 2000)





Multipole Ratios R_{EM}, R_{SM} before 1999



⟸ Sign?

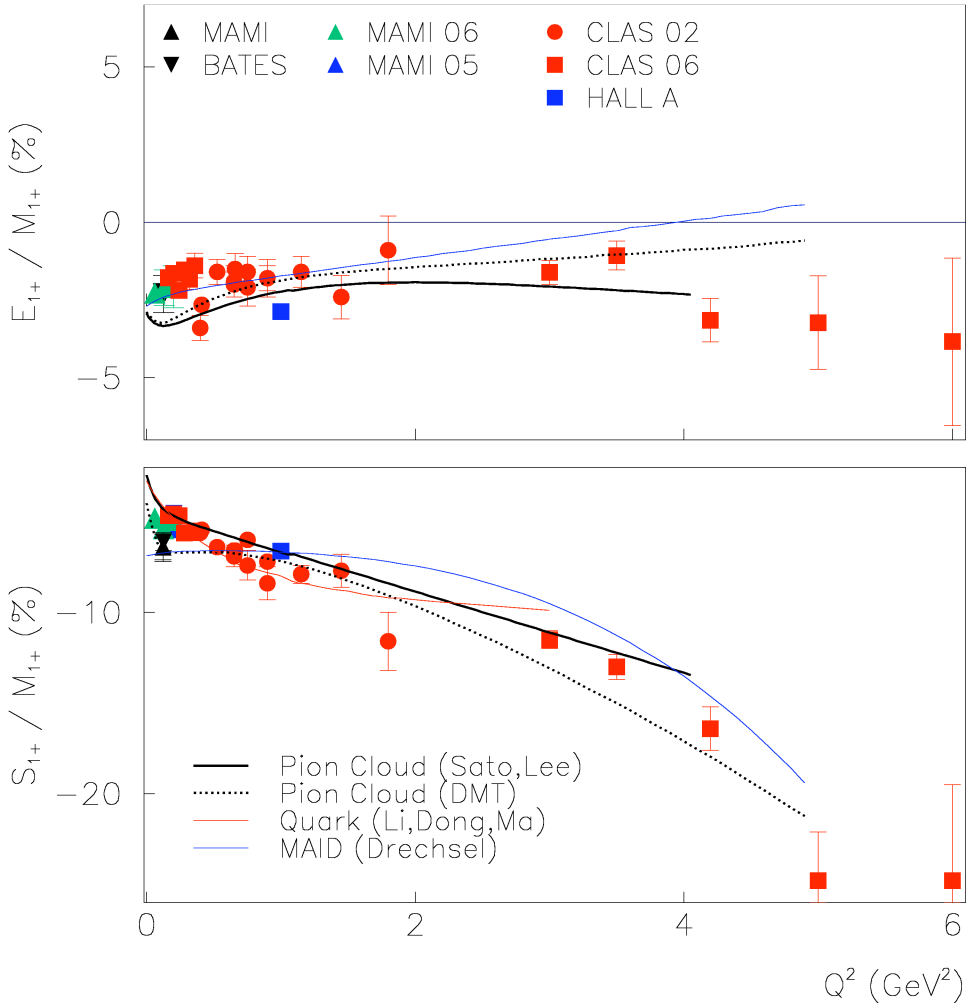
⟸ Q^2 dependence?

➢ Data could not determine sign or Q^2 dependence

N Δ electroproduction experiments after 1999

Reaction	Observable	W	Q^2	Author, Conference, Publication	LAB
$p(e,e'p)\pi^0$	σ_0 σ_{TT} σ_{LT} σ_{LTP}	1.221	0.060	S. Stave, EPJA, 30, 471 (2006)	MAMI
$p(e,e'p)\pi^0$	$R^t_{LT'}$ R^n_{LT} R^l_{LT}	1.232	0.121	H. Schmieden, EPJA, 28, 91 (2006)	MAMI
$p(e,e'p)\pi^0$	$R^t_{LT'}$ R^n_{LT} R^l_{LT}	1.232	0.121	Th. Pospischil, PRL 86, 2959 (2001)	MAMI
$p(e,e'p)\pi^0$	σ_0 σ_{TT} σ_{LT} σ_{LTP}	1.232	0.127	C. Mertz, PRL 86, 2963 (2001) C. Kunz, PLB 564, 21 (2003) N. Sparveris, PRL 94, 22003 (2005)	BATES
$p(e,e'p)\pi^0$	σ_0 σ_{TT} σ_{LT} σ_{LTP}	1.232 1.221	0.127 0.200	N. Sparveris, SOH Workshop (2006) N. Sparveris, nucl-ex/611033	MAMI
$p(e,e'p)\pi^0$	A_{LT} A_{LTP}	1.232	0.200	P. Bartsch, PRL 88, 142001 (2002) D. Elsner, EPJA, 27, 91 (2006)	MAMI
$p(e,e'p)\pi^0$ $p(e,e'\pi+)n$	σ_0 σ_{TT} σ_{LT} σ_{LTP}	1.10-1.40	0.16-0.35	C. Smith, SOH Workshop (2006)	JLAB / CLAS
$p(e,e'p)\pi^0$	σ_0 σ_{TT} σ_{LT}	1.11-1.70	0.4-1.8	K. Joo, PRL 88, 122001 (2001)	JLAB / CLAS
$p(e,e'p)\pi^0$ $p(e,e'\pi+)n$	σ_{LTP}	1.11-1.70	0.40,0.65	K. Joo, PRC 68, 32201 (2003) K. Joo, PRC 70, 42201 (2004) K. Joo, PRC 72, 58202 (2005)	JLAB / CLAS
$p(e,e'\pi+)n$	σ_0 σ_{TT} σ_{LT}	1.11-1.60	0.3-0.6	H. Egiyan, PRC 73, 25204 (2006)	JLAB / CLAS
$p(e,e'p)\pi^0$	16 response functions	1.17-1.35	1.0	J. Kelly, PRL 95, 102001 (2005)	JLAB / Hall A
$p(e,e'p)\pi^0$	σ_0 σ_{TT} σ_{LT}	1.10-1.40	3.0-6.0	M. Ungaro, PRL 97, 112003 (2006)	JLAB / CLAS
$p(e,e'p)\pi^0$	σ_0 σ_{TT} σ_{LT}	1.10-1.35	2.8, 4.0	V. Frolov, PRL 82 , 45 (1999)	JLAB / Hall C

NΔ Multipole Ratios R_{EM}, R_{SM} in 2007

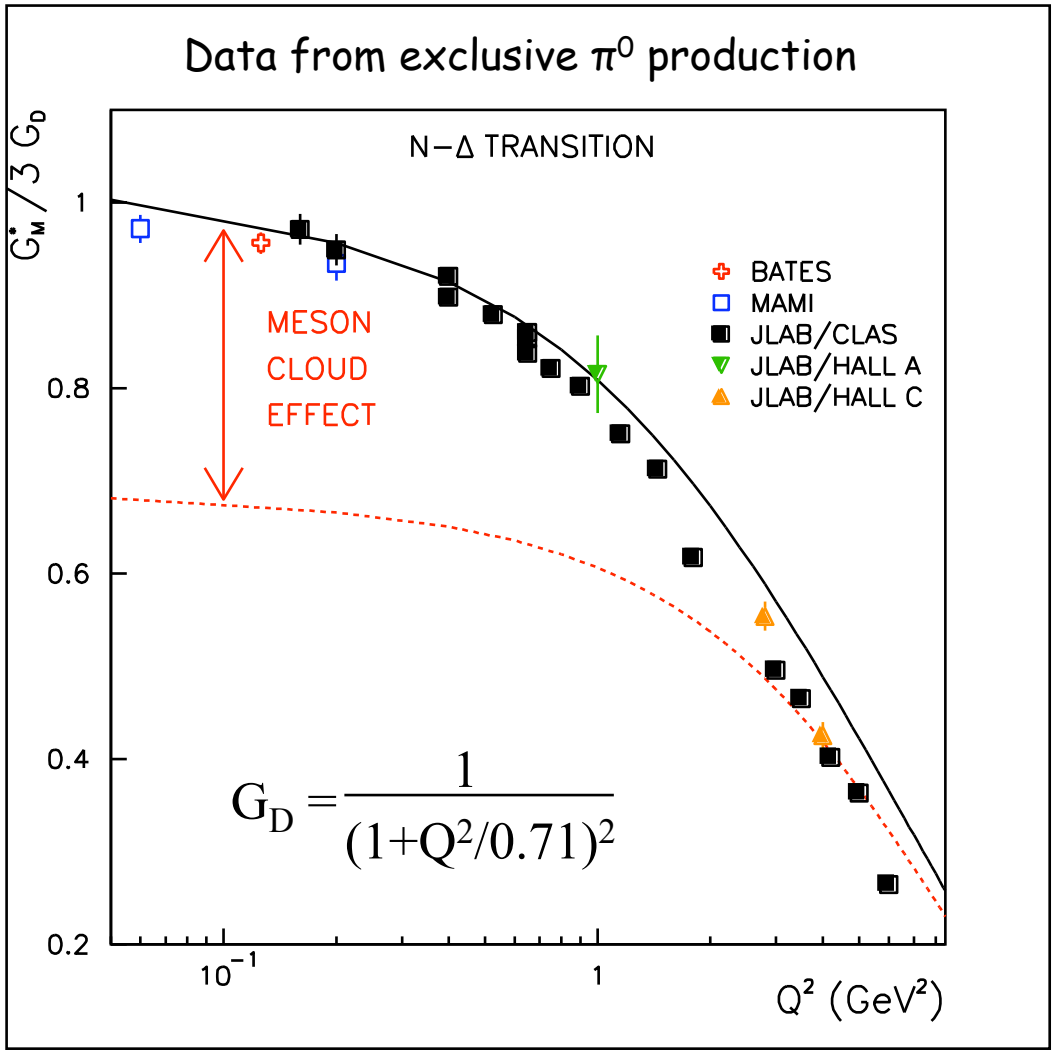


- There is no sign for asymptotic pQCD behavior in R_{EM} or R_{SM}.
- $R_{EM} < 0$ at low Q^2 favors oblate shape of Δ(1232) and prolate shape of the proton.
- Dynamical models attribute the deformation to contributions of the pion cloud at low Q^2.
- Data at Q^2=7 GeV^2 still to come from Jlab Hall C.

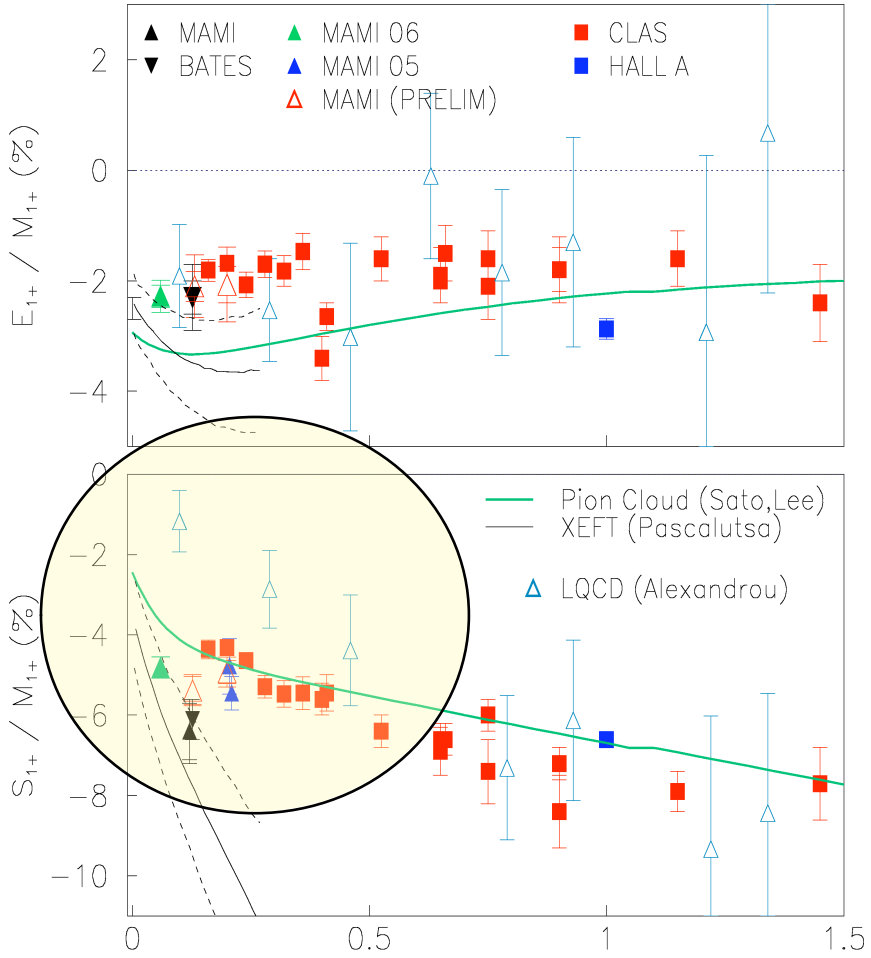
NΔ Transition Form Factors - G_M^*

- 1/3 of G^*_M at low Q^2 is due to vertex dressing and pion cloud contributions.

Meson contributions play a role even at relatively high Q^2.



Comparison with Theory



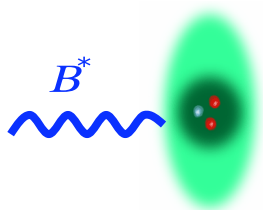
Quenched Lattice QCD

- E_{1+}/M_{1+}: Good agreement within large errors.
- S_{1+}/M_{1+}: Undershoots data at low Q^2.
- Linear chiral extrapolations may be naïve and/or dynamical quarks required

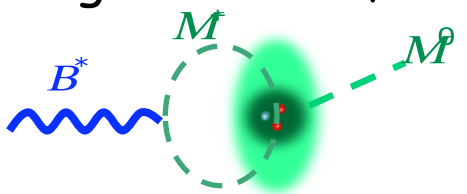
Dynamical Models

- Pion cloud model allows reasonable description of quadrupole ratios over large Q^2 range.

What are we learning from E/M, S/M?



Deformation of N, Δ quark core?



Shape of pion cloud?

LQCD consistent with observed rise in magnitude with Q^2 of RSM

Need to isolate the first term (within model) or go to high Q^2 to study quark core.

2nd and 3rd nucleon resonance regions

(PDG 2006)

State	$\eta_{N\pi}$	$\eta_{N\eta}$	$\eta_{N\pi\pi}$
$P_{11}(1440)$	0.55-0.75		0.3-0.4
$D_{13}(1520)$	0.55-0.65	0.0023	0.4-0.5
$S_{11}(1535)$	0.35-0.55	0.45-0.60	< 0.1
$D_{33}(1700)$	0.1-0.2		0.8-0.9
$P_{13}(1720)$	0.1-0.2	0.04	> 0.7

Analysis tools:

- Unitary isobar model (UIM), starting from MAID.
- Dispersion relations (DR), for 1-pion analysis.
- Isobar model (JM06) for 2-pion analysis with leading contributions as observed in the data. Fit to 9 independent one-dimensional projections of 5-dim. cross sections.

UIM & DR Fit at low & high Q^2

data points > 50,000 , E_e = 1.515, 1.645, 5.75 GeV

Observable	Q^2	Number of Data points
$d\sigma/d\Omega(\pi^0)$	0.40 0.65	3 530 3 818
$d\sigma/d\Omega(\pi^+)$	0.40 0.65 1.7-4.3	2 308 1 716 33 000
$A_e(\pi^0)$	0.40 0.65	956 805
$A_e(\pi^+)$	0.40 0.65 1.7 - 4.3	918 812 3 300
$d\sigma/d\Omega(\eta)$	0.375 0.750	172 412

Low Q^2 results:

I. Aznauryan et al., PRC71, 015201, 2005; PRC 72, 045201, 2005;

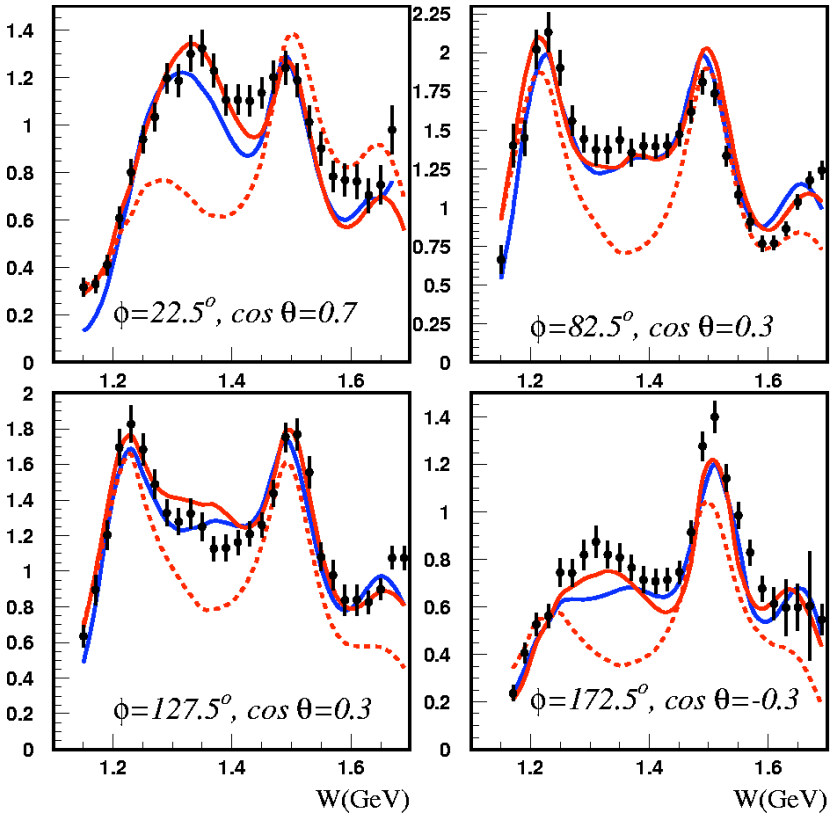
High Q^2 results on Roper:

I. Aznauryan et al., arXiv:0804.0447 [nucl-ex].

Fits to diff. cross sections & structure functions

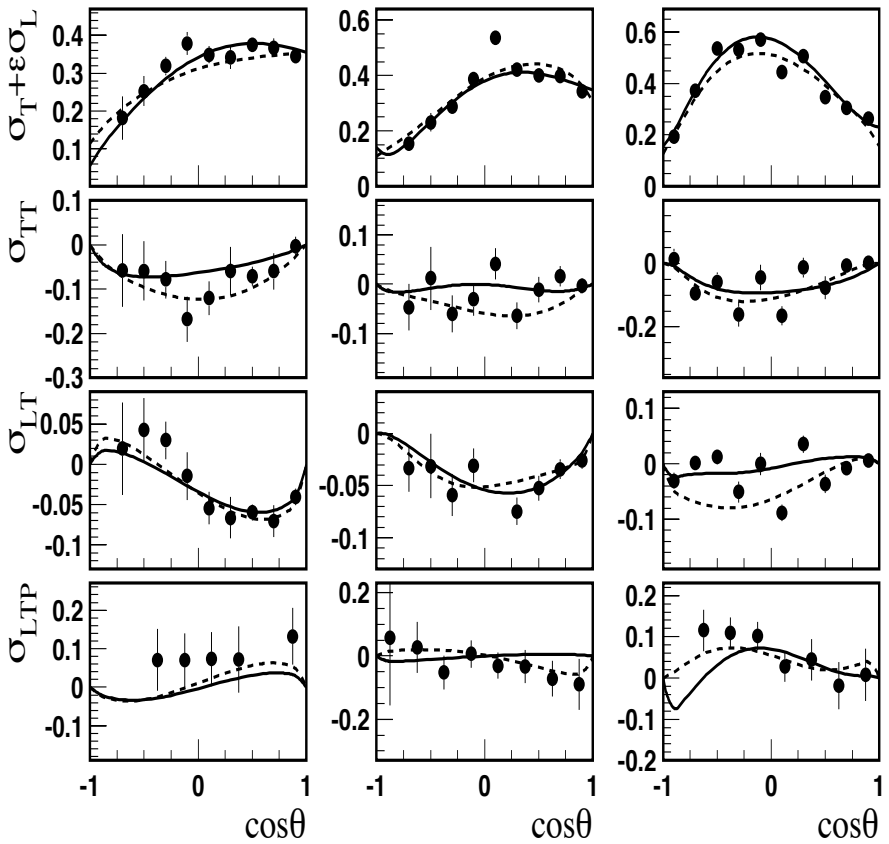
Q^2=2.05GeV^2

DR
DR w/o P11
UIM



Q^2=3.48GeV^2

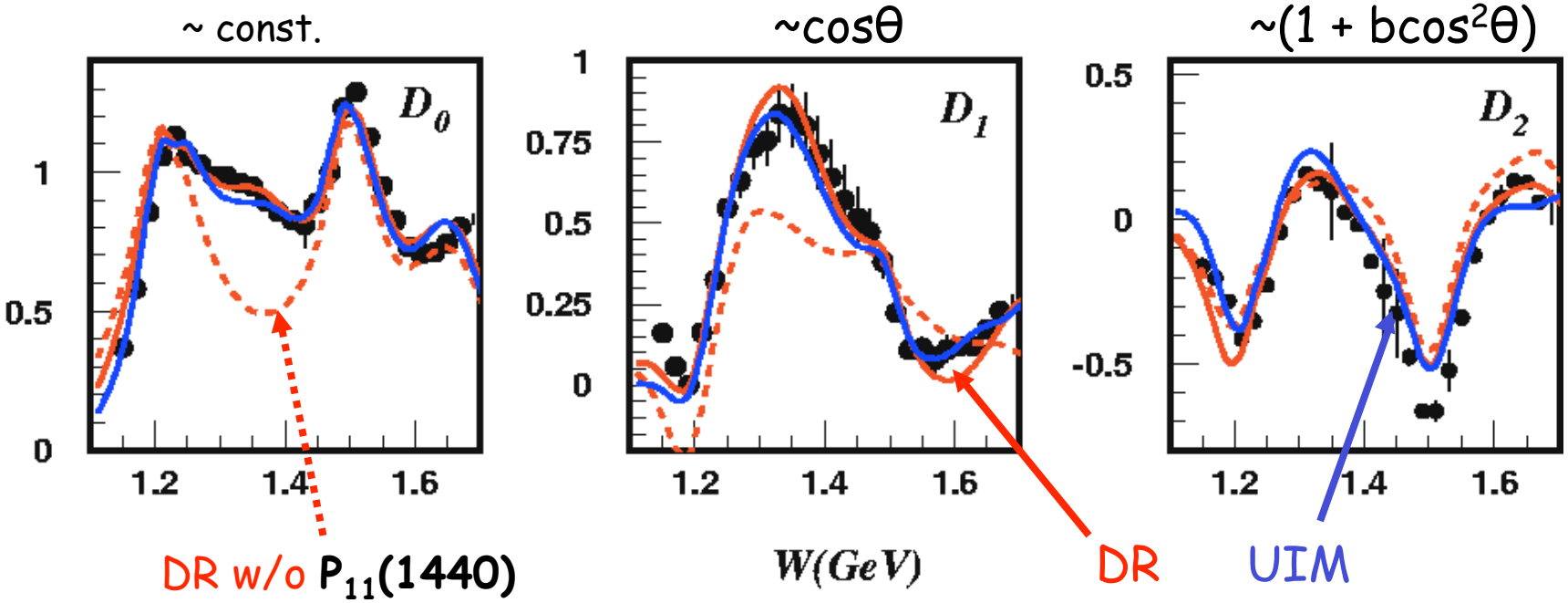
DR
UIM



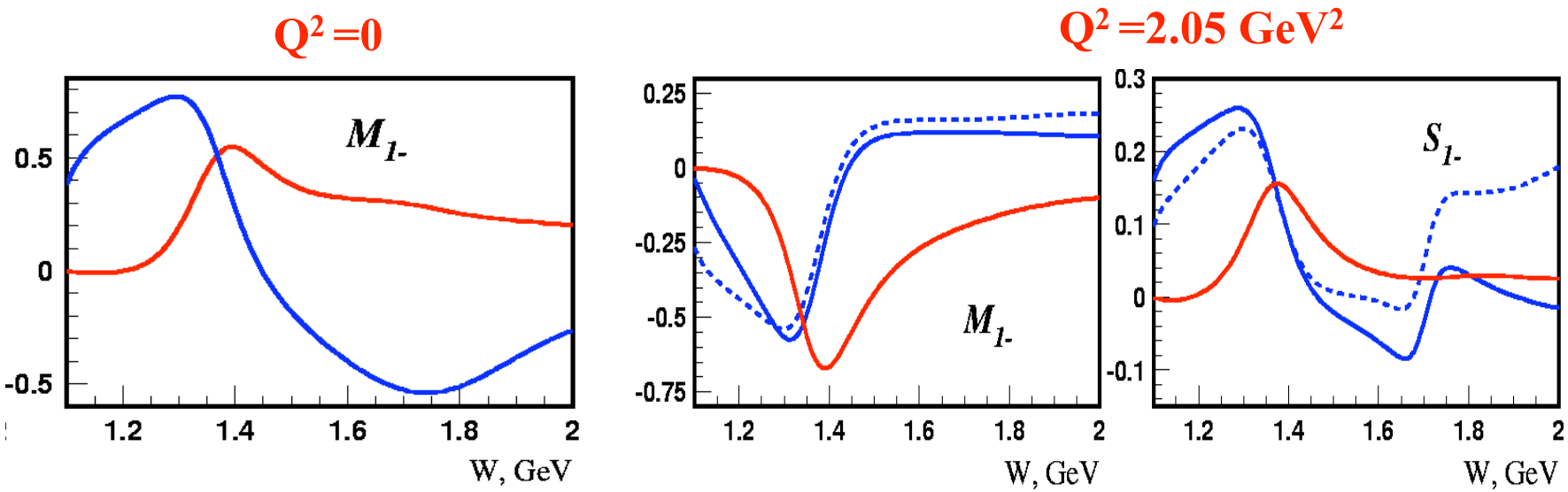
Legendre moments for $\sigma_T + \varepsilon\sigma_L$

$$\sigma_T + \epsilon\sigma_L = \sum_{l=0}^{n} D_l^{T+L} P_l(\cos\theta_\pi^*)$$

$Q^2 = 2.05\ \mathrm{GeV}^2$



Multipole amplitudes for $\gamma^* p \rightarrow \pi^+ n$

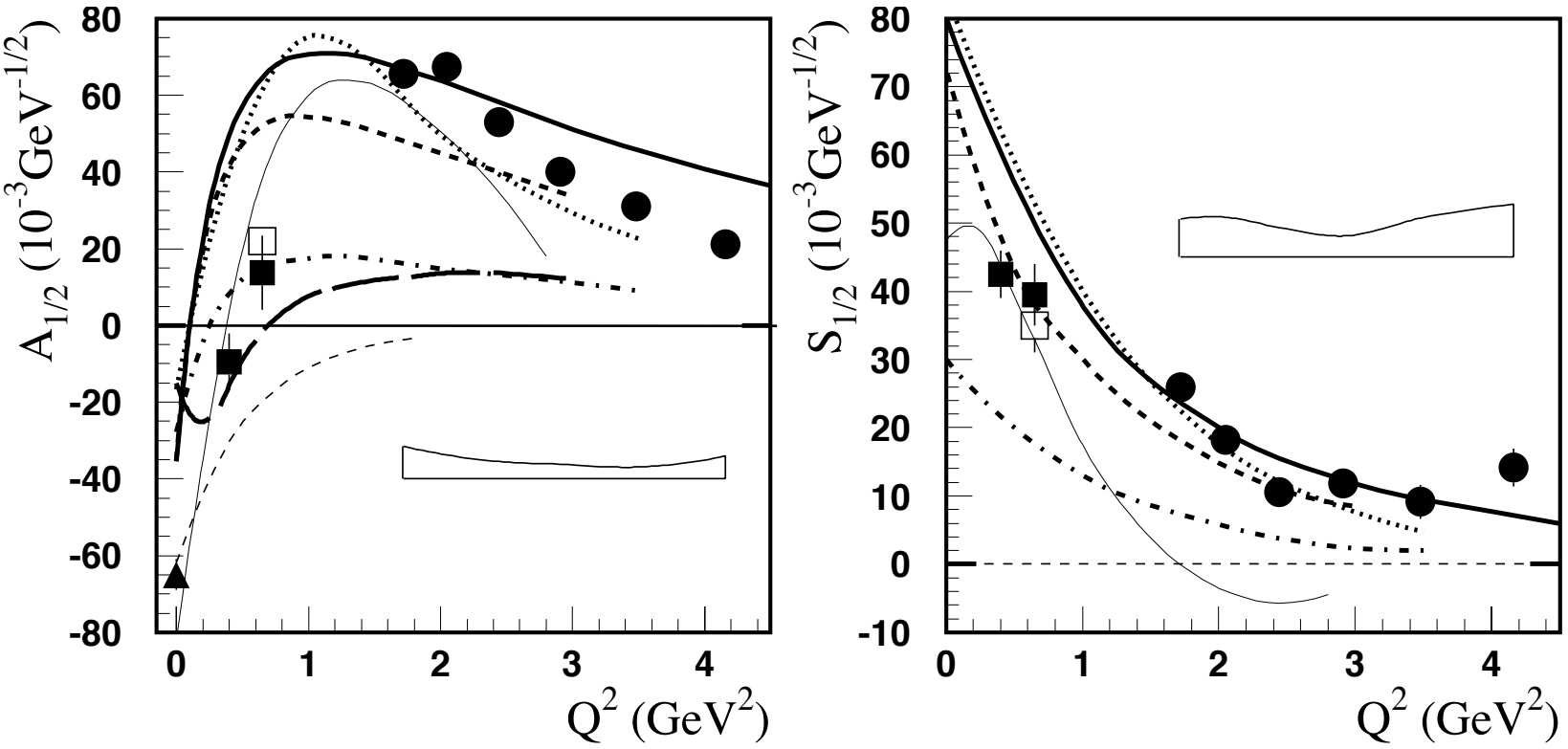


- At Q^2=1.7-4.2, resonance behavior is seen in these amplitudes more clearly than at Q^2 =0

- DR and UIM give close results for real parts of multipole amplitudes

Im
Re_UIM
Re_DR

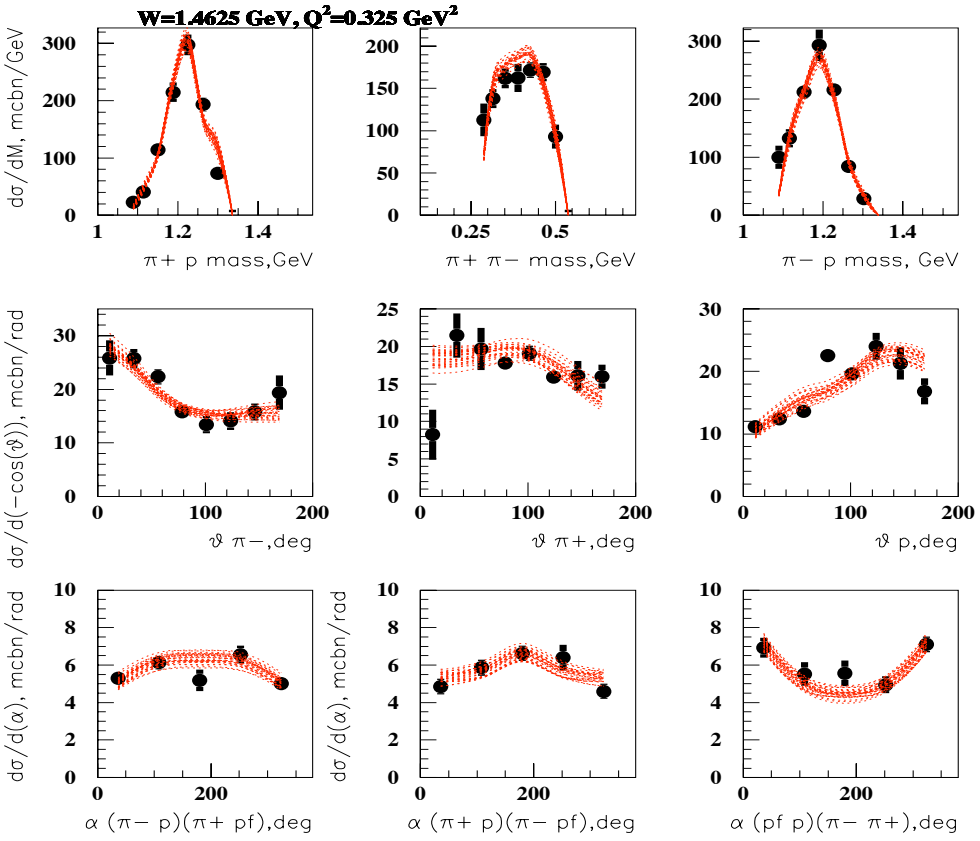
Roper transition amplitudes from Nπ data



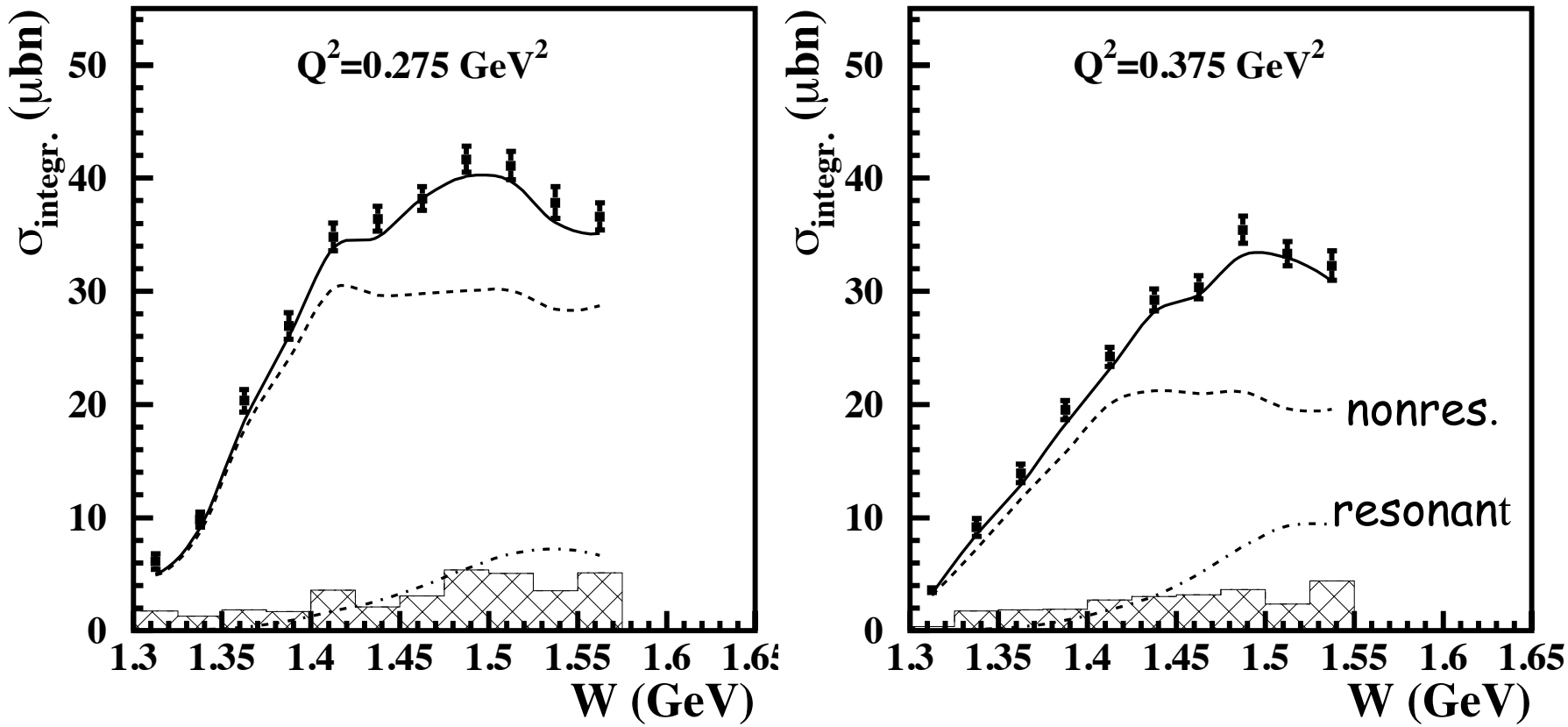
1.Weber, PR C41(1990)2783 **2**.Capstick..PRD51(1995)3598
3.Simula…PL B397 (1997)13 **4**.Riska..PRC69(2004)035212
5.Aznauryan, PRC76(2007)025212 **6**. Cano PL B431(1998)270

JM06 Fit to $p(\gamma_v,p\pi^-\pi^+)$

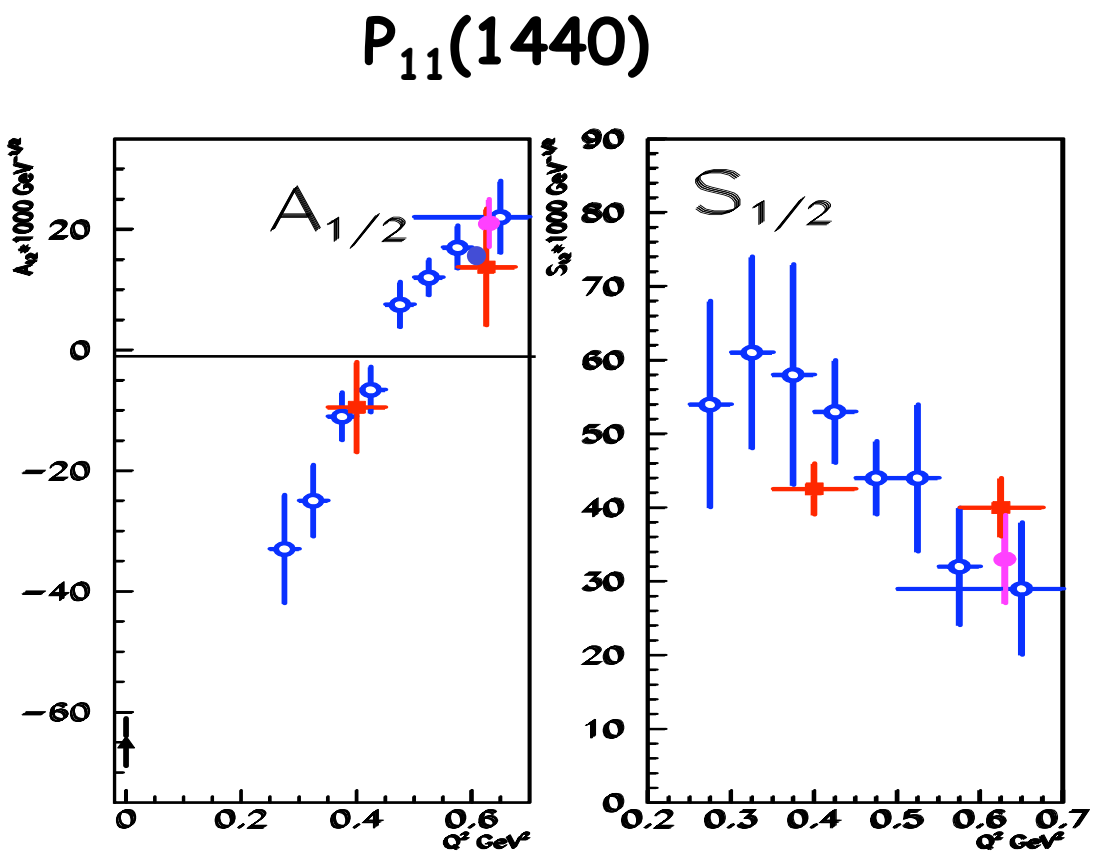
Simultaneous fit to 9 one-dimensional integrated cross sections.



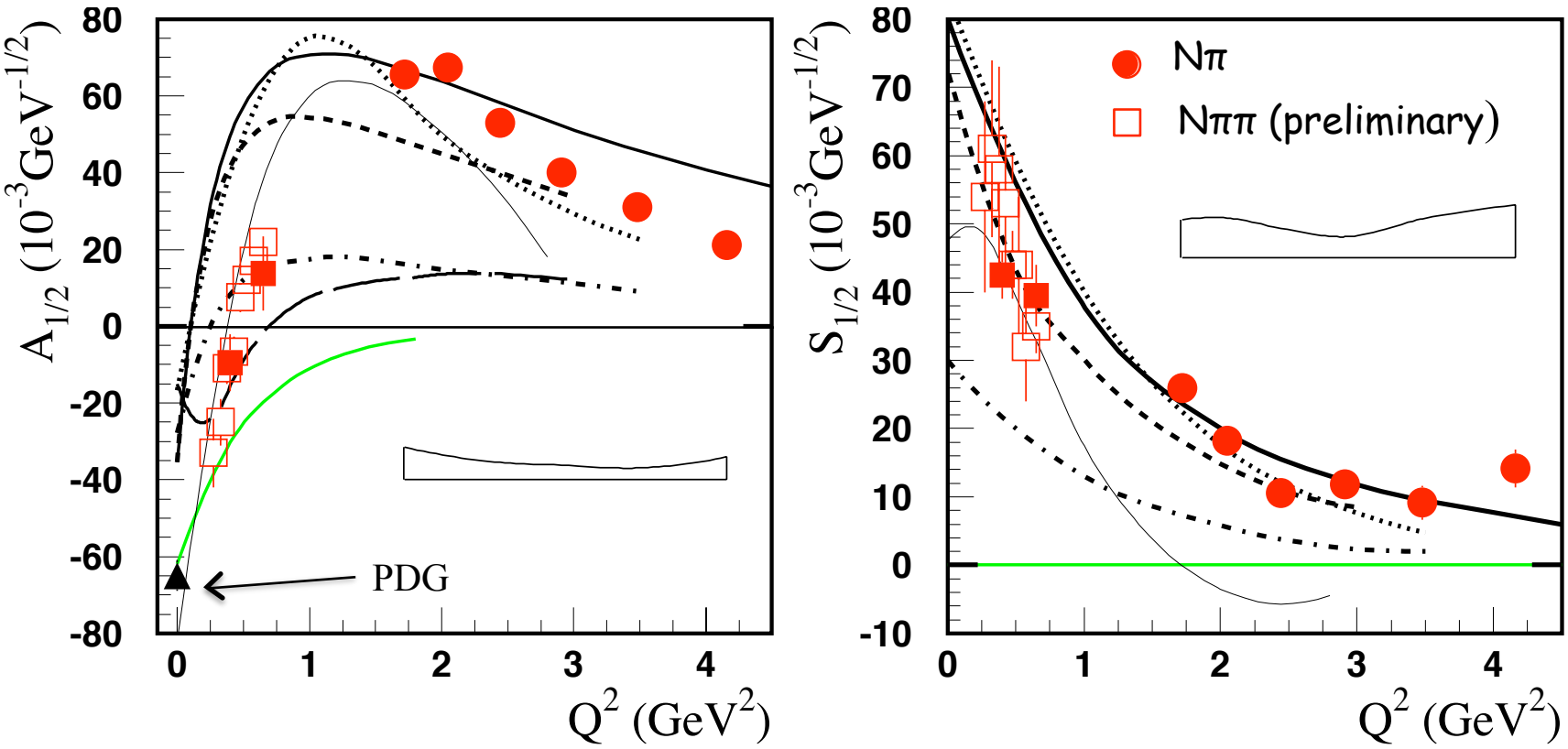
Integrated cross sections for $p(\gamma_v,p\pi^+\pi^-)$



$P_{11}(1440)$ amplitudes from $p\pi^+\pi^-$ data.

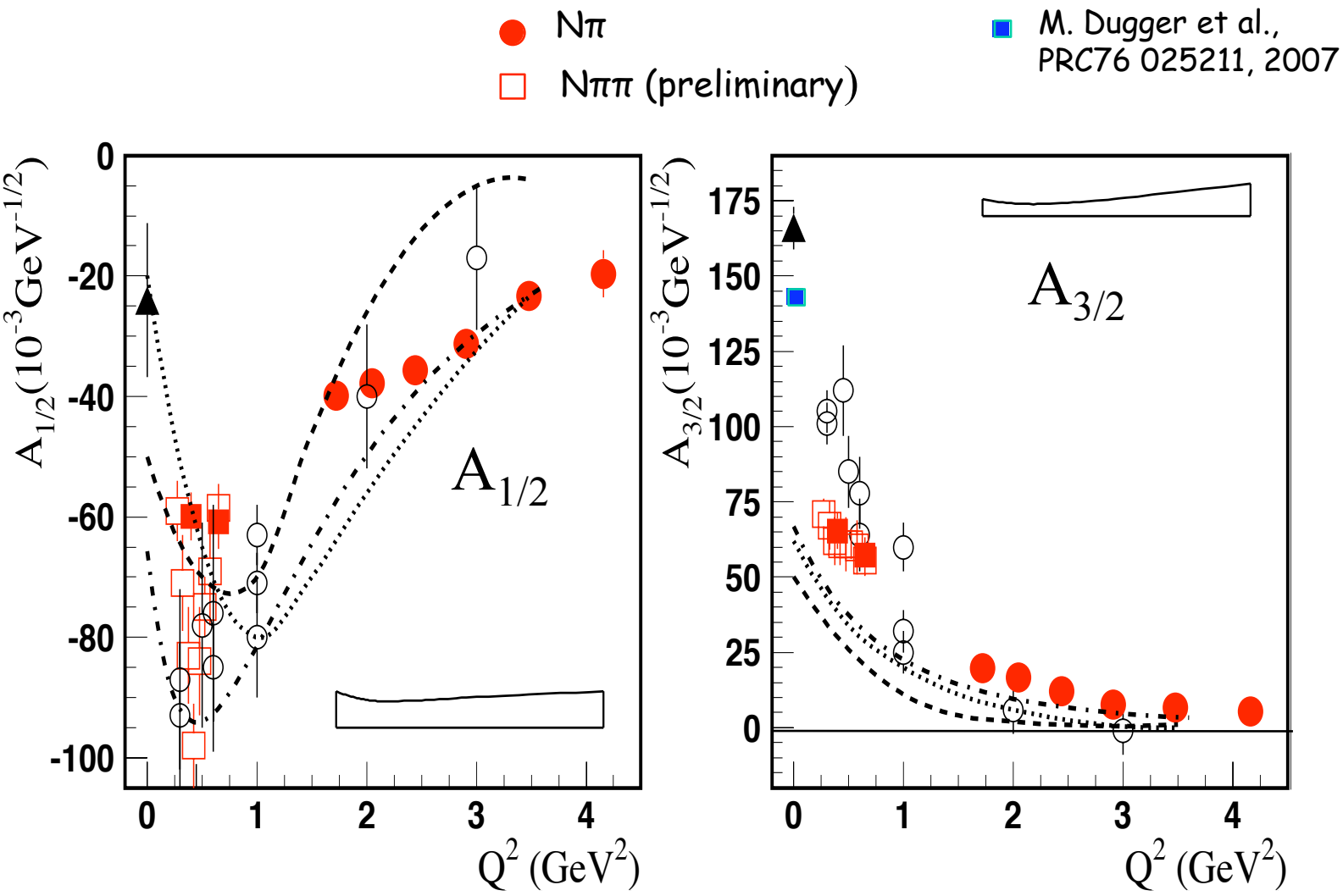


$P_{11}(1440)$ amplitudes from Nπ and Nππ

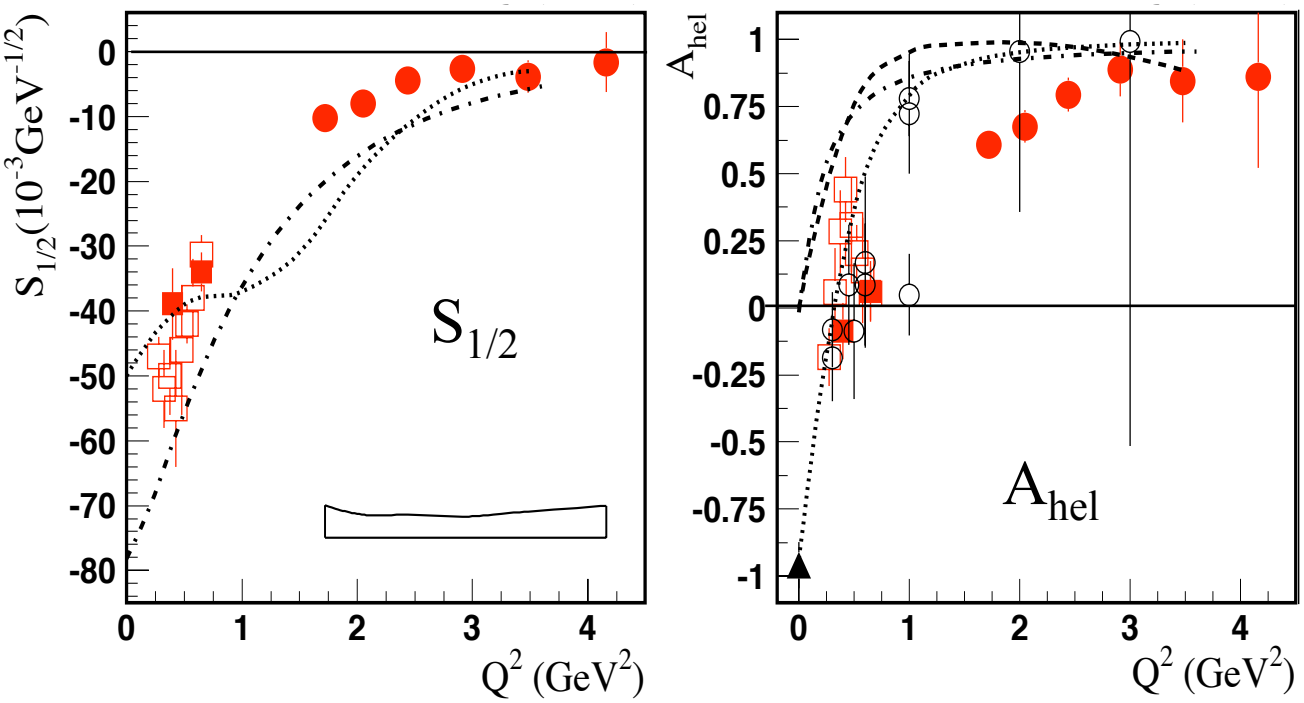


First observed zero crossing of a nucleon form factor!

Transition amplitudes for $\gamma_v p D_{13}(1520)$

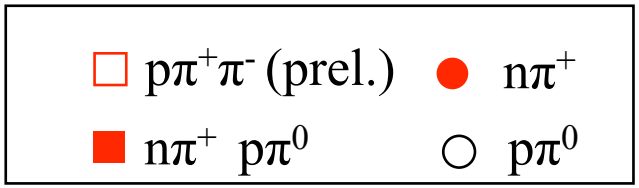


Transition amplitudes for $\gamma_v p D_{13}(1520)$



$$A_{hel} = \frac{A^2_{1/2} - A^2_{3/2}}{A^2_{1/2} + A^2_{3/2}}$$

CQM predictions: $A_{1/2}$ dominance with increasing Q^2.



The $S_{11}(1535)$

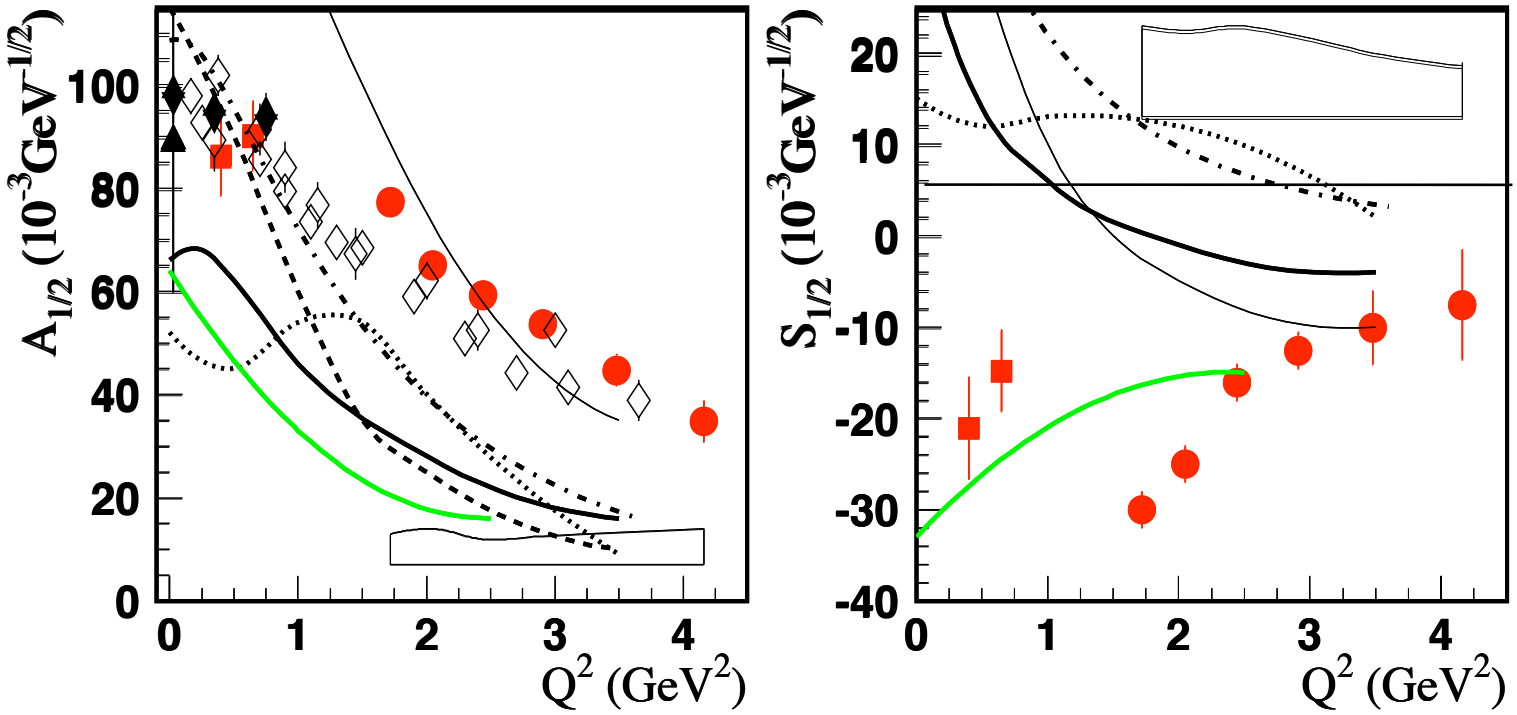
- This state has traditionally been studied in the $S_{11}(1535) \rightarrow p\eta$ channel, which a prominent decay.

  $S_{11}(1535) \rightarrow p\eta$; $p\eta$ selects isospin I=1/2

  $S_{11}(1535) \rightarrow N\pi$; $N\pi$ sensitive to I=1/2, 3/2

- For the study of $S_{1/2}$ $N\pi$ channel is important. $S_{1/2}$ difficult to extract in $p\eta$ channel.

Transition amplitudes for $S_{11}(1535)$



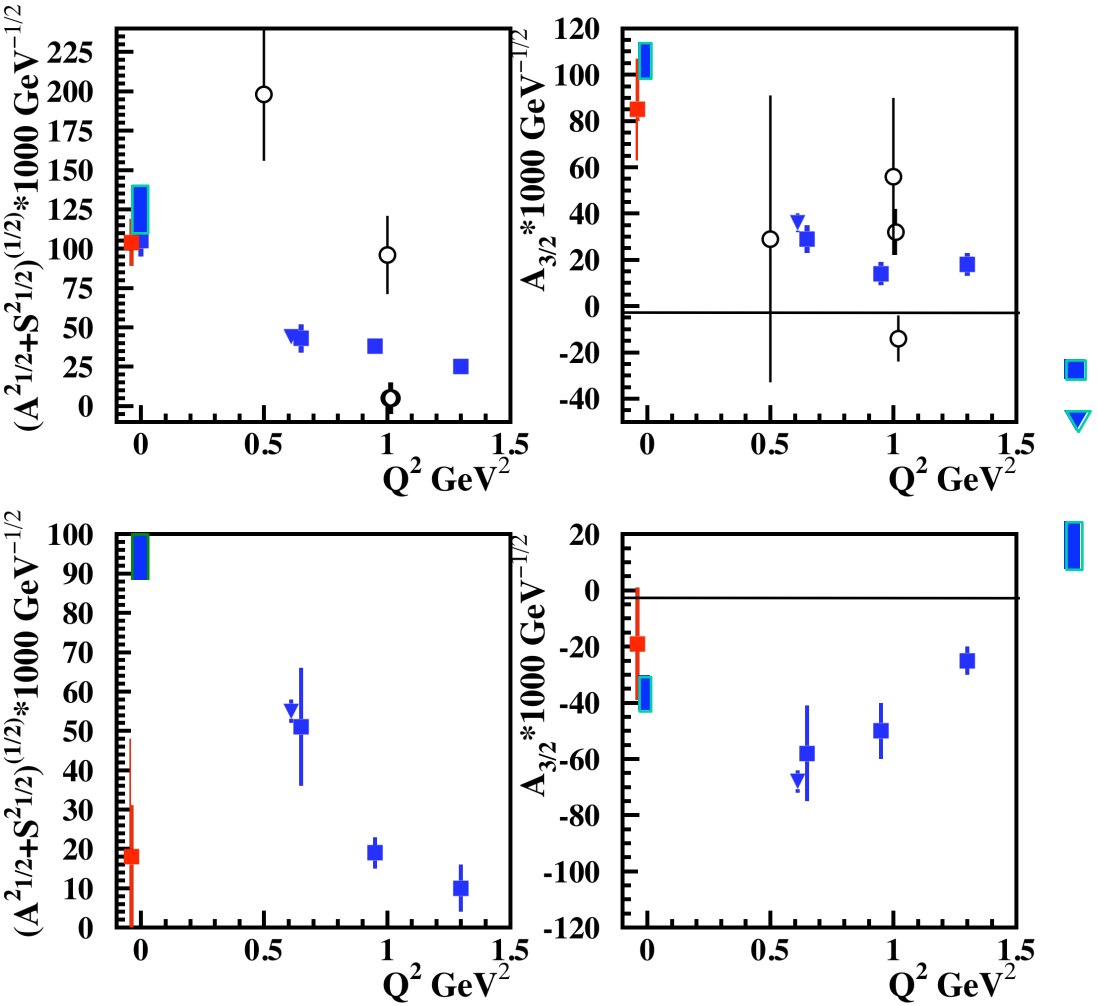
- $A_{1/2}$ from $n\pi^+$ consistent with $p\eta$ within uncertainties of b.r.
- In $n\pi^+$ the S_{0+} amplitude interferes with the strong M_{1-} allowing access to the longitudinal coupling. $D_0^{LT} \sim Re(E_{0+}S^*_{1-} + S_{0+}M_{1-}^*)$.
- Sign not consistent with CQM, but agrees with dynamically generated resonance prediction.

This may indicate that CQM's must take into account meson cloud to reproduce sign of $S_{1/2}$, see: B. Julia-Diaz, et.al. (EBAC), Phys. Rev. C77:045205(2008).

Transition amplitudes for $D_{33}(1700)$, $P_{13}(1720)$

$D_{33}(1700)$

$P_{13}(1720)$



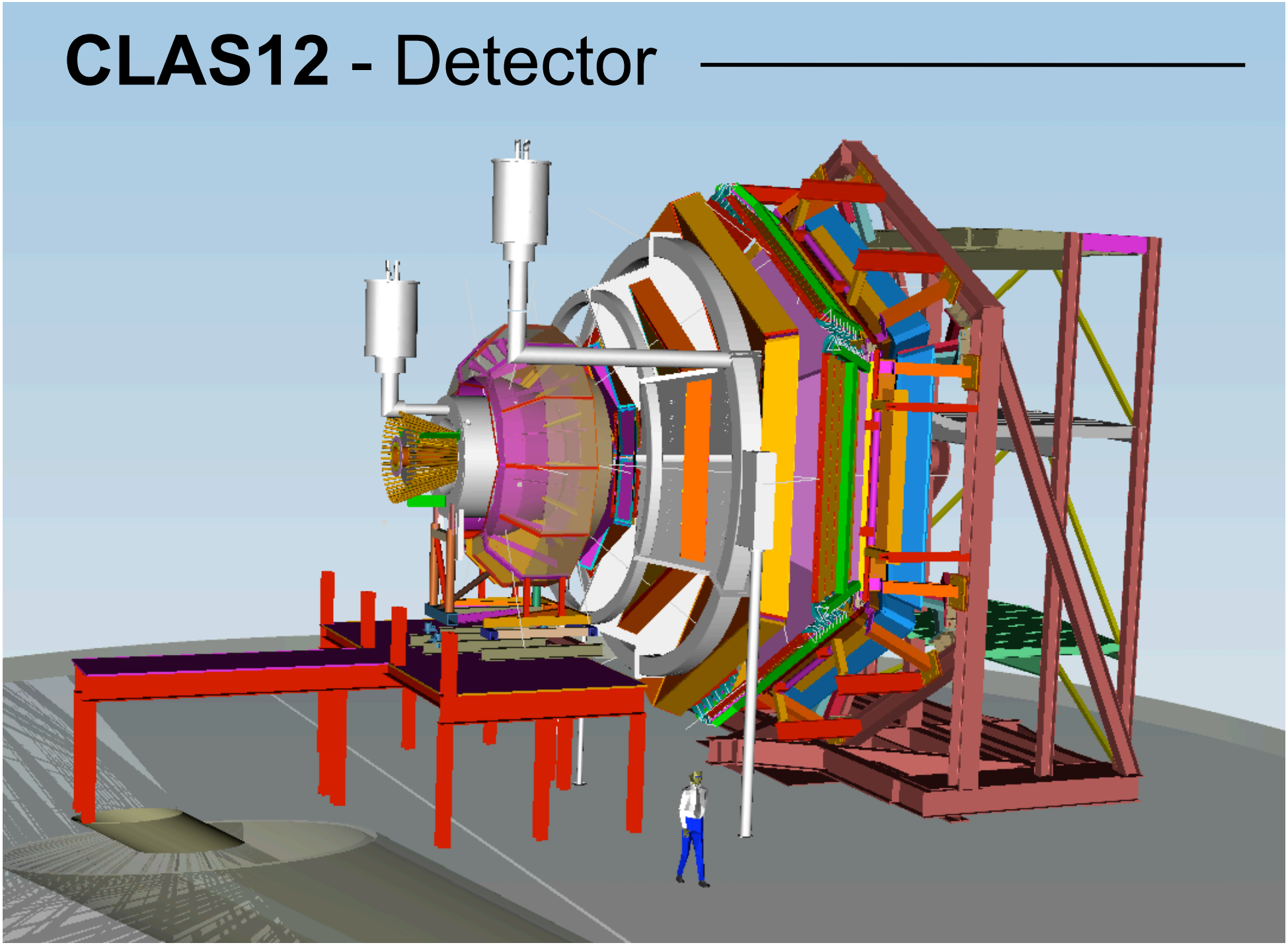
Conclusions & Outlook

- $N\Delta(1232)$ amplitudes are well determined at Q^2 up to 6 GeV^2.
  - No sign of transition to asymptotic QCD behavior
- Roper $P_{11}(1440)$ amplitudes determined up to 4.5 GeV^2 using two different analysis approaches (DR, UIM), and two channels
  - Sign change of $A_{1/2}$ seen in $N\pi$ and $N\pi\pi$
  - High Q^2 behavior consistent with radial excitation of the nucleon as in CQM
- $S_{11}(1535)$ amplitudes measured in $n\pi^+$ channel, for the first time
  - Hard $A_{1/2}$ form factor confirmed
  - First measurement of $S_{1/2}$. Sign inconsistent with CQM, consistent with dynamically generated state
- $D_{13}(1520)$ in $n\pi^+$ and $p\pi^+\pi^-$
  - Helicity switch from $A_{3/2}$ dominance to $A_{1/2}$ dominance at $Q^2>0.6$ GeV^2
- $P_{13}(1720)$ and $D_{33}(1700)$ in $p\pi^+\pi^-$
  - the first consistent mapping of their Q^2 dependence

Future prospects of N* Physics at the Jlab

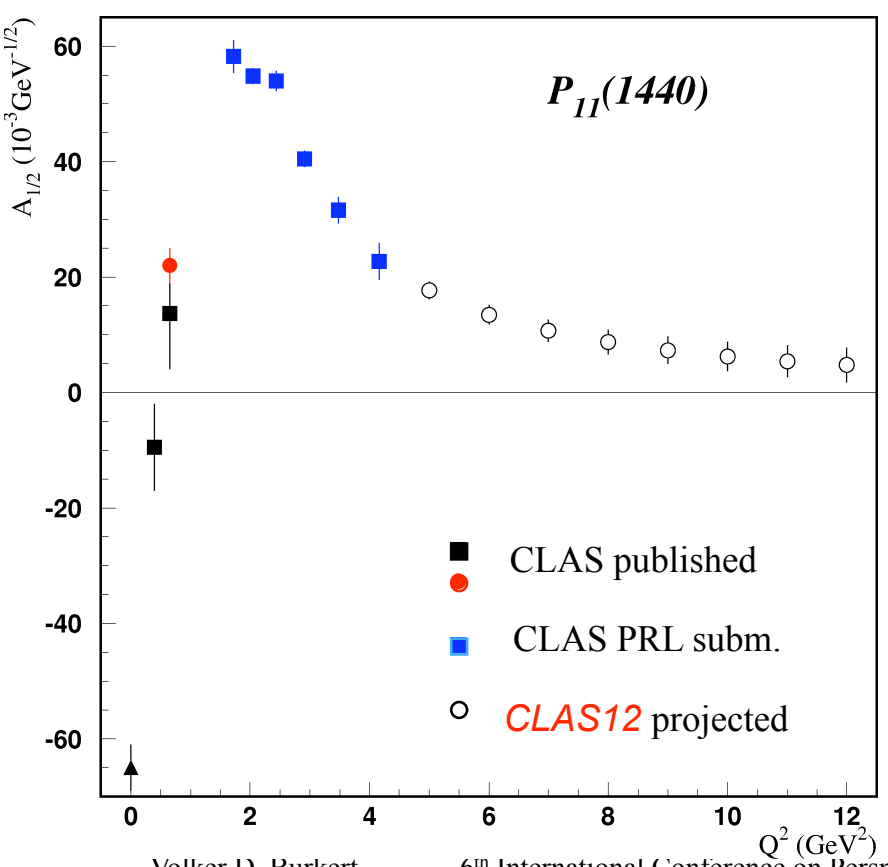
- Hall C data on NΔ at high Q^2 expected soon
- New data on Q^2 dependence of high mass states (CLAS)
- An experiment is planned in Hall A to study NΔ at very low Q^2
- An extensive program is underway with polarized photon beams and polarized targets to search for new baryon states (CLAS)
- Large effort underway at EBAC to develop the coupled channel analysis of these and other data
- Proposal for a transition form factor program at high Q^2 for the JLab 12 GeV upgrade with CLAS12

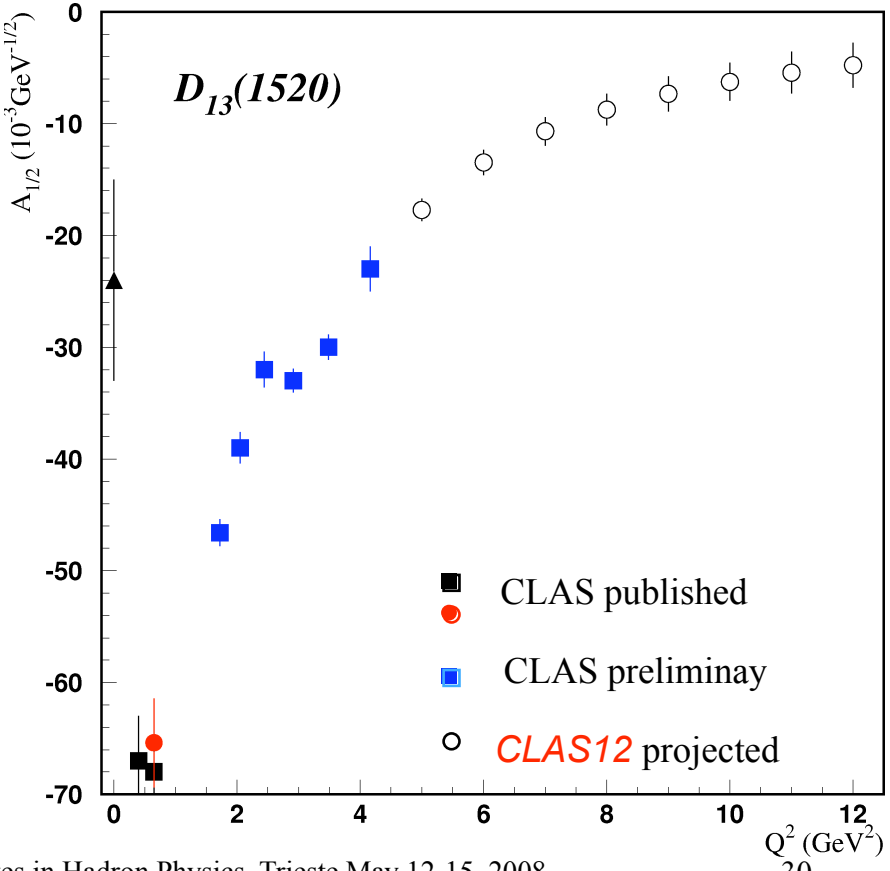
CLAS12 - Detector



Projections for N* Transition Amplitudes @ 12 GeV

Probe the transition from effective degrees of freedom, e.g. constituent quarks, to elementary quarks, with characteristic Q^2 dependence.

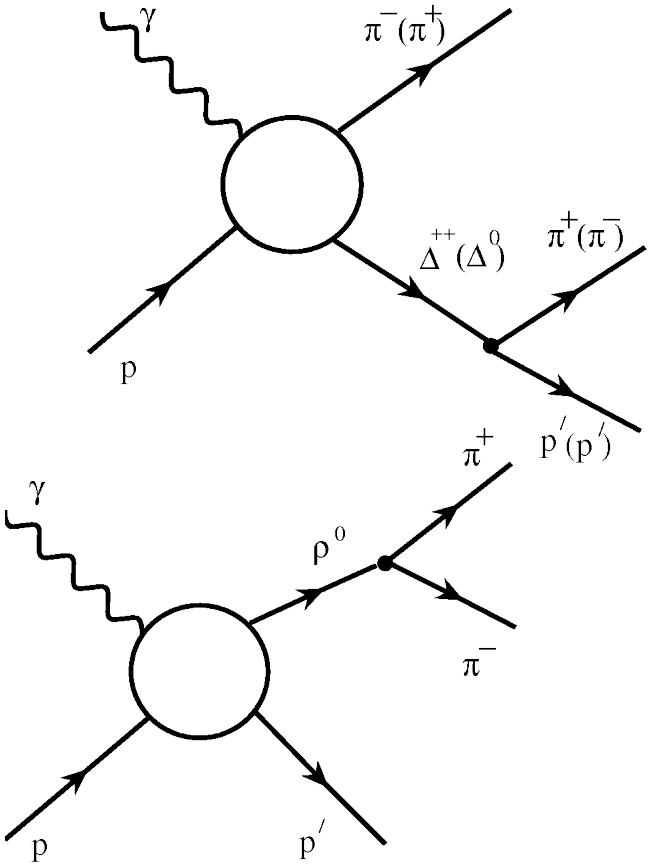




Additional Slides

JLAB-MSU model (JM06) for 2π electroproduction.

3-body processes:



Isobar channels included:

$\pi^-\Delta^{++}$

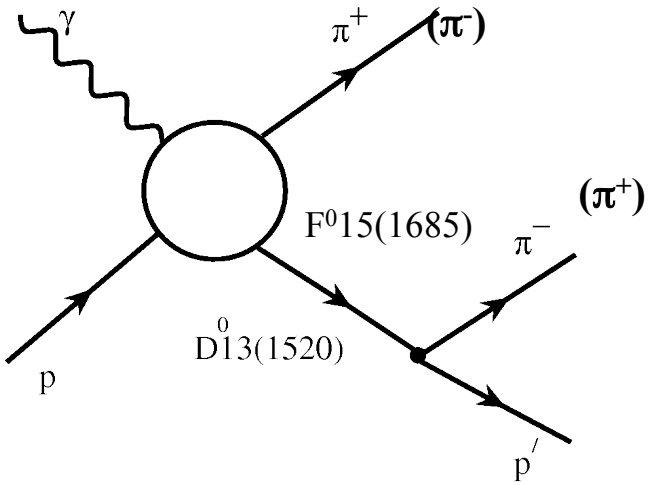
- **All well established N* with πΔ decays and $3/2^+(1720)$ candidate, seen in CLAS 2π data.**
- **Reggetized Born terms & effective FSI&ISI treatment .**
- **Extra πΔ contact term.**

ρp

- **All well established N* with ρp decays and $3/2^+(1720)$ candidate.**
- **Diffractive ansatz for non-resonant part & ρ-line shrinkage in N* region.**

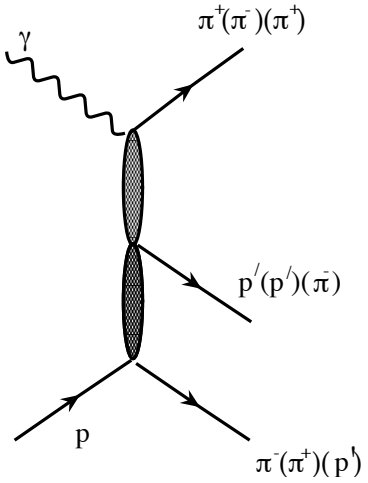
JM06 Model, cont'd

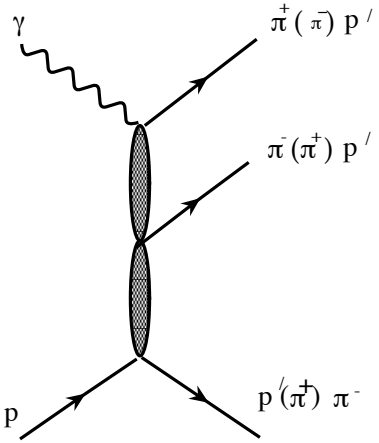
3-body processes:



Isobar channels included:

- **$\pi^+ D^0_{13}(1520)$, $\pi^+ F^0_{15}(1685)$ isobar channels.**





Direct 2π production

V.Mokeev, et al., J. Phys. 69, 012019 (2007).