Nucleon Transition Form Factors at JLab: Status and Outlook

Ralf W. Gothe
University of South Carolina

Beijing, April 19 – 22, 2009

- Motivation: Why Baryon Transition Form Factors?
- Consistency: N→Δ, N→Roper, and other N→N* Transitions
- Outlook: Experiment and Theory

Physics Goals

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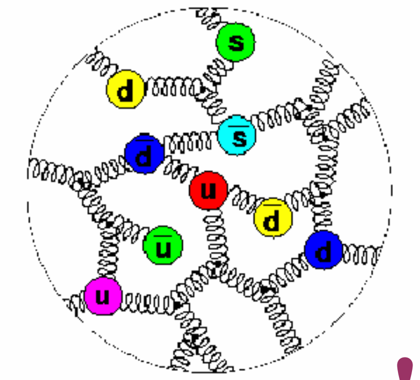
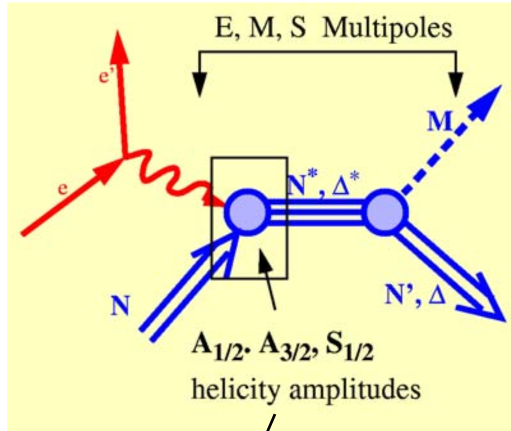
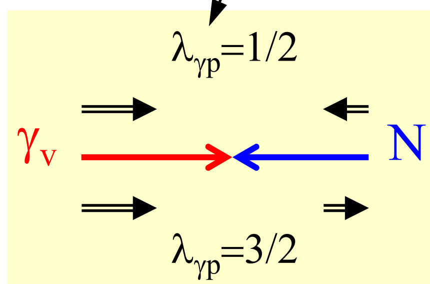


pQCD

q, g, $q\bar{q}$

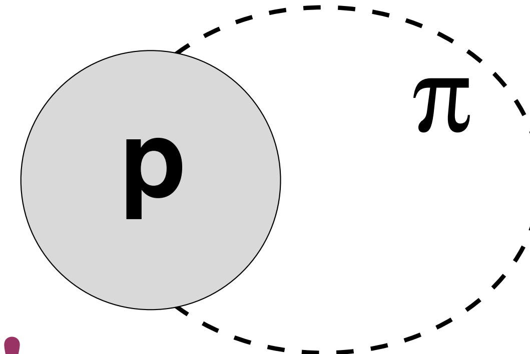
? ! ↔ ! ?





? ! ↔ ! ?

> 1.0 fm

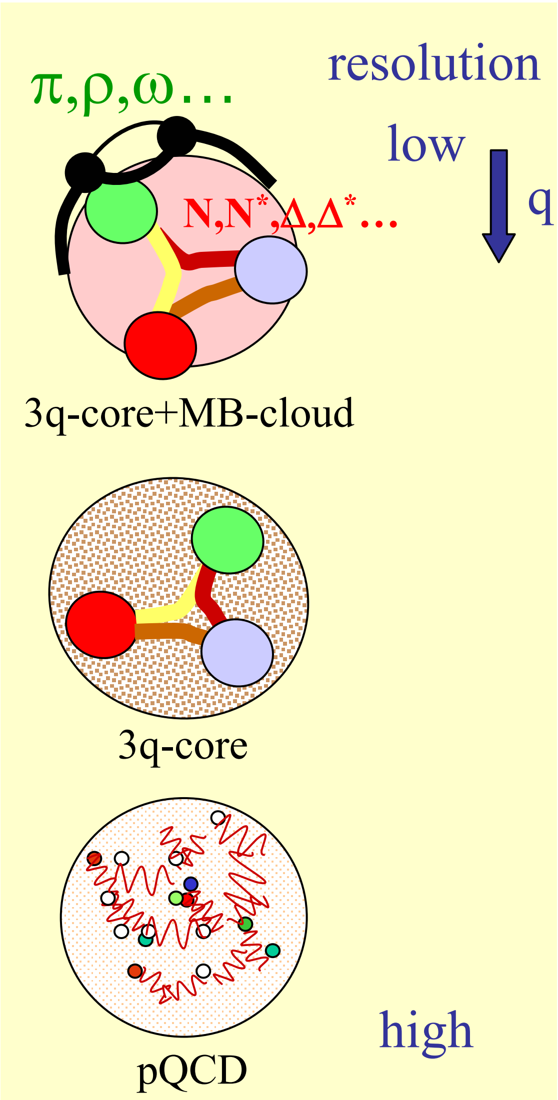


ChPT

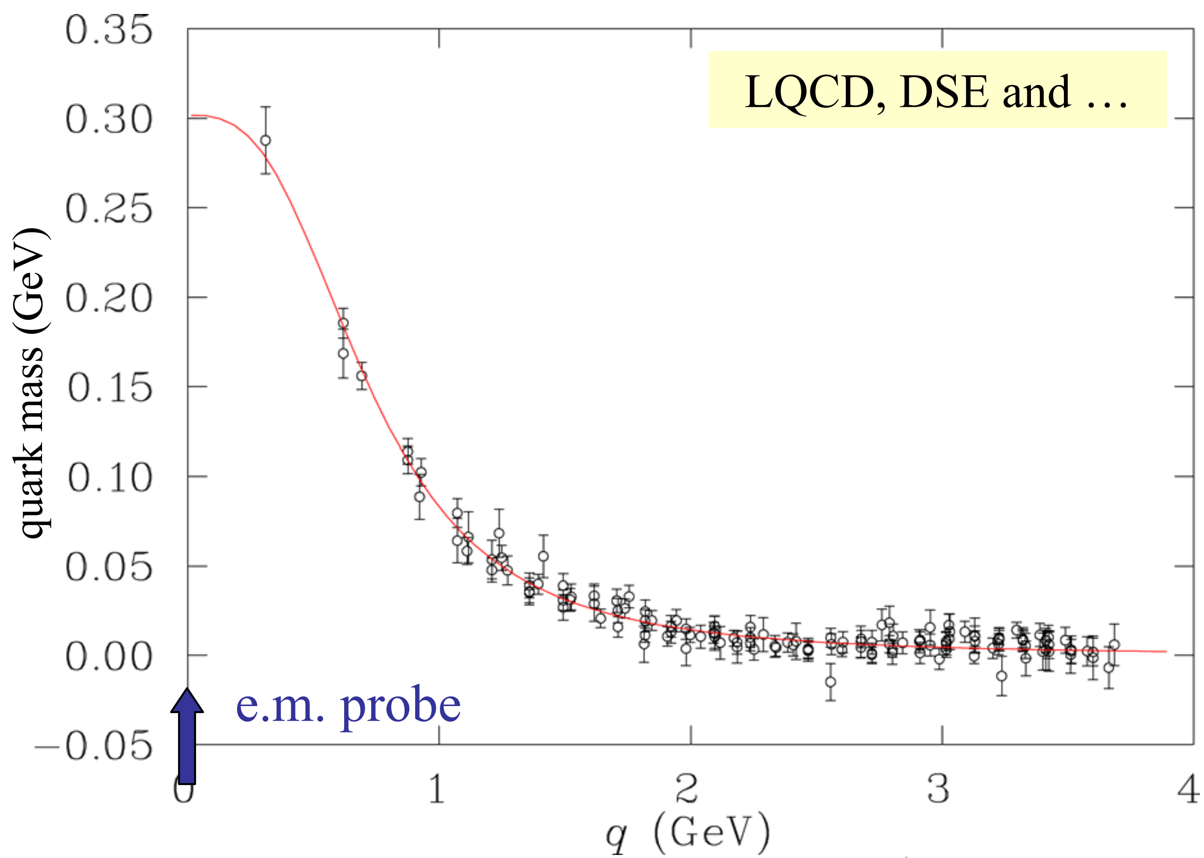
Nucleon and Mesons

- Determine the electrocouplings of prominent excited nucleon states (N^*, Δ^*) in the unexplored Q^2 range of 0-5-12 GeV^2 that will allow us to:
  - Study the structure of the nucleon spectrum in the domain where dressed quarks are the major active degree of freedom.
  - Explore the formation of excited nucleon states in interactions of dressed quarks and their emergence from QCD.

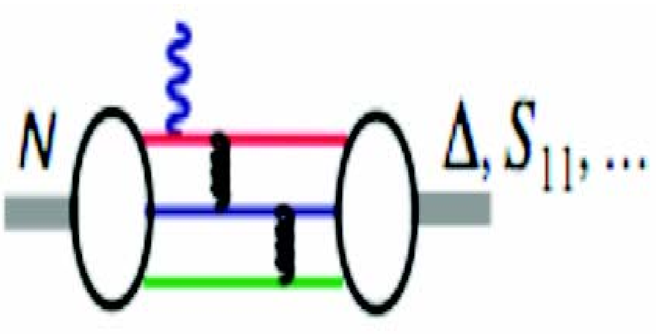
Hadron Structure with Electromagnetic Probes

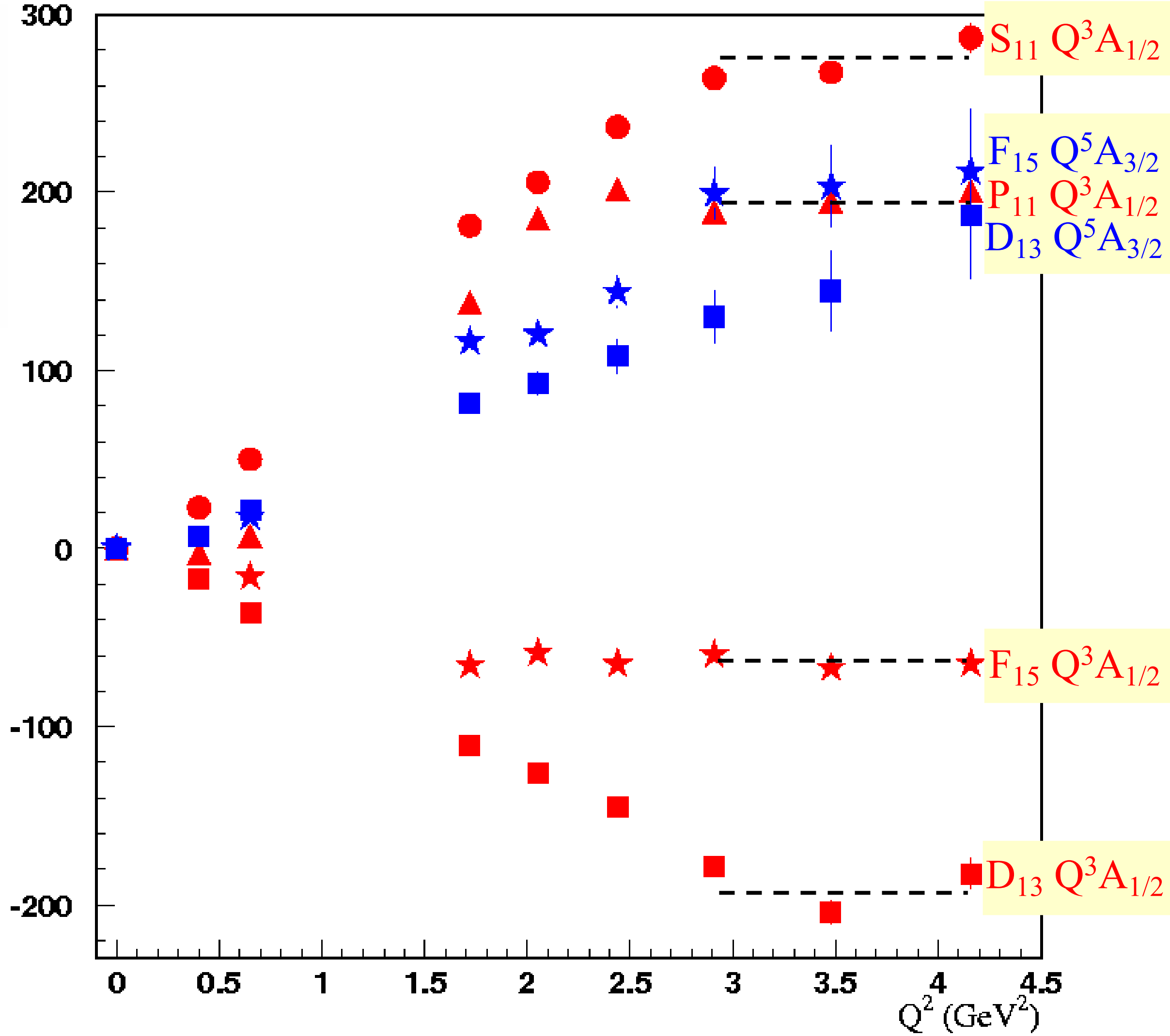


Quark mass extrapolated to the chiral limit, where *q* is the momentum variable of the tree-level quark propagator using the Asquat action.



Constituent Counting Rule

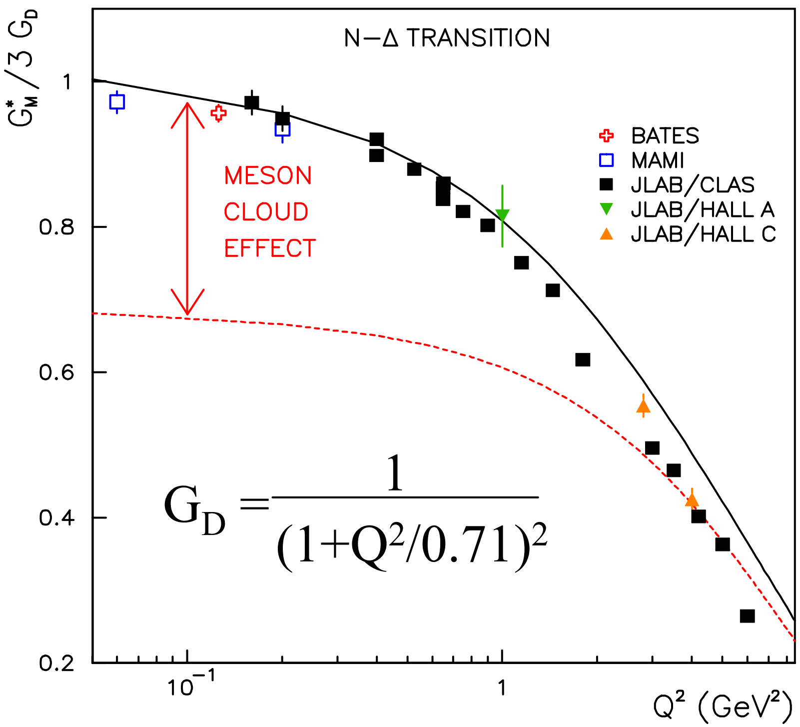


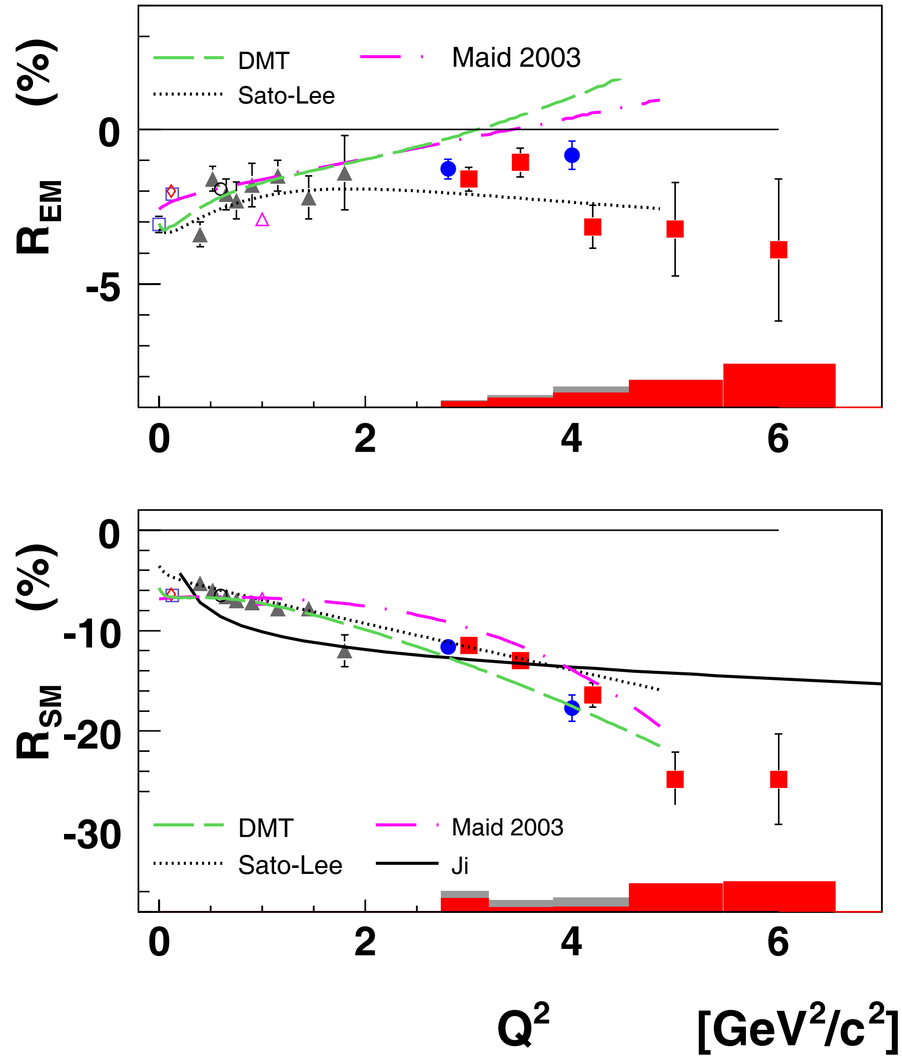


- $A_{1/2} \; \alpha \; 1/Q^3$
- $A_{3/2} \; \alpha \; 1/Q^5$
- $G_M^* \; \alpha \; 1/Q^4$

$N \rightarrow \Delta$ Multipole Ratios R_{EM} , R_{SM}

M. Ungaro



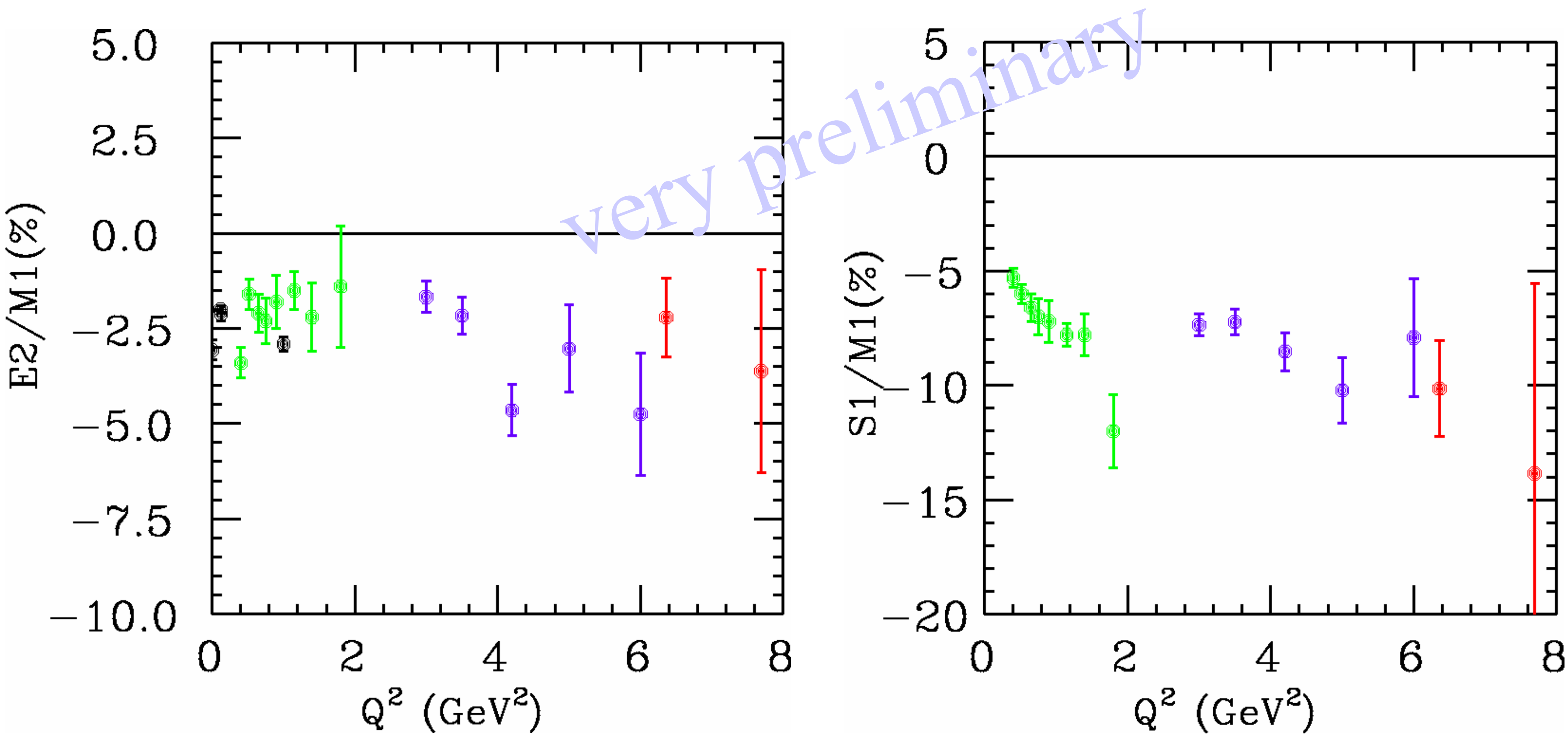


- New trend towards pQCD behavior does not show up.
  - $R_{EM} \rightarrow +1$
  - $G^*_M \rightarrow 1/Q^4$
- CLAS12 can measure R_{EM} and R_{SM} up to Q^2~12 GeV².

$N \to \Delta$ Multipole Ratios R_{EM} , R_{SM}

A. Villano

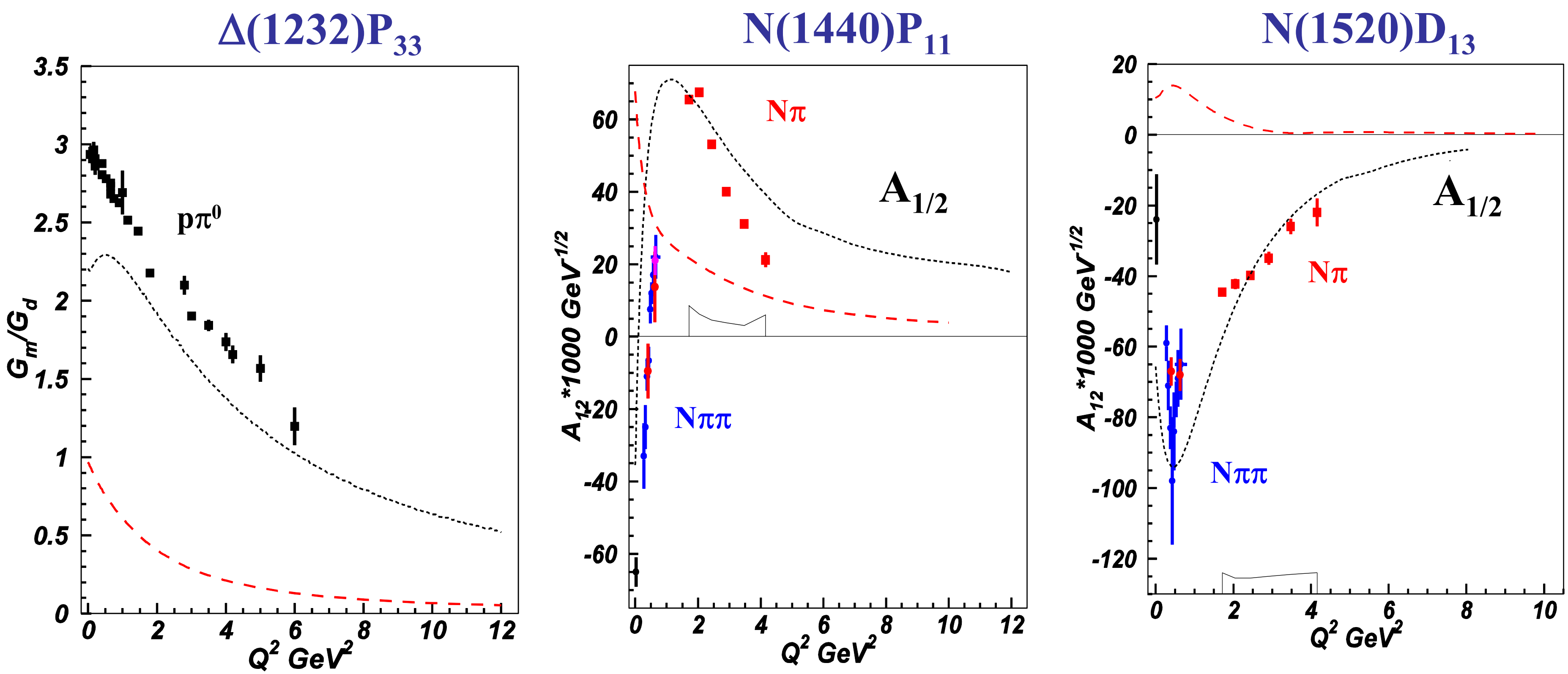
$\vec{e}\, p \to e' p \pi^0$



… but the trend that R_{SM} becomes constant in the limit of $Q^2 \to \infty$ seems to show up in the latest MAID 2007 analysis of the high Q^2 data.

Progress in Experiment and Phenomenology

Recent experimental and phenomenological efforts show that meson-baryon contributions to resonance formations drop faster with Q^2 than contributions from dressed quarks.

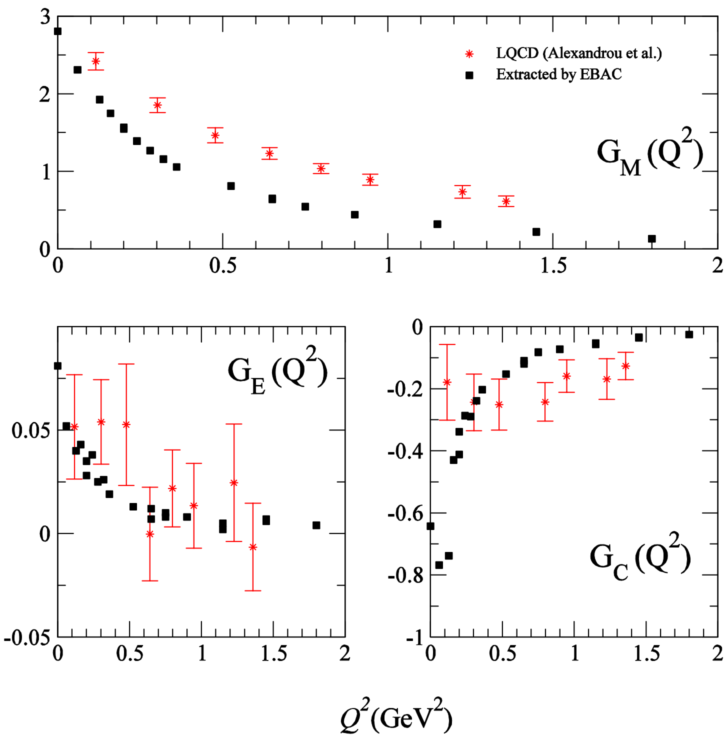


······· Dressed quarks (I. Aznauryan, M. Giannini *et al.*, B. Julia-Diaz *et al.*)

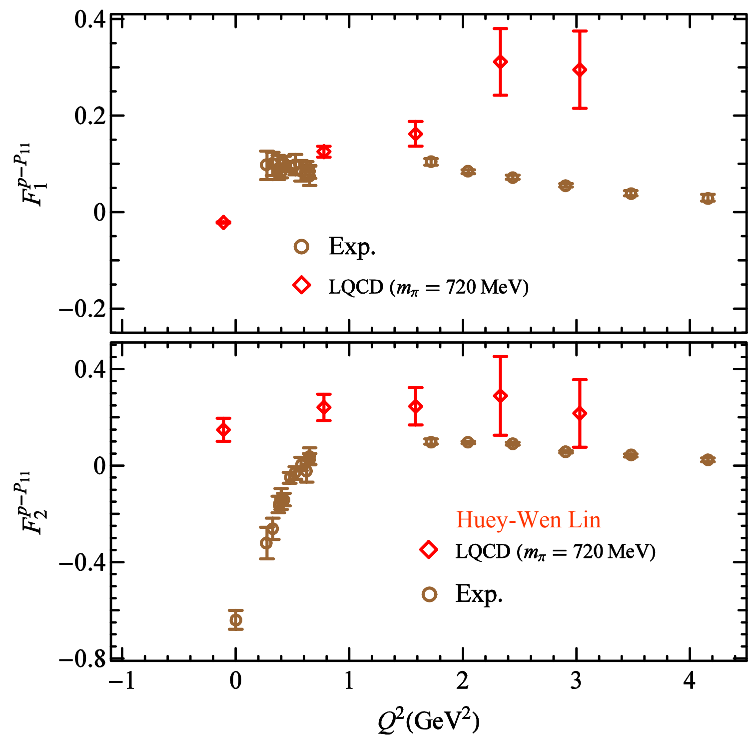
- - - - Meson-baryon cloud (EBAC)

Resonance Electrocouplings in Lattice QCD

$\Delta(1232)P_{33}$



$N(1440)P_{11}$

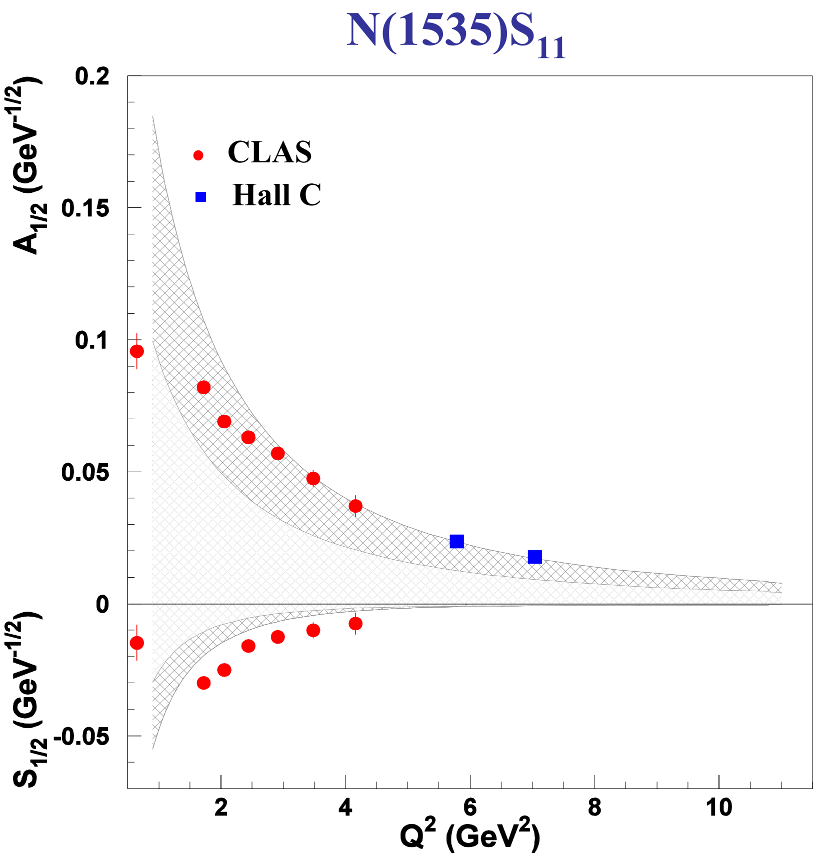


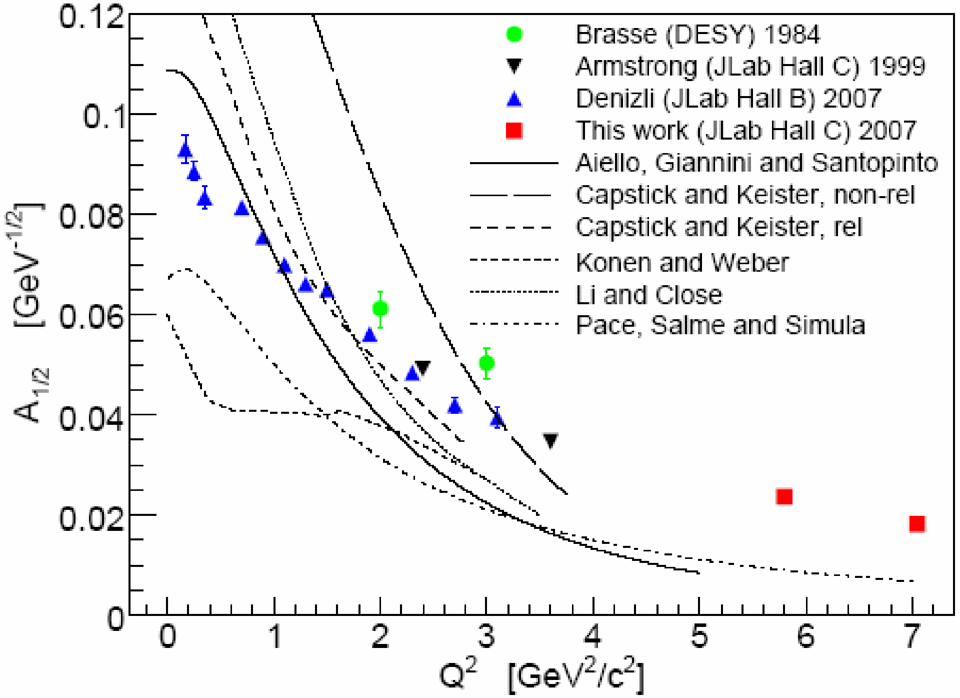
LQCD calculations of the $\Delta(1232)P_{33}$ and $N(1440)P_{11}$ transitions have been carried out with large π-masses.

By the time of the upgrade LQCD calculations of N* electrocouplings will be extended to $Q^2 = 10$ GeV^2 near the physical π-mass as part of the commitment of the JLab LQCD and EBAC groups in support of this proposal.

see White Paper Sec. II and VIII

LQCD & Light Cone Sum Rule (LCSR) Approach



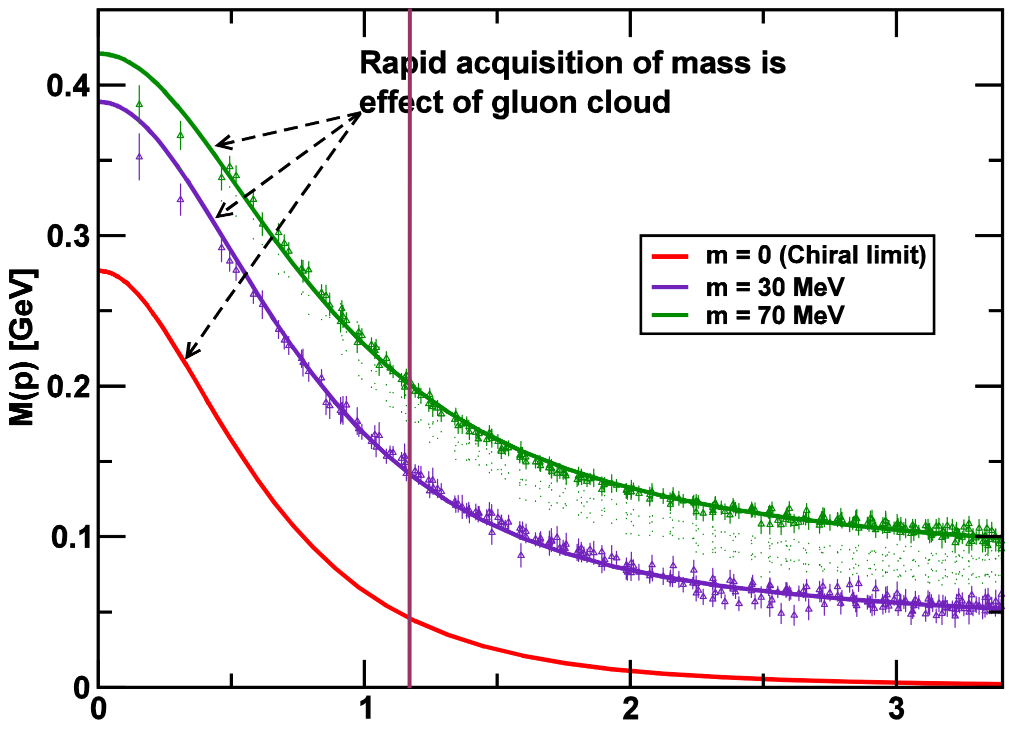


Calculations of $N(1535)S_{11}$ electrocouplings at Q^2 up to 12 GeV^2 are already available and shown by shadowed bands on the plot.

By the time of the upgrade electrocouplings of others N*s will be evaluated. These studies are part of the commitment of the Univ. of Regensburg group in support of this proposal.

see White Paper Sec. V

Dynamical Mass of Light Dressed Quarks



DSE and LQCD predict the dynamical generation of the momentum dependent dressed quark mass that comes from the gluon dressing of the current quark propagator.

These dynamical contributions account for more than 98% of the dressed light quark mass.

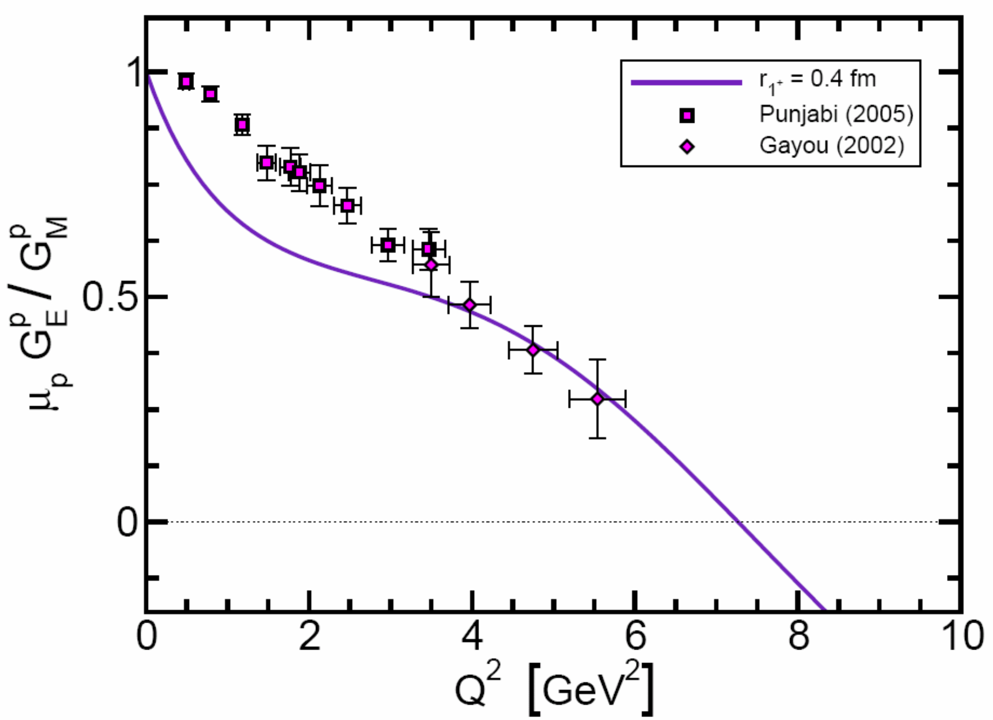
DSE: lines and LQCD: triangles

$Q^2 = 12\ \text{GeV}^2$ = (p times number of quarks)^2 = $12\ \text{GeV}^2$ → p = 1.15 GeV

The data on N* electrocouplings at $5<Q^2<12\ \text{GeV}^2$ will allow us to chart the momentum evolution of dressed quark mass, and in particular, to explore the transition from dressed to almost bare current quarks as shown above.

Dyson-Schwinger Equation (DSE) Approach

DSE provides an avenue to relate N* electrocouplings at high Q^2 to QCD and to test the theory's capability to describe N* formations based on QCD.



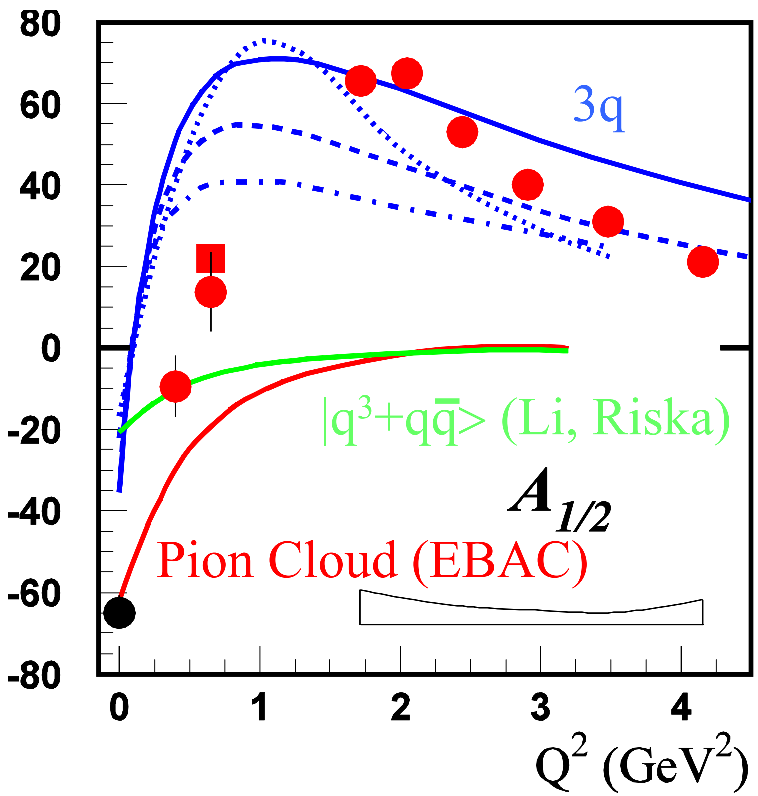
DSE approaches provide a link between dressed quark propagators, form factors, scattering amplitudes, and QCD.

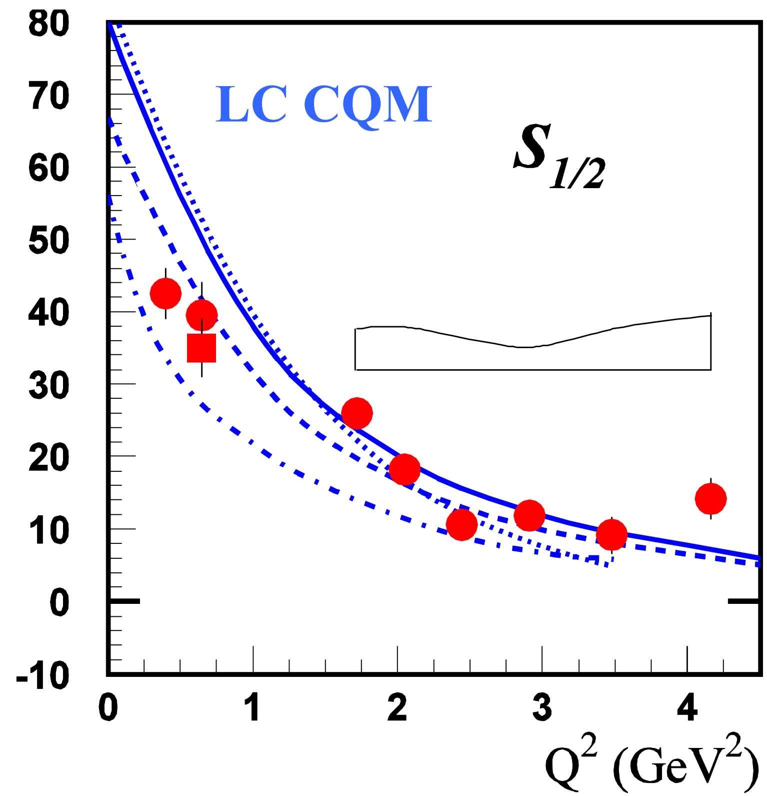
N* electrocouplings can be determined by applying Bethe-Salpeter /Fadeev equations to 3 dressed quarks while the properties and interactions are derived from QCD.

By the time of the upgrade DSE electrocouplings of several excited nucleon states will be available as part of the commitment of the Argonne NL and the University of Washington.

see White Paper Sec. III

Constituent Quark Models (CQM)





N(1440)P_{11}: ● PDG value ● Nπ ■ Nπ, Nππ combined analysis

Relativistic CQM are **currently** the only available tool to study the electrocouplings for the majority of excited proton states.

This activity represent part of the commitment of the Yerevan Physics Institute, the University of Genova, INFN-Genova, and the Beijing IHEP groups to refine the model further, e.g., by including $q\bar{q}$ components.

see White Paper Sec. VI

Phenomenological Analyses in Single Meson Production

Unitary Isobar Model (UIM)

Nonresonant amplitudes: gauge invariant Born terms consisting of *t*-channel exchanges and *s*- / *u*-channel nucleon terms, reggeized at high W.
πN rescattering processes in the final state are taken into account in a K-matrix approximation.

Fixed-*t* Dispersion Relations (DR)

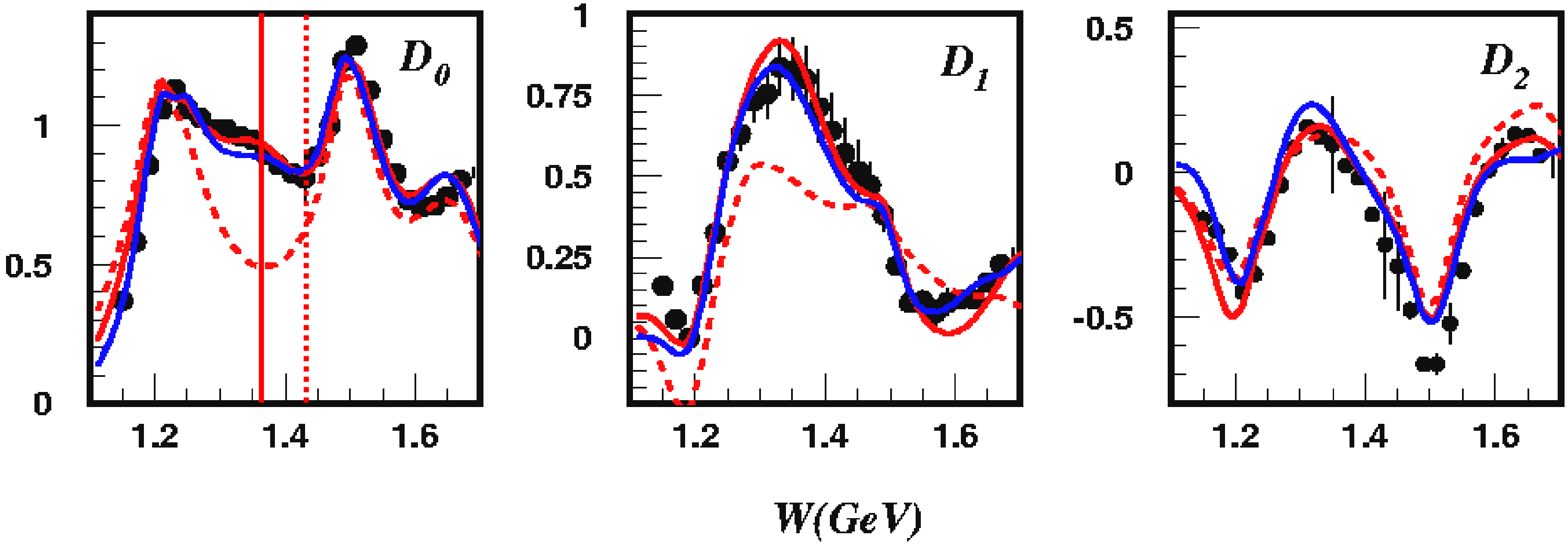
Relates the real and the imaginary parts of the six invariant amplitudes in a model-independent way. The imaginary parts are dominated by resonance contributions.

see White Paper Sec. VII

Legendre Moments of Unpolarized Structure Functions

K. Park *et al.* (CLAS), Phys. Rev. C77, 015208 (2008)

Q^2=2.05GeV^2



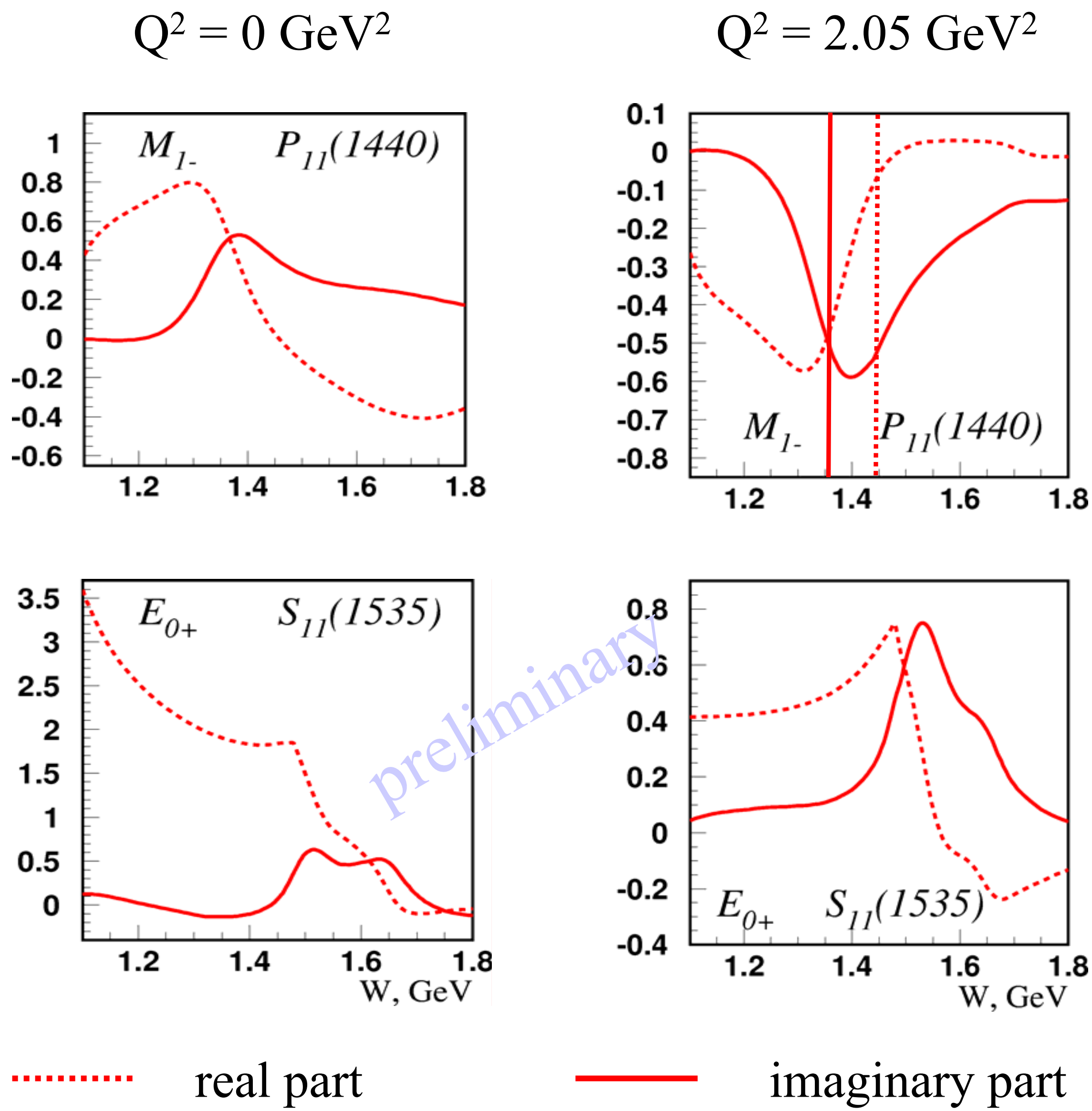
$$\sigma_T + \epsilon\sigma_L = \sum_{l=0}^{n} D_l^{T+L} P_l(\cos\theta_\pi^*)$$

I. Aznauryan —— DR fit
I. Aznauryan - - - DR fit w/o P_{11}
I. Aznauryan —— UIM fit

Two conceptually different approaches DR and UIM are consistent. CLAS data provide rigid constraints for checking validity of the approaches.

Energy-Dependence of π^+ Multipoles for P_{11}, S_{11}

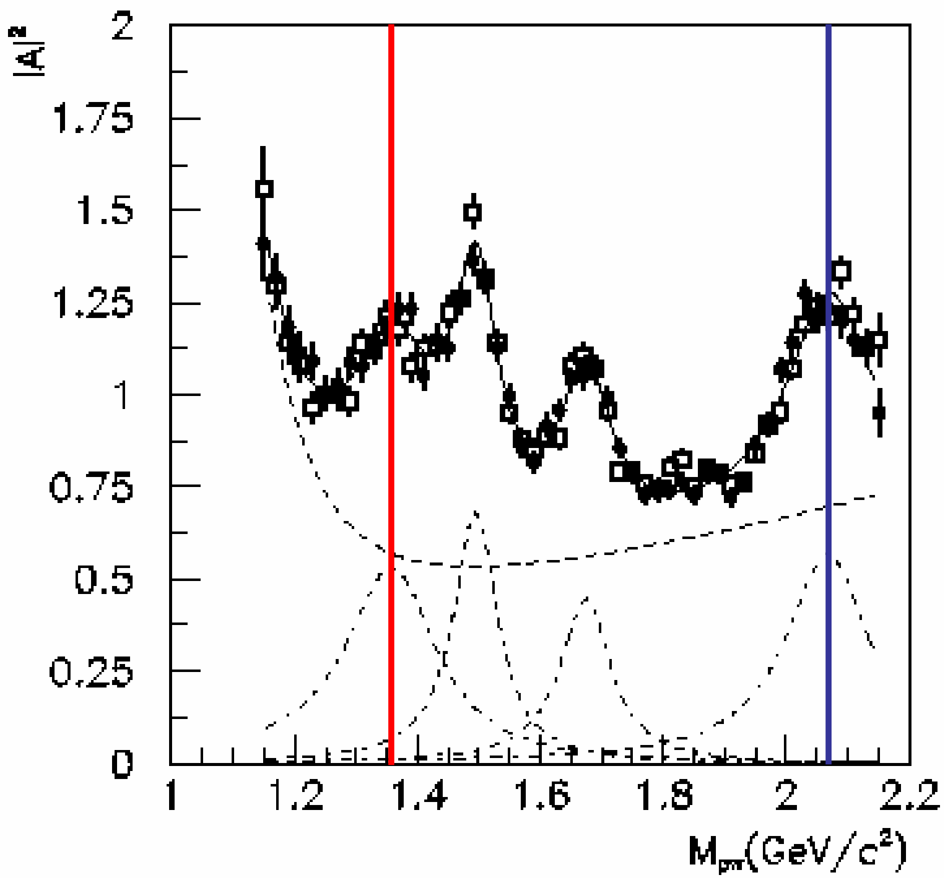
The study of some baryon resonances becomes easier at higher Q^2.



$J/\psi \to p\pi^-\bar{n}$ and $J/\psi \to \bar{p}\pi^+ n$

BES/BEPC, Phys. Rev. Lett. 97 (2006)

Bing-Song Zou



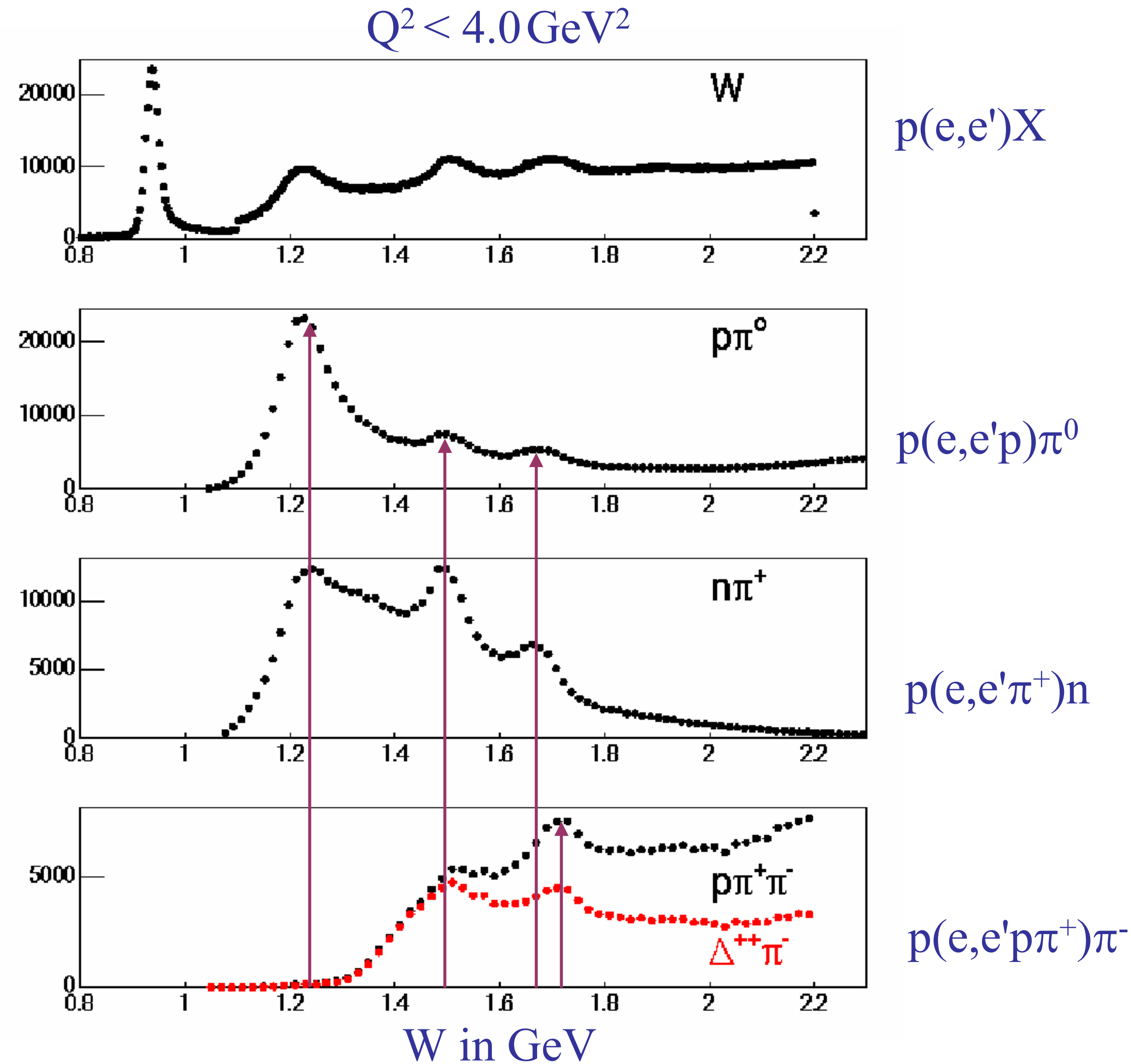
N*(1440): M = 1358 ± 17
Γ = 179 ± 56

N*(2050): M = 2068 +15-40
Γ = 165 ± 42

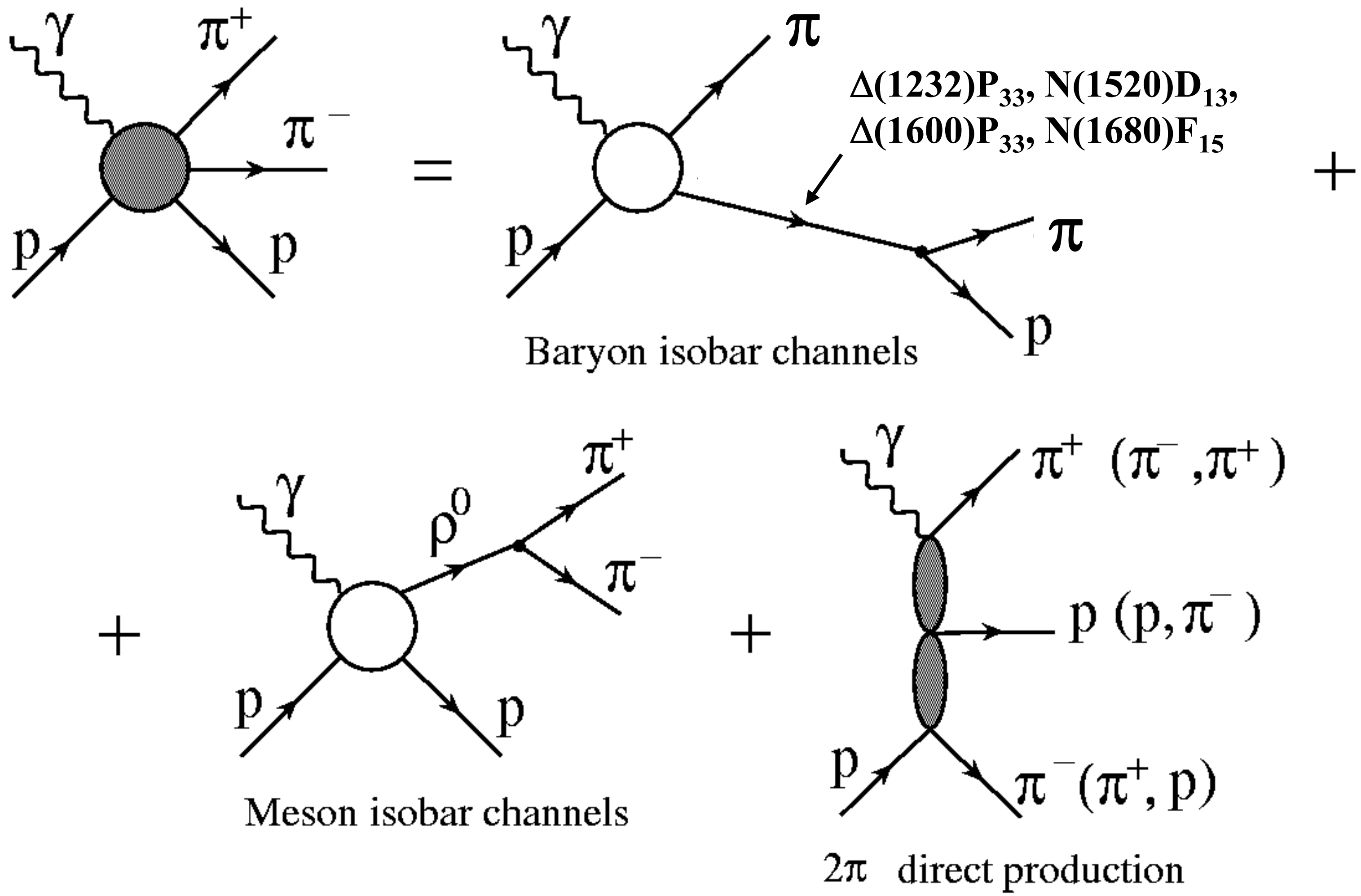
πN invariant mass / MC phase space

Nucleon Resonances in Nπ and Nππ Electroproduction

- Nππ channel is sensitive to N*s heavier than 1.4 GeV
- Provides information that is complementary to the Nπ channel
- Many higher-lying N*s decay preferentially into Nππ final states

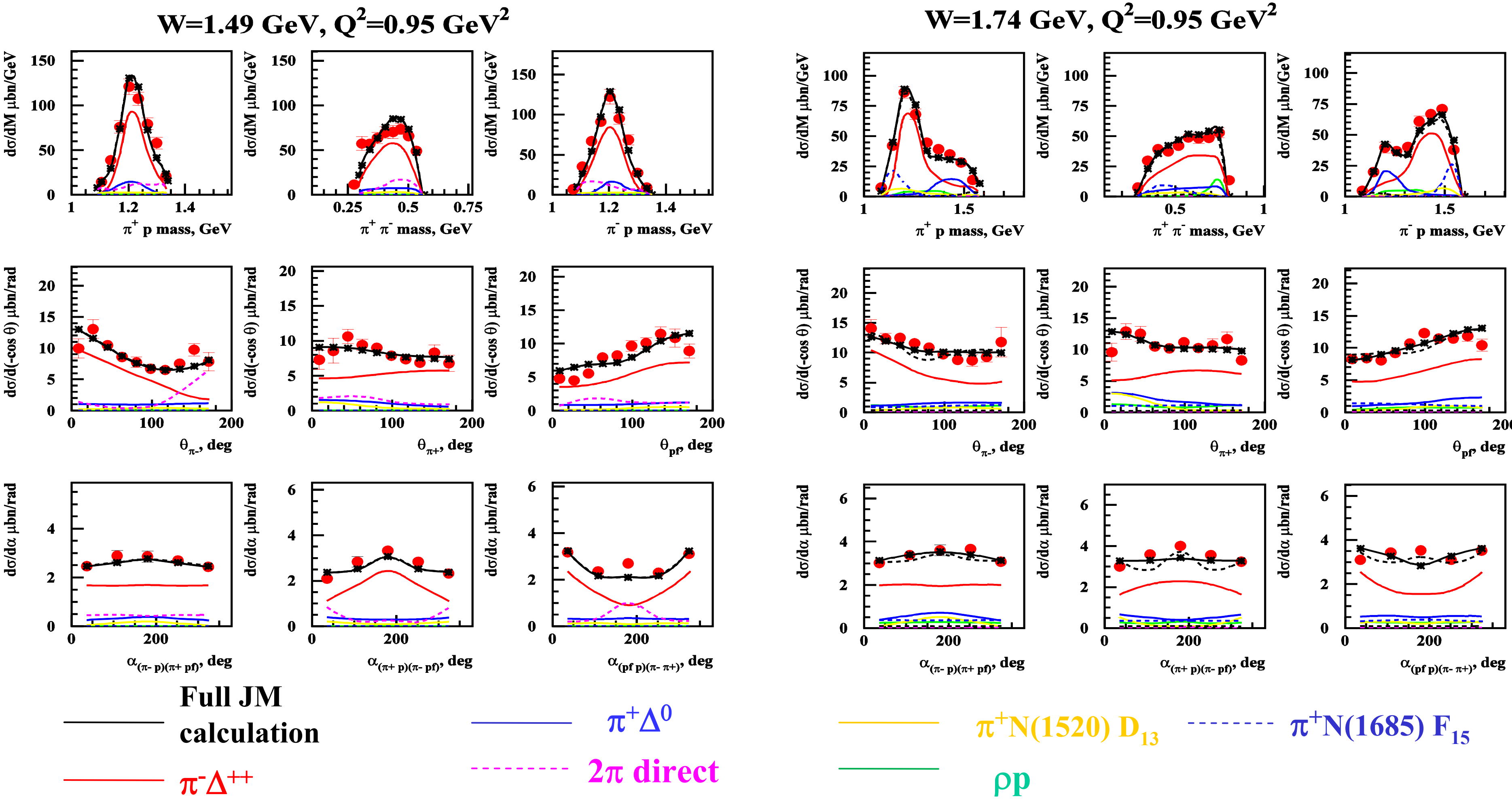


JM Model Analysis of the $p\pi^+\pi^-$ Electroproduction



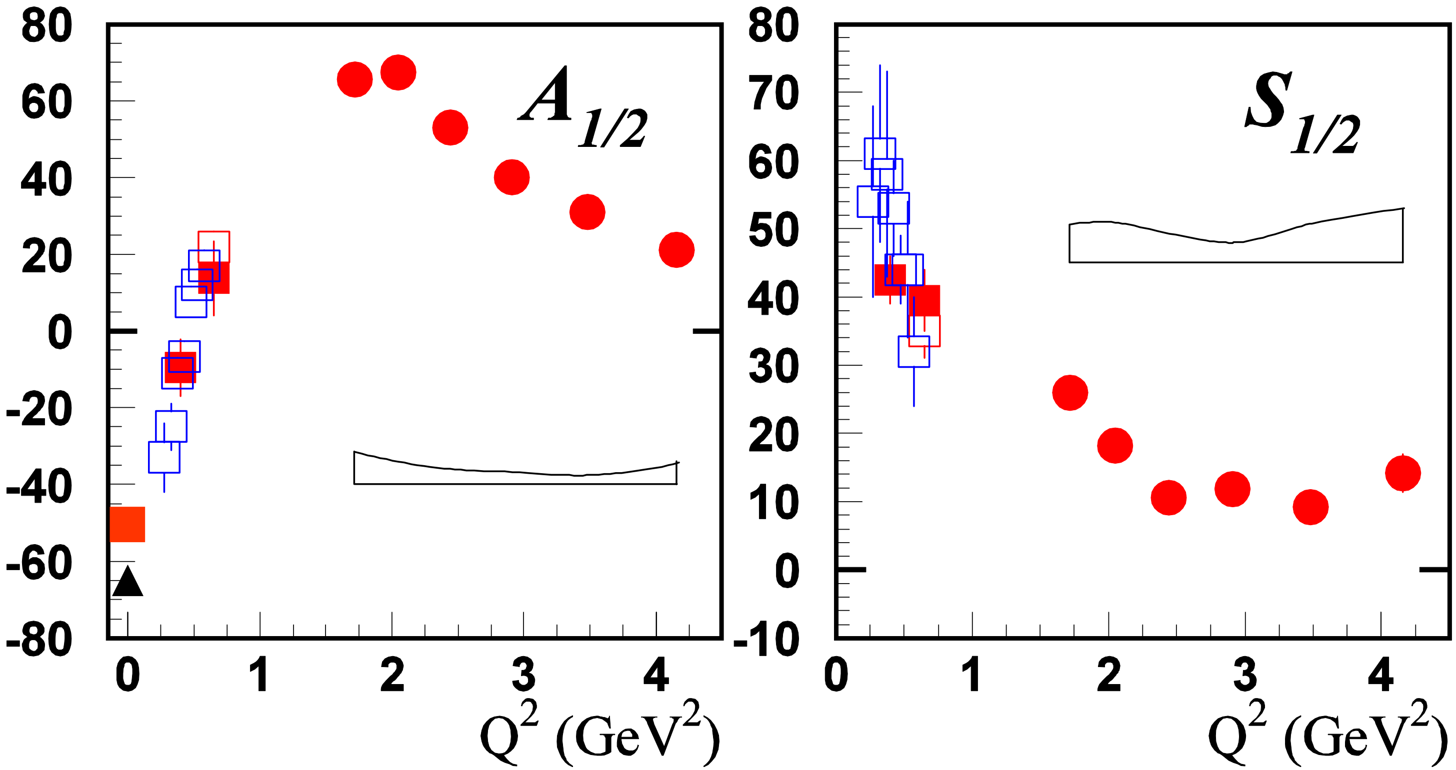
see White Paper Sec. VII

JM Mechanisms as Determined by the CLAS 2π Data



Each production mechanism contributes to all nine single differential cross sections in a unique way. Hence a successful description of all nine observables allows us to check and to establish the dynamics of all essential contributing mechanisms.

Electrocouplings of N(1440)P_{11} from CLAS Data

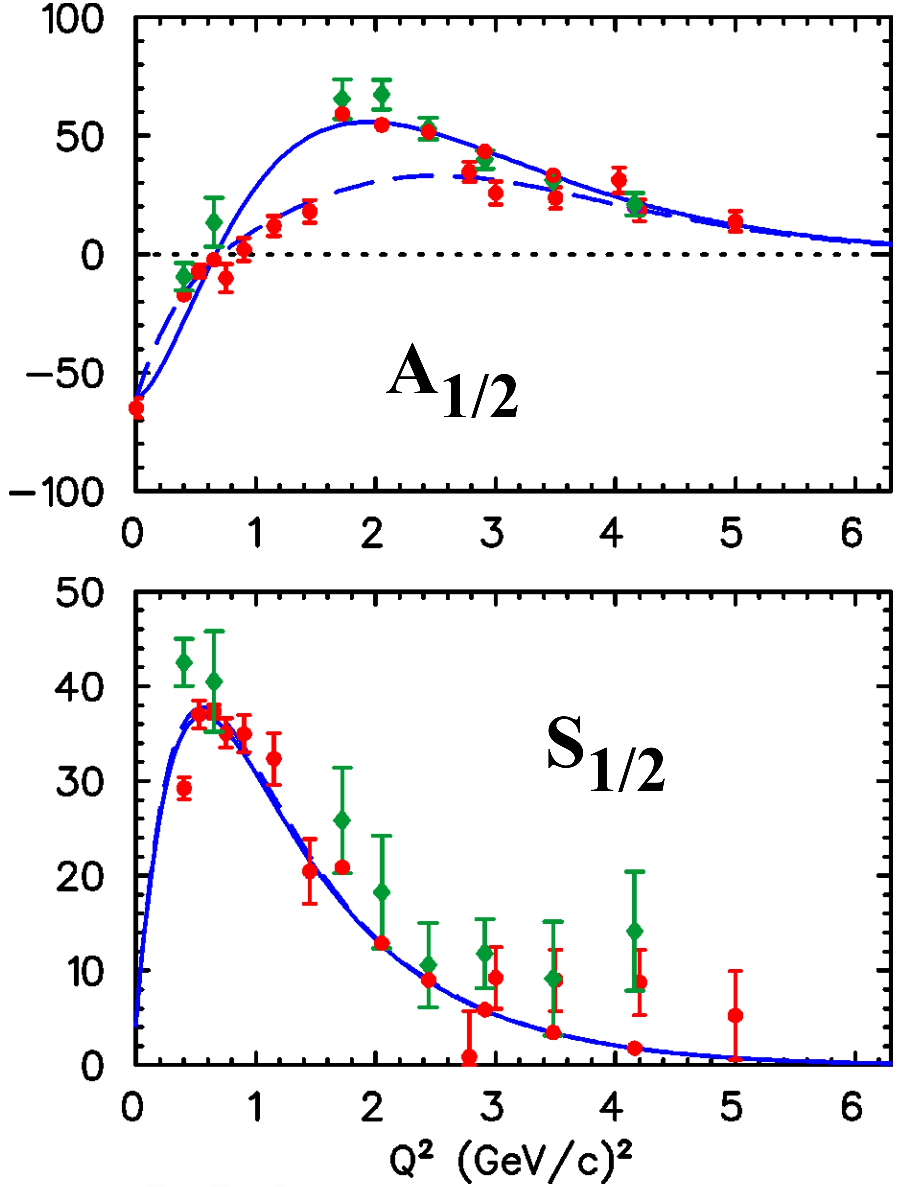


▲ PDG estimation ●■ Nπ (UIM, DR) □ Nπ, Nππ combined analysis □ Nππ (JM)

The good agreement on extracting the N* electrocouplings between the two exclusive channels (1π/2π) – having fundamentally different mechanisms for the nonresonant background – provides evidence for the reliable extraction of N* electrocouplings.

Roper Electro-Coupling Amplitudes $A_{1/2}$, $S_{1/2}$

L. Tiator



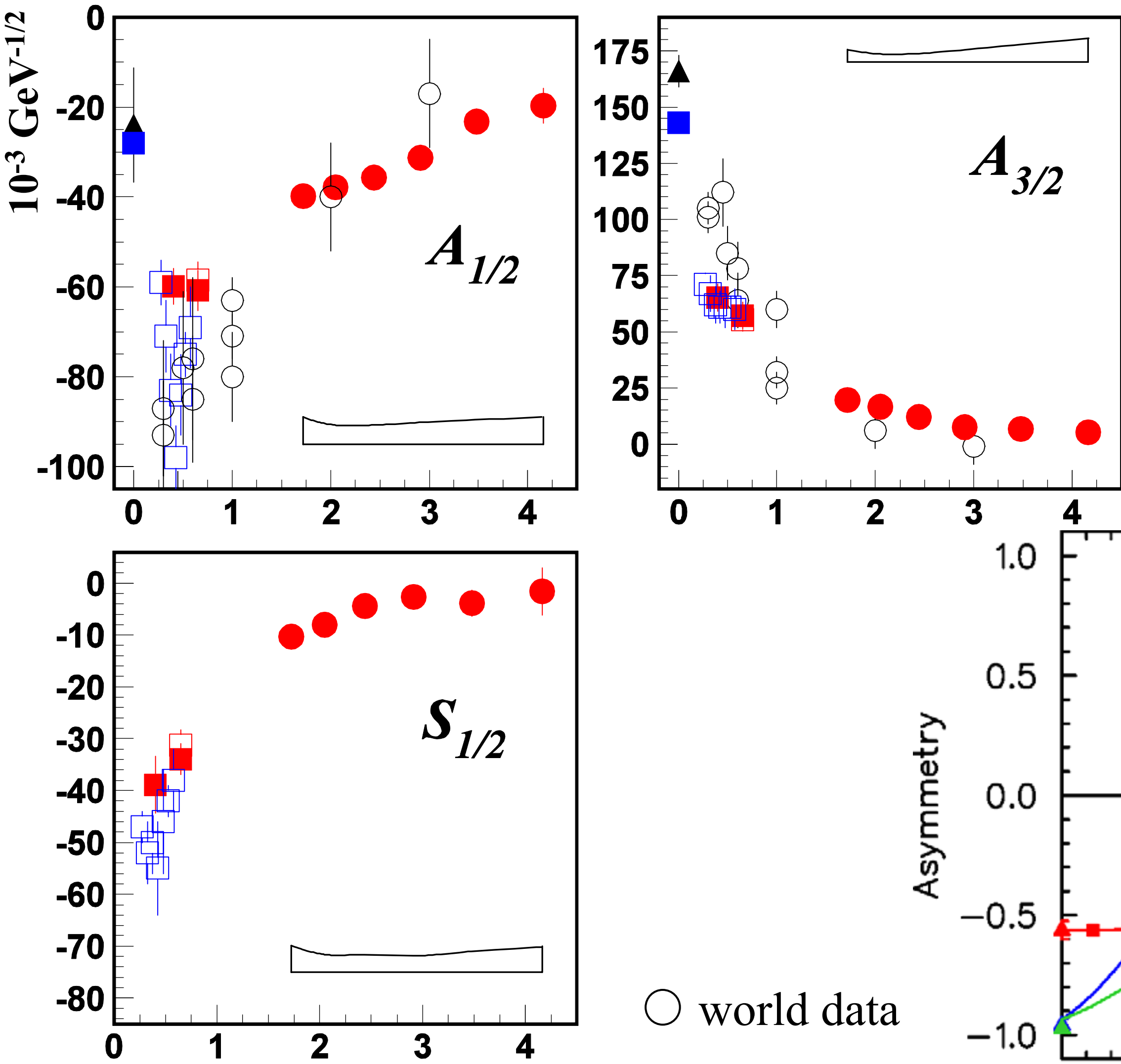
Comparison of **MAID 08** and **JLab** analysis

MAID 07 - - - - - - - -

and new Maid analysis with Park data

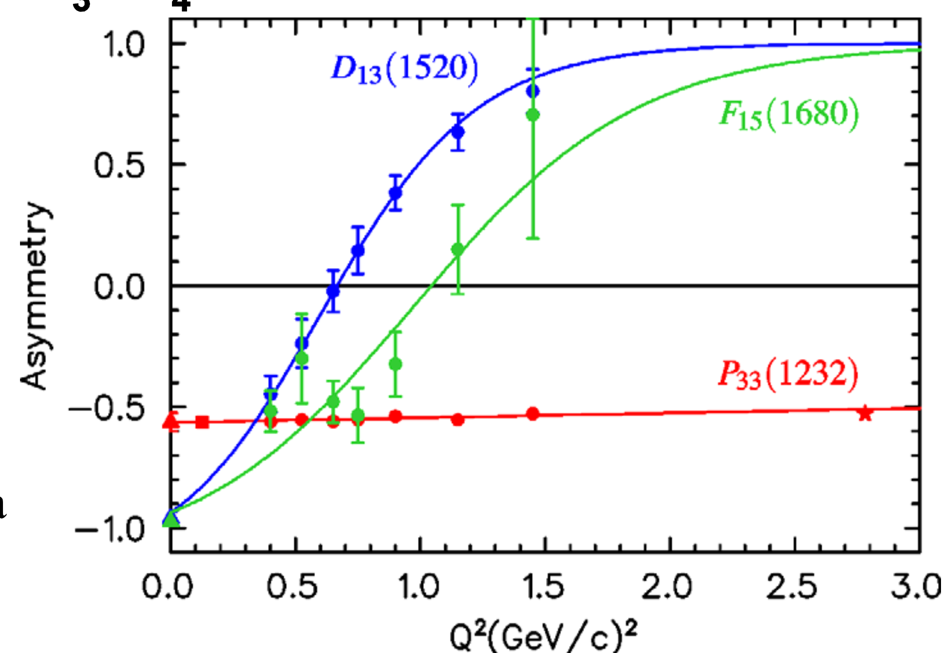
MAID 08 ————

Electrocouplings of N(1520)D_{13} from the CLAS 1π/2π data



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

L. Tiator



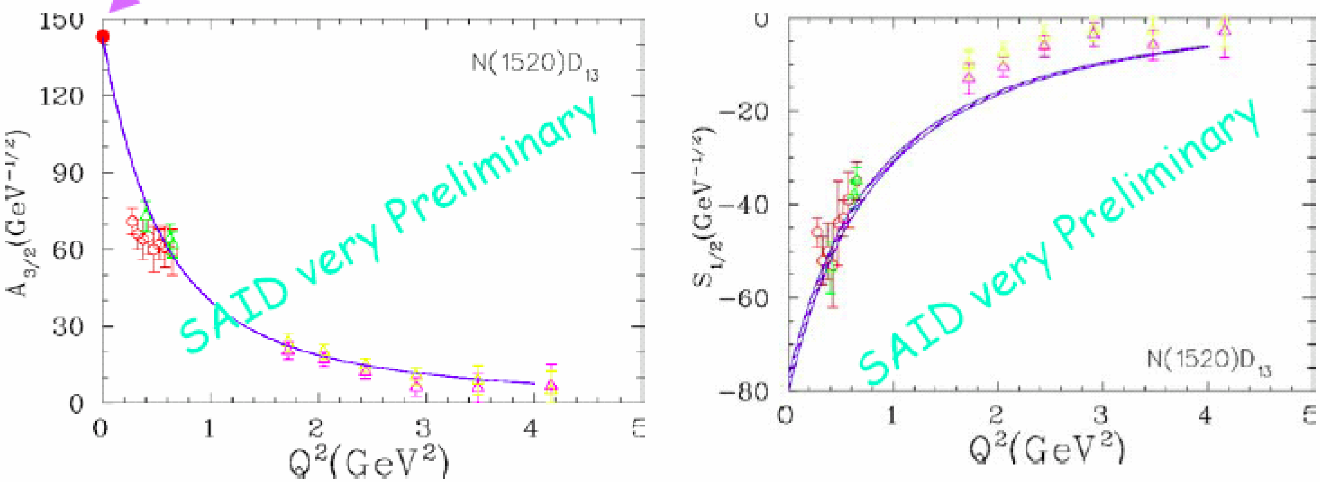
○ world data

▲ PDG estimation ●■ Nπ (UIM, DR)

$N(1520)D_{13}$ Electrocoupling Amplitudes $A_{3/2}$, $S_{1/2}$

I. Starkovski

• GW: $A_{3/2}$ = 143.1±2.0



Resonance fit done over a narrow range in W but for all Q^2
a and b are free prmts
(no W dependence for the polynomial piece of the structure function)

χ^2/dp

W < 1650 MeV Q^2 = 0.40±0.05 GeV²

	SM08	CLAS40	MAID07	Data
π^0	1.6	1.6	1.5	5820
π^+	1.5	1.2	2.2	3352

W < 1650 MeV Q^2 = 0.65±0.05 GeV²

	SM08	CLAS65	MAID07	Data
π^0	1.3	1.3	1.1	8271
π^+	1.1	1.3	1.8	2515

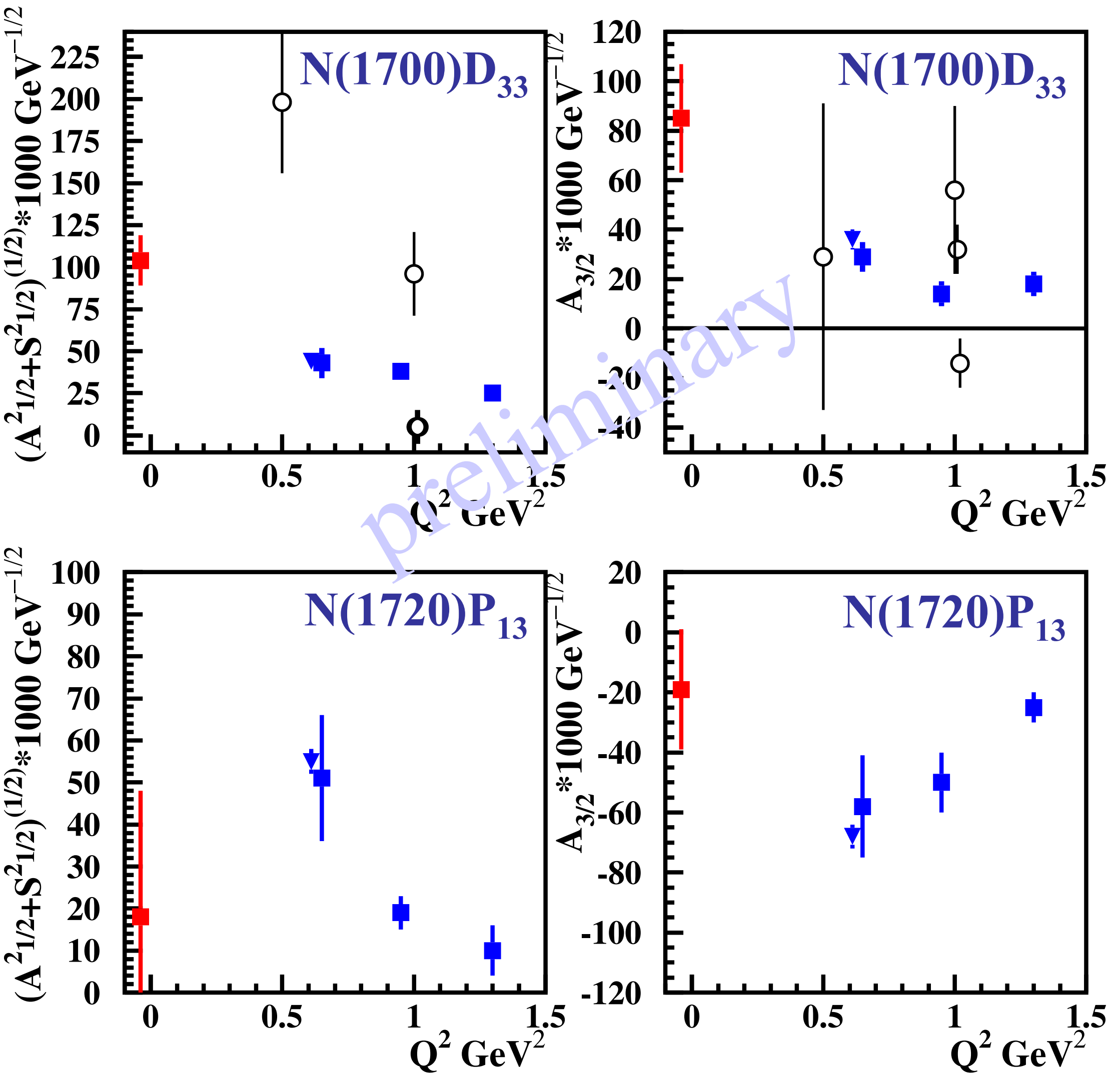
— SM08
• FA06 [Q^2 = 0]
o CLAS [2π]
Δ CLAS [1π]
Δ DR [1π]
Δ Isobar [1π]

Viktor Mokeev, PC 2008

• The good agreement for $A_{3/2}$ and $S_{1/2}$ determination between various resonance extractions gives a more reliable estimate of systematics

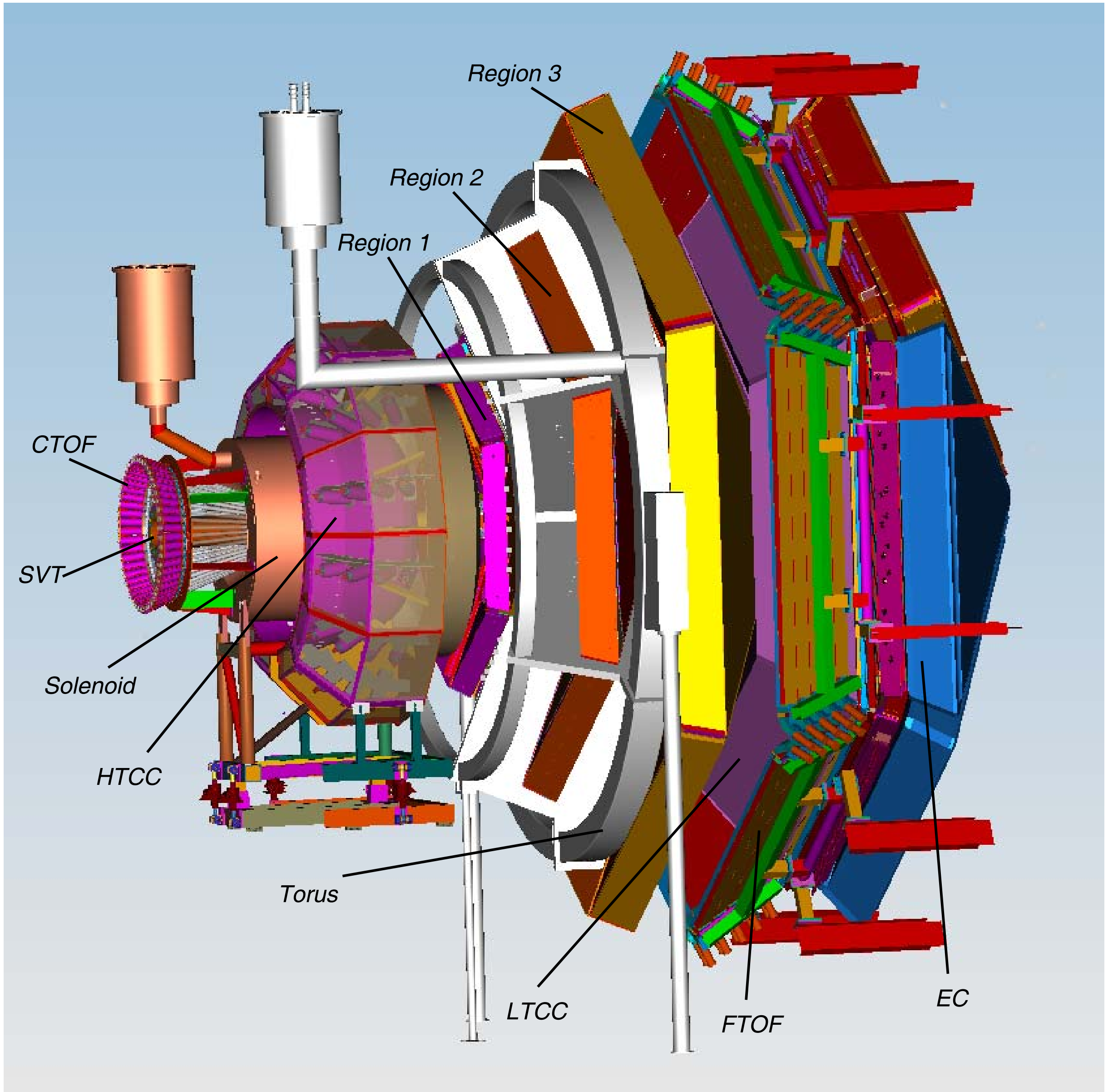
• CLAS12 is favorable for Q^2 evaluation

Combined 1π-2π JM Analysis of CLAS Data



- PDG at $Q^2=0$
- Previous world data
- 2π analysis
- 1π-2π combined at $Q^2=0.65$ GeV^2
- Many more examples:
  $P_{11}(1440)$, $D_{13}(1520)$, $S_{31}(1650)$, $S_{11}(1650)$, $F_{15}(1685)$, $D_{13}(1700)$, …

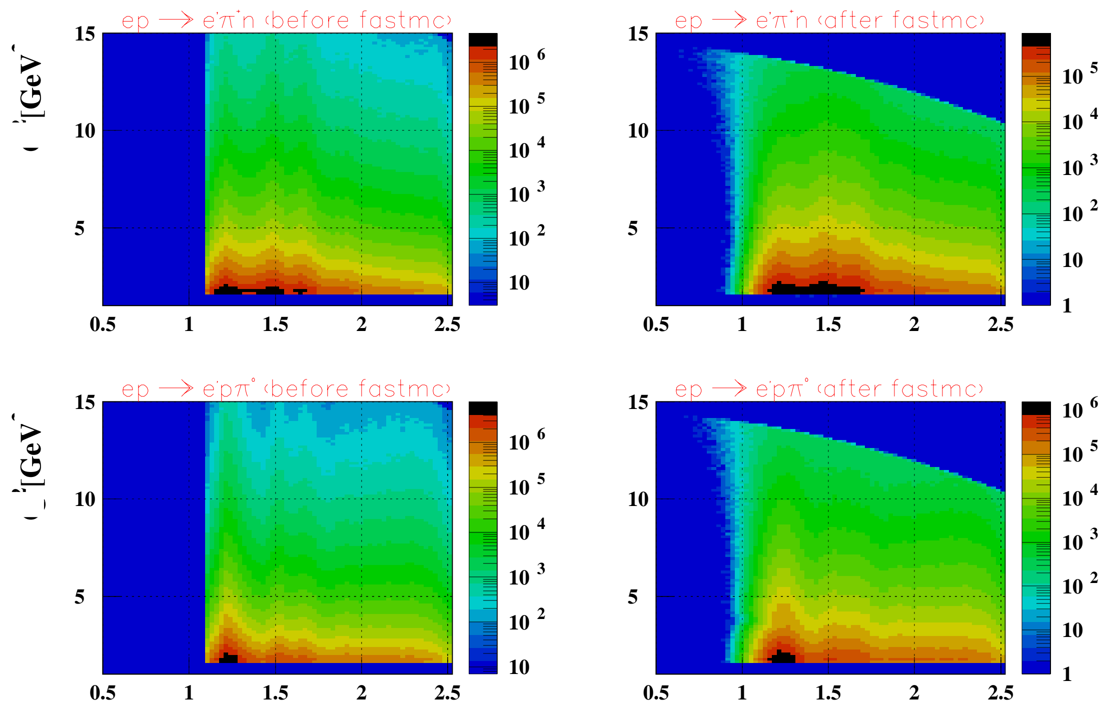
CLAS12 Detector Base Equipment



CLAS 12 Kinematic Coverage and Counting Rates

Genova-EG

Genova-EG



(e',π+) detected

(e',p) detected

(E,Q^2)	(5.75 GeV, 3 GeV^2)	(11 GeV, 3 GeV^2)	(11 GeV, 12 GeV^2)
$N^{\pi+}$	$1.41*10^5$	$6.26*10^6$	$5.18*10^4$
$N^{p\pi 0}$	-	$4.65*10^5$	$1.45*10^4$
$N^{p\eta}$	-	$1.72*10^4$	$1.77*10^4$

60 days

$L=10^{35}$ cm^{-2} sec^{-1}, W=1535 GeV, ΔW= 0.100 GeV, $\Delta Q^2 = 0.5$ GeV^2

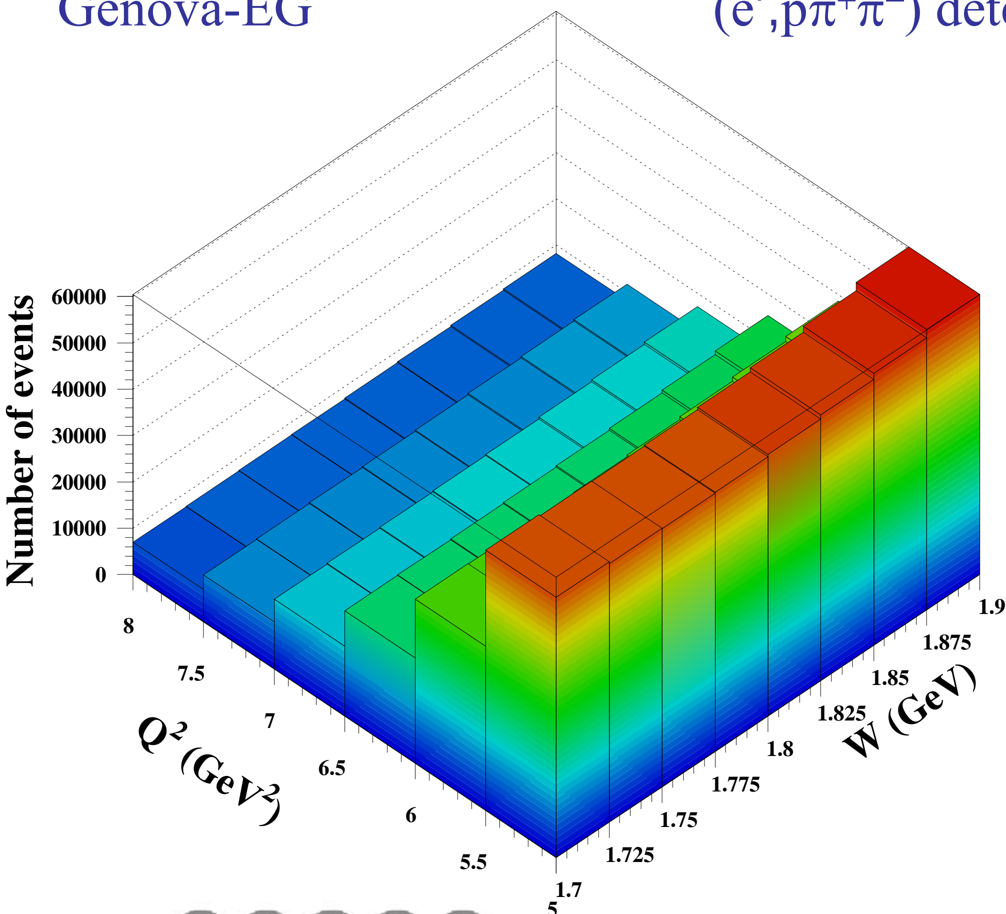
Kinematic Coverage of CLAS12

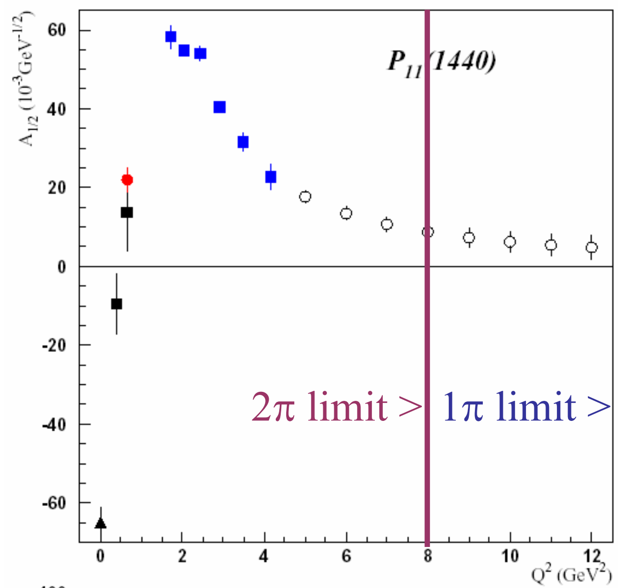
60 days

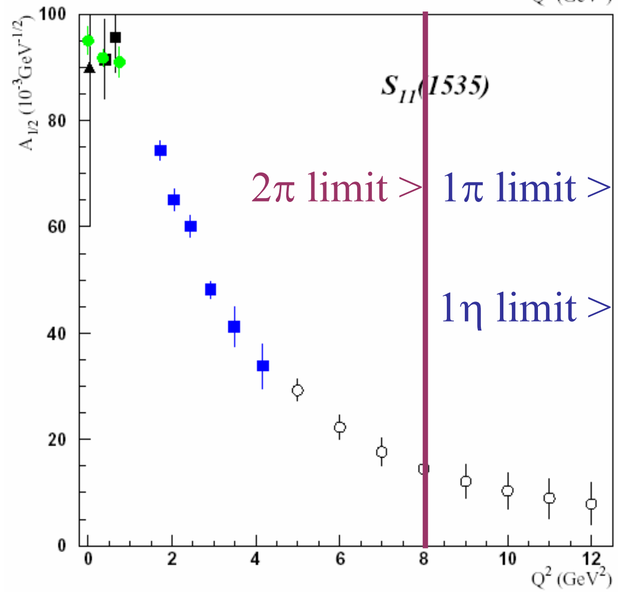
L= 10^{35} cm^{-2} sec^{-1}, $\Delta W = 0.025$ GeV, $\Delta Q^2 = 0.5$ GeV^2

Genova-EG

$(e', p\pi^+\pi^-)$ detected







Summary

- We will measure determine the electrocouplings $A_{1/2}$, $A_{3/2}$, $S_{1/2}$ as a function of Q^2 for prominent nucleon and Δ states,
  - see our Proposal http://www.physics.sc.edu/~gothe/research/pub/nstar12-12-08.pdf.
- Comparing our results with LQCD, DSE, LCSR, and rCQM will gain insight into
  - the strong interaction of dressed quarks and their confinement in baryons,
  - the dependence of the light quark mass on momentum transfer, thereby shedding light on chiral-symmetry breaking, and
  - the emergence of bare quark dressing and dressed quark interactions from QCD.
- This unique opportunity to understand origin of 98% of nucleon mass is also an experimental and theoretical challenge. A wide international collaboration is needed for the:
  - theoretical interpretation on N* electrocouplings, see our White Paper http://www.physics.sc.edu/~gothe/research/pub/white-paper-09.pdf, and
  - development of reaction models that will account for hard quark/parton contributions at high Q^2.
- Any constructive criticism or direct participation is very welcomed, please contact:
  - Viktor Mokeev mokeev@jlab.org or Ralf Gothe gothe@sc.edu.