Transition Form Factors:
A unique Opportunity to Connect Non-Perturbative Strong Interaction to QCD

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NSTAR 2013

9th International Workshop on the Physics of Excited Nucleons

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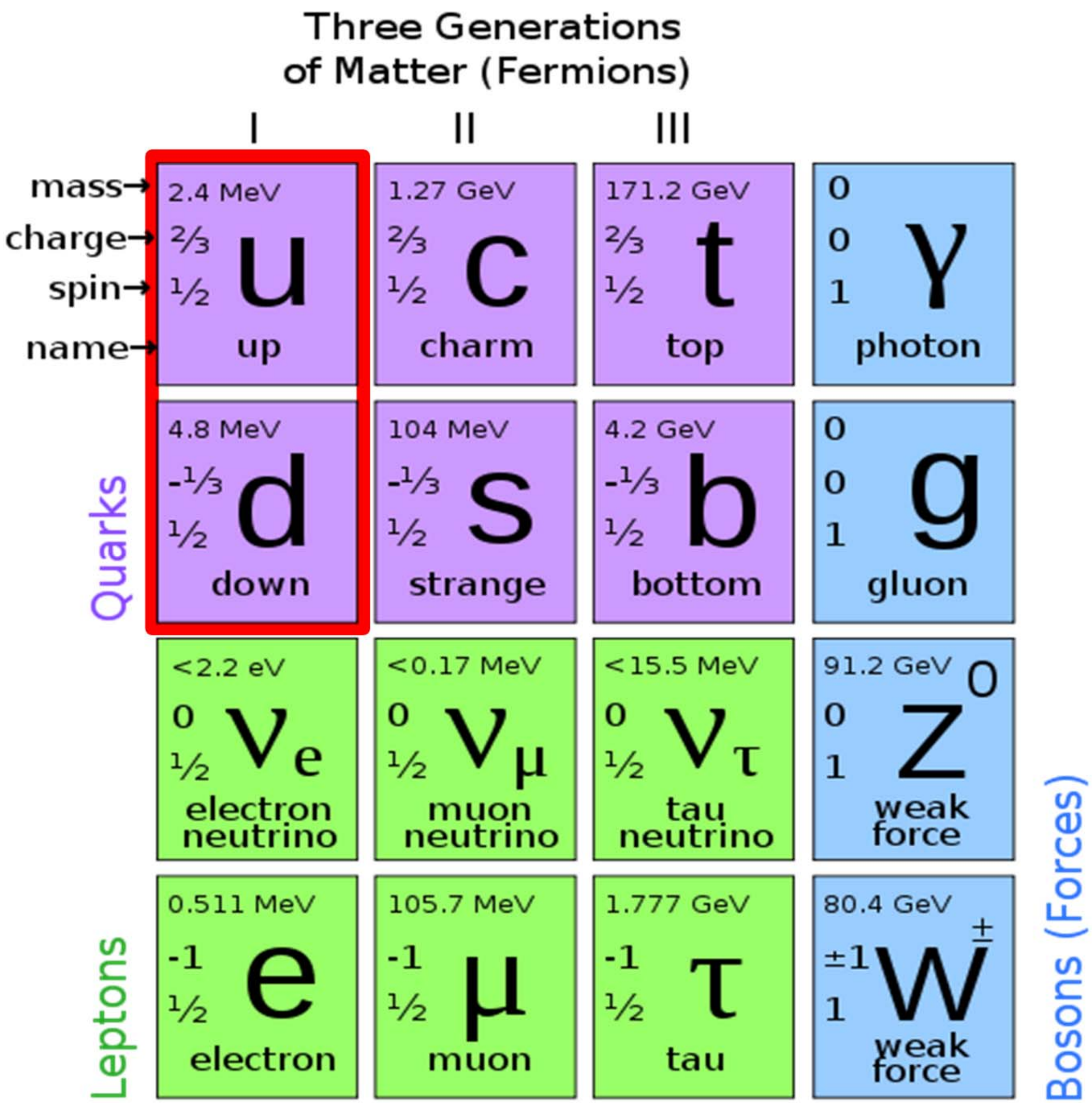
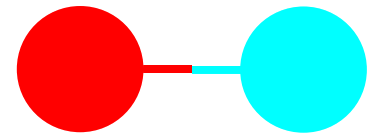
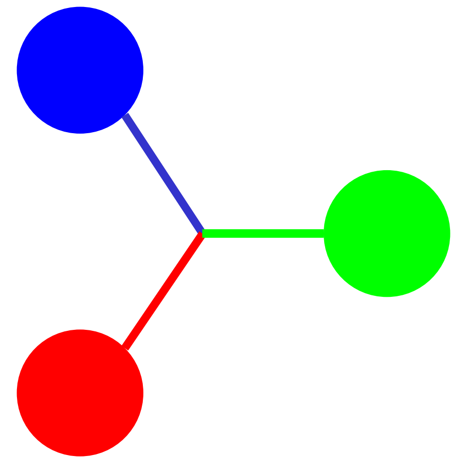
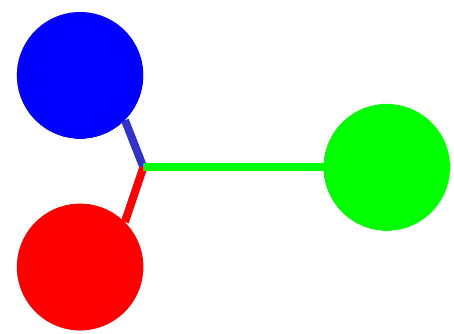
- **γ_vNN* Experiments:** The Best Access to the Baryon and Quark Structure?
  - Spectroscopy, Elastic Form Factors, and Transition Form Factors
- **Analysis:** Phenomenological Extraction … who can do better?
  - Consistent extraction of γ_vNN* electrocouplings in various decay channel with various models
- **QCD based Theory:** Solve Non-Perturbative QCD and Confinement?
- **Outlook:** Extended kinematics, new experiments … what can be done next?

Build your Mesons or Excite Baryons …



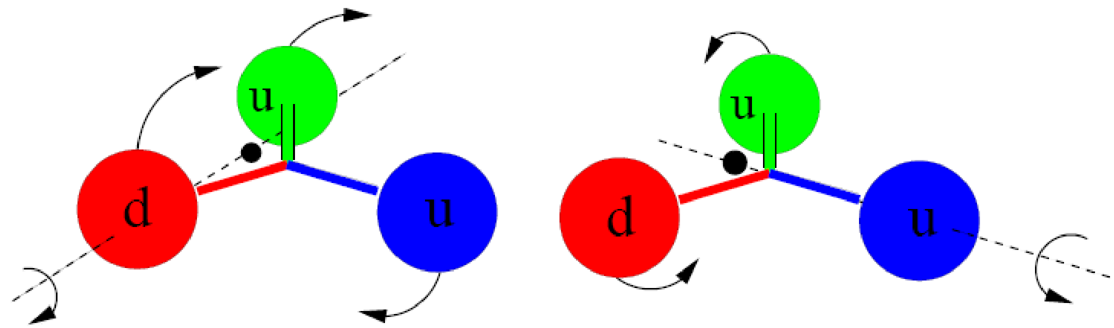




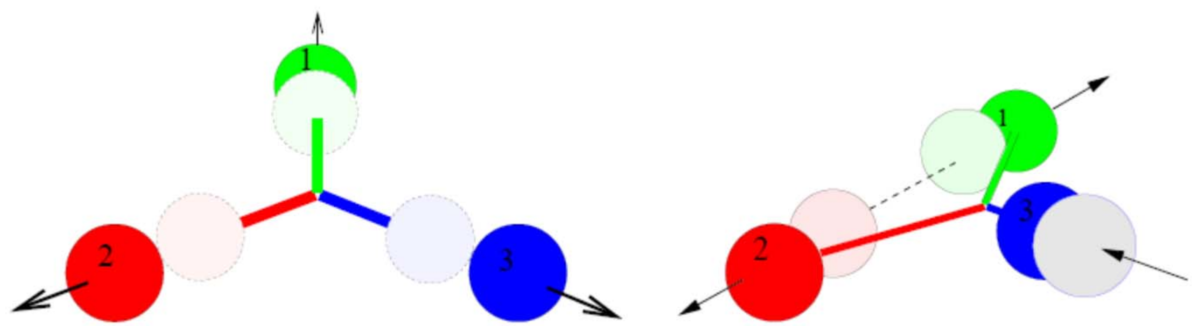


N and Δ Excited Baryon States …

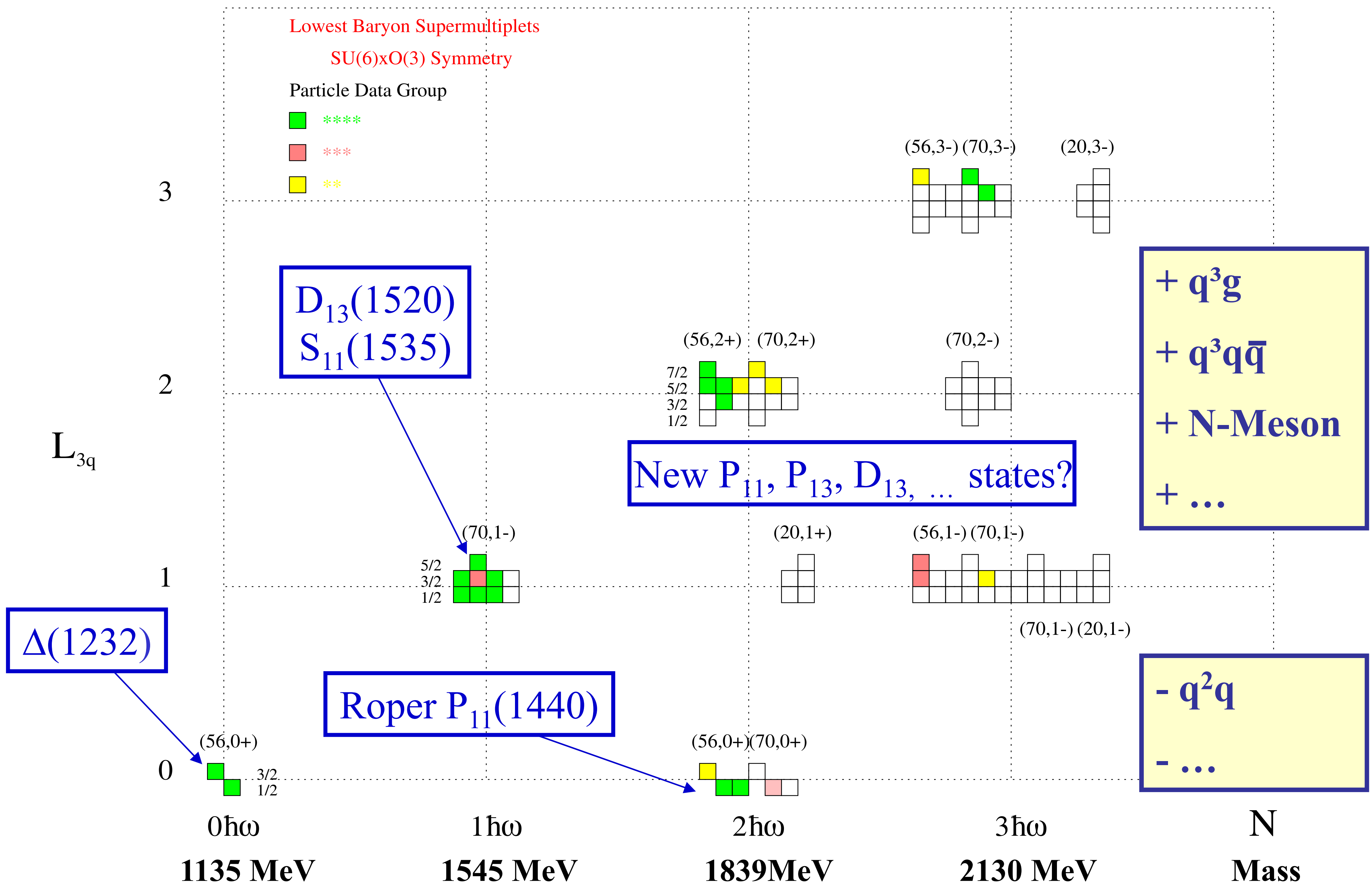
- Orbital excitations (two distinct kinds in contrast to mesons)



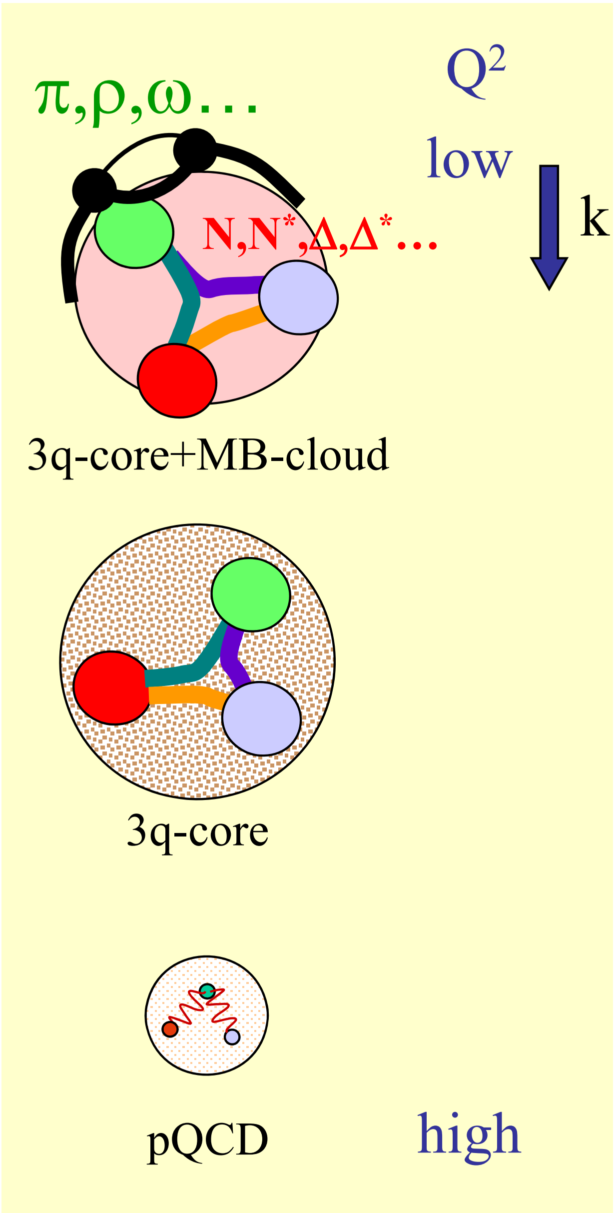
- Radial excitations (also two kinds in contrast to mesons)



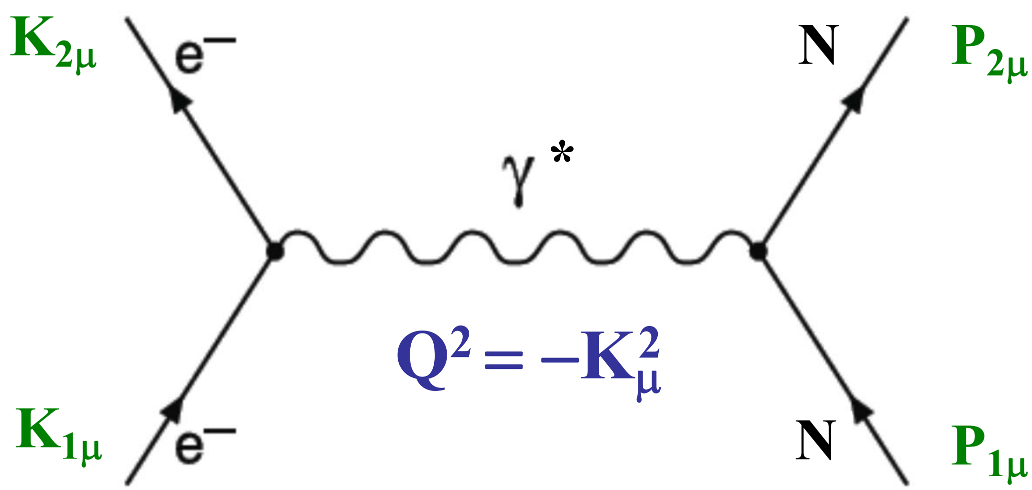
Quark Model Classification of N*



Hadron Structure with Electromagnetic Probes

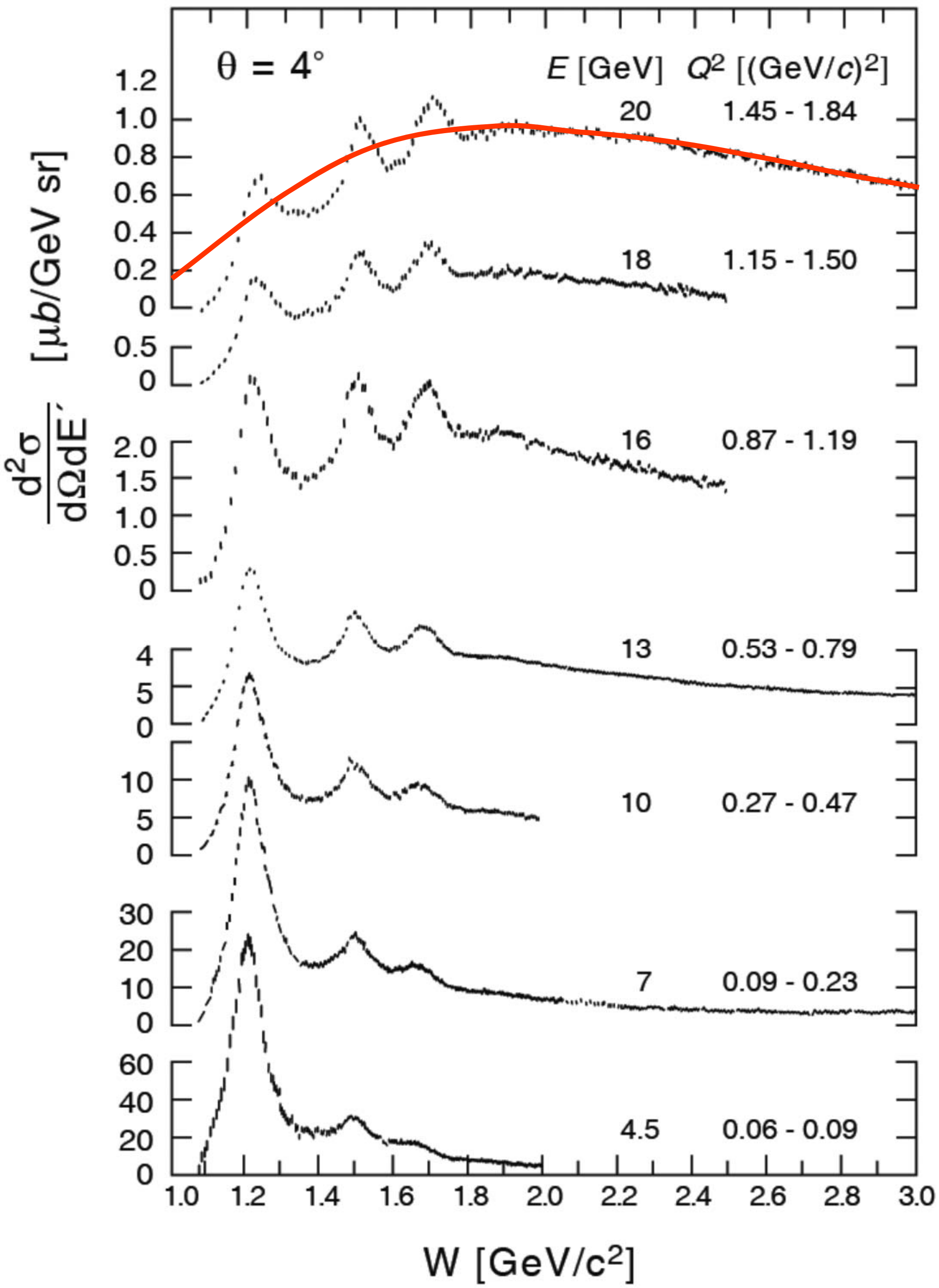


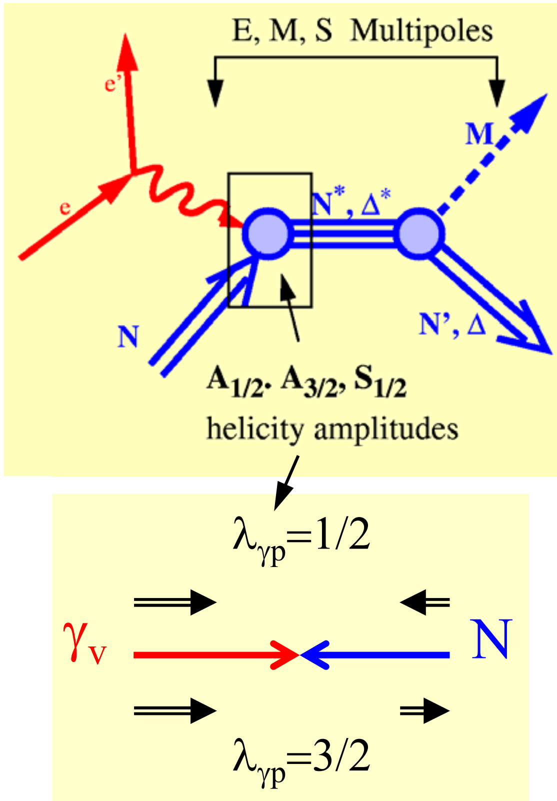
- Study the structure of the nucleon spectrum in the domain where dressed quarks are the major active degree of freedom.
- Explore the formation of excited nucleon states in interactions of dressed quarks and their emergence from QCD.



Hard Scattering off Bound and Confined Quarks

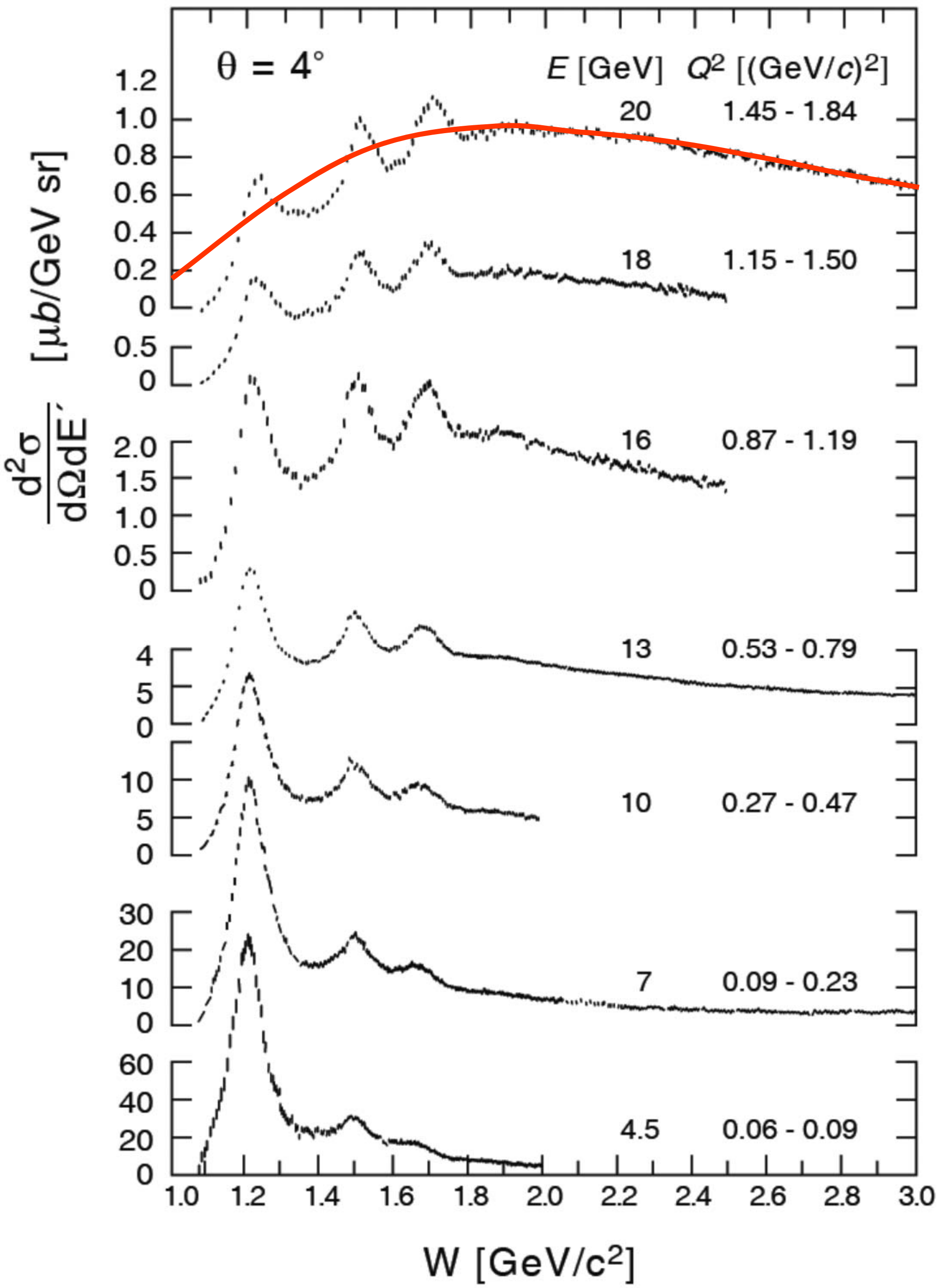
Baryon Excitations and Quasi-Elastic Scattering



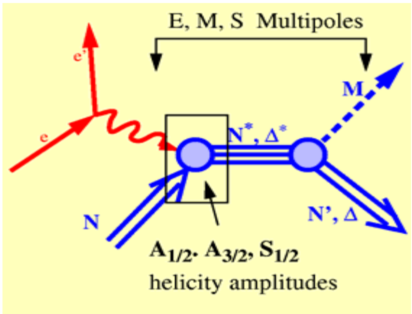


Deep Inelastic Scattering
S. Stein et al., PR **D22** (1975) 1884

Baryon Excitations and Quasi-Elastic Scattering



hard and confined

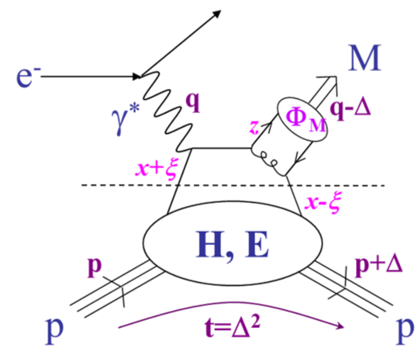


Elastic Form Factors

Transition Form Factors

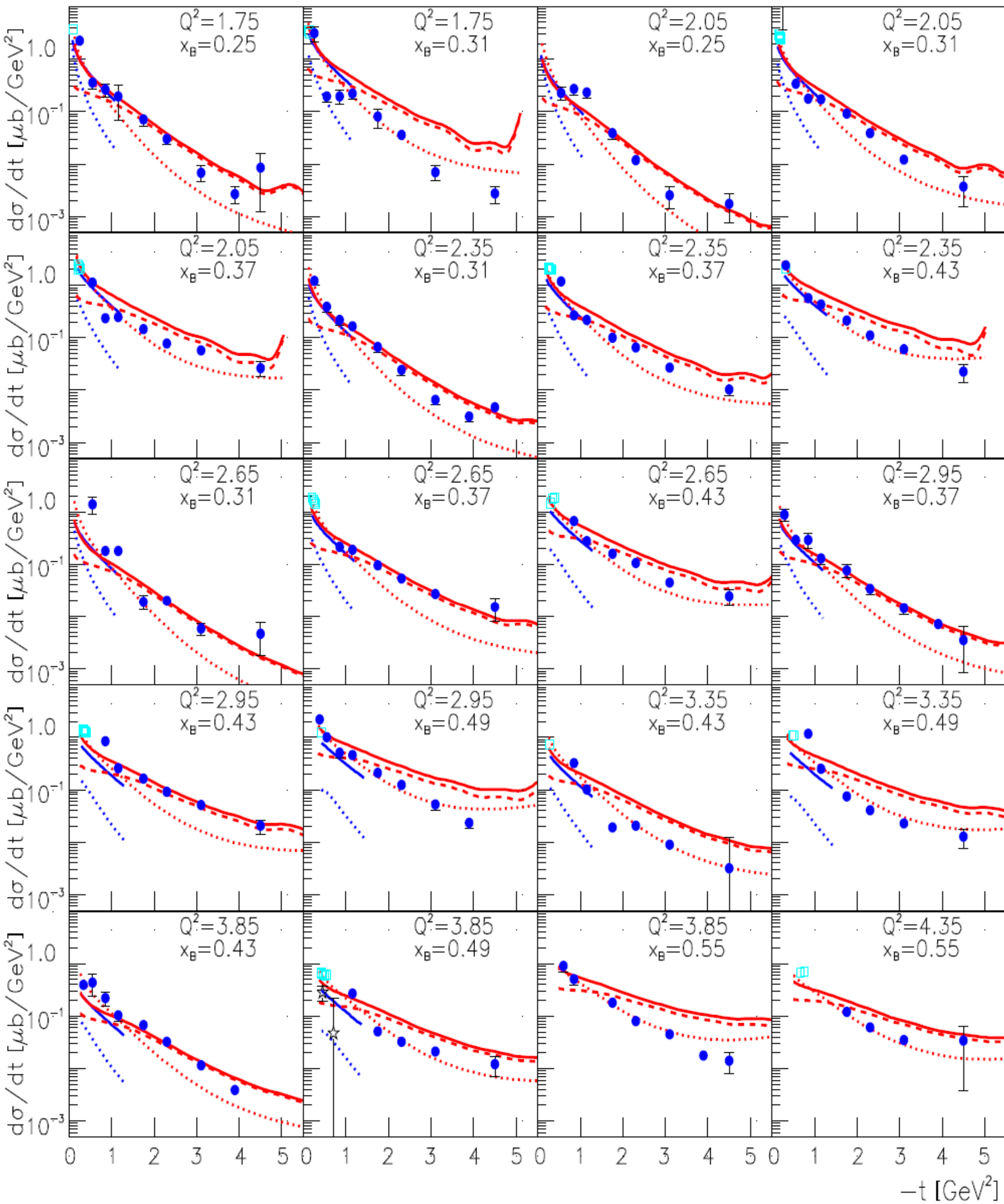
hard

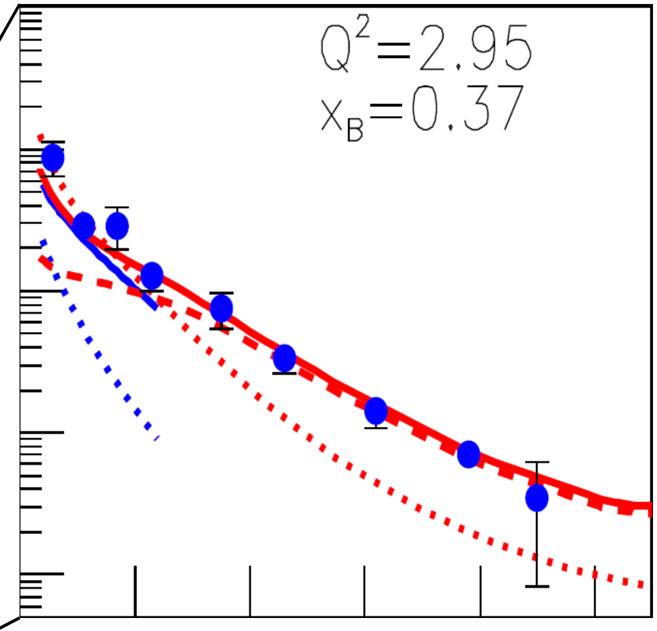
soft



Deep Inelastic Scattering
S. Stein et al., PR **D22** (1975) 1884

Deep Exclusive π^+ Electroproduction off the Proton





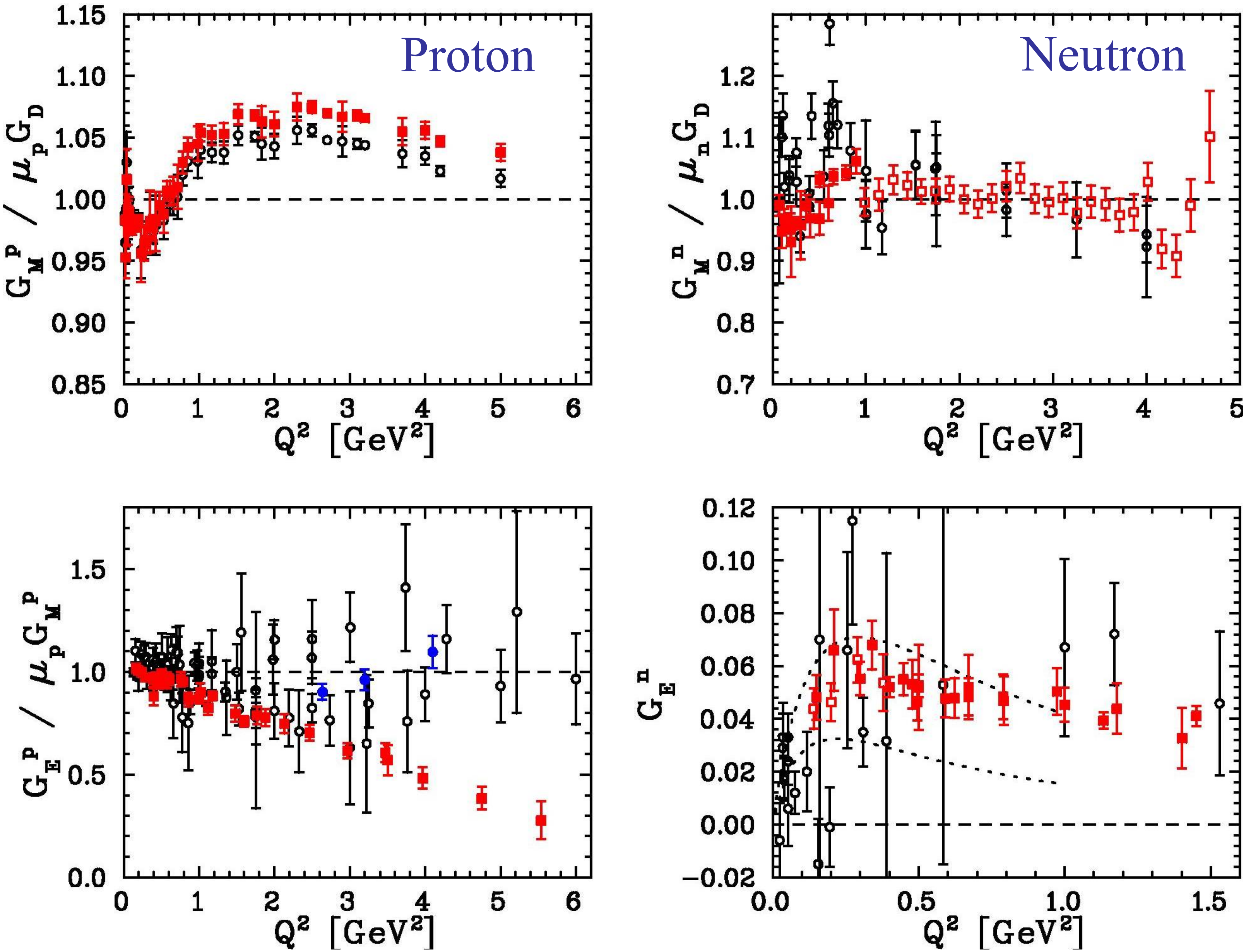
K. Park et al., Eur. Phys. J. A 49 (2013) 16

The red solid ($d\sigma/dt$), dotted ($d\sigma_L/dt$), and dashed ($d\sigma_T/dt$) curves are the calculations from a hadronic model (Regge phenomenology) with (Q^2, t)-dependent form factors at the photon-meson vertices. The blue solid and dotted curves are the calculations of $d\sigma/dt$ and $d\sigma_L/dt$, respectively, of a partonic model (handbag diagrams).

Elastic Form Factors

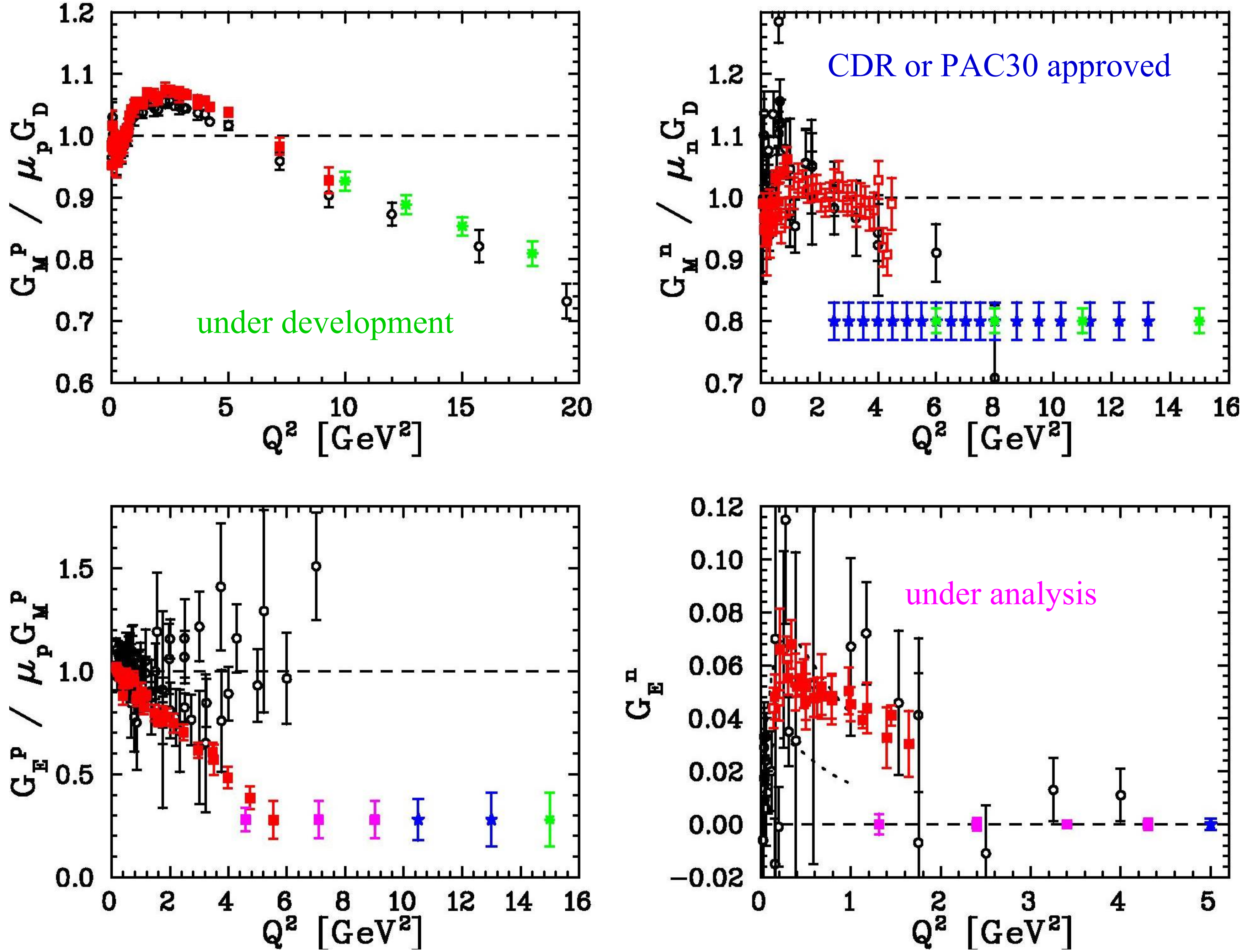
Nucleon Form Factors: Last Ten Years

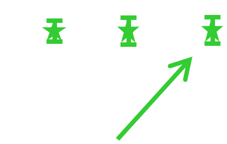
J. Arrington



Extensions with JLab 12 GeV Upgrade

J. Arrington

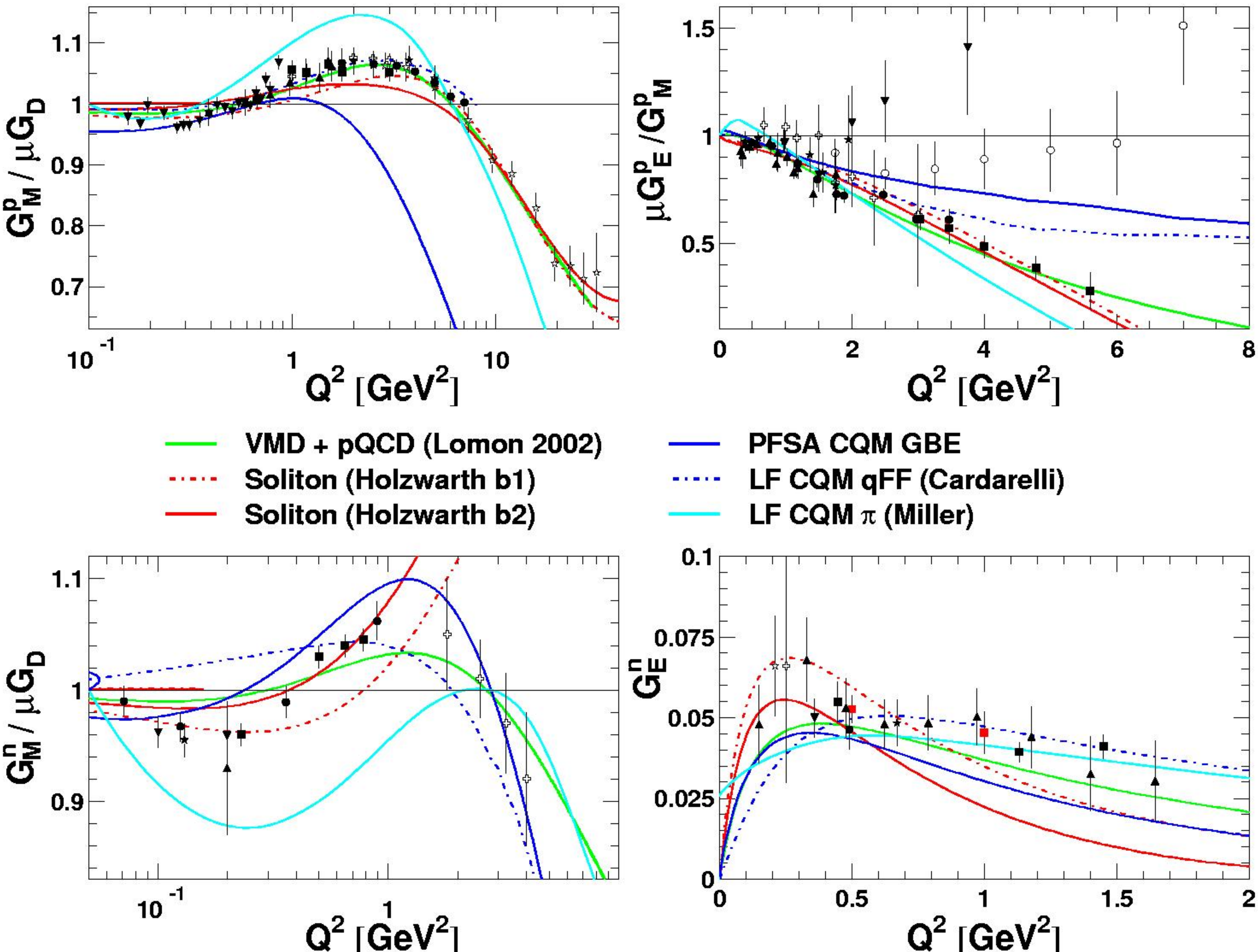




~8 GeV^2

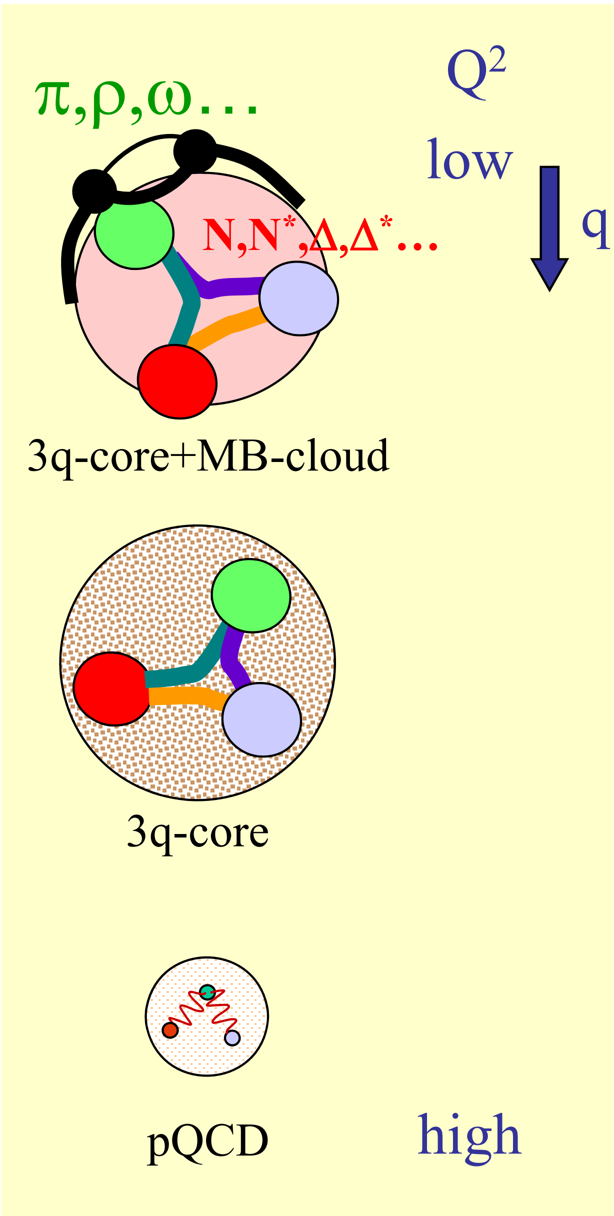
Small Sample of Recent Calculations

J. Arrington



Transition Form Factors

Hadron Structure with Electromagnetic Probes



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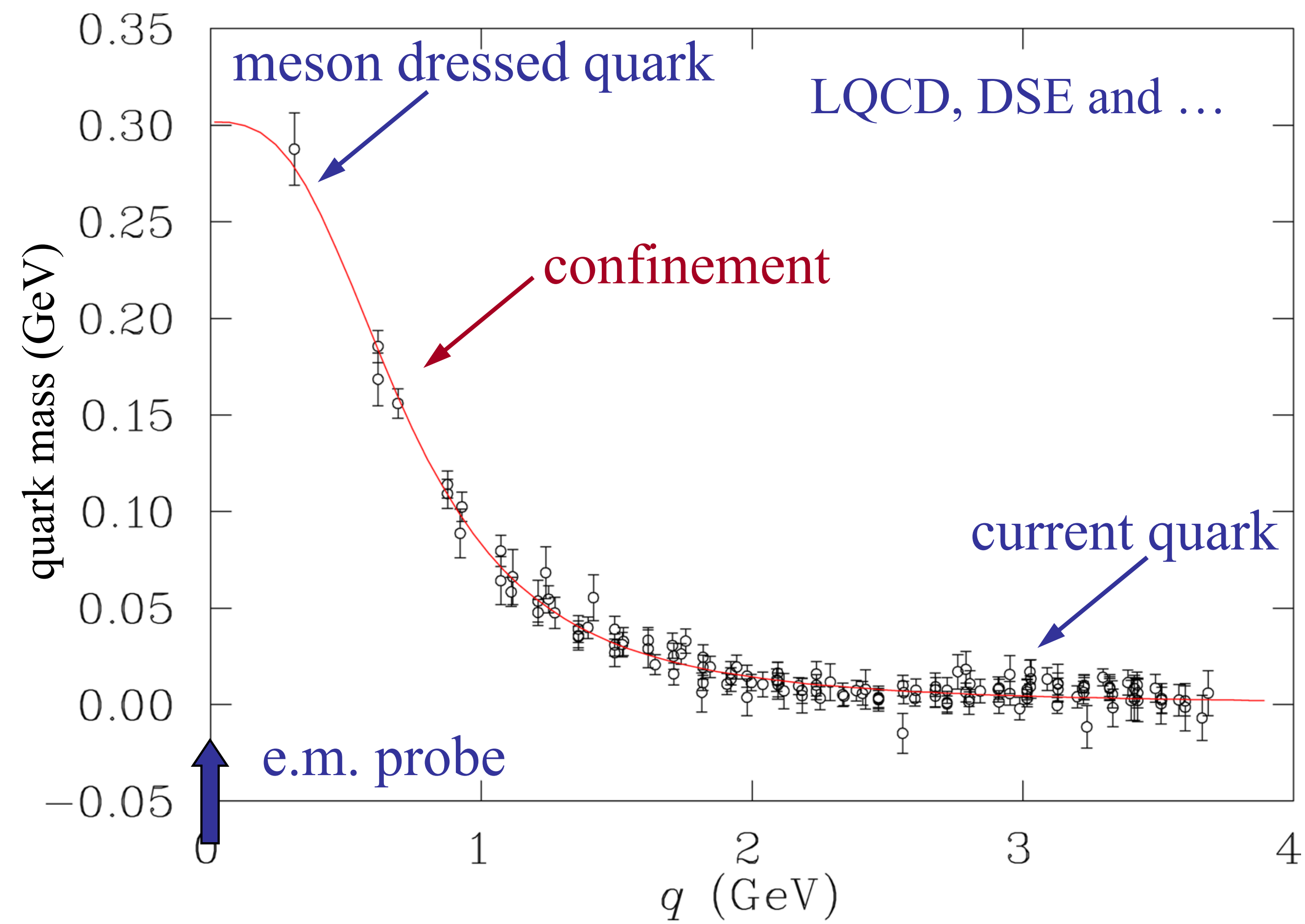
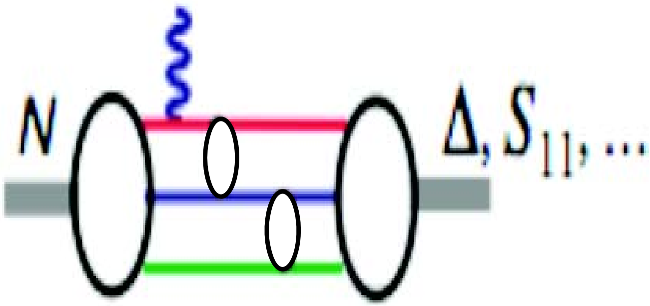
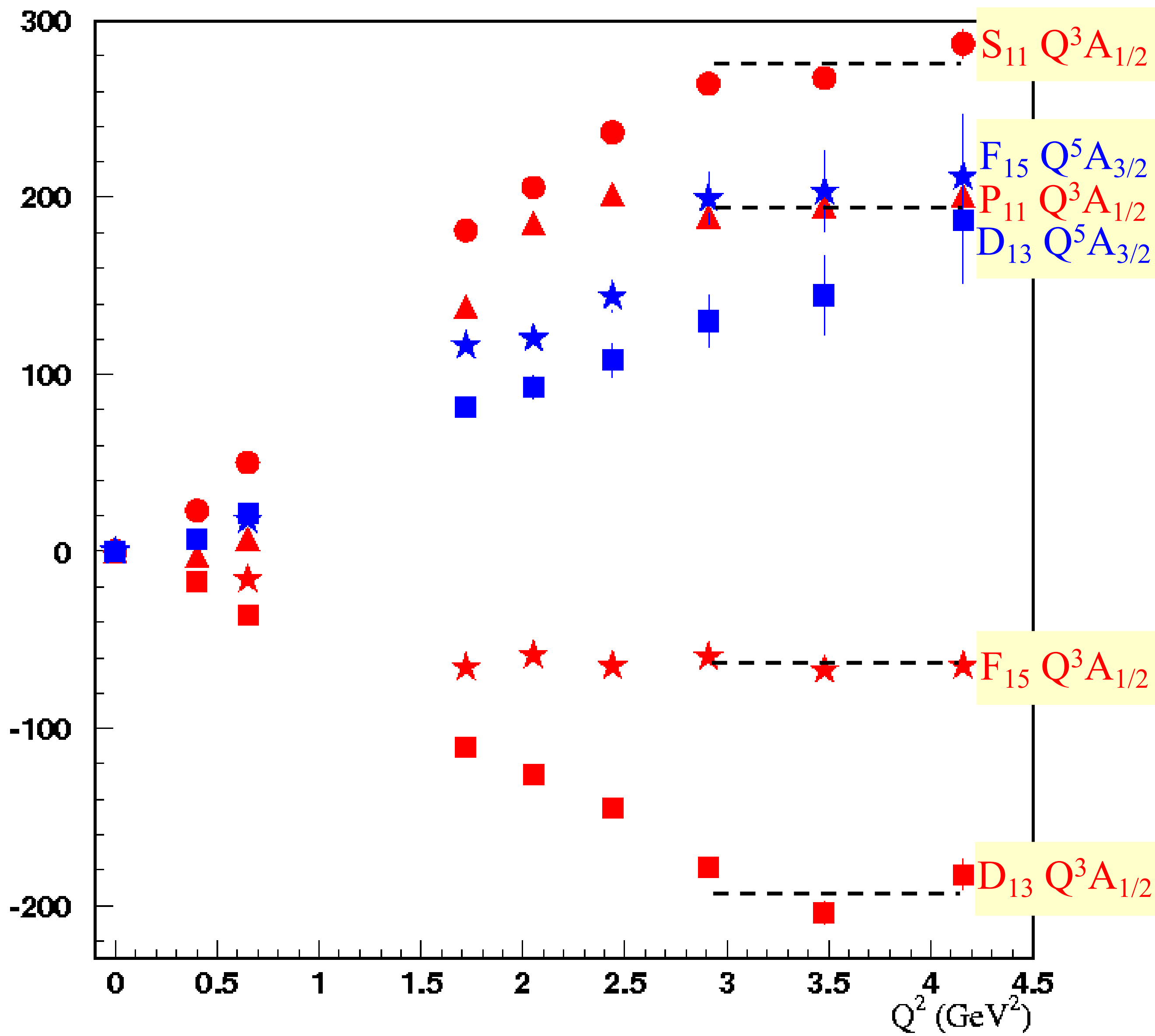


Evidence for the Onset of Scaling?

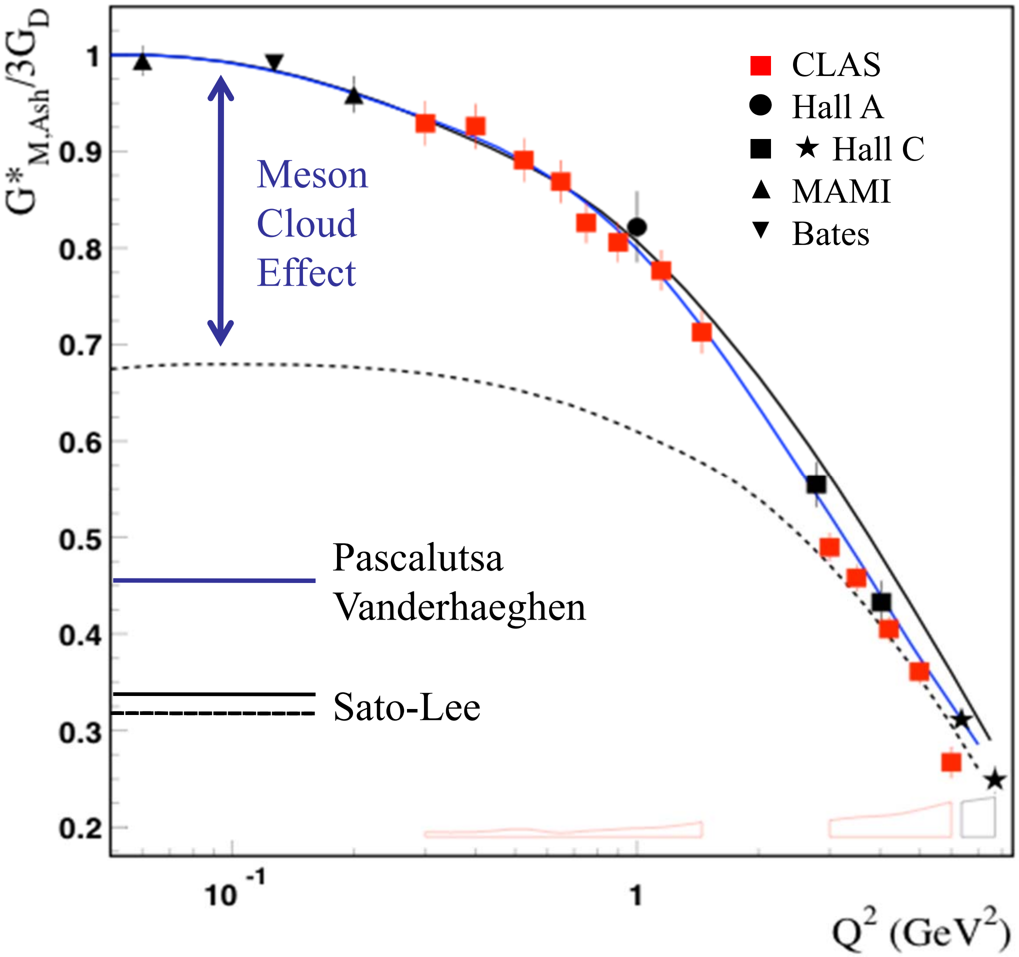


- $A_{1/2}$ α $1/Q^3$
- $A_{3/2}$ α $1/Q^5$
- G^*_M α $1/Q^4$

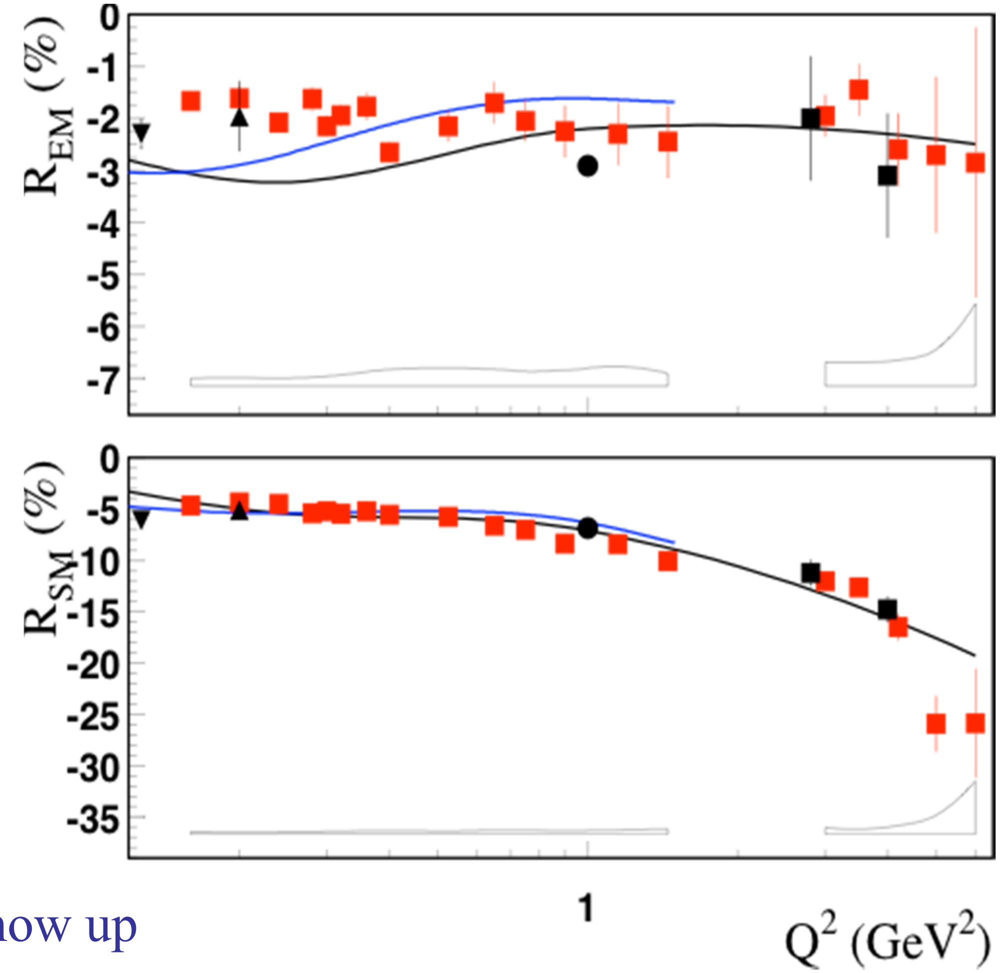
Phys. Rev. C80, 055203 (2009)



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

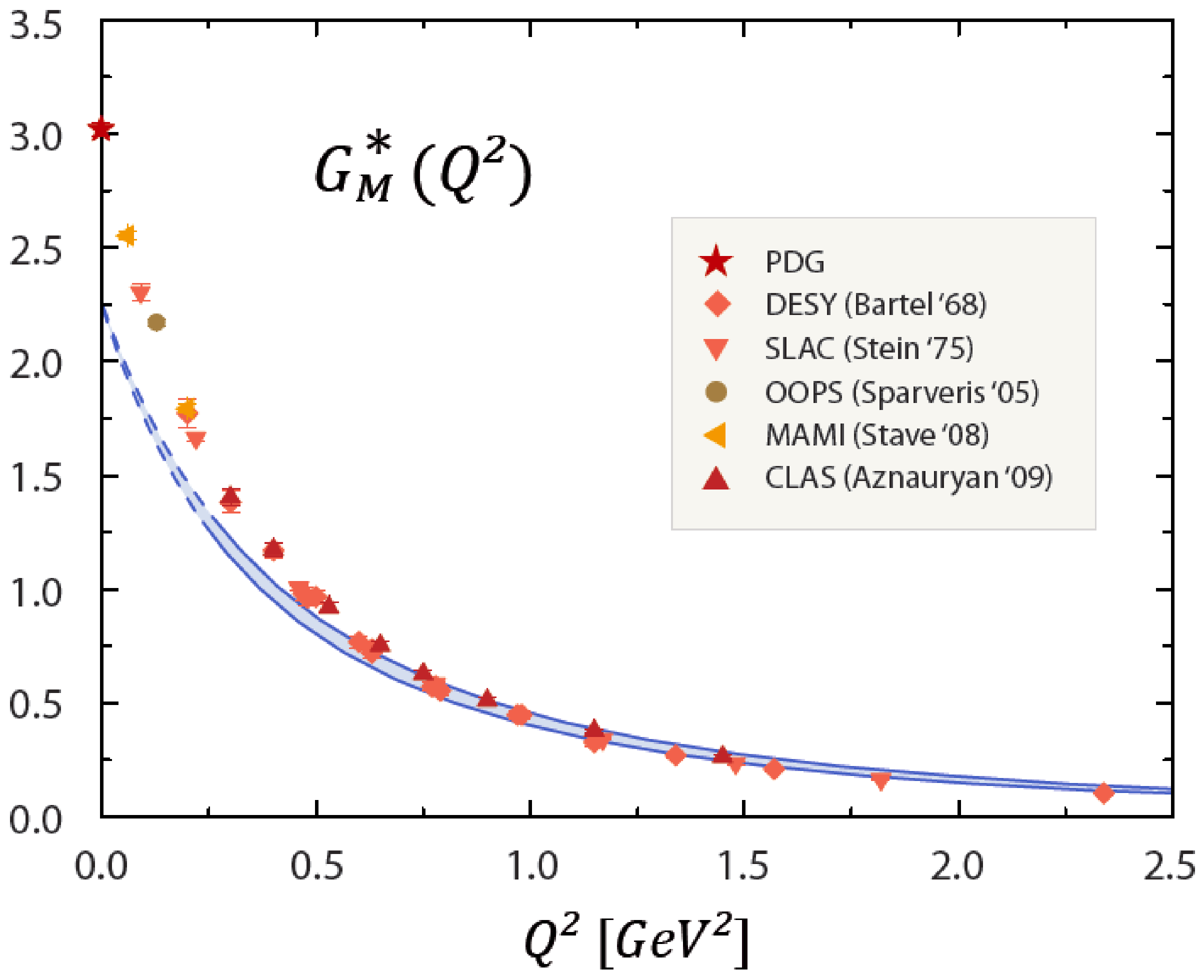


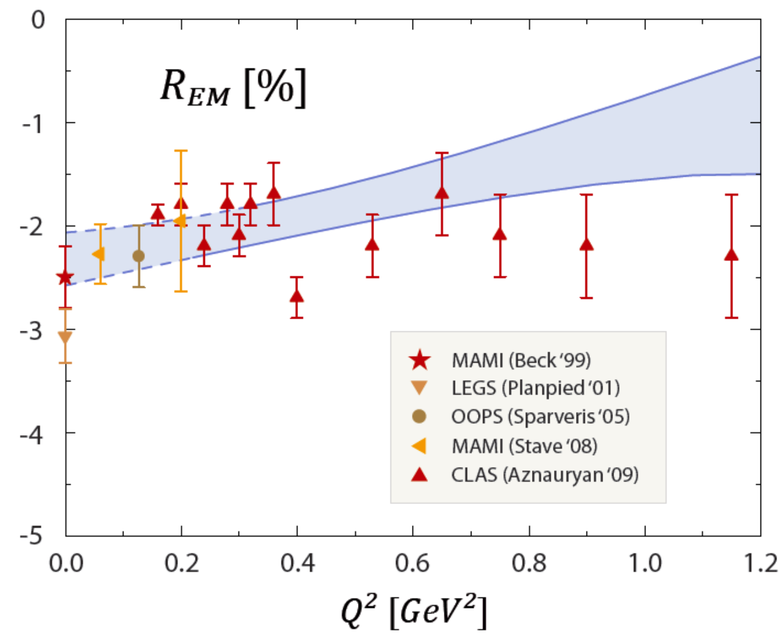
Phys. Rev. Lett. 97, 112003 (2006)

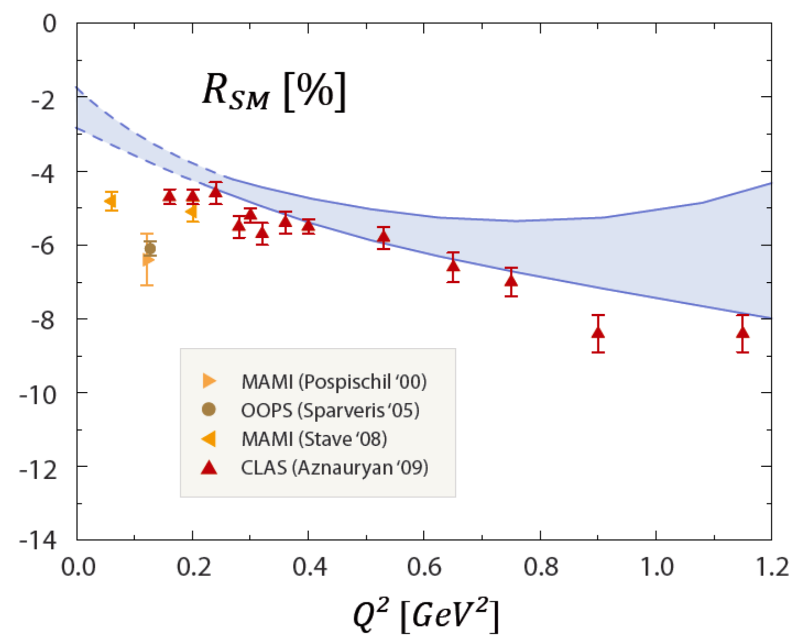


- New trend towards pQCD behavior does not show up
  - $R_{EM} \rightarrow +1$ $\quad R_{SM} \rightarrow$ const
  - $G^*_M \rightarrow 1/Q^4$ $\quad G^*_{M,Ash} \rightarrow 1/Q^5$
- CLAS12 can measure G^*_M, R_{EM}, and R_{SM} up to Q^2~12 GeV^2

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



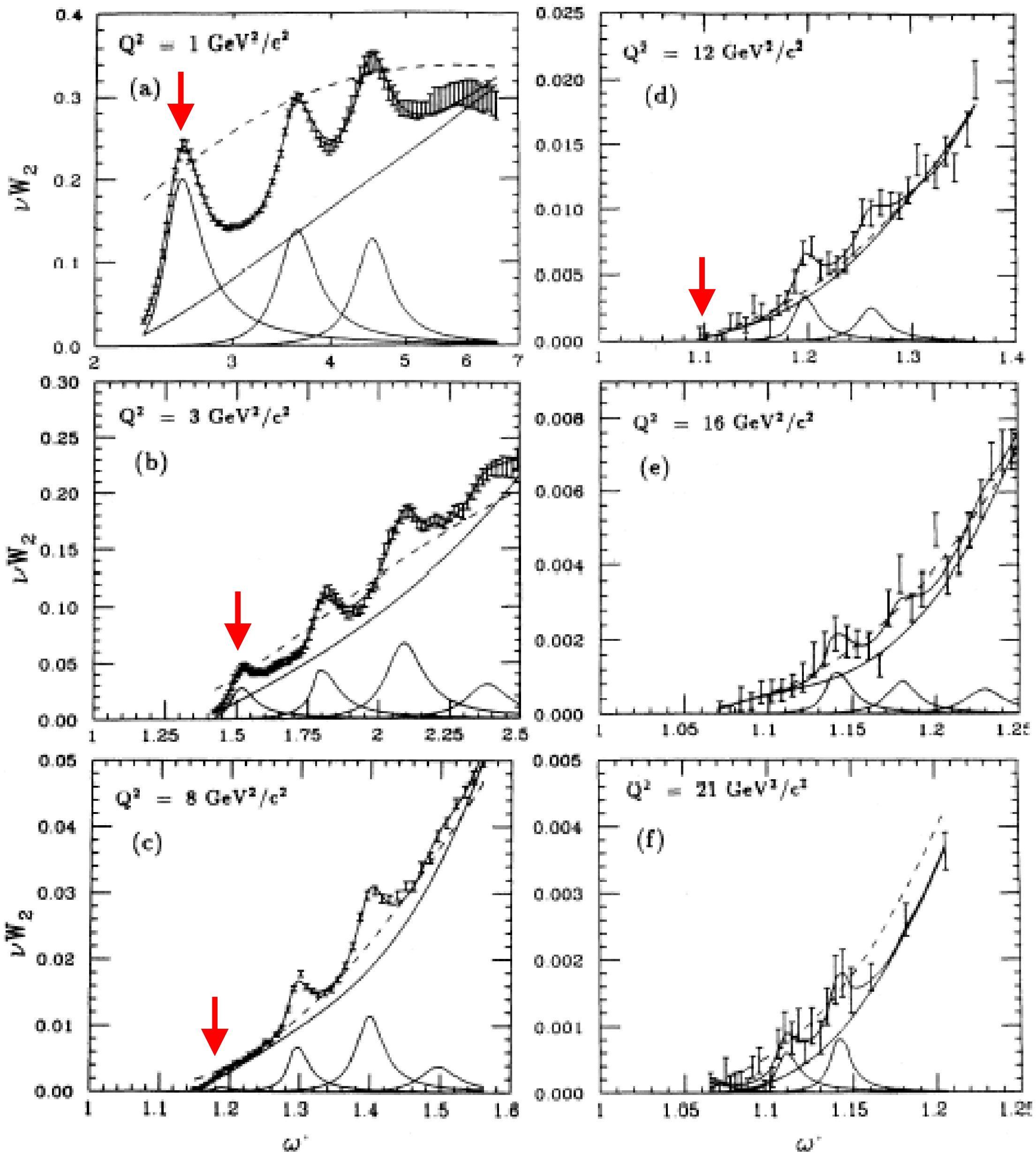


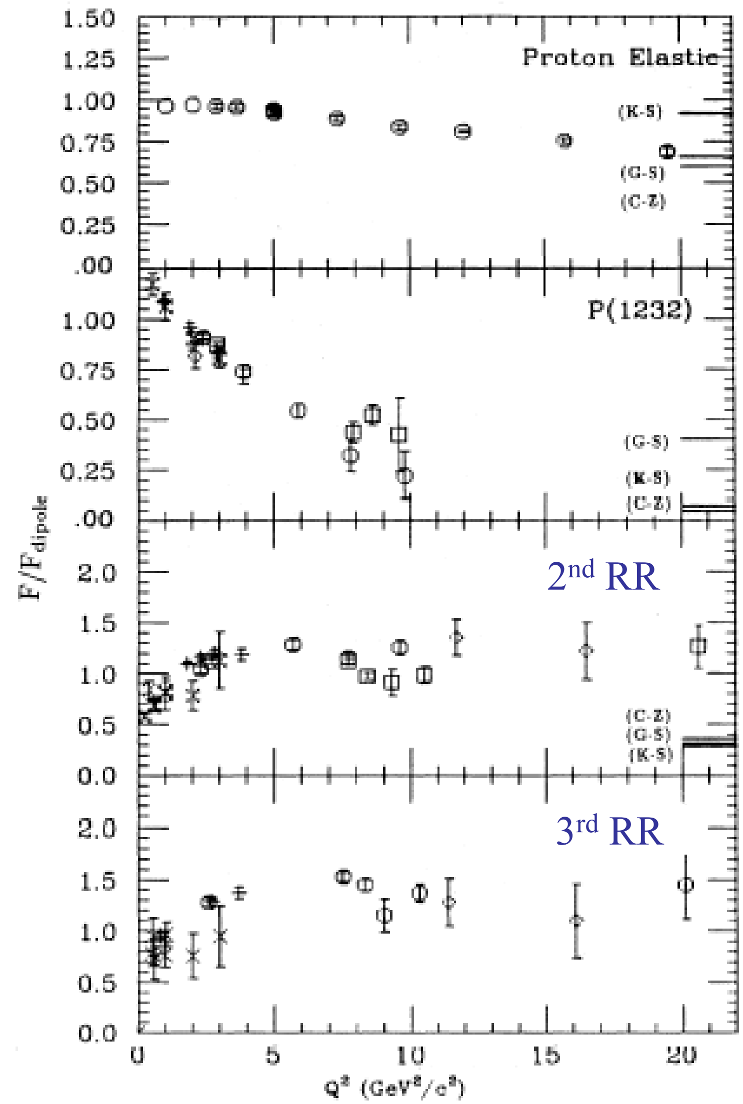


$$G^*_{M,Ash}(Q^2) = G^*_M(Q^2)/[1 + Q^2/t_+]^{1/2}$$

G. Eichmann et al., Phys. Rev. D85 (2012) 093004

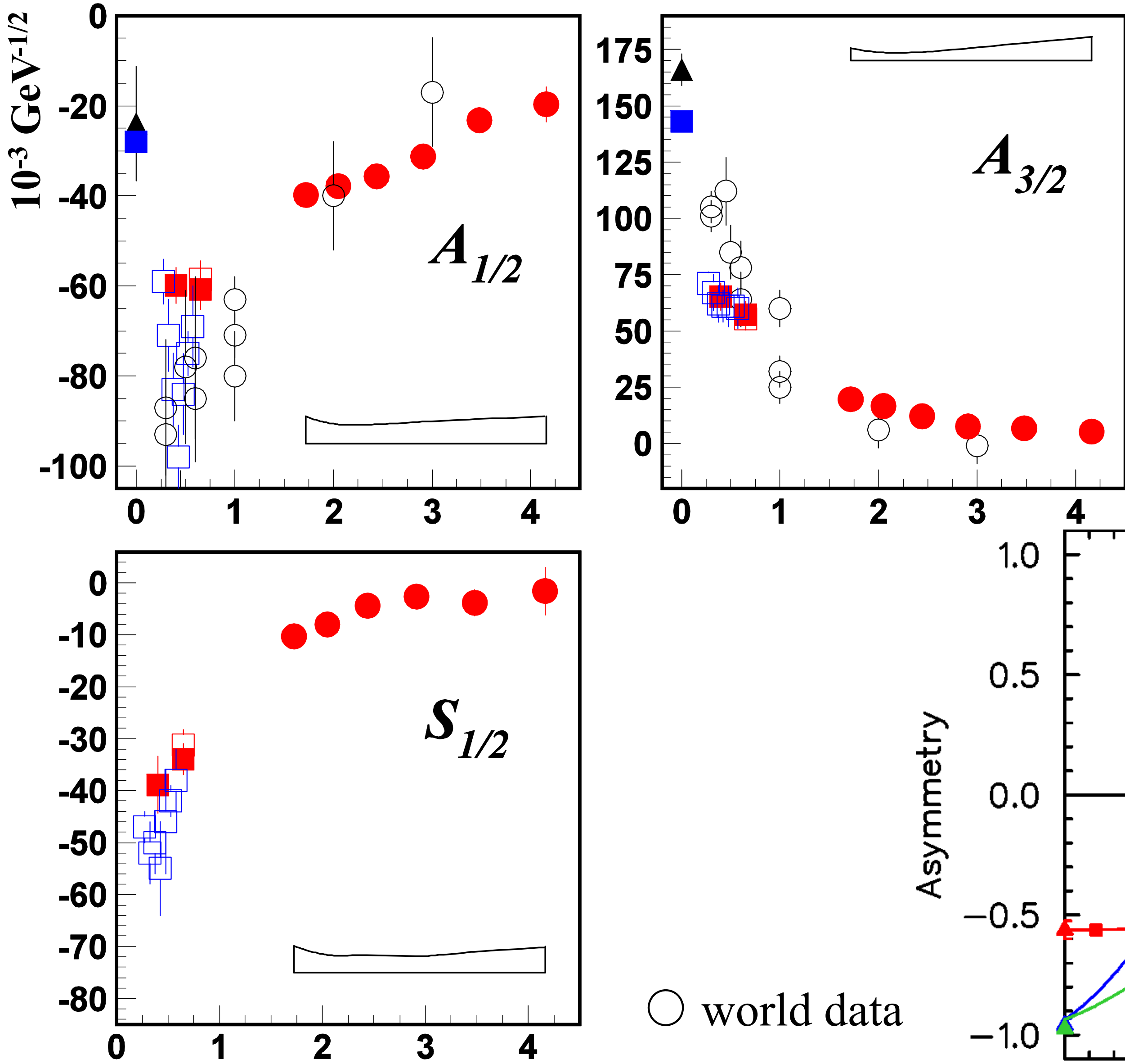
Inclusive Structure Function in the Resonance Region





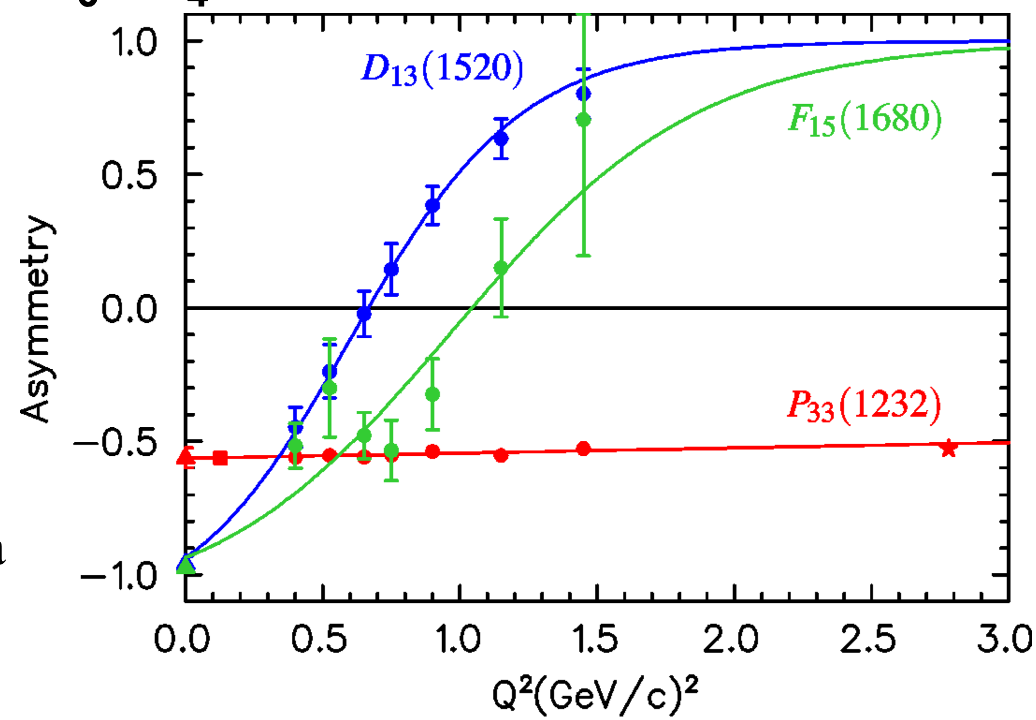
P. Stoler, PRPLCM 226, 3 (1993) 103-171

N(1520)D_{13} Helicity Asymmetry



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

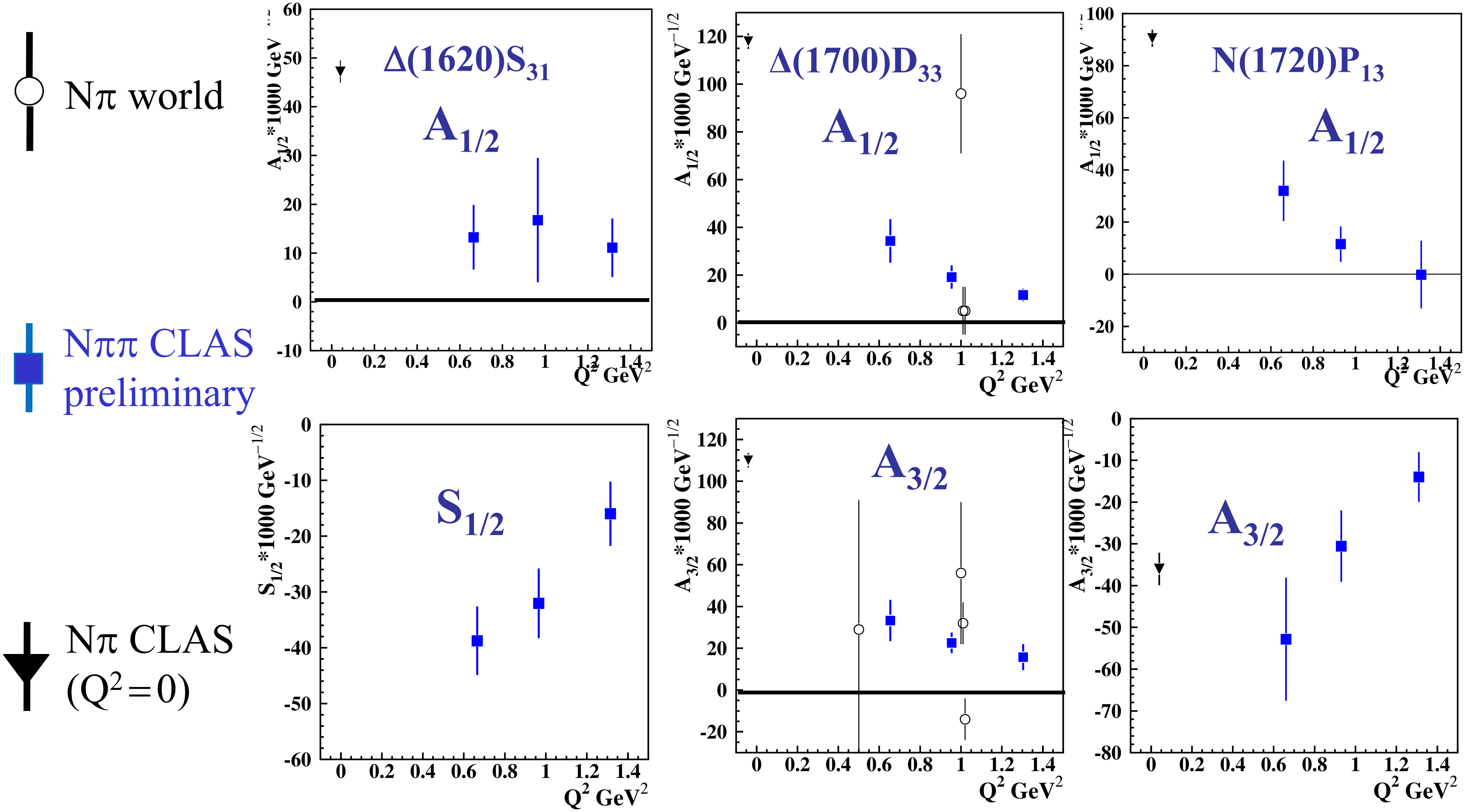
L. Tiator



○ world data

▲ PDG estimation ● ■ Nπ (UIM, DR)

High-Lying Resonance in Nππ CLAS Data Analysis



- $\pi^+\pi^-p$ electroproduction channel provided first preliminary results on $S_{31}(1620)$, $S_{11}(1650)$, $F_{15}(1685)$, $D_{33}(1700)$, and $P_{13}(1720)$ electrocouplings of a good accuracy
- new features: a) $S_{1/2}$ dominance for $S_{31}(1620)$ and b) $|A_{3/2}| \geq |A_{1/2}|$ for $D_{33}(1700)$ and $P_{13}(1720)$

$\gamma_v NN^*$ Extraction

Phenomenological Analyses

- Unitary Isobar Model (UIM) approach in single pseudoscalar meson production
- Fixed-*t* Dispersion Relations (DR)
- Unitarized Isobar Model for $N\pi\pi$ final state (JM)

Int. J. Mod. Phys. E, Vol. 22, 1330015 (2013) 1-99

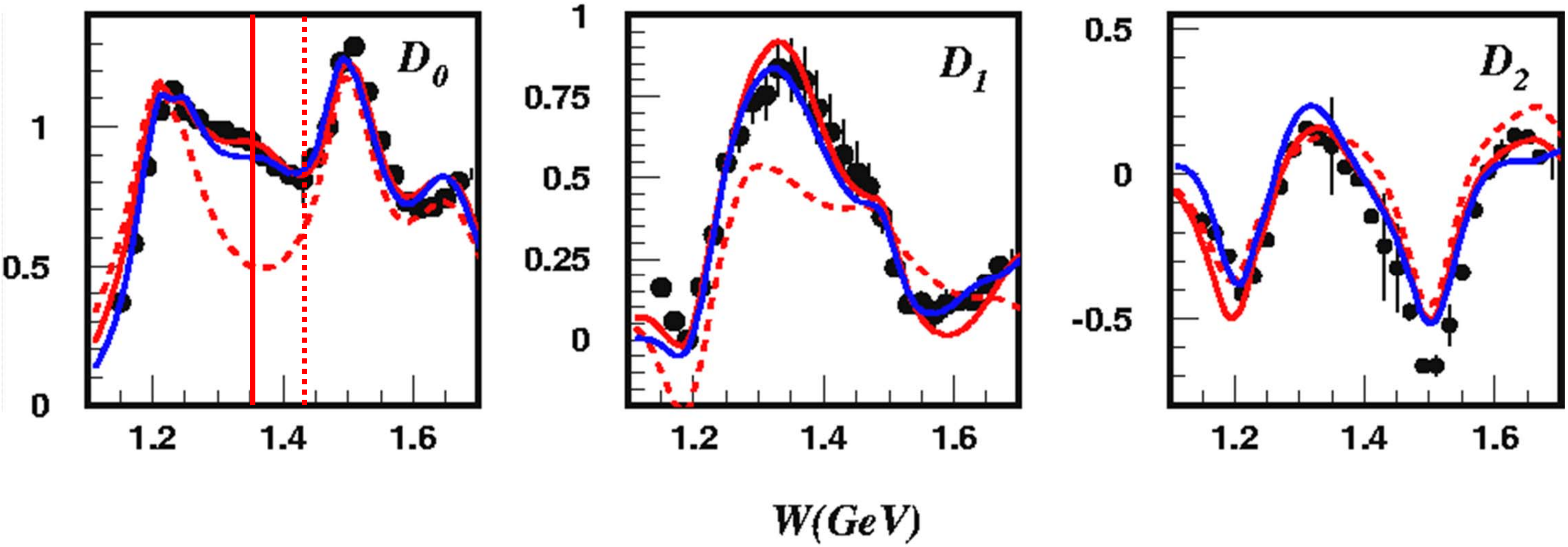
- Coupled-Channel Approach (EBAC, Argonne-Osaka, Georgia-Jülich)

Int. J. Mod. Phys. E, Vol. 22, 1330015 (2013) 1-99

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

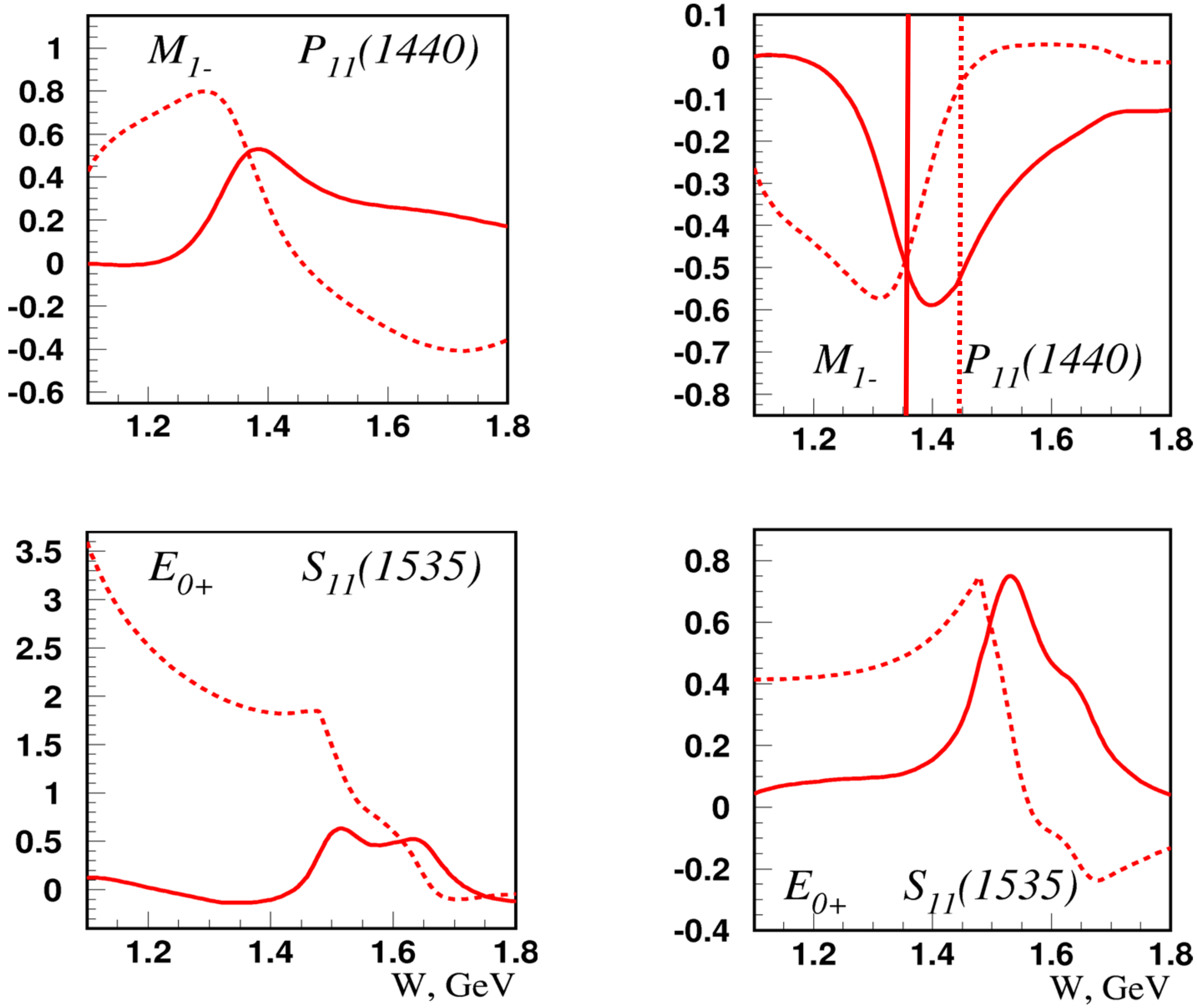
Two conceptually different approaches DR and UIM are consistent. CLAS data provide rigid constraints for checking validity of the approaches.

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

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

Cross sections are extracted in the $p\pi^0$, $p\pi^+$, $p\eta$; and more are currently under analysis in the $p\omega$ and $p\pi^-$ final states.

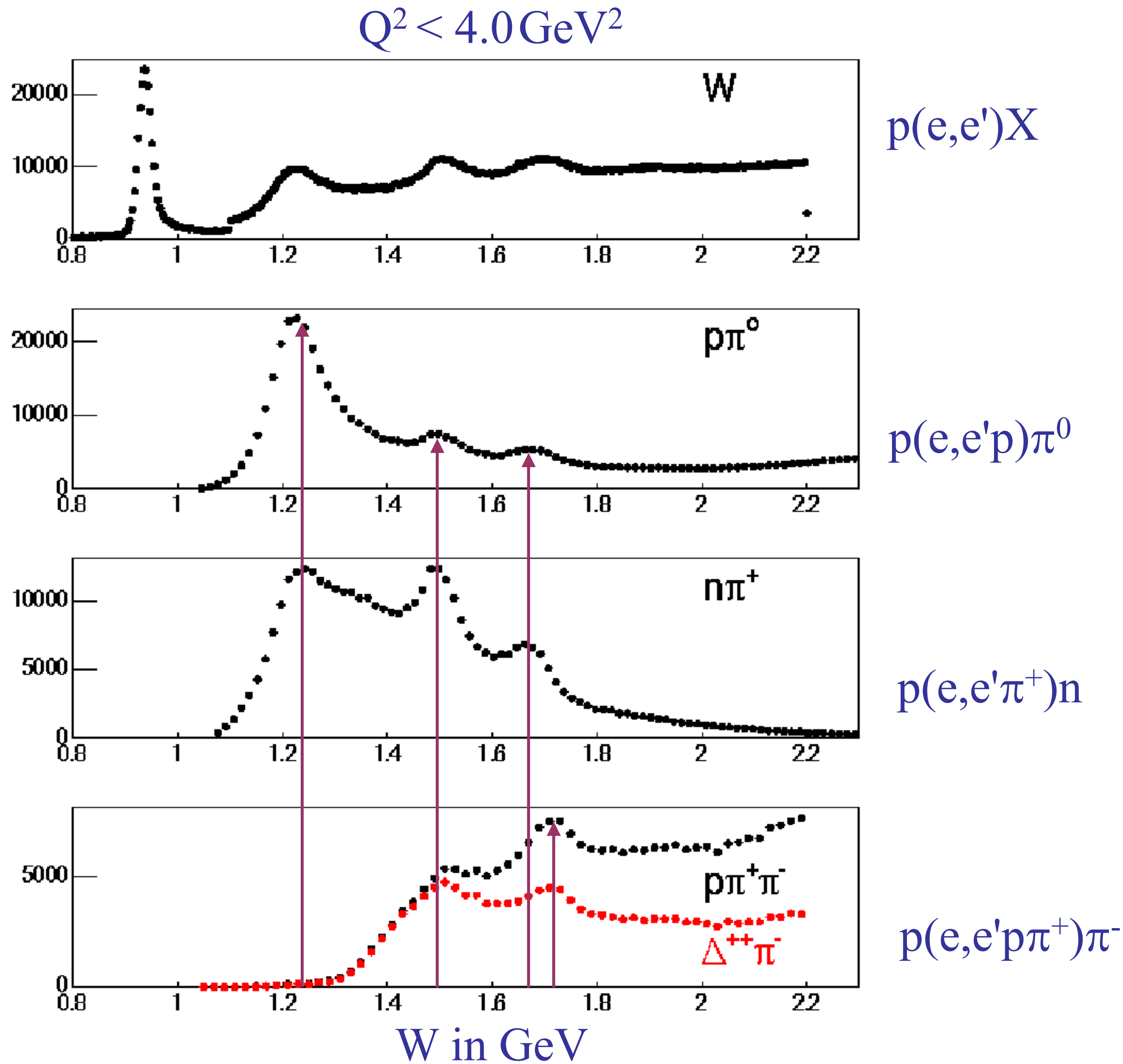
$Q^2 = 0$ GeV^2 $\quad$ $Q^2 = 2.05$ GeV^2



real part $\quad$ imaginary part

Nucleon Resonances in Nπ and Nππ Electroproduction

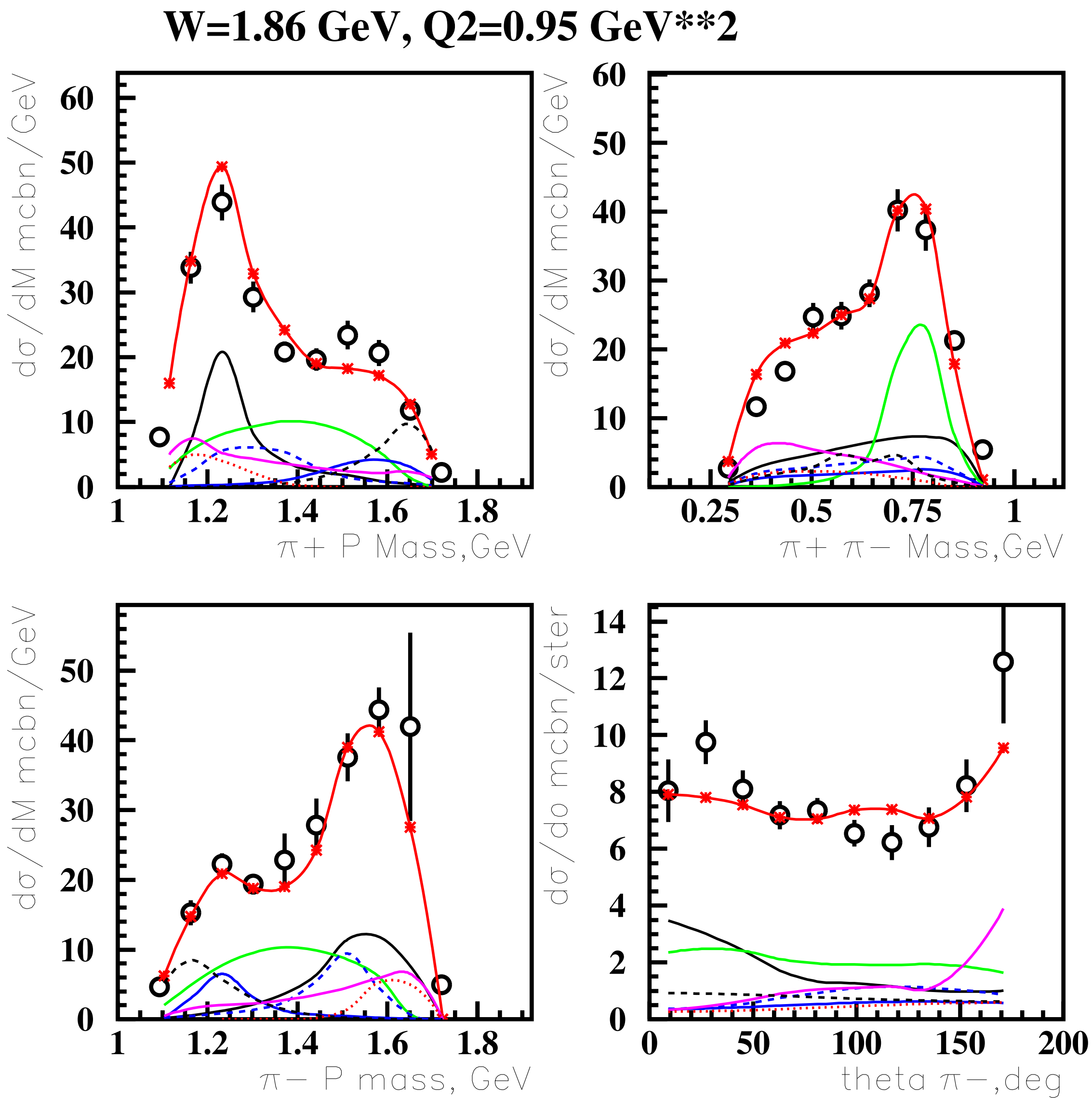
- Nππ channel is sensitive to N*s heavier than 1.4 GeV
- Provides information that is complementary to the Nπ channel
- Many higher-lying N*s decay preferentially into Nππ final states



Contributing Mechanisms to $\gamma^{(*)}p \rightarrow p\pi^+\pi^-$

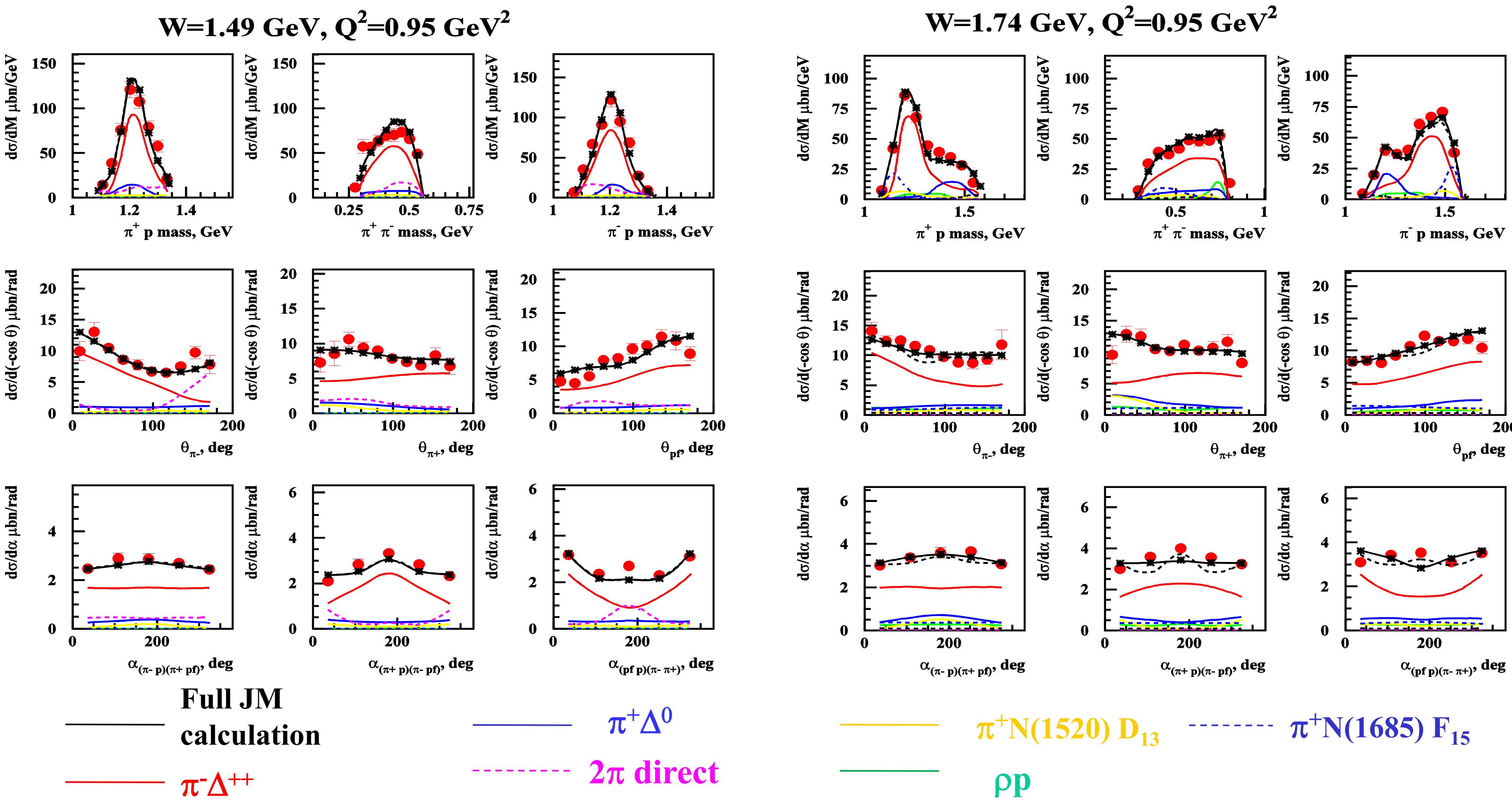
Isobar Model JM05

- Full calculations
- $\gamma p \rightarrow \pi^-\Delta^{++}$
- $\gamma p \rightarrow \pi^+\Delta^0$
- $\gamma p \rightarrow \pi^+D_{13}(1520)$
- $\gamma p \rightarrow \rho p$
- $\gamma p \rightarrow \pi^-\Delta^{++}(1600)$
- $\gamma p \rightarrow \pi^+F^0_{15}(1685)$
- direct 2π production



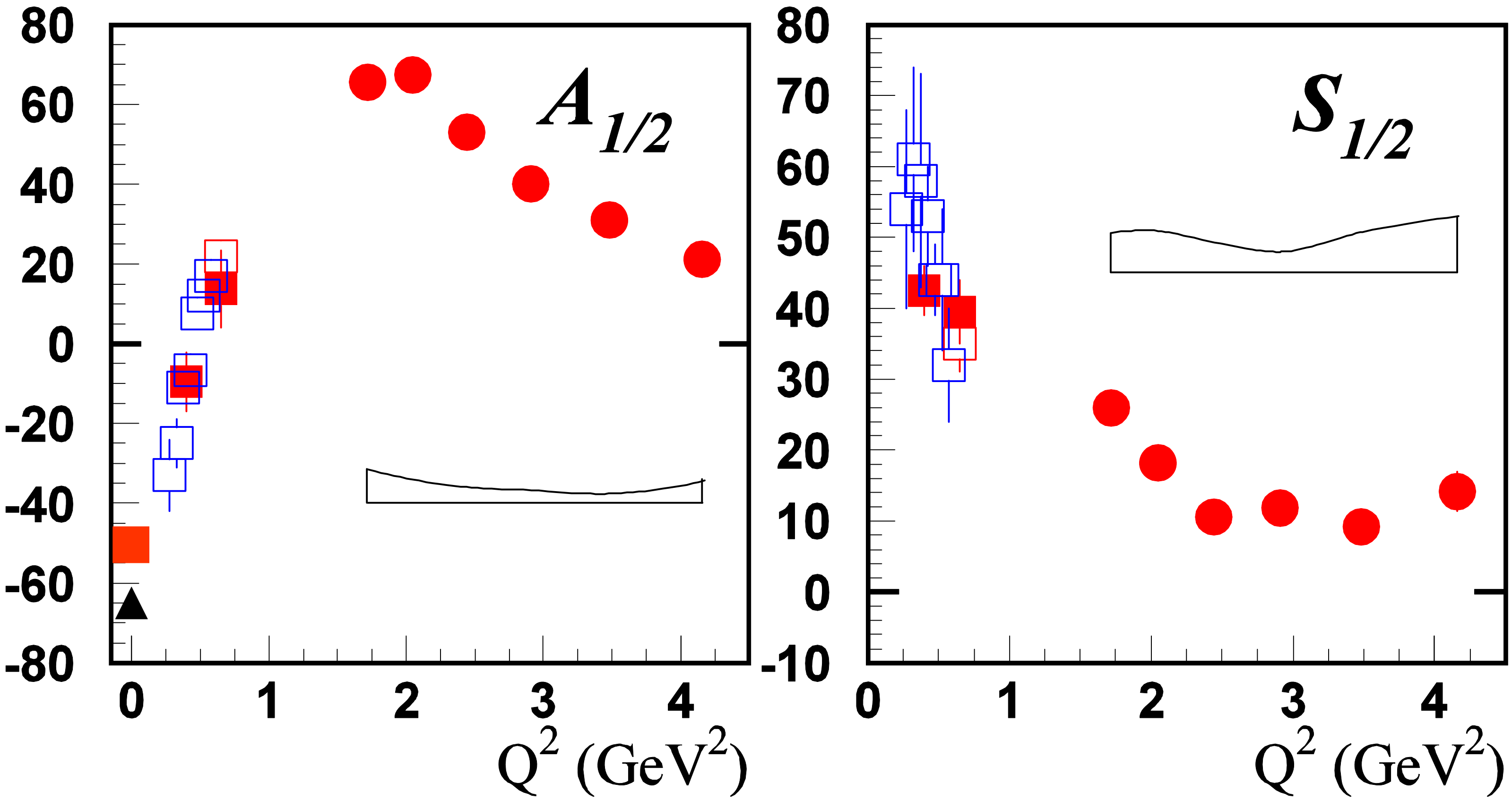
➢ The combined fit of nine single differential cross sections allowed to establish all significant mechanisms.

JM Contributions 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



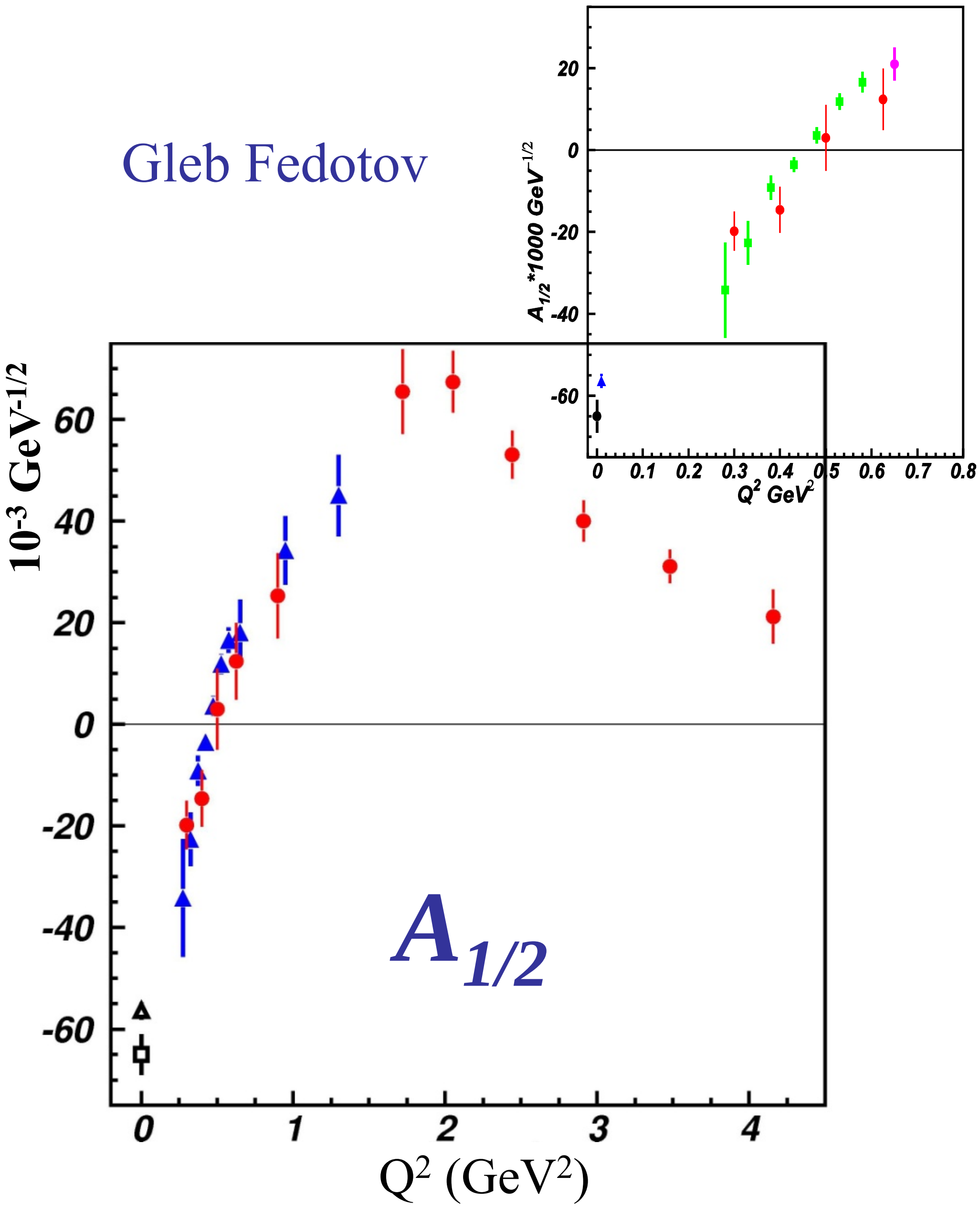
▲ PDG estimation ●■ Nπ (UIM, DR) □ Nπ, Nππ combined analysis □ Nππ (JM)

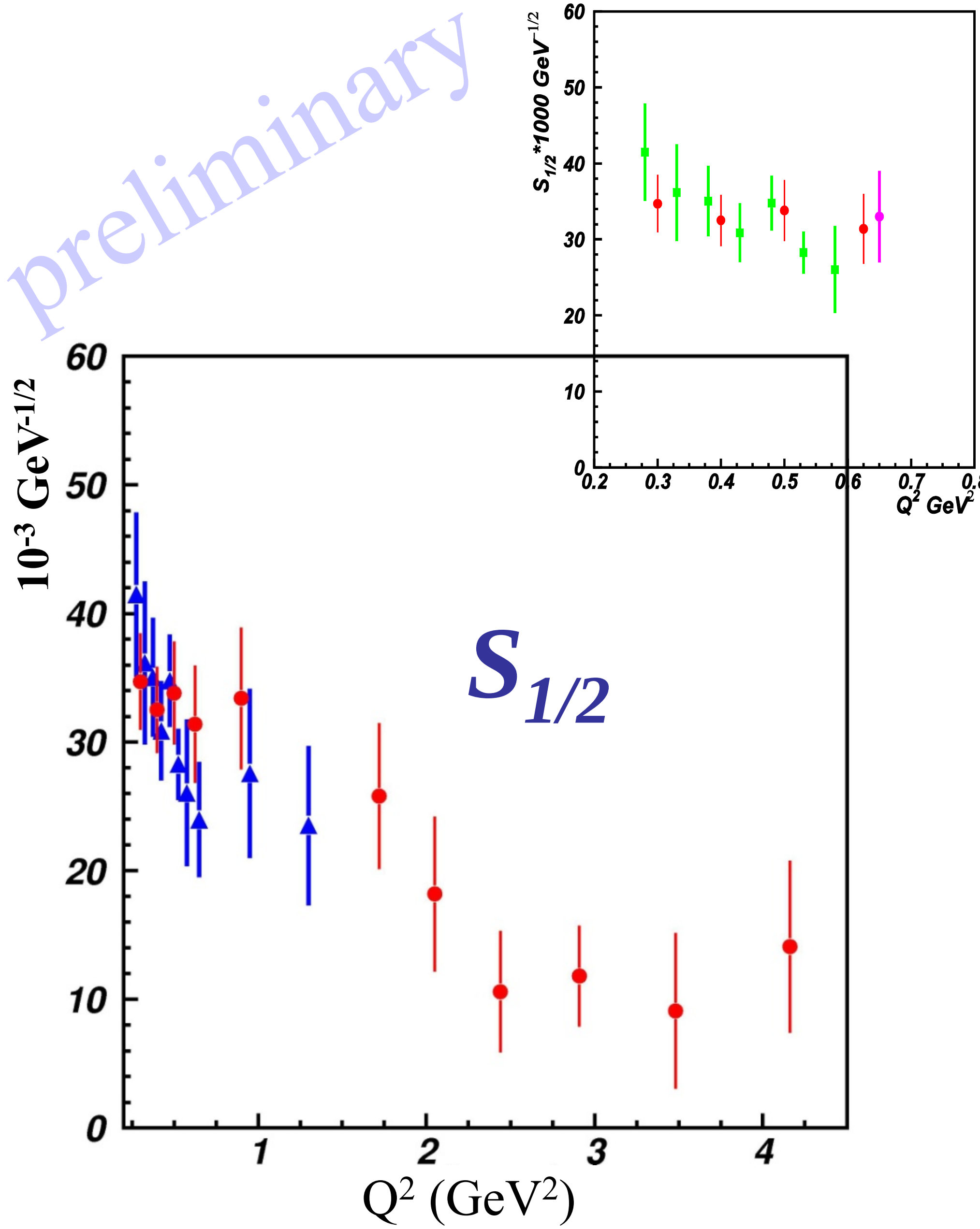
The good agreement on extracting the N* electrocouplings between the two exclusive channels (1π/2π) – having fundamentally different mechanisms for the nonresonant background – provides evidence for the reliable extraction of N* electrocouplings.

Phys. Rev. C 86, 035203 (2012) 1-22

Most recent Electrocouplings of N(1440)P_{11}

Gleb Fedotov





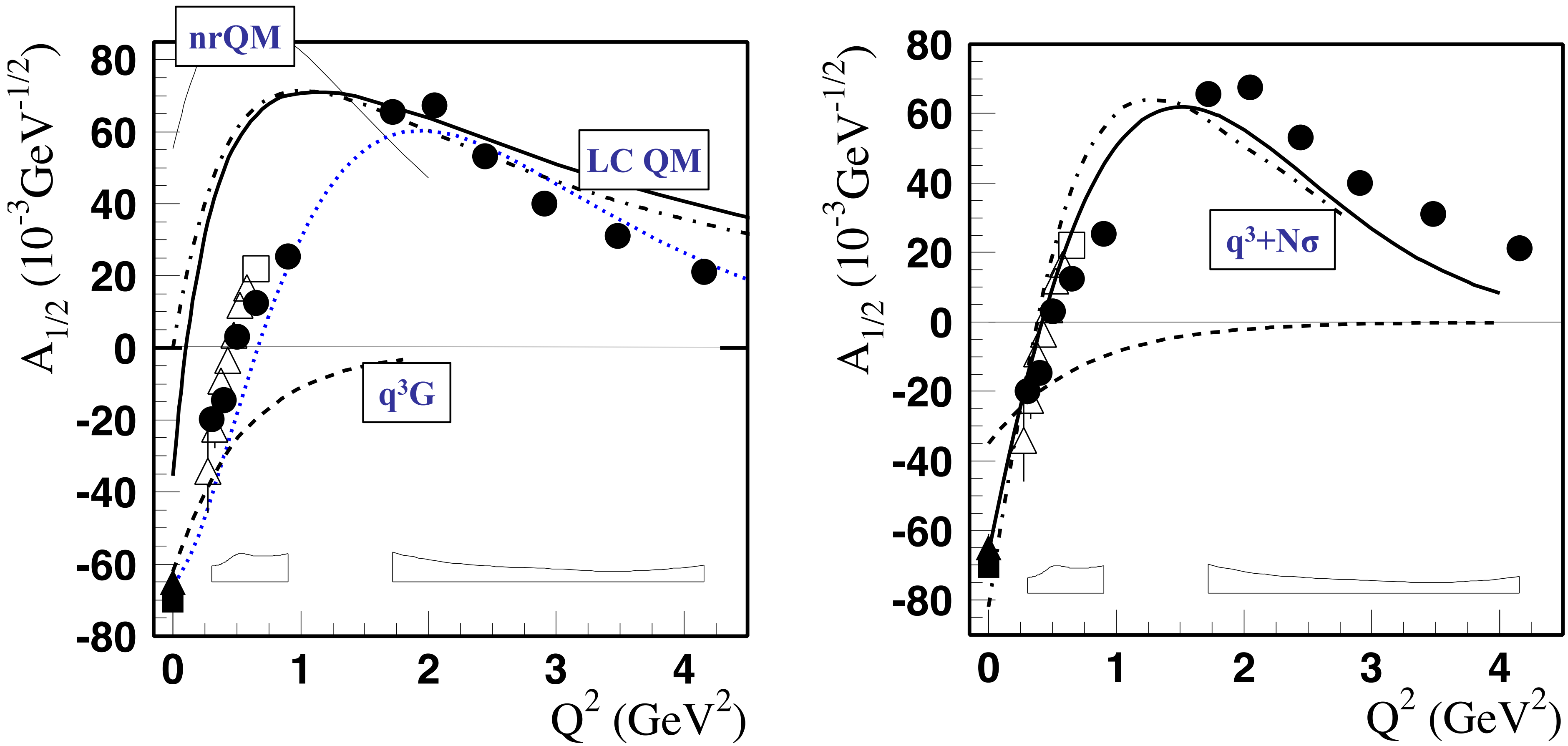
… and beam-helicity dependent 2π cross sections are currently under analysis.

QCD-Based

Models and Theory?

Constituent Quark Models (CQM)

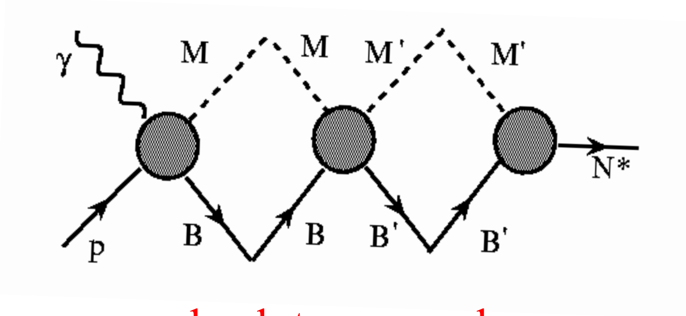
With Roper resonance $P_{11}(1440)$ data



- $A_{1/2}$ has zero-crossing near Q^2=0.5 and becomes dominant amplitude at high Q^2
- Eliminates gluonic excitation (q^3G) as a dominant contribution
- Consistent with radial excitation at high Q^2 and large meson-baryon coupling at small Q^2

Progress in Experiment and Phenomenology

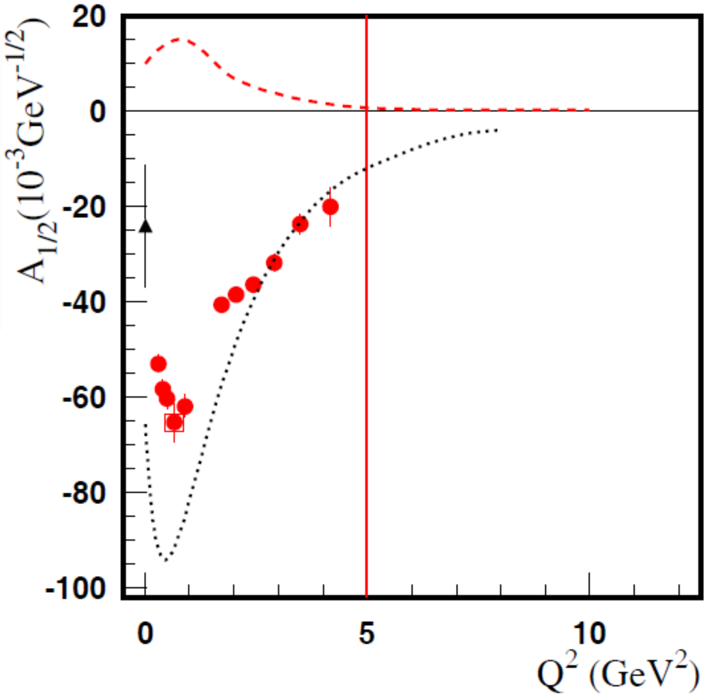
Meson-Baryon Dressing



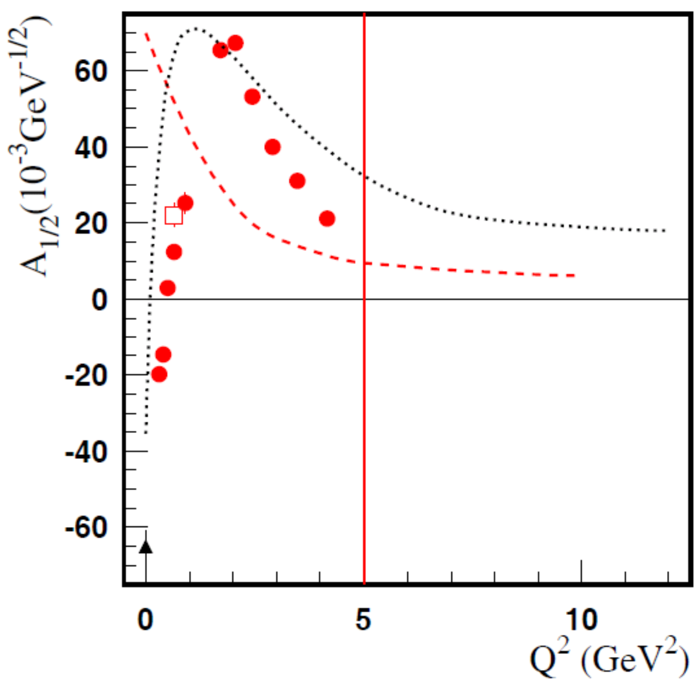
absolute meson-baryon cloud amplitudes (EBAC now ANL-Osaka)

quark core contributions (constituent quark models)

$D_{13}(1520)$



$P_{11}(1440)$

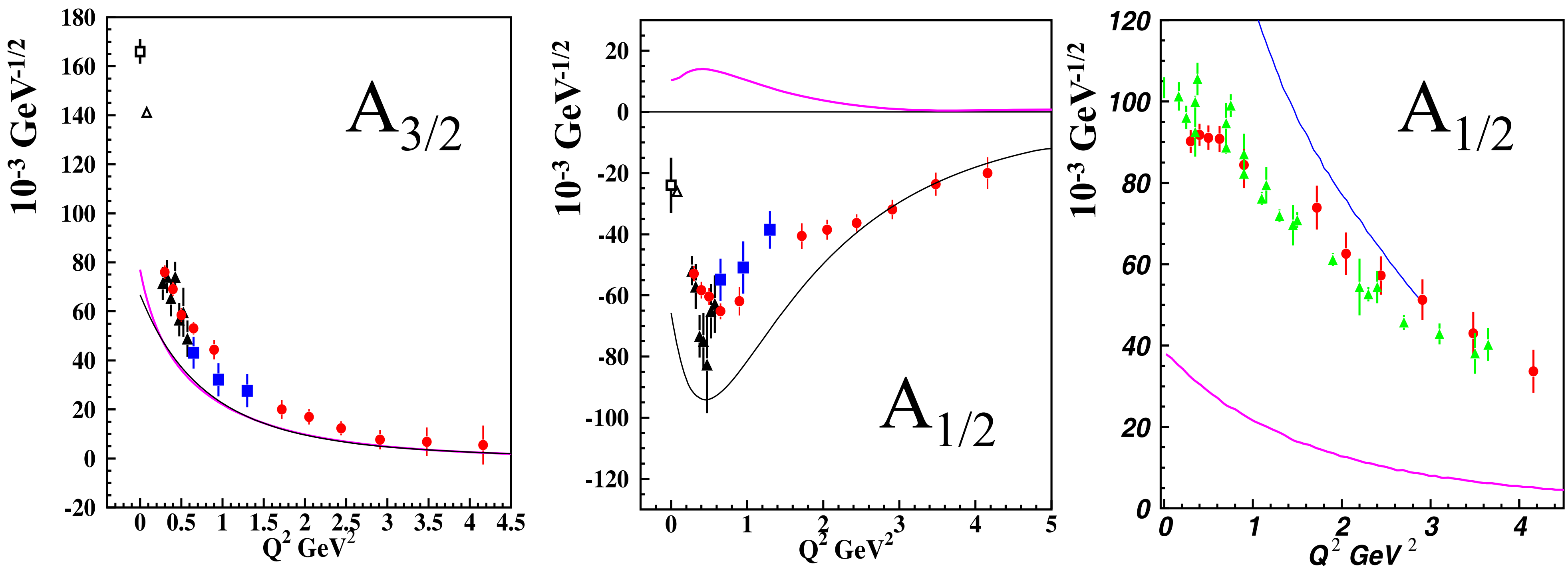


CLAS: Nπ and Nπ/Nππ combined (Phys. Rev. C80, 055203, 2009)

➢ Resonance structures can be described in terms of an internal quark core and a surrounding meson-baryon cloud whose relative contribution decreases with increasing Q^2.

➢ Data on $\gamma_v NN^*$ electrocouplings from this experiment ($Q^2 > 5$ GeV^2) will afford for the first time direct access to the non-perturbative strong interaction among dressed quarks, their emergence from QCD, and the subsequent N* formation.

Electrocouplings of N(1520)D_{13} and N(1535)S_{11}



Argonne Osaka / EBAC DCC MB dressing (absolute values)

E.Santopinto, M.Giannini, hCQM PRC 86, 065202 (2012)

S.Capstick, B.D.Keister (rCQM) PRD51, 3598 (1995)

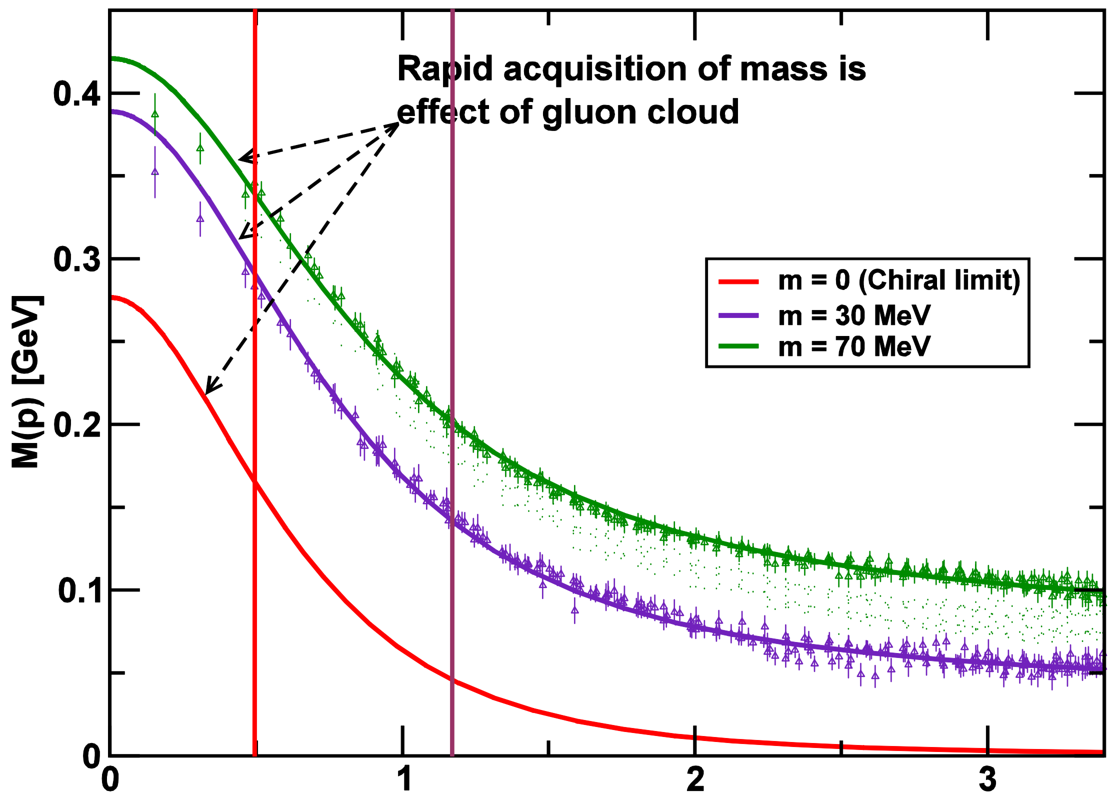
$\pi^+\pi^-p$ 2012

$\pi^+\pi^-p$ 2010

$N\pi$ 2009

ηp CLAS/Hall-C

Dynamical Mass of Light Dressed Quarks



$Q^2 = 2.75\ GeV^2$ p [GeV] per dressed quark

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.

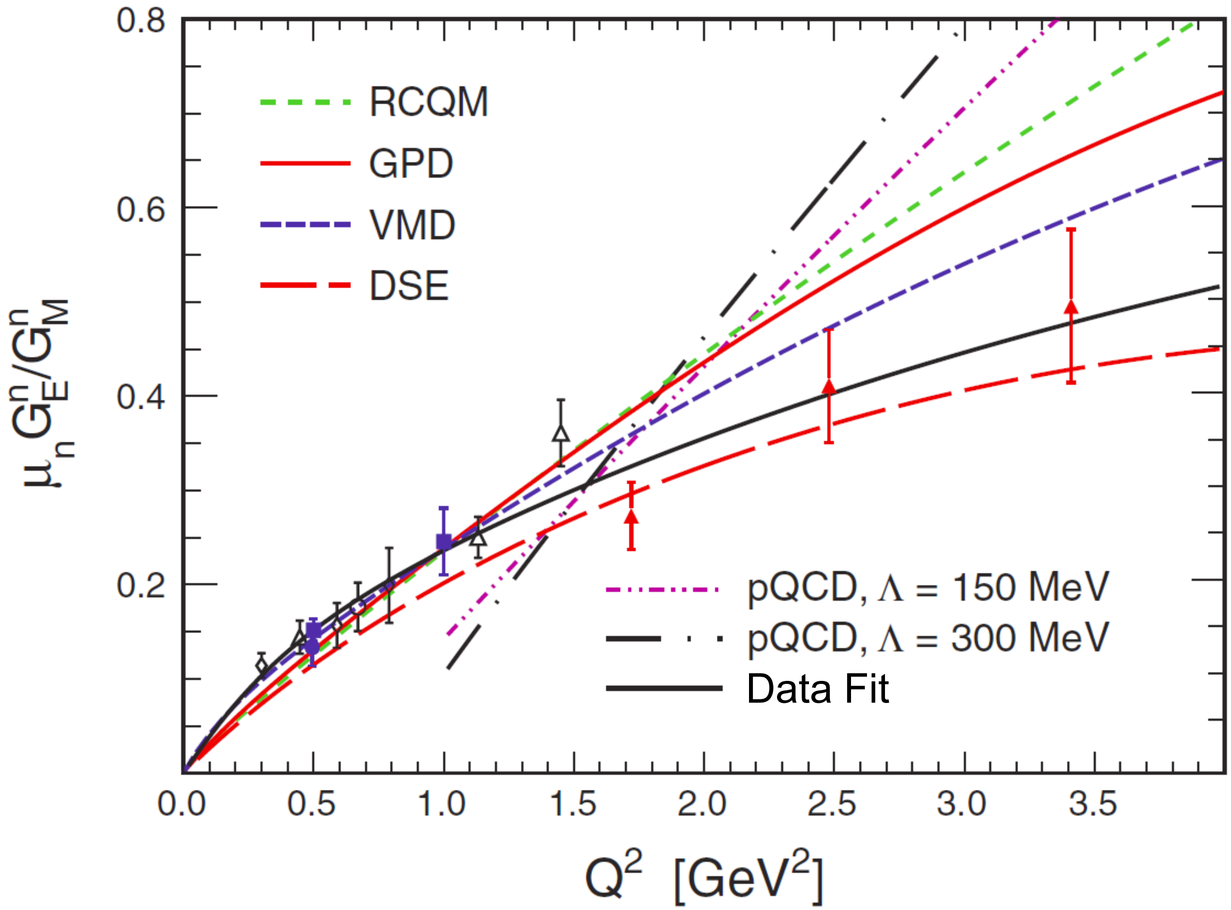
DSE: lines and LQCD: triangles

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

The data on N* electrocouplings at $5\ GeV^2 < Q^2 < 12\ GeV^2$ 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 approaches provide links between dressed quark propagators, form factors, scattering amplitudes, and QCD.



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

The Faddeev-DSE calculation is very sensitive to the momentum dependence of the dressed-quark propagator.

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 Adelaide.

Int. J. Mod. Phys. E, Vol. 22, 1330015 (2013) 1-99

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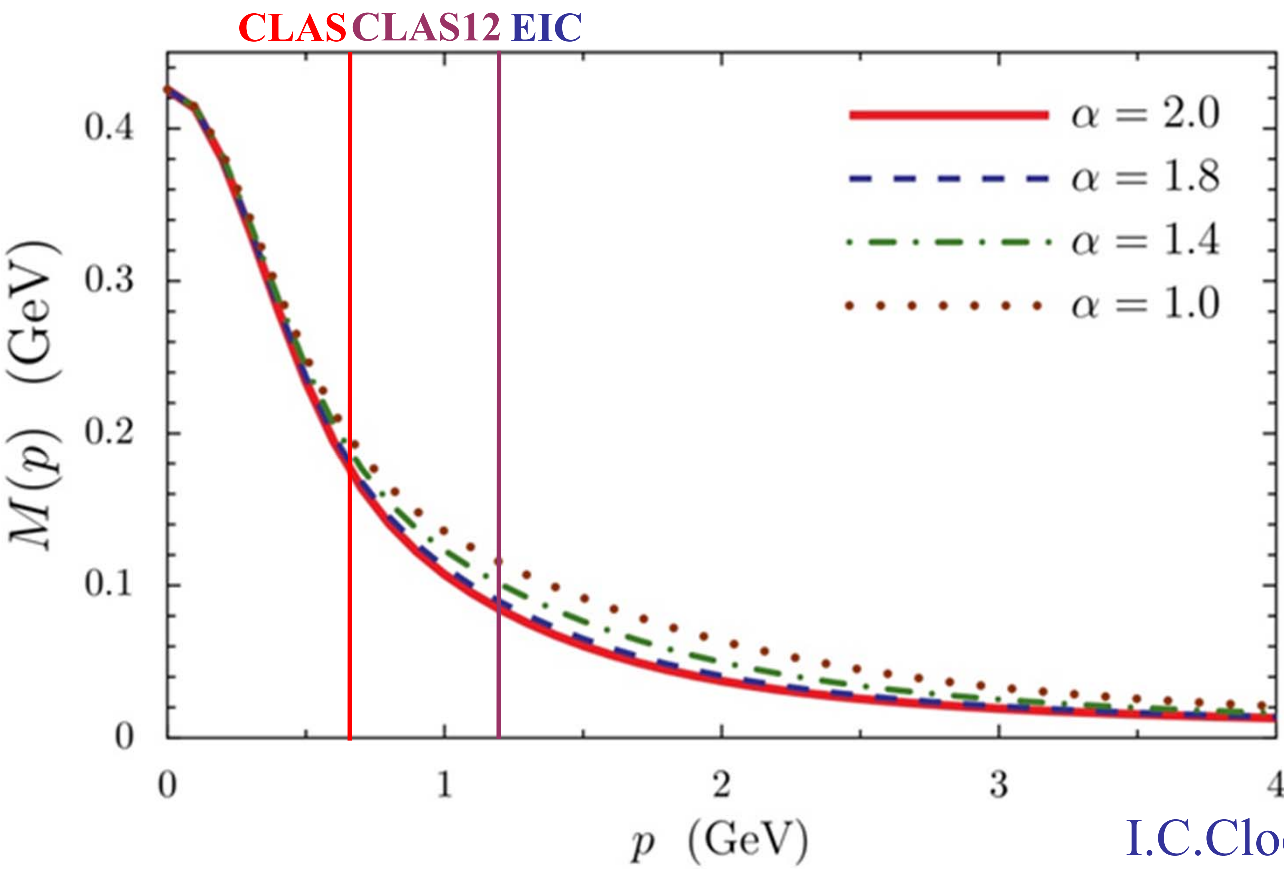

N* electrocouplings can be determined by applying Bethe-Salpeter / Faddeev equations to 3 dressed quarks while the properties and interactions are derived from QCD.

The Faddeev-DSE calculation is very sensitive to the momentum dependence of the dressed-quark propagator.

I.C.Cloet et al., arXiv:1304.0855[nucl-th]

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 Adelaide.

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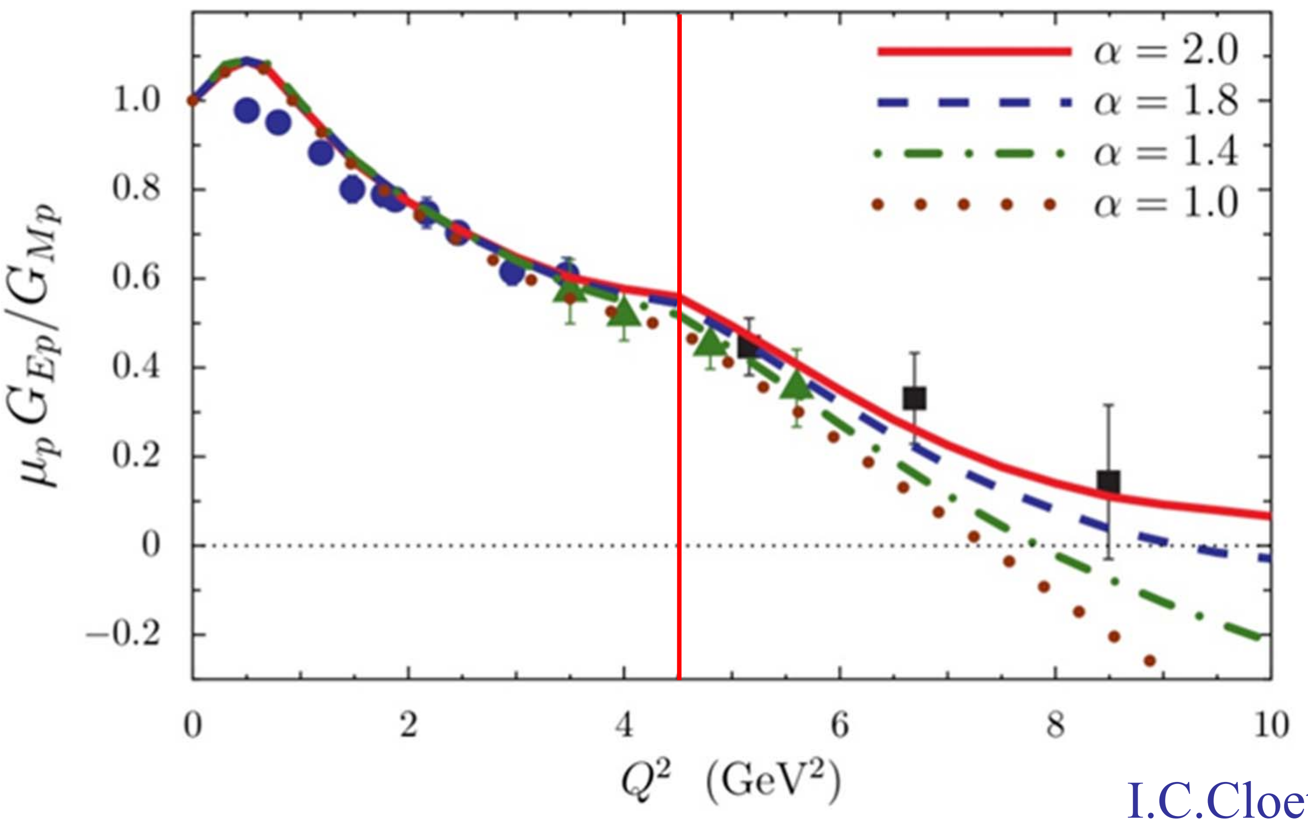
Dyson-Schwinger Equation (DSE) Approach

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



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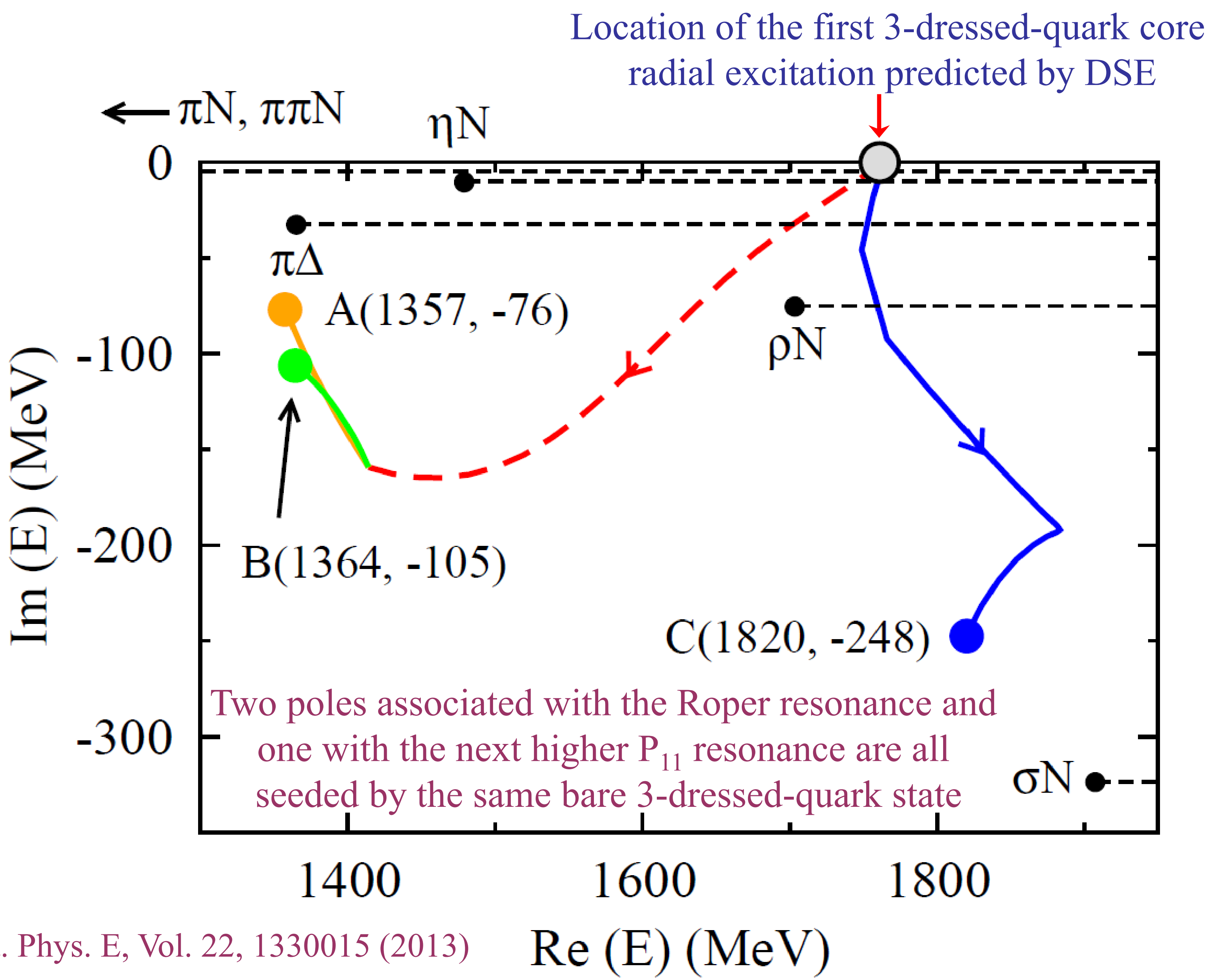
DSE and EBAC Approaches



Two poles associated with the Roper resonance and one with the next higher P_{11} resonance are all seeded by the same bare 3-dressed-quark state

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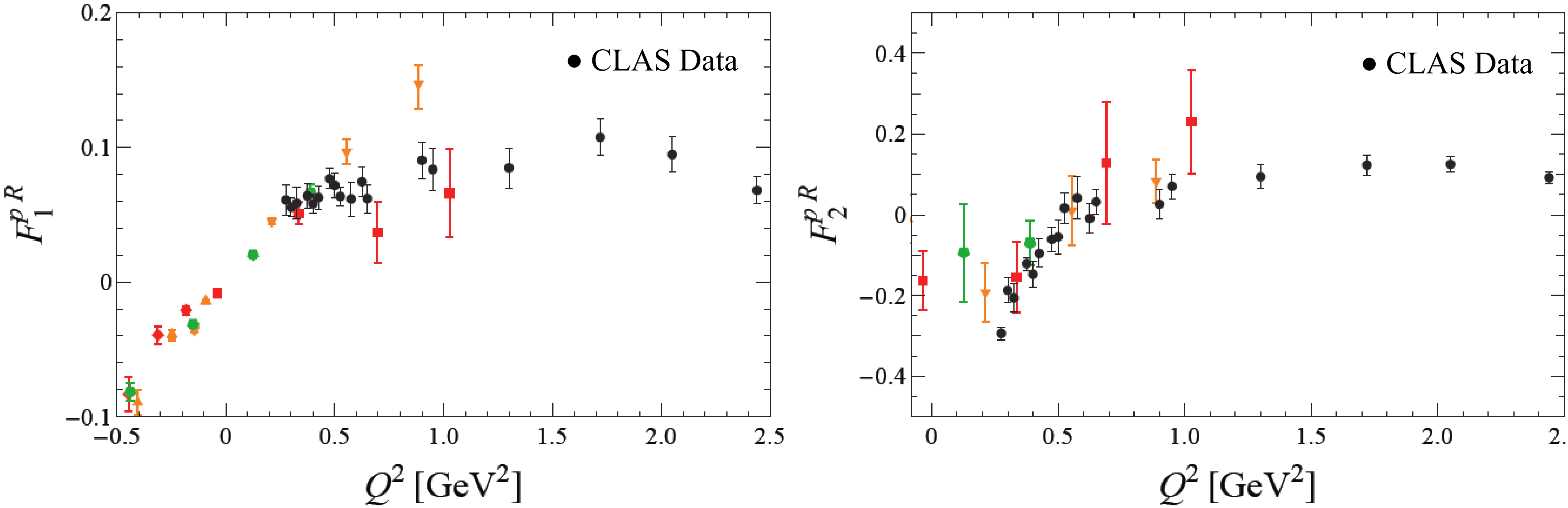
Roper Transition Form Factors in LQCD

$p(1440)P_{11}$ Huey-Wen Lin and S.D Cohen



Lattice QCD calculations of the $p(1440)P_{11}$ transition form factors have been carried out with various pion masses, m_π= 390, 450, and 875 MeV. Particularly remarkable is the zero crossing in F_2 that appears at the current statistics in the unquenched but not in the quenched calculations. This suggests that at low Q^2 the pion-cloud dynamics are significant in full QCD.

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.

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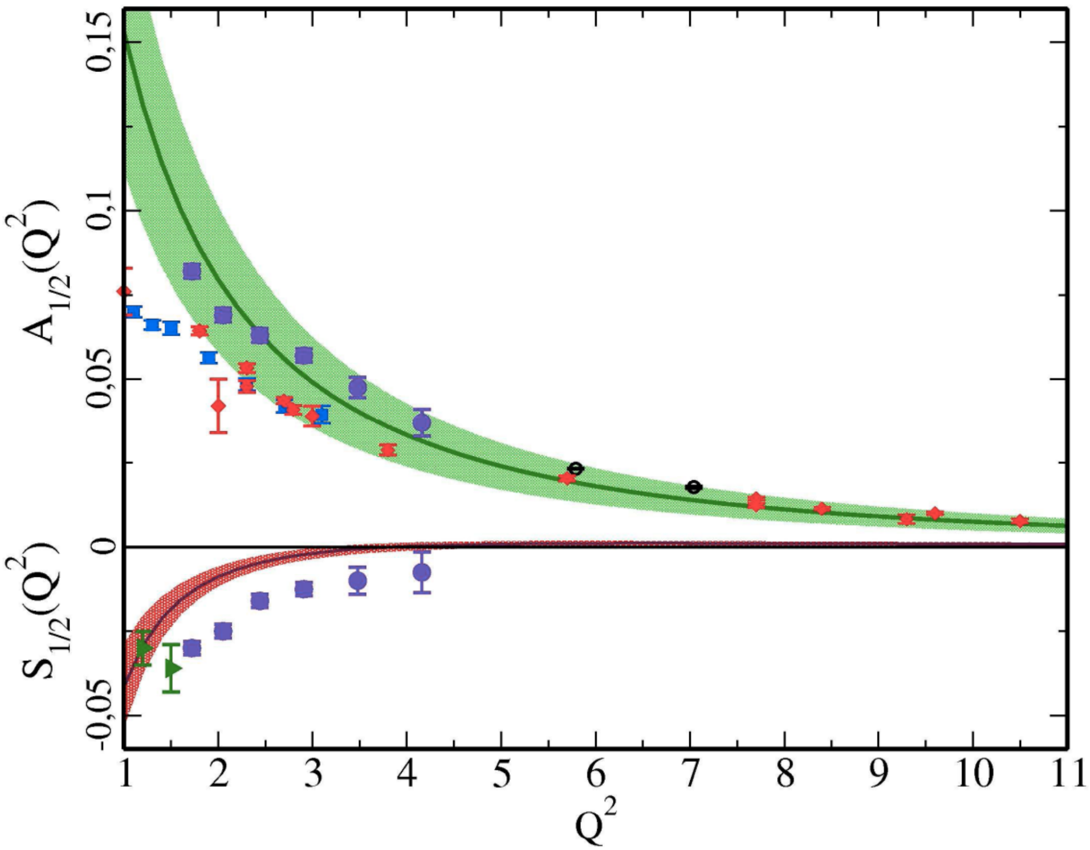
LQCD & Light Cone Sum Rule (LCSR) Approach

N(1535)S_{11}



LQCD is used to determine the moments of N* distribution amplitudes (DA) and the N* electrocouplings are determined from the respective DAs within the LCSR framework.

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.

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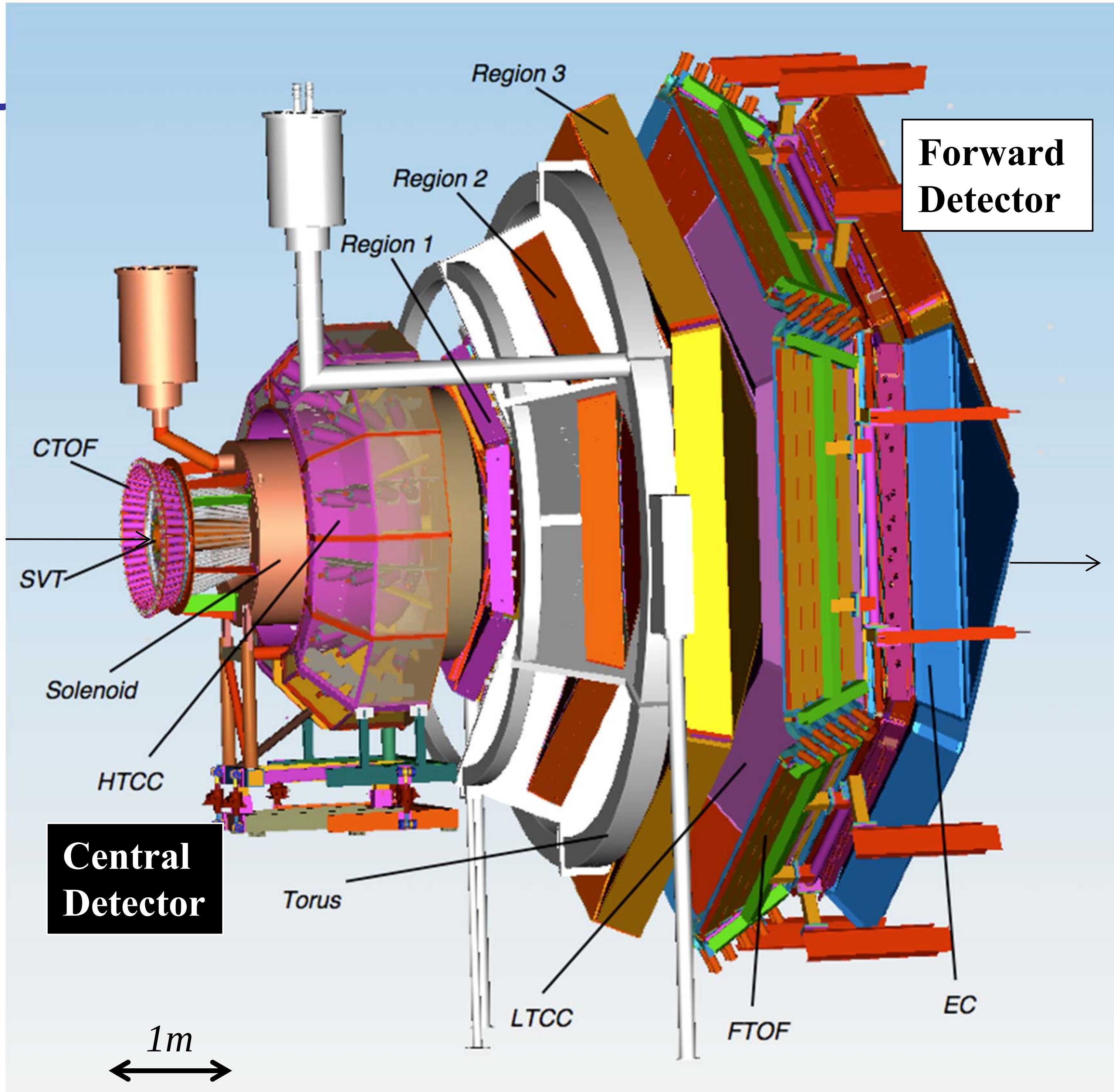
E-09-003

… and more?

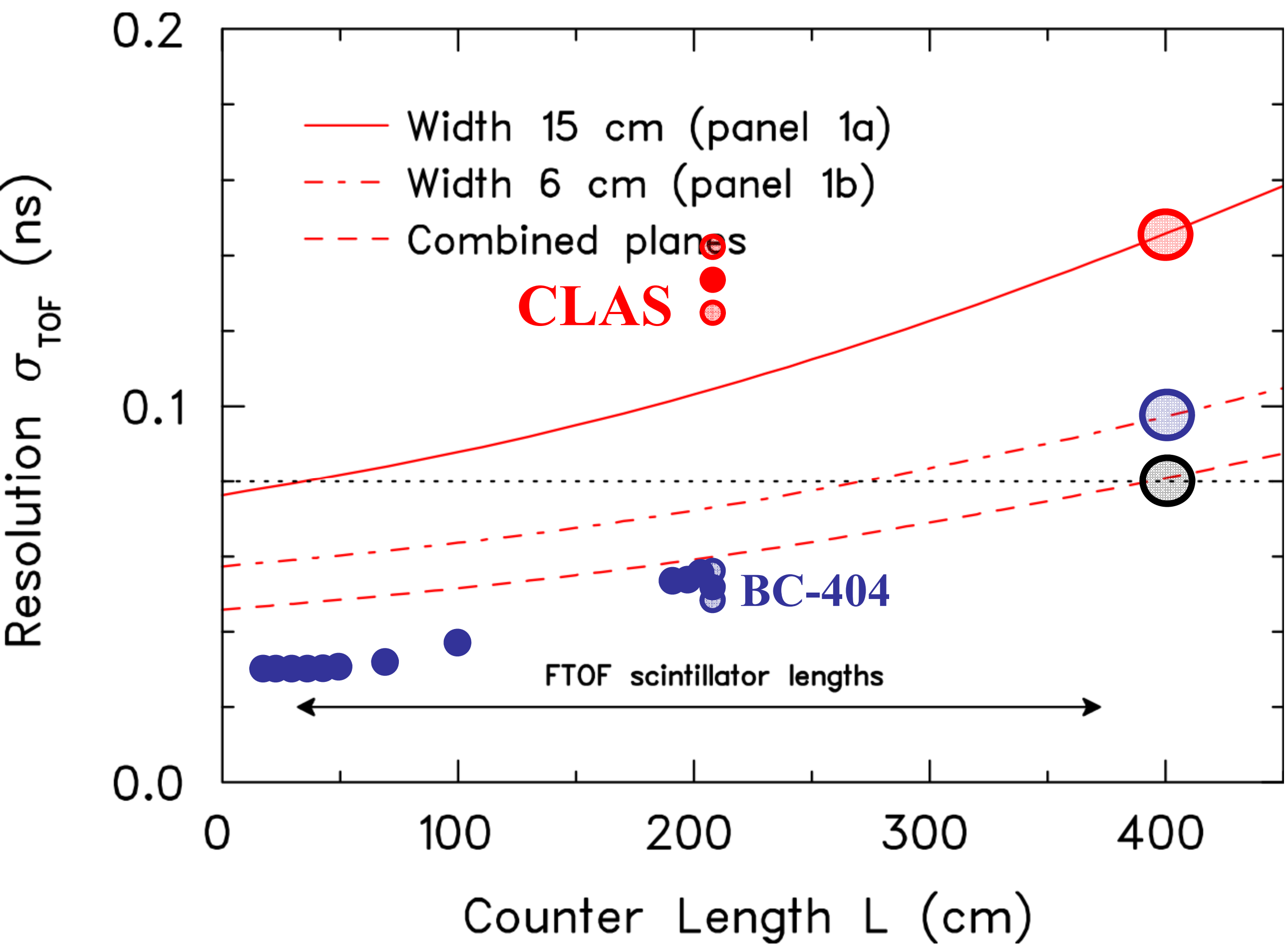
CLAS12

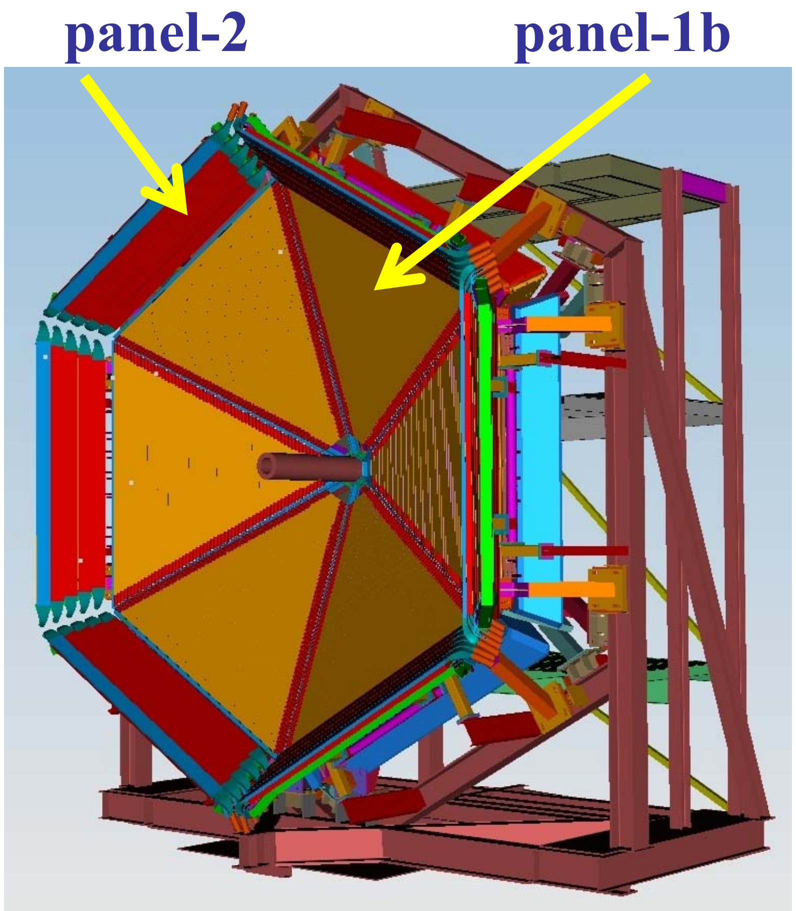


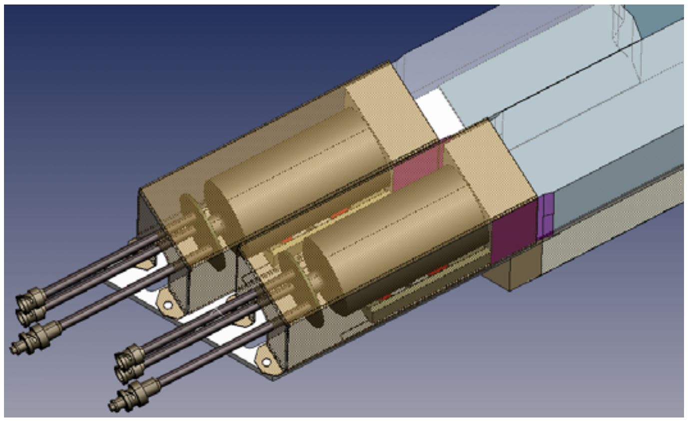
- Luminosity > 10^{35} $cm^{-2}s^{-1}$
- Hermeticity
- Polarization

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

New Forward Time of Flight Detector for CLAS12

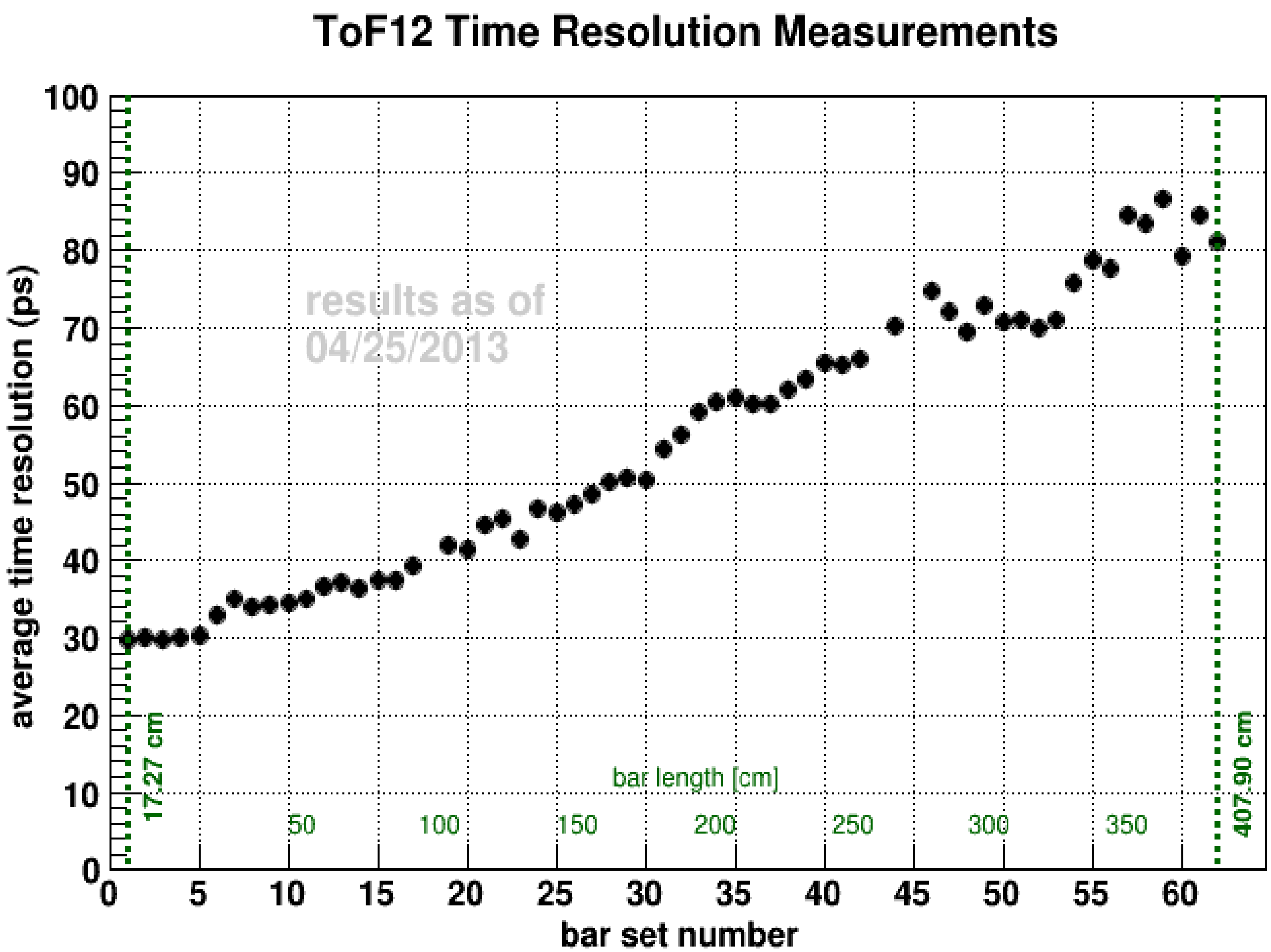




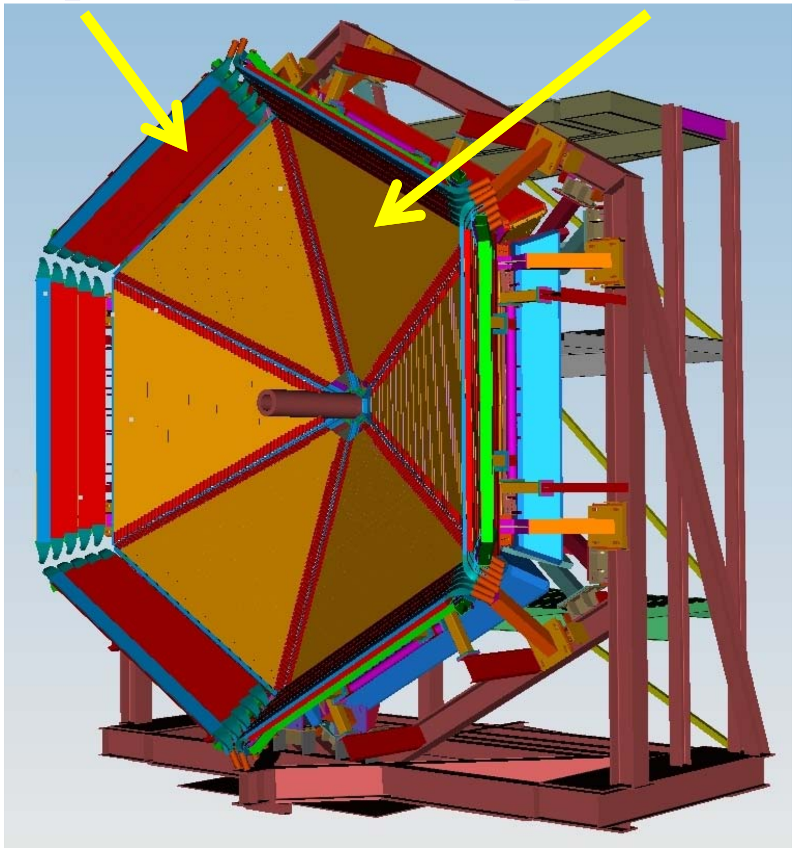


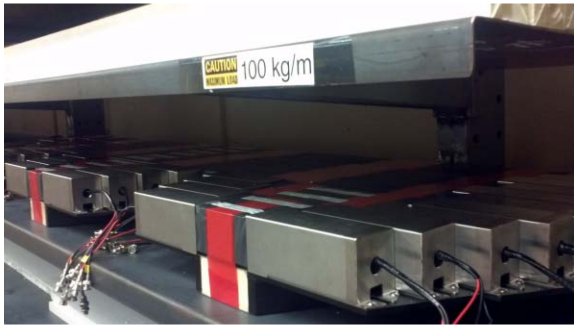
World-record time resolution of 48 ns averaged over the full length of 210 cm

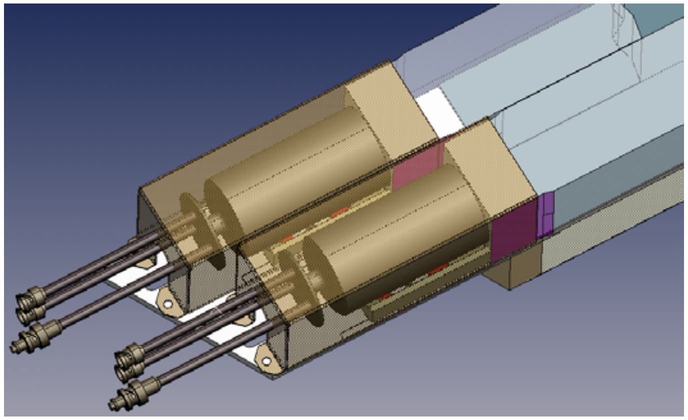
New Forward Time of Flight Detector for CLAS12



panel-2 panel-1b

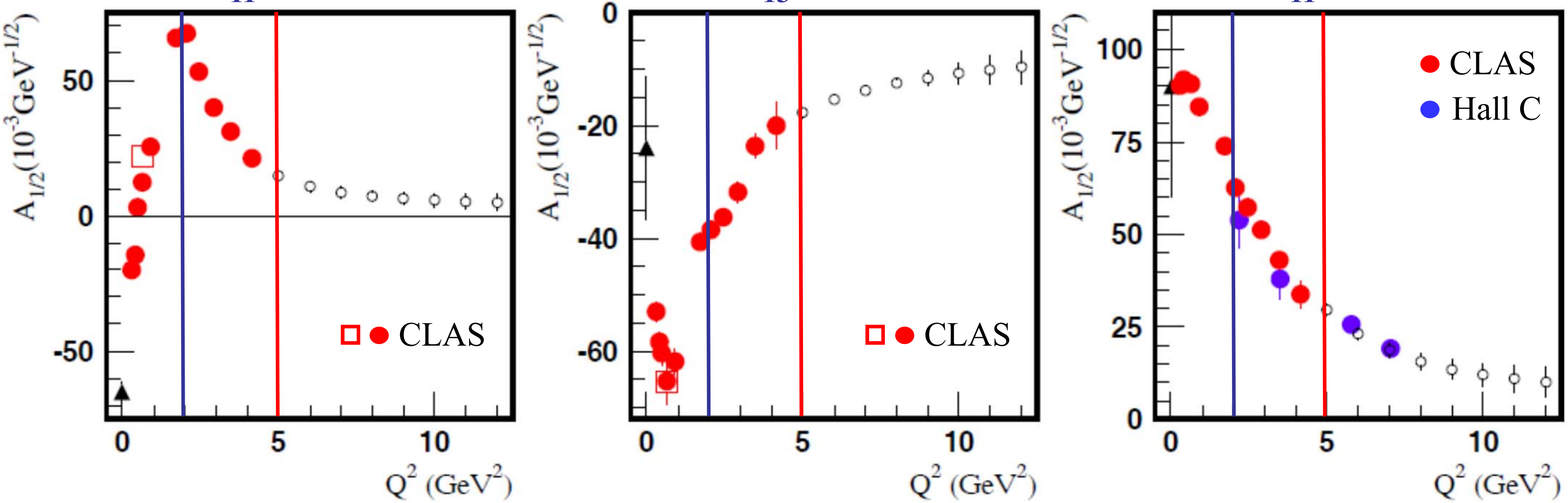






Anticipated N* Electrocouplings from a Combined Analysis of Nπ & Nππ

$P_{11}(1440)$ **$D_{13}(1520)$** **$S_{11}(1535)$**



Open circles represent projections and all other markers the available results with the 6-GeV electron beam

- Examples of published and projected results obtained within 60d for three prominent excited proton states from analyses of Nπ and Nππ electroproduction channels. Similar results are expected for many other resonances at higher masses, e.g. $S_{11}(1650)$, $F_{15}(1685)$, $D_{33}(1700)$, $P_{13}(1720)$, …

- This experiment will – for the foreseeable future – be the only experiment that can provide data on $\gamma_v NN^*$ electrocouplings for almost all well established excited proton states at the highest photon virtualities ever achieved in N* studies up to Q^2 of 12 GeV^2.

Summary

- We will measure and 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 DSE, LQCD, 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 dynamical 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 development of reaction models that will account for hard quark/parton contributions at high Q^2 and
  - the theoretical interpretation on N* electrocouplings, see our Review Article Int. J. Mod. Phys. E, Vol. 22, 1330015 (2013) 1-99.
- Any constructive criticism, help, or participation is always most welcomed, contact:
  - Viktor Mokeev mokeev@jlab.org or Ralf Gothe gothe@sc.edu.