Baryon Spectroscopy and Transition Form Factors: A Long Road to QCD in the Confinement Regime

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Workshop on Confinement Physics

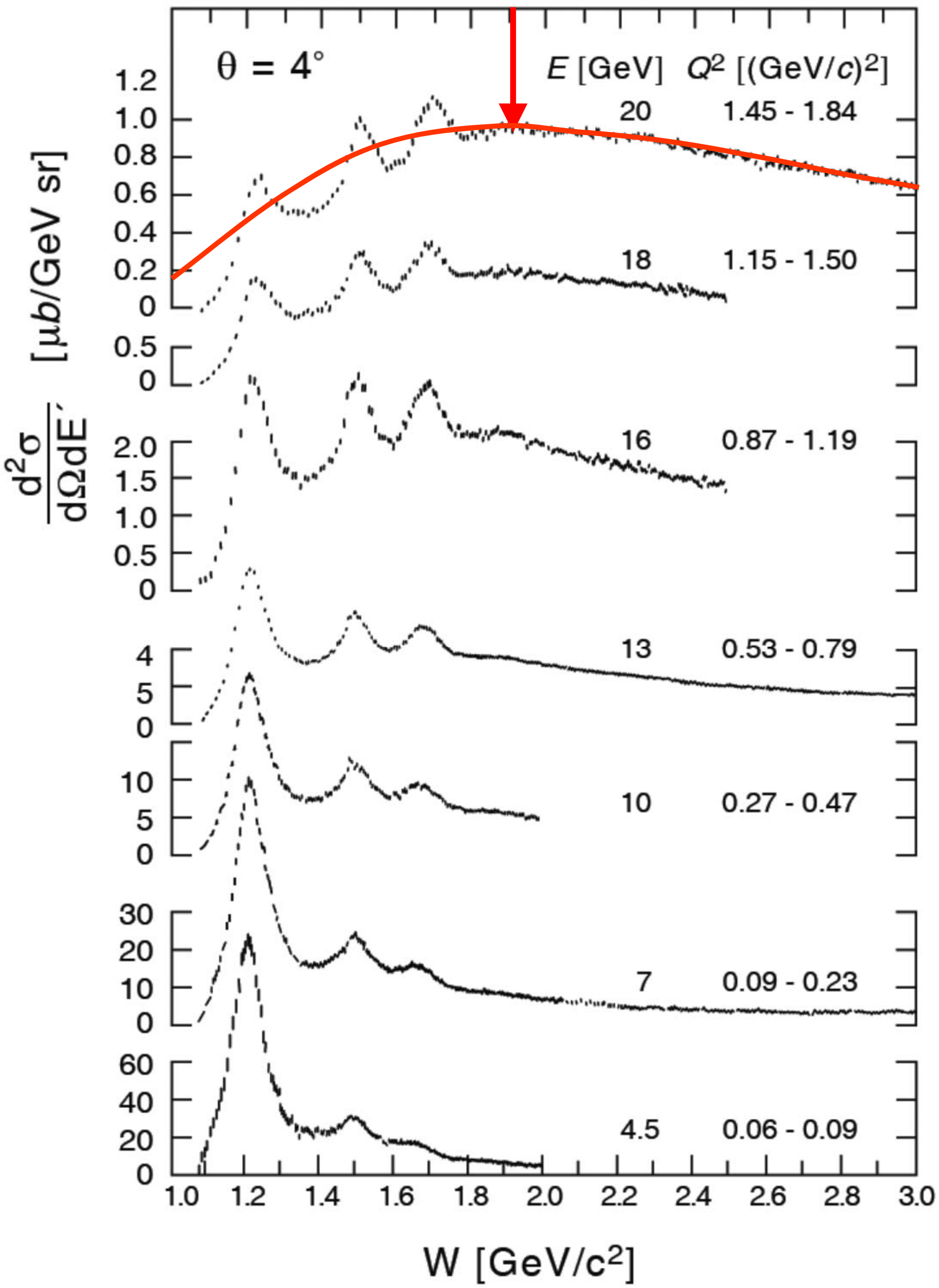
March 12-15, 2012

Jefferson Lab, Newport News, VA

- **γNN* Experiments:** A Unique Window into the Quark Structure?
  - Baryon spectroscopy, Elastic Form Factors, and Transition Form Factors
- **Analysis:** Mostly Model Independent and Model Dependent?
  - Complete Experiments and Phenomenological Extraction
- **QCD based Theory:** Confinement and Non-Perturbative QCD?

QCD for Bound and Confined Quarks?

Baryon Excitations and Quasi-Elastic Scattering



PRL **16** (1970) 1140, PR **D4** (1971) 2901
E.D. Bloom and F.J. Gilman

W = 1.9 GeV

E' = 17.6 GeV

ν = 2.37 GeV

Q^2 = 1.72 GeV

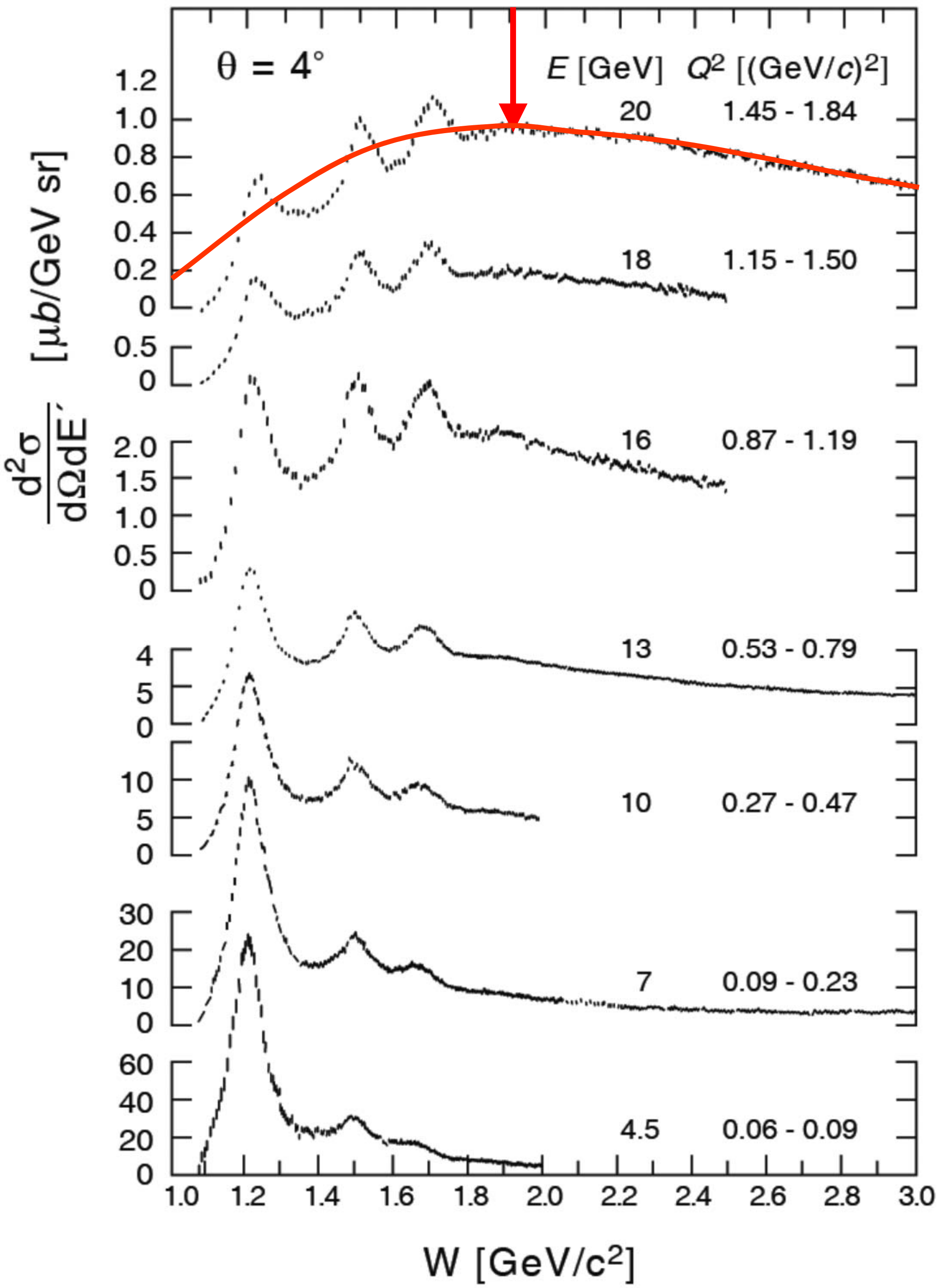
m_q = 0.36 GeV $\qquad m_q = Q^2/2\nu$

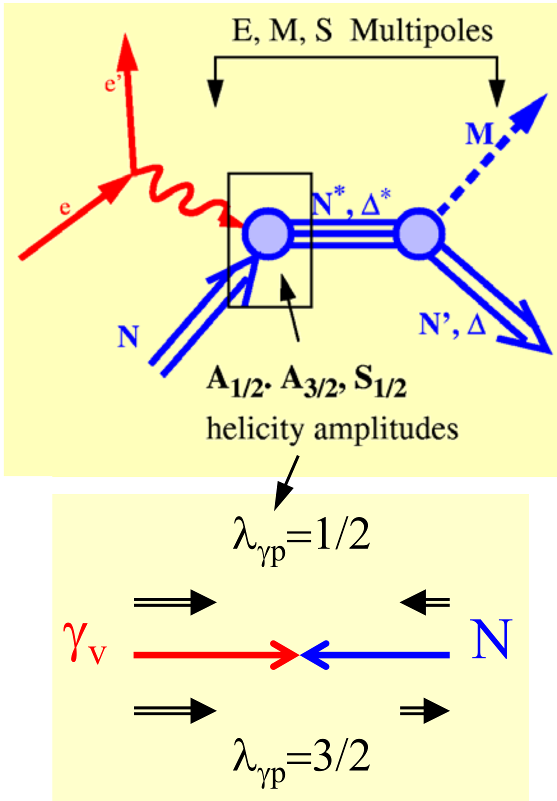
p_F = 0.67 GeV

r_F = 0.79 fm $\qquad \Delta r_F = \frac{\hbar c}{\Delta p_F} * \sqrt{9\pi/2}$

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

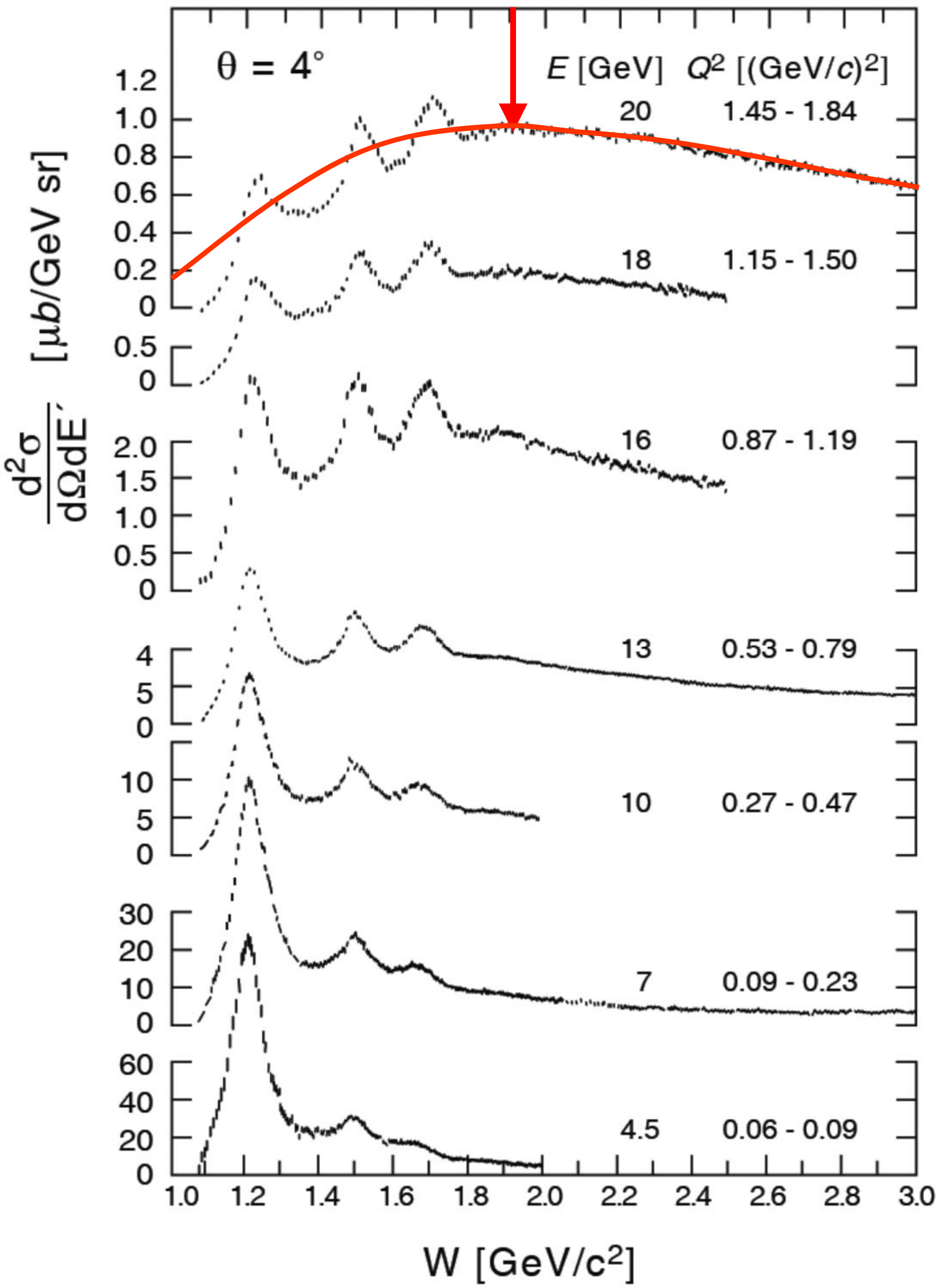
Baryon Excitations and Quasi-Elastic Scattering



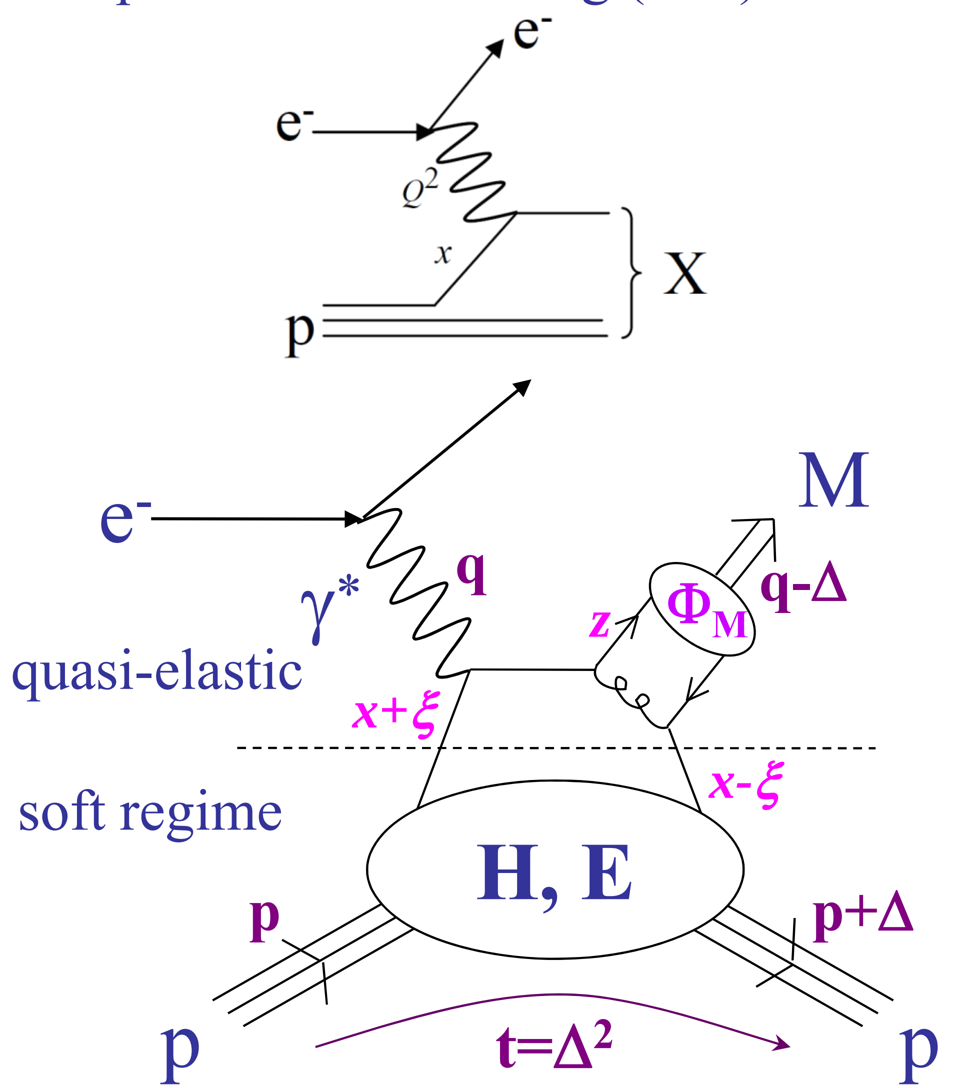


Deep Inelastic Scattering
S. Stein et al., PR **D22** (1975) 1884

Baryon Excitations and Quasi-Elastic Scattering

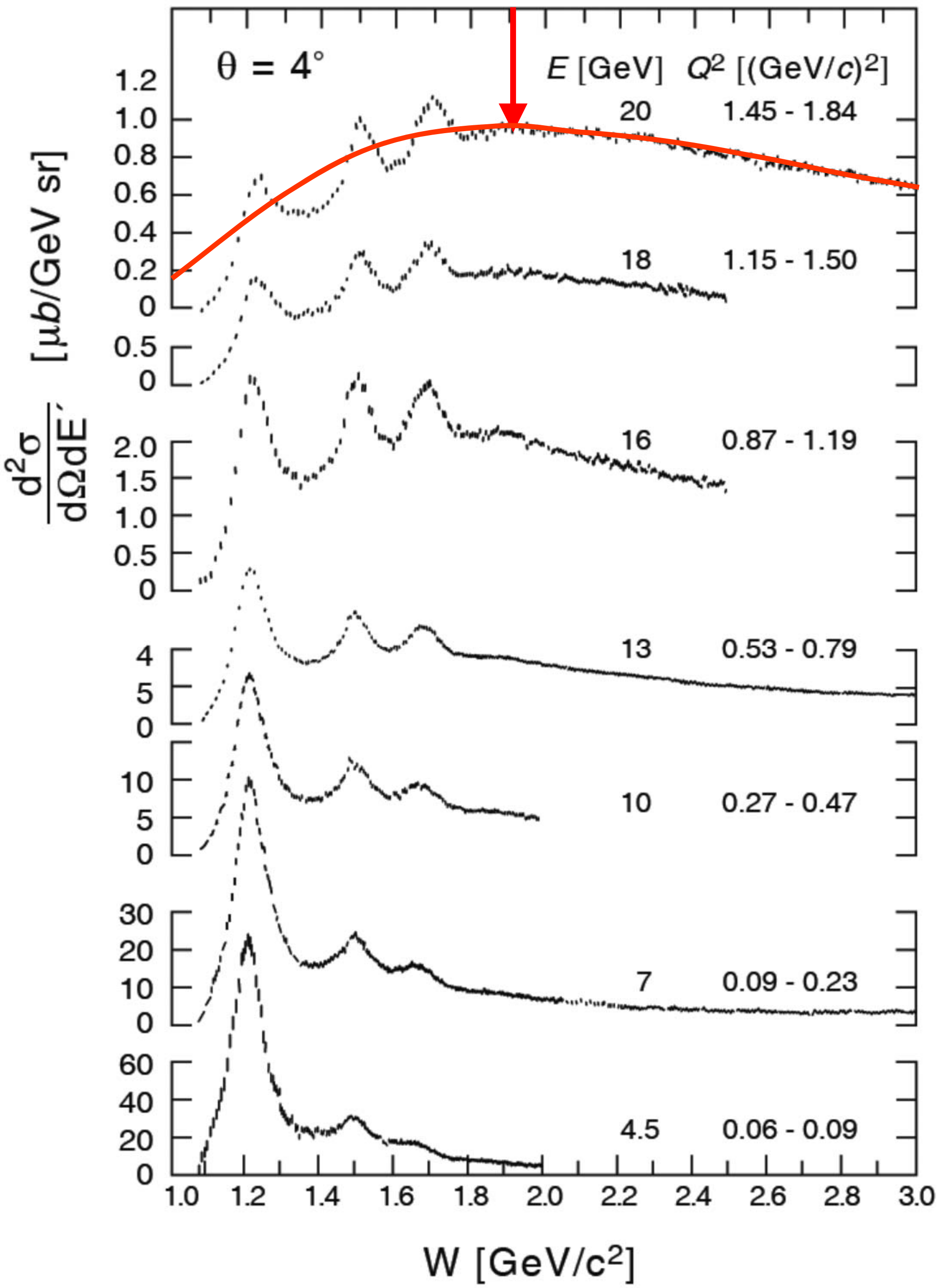


Deep Inelastic Scattering (DIS)

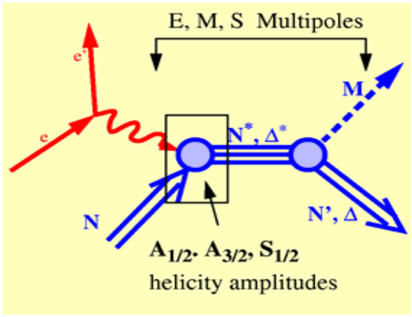


Deep Inelastic Scattering
S. Stein et al., PR **D22** (1975) 1884

Baryon Excitations and Quasi-Elastic Scattering



hard and confined



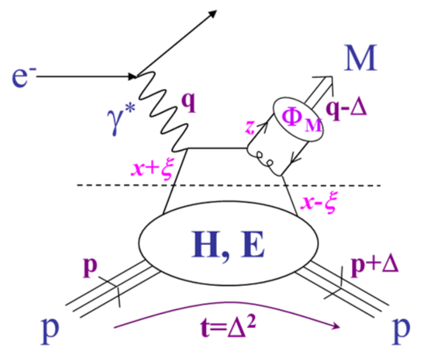
Spectroscopy

Elastic Form Factors

Transition Form Factors

quasi-elastic

soft

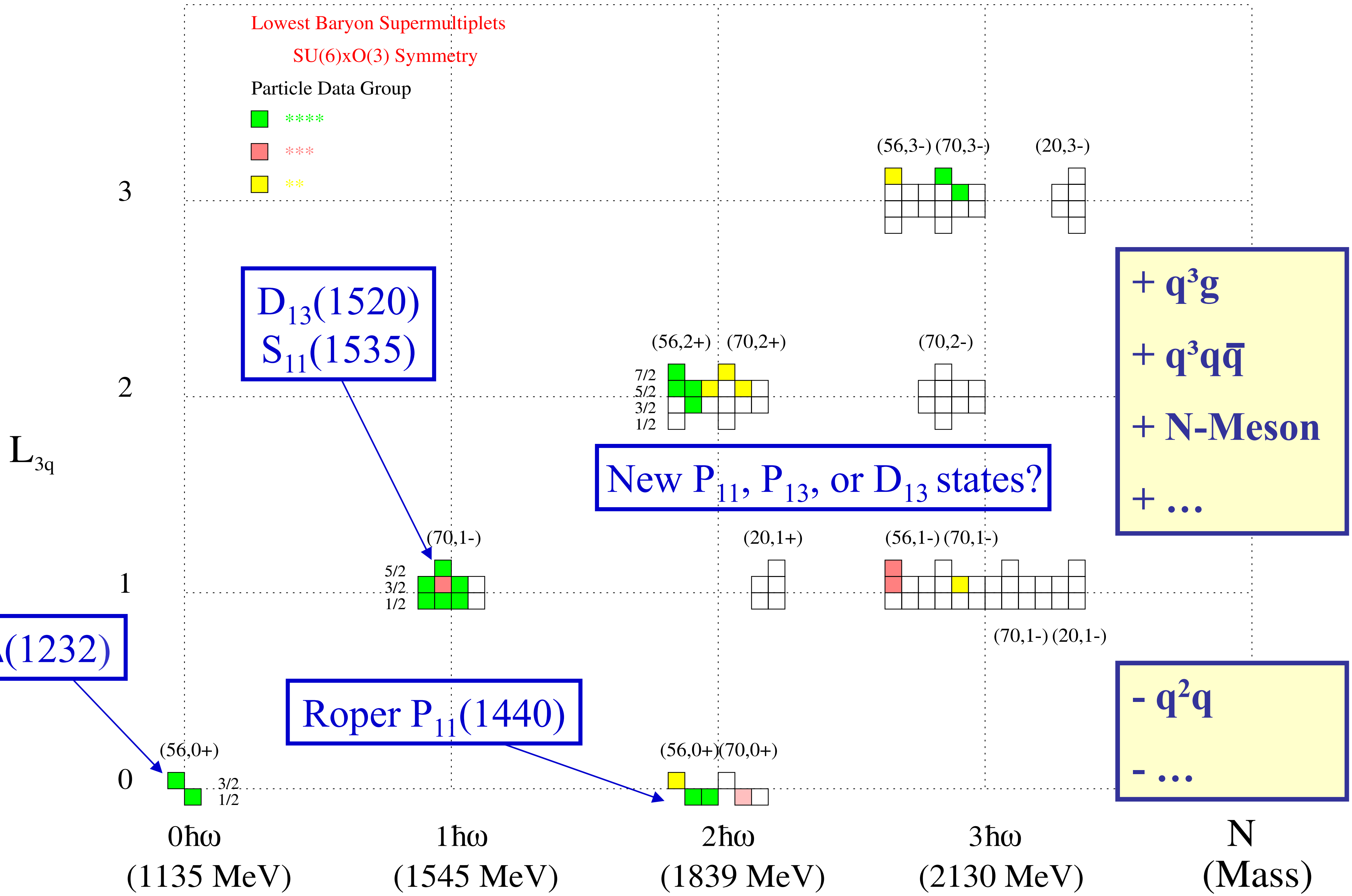


Deep Inelastic Scattering

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

Spectroscopy

Quark Model Classification of N*



Evidence for New N* States

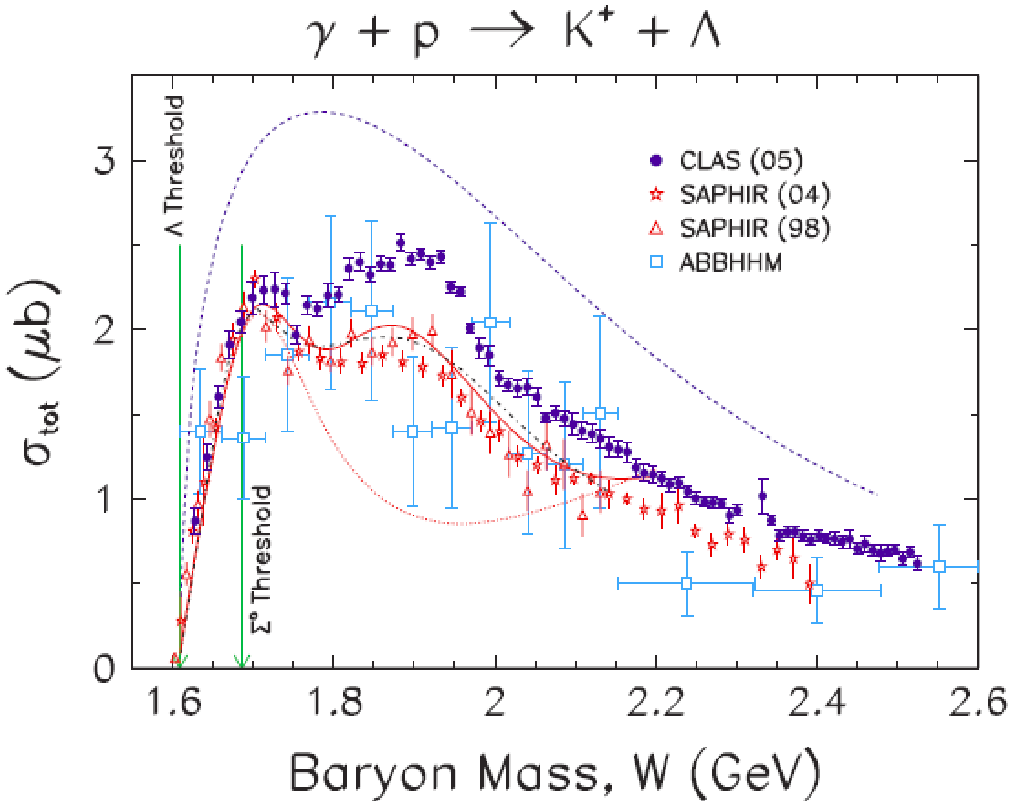


FIG. 20. (Color online) Total cross section for $\gamma + p \rightarrow K^+ + \Lambda$. The data from CLAS (blue circles) are shown with combined statistical and fitting uncertainties. Also shown are results from two publications from SAPHIR (red stars (2004) [18] and red triangles (1998) [8]) and the ABBHHM Collaboration (light blue squares) [43]. The curves are from a Regge model (dashed blue) [20,21], KAON-MAID (solid red) [5], KAON-MAID with the $D_{13}(1895)$ turned off (dotted red), and Saghai *et al.* (dot-dashed black) [9].

R. Bradford et al., Phys. Rev. C 73, 035202

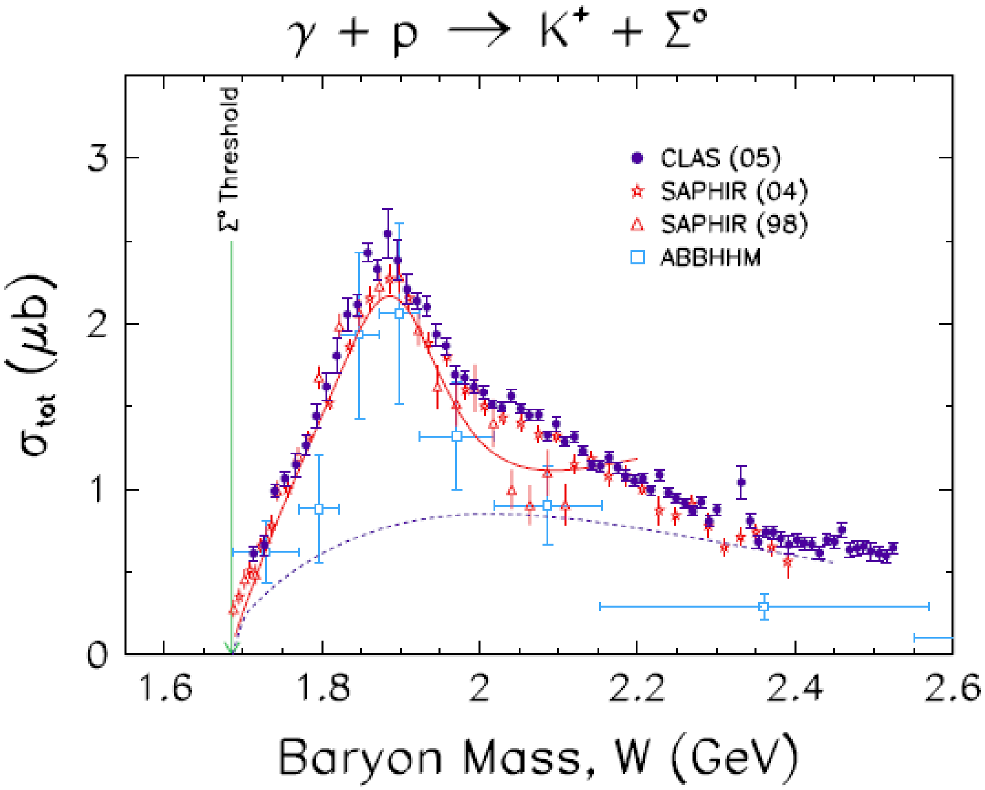
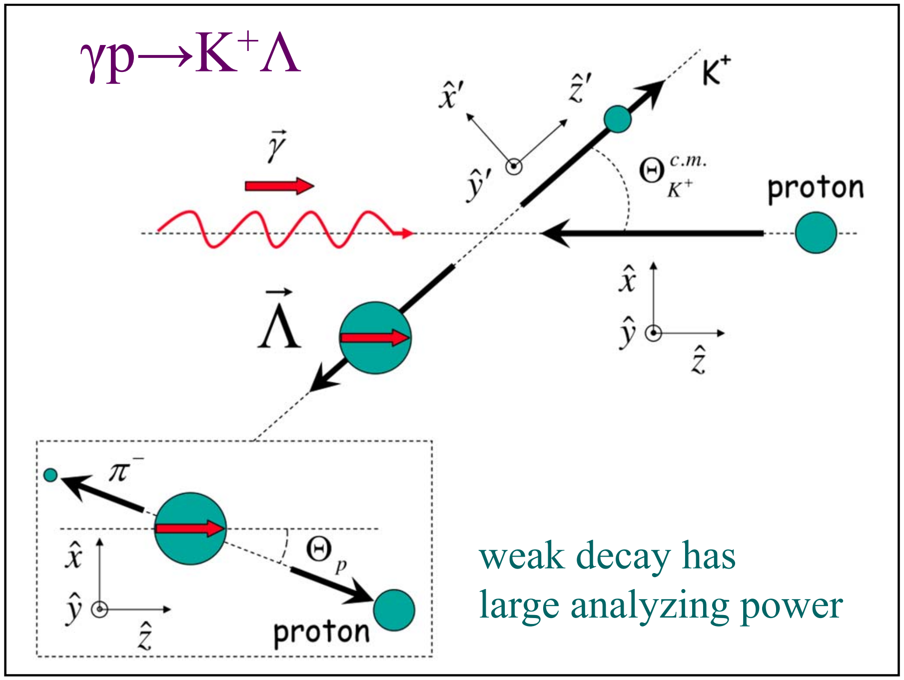


FIG. 21. (Color online) Total cross section for $\gamma + p \rightarrow K^+ + \Sigma^0$. The data from CLAS (blue circles) are shown with combined statistical and fitting uncertainties. Also shown are results from two publications from SAPHIR (red stars (2004) [18] and red triangles (1998) [8]) and the ABBHHM Collaboration (light blue squares) [43]. The curves are from a Regge model (dashed blue) [20,21] and from KAON-MAID (solid red) [5].

One or more D_{13} (Bennhold, Mart), P_{13} (BoGa), or P_{11} (Ghent) states needed in different models.

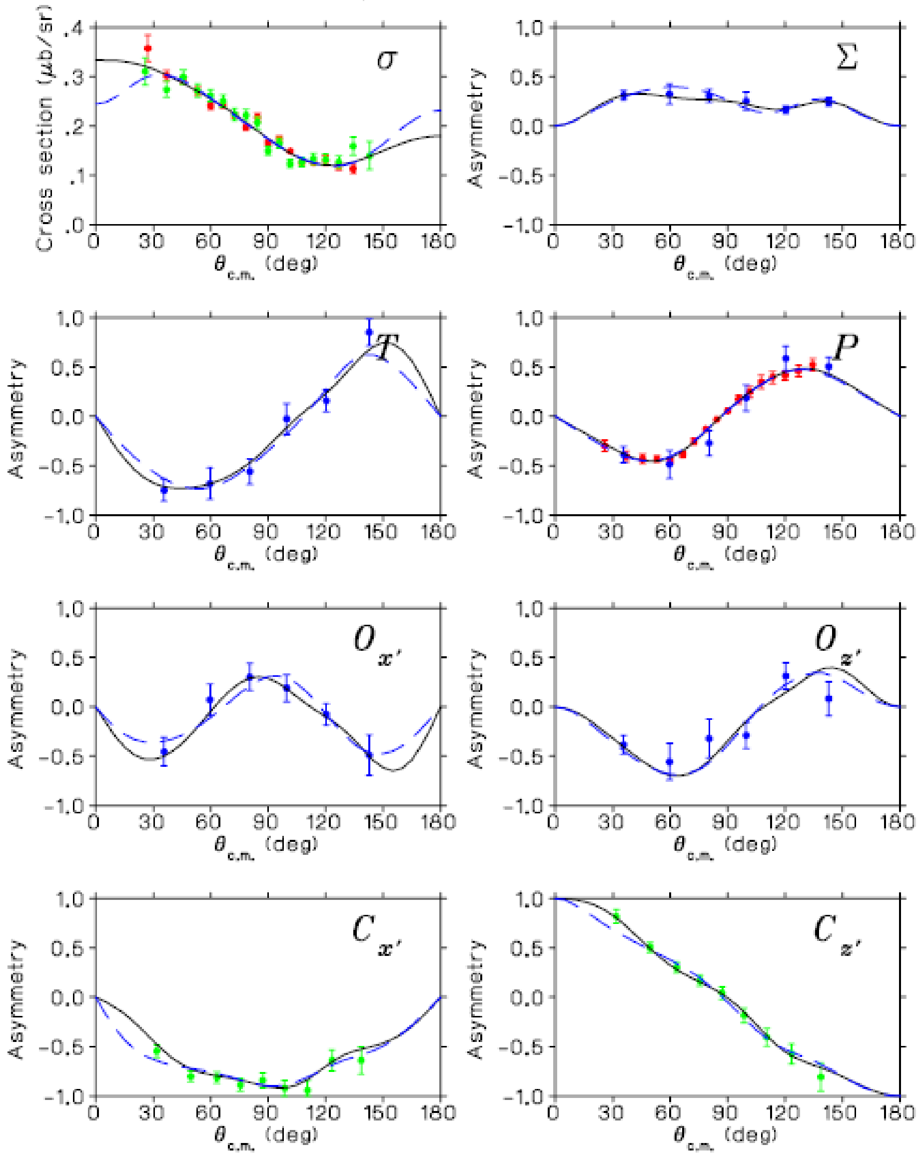
FROST/HD $\vec{\gamma}\vec{N} \rightarrow \pi N, \eta N, K\vec{\Lambda}, K\vec{\Sigma}, N\pi\pi$



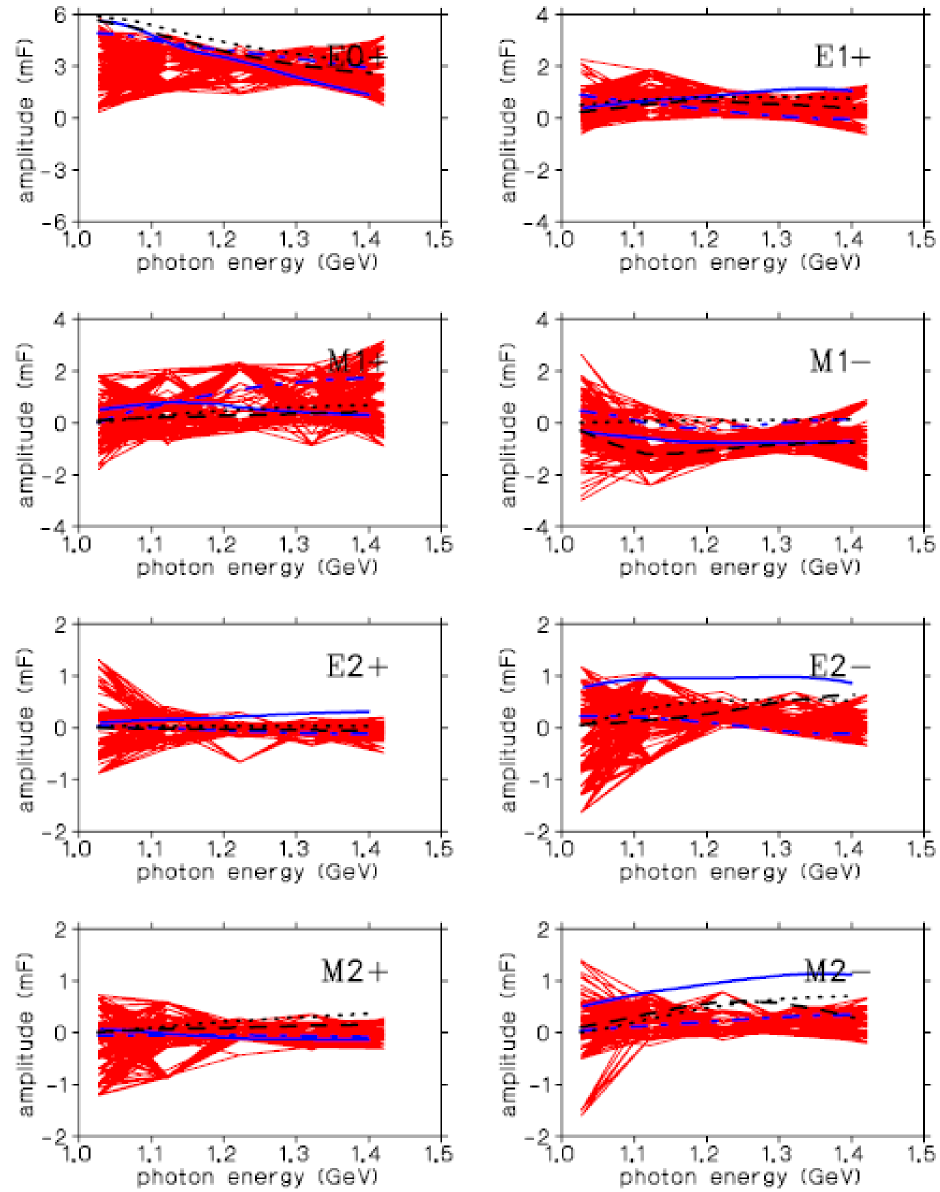
- Process is described by 4 complex, parity conserving amplitudes
- 8 well-chosen measurements are needed to determine amplitude
- For hyperon finals state 16 observables will be measured in CLAS ➠ large redundancy in determining the photo-production amplitudes ➠ allows many cross checks and increased accuracy
- 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		$O_{x'}$	

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



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



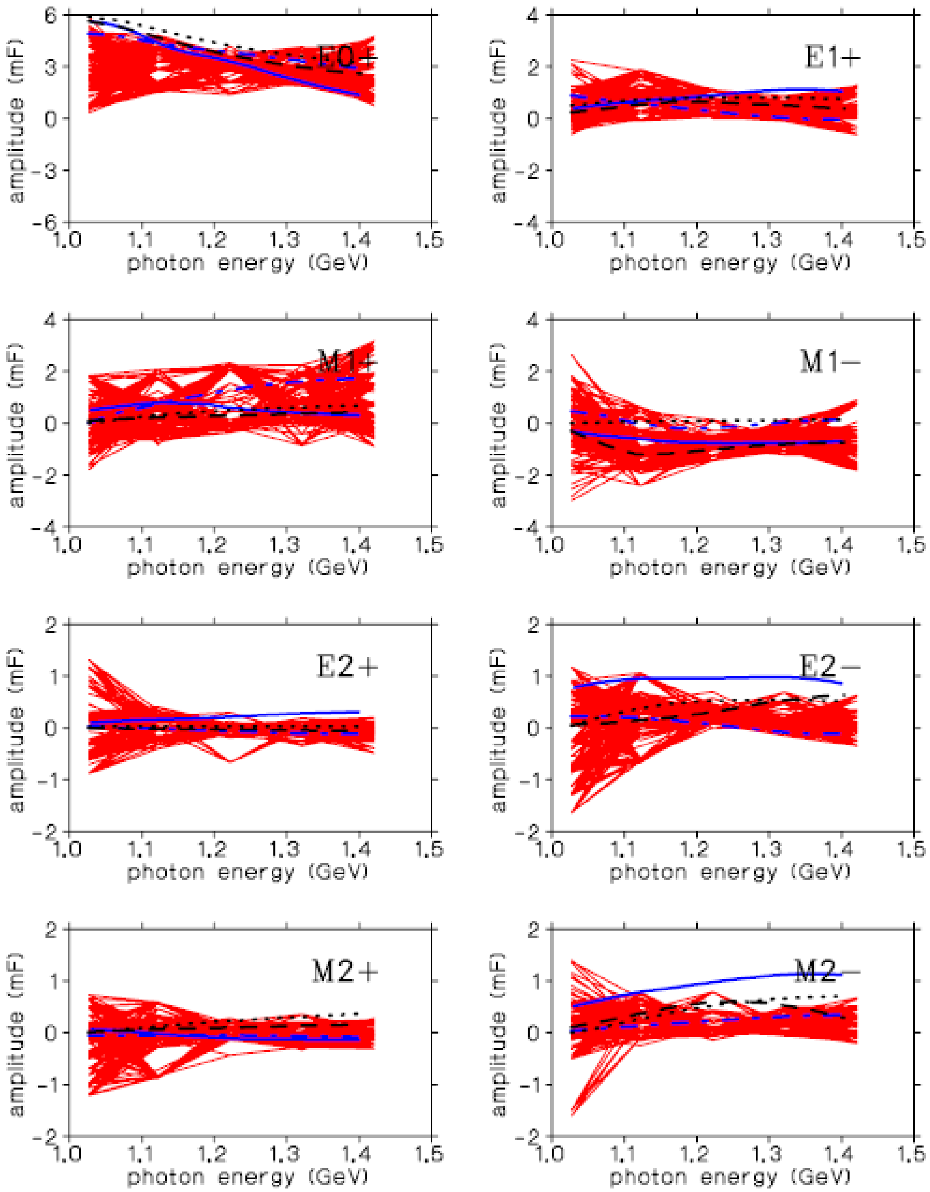
CLAS (g1c, g11a) and GRAAL

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

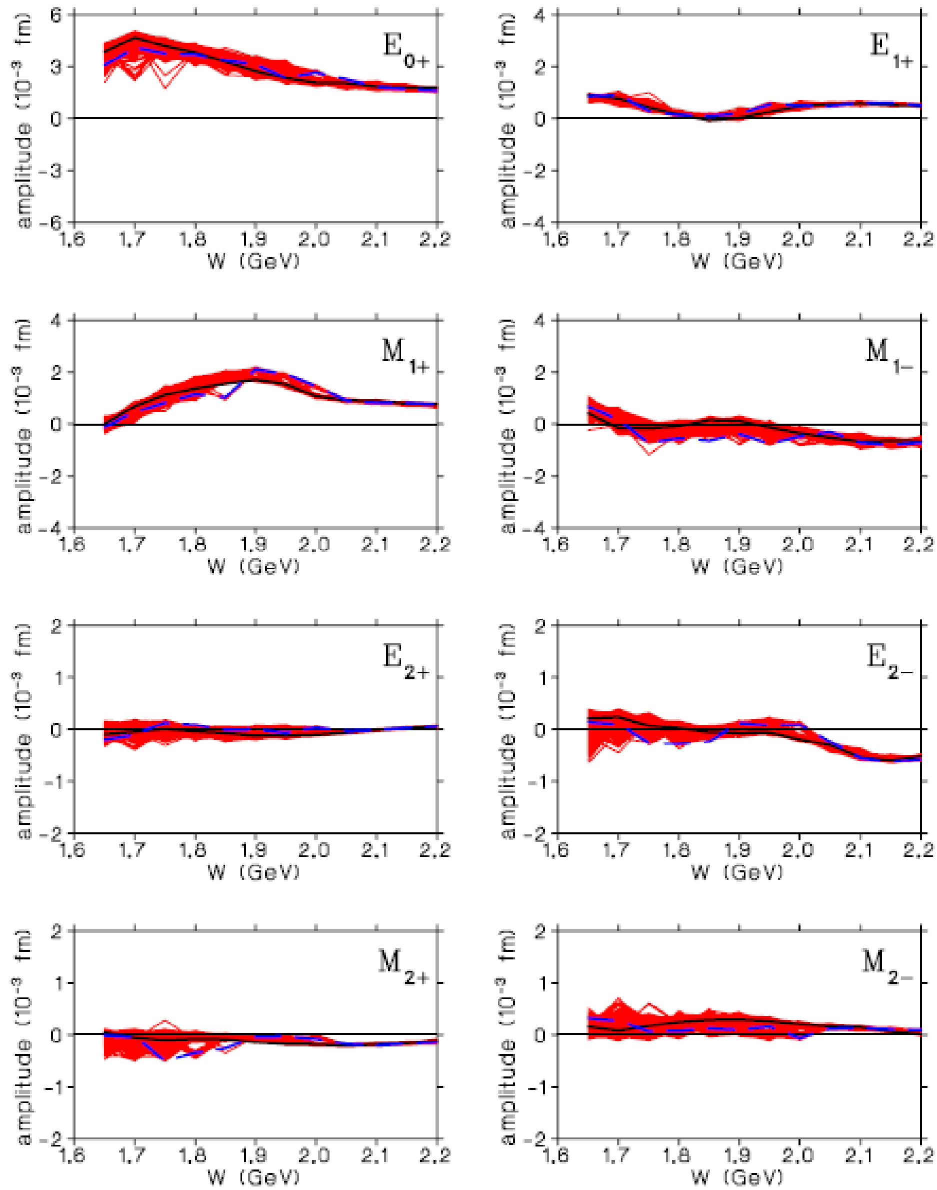
Real parts of the PWA multipoles

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

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



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



Real parts of the PWA multipoles

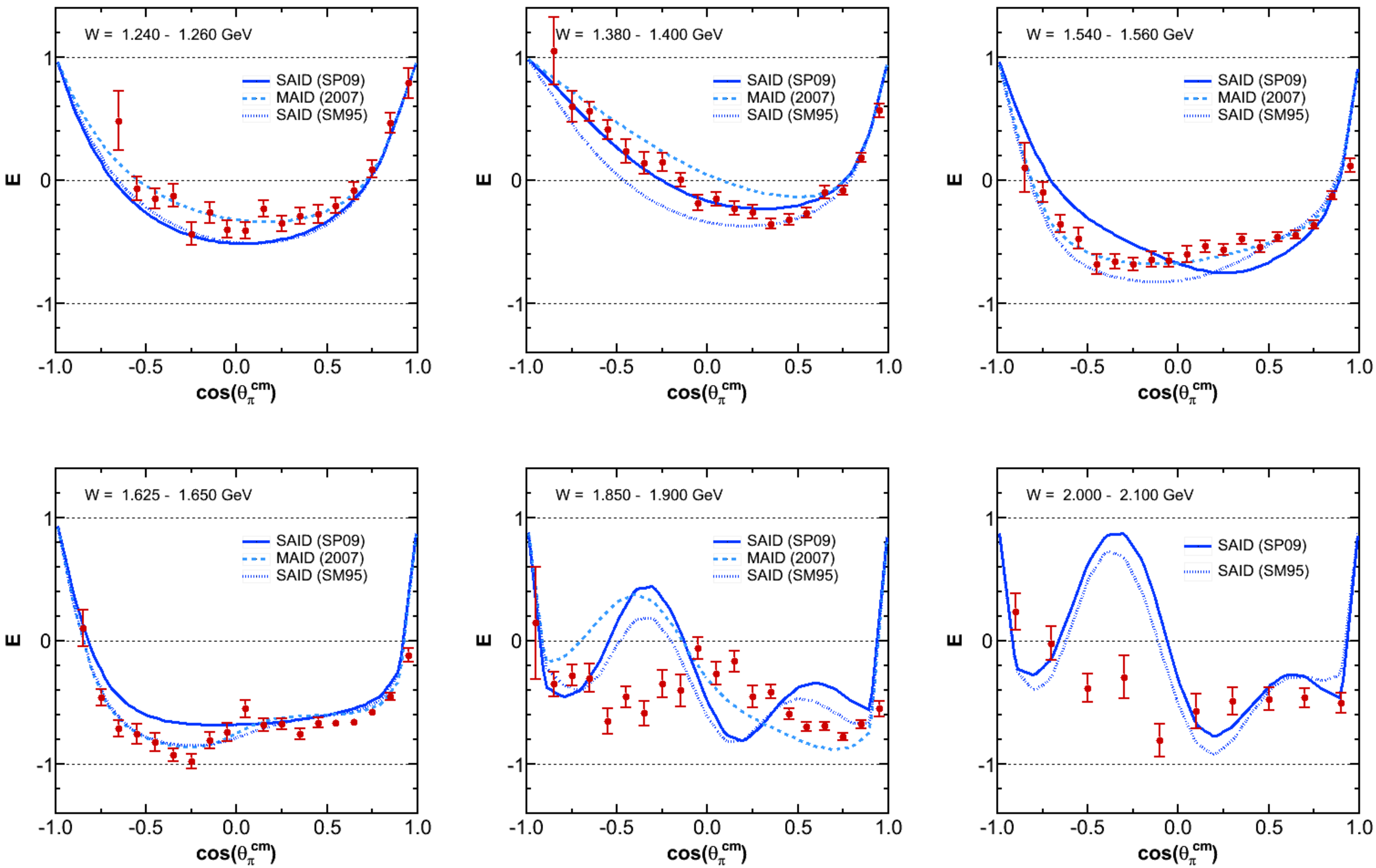
with 8 observables D_{13} excluded and with 16 observables P_{11} to be validated

$\vec{\gamma}(\vec{p},\pi^+)n$ - Selected Preliminary Results for E

Circular polarized beam and longitudinally polarized target

S. Strauch

E

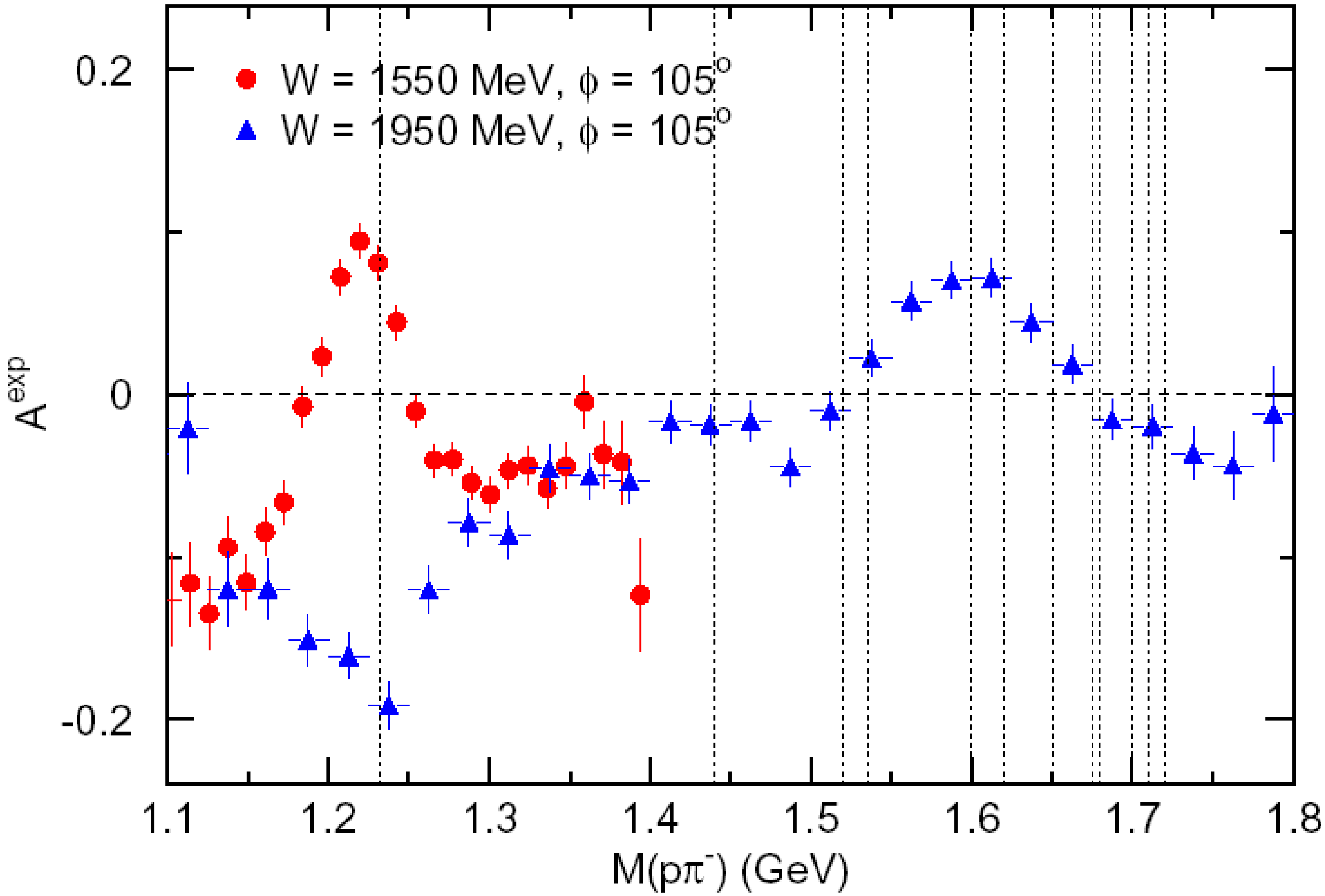


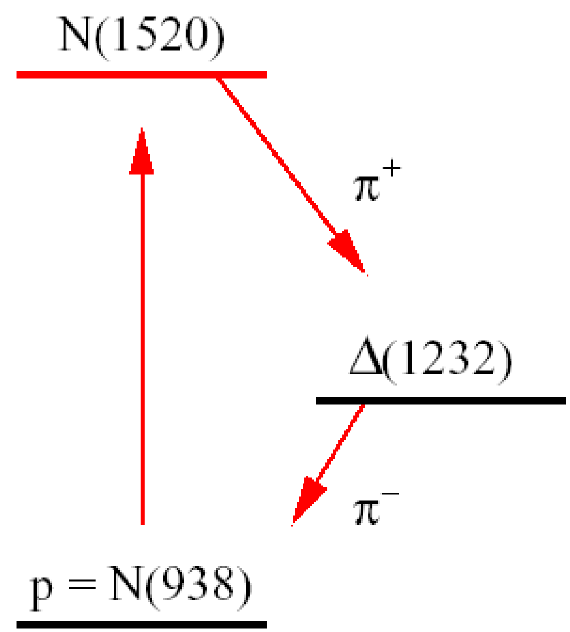
SP09: M. Dugger, et al., Phys. Rev. C 79, 065206 (2009); SM95: R. A. Arndt, I. I. Strakovsky, R. L. Workman, Phys. Rev. C 53, 430 (1996); MAID: D. Drechsel, S.S. Kamalov, L. Tiator Nucl. Phys. A645, 145 (1999)

Helicity Asymmetry in 2π Photoproduction

S. Strauch

Circular polarized beam



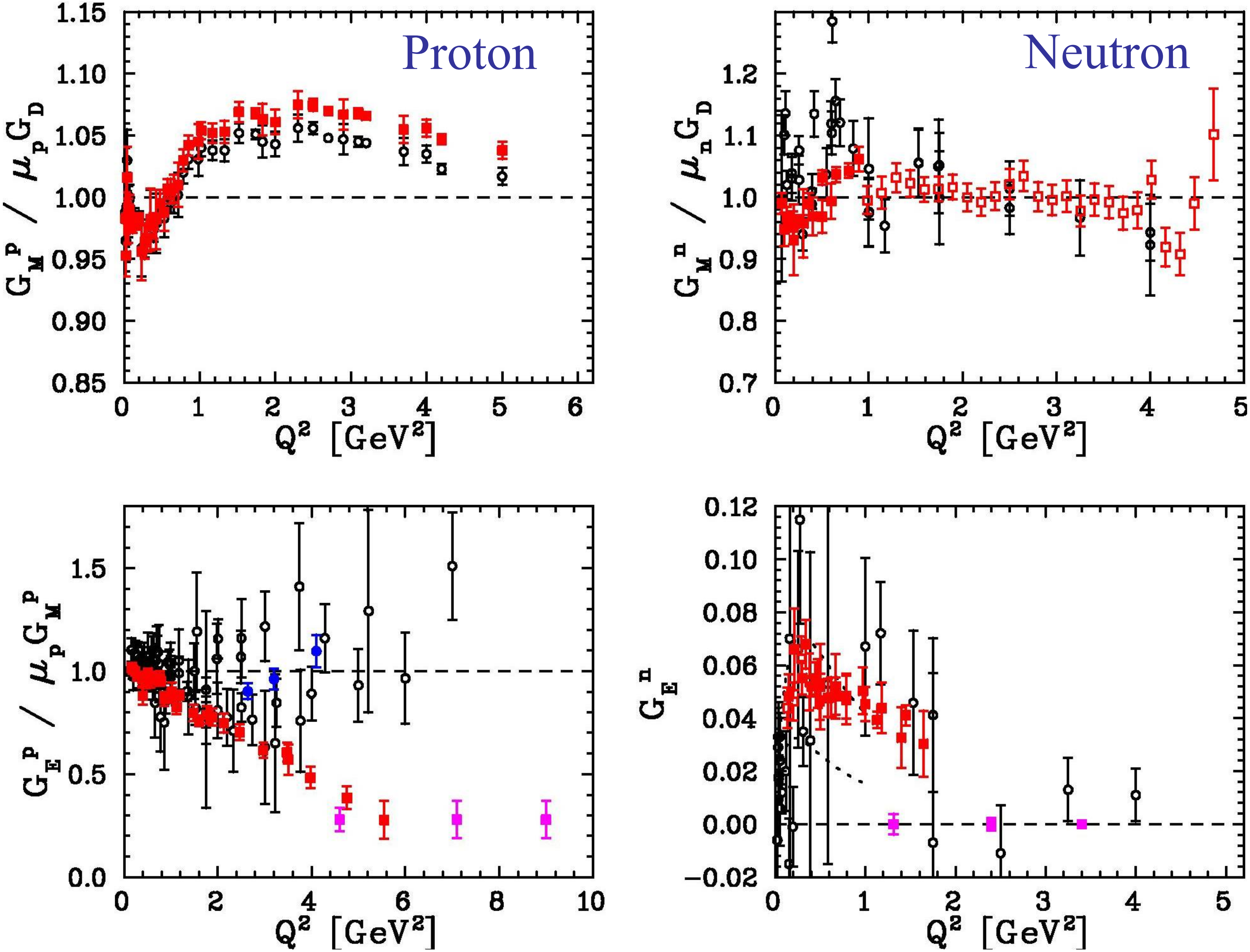


- Sequential Decay of the D_{13}(1520) resonance via πΔ
  … or higher lying resonances

Phys. Rev. Lett. 95, 162003 (2005)

Elastic Form Factors

Nucleon Form Factors: Last Ten Years

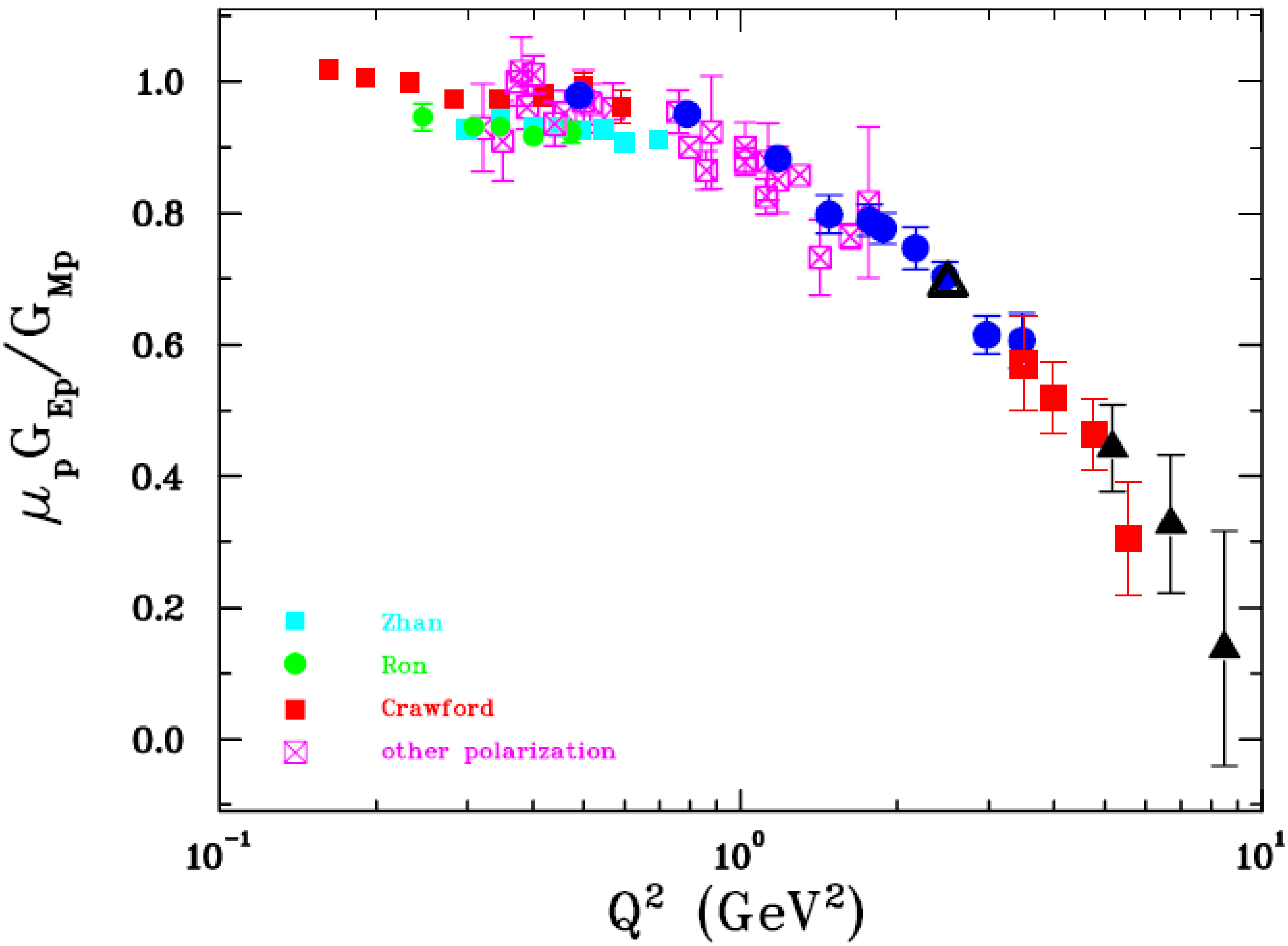


J. Arrington

under analysis

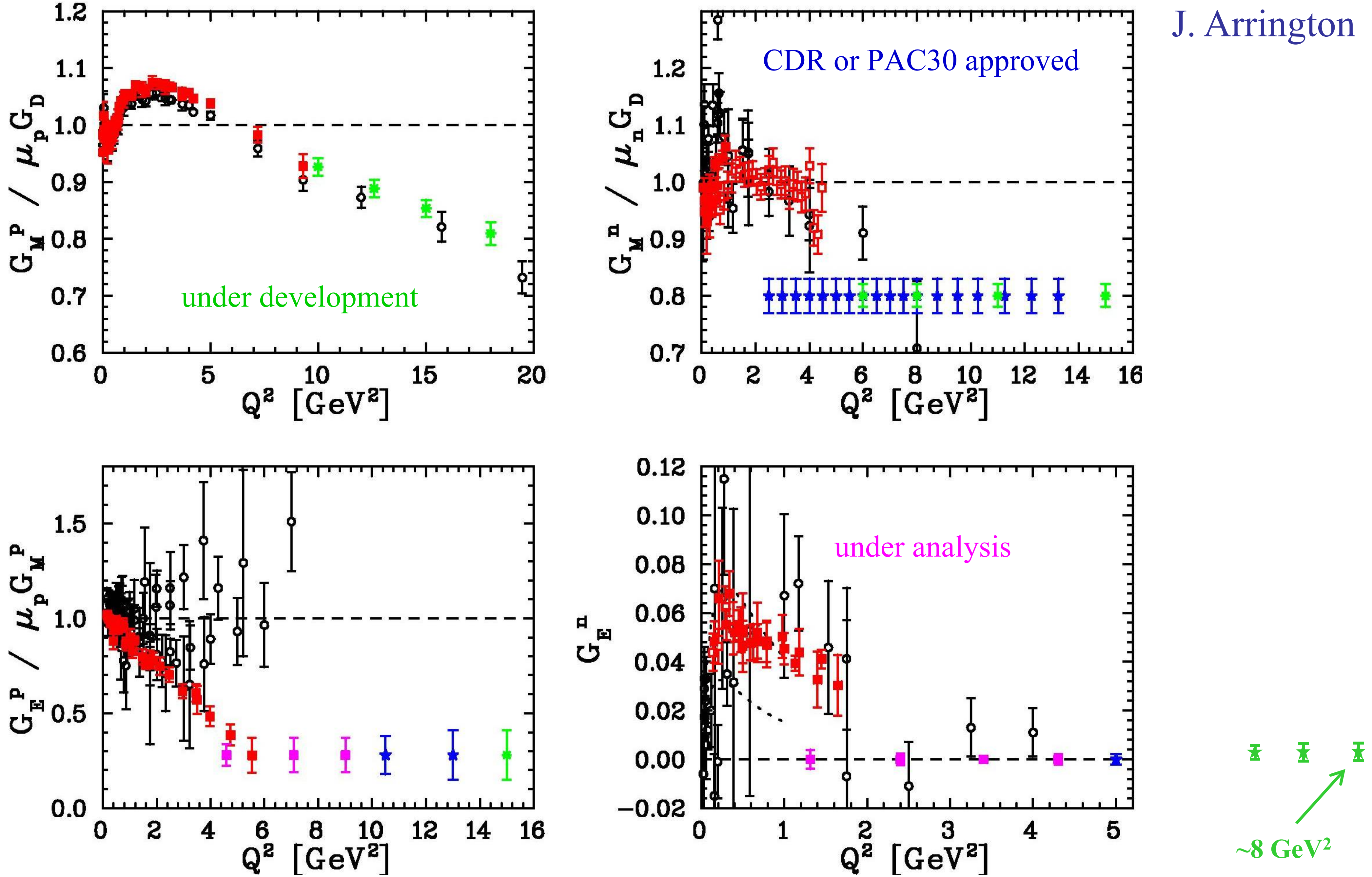
Recent Proton Form Factor Ratios

C. Perdrisat



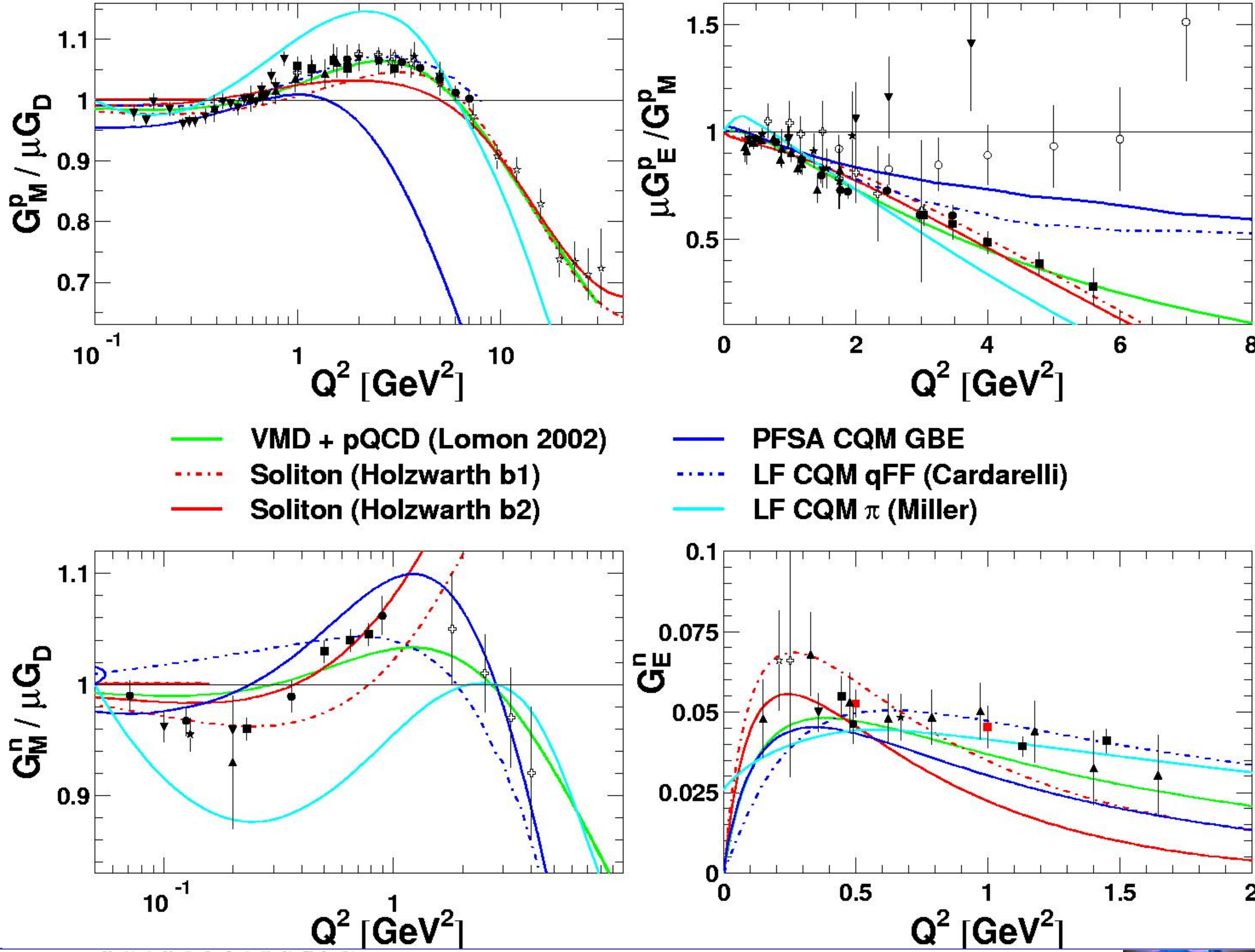
Extensions with JLab 12 GeV Upgrade

J. Arrington



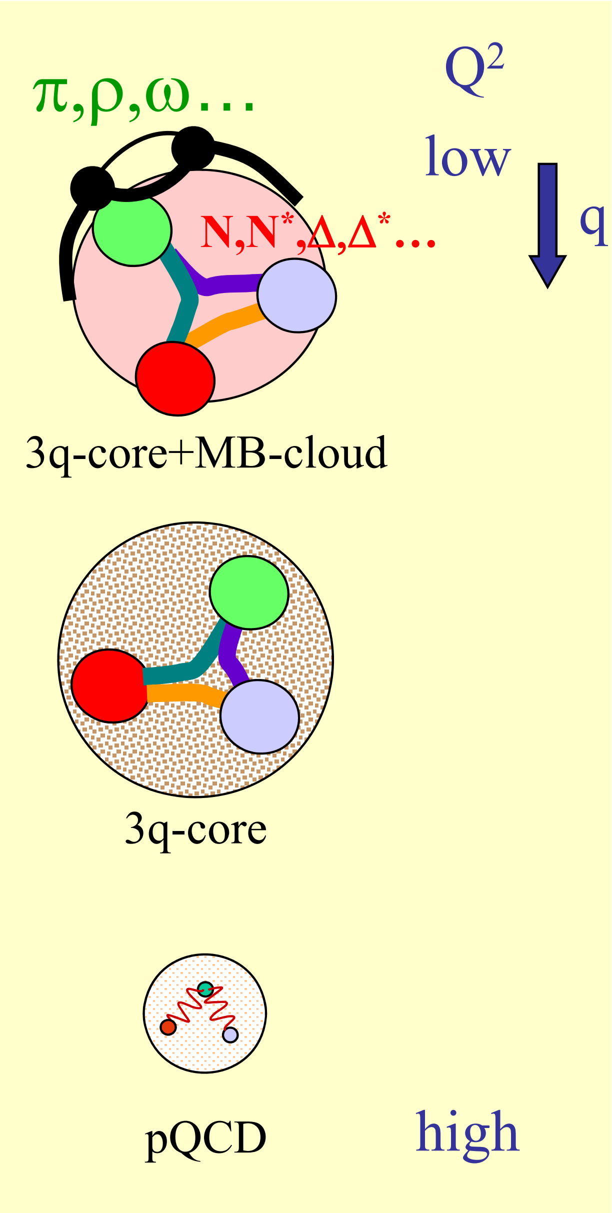
Small Sample of Recent Calculations

J. Arrington

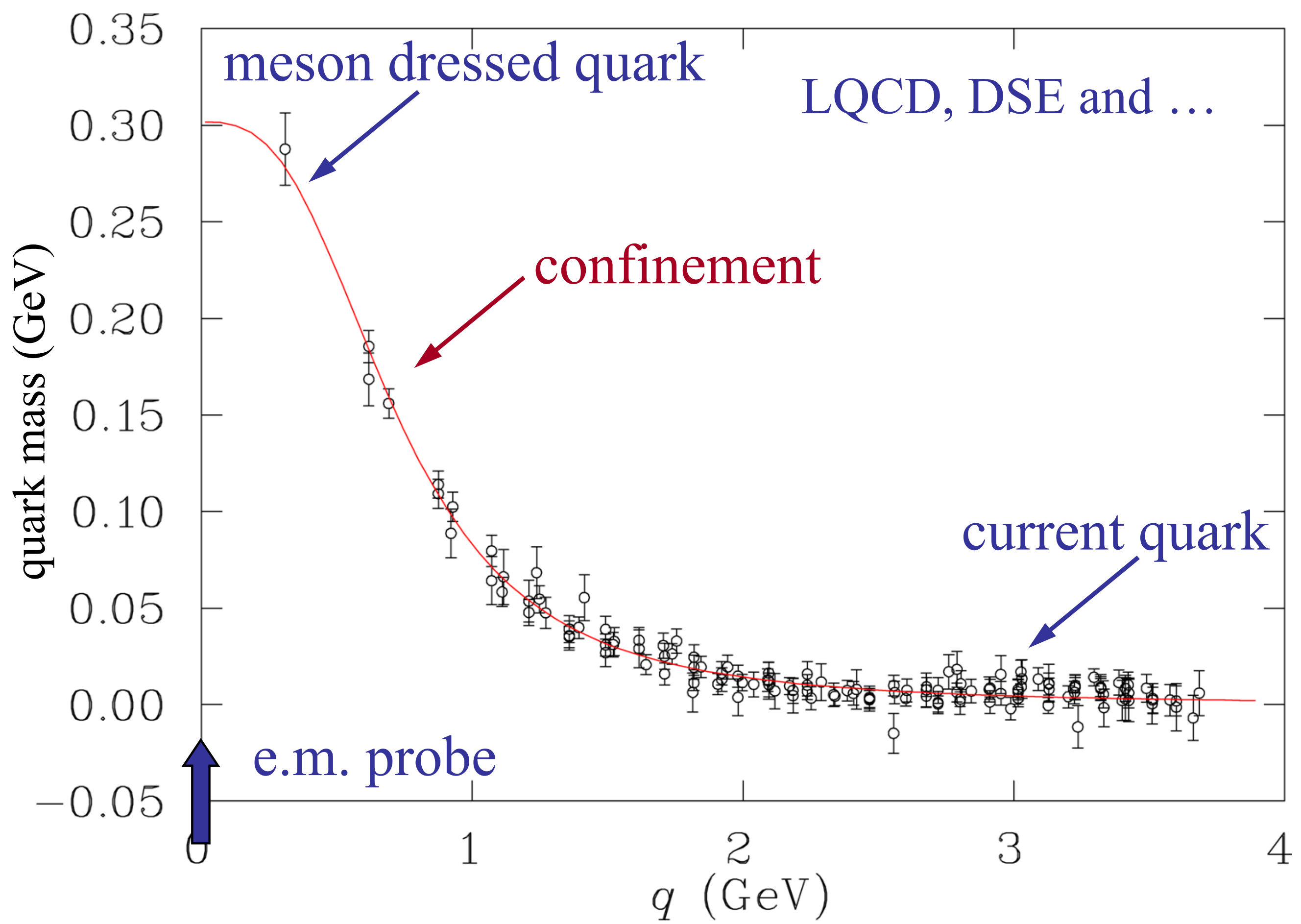


Transition Form Factors

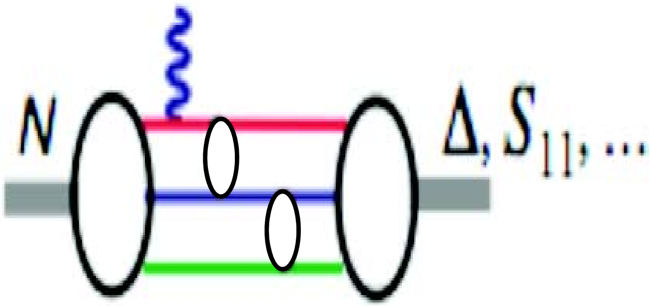
Hadron Structure with Electromagnetic Probes



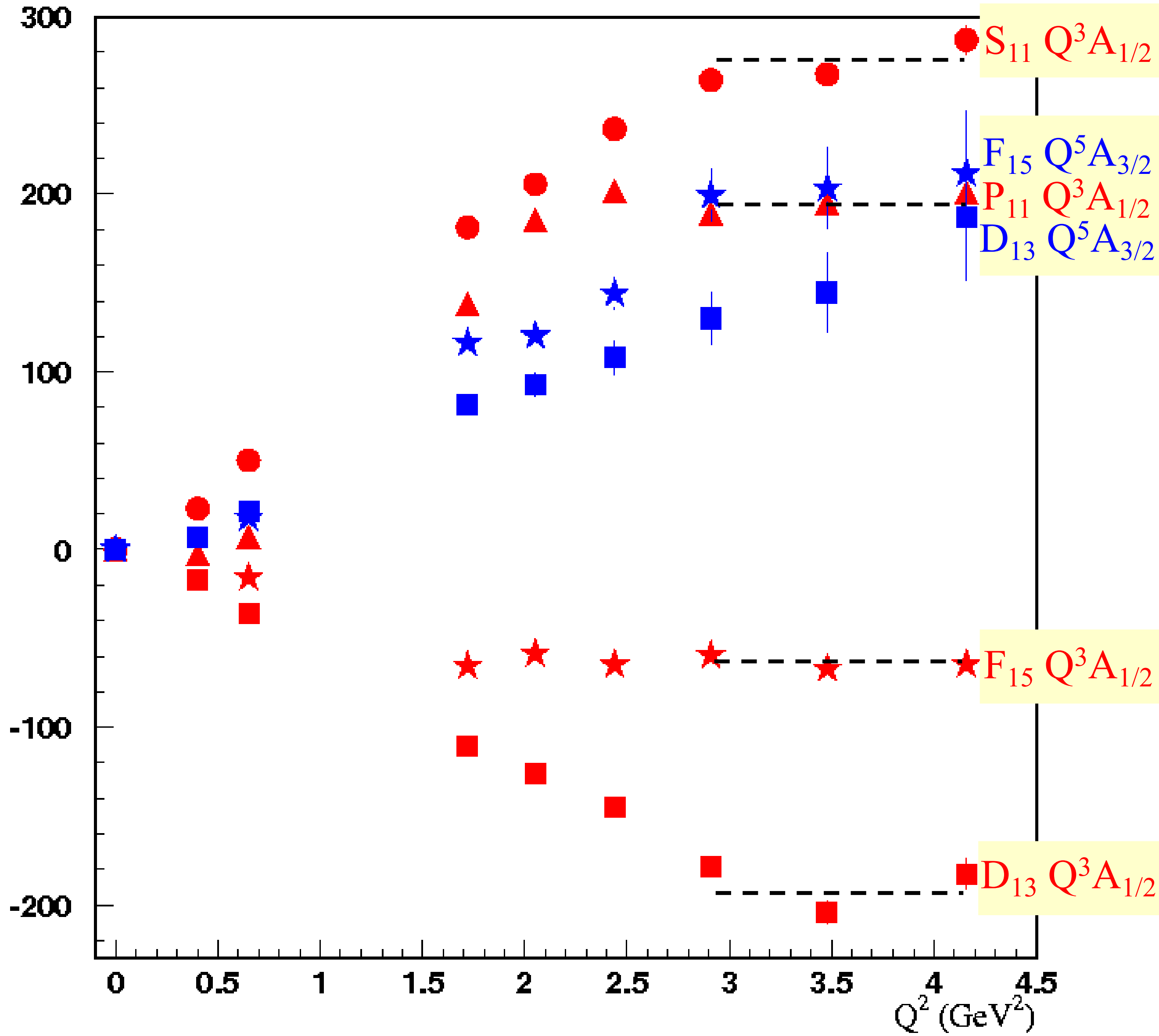
- Study the structure of the nucleon spectrum in the domain where dressed quarks are the major active degree of freedom.
- Explore the formation of excited nucleon states in interactions of dressed quarks and their emergence from QCD.



Evidence for the Onset of Scaling?

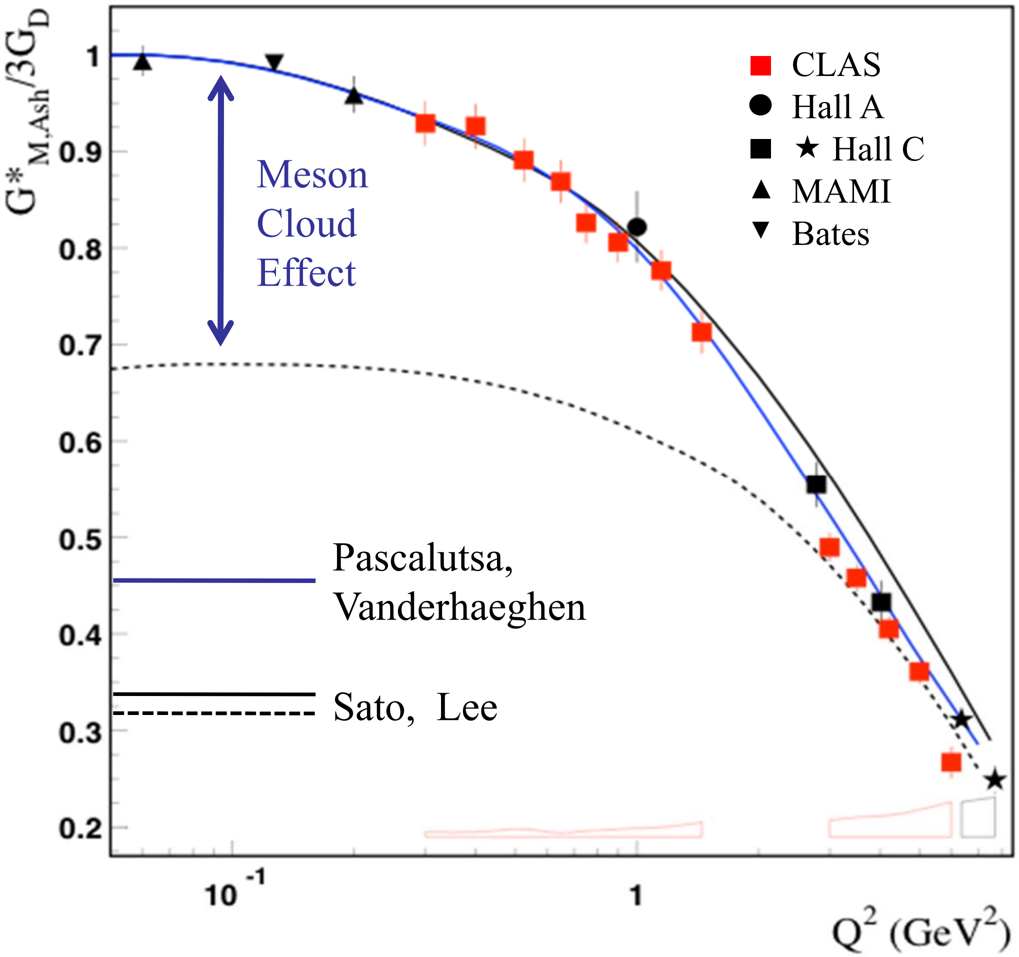


Phys. Rev. C80, 055203 (2009)

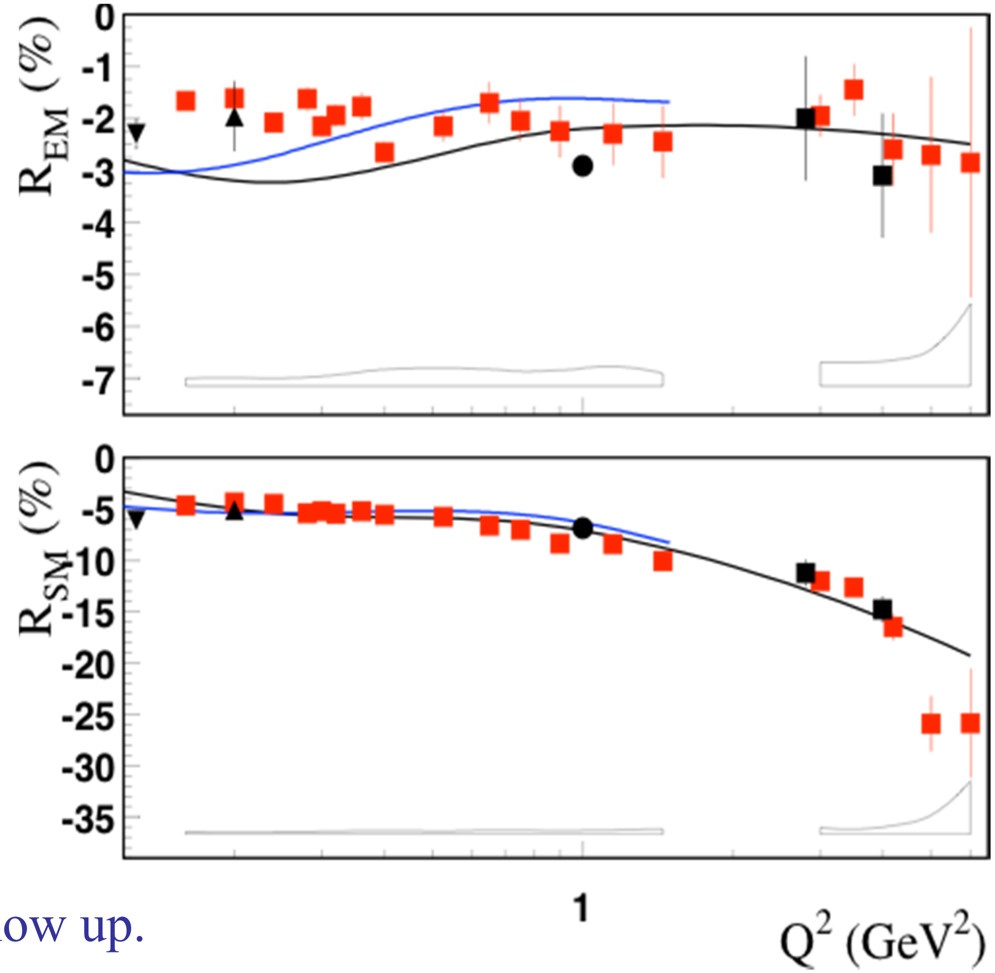


- $A_{1/2}$ α $1/Q^3$
- $A_{3/2}$ α $1/Q^5$
- G^*_M α $1/Q^4$

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

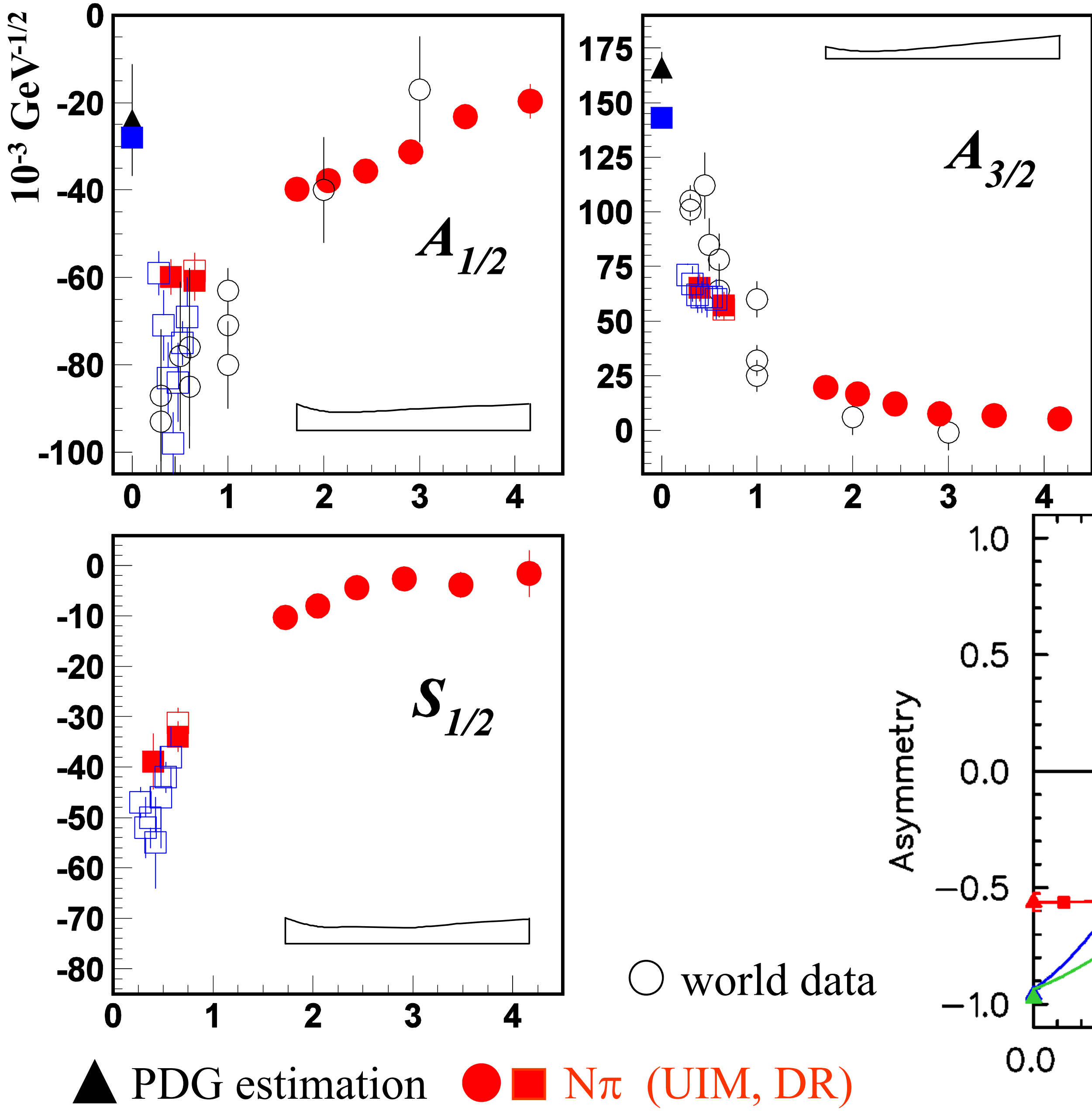


Phys. Rev. Lett. 97, 112003 (2006)



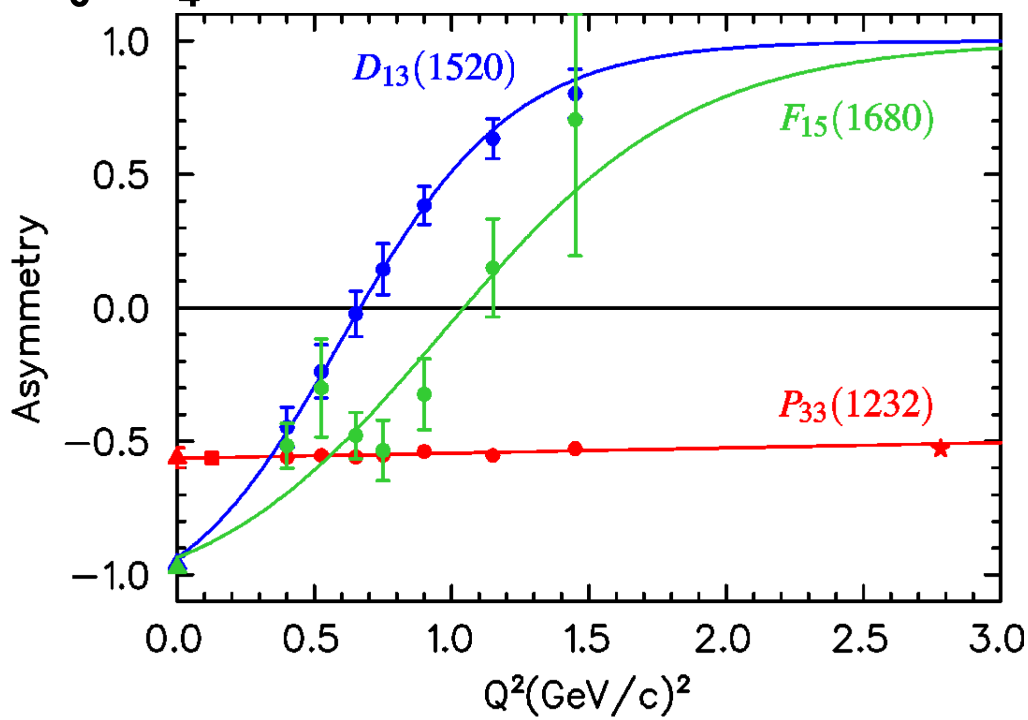
- New trend towards pQCD behavior does not show up.
  - $R_{EM} \rightarrow +1$
  - $G^*_M \rightarrow 1/Q^4$
- CLAS12 can measure G^*_M, R_{EM}, and R_{SM} up to Q^2~12 GeV^2.

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



Phenomenological Analyses

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

see White Paper Sec. VII

- Coupled-Channel Approach (EBAC)

see White Paper Sec. VIII

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)

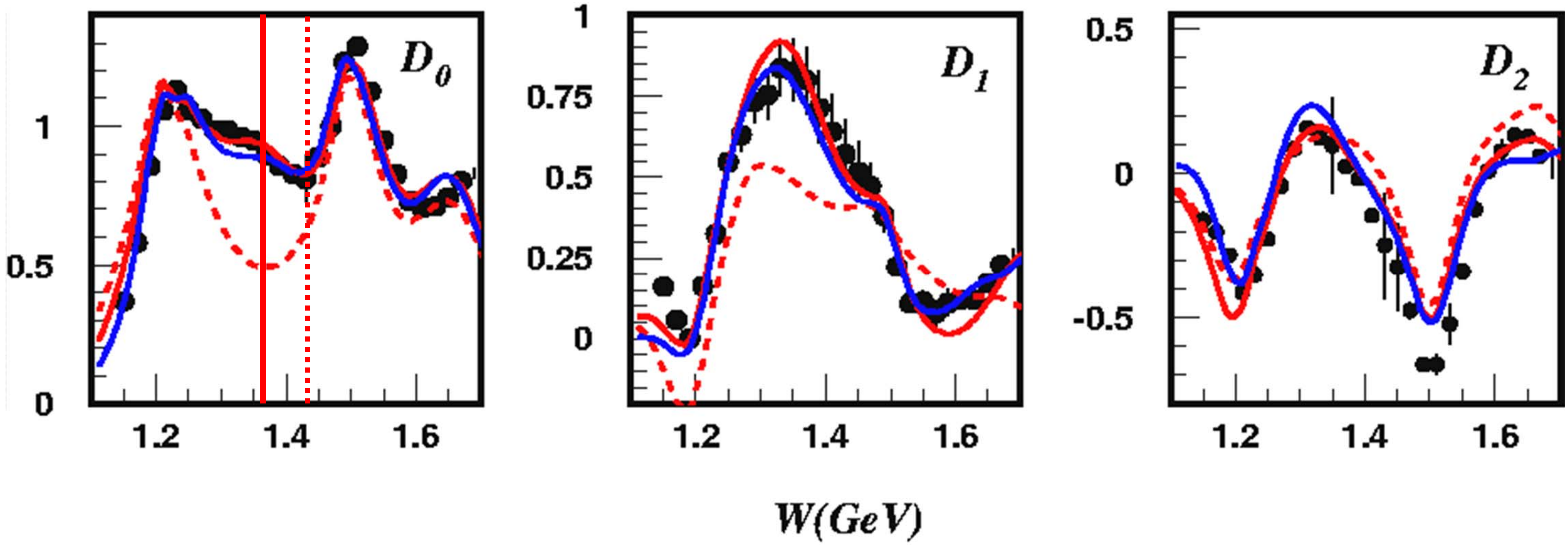
Relates the real and the imaginary parts of the six invariant amplitudes in a model-independent way. The imaginary parts are dominated by resonance contributions.

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

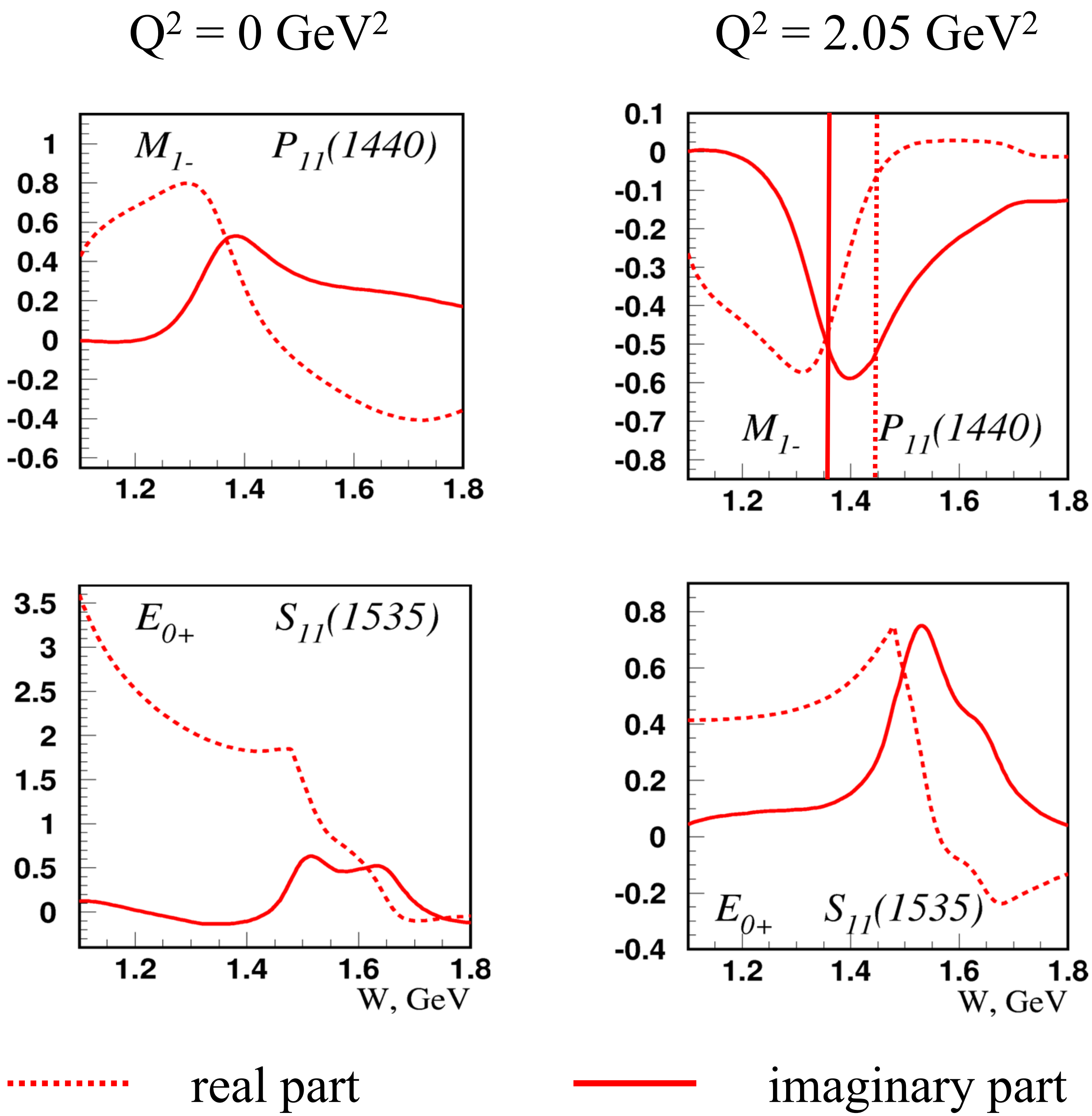
I. Aznauryan - - - DR fit w/o P_{11}

I. Aznauryan —— UIM fit

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

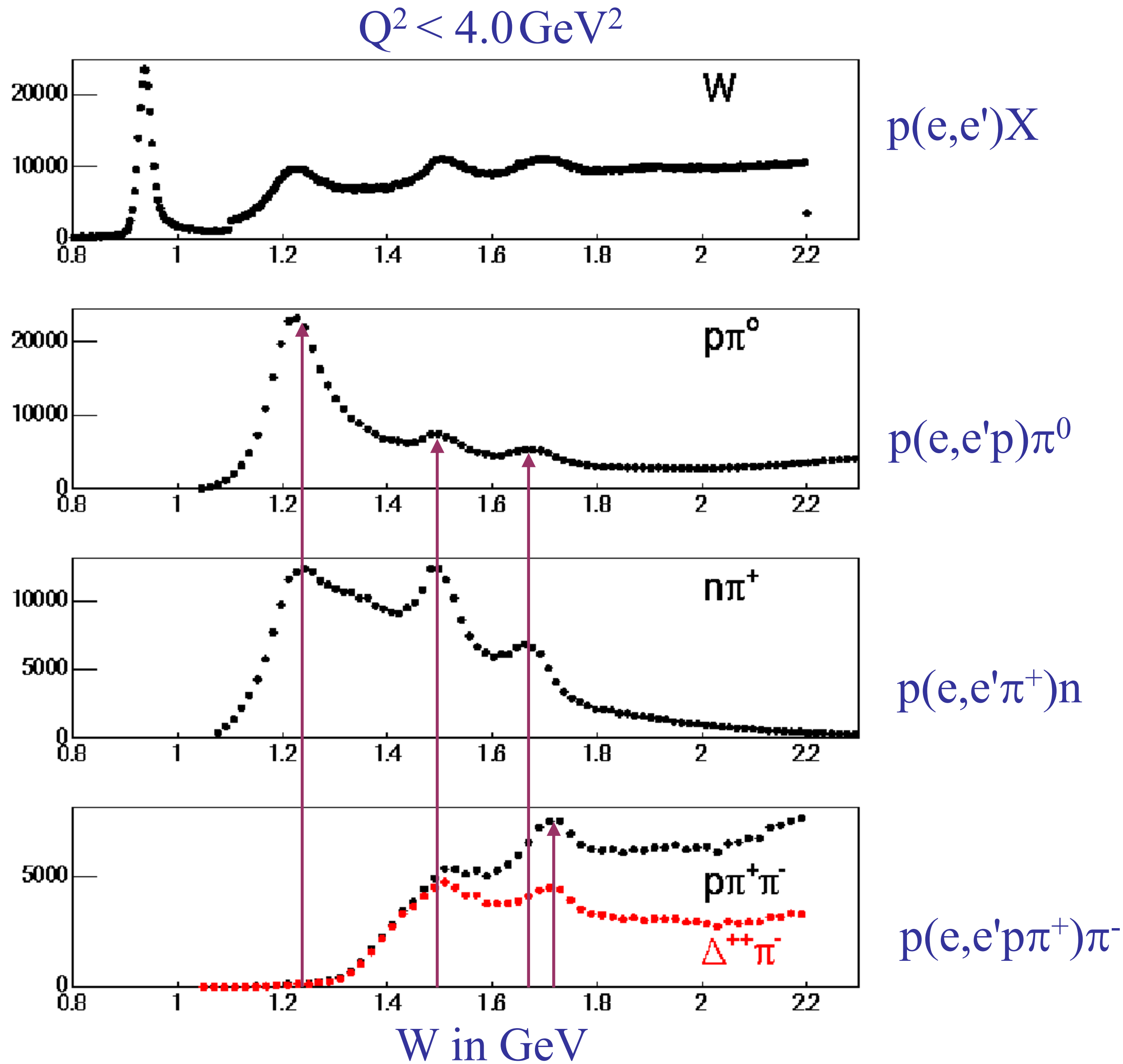
Energy-Dependence of π^+ Multipoles for P_{11}, S_{11}

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

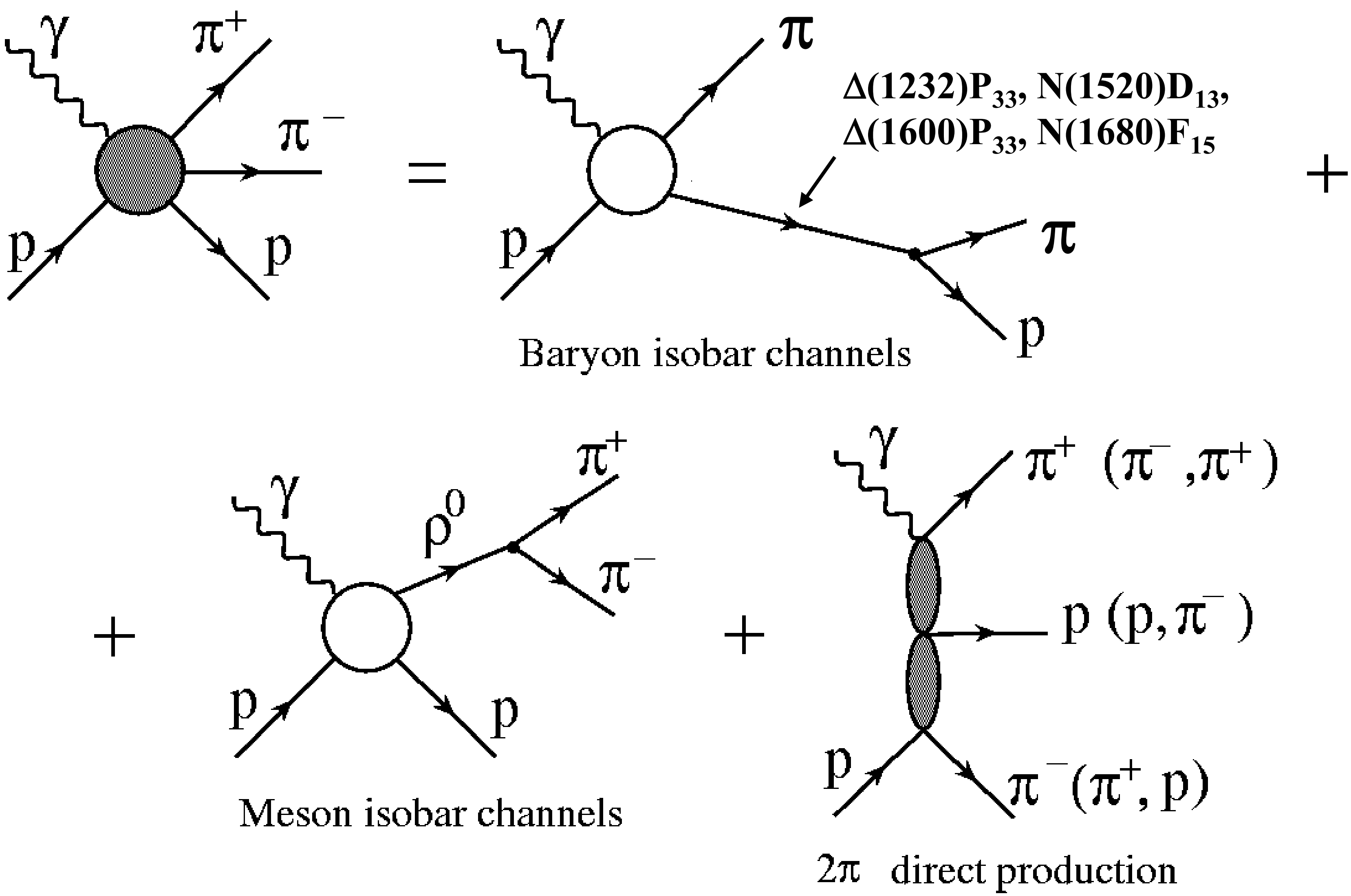


Nucleon Resonances in Nπ and Nππ Electroproduction

- 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

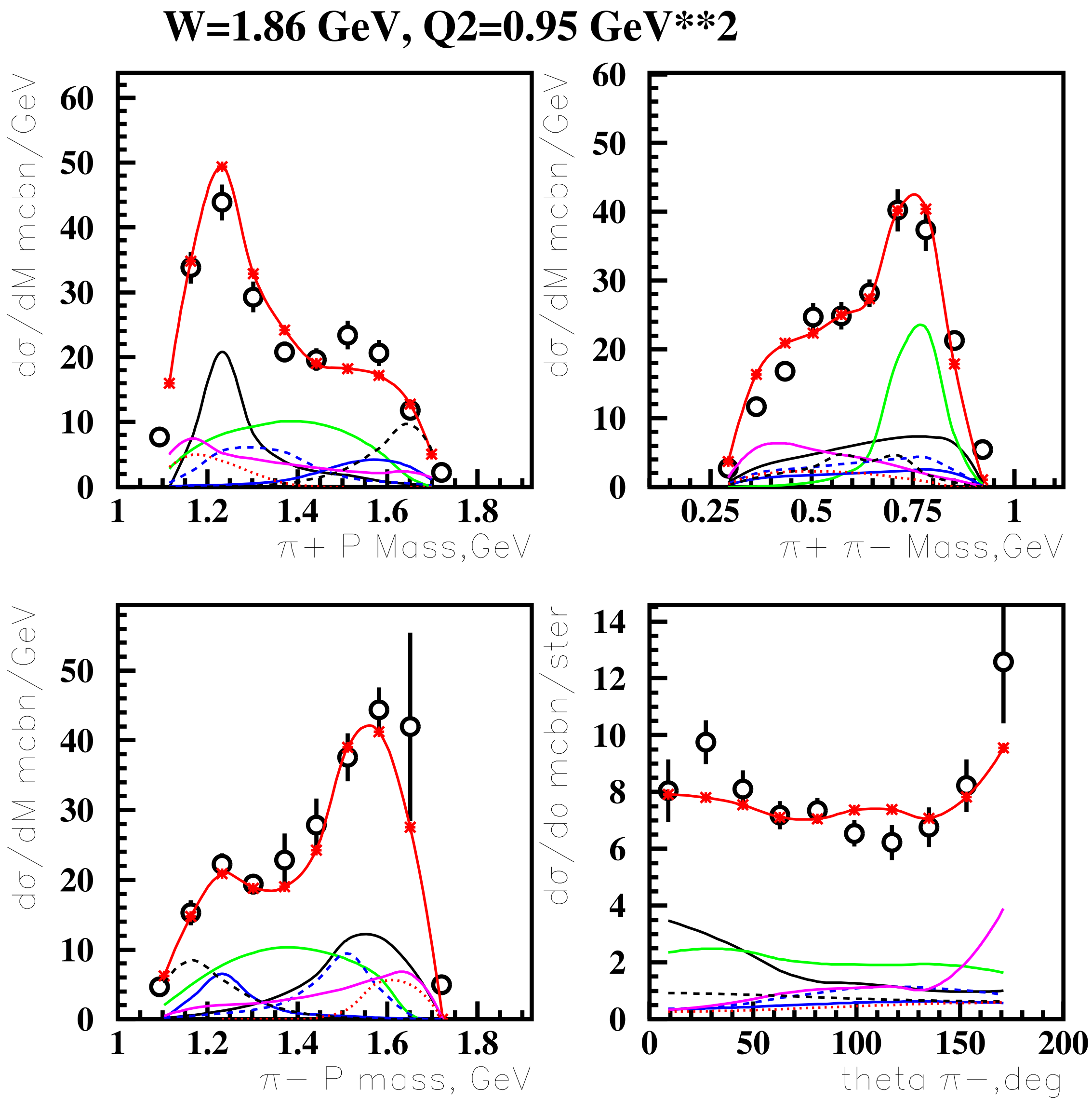


see White Paper Sec. VII

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

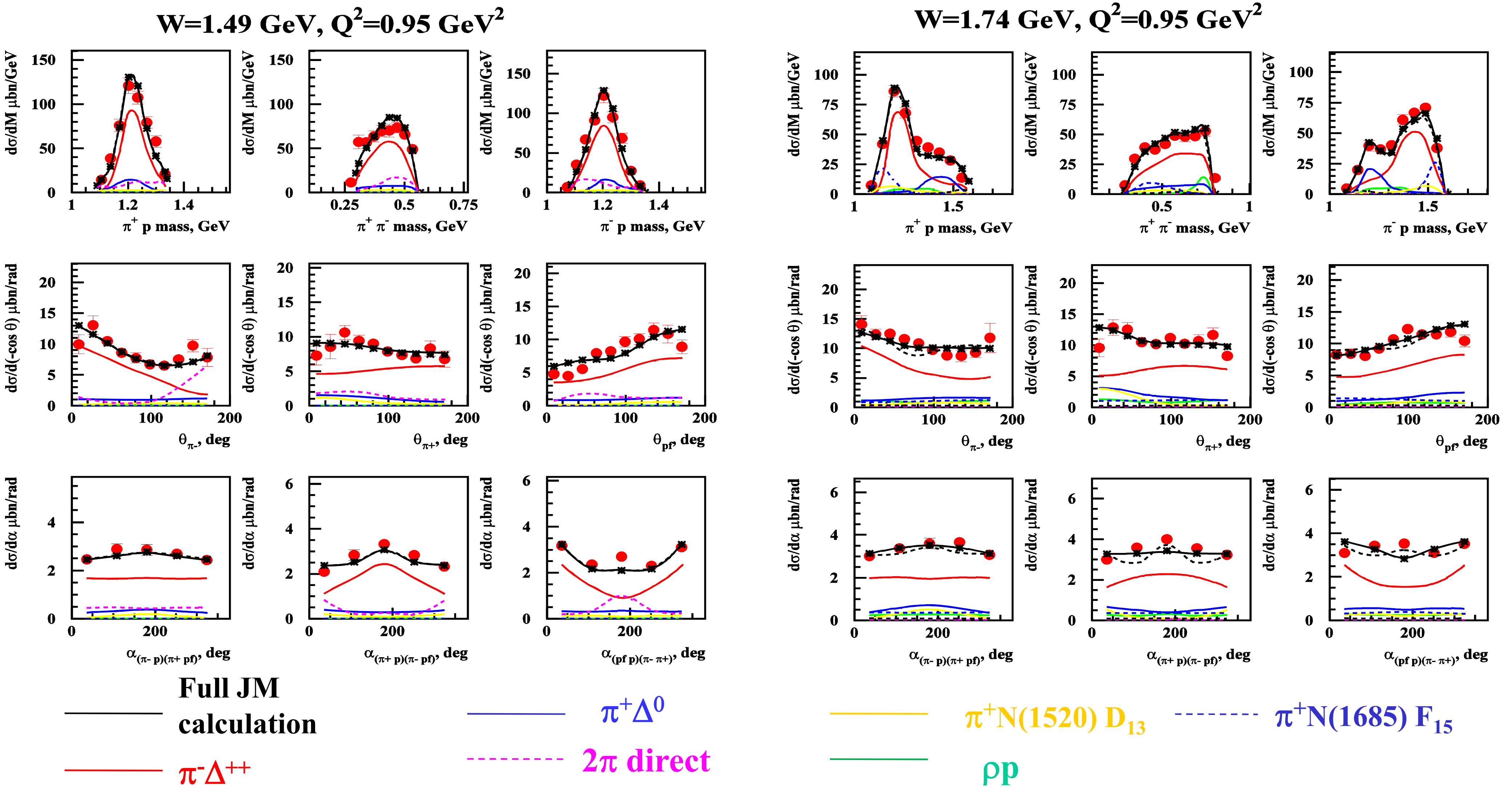
Isobar Model JM05

- 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



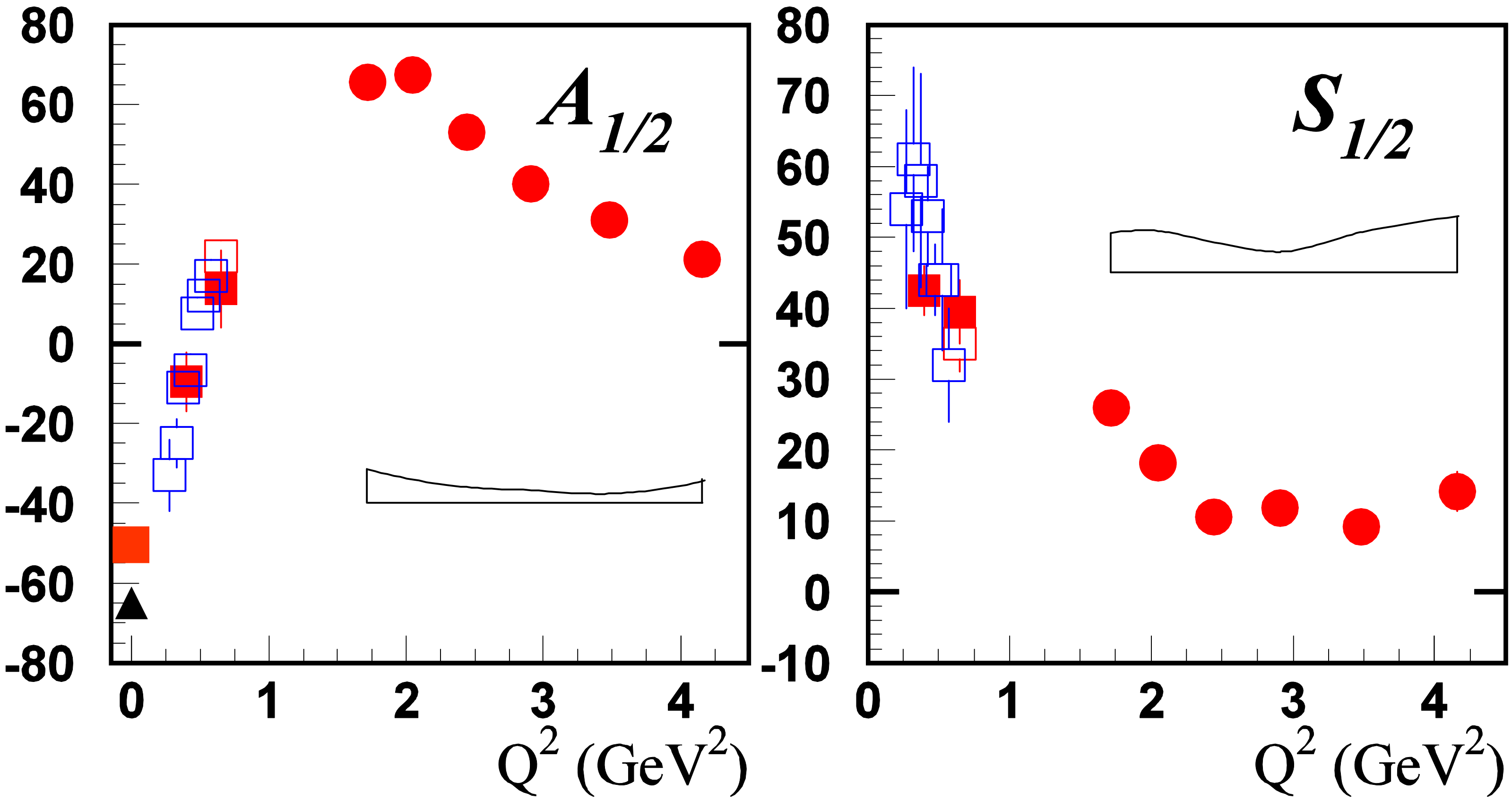
➢ The combined fit of nine single differential cross sections allowed to establish all significant mechanisms.

JM 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



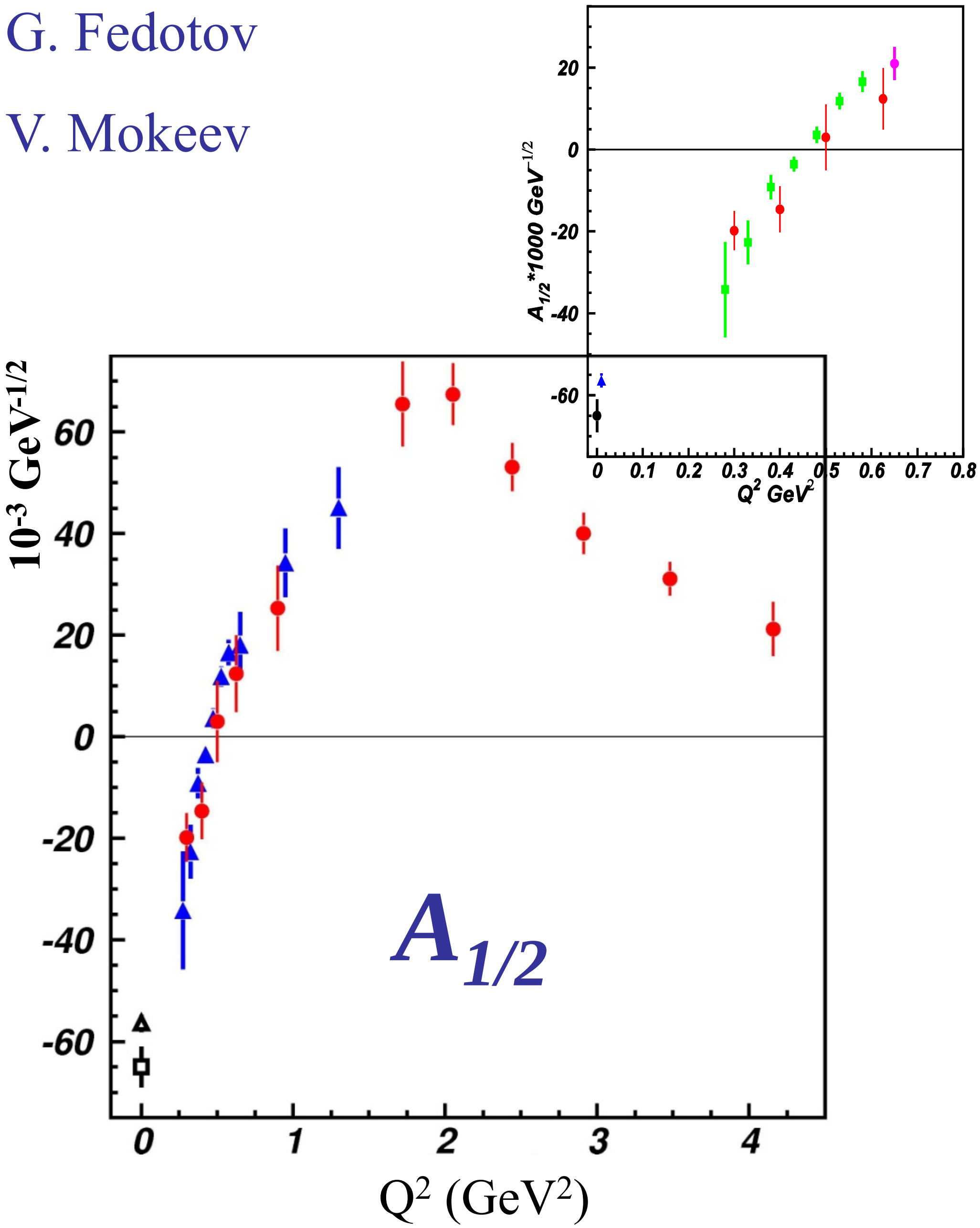
▲ PDG estimation ● ■ Nπ (UIM, DR) □ Nπ, Nππ combined analysis □ Nππ (JM)

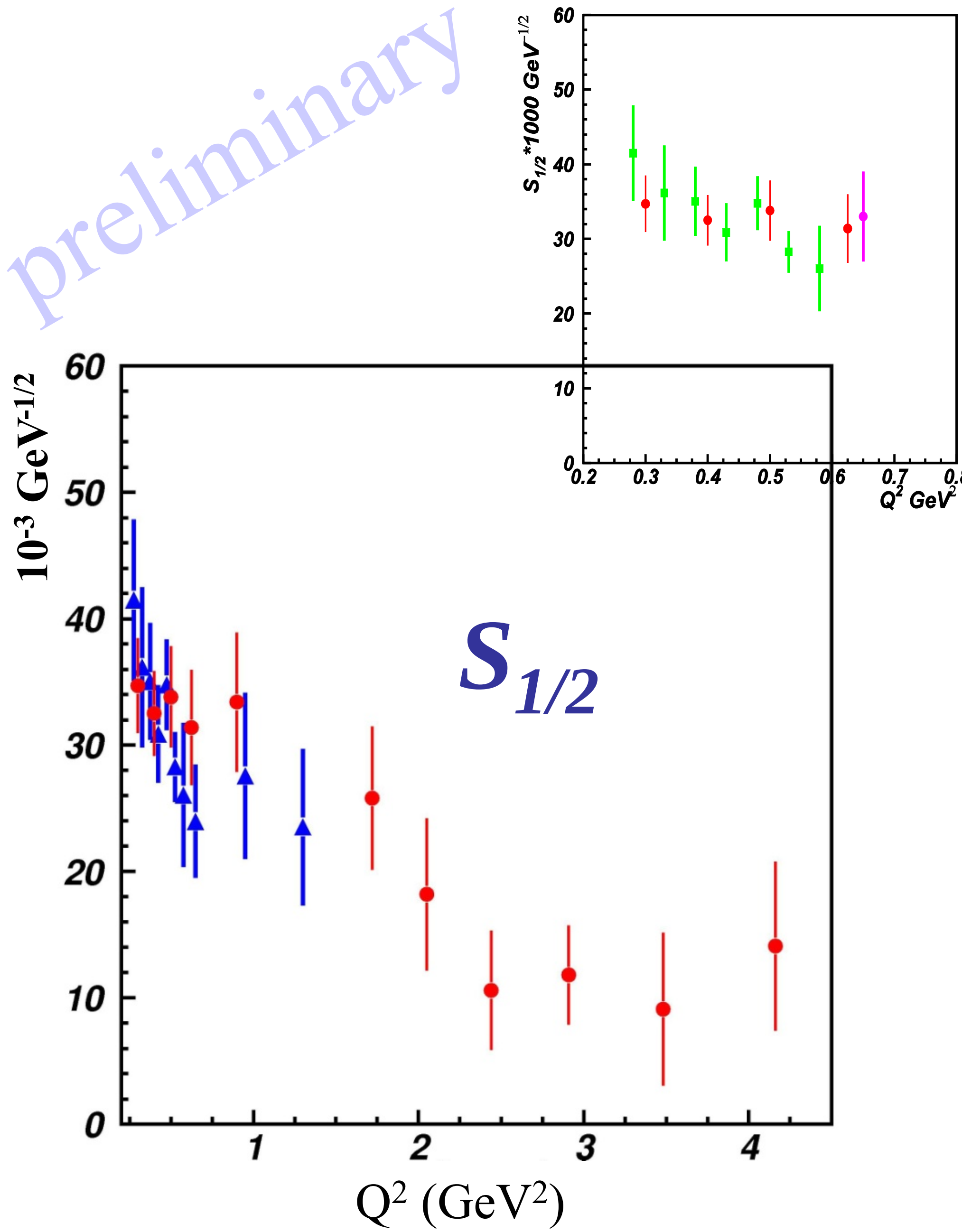
The good agreement on extracting the N* electrocouplings between the two exclusive channels (1π/2π) – having fundamentally different mechanisms for the nonresonant background – provides evidence for the reliable extraction of N* electrocouplings.

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

G. Fedotov

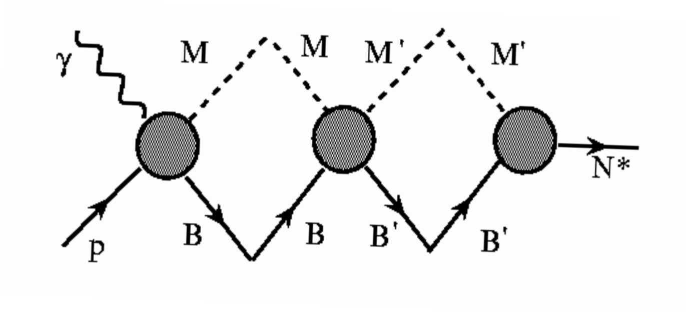
V. Mokeev





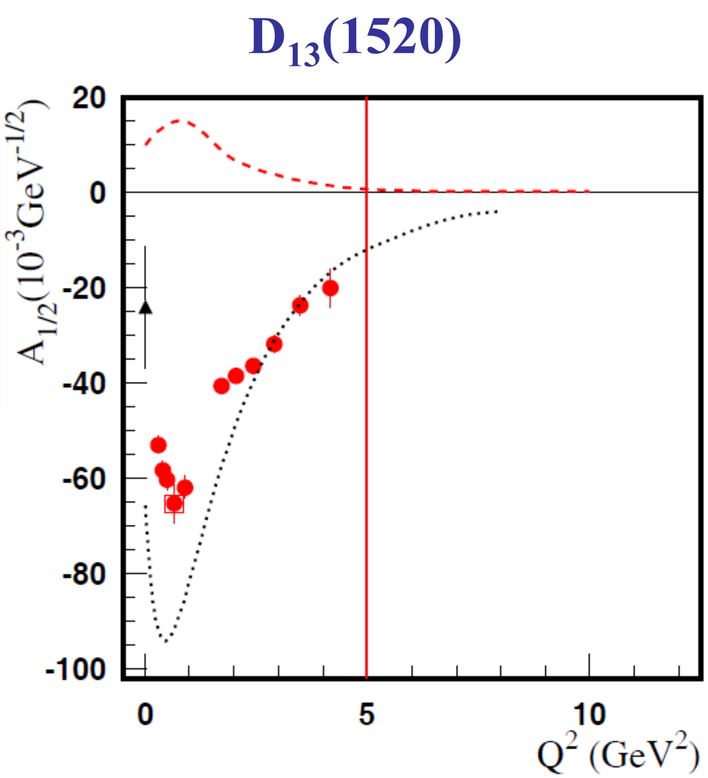
Progress in Experiment and Phenomenology

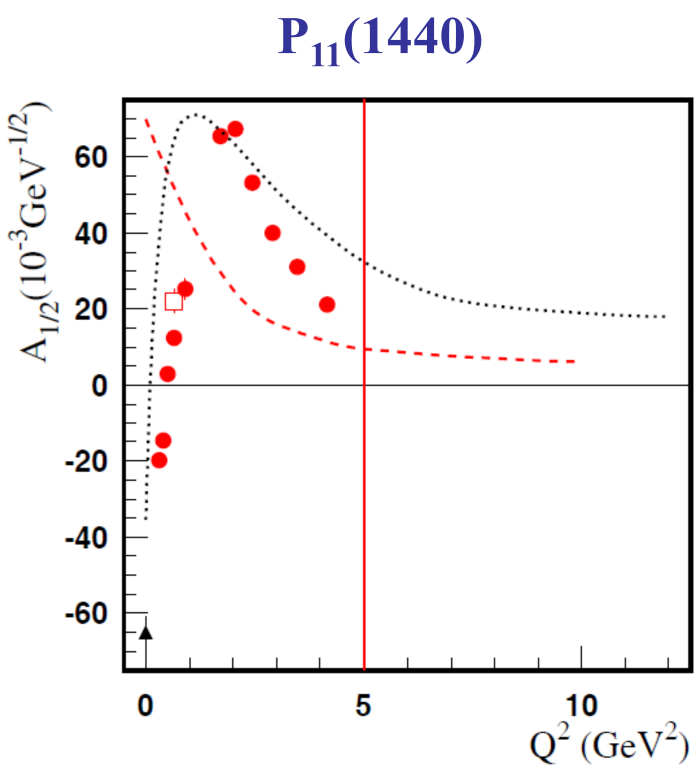
Meson-Baryon Dressing



absolute meson-baryon cloud amplitudes (EBAC)

quark core contributions (constituent quark models)

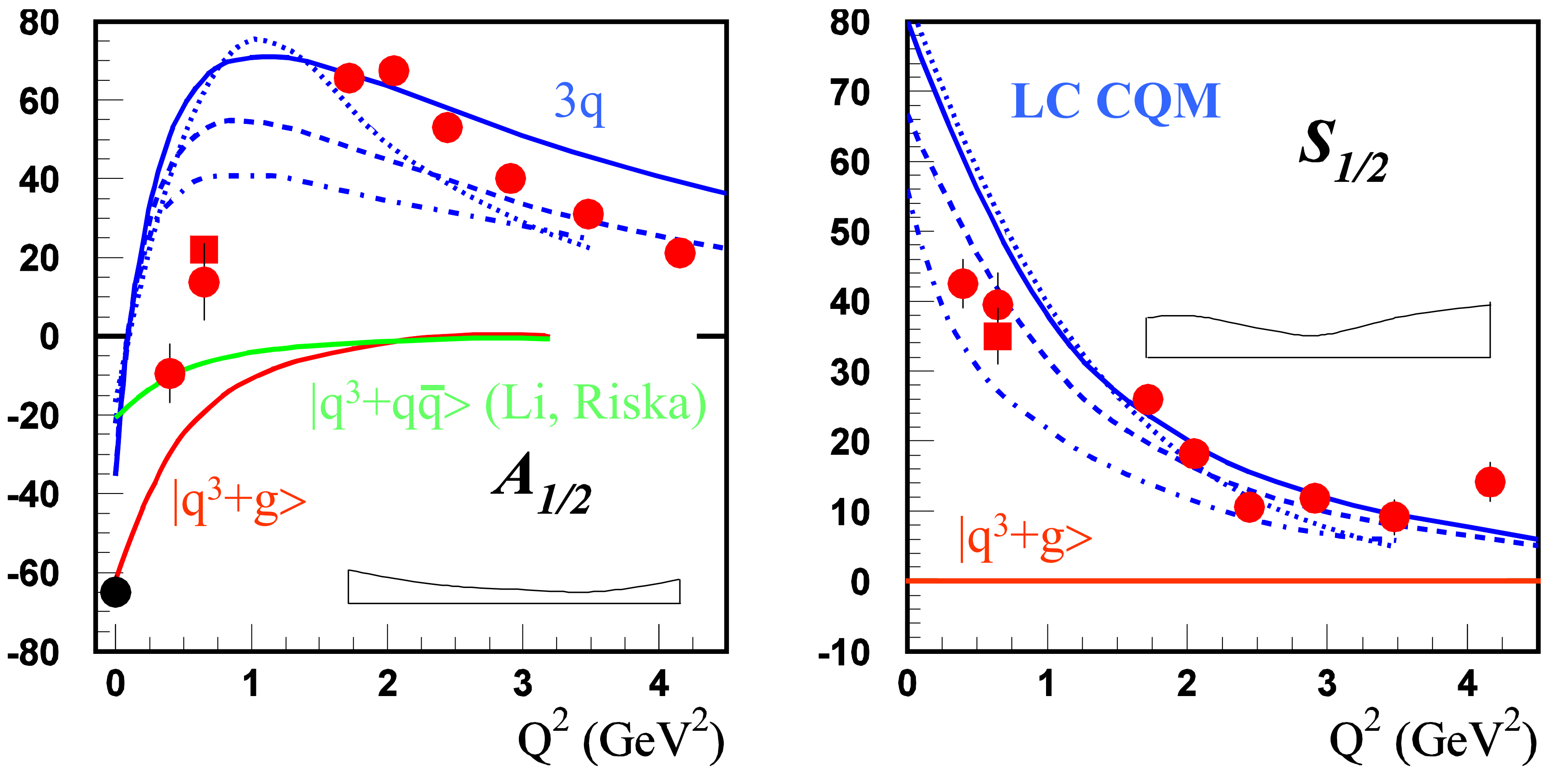




CLAS: Nπ and Nπ/Nππ combined (Phys. Rev. C80, 055203, 2009)

- 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.

Constituent Quark Models (CQM)



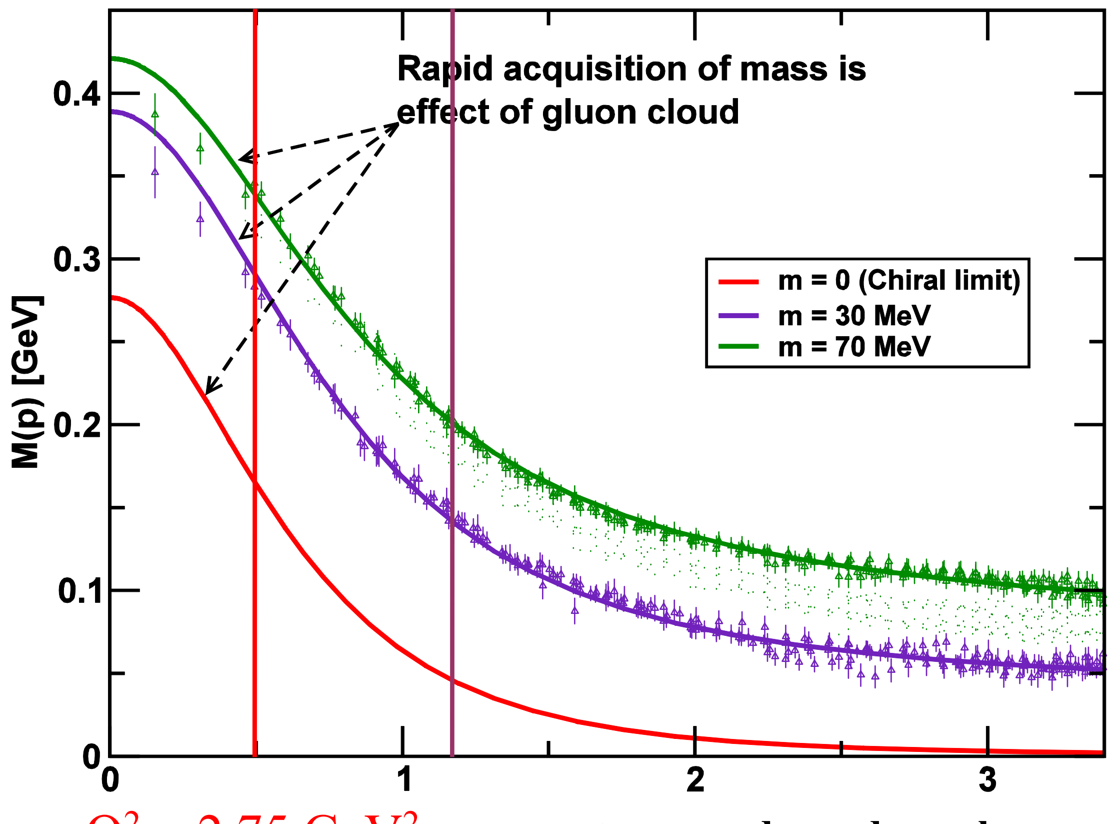
N(1440)P_{11}: ● PDG value ● Nπ ■ Nπ, Nππ combined analysis

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

Dynamical Mass of Light Dressed Quarks



$Q^2 = 2.75\ GeV^2$

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.

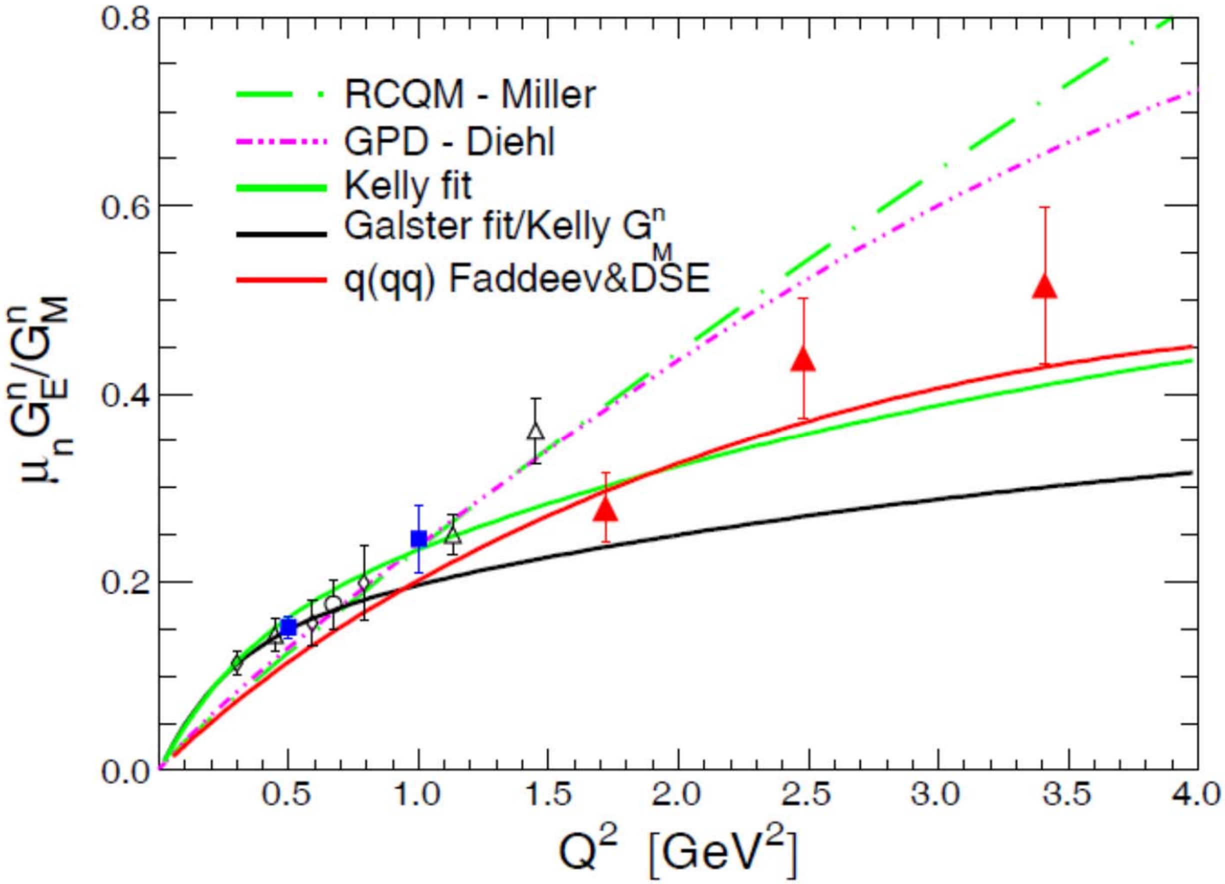
DSE: lines and LQCD: triangles

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

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.

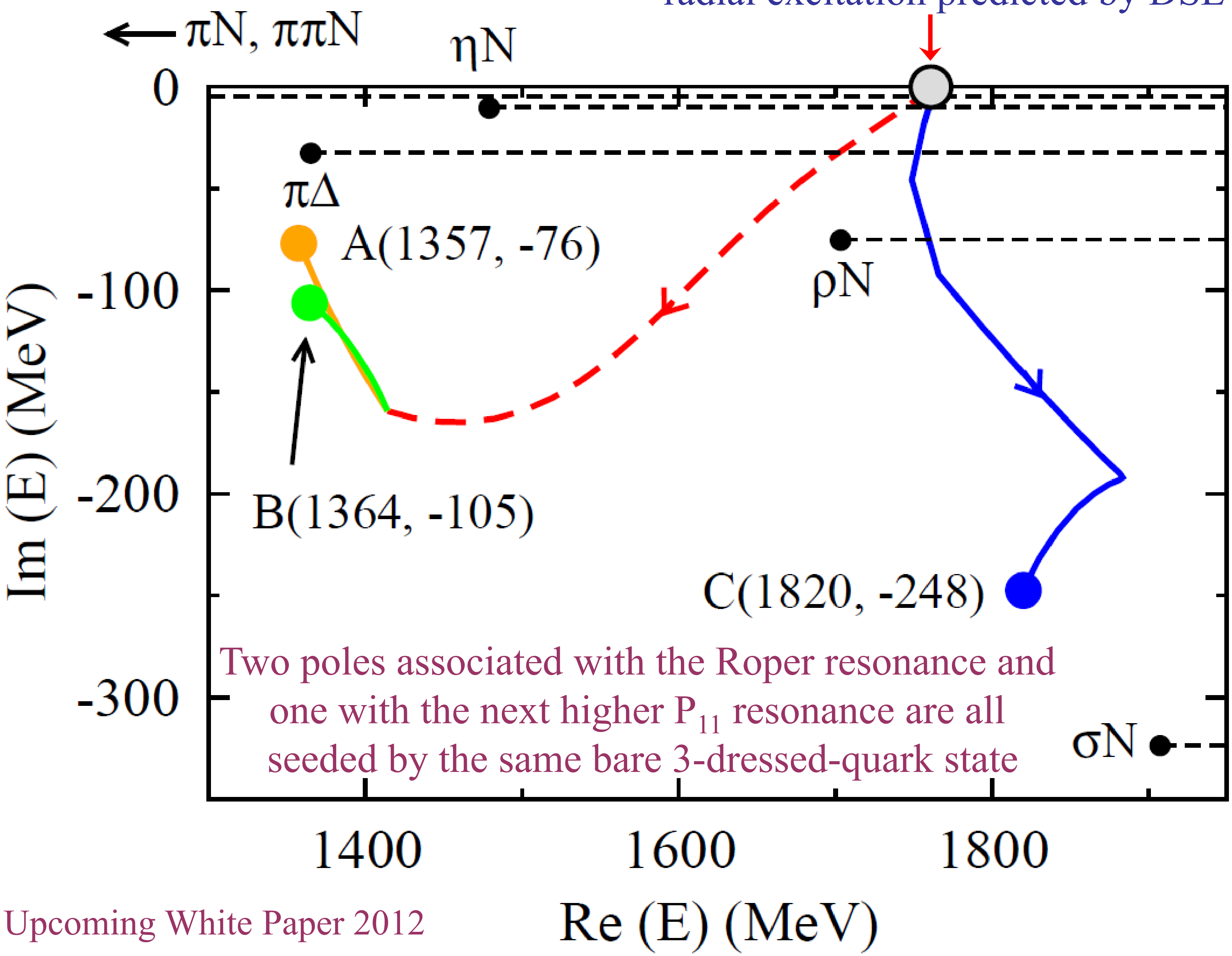
The Faddeev-DSE calculation is very sensitive to the momentum dependence of the dressed-quark propagator.

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 Washington.

see White Paper Sec. III

DSE and EBAC Approaches

Location of the first 3-dressed-quark core radial excitation predicted by DSE



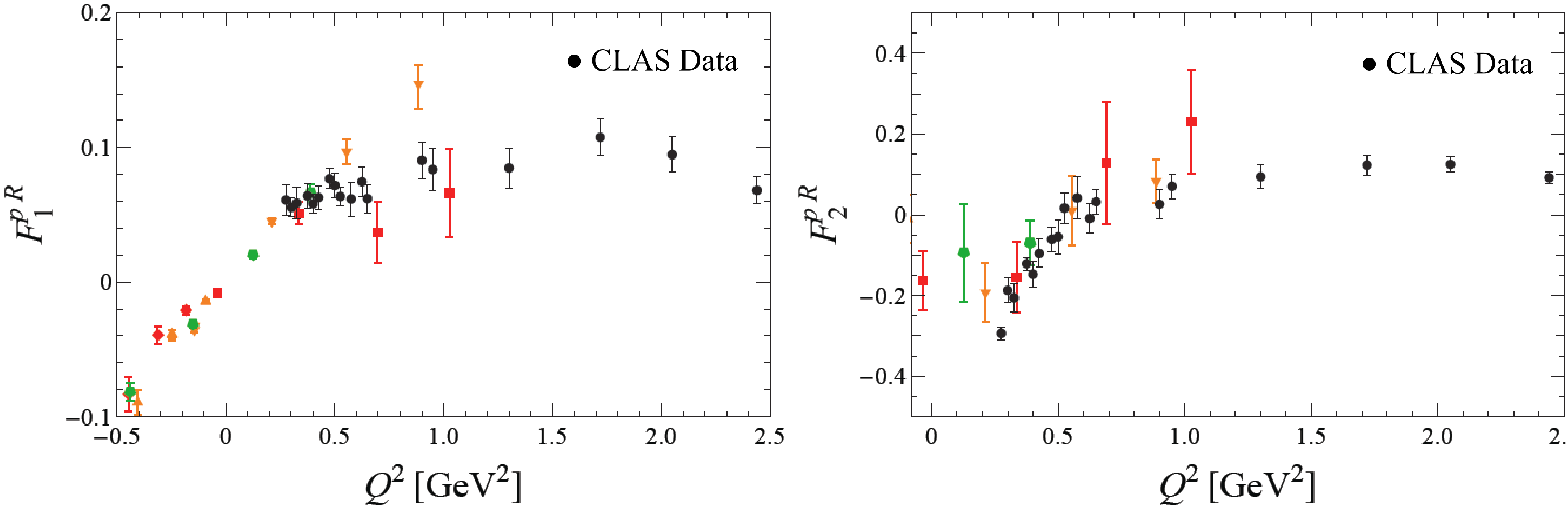
Two poles associated with the Roper resonance and one with the next higher P_{11} resonance are all seeded by the same bare 3-dressed-quark state

Upcoming White Paper 2012

Roper Transition Form Factors in LQCD

$p(1440)P_{11}$

Huey-Wen Lin and S.D Cohen



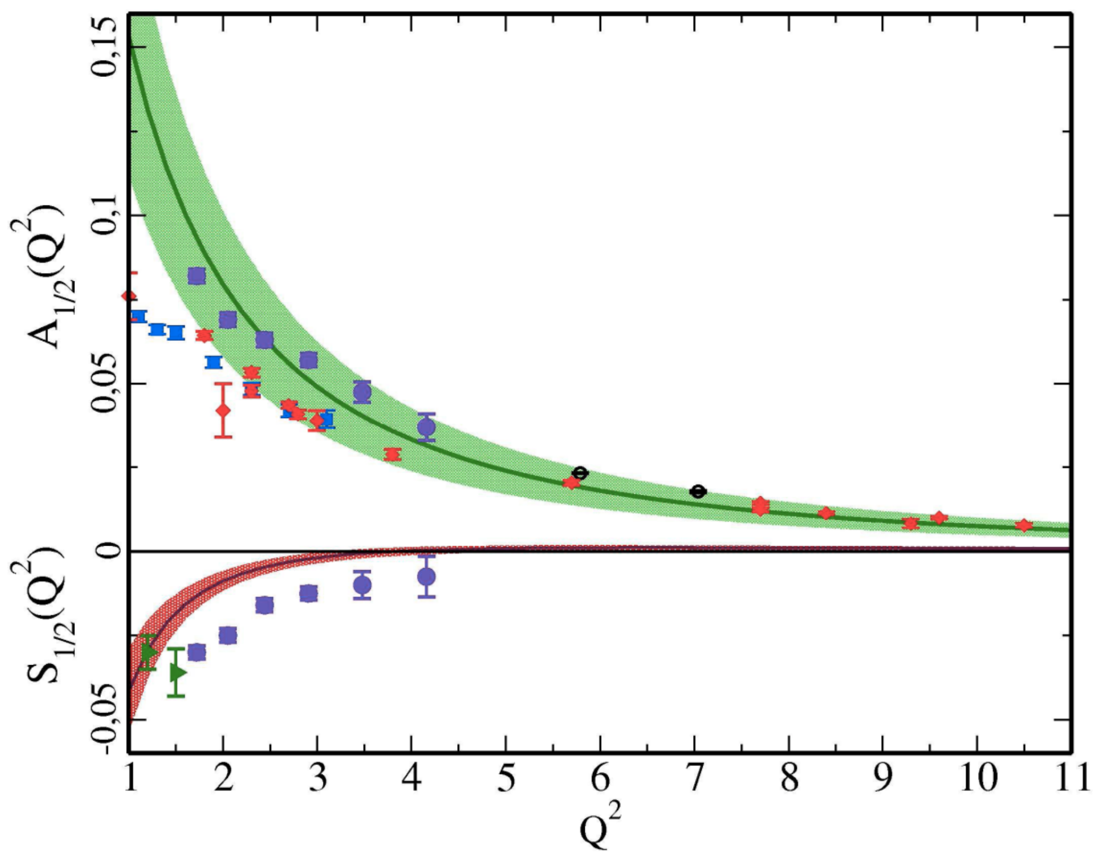
Latice QCD calculations of the $p(1440)P_{11}$ transition form factors have been carried out with various pion masses, m_π= 390, 450, and 875 MeV. Particularly remarkable is the zero crossing in F_2 that appears at the current statistics in the unquenched but not in the quenched calculations. This suggests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

Upcoming White Paper 2012

LQCD & Light Cone Sum Rule (LCSR) Approach

N(1535)S_{11}



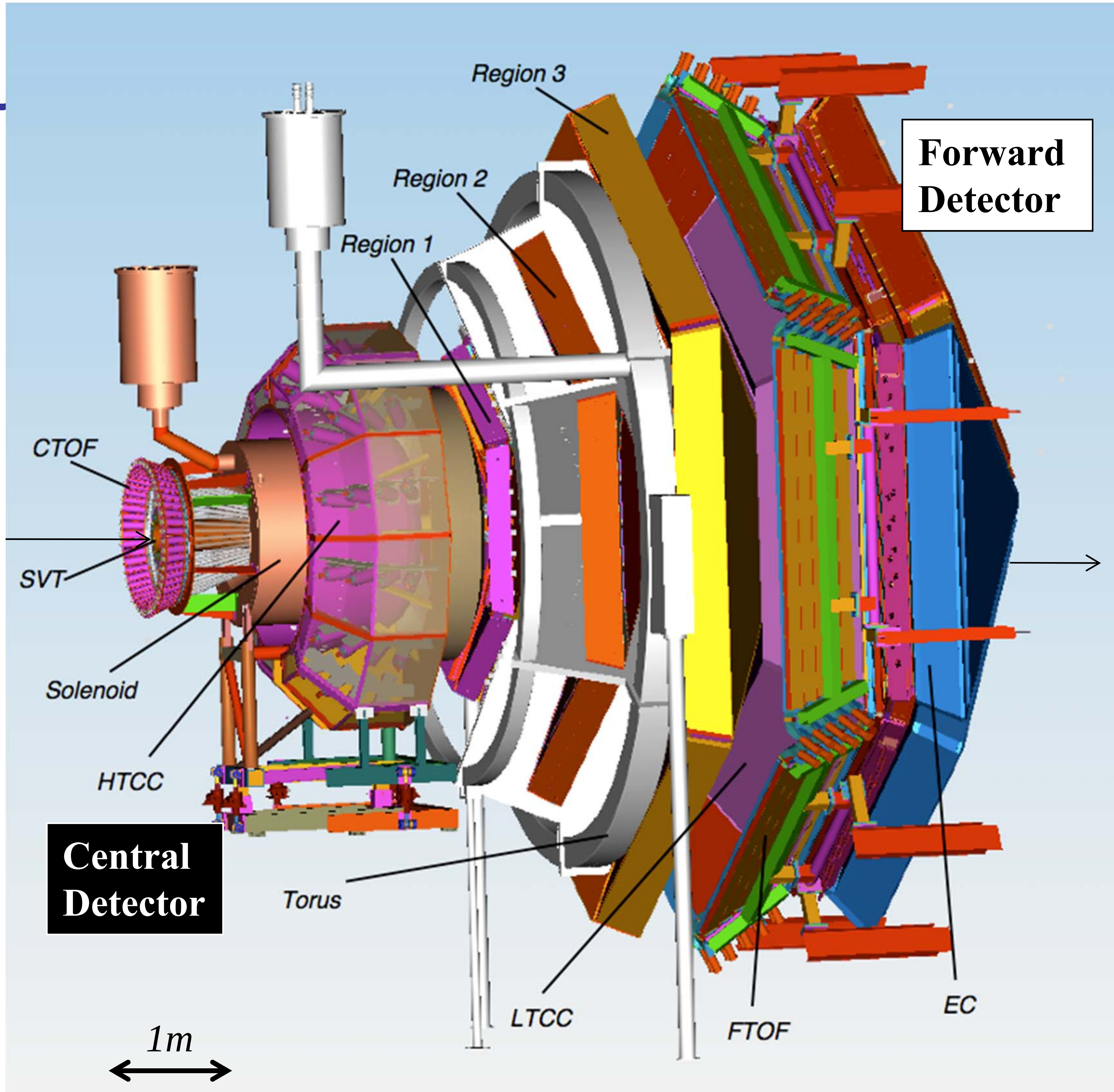
LQCD is used to determine the moments of N* distribution amplitudes (DA) and the N* electrocouplings are determined from the respective DAs within the LCSR framework.

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.

Upcoming White Paper 2012

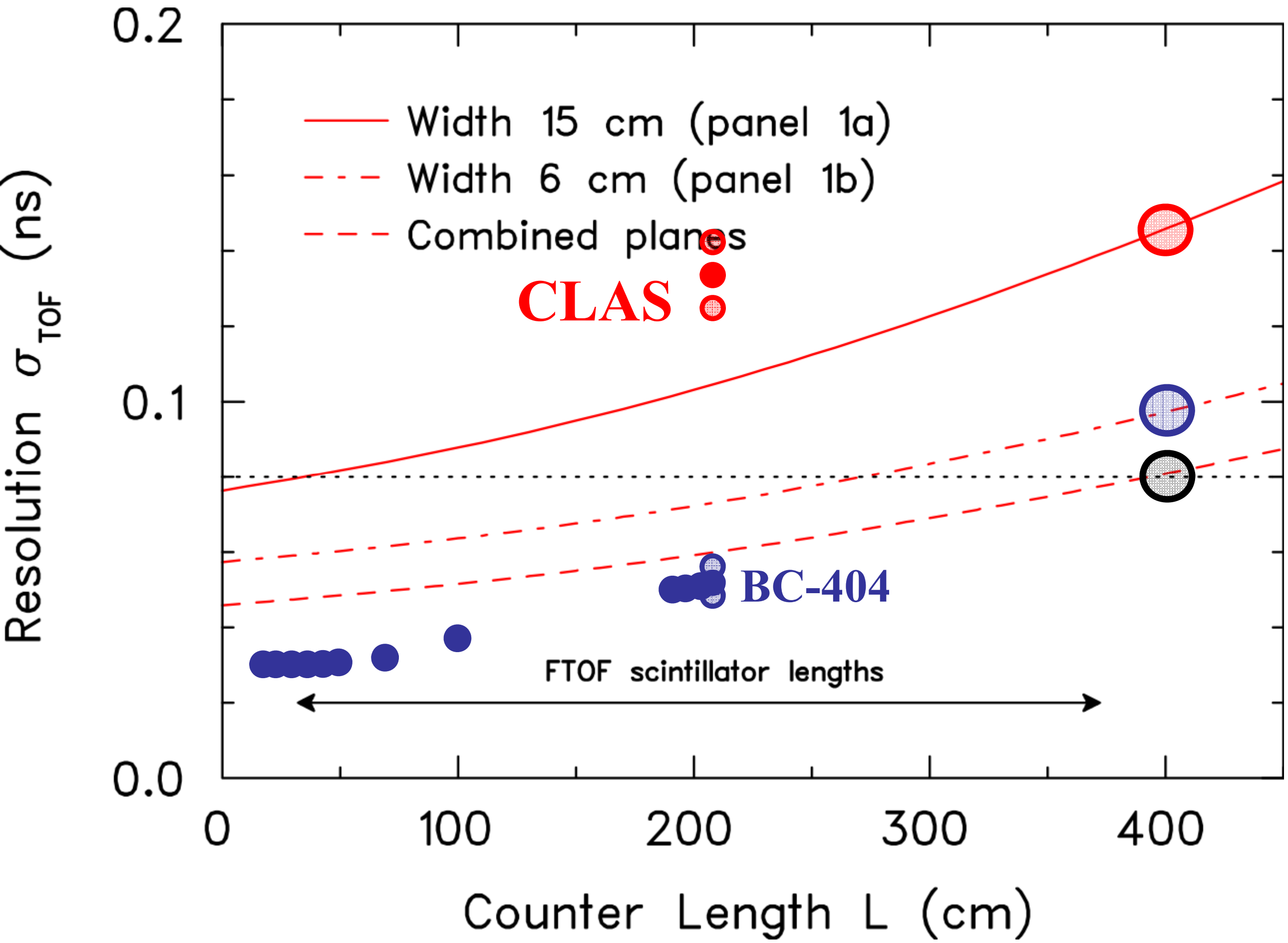
CLAS12

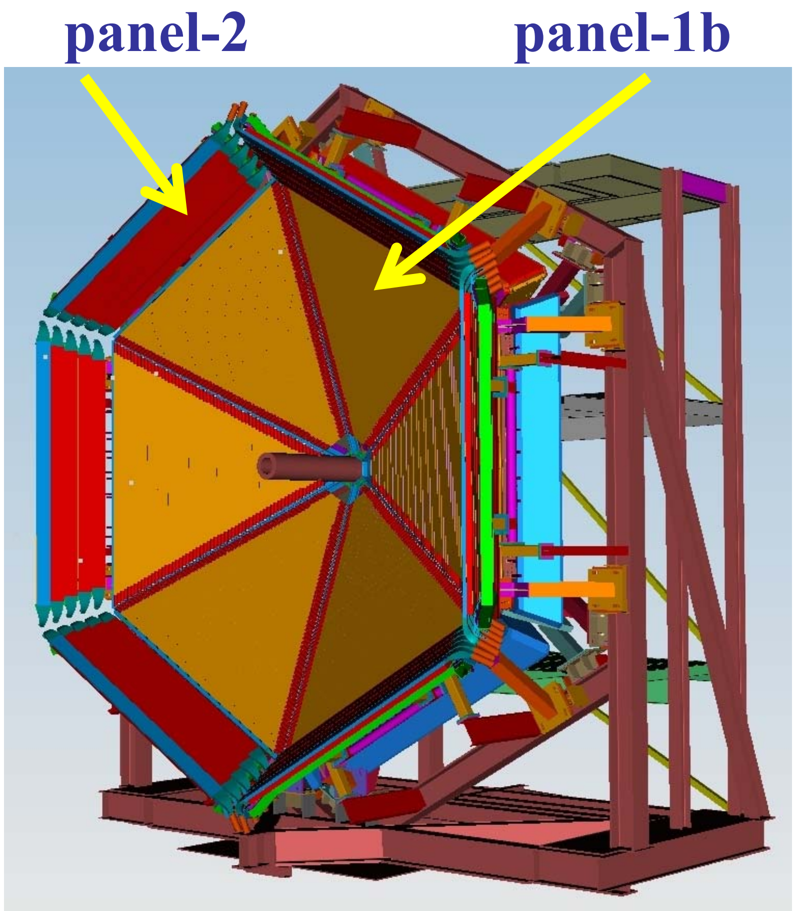


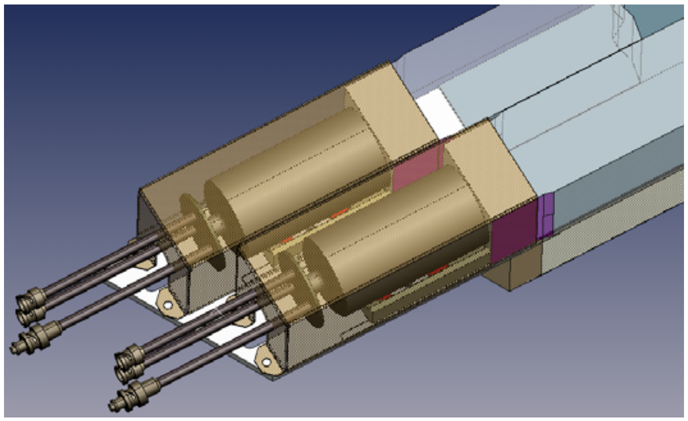
- Luminosity > 10^{35} $cm^{-2}s^{-1}$
- Hermeticity
- Polarization

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

New Forward Time of Flight Detector for CLAS12

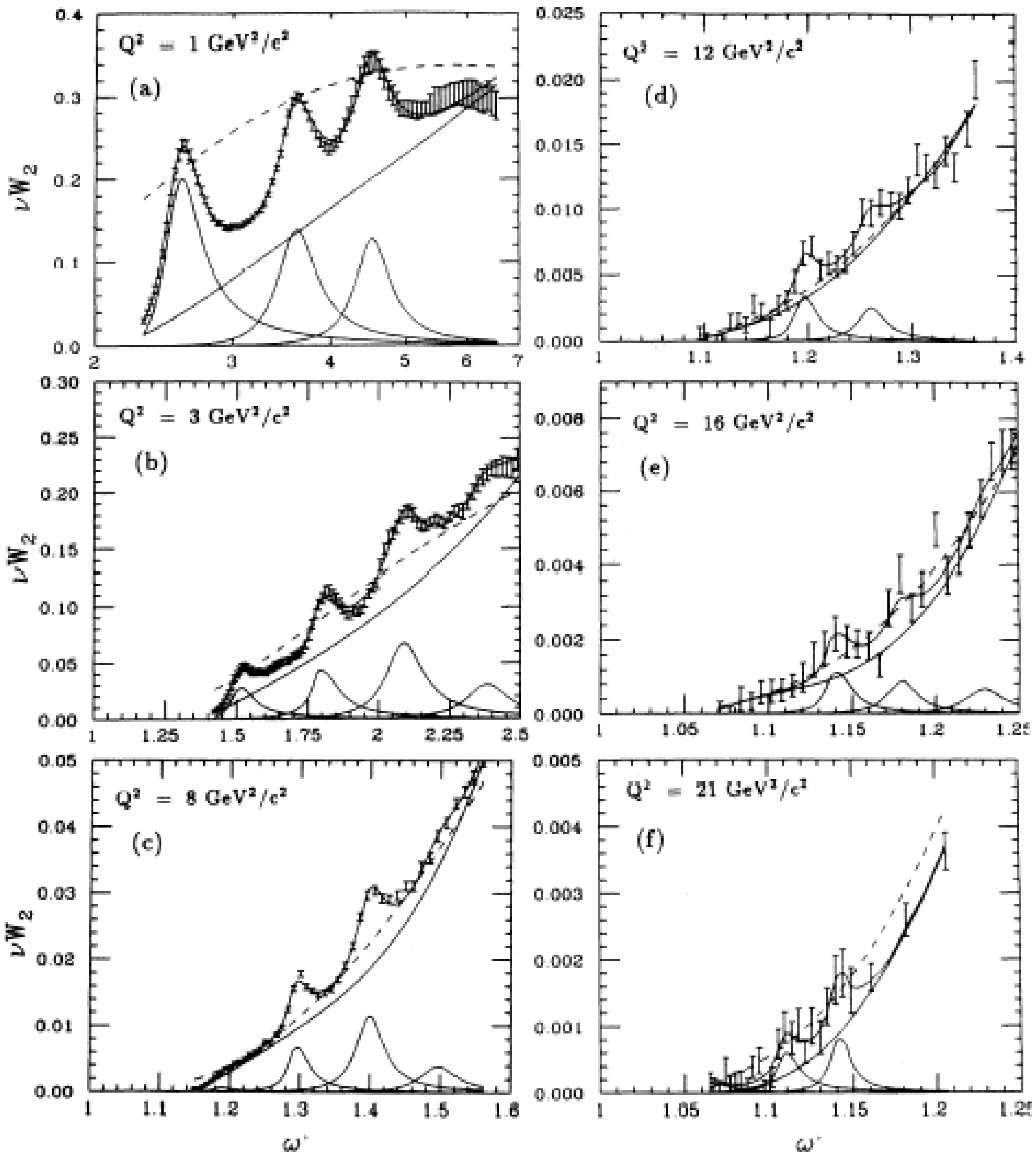


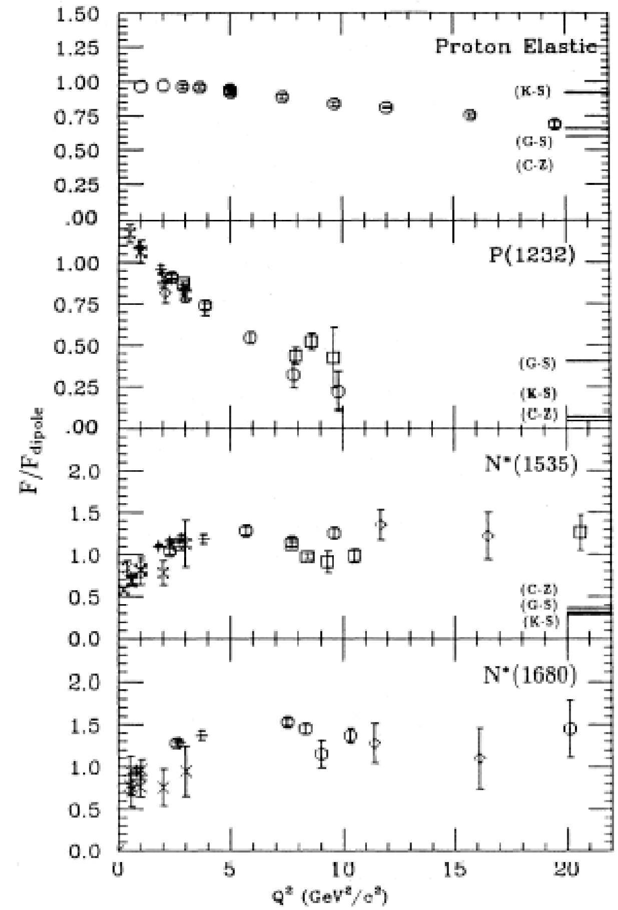




World-record time resolution of 44 ns averaged over the full length of 210 cm

Inclusive Structure Function in the Resonance Region

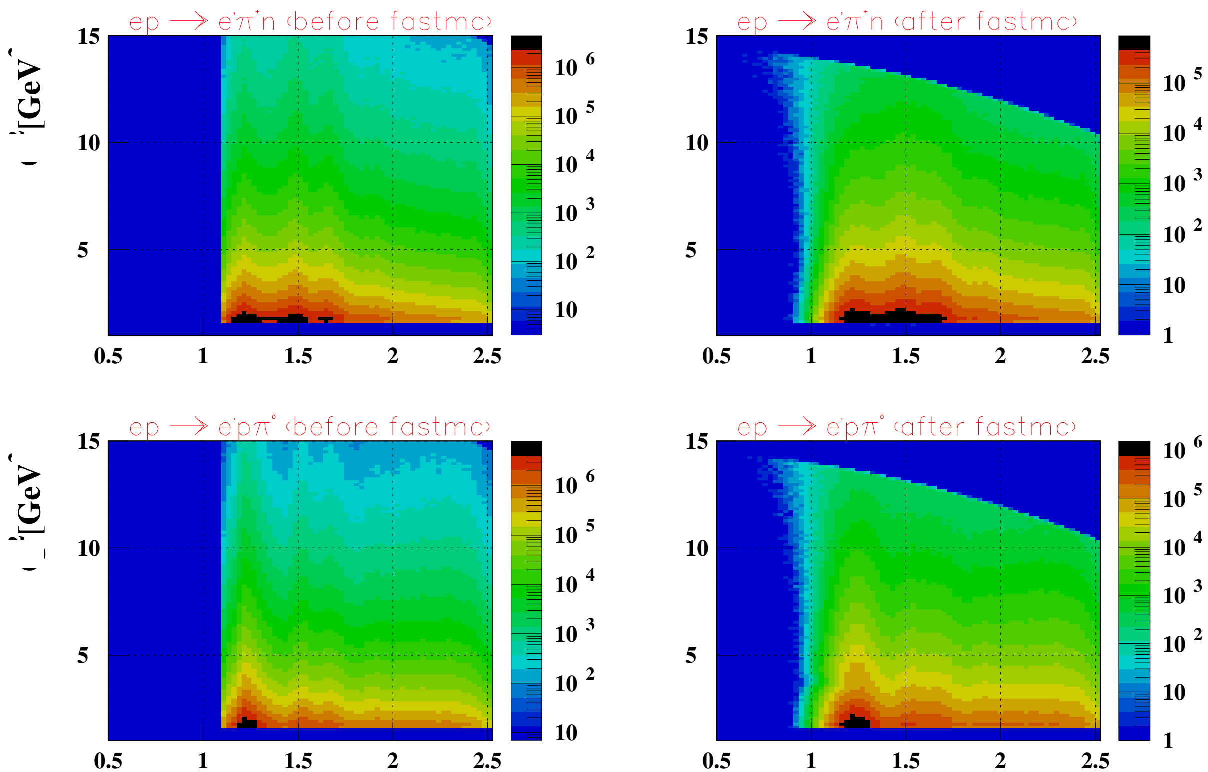




P. Stoler, PRPLCM 226, 3 (1993) 103-171

CLAS 12 Kinematic Coverage and Counting Rates

Genova-EG



(e',π^+) detected

Genova-EG

(e',p) detected

(E,Q²)	(5.75 GeV, 3 GeV²)	(11 GeV, 3 GeV²)	(11 GeV, 12 GeV²)
$N^{n\pi+}$	$1.41*10^5$	$6.26*10^6$	$5.18*10^4$
$N^{p\pi 0}$	-	$4.65*10^5$	$1.45*10^4$
$N^{p\eta}$	-	$1.72*10^4$	$1.77*10^4$

L=10^{35} cm^{-2} sec^{-1}, W=1535 GeV, ΔW= 0.100 GeV, ΔQ^2 = 0.5 GeV^2

40 days

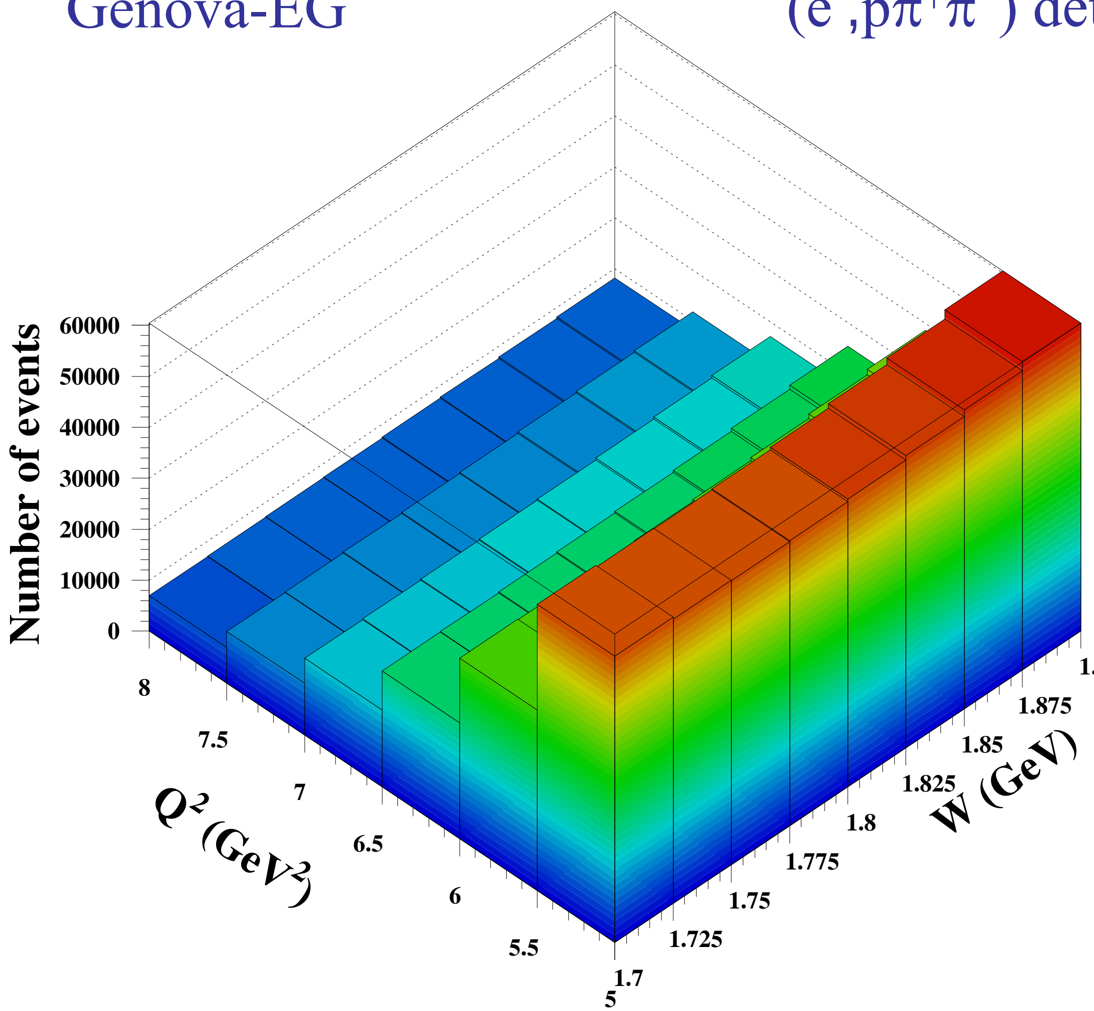
PAC35

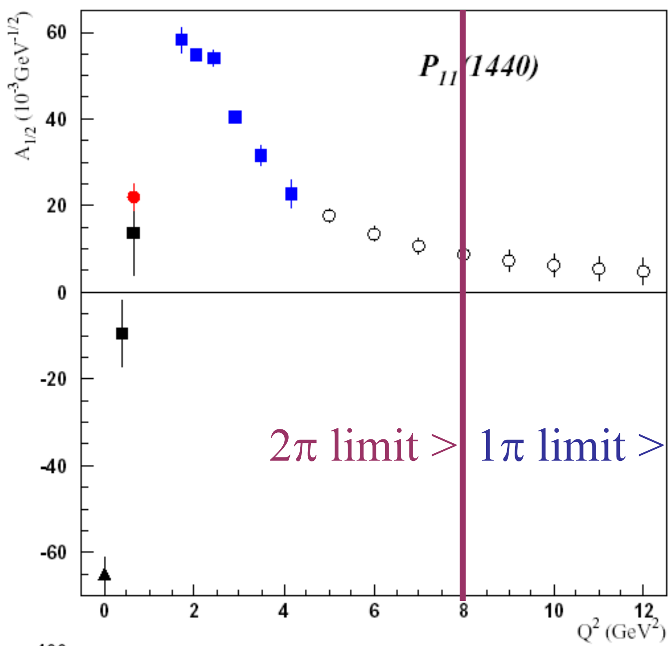
Kinematic Coverage of CLAS12

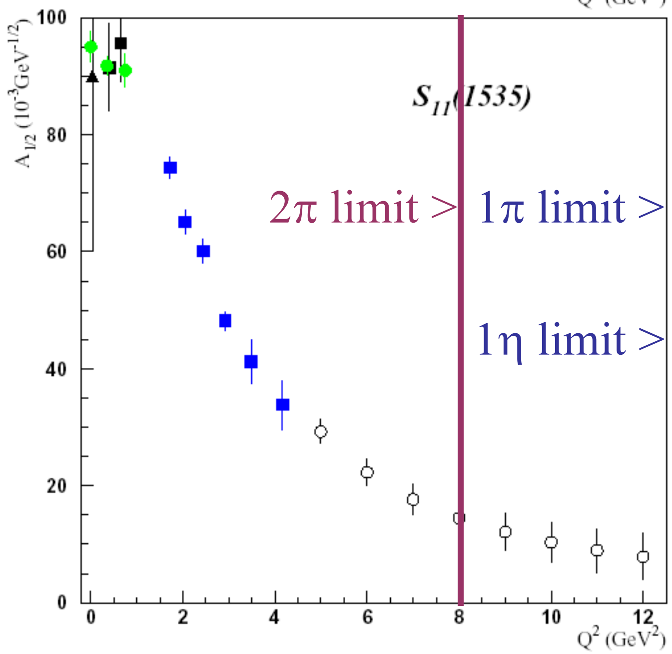
60 days

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

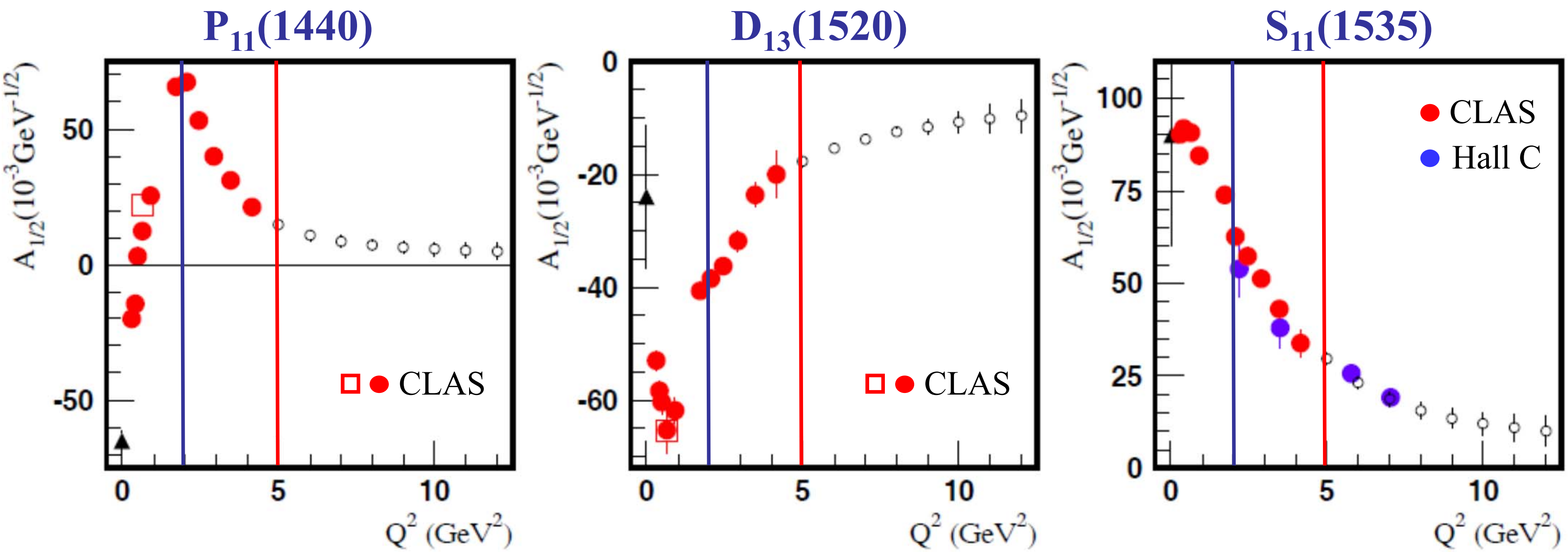
Genova-EG (e',p$\pi^+\pi^-$) detected







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

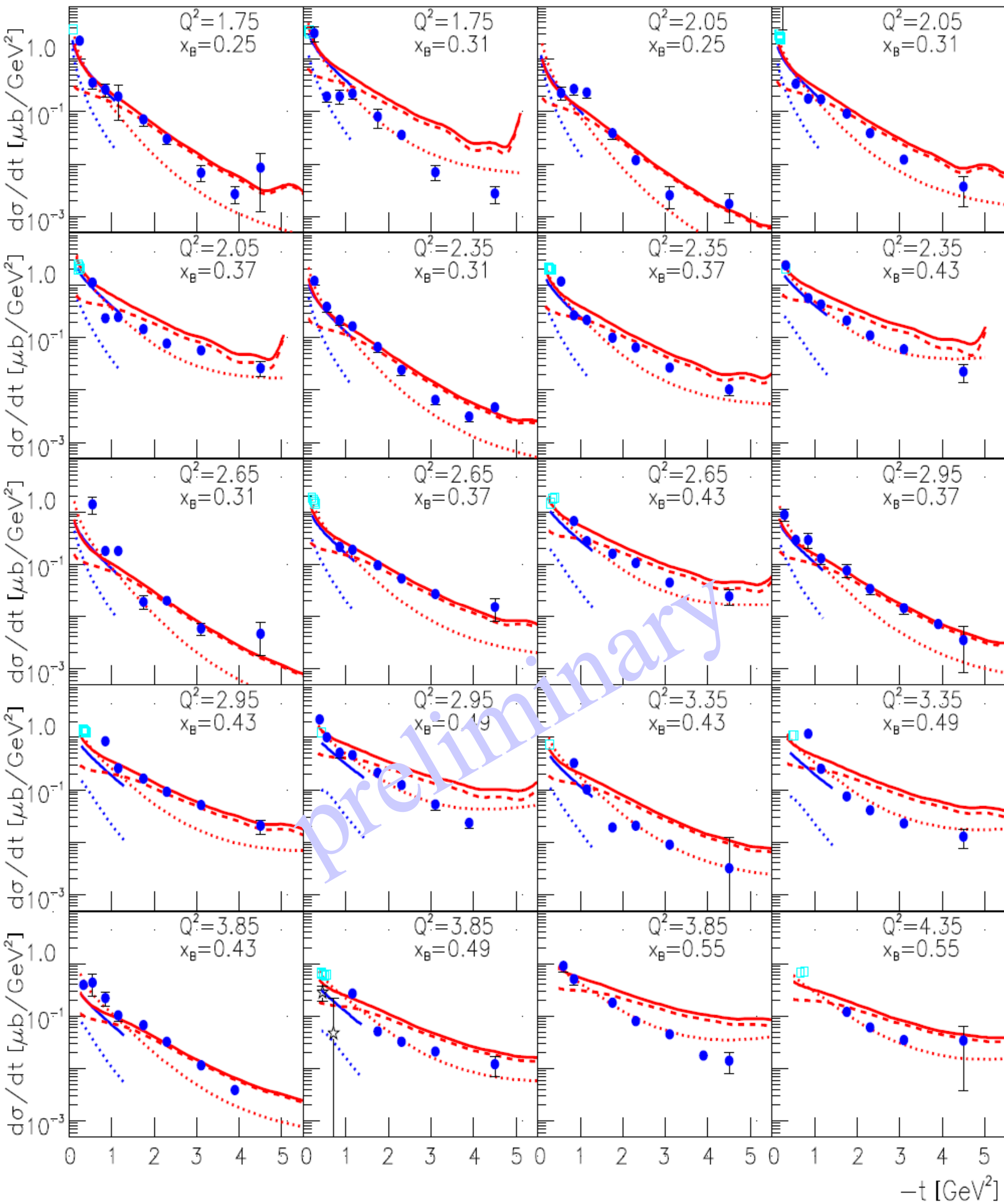


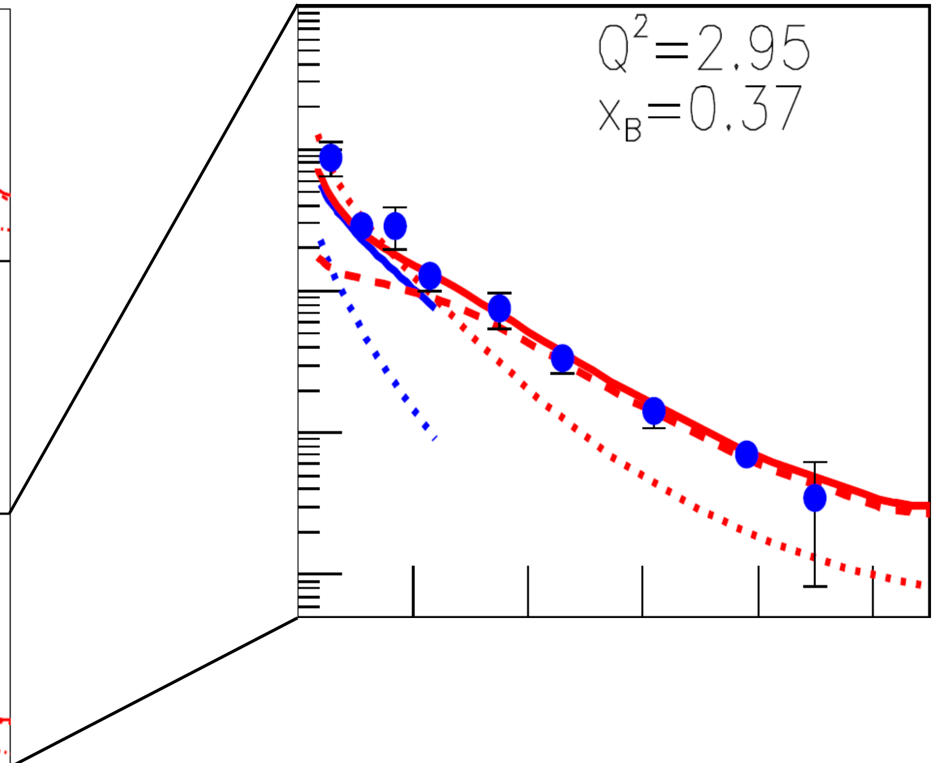
Open circles represent projections and all other markers the available results with the 6-GeV electron beam

- 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.

Deep exclusive π^+ electroproduction off the proton





The red solid ($d\sigma/dt$), dotted ($d\sigma_L/dt$), and dashed ($d\sigma_T/dt$) curves are the calculations from the 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 the partonic model (handbag diagrams).

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:
  - theoretical interpretation on N* electrocouplings, see our previous White Paper arXiv:0907.1901v3 [nucl-th], and
  - development of reaction models that will account for hard quark/parton contributions at high Q^2.
- Any constructive criticism, help, or participation is very welcomed, please contact:
  - Viktor Mokeev mokeev@jlab.org or Ralf Gothe gothe@sc.edu.

Next Opportunities to Get Involved

The next workshop in our series "Nucleon Resonance Structure in Exclusive Electroproduction at High Photon Virtualities" will be held at the University of South Carolina in Columbia on **August 13-15, 2012**. This three-day workshop will provide us extended opportunities to present and discuss in depth future developments and preliminary results on the continuous exploration of hadronic physics towards smaller distances.

COLLEGE OF ARTS AND SCIENCES
PHYSICS AND ASTRONOMY

A first of its kind three-week graduate student summer school on "Dyson-Schwinger Equations to tackle non-perturbative physics, their applications in Quantum Chromodynamics and condensed matter physics, and their mathematical connection to the Hopf algebras", which will be held at USC from **July 26 to August 11**, directly precedes our three-day workshop. The main lecturers are Piers Coleman, Ian Cloet, Craig Roberts, and Karen Yeats. There will be a limited number of spots for outside graduate students available. If you would like to send a graduate student or know one who would like to come please contact me (gothe@sc.edu) directly.