Challenges of the N* Program

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The 8th International Workshop on the Physics of Excited Nucleons

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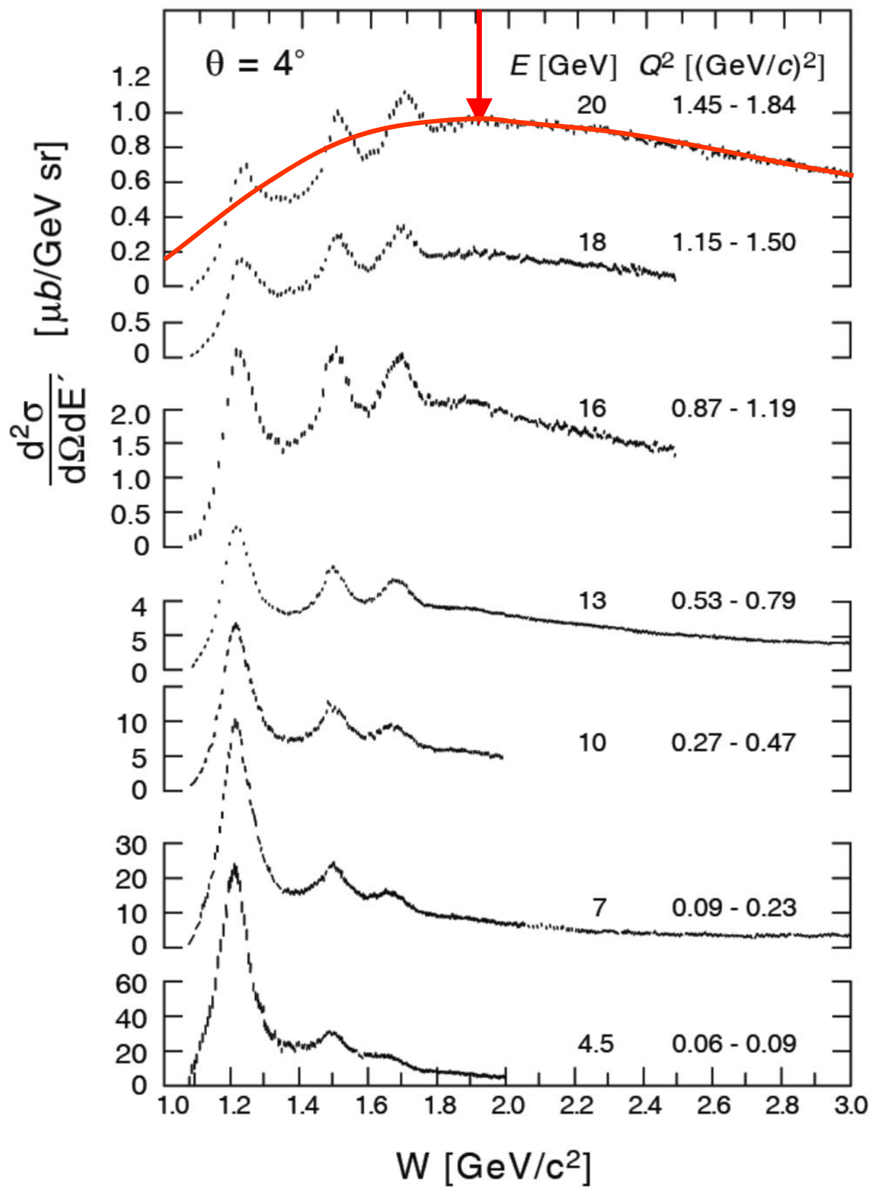
Jefferson Lab, Newport News, VA

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

QCD for Bound and Confined Quarks?

Quark-Hadron Duality



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

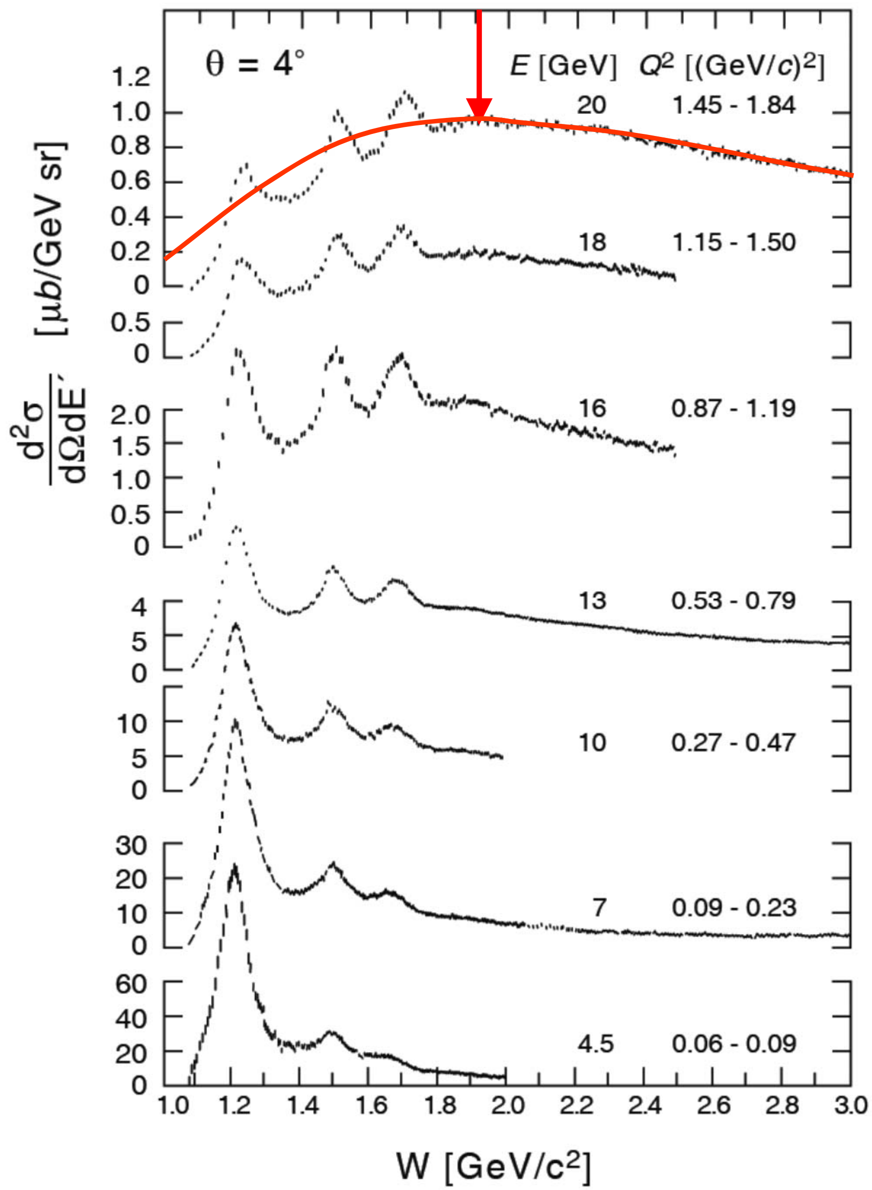
m_q = 0.36 GeV $\qquad m_q = Q^2/2\nu$

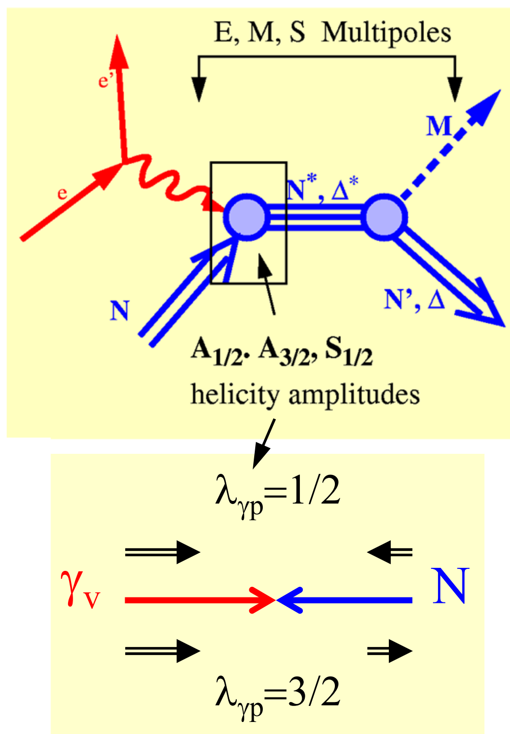
p_F = 0.67 GeV

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

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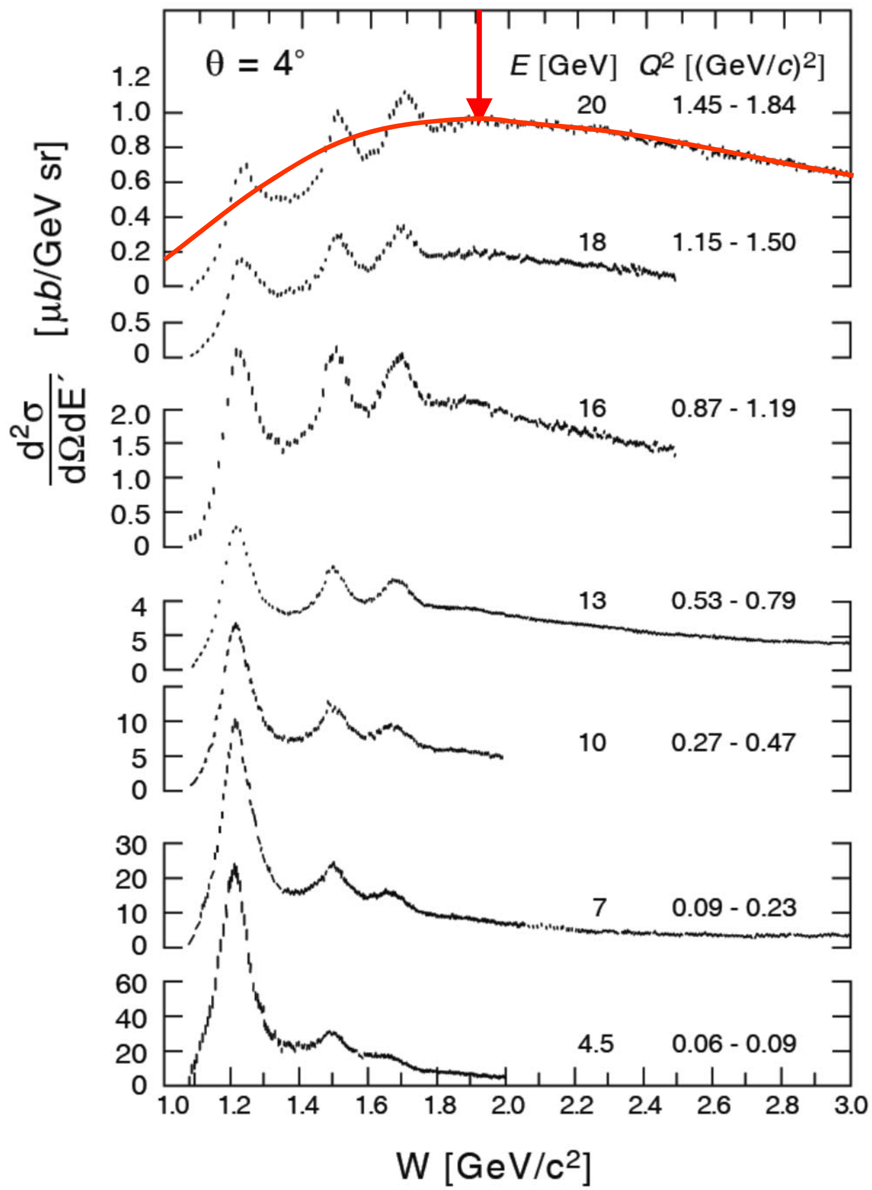
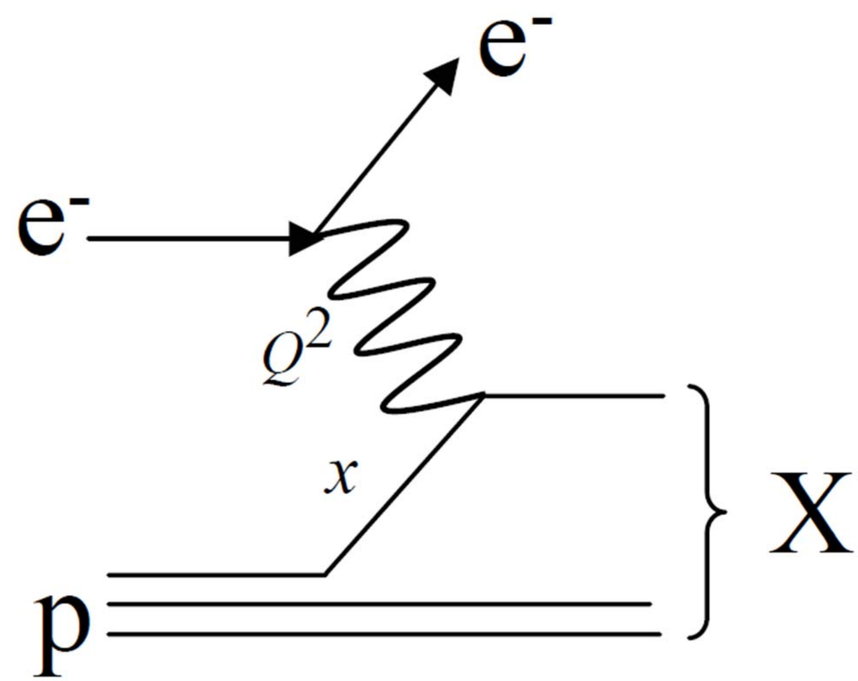


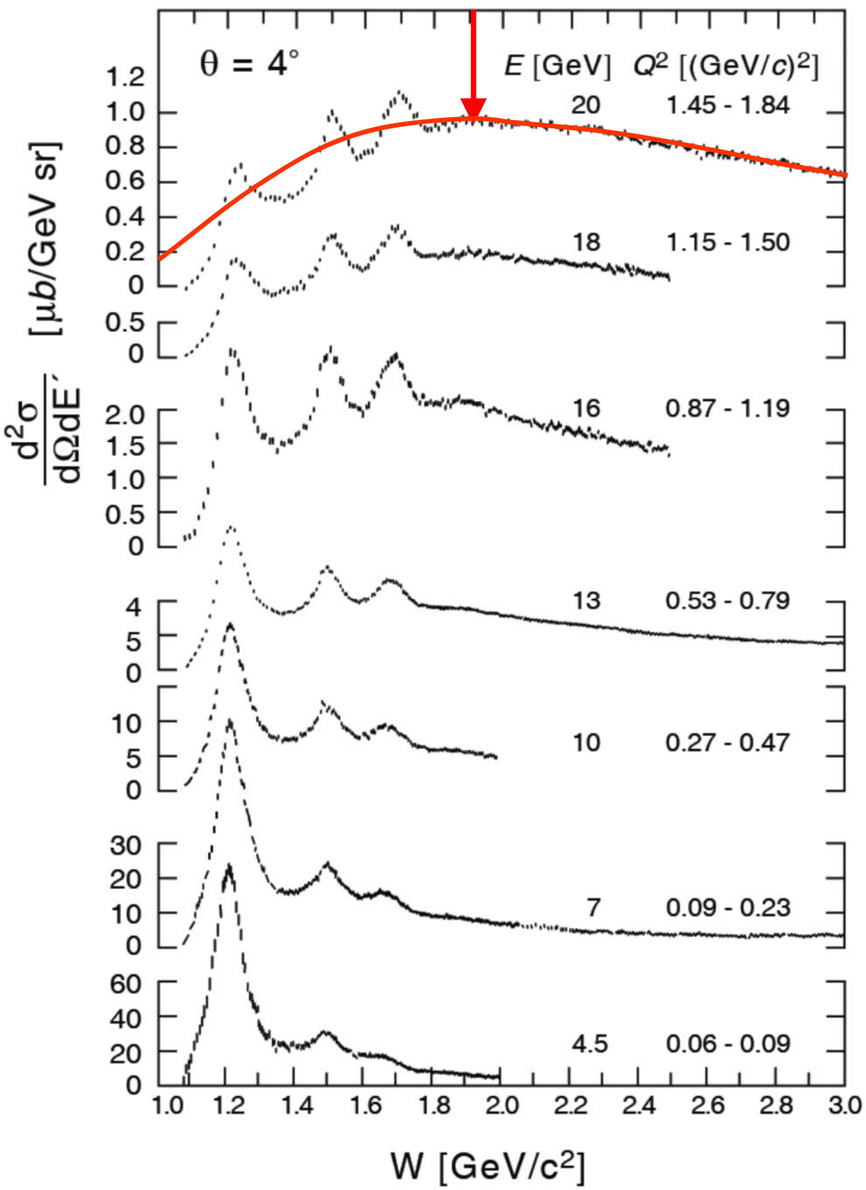
Deep Inelastic Scattering (DIS)

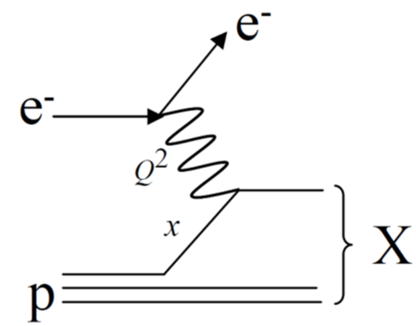


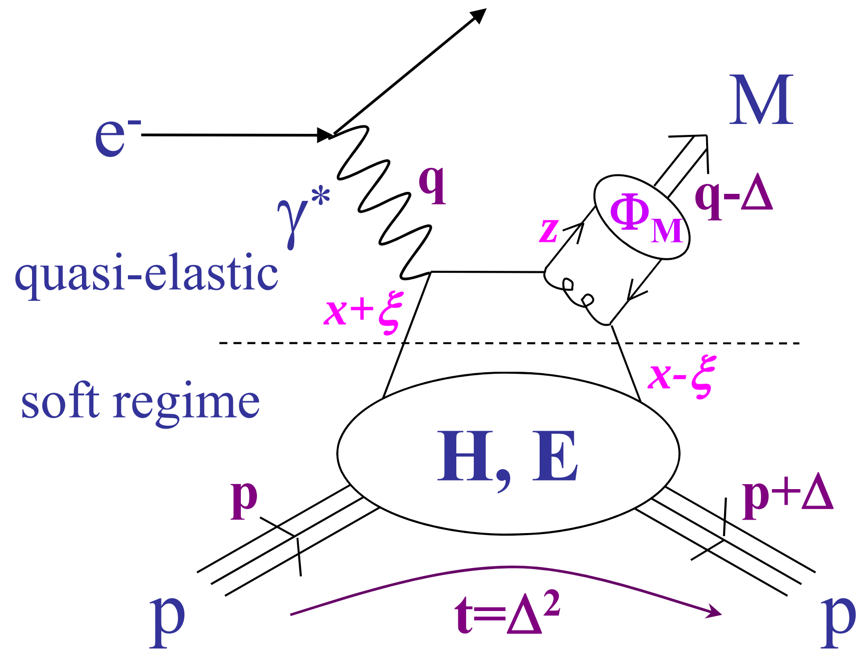
Parton Distributions

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

Baryon Excitations and Quasi-Elastic Scattering



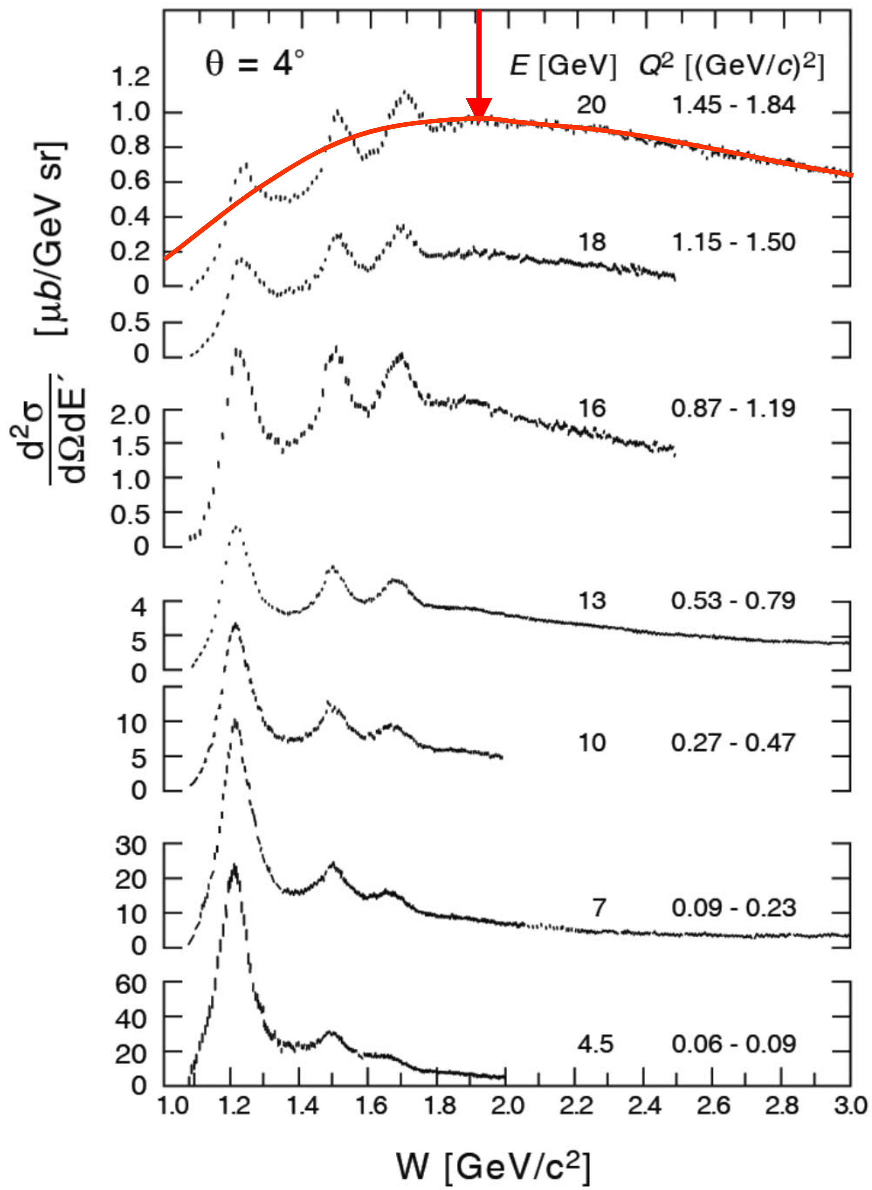




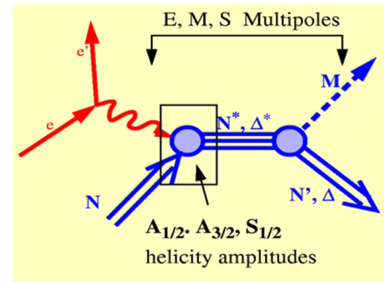
Deep Inelastic Scattering

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

Baryon Excitations and Quasi-Elastic Scattering



confined



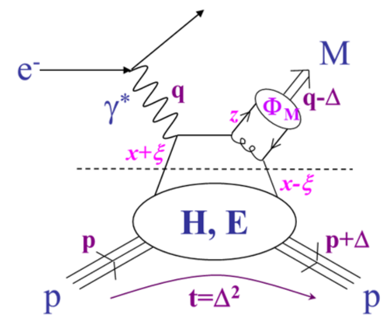
Spectroscopy

Elastic Form Factors

Transition Form Factors

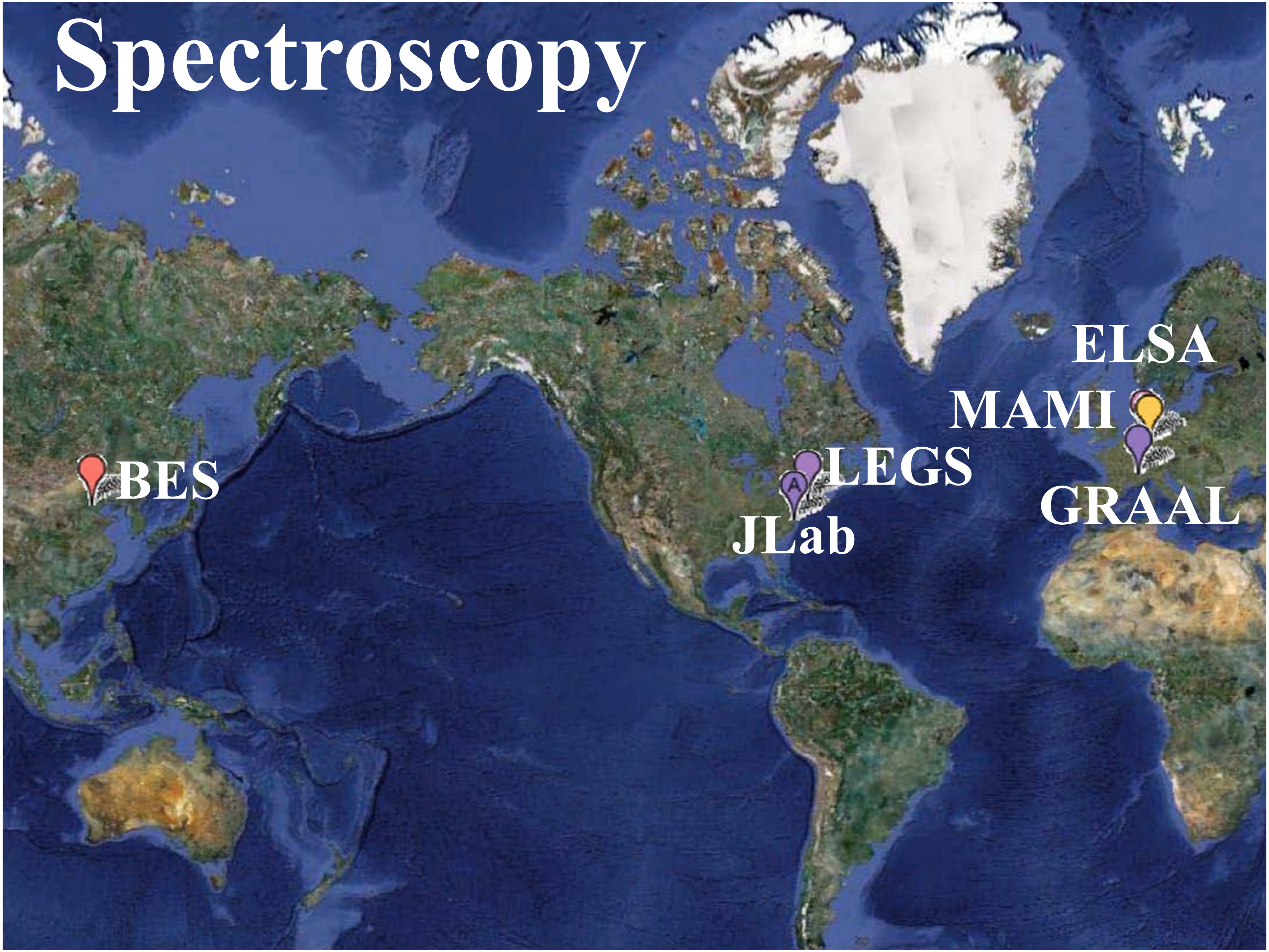
quasi-elastic

soft



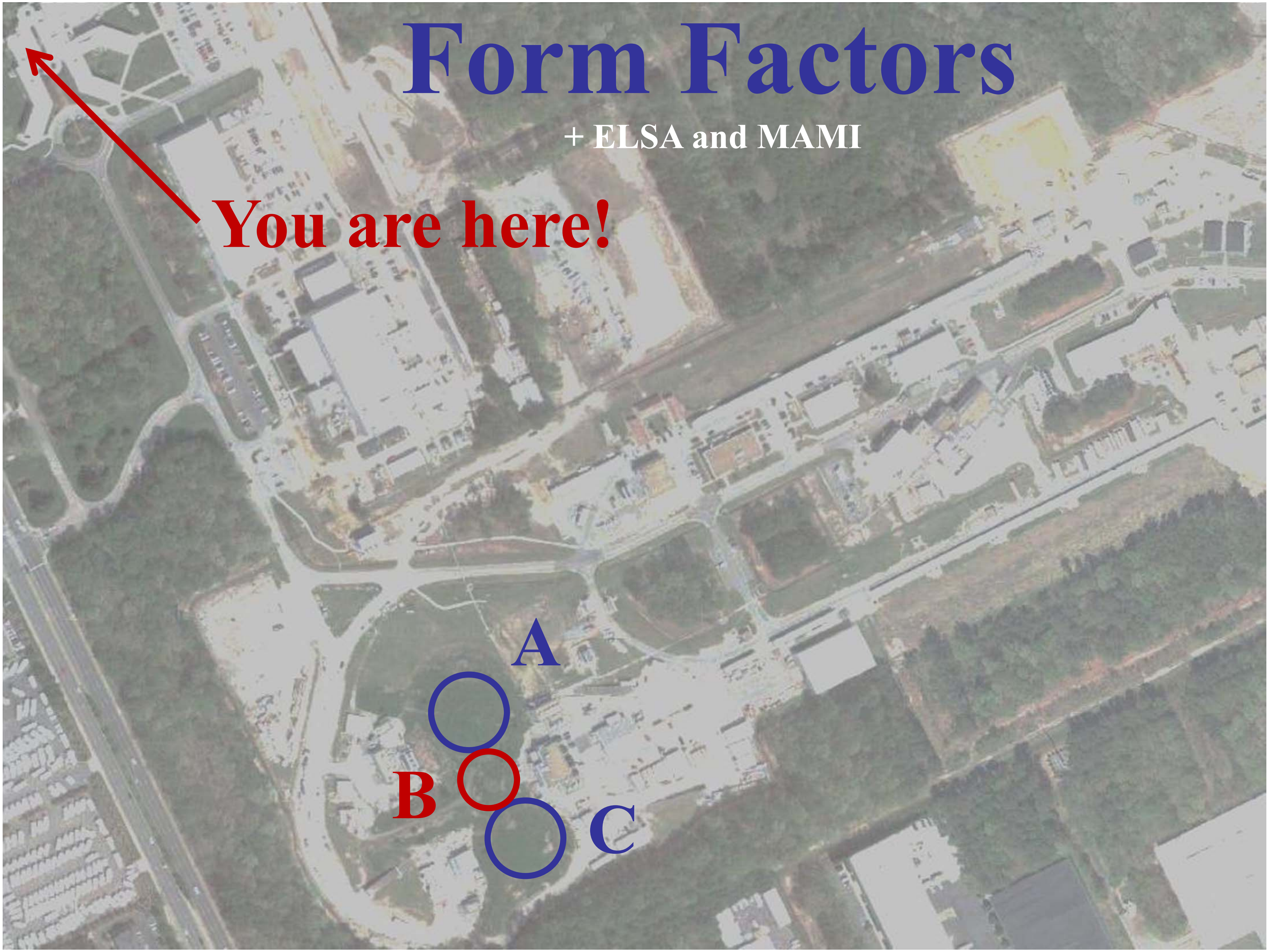
Deep Inelastic Scattering
S. Stein et al., PR **D22** (1975) 1884

Experimental Facilities

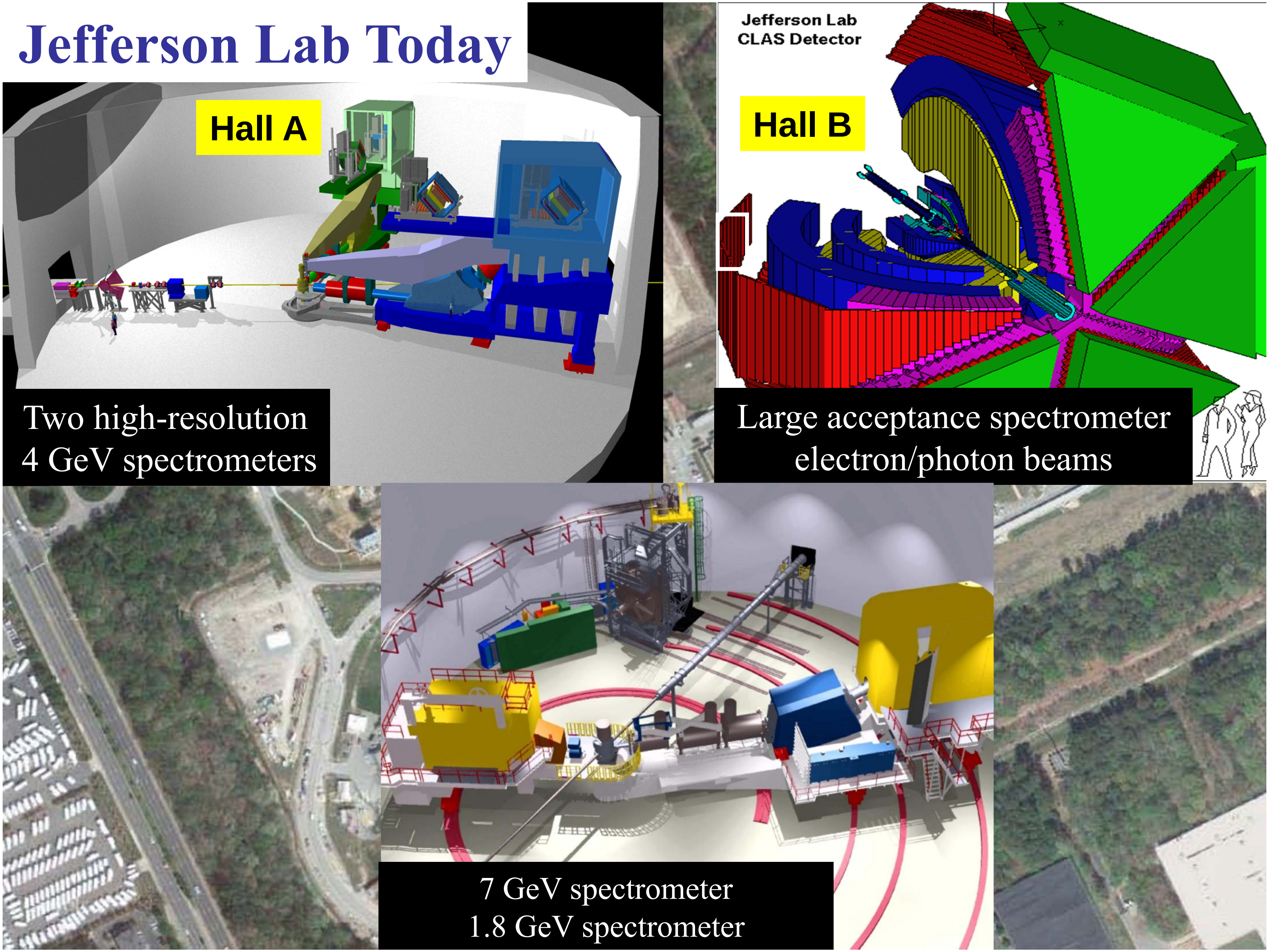

Spectroscopy
ELSA
MAMI
LEGS
BES
GRAAL
JLab

Form Factors

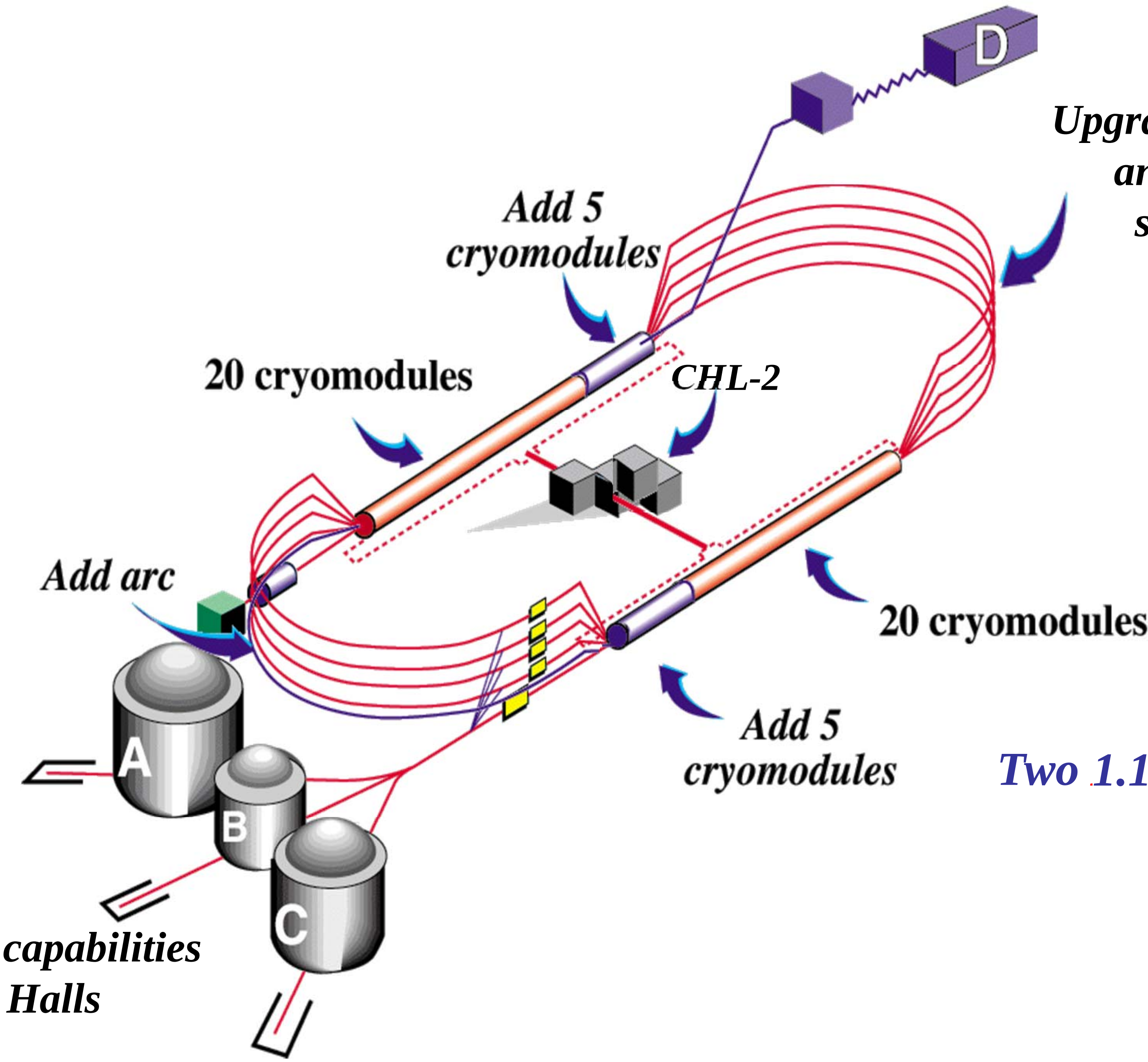
+ ELSA and MAMI



Jefferson Lab Today



12 GeV CEBAF

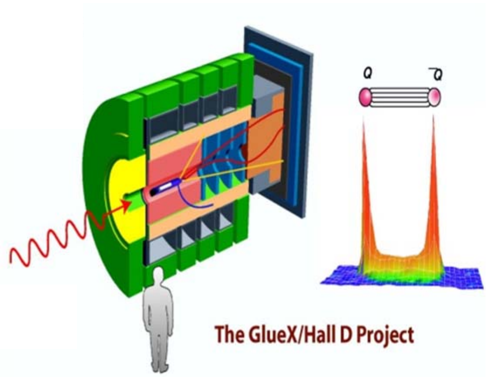


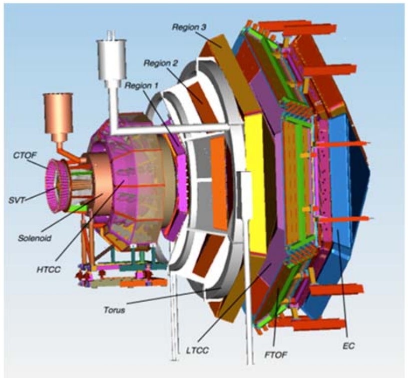
Upgrade magnets and power supplies

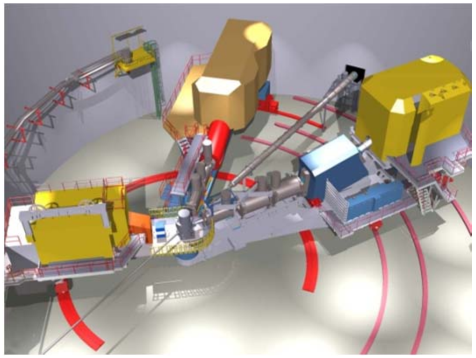
Two 1.1 GeV linacs

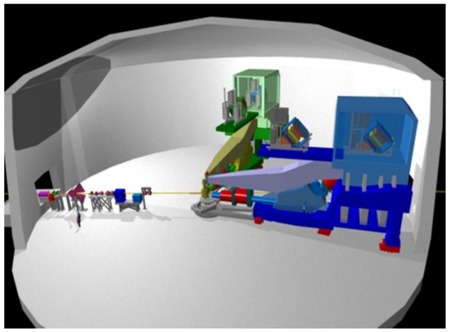
Enhanced capabilities in existing Halls

Overview of Upgrade Technical Performance Requirements





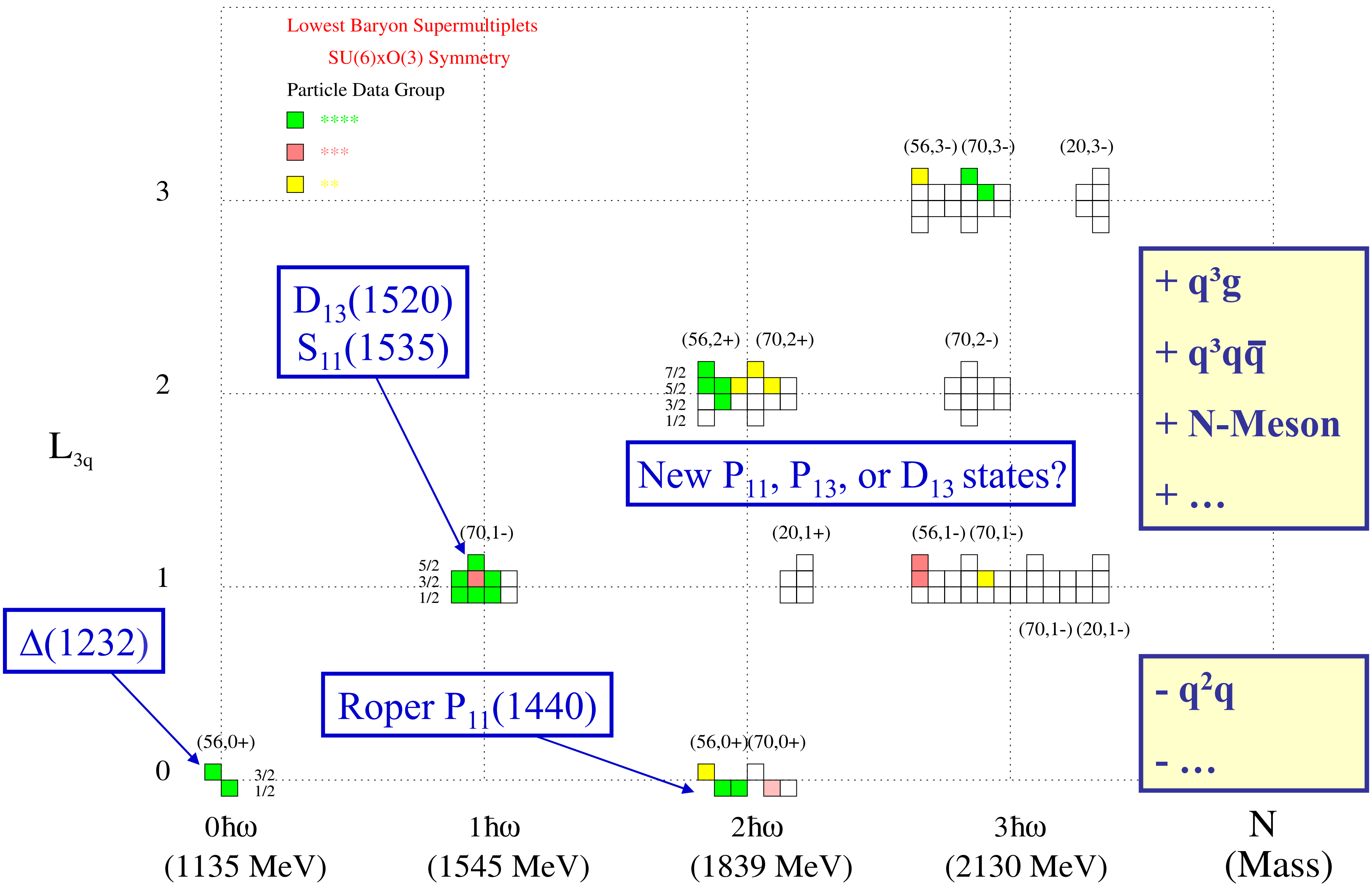




Hall D	Hall B	Hall C	Hall A
4π hermetic detector GlueEx	luminosity 10^{35} CLAS12	High Momentum Spectrometer SHRS	High Resolution Spectrometer HRS
polarized photons	hermeticity	precision	space
$E_\gamma \sim 8.5\text{-}9.0$ GeV	11 GeV beamline		
10^8 photons/s	target flexibility		
good momentum/angle resolution		excellent momentum resolution	
high multiplicity reconstruction		luminosity up to 10^{38}	

Spectroscopy

Quark Model Classification of N*



Evidence for New N* States

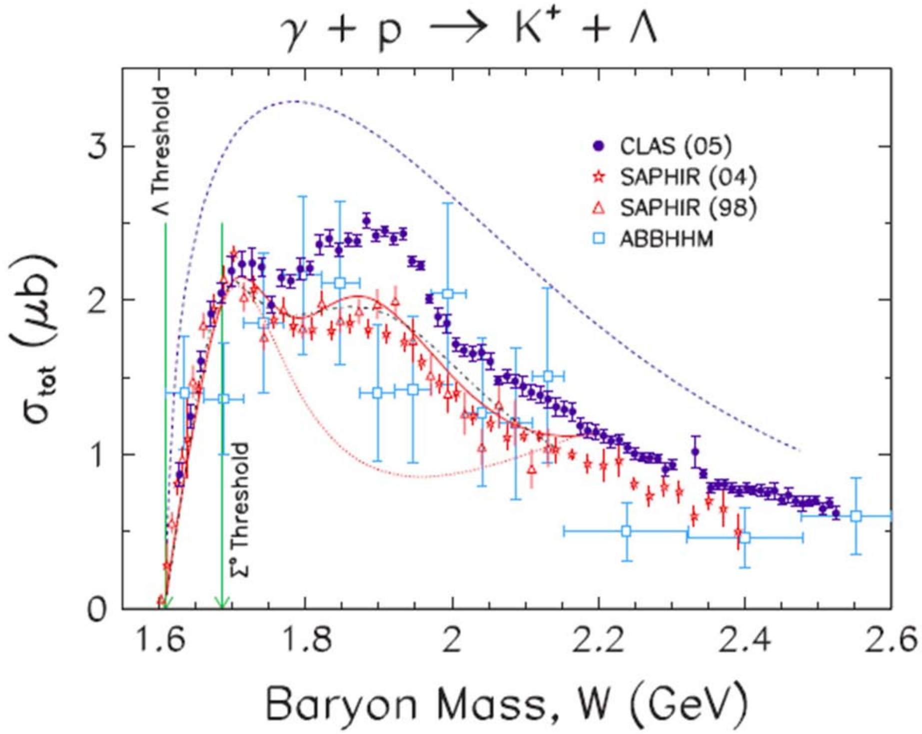


FIG. 20. (Color online) Total cross section for $\gamma + p \rightarrow K^+ + \Lambda$. The data from CLAS (blue circles) are shown with combined statistical and fitting uncertainties. Also shown are results from two publications from SAPHIR (red stars (2004) [18] and red triangles (1998) [8]) and the 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

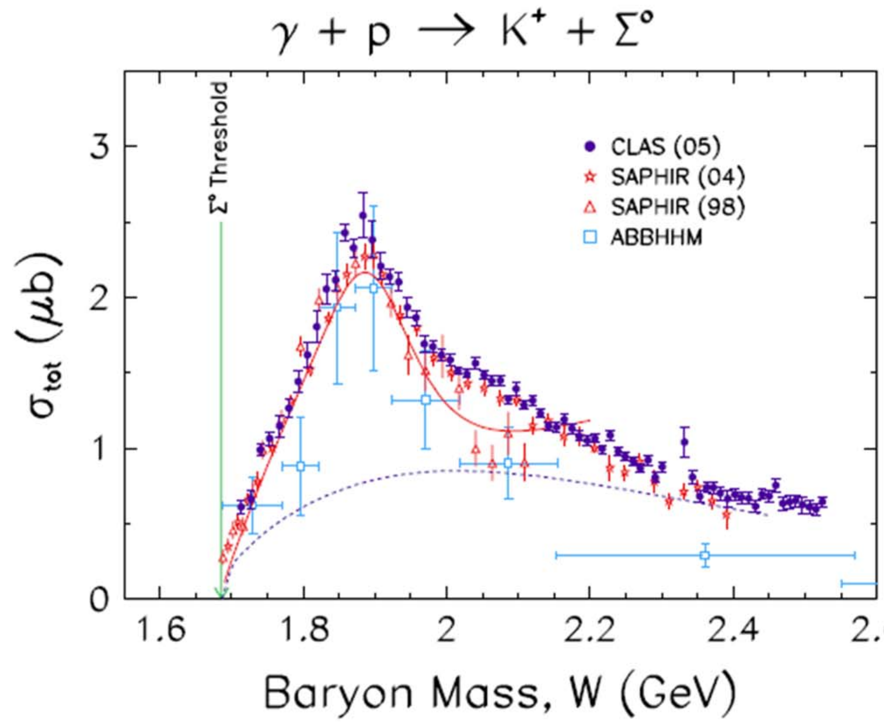
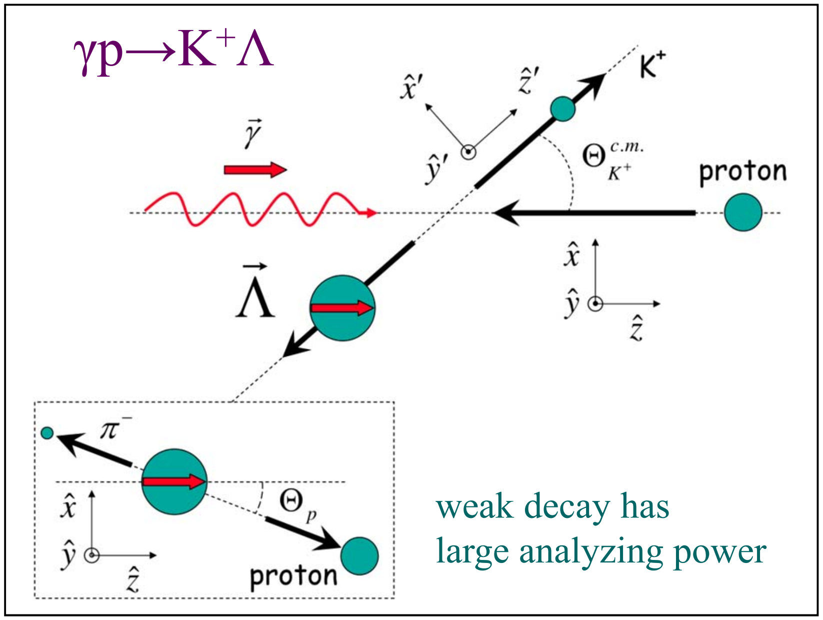


FIG. 21. (Color online) Total cross section for $\gamma + p \rightarrow K^+ + \Sigma^0$. The data from CLAS (blue circles) are shown with combined statistical and fitting uncertainties. Also shown are results from two publications from SAPHIR (red stars (2004) [18] and red triangles (1998) [8]) and the 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.

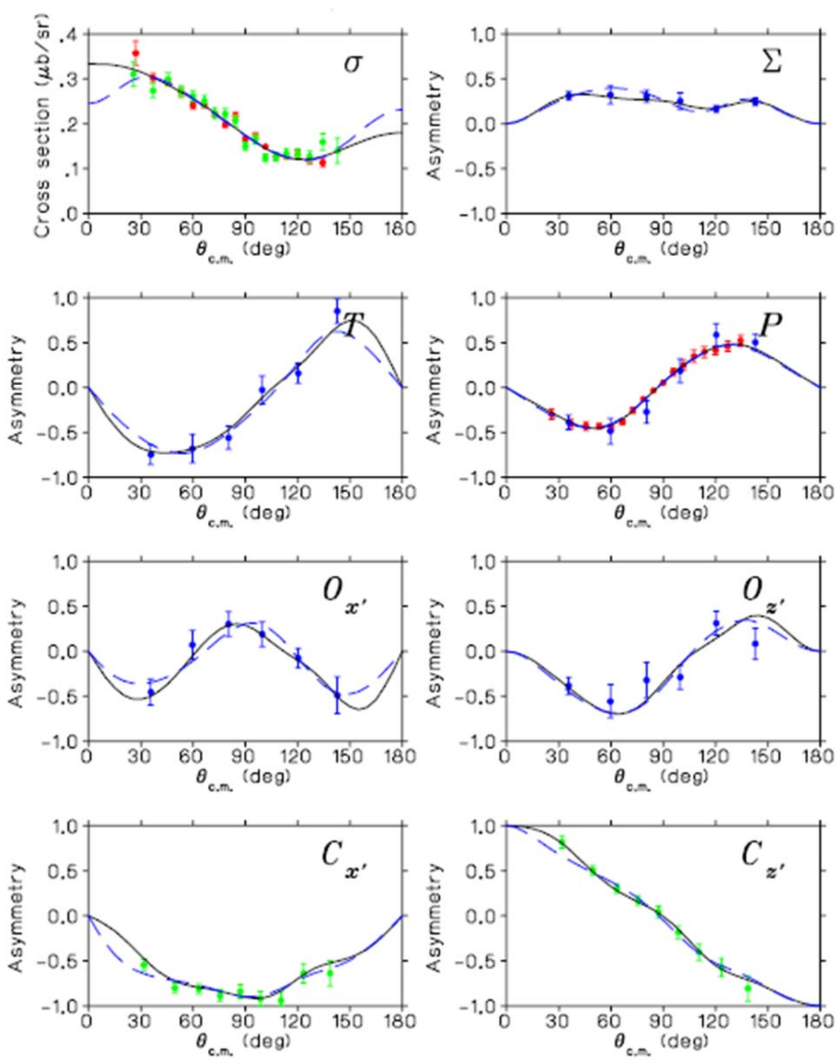
FROST/HD $\vec{\gamma}\vec{N}\rightarrow \pi N, \eta N, K\vec{\Lambda}, K\vec{\Sigma}, N\pi\pi$



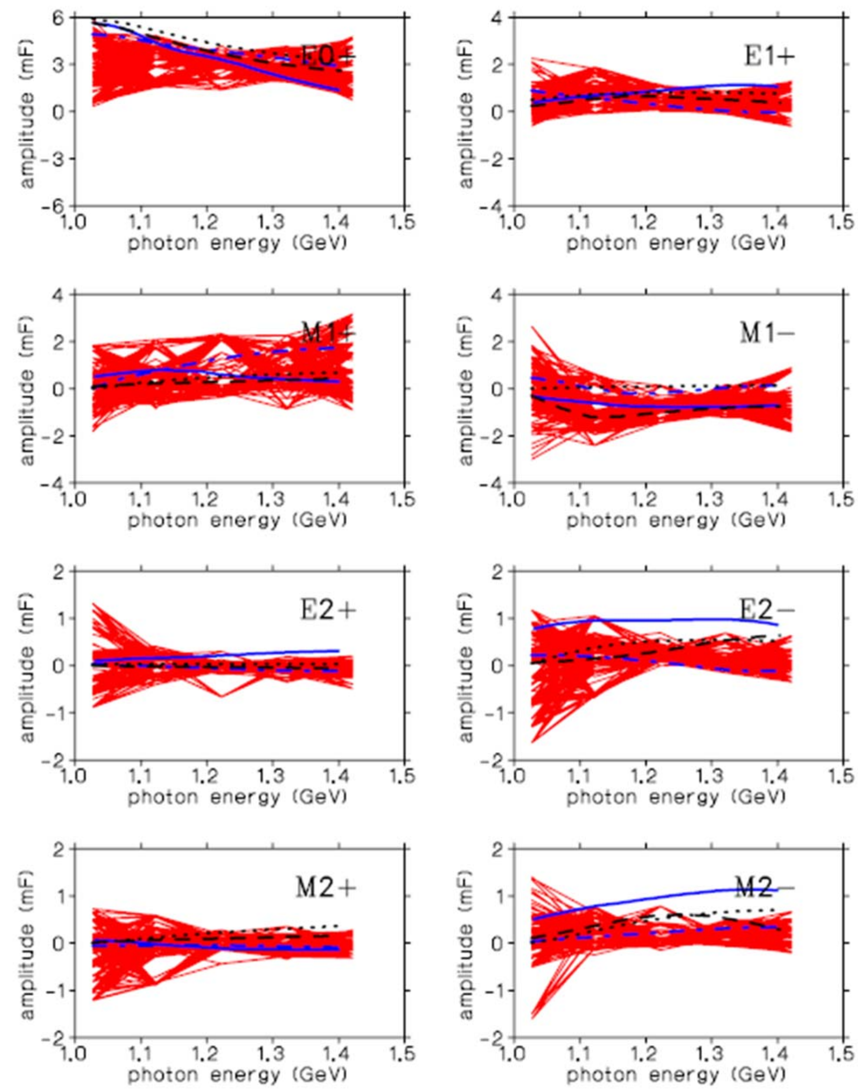
- Process is described by 4 complex, parity conserving amplitudes
- 8 well-chosen measurements are needed to determine amplitude
- For hyperon finals state 16 observables will be measured in CLAS ➠ large redundancy in determining the photo-production amplitudes ➠ allows many cross checks
- 8 observables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



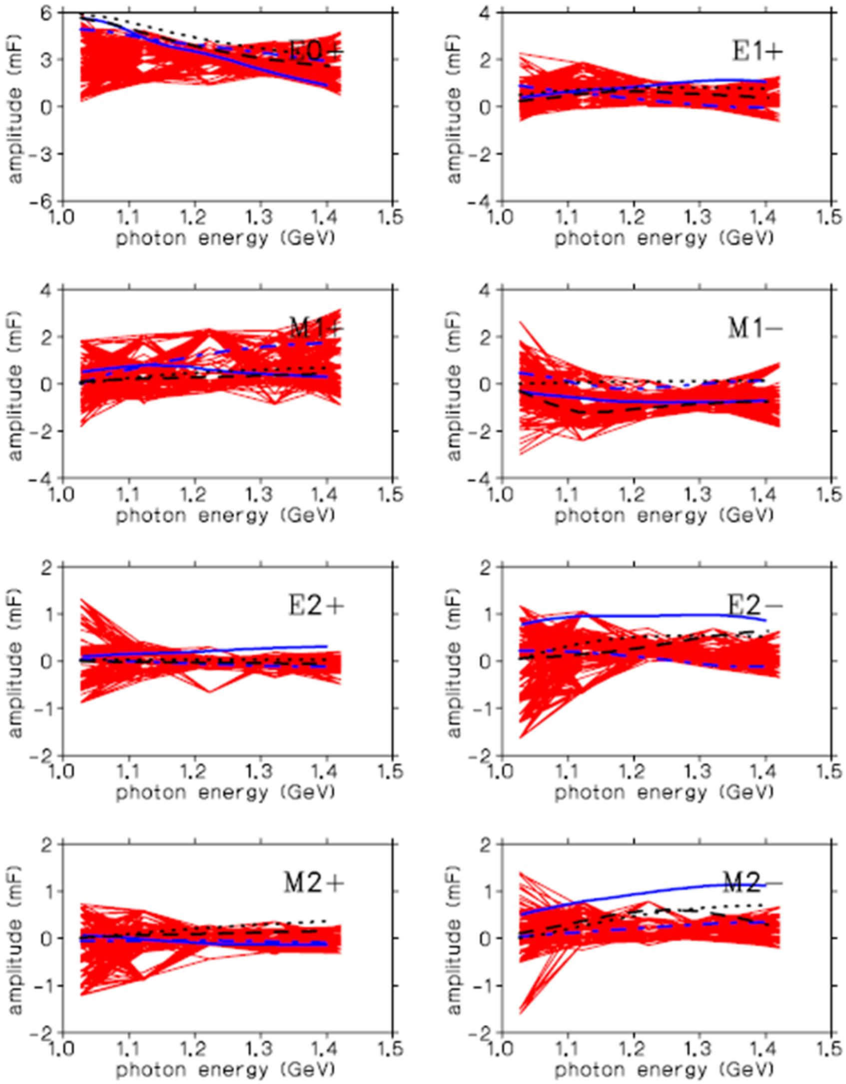
CLAS (g1c, g11a) and GRAAL

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

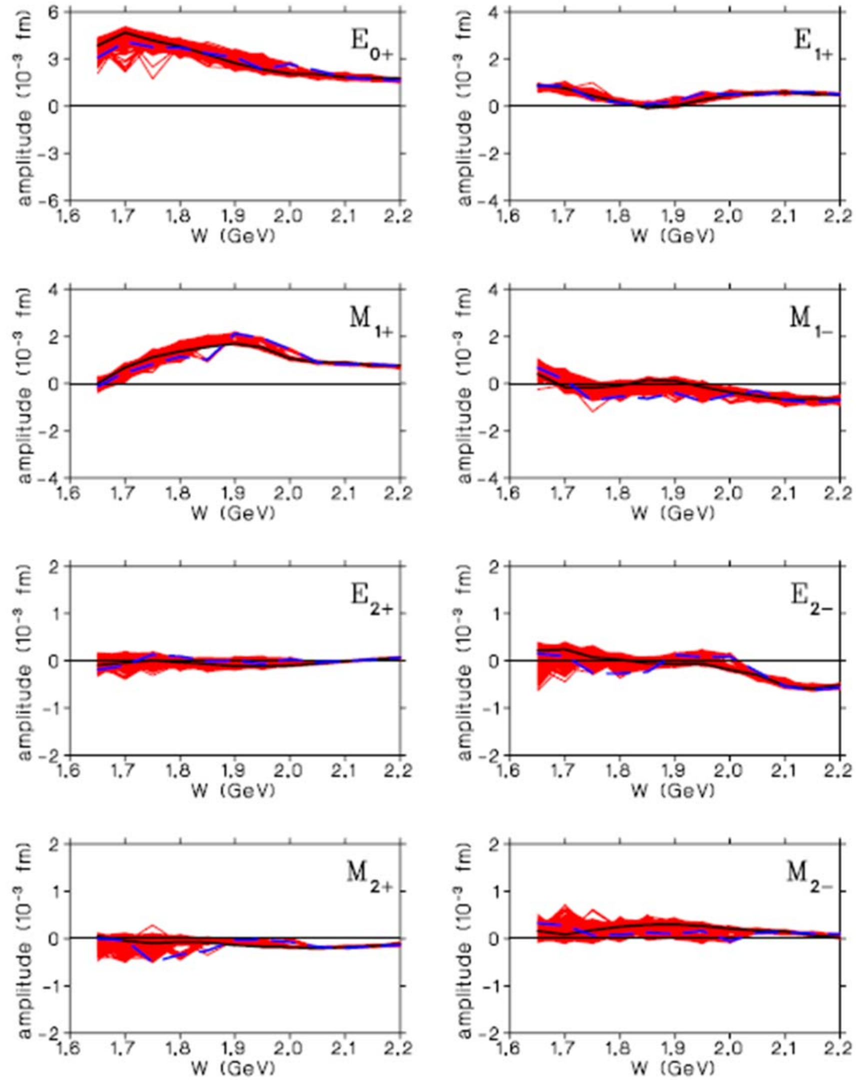
Real parts of the PWA multipoles

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

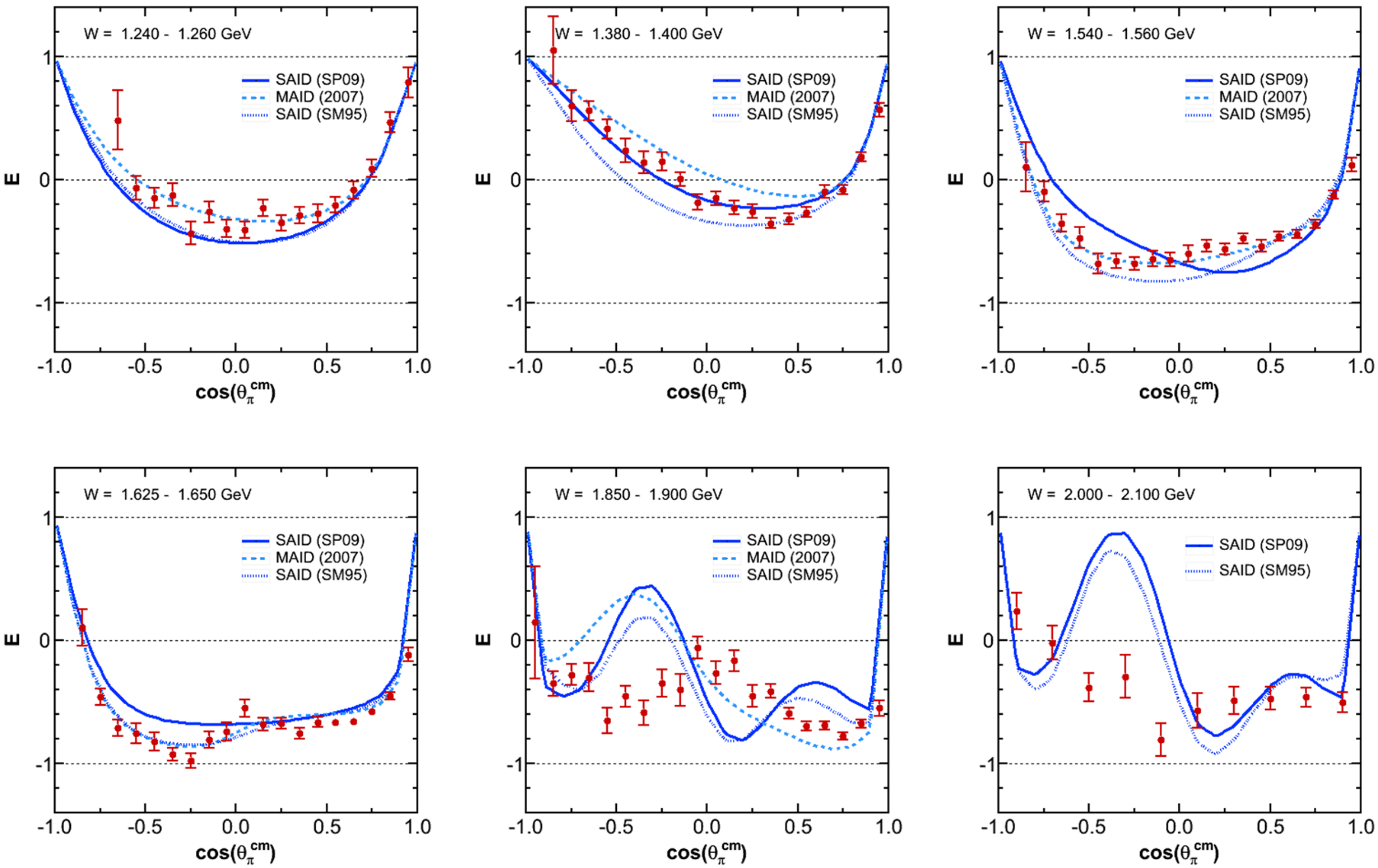
with 8 observables D_{13} excluded and with 16 observables P_{11} to be validated

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

Circular polarized beam and longitudinally polarized target

S. Strauch

E

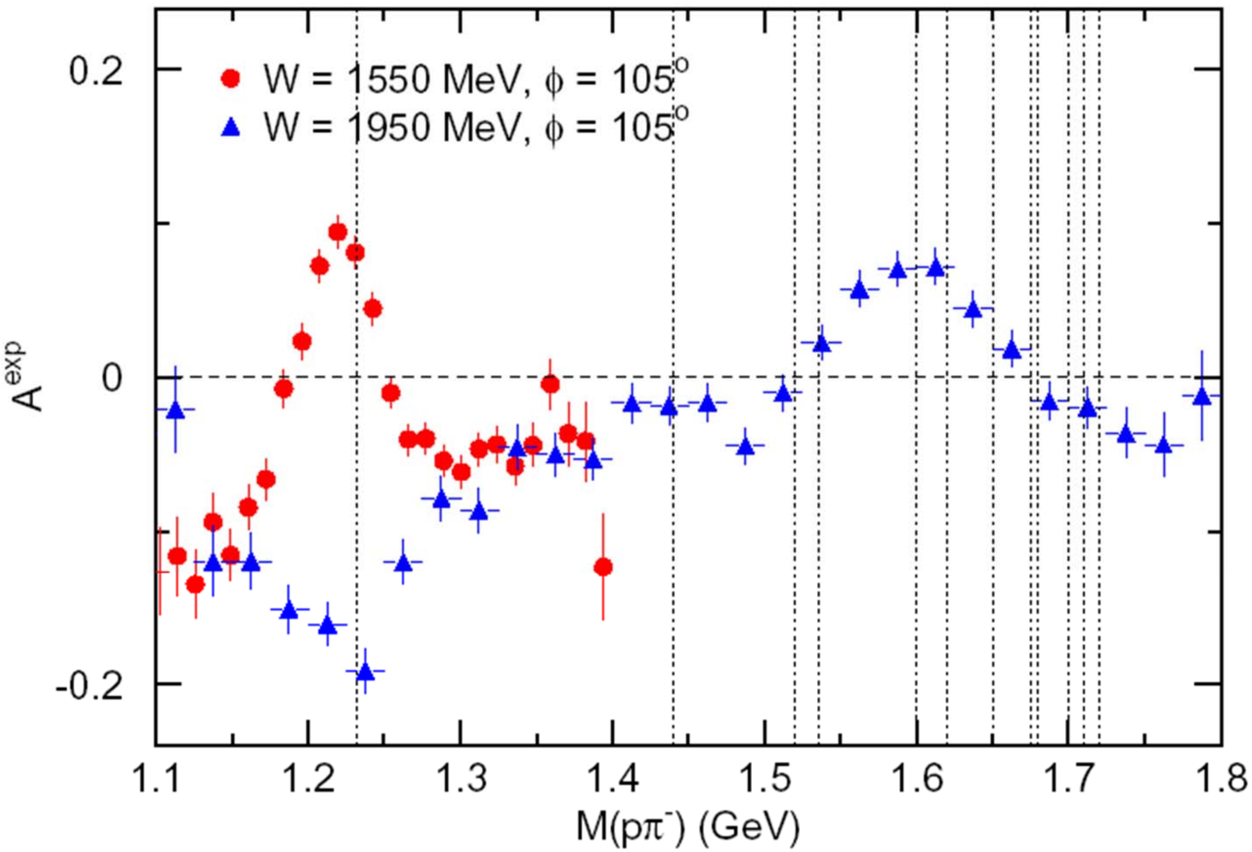


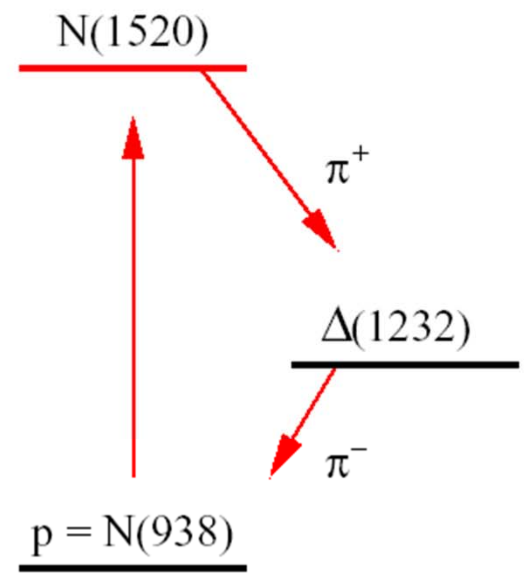
SP09: M. Dugger, et al., Phys. Rev. C 79, 065206 (2009); SM95: R. A. Arndt, I. I. Strakovsky, R. L. Workman, Phys. Rev. C 53, 430 (1996); MAID: D. Drechsel, S.S. Kamalov, L. Tiator Nucl. Phys. A645, 145 (1999)

Helicity Asymmetry in 2π Photoproduction

S. Strauch

Circular polarized beam





- Sequential Decay of the D_{13}(1520) resonance via πΔ

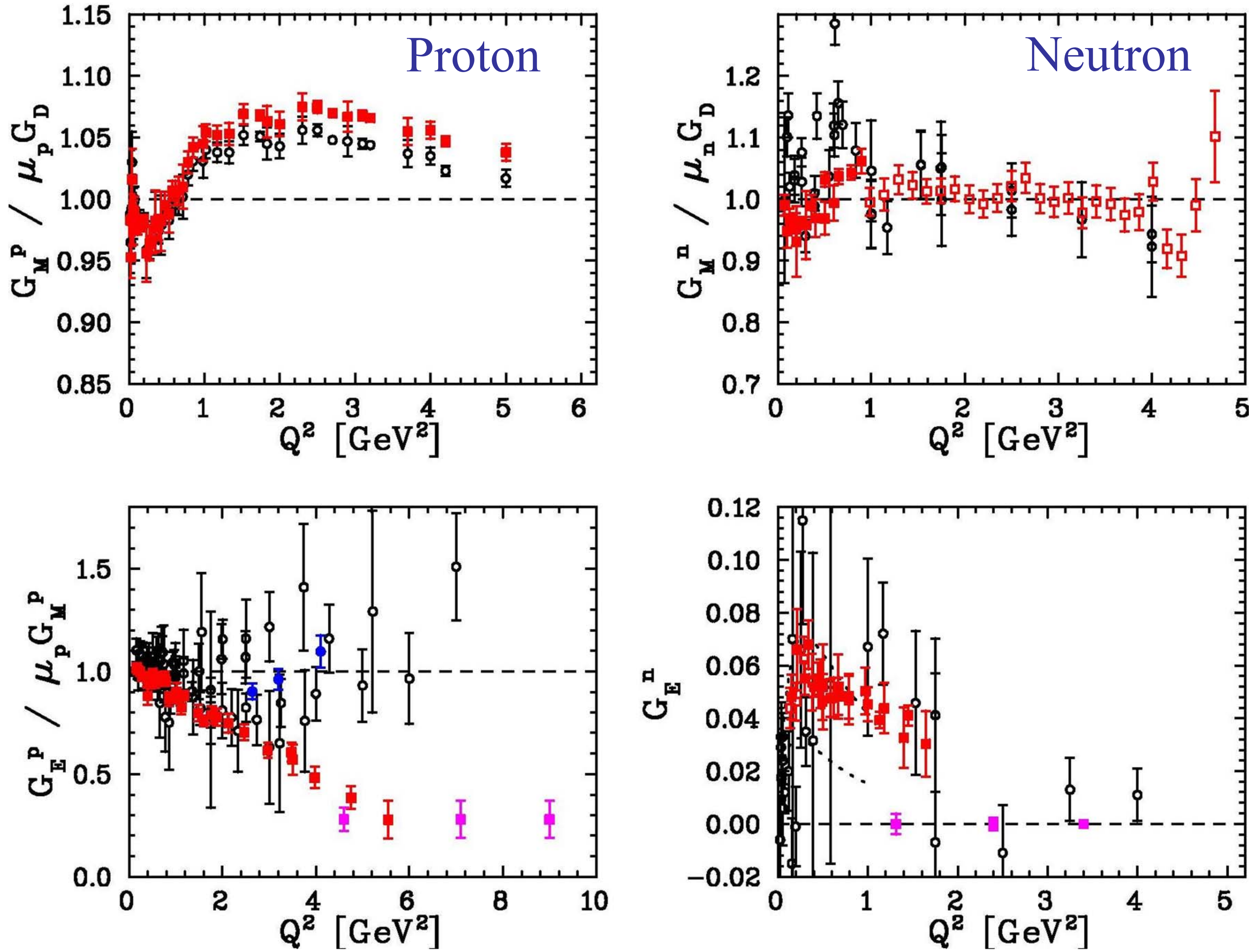
  … or higher lying resonances

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

Elastic Form Factors

Nucleon Form Factors: Last Ten Years

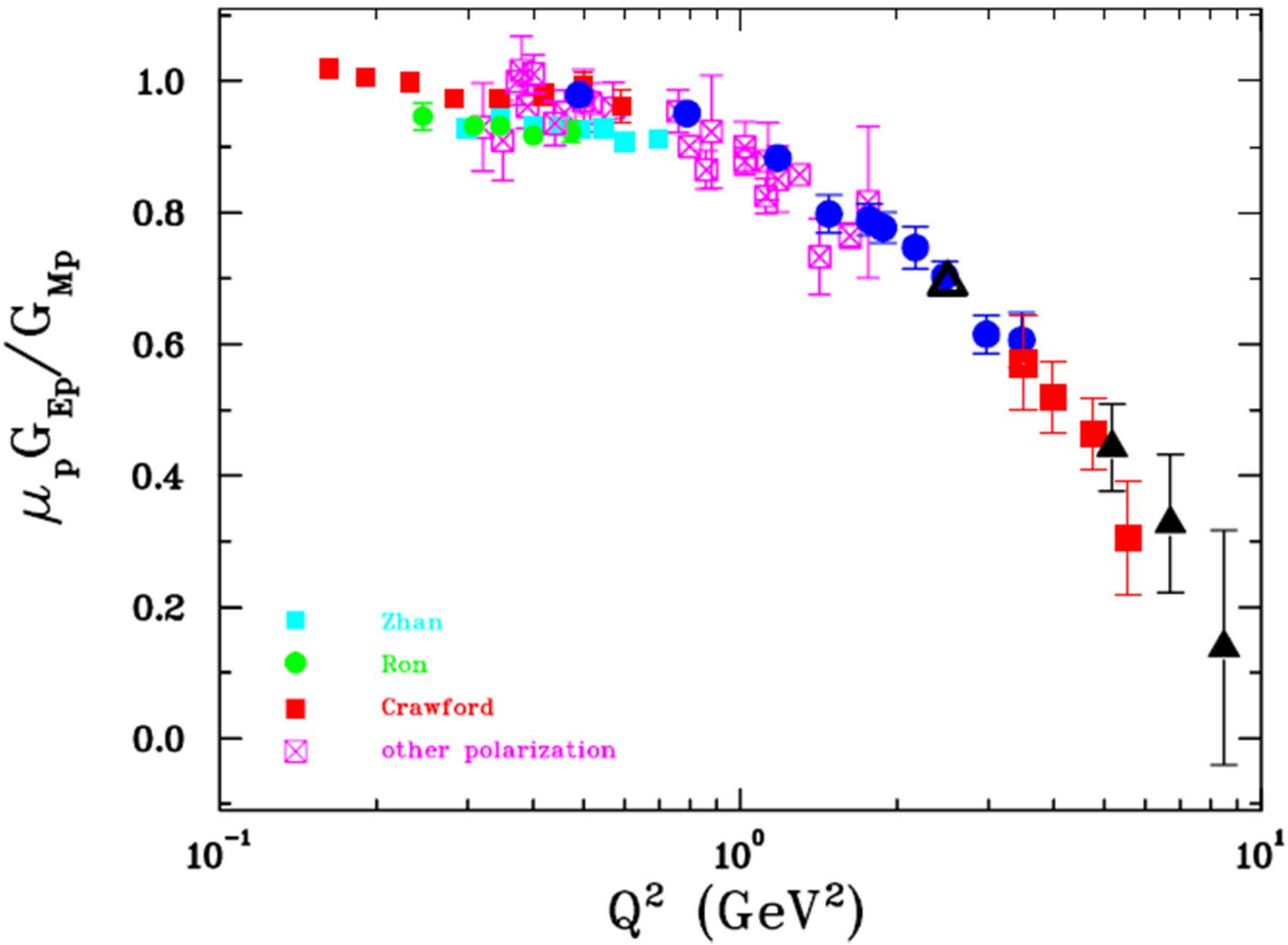
J. Arrington



under analysis

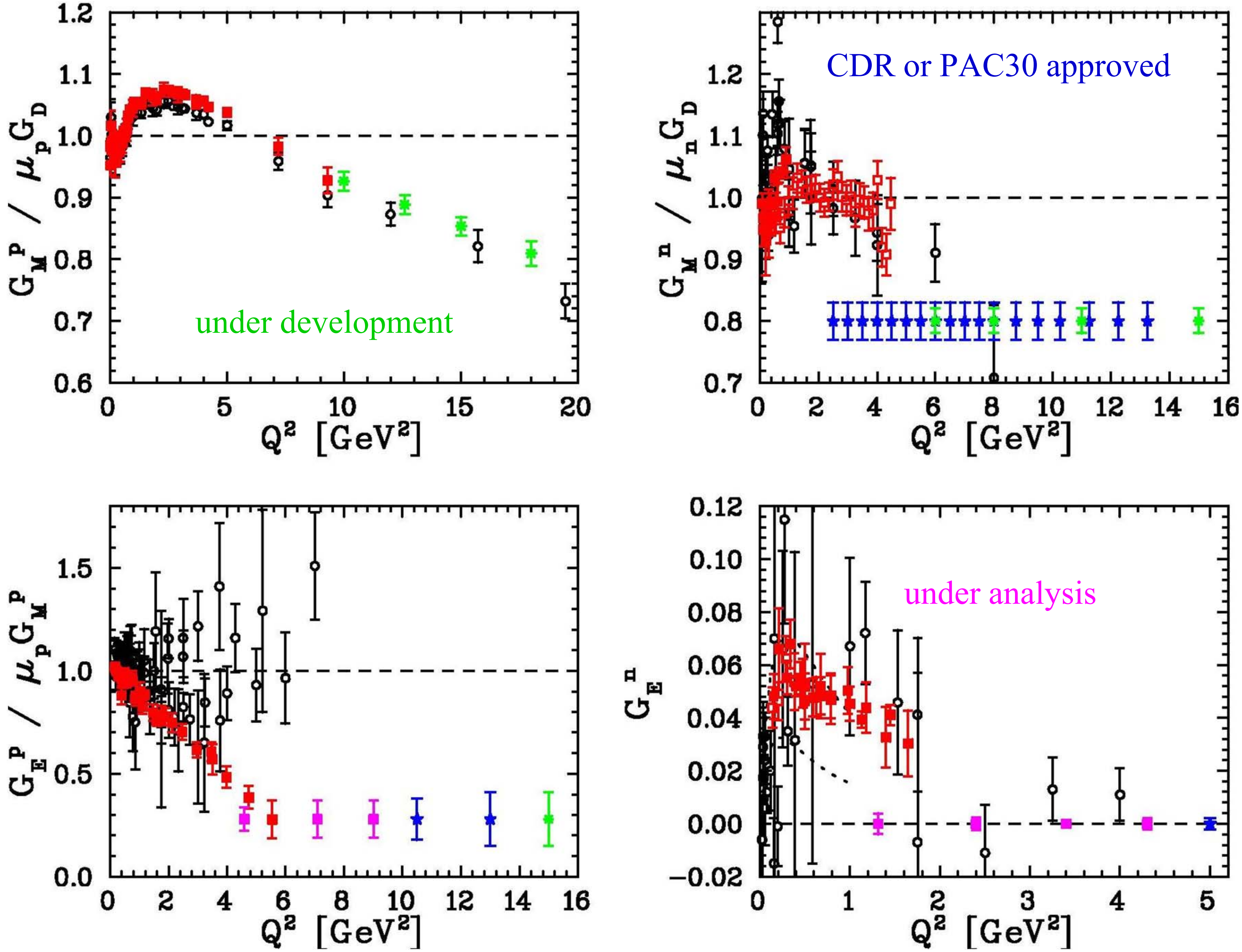
Most recent Form Factor Ratio

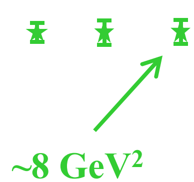
C. Perdrisat



Extensions with JLab 12 GeV Upgrade

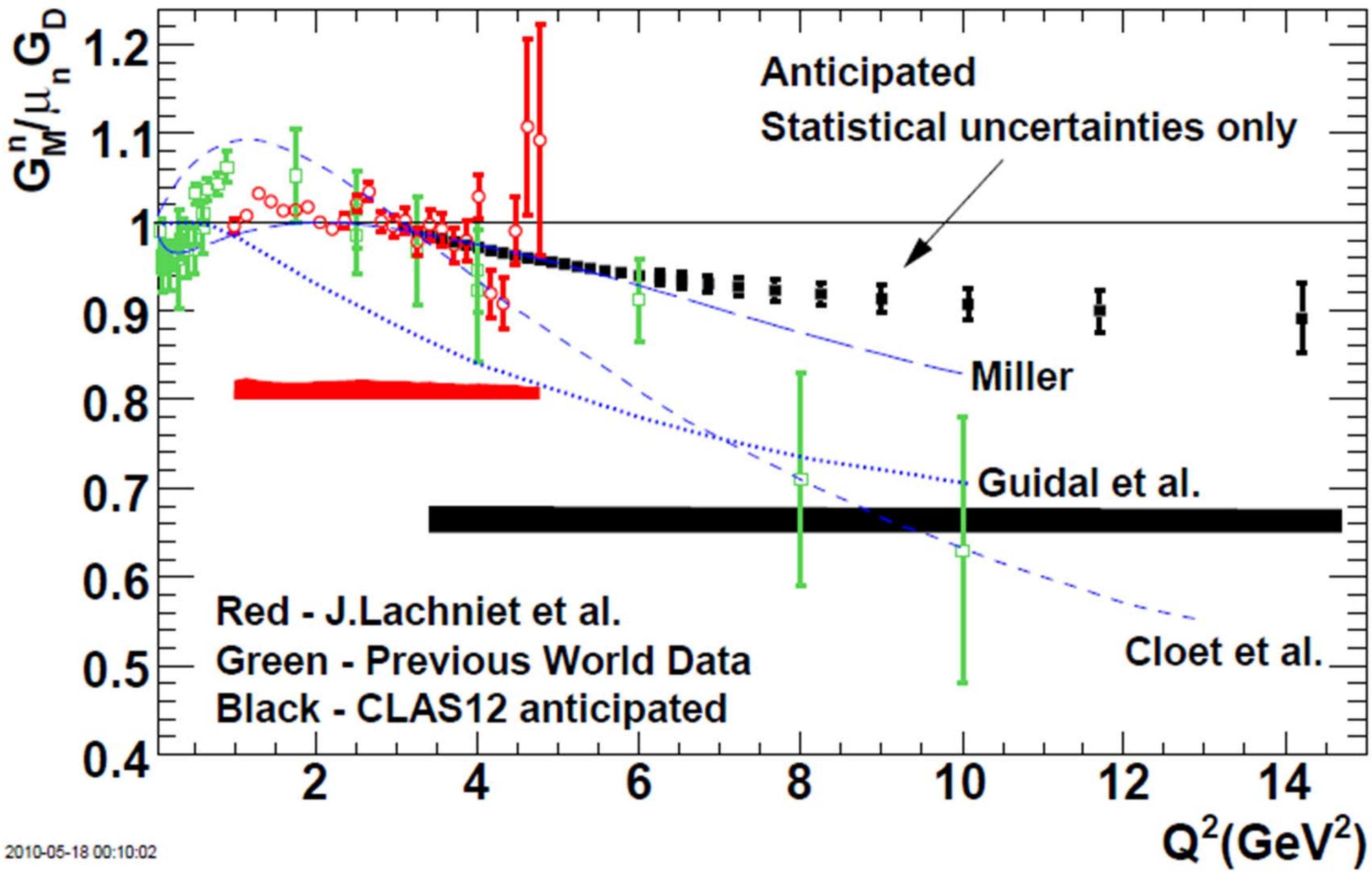
J. Arrington





Extensions with JLab 12 GeV Upgrade

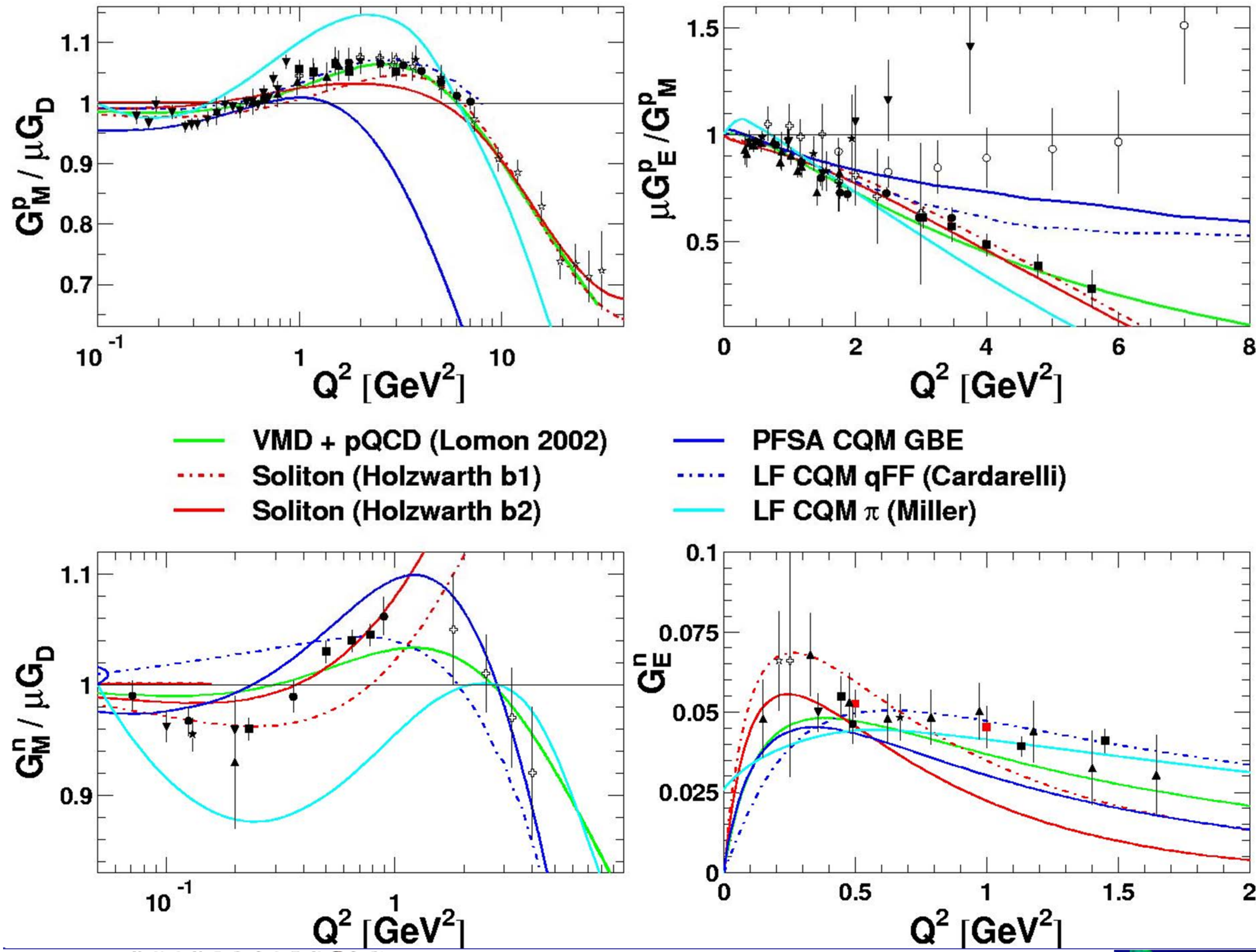
G. Gilfoyle



Uncertainty bands are for CLAS6 (Lachniet *et al.*).and CLAS12 anticipated.
Miller - PRC 66, 032201(R) (2002); Guidal - PRD 72, 054013 (2005); Cloët - Few Body Syst., 46:1-36 (2009).

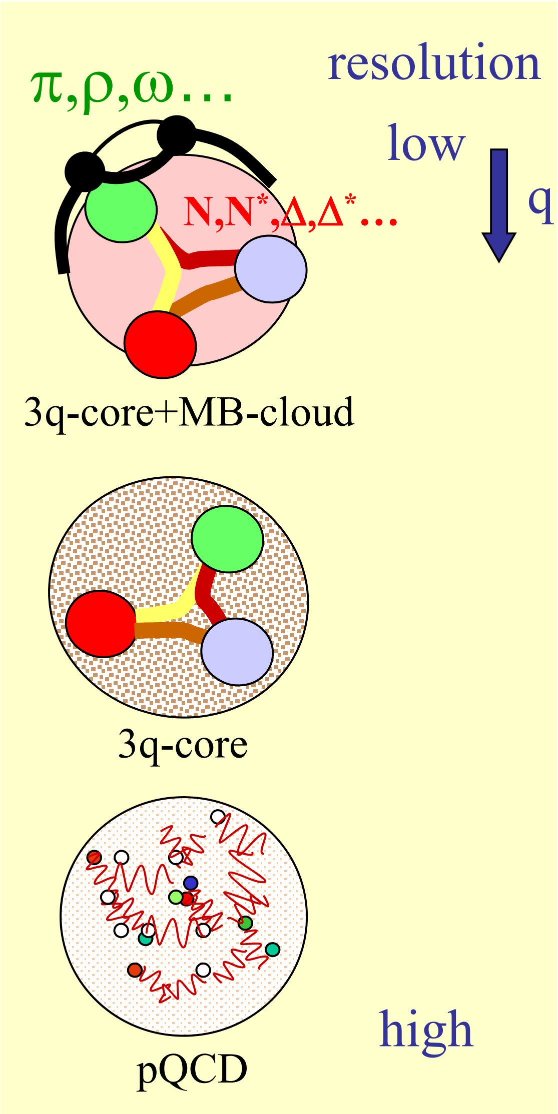
Small Sample of Recent Calculations

J. Arrington

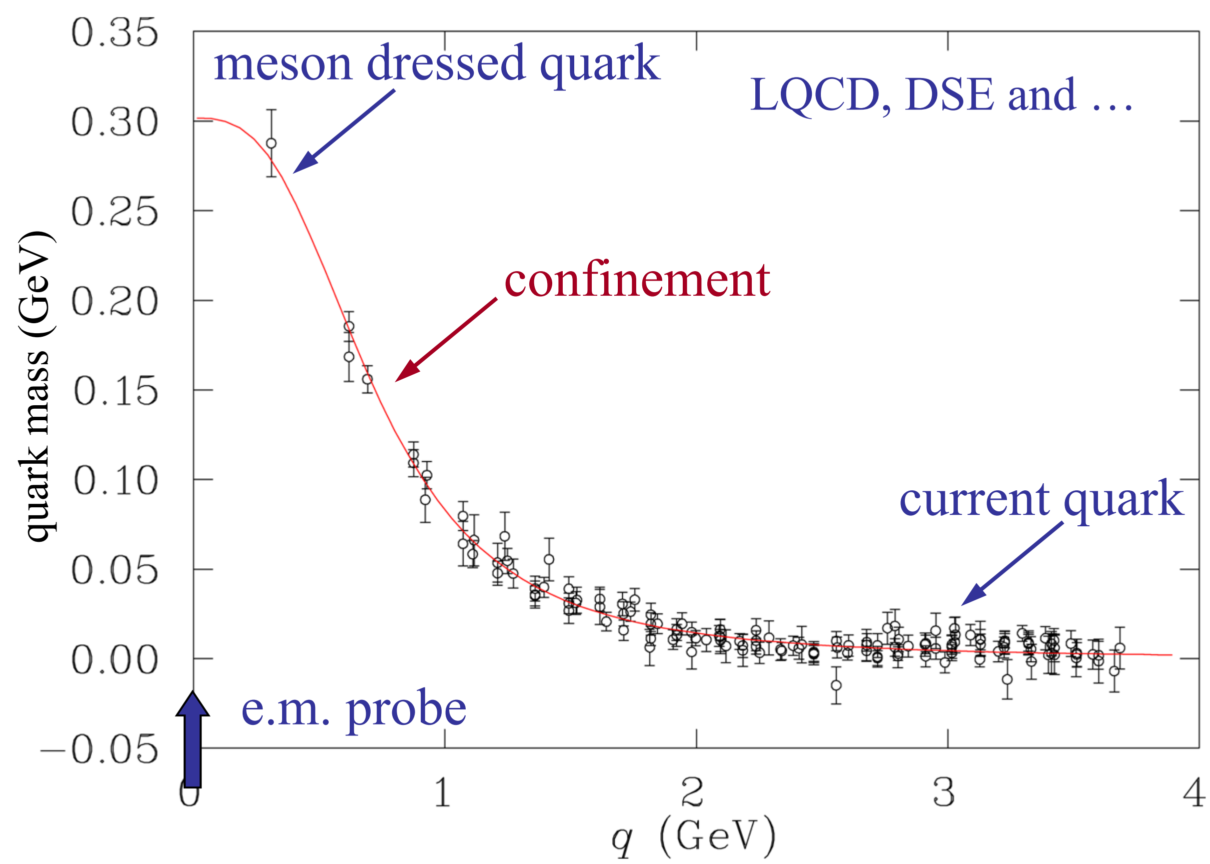


Transition Form Factors

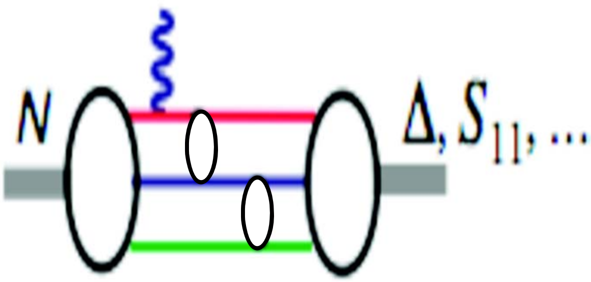
Hadron Structure with Electromagnetic Probes



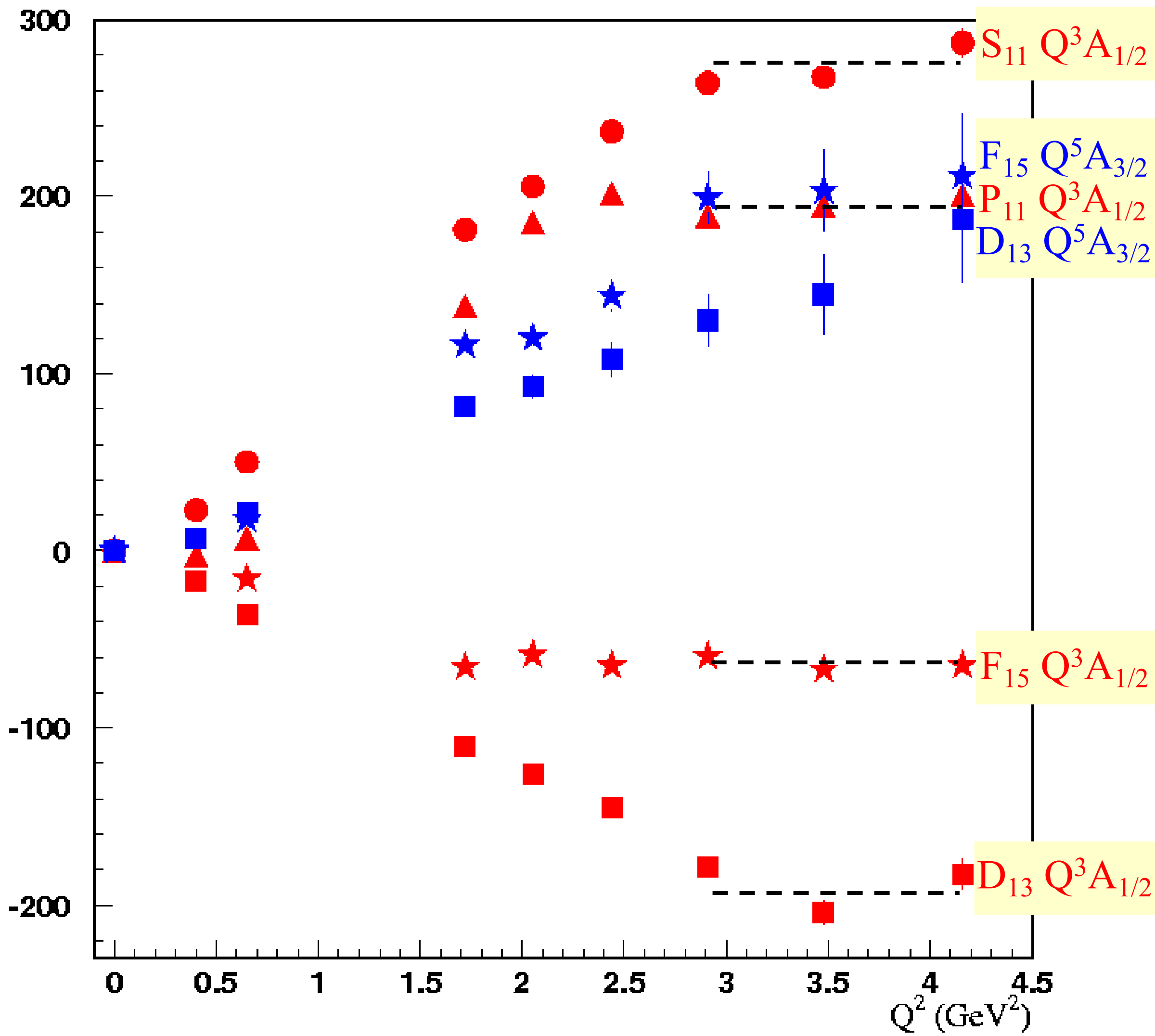
- Study the structure of the nucleon spectrum in the domain where dressed quarks are the major active degree of freedom.
- Explore the formation of excited nucleon states in interactions of dressed quarks and their emergence from QCD.



Evidence for the Onset of Scaling?

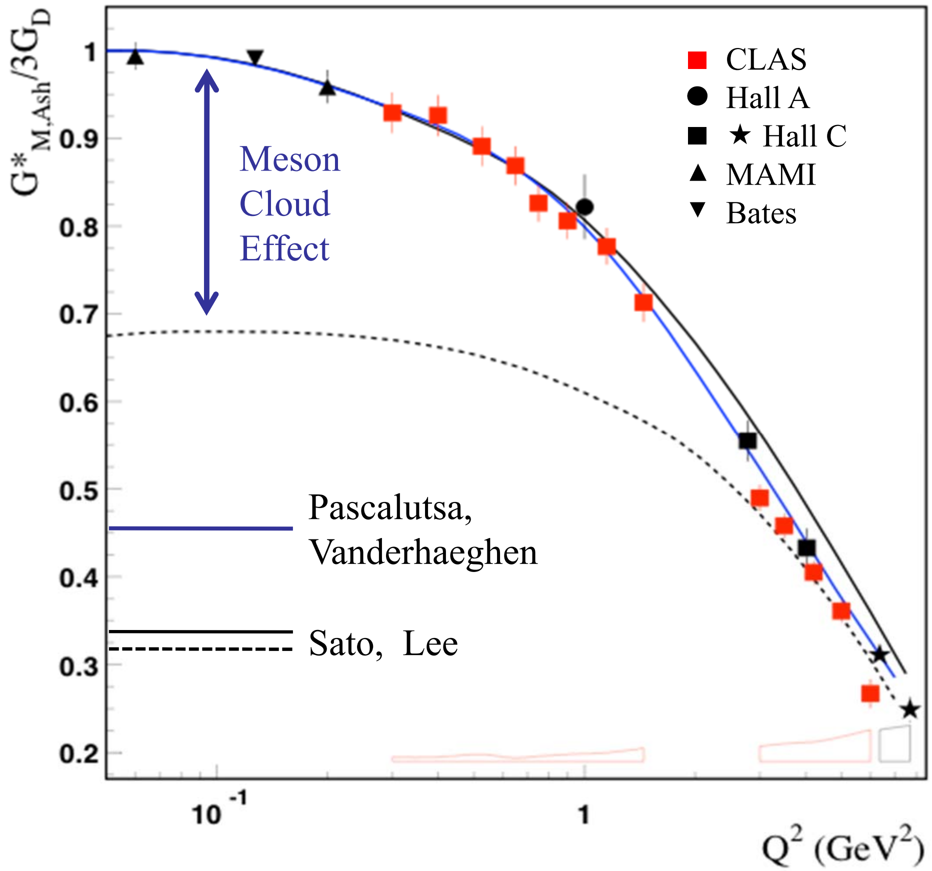


Phys. Rev. C80, 055203 (2009)

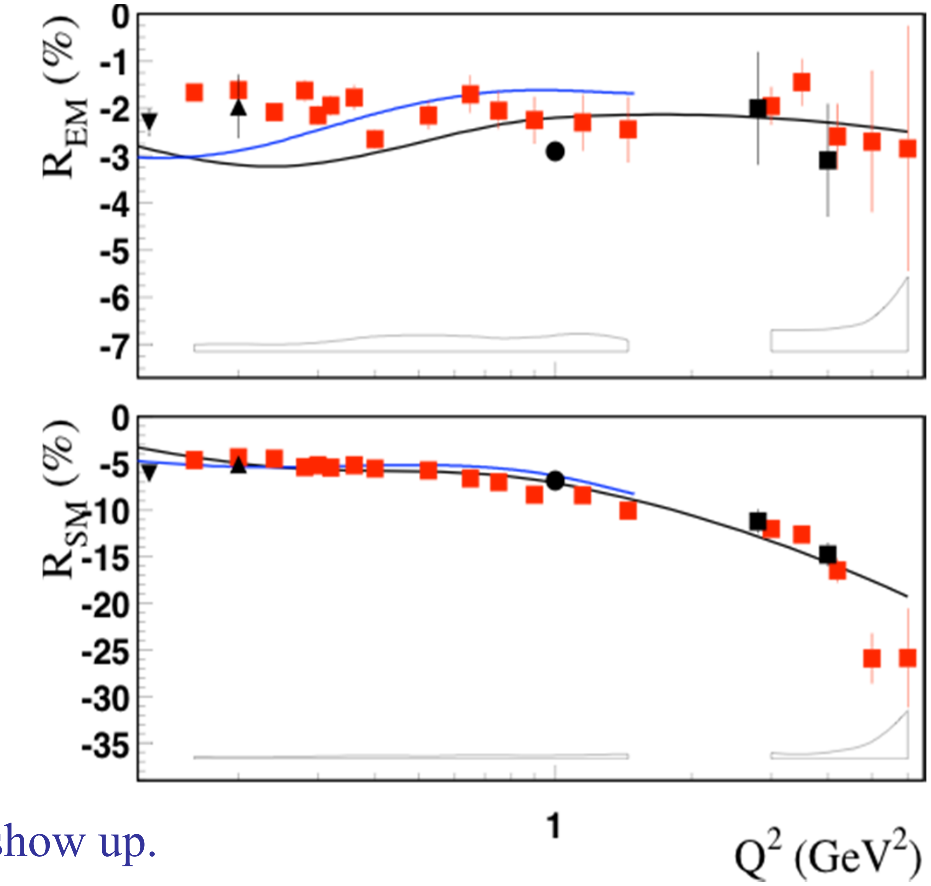


- $A_{1/2}$ α $1/Q^3$
- $A_{3/2}$ α $1/Q^5$
- G^*_M α $1/Q^4$

N → Δ Multipole Ratios R_{EM} , R_{SM}

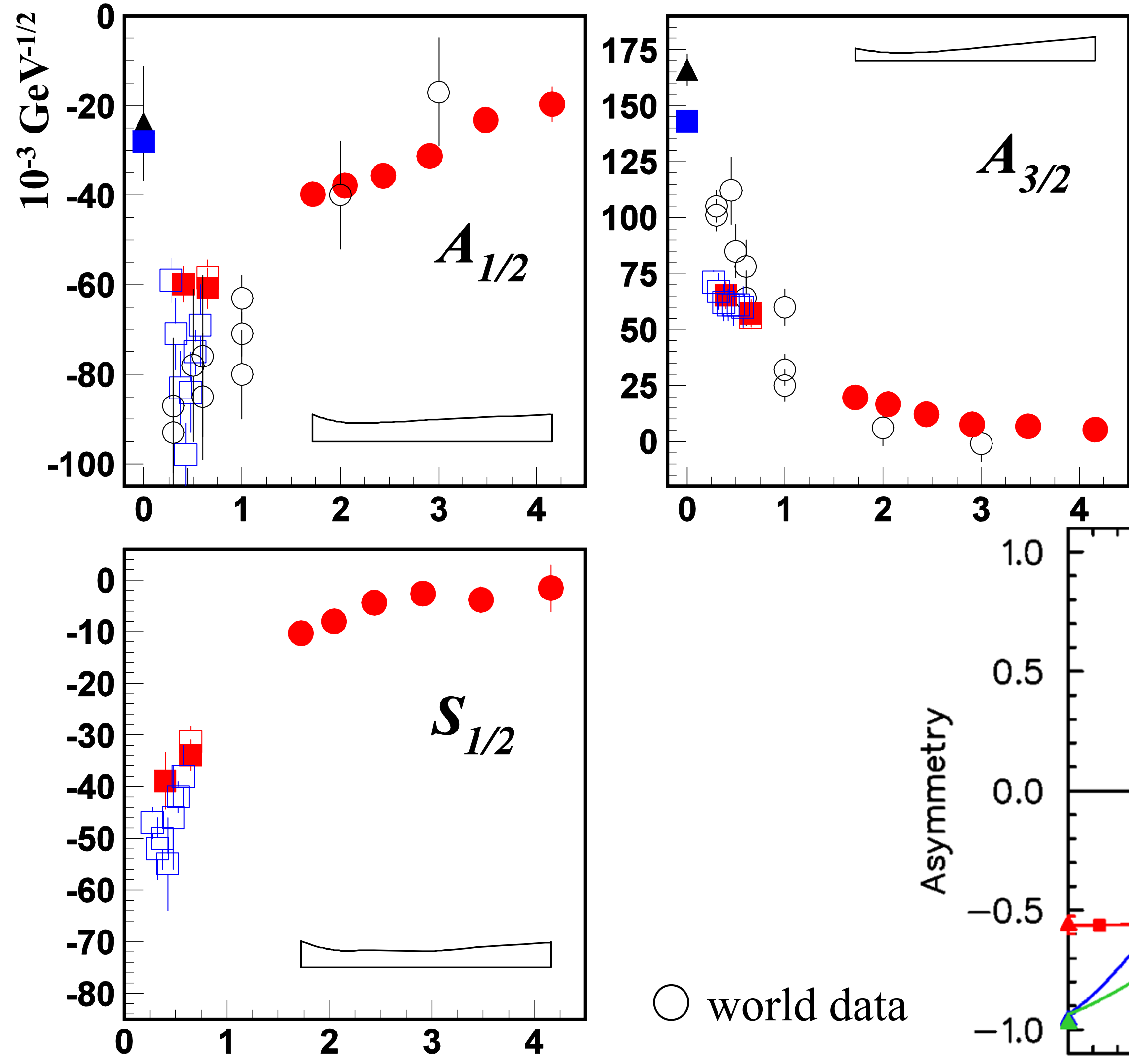


Phys. Rev. Lett. 97, 112003 (2006)



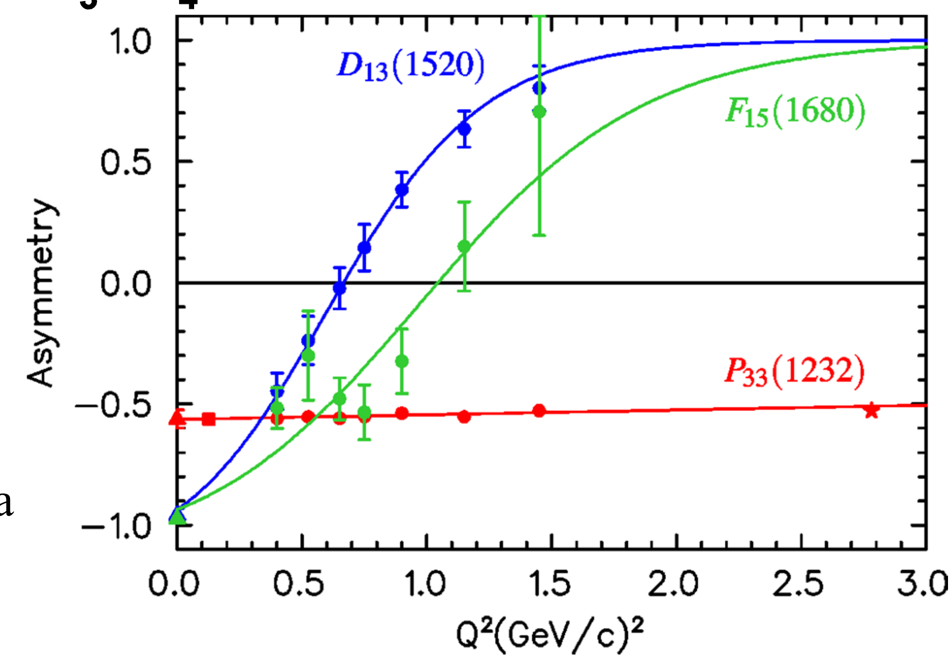
- New trend towards pQCD behavior does not show up.
  - $R_{EM} \rightarrow +1$
  - $G^*_M \rightarrow 1/Q^4$
- CLAS12 can measure G^*_M, R_{EM}, and R_{SM} up to Q^2~12 GeV^2.

$N(1520)D_{13}$ Helicity Asymmetry



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

L. Tiator



○ world data

▲ PDG estimation ●■ Nπ (UIM, DR)

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.

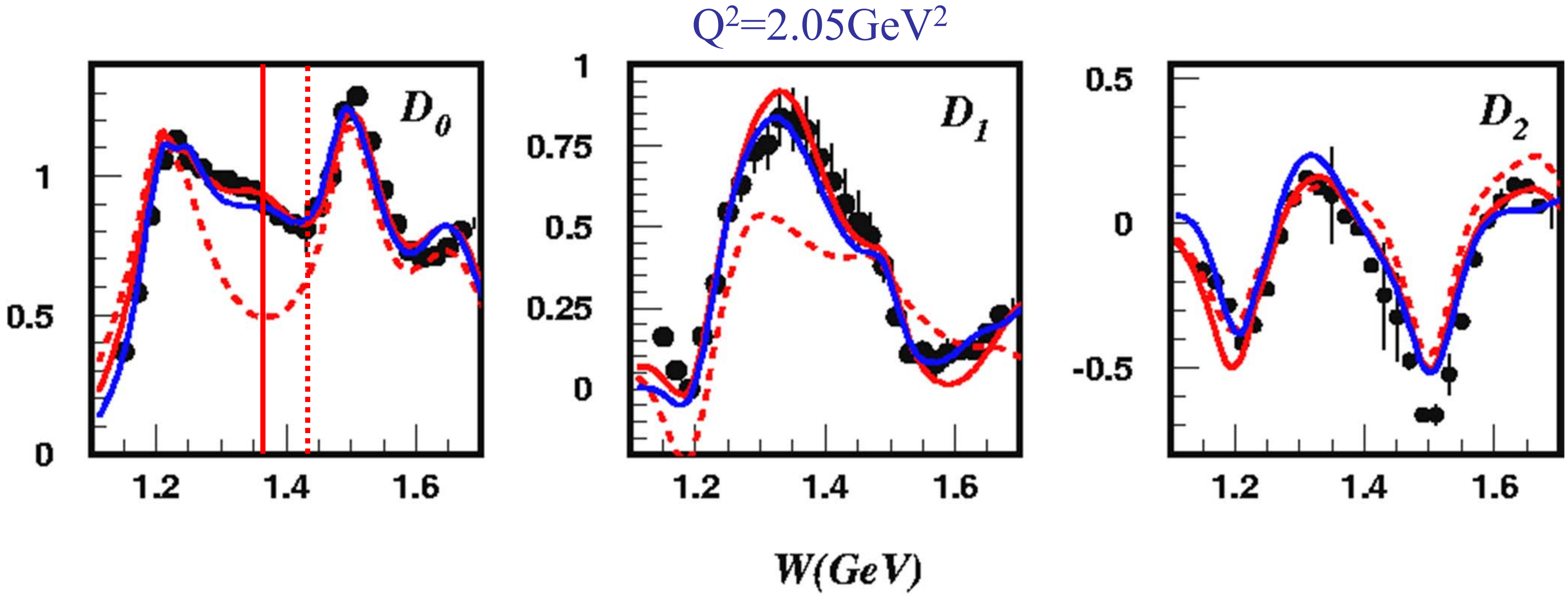
Fixed-*t* Dispersion Relations (DR)

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)



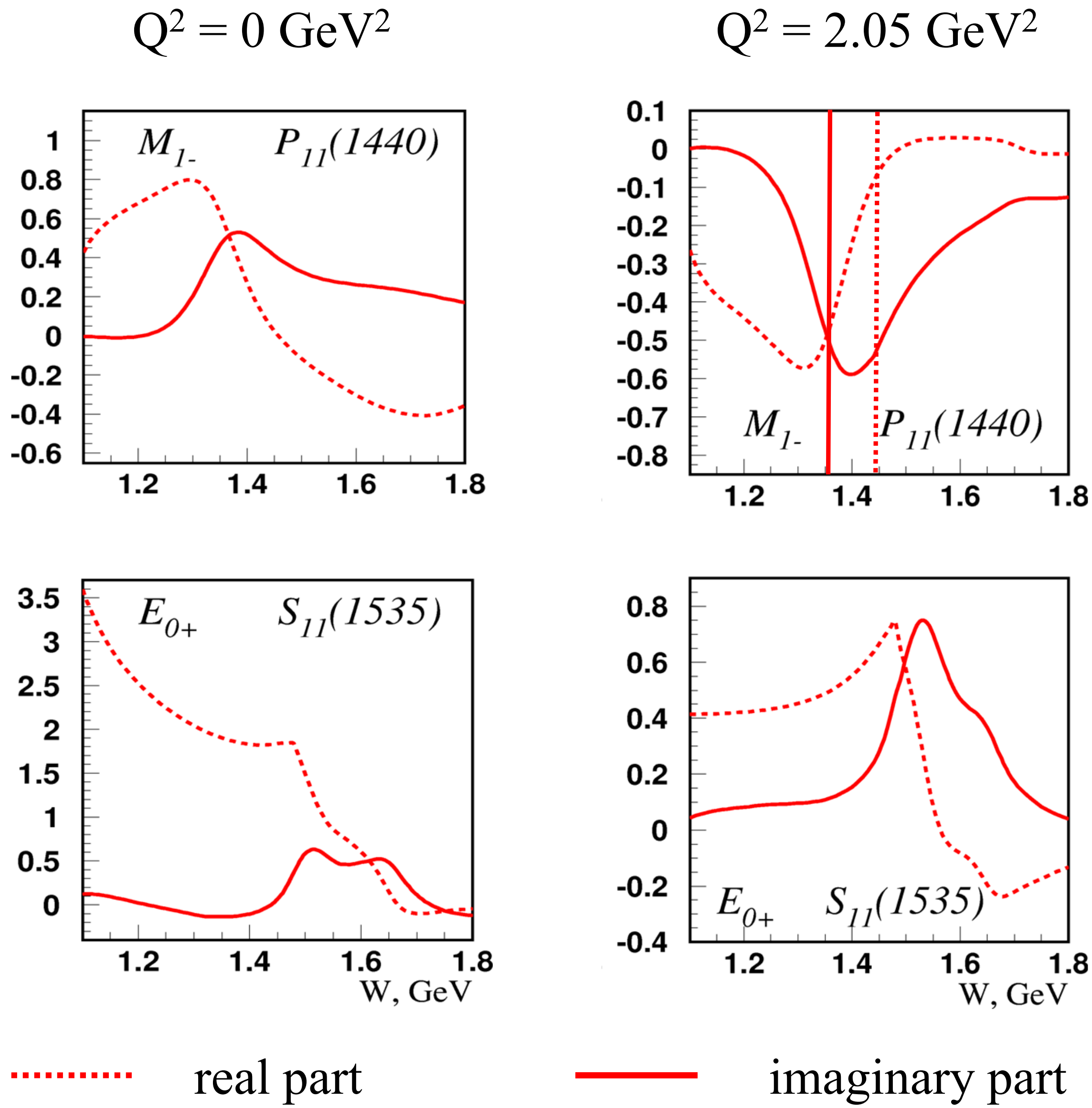
$$\sigma_T + \epsilon\sigma_L = \sum_{l=0}^{n} D_l^{T+L} P_l(\cos\theta_\pi^*)$$

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.

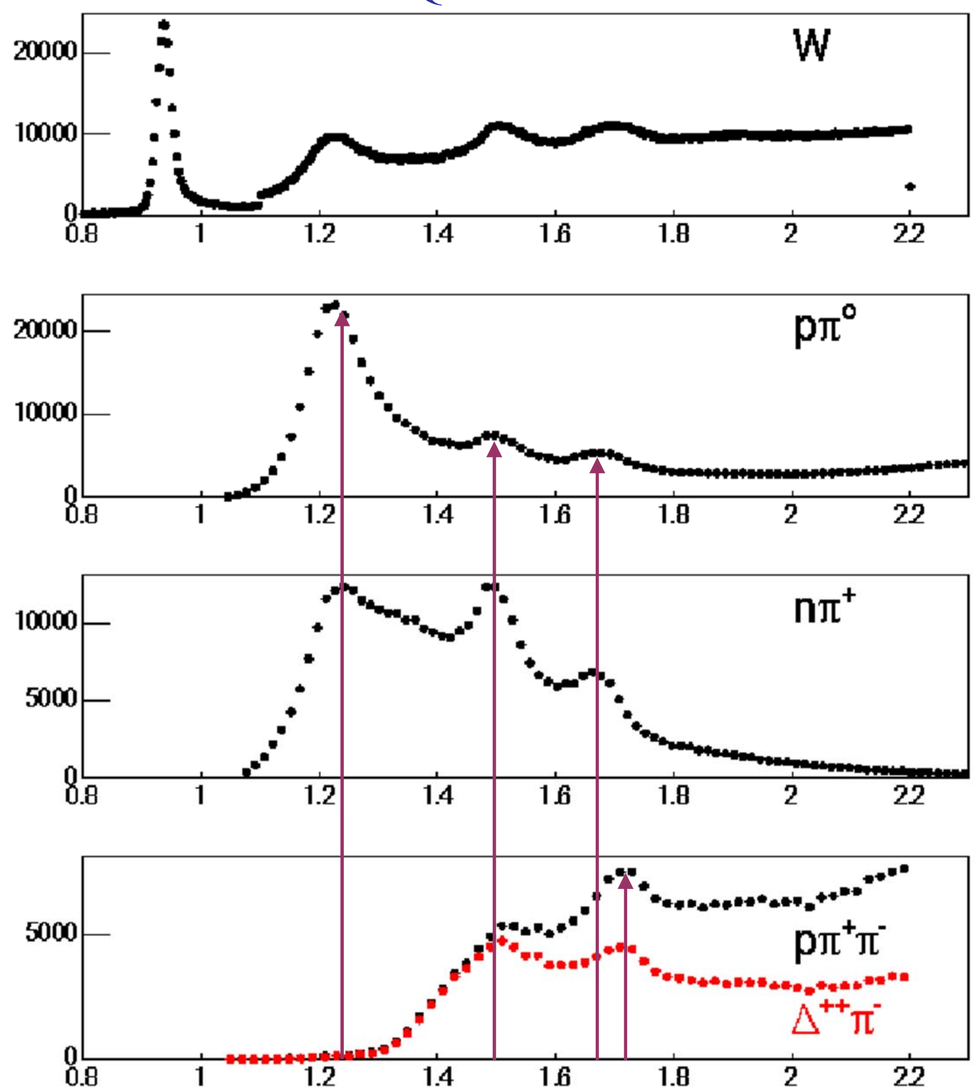
Energy-Dependence of π^+ Multipoles for P_{11}, S_{11}

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



Nucleon Resonances in Nπ and Nππ Electroproduction

$Q^2 < 4.0\,GeV^2$



p(e,e')X

p(e,e'p)π^0

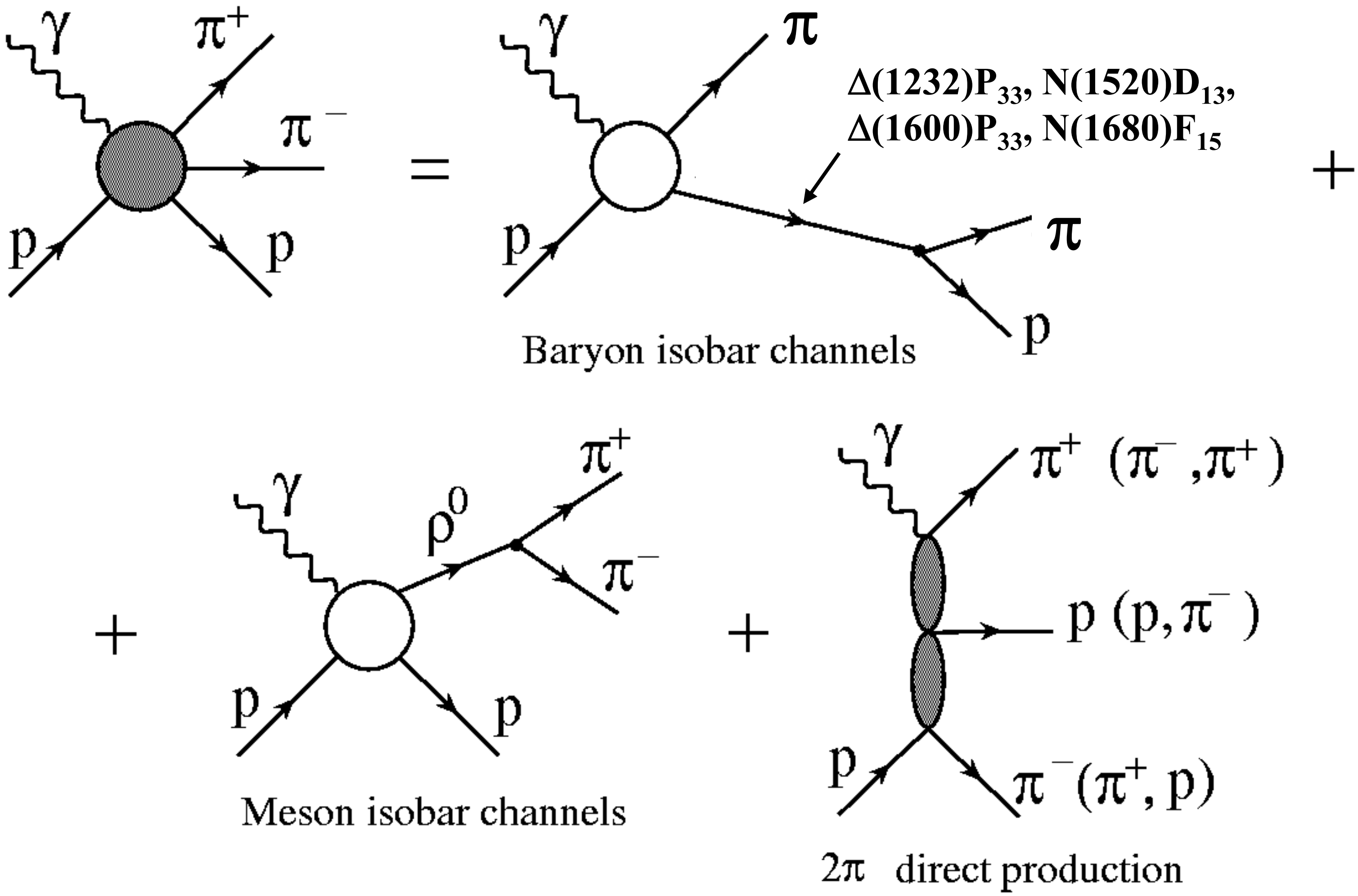
p(e,e'π^+)n

p(e,e'pπ^+)π^-

W in GeV

- 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

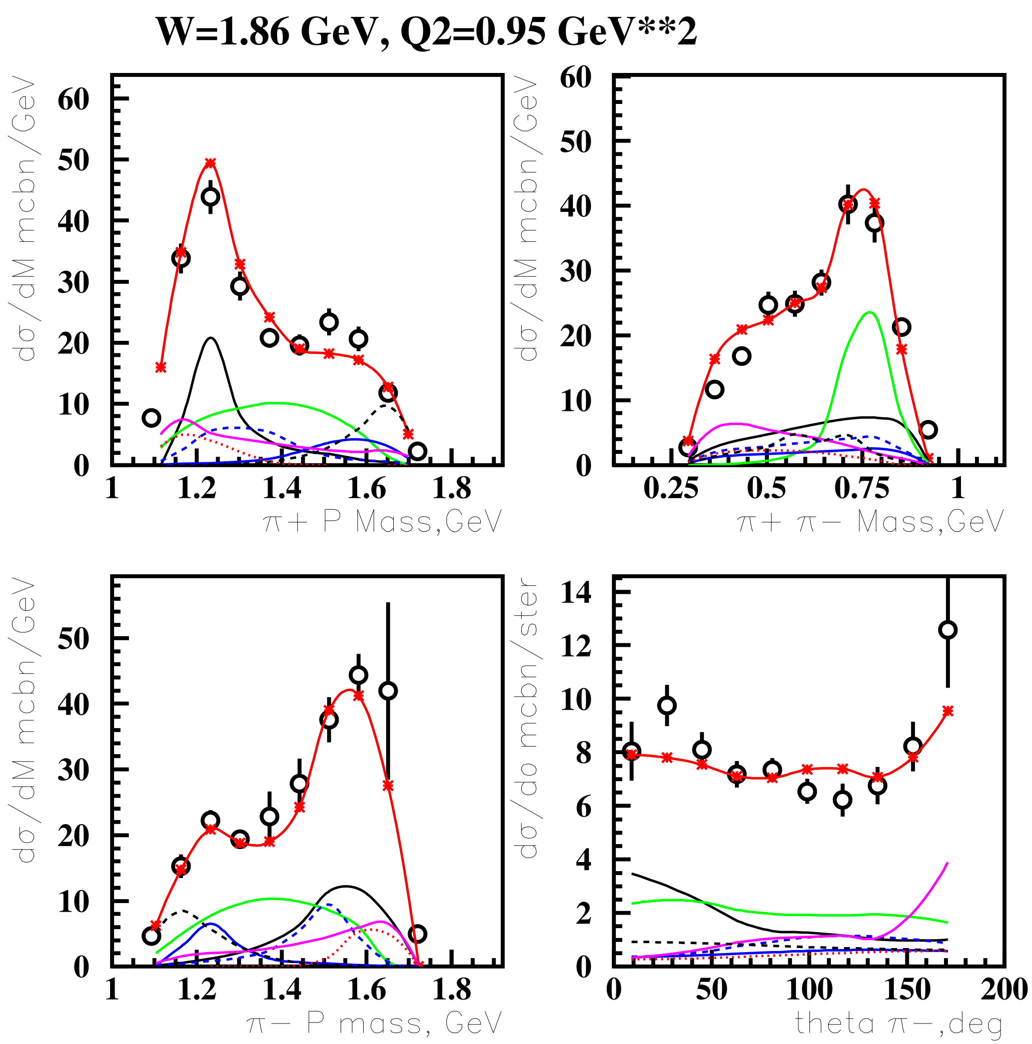


see White Paper Sec. VII

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

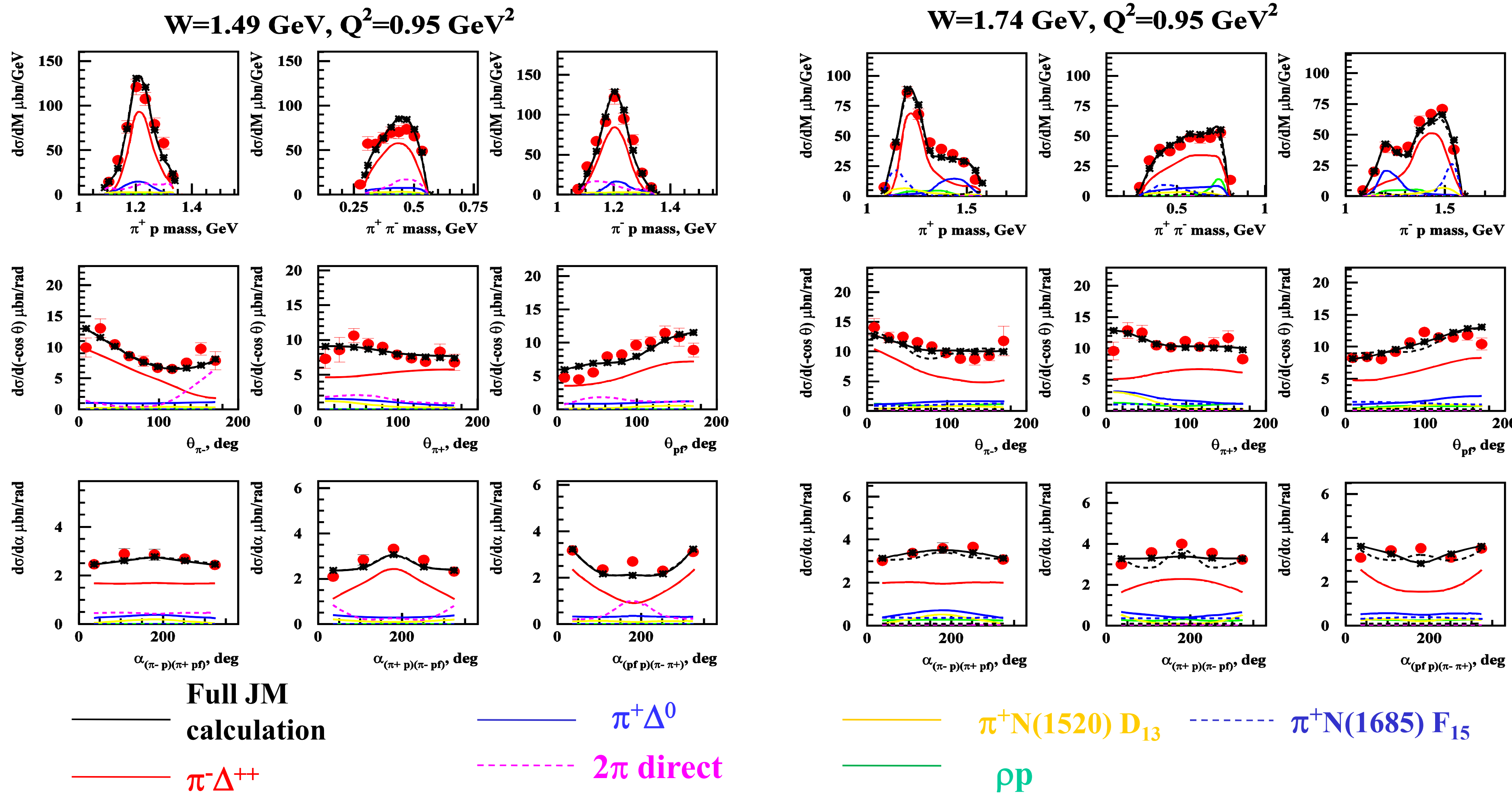
Isobar Model JM05

- 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



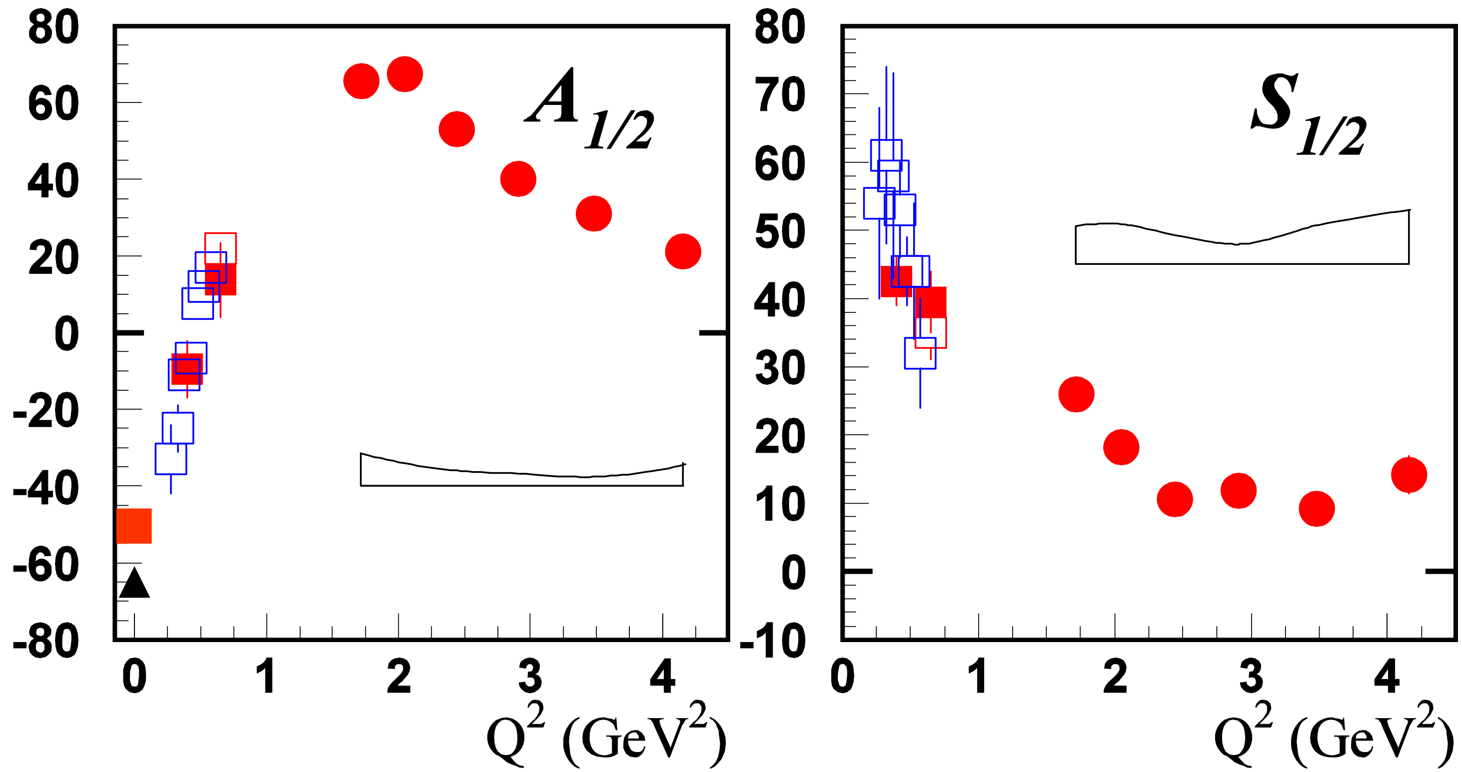
➢ The combined fit of nine single differential cross sections allowed to establish all significant mechanisms.

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



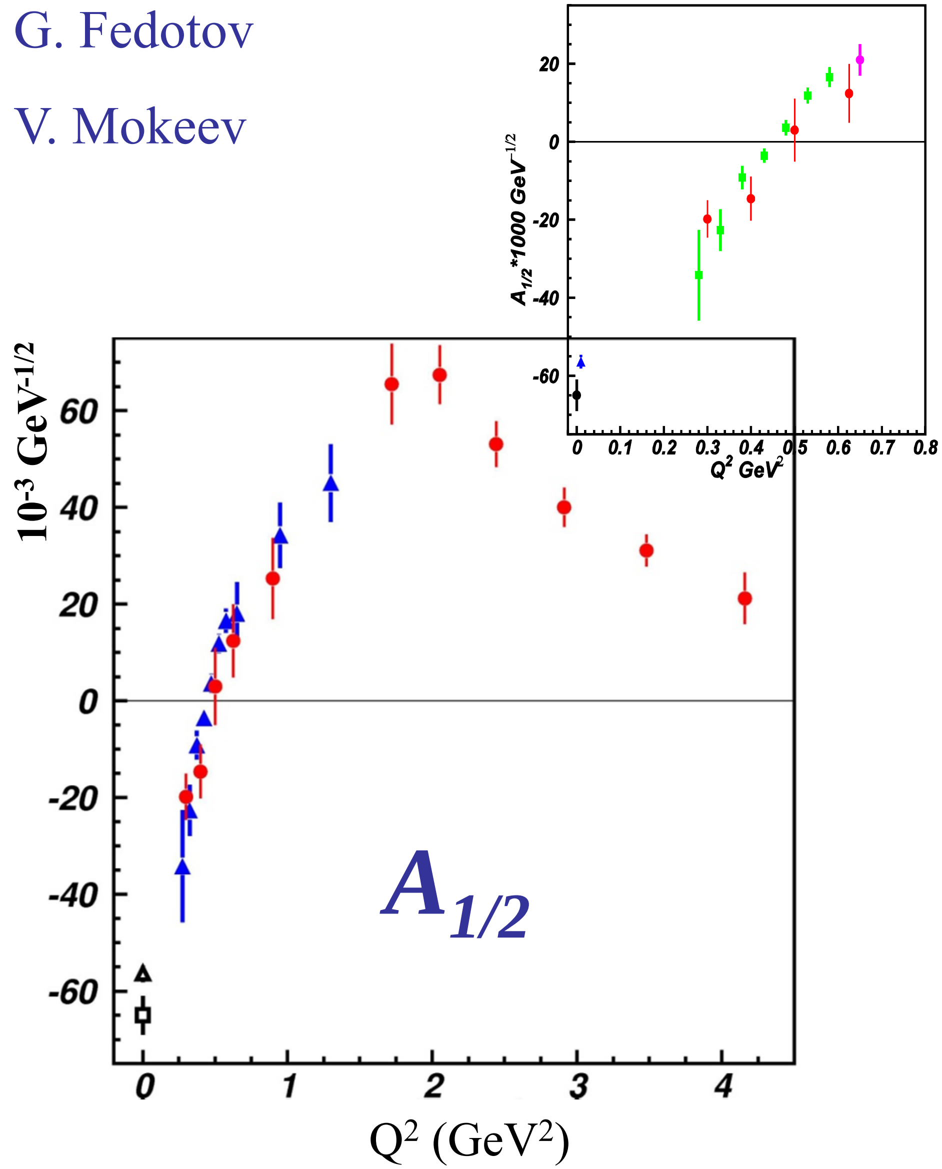
▲ PDG estimation ● ■ Nπ (UIM, DR) □ Nπ, Nππ combined analysis □ Nππ (JM)

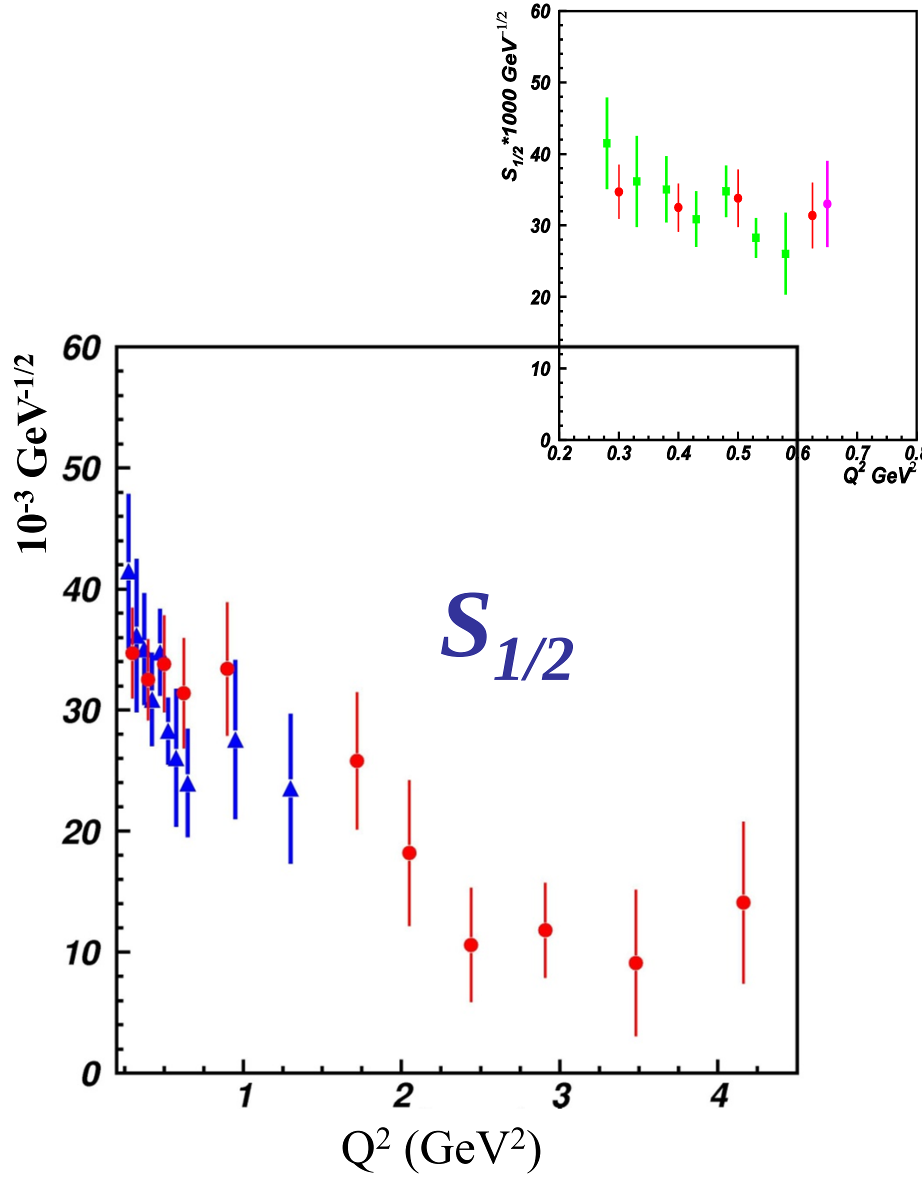
The good agreement on extracting the N* electrocouplings between the two exclusive channels (1π/2π) – having fundamentally different mechanisms for the nonresonant background – provides evidence for the reliable extraction of N* electrocouplings.

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

G. Fedotov

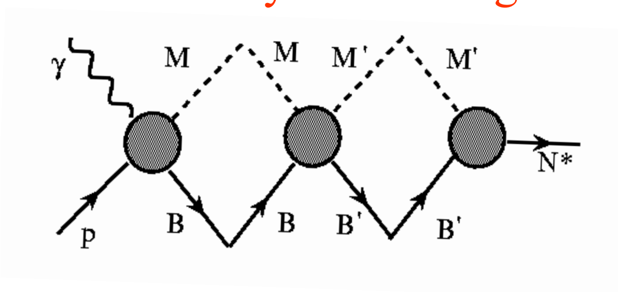
V. Mokeev





Progress in Experiment and Phenomenology

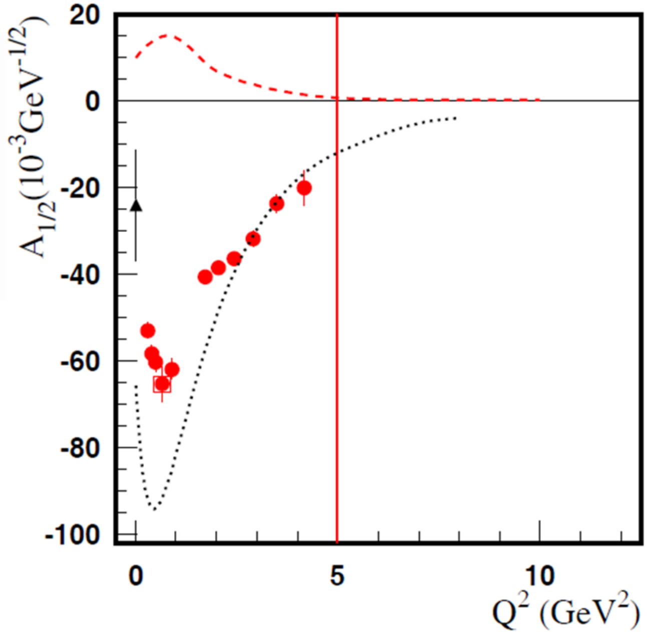
Meson-Baryon Dressing



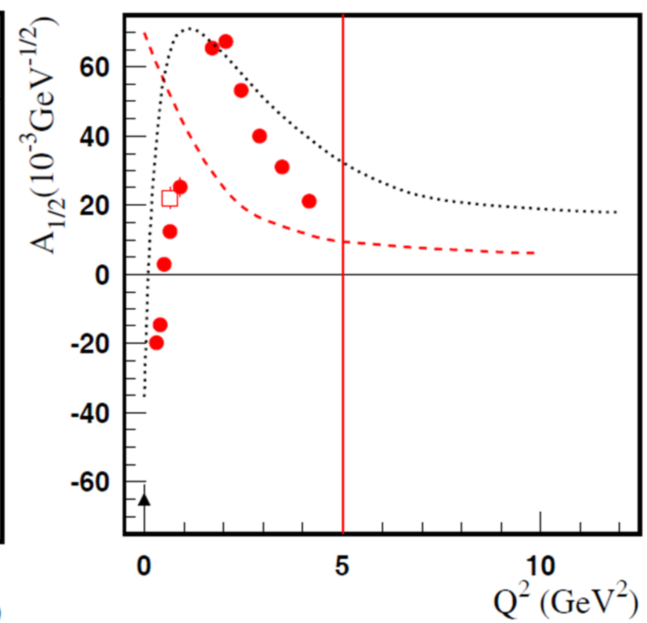
absolute meson-baryon cloud amplitudes (EBAC)

quark core contributions (constituent quark models)

$D_{13}(1520)$



$P_{11}(1440)$

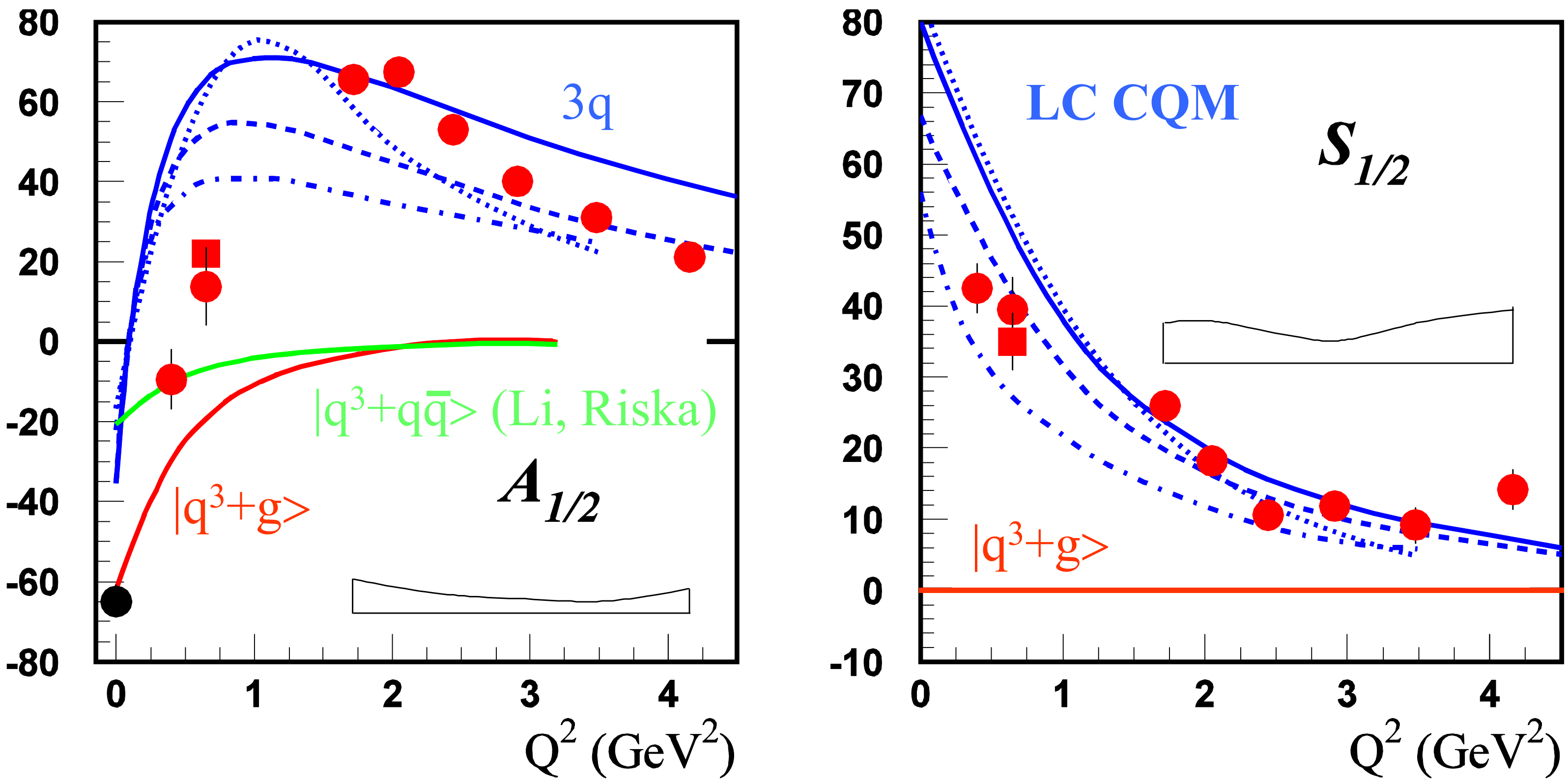


CLAS: Nπ and Nπ/Nππ combined (Phys. Rev. C80, 055203, 2009)

➢ 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.

Constituent Quark Models (CQM)



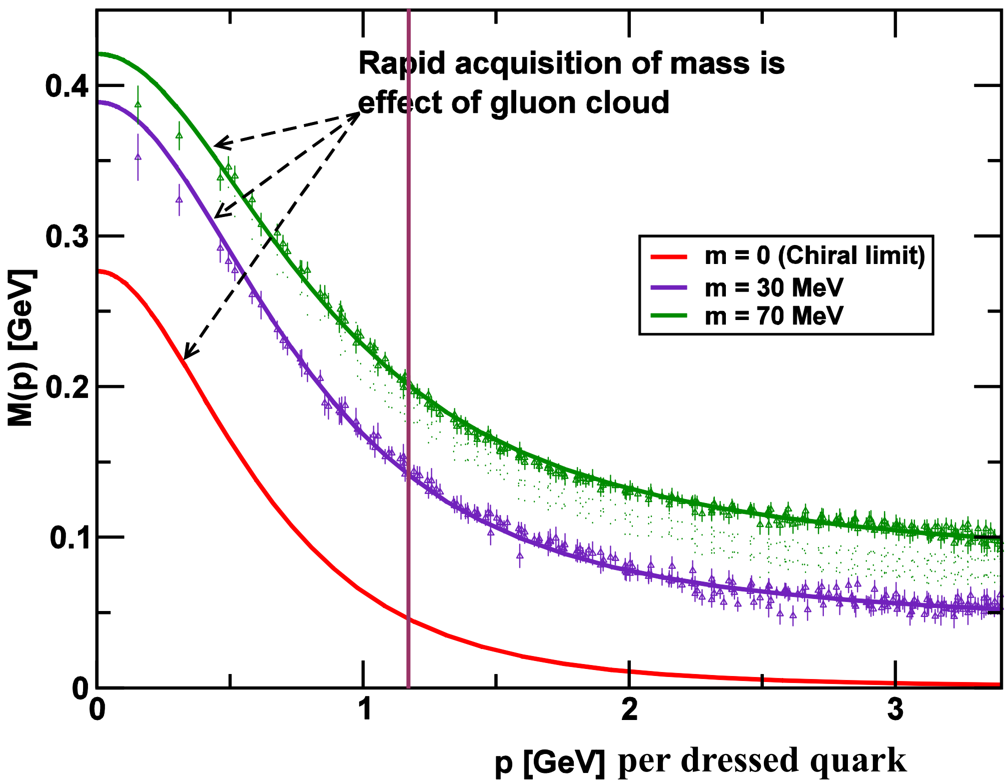
N(1440)P_{11}: ● PDG value ● Nπ ■ Nπ, Nππ combined analysis

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



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.

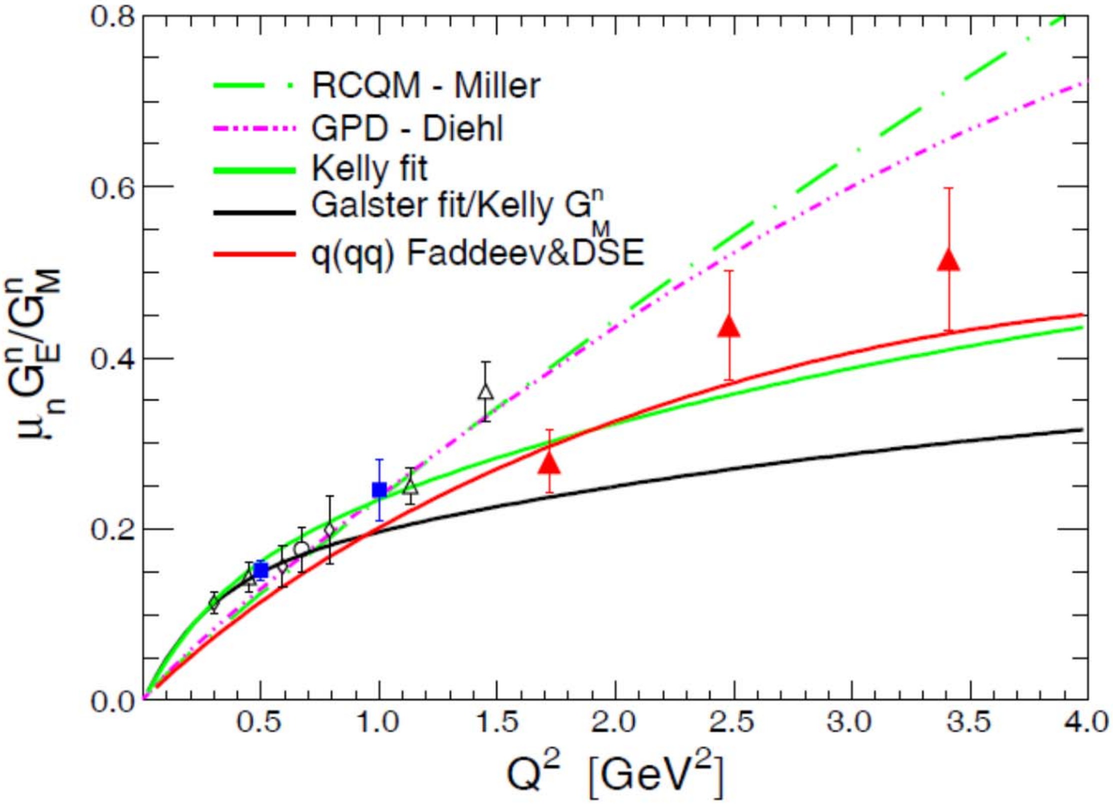
DSE: lines and LQCD: triangles

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

The data on N* electrocouplings at $5<Q^2<12\ GeV^2$ 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.

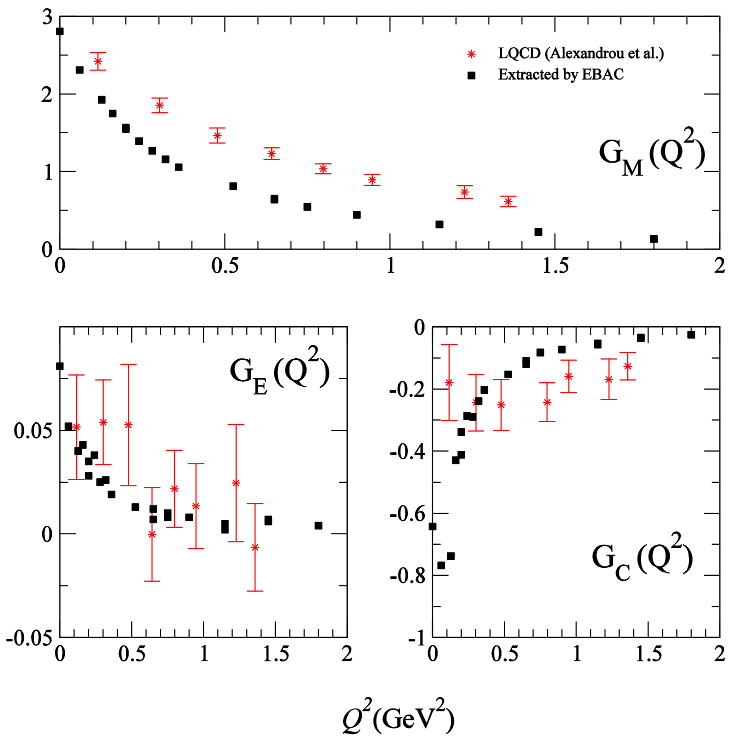
The Faddeev-DSE calculation is very sensitive to the momentum dependence of the dressed-quark propagator.

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.

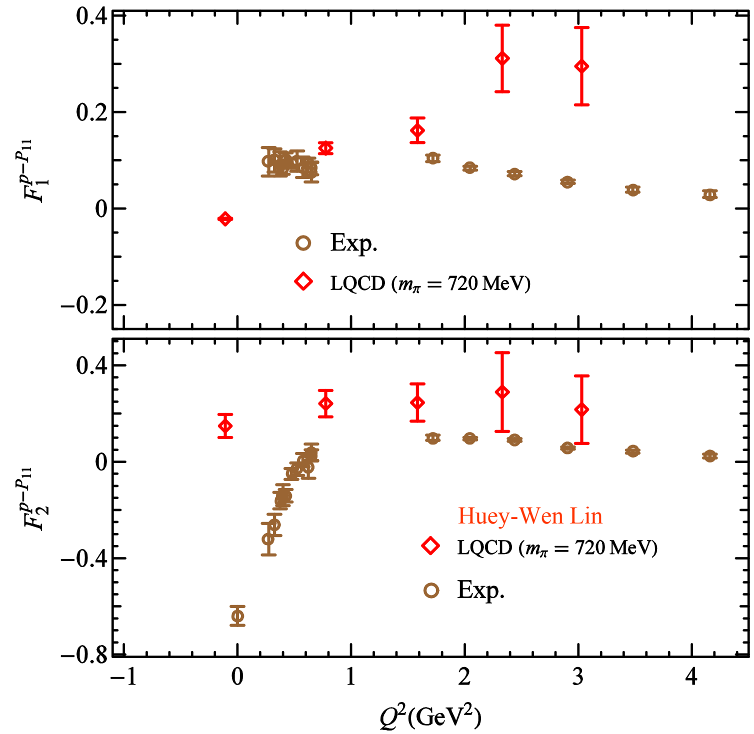
see White Paper Sec. III

Resonance Electrocouplings in Lattice QCD

Δ(1232)P_{33}



N(1440)P_{11}

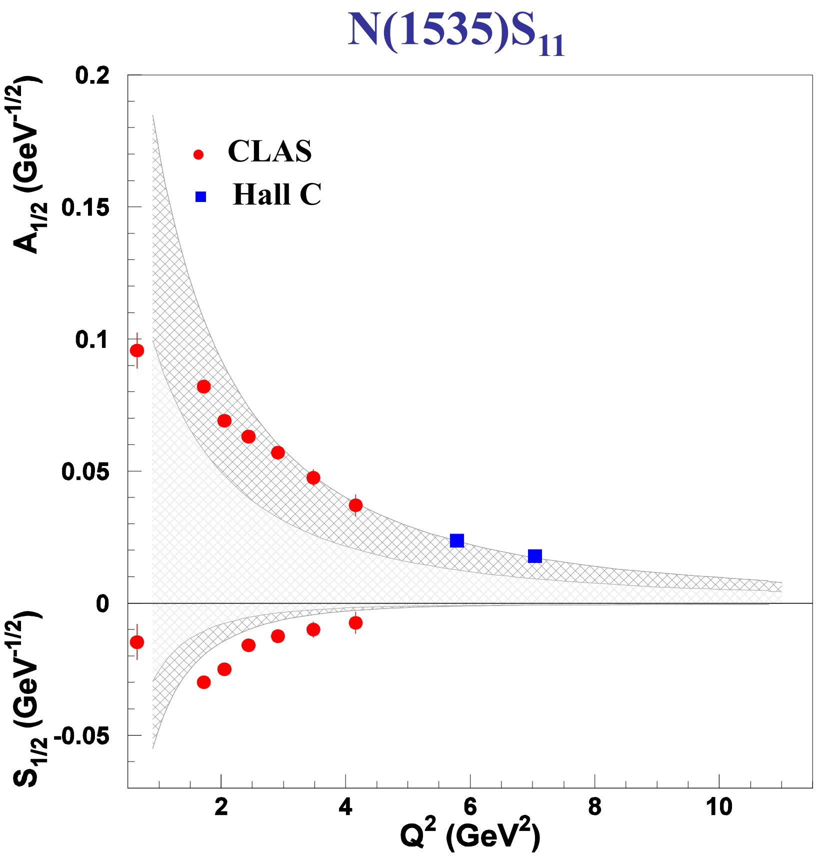


LQCD calculations of the Δ(1232)P_{33} and N(1440)P_{11} transitions have been carried out with large π-masses.

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



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.

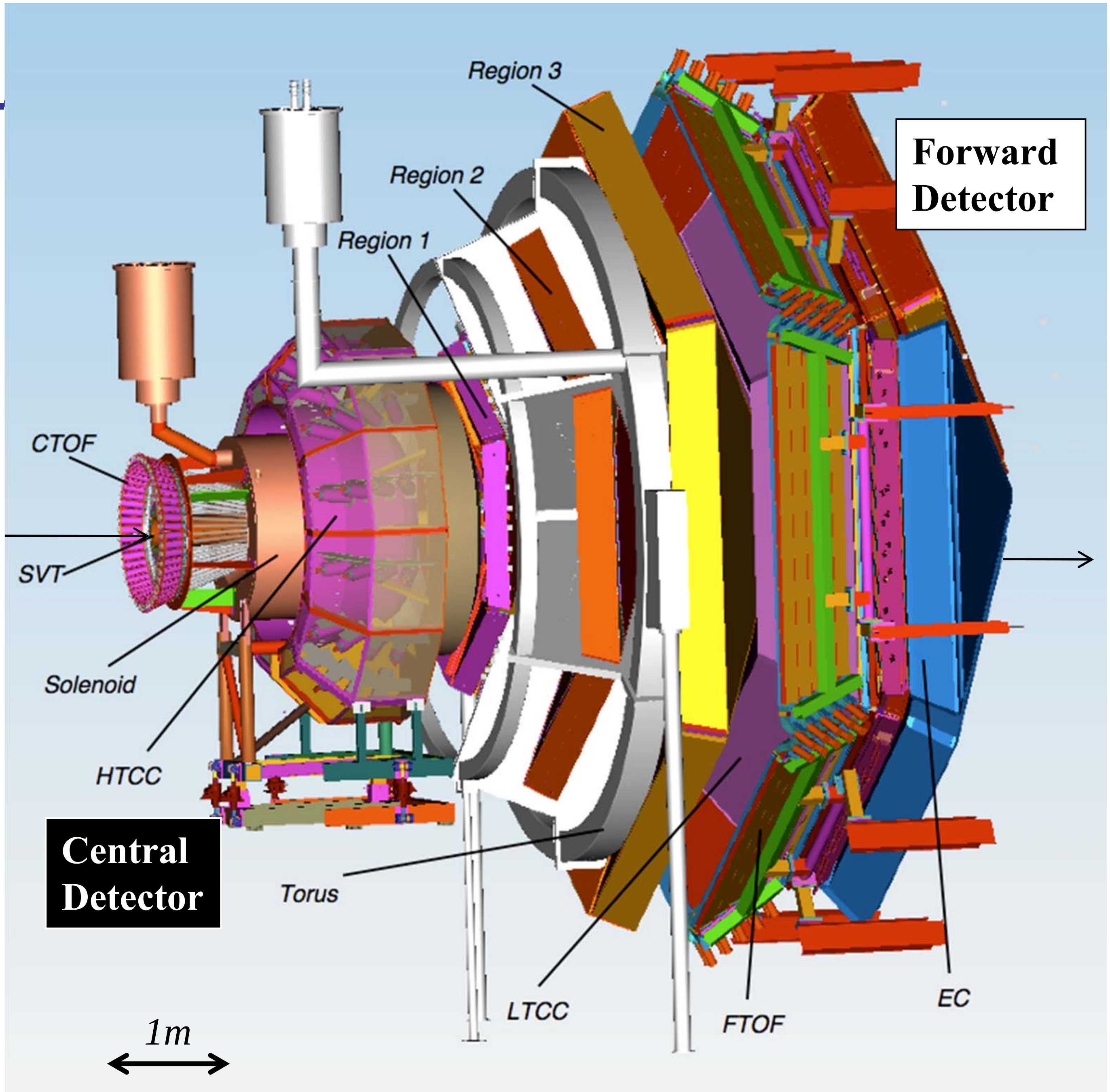
By the time of the upgrade electrocouplings of others N*s will be evaluated. These studies are part of the commitment of the Univ. of Regensburg group in support of this proposal.

see White Paper Sec. V

CLAS12

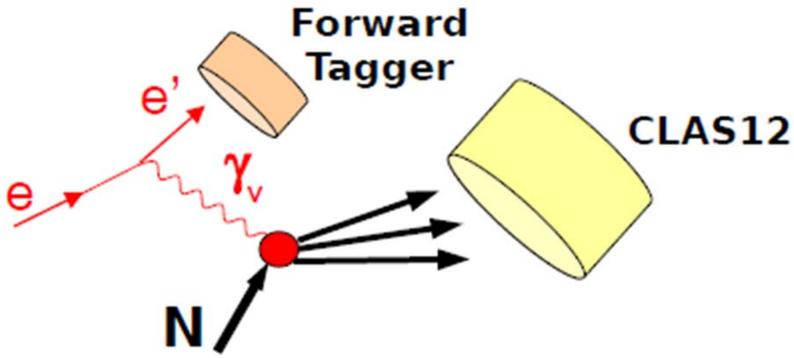
- Luminosity > 10^{35} cm^{-2}s^{-1}
- Hermeticity
- Polarization

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



Forward Photon Tagger for Spectroscopy

M. Battaglieri



$E_{scattered}$	0.5 - 4.5 GeV
θ	2.5^o - 4.5^o
ϕ	0^o - 360^o
ν	6.5 - 10.5 GeV
Q^2	0.01 - 0.3 GeV^2 ($< Q^2 >$ 0.1 GeV^2)
W	3.6 - 4.5 GeV

Calorimeter + hodoscope + tracker

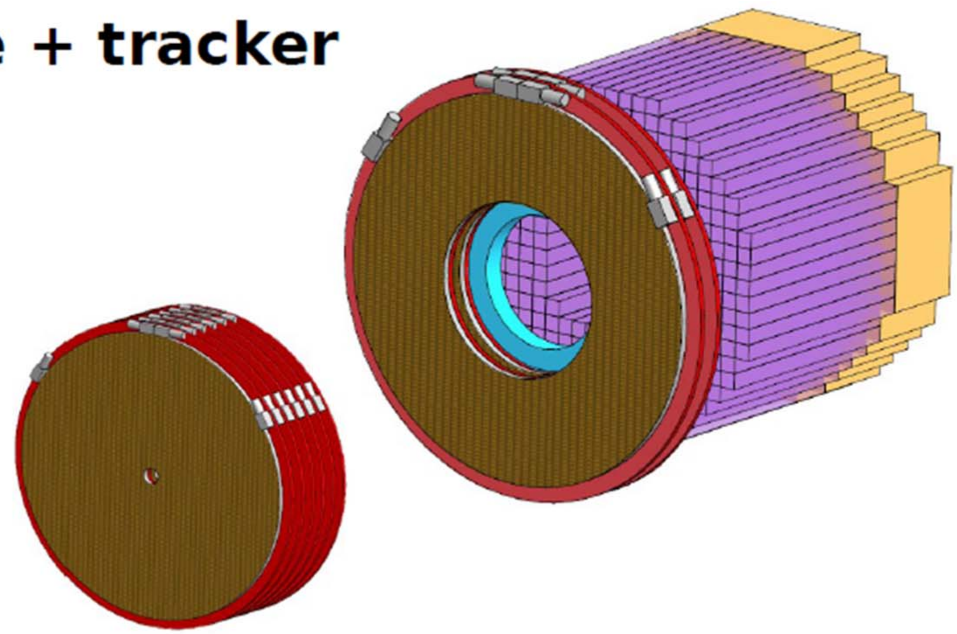
Electron energy/momentum

- Photon energy (ν=E-E')
- Polarization $\varepsilon^{-1} \sim 1 + \nu^2/2EE'$

Veto for photons

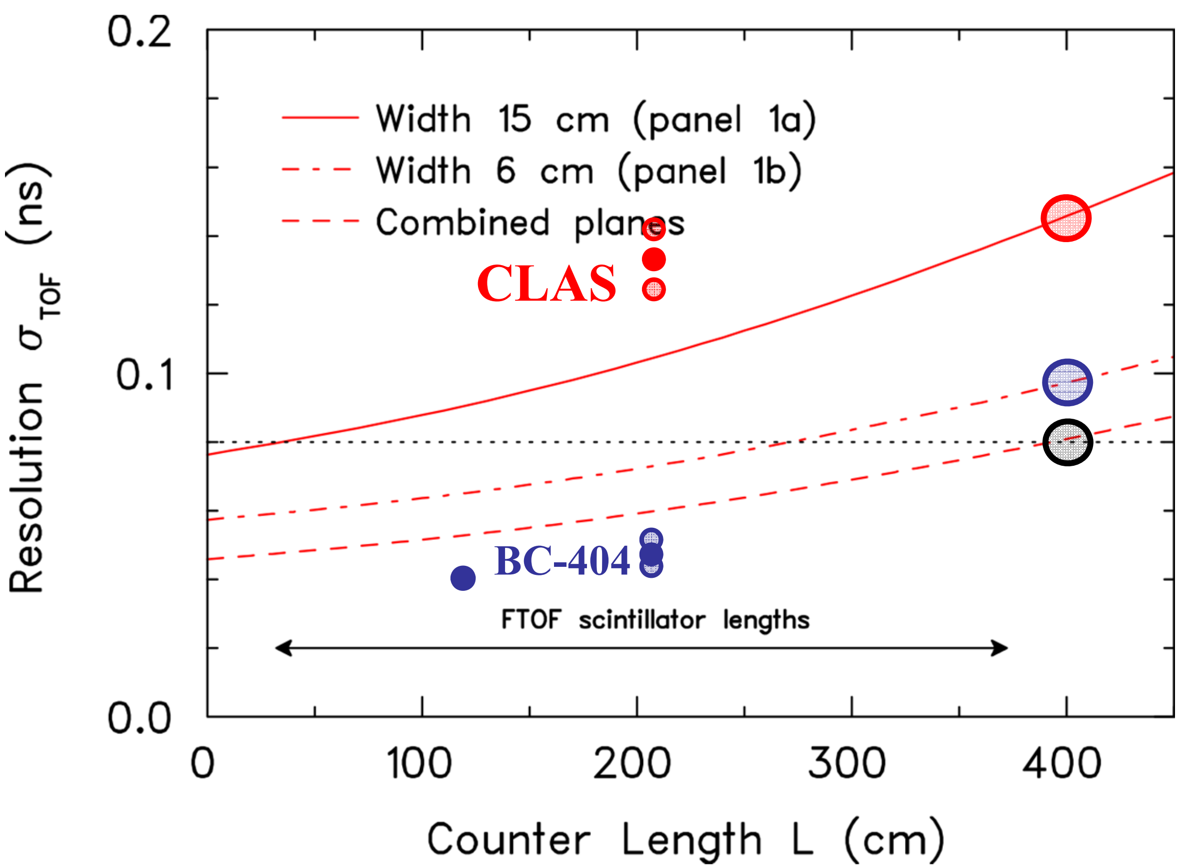
Electron angles

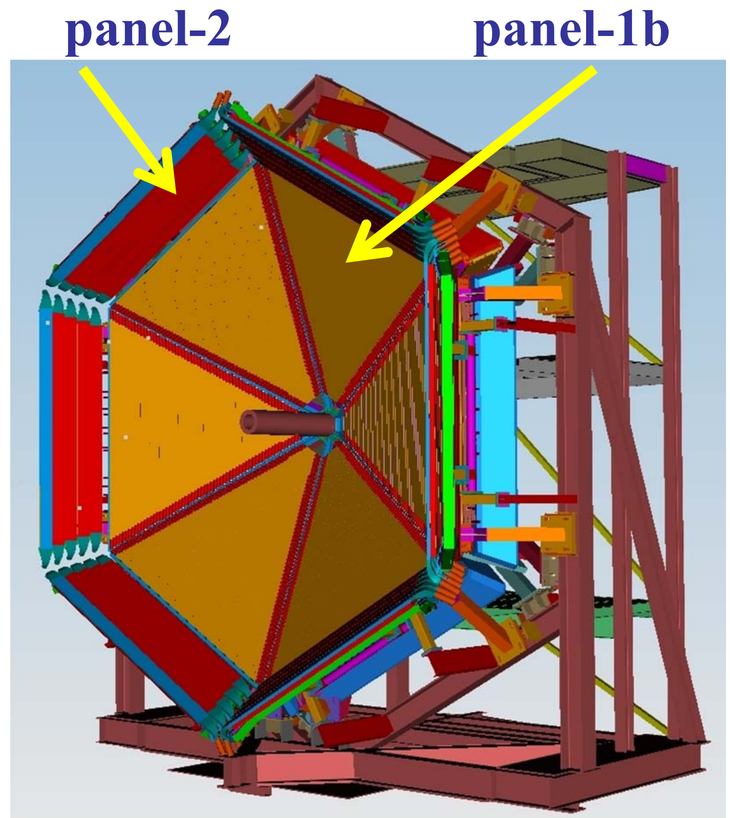
- Q^2= 4 E E' $\sin^2 \vartheta/2$
- Scattering plane

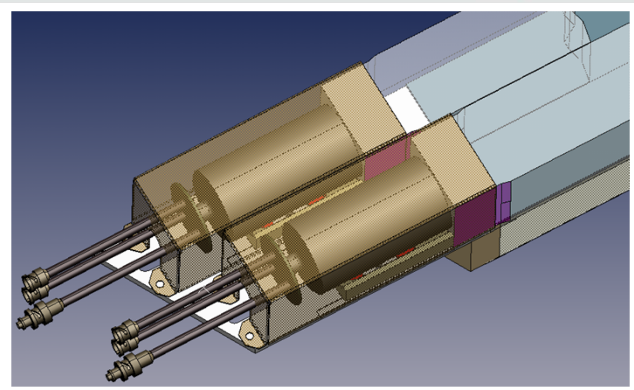


Rates in the forward tagger $L_e \sim 10^{35}$ cm^{-2} s^{-1} ($N_\gamma \sim 5\ 10^8\ \gamma$/s)

New Forward Time of Flight Detector for CLAS12

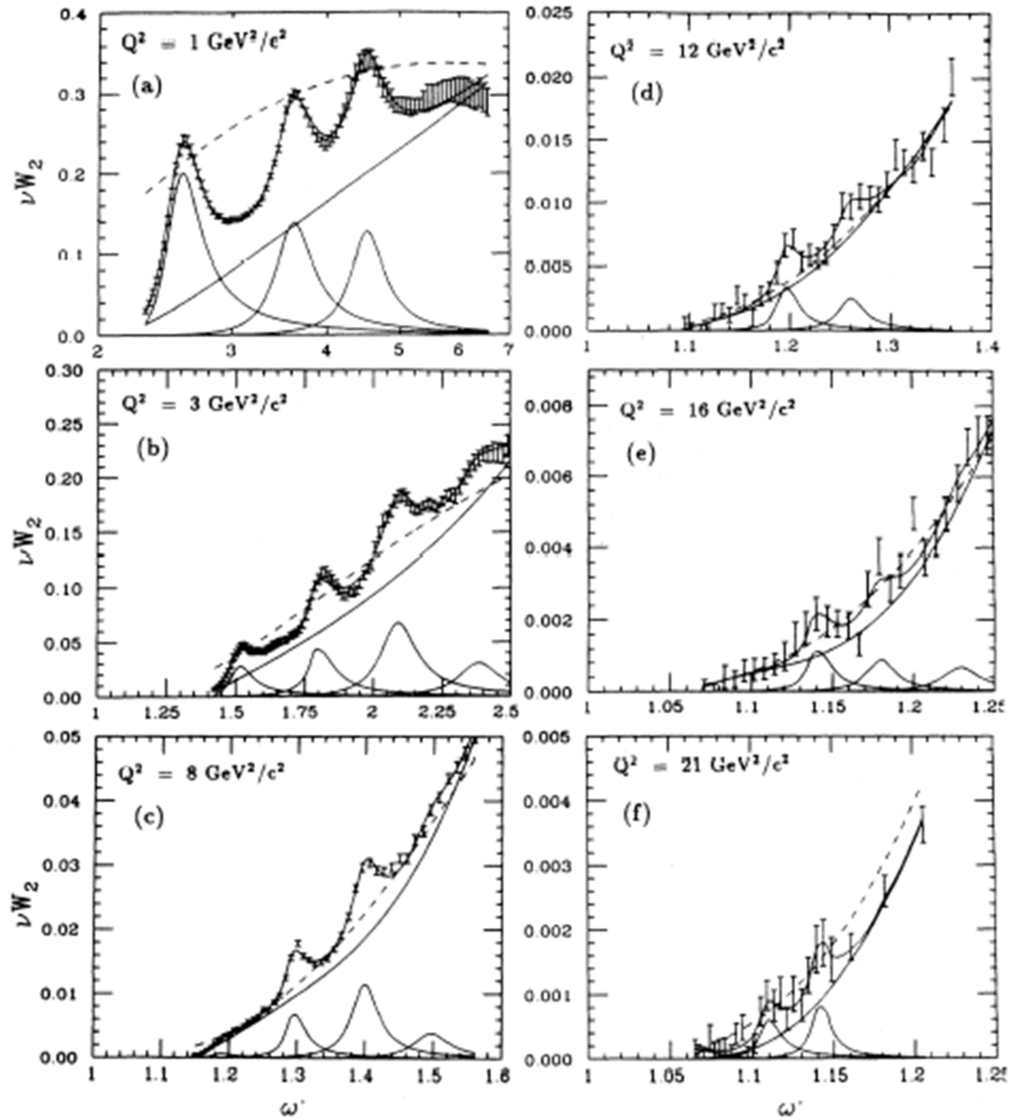


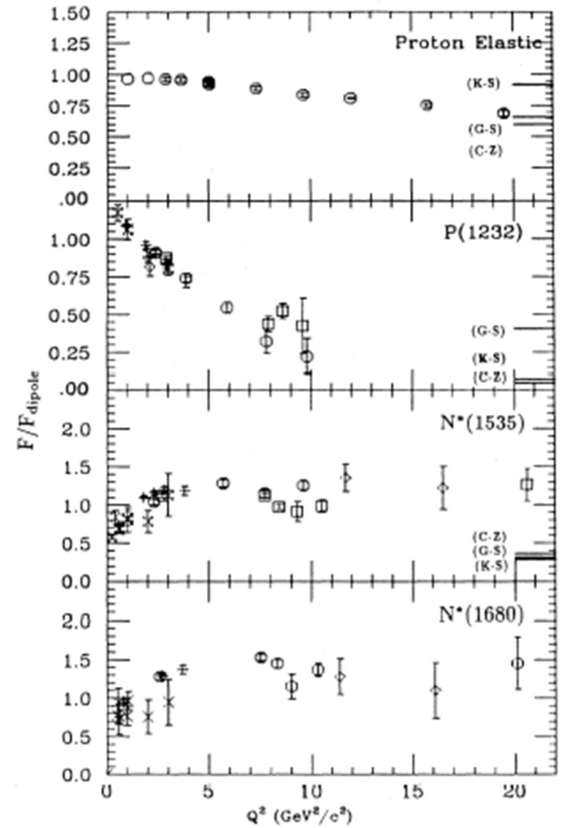




World-record time resolution of 44 ns
averaged over the full length of 210 cm

Inclusive Structure Function in the Resonance Region





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

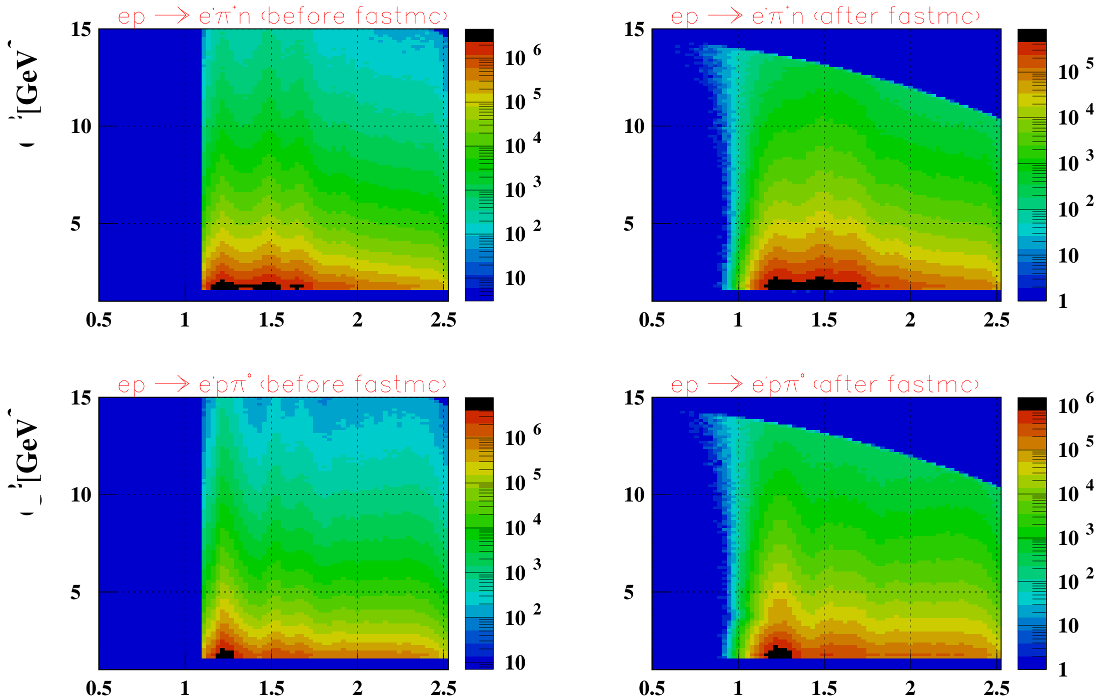
CLAS 12 Kinematic Coverage and Counting Rates

Genova-EG

(e',π^+) detected

Genova-EG

(e',p) detected



(E,Q^2)	(5.75 GeV, 3 GeV^2)	(11 GeV, 3 GeV^2)	(11 GeV, 12 GeV^2)
$N^{n\pi+}$	$1.41*10^5$	$6.26*10^6$	$5.18*10^4$
$N^{p\pi0}$	-	$4.65*10^5$	$1.45*10^4$
$N^{p\eta}$	-	$1.72*10^4$	$1.77*10^4$

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

40 days

PAC35

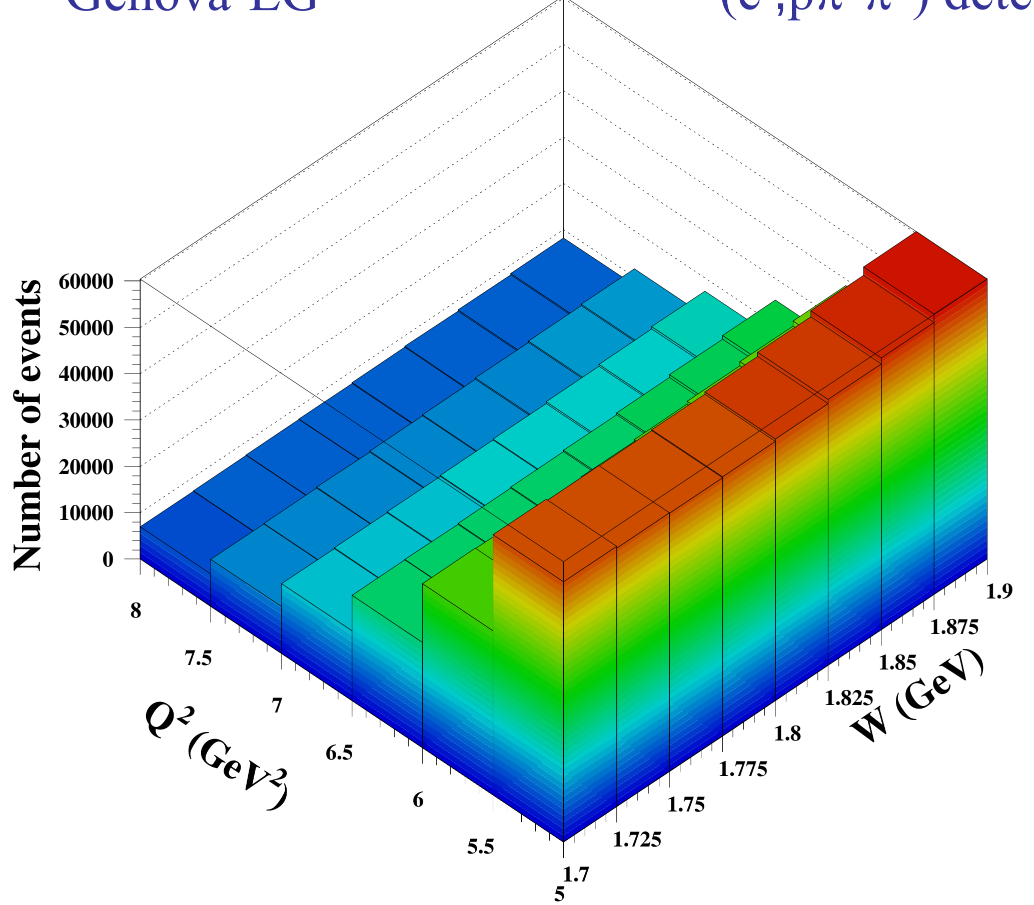
Kinematic Coverage of CLAS12

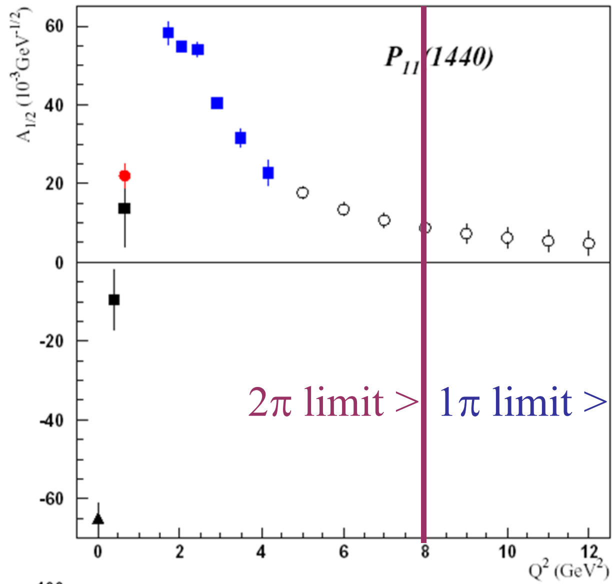
60 days

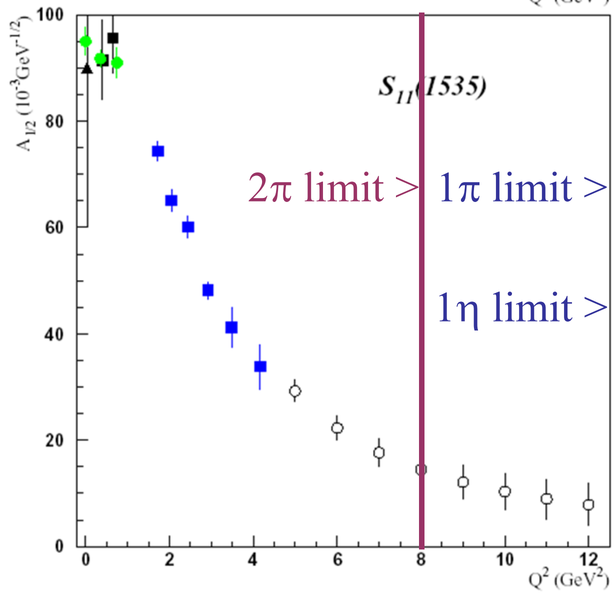
$L = 10^{35}\ cm^{-2}\ sec^{-1}$, $\Delta W = 0.025$ GeV, $\Delta Q^2 = 0.5$ GeV^2

Genova-EG

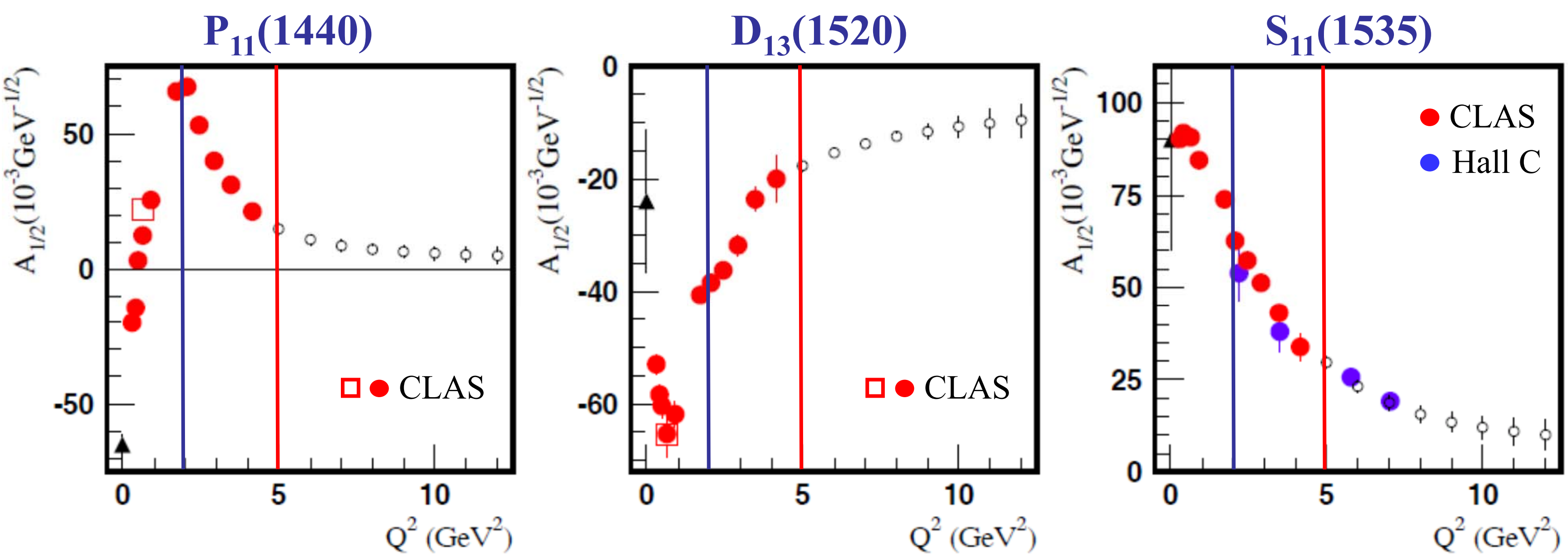
($e', p\pi^+\pi^-$) detected







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.

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 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, help, or participation is very welcomed, please contact:
  - Viktor Mokeev mokeev@jlab.org or Ralf Gothe gothe@sc.edu.

Challenges of the N* Program

Ralf W. Gothe

University of South Carolina

The 8th International Workshop on the Physics of Excited Nucleons

May 17-20, 2011

Jefferson Lab, Newport News, VA

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