N* Transition Form Factors: Transition to Large Q^2

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Meson-Nucleon Physics and the Structure of the Nucleon

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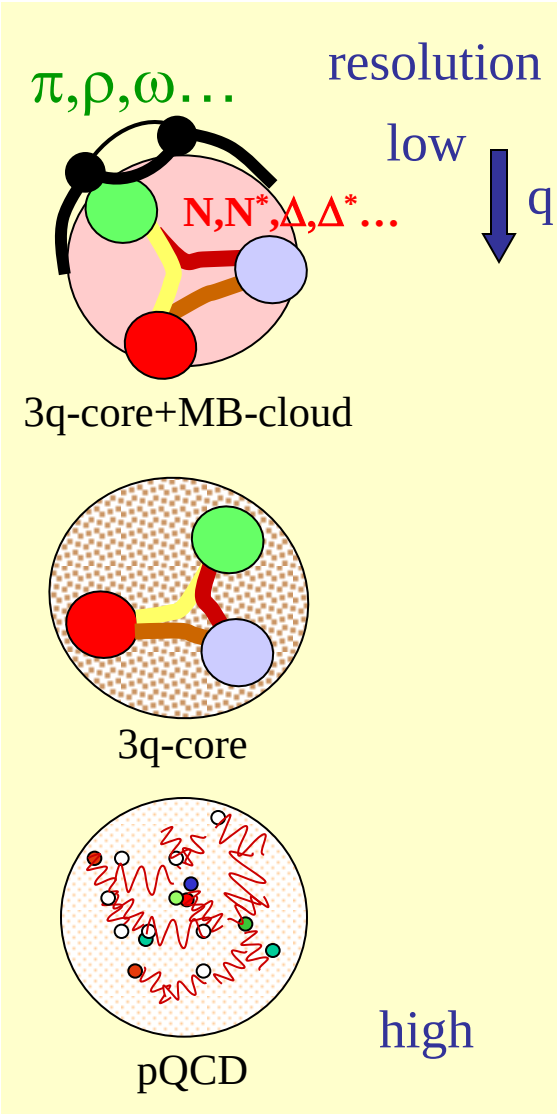
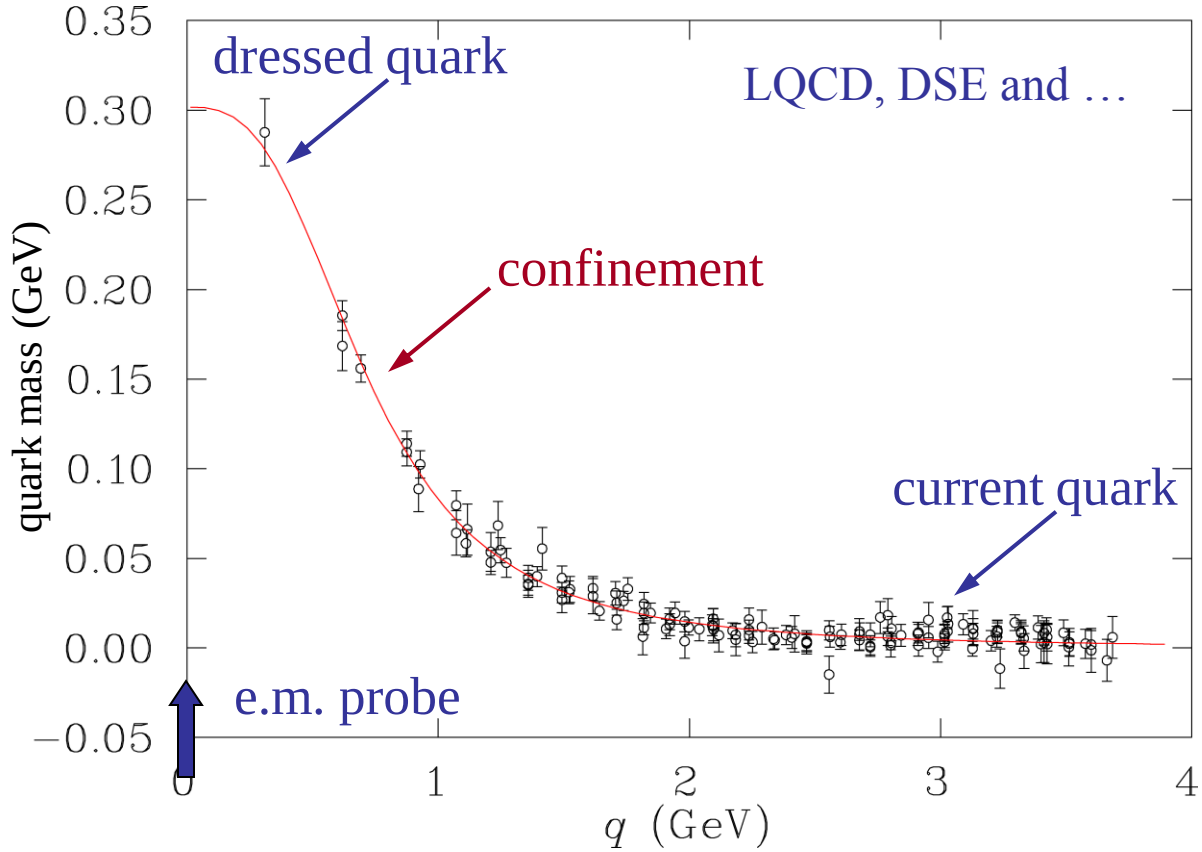
Meson-Nucleon Physics and the Structure of the Nucleon

- g_vNN* Electrocouplings: A Unique Window into the Quark Structure?
- Potential Impact on Studies of Confinement and Non-Perturbative QCD
- Anticipated N* Electrocouplings from a Combined Analysis of Nπ & N$\pi\pi$

Hadron Structure with Electromagnetic Probes

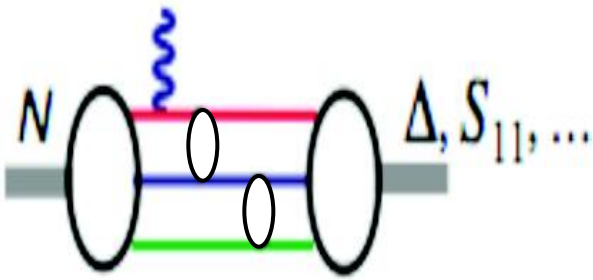


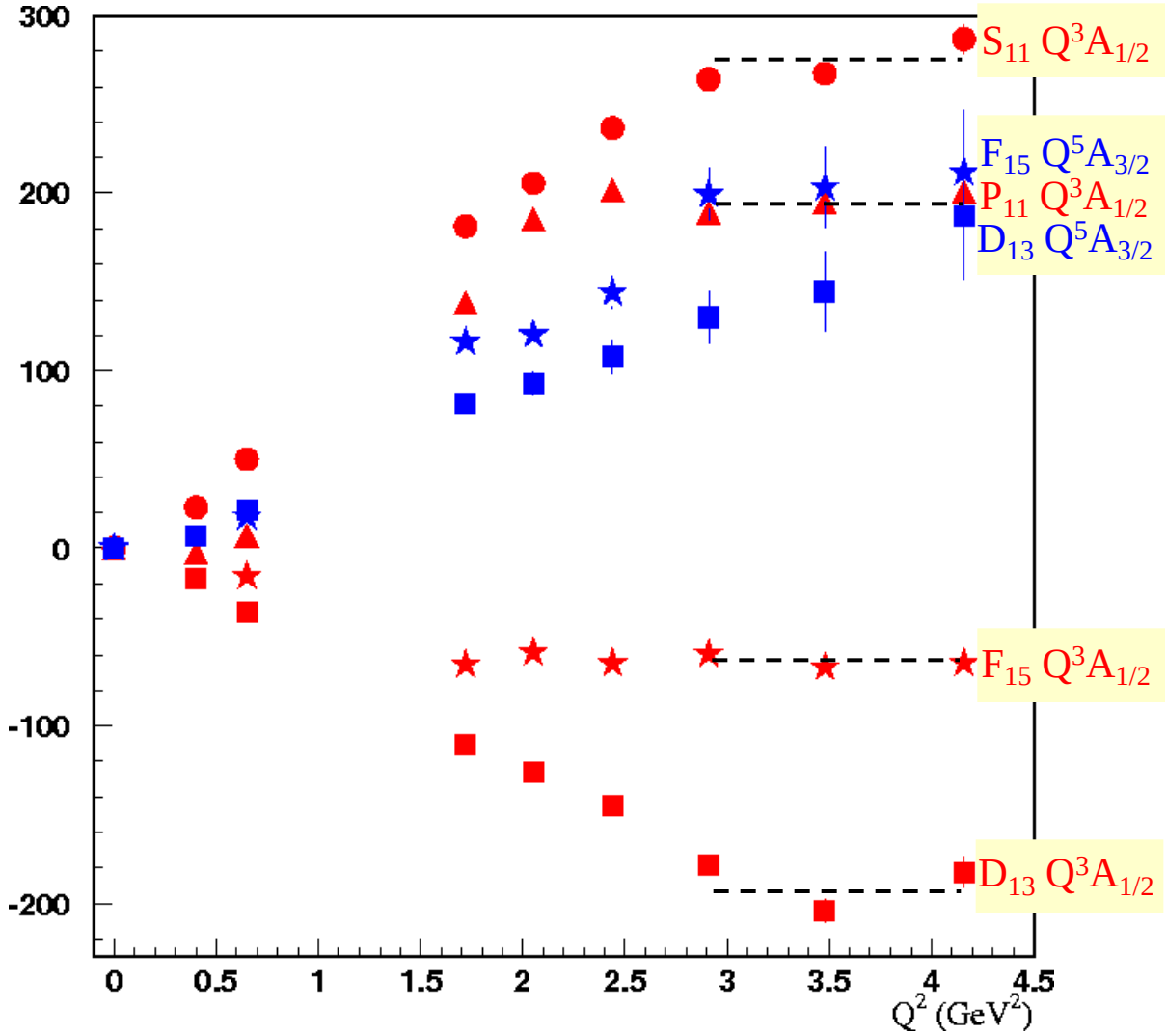
Quark mass extrapolated to the chiral limit, where q is the momentum variable of the tree-level quark propagator using the Asqtad action.



Evidence for the Onset of Scaling?

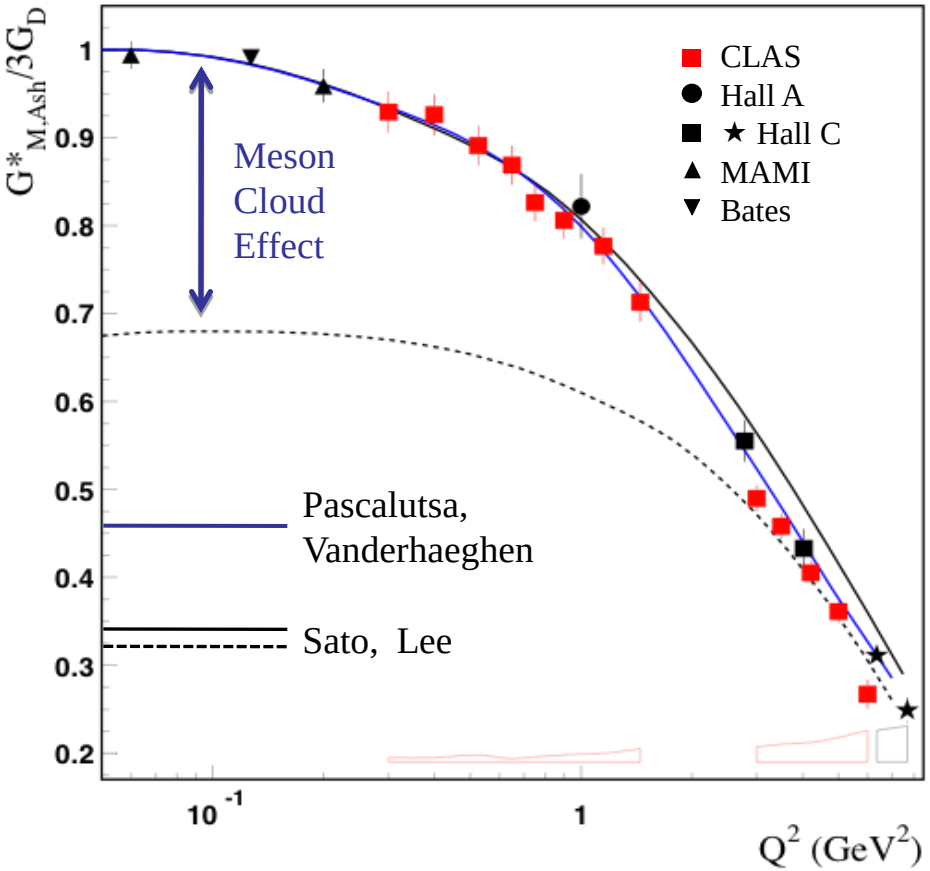
Phys. Rev. C80, 055203 (2009)



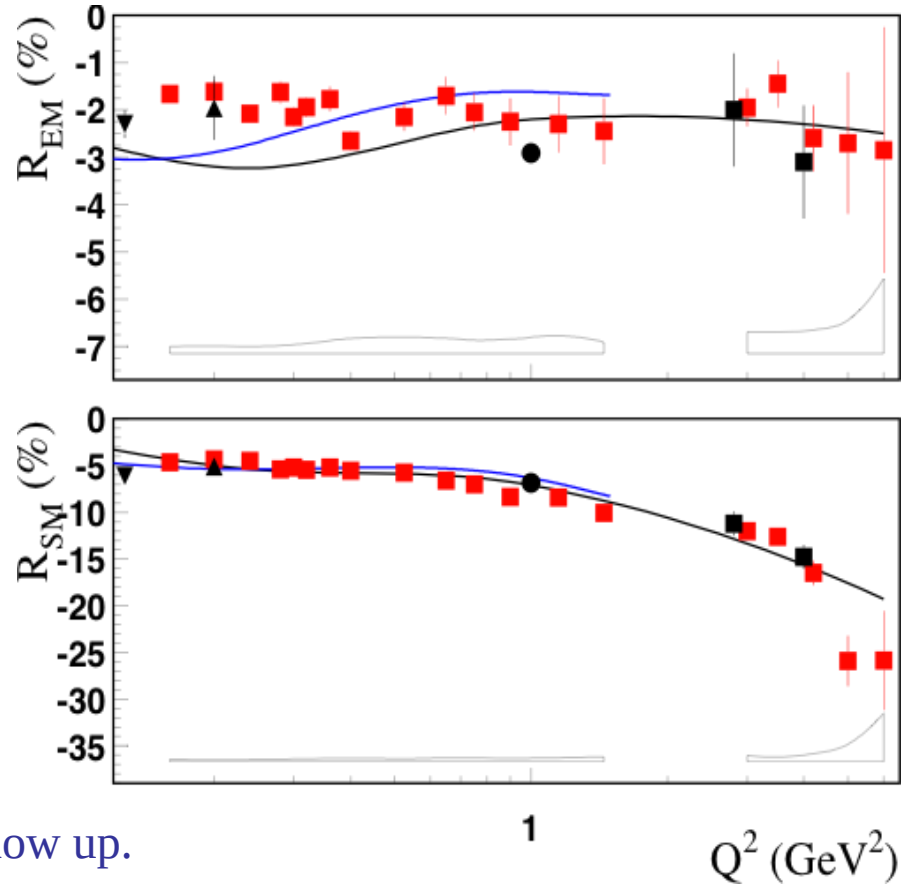


- $A_{1/2} \alpha 1/Q^3$
- $A_{3/2} \alpha 1/Q^5$
- $G_M^* \alpha 1/Q^4$

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

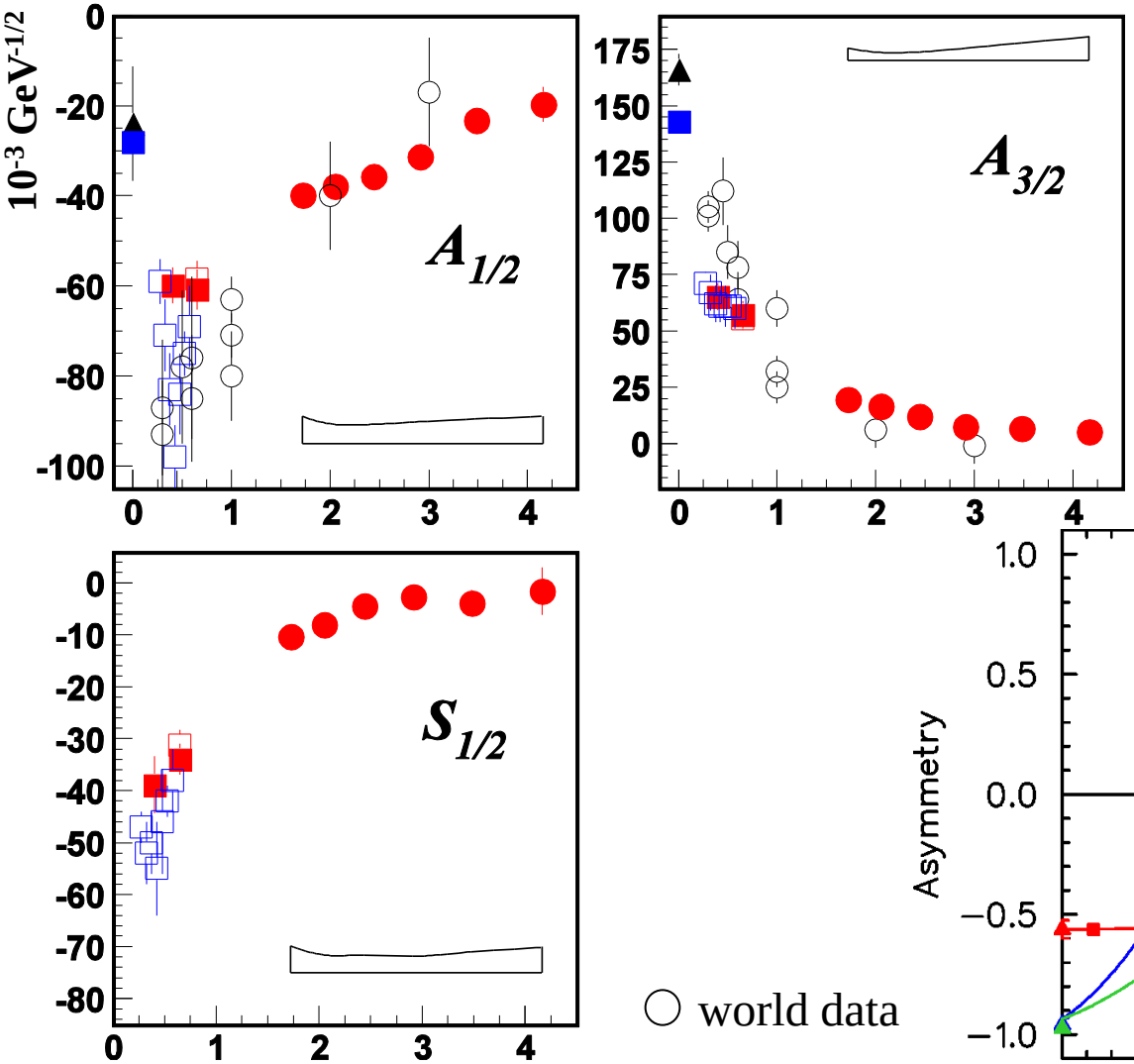


Phys. Rev. Lett. 97, 112003 (2006)



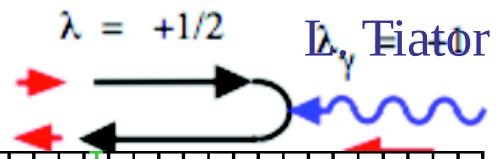
- New trend towards pQCD behavior does not show up.
  - $R_{EM} \rightarrow +1$
  - $G^*_M \rightarrow 1/Q^4$
- CLAS12 can measure G^*_M, R_{EM}, and R_{SM} up to Q^2~12 GeV².

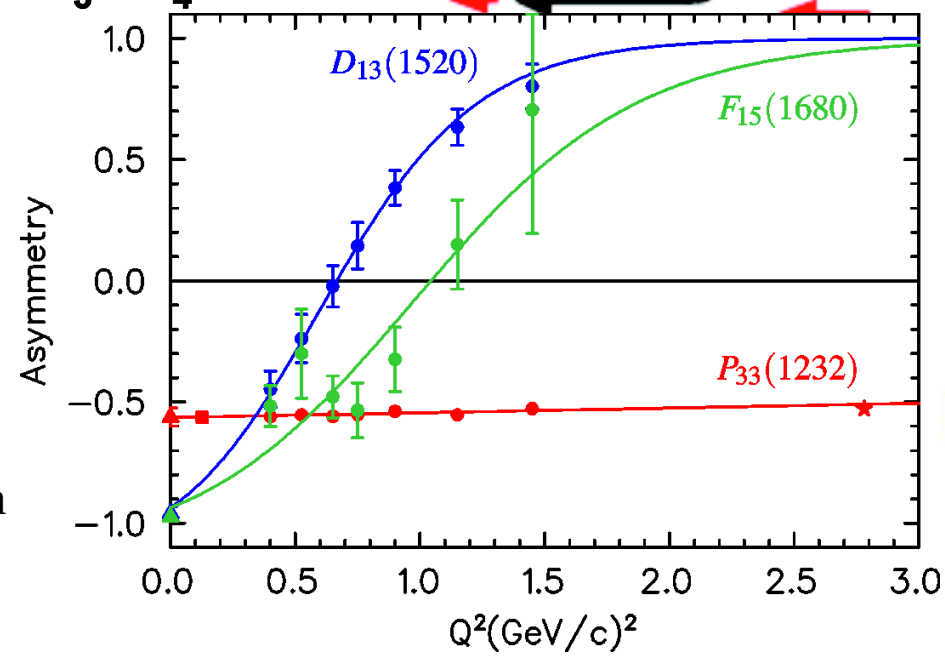
N(1520)D_{13} Helicity Asymmetry



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

$A_{1/2}$



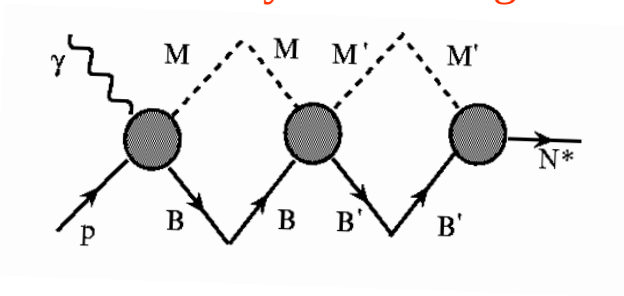


○ world data

▲ PDG estimation ● ■ Nπ (UIM, DR)

Progress in Experiment and Phenomenology

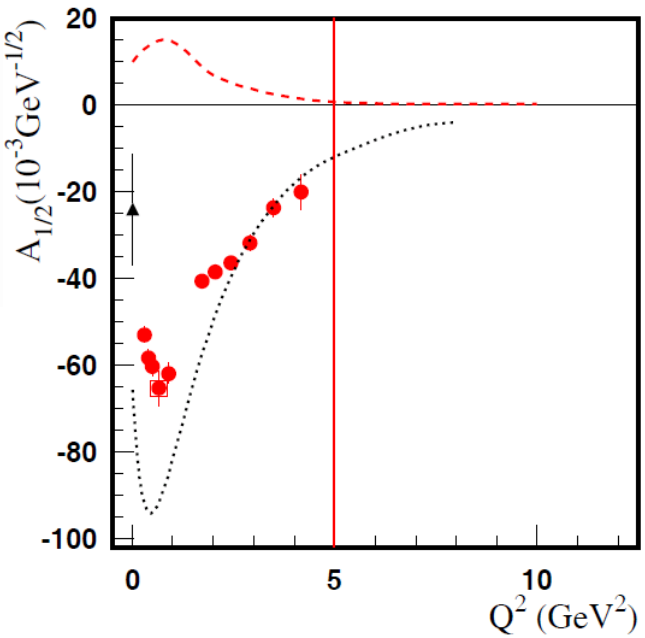
Meson-Baryon Dressing



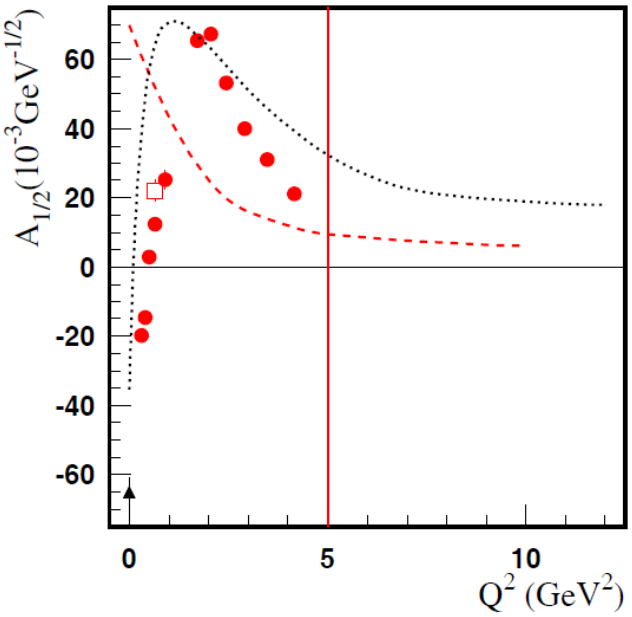
absolute meson-baryon cloud amplitudes (EBAC)

quark core contributions (constituent quark models)

$D_{13}(1520)$



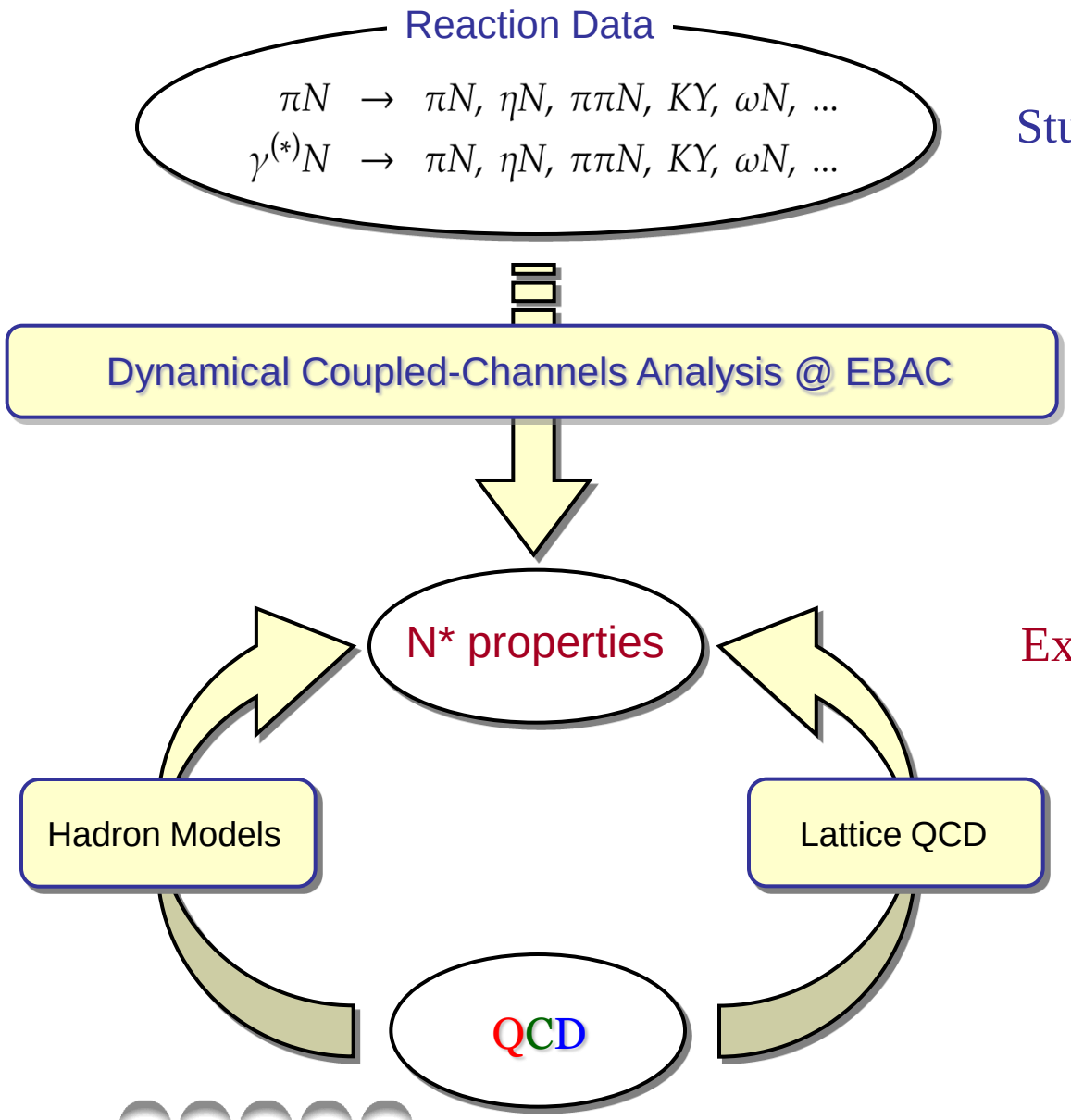
$P_{11}(1440)$



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.

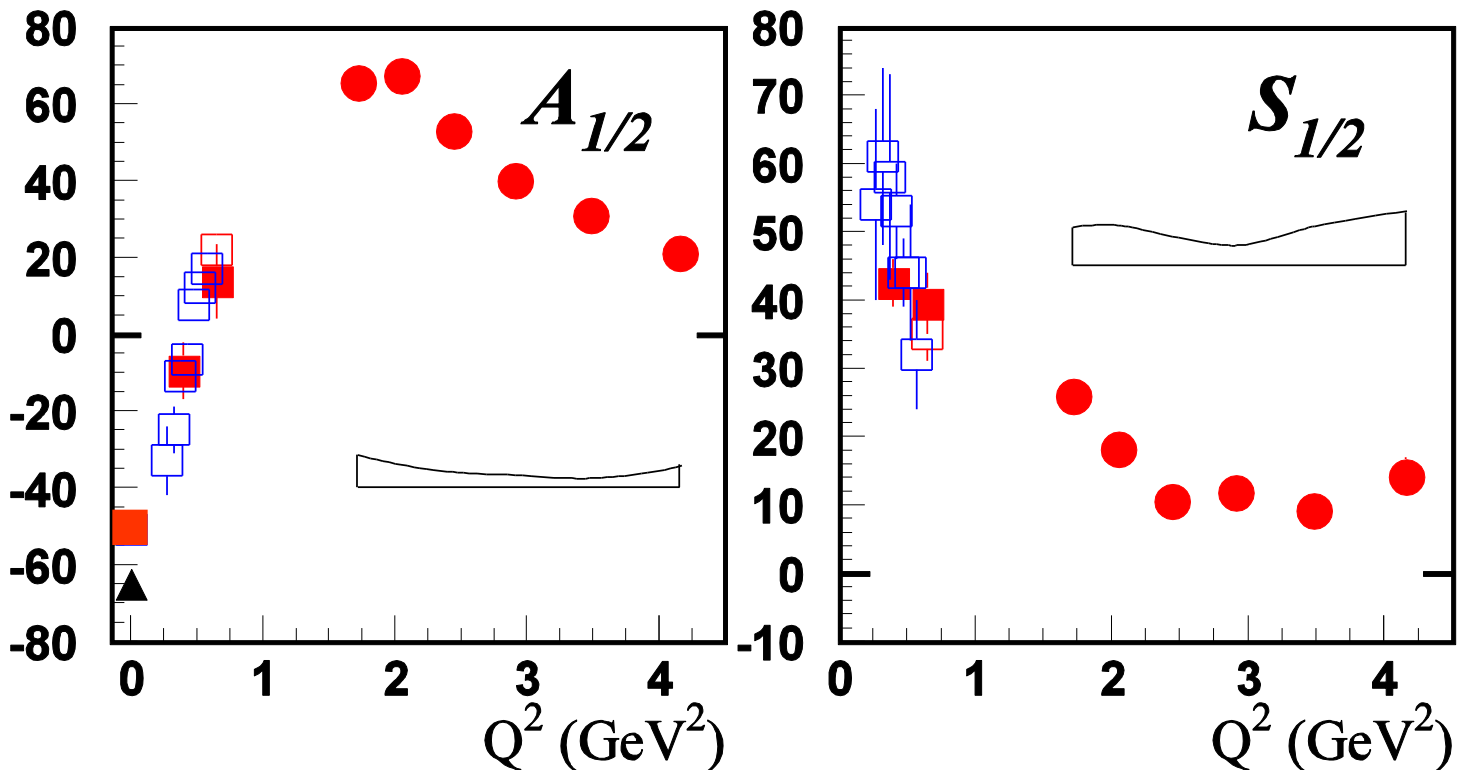
Dynamical Coupled Channel Model



Study reactions with EBAC-DCC

Extracted $\gamma_v NN^*$ electrocouplings

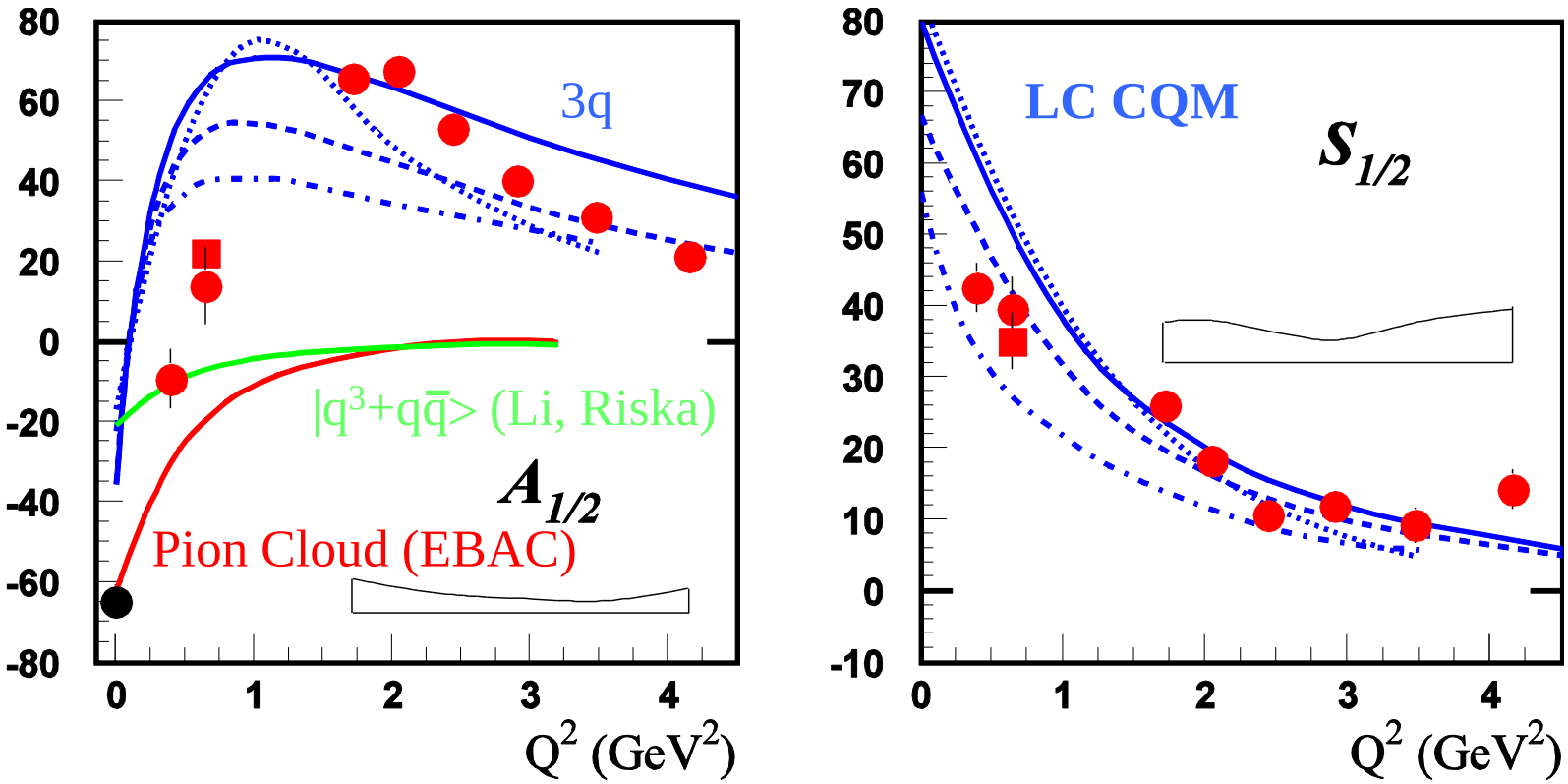
Electrocouplings of N(1440)P_{11} from CLAS Data



▲ 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.

Constituent Quark Models (CQM)



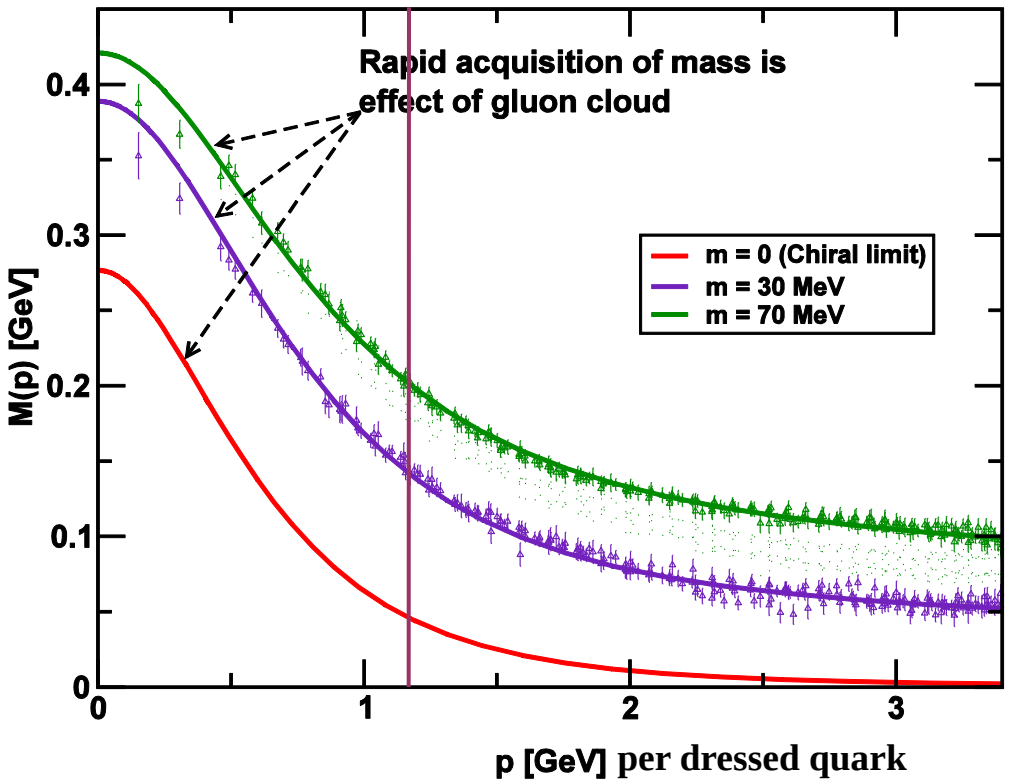
N(1440)P$_{11}$: ● PDG value ● Nπ ■ Nπ, Nππ combined analysis

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.

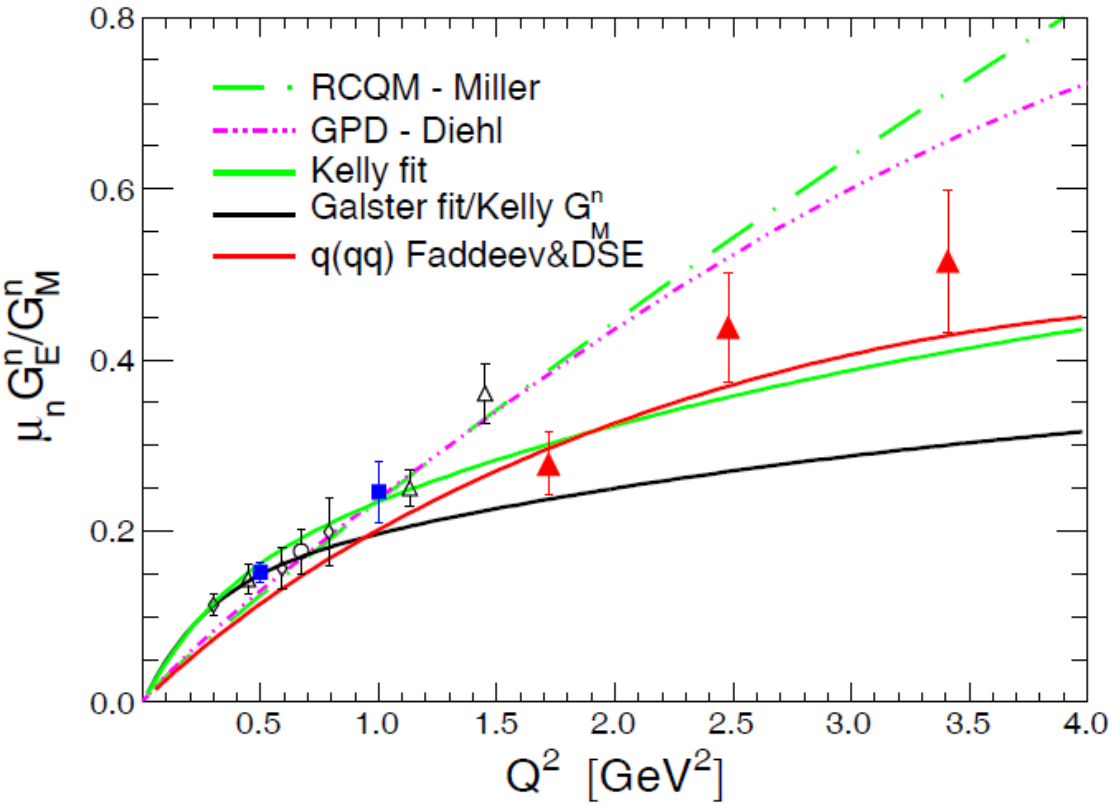
DSE: lines and LQCD: triangles

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

The data on N* electrocouplings at $5<Q^2<12\ \mathrm{GeV}^2$ 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 a link 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.

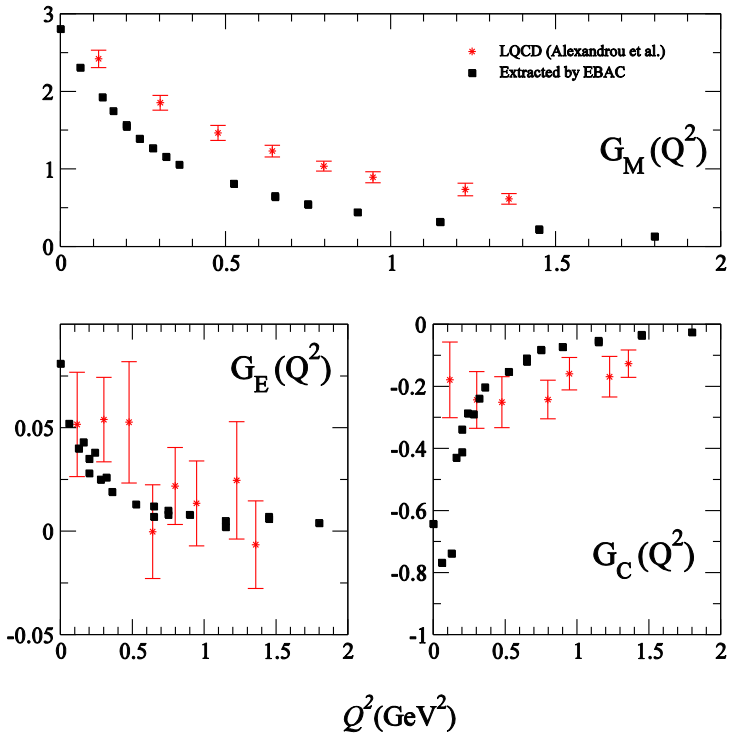
The Faddeev-DSE calculation is very sensitive to the momentum dependence of the dressed-quark propagator.

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.

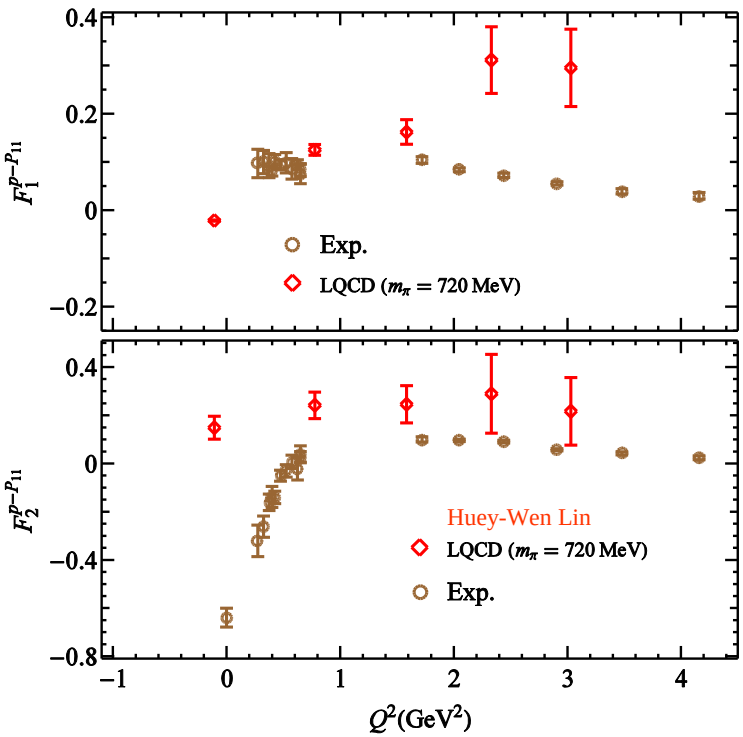
see White Paper Sec. III

Resonance Electrocouplings in Lattice QCD

$\Delta(1232)P_{33}$



$N(1440)P_{11}$

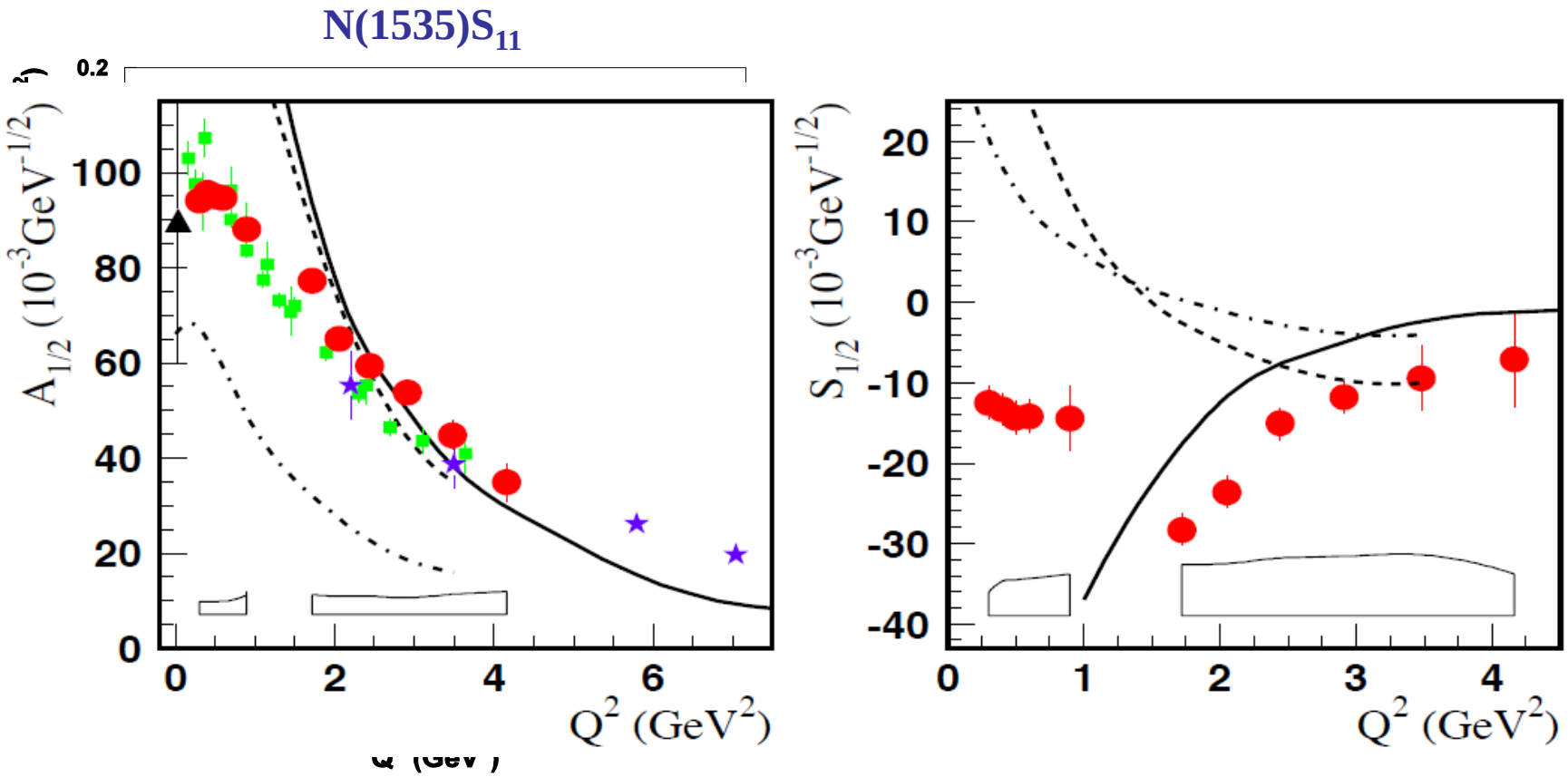


LQCD calculations of the $\Delta(1232)P_{33}$ and $N(1440)P_{11}$ transitions have been carried out with large π-masses.

By the time of the upgrade LQCD calculations of N* electrocouplings will be extended to $Q^2 = 10\ \mathrm{GeV}^2$ 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

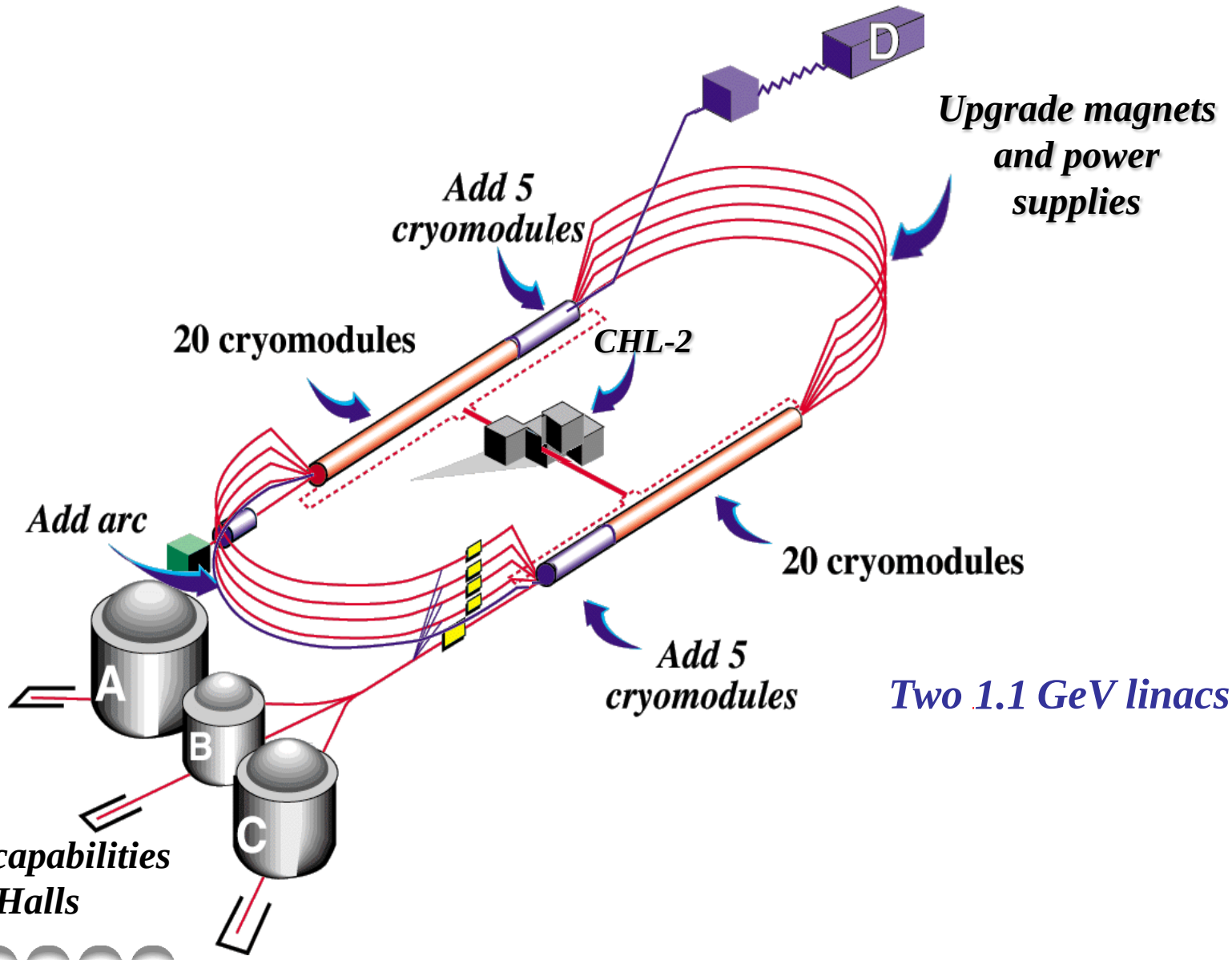


Calculations of N(1535)S_{11} electrocouplings at Q^2 up to 12 GeV^2 are already available and shown by shadowed bands on the plot.

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

12 GeV CEBAF



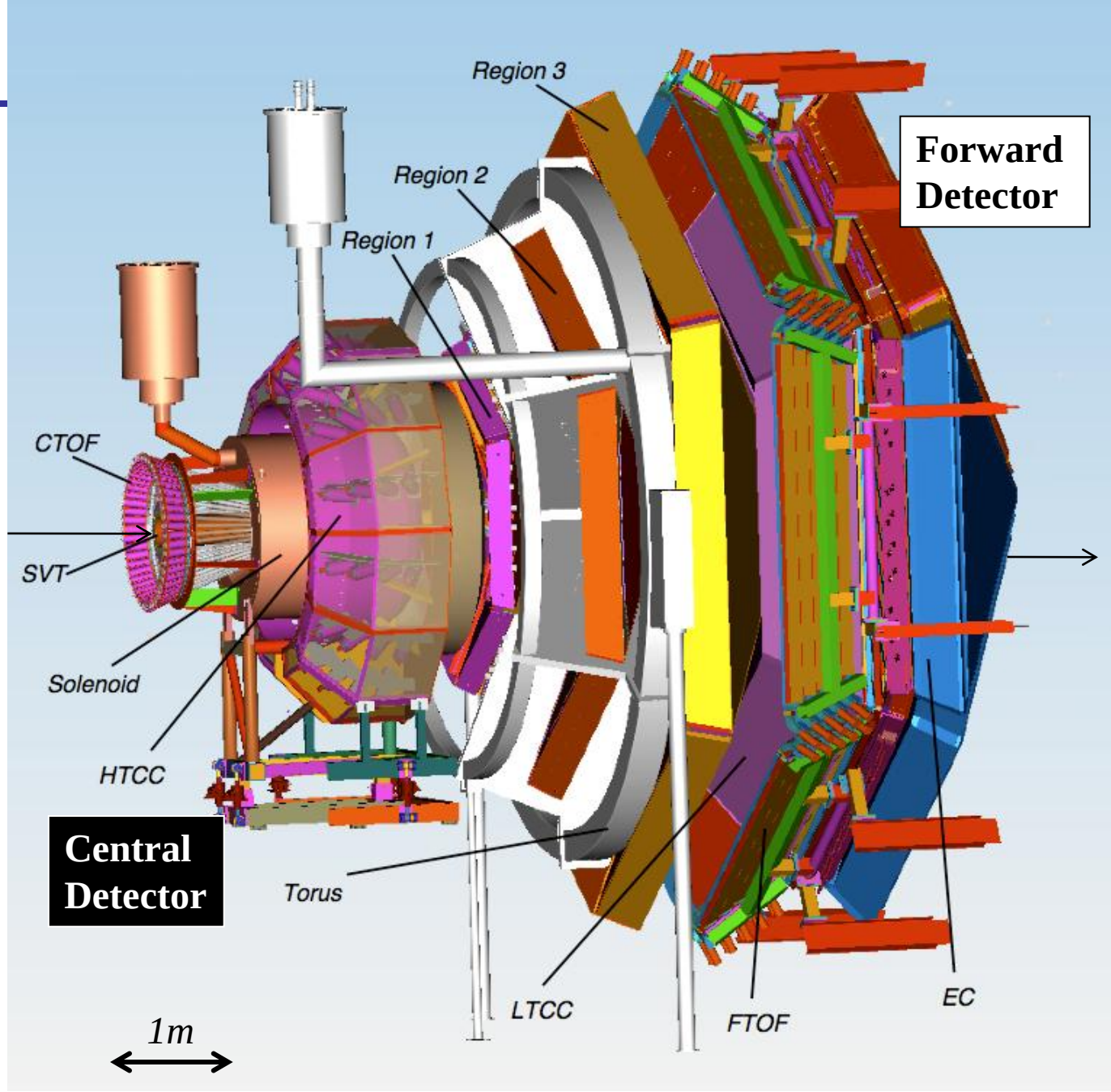
Two 1.1 GeV linacs

Enhanced capabilities in existing Halls

CLAS12

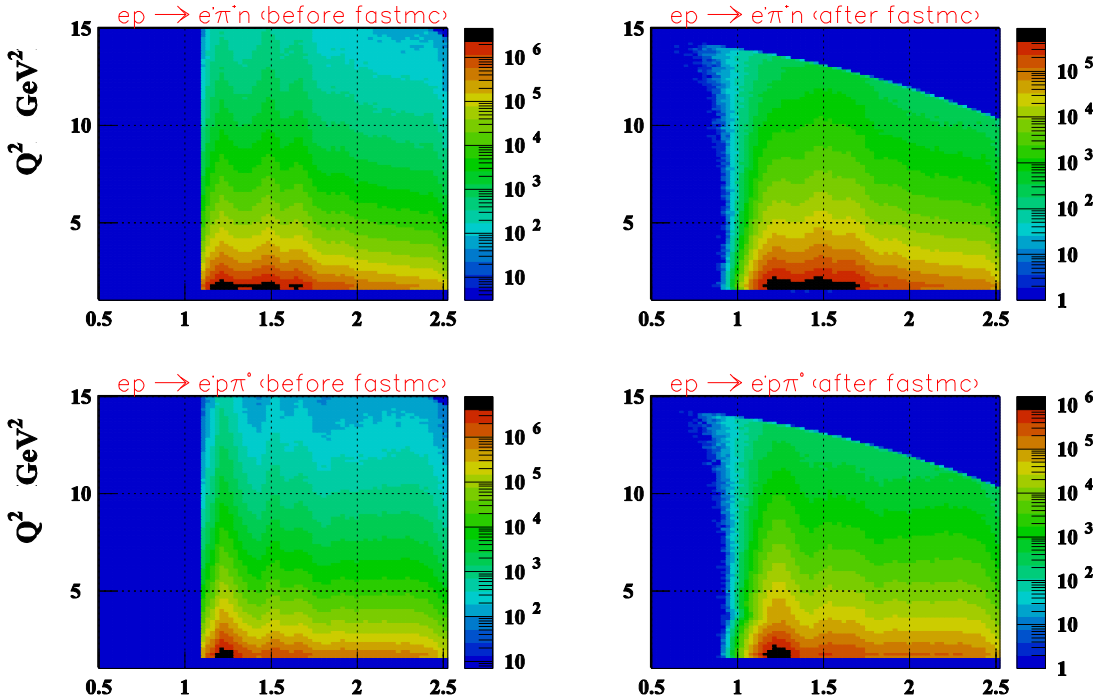
- Luminosity > 10^{35} $cm^{-2}s^{-1}$
- Hermicity
- Polarization

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



CLAS 12 Kinematic Coverage and Counting Rates

Genova-EG



(e',π⁺) detected

Genova-EG

(e',p) detected

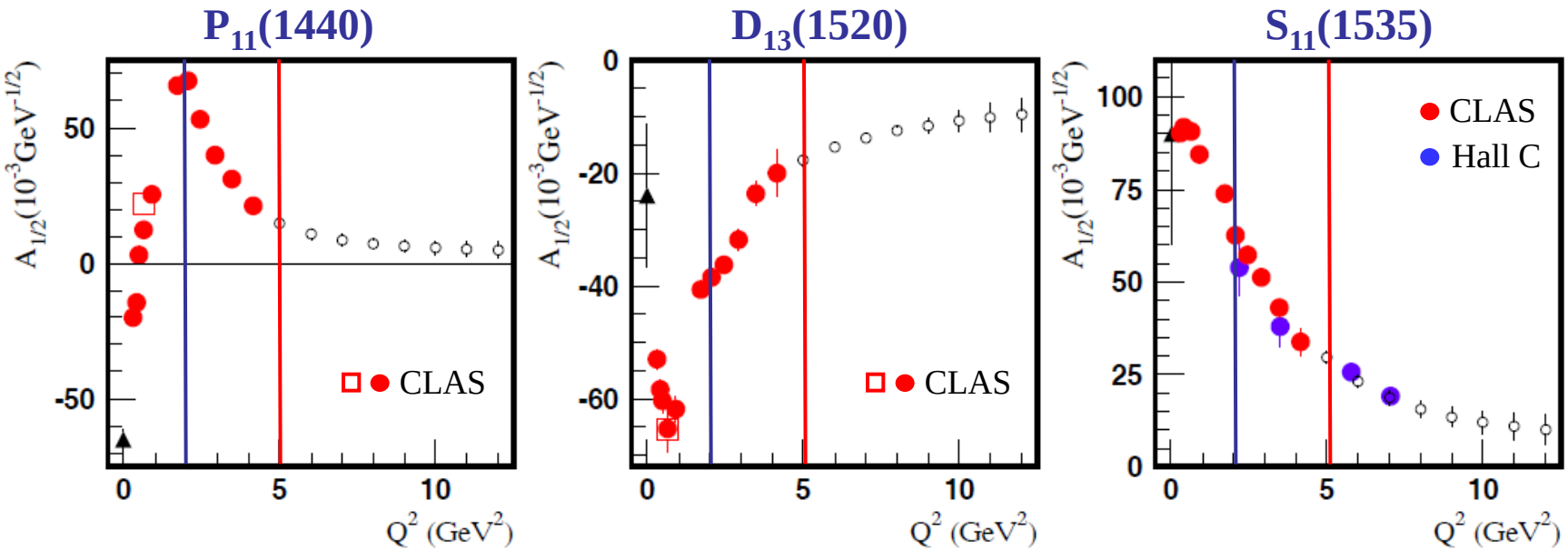
(E,Q²)	(5.75 GeV, 3 GeV²)	(11 GeV, 3 GeV²)	(11 GeV, 12 GeV²)
$N^{n\pi+}$	$1.41*10^5$	$6.26*10^6$	$5.18*10^4$
$N^{p\pi0}$	-	$4.65*10^5$	$1.45*10^4$
$N^{p\eta}$	-	$1.72*10^4$	$1.77*10^4$

40 days

PAC35

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

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. $S_{11}(1650)$, $F_{15}(1685)$, $D_{33}(1700)$, $P_{13}(1720)$, …
- Our 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 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.