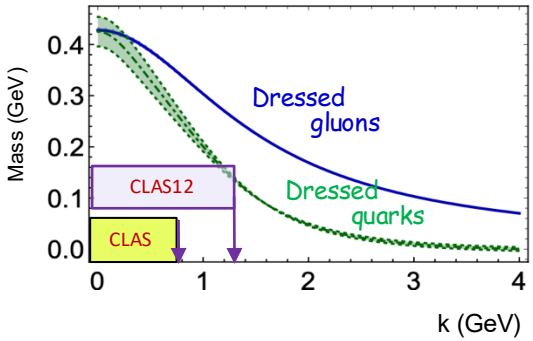
Physics Opportunities on High-Precision High-Q^2 N* Electroexcitations





P. Achenbach, D.S. Carman, R.W. Gothe, K. Joo, V.I. Mokeev, and C.D. Roberts, Symmetry 17, 1106 (2025)

M. Ding, C.D. Roberts, and S.M. Schmidt, Particles 6, 57 (2023)

- Gaining insight into the emergence of hadron mass (EHM) from CLAS results on $\gamma_v pN^*$ electrocouplings
- Extending Q^2 coverage for extracted $\gamma_v pN^*$ electrocouplings from the CLAS12 measurements
- New opportunities after increase of CLAS12 luminosity and angular acceptance for scattered electrons

Higher luminosity operations with the large acceptance CLAS12 detector enable significant gains in extracting $\gamma_v pN^*$ electrocouplings for Q^2 up to 16 GeV^2. These studies, combined with pseudoscalar-meson and ground-state nucleon structure, address a challenging Standard Model problem: understanding the origin of the dominant fraction of hadron mass and the emergence of hadron structure from strong interactions.

V.I. Mokeev, University of South Carolina
and Jefferson Lab

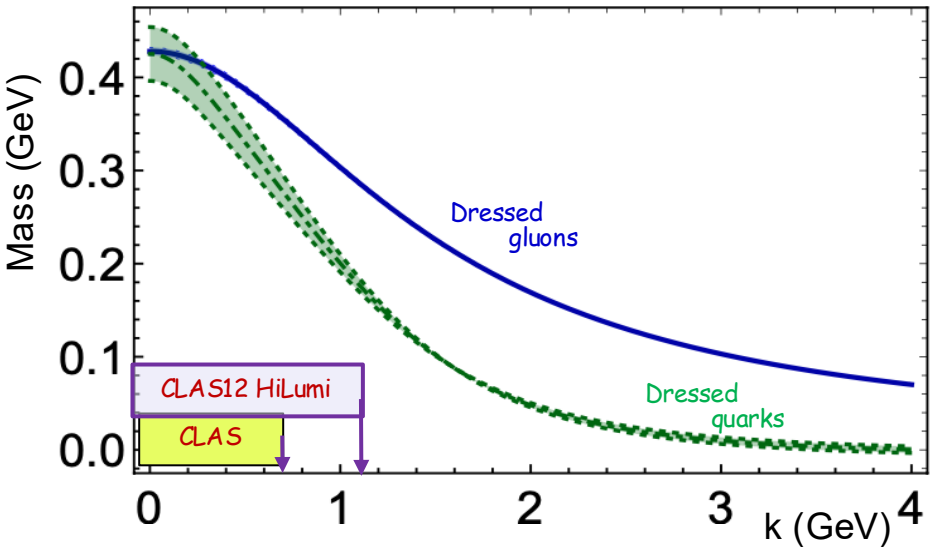
Nucleon Resonance Electrocouplings from Data on Exclusive Meson Electroproduction of the 6-GeV Era with CLAS

Exclusive meson electroproduction channels	Excited proton states	Q^2-ranges for extracted $\gamma_v pN^*$ electrocouplings, GeV^2
$\pi^0 p$, $\pi^+ n$	$\Delta(1232)3/2^+$ $N(1440)1/2^+$,$N(1520)3/2^-$, $N(1535)1/2^-$	0.16-6.0 0.30-4.16
$\pi^+ n$	$N(1675)5/2^-$, $N(1680)5/2^+$,$N(1710)1/2^+$	1.6-4.5
ηp	$N(1535)1/2^-$	0.2-2.9
$\pi^+\pi^- p$	$N(1440)1/2^+$, $N(1520)3/2^-$ $N(1440)1/2^+$, $N(1520)3/2^-$, $\Delta(1600)3/2^+$, $N(1675)5/2^-$, $N(1680)5/2^+$, $\Delta(1700)3/2^-$, $N(1720)3/2^+$, $N'(1720)3/2^+$	0.25-1.50 2.0-5.0 2.0-5.0 0.5-5.0

- The $\gamma_v pN^*$ electrocouplings have become available from independent analyses of CLAS πN and $\pi^+\pi^- p$ electroproduction data for most N^* states up to 1.8 GeV for $Q^2 < 5$ GeV^2.
- Numerical results can be found at:
  https://userweb.jlab.org/~mokeev/resonance_electrocouplings23/

A.N. Hiller Blin et al., PRC 100, 035201 (2019), V.I. Mokeev et al., arXiv:2608.04997

CSM Concept on EHM and Insight from $\gamma_v pN^*$ Electrocoupling Data



Continuum Schwinger Method (CSM) Concept on Emergence of Hadron Mass (EHM)

P. Achenbach, D.S. Carman, R.W. Gothe, K. Joo, V.I. Mokeev, and C.D. Roberts, Symmetry, 17, 1106 (2025)

M. Ding, C.D. Roberts, and S.M. Schmidt, Particles 6, 57 (2023)

Other QCD-connected theory approaches and quark models are encouraged.

- The dominant part of N/N* masses (94-98%) is generated by the strong interactions between dressed gluons and quarks. EHM is encoded in the evolution of the dressed quark/gluon masses and the QCD running coupling α_s with momenta/distances.
- The successful description of the pion and nucleon elastic EM form factors and $\gamma_v pN^*$ electrocouplings measured with CLAS at $Q^2 < 5$ GeV^2 within the CSM framework enables exploration of EHM across a range of distance scales over which ~30% of the hadron mass is generated
- Available CLAS12 luminosity offers an extension of Q^2 coverage for $\gamma_v pN^*$ electrocouplings to $Q^2 <$ 8-10 GeV^2, where ~50% of hadron mass emerges.

Insight into Dressed Quark Mass Function from Experimental Results

- A successful description of the pion and nucleon elastic FFs and the electrocouplings of the $\Delta(1232)3/2^+$ and $N(1440)1/2^+$ has been achieved in CSM *with the same dressed quark/gluon mass functions*.

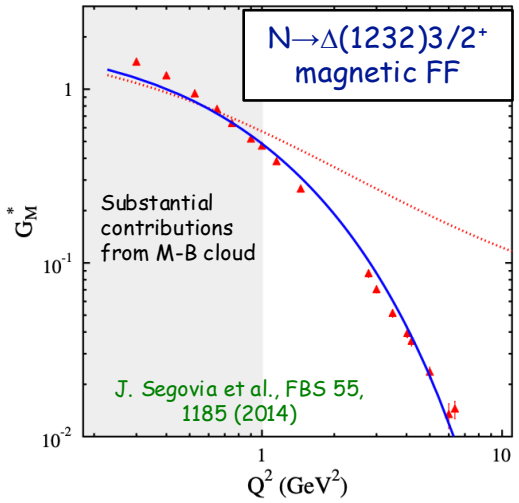
- Dressed quarks with dynamically generated masses represent active degrees of freedom in the structure of the pion, nucleon, and the $\Delta(1232)3/2^+$, $N(1440)1/2^+$.

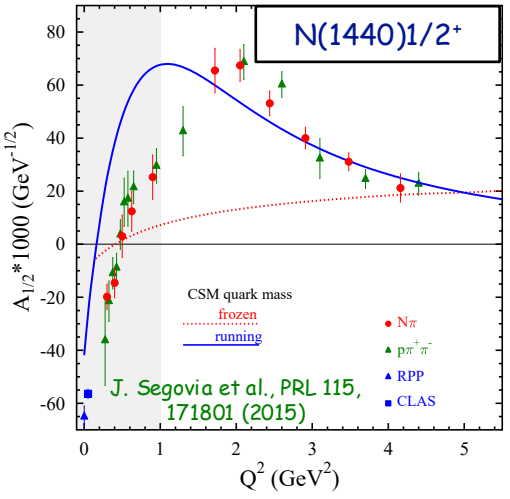
- Strong evidence for insight into the momentum dependence of the dressed quark mass.

- CLAS results on $N(1520)3/2^-$, $\Delta(1600)3/2^+$, and $\Delta(1700)3/2^-$ electrocouplings confirmed the CSM prediction across $Q^2 > 2$ GeV^2, solidifying evidence for insight into the dressed quark mass function and, consequently, into EHM from the $\gamma_v pN^*$ electrocouplings.

- Sensitivity of the in-hadron environment to the dressed-quark mass is crucial for validating insight to EHM, its connection to DCSB, and access to diquark correlation amplitudes with different spin-parities.

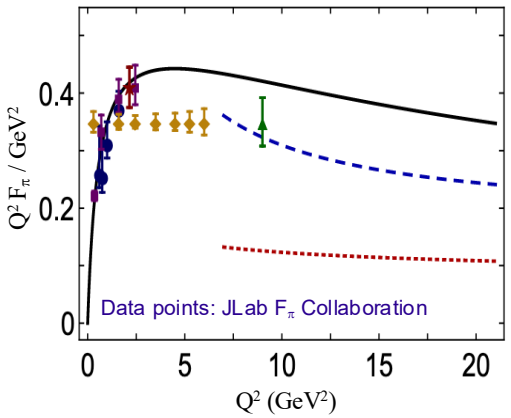
CLAS/Hall A/C results vs. CSM expectations





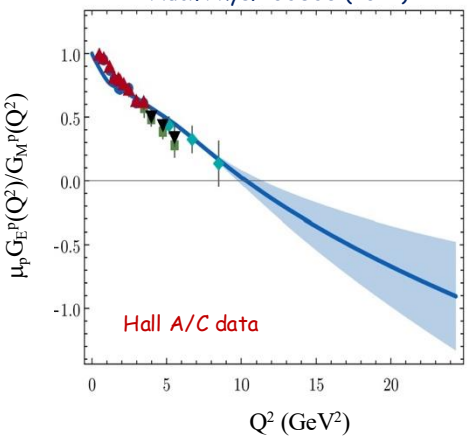
Pion Elastic FF

C.D. Roberts et al., Prog. Part. Nucl Phys. 120, 103883 (2021)



Nucleon Elastic FF

M. Barabanov et al., Prog. Part. Nucl. Phys. 103835 (2021)

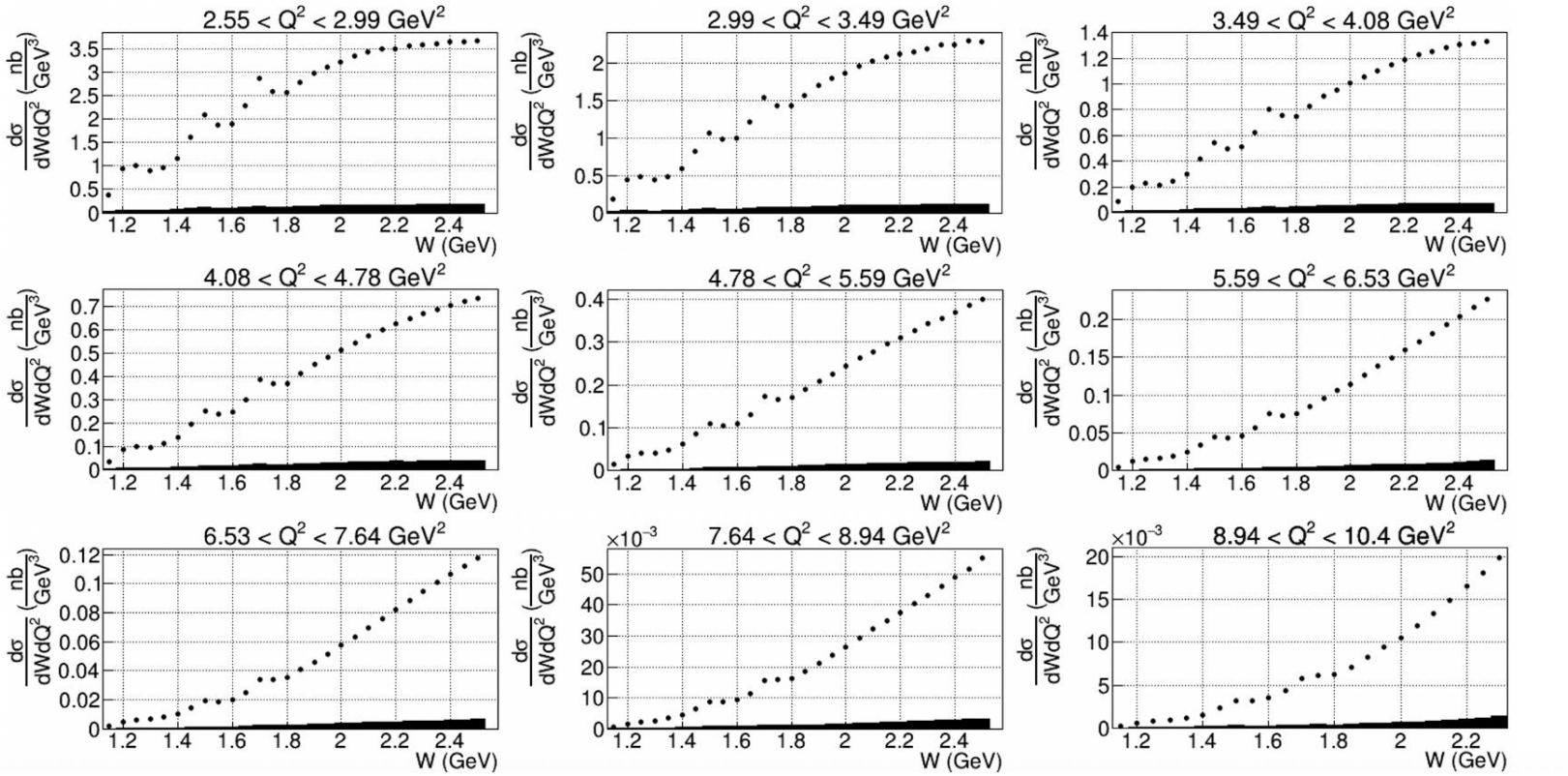


One of the most important achievements in hadron physics of the last decade, resulting from synergistic efforts among experiment, phenomenology, and theory.

Extension of N* Structure Studies with CLAS12

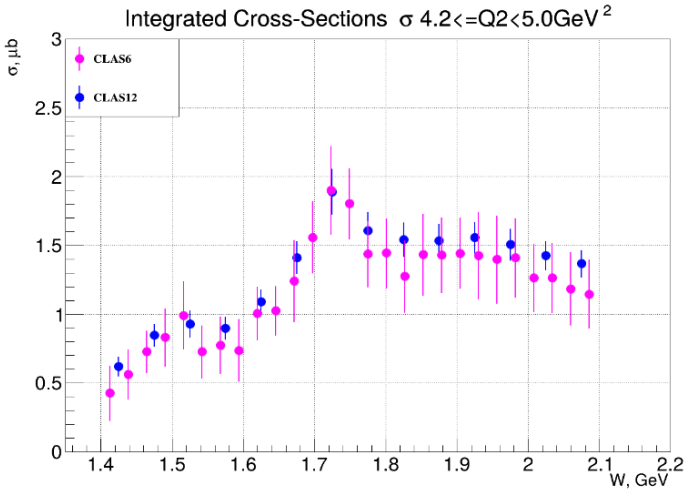
CLAS12: Extension of the results on $\gamma_v pN^*$ electrocouplings of most N* states in the range W < 2.5 GeV and Q^2 up to 10 GeV^2 from exclusive channels: πN, $\pi\pi N$, KY, K*Y, KY*.

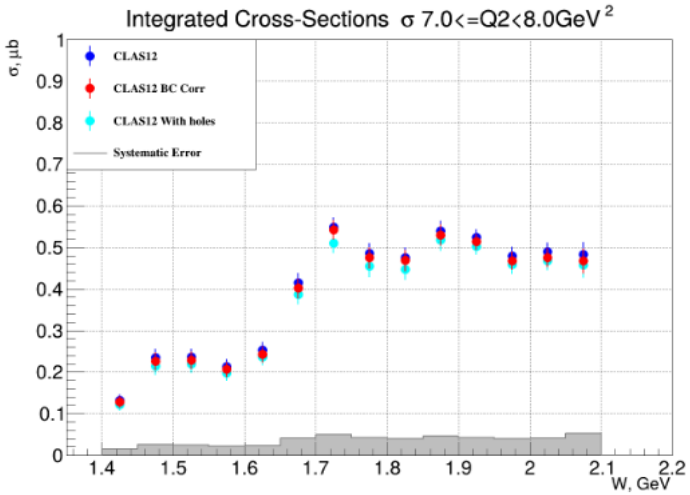
Measurements of the inclusive (e,e′X) cross section with CLAS12. V. Klimenko et al. (CLAS Collaboration), PRC 112, 025201 (2025).

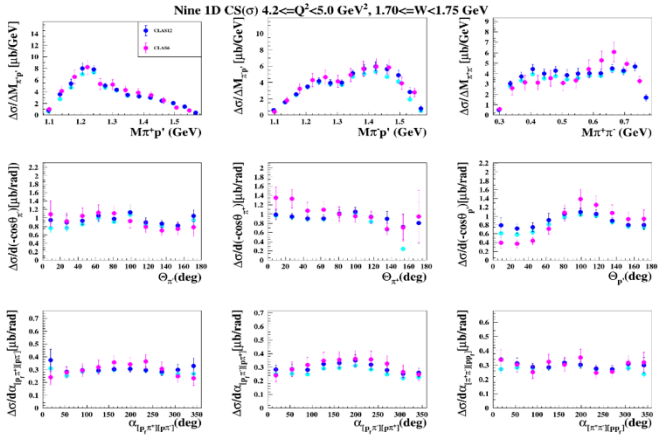


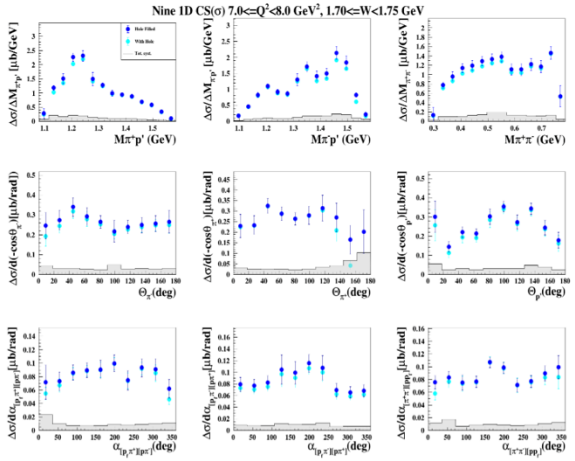
Resonance-like structures are clearly seen in the first, second, and third resonance regions for $Q^2 < 10$ GeV^2.

Results on CLAS12 $\pi^+\pi^-$p Electroproduction Cross Sections







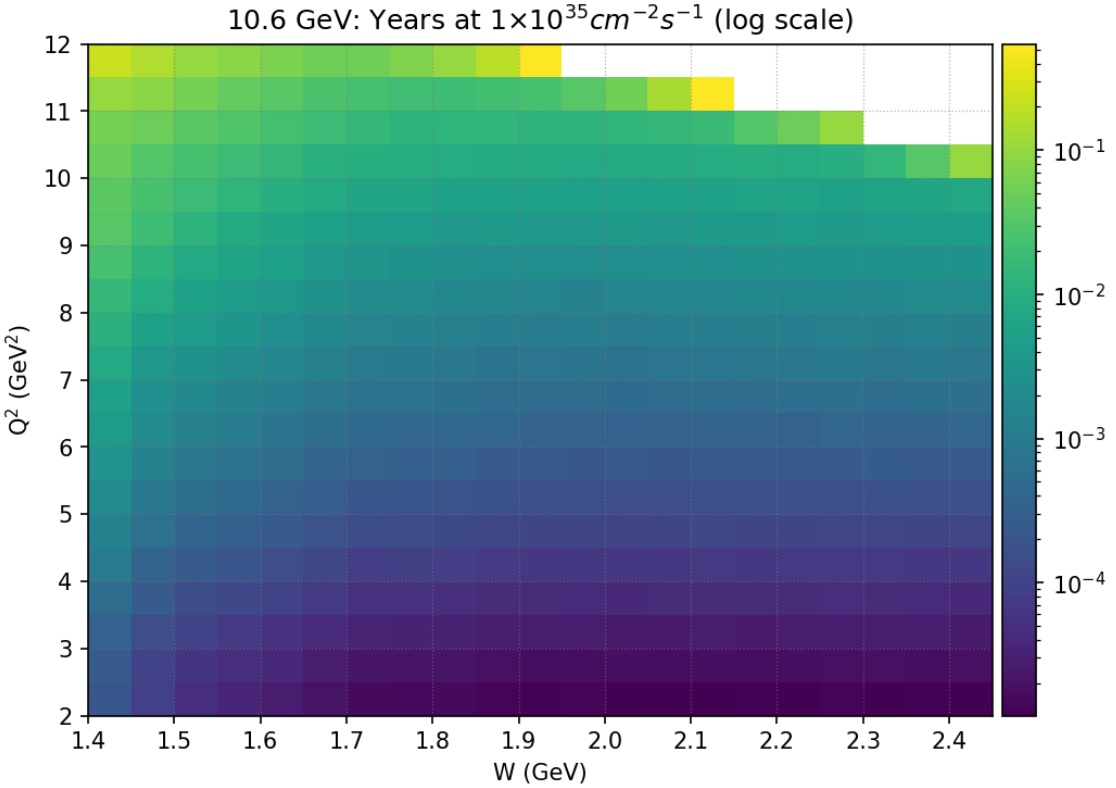


K. Neupane, R.W. Gothe, D.S. Carman, V.I. Mokeev et al., (CLAS Collaboration) arXiv:2609.19395, submitted to PRC

- Integrated and nine 1D differential $\pi^+\pi^-$p cross sections are available for W=[1.4-2.1] GeV, Q^2=[2.4-8.0] GeV^2
- Consistency with the CLAS data in the overlapping range of Q^2<5.0 GeV^2
- Allows us to extend the JM model over the mass range up to 2 GeV for Q^2<8 GeV^2, paving the way to obtain the $\gamma_v pN^*$ electrocouplings over a much broader range of Q^2 compared to existing CLAS data

Beam Time Evaluation for Sufficient Statistics to Extract $\gamma_v pN^*$ Electrocouplings from $\pi^+\pi^- p$ Electroproduction Data in Full MC Simulation

Beam time (in years) needed for sufficient statistics vs. bins in (Q^2,W) to extract $\gamma_v pN^*$ electrocouplings



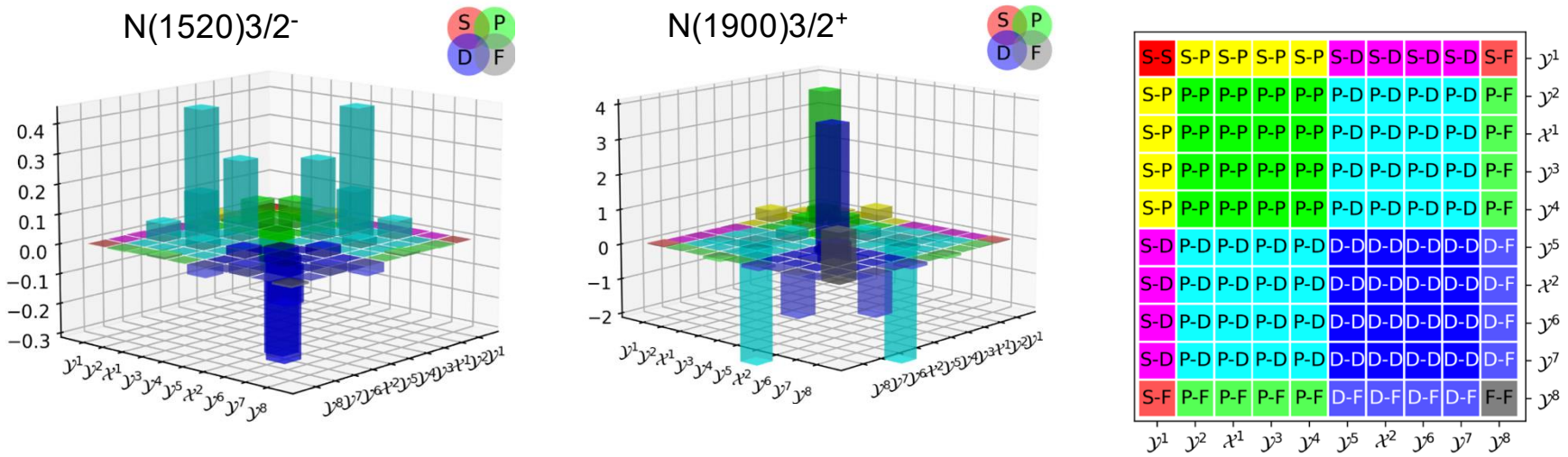
Rate estimates for the accepted events using TWOPEG EG with CLAS12 (eff*ACC), employing event selection as: K. Neupane et al. (CLAS Collaboration), arXiv:2609.19395, submitted to PRC

At $\mathcal{L} = 10^{35}$ cm^{-2}s^{-1}, decreasing Q^2-bin size by a factor of two would require beam time of 0.6 years.

R.W. Gothe, A. Osmond (USC)

- After $\mathcal{L}$ increase to 2 × 10^{35} cm^{-2}s^{-1}, the □$^+$□$^-$p cross sections can be measured up to Q^2 < 12 GeV^2 in (Q^2, W) bins, with sufficient statistics for extraction of resonance electrocoupling exceeding those collected in the Q^2 = 7.0–8.0 GeV^2 bin in the Neupane paper with finer binning over Q^2.

HiLumi Impact on Physics: Extended Insight into the N* Faddeev Amplitudes from $\gamma_v pN^*$ Data



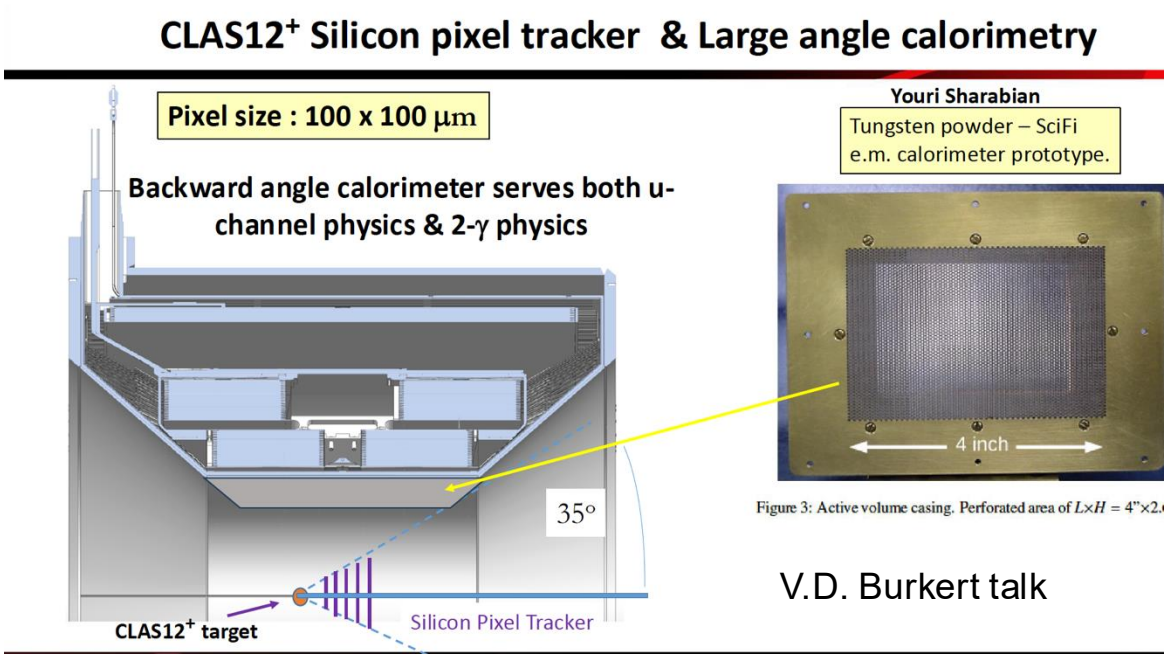
Rest-frame quark-di-quark orbital momentum content of N(1520)3/2$^-$ and N(1900)3/2$^+$

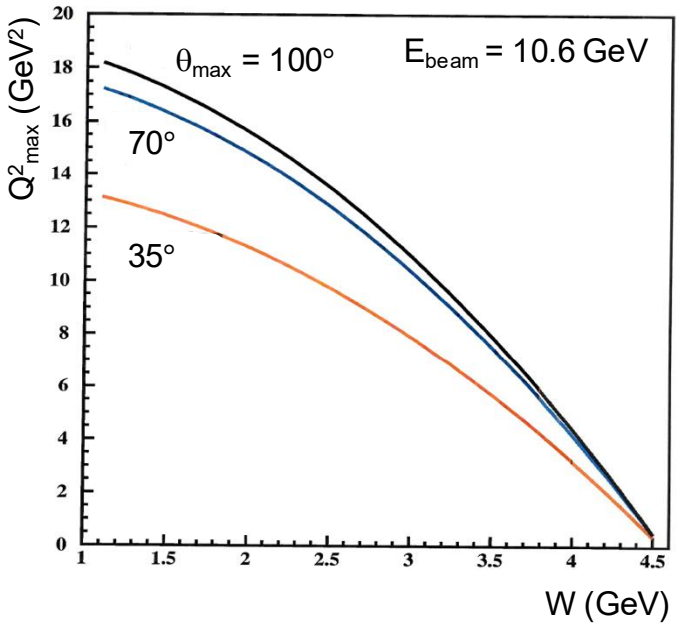
L. Liu, Ch. Chen, and C.D. Roberts, Phys. Rev. D 107, 014002 (2023)

- CSM predictions of the rest-frame dressed-quark–diquark orbital-angular-momentum (L) content demonstrated significant off-diagonal mixed L–L′ components, revealing a level of structural complexity far beyond that anticipated from quark models. *Should be tested in confronting with the results on Q^2 evolution of $\gamma_v pN^*$ electrocouplings*.
- Experimental results on the Q^2 evolution of ©$_v$pN* electrocouplings over a Q^2 range up to 12 GeV^2, with finer Q^2 binning than currently achieved, or with improved precision of the $\gamma_v pN^*$ electrocouplings, *are critical for testing these QCD-connected predictions*.

Looking Towards CEBAF-2037 Era

- An increase in the maximum lab polar angle for detected scattered electrons up to 70° opens a new opportunity to explore the Q^2-evolution of the $\gamma_v pN^*$ electrocouplings for $Q^2<16$ GeV^2.
- A unique opportunity to explore in-hadron sensitivity to the emergence of N* structure across the range of distances where ~75% of hadron mass is generated *addressing a challenging problem in Standard Model on the nature of dominant part of the visible hadron mass in the Universe*.





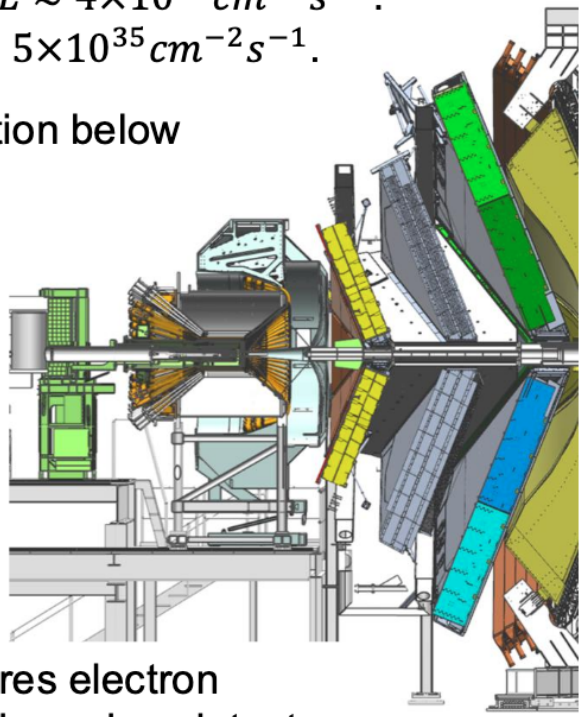
Beam time estimates to collect statistics sufficient for the extraction of the $\gamma_v pN^*$ electrocouplings for $Q^2<16$ GeV^2 for bin sizes $\Delta Q^2 = 0.5$ GeV^2 and $\Delta W = 0.05$ GeV:

0.5 year for $\mathcal{L} = 2\times10^{35}$ cm^{-2}s^{-1}

Upgrades: Next few years

Dr. S. Stepanyan, Hall B CEBAF-2037 Kickoff Meeting

- Variations of CLAS12 configurations with different Moller cone coverage have already been used to lower the background (FT-Off and No-FT configs).
  - A large Moller cone, covering up 5° (*Elmo*) will get us to $L \approx 4\times10^{35} cm^{-2}s^{-1}$. Cone covering up to 7°, *Elmo7,* can allow running at $L \approx 5\times10^{35} cm^{-2}s^{-1}$.
  - NO FT, no e'/γ tagging, and for Elmo7, no particle detection below 7°. May require enhanced capabilities for CVT and FVT.

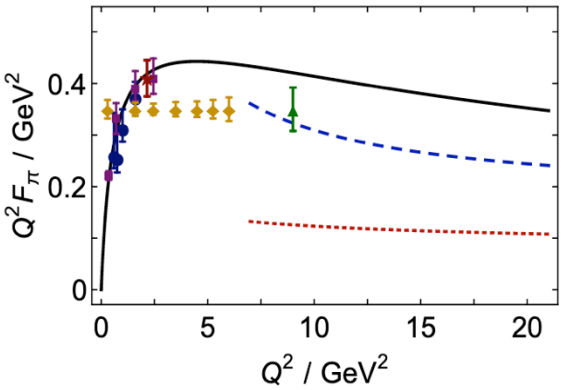


The loss of particle detection at very forward angles has a limited impact on the existing physics program (MesonX and DVCS are most impacted) while enabling ***high-statistics measurements in demanding kinematic domains such as high Q^2*** *and* ***-t****.*

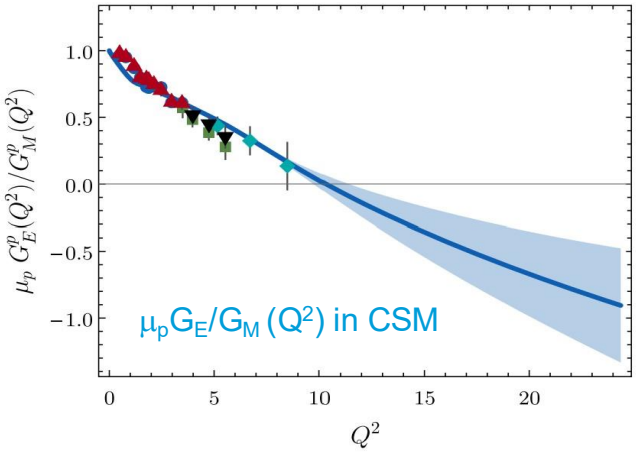
One of the physics topics discussed (N* program) requires electron detection in CD. Replacing the CTOF with an aerogel Cherenkov detector using SiPM-based light readout could provide the required capability. Further studies are needed to evaluate its feasibility and performance.

Prospects for Global Hadron Structure Analysis

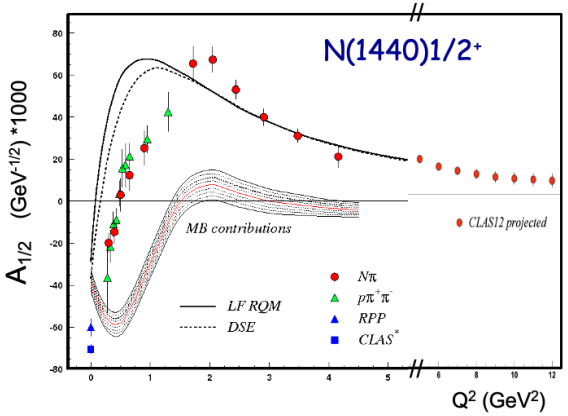
Pion Elastic FF



Nucleon Elastic FF



γ_vpN* Electrocouplings



Nucleon D-term

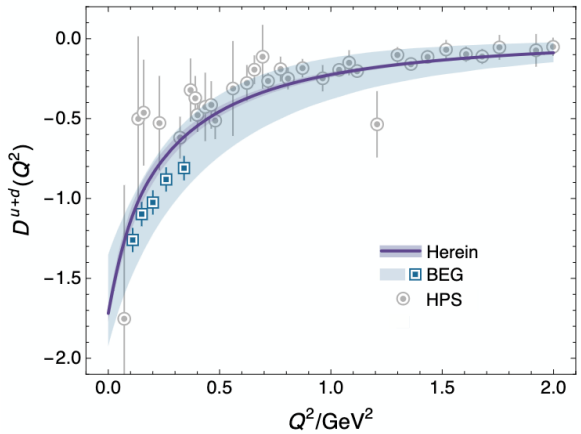


FIG. 2. Light-quark contribution to the proton D-term: $D^{u+d}(Q^2;\zeta_2)$. Herein – solid purple curve within like-coloured 1σ SPM uncertainty band; BEG – squares and associated fit from Ref. [22]; circles – lQCD results from Ref. [25].

[22] V.D. Burkert et al., Nature 557, 7705 (2018)

- Experimental results on the structure of mesons and ground/excited states of the proton, available and anticipated from 12-GeV-era JLab experiments at HiLumi, analyzed within a multi-pronged, QCD-connected theoretical framework, offer the only foreseeable opportunity for gaining insight into the strong-interaction dynamics underlying the emergence of hadron mass and structure.
- **CSM capabilities:** With its basic ingredients validated against experimental results on meson and nucleon elastic FF and γ_vpN* electrocouplings, CSM can predict the nucleon ground-state gravitational form factors. These predictions can then be incorporated into reaction models and tested against measured observables.
- Success in this endeavor would provide compelling evidence for a deeper understanding of the dynamics underlying the emergence of hadron mass and structure.

Conclusions and Outlook

- A good description of the $N(938)1/2^+$, $N(1440)1/2^+$, $\Delta(1232)3/2^+$, $\Delta(1600)3/2^+$, $N(1520)3/2^-$, and $\Delta(1700)3/2^-$ electrocouplings for $Q^2<5$ GeV^2 achieved within CSM with the same dressed quark mass function inferred from the QCD Lagrangian offers sound evidence for insight into the momentum dependence of the dressed quark mass, but in a range of distances where <30% of hadron mass is generated.

- An increase in luminosity by a factor of 2 (with unchanged beam energy and maximum polar scattering angle for detected electrons), would enable CLAS12 to access the electrocouplings of all prominent N* states in the unexplored Q^2 range of 5–12 GeV^2, allowing us to cover a range of distances where up to 60% of hadron mass is generated.

- As a prospect for CEBAF2037 and beyond, increasing the maximum laboratory scattering angle for detected electrons to 70° may enable the extension of $\gamma_v pN^*$ electrocoupling measurements to Q^2 up to 16 GeV^2. This would offer the only foreseen opportunity to map the dressed-quark mass function and investigate the transition from pQCD to sQCD dynamics at the distances where the largest fraction of N/N* masses (~75%) is generated. These studies would address one of the most challenging open questions in the Standard Model: the origin of ~94–98% of the visible mass of hadrons in the Universe.

- Other existing and planned facilities will be unable to explore exclusive meson electroproduction in the nucleon-resonance region at Q^2 up to 16 GeV^2, owing to the demanding requirements for high luminosity over a large detector acceptance.