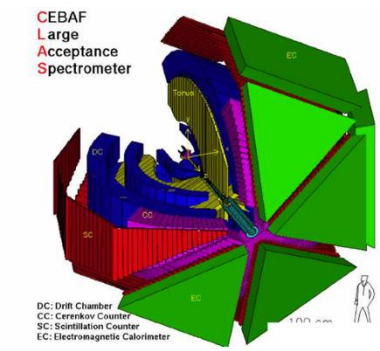
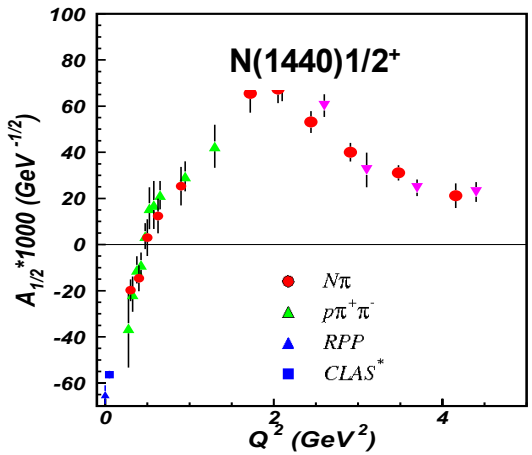
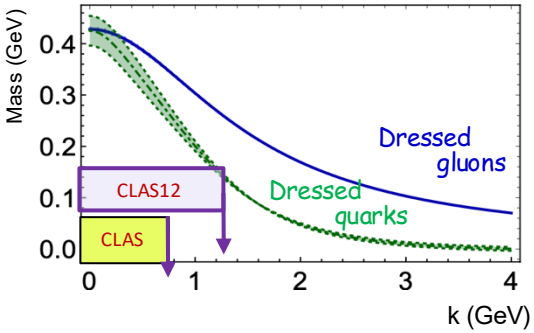
High Q^2 Nucleon Resonance Study





- N* electroexcitation amplitudes ($\gamma_v pN^*$ electrocouplings) as a window into strong interaction dynamics in the non-perturbative regime
- $\gamma_v pN^*$ electrocouplings from exclusive meson electroproduction with CLAS
- Insight into emergence of hadron mass
- New opportunities with CLAS12
- Gains foreseen from experiments with increased luminosity over large acceptance



Higher luminosity operations with large acceptance CLAS12 detector enable significant gains in extracting $\gamma_v pN^*$ electrocouplings for Q^2 to 13 GeV². These studies, combined with pseudoscalar-meson and ground-state nucleon structure, address a challenging Standard Model problem: understanding the origin of >98% of hadron mass and the emergence of hadron structure from strong interactions.

V.I. Mokeev, University of South Carolina and Jefferson Lab (CLAS Collaboration)

N* Structure in Experiments of 6/12 GeV Eras at Hall B

The experimental program on studies of N* structure in exclusive meson photo- and electroproduction with CLAS/CLAS12 seeks to determine:

- $\gamma_v pN^*$ electrocouplings at Q^2 up to 10 GeV^2 for most excited proton states up to 2.5 GeV by analyzing the data of meson electroproduction channels in the N* region.
- search for new states of baryon matter, so-called hybrid baryons with glue as an active structural component.

A unique source of information on many facets of strong QCD (sQCD, when α_s/π is comparable with unity) in generating excited nucleon states with different structural features:

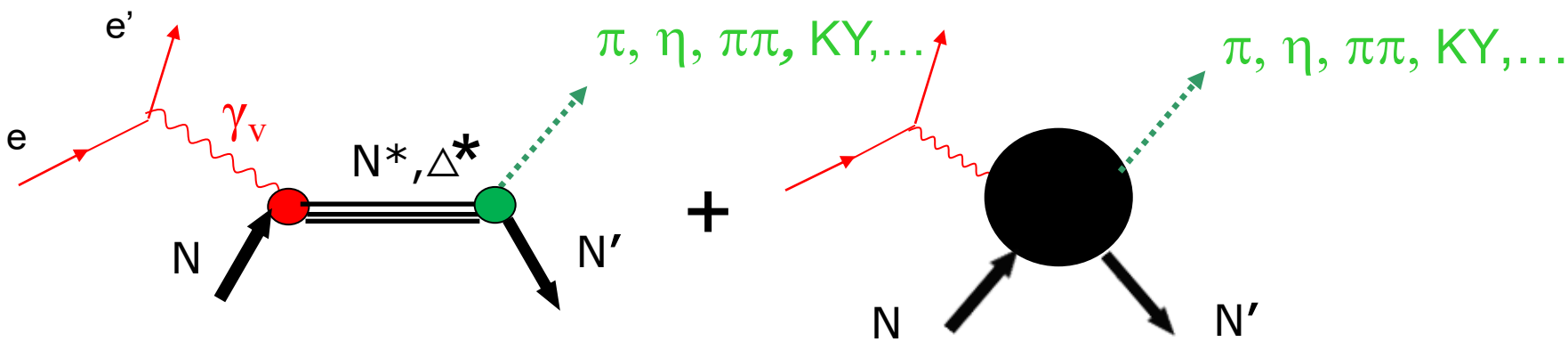
1. V.D. Burkert et al, Prog. Part. Nucl. Phys. 146, 104214 (2026)
2. P. Cheng, L. Liu, Ya Lu, and C.D. Roberts, Acta Phys. Polon. B57 2-A13 (2026)
3. V.I. Mokeev and D.S. Carman Few Body Syst. 63, 59 (2022)

Explore emergence of hadron mass (EHM) and structure in the transition from the pQCD to the sQCD regime

4. P. Achenbach, D.S. Carman, R.W. Gothe, K. Joo, V.I. Mokeev, and C.D. Roberts, Symmetry 7,1106 (2025)
5. M. Ding, C.D. Roberts, and S.M. Schmidt, Particles 6, 57 (2023)
6. D.S. Carman, R.W. Gothe, V.I. Mokeev. and C.D. Roberts, Particles 6, 416 (2023)

N* Photo-/Electrocouplings and their Extraction from Exclusive Data

Resonant amplitudes **Non-resonant amplitudes**



Definition of N* photo-/electrocouplings in CLAS analyses:

$$\Gamma_\gamma^T(Q^2) = \frac{k_{\gamma N^*}^2}{\pi}\frac{2M_N}{(2J_r+1)M_{N^*}}\left[|A_{\frac{1}{2}}(Q^2)|^2 + |A_{\frac{3}{2}}(Q^2)|^2\right]$$

$$\Gamma_\gamma^L(Q^2>0) = \frac{k_{\gamma N^*}^2}{\pi}\frac{2M_N}{(2J_r+1)M_{N^*}}\left[\,|S_{\frac{1}{2}}(Q^2)|^2\right]$$

- Real $A_{1/2}(Q^2)$, $A_{3/2}(Q^2)$, $S_{1/2}(Q^2)$

  I.G. Aznauryan and V.D. Burkert, Prog. Part. Nucl. Phys. 67, 1 (2012)

- Consistent results on the $\gamma_{r,v}pN^*$ photo-/electrocouplings from different meson photo-/electroproduction channels allow us to validate the capabilities of the reaction models for reliable extraction of these quantities.

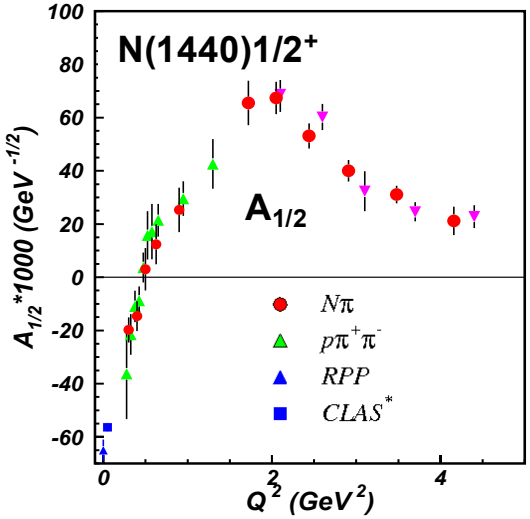
Nucleon Resonance Electrocouplings from Data on Exclusive Meson Electroproduction of 6 GeV Era with CLAS

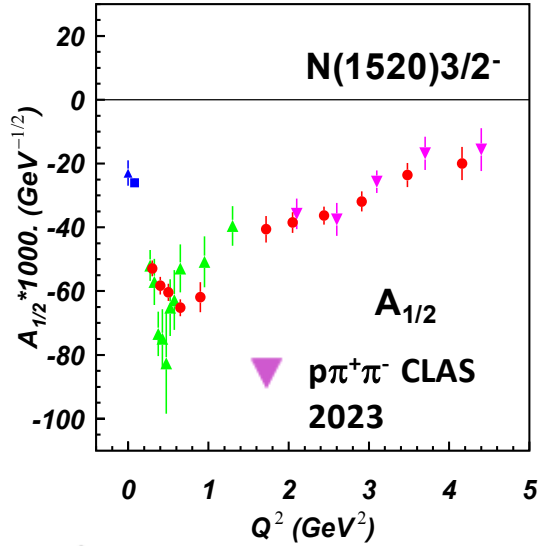
Exclusive meson electroproduction channels	Excited proton states	Q^2-ranges for extracted $\gamma_v pN^*$ electrocouplings, GeV^2
$\pi^0 p$, $\pi^+ n$	$\Delta(1232)3/2^+$ $N(1440)1/2^+$,$N(1520)3/2^-$, $N(1535)1/2^-$	0.16-6.0 0.30-4.16
$\pi^+ n$	$N(1675)5/2^-$, $N(1680)5/2^+$,$N(1710)1/2^+$	1.6-4.5
ηp	$N(1535)1/2^-$	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 analysis of CLAS data for most N* states in the mass range <1.8 GeV and in the range of $Q^2 < 5$ GeV^2.
- Numerical results can be found at https://userweb.jlab.org/~mokeev/resonance_electrocouplings23/

A.N. Hiller Blin et al, PRC100, 035201 (2019), V.I. Mokeev et al., arXiv:2608.04997

N* Electrocouplings from πN and $\pi^+\pi^-$p CLAS Electroproduction Data



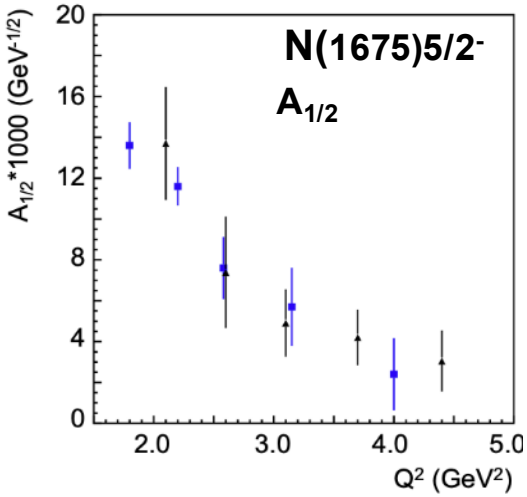


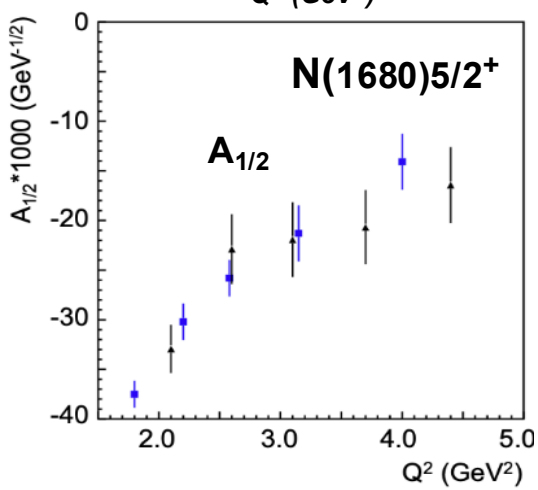
I.G. Aznauryan et al. (CLAS), PRC 80, 055203 (2009)

V.I. Mokeev et al., PRC 86, 035203 (2012)

V.I. Mokeev et al., PRC 93, 025206 (2016)

V.I. Mokeev et al., PRC 108, 025204 (2023)





I.G. Aznauryan et al. (CLAS), PRC 91, 045203 (2015)

black: CLAS $\pi^+\pi^-$p
V.I. Mokeev et al., arXiv:2608.04997

Consistent results on the γ_vpN* electrocouplings from independent studies of the two major πN and $\pi^+\pi^-$p electroproduction channels with different non-resonant contributions demonstrated the reliability of the JANR/JM reaction models and allow for evaluation of their systematic uncertainties.

How do the Ground/Excited Nucleon Masses Emerge?

Composition of the Nucleon Mass:

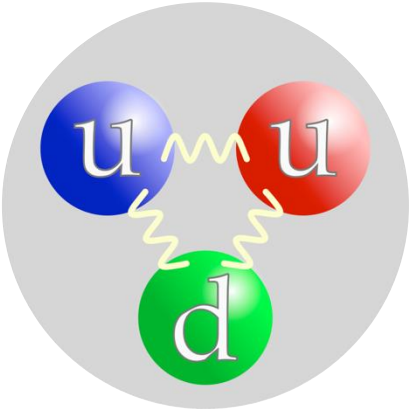
M_p, MeV (PDG23)

938.2720813
±0.0000058

Sum of bare quark masses, MeV

2.16+2.16+4.67
$=8.99^{+1.45}_{-0.65}$ or < 1.1%

proton



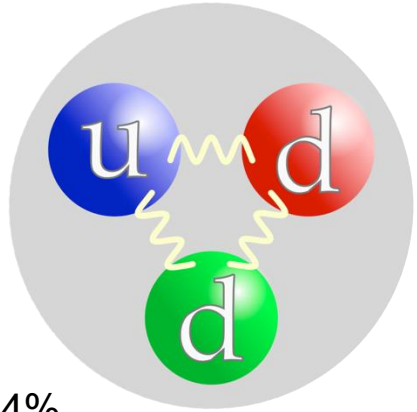
M_n, MeV (PDG23)

939.5654133
±0.0000058

Sum of bare quark masses, MeV

4.67+4.67+2.16
$= 11.50^{+1.45}_{-0.60}$ or < 1.4%

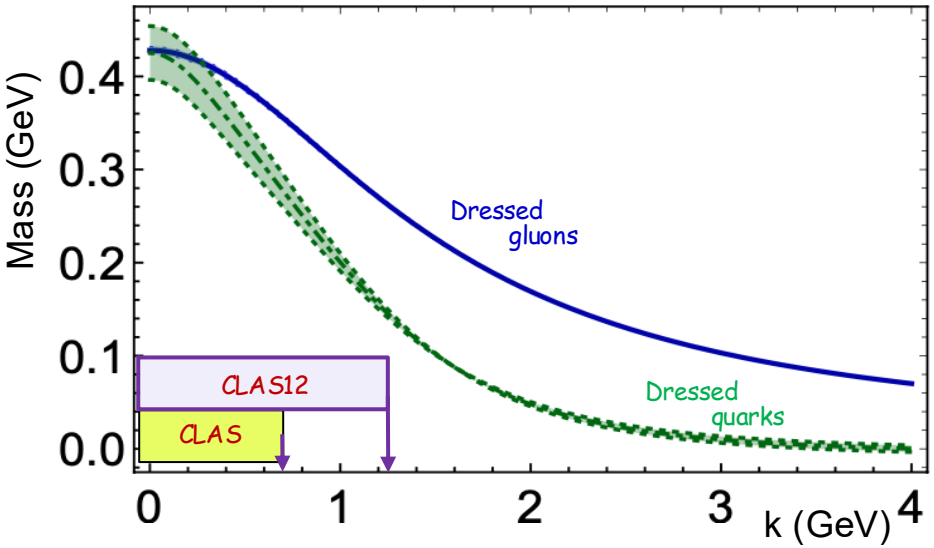
neutron



$\overline{\text{MS}}$ scheme at a renormalization scale of 2.0 GeV

- The Higgs mechanism only generates the renormalization-group-invariant masses of bare quarks relevant to the pQCD regime.
- The dominant part of N/N* masses is generated in processes other than the Higgs mechanism.

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



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

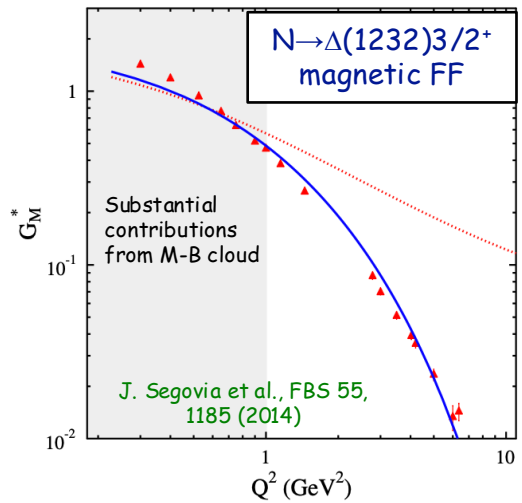
M. Ding, C.D. Roberts, and S.M. Schmidt, Particles 6, 57 (2023)

- The dominant part of hadron mass (>98%) is generated by strong interactions between dressed gluons and quarks at distances where the transition from pQCD to sQCD takes place. EHM is encoded in the evolution of dressed quark/gluon masses and QCD running coupling α_s with momenta/distances. Studies of the nucleon elastic e.m. form factors and $\gamma_v pN^*$ electrocouplings within CSM across a broad range of Q^2 allow us to map out the momentum dependence of dressed quark mass. Other QCD-connected theory approaches are encouraged.
- The CLAS experiments, limited to $Q^2 < 5$ GeV², allowed exploration of a range of distances where ~30% of hadron mass is generated. Available CLAS12 luminosity offers extension of the Q^2 coverage for ©$_v$pN* electrocouplings to $Q^2 < 8$-10 GeV². CLAS12 $\mathcal{L} = 2$–3×10^{35} cm^{-2}s^{-1} enables extension of the Q^2 coverage up to 12-13 GeV², offering insight into the distances where ~50–60% of hadron mass emerges and into half of the distance range where hadron structure is generated in the transition from pQCD to sQCD.

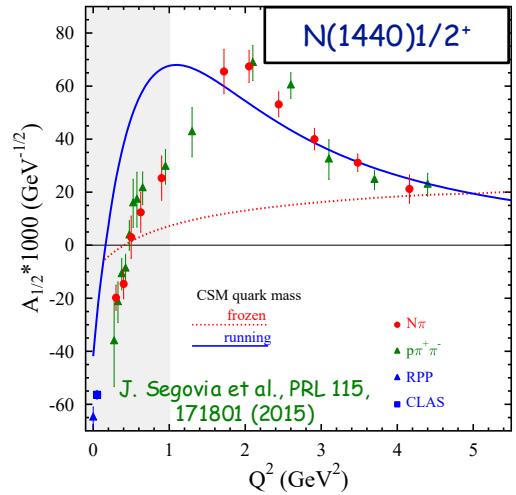
Insight into Dressed Quark Mass Function from Experimental Results

- 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 momentum dependence of dressed quark mass

CLAS/Hall A/C results vs. CSM expectations

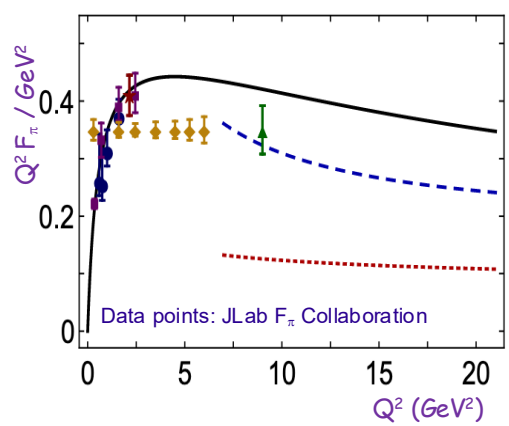


Pion Elastic FF

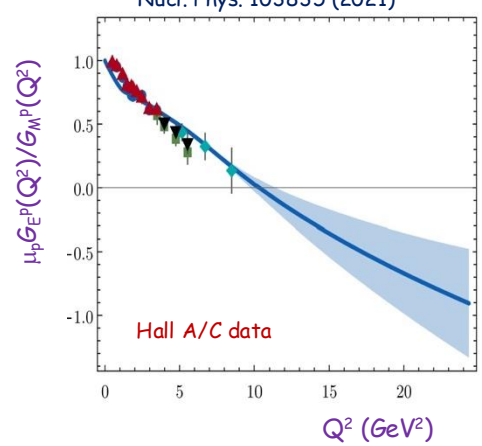


Nucleon Elastic FF

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

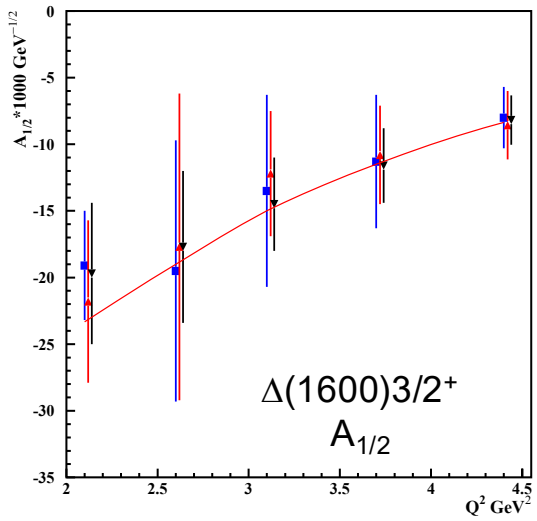


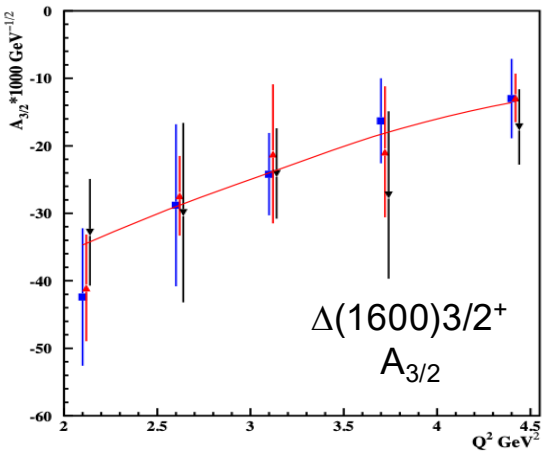
M. Barabanov et al., Prog. Part. Nucl. Phys. 103835 (2021)

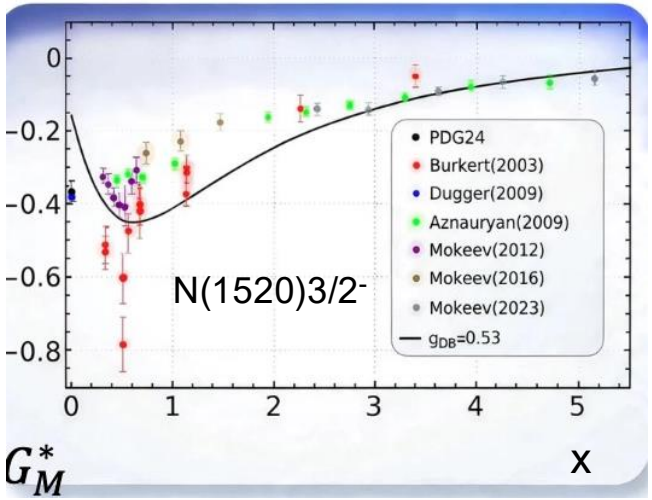


One of the most important achievements in hadron physics of the last decade in synergistic efforts between experimentalists, phenomenologists, and theorists.

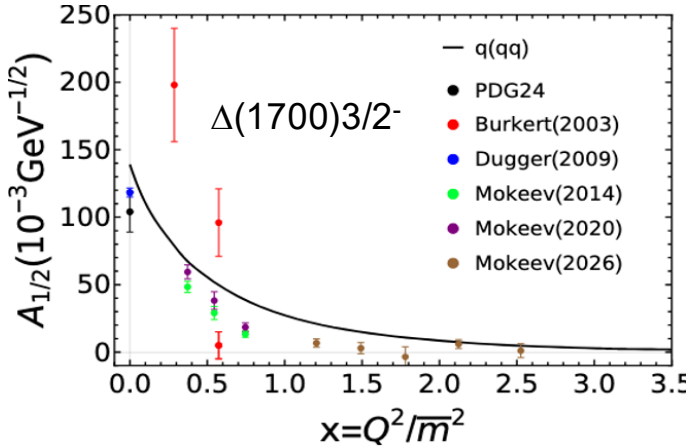
CSM Prediction vs. Data Determination







P. Cheng, L. Liu, Ya Lu, and C.D. Roberts. Acta Phys. Pol., B57, A13 (2026)



Ya Lu et al., PRD 100, 034001 (2019)

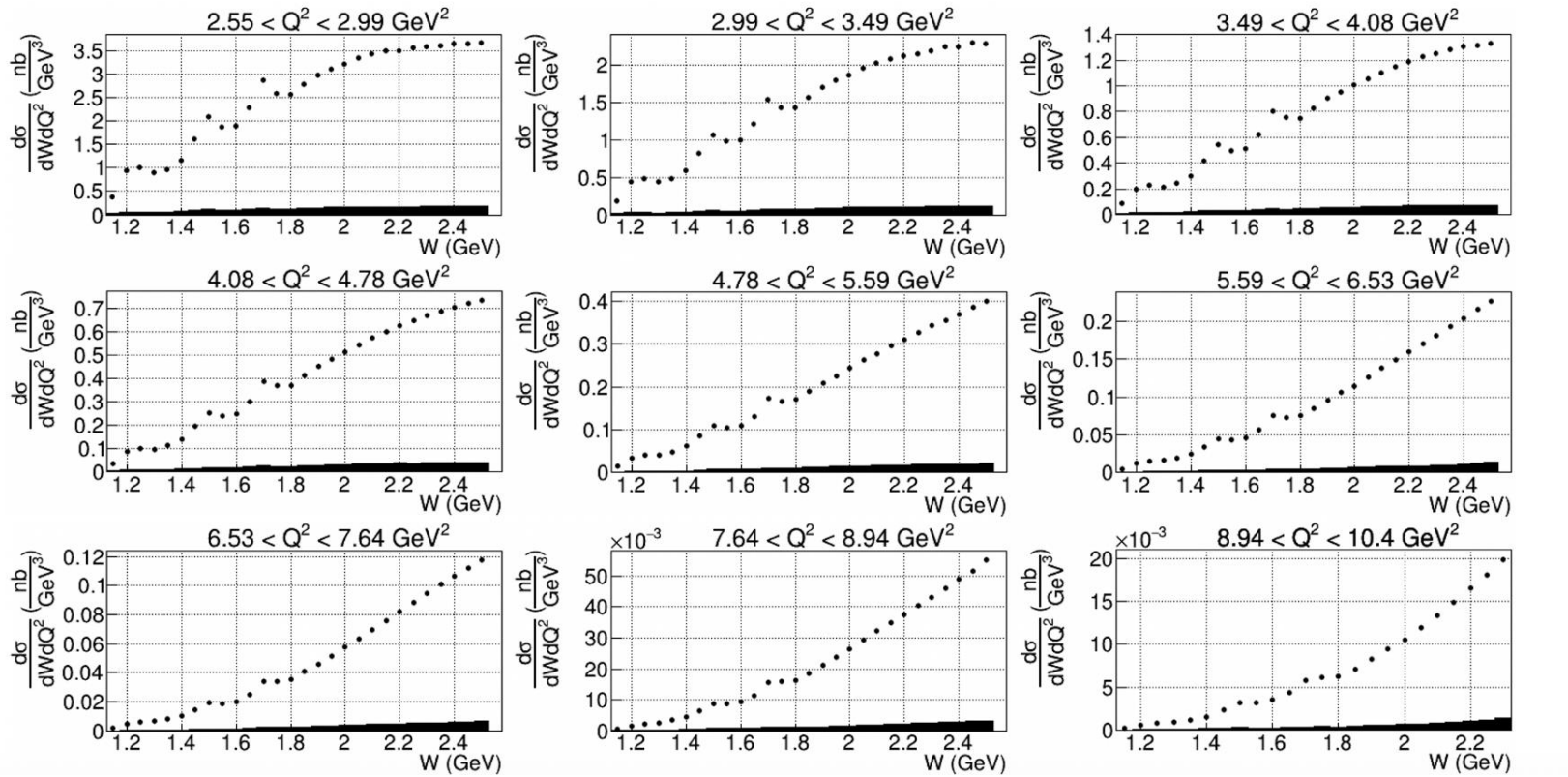
$2\overline{m}=m_N+m_{N^*}$

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

Extension in N* Structure Studies with CLAS12

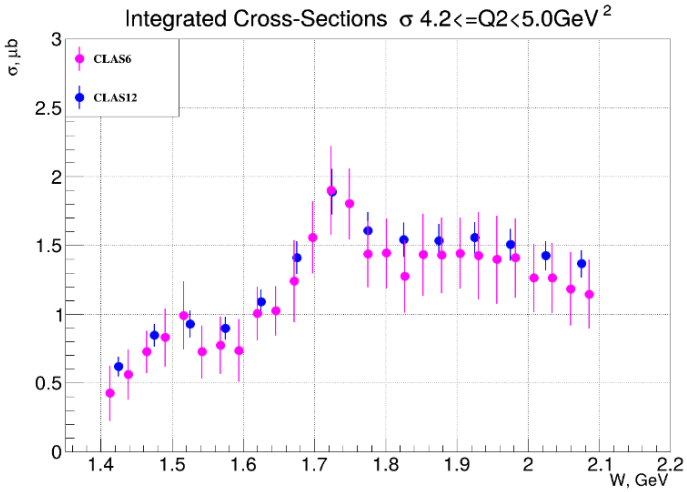
CLAS12: Extension of the results on $\gamma_v pN^*$ electrocouplings of most N* states in the range W < 2.5 GeV and Q^2 up to 10 GeV^2 from exclusive channels: πN, $\pi\pi N$, KY, K*Y, KY*.

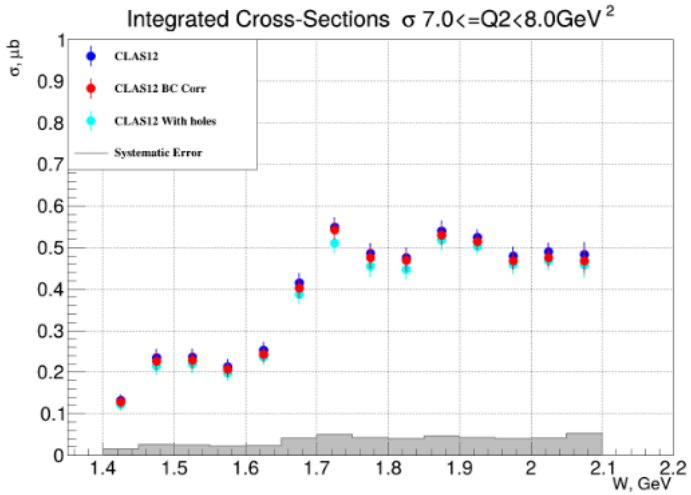
Measurements of inclusive (e,e′X) cross section with CLAS12. V. Klimenko et al. (CLAS Collaboration), PRC 112, 025201 (2025)

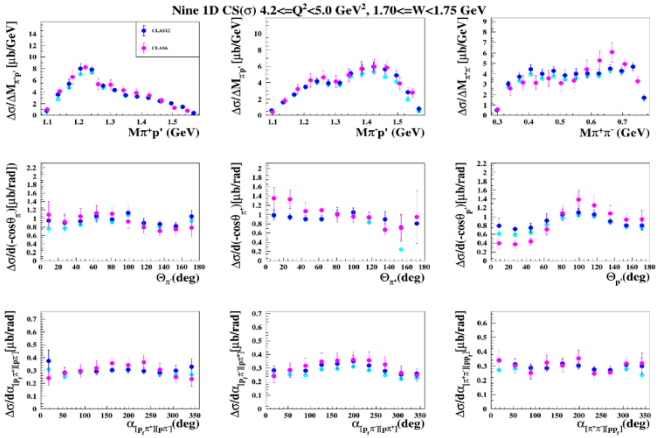


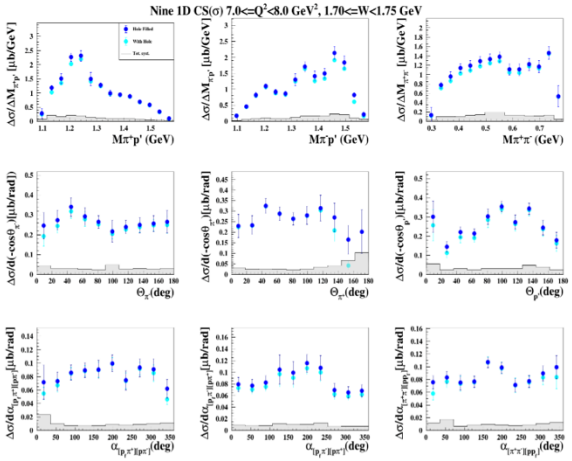
Resonance-like structures are clearly seen in the first, second and third resonance regions for Q^2<10 GeV^2

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







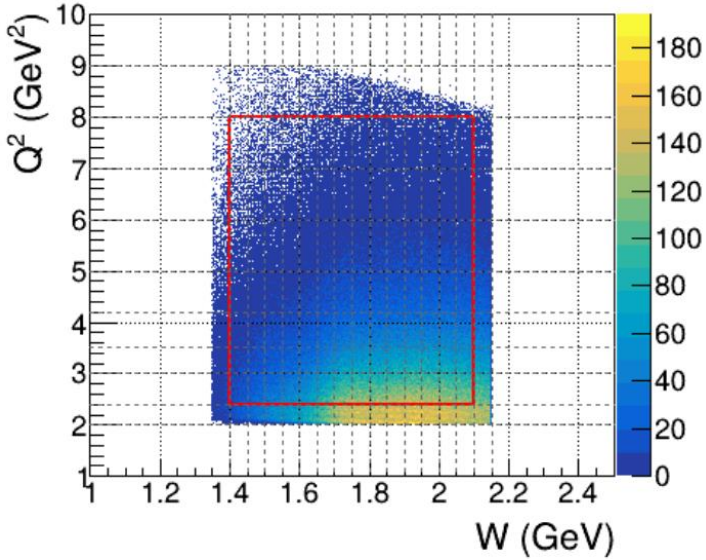


K. Neupane, R.W. Gothe, D.S. Carman V.I. Mokeev et al., (CLAS Collaboration) arXiv:2609.19395, submitted to PRC

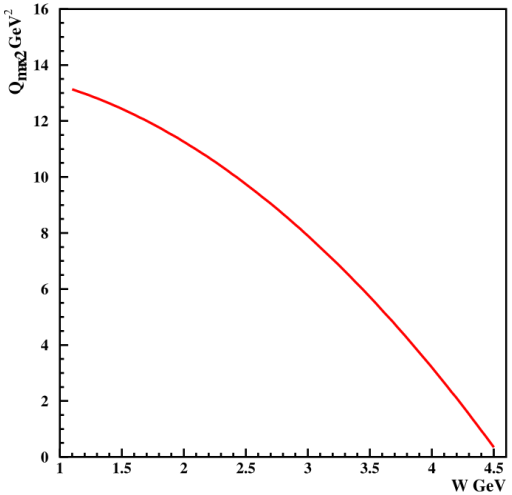
- Integrated and nine 1D differential $\pi^+\pi^-p$ cross sections are available for W=[1.4-2.1] GeV, Q^2=[2.4-8.0] GeV^2
- Consistency with the CLAS data in the overlapping range of Q^2<5.0 GeV^2
- Allows us to extend the JM model over the mass range up to 2 GeV for Q^2<8 GeV^2, paving the way to obtain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

Prospects for Extension of $\pi^+\pi^-p$ Electroproduction Data after CLAS12 Luminosity Increase

Q^2 vs. W coverage for $\pi^+\pi^-p$ electroproduction data with CLAS12

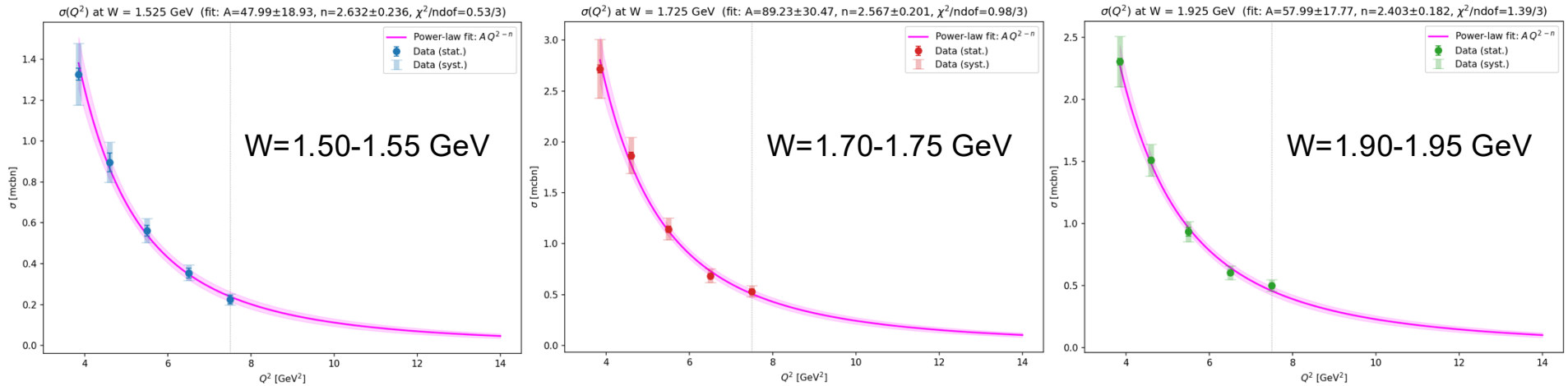


Allowed Q^2 vs. W coverage for beam energy of 10.6 GeV



- Available CLAS12 data cover Q² to 8.0 GeV² (left plot), while the kinematically allowed Q² range in the resonance region extends up to 13 GeV² for a 10.6 GeV beam and maximum detected electron angle of 35° (right plot).
- An increase in luminosity is critical for extending the Q² coverage of □⁺□⁻p electroproduction data, reducing the Q² bin widths, or increasing statistics in broader Q² bins. This will provide more extensive and precise information on the Q² evolution of ©$_\nu$pN* electrocouplings.
- Detailed MC simulations are in progress. The potential gains from an increase in luminosity, assuming a 10.6 GeV beam, have been evaluated using a simplified approach.

Potential Gains in $\pi^+\pi^-p$ Electroproduction after CLAS12 Luminosity Increase (simplified approach)



Q^2-evolution of fully integrated $\pi^+\pi^-p$ electroproduction cross sections measured with CLAS12 and extrapolated across Q^2<14 GeV^2 - K. Neupane et al., arXiv:2609.19395

- Results from CLAS12 available with a Q^2-bin size of 1.0 GeV^2 for 6.0 < Q^2 < 8.0 GeV^2, based on a relatively small dataset. An increase in luminosity by a factor of 3 and beam time by a factor of 3–4 would enable □$^+$□$^-$p electroproduction cross sections to be measured with sufficient statistics to extract $\gamma_v pN^*$ electrocouplings in a Q^2-bin size of 0.1 GeV^2 over Q^2 < 8.0 GeV^2.

Reduction factor in fully integrated cross section from the data fit $R=\sigma(Q^2=11.8\ \text{GeV}^2)/\sigma(Q^2=7.5\ \text{GeV}^2)$

W, GeV	1.50-1.55	1.70-1.75	1.90-1.95
R	3.2±0.3	3.1±0.3	2.9±0.2

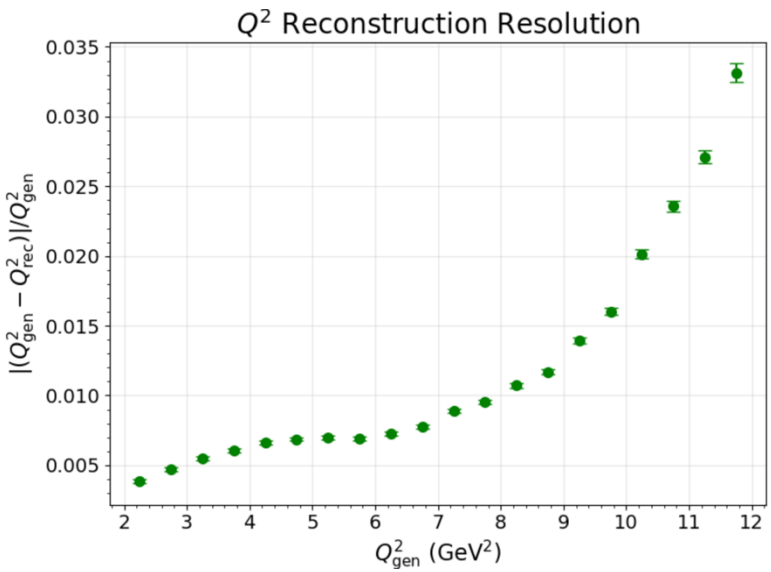
- The Q^2-bin size at Q^2=12 GeV^2 needed to collect statistics sufficient for extraction of $\gamma_v pN^*$ electrocouplings was determined as: ΔQ^2_{stat}=0.1 (GeV^2)*R

W, GeV	1.50-1.55	1.70-1.75	1.90-1.95
ΔQ^2_{stat}, GeV^2	0.32	0.31	0.29

Potential Gains in $\pi^+\pi^-p$ Electroproduction after CLAS12 Luminosity Increase (simplified approach)

MC results for relative Q^2 resolution averaged over the N* region of W=[1.4-2.0] GeV for E_{beam}=10.6 GeV.

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



$$\alpha(Q^2) = |Q^2_{gen} - Q^2_{rec}|/Q^2_{gen}$$

The estimated numerical values:

$\alpha(Q^2=11.8\ \text{GeV}^2)=0.034$

$\alpha(Q^2=7.5\ \text{GeV}^2)=0.009$

The Q^2-bin size imposed by resolution:

$\Delta Q^2_{res}(Q^2=11.8\ \text{GeV}^2)= \alpha(Q^2=11.8\ \text{GeV}^2)*11.8\ \text{GeV}^2=0.40\ \text{GeV}^2$

$\Delta Q^2_{res}(Q^2=7.5\ \text{GeV}^2)= \alpha(Q^2=7.5\ \text{GeV}^2)*7.5\ \text{GeV}^2=0.068\ \text{GeV}^2$

The overall Q^2-bin size ΔQ^2_{tot} accounting for statistics needed for $\gamma_v pN^*$ electrocoupling extraction ΔQ^2_{stat} and resolution over Q^2 ΔQ^2_{res} for Q^2<12 GeV^2 is:

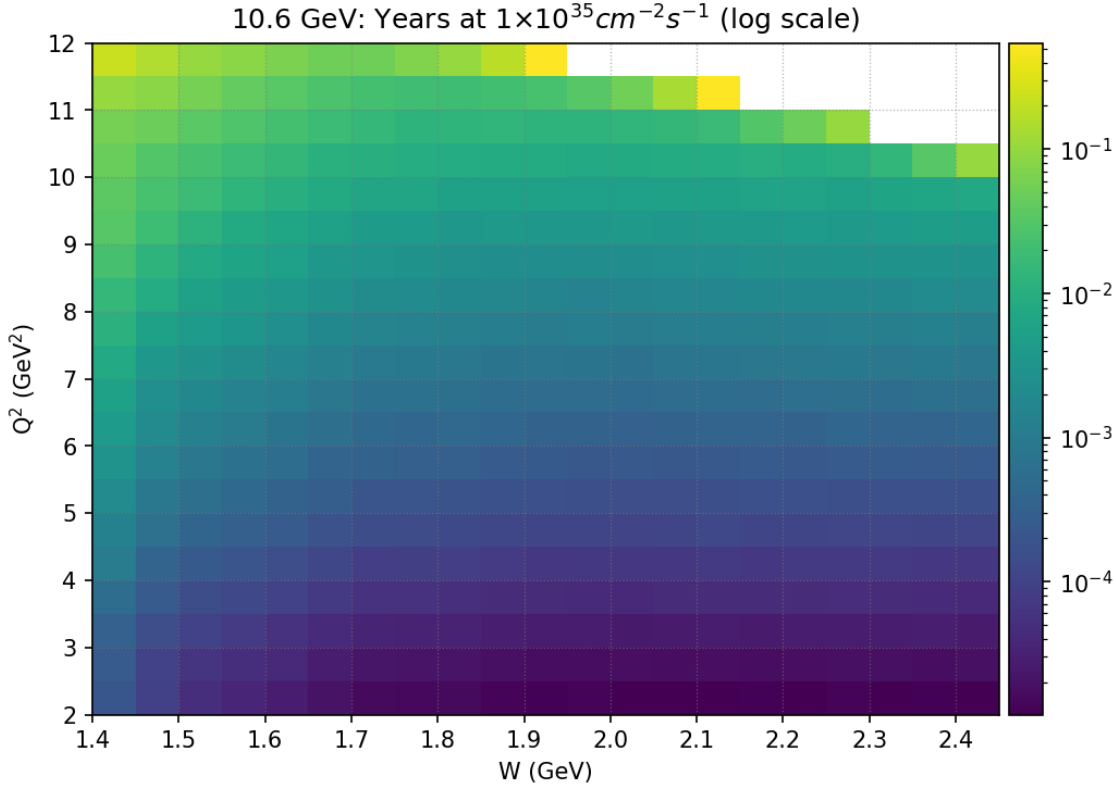
$$\Delta Q^2_{tot} = \sqrt{(\Delta Q^2_{res})^2 + (\Delta Q^2_{stat})^2}$$

- An increase in luminosity by a factor of 3 and beam time by a factor of 3–4 will allow us to extend the Q^2 coverage of □⁺□⁻p electroproduction cross sections to Q^2 < 12.0 GeV², with Q^2-bin sizes of < 0.5 GeV² over the nucleon resonance region up to 2 GeV.

- After the luminosity increase, for Q^2 < 8 GeV², the □⁺□⁻p electroproduction cross sections can be measured with Q^2-bin sizes of 0.12 GeV² across the entire resonance region. Alternatively, broader Q^2 bins, up to 0.5 GeV², will provide more statistics and may improve the precision of the extracted ©$_v$pN* electrocouplings.

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}, 0.6 year of beam time required for sufficient statistics to extract $\gamma_v pN^*$ electrocouplings.

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

- After $\mathcal{L}$ increased to 3×10^{35} cm^{-2}s^{-1}, □$^+$□$^-$p cross sections can be measured up to $Q^2 < 12$ GeV^2 in (Q^2,W) bins $\Delta Q^2 = 0.5$ GeV^2 and $\Delta W = 0.05$ GeV, with sufficient statistics to extract ©$_v$pN* electrocouplings using a data-taking time of *0.6 year × (1/3) = 0.2 year*.
- Sufficient statistics means exceeding those collected in the $Q^2 = 7.0–8.0$ GeV^2 bin in the arXiv publication cited on this slide.

Conclusions and Outlook

- High-quality data from the 6-GeV era with CLAS have allowed for the determination of the electrocouplings of most N*s in the mass range up to 1.8 GeV for Q^2<5 GeV^2.

- A good description of the N(938)$1/2^+$, N(1440)$1/2^+$, Δ(1232)$3/2^+$, Δ(1600)$3/2^+$, N(1520)$3/2^-$, and Δ(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 3 (with unchanged beam energy and maximum polar scattering angle for detected electrons), would enable CLAS12 to uniquely access the electrocouplings of all prominent N* states in the unexplored Q^2 range of 5–12 GeV^2, providing *the only foreseen opportunity* to map out the dressed-quark mass function and study the transition from *pQCD to sQCD dynamics at distances where up to 60% of hadron mass is generated.*

- Q^2-bin sizes for measured observables and extracted $\gamma_v pN$ electrocouplings will be substantially reduced, down to 0.12–0.5 GeV^2, or the precision of the extracted electrocouplings will be improved in broader Q^2 bins. Therefore, a luminosity upgrade is particularly important for exploring sQCD dynamics that underlie the N* structural complexity.

Back up

Summary of Published CLAS Data on Exclusive Meson Electroproduction off Protons in N* Excitation Region

Hadronic final state	Covered W-range, GeV	Covered Q^2-range, GeV^2	Measured observables
π^+n	**1.1-1.38** **1.1-1.55** **1.1-1.70** **1.6-2.00**	**0.16-0.36** **0.3-0.6** **1.7-4.5** **1.8-4.5**	**$d\sigma/d\Omega$** **$d\sigma/d\Omega$** **$d\sigma/d\Omega$, A_b** **$d\sigma/d\Omega$**
π^0p	**1.1-1.38** **1.1-1.68** **1.1-1.39** **1.1-1.80**	**0.16-0.36** **0.4-1.8** **3.0-6.0** **0.4-1.0**	**$d\sigma/d\Omega$** **$d\sigma/d\Omega$, A_b,A_t,A_{bt}** **$d\sigma/d\Omega$** **$d\sigma/d\Omega$, A_b**
ηp	**1.5-2.3**	**0.2-3.1**	**$d\sigma/d\Omega$**
$K^+\Lambda$	**thresh-2.6**	**1.40-3.90** **0.70-5.40**	**$d\sigma/d\Omega$** **P^0, P'**
$K^+\Sigma^0$	**thresh-2.6**	**1.40-3.90** **0.70-5.4**	**$d\sigma/d\Omega$** **P'**
$\pi^+\pi^-p$	**1.3-1.6** **1.4-2.1** **1.4-2.0**	**0.2-0.6** **0.5-1.5** **2.0-5.0**	**Nine 1-fold differential cross sections**

- $d\sigma/d\Omega$–CM angular distributions
- A_b,A_t,A_{bt}-longitudinal beam, target, and beam-target asymmetries
- P^0, P' –recoil and transferred polarization of strange baryon

Around 150,000 data points!

Almost full coverage of the final state hadron emission angles in CM-frame

The measured observables from CLAS are stored in the CLAS Physics Data Base http://clas.sinp.msu.ru/cgi-bin/jlab/db.cgi

Approaches for Extraction of $\gamma_v pN^*$ Electrocouplings from the Meson Electroproduction Data

Analyses of different meson electroproduction channels independently:

- **π^+n and π^0p channels:**
  Unitary Isobar Model (UIM) and Fixed-t Dispersion Relations (DR)
  I.G. Aznauryan, Phys. Rev. C67, 015209 (2003)
  I.G. Aznauryan et al. (CLAS), Phys. Rev. C80, 055203 (2009)
  I.G. Aznauryan et al. (CLAS), Phys. Rev. C91, 045203 (2015)

  JANR

- **ηp channel:**
  Extension of UIM and DR
  I.G. Aznauryan, Phys. Rev. C68, 065204 (2003)
  Data fit at W<1.6 GeV, assuming N(1535)1/2$^-$ dominance
  H. Denizli et al. (CLAS), Phys. Rev. C76, 015204 (2007)
- **$\pi^+\pi^-p$ channel:**
  Data driven JLab-MSU meson-baryon model (JM)
  V.I. Mokeev, V.D. Burkert et al., Phys. Rev. C80, 045212 (2009)
  V.I. Mokeev et al. (CLAS), Phys. Rev. C86, 035203 (2012)
  V.I. Mokeev, V.D. Burkert et al., Phys. Rev. C93, 054016 (2016)
  V.I. Mokeev et al., Phys. Rev. C108, 025204 (2023)=**JM23**

  JM

Global coupled-channel analysis of $\gamma_{r,v}N$, πN, ηN, $\pi\pi N$, $K\Lambda$, $K\Sigma$ exclusive channels:

H. Kamano, Few Body Syst. 59, 24 (2018) Argonne-Osaka
H. Kamano, JPS Conf. Proc. 13, 010012 (2017) Argonne-Osaka

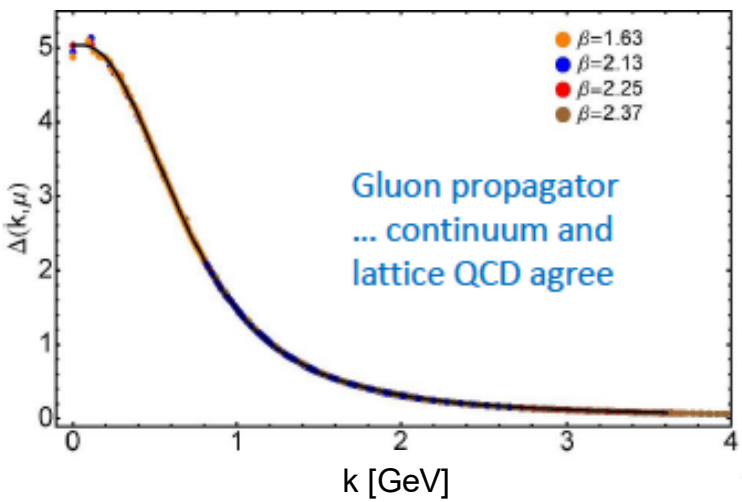
See T. Sato talk on Monday, September 7 at 10:30 am

M. Mai et al., Phys. Rev. C106, 015201 (2022)=**Julich-Bonn-Washington**
Yu-Fei Wang et al, Phys. Rev. Lett. 133, 101901 (2024)=**Julich-Bonn-Washington.**

See M. Mai talk on Tuesday, September 8 at 10:30 am, M. Doering talk on Tuesday, September 8 at 6:00 pm

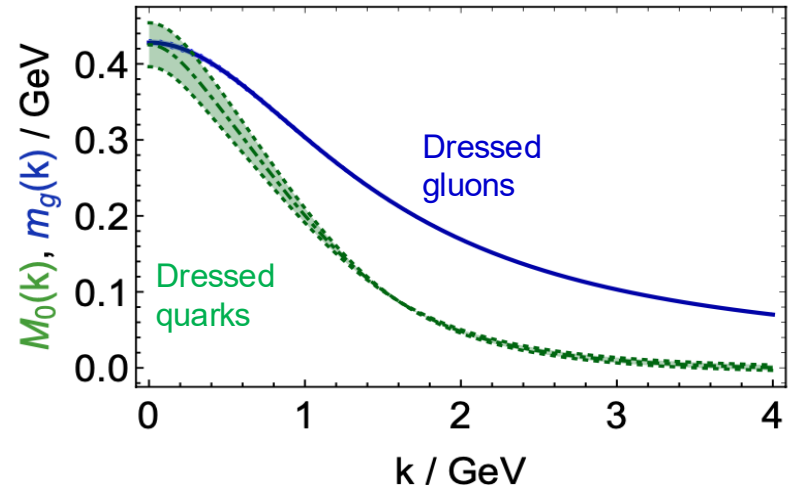
Continuum/Lattice QCD and Experiment Synergy for Insight into EHM

- Dressed quark/gluon masses converge at the complete QCD mass scale of 0.43(1) GeV.
- Express the fundamental feature: emergence of the quark and gluon masses even in the case of massless quarks in chiral limit and massless QCD gluons.
- LQCD confirms continuum QCD results.



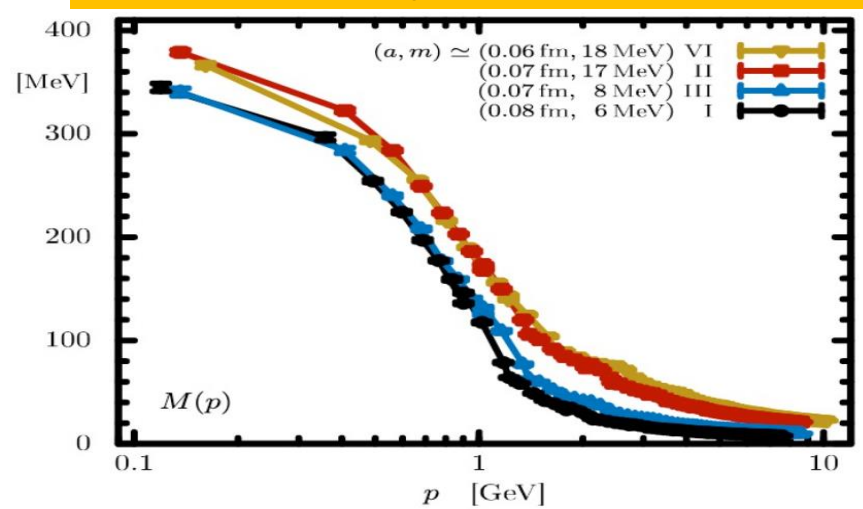
- The sensitivity of N* electroexcitation amplitudes to the dressed quark propagator allows us to map out the quark mass function.

Dressed Quark/Gluon Masses (continuum QCD)
C.D. Roberts, Symmetry 12, 1468 (2020), AAPS Bull 31, 6 (2021)

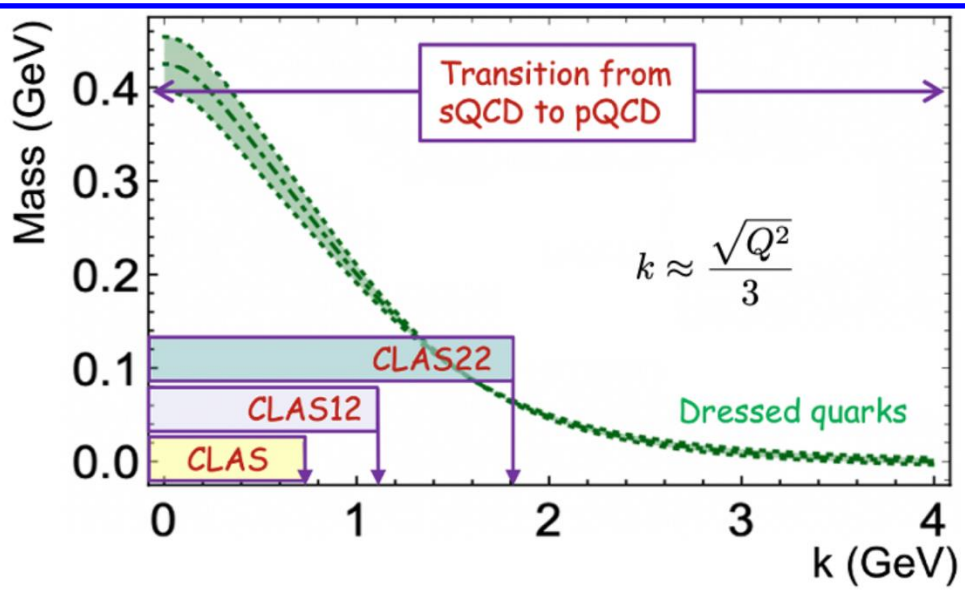


Inferred from QCD Lagrangian with only the Λ_{QCD} parameter

Dressed Quark Mass (lattice QCD)
O. Olivera et al., Phys. Rev. D 99, 094506 (2019)



Impact of the Extension of $\gamma_v pN^*$ Electrocouplings Results for Q^2>5.0 GeV^2 on Insight into EHM



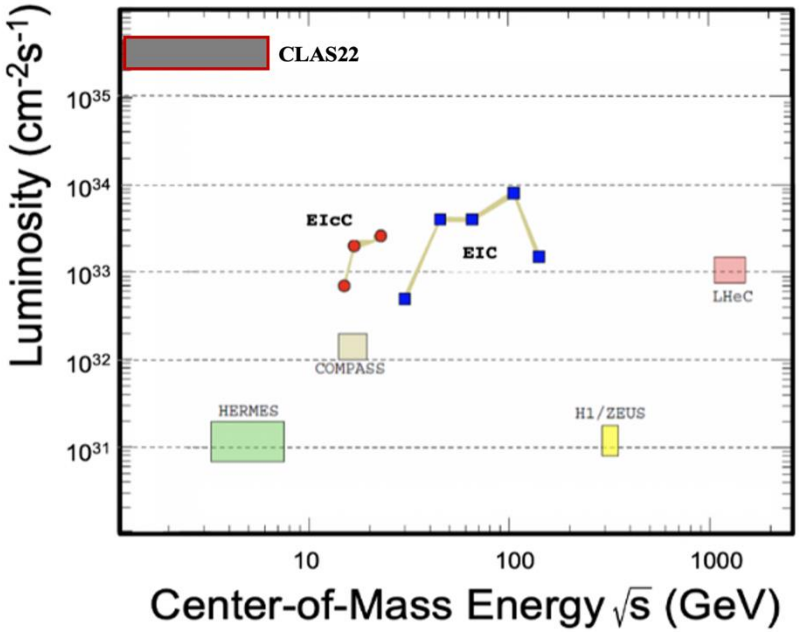
P. Achenbach, D.S. Carman, R.W. Gothe, K. Joo, V.I. Mokeev, and C.D. Roberts, Symmetry, 17, 1106 (2025)

- To resolve the challenging problem on EHM, the dressed quark mass function $M_q(k)$ should be mapped out in experiments over the entire range of quark momenta to ~2 GeV, where the transition from strongly coupled to perturbative QCD takes place, and the dominant part of hadron mass and N* structure emerge.
- The CLAS experiments, limited to $Q^2 < 5.0$ GeV^2, allow exploration of a restricted range of distances where ~30% of hadron mass is generated. Extending the Q^2 coverage up to 10 GeV^2 with measurements from CLAS12 will offer insight into the distance scales where ~50% of hadron mass emerges.
- A potential increase of CEBAF energy to 22 GeV would provide a unique opportunity to explore the full range of distance scales over which the dominant portion of hadron mass and the structure of excited nucleon states are generated.

Unique Opportunities for Gaining Insight into EHM through Studies of N* Structure within a Potential CEBAF 22 GeV Energy Upgrade Including CLAS22

- Simulations of πN, KY, and $\pi^+\pi^-$p electroproduction with CEBAF@22 GeV show:

  $\gamma_v pN^*$ electrocouplings can be determined up to $Q^2 \sim 30$ GeV^2 for $\mathcal{L} \sim 2 - 5 \times 10^{35}$ cm^{-2}s^{-1}



Both EIC and EIcC would need much higher luminosity to carry out such a program

The luminosity "frontier" is a *unique* advantage of JLab

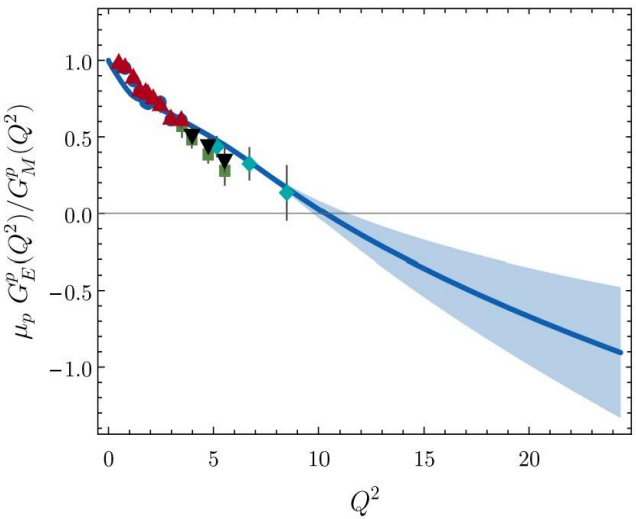
- Beam energy 22 GeV
- Large acceptance
- High luminosity
- Studies of exclusive reactions

- Extending the $\gamma_v pN^*$ electrocoupling results into the Q^2 range from 10 - 30 GeV^2 after the CEBAF energy increase and pushing the capabilities of CLAS12 to measure exclusive electroproduction to the highest possible luminosity within a large acceptance, will offer the only foreseen opportunity to explore how the emergent part of the hadron mass and N* structures are coming from QCD and will make CEBAF@22 GeV unique and the ultimate QCD-facility at the luminosity frontier.

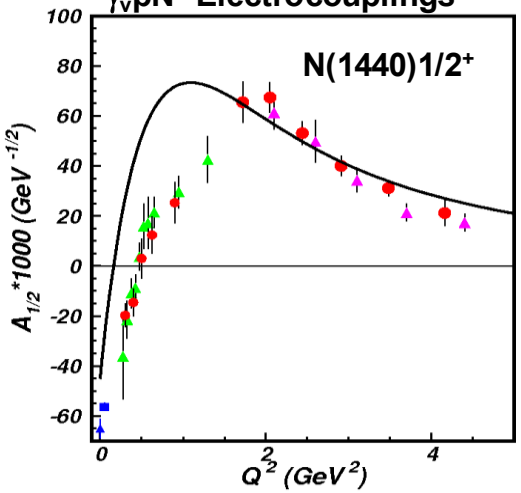
EHM from Global Hadron Structure Analysis within CSM

This will be extended by the future data on $\gamma_v pN^*$ electrocouplings from CLAS12 in the 12 GeV era

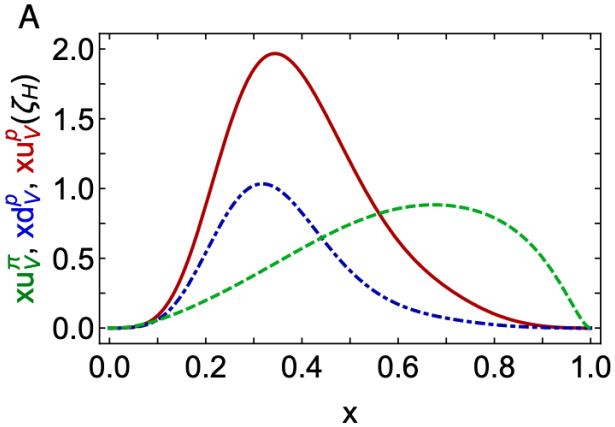
Nucleon Elastic FF



$\gamma_v pN^*$ Electrocouplings

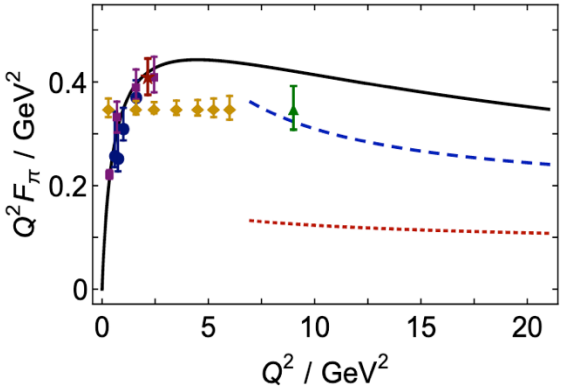


Proton and pion PDF for valence quarks

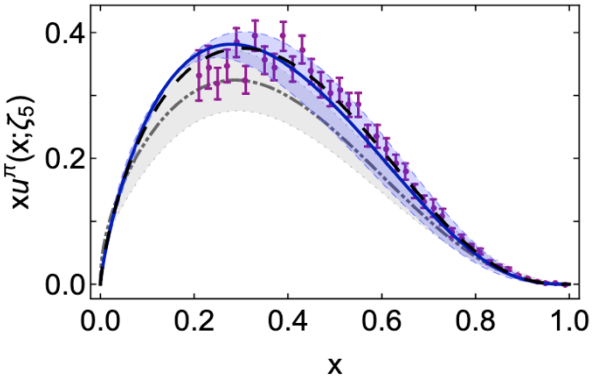


New data from studies of D-Y at AMBER and Sullivan processes at JLab

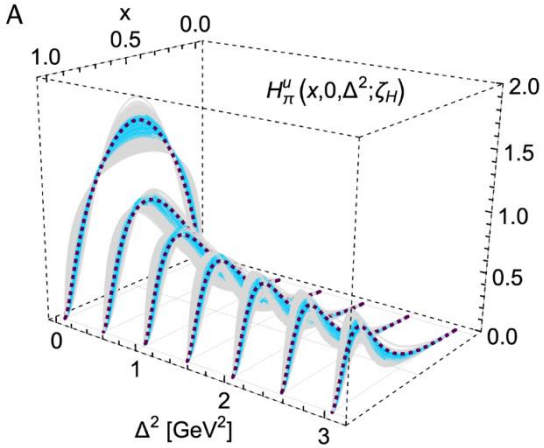
Pion Elastic FF



Pion PDF

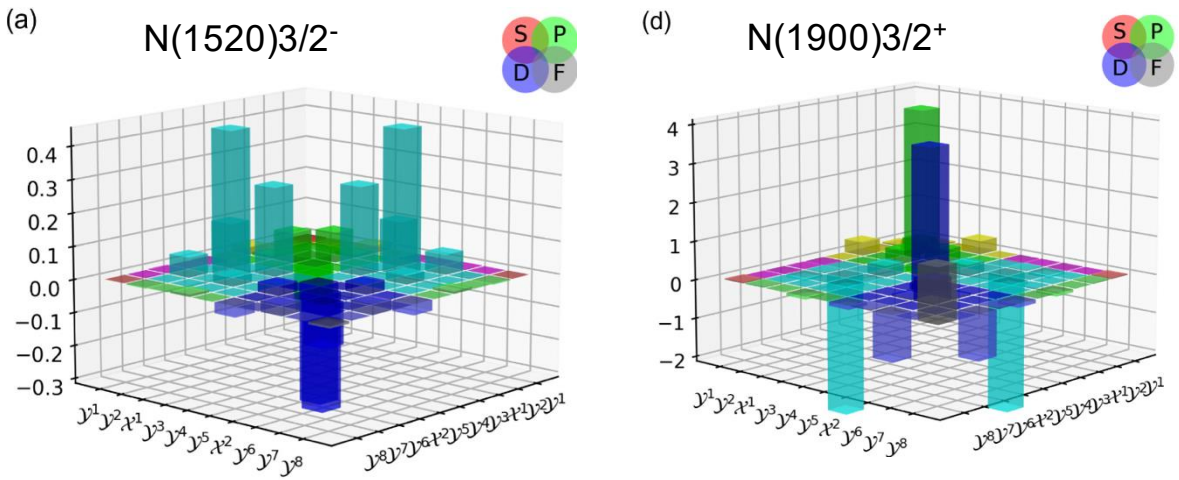


Pion GPDs

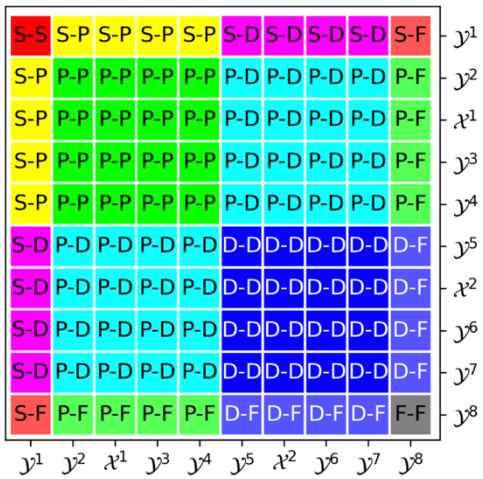


- CSM is currently the only approach that offers insight into EHM from combined studies of meson/baryon structure with connection to QCD. Ref. C.D. Roberts, FBS 64, 51 (2023).

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⁺ resonances



Legend for interpretation of the two plots on the left

L. Liu, Ch. Chen, and C.D. Roberts, Phys. Rev. D107, 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 12–13 GeV², with finer Q^2 binning at $Q^2 < 8.0$ GeV² than currently achieved, or with improved precision of the $\gamma_v pN^*$ electrocouplings, ***are critical for testing these QCD-connected predictions.***