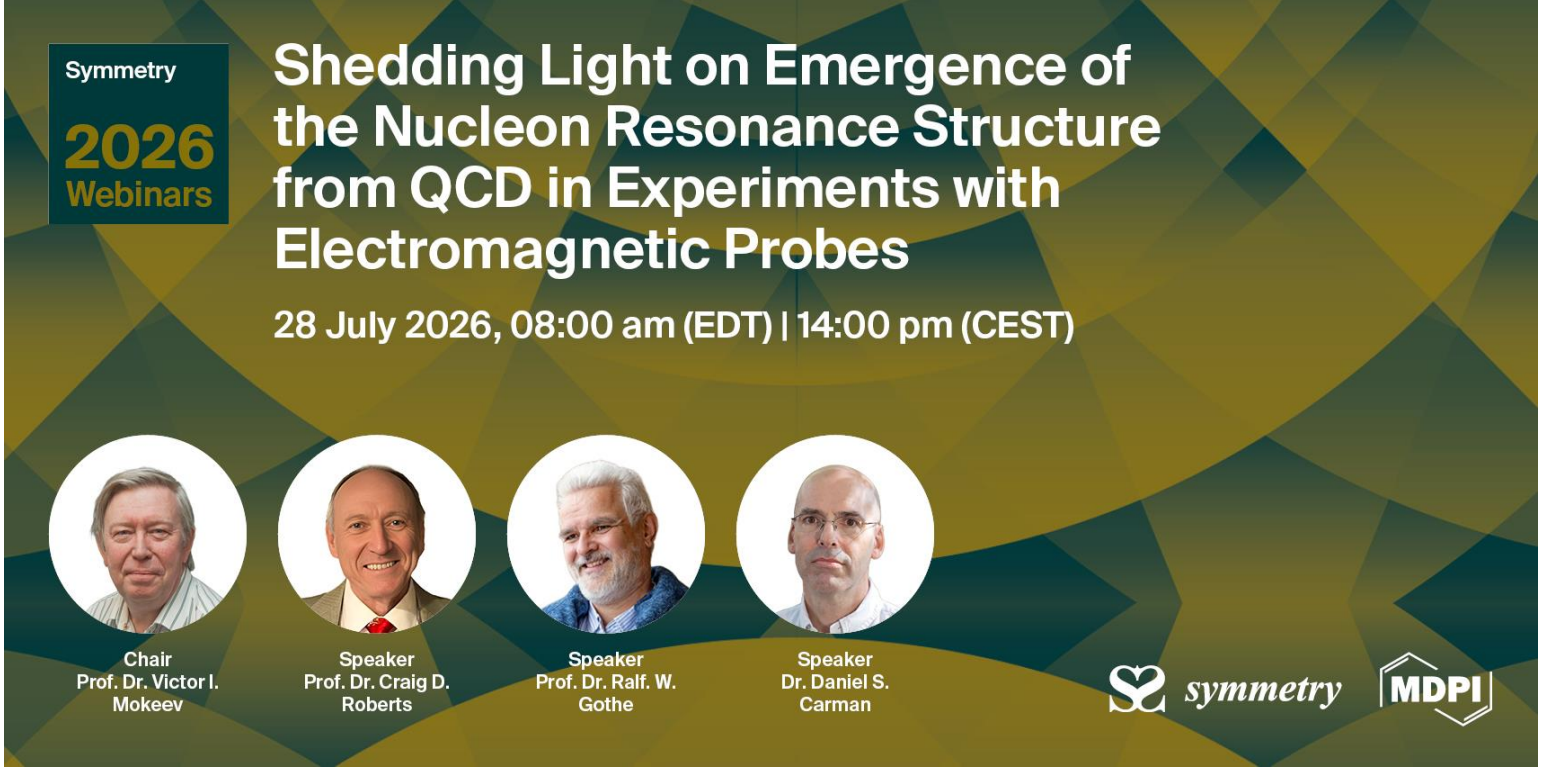


Connection link:

https://urldefense.proofpoint.com/v2/url?u=https-3A__sciforum.net_event_Symmetry-2D20&d=DwIFaQ&c=CJqEzB1piLOyyvZjb8YUQw&r=5d2A05CBcg701rhFXA73zw&m=snpgdZcdBhrBJmg8JV7HDrRQyqhN7lbM_4kts3hk9yk7M2V6UAPc6Qi0FHsEx38U&s=kzNeVNAabf-fiJcGJ1aimIiDQKYtfq3dgcTYdqfw3yc&e=

Topics:

- Studies of nucleon resonance electroexcitation amplitudes from exclusive meson electroproduction data obtained in 6-GeV era CLAS experiments
- Extension of N* structure studies anticipated from CLAS12 experiments in the 12-GeV era and beyond
- Theory framework(s) for understanding the emergence of hadron mass (EHM) and structure from results on the N* electroexcitation amplitudes

Emergence of Hadron Mass and the N* Structure in Experiments of 6/12 GeV Eras at Hall B

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

- $\gamma_v pN^*$ electrocouplings at photon virtualities Q^2 up to 10 GeV^2 for most excited proton states in the mass range < 2.5 GeV through analyzing the data of most meson electroproduction channels in the N* region.

A unique source of information on many facets of sQCD (i.e. QCD at distance scales where α_s becomes comparable with unity) in generating N* states with different structural features:

1. V.D. Burkert et al, Prog. Part. Nucl. Phys. 146, 104214 (2026)
2. P. Cheng et al., Acta Phys. Polon, B57, 2-A13 (2026)
3. V.I. Mokeev and D.S. Carman Few Body Syst. 63, 59 (2022)
4. V.D. Burkert and C.D. Roberts, Rev. Mod. Phys. 91, 011003 (2019)

- Explore EHM by mapping out the dressed quark mass in the transition from almost massless pQCD quarks to fully dressed quarks with dynamically generated ~400 MeV masses at the hadron size distance scale.

An important part of the efforts of EHM exploration from the data on N*/N structure combined with the results on meson structure:

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

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

Hadronic final state	W-range, GeV	Q^2-range, GeV^2	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 phase space

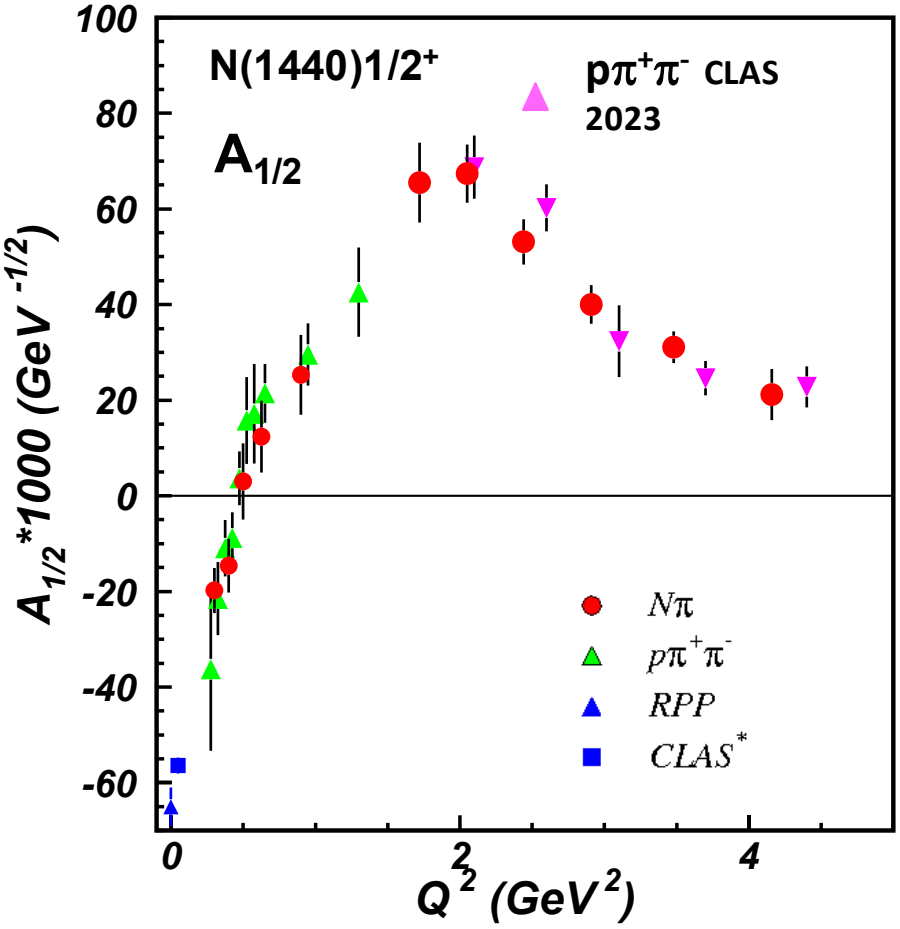
The measured observables from CLAS are stored in the CLAS Physics Data Base http://clas.sinp.msu.ru/cgi-bin/jlab/db.cgi

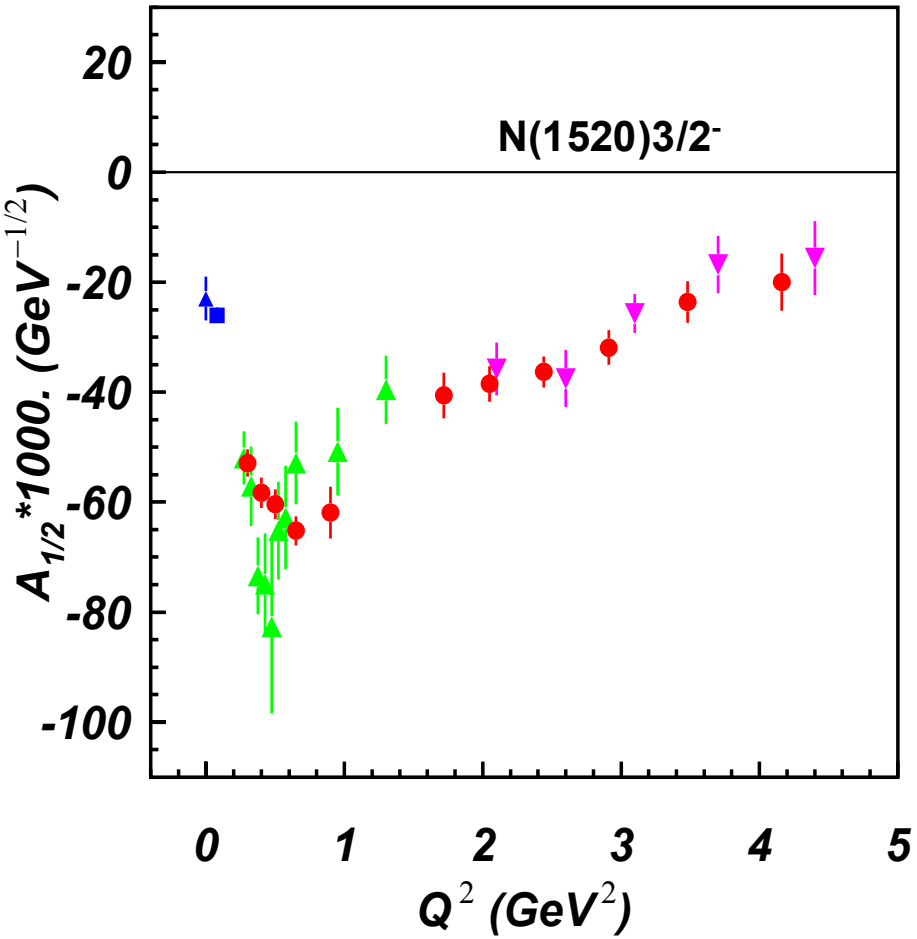
Nucleon Resonance Electrocouplings from Data on Exclusive Meson Electroproduction of 6 GeV Era with CLAS

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 0.5-1.5

- The $\gamma_v pN^*$ electrocouplings are 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/, Ref. A.N. Hiller Blin et al, PRC100, 035201 (2019)

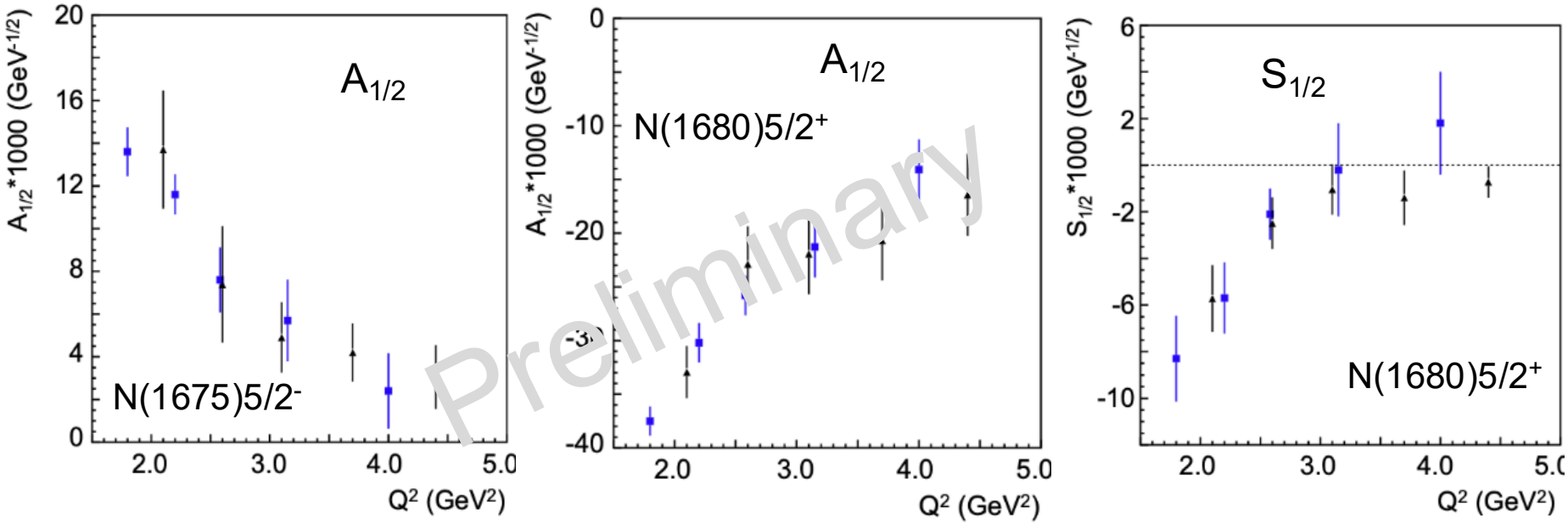
Electrocouplings of N(1440)1/2$^+$ and N(1520)3/2$^-$ Resonances from πN and $\pi^+\pi^-$p Electroproduction off Proton Data





Consistent results on the N(1440)1/2$^+$ and N(1520)3/2$^-$ electrocouplings from independent studies of the two major πN and $\pi^+\pi^-$p electroproduction channels with different non-resonant contributions demonstrated the capabilities of the reaction models for their reliable extraction and allow us to evaluate their systematic uncertainties in a nearly model-independent way.

Electrocouplings of N*s in the Third Region from πN and $\pi^+\pi^-$p Electroproduction



blue: π^+n
K. Park et al. (CLAS), PRC 91, 045203 (2015)
UIM/DR-reaction models: I.G. Aznauryan et al. (CLAS), PRC 80, 055203 (2009)

black: CLAS $\pi^+\pi^-$p
preliminary, December 2025 (unpublished)
JM23-reaction model: V.I. Mokeev et al., to be submitted to PRC

Consistent results on the N(1675)5/2$^-$ and N(1680)5/2$^+$ electrocouplings from π^+n and $\pi^+\pi^-$p channels demonstrated the capability of the reaction models UIM/DR and JM23 for the credible extraction of the N* electrocouplings for states in the mass range up to 1.8 GeV for Q^2<5.0 GeV^2

Electrocouplings of N* in mass range < 1.8 GeV for Q^2<5.0 GeV^2 have become available from the global coupled-channel analysis of $\gamma_{r,v}$N , πN, ηN, KΛ, KΣ channels:

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

How do the Ground/Excited Nucleon Masses Emerge?

Composition of the Nucleon Mass:

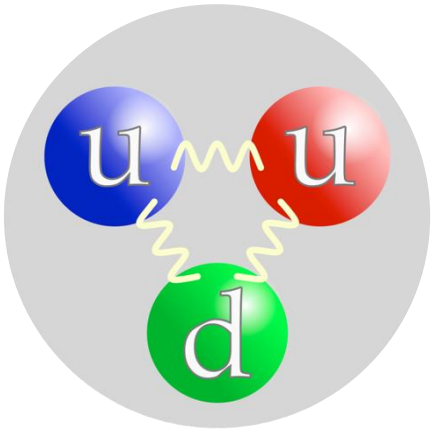
M_p, MeV (PDG23)

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



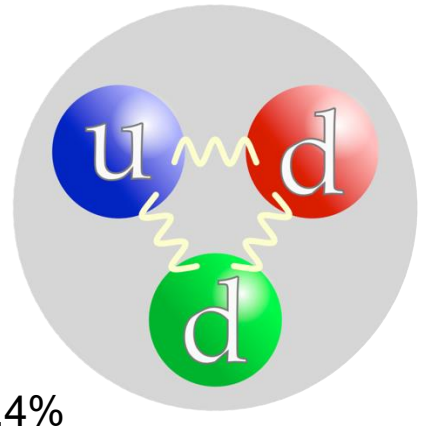
M_n, MeV (PDG23)

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

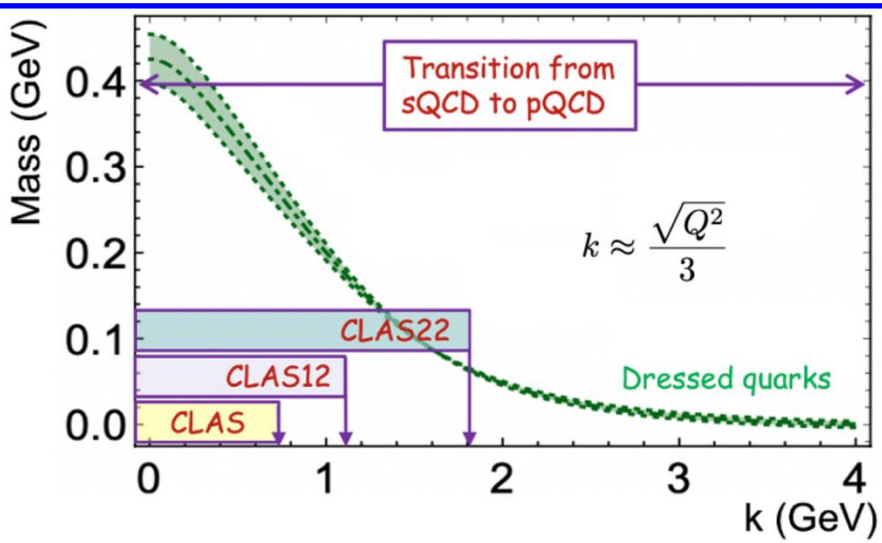


$\overline{\text{MS}}$ scheme at a renormalization scale of 2.0 GeV

- **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.**

Studies of the structure of the nucleon ground state and N* electroexcitation within Continuum Schwinger methods (CSM) over a broad range of Q^2 shed light on the emergence of N/N* masses and structure.

Impact of the $\gamma_v pN^*$ Electrocouplings Results 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)

- The dominant part of hadron mass (>98%) is generated by strong interaction encoded in QCD Lagrangian and evolving with distances in the transition from perturbative to strongly coupled regimes. Studies of the ground and excited state of the nucleon structure within CSM across a broad range of Q^2 allow us to map out the momentum dependence of dressed quark mass.
- 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.
- The future experiments at facilities capable to measure exclusive meson electroproduction across $Q^2 < 30$ GeV^2 provide a unique opportunity to explore the full range of distances over which the dominant portion of hadron mass and the structure of N/N* states are generated.

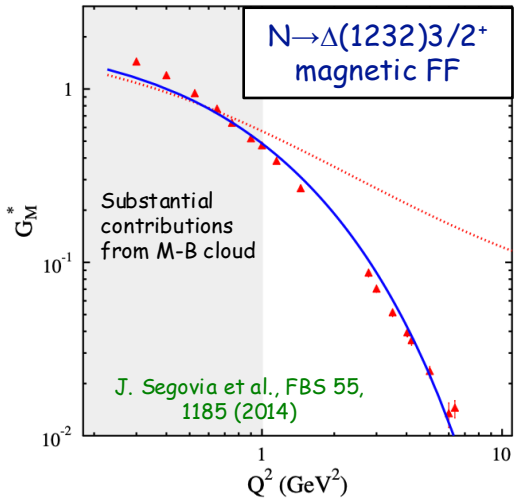
EHM: Concept from CSM vs. Available Experimental Results

- 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 *with the same dressed quark/gluon mass functions.*

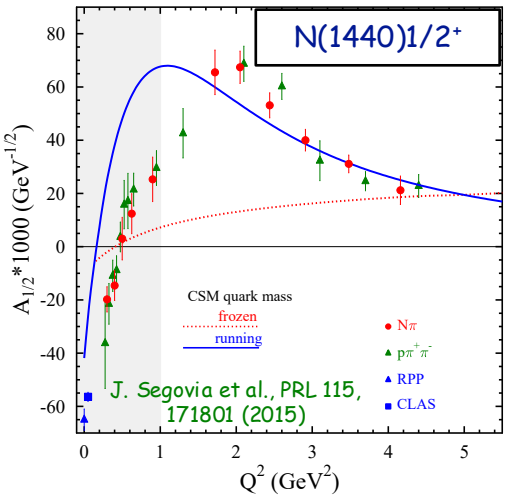
- Dressed quarks with dynamically generated masses represent active degrees of freedom in the structure of the pion, nucleon, and the $\Delta(1232)3/2^+$, $N(1440)1/2^+$.

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

CLAS/Hall A/C results vs. CSM expectations

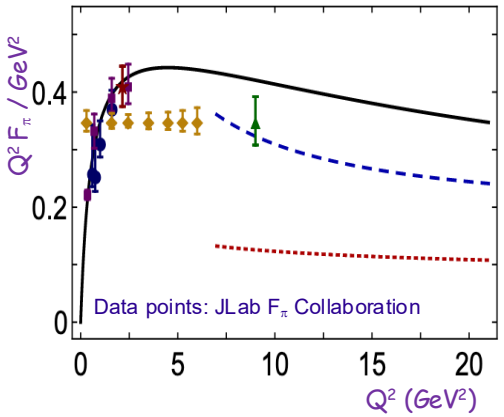


Pion Elastic FF

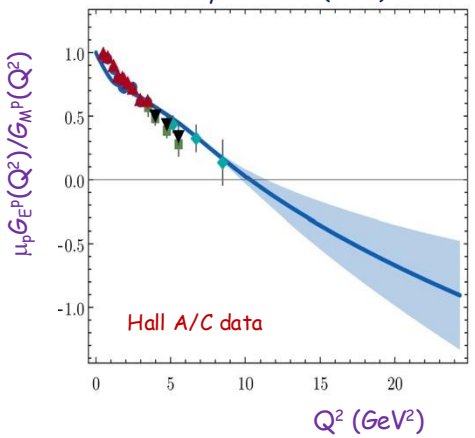


Nucleon Elastic FF

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

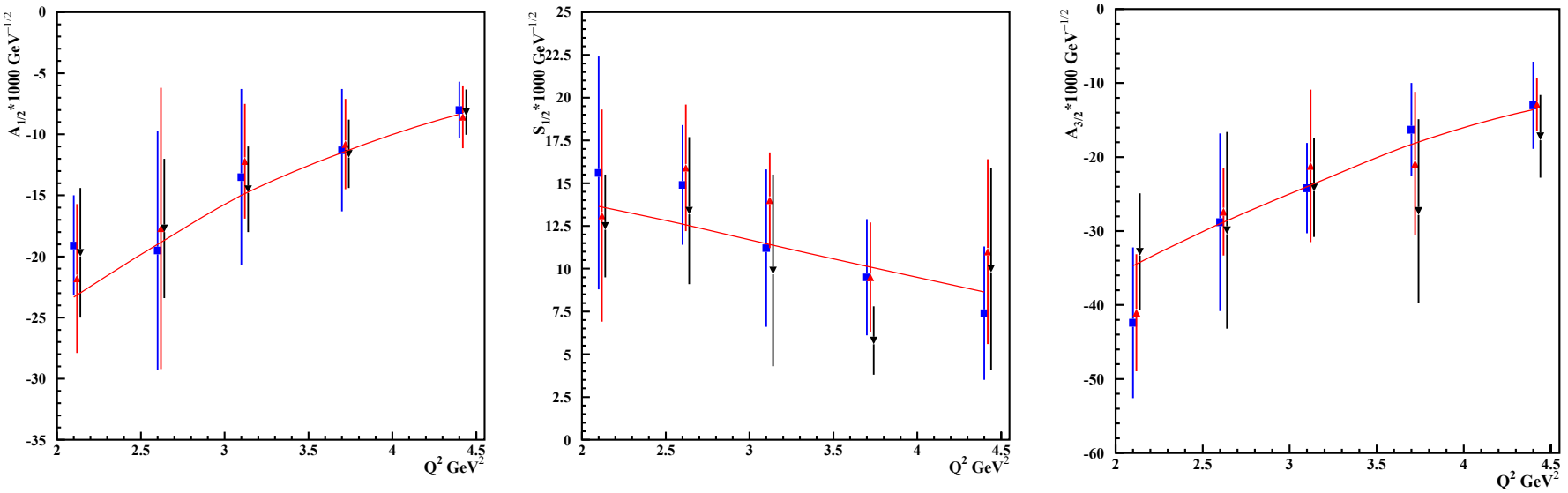


M. Barabanov et al., Prog. Part. Nucl. Phys. 103835 (2021)



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

$\Delta(1600)3/2^+$ Electrocouplings : CSM Prediction vs. Data Determination



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

Electrocouplings from independent analyses of $\pi^+\pi^-$p differential cross sections within three W-intervals, 1.46<W<1.56 GeV, 1.51<W<1.61 GeV, and 1.56<W<1.66 GeV for $2.0<Q^2<5.0$ GeV^2 [V.I. Mokeev et al., PRC 108, 025204 (2023)].

CLAS results on the $\Delta(1600)3/2^+$ electrocouplings confirmed the CSM prediction, solidifying evidence for insight into dressed quark mass function and, consequently, into EHM from studies of γ_vpN* electrocouplings.

Webinar Program

Chair Introduction, Dr. Victor I. Mokeev (USC), July 28, 8.00-8.20 am EST

Insight into EHM from the experimental results on meson/baryon structure analyzed within the common, QCD connected theory framework(s) will be the central topic

Prof. Dr. Ralf W. Gothe (USC), Nucleon Resonance Structure in Exclusive Meson Electroproduction Experiments: From Strong to Perturbative QCD Regimes, (35+5'), July 28, 8.20-9.00 am EST

Dr. Daniel S. Carman (JLab), Studies of Nucleon Resonances at JLab in the 12 GeV Era and Beyond (35+5'), July 28, 9.00-9.40 am EST

Prof. Dr. Craig D. Roberts (Head of INP at Nanjing U.), Insight into the Emergence of Hadron Mass and Structure from N* Electroexcitation (35+5'), July 28, 9.40-10.20 am EST

Discussion session moderated by Dr. Victor I. Mokeev (USC) & Ms. Isabella Theodora Toth's Instruction for the paper submission to the Symmetry topical issue (TBD), July 28, 10.20-11.00 am EST

Webinar's Follow-Up

- Insight into EHM requires experimental results on the structure of both meson and baryon ground and excited states in terms of elastic and transition form factors, PDAs, PDFs, GPDs, TMDs, and the structure functions of the energy-momentum tensor, analyzed jointly within common theoretical framework(s) connected to the QCD Lagrangian.

- At present, a common theoretical framework has been developed within the CSM. Further progress toward the development of a multi-pronged theoretical framework is strongly encouraged.

- Success in addressing the challenging open problem of the Standard Model related to the emergence of hadron mass and structure relies critically on close synergy between experiment, phenomenology, and theory.

- To facilitate these efforts, a topical issue of the Symmetry journal:

"Emergence of Hadron Mass from Experiments at High Luminosity Facilities"

is currently in preparation. Contributions are welcome, with publication anticipated in 2027. More details will be provided during the webinar.