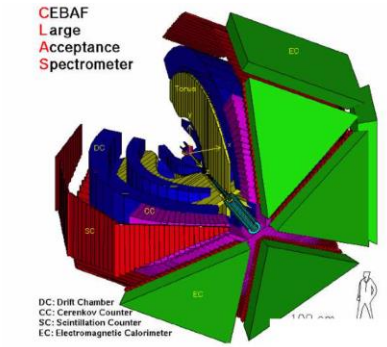
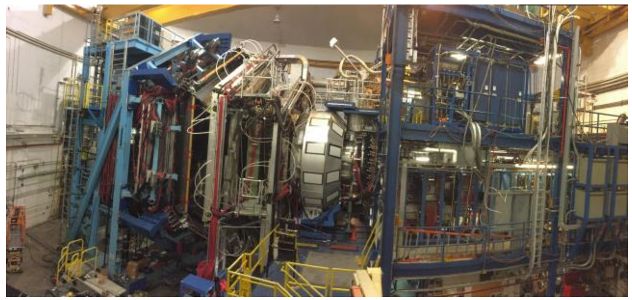
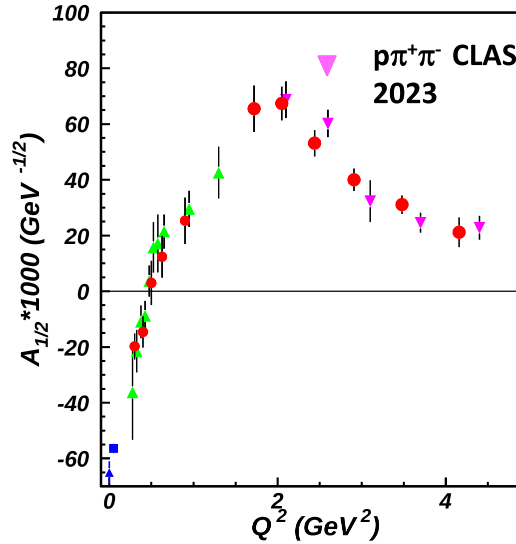
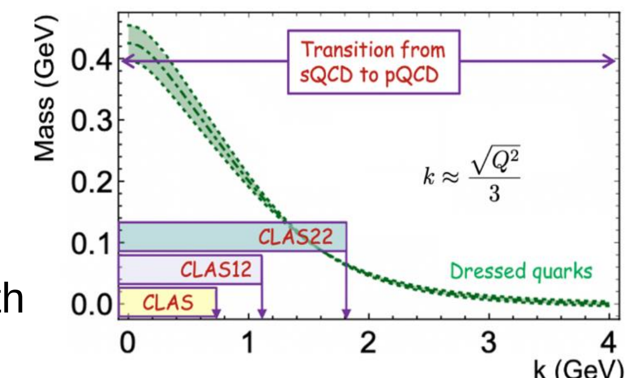
N* Electroexcitation and Strong QCD from the Data of Experiments at JLab







- N* structure as a window into strong interaction in the regime of comparable-to-unity QCD running coupling (strong QCD=sQCD)
- $\gamma_v pN^*$ electrocouplings from exclusive meson electroproduction with CLAS
- Quark core vs. meson-baryon cloud interplay
- Insight into emergence of hadron mass (EHM) from N* electroexcitation, N and π elastic form factors
- New opportunities with CLAS12 and beyond: high luminosity with large acceptance



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

15th International Workshop on the Physics of Excited Nucleons

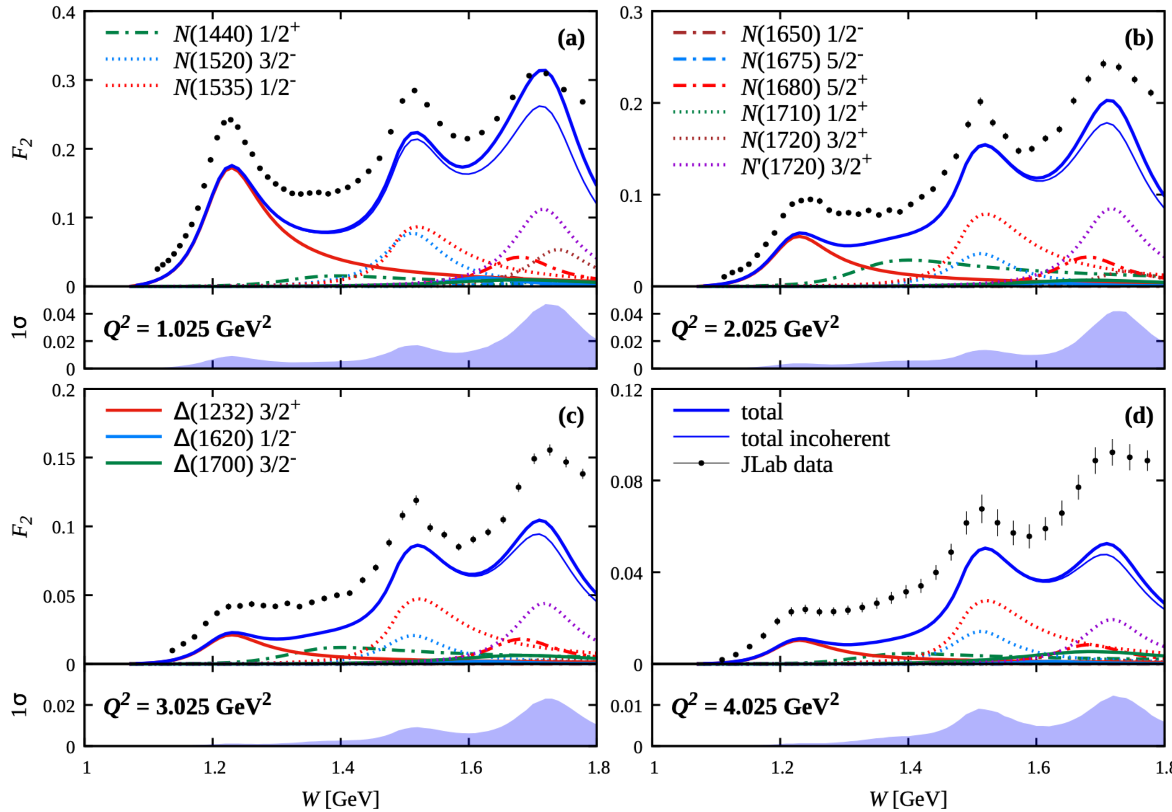
Resonant Contributions to Inclusive $F_2(W,Q^2)$ Structure Function

CLAS data: M. Osipenko et al., PRD 67, 092001 (2003)
Hall C data: Y. Liang, Ph.D., American Univ. (2003)
Interpolation of the CLAS/world data: V. Chesnokov et al., Phys Part. Nucl. 53, 184 (2022)

Nucleons as bound systems of quark/gluons that are in permanent creation/annihilation processes possess a rich spectrum of excited states (N*)

N* have been observed in photo-, electro-, and hadroproduction with consistent masses and hadronic decay widths

N* contributions computed with $\gamma_v pN^*$ electrocouplings from CLAS data:
A.N. Hiller Blin et al, PRC100, 035201 (2019);
A.N. Hiller Blin et al, PRC104, 025201 (2021)



- **Differences in the structure of the resonances that contribute to the three resonance-like maxima result in their different evolution with Q^2.**
- Nucleons and their resonances are the most fundamental three-body systems in Nature. If we don't understand how QCD builds each state in the complete spectrum, then our understanding of the sQCD regime remains incomplete.

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 meson electroproduction channels in the N* region.

A unique source of information on many facets of sQCD in generating excited nucleon states with different structural features:

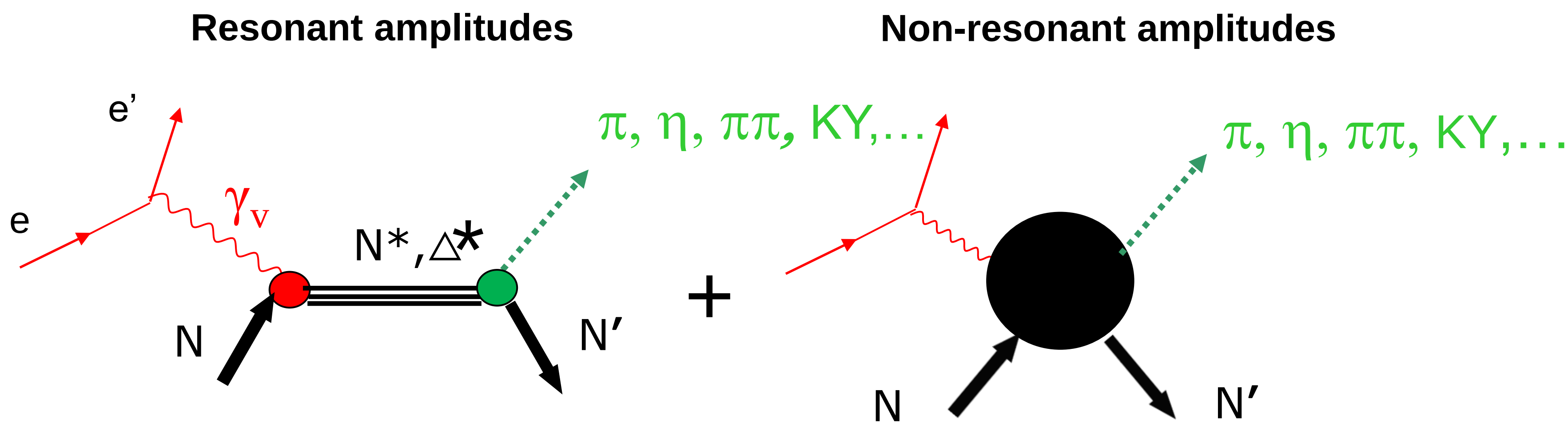
1. V.D. Burkert et al, Prog. Part. Nucl. Phys. 146, 104214 (2026)
2. P. Cheng, L. Liu, Ya Lu, and C. D. Roberts, Acta Phys. Polon. B57 2-A13 (2026)
3. V.I. Mokeev and D.S. Carman Few Body Syst. 63, 59 (2022)
4. V.D. Burkert and C.D. Roberts, Rev. Mod. Phys. 91, 011003 (2019)

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

An important part of the efforts to address challenging problem on the nature of > 98% of hadron mass from the data on the N*/N structure, analyzed combined with the results on the 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)

N* Photo-/Electroexcitation Amplitudes ($\gamma_{r,v}$pN* Photo-/Electrocouplings) and their Extraction from Exclusive Photo-/Electroproduction Data



- **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)

<u>Definition of N* photo-/electrocouplings employed in CLAS data analyses:</u>

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

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

- **Consistent results on $\gamma_{r,v}$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.**

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
$\pi^+ n$	**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** **$d\sigma/d\Omega$**
$\pi^0 p$	**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.**

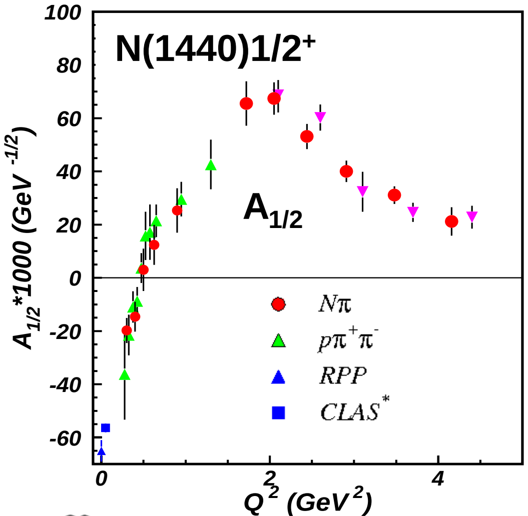
See M. Mai talk on Tuesday, September 8 at 10:30 am, M. Doering talk on Tuesday, September 8 at 6:00 pm

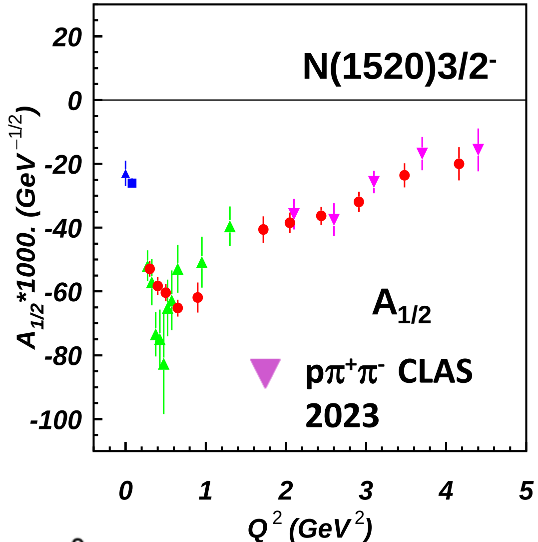
Nucleon Resonance Electrocouplings from Data on Exclusive Meson Electroproduction of 6 GeV Era with CLAS

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/,** Ref. A.N. Hiller Blin et al, PRC100, 035201 (2019), V.I. Mokeev et al., arXiv:2608.04997[nucl-ex]

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



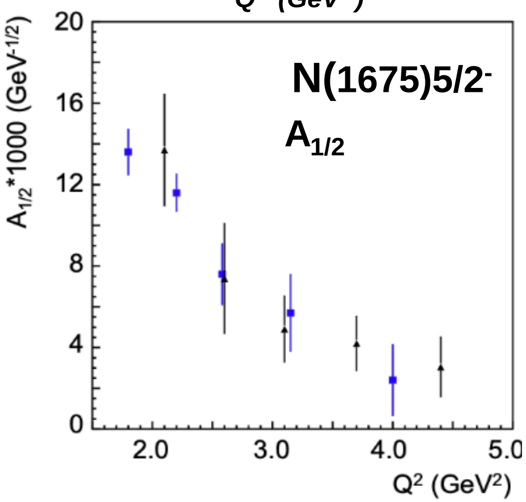


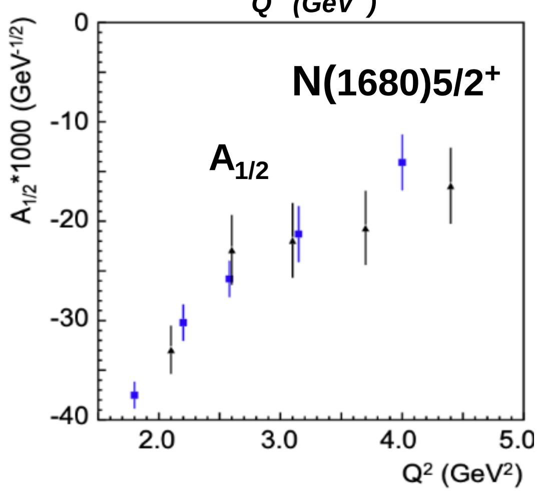
I.G. Aznauryan et al. (CLAS), PRC 80, 055203 (2009)

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)





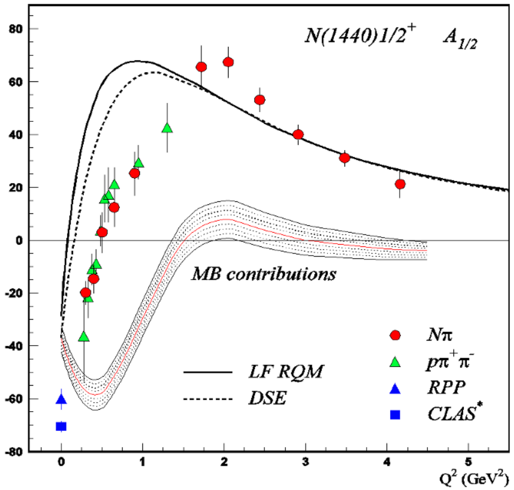
I.G. Aznauryan et al. (CLAS), PRC 91, 045203 (2015)

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

Consistent results on the $\gamma_v pN^*$ 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 JANR/JM reaction models for their reliable extraction and allow us to evaluate their systematic uncertainties.

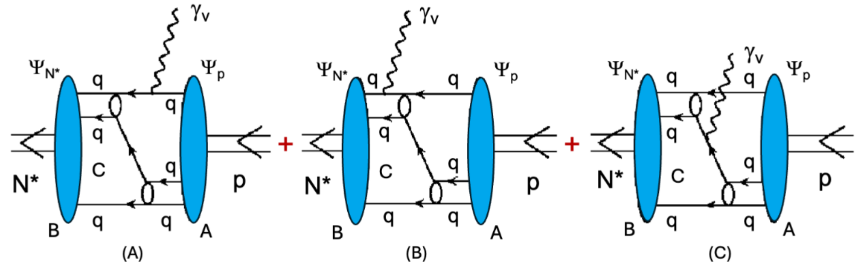
See the talk by R.W. Gothe, Monday, September 7, at 3:00 pm

Interplay Between Meson-Baryon Cloud and Quark Core in N* Structure



V.D. Burkert and C.D. Roberts, Rev. Mod. Phys. 91, 011003 (2019)

Peng Cheng, et al, Acta Phys. Pol. B57, A13 (2026)



G. Ramalho, Acta Phys. Pol. B57, A11 (2026)

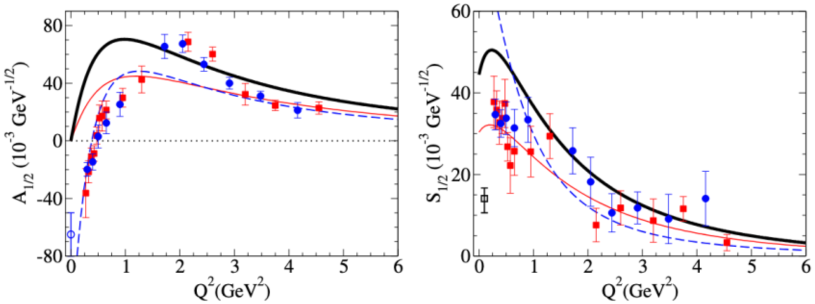


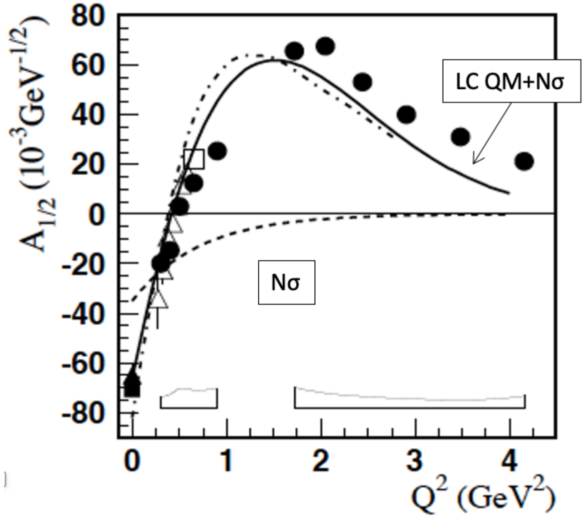
Fig. 1. $\gamma^* N \to N(1440)$ helicity amplitudes. Calculations from the covariant spectator quark model [48] for $M_R = 1.440$ GeV (thick solid line) and $M_R = 1.600$ GeV (thin solid line), and holographic model [54] (dashed line). The data are from JLab/CLAS for one-pion production (circles) [7] and two-pion production (squares) [8–10], and PDG 2024 (empty circle) [1]. For $S_{1/2}$ we also include a data point from MAMI at $Q^2 = 0.1$ GeV^2 (empty square) [80].

Good description of the CLAS data on N(1440)1/2$^+$ electrocouplings have been achieved for Q^2>2 GeV^2 within CSM, assuming quark core contribution only, offering evidence for a major contribution from quark core to the N(1440)1/2$^+$ structure at Q^2>2.0 GeV^2

The same conclusion comes from the relativistic quark model (LF RQM) that employs phenomenological quark running mass (I.G. Aznauryan, V.D. Burkert, PRC 85, 055202 (2012) (top) and different quark models (bottom)

Comparison experimental results vs theory expectations suggests presence of the contributions from other component(s) beyond quark core to N(1440)1/2$^+$ electroexcitations at Q^2<1.0 GeV^2

Further Evidence for Quark Core-Meson-Baryon Cloud Interplay in N(1440)1/2$^+$ Structure



I.T. Obukhovsky et al., PRD 89, 014032 (2012)

Accounting for the contributions from both meson-baryon cloud and quark core allowed us to improve the description of N(1440)1/2$^+$ electrocouplings for Q^2<1 GeV^2

<u>Q^2-evolution of hadron decay parameters of N(1440)1/2$^+$ from $\pi^+\pi^-$p electroproduction data</u>

Q^2 Interval [GeV^2]	Mass [GeV]	Γ_{tot} [MeV]	$\Gamma_{\pi\Delta}$ [MeV]	$BF_{\pi\Delta}$ %	$\Gamma_{\rho p}$ [MeV]	$BF_{\rho p}$ %
0.25–0.60	1.458±0.012	363±39	142±48	23–58	6±4	<2
0.5–1.5	1.450±0.011	352±37	120±41	20–52	5±2	<2
2.0–3.5	1.457±0.008	331±54	129±52	20–65	6±2	1.1–2.6
3.0–5.0	1.446±0.013	352±33	151±32	31–57	5±1	1.2–2.0

V.I. Mokeev and D.S. Carman, Acta Phys. Pol. 57, A5 (2026)

- A good description of the CLAS $\pi^+\pi^-$p electroproduction data has been achieved using Q^2-independent mass, total and partial hadronic decay suggesting presence of quark core

$\gamma_v pN^*$ Electrocouplings in Resolving Theory Expectation Controversy on N* Structure

- The CLAS results on the Q^2-evolution of $\gamma_v pN^*$ electrocouplings, analyzed within the QCD-connected CSM and the broad array of quark models, revealed the structure of nucleon resonances across the mass range up to 1.8 GeV as a complex interplay between the inner core of three dressed quarks and the external meson-baryon cloud.

- Contributions from meson-baryon cloud are pronounced mostly at Q^2<1.0 GeV^2 while the transition to quark core dominance has been revealed with increasing Q^2.

- LQCD & HEFT describe the N(1440)1/2$^+$ and Δ(1600)3/2$^+$ as predominantly dynamically generated, with little or no contribution from a 3-quark core. This conclusion follows from the successful description of πN elastic scattering phase shifts and inelasticities within HEFT, projected onto the finite-volume box used in LQCD calculations (A.W. Thomas, Acta Phys. Pol. B 57, A6 (2026)).

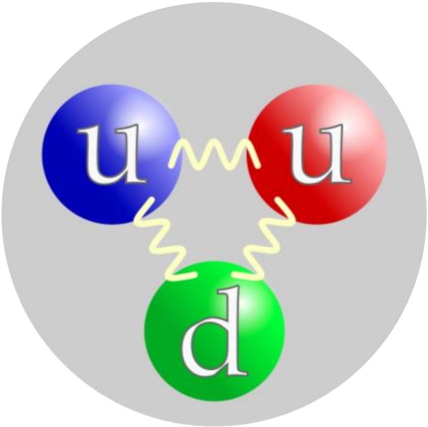
- Predictions on Q^2-evolution of N(1440)1/2$^+$ and for Δ(1600)3/2 electrocouplings for Q^2 range up to 3 GeV^2, at least, within LQCD & HEFT confronted with the experimental results from CLAS are critical for insight into the origin of the differences mentioned above, with *all* approaches capable of predicting the Q^2-evolution of both resonance electrocouplings and potentially converge in understanding of their structure.

How do the Ground/Excited Nucleon Masses Emerge?

Composition of the Nucleon Mass:

M_p, MeV (PDG23)

proton



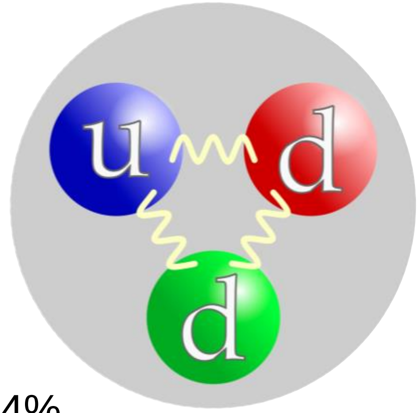
938.2720813
±0.0000058

Sum of bare quark masses, MeV

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

M_n, MeV (PDG23)

neutron



939.5654133
±0.0000058

Sum of bare quark masses, MeV

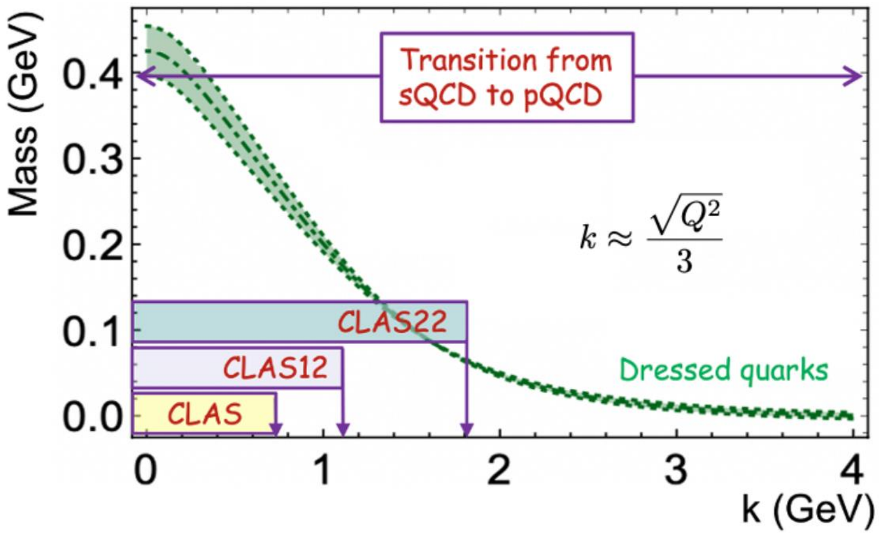
4.67+4.67+2.16
$= 11.50^{+1.45}_{-0.60}$ or < 1.4%

$\overline{\text{MS}}$ 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 a broad range of Q^2 shed light on the emergence of N/N* masses at distances where the transition from pQCD to sQCD regimes is expected.

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



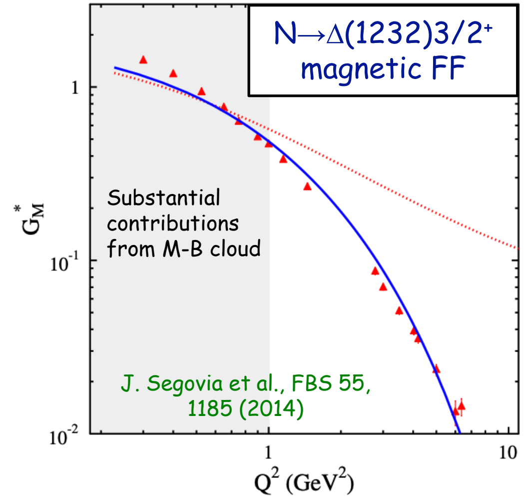
P. Achenbach, D.S. Carman, R.W. Gothe, K. Joo, V.I. Mokeev, and C.D. Roberts, Symmetry, 17, 1106 (2025)

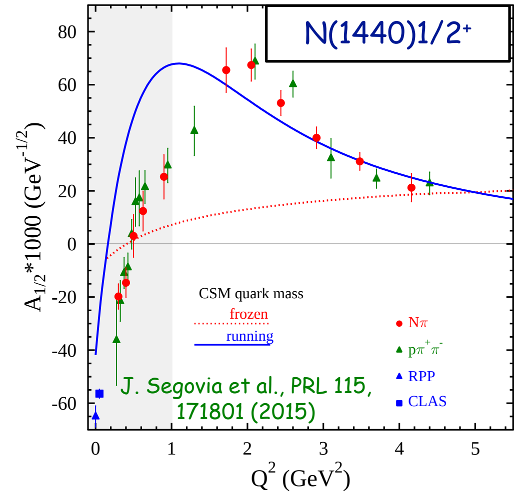
M. Ding, C.D. Roberts, and S.M. Schmidt, Particles 6, 57 (2023)

- 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. Studies of the structure of ground and excited nucleon states within CSM across a broad range of Q^2 allow us to map out the momentum dependence of dressed quark mass. EHM is encoded in the evolution of dressed quark mass with momenta/distances
- The CLAS experiments, limited to $Q^2 < 5$ GeV^2, allowed exploration of a range of distances where ~30% of hadron mass is generated. Extending the Q^2 coverage up to 10 GeV^2 with the CLAS12 will offer insight into the distance scales where ~50% of hadron mass emerges.
- Future potential experiments at facilities capable of measuring exclusive meson electroproduction for $Q^2 < 30$ GeV^2 across a large acceptance with luminosities at least 2-5 x 10^{35} cm^{-2}s^{-1} 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.

- 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.*

CLAS/Hall A/C results vs. CSM expectations





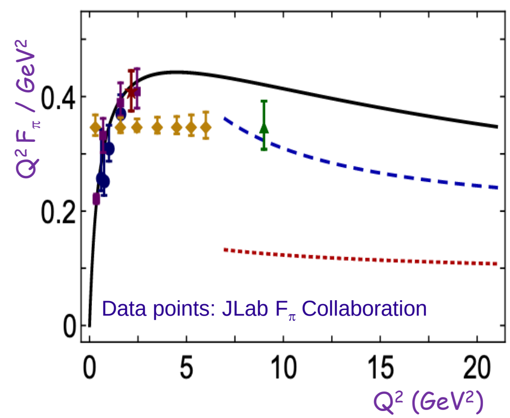
Pion Elastic FF

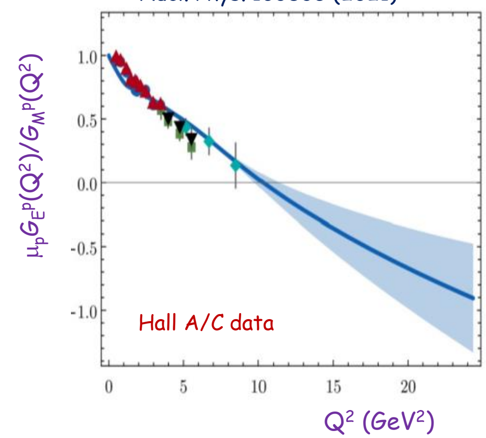
C.D. Roberts et al., Prog. Part. Nucl Phys. 120, 103883 (2021)

Nucleon Elastic FF

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

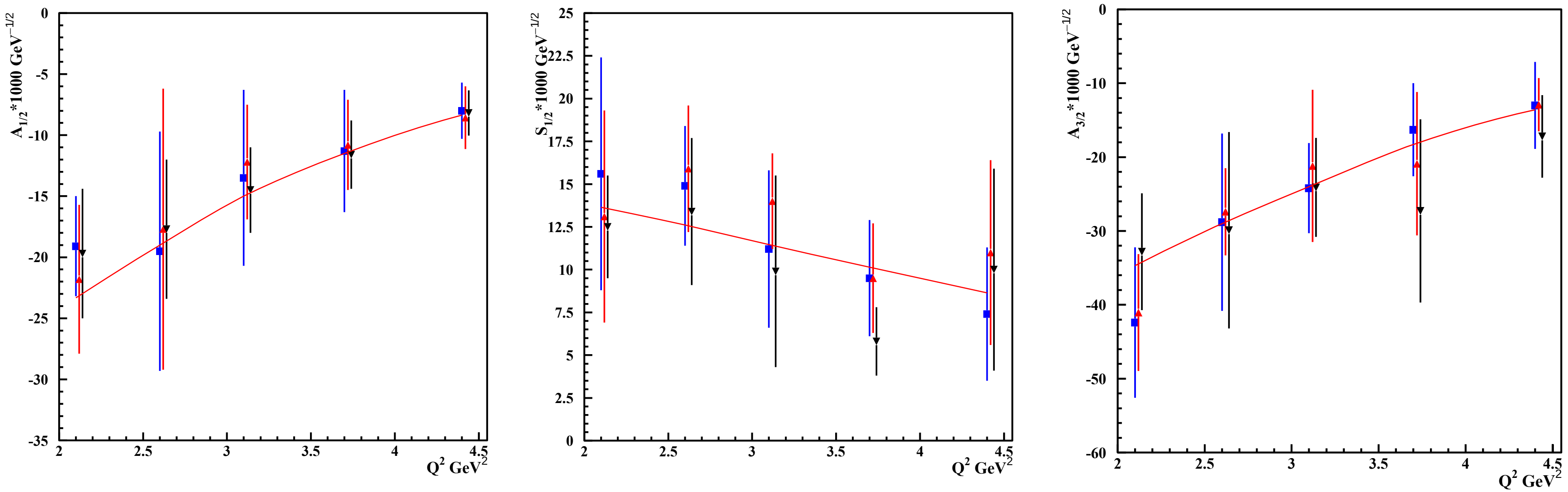
- Dressed quarks with dynamically generated masses represent active degrees of freedom in the structure of the pion, nucleon, and the $\Delta(1232)3/2^+$, $N(1440)1/2^+$.
- **Strong evidence for insight into momentum dependence of dressed quark mass**





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



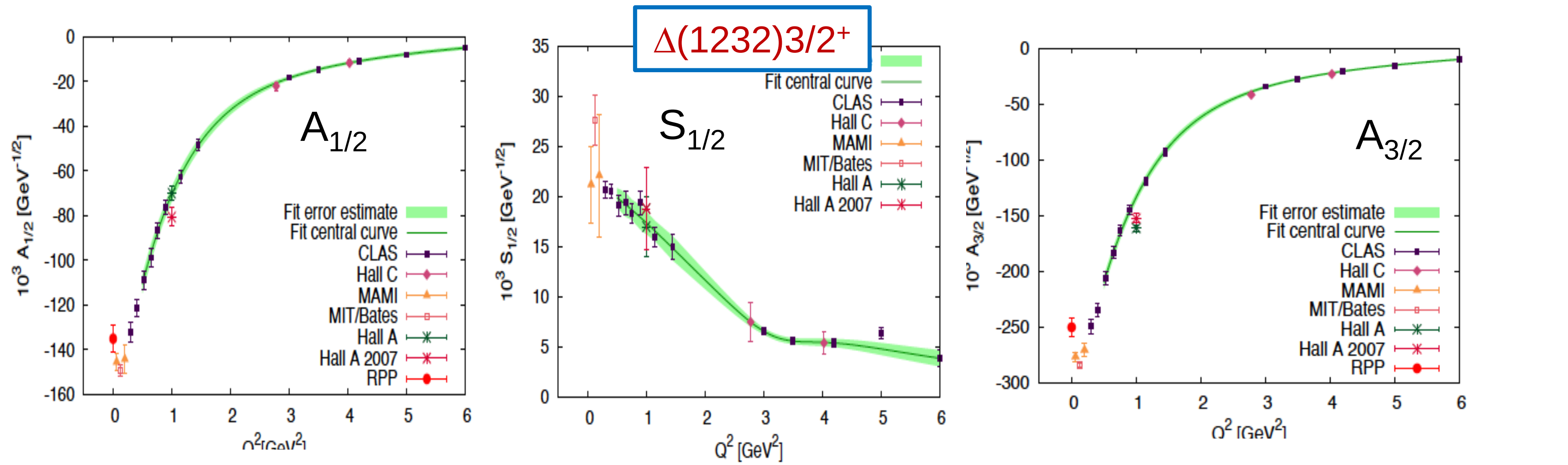
CSM predictions, Ya Lu et al., Phys. Rev. D 100, 034001 (2019)

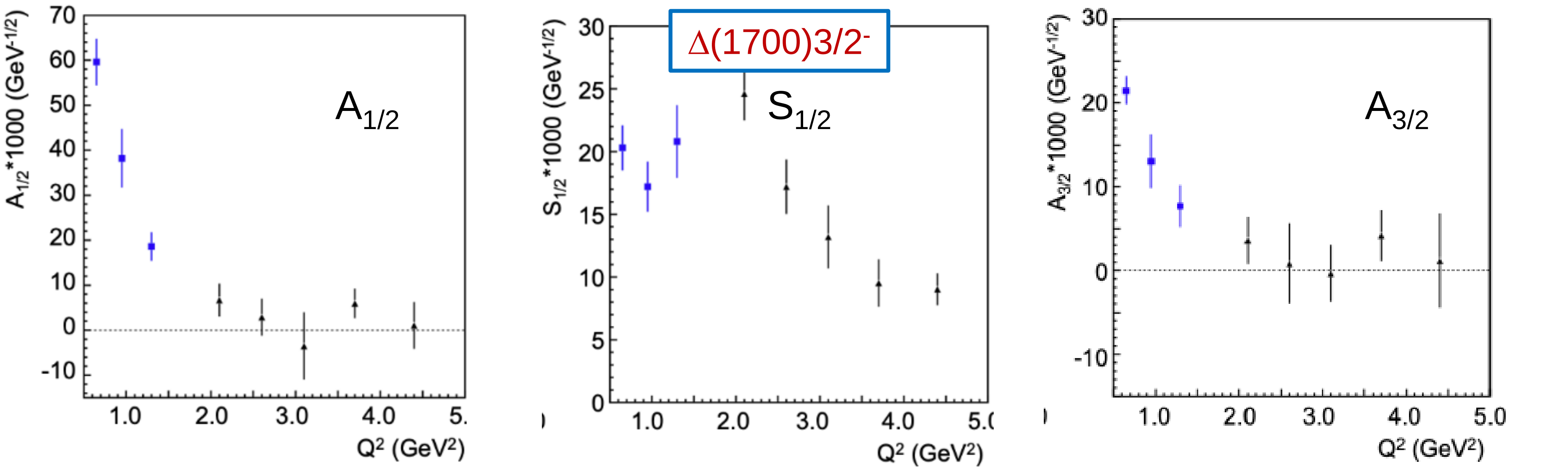
Electrocouplings from independent analyses of $\pi^+\pi^-p$ differential cross sections within three W-intervals, 1.46<W<1.56 GeV, 1.51<W<1.61 GeV, and 1.56<W<1.66 GeV for $2.0<Q^2<5.0$ GeV^2 [V.I. Mokeev et al., PRC 108, 025204 (2023)].

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

See the review talk by C.D. Roberts, Monday, September 9 at 10:30 am

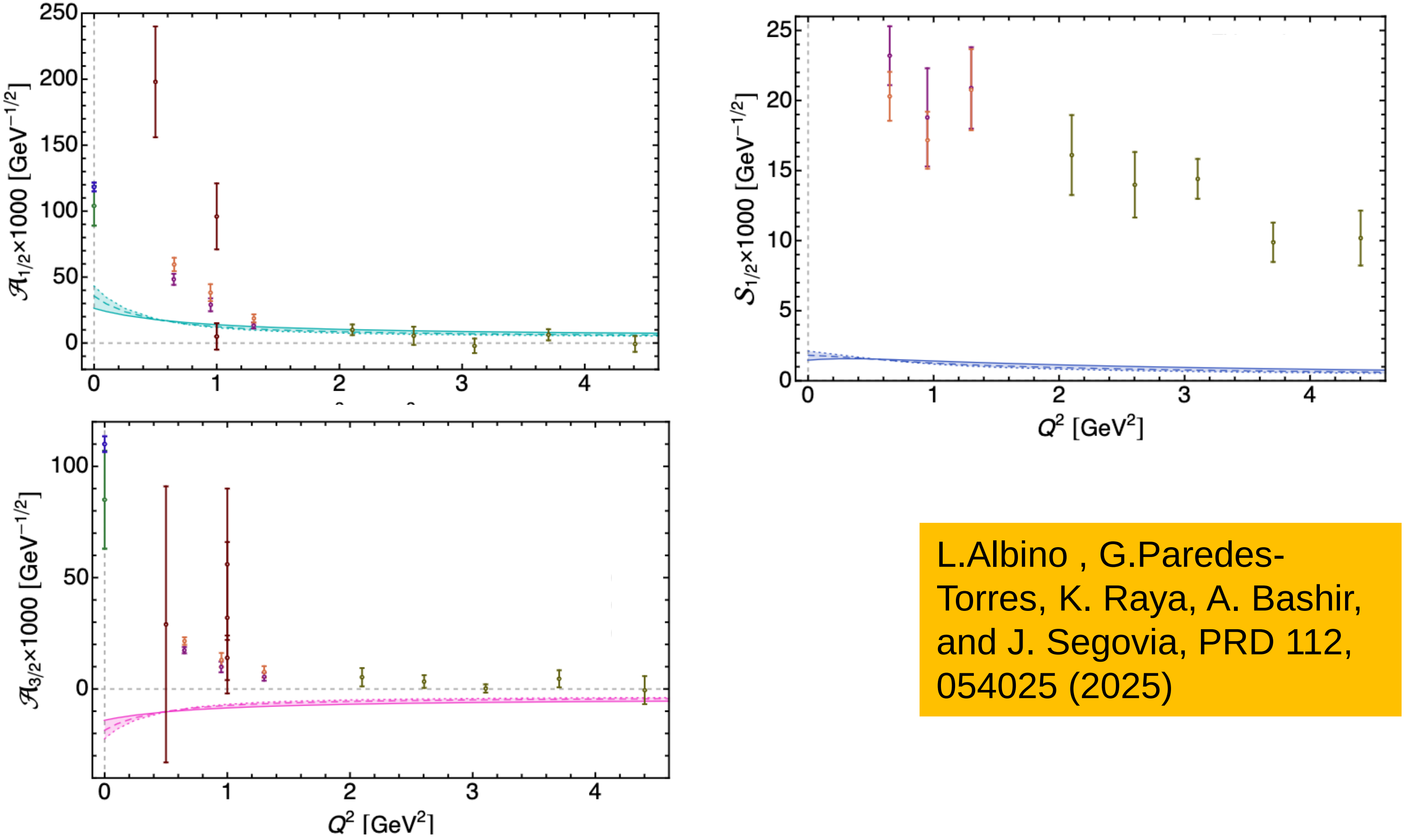
Connecting EHM and DCSB from Δ(1232)3/2$^+$ and Δ(1700)3/2$^-$ Electrocouplings





- The results show substantial differences in Q^2-evolution of Δ(1232)3/2$^+$/Δ(1700)3/2$^-$ chiral partner electrocouplings.
- This is a promising opportunity to explore DCSB in connection to EHM by comparing the experimental results and the CSM predictions for Δ(1232)3/2$^+$ and Δ(1700)3/2$^-$ electrocouplings

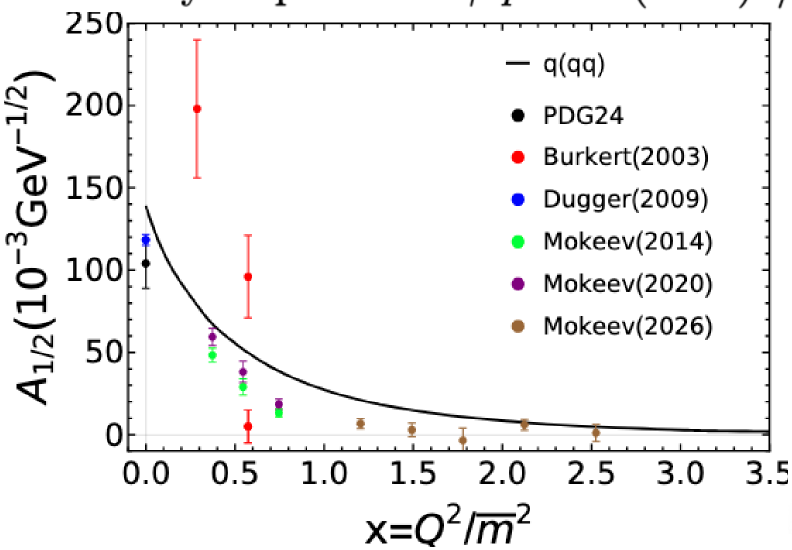
CSM Evaluations of Δ(1700)3/2⁻ Electrocouplings with Contact qq-Interaction

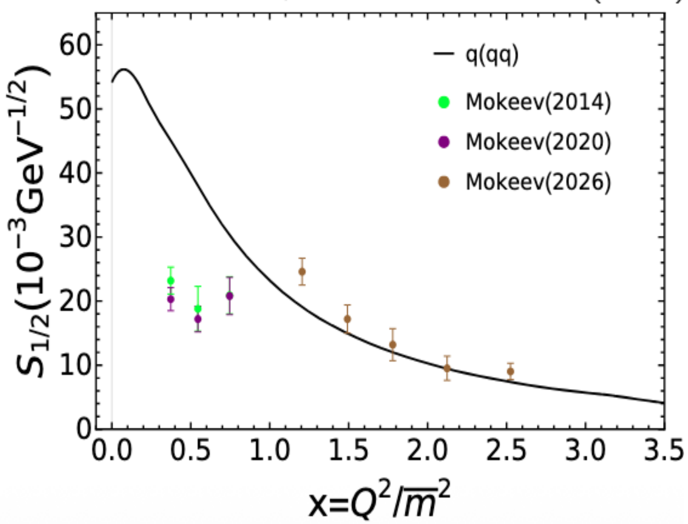


L.Albino , G.Paredes-Torres, K. Raya, A. Bashir, and J. Segovia, PRD 112, 054025 (2025)

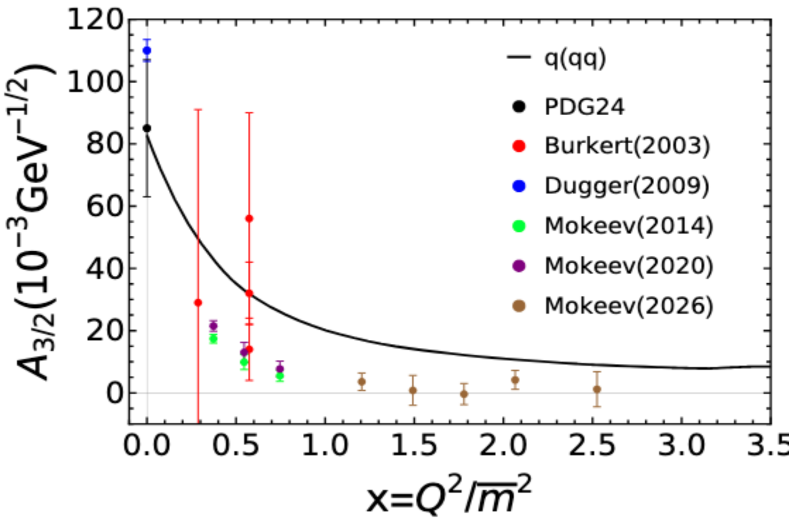
Employing realistic qq-interaction that generates momentum dependent dressed quark mass is essential in exploration of the EHM and DCSB connection.

Helicity amplitudes: $\gamma^* p \to \Delta(1700)3/2^-$ transition $(2\bar{m} = m_N + m_{\Delta(1700)})$.





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



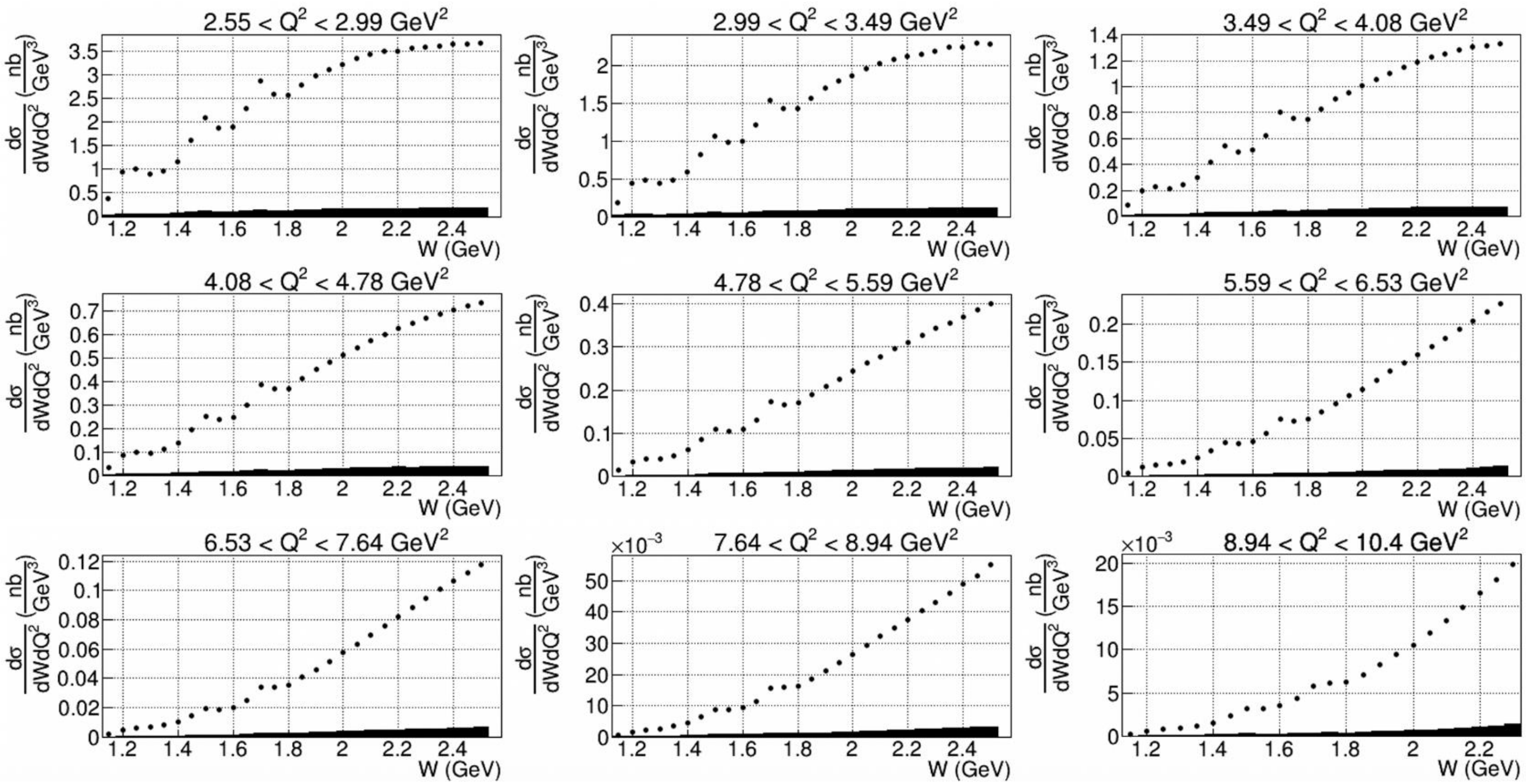
- CSM accounts for the connection between EHM and DCSB in the evaluation of the dressed quark propagator and for qq-interaction amplitudes
- Successful description of the leading $S_{1/2}$ electrocoupling has been achieved for Q^2> 2.0 GeV^2, while for $A_{1/2}$ and $A_{3/2}$ electrocouplings for Q^2>2.65 GeV^2
- Chiral partner Δ(1232)3/2$^+$ electrocouplings have been successfully described earlier within the same theory framework (J. Segovia et al., FBS 55, 1185 (2014))

Comparative studies of the CLAS results on Δ(1232)3/2$^+$/Δ(1700)3/2$^-$ electrocouplings within CSM revealed a connection between DCSB and EHM in the baryon sector for the first time.

Extension in N* Structure Studies with CLAS12

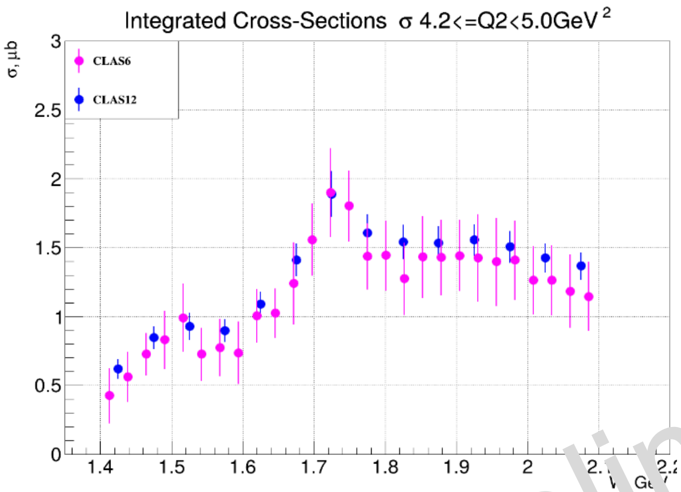
CLAS12: Extension of the results on $\gamma_v pN^*$ electrocouplings of most N* states in the range W < 2.5 GeV and Q^2 up to 10 GeV^2 from exclusive channels: πN, $\pi\pi N$, KY, K*Y, KY*.

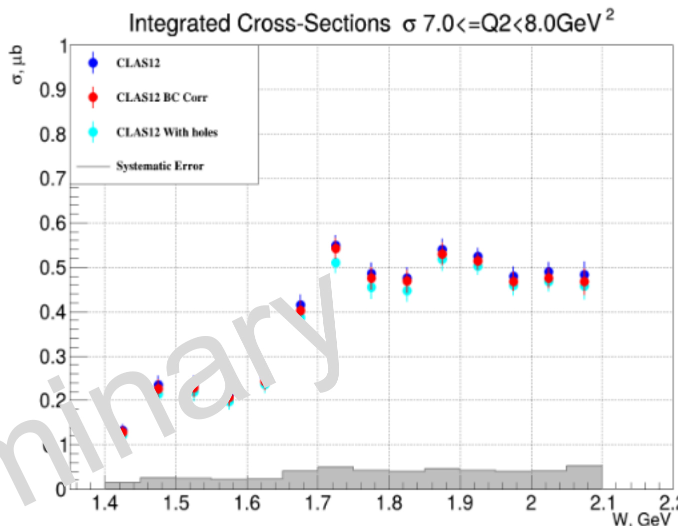
Measurements of inclusive (e,e'X) cross section with the CLAS12. V. Klimenko et al. (CLAS collaboration), PRC 112, 025201 (2025)



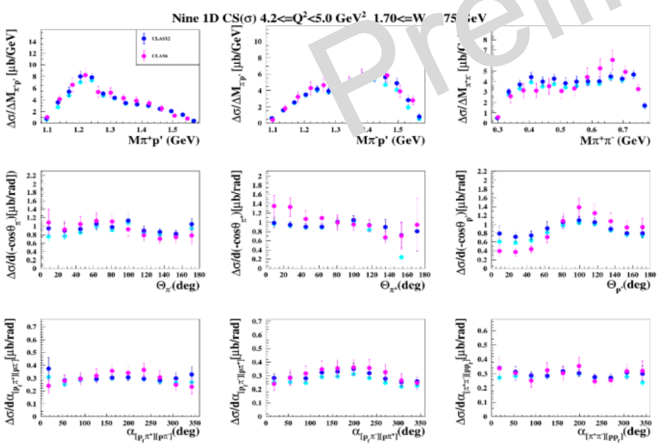
Resonance-like structures are clearly seen in the first, second, and third resonance regions for Q^2<10 GeV^2

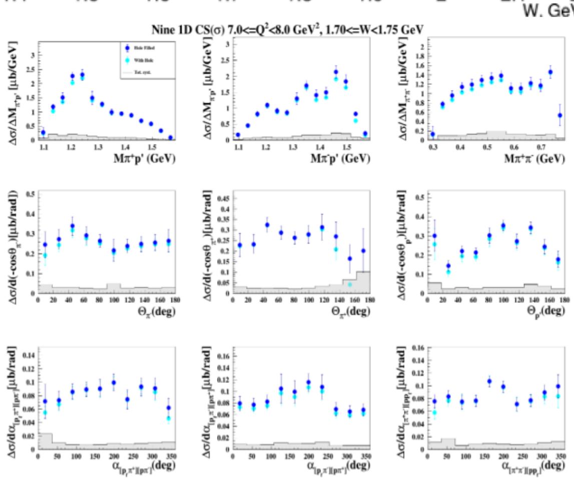
Preliminary Results on $\pi^+\pi^-p$ Electroproduction Cross Sections from CLAS12





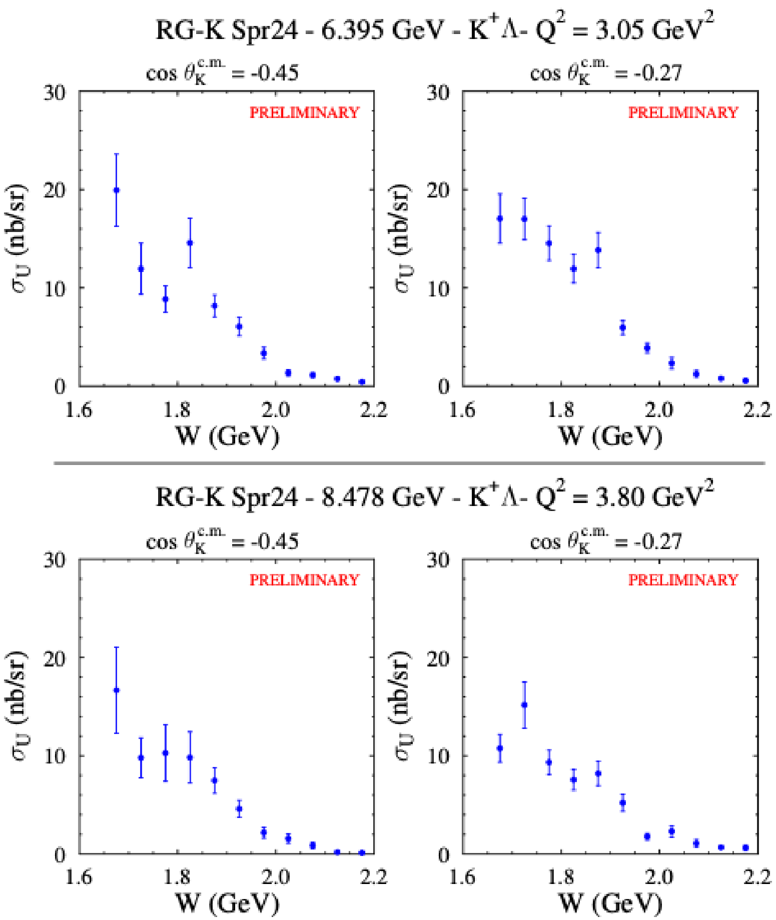
K. Neupane, R.W. Gothe,
V.I. Mokeev (USC),
D.S. Carman (JLab)





- Integrated and nine one-fold differential $\pi^+\pi^-p$ cross sections have become available across the range of W=[1.4-2.1] GeV for Q^2=[2.4-8.0] GeV^2
- Consistency with the CLAS data in the overlapping range of Q^2<5.0 GeV^2
- Allow us to extend the JM model over the range of Q^2<8.0 GeV^2, paving the way to obtain $\gamma_v pN^*$ electrocouplings of prominent resonances across the mass range up to 2.0 GeV for Q^2<8.0 GeV^2

Extension of the Results on $\gamma_v pN^*$ Electrocouplings in Experiments of 12 GeV Era : $K\Lambda$ and $K\Sigma$ Electroproduction



Resonance-like structures appear in the W-dependence of $\sigma_u(W)$ structure function.

Opportunities for the extraction of $\gamma_v pN^*$ electrocouplings from the CLAS12 $K\Lambda$ and $K\Sigma$ electroproduction data.

$\pi^+\pi^- p$, $K\Lambda$, and $K\Sigma$ electroproduction channels are promising to discover new state of baryon matter known as “missing” resonances and hybrid-baryons with glue as the active structural component.

See the talk by D.S. Carman on Monday, September 7, at 9:30 am

Conclusions and Outlook

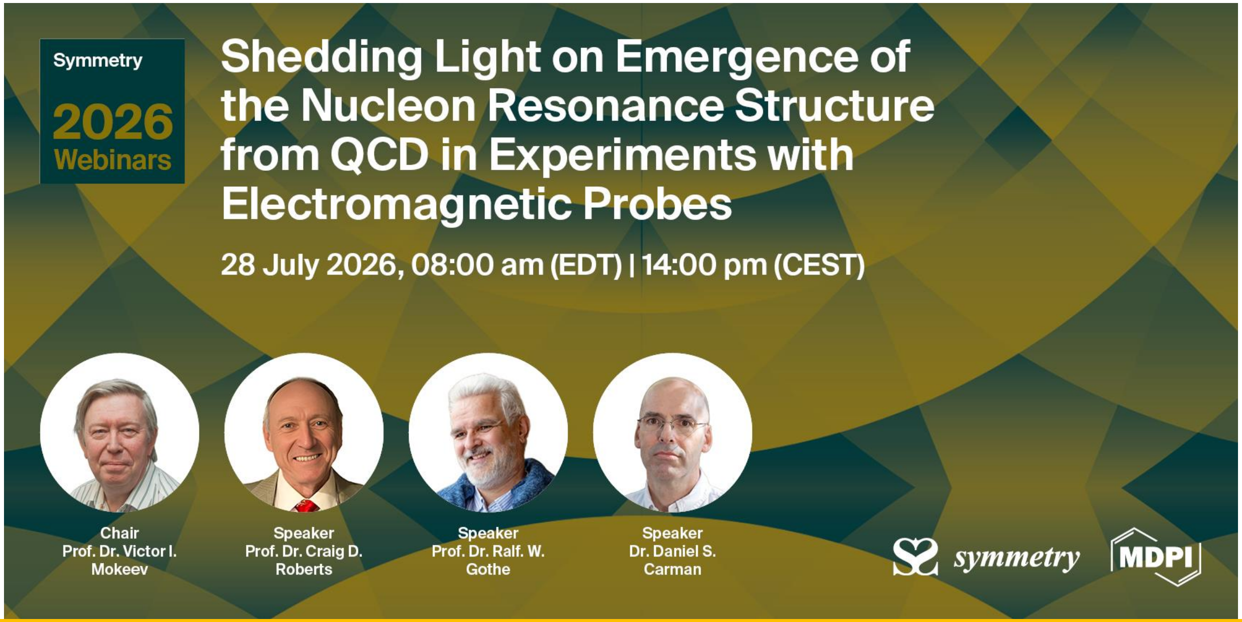
- **High-quality data of the 6-GeV era from CLAS have allowed for the determination of the electrocouplings of most N*s in the mass range up to 1.8 GeV for Q^2<5 GeV^2. Consistent results on $\gamma_v pN^*$ electrocouplings from πN and $\pi^+\pi^- p$ channels demonstrated the capabilities of the JANR/JM reaction models for credible extraction of these quantities from the data.**

- **Analyses of CLAS data on $\gamma_v pN^*$ electrocouplings within the QCD-rooted CSM framework, together with studies using various quark models, revealed the N* structure as a complex interplay between an inner core of three dressed quarks and an external meson–baryon cloud with the transition to the quark core dominance as Q^2 increases**

- **A good description of the $\Delta(1232)3/2^+$, $N(1440)1/2^+$, and $\Delta(1600)3/2^+$ electrocouplings for Q^2<5 GeV^2 *achieved within CSM with the same dressed quark mass function inferred from the QCD Lagrangian and* used in the successful description of the elastic nucleon and pion EM form factors, offers sound evidence for insight into the momentum dependence of the dressed quark mass.**

- **CLAS12 is the only facility capable of obtaining the electrocouplings of all prominent N* states in the unexplored Q^2 range from 5 - 10 GeV^2, allowing for mapping of the dressed quark mass function at quark momenta where ~50% of hadron mass is generated.**

- **Studies of exclusive meson electroproduction at W<2.5 GeV in facilities with luminosities at least 2-5*10^{35}cm^{-2}s^{-1} across large acceptance will allow us to determine $\gamma_v pN^*$ electrocouplings for Q^2<30 GeV^2, offering the only foreseen opportunity to explore the full range of distances where hadron mass and N* structure emerge from QCD. Synergy between experiment, phenomenology, and theory are needed.**



Special Issue: Emergence of Hadron Mass from Experiments at High Luminosity Facilities

Topics:

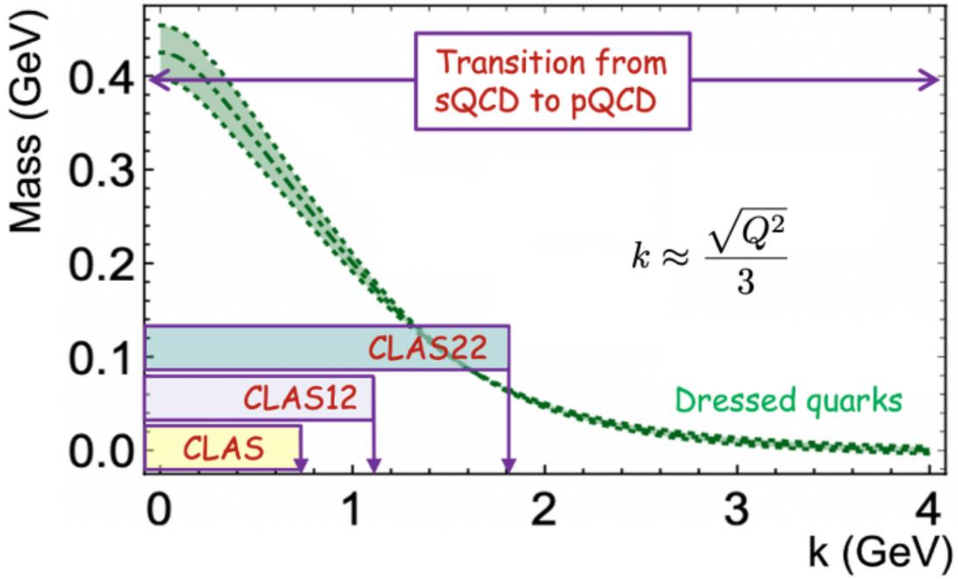
- Studies of nucleon resonance electroexcitation amplitudes from exclusive meson electroproduction data obtained in 6-GeV era CLAS experiments
- Extension of N* structure studies anticipated from CLAS12 experiments in the 12-GeV era and beyond
- Theory framework(s) for understanding the emergence of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

Webinar website:
https://sciforum.net/event/Symmetry-20

Related topical collection;
https://www.mdpi.com/journal/symmetry/topical_collections/67E84K92L5?webinar_id=218&_utm_from=3591e00bb3

Back up

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



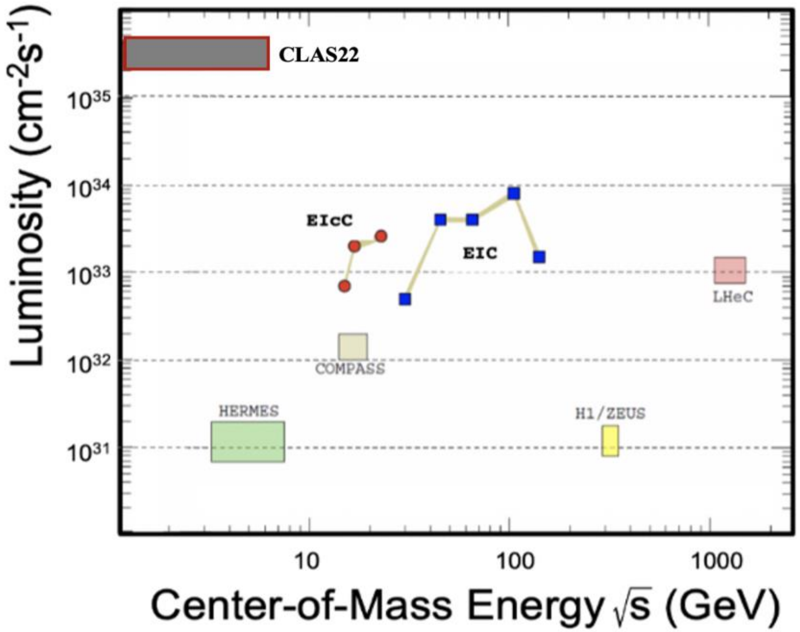
P. Achenbach, D.S. Carman, R.W. Gothe, K. Joo, V.I. Mokeev, and C.D. Roberts, Symmetry, 17, 1106 (2025)

- 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

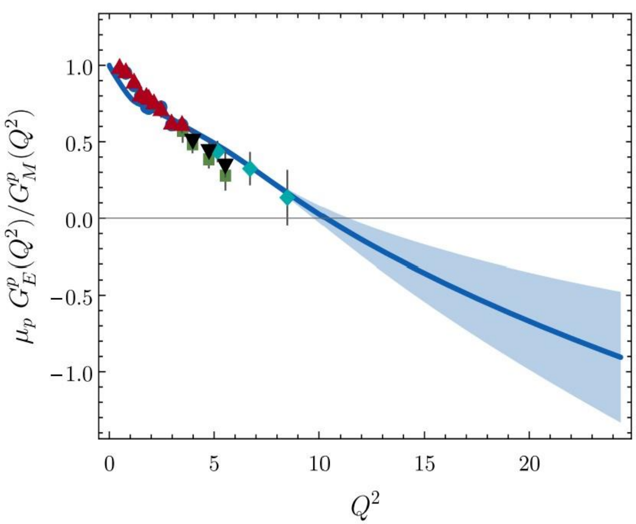
- Beam energy 22 GeV
- Large acceptance
- High luminosity
- Studies of exclusive reactions

- 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.

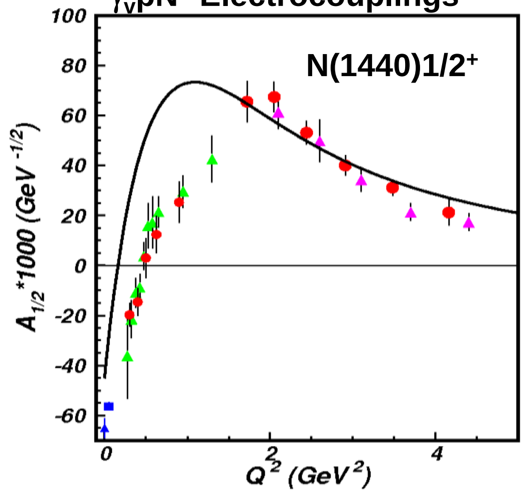
EHM from Global Hadron Structure Analysis within CSM

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

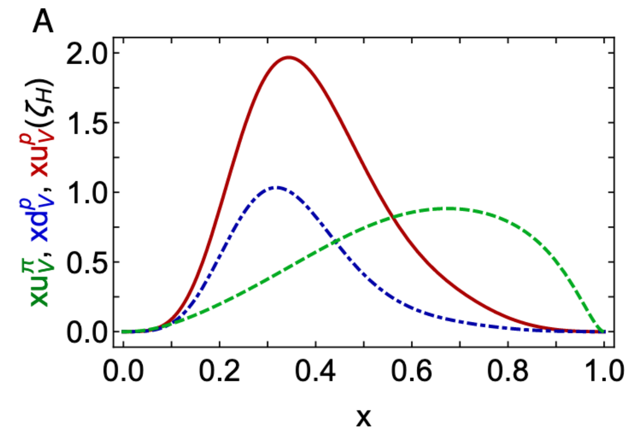
Nucleon Elastic FF



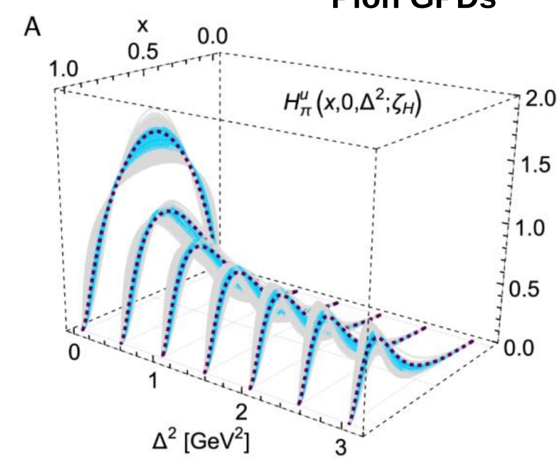
$\gamma_v pN^*$ Electrocouplings



Proton and pion PDF for valence quarks

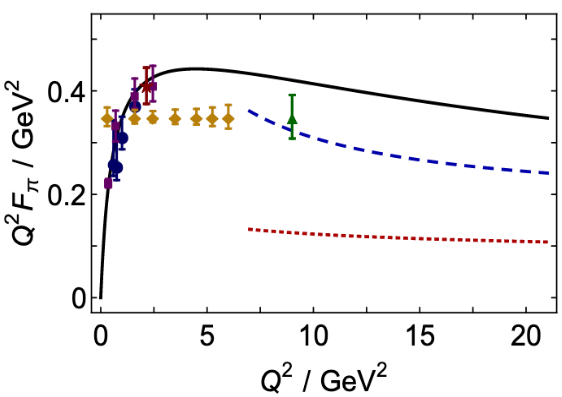


Pion GPDs

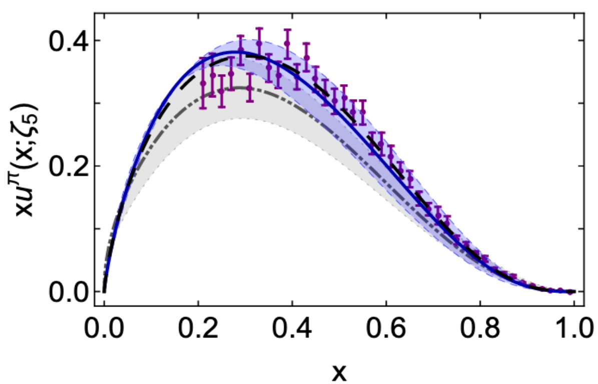


New data from studies of D-Y at AMBER and Sullivan processes at JLab

Pion Elastic FF

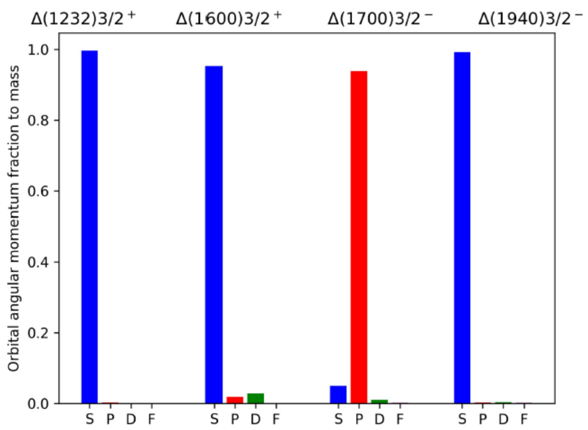


Pion PDF



- 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).

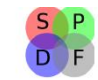
EHM and DCSB from Electroexcitation of Nucleon Resonances

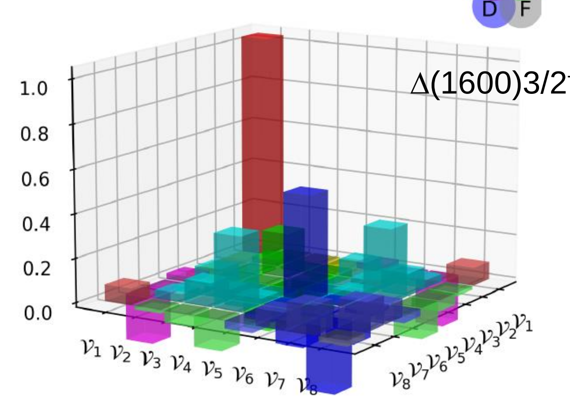


L-L' color map

	ν_1	ν_2	ν_3	ν_4	ν_5	ν_6	ν_7	ν_8
ν_1	S-S	S-P	S-P	S-P	S-D	S-D	S-D	S-F
ν_2	S-P	P-P	P-P	P-P	P-D	P-D	P-D	P-F
ν_3	S-P	P-P	P-P	P-P	P-D	P-D	P-D	P-F
ν_4	S-P	P-P	P-P	P-P	P-D	P-D	P-D	P-F
ν_5	S-D	P-D	P-D	P-D	D-D	D-D	D-D	D-F
ν_6	S-D	P-D	P-D	P-D	D-D	D-D	D-D	D-F
ν_7	S-D	P-D	P-D	P-D	D-D	D-D	D-D	D-F
ν_8	S-F	P-F	P-F	P-F	D-F	D-F	D-F	F-F

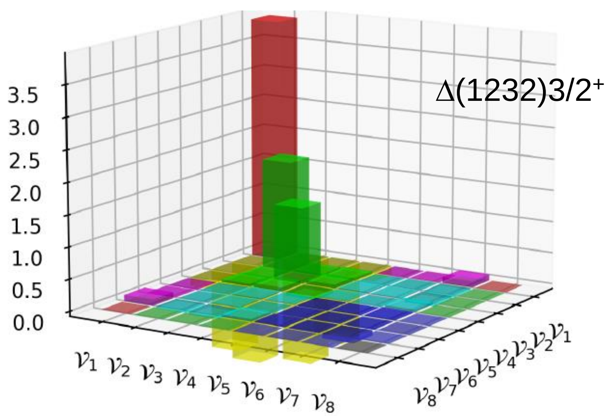
L. Liu et al., PRD 105, 114047 (2022)

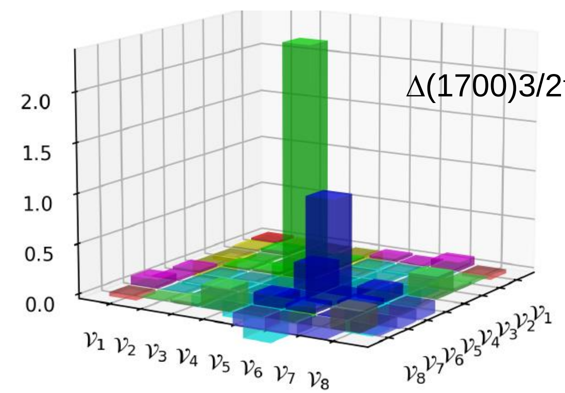




DCSB manifestation in the structure of chiral partners

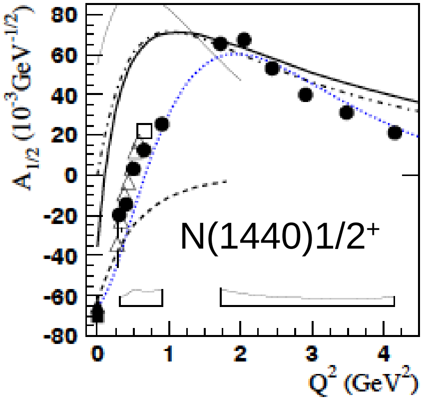
- Resonance masses/spectrum are determined mostly by a single quark-diquark configuration expected from SU(6) assignment
- Resonance wave functions reveal more complex quark-diquark composition accessible from the results on Q^2-evolution of γ_vpN* electrocouplings

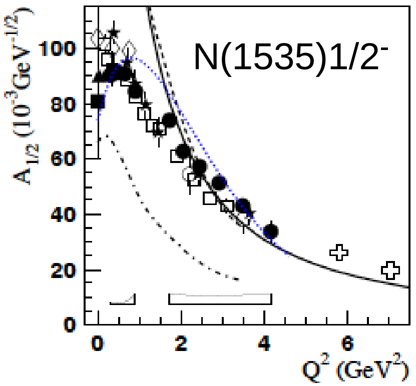




Electrocouplings of most N* in the mass range < 2 GeV will become available from the CLAS exclusive meson electroproduction data for $2.0<Q^2<5.0$ GeV^2, allowing us to establish either universality or environmental sensitivity of dressed quark mass function and to explore connection between EHM and DCSB

Facets of Strong QCD from Combined Studies of the Ground/Excited Nucleon State Structure



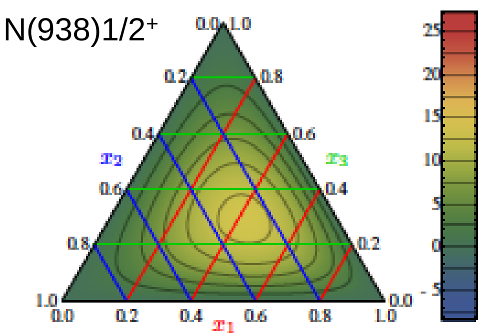


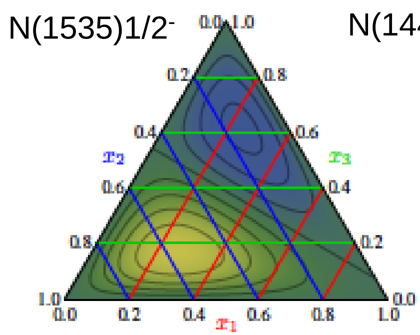
V.D.Burkert and I.G. Aznauryan, Prog. Part Nucl. Phys. 67, 1 (2012)

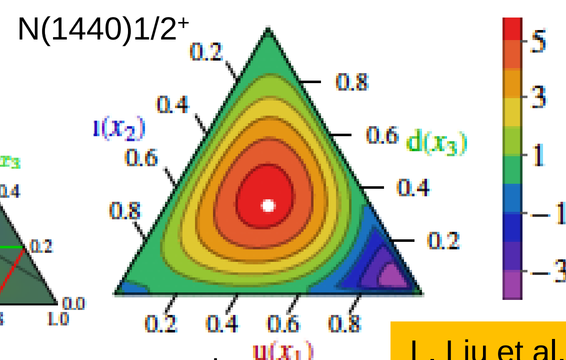
The results on electroexcitation of different resonances allow us to rigorously test the quark model ingredients for the description of the ground/excited hadron structure

V.M. Braun et al., Phys. Rev. D 89, 094511 (2014)
C. Mezrag et al., Phys. Rev. Lett. B 783, 263 (2018)

Parton distribution amplitudes (PDA) in:



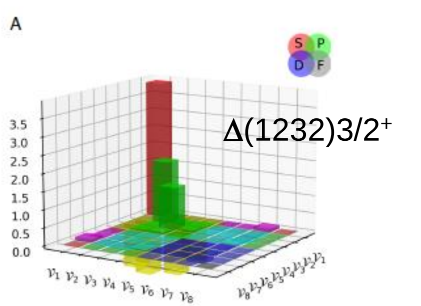


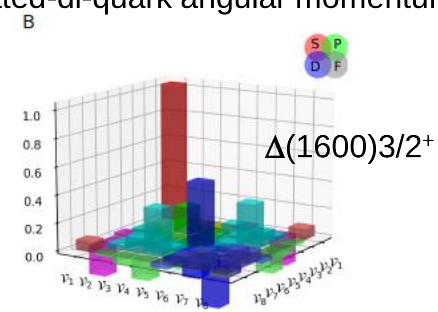


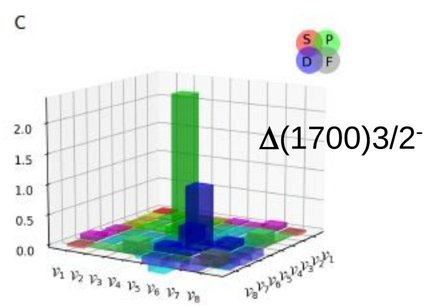
Pronounced differences predicted for N/N* PDAs can be explored in N* electroexcitation, offering insight into the sQCD mechanisms that underlie these differences

L. Liu et al., e-print: 2203-12083 [hep-ph]

Rest frame quark-correlated-di-quark angular momentum content in:







Studies of N* electroexcitation will contribute to understanding of the nature of spin of the ground and excited states of the nucleon

Exploration of N* electroexcitations is an important part of efforts aimed to considerably extend knowledge on sQCD