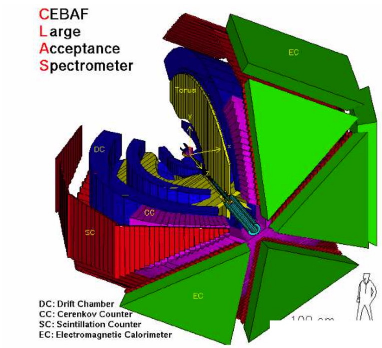
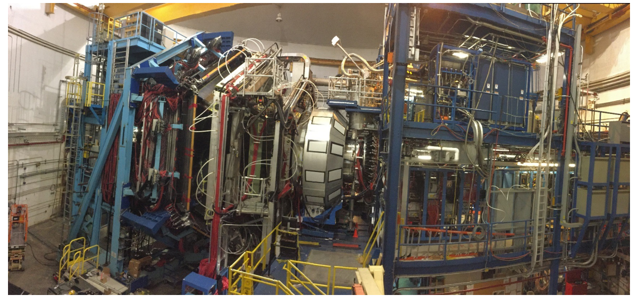
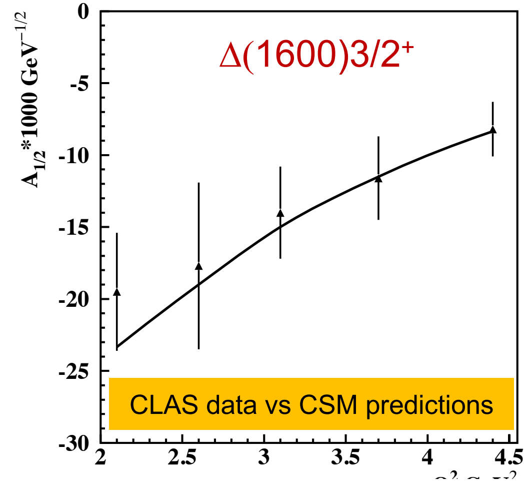
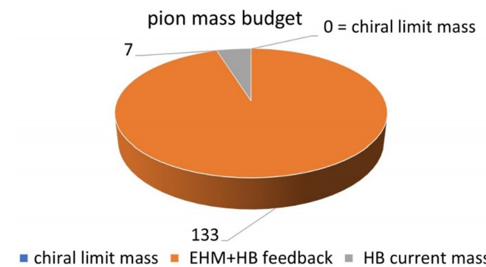
N* Structure and the Emergence Hadron Mass

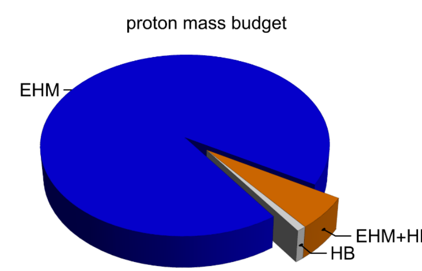






- The Continuum Schwinger Method (CSM) concept on the emergence of hadron mass (EHM)
- Dressed quark mass function from $\gamma_v pN^*$ electrocouplings for N*'s within the mass range of M_{N^*}<1.6 GeV
- Extending insight to EHM from electroexcitation of N* within the mass range > 1.6 GeV
- Needs the global analysis of π, K, N/N* structure
- New opportunities from the results of CLAS12 and beyond





V.I. Mokeev, Jefferson Lab
(CLAS Collaboration)

NSTAR24, June 17-21 2024, York, UK

How do the Ground/Excited Nucleon Masses Emerge?

Composition of the Nucleon Mass:

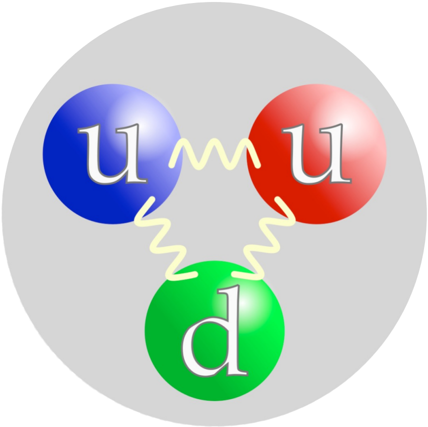
M_p, MeV (PDG23)

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



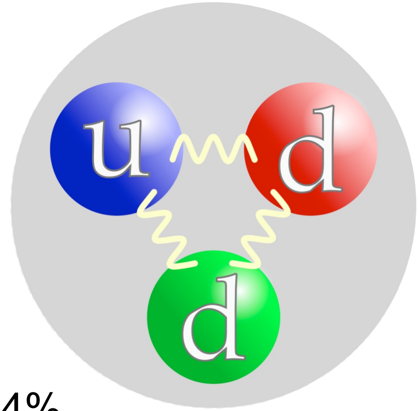
M_n, MeV (PDG23)

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

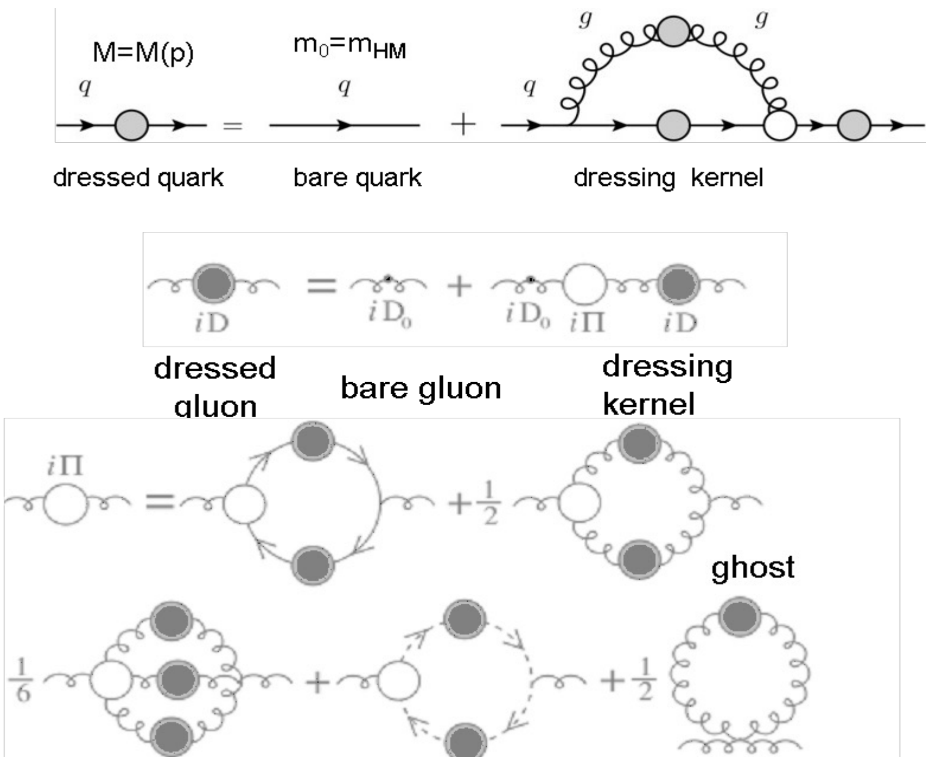
- **The Higgs mechanism only generates the masses of bare quarks relevant to the pQCD regime.**

- **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 photon virtuality Q^2 shed light on the emergence of N/N* masses at distances where the transition from the strongly coupled to pQCD regimes is expected.

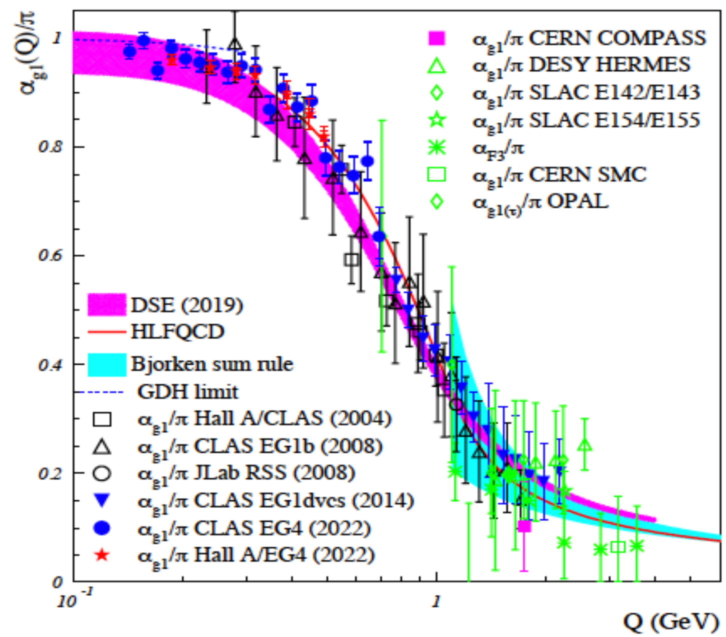
EHM Concept Developed within Continuum Schwinger Method

Emergence of Dressed Quarks and Gluons
D. Binosi et al., Phys. Rev. D 95, 031501 (2017)



QCD Running Coupling α(Q)
Zh-F. Cui et al., Chin. Phys. C44, 083102 (2020)
A. Deur et al., Particles 5, 171 (2022)

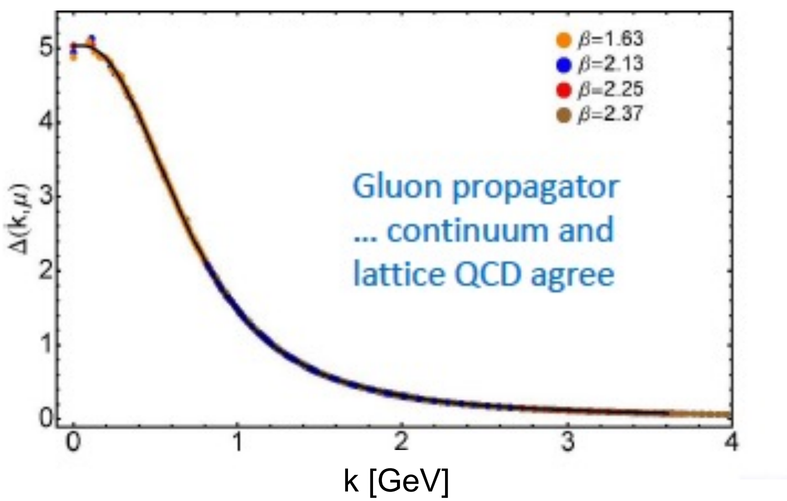
Owing to non-zero gluon running mass, α(Q) becomes finite at Q<0.5 GeV, making QCD a well-defined theory without divergences in the infrared/ultraviolet



- **Gluon self-interaction encoded in QCD Lagrangian represents a seed for the emergent part of hadron masses, producing dressed gluon running mass via the Schwinger mechanism.**
- **In the regime of QCD running coupling comparable with unity, dressed quarks and gluons with momentum (distance) dependent masses emerge from QCD, as follows from the equations of the motion for the QCD fields depicted above. The bound states of three dressed quarks generate the quark cores for the ground and excited states of the nucleon at a 1-2 GeV mass scale.**

Continuum/Lattice QCD and Experiment Synergy for Insight into EHM

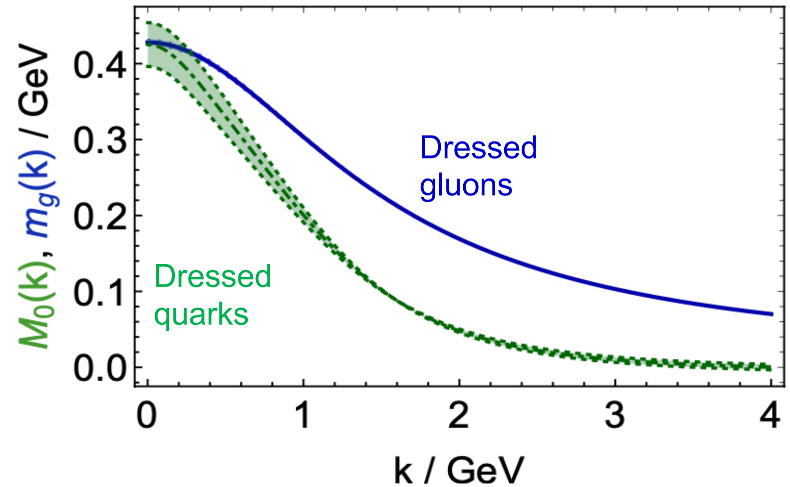
- **Dressed quark/gluon masses converge at the complete QCD mass scale of 0.43(1) GeV.**
- **Express the fundamental feature: emergence of the quark and gluon masses even in the case of massless quarks in chiral limit and massless QCD gluons.**
- **LQCD confirms continuum QCD results.**



.

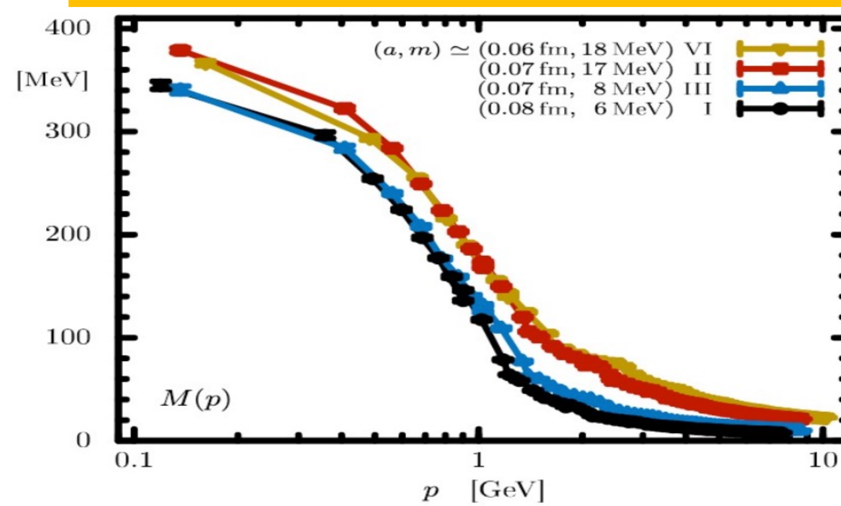
- **The sensitivity of N* electroexcitation amplitudes to the dressed quark propagator allows us to map out the quark mass function.**

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)



EHM from N* Structure in Experiments of 6/12 GeV Eras at JLab

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 major meson electroproduction channels.

- Explore hadron mass emergence (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 in the EHM exploration from the experimental data on the hadron structure with electromagnetic probes:

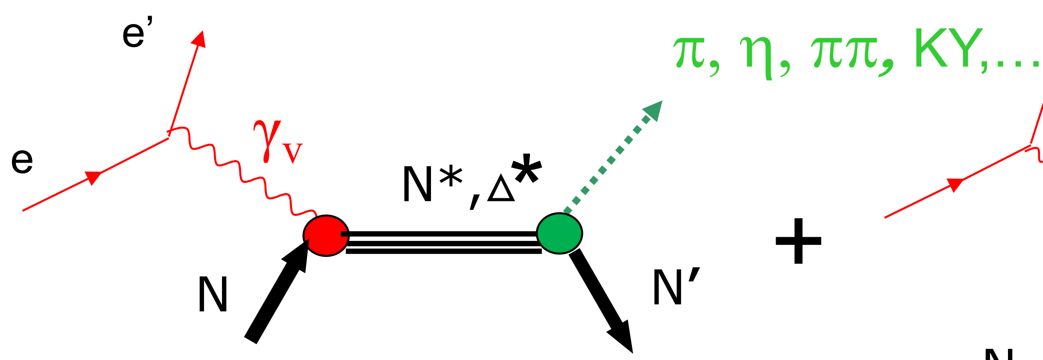
1. D.S. Carman, R.W. Gothe, V.I. Mokeev. and C.D. Roberts, Particles 6, 416 (2023)
2. M. Ding, C.D. Roberts, and S.M. Schmidt, Particles 6, 57 (2023)
3. S.J. Brodsky et al., Int. J. Mod. Phys. E29, 203006 (2020)

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

1. V.D. Burkert, Eur. Phys. J. C83, 1125 (2023).
2. D.S. Carman, K. Joo, and V.I. Mokeev, Few Body Syst. 61, 29 (2020)
3. V.D. Burkert and C.D. Roberts, Rev. Mod. Phys. 91, 011003 (2019)

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

Resonant amplitudes **Non-resonant amplitudes**



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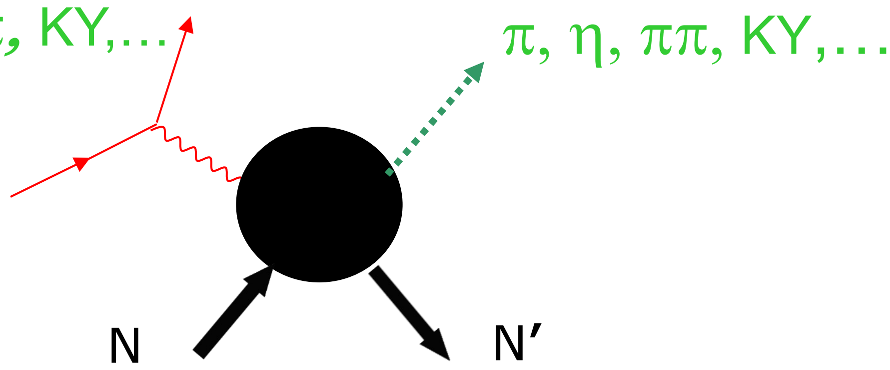


- **Real $A_{1/2}(Q^2)$, $A_{3/2}(Q^2)$, $S_{1/2}(Q^2)$**

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

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

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

- **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 phase space

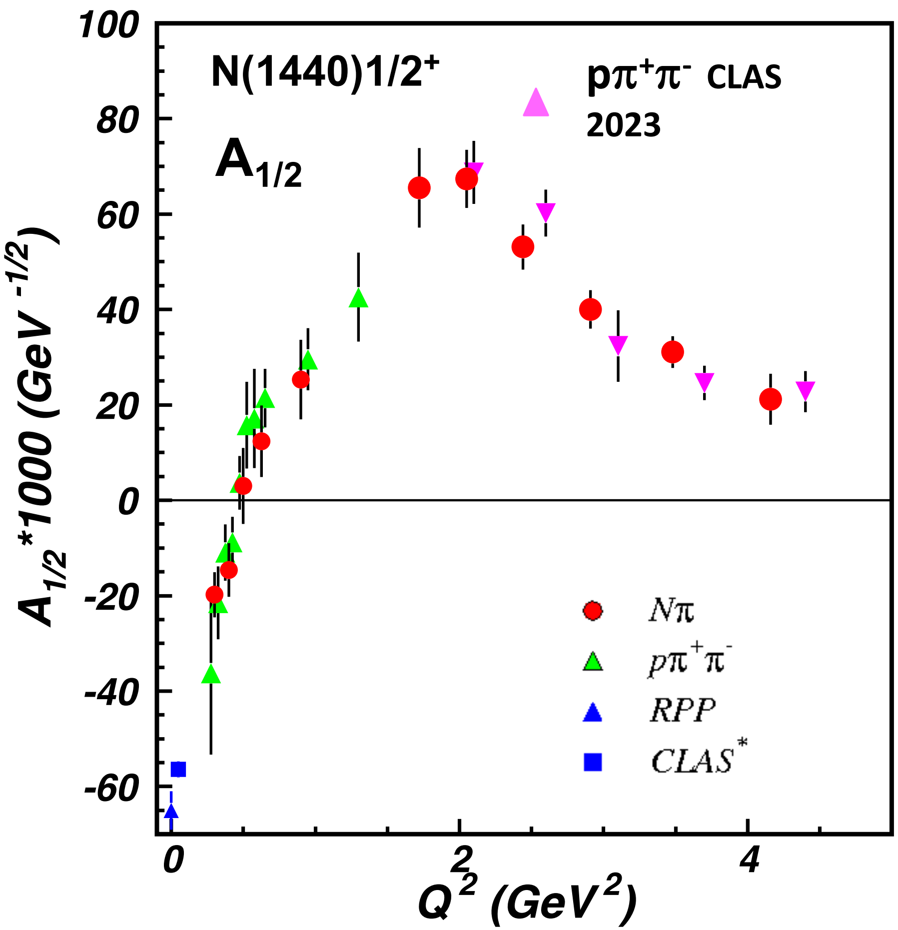
The measured observables from CLAS are stored in the
CLAS Physics Data Base http://clas.sinp.msu.ru/cgi-bin/jlab/db.cgi

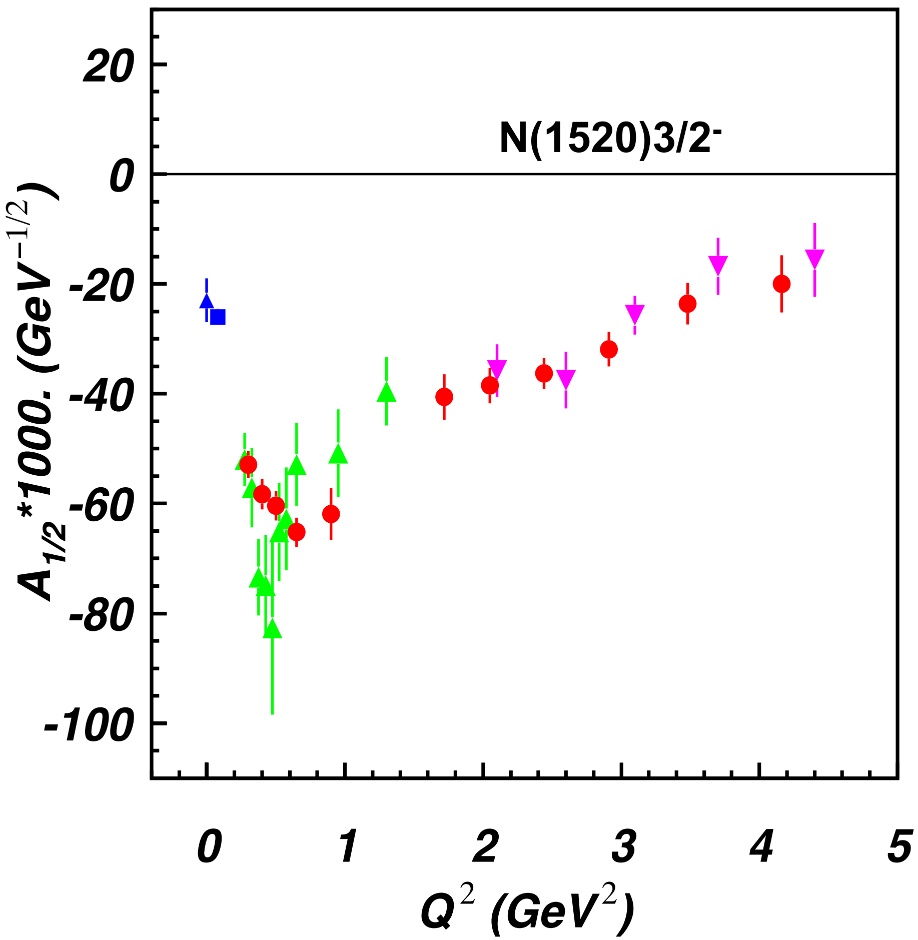
Nucleon Resonance Electrocouplings from Data on Exclusive Meson Electroproduction of 6 GeV Era with CLAS

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
$\pi^+\pi^- p$	$N(1440)1/2^+$, $N(1520)3/2^-$ $N(1440)1/2^+$, $N(1520)3/2^-$, $\Delta(1600)3/2^+$ $\Delta(1620)1/2^-$, $N(1650)1/2^-$, $N(1680)5/2^+$, $\Delta(1700)3/2^-$, $N(1720)3/2^+$, $N'(1720)3/2^+$	0.25-1.50 2.0-5.0 0.5-1.5

- **The $\gamma_v pN^*$ electrocouplings 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)
- **The experiments in Halls A/C extended the results on $\gamma_v pN^*$ electrocouplings of $\Delta(1232)3/2^+$ and $N(1535)1/2^-$ for $Q^2 < 7.5$ GeV^2.**

Electrocouplings of N(1440)1/2⁺ and N(1520)3/2⁻ Resonances from πN and π⁺π⁻p Electroproduction off Proton Data



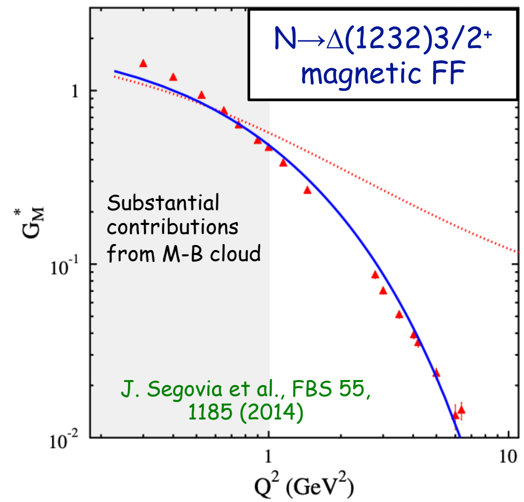


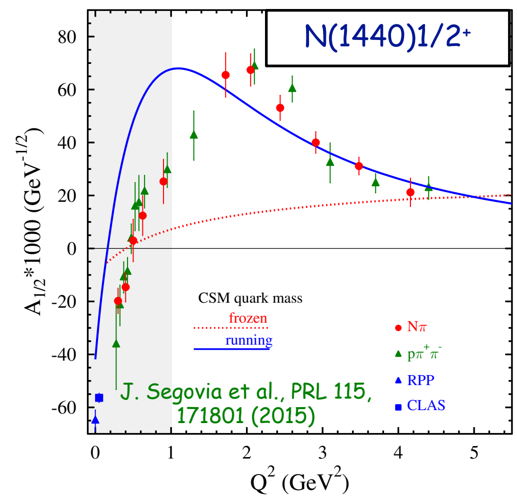
Consistent results on the N(1440)1/2⁺ and N(1520)3/2⁻ electrocouplings from independent studies of the two major πN and $\pi^+\pi^-p$ electroproduction channels with different non-resonant contributions demonstrated the capabilities of the reaction models for their reliable extraction and allow us to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

EHM: Concept from CSM vs. Available Experimental Results

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

CLAS/Hall A/C results vs. CSM expectations



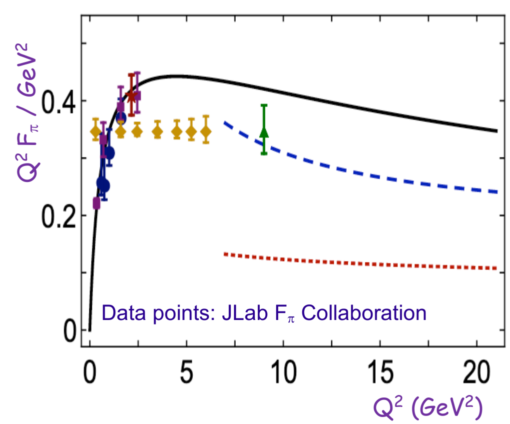


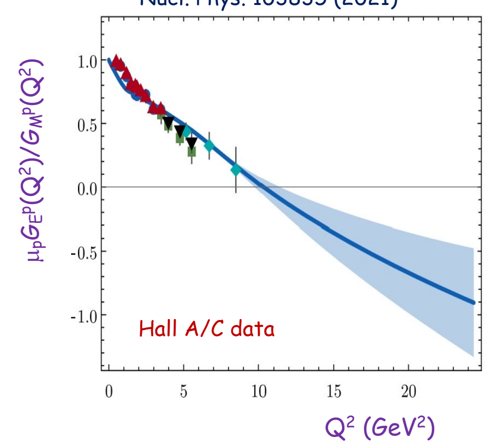
Pion Elastic FF

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 Δ(1232)3/2⁺, N(1440)1/2⁺.
- **Strong evidence for insight into momentum dependence of dressed quark mass**

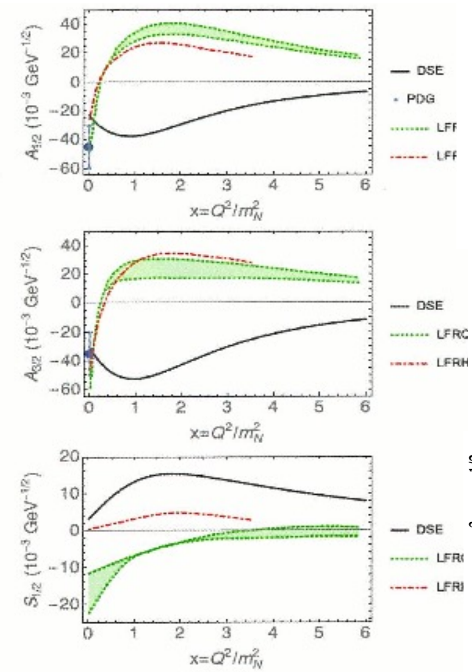
One of the most important achievements in hadron physics of the last decade in synergistic efforts between experimentalists, phenomenologists, and theorists.

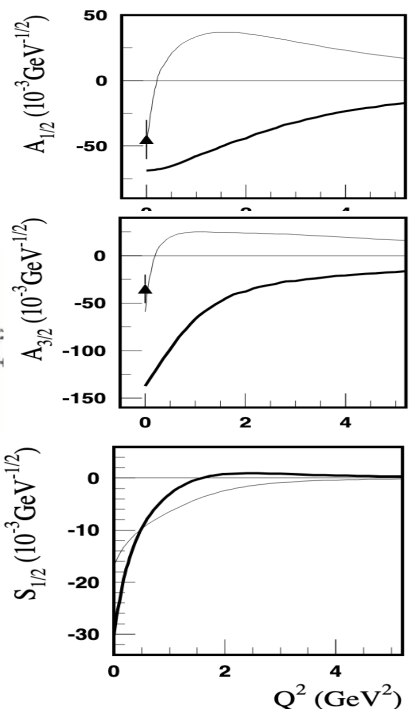
Δ(1600)3/2⁺ Electrocouplings: CSM Prediction vs. Data Determination

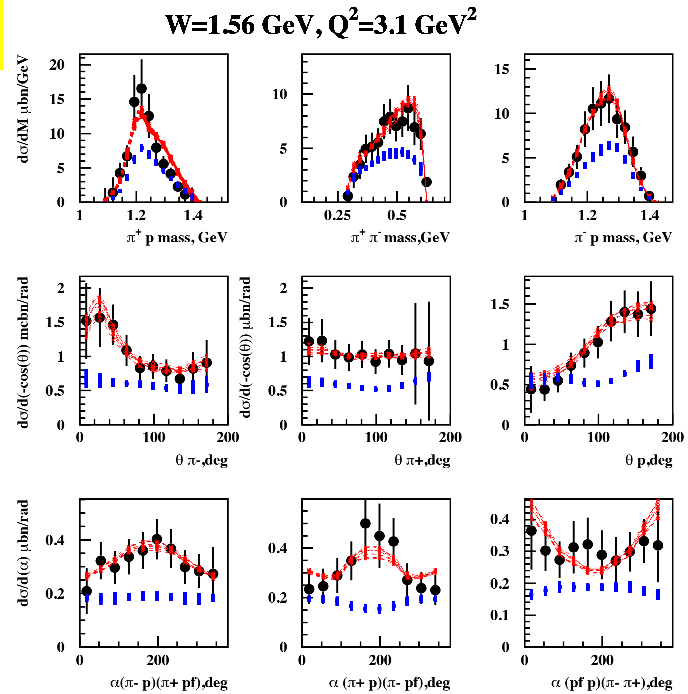
Parameter-free CSM predictions for Δ(1600)3/2⁺ electrocouplings Ya Lu et al., Phys. Rev. D 100, 034001 (2019)

LFRQM accounting for 3-quark configuration mixing : I.G. Aznauryan and V.D. Burkert arXiv: 1603.06692 [nep-ph]

Extraction of Δ(1600)3/2⁺ electrocouplings from the CLAS $\pi^+\pi^-p$ electroproduction data at 2.0 GeV^2<Q^2<5.0 GeV^2 within the JM23 reaction model







Computed 1-fold differential cross sections selected in the data fit

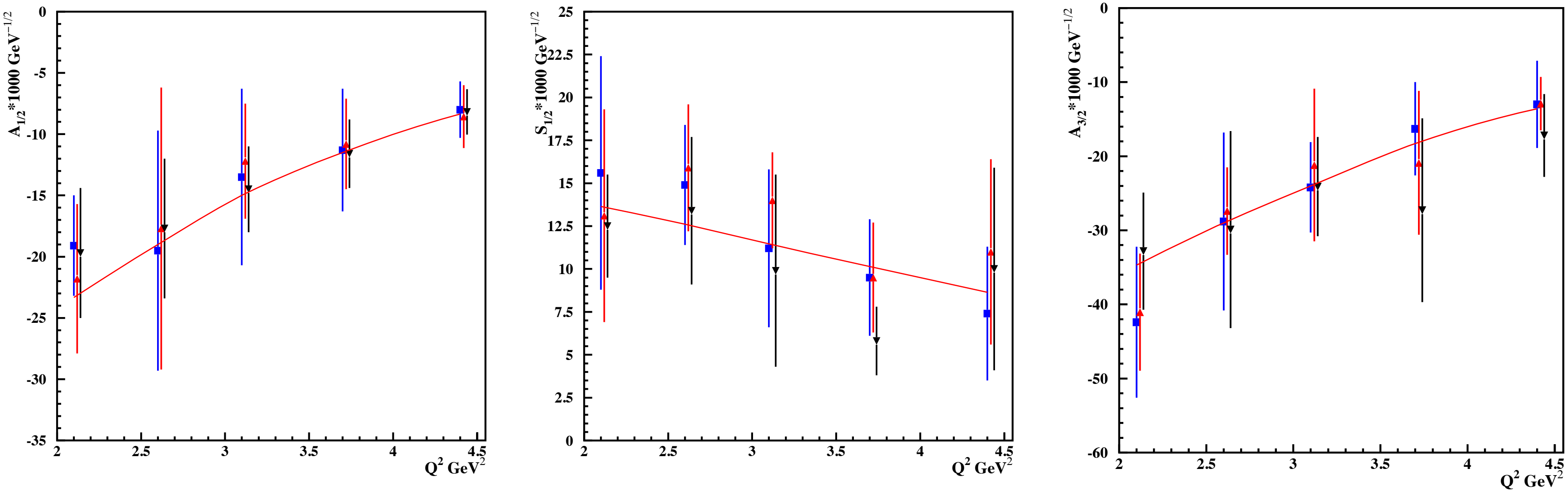
Resonant contributions

The data fit within JM23 model

W-intervals, GeV	1.41-1.51	1.46-1.56	1.51-1.61	1.56-1.66
$\chi^2/d.p.$ Ranges	0.51-0.57	0.52-0.67	0.52-0.69	0.69-0.76

$\gamma_v pN^*$ electrocouplings determined from the resonant contributions accounting for restrictions imposed by unitarity on the resonant amplitudes

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

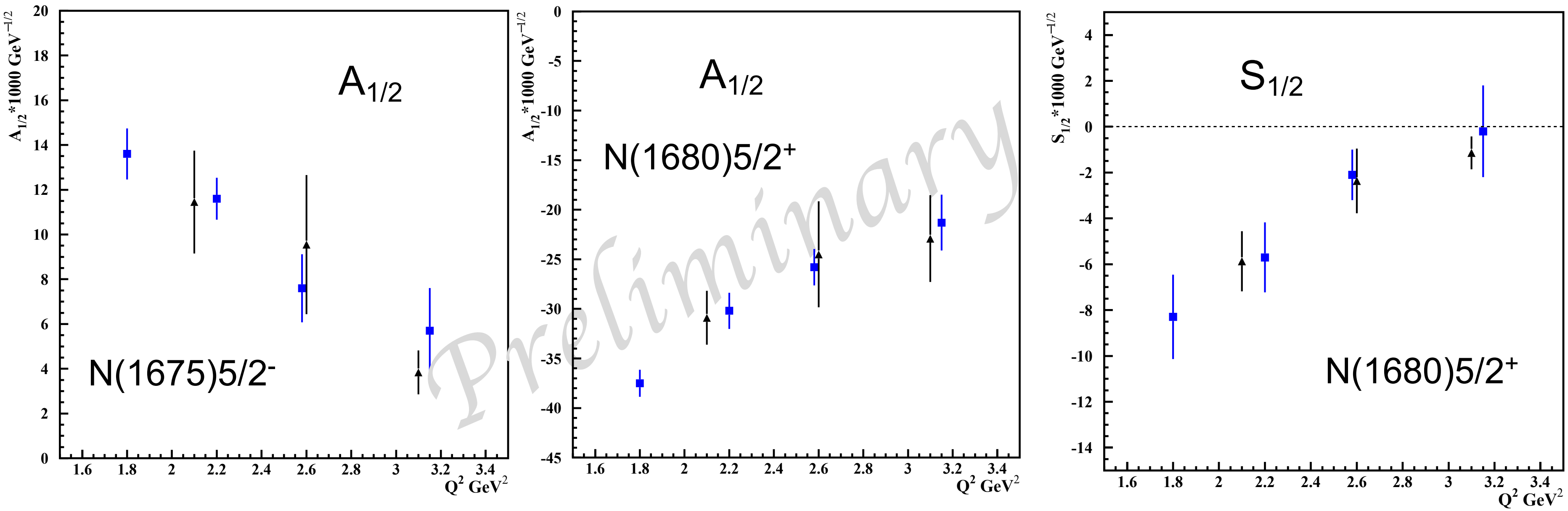


CSM predictions, Ya Lu et al., Phys. Rev. D 100, 034001 (2019)

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., Phys. Rev. C108, 025204 (2023)].

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

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

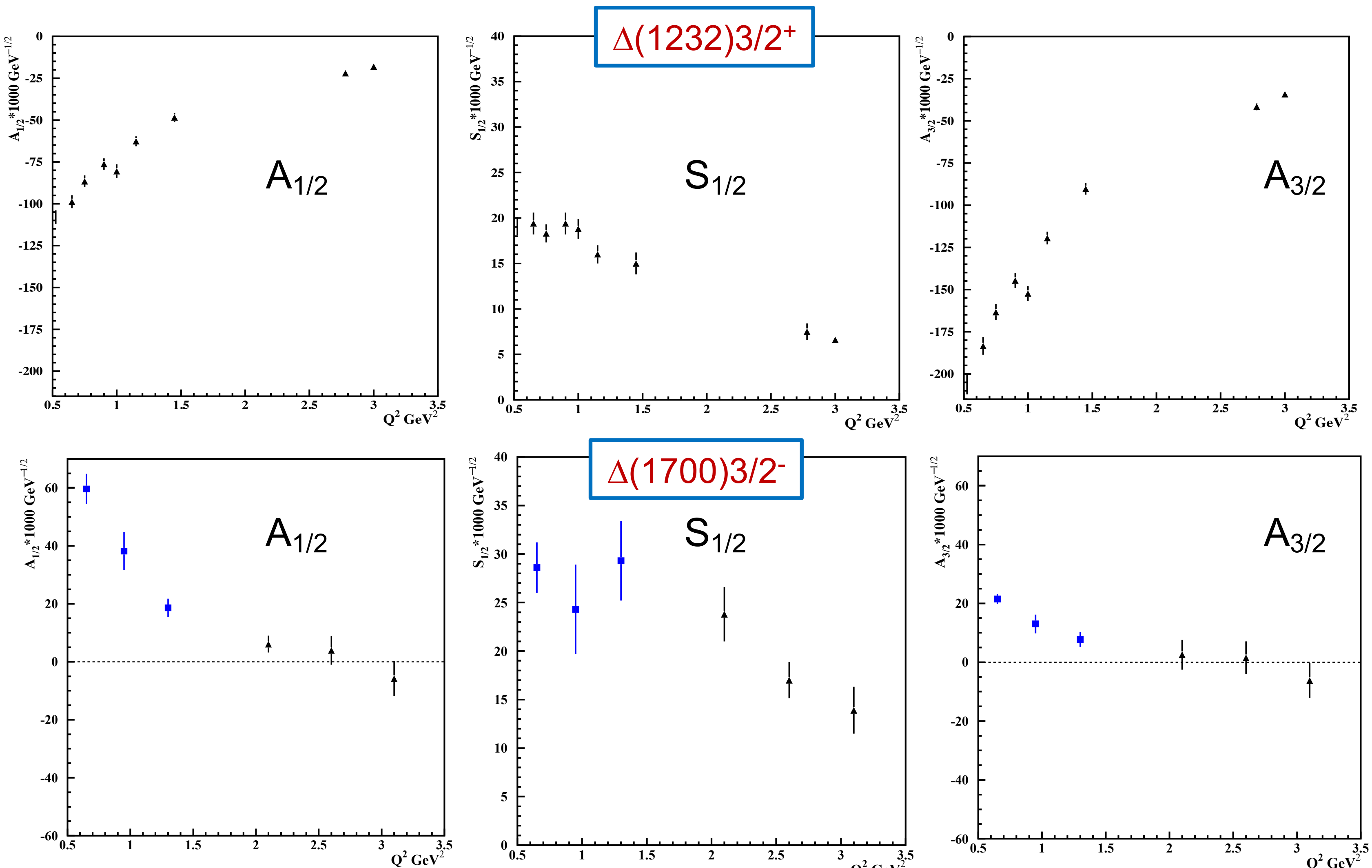


blue: π^+n
K. Park et al. (CLAS), Phys. Rev. C91, 045203 (2015)
UIM/DR-reaction models: I.G. Aznauryan et al. (CLAS), Phys. Rev. C80, 055203 (2009)

black: CLAS $\pi^+\pi^-p$
preliminary, May 2024
JM23-reaction model: V.I. Mokeev et al., Phys. Rev. C108, 025204 (2023)

Consistent results on 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 credible extraction of electrocouplings for the excited states of the nucleon in the third resonance region from the data of these exclusive channels

Shedding light on 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 available for Δ(1232)3/2+ and expected for Δ(1700)3/2-

EHM from $\gamma_v pN^*$ Electrocouplings Determined from the CLAS Data

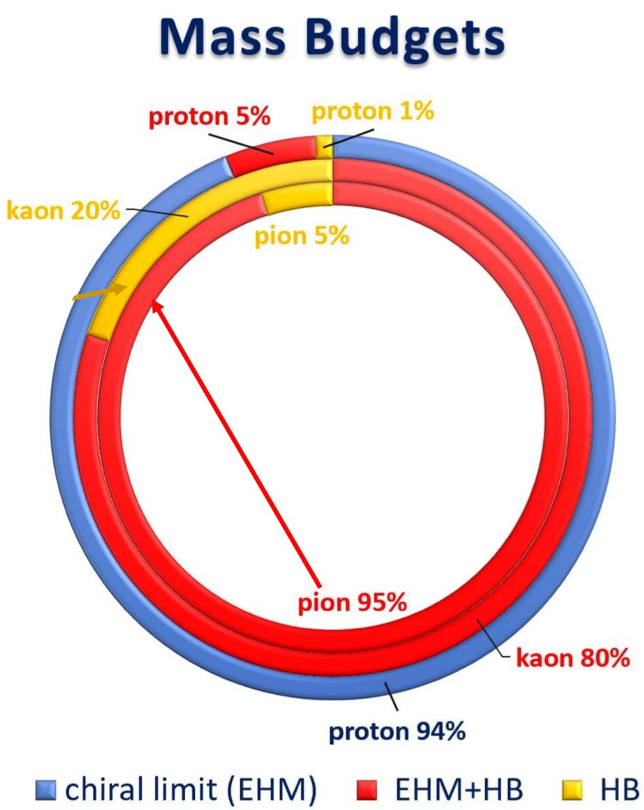
- The $\gamma_v pN^*$ electrocouplings of most N* within the mass range up to 1.8 GeV for Q^2<5 GeV^2 will become available by 2024. In a few years, this information will be extended for most N* states within the mass range up to 2 GeV for Q^2<5 GeV^2.

- Recently, electroexcitation amplitudes for N* within the mass range up to 1.8 GeV were determined for Q^2<5 GeV^2 at the pole positions within coupled channel analysis of $N\pi$ $N\eta$, KY photo-/electro- and hadroproduction data in ***Y-F. Wang et al., arXiv:2404v2 [nucl-th] .*** The authors conclude *"…. qualitative comparisons with Breit-Wigner determinations of other studies show no obvious disagreement."*
- Bonn-Gatchina coupled channel approach provided preliminary results on electroexcitation amplitudes for N* within the mass range up to 1.8 GeV for Q^2<1 GeV^2 at the pole positions

- Analyses of these results within CSM will allow us:
  a) to establish either universality or environmental sensitivity of dressed quark mass function by comparing the CSM expectation and the electrocouplings of resonances of distinctively different structures extracted from the data;
  b) shed light on DCSB manifestation in comparative studies of the chiral partner electrocouplings;
  c) Explore di-quark correlations of different spin-parities/isospins.

- Comprehensive treatment by other strong QCD theory tools is highly desirable.

Complementarities for EHM Understanding from Exploration of the Meson and N/N* Structure



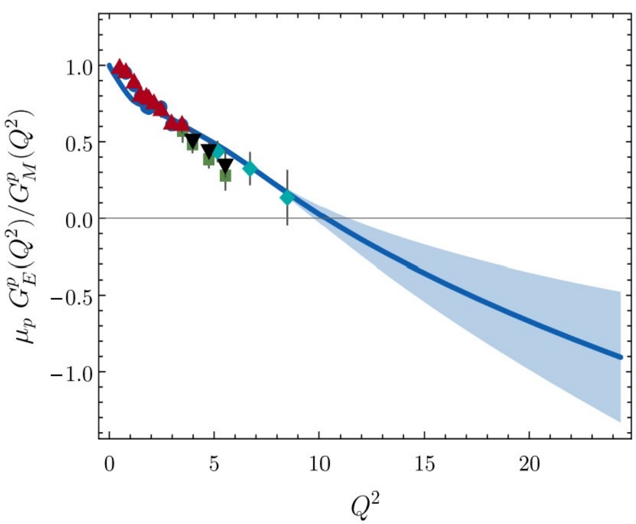
- Studies of π/K structure elucidate the interference between emergent and Higgs mechanisms in EHM
- Studies of ground/excited state nucleon structure allow us to explore the dressed quark mass function in a different environment where the sum of dressed quark masses is the dominant contribution to the physical masses of these states, offering insight into emergent mechanisms

- The successful description of the π/K elastic FFs and PDFs, nucleon elastic FFs, and the γ_vpN* electrocouplings of prominent nucleon resonances of different structure achieved with the *same* dressed quark mass function is of particular importance for the validation of insight into EHM.

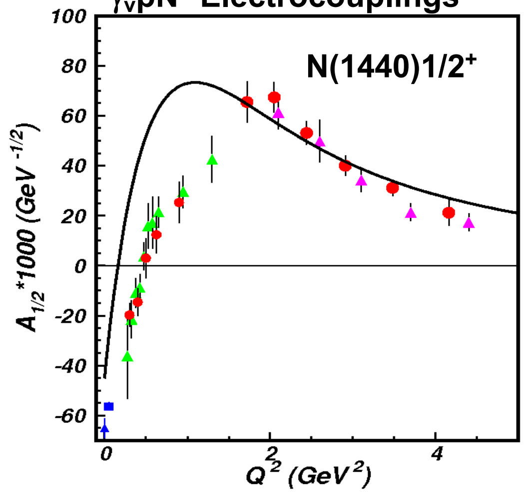
EHM from Global Hadron Structure Analysis within CSM

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

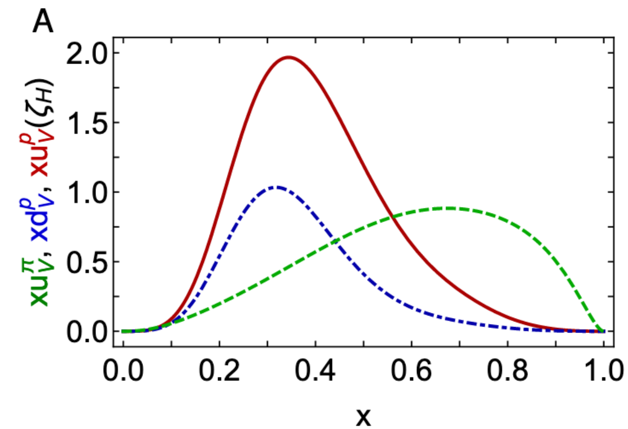
Nucleon Elastic FF



$\gamma_v pN^*$ Electrocouplings

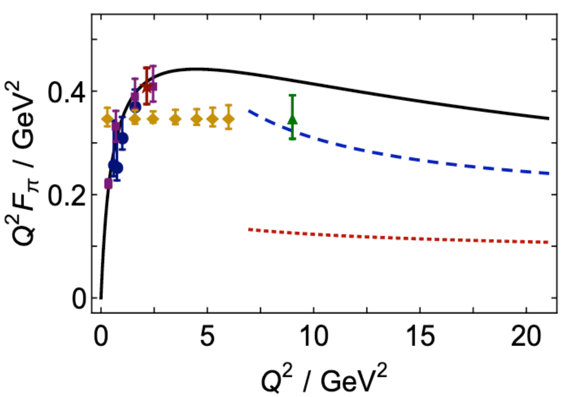


Proton and pion PDF for valence quarks

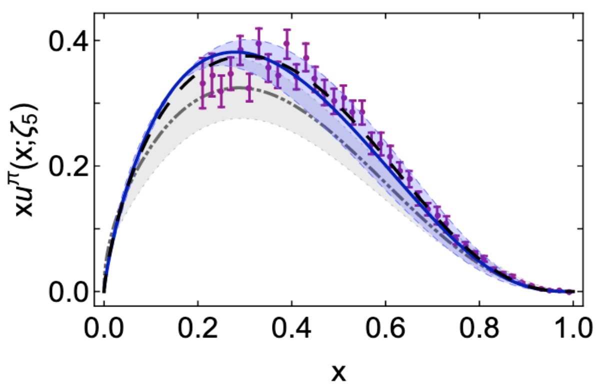


New data from studies of D-Y at AMBER and Sullivan processes at JLab

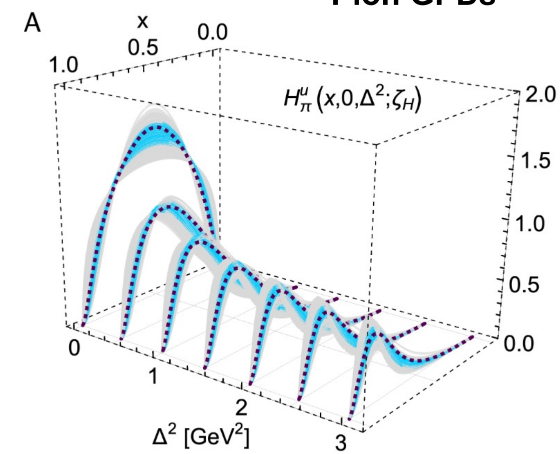
Pion Elastic FF



Pion PDF



Pion GPDs

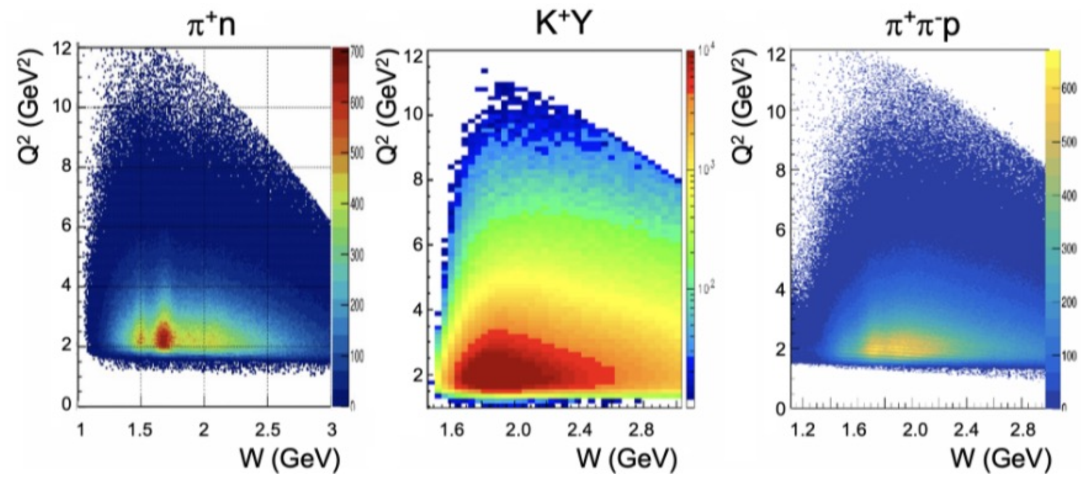


- CSM is currently the only approach that offers insight into EHM from combined studies of meson/baryon structure with connection to QCD. Ref. C.D. Roberts, FBS 64, 51 (2023).

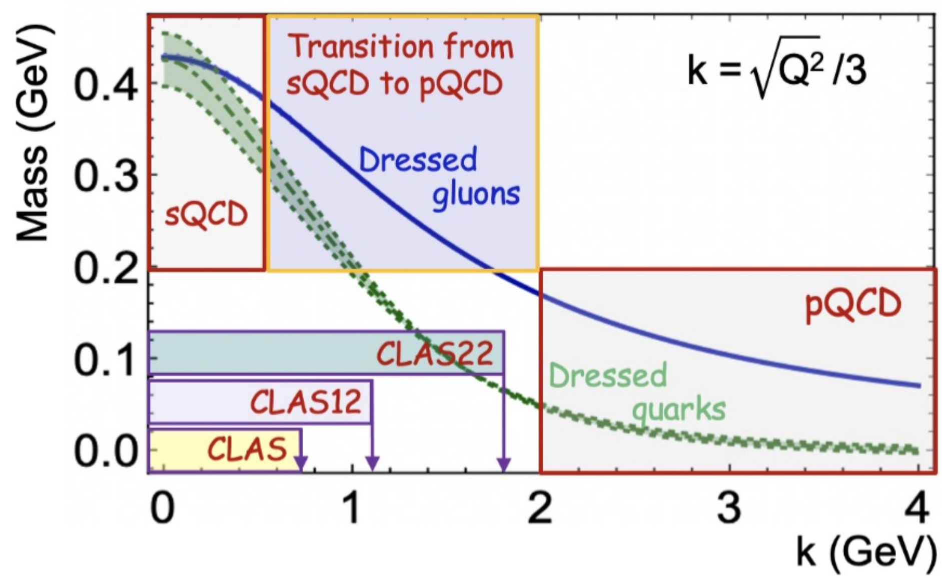
Extending Insight into EHM from CLAS12 Measurements and after CEBAF 22 GeV Energy Upgrade

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, ππN, KY, K*Y, KY* allows us to map-out range of quark momenta where ~50% of dressed quark mass is generated.

Meson electroproduction yields measured with the CLAS12



- In order to resolve the challenging problem on EHM, the dressed quark mass function $M_q(k)$ should be mapped out over the entire range of quark momenta to ~2 GeV, where the transition from strongly coupled to perturbative QCD takes place.



Conclusions and Outlook

- **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.**

- **High-quality meson electroproduction data of 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. In a few years, electrocouplings of the most prominent resonances will become available in the mass range of < 2 GeV for Q^2<5 GeV^2**

- **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 electromagnetic form factors, offers sound evidence for insight into the momentum dependence of the dressed quark mass.**

- **Global CSM analyses of $\gamma_v pN^*$ electrocouplings of N* states in the mass range to 2 GeV for Q^2 < 5 GeV^2, the structure of ground nucleon, π, and K are essential to understand the EHM. Comprehensive treatment by other strong QCD theory tools is highly desirable.**

- **CLAS12 is the only facility in the world capable of obtaining the electrocouplings of all prominent N* states in the still unexplored Q^2 range from 5 - 10 GeV^2 from measurements of $N\pi$, $\pi^+\pi^-p$, $N\eta$, $K\Lambda$, and $K\Sigma$ electroproduction, allowing for the mapping of the dressed quark mass function at quark momenta where ~50% of hadron mass is generated.**

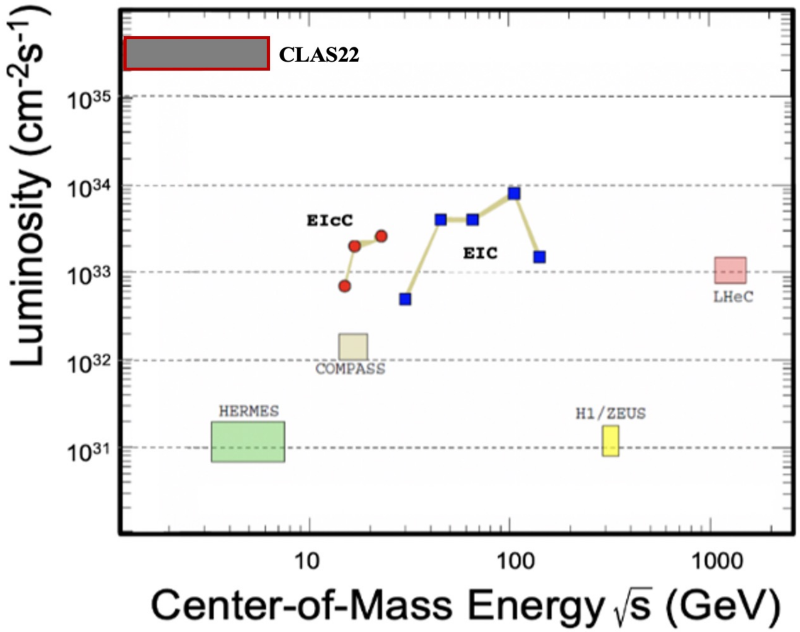
- **Extension of the results on the $\gamma_v pN^*$ electrocouplings into the Q^2 range from 10 - 30 GeV^2 after the increase of the CEBAF energy and pushing the CLAS12 detector capabilities to measure exclusive electroproduction to the highest possible luminosity, will offer the only foreseen opportunity to explore how the hadron mass and N* structure emerge from QCD and will make CEBAF@22 GeV unique and the ultimate QCD-facility at the luminosity frontier.**

Back up

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:

  γ_vpN* 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}



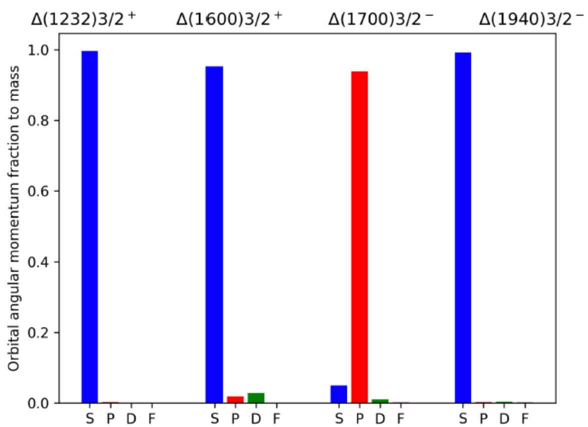
Both EIC and EIcC would need much higher luminosity to carry out such a program

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

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

- Extending the γ_vpN* 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, 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.

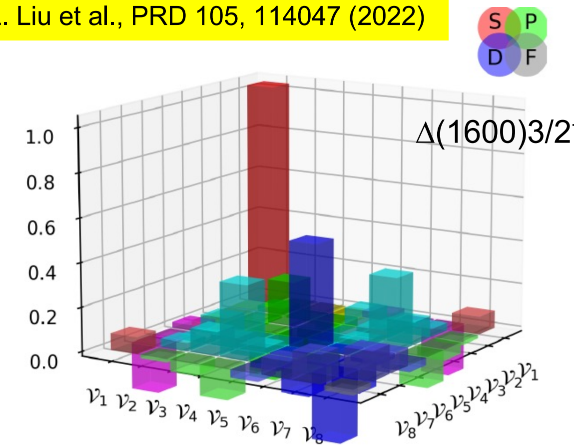
EHM and DCSB from Electroexcitation of Nucleon Resonances



L-L' color map

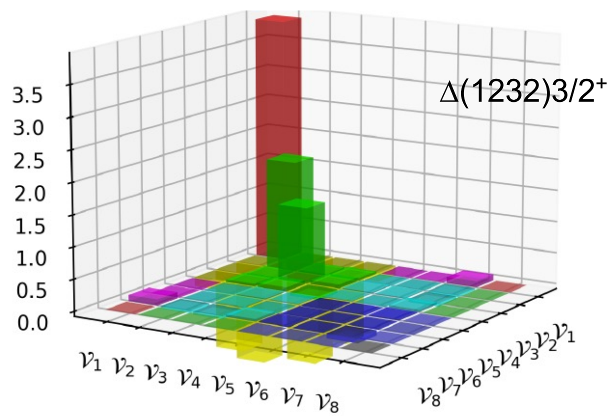
	ν_1	ν_2	ν_3	ν_4	ν_5	ν_6	ν_7	ν_8
ν_1	S-S	S-P	S-P	S-P	S-D	S-D	S-D	S-F
ν_2	S-P	P-P	P-P	P-P	P-D	P-D	P-D	P-F
ν_3	S-P	P-P	P-P	P-P	P-D	P-D	P-D	P-F
ν_4	S-P	P-P	P-P	P-P	P-D	P-D	P-D	P-F
ν_5	S-D	P-D	P-D	P-D	D-D	D-D	D-D	D-F
ν_6	S-D	P-D	P-D	P-D	D-D	D-D	D-D	D-F
ν_7	S-D	P-D	P-D	P-D	D-D	D-D	D-D	D-F
ν_8	S-F	P-F	P-F	P-F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

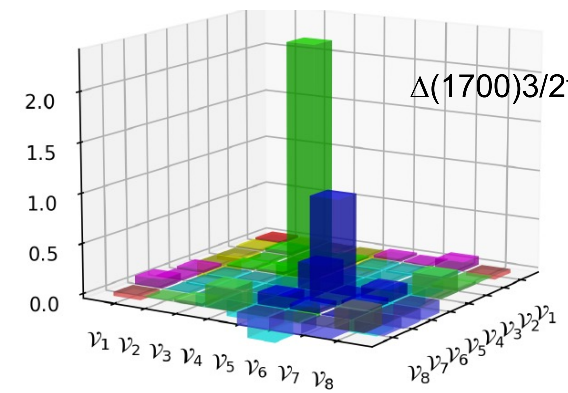
L. Liu et al., PRD 105, 114047 (2022)



- 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 $\gamma_v pN^*$ electrocouplings

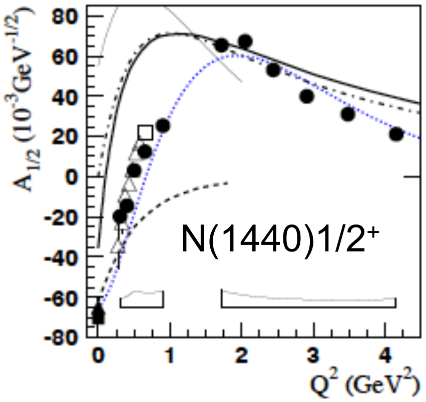
DCSB manifestation in the structure of chiral partners

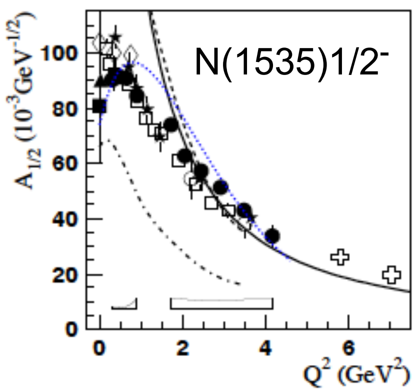




Electrocouplings of most N* in the mass range < 2 GeV will become available from the CLAS exclusive meson electroproduction data for $2.0<Q^2<5.0$ GeV^2, allowing us to establish either universality or environmental sensitivity of dressed quark mass function and to explore connection between EHM and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

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



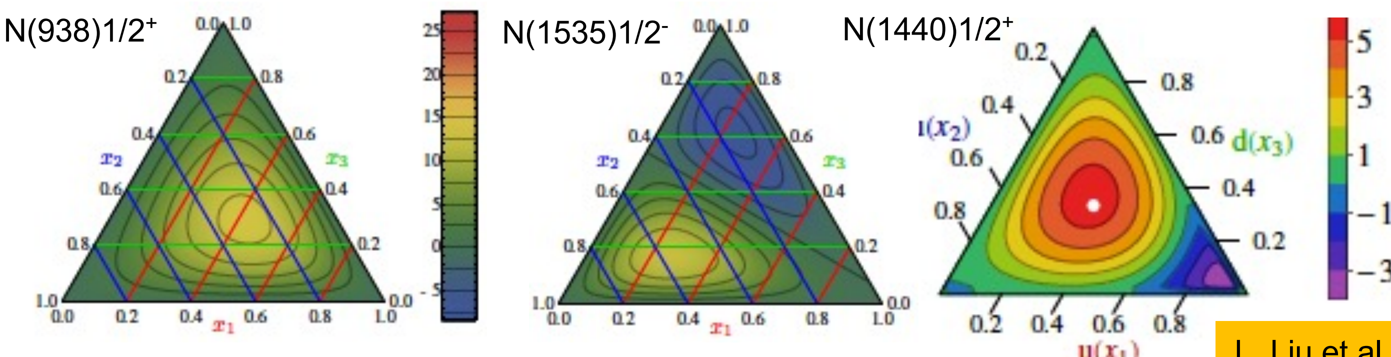


V.D.Burkert and I.G. Aznauryan, Prog. Part Nucl. Phys. 67, 1 (2012)

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)

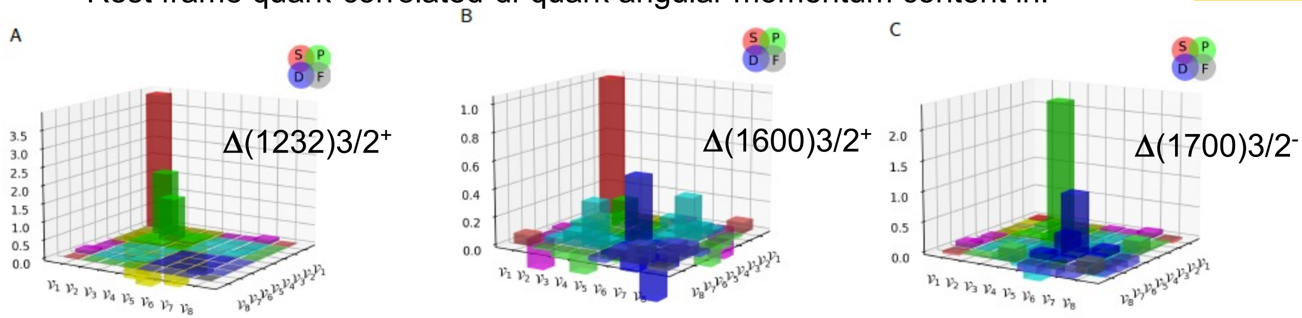
Parton distribution amplitudes (PDA) in:



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