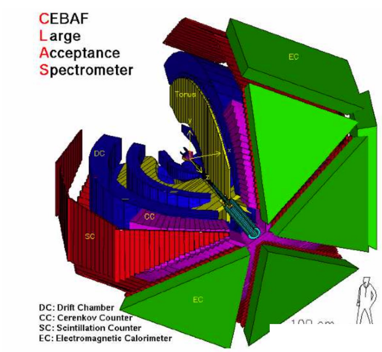
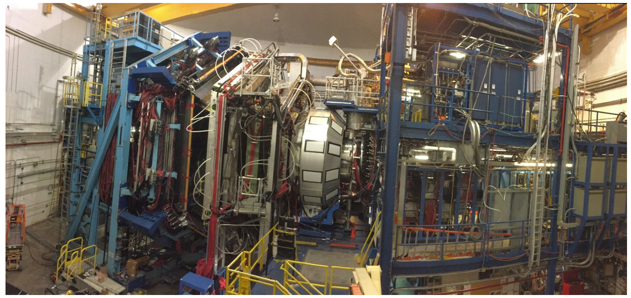
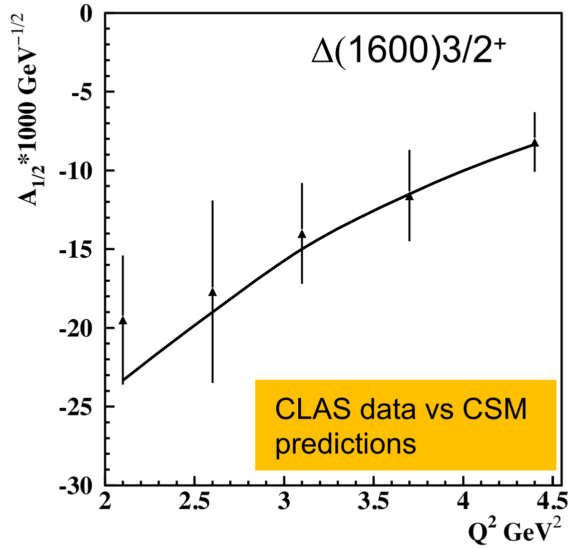
Insight into Strong QCD and the Emergence of Mass from N* Experiments







- The structure of hadrons as a window into the emergence of hadron mass (EHM)
- Complementarity in EHM exploration from studies of the pion, kaon, N/N* structure
- EHM and connection to dynamical chiral symmetry breaking (DCSB) from the results of $\gamma_v pN^*$ electrocouplings in experiments of 6 GeV era at JLab
- Extending insight into EHM from N* electroexcitation studies with CLAS12 and beyond

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

Office of Science

The 20th International Conference on Hadron Spectroscopy and Structure

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 as well as with spectrometers in Halls A/C 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 dynamical quark mass in the transition from almost massless pQCD quarks to fully dressed quarks with dynamically generated masses at the hadron size distance scale.

An important part of the efforts on the exploration of strong QCD (sQCD) from the experimental data 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, eprint::2212.08980 [hep-ph]
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)

Composition of the Nucleon Mass:

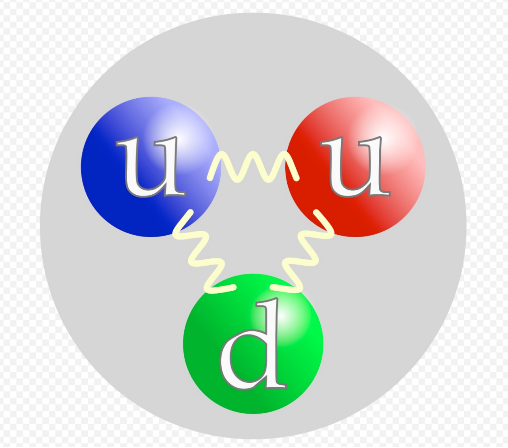
M_p, MeV (PDG20)

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



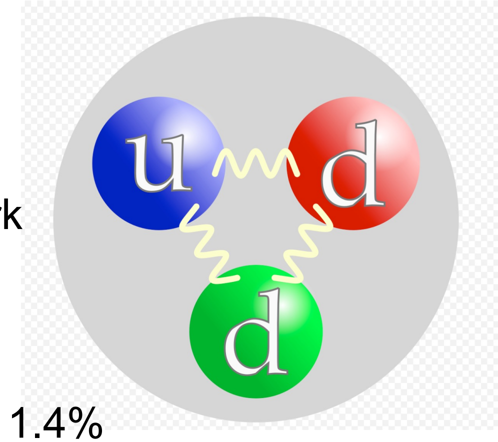
M_n, MeV (PDG20)

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

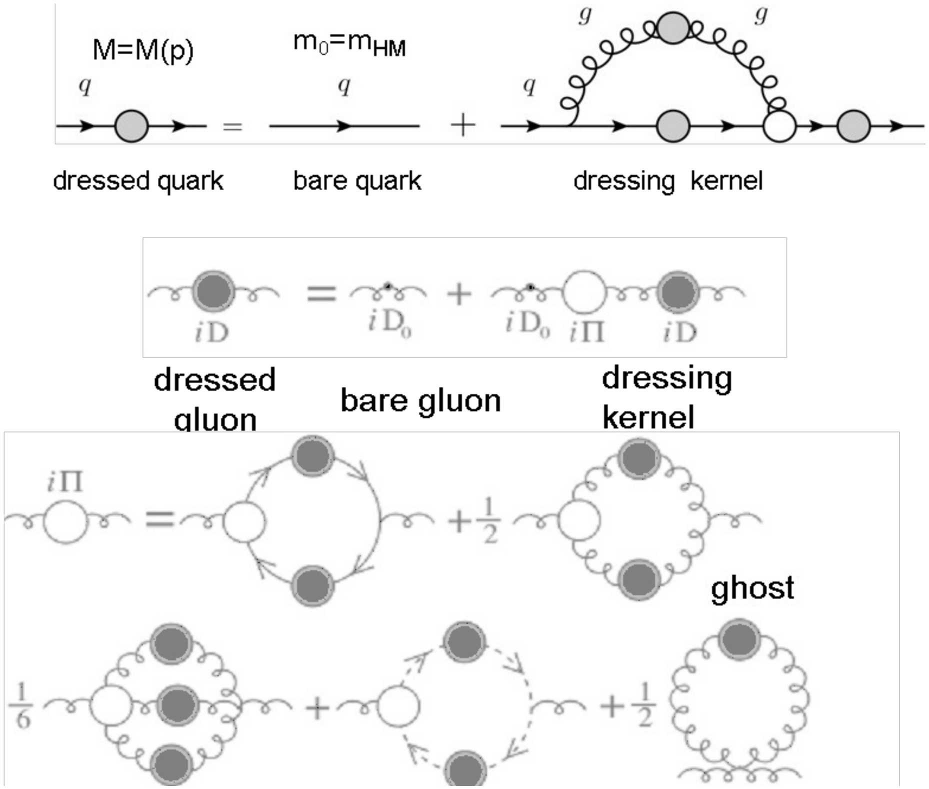


- **Higgs mechanism generates the masses of bare quarks.**
- **Dominant part of nucleon mass is generated in processes other than the Higgs mechanism.**

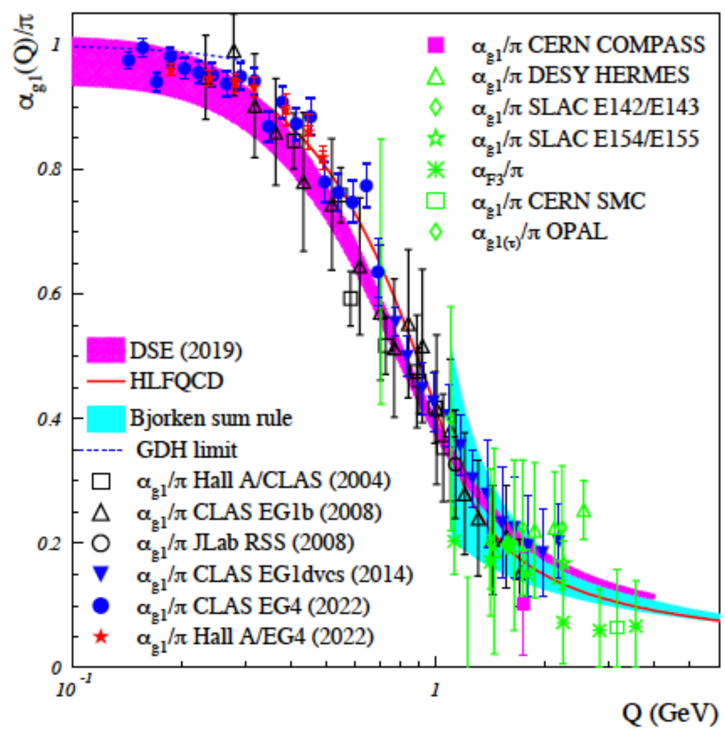
Studies of nucleon resonance electroexcitation within a broad range of Q^2 shed light on the emergence of the dominant part of hadron mass in the transition from the perturbative to quark-gluon confinement regimes of the strong interaction.

Basics for Insight into EHM: Continuum and Lattice QCD Synergy

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



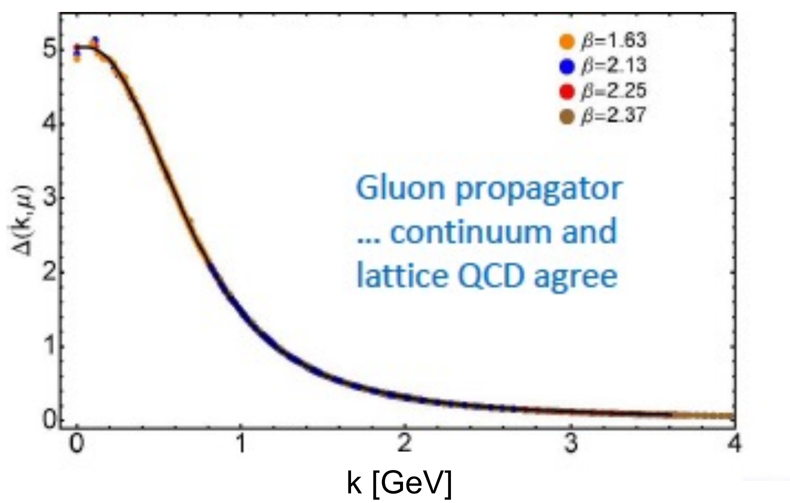
QCD Running Coupling α(k)
Zh-F. Cui et al., Chin. Phys. C44, 083102 (2020)
A. Deur et al., Particles 5, 171 (2022)



In the regime of the QCD running coupling comparable with unity, dressed quarks and gluons with distance (momentum) dependent masses emerge from QCD, as follows from the equations of the motion for the QCD fields depicted above.

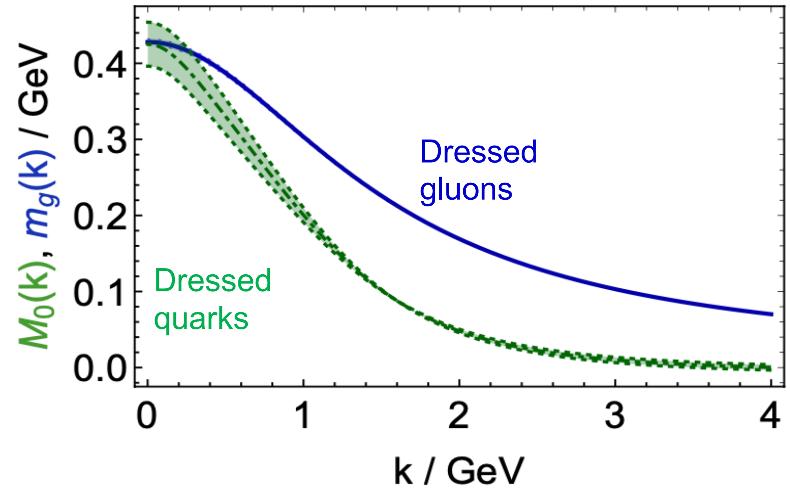
Basics for Insight into EHM: Continuum and Lattice QCD Synergy

- 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.
- Continuum QCD results are confirmed by LQCD.



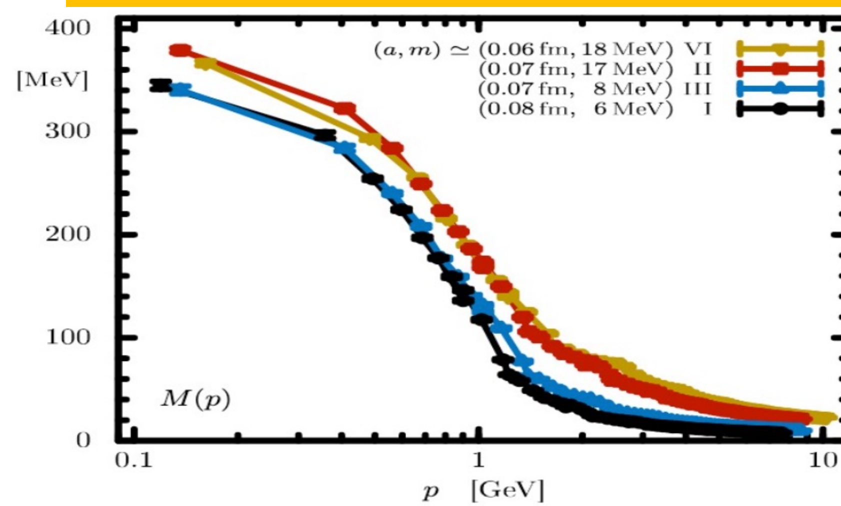
- Insight into dressed quark mass function from data on hadron structure represents a challenge for experimental hadron physics.

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

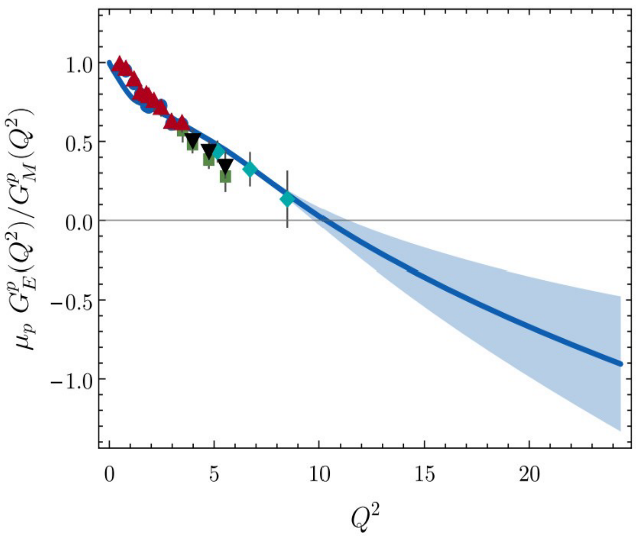
Dressed Quark Mass (lattice QCD)
O. Olivera et al., Phys. Rev. D 99, 094506 (2019)



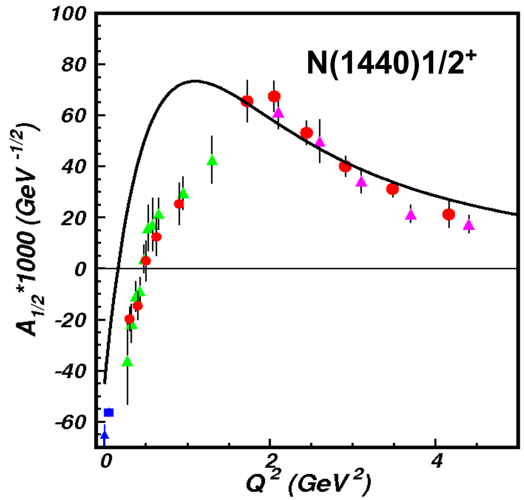
EHM from Global Hadron Structure Analysis within CSM

Will be extended by the future data from JLab in the 12 GeV era

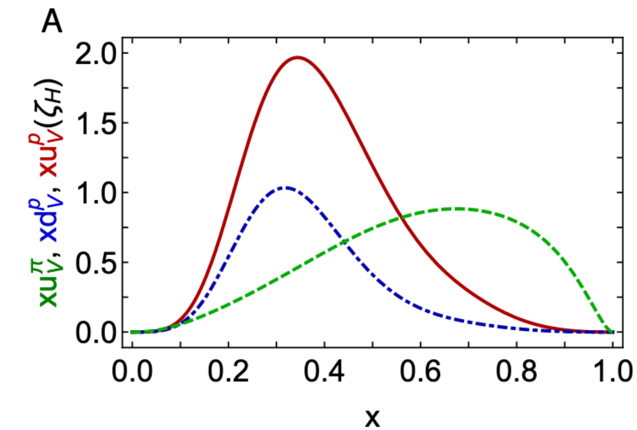
Nucleon Elastic FF



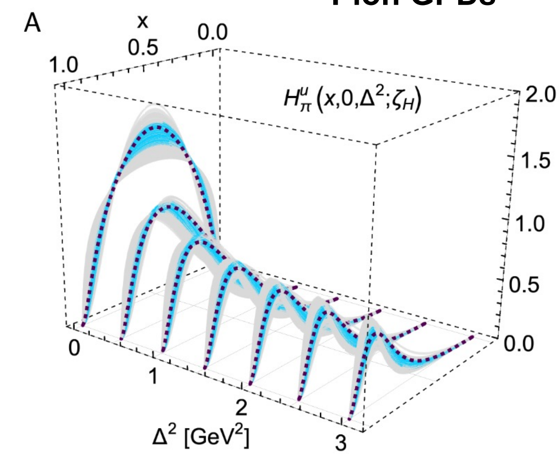
$\gamma_v pN^*$ Electrocouplings



Proton and pion PDF for valence quarks

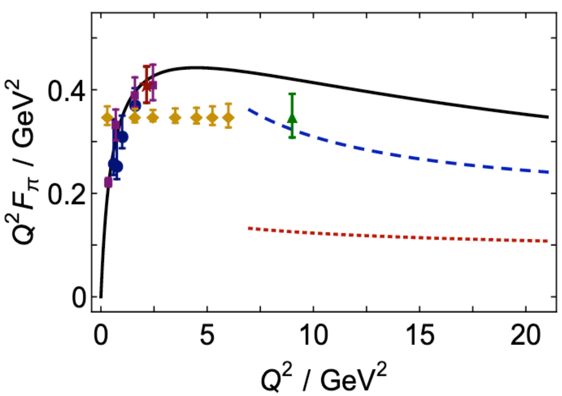


Pion GPDs

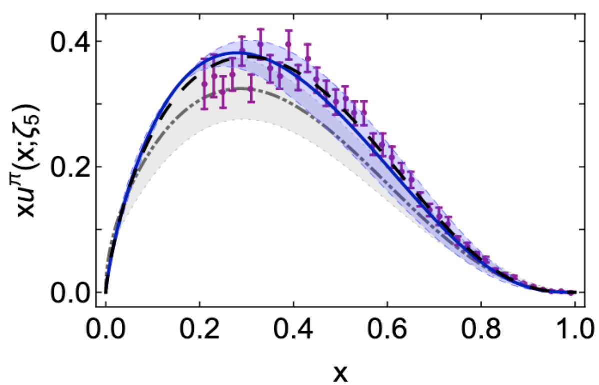


New data from studies of D-Y at AMBER and Sullivan processes at JLab

Pion Elastic FF



Pion PDF



- Insight into the dressed quark/gluon running masses from all of the experimental results above within continuum QCD approach

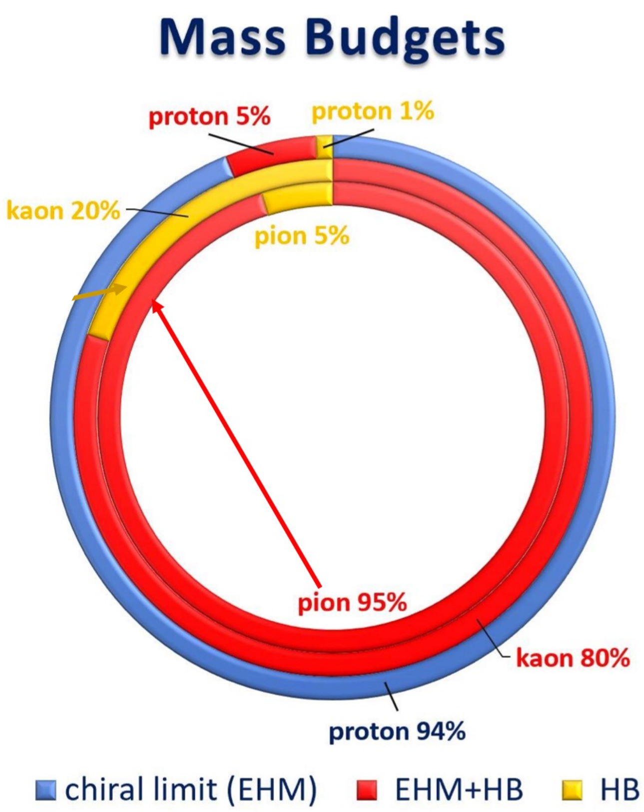
Insight into EHM from the Data on Pion/Kaon Structure

- The model, frame, and renormalization scheme/scale independent Goldberger-Treiman relations connect the momentum dependence of the dressed quark mass to the pion/kaon Bethe-Salpeter amplitudes, making studies of pion and kaon structure a promising way to map out the momentum dependence of the dressed quark mass.

$$f_\pi E_\pi(p^2) = B(p^2)$$

- Pions and kaons are simultaneously $q\bar{q}$ bound states and Goldstone bosons in chiral symmetry breaking. Their masses should be reduced to zero in the chiral limit and, in the real world, down to small values in comparison with the hadron mass scale owing to DCSB.

Insight into EHM from the Data on N/N* Structure

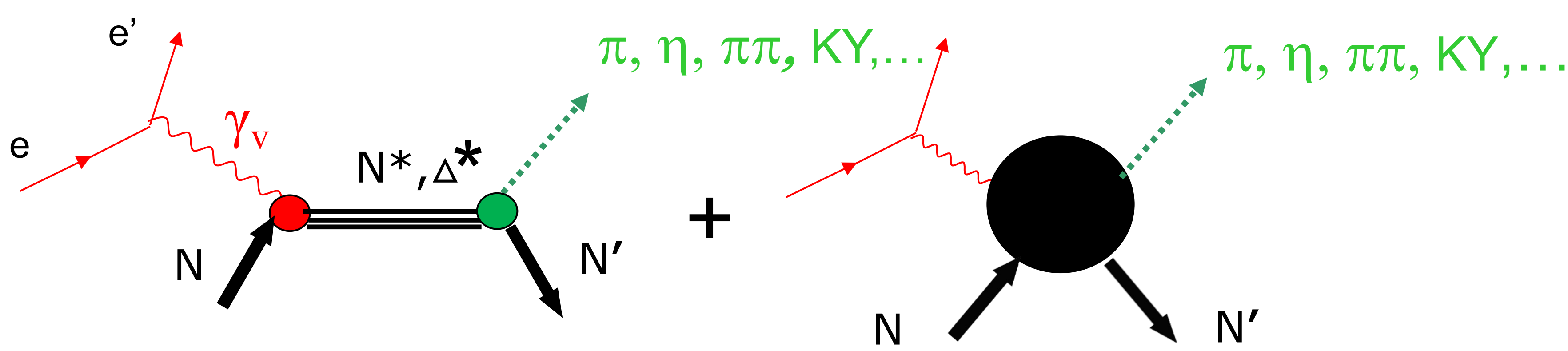


- Studies of π/K structure elucidate the interference between emergent and Higgs mechanisms in EHM
- Studies of ground/excited state nucleon structure allow us to explore the dressed quark mass function in a different environment where the sum of dressed quark masses is the dominant contribution to the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

- The successful description of the π/K elastic FF and PDF, nucleon elastic FFs, and the $\gamma_v pN^*$ 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.

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

Resonant amplitudes **Non-resonant amplitudes**



- **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 asym-metries
- 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

Approaches for Extraction of $\gamma_v NN^*$ Electrocouplings from the CLAS Exclusive Meson Electroproduction Data

Analyses of different meson electroproduction channels independently:

- **$\pi^+ n$ and $\pi^0 p$ 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)
- **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)

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

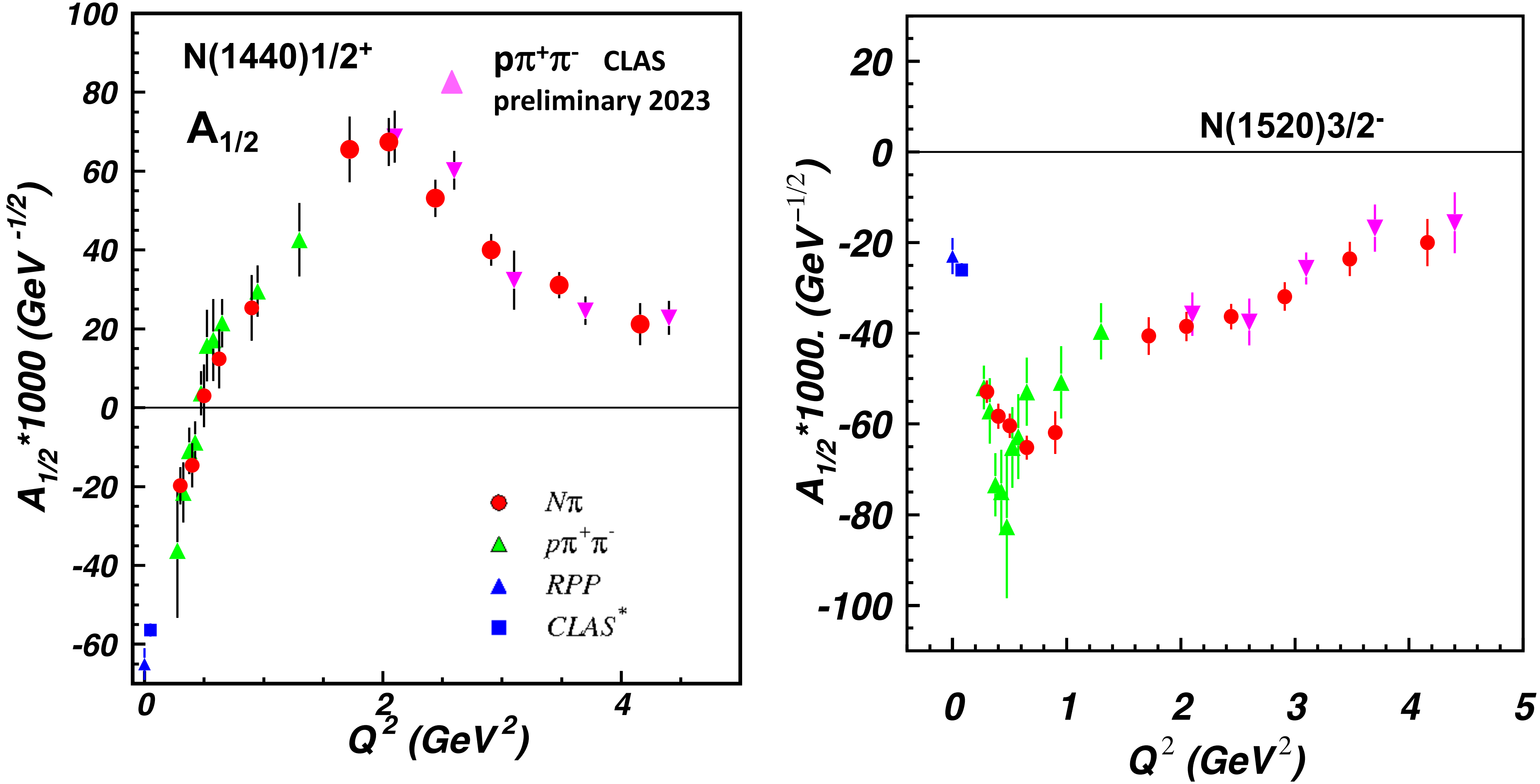
H. Kamano, Few Body Syst. 59, 24 (2018) Argonne-Osaka
H. Kamano, JPS Conf. Proc. 13, 010012 (2017) Argonne-Osaka
M. Mai et al., Phys. Rev. C103, 065204 (2021) Julich-Bonn-Washington
M. Mai et al., Phys. Rev. C106, 015201 (2022) Julich-Bonn-Washington

Nucleon Resonance Electrocouplings from Data on Exclusive Meson Electroproduction of 6 GeV Era at JLab

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 excited states of the nucleon in the mass range <1.8 GeV and in a broad range of $Q^2 < 5.0$ GeV^2.
- 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.
- The recent results can be found in: 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

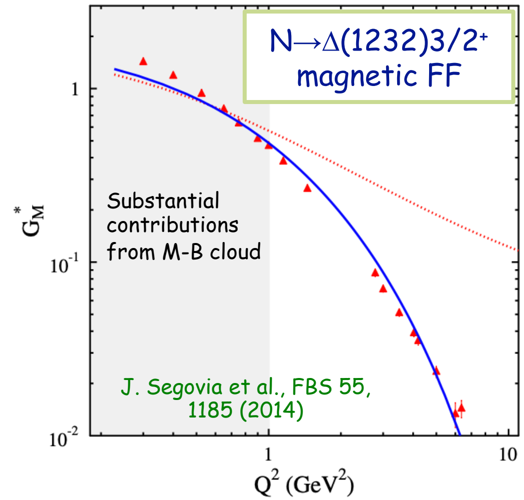


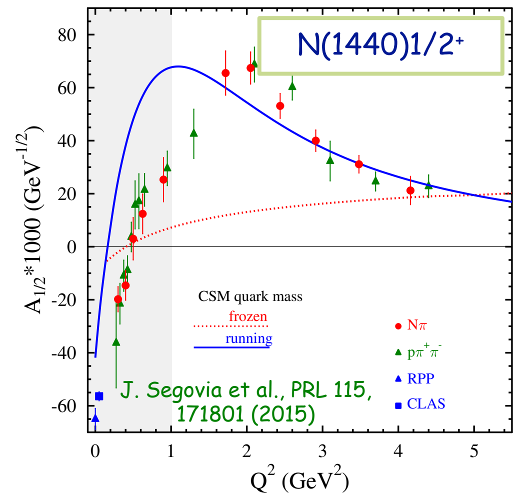
Consistent results on the N(1440)1/2$^+$ and N(1520)3/2$^-$ electrocouplings from independent studies of the two major πN and $\pi^+\pi^-$p electroproduction channels with different non-resonant contributions demonstrated the capabilities of the reaction models for reliable extraction of electrocouplings 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.*

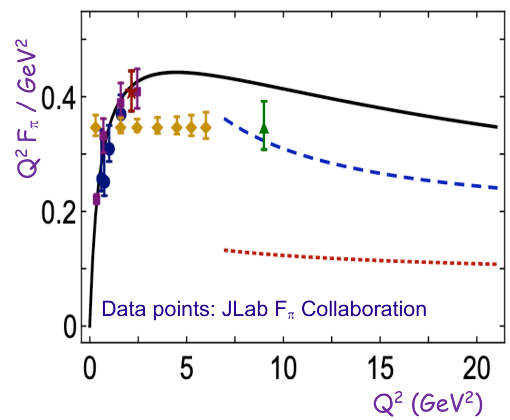
CLAS/Hall A/C results vs. CSM expectations





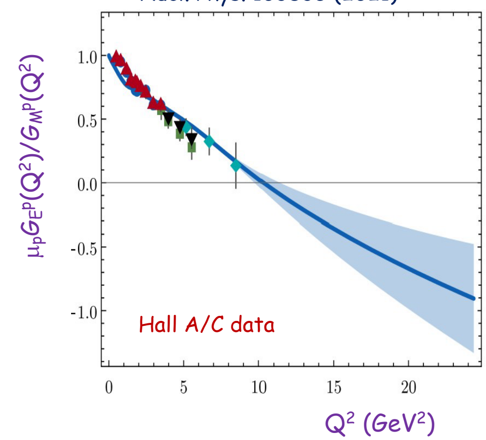
Pion Elastic FF

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



Nucleon Elastic FF

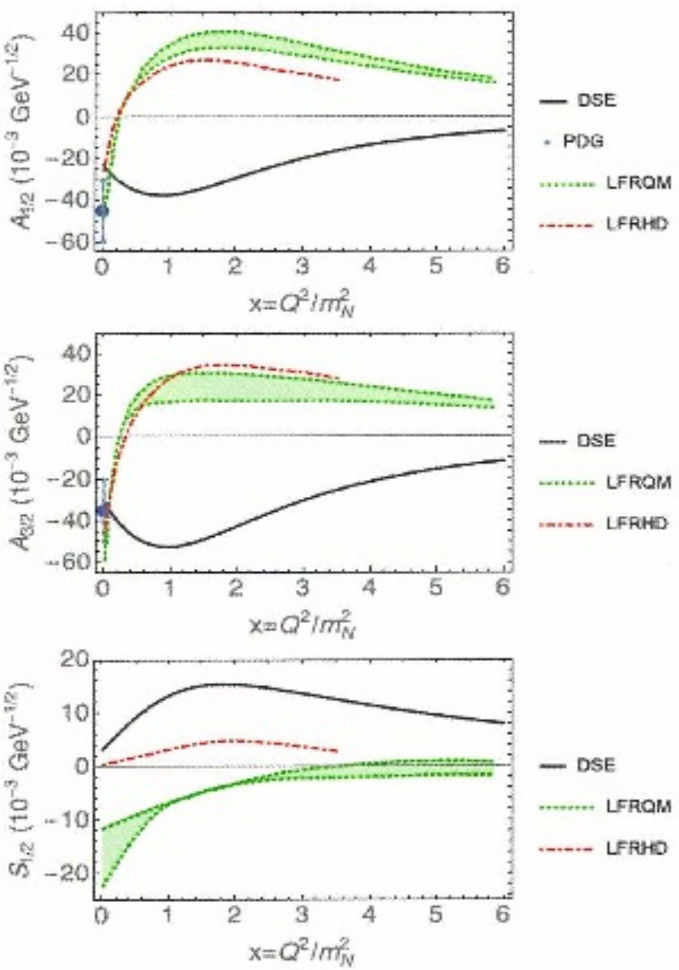
M. Barabanov et al., Prog. Part. Nucl. Phys. 103835 (2021)



- *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***

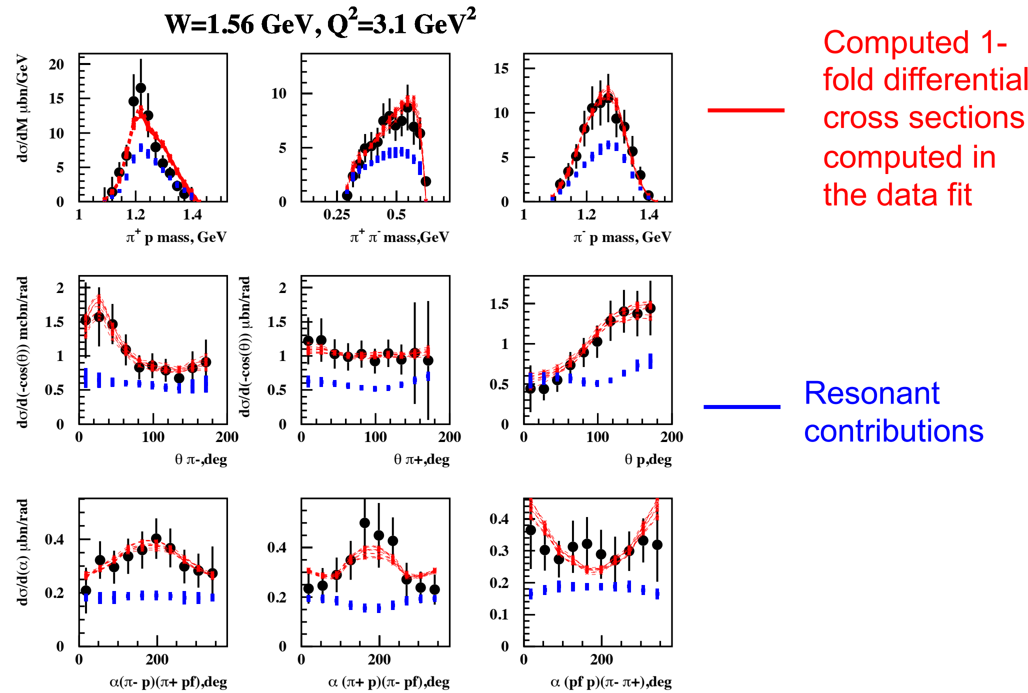
One of the most important achievements in hadron physics of the last decade in synergistic efforts between experimentalists, phenomenologists, and theorists.

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



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

Extraction of $\Delta(1600)3/2^+$ 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

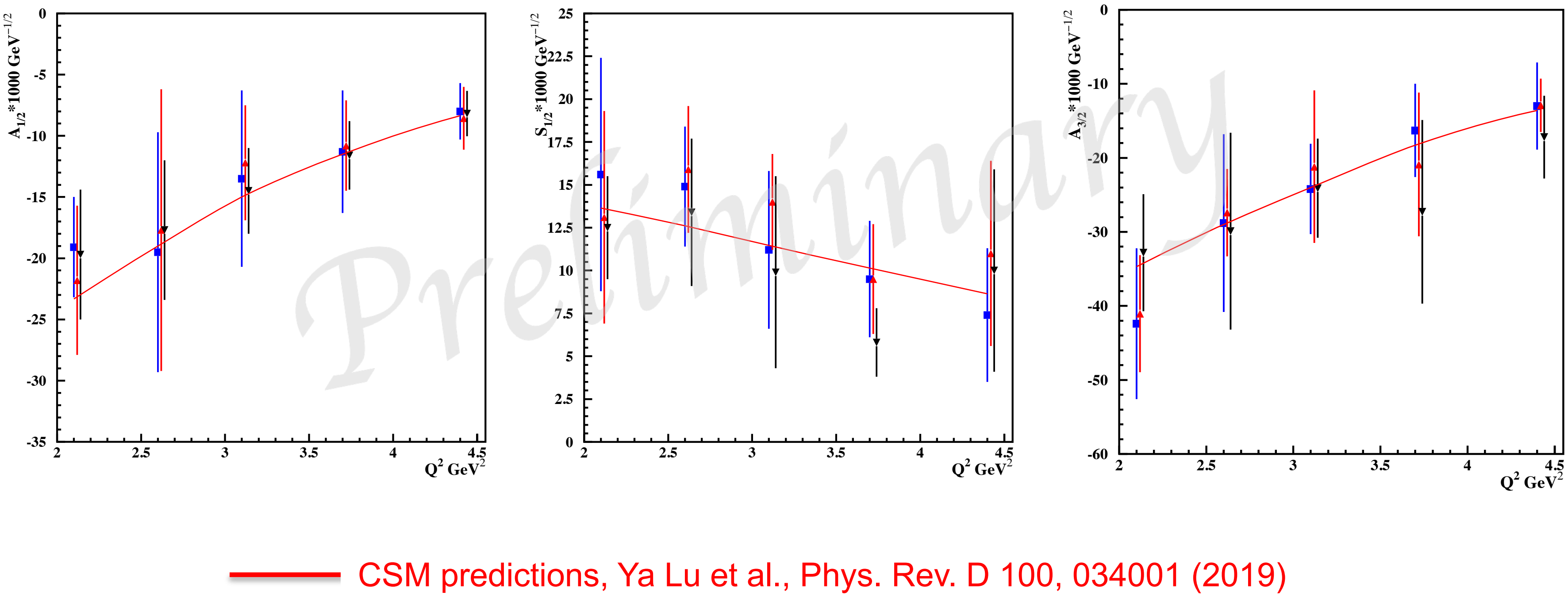


Quality of the data fit achieved within JM23 model

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 were determined from the resonant contributions accounting for the restrictions imposed by unitarity on the resonant amplitudes

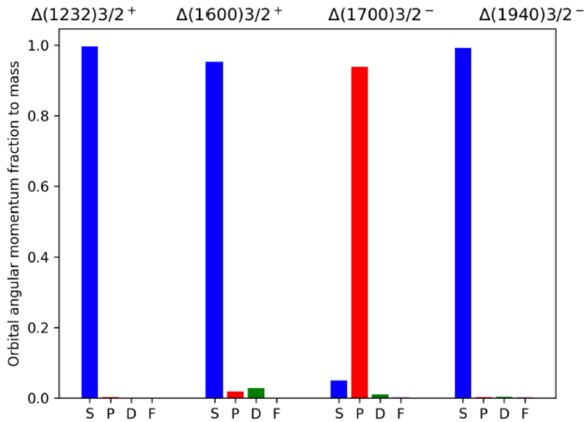
Δ(1600)3/2+ Electrocouplings : CSM Prediction vs. Data Determination



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

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

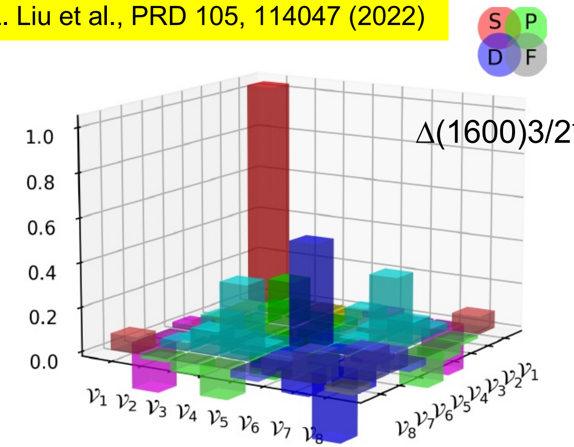
EHM and DCSB from Electroexcitation of Nucleon Resonances



L-L' color map

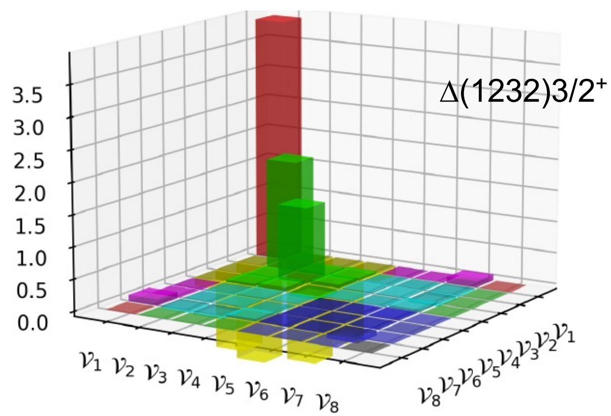
	ν_1	ν_2	ν_3	ν_4	ν_5	ν_6	ν_7	ν_8
ν_1	S-S	S-P	S-P	S-P	S-D	S-D	S-D	S-F
ν_2	S-P	P-P	P-P	P-P	P-D	P-D	P-D	P-F
ν_3	S-P	P-P	P-P	P-P	P-D	P-D	P-D	P-F
ν_4	S-P	P-P	P-P	P-P	P-D	P-D	P-D	P-F
ν_5	S-D	P-D	P-D	P-D	D-D	D-D	D-D	D-F
ν_6	S-D	P-D	P-D	P-D	D-D	D-D	D-D	D-F
ν_7	S-D	P-D	P-D	P-D	D-D	D-D	D-D	D-F
ν_8	S-F	P-F	P-F	P-F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

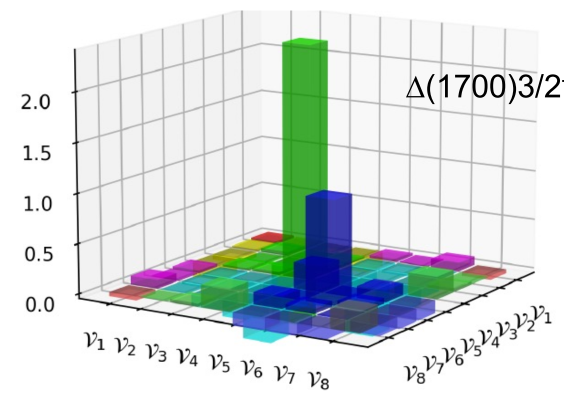
L. Liu et al., PRD 105, 114047 (2022)



- 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



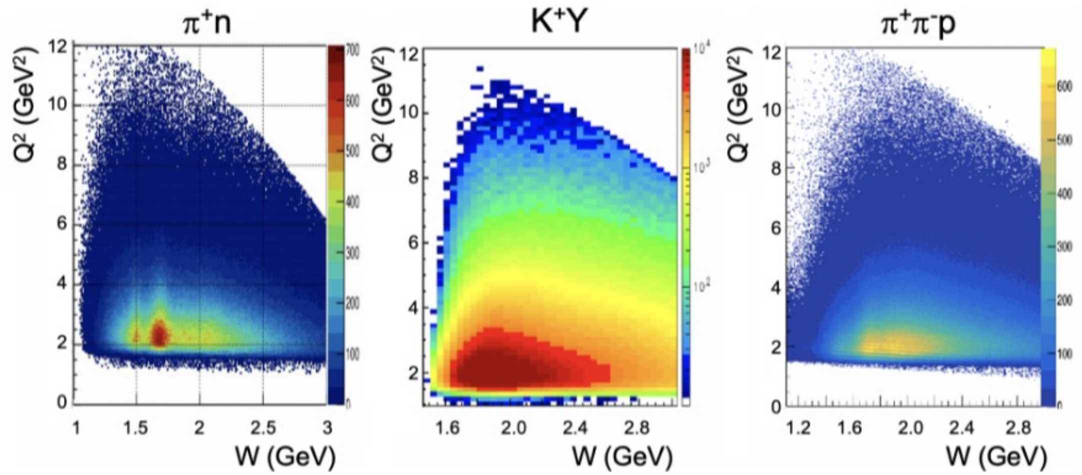


Electrocouplings of most N* in the mass range < 2 GeV will become available from the CLAS exclusive meson electroproduction data for $2.0<Q^2<5.0$ GeV^2, allowing us to establish either universality or environmental sensitivity of dressed quark mass function and to explore connection between EHM and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

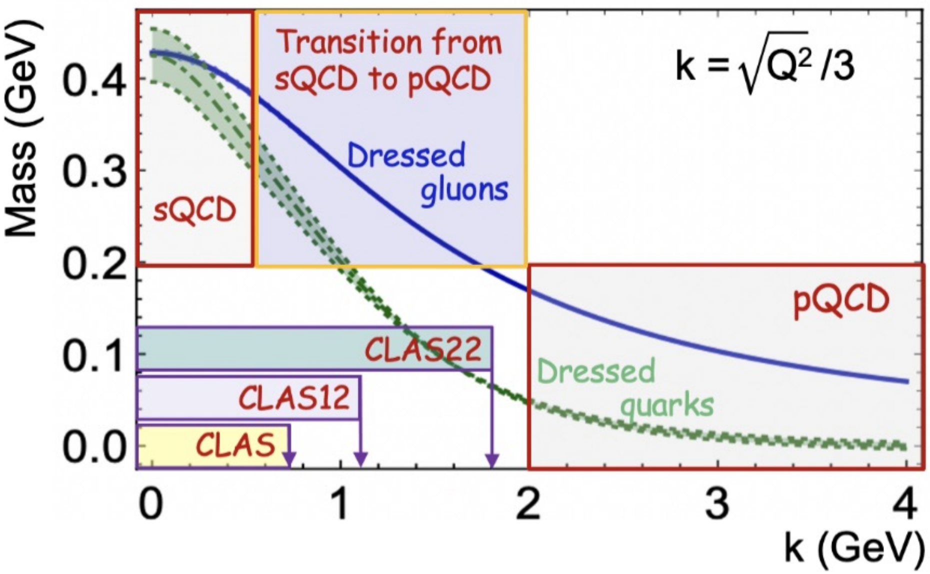
Emergence of Hadron Mass from CLAS12 Measurements and after CEBAF 22 GeV Energy Upgrade

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, $\pi\pi N$, 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



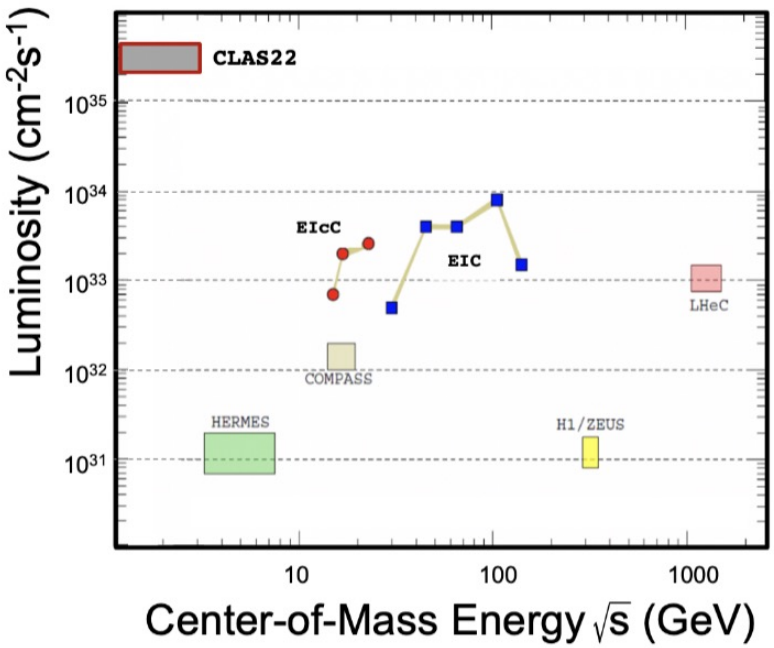
- In order to resolve the challenging problem on EHM, the dressed quark mass function $M_q(k)$ should be mapped out over the entire range of quark momenta to ~2 GeV, where the transition from strongly coupled to perturbative QCD takes place and where dressed quarks/gluons emerge as $\alpha_s/\pi \rightarrow 1$.



Unique Opportunities for Gaining Insight into EHM through Studies of the 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, will offer the only foreseen opportunity to explore how the dominant part of the hadron mass and N* structures emerge from QCD and will make CEBAF@22 GeV unique and the ultimate QCD-facility at the luminosity frontier.

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 at JLab have allowed for the determination of the electrocouplings of most N*s in the mass range up to 1.8 GeV for $Q^2<7.5$ GeV^2.**

- **A good description of the $\Delta(1232)3/2^+$, $N(1440)1/2^+$, and $\Delta(1600)3/2^+$ electrocouplings at $Q^2<5.0$ 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.**

- **In the near future, electrocouplings of high-lying N*s in the mass range from 1.8-2.0 GeV and $Q^2 < 5$ GeV^2 will be determined, allowing us to establish universality/environmental sensitivity of dressed quark mass function and to explore connection between EHM and DCSB.**

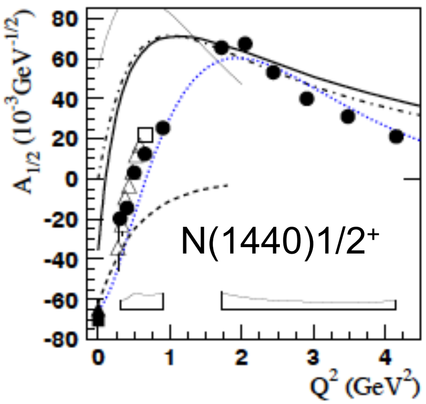
- **Similarly comprehensive treatment by other strong QCD theory tools is highly desirable.**

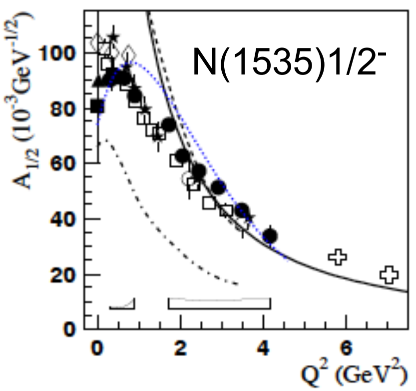
- **CLAS12 is the only facility in the world capable of obtaining the electrocouplings of all prominent N* states in the still unexplored Q^2 range from 5 - 10 GeV^2 from measurements of $N\pi$, $\pi^+\pi^-p$, $N\eta$, $K\Lambda$, and $K\Sigma$ electroproduction, allowing for the mapping of the dressed quark mass function at quark momenta < 1.3 GeV 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 dominant part of 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

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



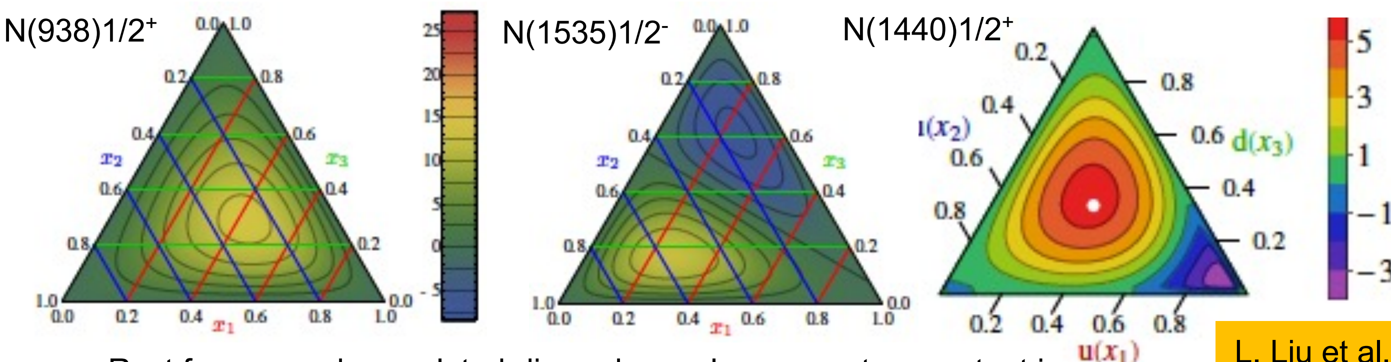


V.D.Burkert and I.G. Aznauryan, Prog. Part Nucl. Phys. 67, 1 (2012)

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)

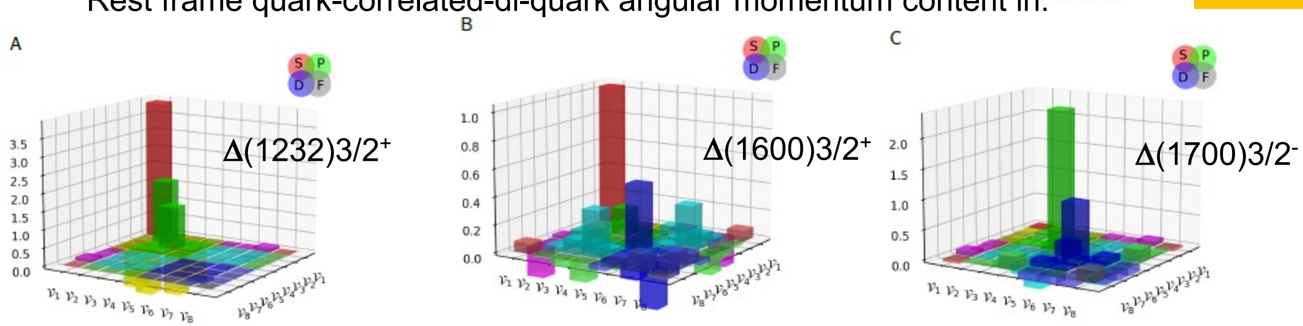
Parton distribution amplitudes (PDA) in:



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:

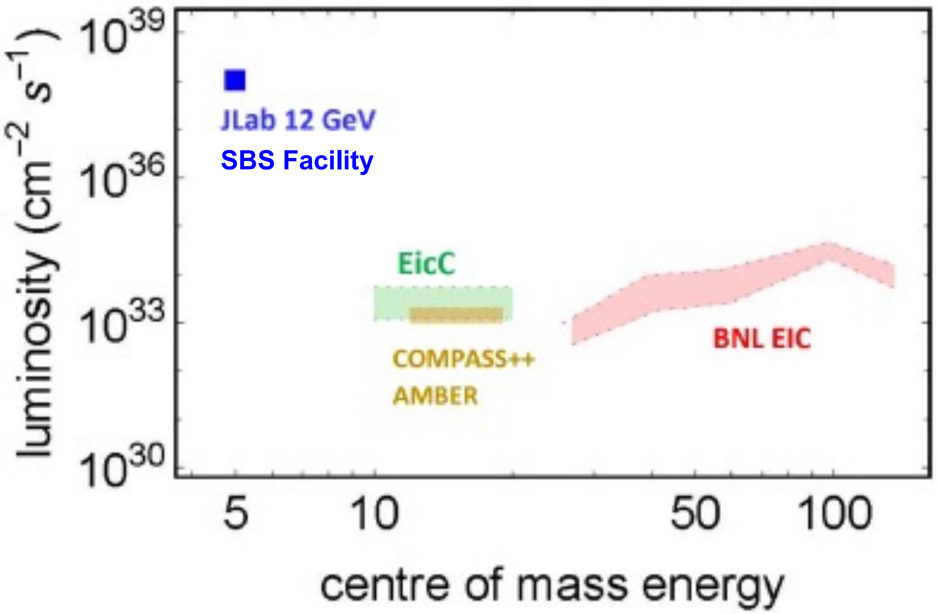


Studies of N* electroexcitation will contribute to understanding of the nature of spin of the ground and excited states of the nucleon

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

Studies of $\gamma_v pN^*$ Electrocouplings at $Q^2 > 10$ GeV^2

Energy and luminosity increase up to $5 \cdot 10^{35}$ cm^{-2}s^{-1} are needed in order to obtain information on the $\gamma_v pN^*$ electrocouplings at $Q^2>10$ GeV^2, allowing us to map out the momentum dependence of the dressed quark mass within the entire range of distances where the dominant part of hadron mass is generated in the transition from sQCD to pQCD.



Both EicC and EIC would need much higher, unlikely feasible luminosity

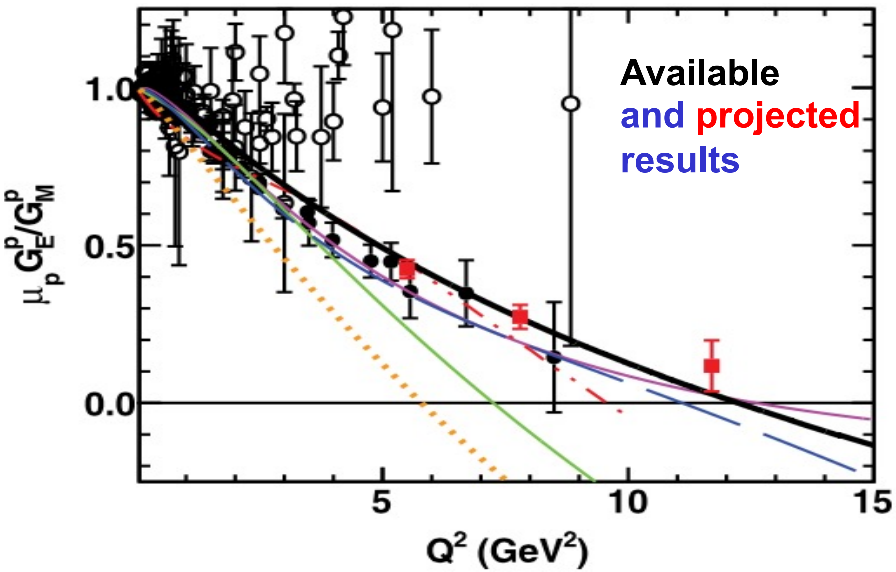
The exclusive electroproduction measurements foreseen at JLab after completion of the 12 GeV program:

- Beam energy at fixed target: 24 GeV
- Nearly 4π coverage
- High luminosity

Offer maximal achievable luminosity for extraction of $\gamma_v pN^*$ electrocouplings at $Q^2>10$ GeV^2

EHM from the Ground Nucleon Structure Exploration in 12 GeV Era

- A unique combination of high luminosity (10^{38} $cm^{-2}s^{-1}$), duty cycle, and polarization capabilities make the **SBS facility at JLab** the most suitable in the world for studies of the nucleon elastic form factor at high Q^2 up to 15 GeV^2
- The **BONUS installation in the CLAS12** detector extends the capabilities in the studies of the F_2 DIS structure function off neutrons at large x_B and Q^2 above 5.0 GeV^2



- Provide strong constraints on the rate of the transition from fully dressed to pQCD quarks
- Further explore the relevance of di-quark correlations through the search for zero crossing in Q^2-evolution of d-quark contribution into Dirac nucleon elastic form factor

Shed light on the presence of di-quark correlations of spin-parity 0^+ and 1^+