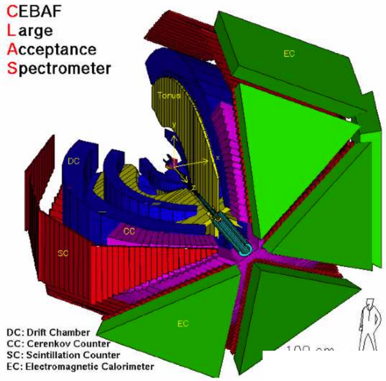
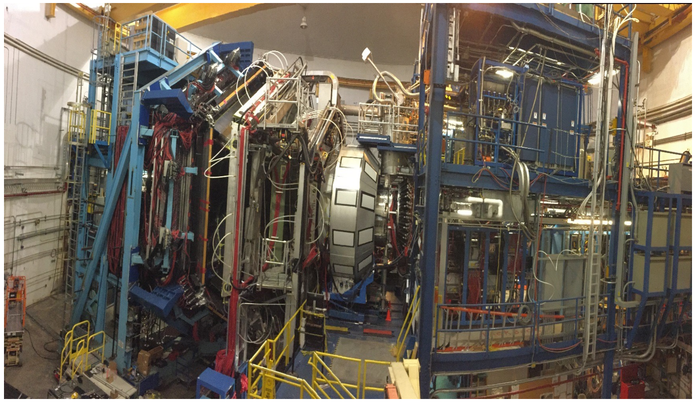
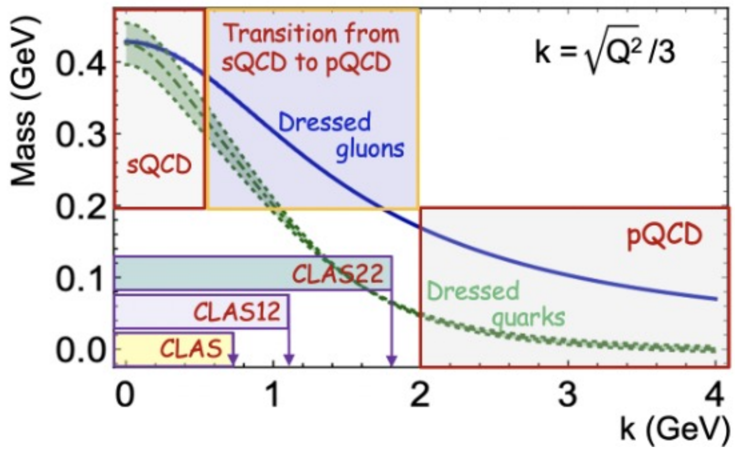
# Resonance Electrocouplings and Emergent Hadron Mass






- Emergence of Hadron Mass (EHM) paradigm as realized within the framework of Continuum Schwinger Method (CSM)
- Insight into EHM through complementary analyses of meson and baryon structure
- Shed light on EHM via study of $\gamma_v pN^*$ electrocouplings
- Unique opportunity to understand EHM from the N* exploration within an anticipated 22 GeV era at JLab


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


Office of Science

## Science at the Luminosity Frontier: Jefferson Lab at 22 GeV Workshop

# Why Emergence of the Ground/Excited Nucleon Mass Remains Open Problem?

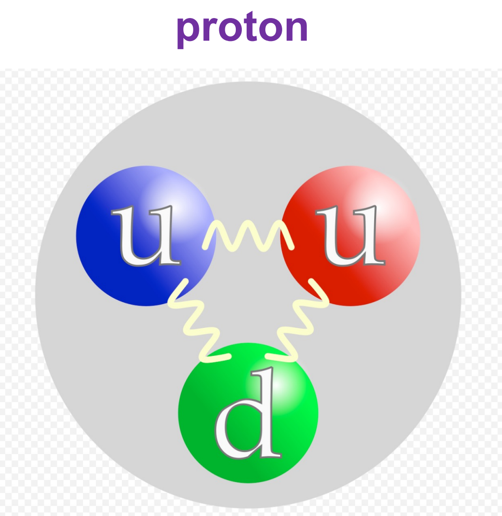
**Composition of the Nucleon Mass:**

**$M_p$, MeV (PDG22)**

938.2720813
±0.0000058

Sum of bare quark masses (in MeV):

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

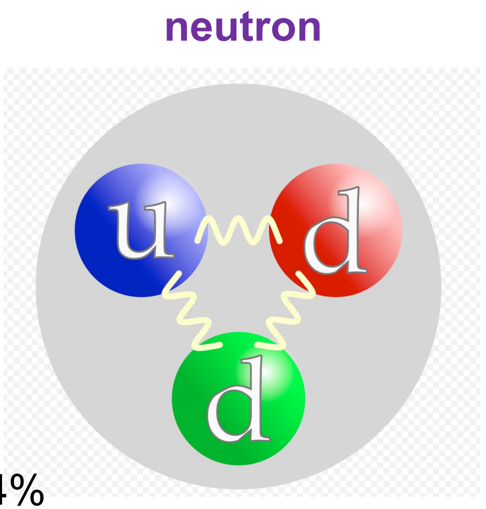



**$M_n$, MeV (PDG22)**

939.5654133
±0.0000058

Sum of bare quark masses (in MeV):

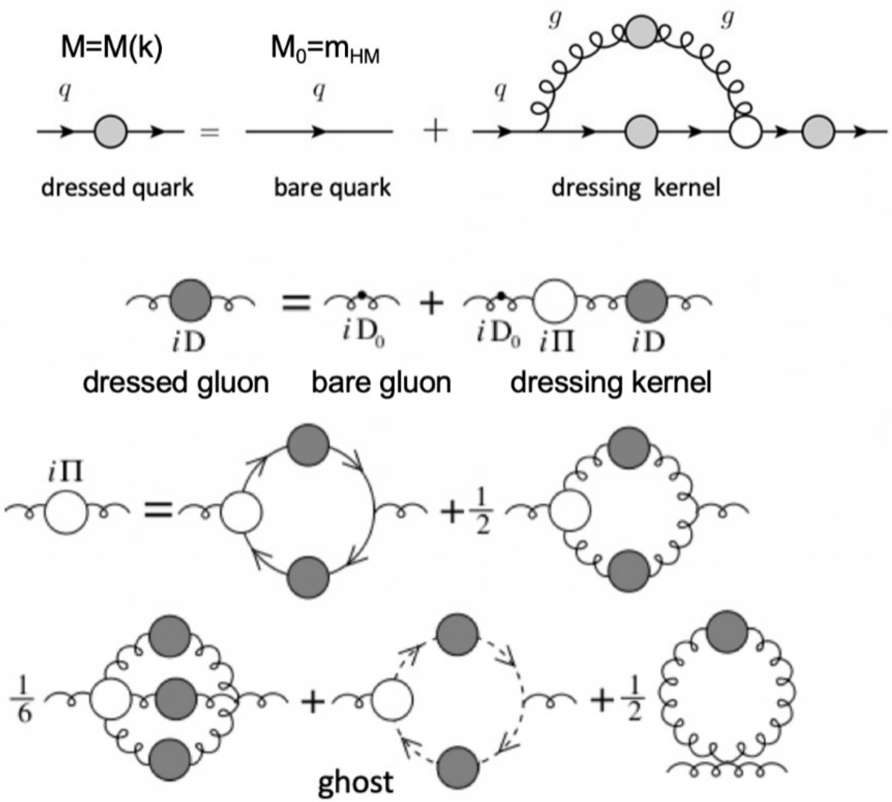
4.67+4.67+2.16
$= 11.50^{+1.45}_{-0.60}$ or < 1.4%



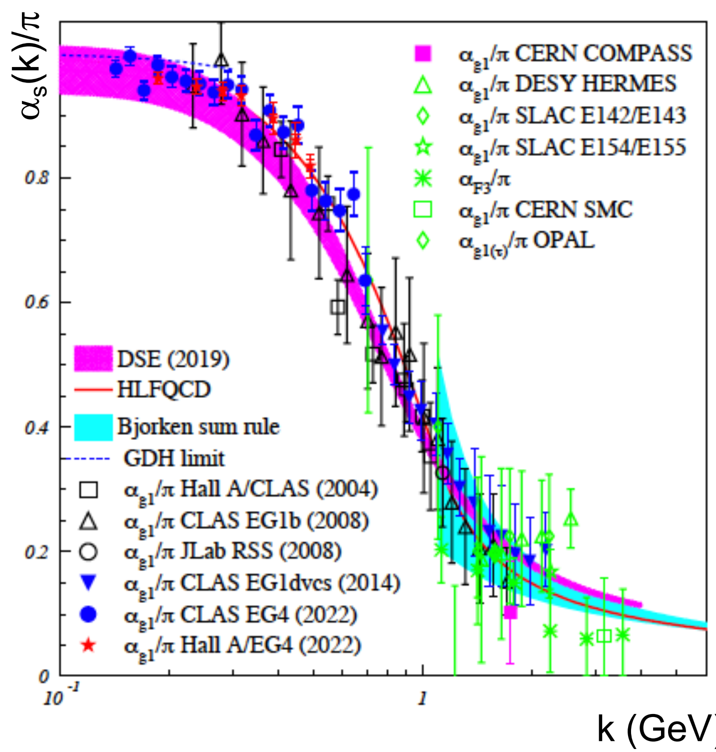

- **Higgs mechanism generates the masses of bare quarks with <2 % contribution into measured nucleon mass**
- **Dominant part of nucleon/N* masses is generated in processes other than the Higgs mechanism.**
- **CSM paradigm on EHM supported by experiments on hadron structure studies demonstrates that the dominant part of hadron mass is created by the strong interaction in a strongly coupled regime when the QCD running coupling $\alpha_s/\pi \rightarrow 1$.**

# Continuum Schwinger Method Paradigm for Emergent Hadron Mass

**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

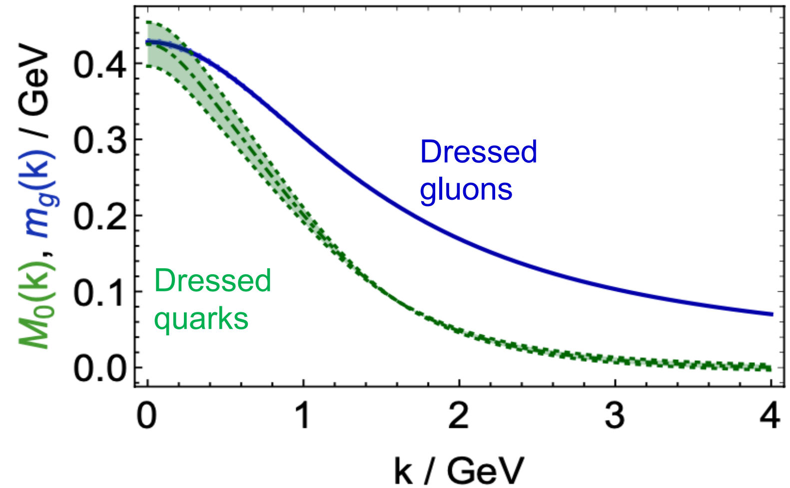
# Basics for Insight into EHM: Continuum and Lattice QCD Synergy

- Dressed quark/gluon masses converge at the complete QCD mass scale of 0.43(1) GeV.
- Express a fundamental feature: emergence of the quark and gluon masses even in the case of zero Higgs couplings to quark fields, the so-called chiral limit of theory.
- Running dressed quark/gluon masses and an effective QCD charge (Slide#3) are the three pillars of the CSM paradigm for the EHM

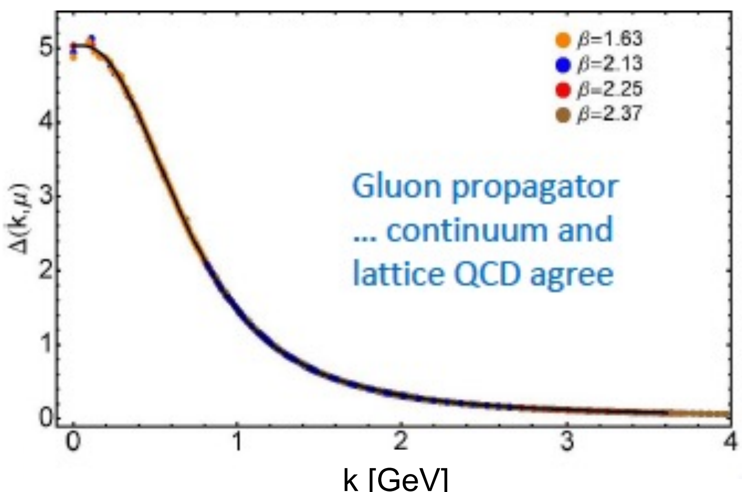
➡ see the upcoming talk by Prof. C.D. Roberts.

- Continuum QCD results are confirmed by LQCD.

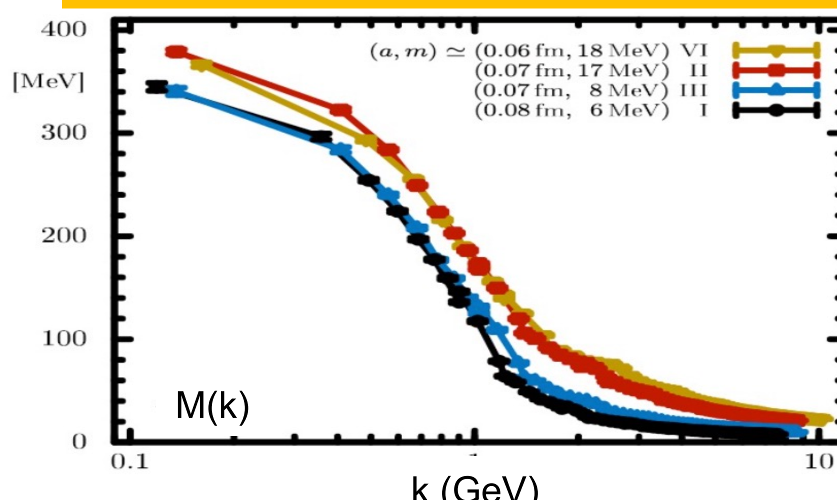
**Dressed Quark/Gluon Masses (continuum QCD)**
**C.D. Roberts, Symmetry 12, 1468 (2020), AAPS Bull 31, 6 (2021)**




Inferred from QCD Lagrangian with only the $\Lambda_{QCD}$ parameter




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

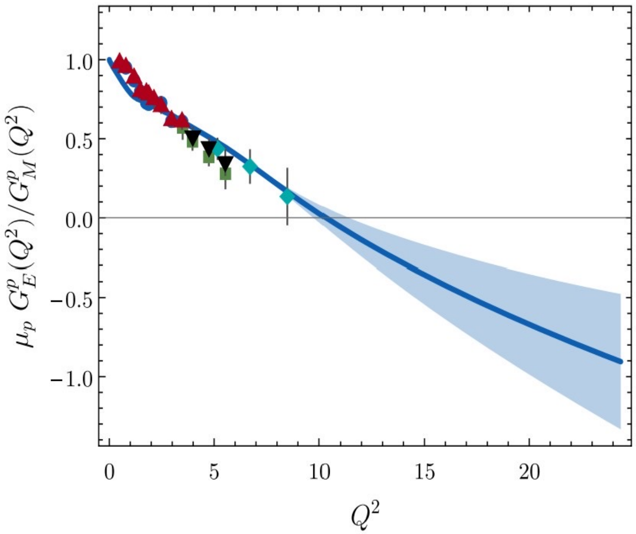



- Insight into dressed quark mass function from data on hadron structure represents a challenge for experimental hadron physics.

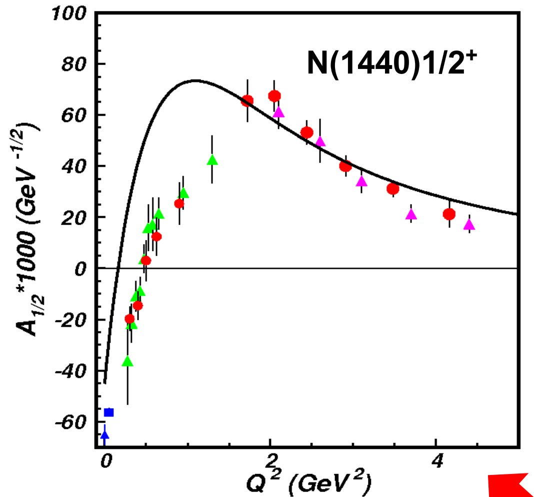
# EHM from Global Hadron Structure Analysis

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

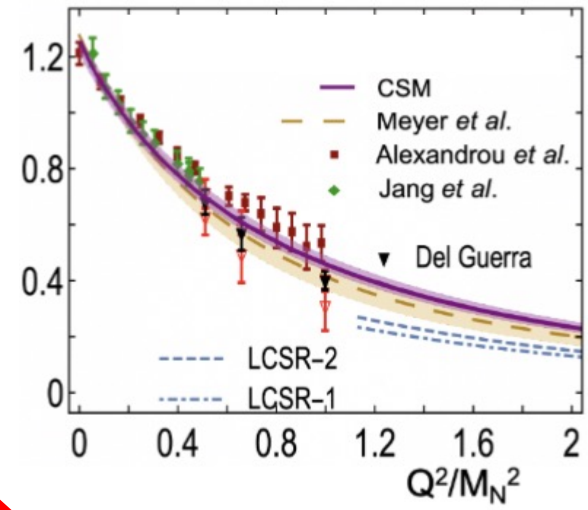
### Nucleon Elastic FF




### $\gamma_v pN^*$ Electrocouplings

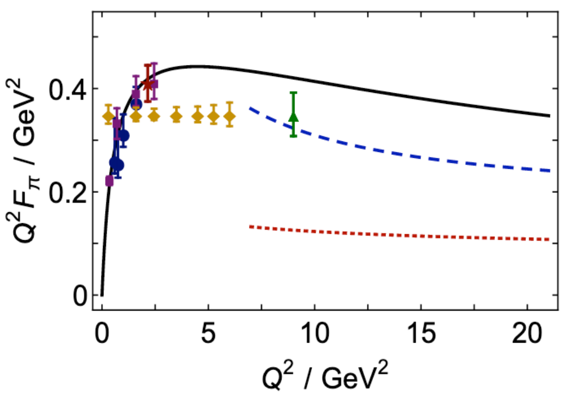



### Nucleon-axial form factor $G_A$

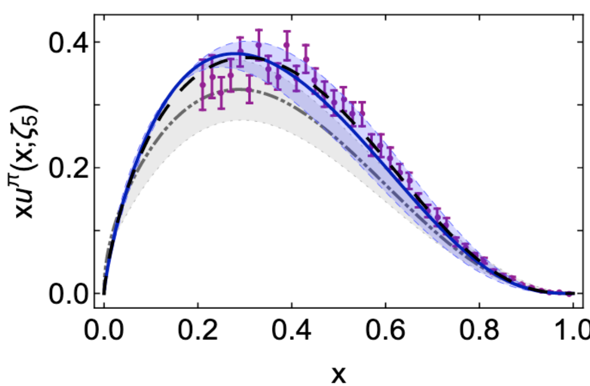



**New data from studies of D-Y at AMBER and Sullivan processes at JLab**

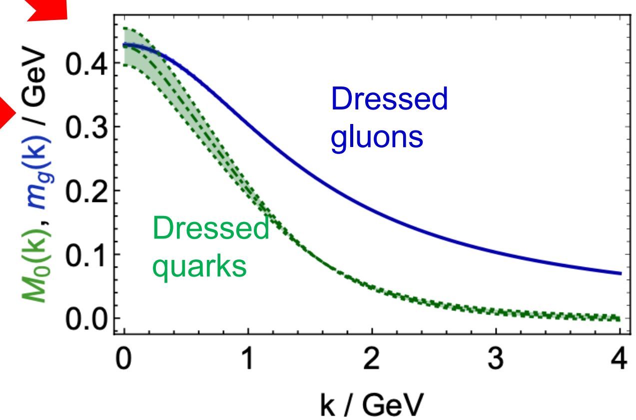
### Pion Elastic FF




### Pion PDF

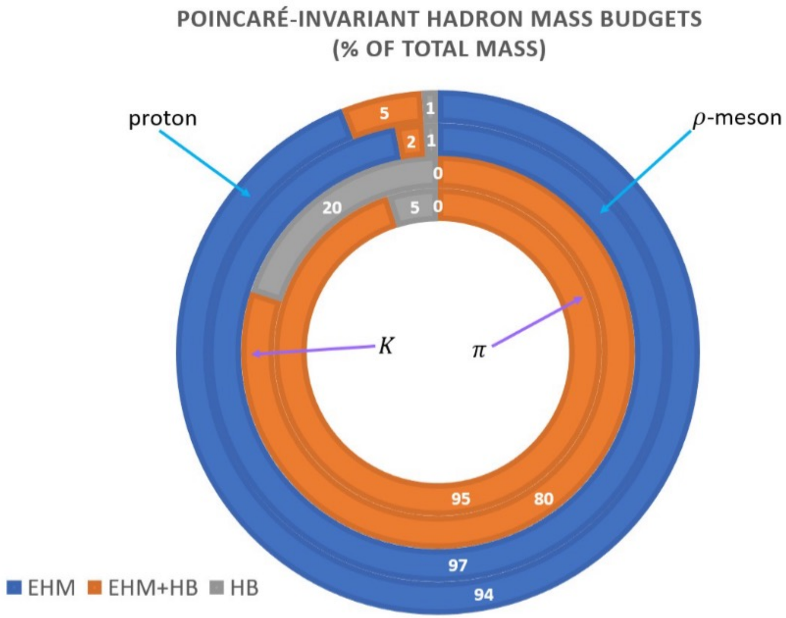



### Dressed Quark/Gluon Running Masses




**The quark running mass as deduced from experimental results above are consistent with the CSM approach**

# Complementarity Insight into EHM from Meson and Baryon Structure Studies



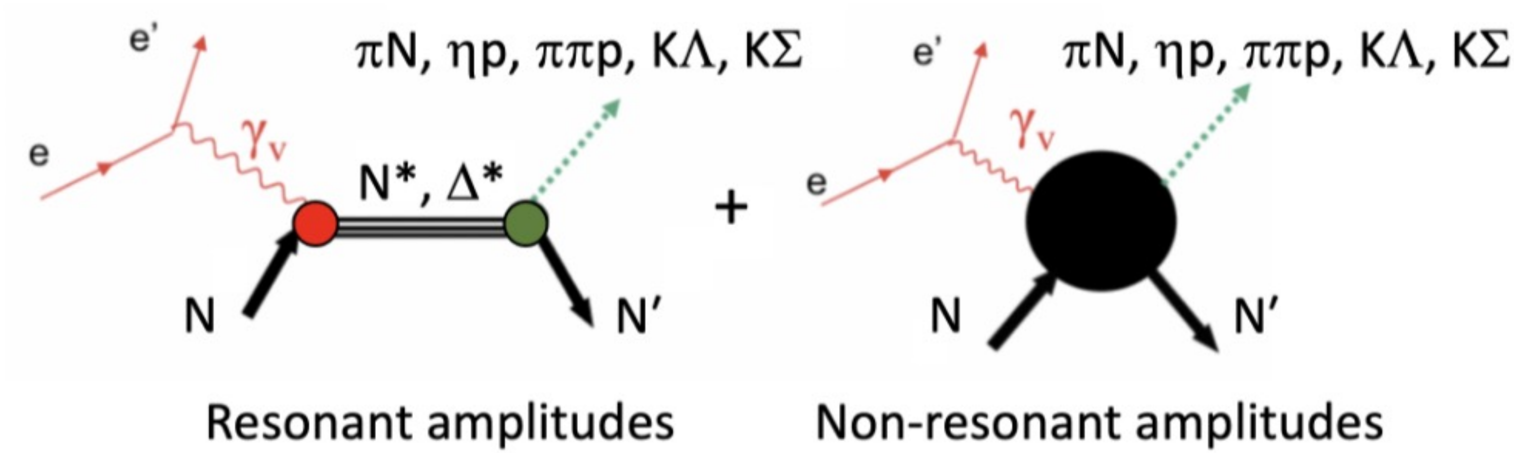

- The Goldberger-Treiman relation connects the dressed quark mass function to the π/K Bethe-Salpeter amplitudes, making studies of pion and kaon structure a straightforward way for gaining insight into EHM.

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

- π and K are simultaneously $q\bar{q}$ bound states and Nambu-Goldstone (NG) bosons in chiral symmetry breaking. Their masses should be zero in the limit of zero Higgs coupling in QCD and, in the real world, remain small in comparison with the hadron mass scale.
- Studies of π/K structure elucidate the interference between emergent and Higgs mechanisms in EHM.
- Studies of ground/excited state nucleon structure as well as the structure of mesons other than NG-bosons offer insight into emergent mechanisms.

- The successful description of the π/K elastic FF and PDF, nucleon elastic/axial FFs, the $\gamma_v pN^*$ electrocouplings of prominent nucleon resonances of different structure and elastic FFs for mesons other than NG-bosons 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




- 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>

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

- **Consistent results on $\gamma_{r,v}pN^*$ photo-/electrocouplings from different meson photo-/electroproduction channels allow us to establish systematic uncertainties for their extraction related to use of reaction models**

# Nucleon Resonance Electrocouplings from Data On Exclusive Meson Electroproduction during the 6 GeV Era at JLab

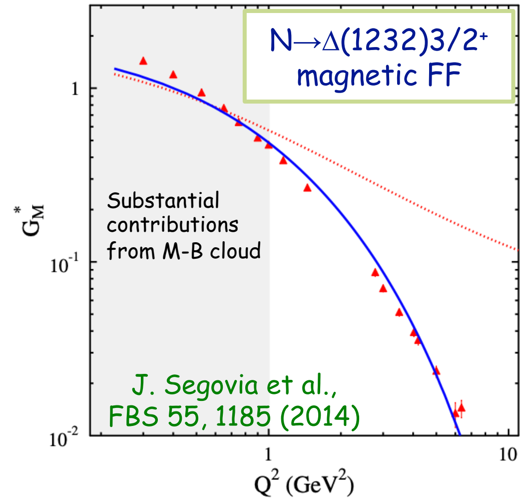
| Exclusive meson electroproduction channels | Excited proton states | $Q^2$-ranges for extracted $\gamma_v pN^*$ electrocouplings, $GeV^2$ |
|---|---|---|
| $\pi^0 p$, $\pi^+ n$ | $\Delta(1232)3/2^+$<br><br>$N(1440)1/2^+$,$N(1520)3/2^-$, $N(1535)1/2^-$ | 0.16-6.0<br><br>0.30-4.16 |
| $\pi^+ n$ | $N(1675)5/2^-$, $N(1680)5/2^+$ $N(1710)1/2^+$ | 1.6-4.5 |
| $\eta p$ | $N(1535)1/2^-$ | 0.2-2.9 |
| $\pi^+\pi^- p$ | $N(1440)1/2^+$, $N(1520)3/2^-$<br><br>$\Delta(1620)1/2^-$, $N(1650)1/2^-$, $N(1680)5/2^+$, $\Delta(1700)3/2^-$, $N(1720)3/2^+$, $N'(1720)3/2^+$ | 0.25-1.50<br>2.0-5.0 (preliminary)<br><br>0.5-1.5 |

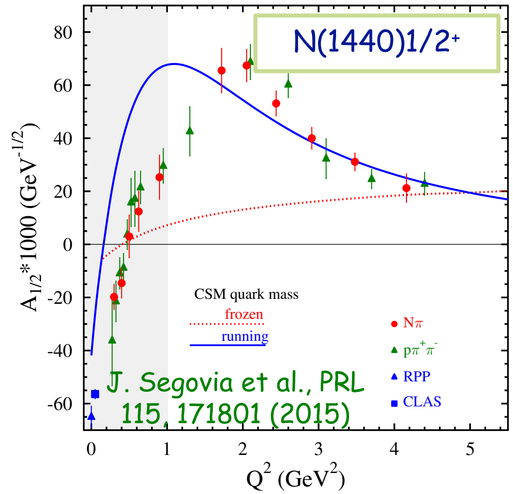
- The $\gamma_v pN^*$ electrocouplings have become available from analysis of CLAS data for most N* in the mass range up to 1.8 GeV and in a broad range of $Q^2<5$ $GeV^2$.
- The experiments in Halls A/C extended the results on $\gamma_v pN^*$ electrocouplings of $\Delta(1232)3/2^+$ and $N(1535)1/2^-$ for $Q^2 < 7.5$ $GeV^2$.
- The recent results can be found in: A.N. Hiller Blin et al, PRC100, 035201 (2019).

# CSM Predictions for Resonance Electroexcitations vs. Available Experimental Results

- A successful description of the pion and nucleon elastic FFs, and the electrocouplings of the $\Delta(1232)3/2^+$ and $N(1440)1/2^+$ resonances has been achieved *with the same dressed quark/gluon mass functions and running effective QCD charge*

CLAS/Hall A/C results vs. CSM predictions

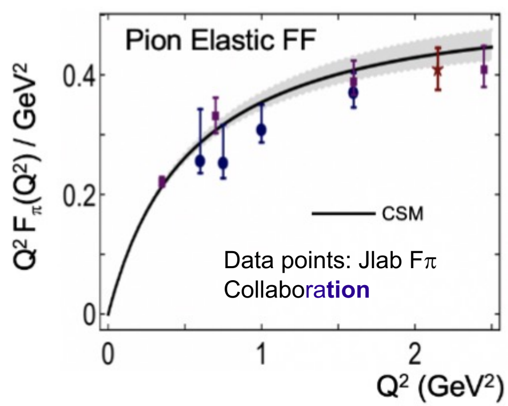



- *Dressed quarks with dynamically generated masses represent active degrees of freedom in the structure of the pion, nucleon, and the* $\Delta(1232)3/2^+$, $N(1440)1/2^+$ resonances
- ***Strong evidence for insight into momentum dependence of dressed quark mass***

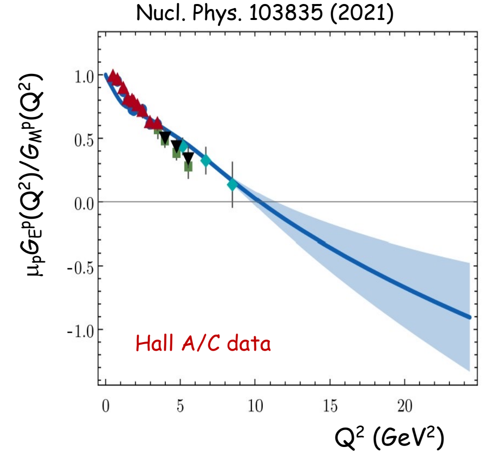
Pion Elastic FF

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



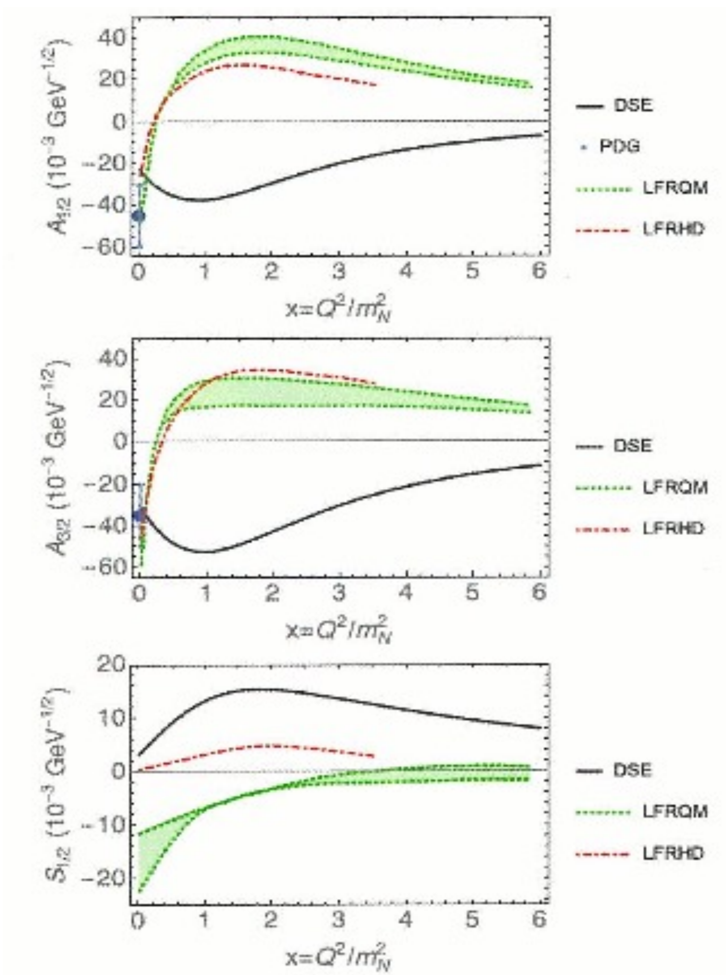

Nucleon Elastic FF

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



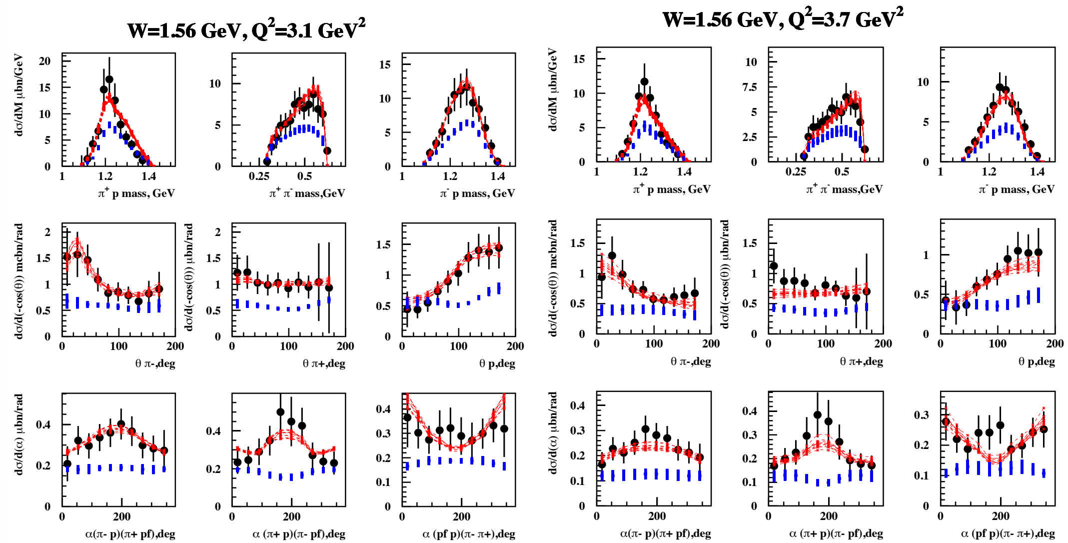

**One of the most important achievements in hadron physics realized in the last decade via synergistic efforts between experimentalists, phenomenologists, and theorists.**

# 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)**

**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 JM reaction model, January-March, 2022**

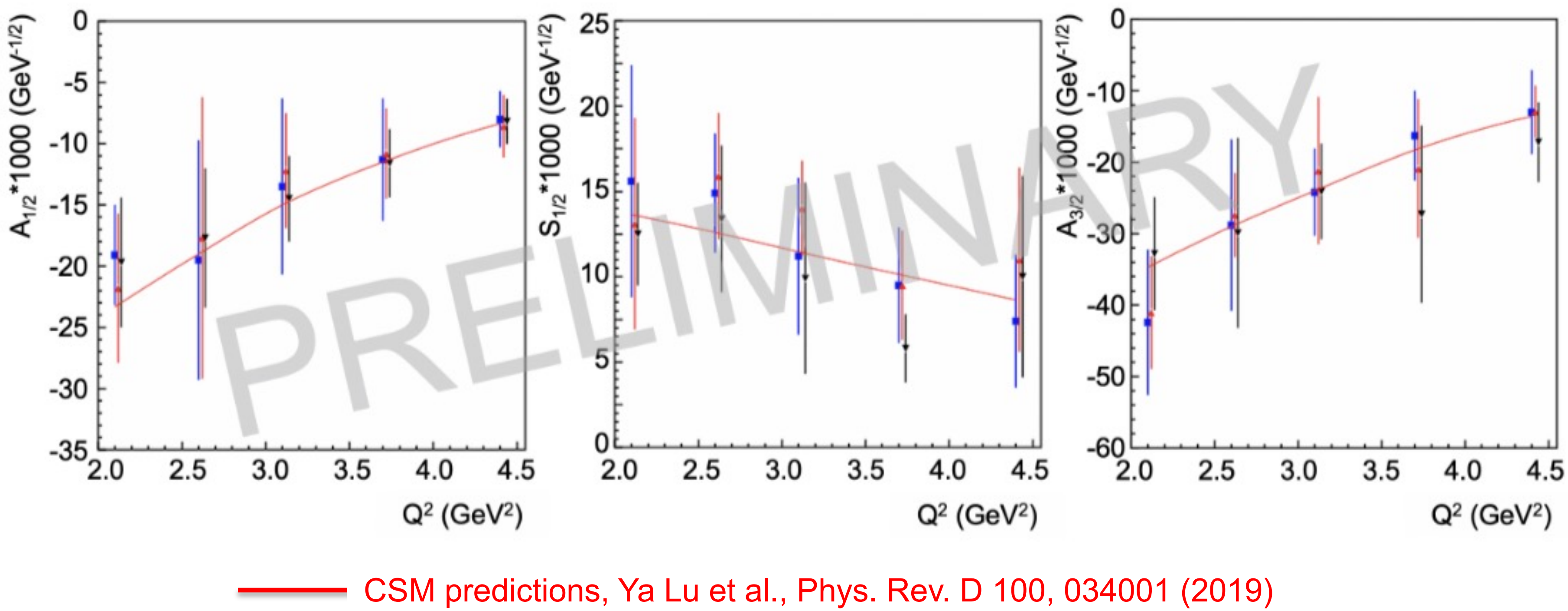



Closest to the data 9 one-fold differential cross sections deduced within the JM model

Resonant contributions into selected in the data fit 9 one-fold differential cross sections

Comparable spread for the selected in the data fit 9 one-fold differential cross sections and the respective resonant contributions suggests credible and unambiguous separation between the resonant/non-resonant contributions

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

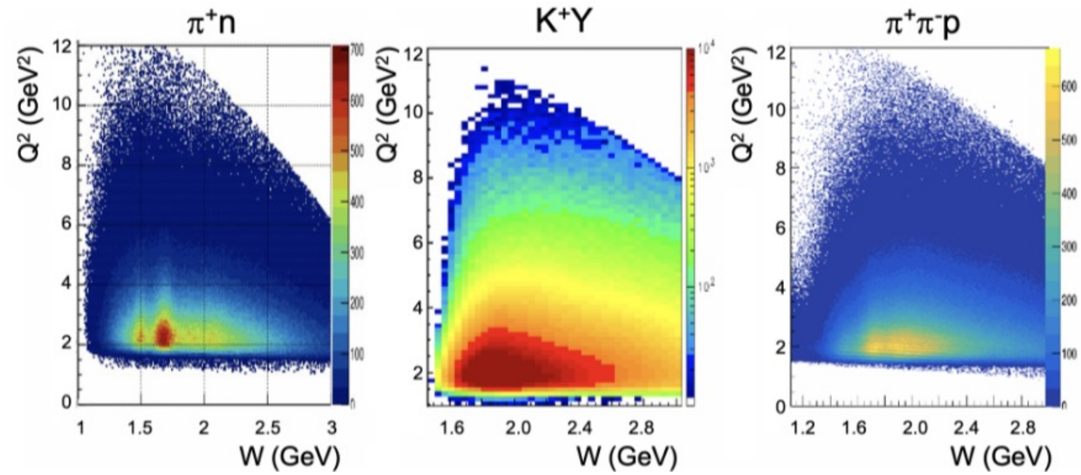



Electrocouplings from independent analyses of $\pi^+\pi^-p$ differential cross sections within three W-intervals, 1.46<W<1.56 GeV, 1.51<W<1.61 GeV, and 1.56<W<1.66 GeV for 2.0<$Q^2$<5.0 GeV$^2$

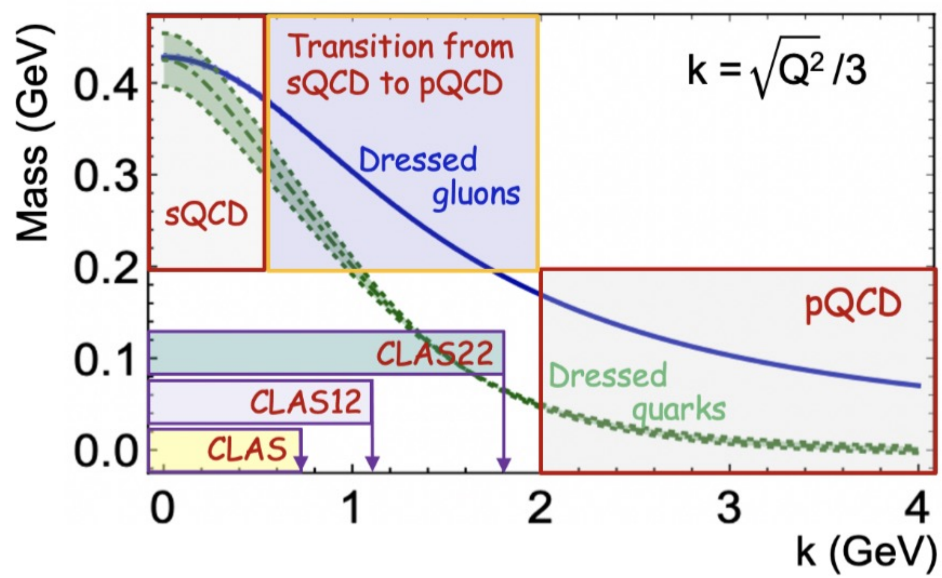
CLAS results on Δ(1600)3/2⁺ electrocouplings confirmed the CSM prediction, solidifying evidence for gaining insight into dressed quark mass function and, consequently, into EHM from the studies of $\gamma_v pN^*$ electrocouplings

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

**Meson electroproduction yields measured with the CLAS12**




CLAS12: Extension of the results on $\gamma_{\varpi} pN^*$ electrocouplings of most N* states in the range W < 2.5 GeV and $Q^2$ up to 10 GeV$^2$ from exclusive channels: $\pi N$, $\pi\pi N$, KY, K*Y, KY* allows to map-out range of quark momenta where ~50 % of dressed quark mass is generated

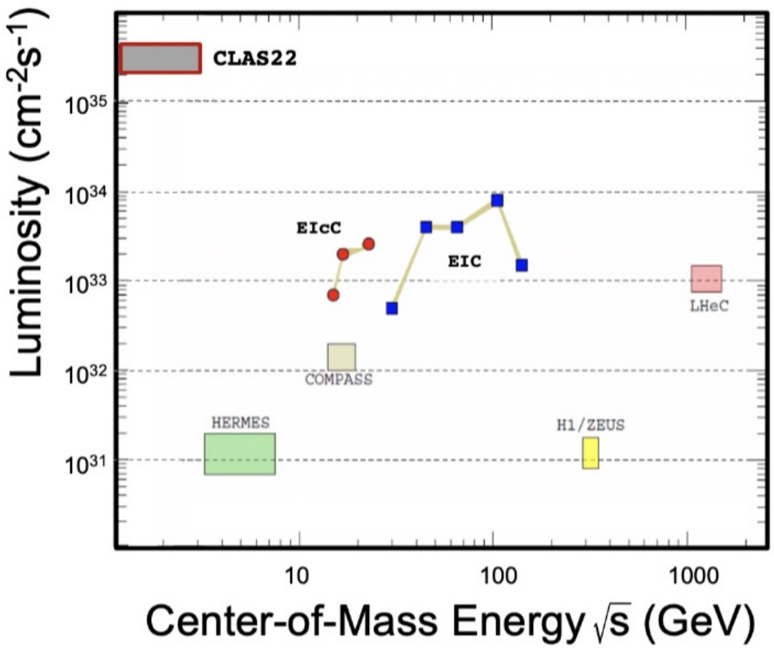



- In order to resolve the challenging problem on EHM, the dressed quark mass function $M_q(k)$ should be mapped out over the entire range of quark momenta to ~2 GeV, where the transition from strongly coupled to perturbative QCD takes place and where dressed quarks/gluons emerge as $\alpha_s/\pi \to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

# Unique Opportunities for Gaining Insight into EHM through Studies of the N* Structure within an Anticipated CEBAF 22 GeV Energy Upgrade Including CLAS22

- Simulations of $\pi N$, 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 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 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.

# Hadron Structure Studies with CLAS22

**Contribution of the Hadron Structure Group to the Physics Motivation to Increase the Energy and Luminosity of JLab**

It is worth recalling that examination of the ground state of the hydrogen atom did not give us sufficient insight into QED. It did not even bring us close. Equally, studies of the ground state of the proton alone cannot reveal whether QCD is truly the theory of strong interactions in the Standard Model. The future of hadron physics lies in high-energy, high-luminosity facilities that are capable of moving beyond the 100-year-long focus on the structure of the ground state of the proton to deliver insights that will dramatically expand our store of knowledge concerning the complete array of Nature's hadrons. In this context, studies of the structure of excited nucleon states ($N^*$s) from the data on exclusive meson electroproduction in terms of the $Q^2$ evolution of their electroexcitation amplitudes, *i.e.* their $\gamma_v pN^*$ electrocouplings, offer a unique opportunity to explore many facets of the strong interaction in the regime of large (comparable with unity) QCD running coupling (*i.e.* the strong QCD regime) that are evident in the distinctively different structural features of these excited states [1-5]. Data on the $\gamma_v pN^*$ electrocouplings over a broad range of $Q^2$ are critical in order to explore the evolution of the strong interaction in the transition from the strong to the perturbative QCD regimes [1,2,6,7]. These electrocouplings provide needed experimental input for the development of the theoretical approaches necessary for the description of the structure of both the ground and excited nucleon states starting from the QCD Lagrangian, as well as within advanced quark models.

The Hadron Structure Group at JLab proposes to extend the studies of the $\gamma_v pN^*$ electrocouplings from exclusive meson electroproduction processes initiated with the CLAS detector in Hall B at beam energies up to 6 GeV and continued with the CLAS12 detector at beam energies up to 11 GeV, to a proposed CLAS24 configuration at beam energies up to 24 GeV. Such experiments at the highest photon virtualities $Q^2$ ever achieved (10-36 GeV$^2$) in studies of exclusive meson electroproduction will allow for the realization of the goal to improve our understanding of the fundamental underpinnings of the mechanism for the emergence of hadron mass (EHM) in these strongly interacting $N^*$ baryon states based on description of these data. The proposed experimental program, along with the associated experiments in JLab Halls A/C and the planned studies at AMBER@CERN, EIC, and EicC focused on the structure of $\pi$ and $K$ mesons [2,11], are of particular importance in order to understand the dynamics of the processes that generate the dominant portion of visible hadron mass in the Universe [1,2,8,9,10].

The current quark masses that enter into the QCD Lagrangian are generated by the Higgs mechanism, and account for less than 2% of the mass of the proton and neutron. Therefore, understanding how these bare current quarks evolve into the fully dressed constituent-like quarks relevant for understanding the structure of baryons and mesons is one of the most fundamental and still open problems within the Standard Model. Recent rapid and significant progress in the development of Continuum Schwinger function Methods (CSMs) [9,10], achieved by an international group of physicists and coordinated by the Institute for Nonperturbative Physics at Nanjing University, has provided a concept for understanding EHM, which has been tested in comparisons with, *inter alia*,

1

Hadron Structure Group in Hall B developing physics case to support CLAS22 upgrade

List of Participating Institutions:

- Jefferson Lab (Hall B and Theory Division)
- University of Connecticut
- Genova University and INFN of Genova
- Lamar University
- Ohio University
- Skobeltsyn Nuclear Physics Institute and Physics Department at Lomonosov Moscow State University
- University of South Carolina
- INFN Sez di Roma Tor Vergata and Universita di Roma Tor Vergata
- Nanjing University Institute for Nonperturbative Physics and affiliated institutes
- Tubingen University
- Tomsk State University and Tomsk Polytechnic University
- James Madison University
- George Washington University

https://userweb.jlab.org/~carman/clas24

# Conclusions and Outlook

- **Baryons are the most fundamental three-body systems in Nature. If we don't understand how QCD builds each of the baryons in the complete spectrum, then we don't understand Nature.**

- **High-quality meson electroproduction data of 6 GeV era at JLab have allowed for the determination of the electrocouplings of most nucleon resonances in the mass range up to 1.8 GeV for $Q^2$<7.5 GeV$^2$. They vastly improved our understanding of the momentum dependence of the dressed quark mass function, which is one of the three pillars of EHM. The remaining two pillars running gluon mass and QCD effective charge are constrained by the results on N* electroexcitation.**

- **A good description of the $\Delta(1232)3/2^+$, $N(1440)1/2^+$, and $\Delta(1600)3/2^+$ electroexcitation amplitudes at $Q^2$<5 GeV$^2$ *achieved within CSM with the same dressed quark mass function* determined by QCD dynamics *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 at quark momenta < 0.7 GeV.**

- **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 $N\pi$, $\pi^+\pi^-p$, and KY electroproduction, allowing to probe the dressed quark mass at quark momenta < 1.1 GeV, a domain where up to ≈ 1 / 2 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

# N* Structure in Experiments of 6.0 GeV Era 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 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 constituent quarks

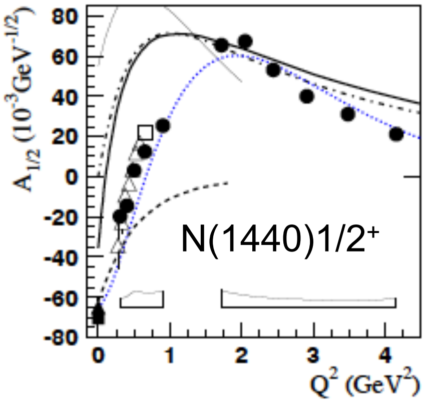
**An important part of the efforts on the exploration of strong QCD (sQCD) from the experimental data with electromagnetic probes:**

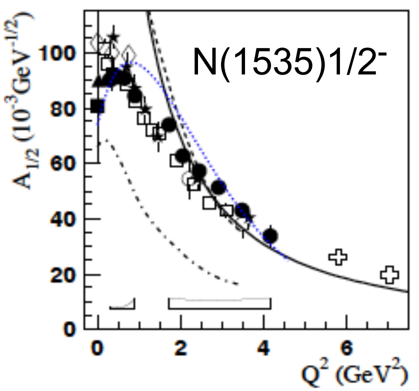
1. S.J. Brodsky et al., Int. J. Mod. Phys. E29, 203006 (2020)
2. C.D. Roberts, Symmetry 12, 1468 (2020)
3. M. Barabanov et al., Prog. Part. Nucl. Phys. 103835 (2021)

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

1. V.I. Mokeev and D.S Carman, Few Body Syst. 63, 59 (2022)
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)

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



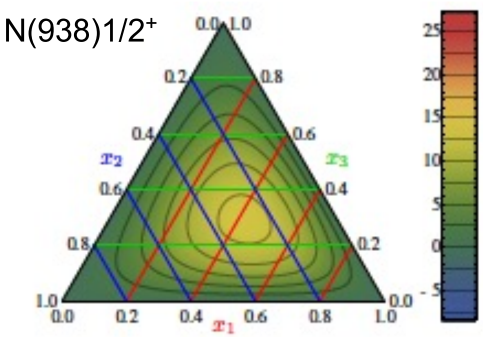



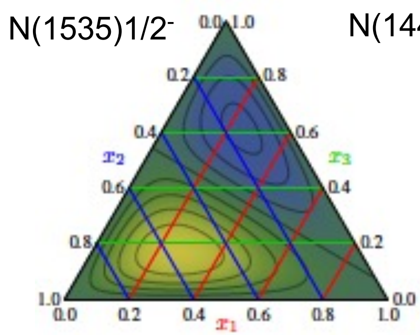

V.D.Burkert and I.G. Aznauryan, Prog. Part Nucl. Phys. 67, 1 (2012)

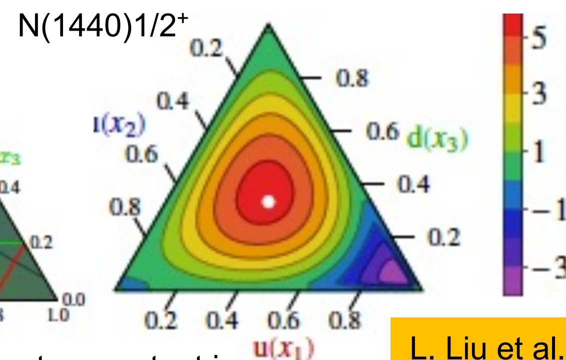
The results on electroexcitation of different resonances allow us to rigorously test the quark model ingredients for the description of the ground/excited hadron structure

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:



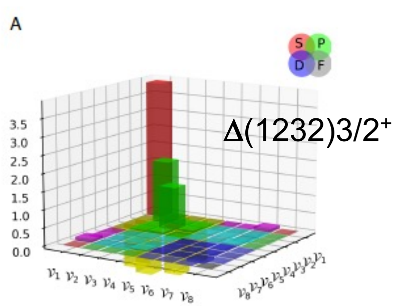



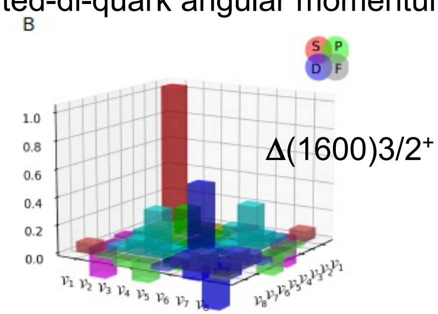



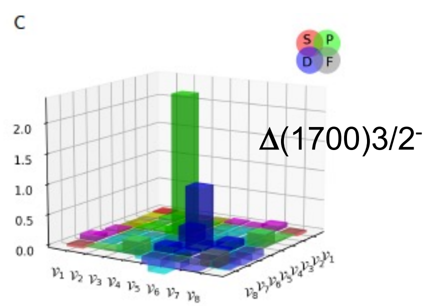

Pronounced differences predicted for N/N* PDAs can be explored in N* electroexcitation, offering insight into the sQCD mechanisms that underlie these differences

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

# 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**<br>**1.1-1.55**<br>**1.1-1.70**<br>**1.6-2.00** | **0.16-0.36**<br>**0.3-0.6**<br>**1.7-4.5**<br>**1.8-4.5** | **$d\sigma/d\Omega$**<br>**$d\sigma/d\Omega$**<br>**$d\sigma/d\Omega$, $A_b$**<br>**$d\sigma/d\Omega$** |
| $\pi^0 p$ | **1.1-1.38**<br>**1.1-1.68**<br>**1.1-1.39**<br>**1.1-1.80** | **0.16-0.36**<br>**0.4-1.8**<br>**3.0-6.0**<br>**0.4-1.0** | **$d\sigma/d\Omega$**<br>**$d\sigma/d\Omega$, $A_b$,$A_t$,$A_{bt}$**<br>**$d\sigma/d\Omega$**<br>**$d\sigma/d\Omega$** |
| $\eta p$ | **1.5-2.3** | **0.2-3.1** | **$d\sigma/d\Omega$** |
| $K^+\Lambda$ | **thresh-2.6** | **1.40-3.90**<br>**0.70-5.40** | **$d\sigma/d\Omega$**<br>**$P^0$, $P'$** |
| $K^+\Sigma^0$ | **thresh-2.6** | **1.40-3.90**<br>**0.70-5.4** | **$d\sigma/d\Omega$**<br>**$P'$** |
| $\pi^+\pi^- p$ | **1.3-1.6**<br>**1.4-2.1**<br>**1.4-2.0** | **0.2-0.6**<br>**0.5-1.5**<br>**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**

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

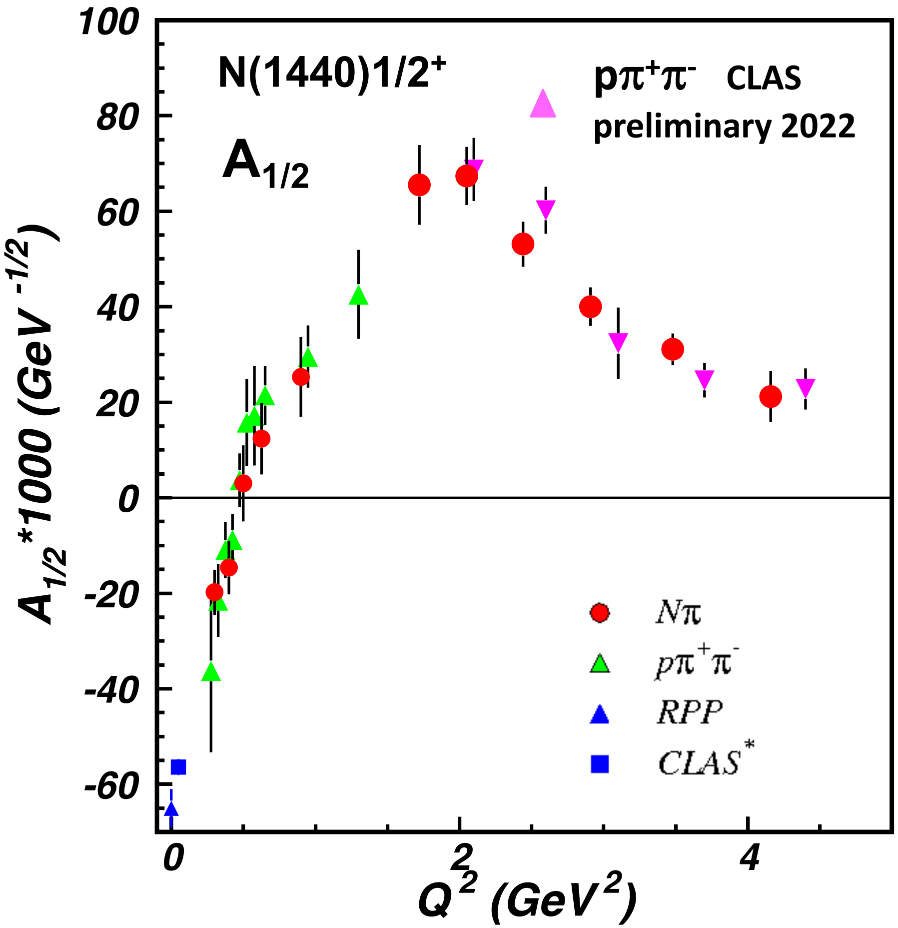
## Analyses of different meson electroproduction channels independently:

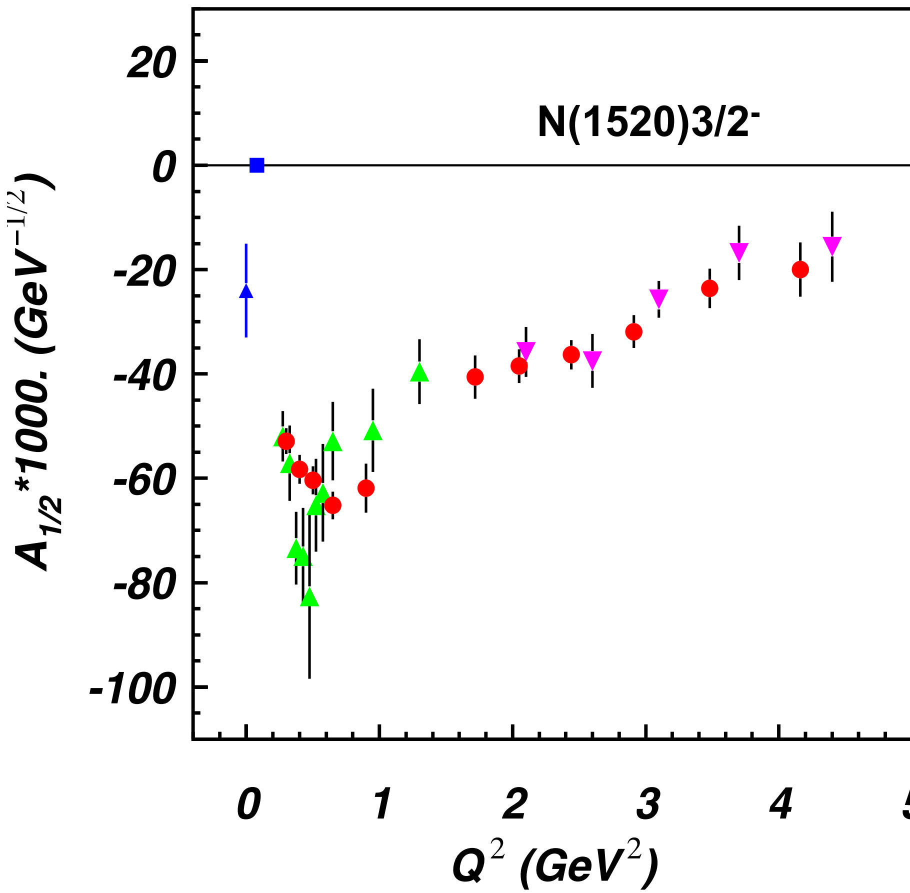
- **$\pi^+ n$ and $\pi^0 p$ channels:**
  - **Unitary Isobar Model (UIM) and Fixed-t Dispersion Relations (DR)**
    - I.G. Aznauryan, Phys. Rev. C67, 015209 (2003)
    - I.G. Aznauryan et al. (CLAS), Phys. Rev. C80, 055203 (2009)
    - I.G. Aznauryan et al. (CLAS), Phys. Rev. C91, 045203 (2015)
- **$\eta p$ 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 $\gamma_{r,v}N$, $\pi N$, $\eta N$, $\pi\pi N$, $K\Lambda$, $K\Sigma$ 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

# Electrocouplings of N(1440)1/2$^+$ and N(1520)3/2$^-$ Resonances from $\pi$N 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 $\pi$N and $\pi^+\pi^-$p electroproduction channels with different non-resonant contributions allow us to evaluate the systematic uncertainties of these quantities in a nearly model-independent way.

# Systematic study of mechanical properties of the proton

Quick Science background

- Mechanical properties appear as gravitational form factors (GFF) in the proton matrix element of the EMT.

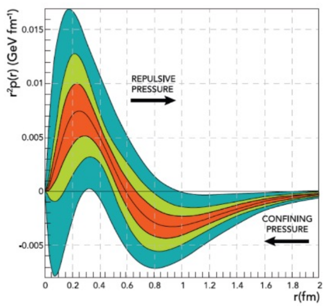
$$\langle p_2|\hat{T}^q_{\mu\nu}|p_1\rangle = \bar{u}(p_2)\left[\underline{M_2^{q,g}(t)}\frac{P_\mu P_\nu}{M} + \underline{J^{q,g}(t)}\frac{i(P_\mu\sigma_{\mu\rho}+P_\nu\sigma_{\mu\rho})\Delta^\rho}{2M} + \underline{d_1^{q,g}(t)}\frac{\Delta_\mu\Delta_\nu - g_{\mu\nu}\Delta^2}{5M}\right]u(p_1)$$

Example of the GFF $d_1^q(t)$ :

Appears in 2nd **x**-moment of GPD *Hq:* $\int \mathrm{d}x\, xH^q(x,\xi,t) = M_2^q(t) + \frac{4}{5}\xi^2 d_1^q(t)$

$$\mathcal{F}(\xi,t;Q^2) = \int_{-1}^{1} dx \left[\frac{1}{\xi - x - i\epsilon} - \frac{1}{\xi + x - i\epsilon}\right] F(x,\xi,t;Q^2)$$

$$\mathrm{Re}\mathcal{H}^q(\xi,t) = \Delta^q(t) + \frac{1}{\pi}\mathcal{P}\int_0^1 \mathrm{d}x \left[\frac{1}{\xi - x} - \frac{1}{\xi + x}\right]\mathrm{Im}\mathcal{H}^q(x,t).$$




- **Dispersion relation** for CFF $\mathcal{H}$ contains subtraction term $\Delta^q(t)$ that relates to $\boxed{d_1^q(t)}$
- **Fourier transform** of $d_1^q(t)$ into coordinate space gives shear and pressure distribution.

# CLAS12 improvements to meet science requirements

- Increase CLAS12 luminosity by repositioning R1 drift chambers (x 2)
- Improve the tracking and vertexing in the CLAS12 forward detector region to accommodate requirements for resolution in spectroscopy and heavy quarks science
- Develop a robust 0-degree electron spectrometer for the energy range 1 – 14 GeV for exotic heavy quark spectroscopy. Could also be useful for TCS
- Provide $\pi^0$, $\gamma$, $e^+/e^-$ detection in backward hemisphere (TDAs, $2\gamma$–physics)
- Upgrade CLAS12 for charged particle ID in full momentum range & all forward sectors (RICH 3-6)
- Improve the PID in the Central Detector for $K/\pi$ separation