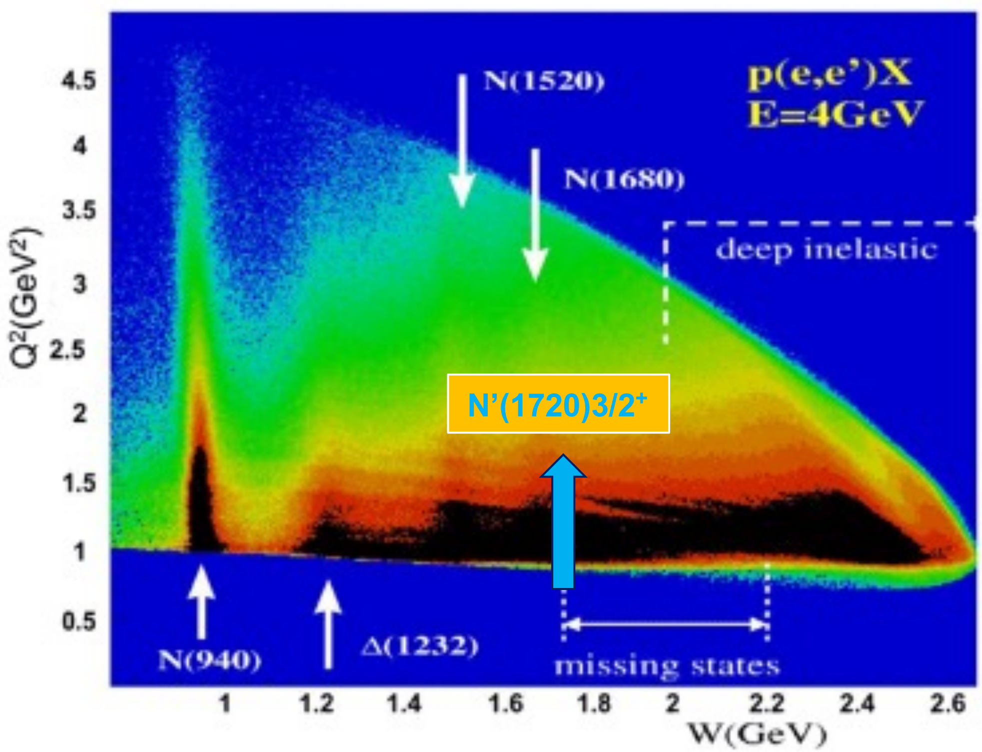
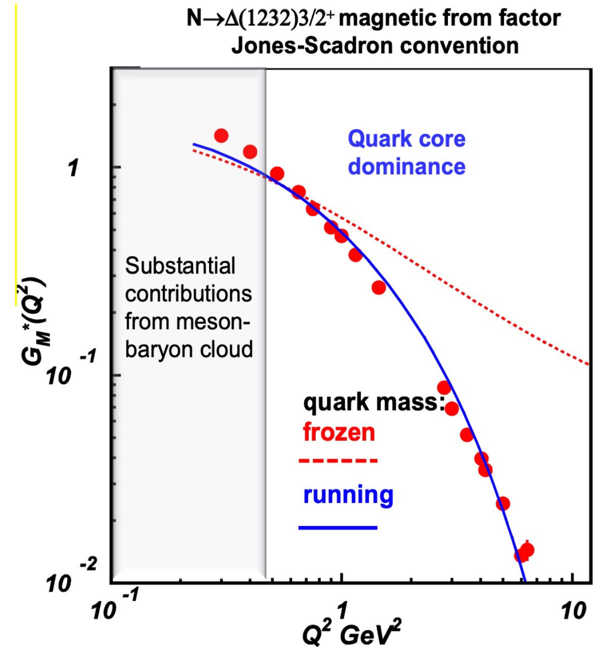
# EHM & Nucleon Resonances





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


Office of Science

Workshop on Hadron Structure at High-Energy, High-Luminosity Facilities

# How the Ground/Excited Nucleon Masses Emerge?

**Composition of the Nucleon Mass:**

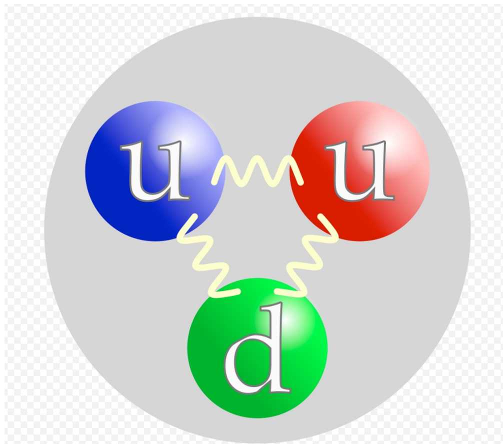
**$M_p$, MeV (PDG20)**

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**



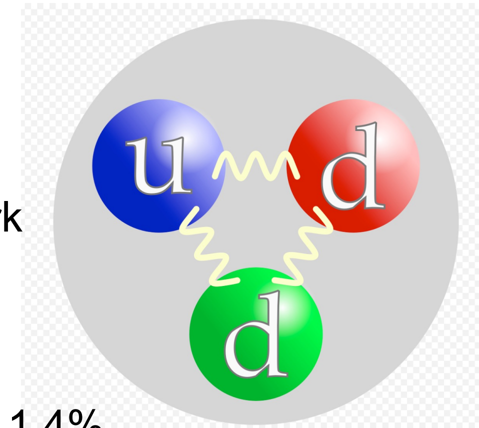

**$M_n$, MeV (PDG20)**

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**

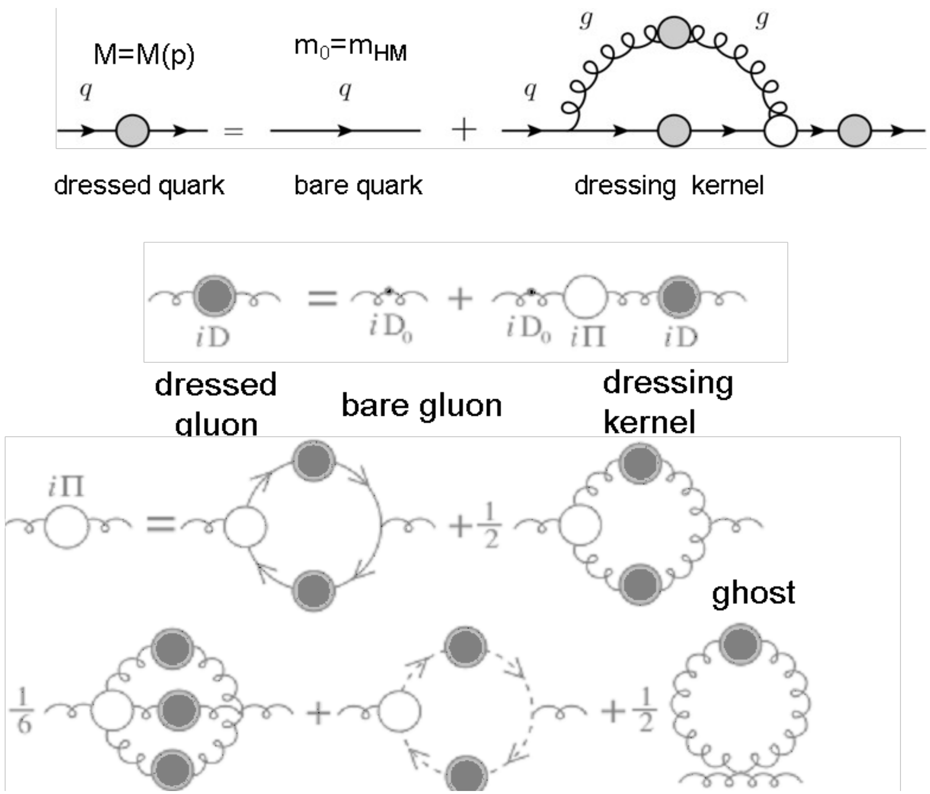



- **Higgs mechanism generates the masses of bare quarks.**
- **Dominant part of nucleon mass is generated in processes other than the Higgs mechanism.**

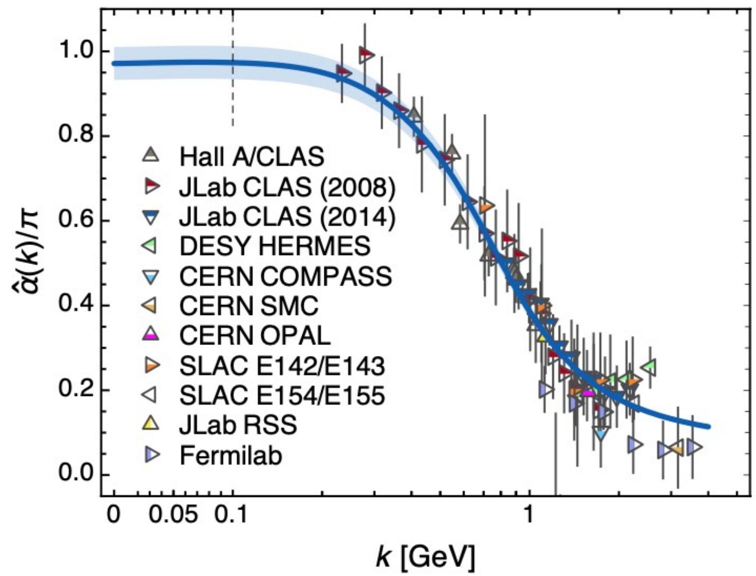
**Studies of nucleon resonance electroexcitation within a broad range of photon virtuality $Q^2$ shed light on emergence of the dominant part of hadron mass in the transition from perturbative to quark-gluon confinement regimes of strong interaction.**

# 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)**




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

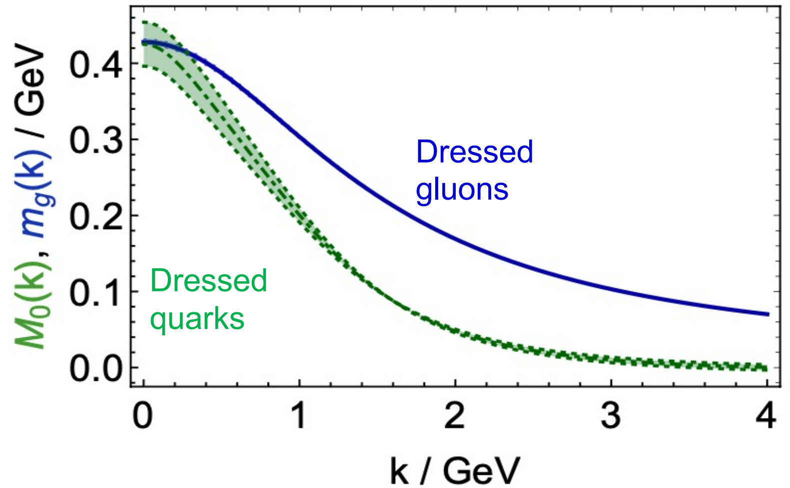
# Basics for Insight into EHM: Continuum and Lattice QCD Synergy

- Dressed quark/gluon masses converge at the complete QCD mass scale of 0.43(1) GeV - value impacted by Higgs mechanism.
- 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 get support from LQCD

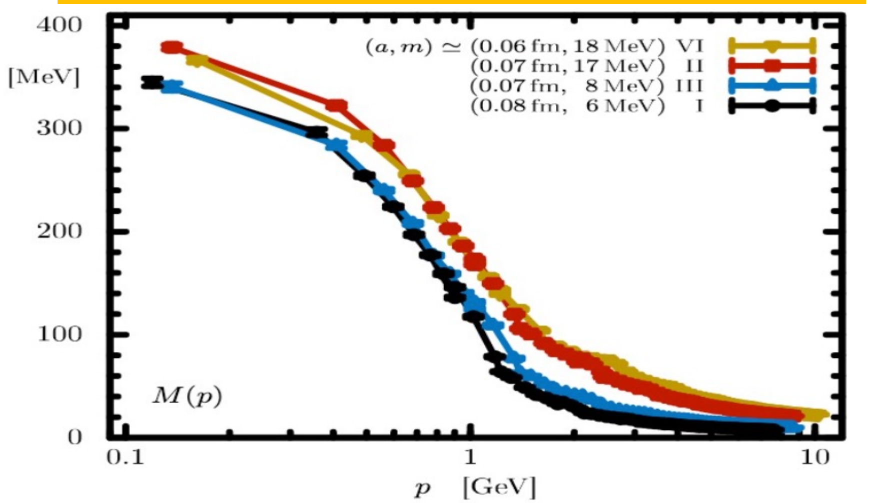
- Insight into dressed quark mass function from data on hadron structure represents a challenge for experimental hadron physics

**Dressed Quark/Gluon Masses (continuum QCD)**
**C.D. Roberts, Symmetry 12, 1468 (2020)**




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

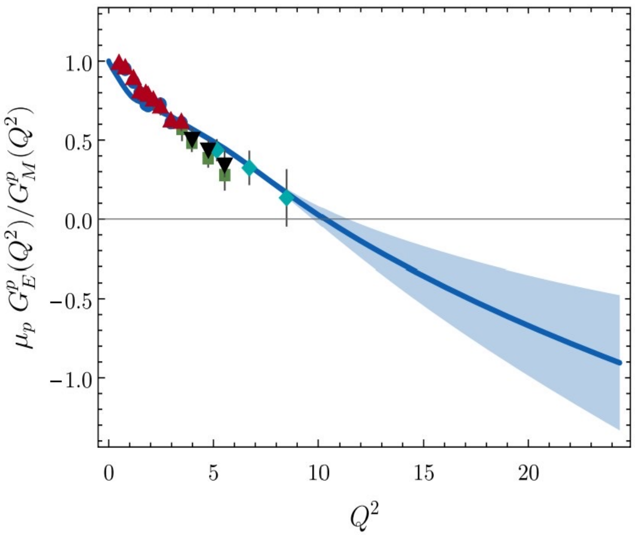
**Dressed Quark Mass (lattice QCD)**
**O. Olivera et al., Phys. Rev. D 99, 094506 (2019)**



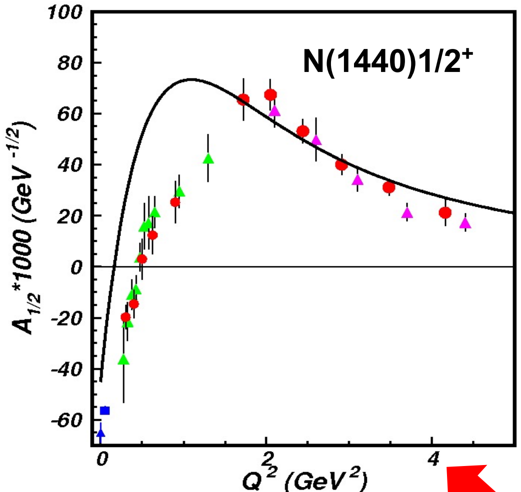
# EHM from Global Hadron Structure Analysis

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

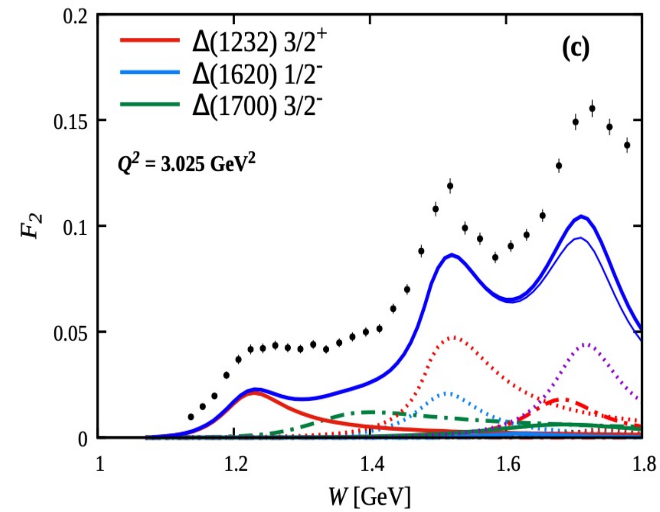
**Nucleon Elastic FF**




**$\gamma_v pN^*$ Electrocouplings**

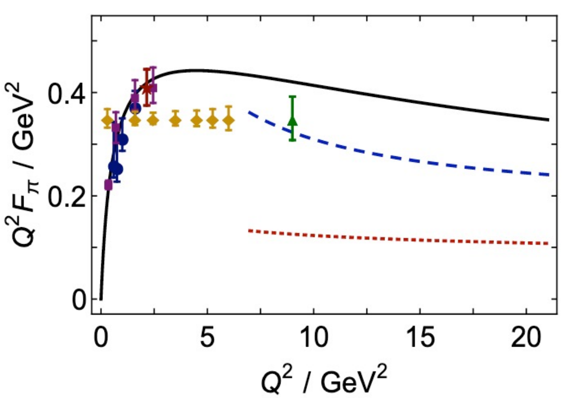



**(e,e'X) Inclusive Scattering**

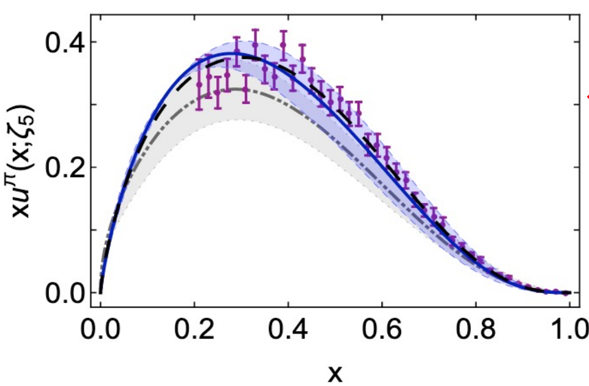



**New data from studies of DY at AMBER and Sullivan processes at JLab**

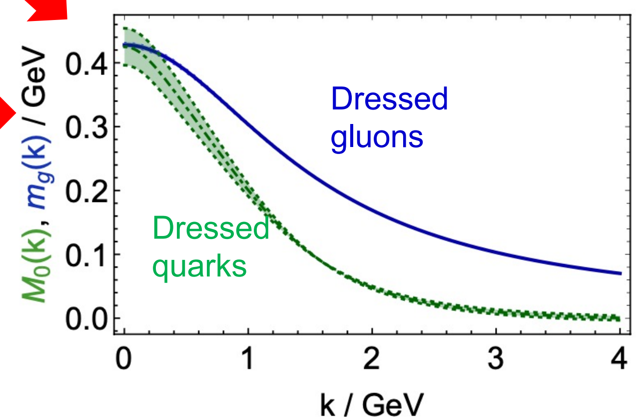
**Pion Elastic FF**




**Pion PDF**




**Dressed Quark/Gluon Running Masses**




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

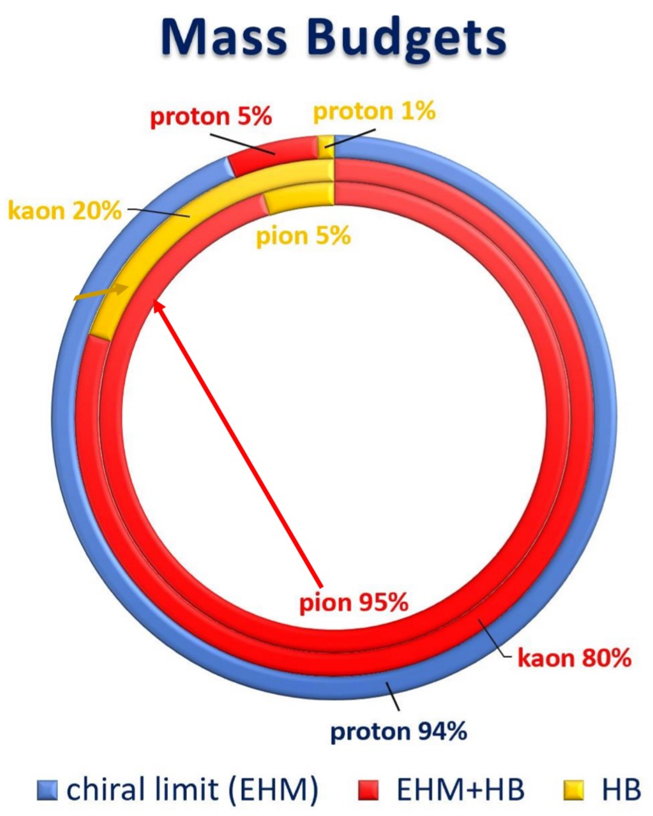
# Insight into EHM from the Data on Pion/Kaon Structure

- The model 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 the 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 the ground and 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 into the physical masses of the ground and excited states of the nucleon

- Consistent results on the momentum dependence of the dressed quark mass function from independent studies of the pseudo-scalar mesons and the ground and excited nucleon structure are of particular importance for the validation of insight into EHM.

# N* Structure in Experiments with CLAS/CLAS12

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

- $\gamma_v pN^*$ electrocouplings at photon virtualities up to 10.0 GeV$^2$ for most of the excited proton states through analyzing major meson electroproduction channels from CLAS/CLAS12 data.
- Explore hadron mass emergence (EHM) and elucidating the trace anomaly 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 exploration of strong QCD from the data of the experiments with the electromagnetic probes:**

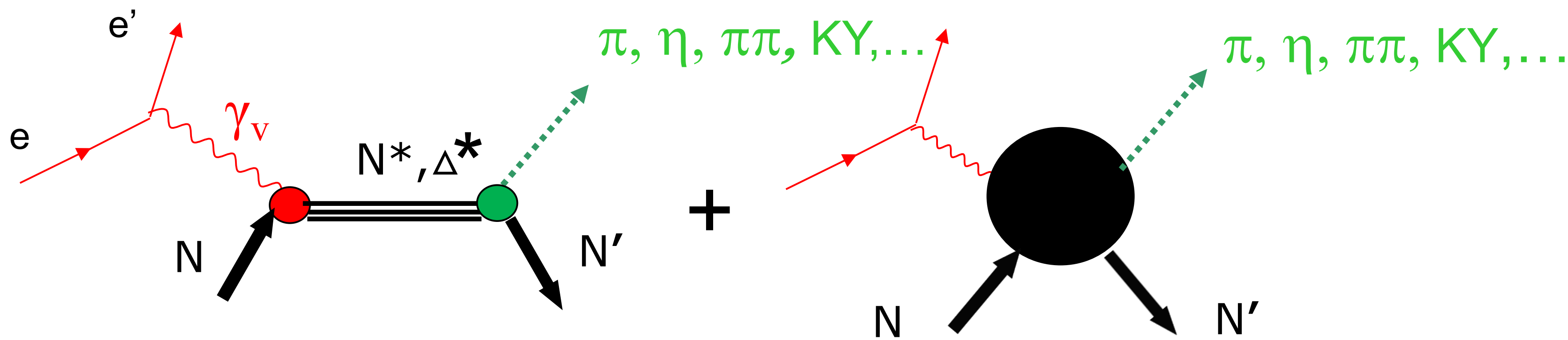
1. **S.J. Brodsky et al., Int. J. Mod. Phys. E29, 203006 (2020).**
2. **C.D. Roberts, Symmetry 12, 1468 (2020).**
3. **M. Barabanov et al., Prog. Part. Nucl. Phys. 103835 (2021).**

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

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




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

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

- 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)**

- **Consistent results on $\gamma_{r,v}pN^*$ photo-/electrocouplings from different meson photo-/electro-production channels allow us to validate 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**<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

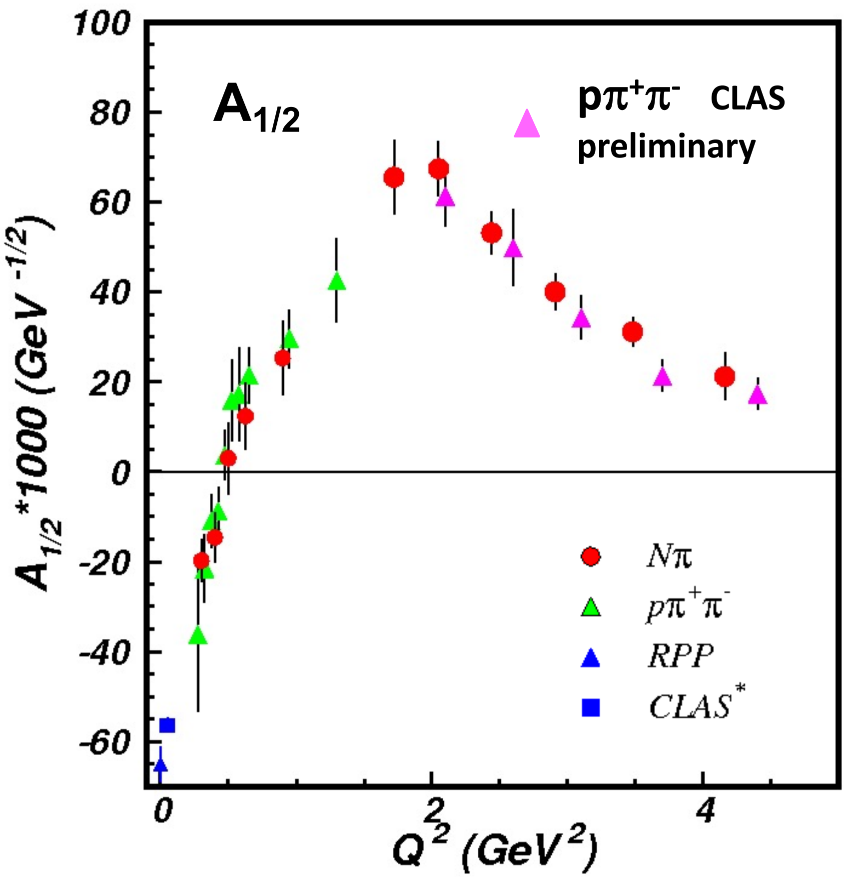
# Nucleon Resonance Electrocouplings from Data On Exclusive Meson Electroproduction with CLAS

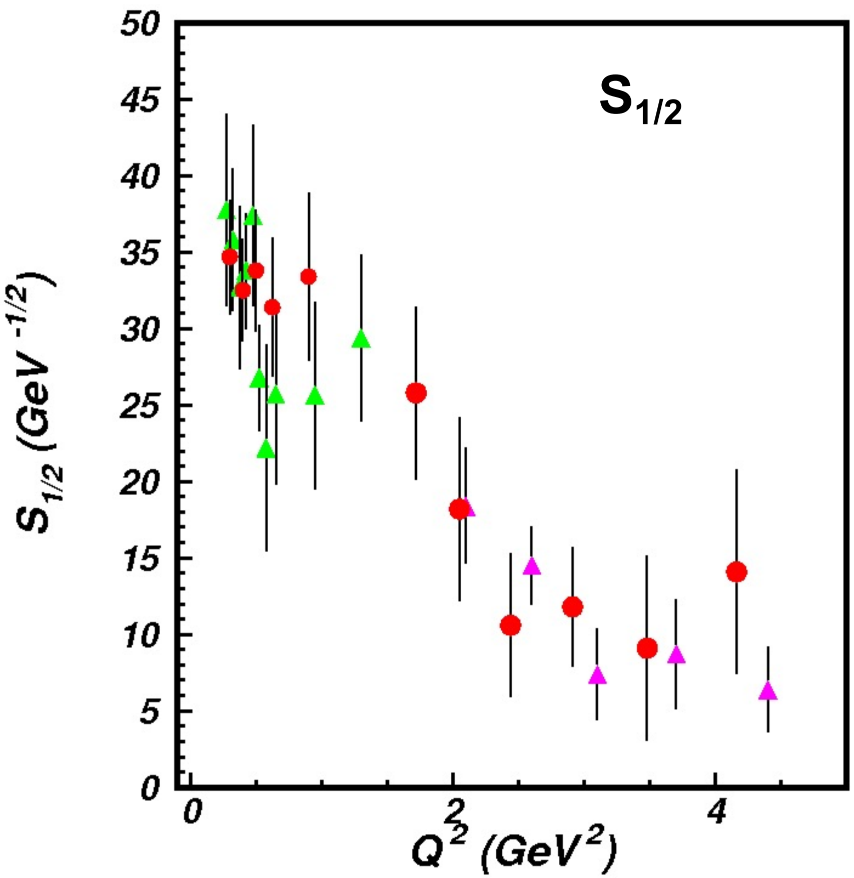
| Exclusive meson electroproduction channels | Excited proton states | $Q^2$-ranges for extracted $\gamma_v pN^*$ electrocouplings, $GeV^2$ |
|---|---|---|
| $\pi^0 p$, $\pi^+ n$ | $\Delta(1232)3/2^+$<br><br>$N(1440)1/2^+$, $N(1520)3/2^-$, $N(1535)1/2^-$ | 0.16-6.0<br><br>0.30-4.16 |
| $\pi^+ n$ | $N(1675)5/2^-$, $N(1680)5/2^+$ $N(1710)1/2^+$ | 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 N* electroexcitation amplitudes ($\gamma_v pN^*$ electrocouplings) have become available in a broad range of $Q^2<5.0$ $GeV^2$ .**
- **In the mass range of W<1.6 GeV the $\gamma_v pN^*$ electrocoupling were obtained from independent studies of $\pi N$, $\eta p$, and $\pi^+\pi^- p$ electroproduction**

**The recent results can be found in:** A.N. Hiller Blin et al, PRC100, 035201 (2019).

# Electrocouplings of N(1440)1/2+ from πN and π+π-p Electroproduction off Proton Data

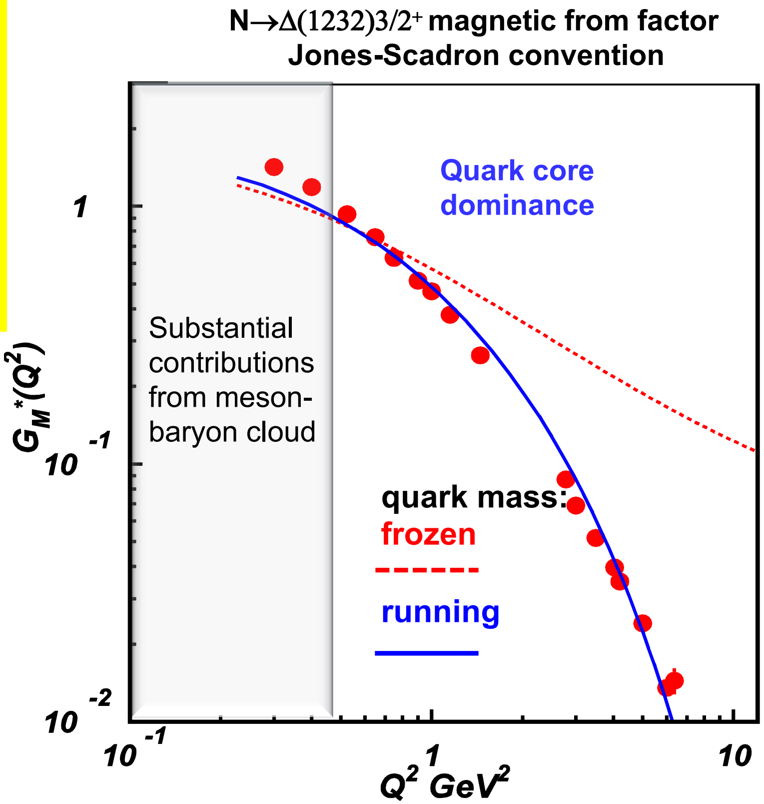


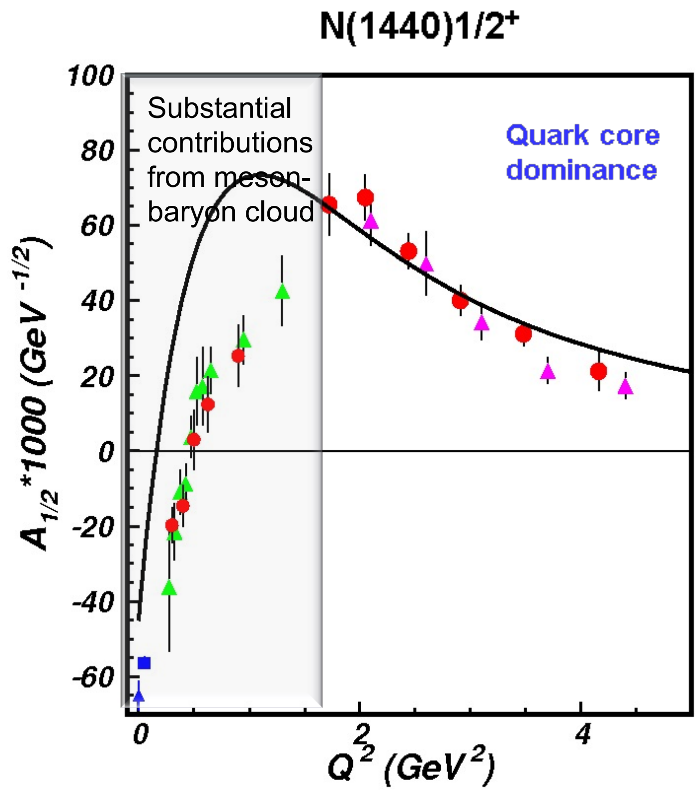




Consistent results on N(1440)1/2+ electrocouplings from independent studies of two major πN and π+π-p electroproduction channels with different non-resonant contributions allow us to evaluate the systematic uncertainties of these quantities in a nearly model-independent way

# Insight to EHM From Resonance Electrocouplings

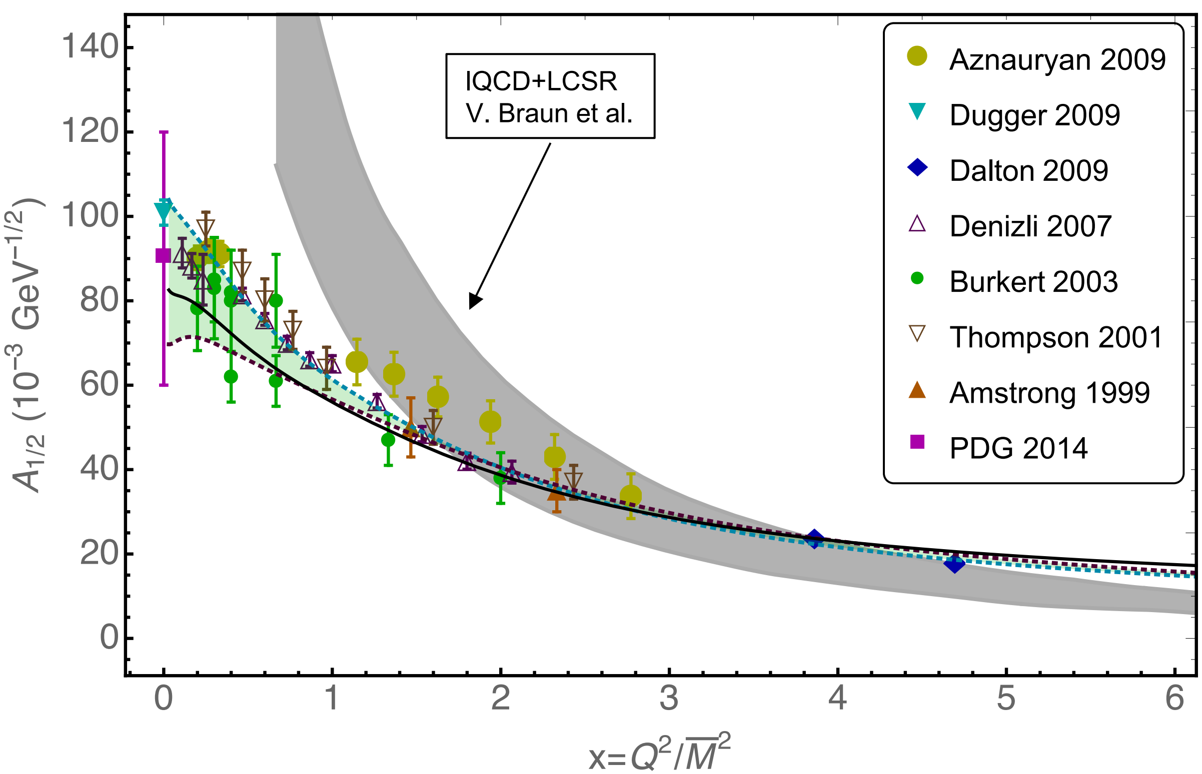
**<u>Dyson-Schwinger Equations (DSE):</u>**
- J. Segovia et al., PRL 115, 171801 (2015)
- J. Segovia et al., Few Body Syst. 55, 1185 (2014)




Good data description at $Q^2$>2.0 GeV$^2$ achieved with <u>the same dressed quark mass function</u> for the ground pion, nucleon and two excited nucleon states of distinctively different structure validates the continuum QCD results on the momentum dependence of the dressed quark mass. $\gamma_v pN^*$ electrocoupling data shed light on the strong QCD dynamics underlying hadron mass generation.

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




Continuum QCD Breakthrough:
N(1535)1/2[-] electrocouplings computed under a traceable connection to the QCD Lagrangian (green area).
C.D Roberts et al, private communication

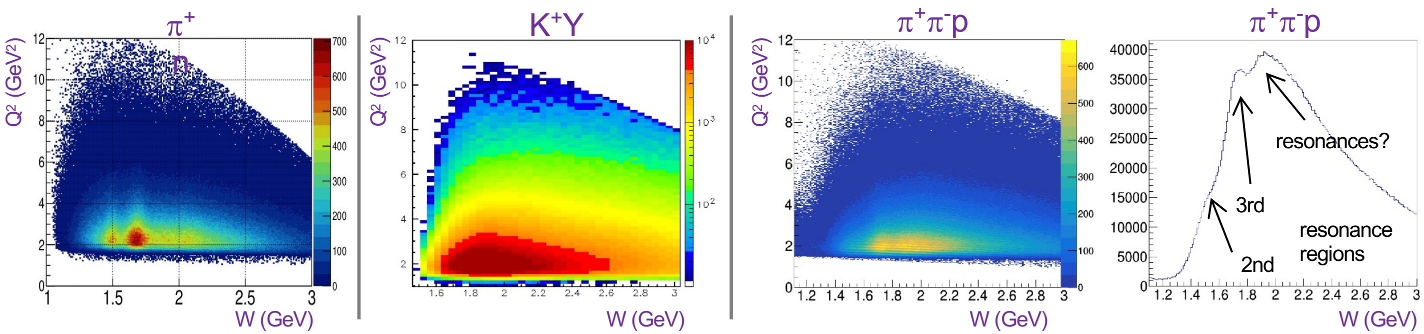
The first preliminary continuum QCD evaluation of electro-excitation amplitudes of the [70,1[-]] supermultiplet resonances ($L_{3q}$=1) with the same dressed quark mass mass function as used for the resonances with $L_{3q}$=0

Studies of electroexcitation amplitudes for the resonances in the second region suggest the universality of dressed quark mass function for the ground and different excited states of the nucleon including the first spin-isospin flip, the first radial, and the first orbital ($L_{3q}$=1) excitations

# N* Electroexcitation to high $Q^2$ with CLAS12

Expected outcome: The first results on the $\gamma_v pN^*$ electrocouplings of most N* states from data in the range W < 3.0 GeV and $Q^2 > 5.0$ GeV$^2$ for exclusive reaction channels: $\pi N$, $\pi\pi N$, KY, K*Y, KY*

kinematic coverage for RG-A data @ 10.6 GeV




Expected events per Q²/W bin for full RG-A dataset

| $\pi^+n$ | | | $K^+\Lambda$ & $K^+\Sigma^0$ | | | | | $\pi^+\pi^-p$ | | |
|---|---|---|---|---|---|---|---|---|---|---|
| $Q^2$ [GeV$^2$] | W [GeV] 1.5-1.55 | W [GeV] 1.7-1.75 | $Q^2$ [GeV$^2$] | $W_\Lambda$ [GeV] 1.7-1.75 | $W_\Sigma$ [GeV] 1.7-1.75 | $W_\Lambda$ [GeV] 1.9-1.95 | $W_\Sigma$ [GeV] 1.9-1.95 | $Q^2$ [GeV$^2$] | W [GeV] 1.7-1.75 | W [GeV] 1.9-1.95 |
| | | | 1.4-2.2 | 63417 | 6012 | 66564 | 33170 | | | |
| | | | 2.2-3.0 | 72144 | 5364 | 77443 | 28720 | | | |
| 5.2-5.8 | 15272 | 4175 | 3.0-4.0 | 52358 | 3945 | 51991 | 18936 | 5.2-5.8 | 2813 | 2808 |
| 5.8-6.5 | 10737 | 2637 | 4.0-5.0 | 24833 | 3103 | 26690 | 5925 | 5.8-6.5 | 1822 | 1969 |
| 6.5-7.2 | 7367 | 1684 | 5.0-6.0 | 11203 | 1598 | 11160 | 2642 | 6.5-7.2 | 1159 | 1294 |
| 7.2-8.1 | 4567 | 1290 | 6.0-7.0 | 5566 | 648 | 6300 | 943 | 7.2-8.1 | 661 | 924 |
| 8.1-9.1 | 2742 | 540 | 7.0-8.0 | 2606 | 338 | 3276 | 633 | 8.1-9.1 | 364 | 414 |
| 9.1-10.5 | 1453 | 194 | 8.0-9.0 | 1440 | 244 | 936 | 86 | 9.1-10.5 | 118 | 179 |

Collecting the remainder of the approved RG-A beam time will give a factor of two more statistics

This will extend the $Q^2$ range of the $\gamma_v pN^*$ electrocouplings to 8-10 GeV$^2$ for each of these channels – *the data collected so far will limit us to 6-8 GeV$^2$*

# Emergence of Hadron Mass and Quark-Gluon Confinement

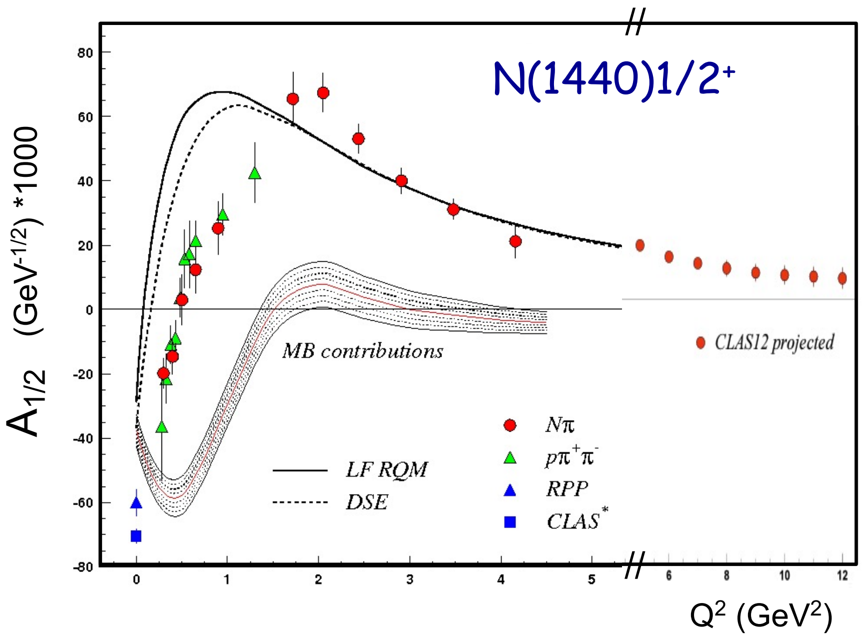
**N* electroexcitation studies at JLab during and after 12 GeV era will address the critical questions:**

*How is >98% of visible mass generated?*

*How does confinement emerge from QCD and how is it related to Dynamical Chiral Symmetry Breaking?*

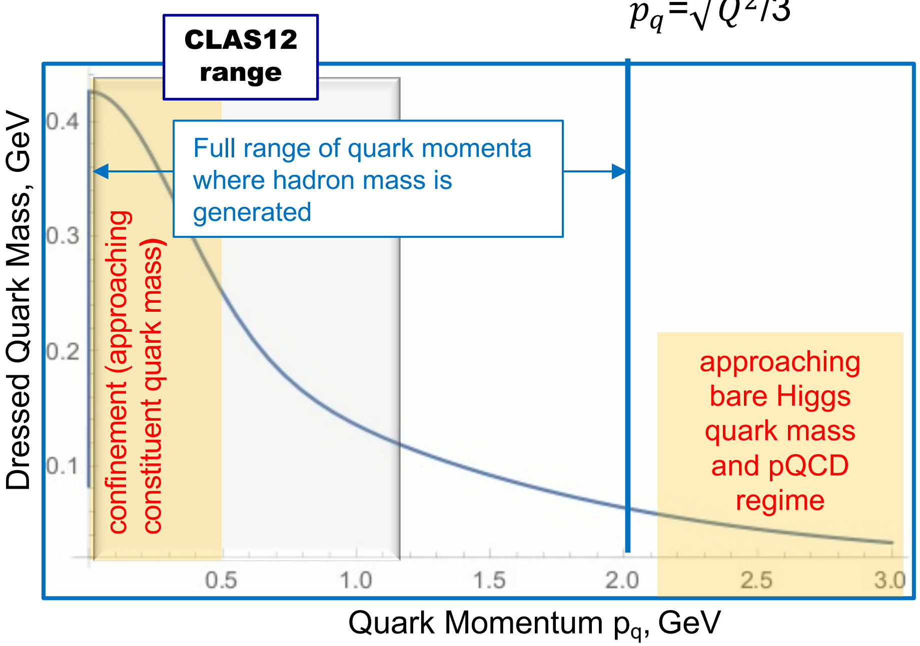
*(S.J, Brodsky et al., Int. J. Mod. Phys. Rev. E29, 2030006 (2020))*

**Mapping-out quark mass function from the results on $\gamma_v pN^*$ electrocouplings of spin-isospin flip, radial, and orbital excited nucleon resonances at $5<Q^2<36$ GeV$^2$ is needed to explore the full range of distances where the dominant part of hadron mass is generated**



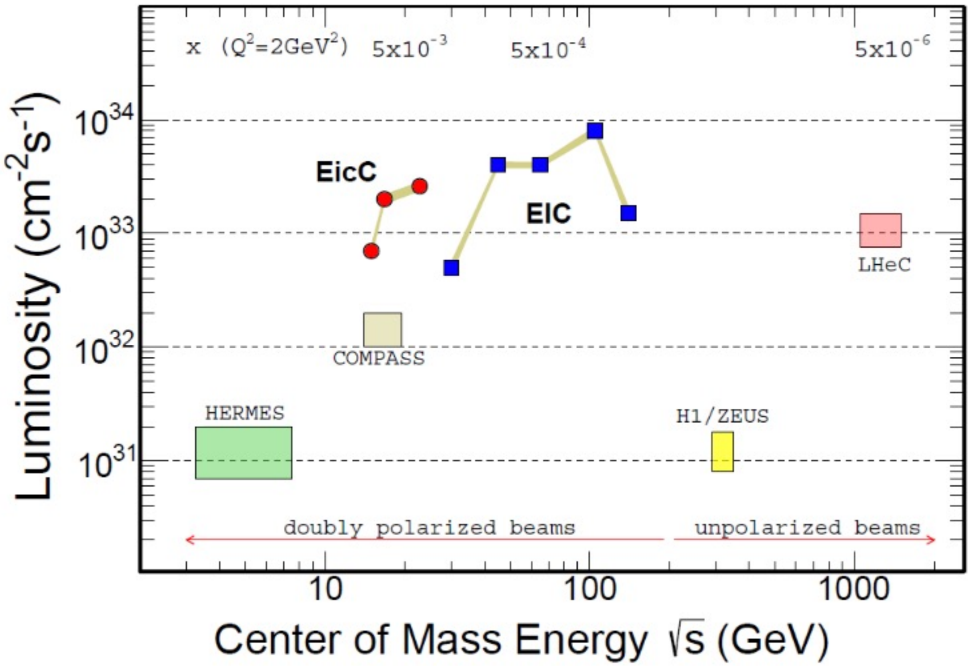

CLAS results vs. theory expectations with running quark mass

Access to the dressed quark/hadron mass generation



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

Energy and luminosity increase 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




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 $4\pi$ coverage
- High luminosity

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

# Conclusions and Outlook

- EHM paradigm makes a broad array of predictions. The predictions it makes for the N/N* structure are worth testing so that the one can gain insight and understanding of the hadron mass generation by mapping the momentum dependence of dressed quark running masses.

- Consistent results on momentum dependence of dressed quark mass function from the studies of pion, kaon, the ground nucleon structure and the CLAS results on $\gamma_v pN^*$ electrocouplings will sherd light on EHM and allow us to check universality or environmental sensitivity of dressed quark mass function.

- A good description of CLAS results on $\Delta(1232)3/2^+$, $N(1440)1/2^+$, and $N(1535)1/2^-$ electroexcitation amplitudes *achieved with the same dressed quark mass function* as used previously in successful evaluations of the elastic ground nucleon and pion form factors, pion PDF validate insight to the dynamics that underlie the emergence of hadron mass. Studies of the $\Delta(1600)3/2^+$ electrocouplings are in progress.

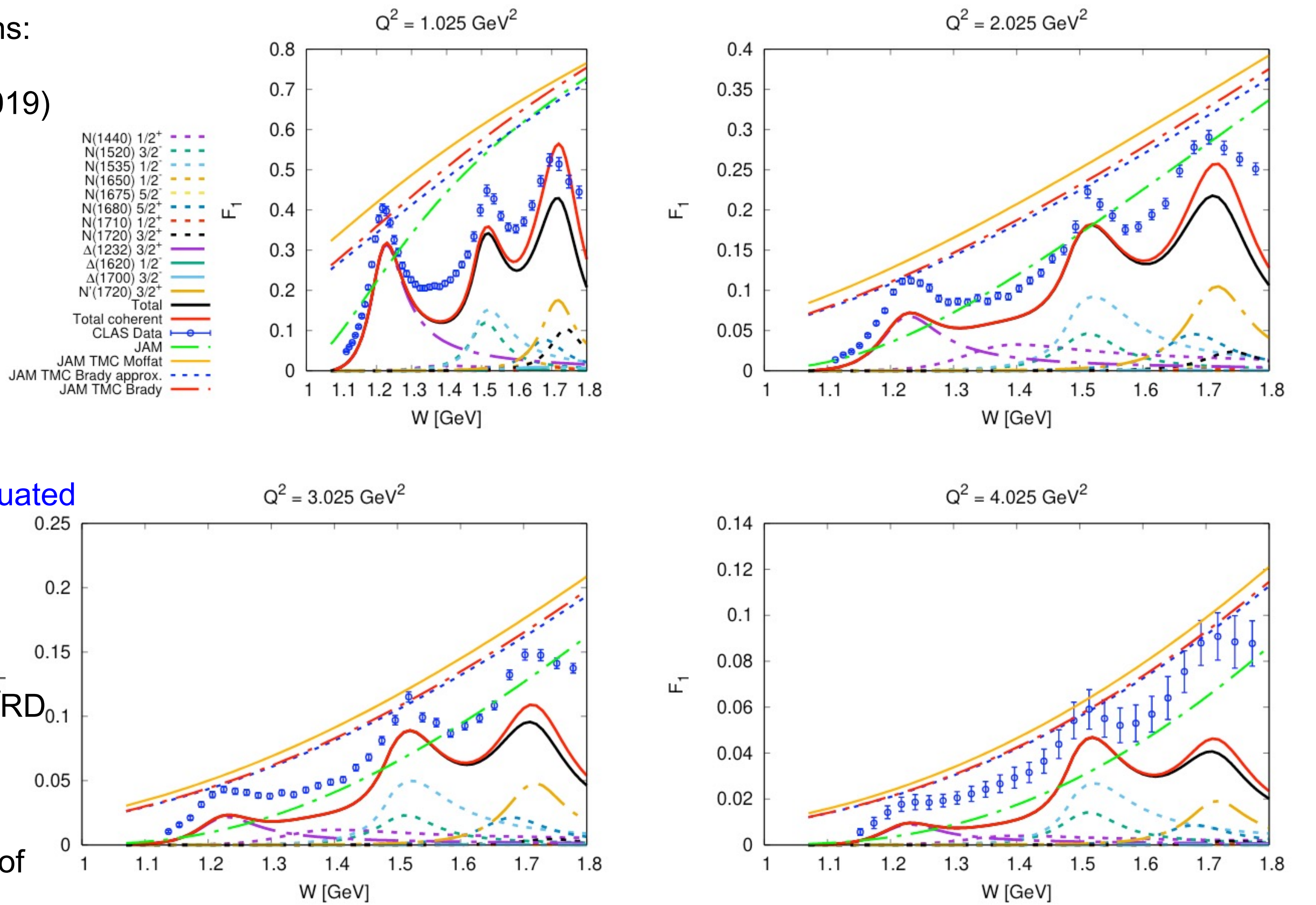
- CLAS12 is the only facility in the world capable of obtaining the electrocouplings of all prominent N* states at still unexplored ranges highest photon virtualities for exclusive reactions from 5.0 GeV$^2$ to 12 GeV$^2$ from measurements of $N\pi$, $\pi^+\pi^-p$, and KY electro-production allowing us to map out the dressed quark mass function at quark momenta < 1.3 GeV

- Extension of the results on $\gamma_v pN^*$ electrocouplings into the $Q^2$ range from 10 GeV$^2$ to 36 GeV$^2$ from the measurements at the future facilities with luminosity $>10^{36}$ cm$^{-2}$sec$^{-1}$ will provide information on dressed quark mass function at the distances where the transition from quark-gluon confinement to pQCD regime is expected, addressing the most challenging problems of the Standard Model on the nature of >98% of hadron mass and of quark-gluon confinement.

# Back up

# Resonant Contributions into Inclusive $F_1(W,Q^2)$ Structure Functions & the Contributions from the PDF in the Ground State of the Nucleon Evaluated from the Data in DIS Region

Resonant contributions:
A.N. Hiller Blin et al.,
PRC 100, 035201 (2019)




Data points are from interpolation of the CLAS results re-evaluated with the $\sigma_L/\sigma_T$ ratio from Hall C data

<u>CLAS data:</u>
M. Osipenko et al., PRD 67, 092001 (2003)

<u>Hall C data</u>:
Y. Liang, PhD thesis of American University (2003)

Green dot-dashed lines: $F_1$ from JAM PDF
Other smooth curves: $F_1$ from JAM PDF after target mass corrections within different prescriptions