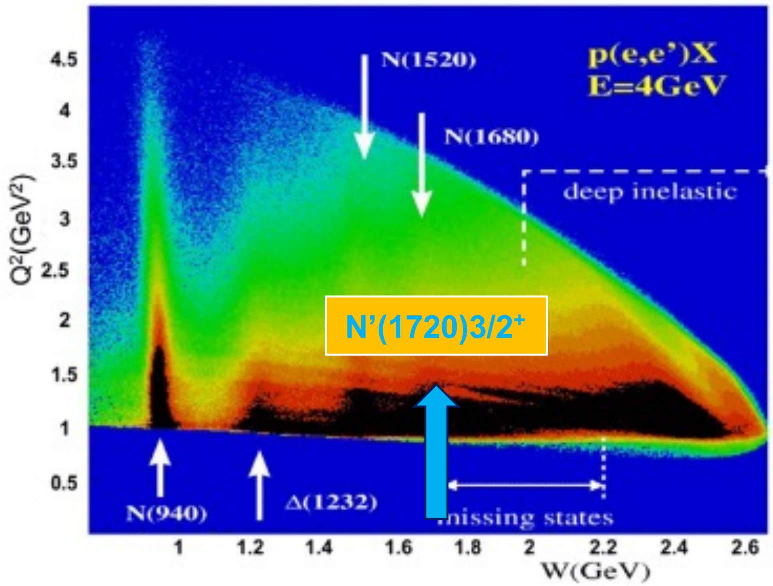
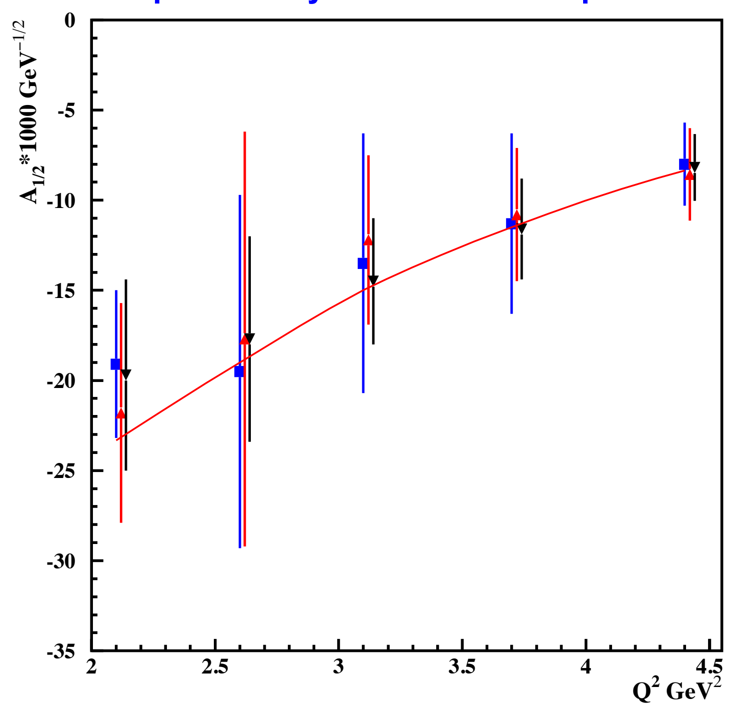
Electrocouplings of Nucleon Resonances



Δ(1600)3/2+ electrocouplings:
CLAS preliminary results vs. CSM predictions



- Resonance electroexcitation and insight into strong QCD
- Extraction of resonance electrocouplings
- Resonance electrocouplings and emergence of hadron mass
- Resonant contributions into (e,e′X) scattering in the N* region
- N* structure and strong QCD from experiments with CLAS12

V.I. Mokeev
Jefferson Lab
(CLAS Collaboration)

Office of Science

2022 JLUO Annual Meeting

N* Structure in Experiments with CLAS/CLAS12

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 of the excited proton states through analyzing the major meson electroproduction channels from CLAS/CLAS12 data
- 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

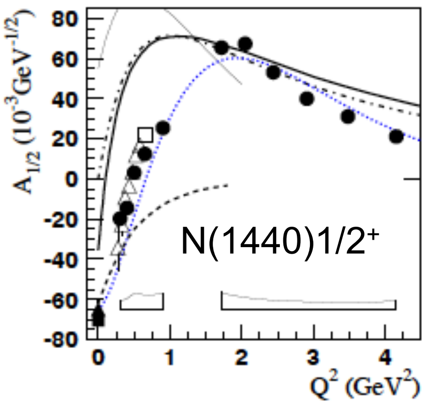
An important part of the efforts on the exploration of strong QCD (sQCD) from the data of the experiments with electromagnetic probes:

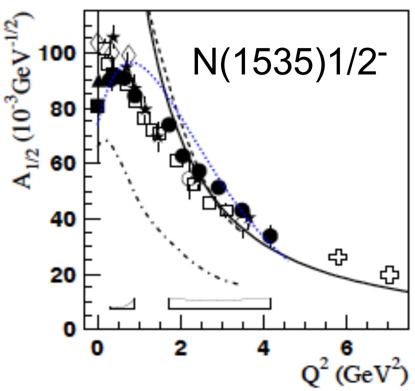
1. S.J. Brodsky et al., Int. J. Mod. Phys. E29, 203006 (2020)
2. C.D. Roberts, Symmetry 12, 1468 (2020)
3. M. Barabanov et al., Prog. Part. Nucl. Phys. 103835 (2021)

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

1. 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)

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



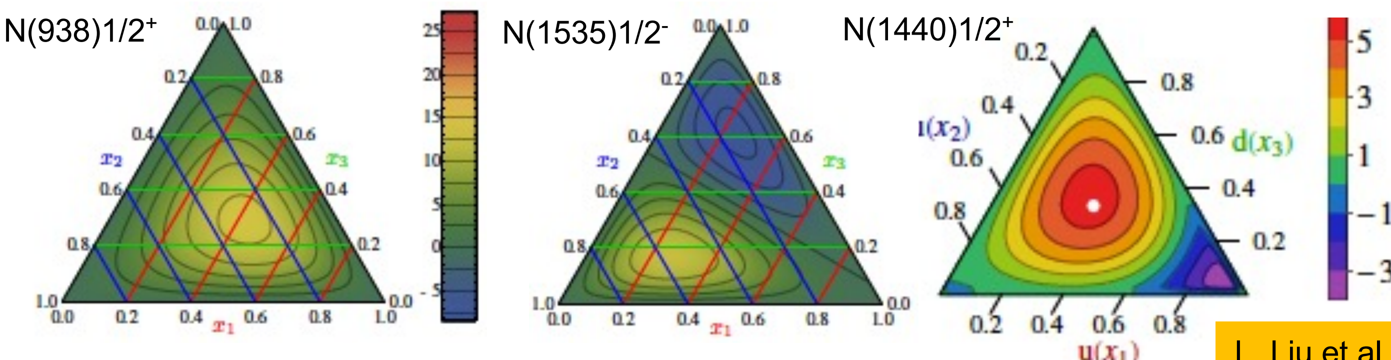


V.D.Burkert and I.G. Aznauryan, Prog. Part Nucl. Phys. 67, 1 (2012)

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)

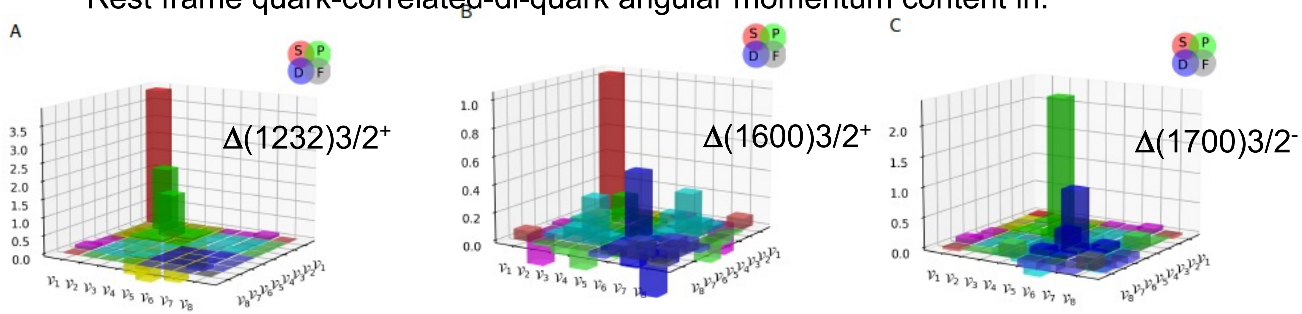
Parton distribution amplitudes (PDA) in:



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:

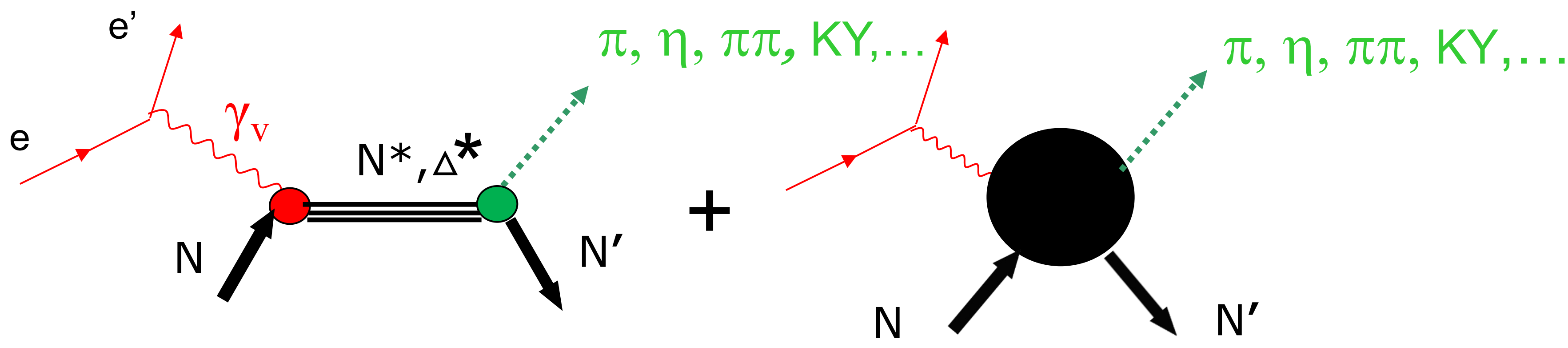


Studies of N* electroexcitation will contribute into understanding of the nature of spin of the ground and excited states of the nucleon

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

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)

<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 the $\gamma_{r,v}$pN* photo-/electrocouplings from different meson photo-/electroproduction 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** **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} $d\sigma/d\Omega$ $d\sigma/d\Omega$
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](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

Independent analyses of different meson electroproduction channels:

- **π^+n and π^0p channels:**
  - **Unitary Isobar Model (UIM) and Fixed-t Dispersion Relations (DR)**
    - I.G. Aznauryan, Phys. Rev. C 67, 015209 (2003)
    - I.G. Aznauryan et al. (CLAS), Phys. Rev. C 80, 055203 (2009)
    - I.G. Aznauryan et al. (CLAS), Phys. Rev. C 91, 045203 (2015)
- **ηp channel:**
  - **Extension of UIM and DR**
    - I.G. Aznauryan, Phys. Rev. C 68, 065204 (2003)
  - **Data fit at W<1.6 GeV, assuming N(1535)1/2$^-$ dominance**
    - H. Denizli et al. (CLAS), Phys. Rev. C 76, 015204 (2007)
- **$\pi^+\pi^-p$ channel:**
  - **Data driven JLab-MSU meson-baryon model (JM)**
    - V.I. Mokeev, V.D. Burkert et al., Phys. Rev. C 80, 045212 (2009)
    - V.I. Mokeev et al. (CLAS), Phys. Rev. C 86, 035203 (2012)
    - V.I. Mokeev, V.D. Burkert et al., Phys. Rev. C 93, 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. C 103, 065204 (2021). Julich-Bonn-Washington
M. Mai et al., e-print: 2111.04774 [nucl-th]

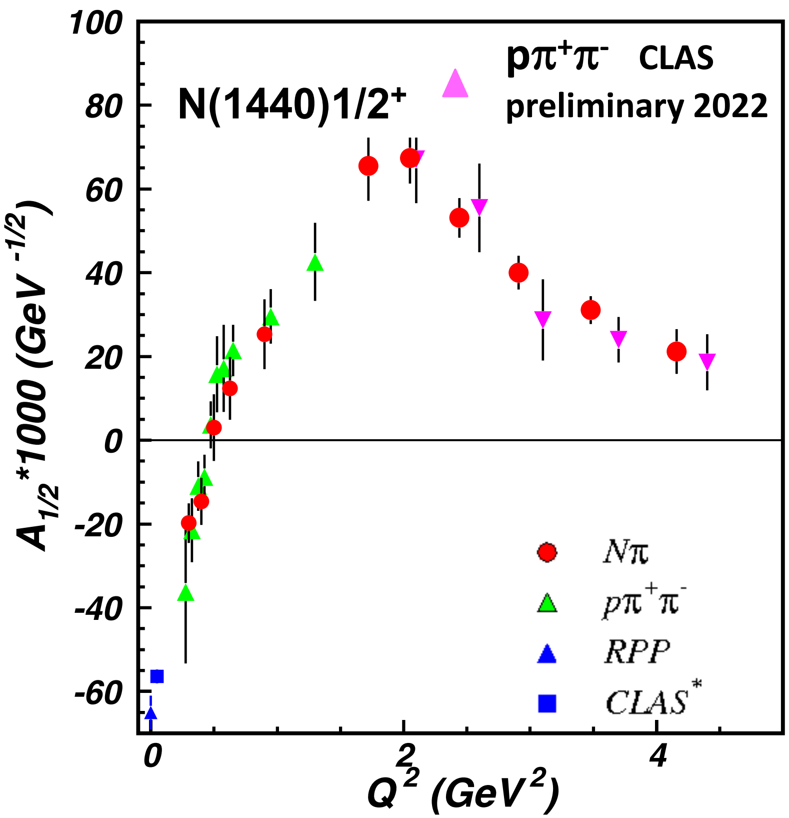
Nucleon Resonance Electrocouplings from Data On Exclusive Meson Electroproduction with CLAS

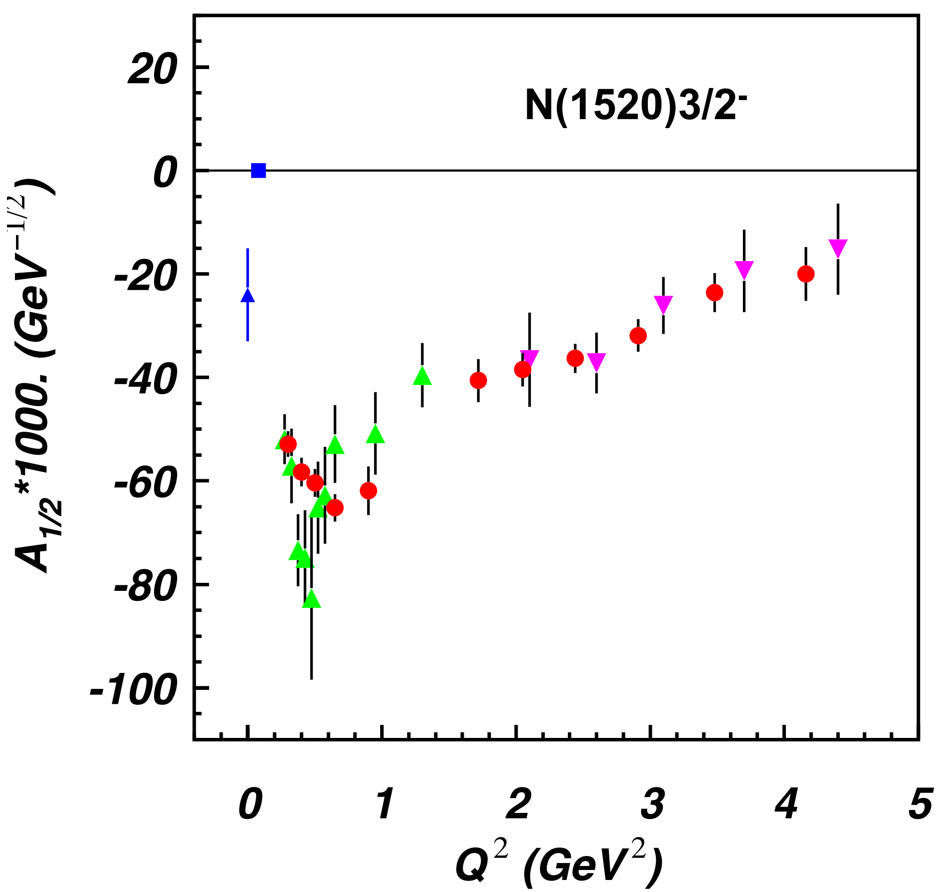
Exclusive meson electroproduction channels	Excited proton states	Q^2-ranges for extracted $\gamma_v pN^*$ electrocouplings, GeV^2
$\pi^0 p$, $\pi^+ n$	$\Delta(1232)3/2^+$ $N(1440)1/2^+$,$N(1520)3/2^-$, $N(1535)1/2^-$	0.16-6.0 0.30-4.16
$\pi^+ n$	$N(1675)5/2^-$, $N(1680)5/2^+$ $N(1710)1/2^+$	1.6-4.5
ηp	$N(1535)1/2^-$	0.2-2.9
$\pi^+\pi^- p$	$N(1440)1/2^+$, $N(1520)3/2^-$ $\Delta(1620)1/2^-$, $N(1650)1/2^-$, $N(1680)5/2^+$, $\Delta(1700)3/2^-$, $N(1720)3/2^+$, $N'(1720)3/2^+$	0.25-1.50 2.0-5.0 (preliminary) 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 W<1.6 GeV the $\gamma_v pN^*$ electrocoupling were obtained from independent studies of πN, ηp, and $\pi^+\pi^- p$ electroproduction

Most 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 allow us to evaluate the systematic uncertainties of these quantities in a nearly model-independent way

How do the Ground/Excited State Nucleon Masses Emerge?

Composition of the Nucleon Mass:

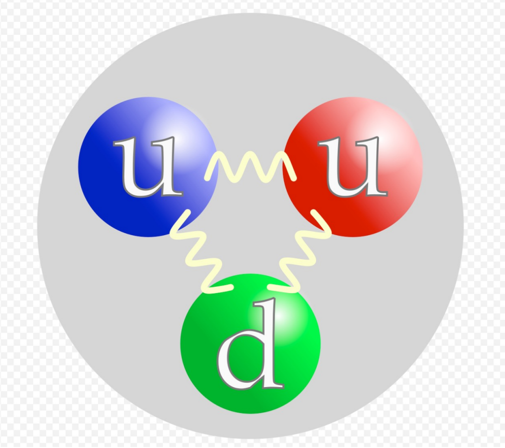
M_p, MeV (PDG20)

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



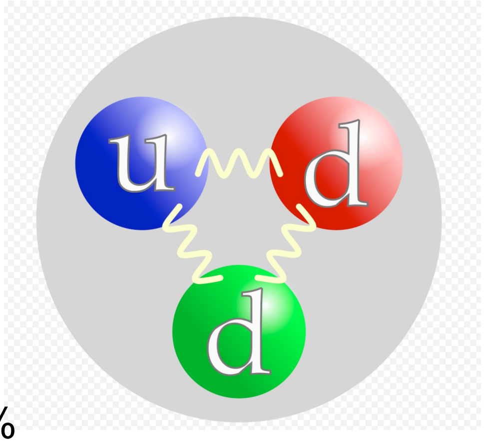
M_n, MeV (PDG20)

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

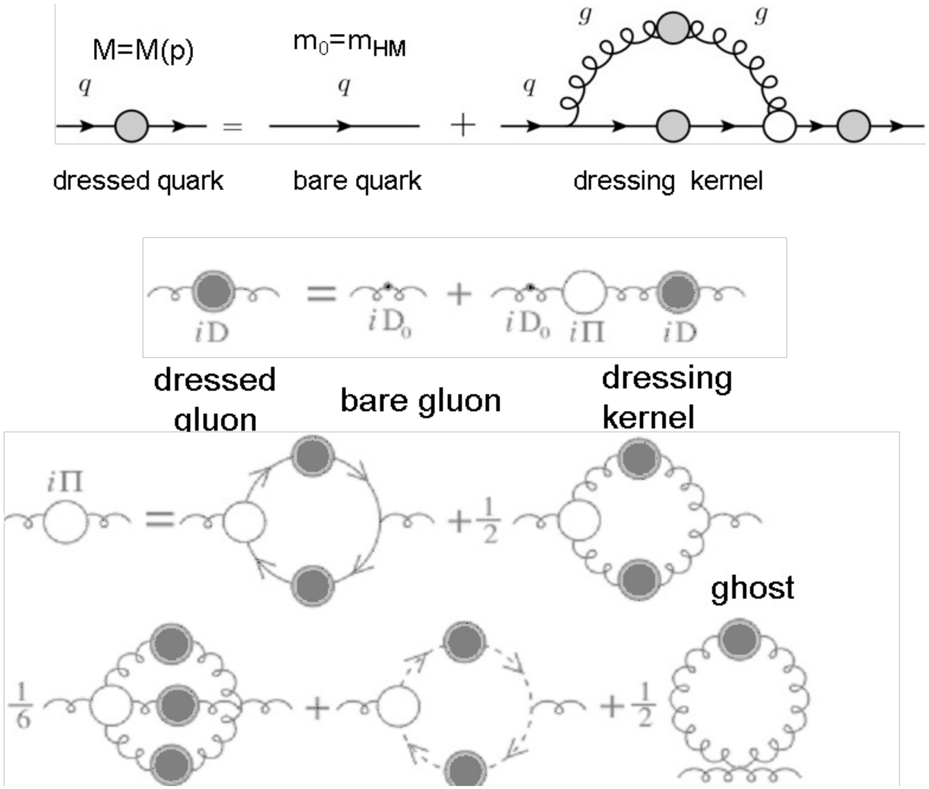


- **Higgs mechanism generates the masses of bare quarks**
- **Dominant part of nucleon mass is generated in processes other than the Higgs mechanism**

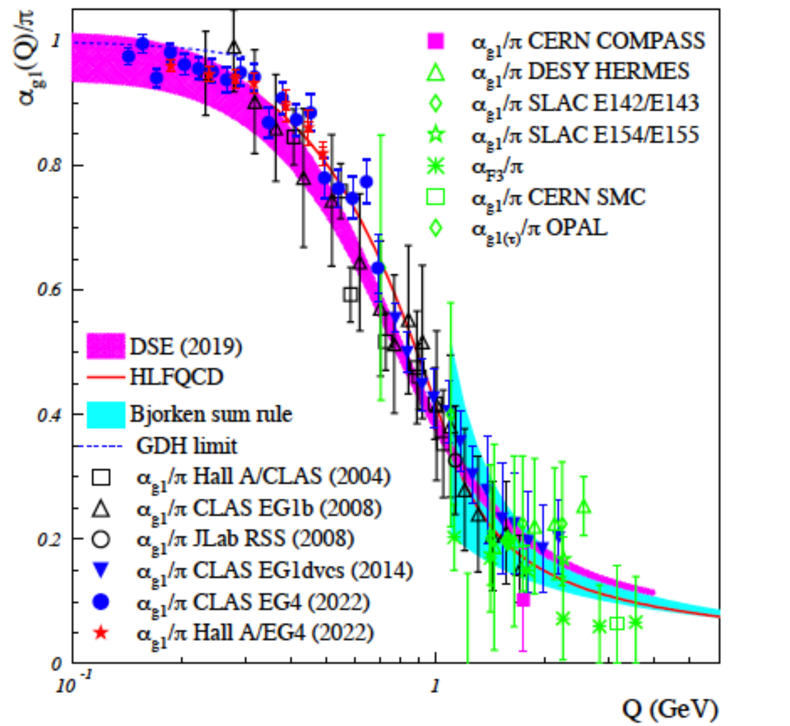
The Continuum Schwinger method (CSM) has conclusively demonstrated that the dominant part of hadron mass is generated by the strong interaction in the regime where the QCD running coupling becomes comparable with unity - the so-called strong QCD regime

Basics for Insight into EHM: CSM 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)

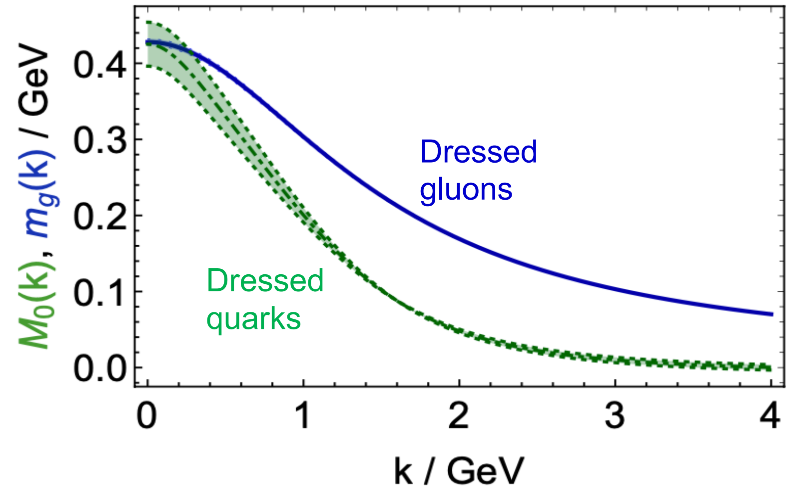


In the regime of the QCD running coupling comparable with unity, the dressed quarks and gluons with distance (momentum) dependent masses emerge from QCD, as follows from the equation of the motion for the QCD fields depicted above.

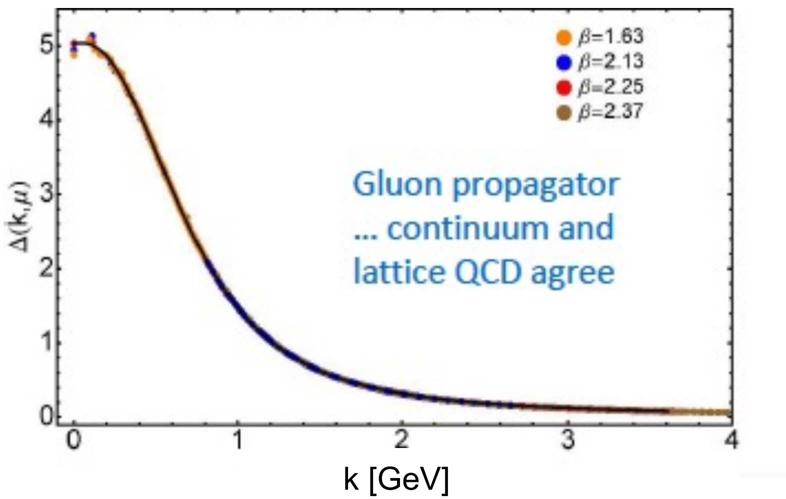
Basics for Insight into EHM: Continuum and Lattice QCD Synergy

- Express the fundamental feature: emergence of the quark and gluon masses even in the case of massless quarks in the 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

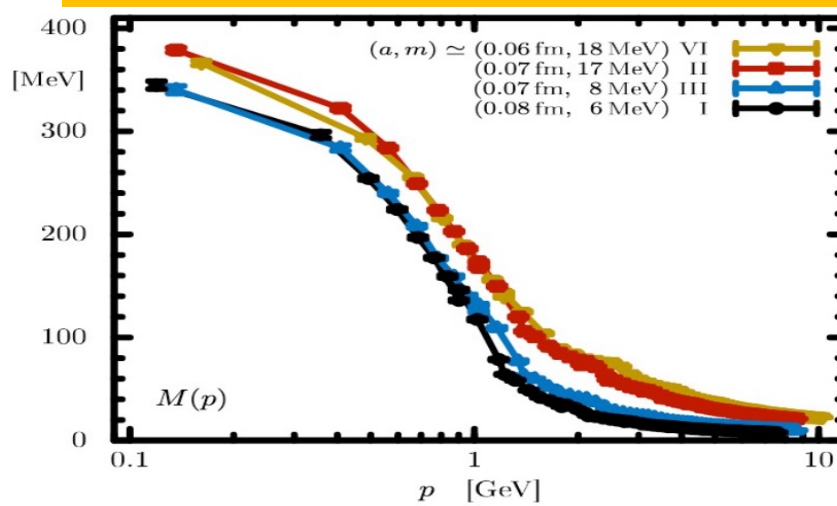
Dressed Quark/Gluon Masses (Continuum QCD)
C.D. Roberts, Symmetry 12, 1468 (2020)



Inferred from QCD Lagrangian with only Λ_{QCD} parameter



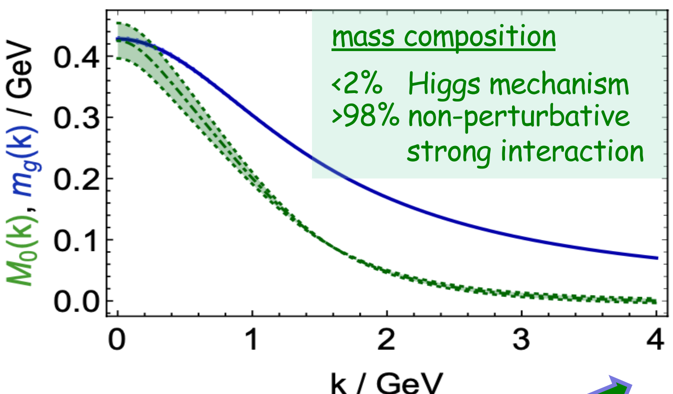
Dressed Quark Mass (Lattice QCD)
O. Olivera et al., Phys. Rev. D 99, 094506 (2019)



Emergence of Hadron Mass: Concept from CSM vs. Available Experimental Results

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*

confinement regime:
- constituent quark mass

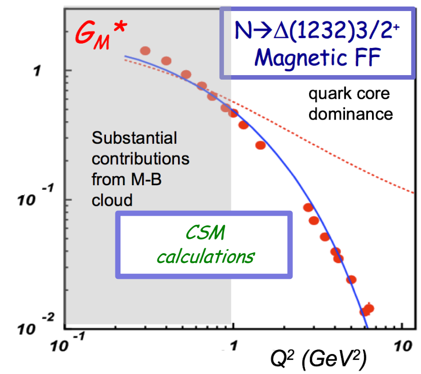


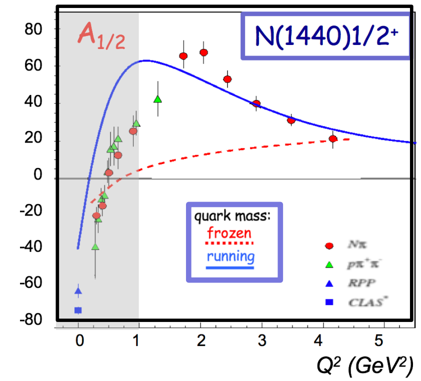
approaching bare quark Higgs mass

Dressed Quark/Gluon Masses from CSM
C.D. Roberts, Symmetry 12, 1468 (2020)

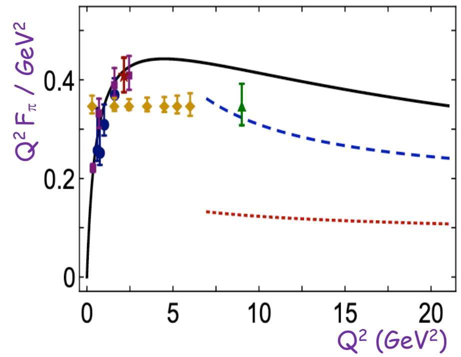
CLAS results vs. CSM expectations with running quark mass

J. Segovia, PRL 115, 171801 (2015)

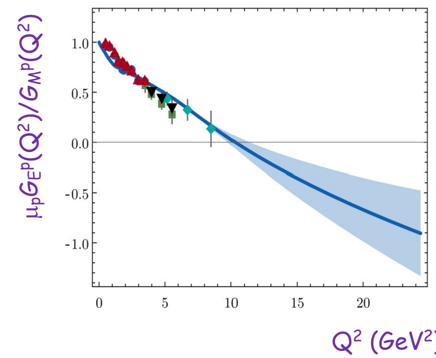




Pion Elastic FF

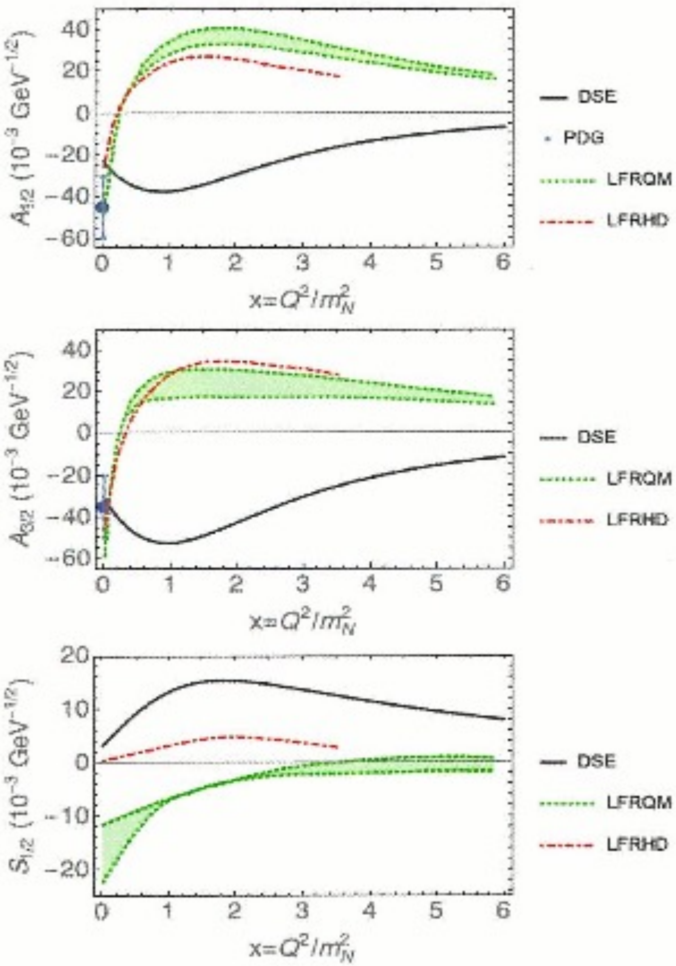


Nucleon Elastic FF



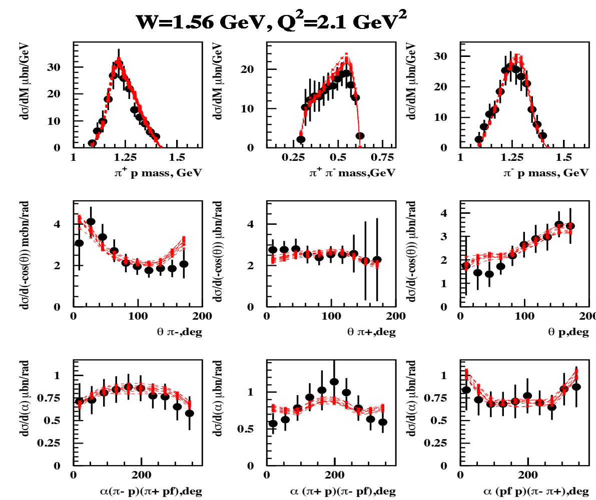
- *Dressed quarks with dynamically generated masses represent active degrees of freedom in the structure of the pion, nucleon, and the $\Delta(1232)3/2^+$, $N(1440)1/2^+$ resonances*
- ***Strong evidence for insight into EHM***

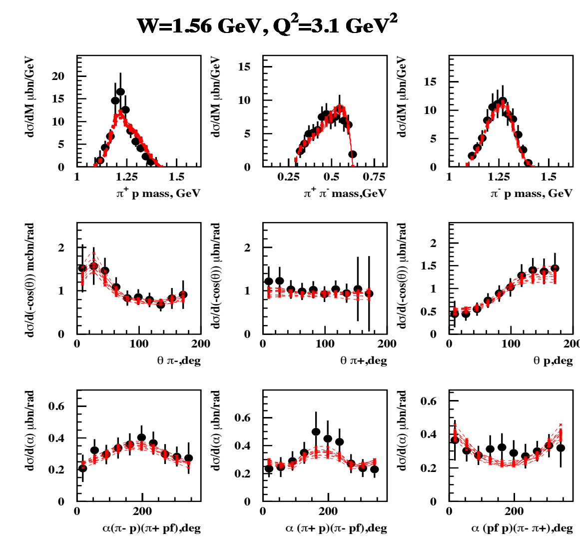
Electrocouplings of the Δ(1600)3/2$^+$: CSM Prediction vs. Data Determination



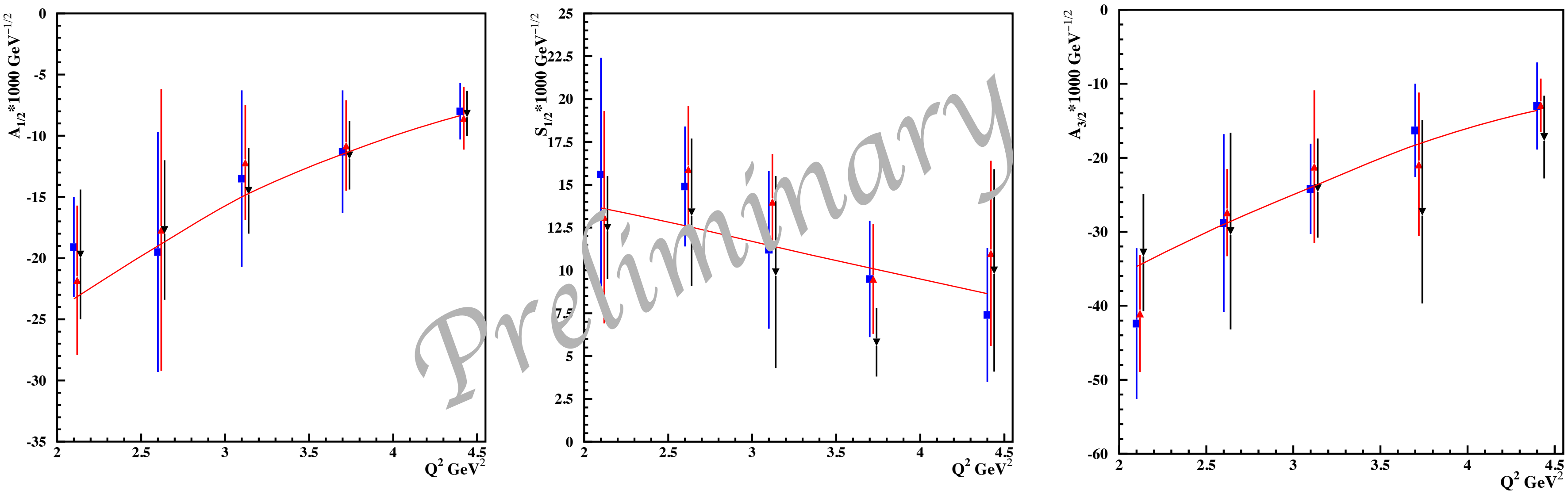
Parameter-free CSM predictions for Δ(1600)3/2$^+$ electrocouplings
Ya Lu et al., Phys. Rev. D 100, 034001 (2019)

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





Electrocouplings of the Δ(1600)3/2$^+$: 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

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

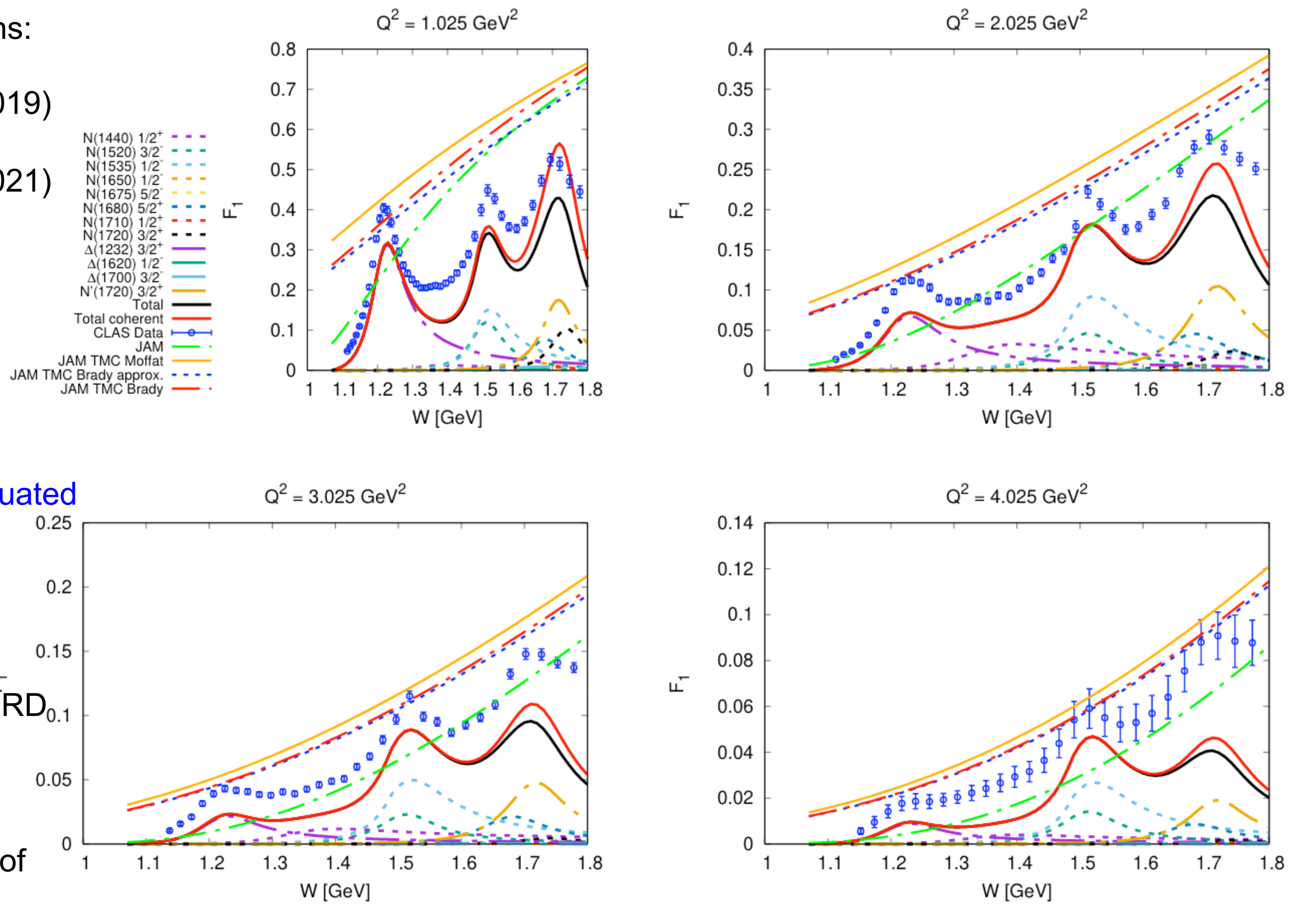
Resonant Contributions into Inclusive $F_1(W,Q^2)$ Structure Functions & the Contributions from the PDF in the Ground State of the Nucleon Evaluated from the Data in DIS Region

Resonant contributions:
A.N. Hiller Blin et al., PRC 100, 035201 (2019)
A.N. Hiller Blin et al., PRC 104, 025201 (2021)

Data points are from interpolation of the CLAS results re-evaluated with the σ_L/σ_T ratio from Hall A/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)

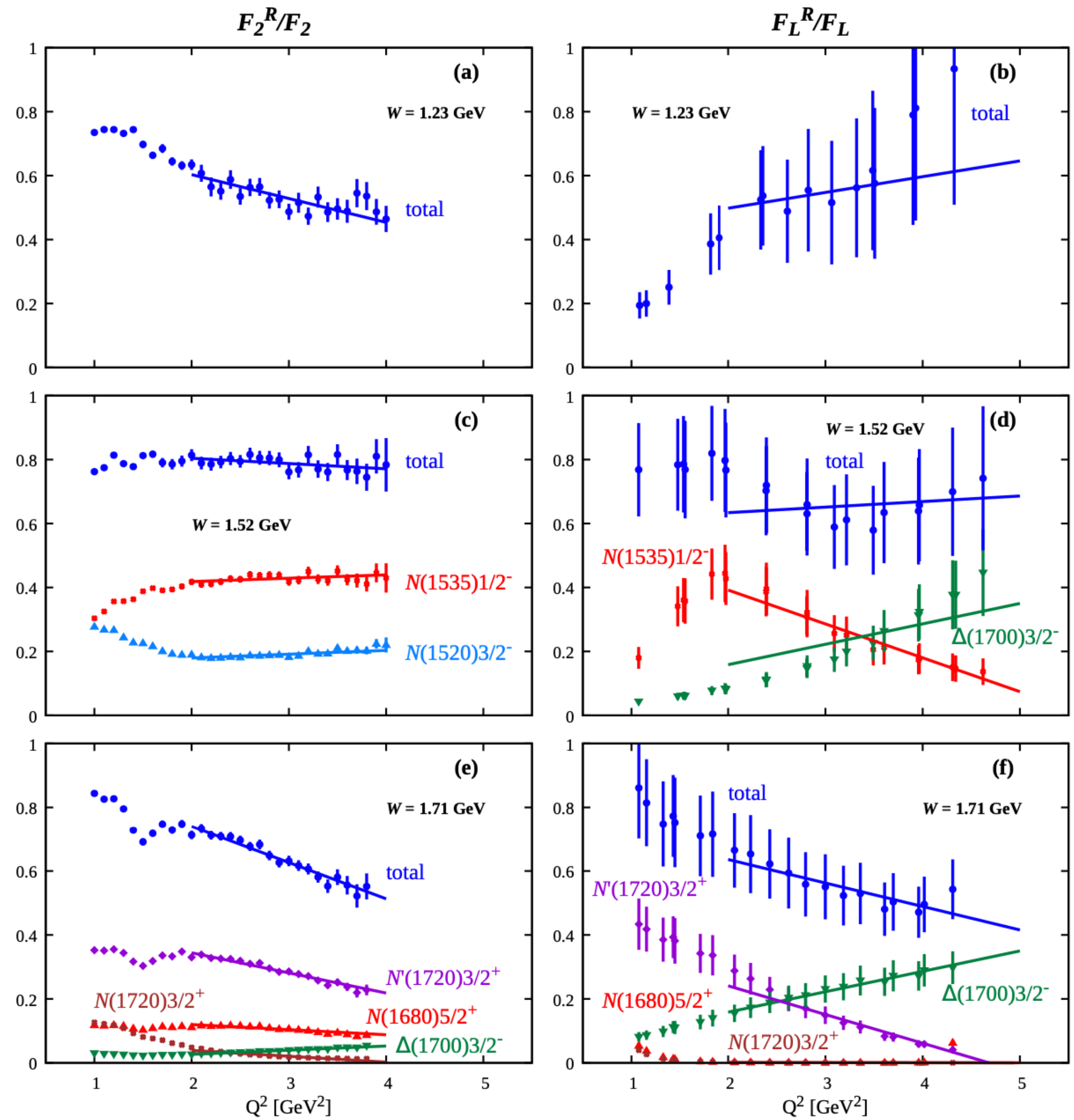


Green dot-dashed lines: F_1 from JAM PDF

Other smooth curves: F_1 from JAM PDF after target mass corrections within different prescriptions

Evolution of the Resonant Contributions with Photon Virtuality

Resonant contributions into the F_2, F_L structure functions are in the range of 40-60%, suggesting good prospects for the extraction of the $\gamma_v pN^*$ electrocouplings at Q^2>4.0 GeV^2



Emergence of Hadron Mass from N* Studies with the CLAS12

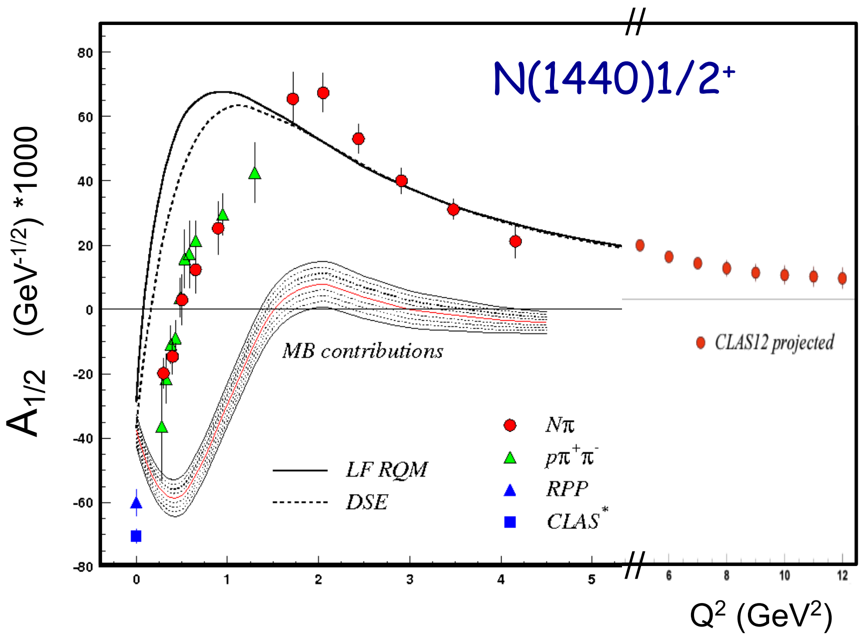
N* electroexcitation studies at JLab during 12 GeV era will address the critical questions:

How is >98% of visible mass generated?

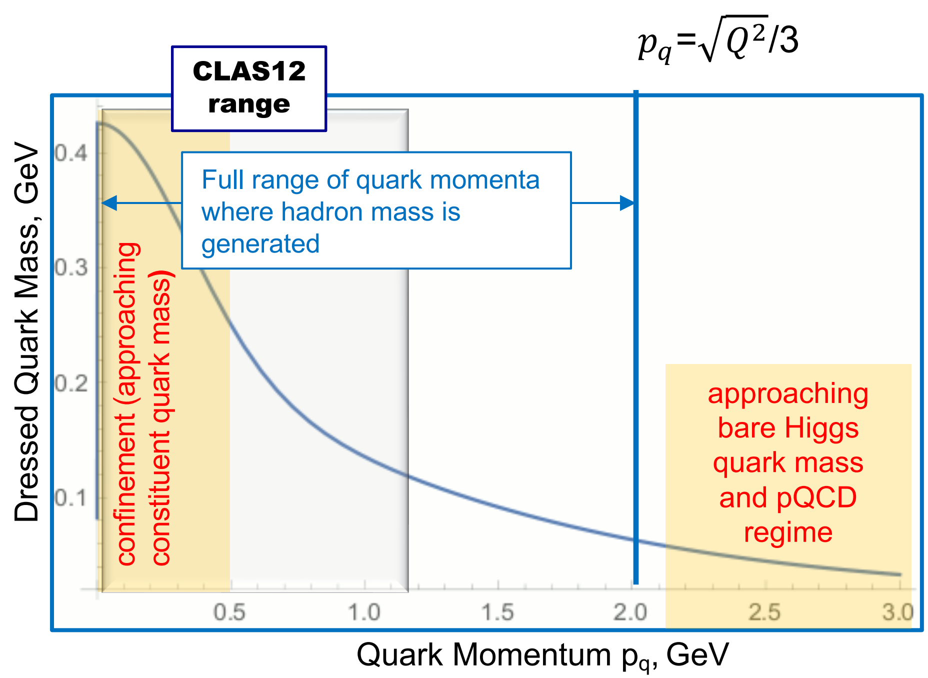
How EHM is related to Dynamical Chiral Symmetry Breaking?

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

Mapping-out dressed quark mass function from the results on $\gamma_v pN^*$ electrocouplings of different spin-isospin flip, radial, and orbital excited states of the nucleon at $5<Q^2<12$ GeV^2 is needed to explore the essential part of the range of distances where the dominant part of hadron mass is generated



CLAS results vs. theory expectations with running quark mass



Conclusions and Outlook

- **The CLAS detector has provided the dominant part of the world data on most exclusive meson electroproduction channels in the resonance region, allowing us to determine the electrocouplings of most resonances in the mass range up to 1.8 GeV and at $Q^2 < 5.0$ GeV^2. In the near future, the electrocouplings of all prominent nucleon resonances in the mass range <2.0 GeV will be determined from the CLAS data.**

- **A good description of the $\Delta(1232)3/2^+$ and $N(1440)1/2^+$ electroexcitation amplitudes *achieved within CSM approach starting from the QCD Lagrangian with the same dressed quark mass function* as used in the successful evaluations of the elastic ground nucleon and pion form factors, and the pion PDF validates insight into EHM.**

- **The CSM parameter-free predictions on the $\Delta(1600)3/2^+$ electrocouplings have been confirmed by the first results on the electrocouplings of this state obtained from $\pi^+\pi^-p$ electroproduction data offering strong evidence in support of the CSM concept for EHM.**

- **The first estimates of the resonant contributions into inclusive (e,e′X) scattering computed with resonance electrocouplings from experimental data open up new opportunities to extend knowledge on PDF in the ground states of the nucleon towards large fractional parton momenta x in the resonance region and to explore quark-hadron duality.**

- **CLAS12 is the only facility in the world that is capable of obtaining the electrocouplings of all prominent N* states at the still unexplored ranges of Q^2 from 5.0 GeV^2 to 12 GeV^2, allowing us to map out the dressed quark mass function at quark momenta < 1.3 GeV, where a substantial part of hadron mass is generated.**

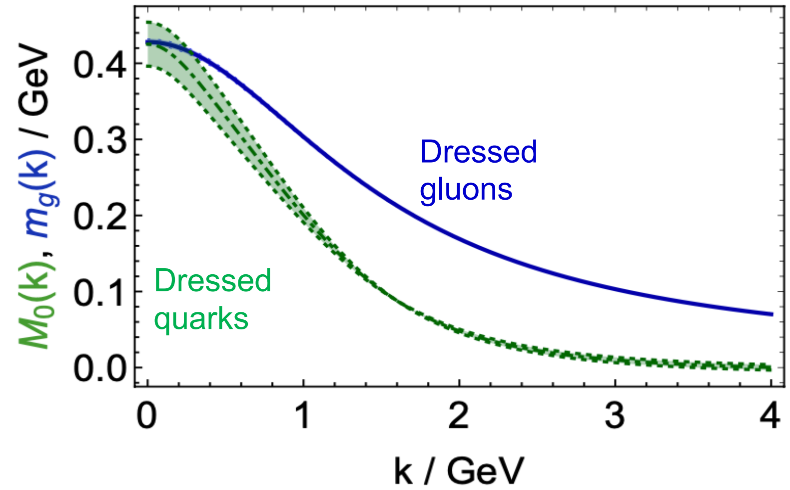
- **The CLAS/CLAS12 results on the $\gamma_v pN^*$ electrocouplings will address the most challenging problems of the Standard Model on the nature of hadron mass and emergence of the N* structure from QCD.**

Back up

Basics for Insight into EHM: Continuum and Lattice QCD Synergy

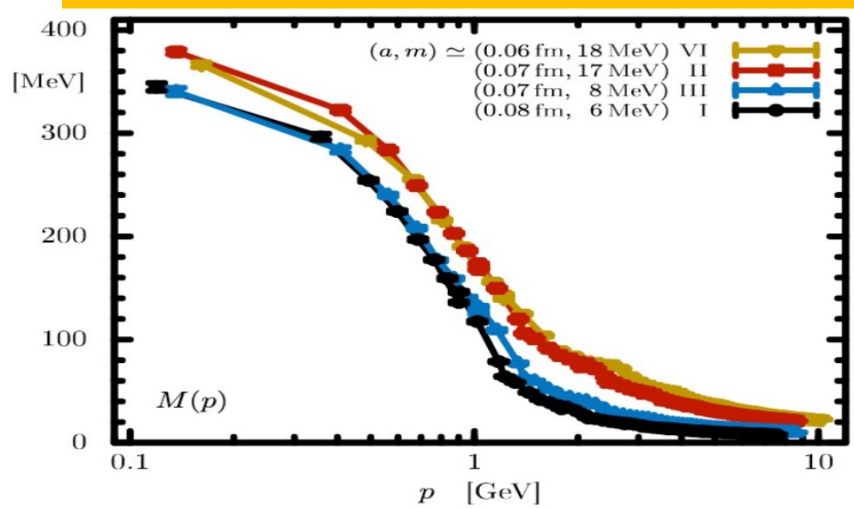
- Dressed quark/gluon masses converge at the complete QCD mass scale of 0.43(1) GeV - value impacted by Higgs mechanism
- Express the fundamental feature: emergence of the quark and gluon masses even in the case of massless quarks in the chiral limit and massless QCD gluons
- Continuum QCD results get 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)

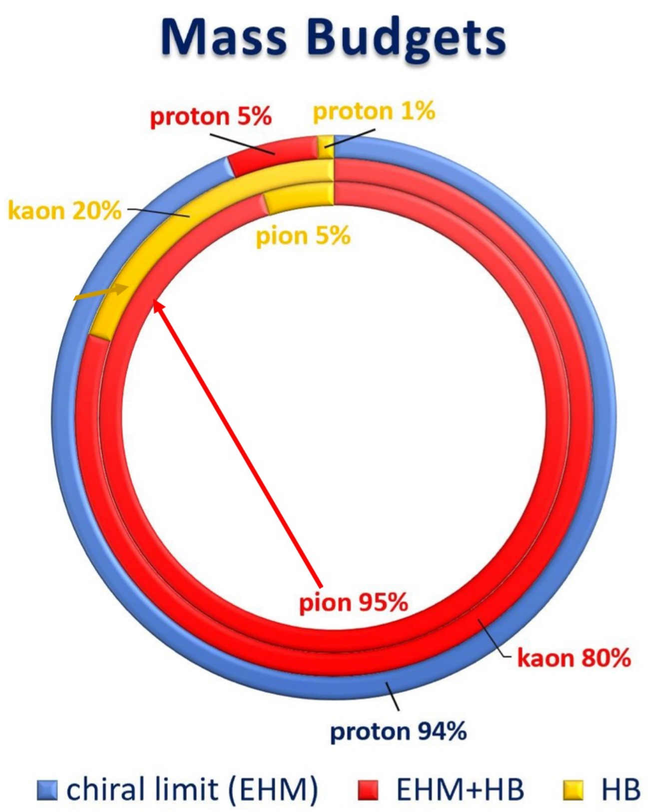


Inferred from QCD Lagrangian with only Λ_{QCD} parameter

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



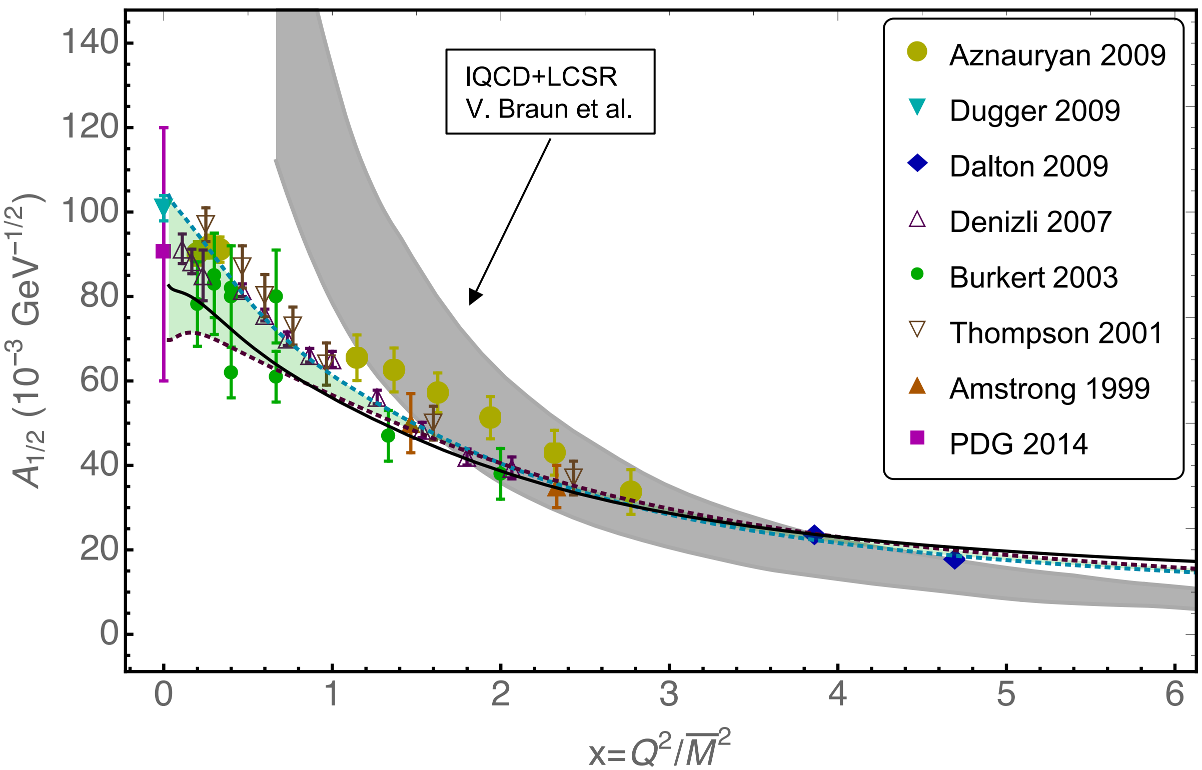
Insight into EHM from the Data on N/N* Structure



- 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 state nucleon structure are of particular importance for the validation of insight into EHM.

Toward Exploration of EHM from Orbital Nucleon Excitations



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

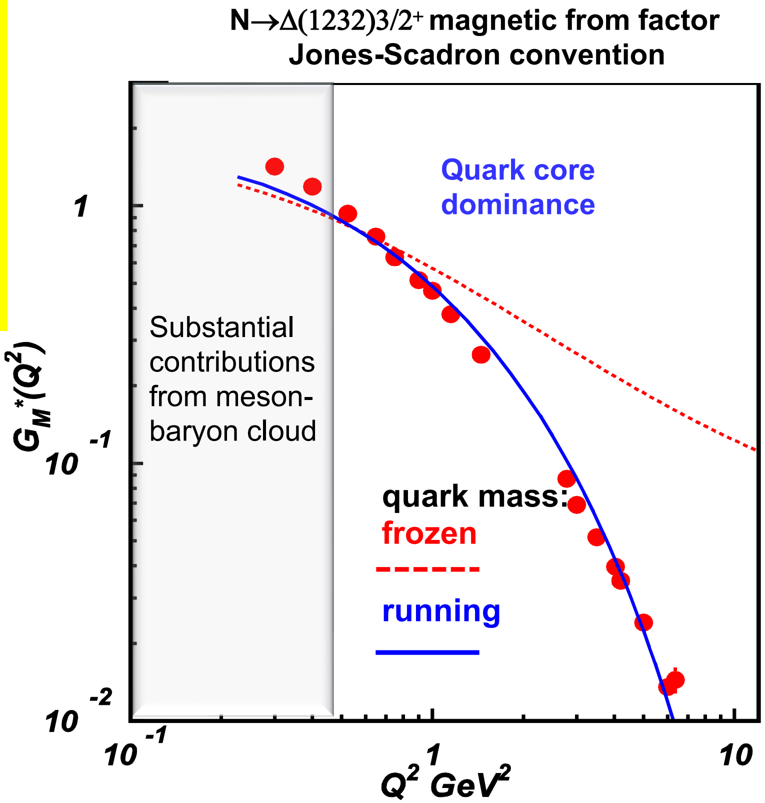
The first preliminary continuum QCD evaluation of electro-excitation amplitudes of the [70,1⁻] supermultiplet resonances (L_{3q}=1) with the same dressed quark mass mass function as used for the resonances with L_{3q}=0

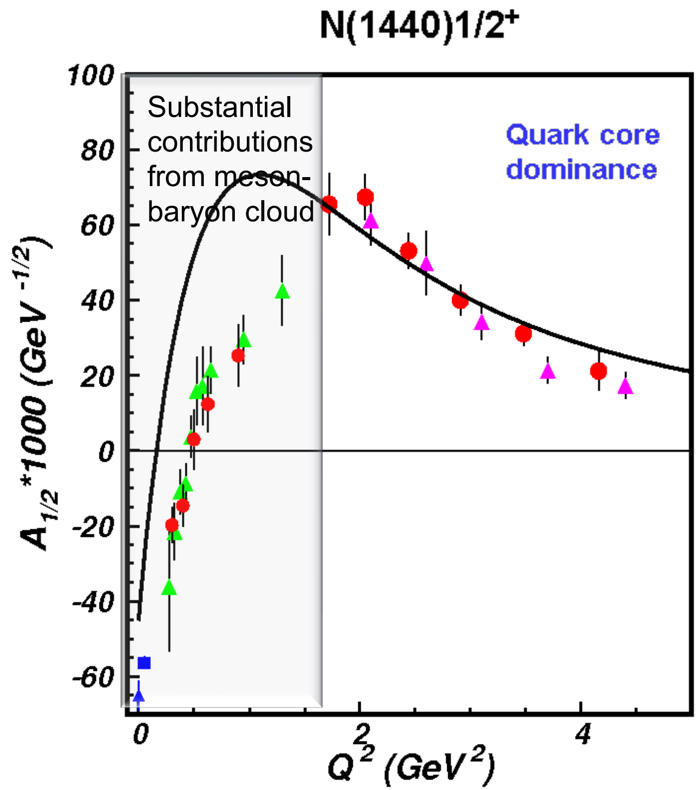
Studies of electroexcitation amplitudes for the resonances in the second region suggest the universality of the dressed quark mass function for the ground and different excited states of the nucleon, including the first spin-isospin flip, the first radial, and the first orbital (L_{3q}=1) excitations.

Insight to EHM From Resonance Electrocouplings

Dyson-Schwinger Equations (DSE):

- **J. Segovia et al., PRL 115, 171801 (2015)**
- **J. Segovia et al., Few Body Syst. 55, 1185 (2014)**



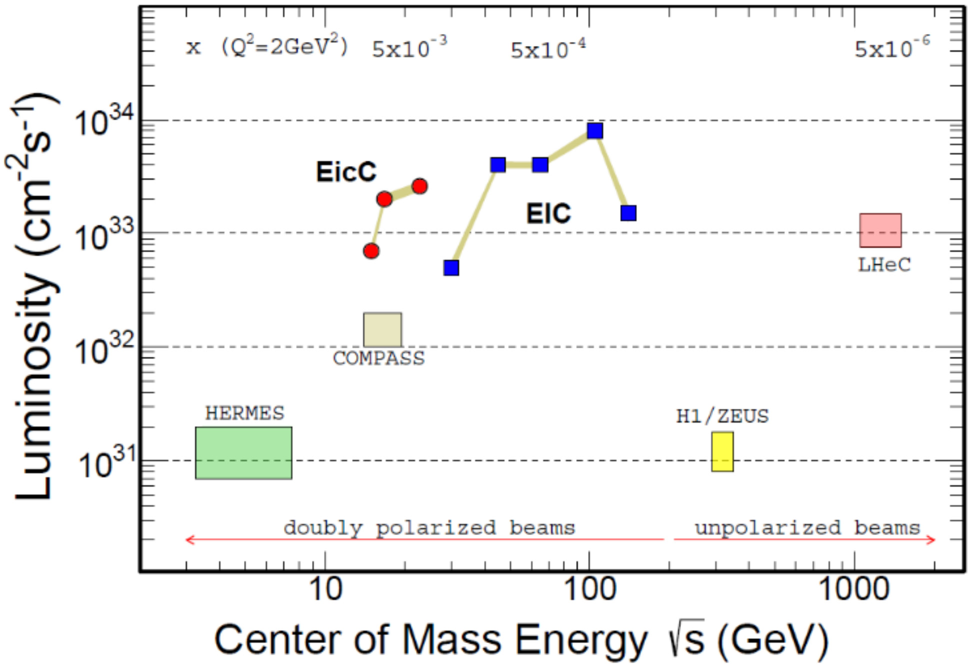


Good data description at Q^2>2.0 GeV^2 achieved with <u>the same dressed quark mass function</u> for the ground pion/nucleon and two excited nucleon states of distinctively different structure validates the continuum QCD results on the momentum dependence of the dressed quark mass. $\gamma_v pN^*$ electrocoupling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

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

Energy and luminosity increase up to $>10^{36}$ 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



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:

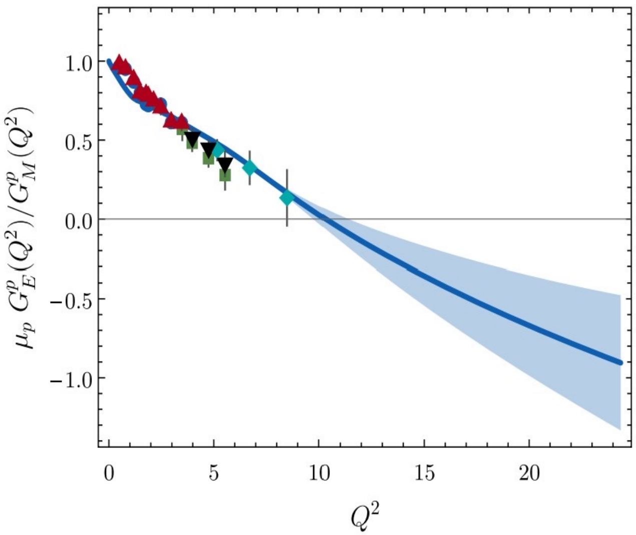
- Beam energy at fixed target: 24 GeV
- Nearly 4π coverage
- High luminosity

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

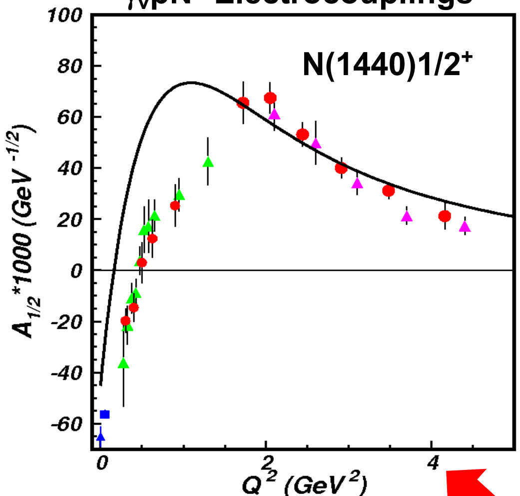
EHM from Global Hadron Structure Analysis

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

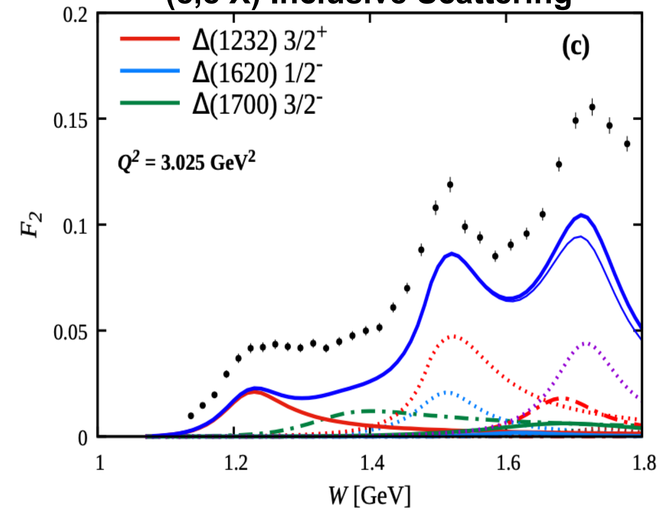
Nucleon Elastic FF



γ_vpN* Electrocouplings

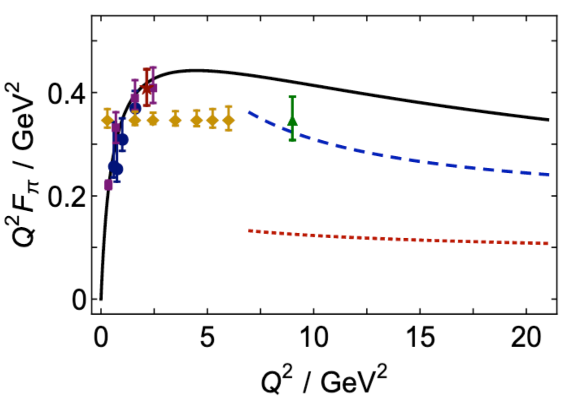


(e,e'X) Inclusive Scattering

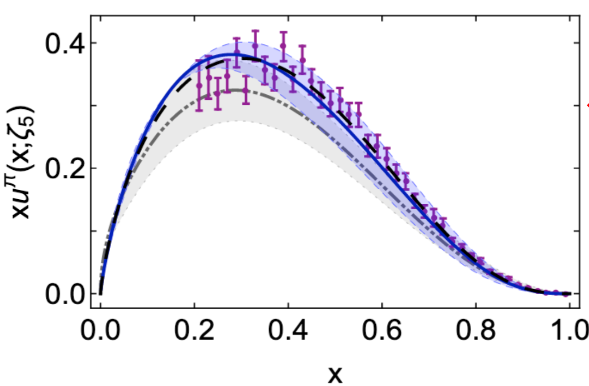


New data from studies of D-Y at AMBER and Sullivan processes at JLab

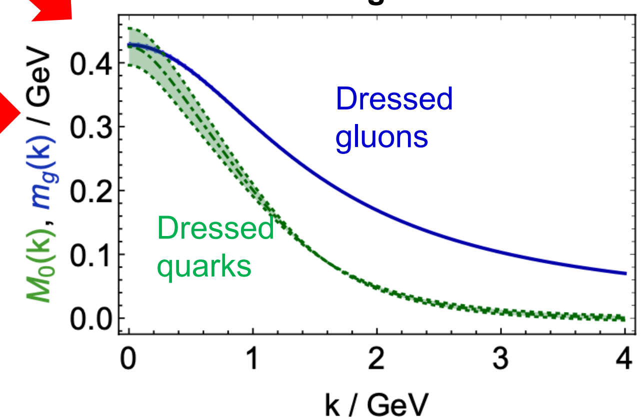
Pion Elastic FF



Pion PDF



Dressed Quark/Gluon Running Masses



- Insight into the dressed quark/gluon running masses from all the above experimental results 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.