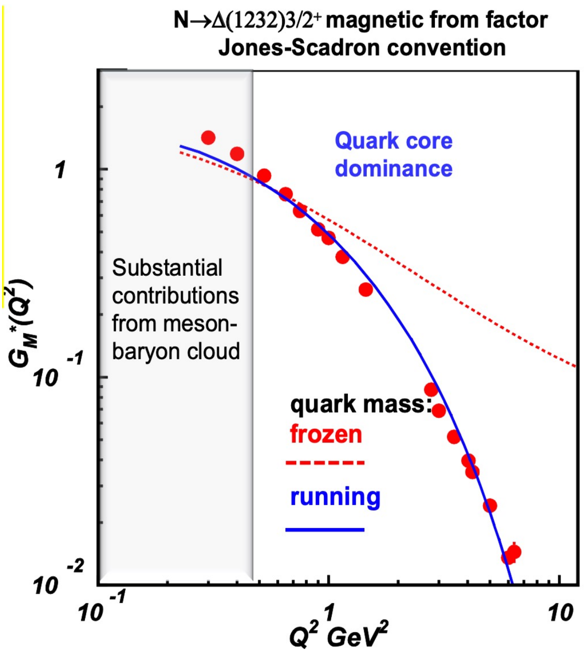
EHM from Resonance Electrocouplings



Talk outline:

- Insight into EHM from experimental studies of hadron structure
- EHM from studies of nucleon resonance electroexcitation amplitudes
- Gaining insight into EHM from inclusive electron scattering data in the resonance region

V.I. Mokeev, Jefferson Laboratory, for the CLAS Collaboration

How the Nucleon Mass Emerges?

Composition of the Nucleon Mass:

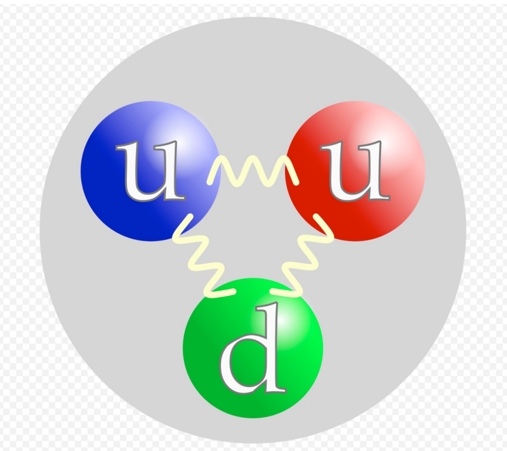
M_p, MeV (PDG20)

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



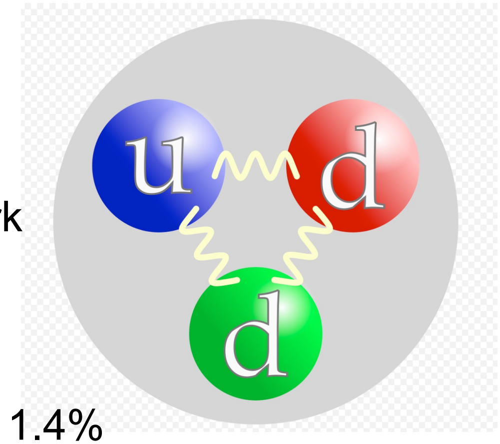
M_n, MeV (PDG20)

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 the processes other then Higgs mechanism**

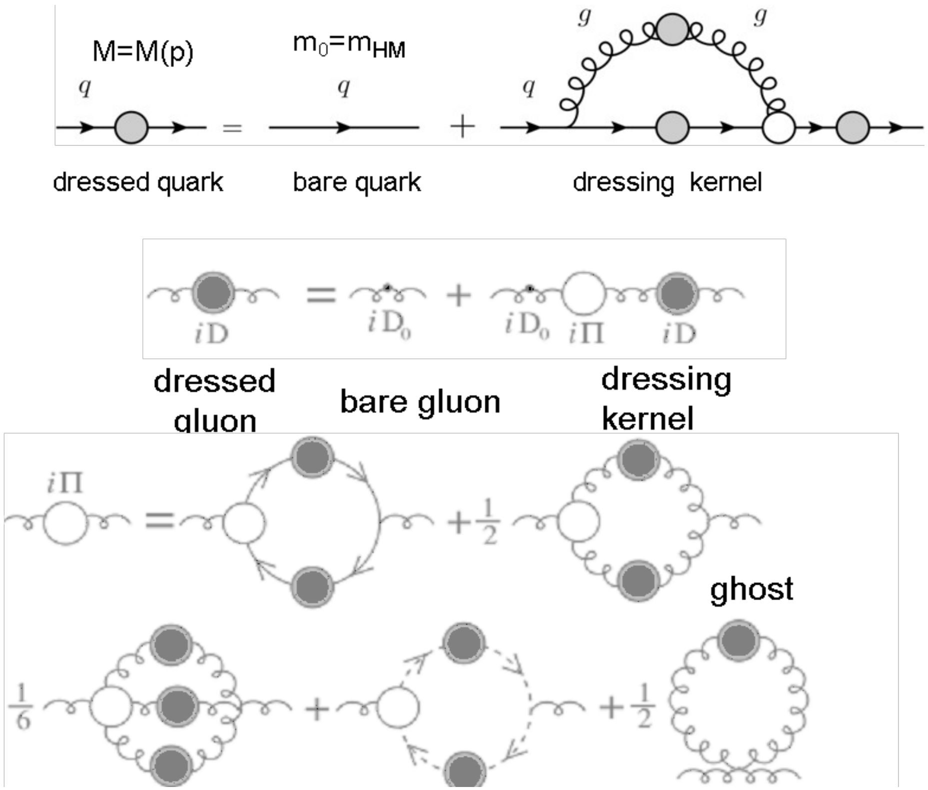
Open Problems in Exploration of the Emergence of Hadron Mass (EHM)

- What is the origin for the dominant part of nucleon mass?
- Is it the strong interaction in regime of a process-independent running-coupling that is consistent with unity?
- What is the role of the Higgs mechanism?
- How does the mass scale of strong QCD define the nucleon mass?
- Why are the pion and kaon much lighter than the sum of the masses of their quark constituents?

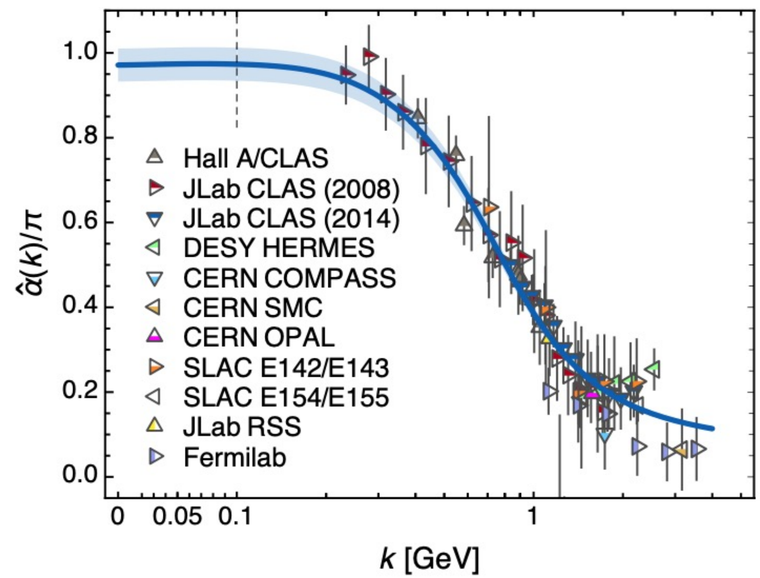
Continuum QCD approach provided viable framework for the EHM exploration offering predictions for the spectra/structure of the ground and excited hadrons in connection with the EHM.

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 a(k) Rodrguez-Quintero J, et al.,
Few Body Syst 59, 121 (2018)



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

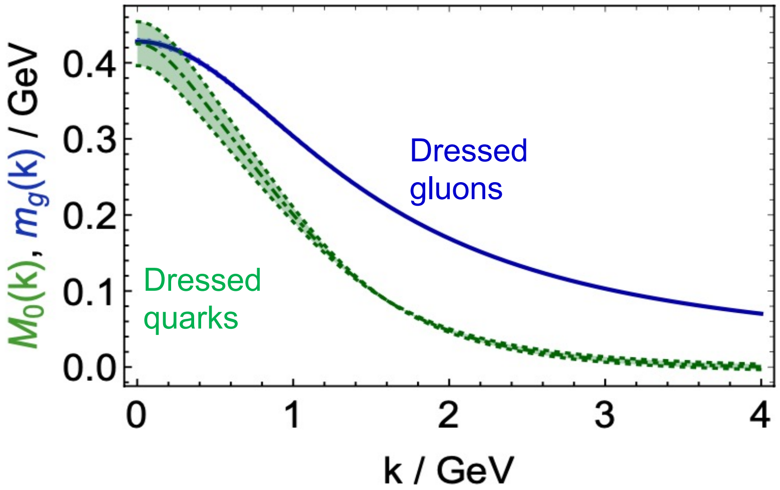
Basics for Insight into EHM: Continuum and Lattice QCD Synergy

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

- Continuum QCD results get support from LQCD

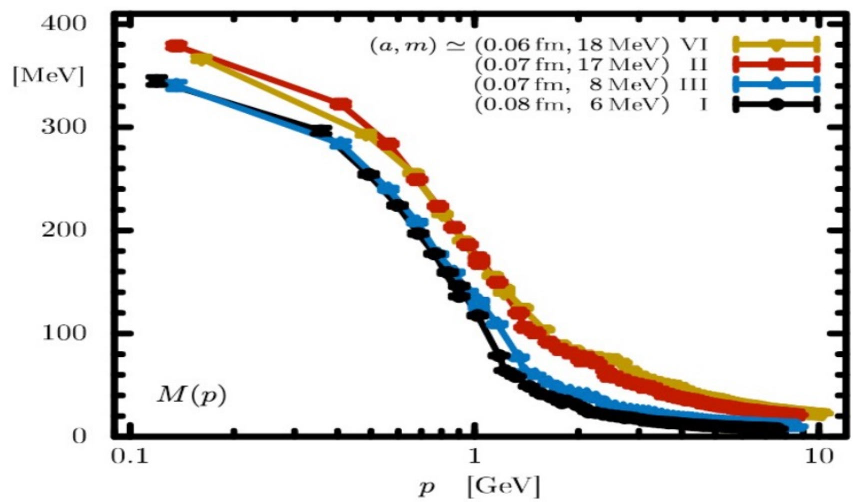
- Insight into dressed quark mass function from data on hadron structure represents a challenge for experimental hadron physics

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



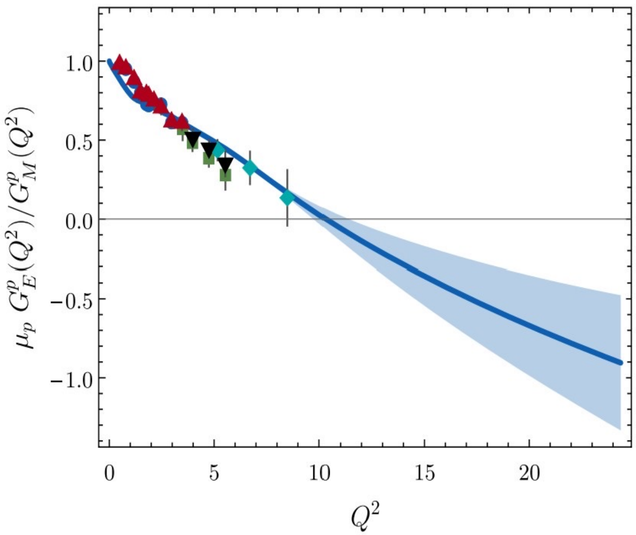
Inferred from QCD Lagrangian with only the Λ_{QCD} parameter

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

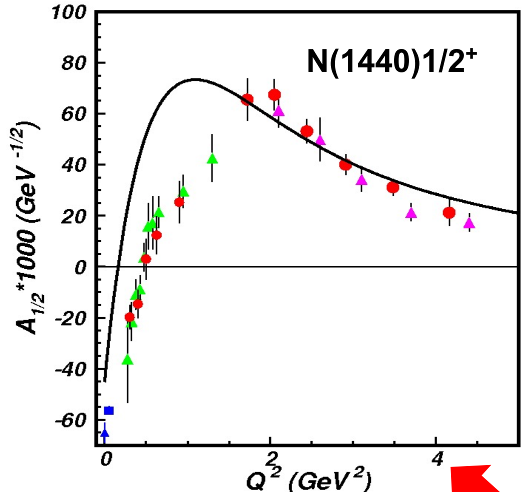


Will be extended by the future data from JLab in the 12 GeV era

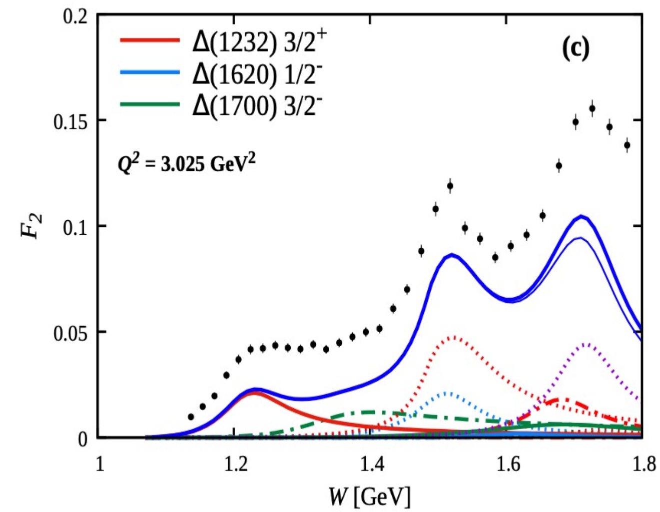
Nucleon Elastic FF



$\gamma_v pN^*$ Electrocouplings

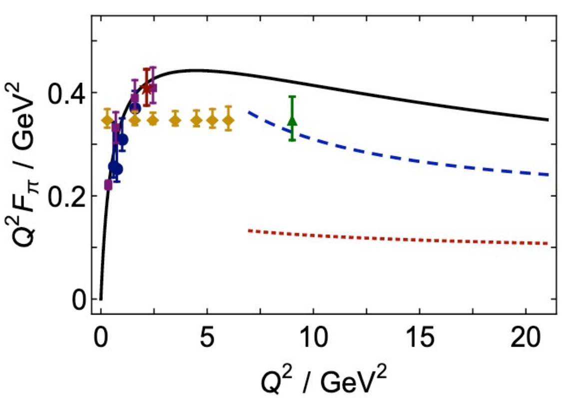


(e,e'X) Inclusive Scattering

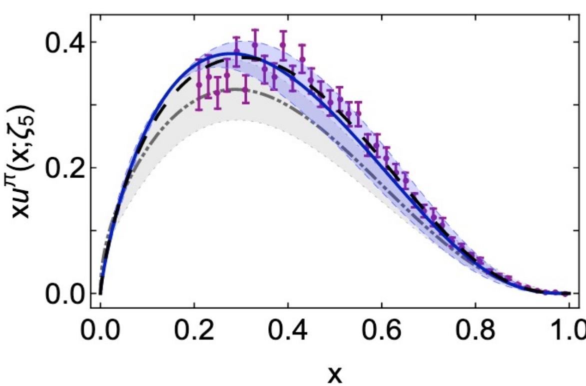


New data from studies of DY at AMBER and Sullivan processes at JLab

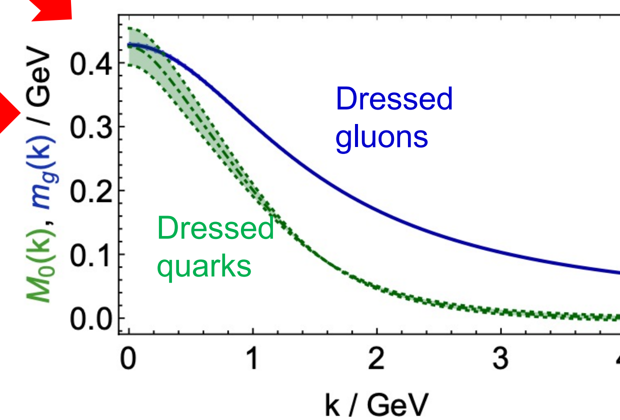
Pion Elastic FF



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

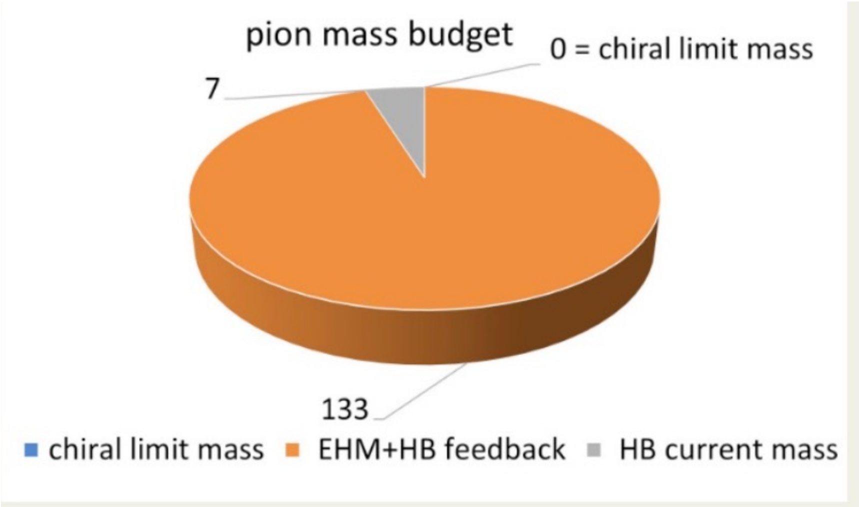
Insight into EHM from the Data on Pion/Kaon Structure

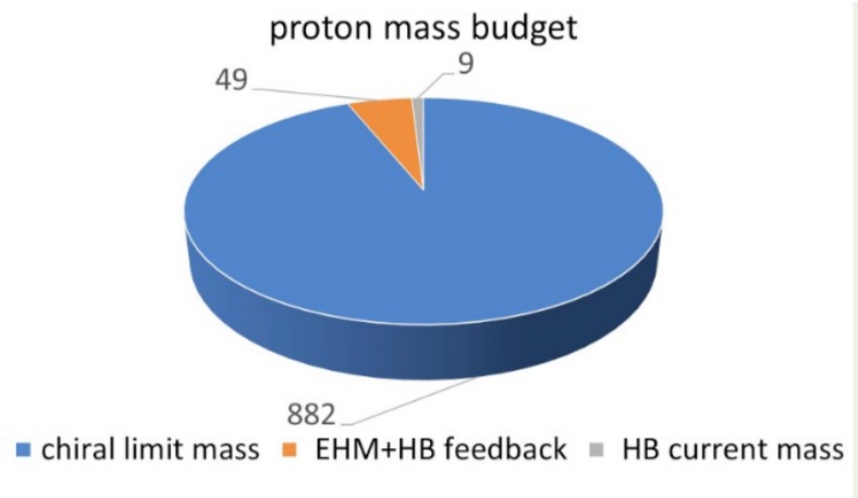
- The model and renormalization scheme/scale independent Goldberger-Treiman relations connect the momentum dependence of the dressed quark mass to the pion/kaon Bethe-Salpeter amplitudes, making the studies of pion and kaon structure a promising way to map out the momentum dependence of the dressed quark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





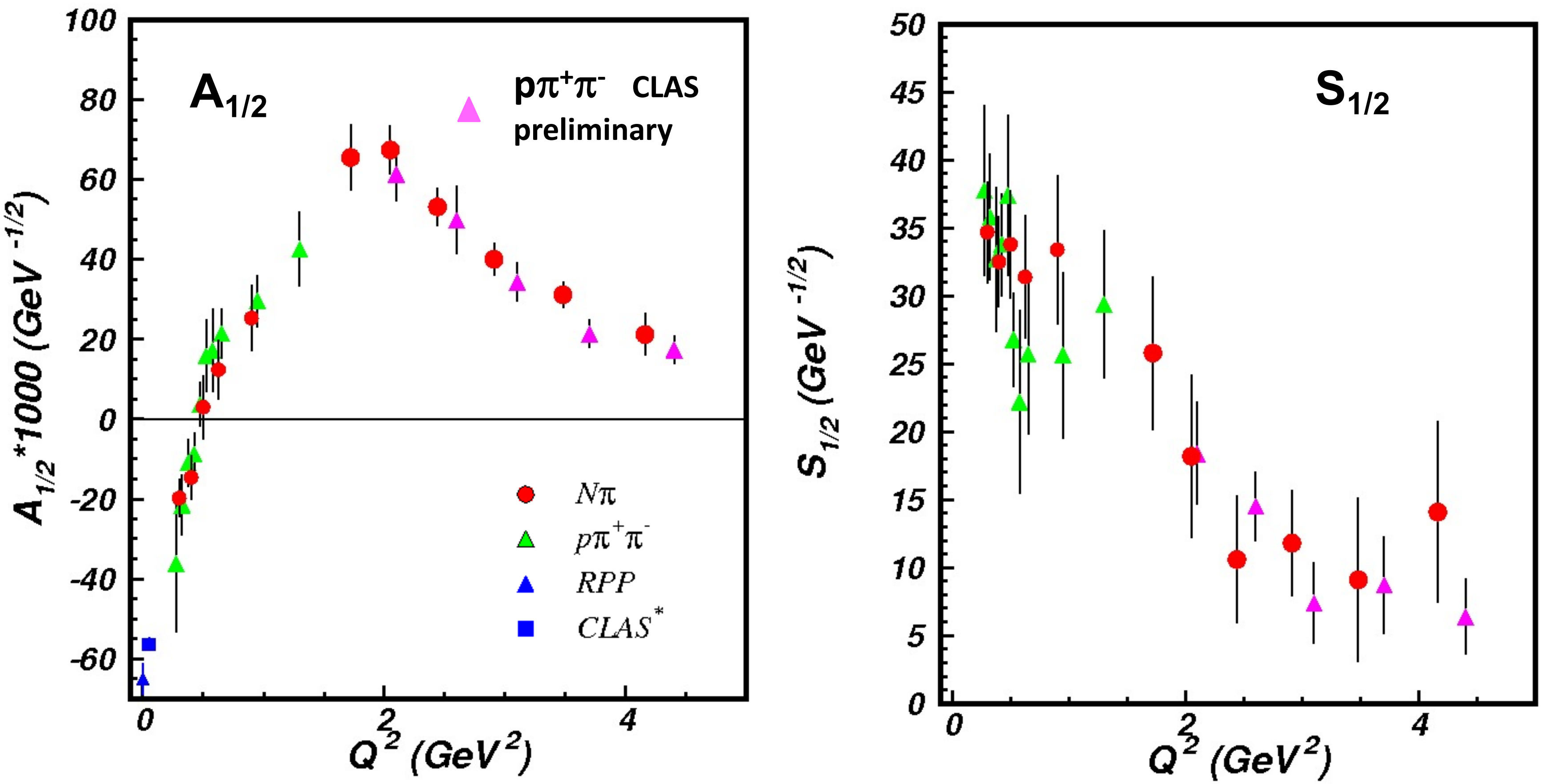
- Studies of the ground and excited nucleon state structure allow us to explore the dressed quark mass function in a different environment when the sum of dressed quark masses is the dominant contribution into the physical masses of the ground and excited states of the nucleon
- Consistent results on 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.

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
$\pi^0 p$, $\pi^+ n$	$\Delta(1232)3/2^+$	0.16-6.0
	$N(1440)1/2^+$,$N(1520)3/2^-$, $N(1535)1/2^-$	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
$\pi^+\pi^- p$	$N(1440)1/2^+$, $N(1520)3/2^-$	0.25-1.50 2.0-5.0 (preliminary)
	$\Delta(1620)1/2^-$, $N(1650)1/2^-$, $N(1680)5/2^+$, $\Delta(1700)3/2^-$, $N(1720)3/2^+$, $N'(1720)3/2^+$	0.5-1.5

- The N* electroexcitation amplitudes ($\gamma_v pN^*$ electrocouplings) in a broad range of Q^2 offer a unique opportunity to explore universality on environmental sensitivity of dressed quark mass function
- Consistent results on dressed quark mass function from $\gamma_v pN^*$ electrocouplings of different resonances validate insight into EHM in a nearly model-independent way

Electrocouplings of N(1440)1/2+ from πN and $\pi^+\pi^-$p Electroproduction off Proton Data



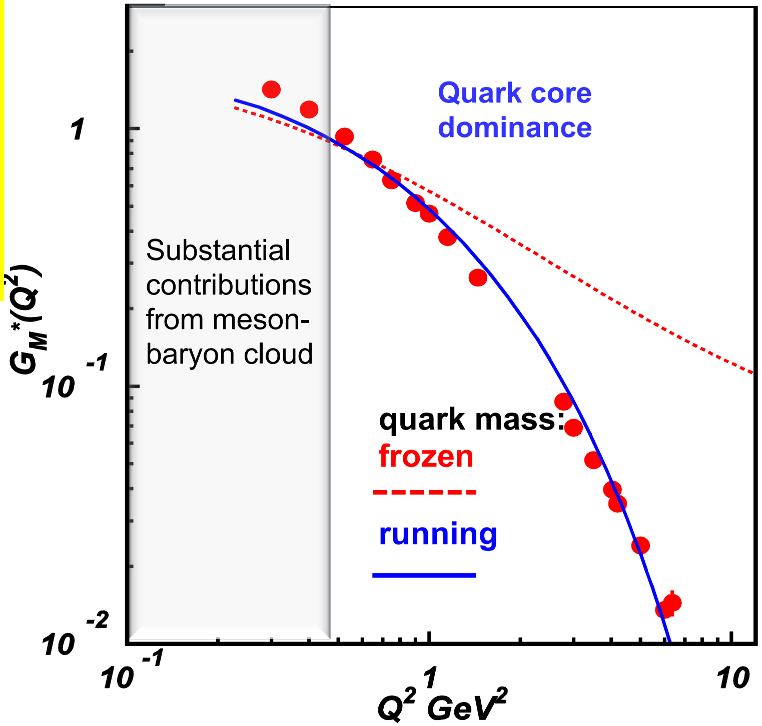
Consistent results on N(1440)1/2+ electrocouplings from independent studies of two major πN and $\pi^+\pi^-$p electroproduction channels with different non-resonant contributions allow us to evaluate the systematic uncertainties of these quantities in a nearly model-independent way

Insight to EHM From Resonance Electrocouplings

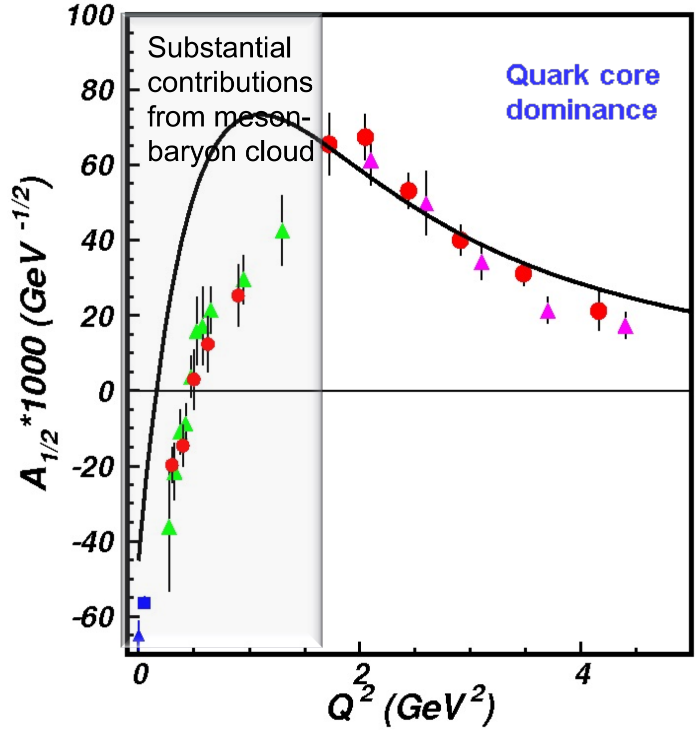
Dyson-Schwinger Equations (DSE):

- J. Segovia et al., Phys. Rev. Lett. 115, 171801 (2015)
- J. Segovia et al., Few Body Syst. 55, 1185 (2014)

N→Δ(1232)3/2+ magnetic from factor
Jones-Scadron convention



N(1440)1/2+

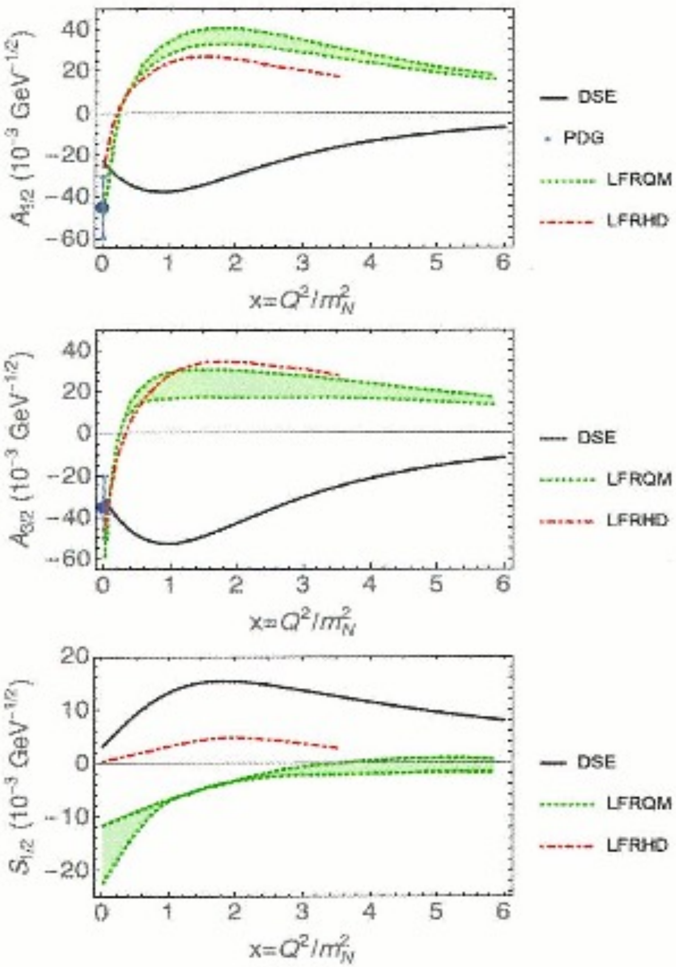


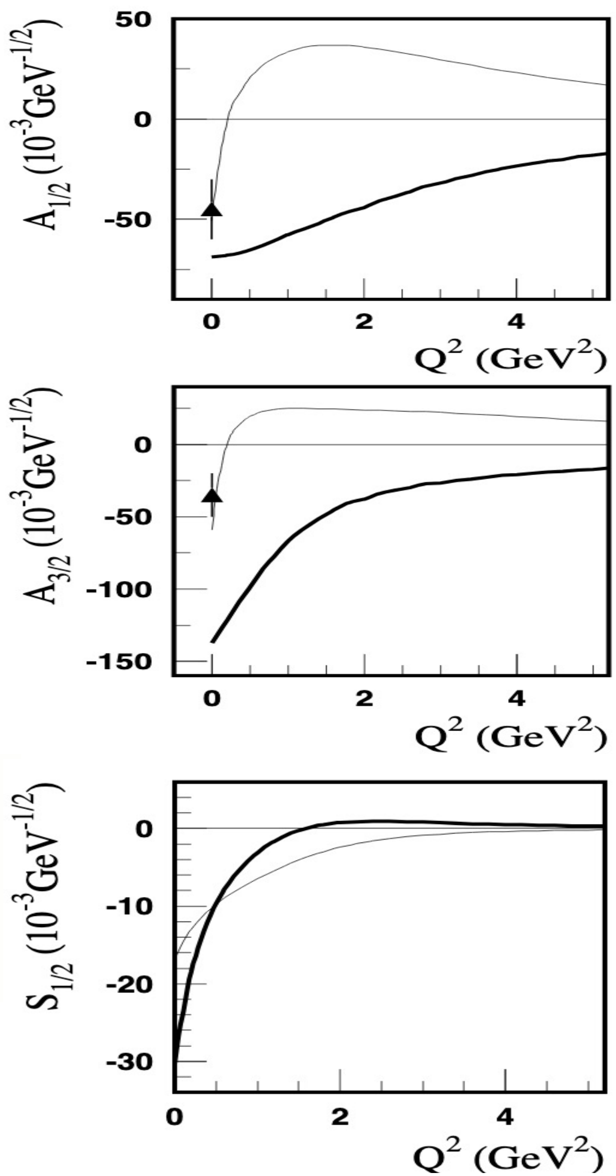
Good data description at Q^2>2.0 GeV^2 achieved with the same dressed quark mass function for the ground and two excited nucleon states of distinctively different structure validates the continuum QCD results on the momentum dependence of the dressed quark mass. $\gamma_v pN^*$ electrocoupling data offer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

Predictions for Electrocouplings of the First Radial Δ-Excitation Δ(1600)3/2+ from Continuum QCD approache with Momentum Dependent Dressed Quark Mass

Δ(1600)3/2+



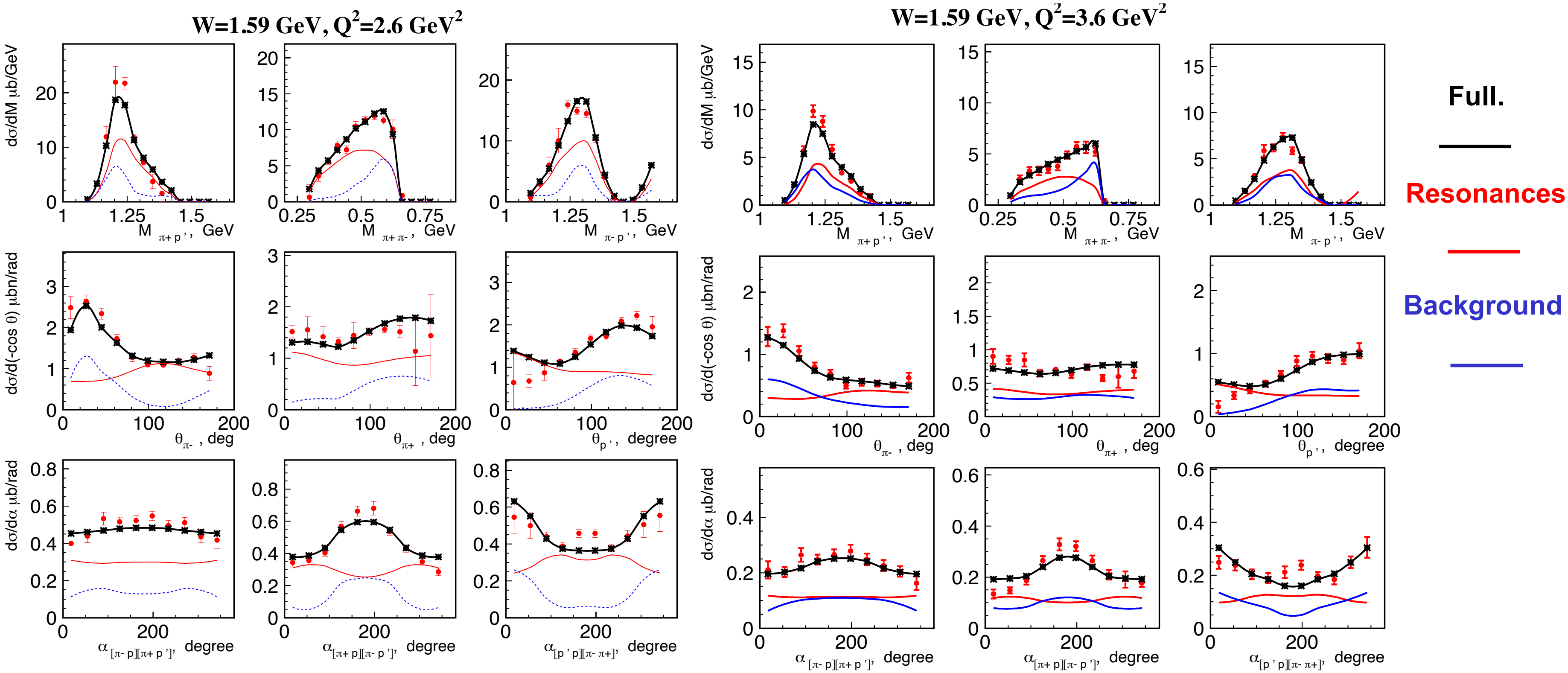


LFRQM accounting for 3-quark configuration mixing : I.G. Aznauryan and V.D. Burkert arXiv: 1603.06692 [nep-ph]

Parameter free continuum QCD (DSE) predictions for Δ(1600)3/2+ electrocouplings. Ya Lu et al., Phys. Rev. D100, 034001 (2019)

Description of the $\pi^+\pi^-p$ CLAS Data with Electrocouplings of $\Delta(1600)3/2^+$ from Continuum QCD Approach

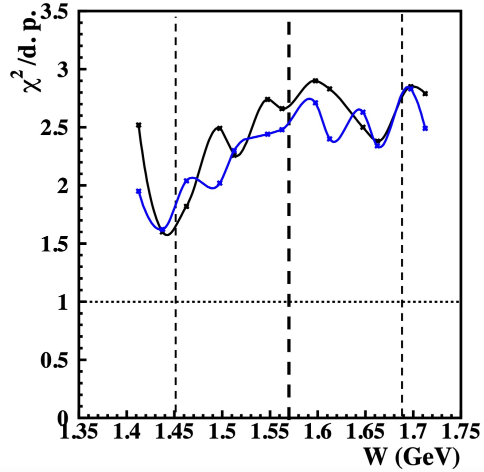
χ^2/d.p. = 2.71 χ^2/d.p. = 2.59



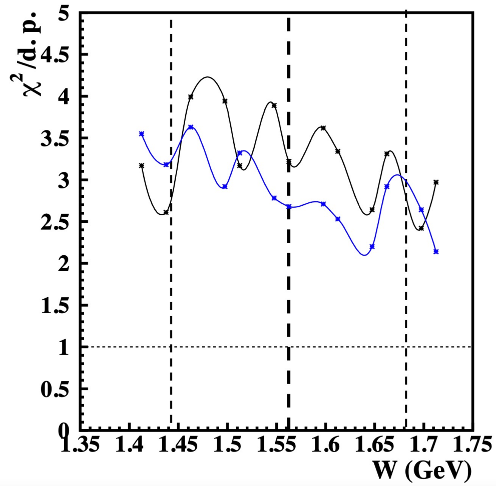
Confirmation of the continuum QCD expectations on the $\Delta(1600)3/2^+$ electrocouplings will provide strong evidence for credible access to the mass functions of u- and-quarks at quark momenta <0.5 GeV

Quality of the $\pi^+\pi^-p$ Data Description with/without $\Delta(1600)3/2^+$

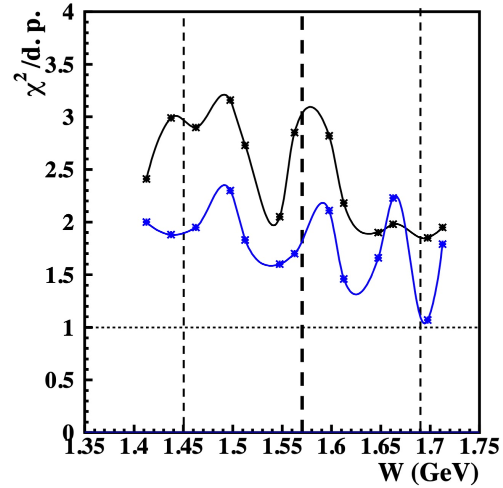
2.0 GeV^2<Q^2<2.4 GeV^2



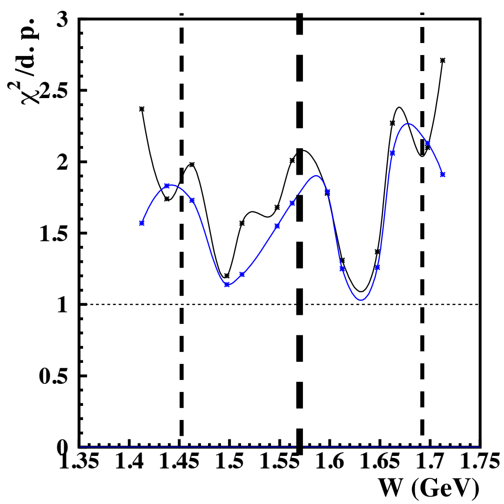
2.4 GeV^2<Q^2<3.0 GeV^2



3.0 GeV^2<Q^2<3.5 GeV^2



4.2 GeV^2<Q^2<5.0 GeV^2



Thick dashed line stands for $\Delta(1600)3/2^+$ mass, the interval between thin dashed lines corresponds to the resonance width

—— $\Delta(1600)3/2^+$ contribution is replaced by the non-resonant processes

—— $\Delta(1600)3/2^+$ resonance is included with electro-couplings predicted within continuum QCD (slide #9)

Implementation of $\Delta(1600)3/2^+$ resonance with electrocouplings from the continuum QCD approach improves description of $\pi^+\pi^-p$ electroproduction data at 1.45 GeV<W<1.68 GeV and 2.0<Q^2<5.0 GeV^2

Emergence of Hadron Mass and Quark-Gluon Confinement

N* electroexcitation studies at JLab will address the critical open questions:

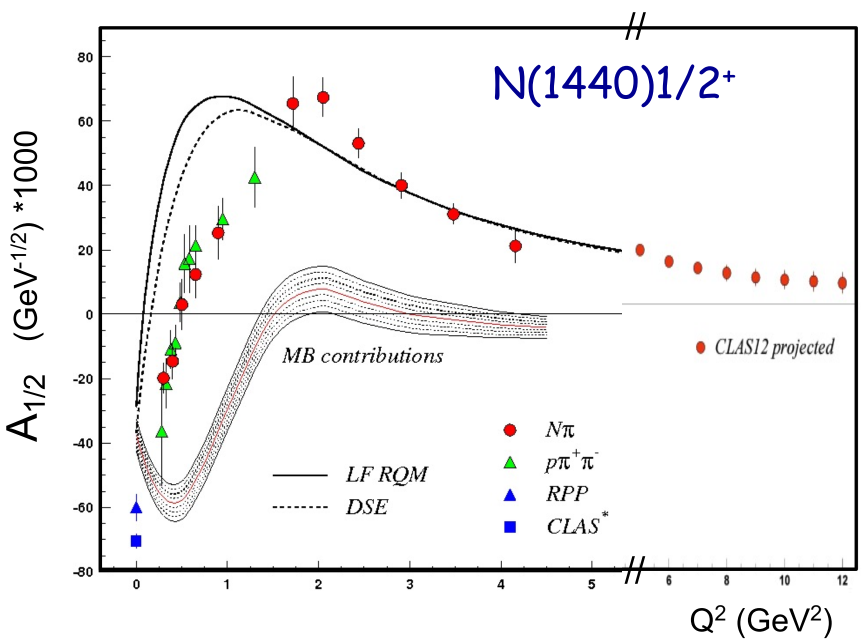
How is >98% of visible mass generated?

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

What is the behavior of QCD's running coupling at infrared momenta?

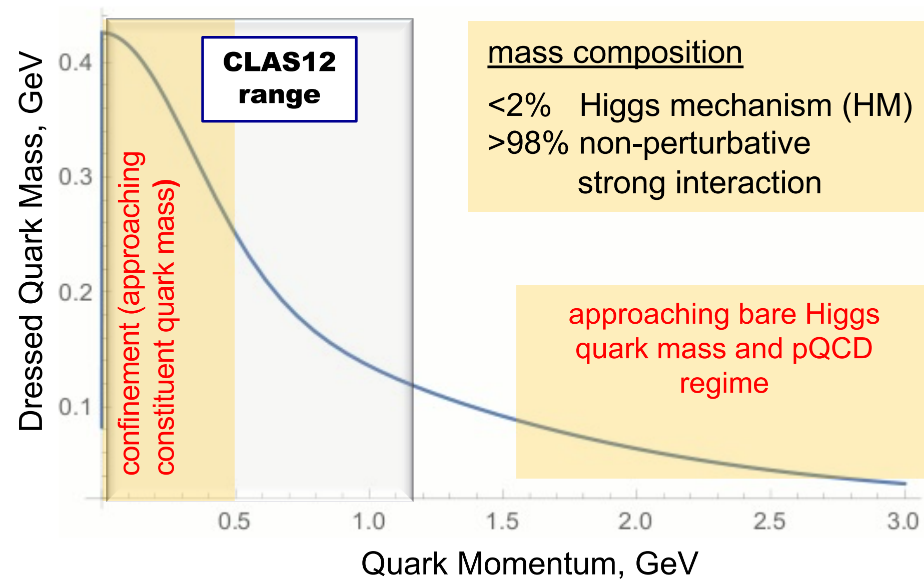
(S.J, Brodsky et al., Int. J. Mod. Phys. Rev. E29, 2030006 (2020))

Mapping-out quark mass function from the CLAS12 results on $\gamma_v pN^*$ electrocouplings of spin-isospin flip, radial, and orbital excited nucleon resonances at $5<Q^2<12$ GeV^2 will allow us to explore the transition from strong QCD to pQCD regimes



CLAS results vs. theory expectations with running quark mass

Access to the dressed quark/hadron mass generation

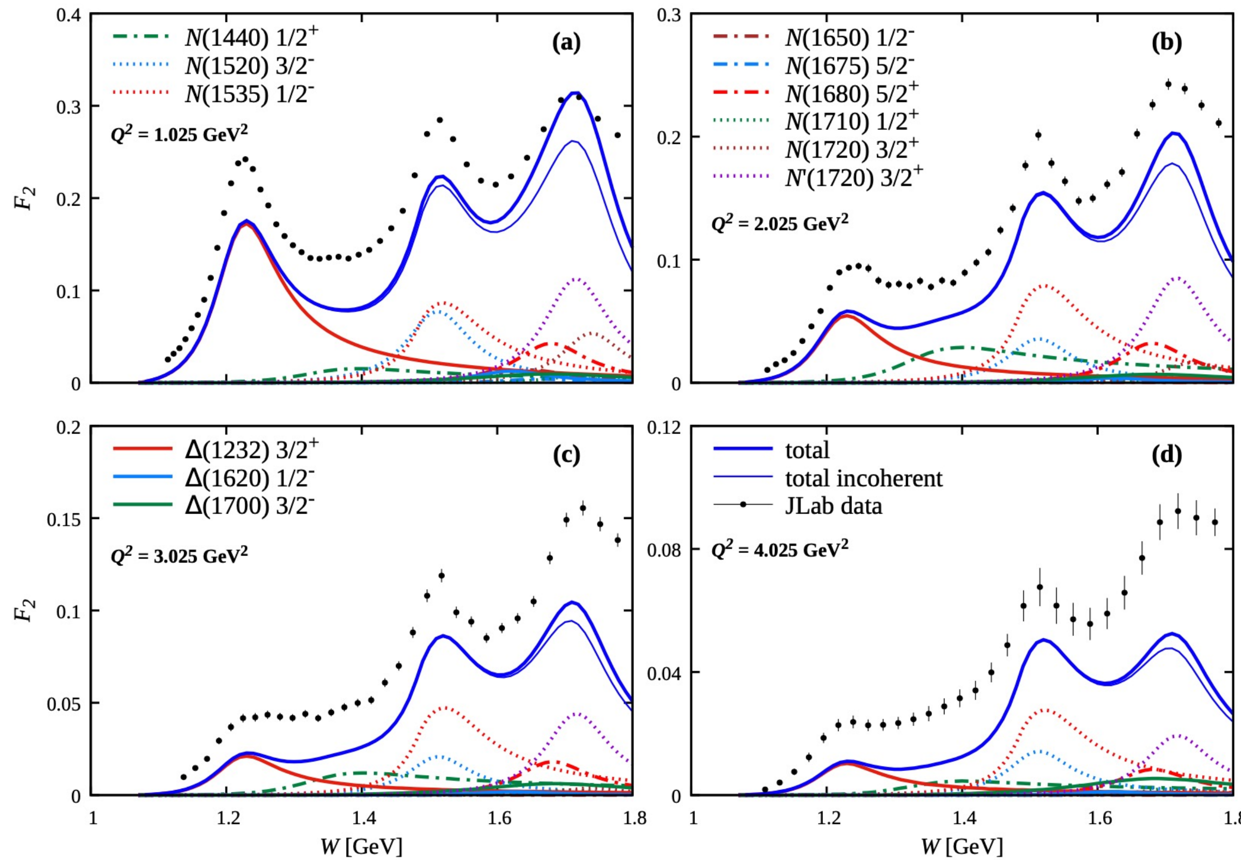


Resonant Contributions into Inclusive $F_2(W,Q^2)$ Structure Functions

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

CLAS data:
M. Osipenko et al., PRD 67, 092001 (2003)
Hall C data:
Y. Liang, Ph.D. thesis of American University (2003)

N* contributions :
A.N. Hiller Blin et al., Phys. Rev. C100, 035201 (2019)



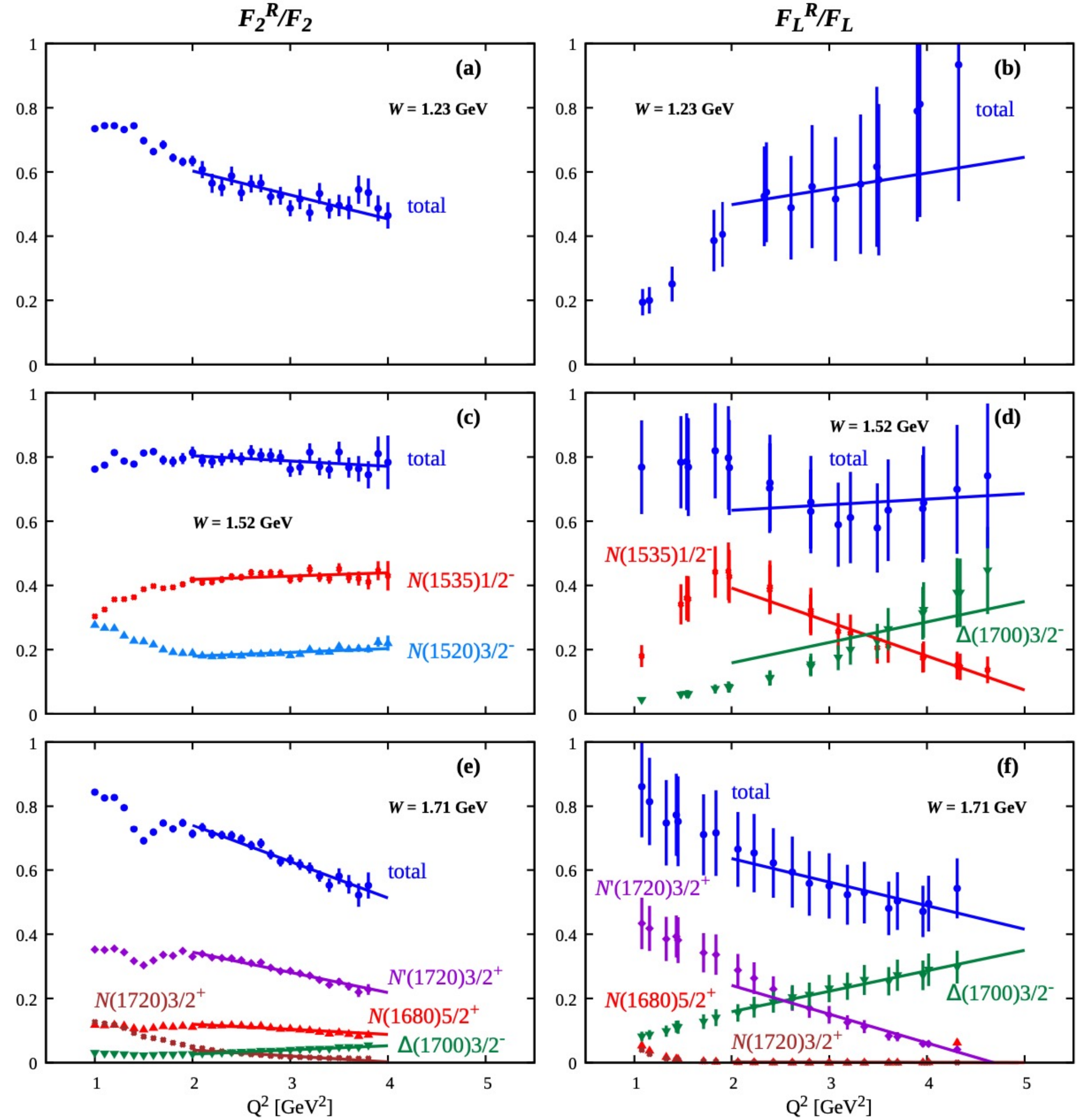
- **Insight into EHM:** **The non-resonant parts of the F_2 structure function can be computed with the dressed quark mass function supported by the results on pion and nucleon elastic FFs, and on $\gamma_v pN^*$ electrocouplings. Estimated from the resonant/non-resonant contributions, full F_2 structure function will be confronted to the data.**

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, allowing to map out the dressed quark mass towards higher quark momenta

Intriguing feature: the same rate in Q^2-evolution of the resonant and non-resonant contributions into the F_2 structure function within the second resonance region at Q^2>2.0 GeV^2

Complementary information from F_2 and F_L



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.

- The CLAS data on $\gamma_v pN^*$ electrocouplings will allow us to check universality on environmental sensitivity of dressed quark mass function.

- A good description of CLAS results on $\Delta(1232)3/2^+$ and $N(1440)1/2^+$ 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, validate insight to the dynamics that underlie the emergence of hadron mass. Studies of the $\Delta(1600)3/2^+$ electrocouplings are in progress.

- Analyses of inclusive (e,e'X) scattering from CLAS/CLAS12 in both resonant and DIS regions with estimates for the resonant contributions computed from the results on $\gamma_v pN^*$ electrocouplings will allow us to probe the momentum dependence of the dressed quark mass from the independent array of the data.

- The expected results from CLAS12 will allow us to map out the dressed quark mass function at the distances where the dominant part of hadron mass is generated, addressing the most challenging problems of the Standard Model on the nature hadron mass and of quark-gluon confinement.