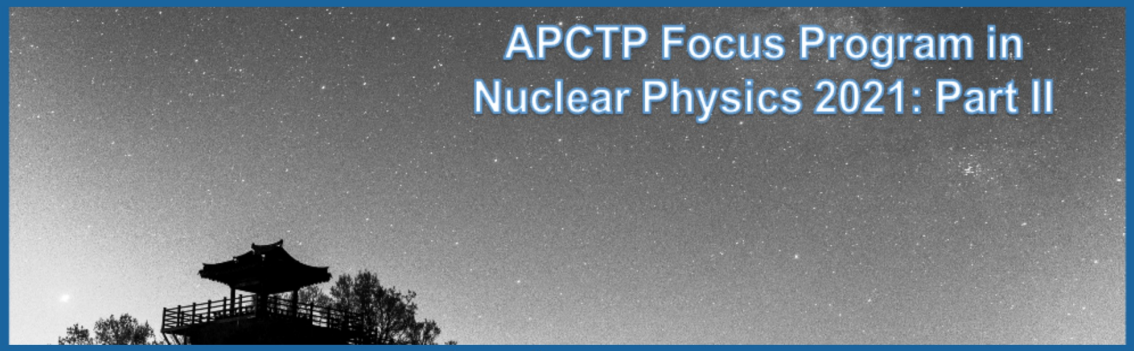
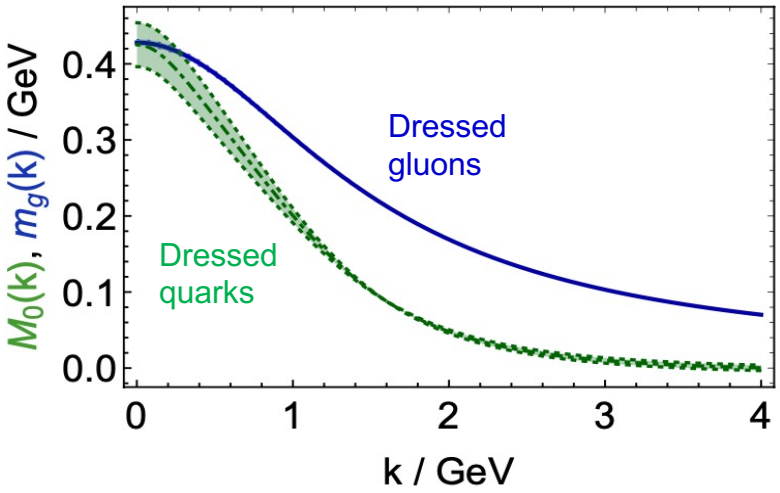
Emergence of Hadron Mass (EHM) from the Experimental Results on Hadron Structure



APCTP Focus Program in Nuclear Physics 2021 Part II: Science Opportunities with EIC

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

Talk outline:



- **Connecting EHM to the hadron structure observables**
- **EHM from the data on pseudo-scalar meson structure**
- **EHM from studies of the ground and excited state nucleon structure**
- **Prospects with increased energy and luminosity**

Office of Science

How Does Nucleon Mass Emerge?

Composition of Nucleon Mass:

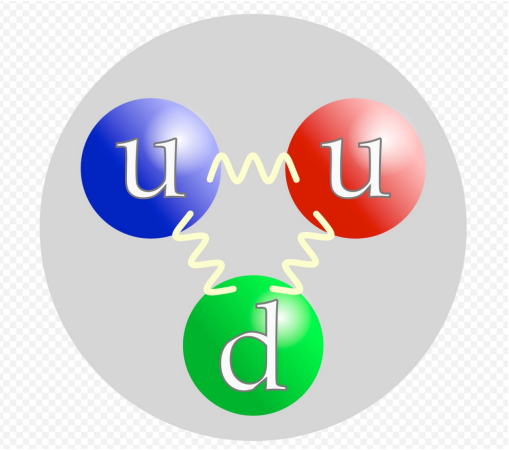
M_p, MeV (PDG20)

938.2720813
±0.0000058 MeV

Sum of bare quark masses, MeV

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

proton



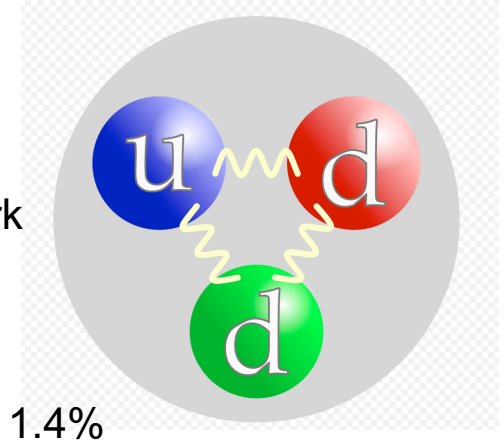
M_n, MeV (PDG20)

939.5654133
±0.0000058 MeV

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**

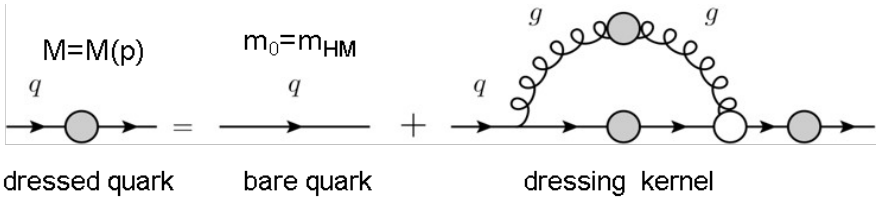
Open Problems in Exploration of the Emergence of Hadron Mass (EHM)

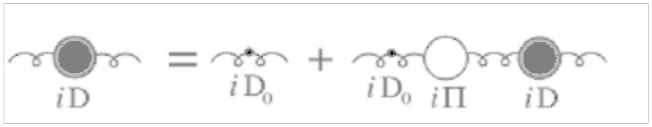
- What is the origin for the dominant part of nucleon mass?
- Is it the strong interaction in the regime of a process-independent running-coupling that is consistent with unity?
- What is the role of the Higgs mechanism?
- How does the mass scale of strong QCD define the nucleon mass?
- Why are the pion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

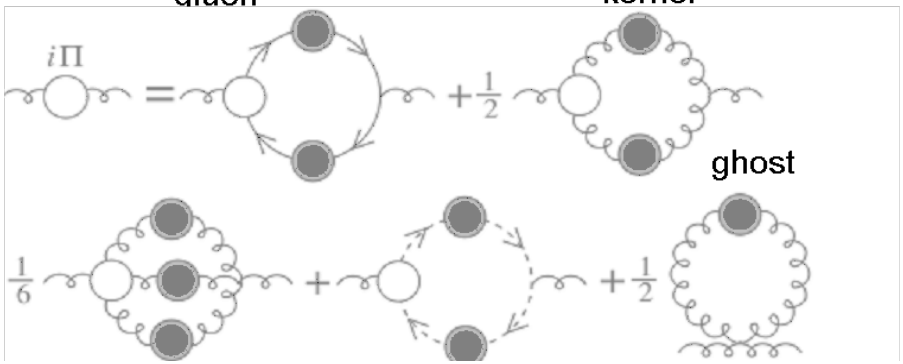
The continuum QCD approach has provided a viable framework for the exploration of EHM, offering predictions for the spectra/structure of the ground and excited state hadrons in connection with the EHM.

Basics for Insight into EHM: Continuum and Lattice QCD Synergy

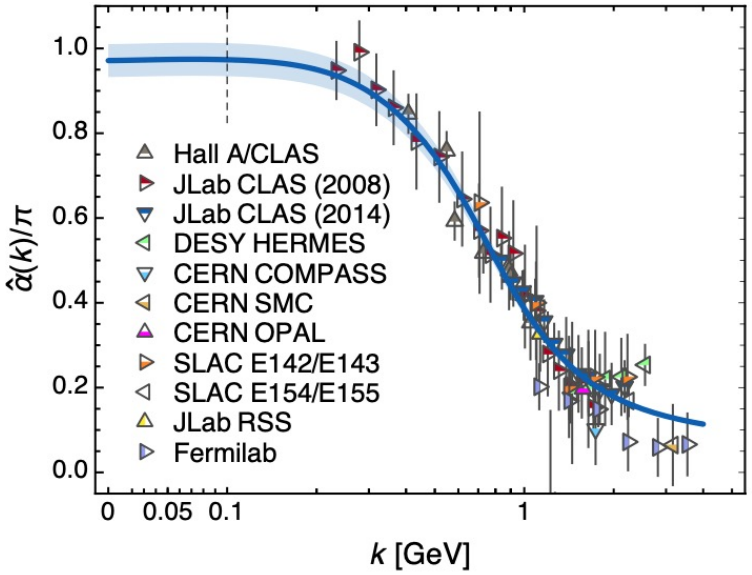
Emergence of Dressed Quarks and Gluons
D. Binosi et al., Phys. Rev. D 95, 031501 (2017)







QCD Running Coupling α(k)
Zh-F. Cui et al., Chin. Phys. C44, 083102 (2020)

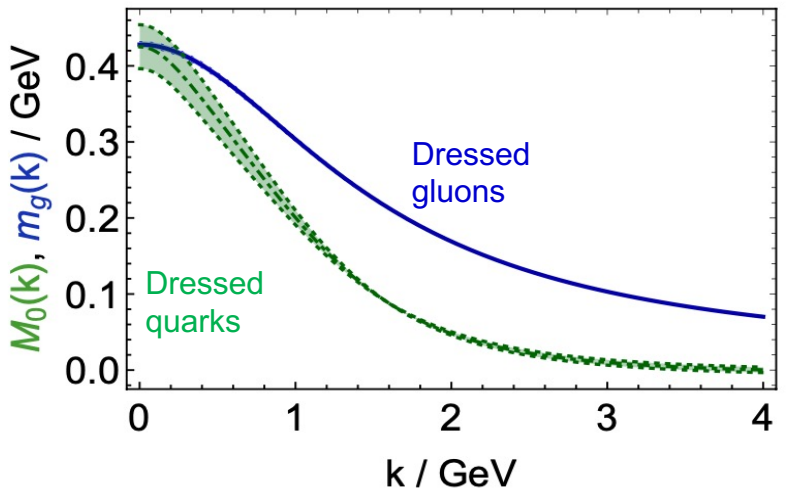


In the regime of the QCD running coupling constant comparable with unity, the dressed quarks and gluons with distance (momentum) dependent masses emerge from QCD, as follows from the equation of the motion for the QCD fields depicted above

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

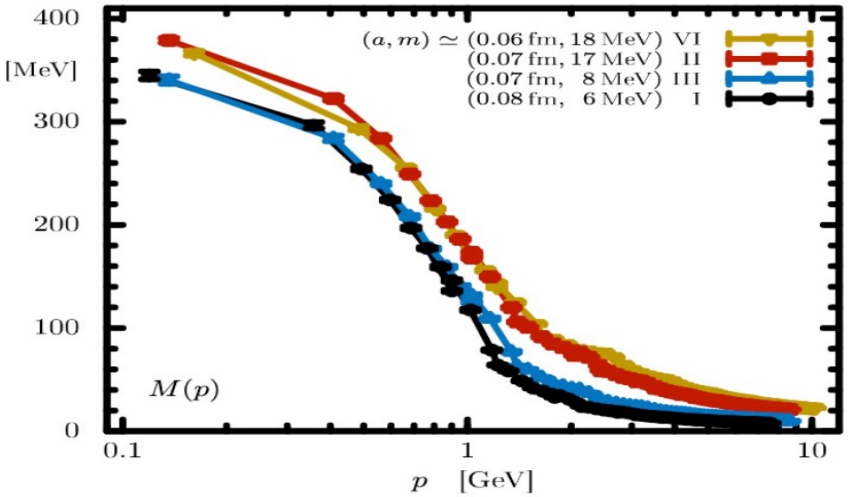
Dressed Quark/Gluon Masses (continuum QCD)
C.D. Roberts, Symmetry 12, 1468 (2020)



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

- Continuum QCD results get support from LQCD

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

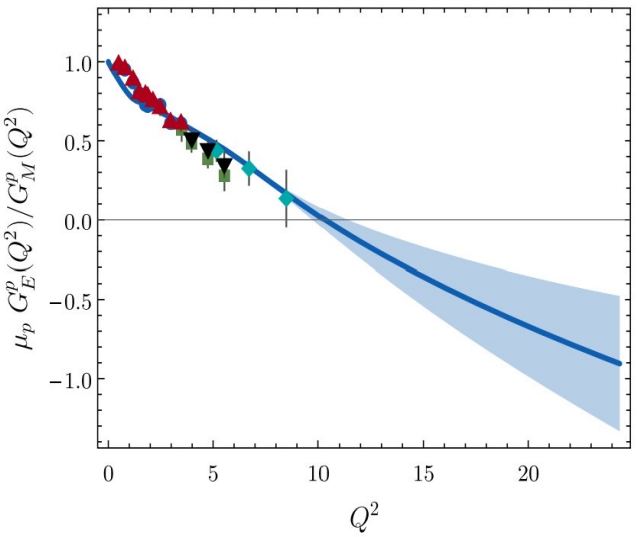


- Insight into dressed quark mass function from data on hadron structure represents a challenge for experimental hadron physics

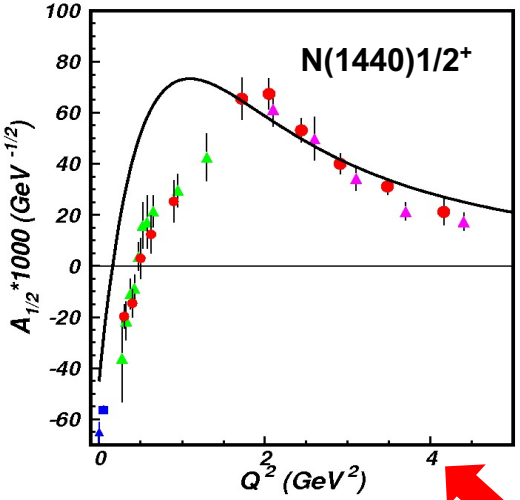
EHM from Global Hadron Structure Analysis

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

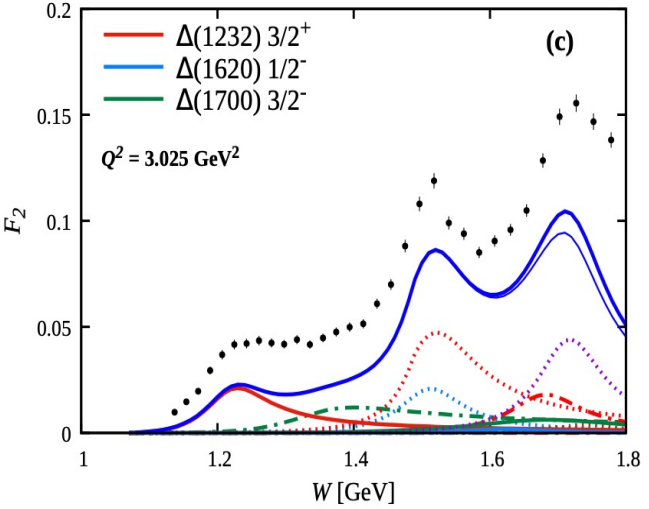
Nucleon Elastic FF



$\gamma_v pN^*$ Electrocouplings

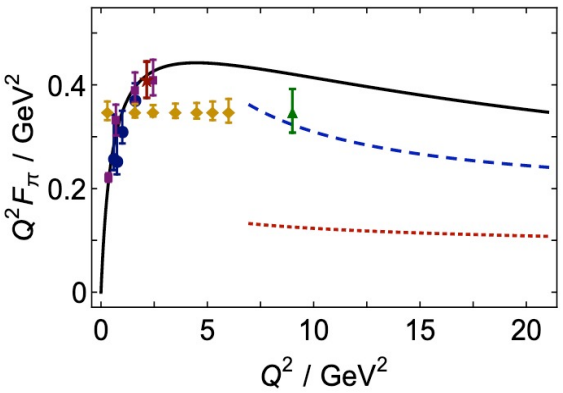


(e,e'X) Inclusive Scattering

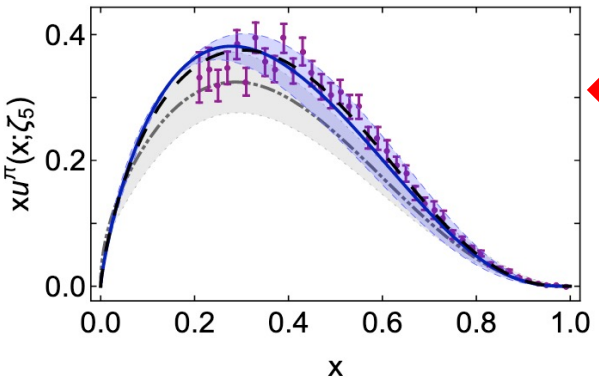


New data from studies of DY at AMBER and Sullivan processes at JLab

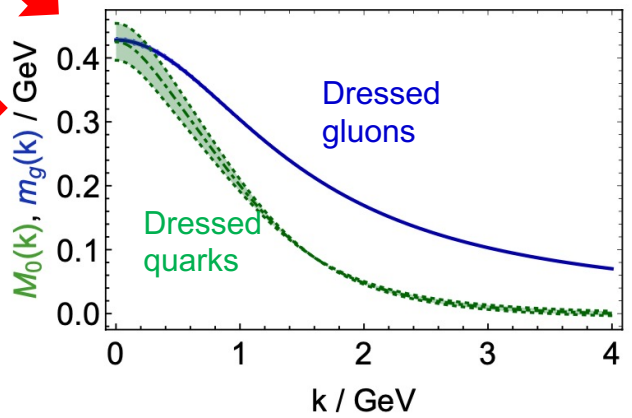
Pion Elastic FF



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 Data on Pion/Kaon Structure

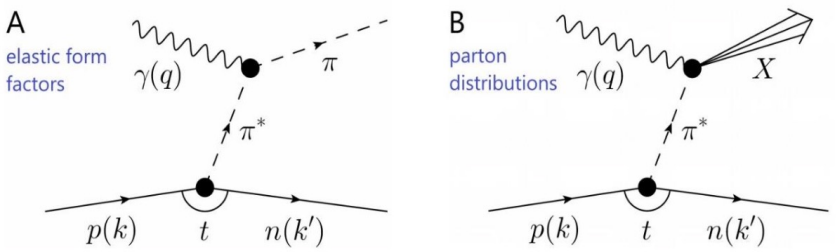
- The model, gauge and renormalization scheme independent Goldberger-Treiman relations connect the momentum dependence of the dressed quark mass to the pion/kaon Bethe-Salpeter amplitudes, making the studies of pion and kaon structure a promising way to map out the momentum dependence of the dressed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

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

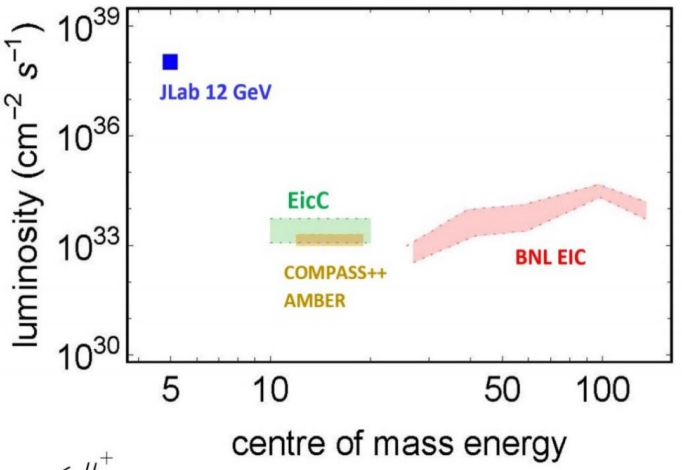
- Pions and kaons are simultaneously $q\bar{q}$ bound states and Goldstone bosons in chiral symmetry breaking. Their masses should be reduced to zero in the chiral limit and, in the real world, down to small values in comparison with the hadron mass scale owing to DCSB.

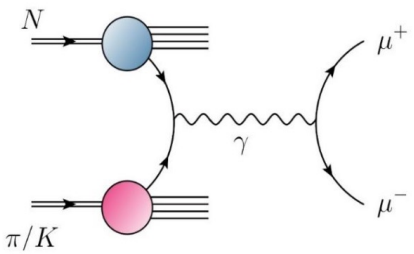
The Structure of Pseudo-Scalar Mesons from Experiments with Electron and π/K Beams

Era of Meson Targets

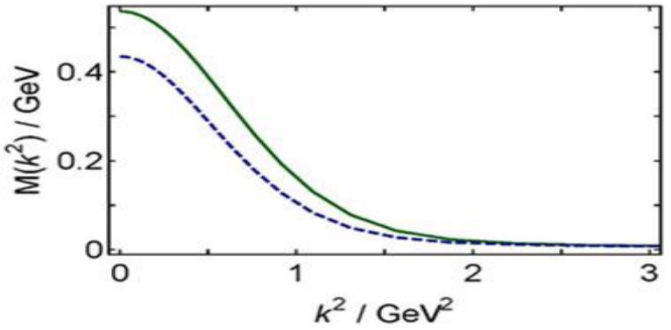


- JLab & EIC & EicC
  - High luminosity electron (+ ion) beams
  - Access to meson targets via the Sullivan Process, i.e., a baryon's "meson cloud"
- AMBER @ CERN SPS
  - High-intensity beams of pions ($\gtrsim 10^7$ pions/sec in Phase-1 = approved) and kaons (5×10^6 kaons/sec Phase-2 = proposal being prepared)
  - Drell-Yan, J/ψ production, prompt photon production … from proton and nuclear targets

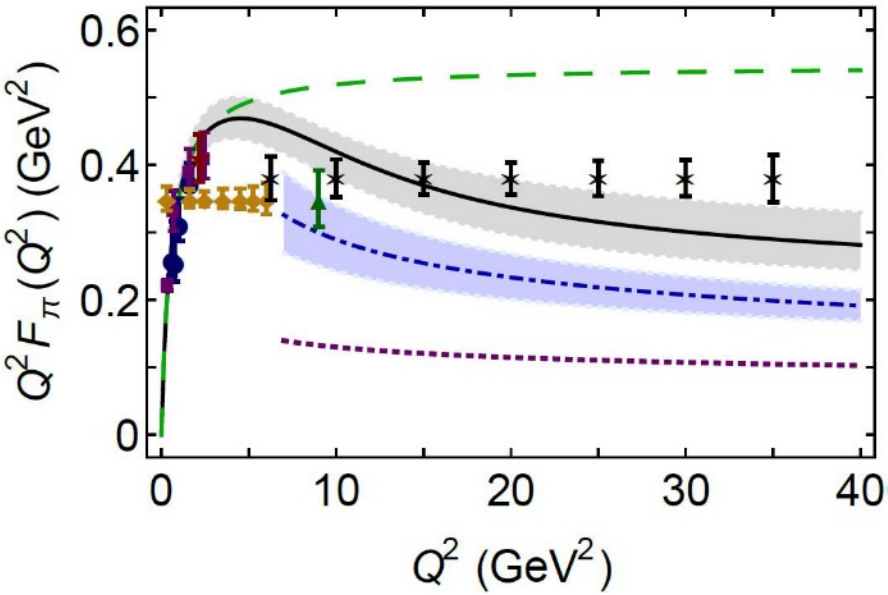




Results on the Pion Elastic Form Factor and Prospects with JLab12 and EIC



JLab12 & EIC eras



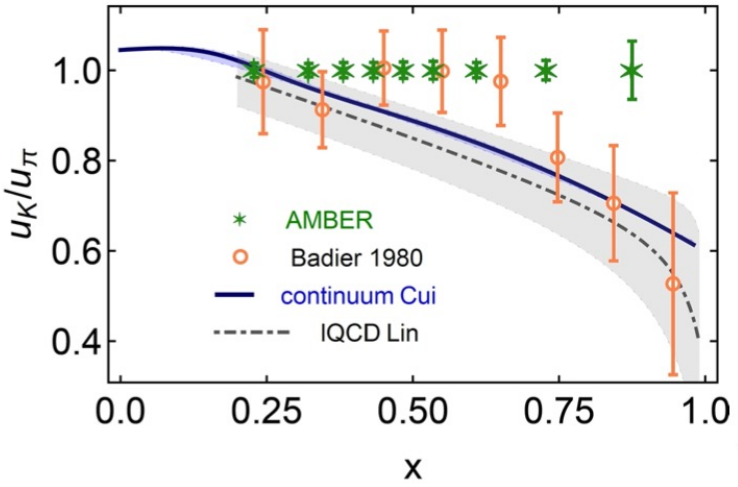
- Continuum QCD Dyson-Schwinger approach with running dressed quark mass provided good description of the available results on pion form factor and PDF (see also slide #6)
- Experiments foreseen at 12 GeV era at JLab (Halls A/C) will extend the results on pion elastic form factor towards Q^2 up to 8 GeV^2
- EIC experiments will provide information on pion elastic form factor at $Q^2<40$ GeV^2 allowing us to map-out the momentum dependence of dressed quark mass at the distances where the dominant part of hadron mass is generated

Insight into Interplay Between Higgs and Emergent Mechanisms

Ratio $u_K(x)/u_\pi(x)$ is sensitive to interplay between Higgs and emergent mechanisms in kaon mass generation

140 days with 2×10^7 s^{-1} 100 GeV K^- beam:

Z-F. Cui, *et al.* EPJC80(2020)1064, H-W. Lin *et al.*, PRD103(2021)014516



Future studies with AMBER@CERN

$$\frac{\sigma_{DY}^{K^- C}}{\sigma_{DY}^{\pi^- C}} \approx \frac{u_K}{u_\pi}(x)$$

Experiment	Target type	Beam type	Beam intensity (part/sec)	Beam energy (GeV)	DY mass (GeV/c^2)	DY events $\mu^+\mu^-$
NA3	6 cm Pt	K^-		200	4.2 – 8.5	700
This exp.	100 cm C	K^-	2.1×10^7	80	4.0 – 8.5	**25,000**
				100	4.0 – 8.5	40,000
				120	4.0 – 8.5	54,000
This exp.	100 cm C	π^-	4.8×10^7	80	4.0 – 8.5	**65,500**
				100	4.0 – 8.5	95,500
				120	4.0 – 8.5	123,600

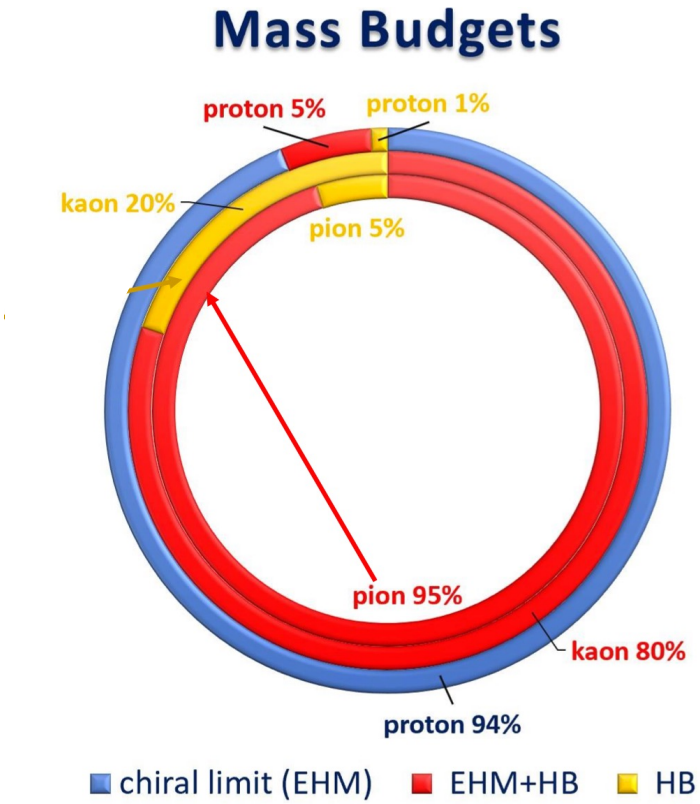
π data taken simultaneously (from beam impurity)

Enlarge world data statistics by a factor 30

Determine u_K/u_π within a few percent

- Lattice QCD supports the continuum QCD results on $u_K(x)/u_\pi(x)$ ratio computed with running quark mass (slide #5).
- The expected results from AMBER@CERN will provide insight into interplay between Higgs and emergent mechanisms in hadron mass generation and shed light on flavor dependence of EHM.

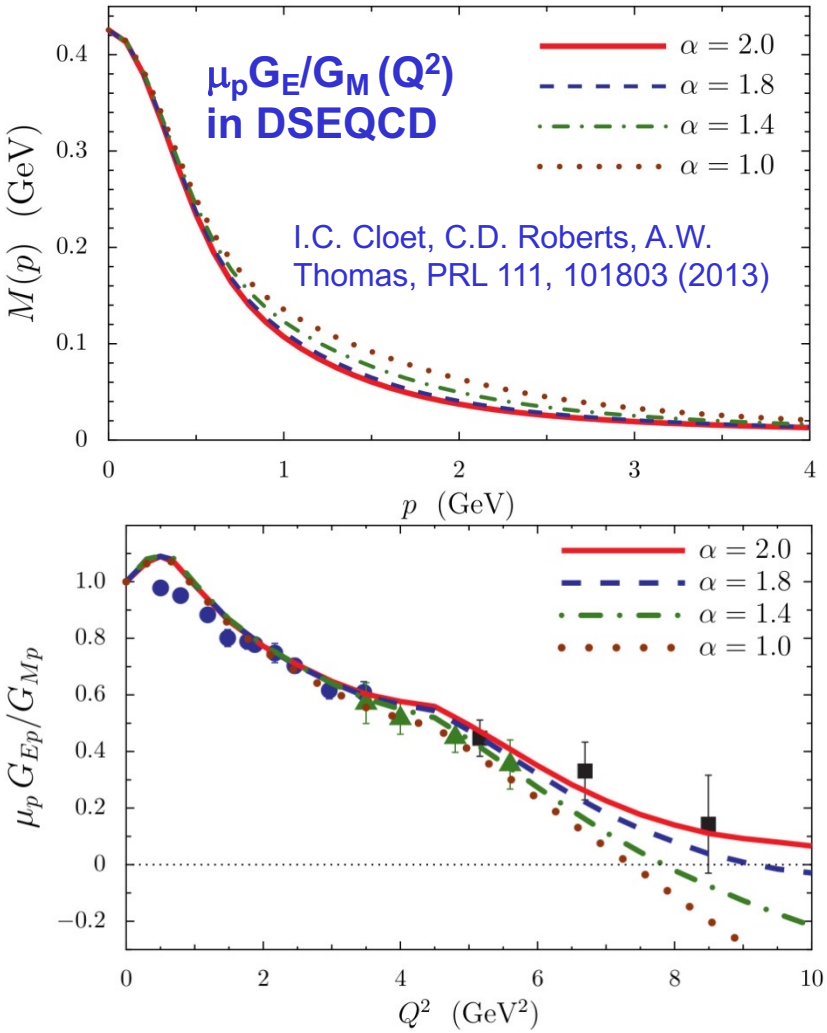
Insight into EHM from the Data on N/N* Structure



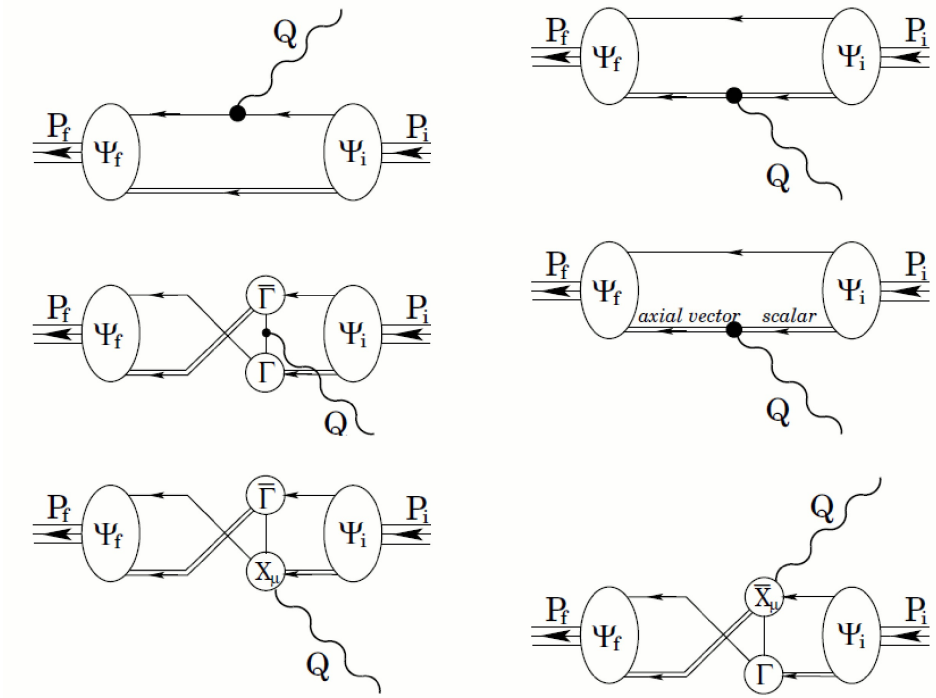
- Studies of the ground and excited state nucleon structure allow us to explore the dressed quark mass function in a different environment where the sum of dressed quark masses is the dominant contribution into the physical masses of the ground and excited states of the nucleon

- 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.

Dressed Quark Mass Function from Nucleon Elastic Form Factor Data



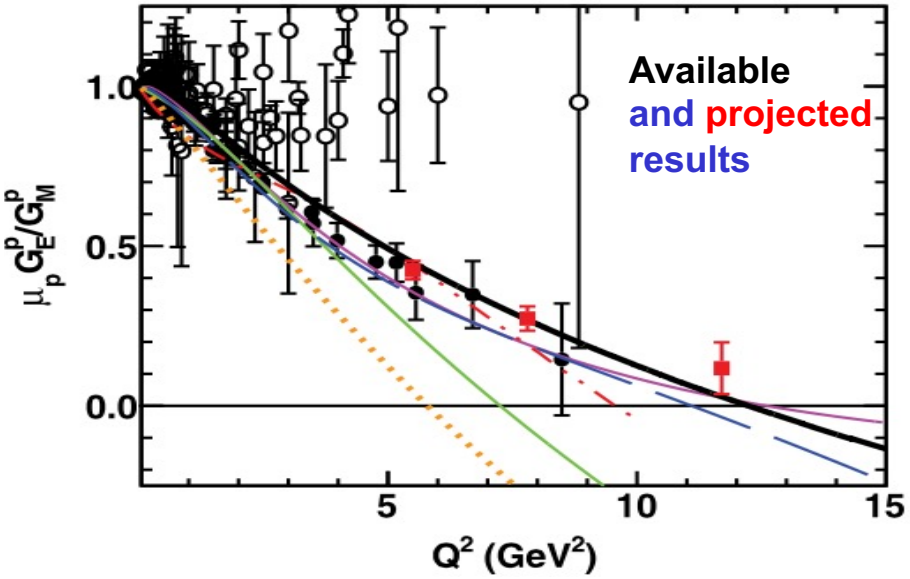
Description of N/N* electroexcitation in DSEQCD



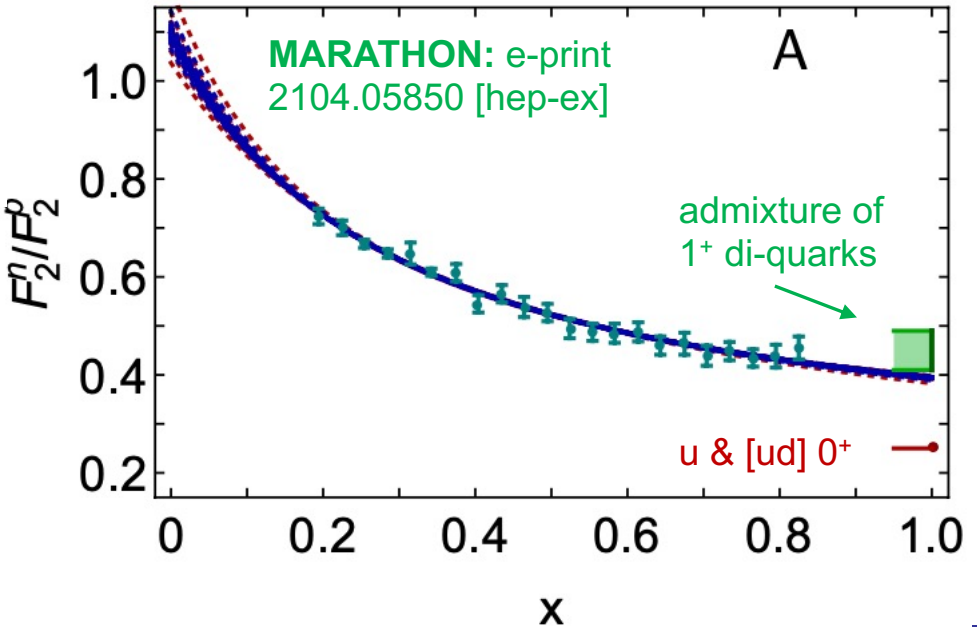
• **Elastic form factors (bottom plot) are sensitive to the rate for the transition between a fully dressed (constituent) quark in the infrared to an almost bare QCD quark in the ultraviolet seen in the momentum dependence of the quark mass function (top plot)**

EHM from the Ground Nucleon Structure Exploration in 12 GeV Era

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



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



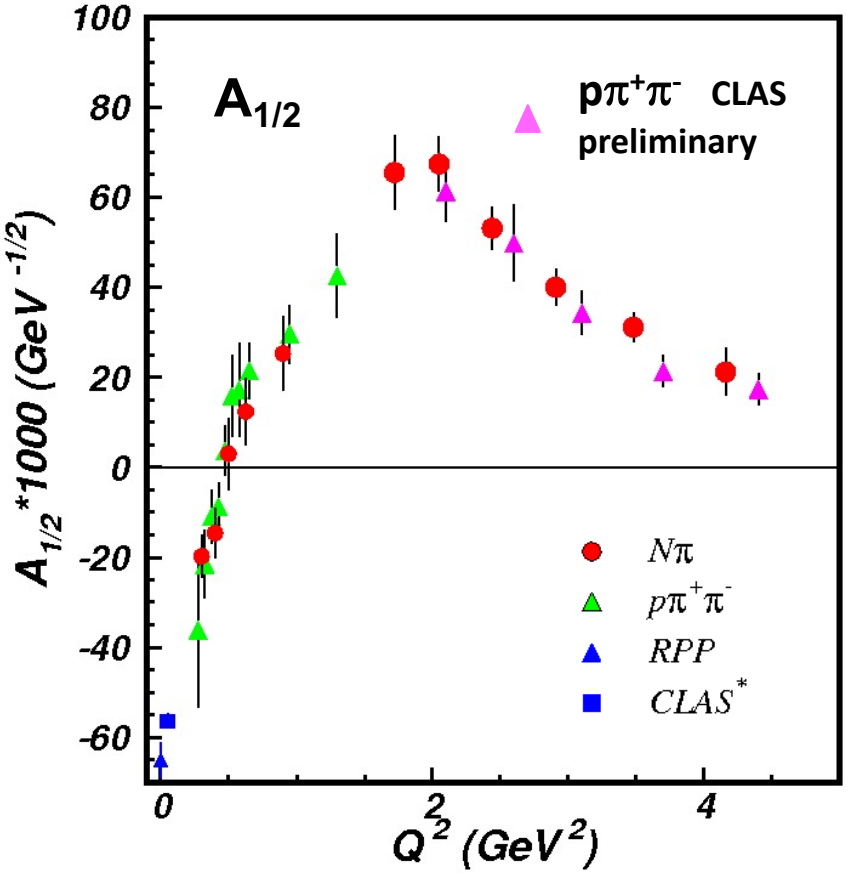
Shed light on the presence of di-quark correlations of spin-parity 0^+ and 1^+

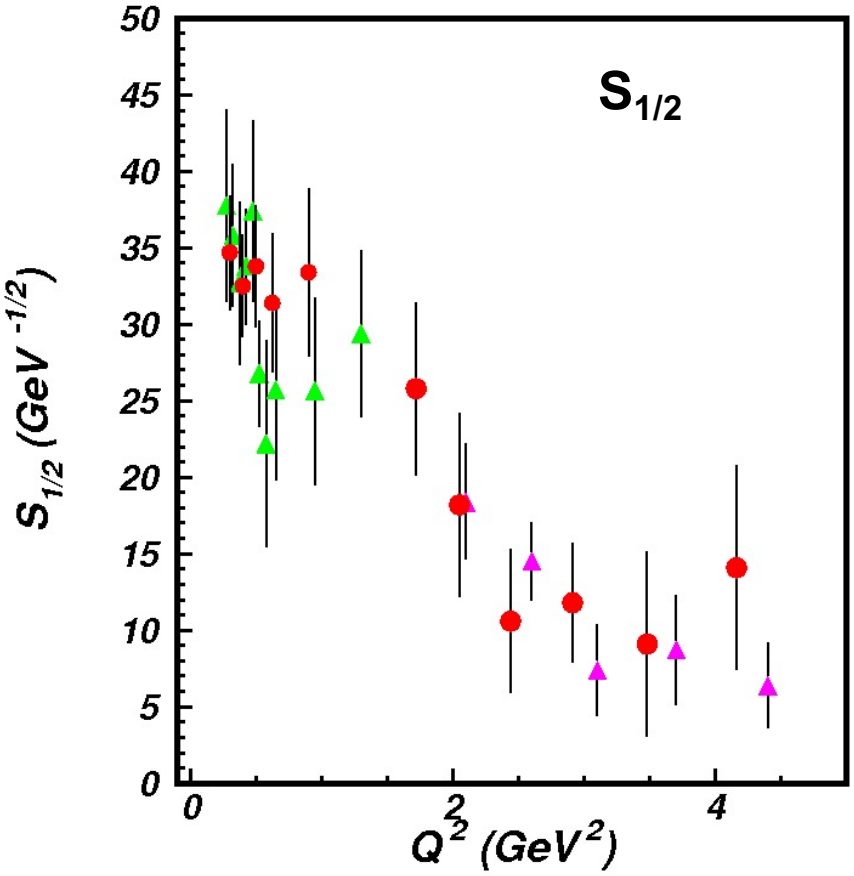
Nucleon Resonance Electrocouplings from Data On Exclusive Meson Electroproduction with CLAS

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



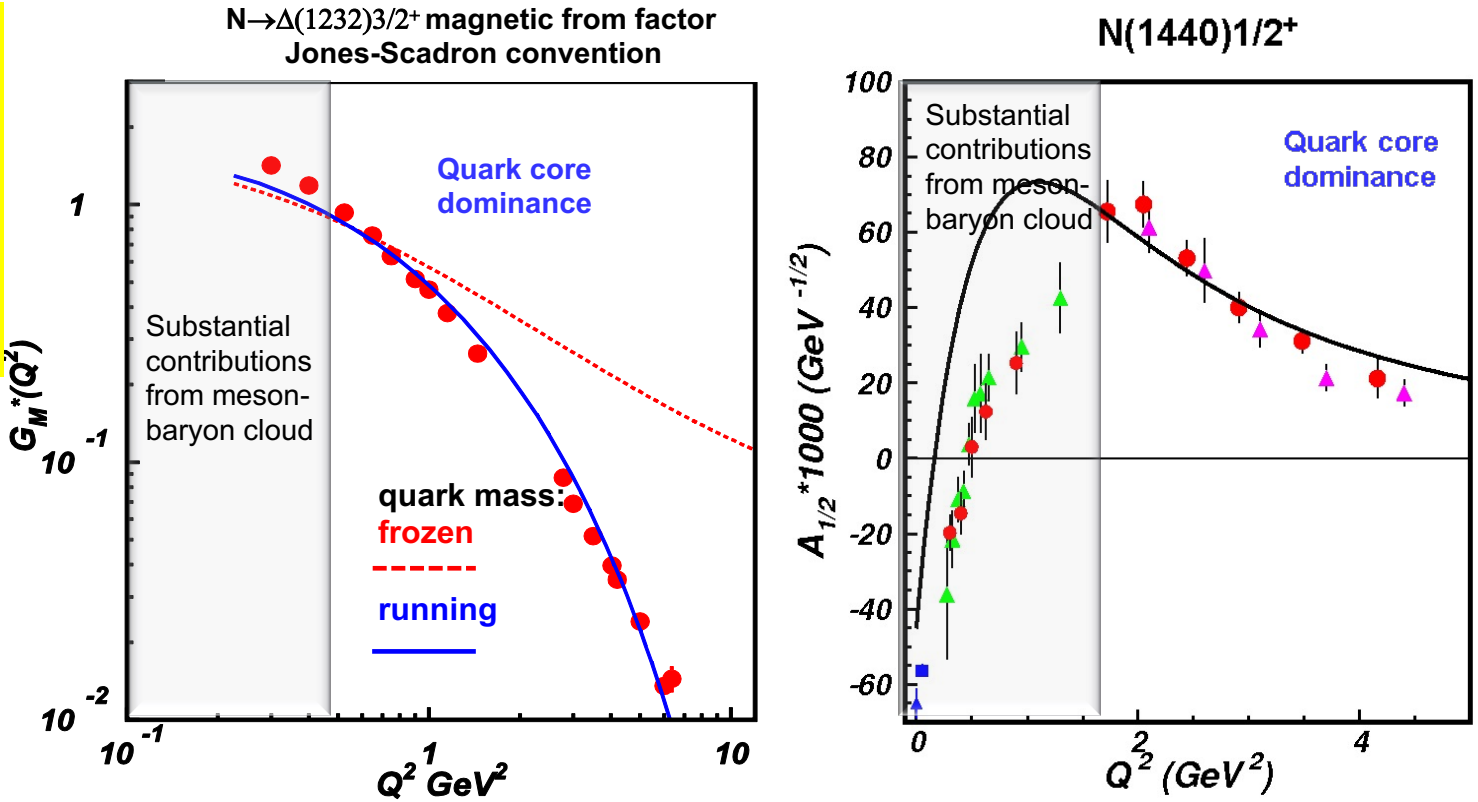


Consistent results on N(1440)1/2$^+$ electrocouplings from independent studies of two major πN and $\pi^+\pi^-$p electroproduction channels with different non-resonant contributions allow us to evaluate the systematic uncertainties of these quantities in a nearly model-independent way

Insight to EHM From Resonance Electrocouplings

Dyson-Schwinger Equations (DSE):

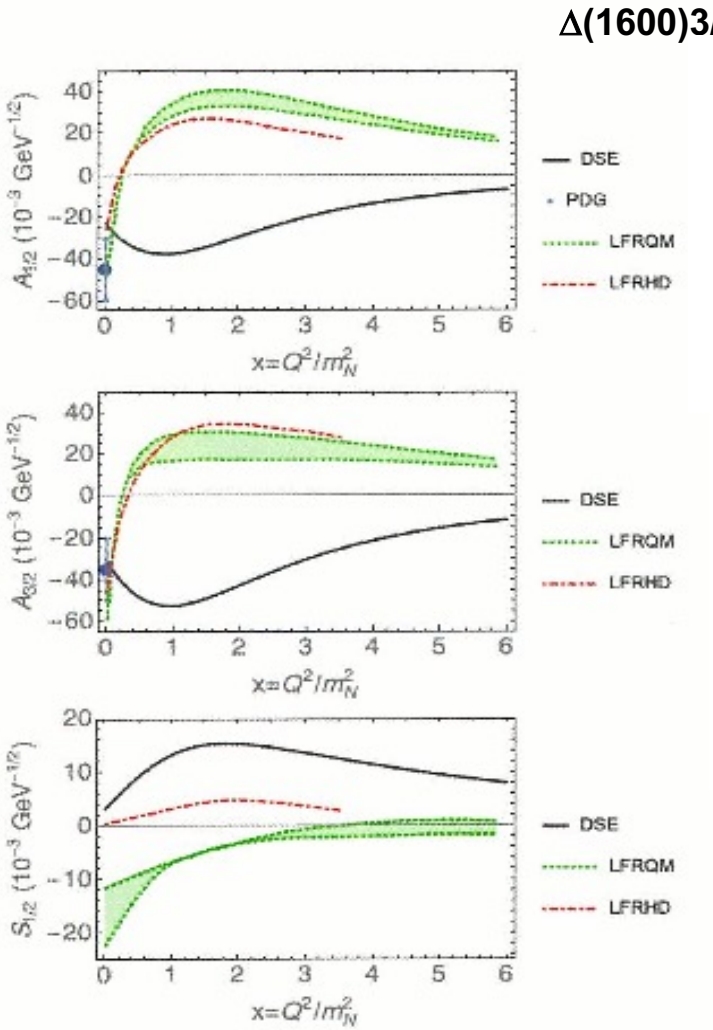
- J. Segovia et al., Phys. Rev. Lett. 115, 171801 (2015)
- J. Segovia et al., Few Body Syst. 55, 1185 (2014)

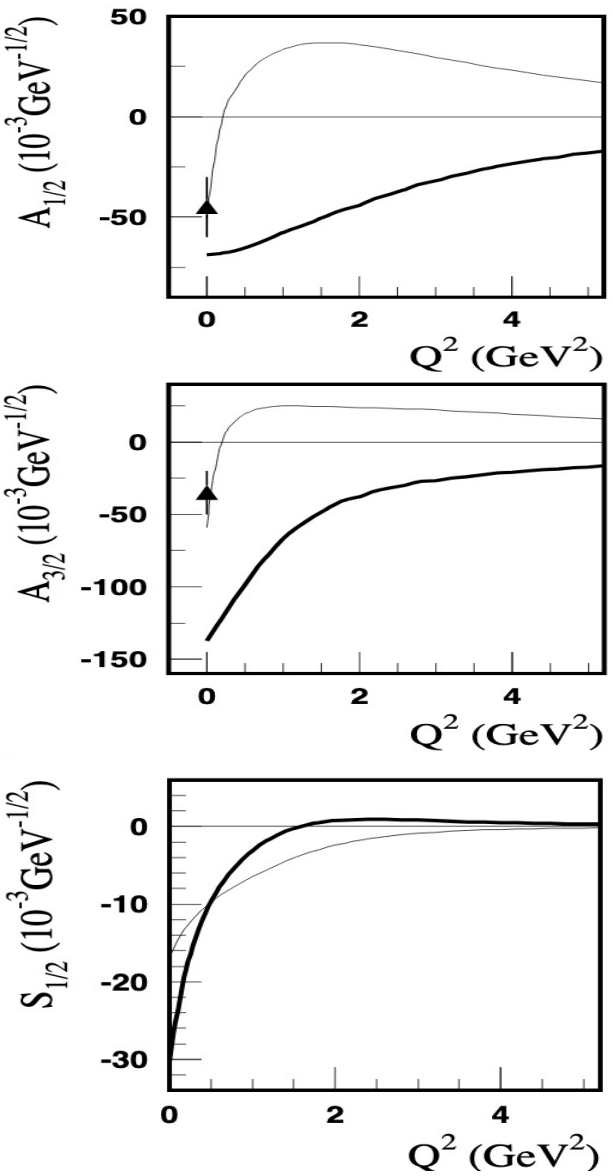


Good data description at Q^2>2.0 GeV^2 achieved with <u>the same dressed quark mass function</u> for the ground and two excited nucleon states of distinctively different structure validates the continuum QCD results on the momentum dependence of the dressed quark mass. γ_vpN* electrocoupling data offer 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 approach with Momentum-Dependent Dressed Quark Mass



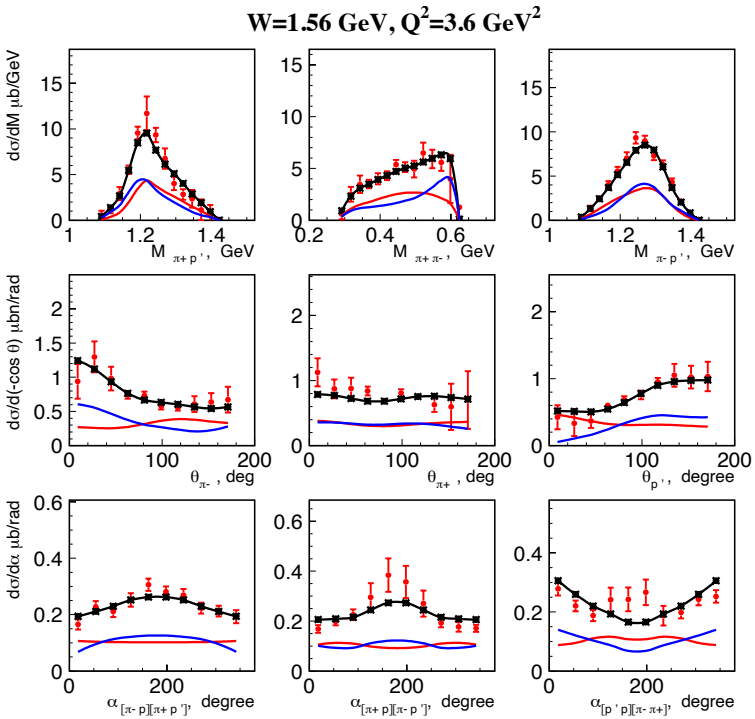


LFRQM accounting for 3-quark configuration mixing: I.G. Aznauryan and V.D. Burkert arXiv: 1603.06692 [nep-ph]

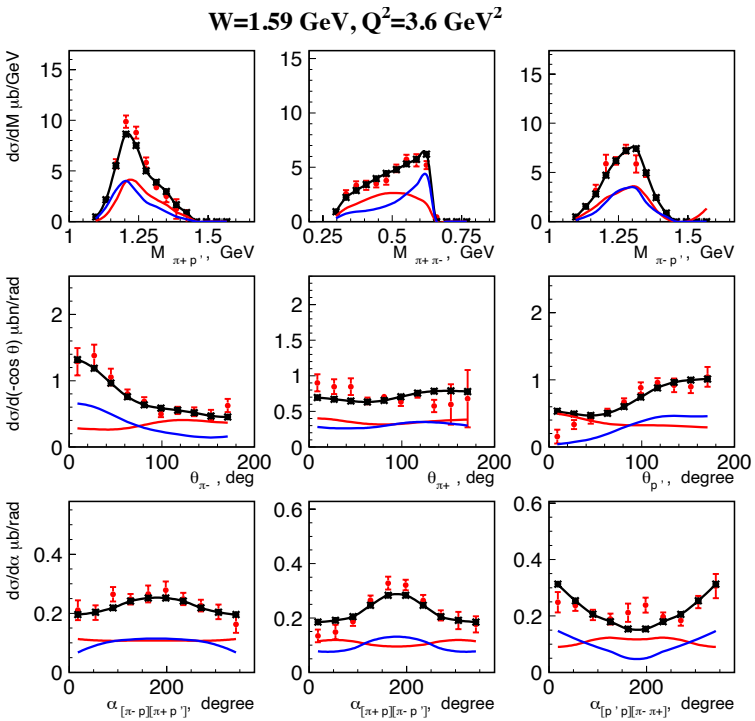
Parameter free continuum QCD (DSE) predictions for Δ(1600)3/2⁺ electrocouplings. Ya Lu et al., Phys. Rev. D100, 034001 (2019)

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

χ^2/d.p. = 1.26



χ^2/d.p. = 1.54



Full.

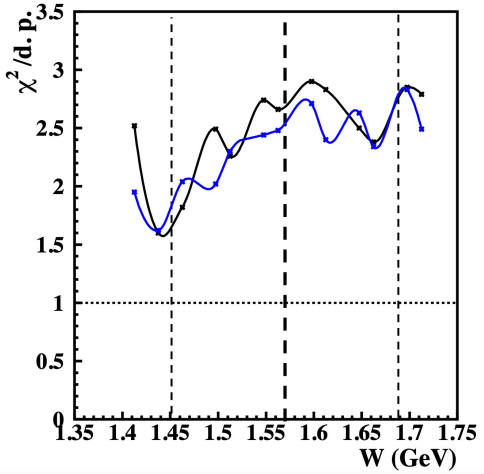
Resonances

Background

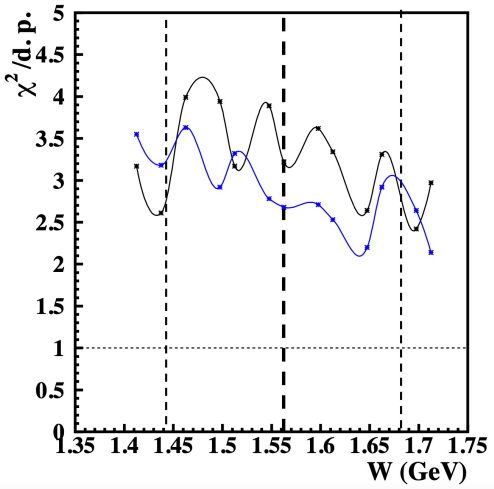
Confirmation of the continuum QCD expectations on the $\Delta(1600)3/2^+$ electrocouplings will provide strong evidence for credible access to the mass functions of u- and d-quarks at quark momenta <0.5 GeV

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

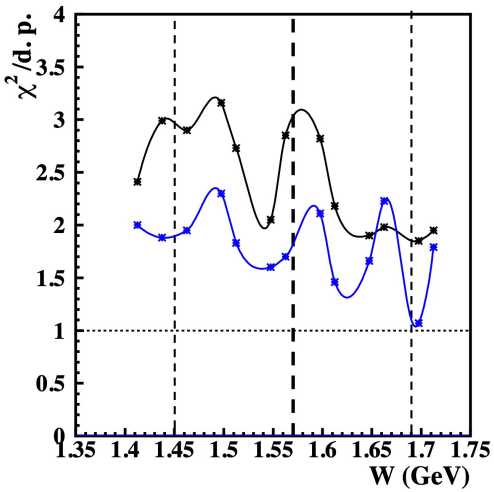
$2.0\ \text{GeV}^2<Q^2<2.4\ \text{GeV}^2$



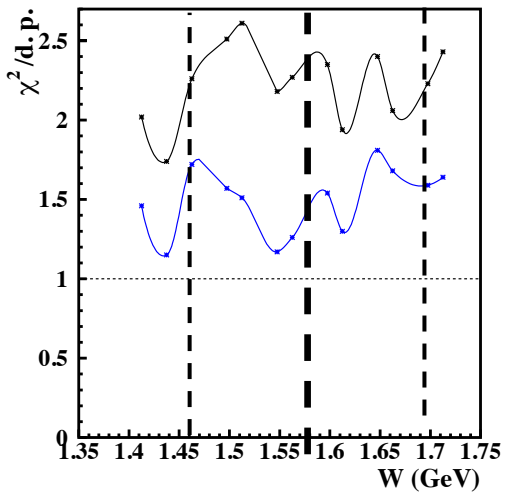
$2.4\ \text{GeV}^2<Q^2<3.0\ \text{GeV}^2$



$3.0\ \text{GeV}^2<Q^2<3.5\ \text{GeV}^2$



$3.5\ \text{GeV}^2<Q^2<4.2\ \text{GeV}^2$



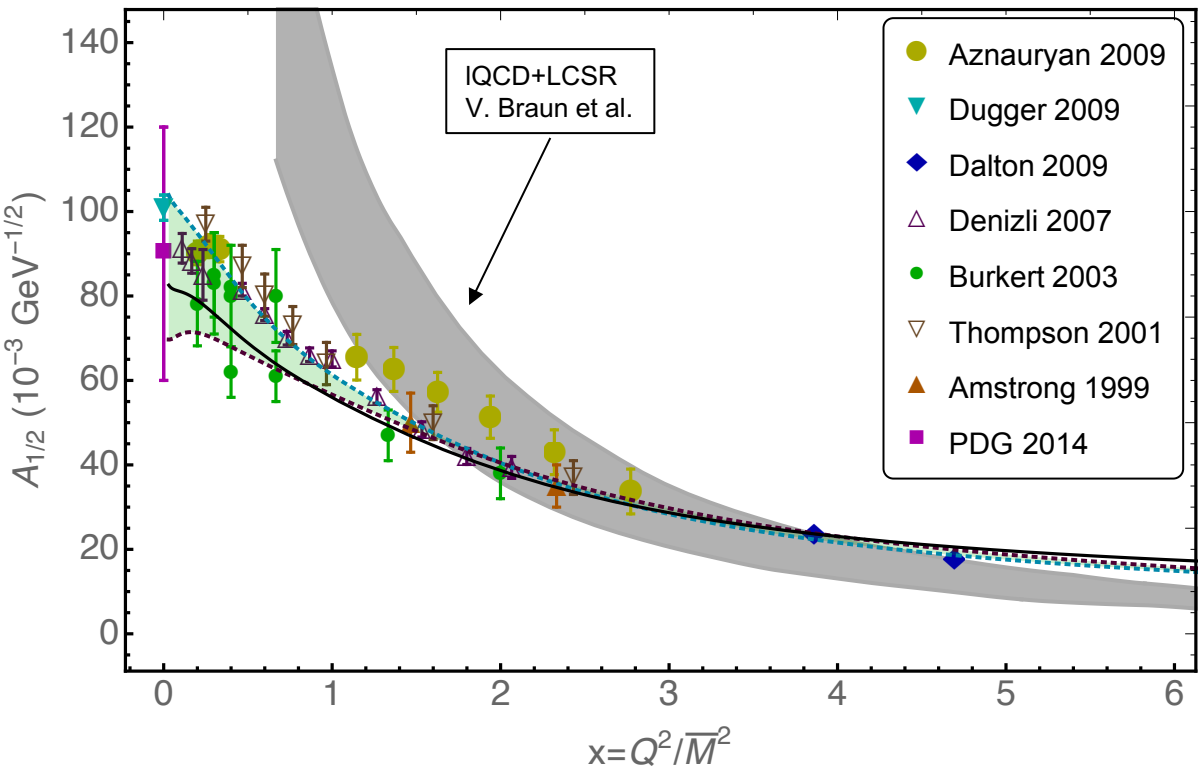
Thick dashed line stands for $\Delta(1600)3/2^+$ mass, the interval between thin dashed lines corresponds to the resonance width

——— $\Delta(1600)3/2^+$ 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 $2.0<Q^2<5.0\ \text{GeV}^2$

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

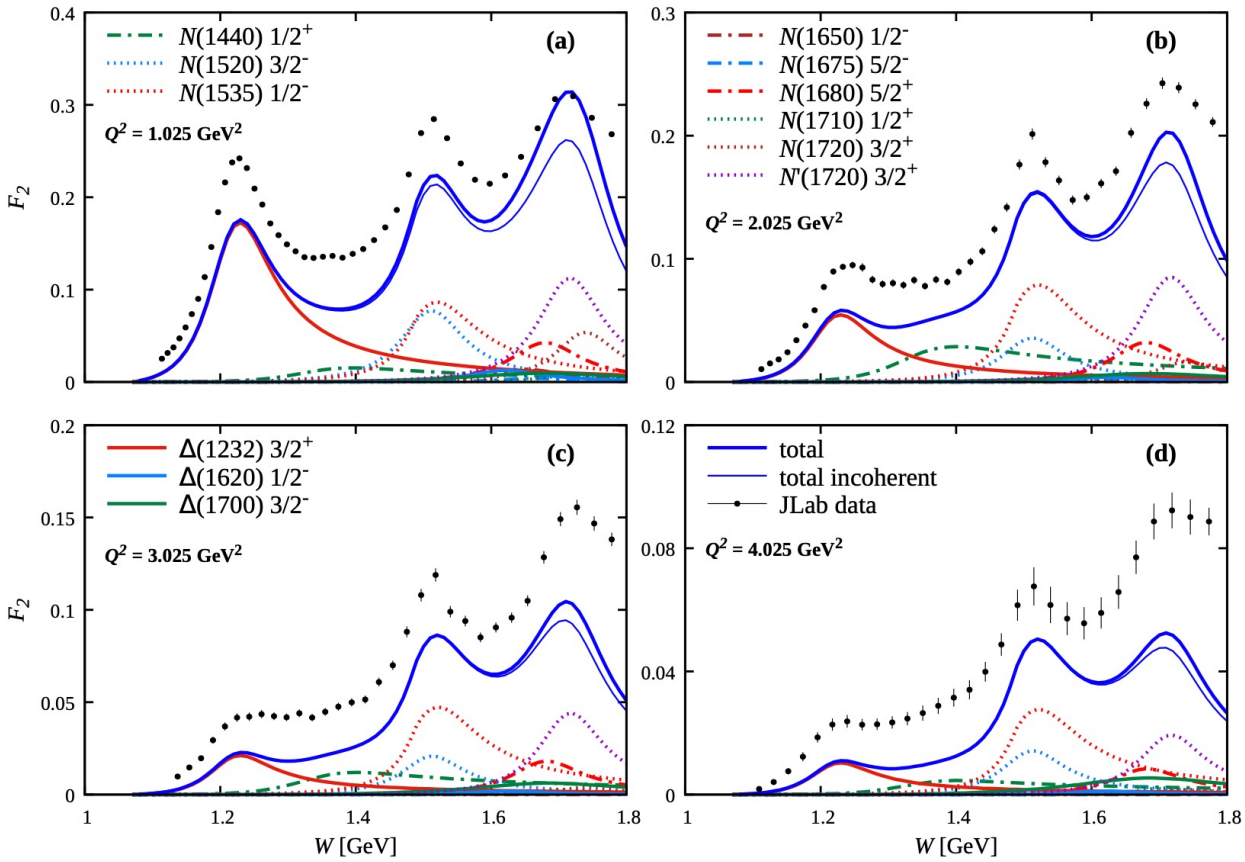
- Studies of electroexcitation amplitudes for the resonances in the second region are expected to shed light on either universality or environmental sensitivity of dressed quark mass function.

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.**

CLAS12 N* Program

- Measure exclusive electroproduction of $N\pi$, $N\eta$, $N\pi\pi$, KY final states from an unpolarized proton target with longitudinally polarized electron beam

E_b = 6.6, 8.8, 11 GeV, Q^2 = 0.05 → 12 GeV^2, W → 3.0 GeV, cos θ_m^* = [-1:1]

E12-09-003	Nucleon Resonance Studies with CLAS12
E12-06-108A	KY Electroproduction with CLAS12
E12-16-010A	N* Studies Via KY Electroproduction at 6.6 and 8.8 GeV
E12-16-010	A Search for Hybrid Baryons in Hall B with CLAS12

RG-A	Spr. 18 126 mC	10.4 GeV, 10.6 GeV 50% of total
	Fall 18 99 mC	
	Spr. 19 58 mC	
RG-K	Fall 18 28 mC	6.5 GeV, 7.5 GeV 10% of total

1. Study higher-lying N* states:
   - confirm signals of new baryon states observed in $\gamma p \rightarrow KY$ with data of comparable statistical precision
   - search for predicted qqqg hybrid baryons
2. Understand effect of meson cloud on N* structure:
   - use transition regime to explore emergence of external meson cloud from the core of confined quarks and gluons
   - expect precision in electroproduction to match photoproduction for Q^2 < 2-3 GeV^2
3. Probe dressed quark mass function and di-quark correlations in N* structure:
   - important aspect of N* structure and $\gamma_v NN^*$ amplitudes
   - provide insight into EHM vs. Q^2
   - different N* quantum numbers allow study different qq correlations

CLAS12 is the only available and foreseen facility in the world capable to provide information on $\gamma_v pN^*$ electrocouplings of all prominent resonances at Q^2>5.0 GeV^2 allowing us to gain insight into the distances where the dominant part of hadron mass is generated

Emergence of Hadron Mass and Quark-Gluon Confinement

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

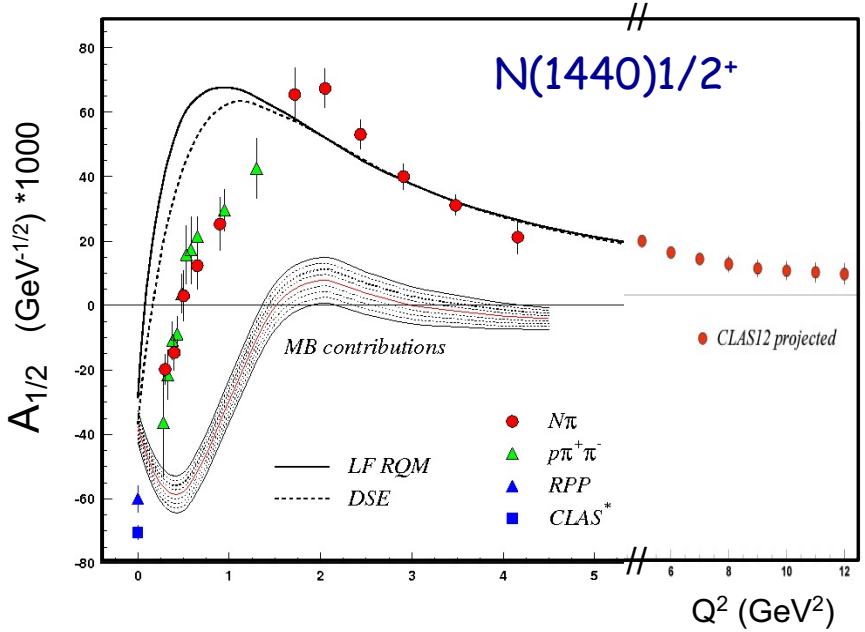
How is >98% of visible mass generated?

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?

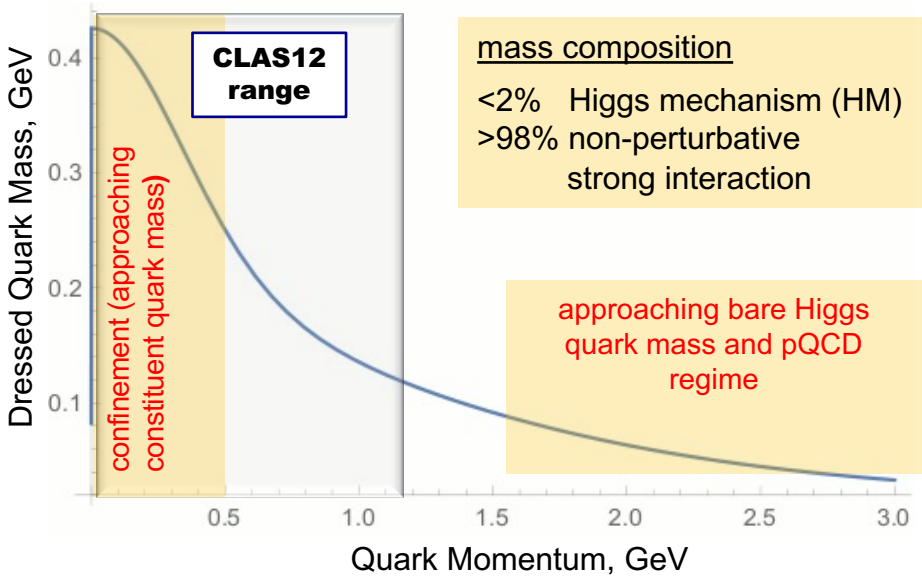
(S.J, Brodsky et al., Int. J. Mod. Phys. Rev. E29, 2030006 (2020))

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 $5<Q^2<10$ GeV^2 will allow us to explore the emergence of the dominant part of dressed quark and hadron mass in connection with QCD



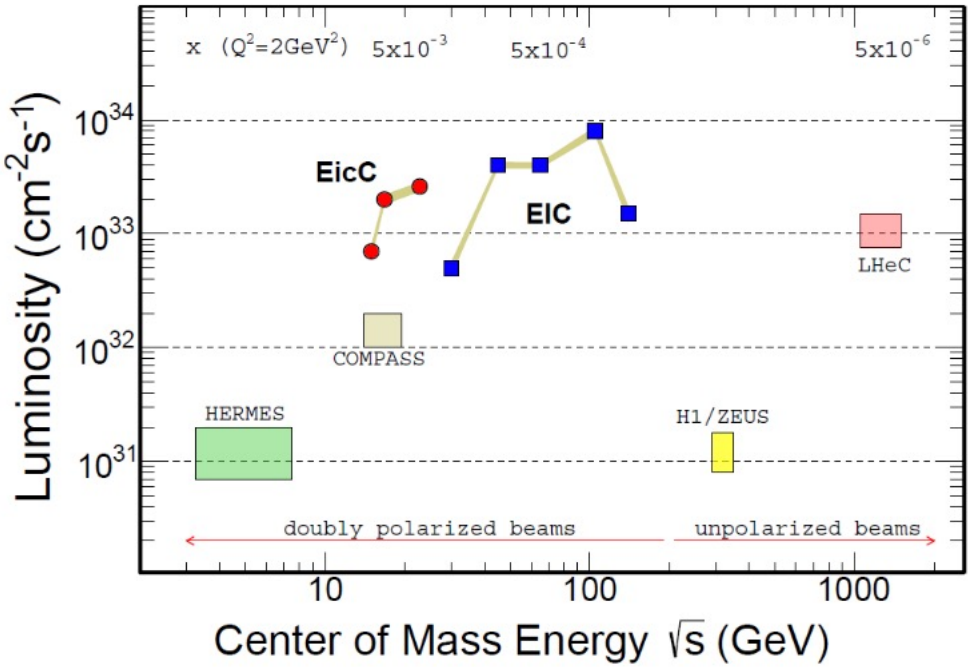
CLAS results vs. theory expectations with running quark mass

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 $\gamma_v pN^*$ electro-couplings at $Q^2>10$ GeV^2 allowing us to map out momentum dependence of dressed quark mass within the entire range of distances where the dominant part of hadron mass is expected to be generated



Both EicC and EIC would need higher luminosity

The exclusive electroproduction measurements foreseen at Jlab after completion of 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

Conclusions and Outlook

- **EHM paradigm makes a broad array of predictions. The predictions it makes for the structure of the ground and excited hadron states 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 from combined analyses of the experimental results on both the meson and baryon structure.**

- **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, 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. Success in description of these results with the same momentum dependence of dressed quark masses will solidify evidence for credible insight into EHM. Studies of $\gamma_v pN^*$ electrocouplings for all prominent N* will allow us to check universality or environmental sensitivity of dressed quark mass function.**

- **The experiments of 12 GeV era at JLab on the studies of pion, kaon elastic form factors and PDF in Sullivan processes, ground and excited nucleon state structure augmented by the studies of pion/kaon structure in Drell-Yan processes with AMBER@CERN 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.**