Emergence of Hadron Mass (EHM) from the Experimental Results on N* Electroexcitation Amplitudes ($\gamma_v pN^*$ Electrocouplings)

Composition of the Nucleon Mass:

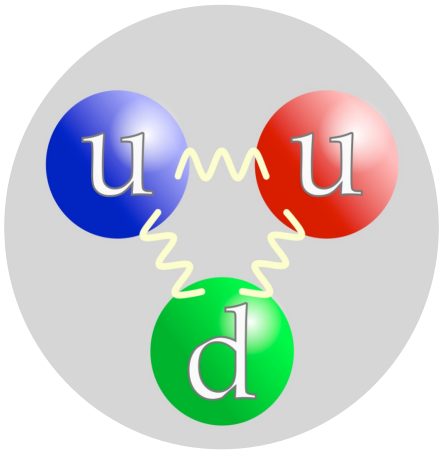
M_p, MeV (PDG20)

938.2720813
±0.0000058

Sum of renormalized quark masses (renormalization point μ=2.0 GeV) in MeV

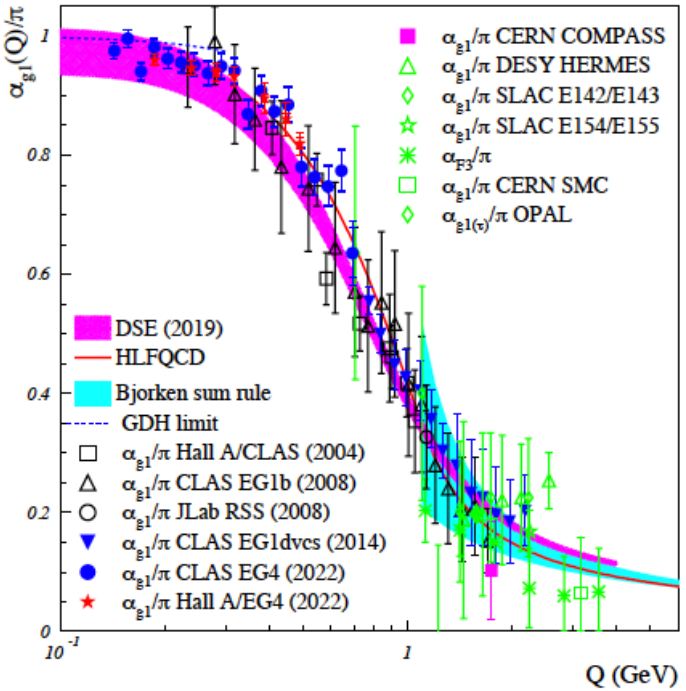
2.16+2.16+4.67
$=8.99^{+1.45}_{-0.65}$ or < 1.1%

proton



Strong interaction in non-perturbative (sQCD) regime underlies the emergence of >98% of hadron mass

A. Deur et al., Particles 5, 171 (2022)



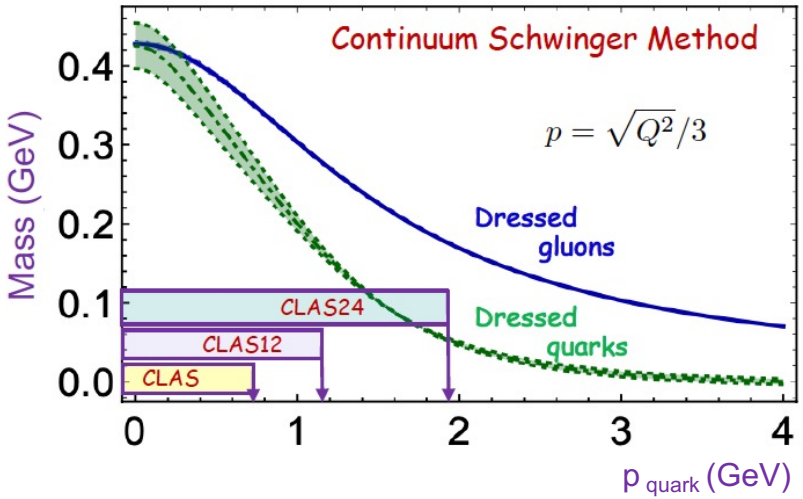
V.I. Mokeev,
on behalf of the Hadron Structure Group of the CLAS Collaboration

Office of Science

Emergence of Hadron Mass: Concept from Continuum Schwinger Method (CSM) vs. the Results from CLAS on N* Electroexcitation

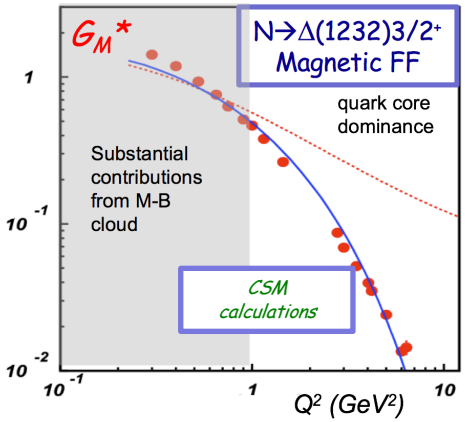
A successful description of the pion and nucleon elastic FFs, and the electrocouplings of the $\Delta(1232)3/2^+$ and $N(1440)1/2^+$ resonances of different structure has been achieved *with the same dressed quark/gluon mass functions*

- ***Strong evidence for insight into EHM***

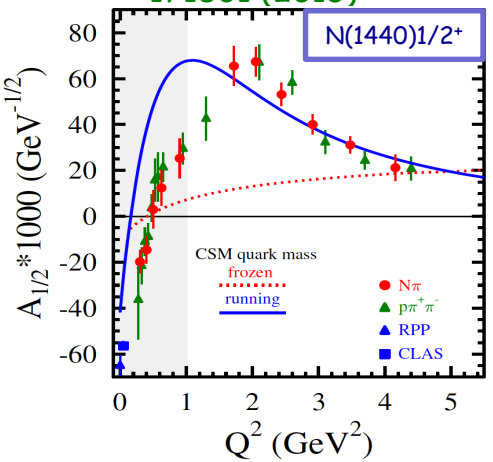


Running Dressed Quark/Gluon Masses from CSM
C.D. Roberts, Symmetry 12, 1468 (2020)

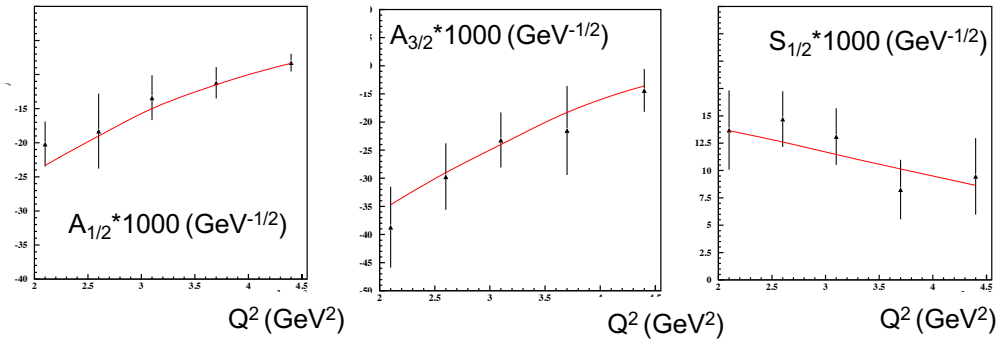
CLAS results vs. CSM expectations



J. Segovia, PRL 115, 171801 (2015)



CSM prediction vs preliminary CLAS results on $\Delta(1600)3/2^+$ electrocouplings



CSM predictions, Ya Lu et al., Phys. Rev. D 100, 034001 (2019)

Preliminary results from $\pi^+\pi^-$p electroproduction, V.I. Mokeev, Invited talk at the APCTP Workshop on Nuclear Physics 2022, 11-16 July 2022, https://indico.knu.ac.kr/event/567/

The results on $\Delta(1600)3/2^+$ electrocouplings confirmed the CSM prediction, solidifying evidence for gaining insight EHM from the studies of the γ_vpN* electrocouplings

Motivations to Increase the CEBAF Energy and Luminosity

- **Increase of CEBAF energy to 20+ GeV with a staged upgrade of detector capabilities to measure exclusive electroproduction events within ~4π acceptance at $\mathcal{L}$ ~10^{36} $cm^{-2}s^{-1}$ will offer only foreseen opportunity to explore N* electroexcitation in the range of Q^2 up to 18 - 22 GeV^2 , where ~90% of hadron mass is expected to be generated.**

- **CSM makes a broad array of predictions on hadron structure by employing the same momentum dependence of the dressed quark mass as is inferred from the QCD Lagrangian. Predictions for N* electroexcitations are worth testing against the results on the Q^2-evolution of the $\gamma_v pN^*$ electrocouplings over the full range of Q^2 where the transition from sQCD to pQCD is expected.**

- **Confirmation of the CSM predictions on the Q^2-evolution of the $\gamma_v pN^*$ electrocouplings of nucleon resonances of different structure by the experimental results within the range of Q^2 up to 18 - 22 GeV^2 will provide sound evidence for understanding how the dominant part of hadron mass and N* structure emerges from QCD and will make JLab@20+ GeV a unique and the ultimate QCD-facility at the luminosity frontier.**

Hadron Structure Studies with CLAS20+

Hadron Structure Group in Hall B developing physics case to support CLAS20+ upgrade

The exclusive electroproduction measurements foreseen at JLab after completion of the 12 GeV program:

- Beam energy at fixed target: 20+ GeV
- Nearly 4π coverage
- High luminosity

Offer optimal experiment conditions for extraction of the $\gamma_v pN^*$ electrocouplings at $Q^2>10$ GeV^2

List of Participating Institutions:

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

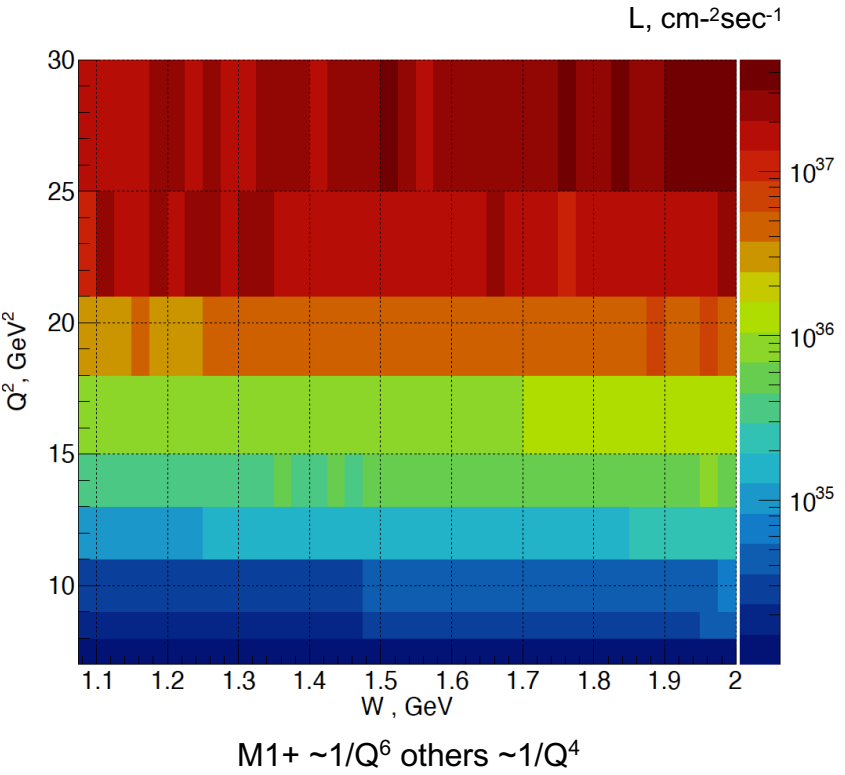
Program Summary Document: https://userweb.jlab.org/~carman/clas24

Outcome from simulation of πN, KY, and $\pi^+\pi^-$p electroproduction at $Q^2>10$ GeV^2 with CEBAF energy increased to 20+ GeV:

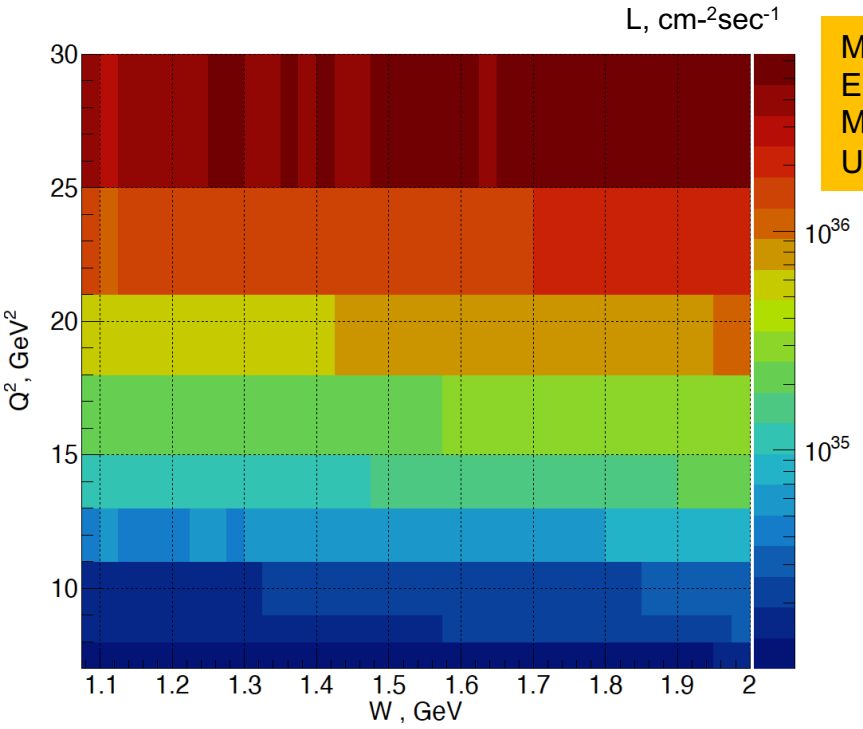
$\gamma_v pN^*$ electrocouplings can be determined up to Q^2_{max} from 18 - 22 GeV^2 for $\mathcal{L} < 10^{36}$ cm^{-2}s^{-1}

Back up

Luminosity to Determine $\gamma_v pN^*$ Electrocouplings at $Q^2>10$ GeV^2 from $N\pi$ Electroproduction



M1+ ~$1/Q^6$ others ~$1/Q^4$



M1+ ~$1/Q^6$ others ~$1/Q^2$

M.Davydov, E. Isupov, Moscow State U.

- Luminosities needed for extraction of $\gamma_v pN^*$ electrocouplings from $N\pi$ electroproduction at $Q^2>10$ GeV^2 were evaluated in each bin of (W,Q^2) as:

$$L(W,Q^2), = 10^{34}\ \text{cm}^{-2}\text{sec}^{-1}\ Y(W,Q^2{}_{\text{current}})/Y(W,Q^2=5.0\ \text{GeV}^2)\quad (1),$$

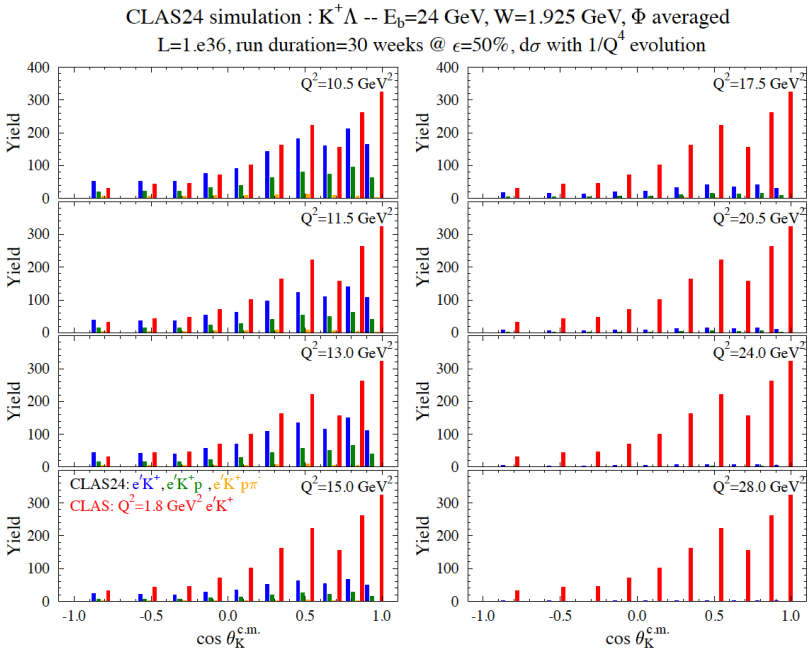
assuming that statistics comparable with those achieved in the measurements with CLAS in the bin of $(W,Q^2=5\ \text{GeV}^2)$ at luminosity 10^{34} cm^{-2}sec^{-1} will be sufficient

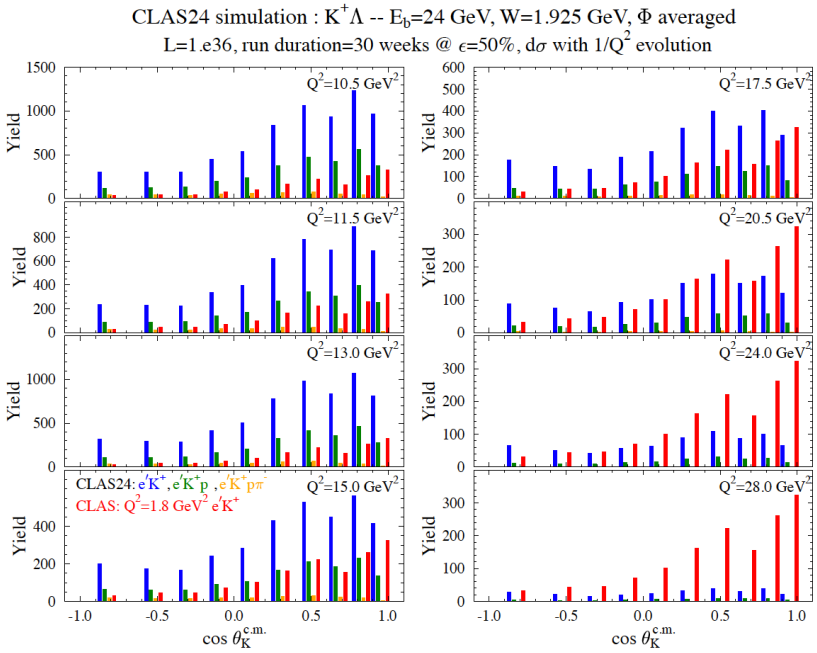
- The ratio $Y(W,Q^2{}_{\text{current}})/Y(W,Q^2=5.0\ \text{GeV}^2)$ was obtained in MC simulation for $E_{beam}=24$ GeV with $N\pi$ cross sections computed from the MAID07 multipoles at $Q^2=5.0$ GeV^2, extrapolated into the range of $Q^2>10$ GeV^2 as the accepted event ratio computed for CLAS12.

$\gamma_v pN^*$ electrocouplings can be determined up to Q^2_{max} in the range from 18 GeV^2 to 22 GeV^2 where the required luminosity remains below ~10^{36} cm^{-2}sec^{-1}

$\gamma_v pN^*$ Electrocouplings at $Q^2>10$ GeV^2 from KΛ Channel

D.S. Carman, Jefferson Lab





Yields of KΛ events in the bins of (W,Q^2,cos $\theta_K{}^{cm}$) were evaluated in MC simulation by employing 2-fold differential cross sections from the CLAS measurements at $Q^2<4$ GeV^2 and extrapolated into the range of $Q^2>10$ GeV^2 as $1/Q^4$ (left panel), $1/Q^2$ (right panel)

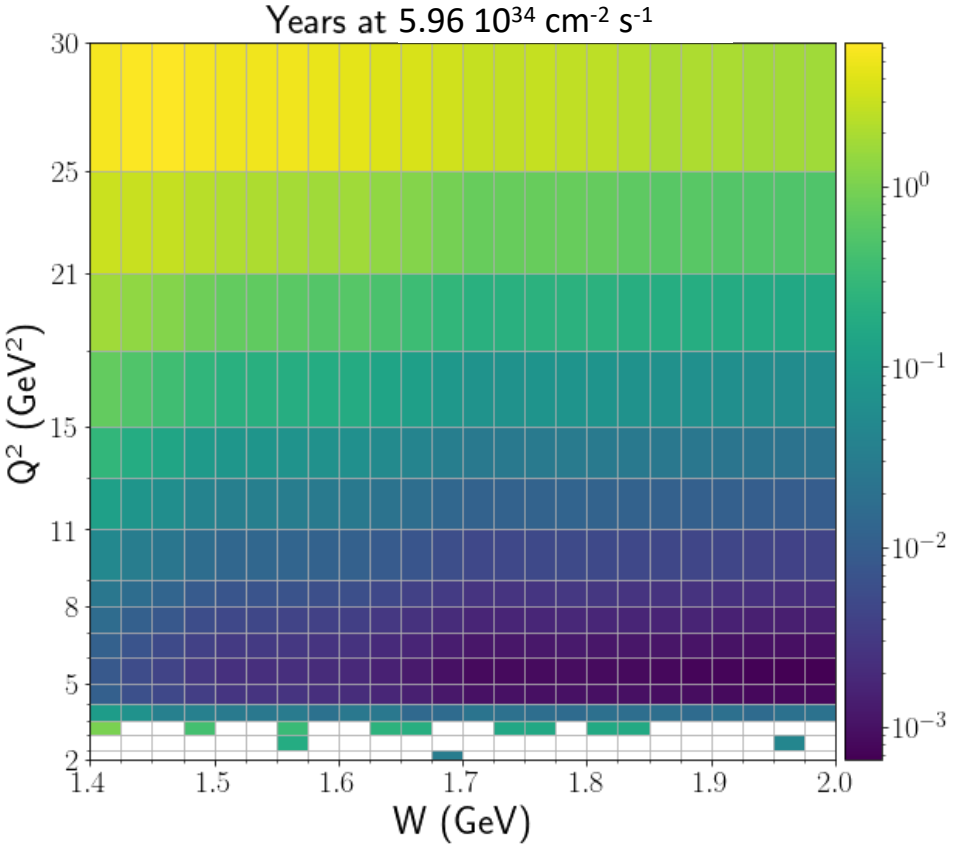
$\gamma_v pN^*$ electrocouplings can be determined up to Q^2_{max} in the range from 14 GeV^2 < Q^2 < 20 GeV^2, where the projected yields remains comparable with those achieved in the CLAS measurements

Beam Time Needs for Exclusive $p\pi^+\pi^-$

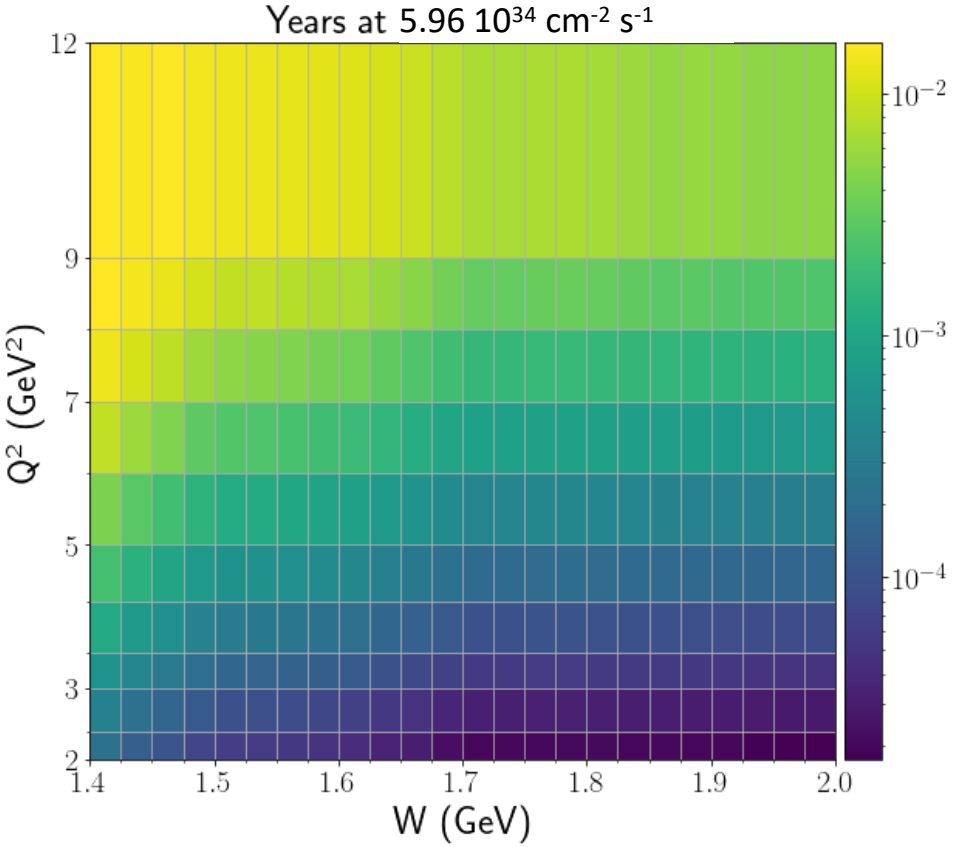
K. Neupane, R.W. Gothe - USC

Based on RG-A fall 2018 Luminosity of 5.96 10^{34} cm^{-2} s^{-1} at 45 nA

Simulated at 24 GeV Beam Energy



Simulated at 10.6 GeV Beam Energy

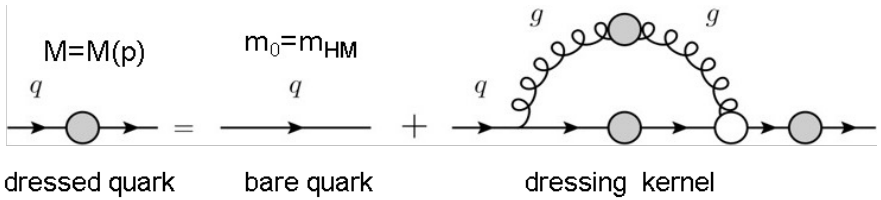


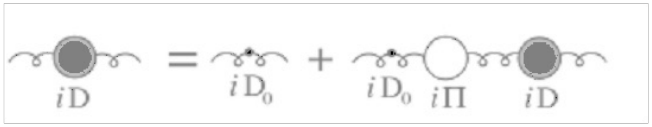
Implementing all analysis cuts (3/2), Golden Run Selection (3), PAC Days (2)

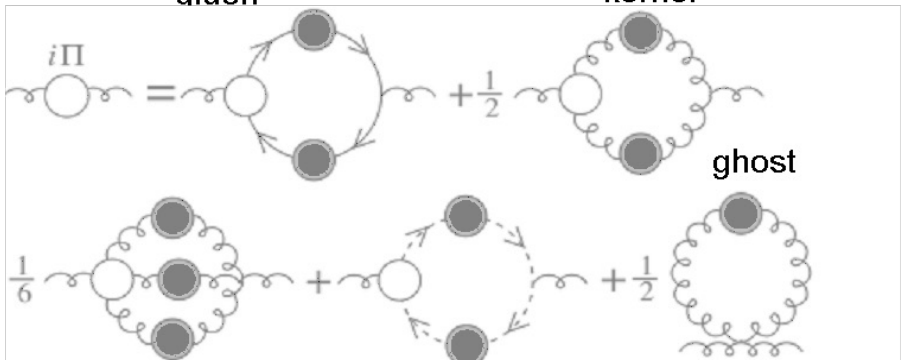
➡ 6 (12) years at 5.96 10^{34} cm^{-2} s^{-1} or 4 (8) month at 10^{36} cm^{-2} s^{-1}

Basics for Insight into EHM: CSM and Lattice QCD Synergy

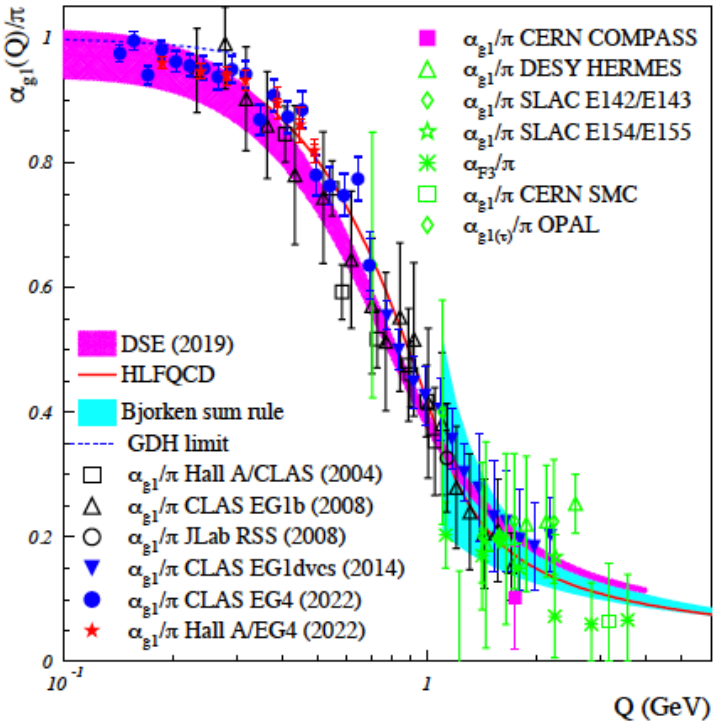
Emergence of Dressed Quarks and Gluons
D. Binosi et al., Phys. Rev. D 95, 031501 (2017)







QCD Running Coupling α(k)
Zh-F. Cui et al., Chin. Phys. C44, 083102 (2020)
A. Deur et al., Particles 5, 171 (2022)

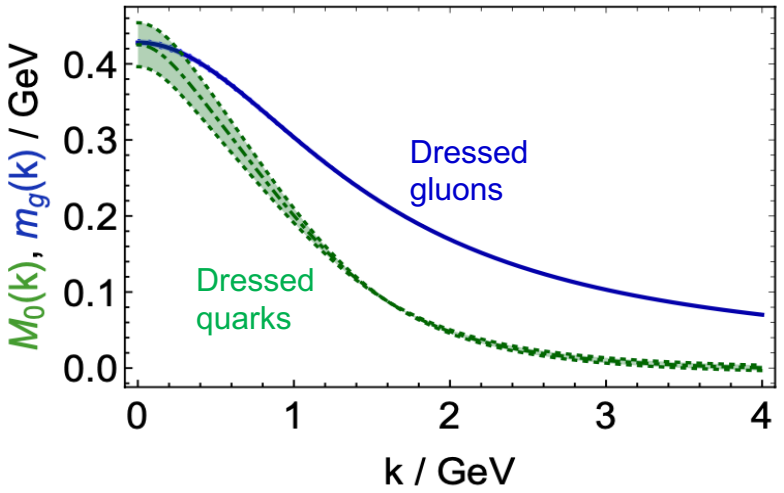


In the regime of the QCD running coupling comparable with unity, dressed quarks and gluons with distance (momentum) dependent masses emerge from QCD, as follows from the equation of the motion for the QCD fields depicted above.

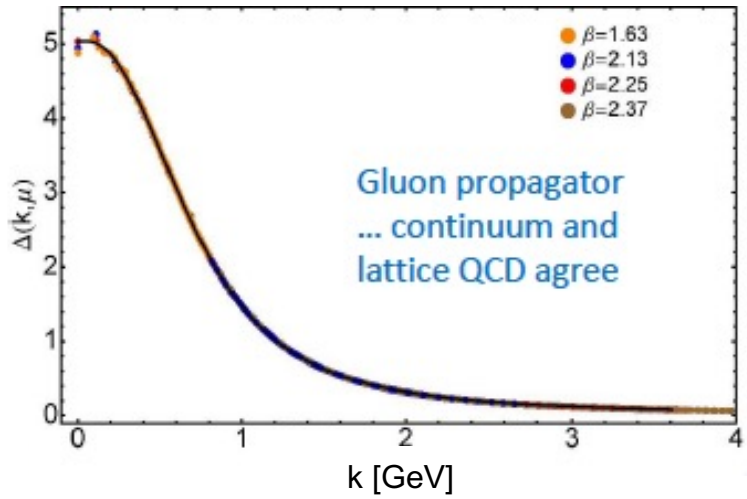
Basics for Insight into EHM: Continuum and Lattice QCD Synergy

- 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

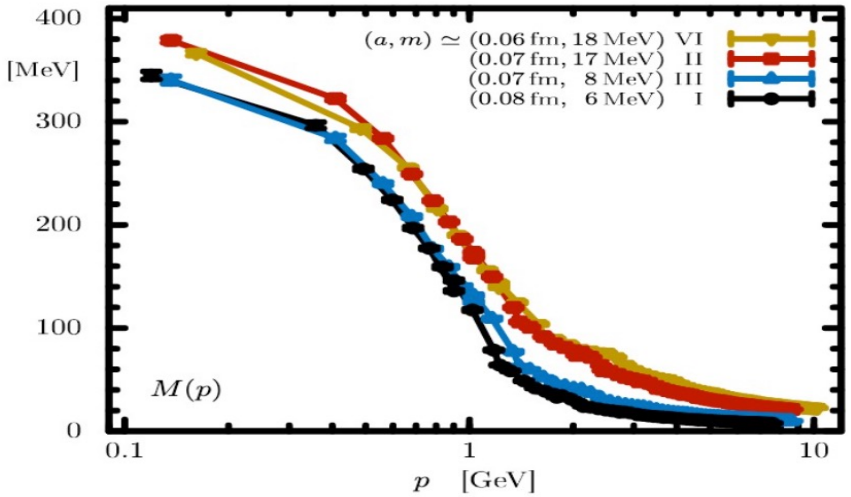
Dressed Quark/Gluon Masses (Continuum QCD)
C.D. Roberts, Symmetry 12, 1468 (2020)



Inferred from QCD Lagrangian with only Λ_{QCD} parameter



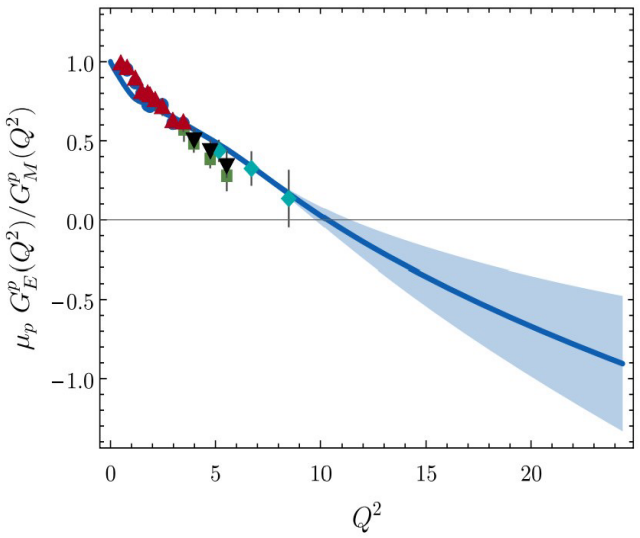
Dressed Quark Mass (Lattice QCD)
O. Olivera et al., Phys. Rev. D 99, 094506 (2019)



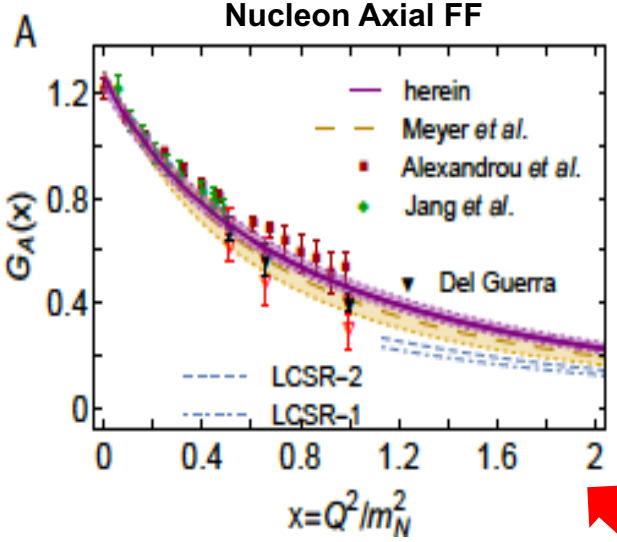
EHM from Global Hadron Structure Analysis

All observables will be extended by the future data from JLab in the 12 GeV era, AMBER@CERN, EIC, EicC

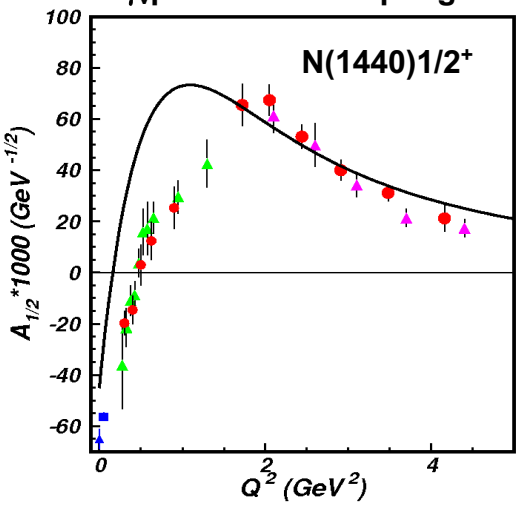
Nucleon Elastic FF



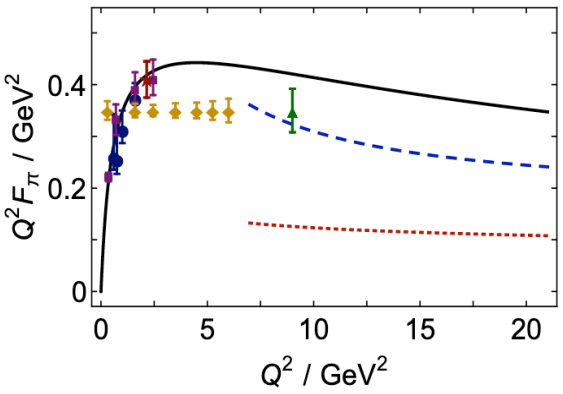
Nucleon Axial FF



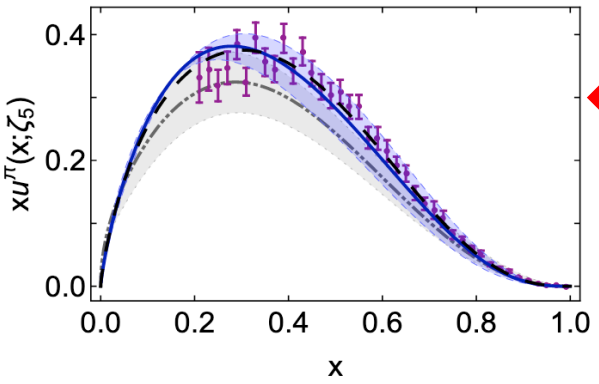
$\gamma_v pN^*$ Electrocouplings



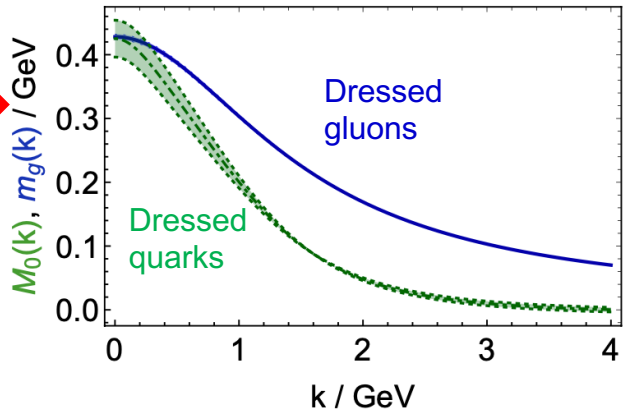
Pion Elastic FF



Pion PDF



Dressed Quark/Gluon Running Masses



- CSM has provided predictions on observables that describe the structure of mesons and the ground/excited states of the nucleon by employing the same dressed quark mass function

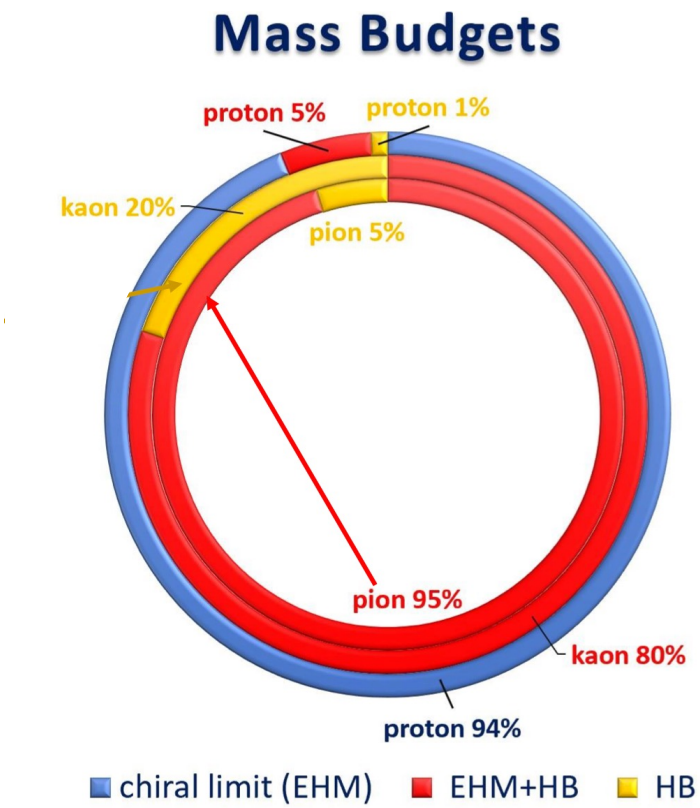
Insight into EHM from Data on Pion/Kaon Structure

- 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.

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

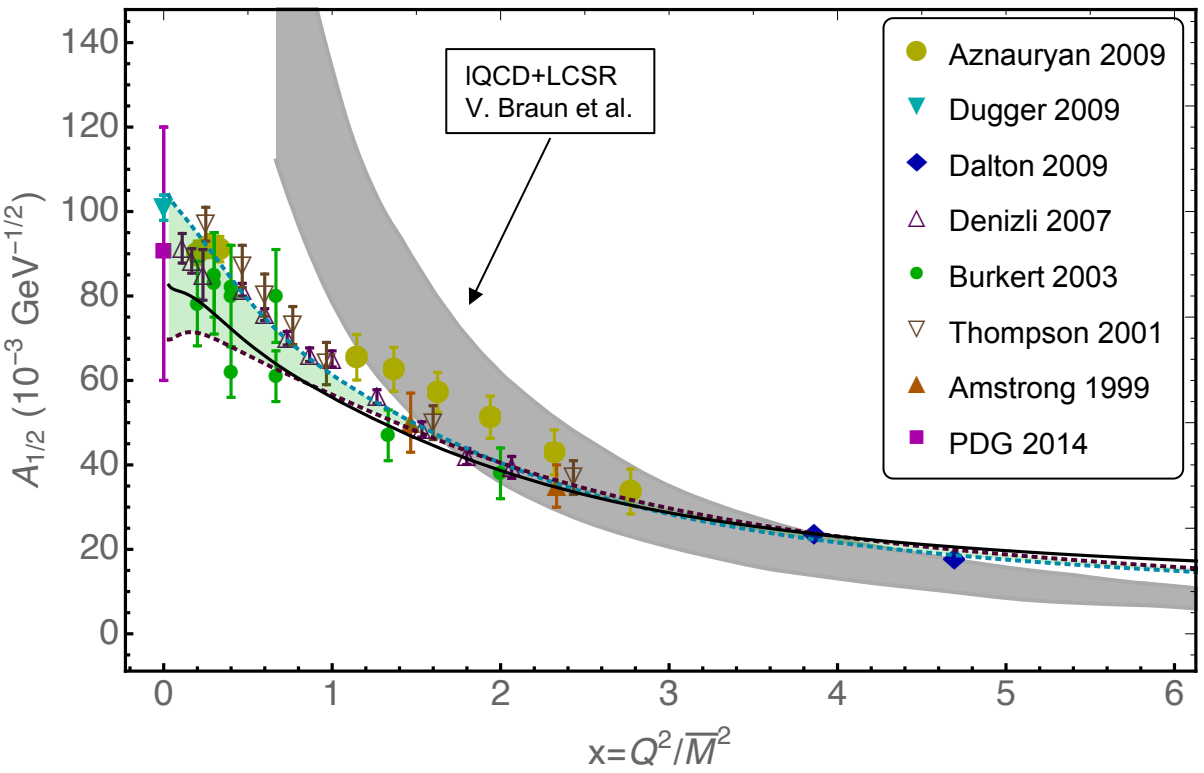
- Pions and kaons are simultaneously $q\bar{q}$ bound states and Goldstone bosons in chiral symmetry breaking. Their masses should be reduced to zero in the chiral limit and, in the real world, down to small values in comparison with the hadron mass scale owing to DCSB.

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



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.

Extending Insight into EHM from N* Electroexcitation Studies with CLAS/CLAS12/CLAS20+

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

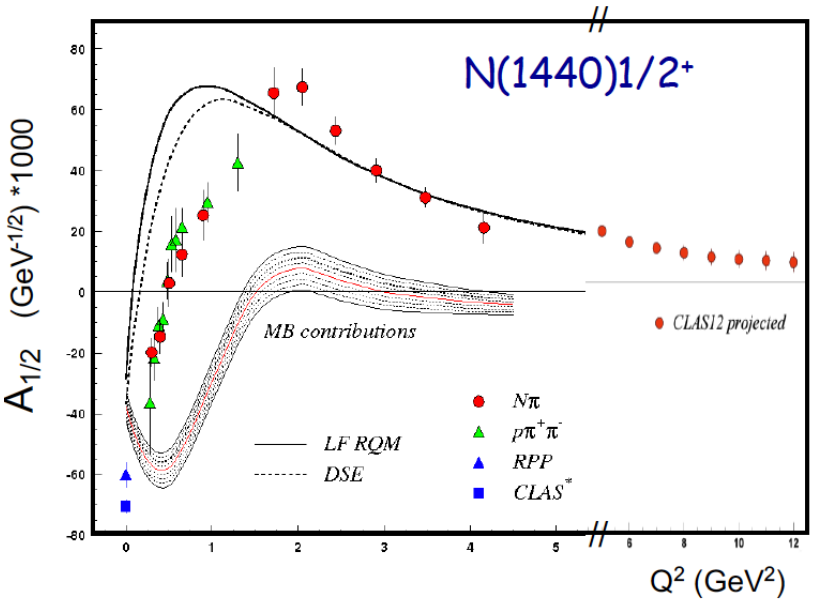
How is >98% of visible mass generated?

How EHM is related to Dynamical Chiral Symmetry Breaking?

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

Mapping-out the dressed quark mass function from $\gamma_v pN^*$ electrocouplings of different spin-isospin flip, radial, and orbital excited nucleon states at $5<Q^2<12$ GeV^2 will increase knowledge on EHM and motivate efforts to determine $\gamma_v pN^*$ electrocouplings for Q^2 up to 35 GeV^2 to explore the full range of distances (quark momenta) where the dominant part of hadron mass is expected to be generated

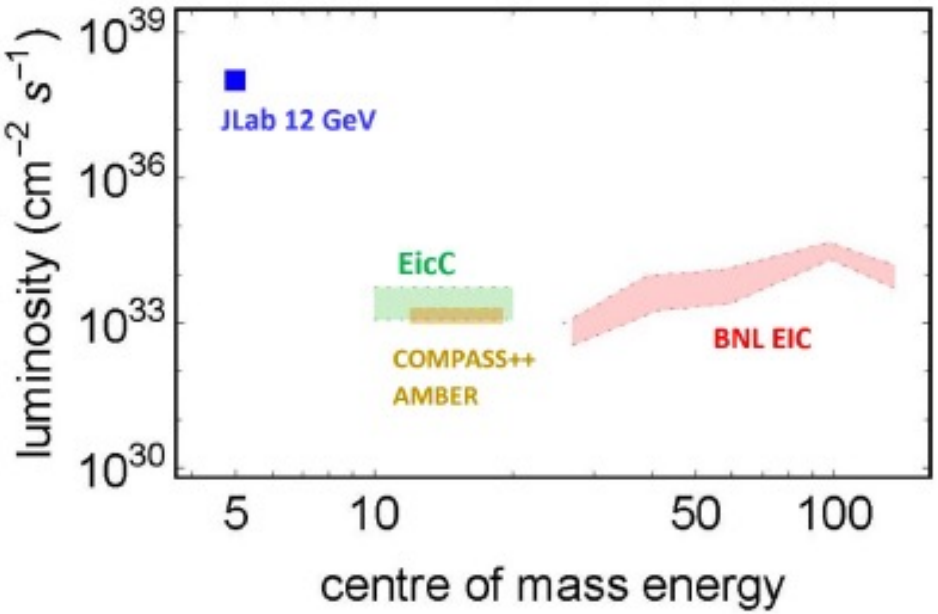
	Q^2-coverage for $\gamma_v pN^*$ electrocoupling results	Accessible range of quark momenta p	Fraction of fully dressed quark mass generated at $p<p_{max}$
CLAS	<5.0 GeV^2	<0.7 GeV	15-20 %
CLAS12	<9.0-10.0 GeV^2	<1.0 GeV	40-50 %
CLAS24	<35.0 GeV^2	<2.0 GeV	>90 %



CLAS results vs. theory expectations with running quark mass

Unique Opportunity for Studies of N* Electroexcitation at $Q^2 > 10$ GeV^2 after Increase of CEBAF Energy

Energy and luminosity increase are needed in order to obtain information on the $\gamma_v pN^*$ electro-couplings 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: 20+ GeV
- Nearly 4π coverage
- High luminosity

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

CLAS12 improvements to meet science requirements

Courtesy V.D. Burkert - JLab

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