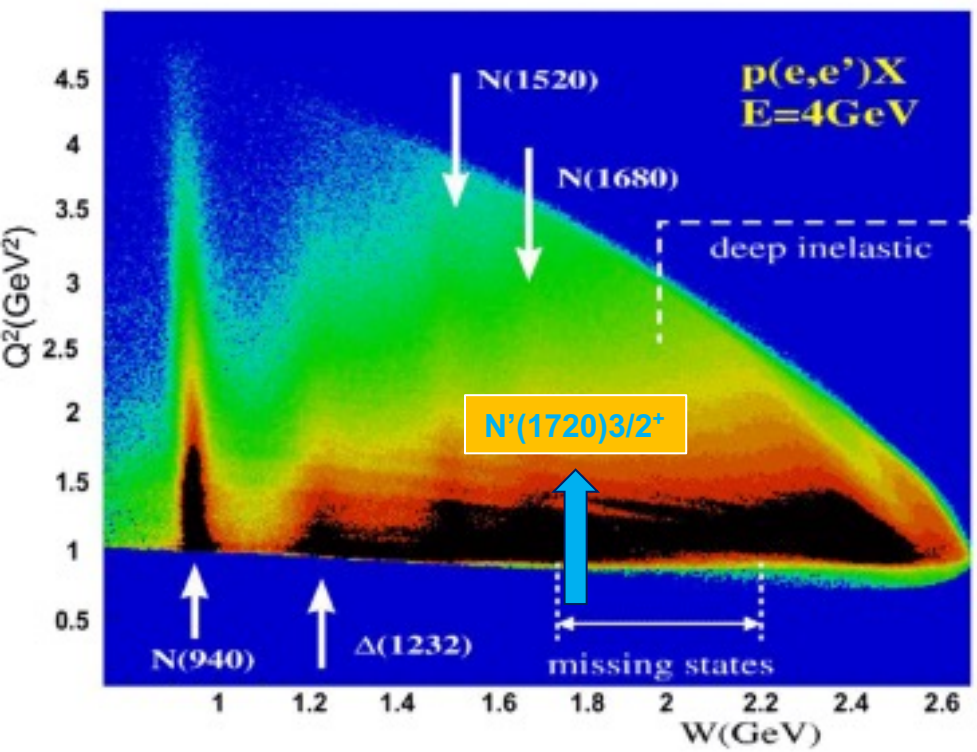
Synergies with EHM at JLab



Talk outline:

- **Insight into EHM from combined exploration of meson and baryon structure**
- **Mapping dressed quark mass function from the data on the ground nucleon structure**
- **EHM from combined studies of the nucleon elastic form factors and $\gamma_v pN^*$ electrocouplings**
- **New opportunities for gaining insight into EHM from inclusive electron scattering data in the resonance region**

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

Office of Science

Perceiving the Emergence of Hadron Mass through AMBER@CERN
April 27-29, 2021, Geneva Switzerland

Studies of the Nucleon and N* Structure as a Window into EHM

Composition of the Nucleon Mass:

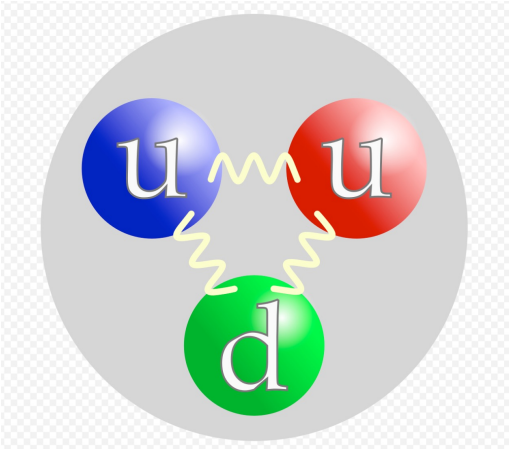
M_p, MeV (PDG20)

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



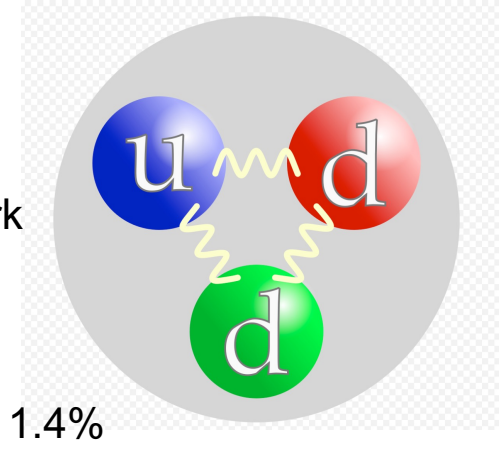
M_n, MeV (PDG20)

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%

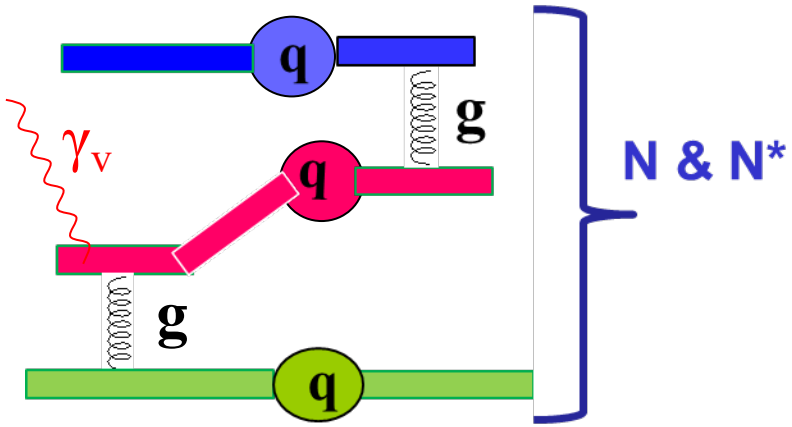
neutron



Dominant part of nucleon mass emerges from strong interaction in the regime when QCD's process-independent running-coupling becomes comparable with unity

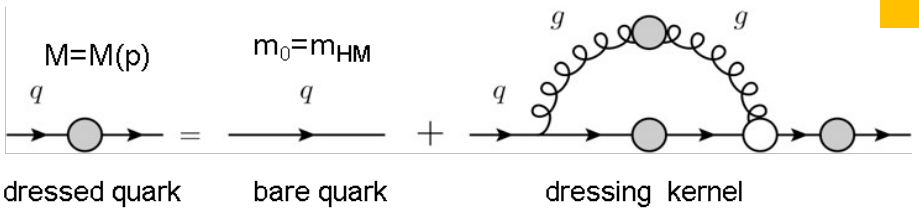
- Elastic/resonance electroexcitation amplitudes are sensitive to dressed quark propagator allowing us to map-out momentum dependence of dressed quark mass

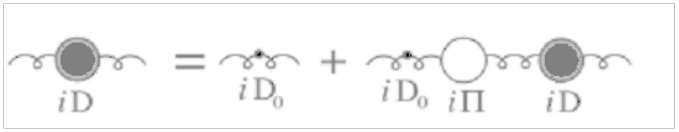
- Consistent results on momentum dependence of dressed quark mass from independent studies of elastic and transition N→N* FFs validate credible insight into the dynamics of hadron mass generation

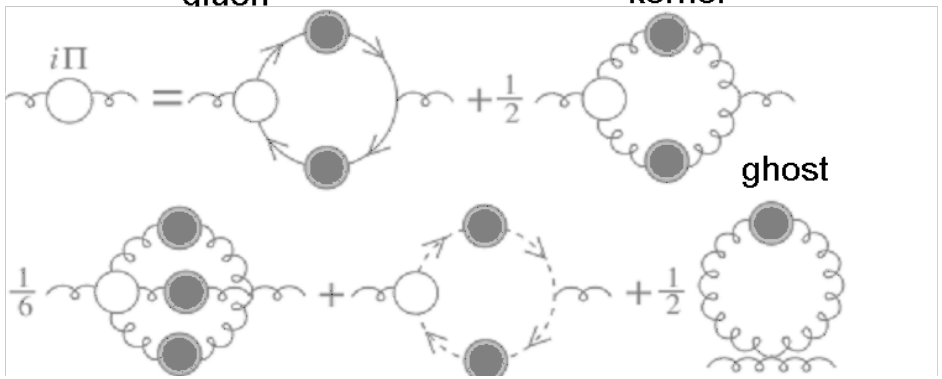


Basics for Insight into EHM with Continuum QCD

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

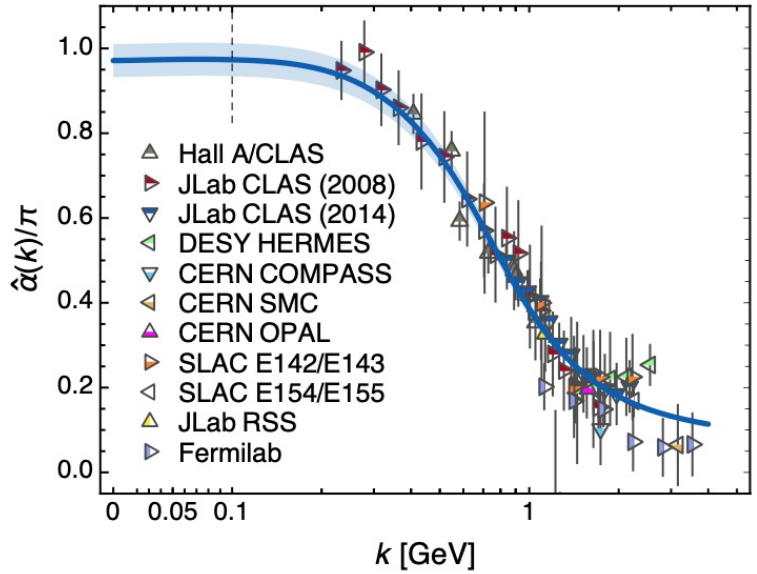


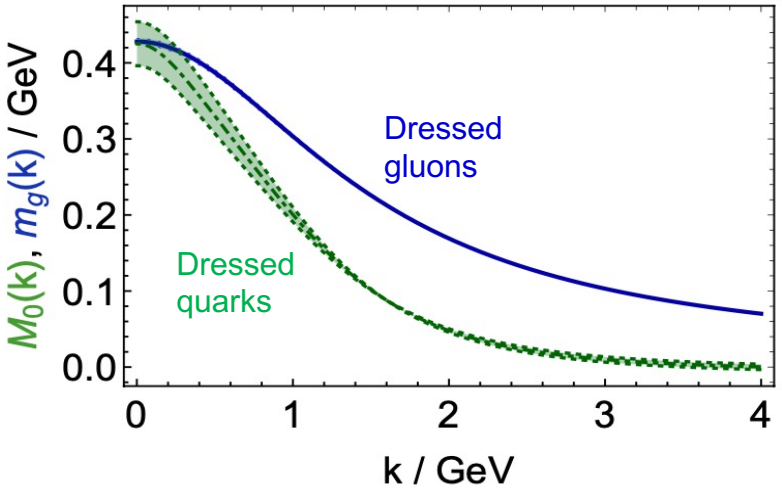




- Dressed quark/gluon masses converge at the complete QCD mass scale of 0.43(1) GeV elucidating the trace anomaly O(M_proton)
- Momentum-dependent quark/gluon masses shape the ground/excited hadron structure and assure that $\alpha(k)$ is free of divergences, making QCD a well-defined theory at all distance scales

QCD Running Coupling $\alpha(k)$ & Dressed Quark/Gluon Masses
C.D. Roberts, Symmetry 12, 1468 (2020)



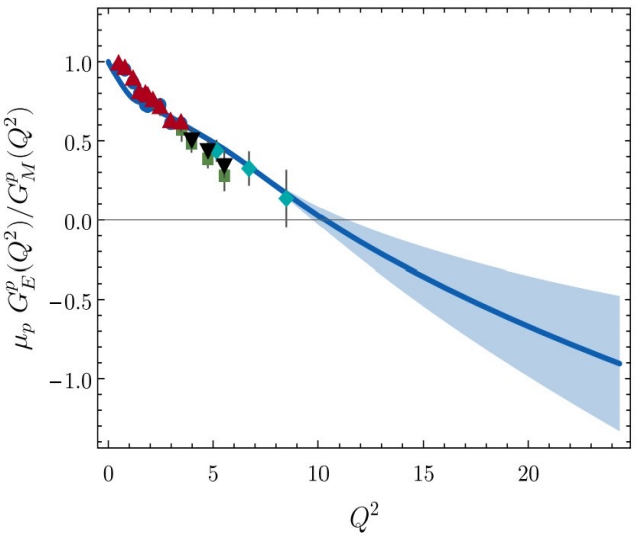


Inferred from QCD Lagrangian with only the Λ_{QCD} parameter

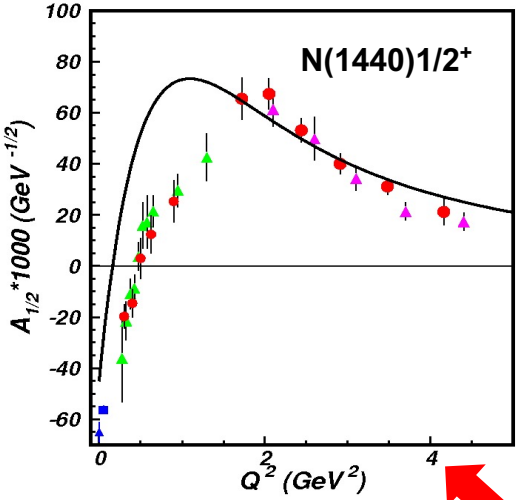
EHM from Global Hadron Structure Analysis

Will be extended by the future data of the 12 GeV era at Jlab

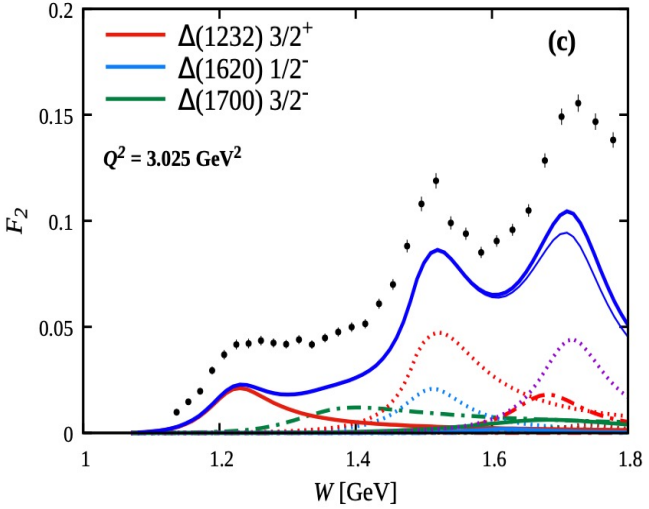
Nucleon Elastic FF



$\gamma_v pN^*$ Electrocouplings

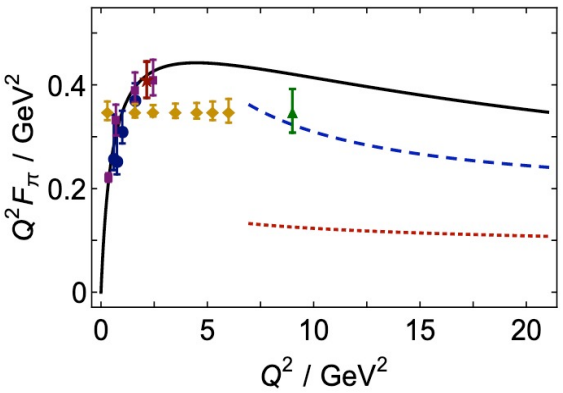


(e,e'X) Inclusive Scattering

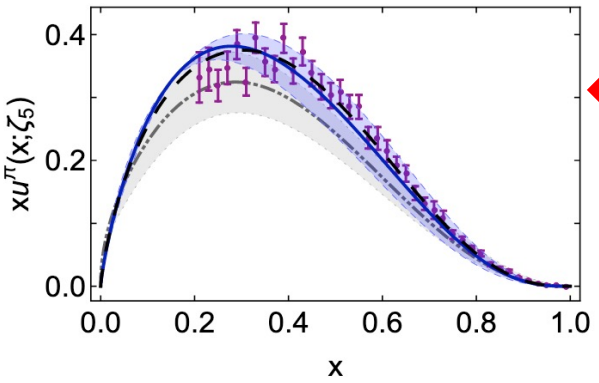


New data from studies of DY at AMBER and Sullivan processes at Jlab

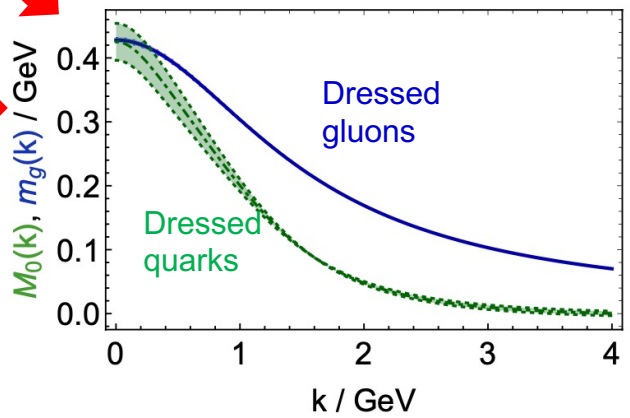
Pion Elastic FF



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

Synergy between the Data on the Meson and N/N* Structure for the Insight into EHM

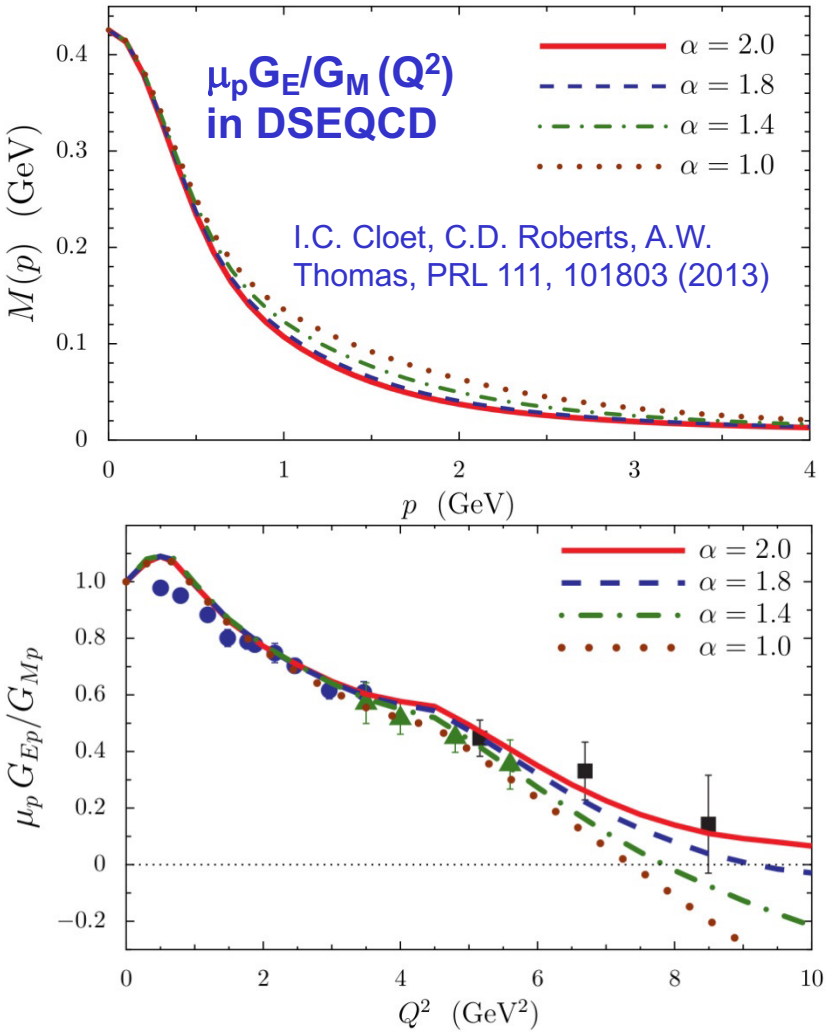
- The model and renormalization scheme/scale independent Goldberger-Treiman relations connects the momentum dependence of dressed quark mass to pion/kaon Bethe-Salpeter amplitudes making the studies of pion and kaon structure the promising way to map out momentum dependence of dressed quark mass.

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

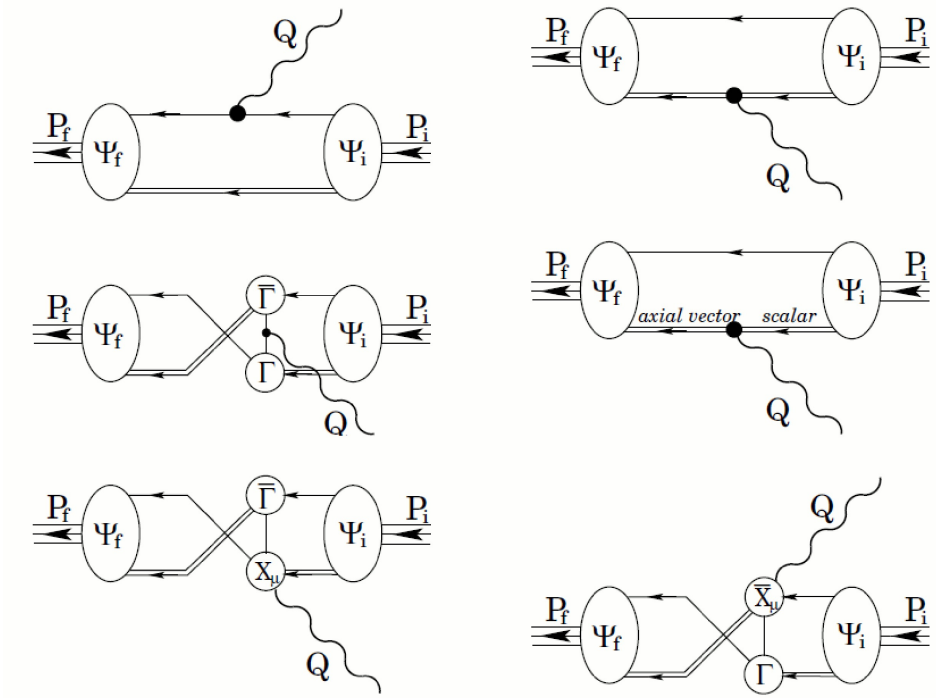
- Studies of the ground and excited nucleon structure states allow us to explore dressed quark mass function in different environment for the bound quark systems with masses expected for hadron mass scale, the biggest contribution from masses of dressed quarks allowing us to probe masses of dressed quarks at low momenta.

- Consistent results on momentum dependence of 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 the insight into EHM.

Dressed Quark Mass Function from the Nucleon Elastic Form Factor Data



Description of N/N* electroexcitation in DSEQCD

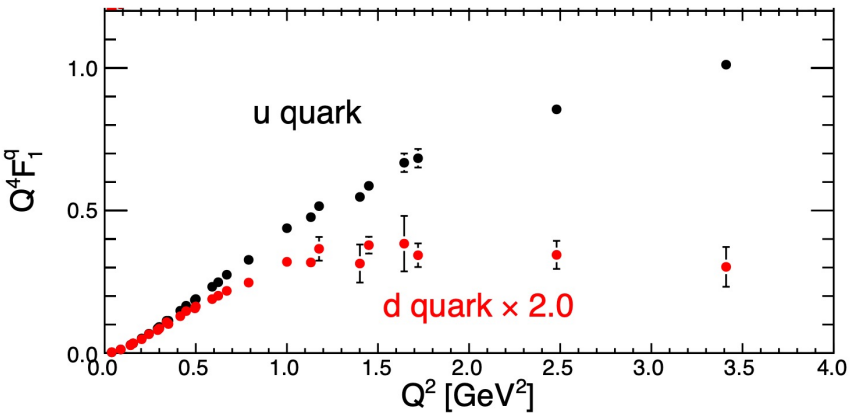


• **Elastic form factors (bottom plot) are sensitive to the rate for the transition between a fully dressed (constituent) quark in the infrared to an almost bare QCD quark in ultraviolet seen in the momentum dependence of quark mass function (top plot)**

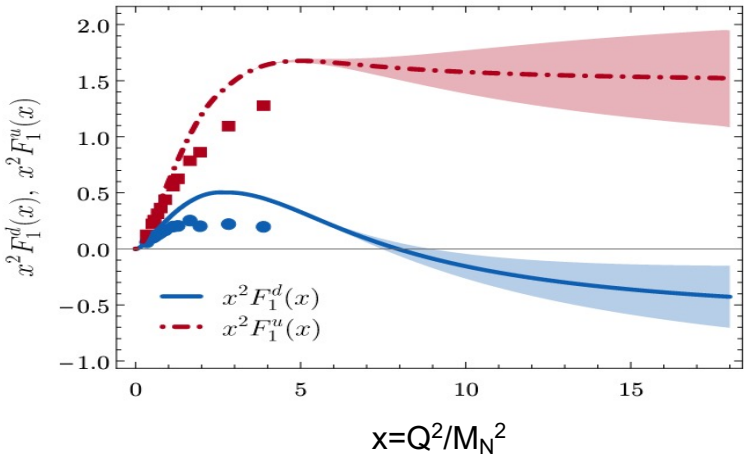
Charting the Contributions from the Di-Quarks

u- and d-quark contributions into F_1 elastic nucleon form factor and their description with continuum QCD

M.Y. Barabanov et al., Prog, Part. Nucl. Phys. 116, 103835 (2021)



Z. Cui et al., Phys. Rev D 102, 014043 (2021)

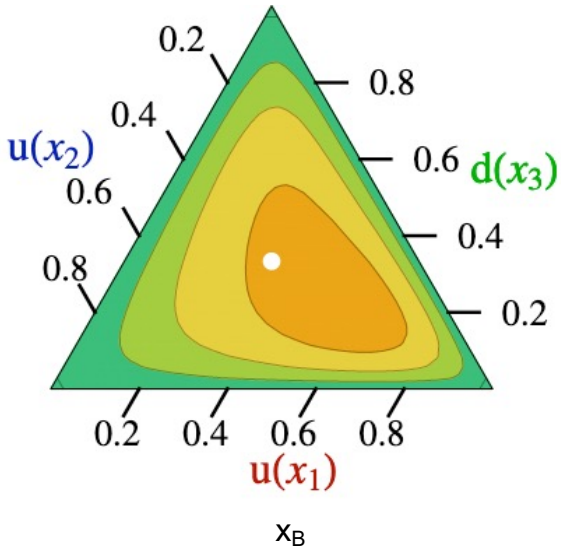


Preferential contributions from [uu] in comparison with [ud] di-quark correlation

Continuum QCD predictions for the proton PDA
C. Mezrag et al., Phys. Rev. Lett B783, 263 (2018)

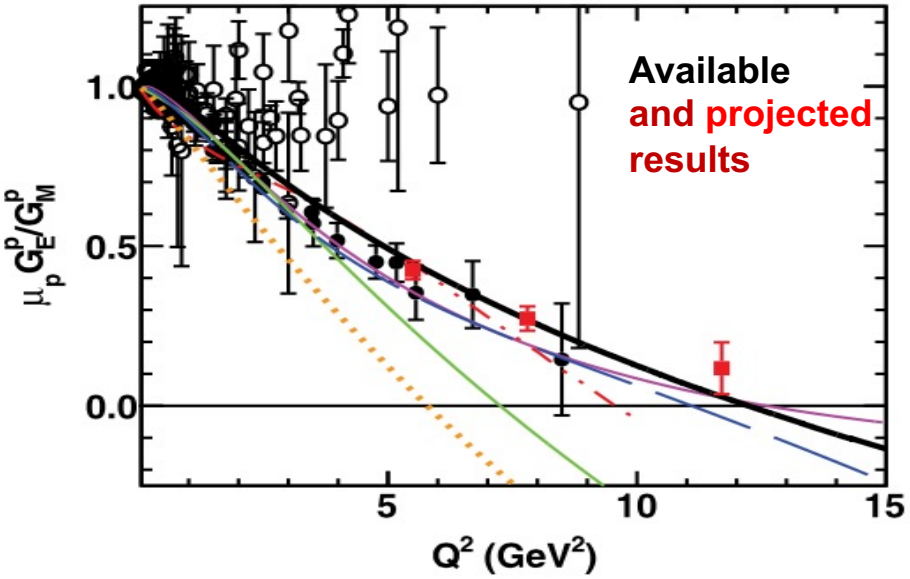
Maximum of the ground nucleon PDA is located at $\{x_i\}=\{0.55, 0.23, 0.22\}$ Asymmetry and gap in x_l values are originated by di-quark correlations.

Studies of the 3-D femto-image of the nucleon will pave a way to check this prediction.

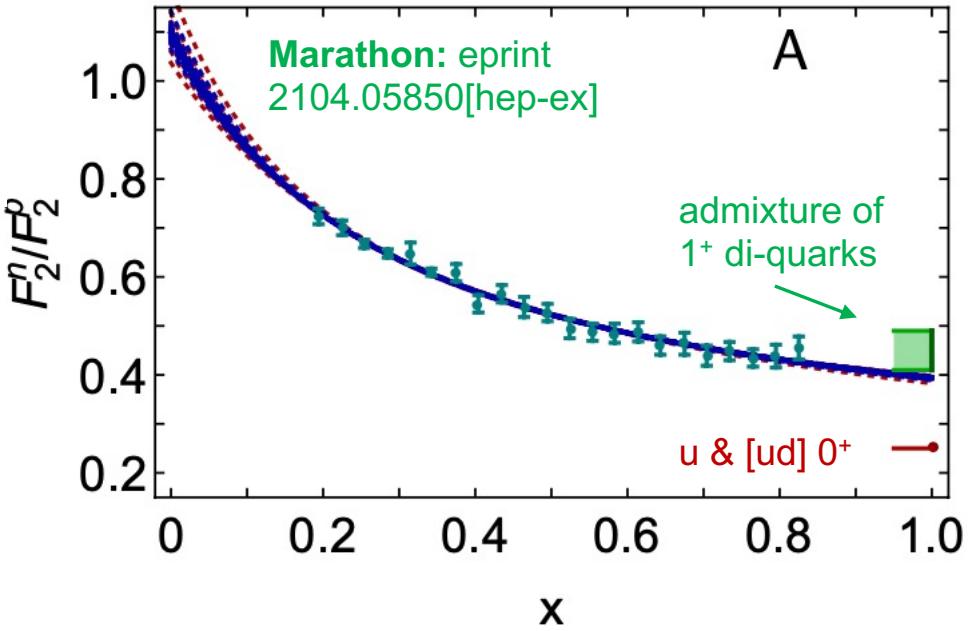


EHM from the Ground Nucleon Structure Exploration in 12 GeV Era

- 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



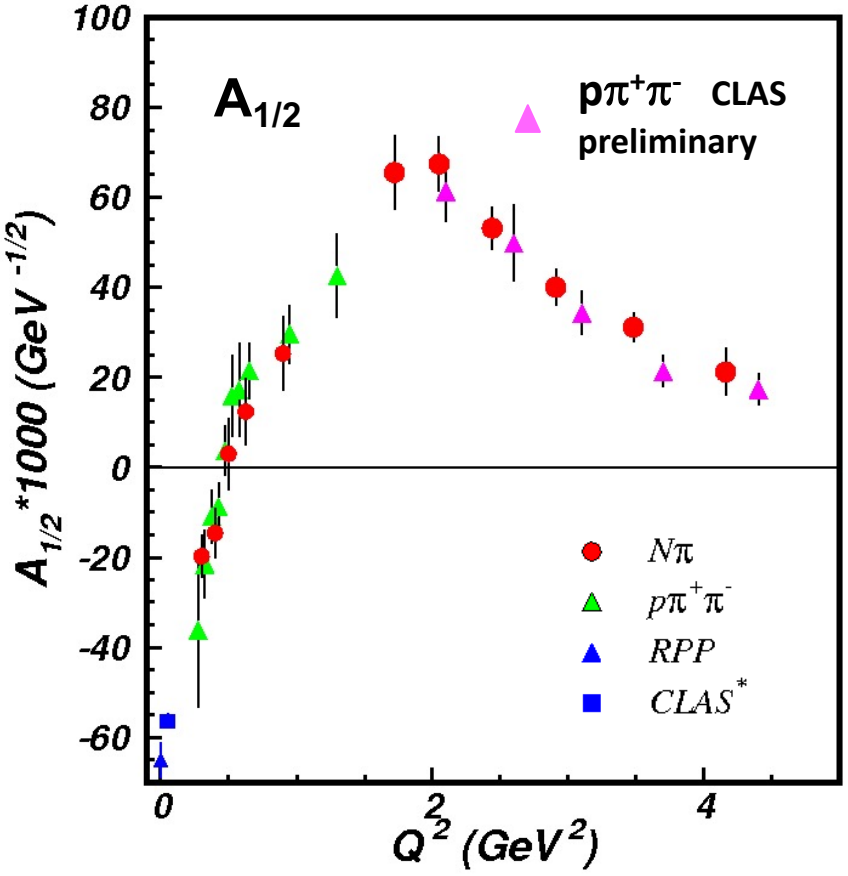
Shed light on the presence of di-quark correlations of spin-parity 0^+ and 1^+

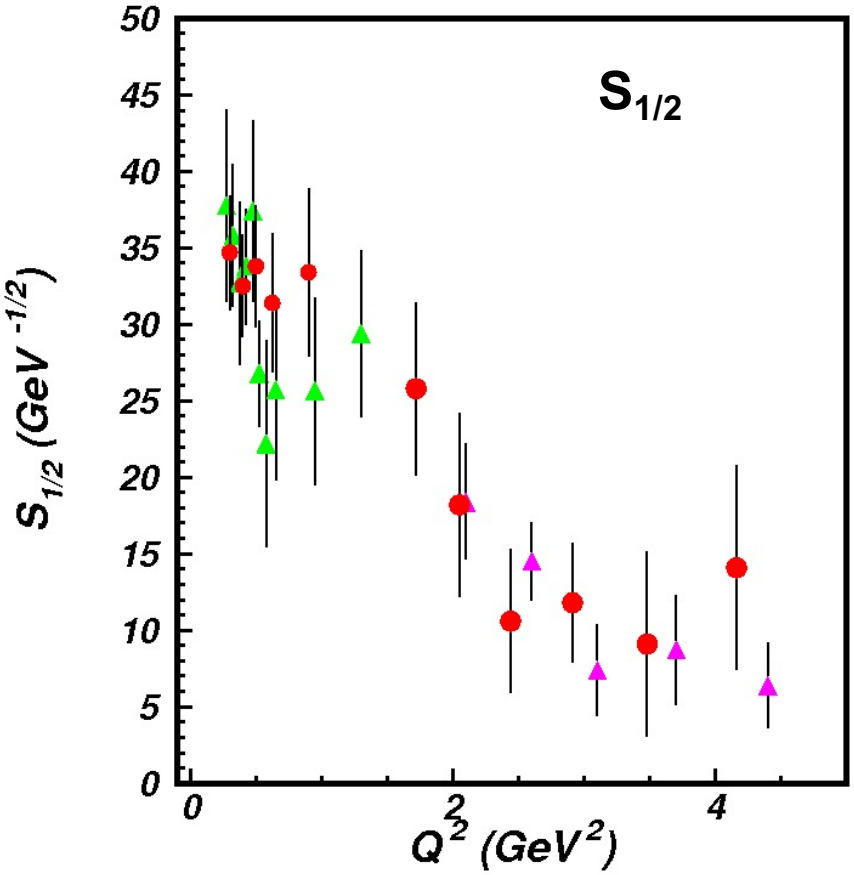
Nucleon Resonance Electrocouplings from Data On Exclusive Meson Electroproduction with CLAS

Exclusive meson electroproduction channels	Excited proton states	Q^2-ranges for extracted $\gamma_v pN^*$ electrocouplings, GeV^2
$\pi^0 p$, $\pi^+ n$	$\Delta(1232)3/2^+$ $N(1440)1/2^+$,$N(1520)3/2^-$, $N(1535)1/2^-$	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) 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



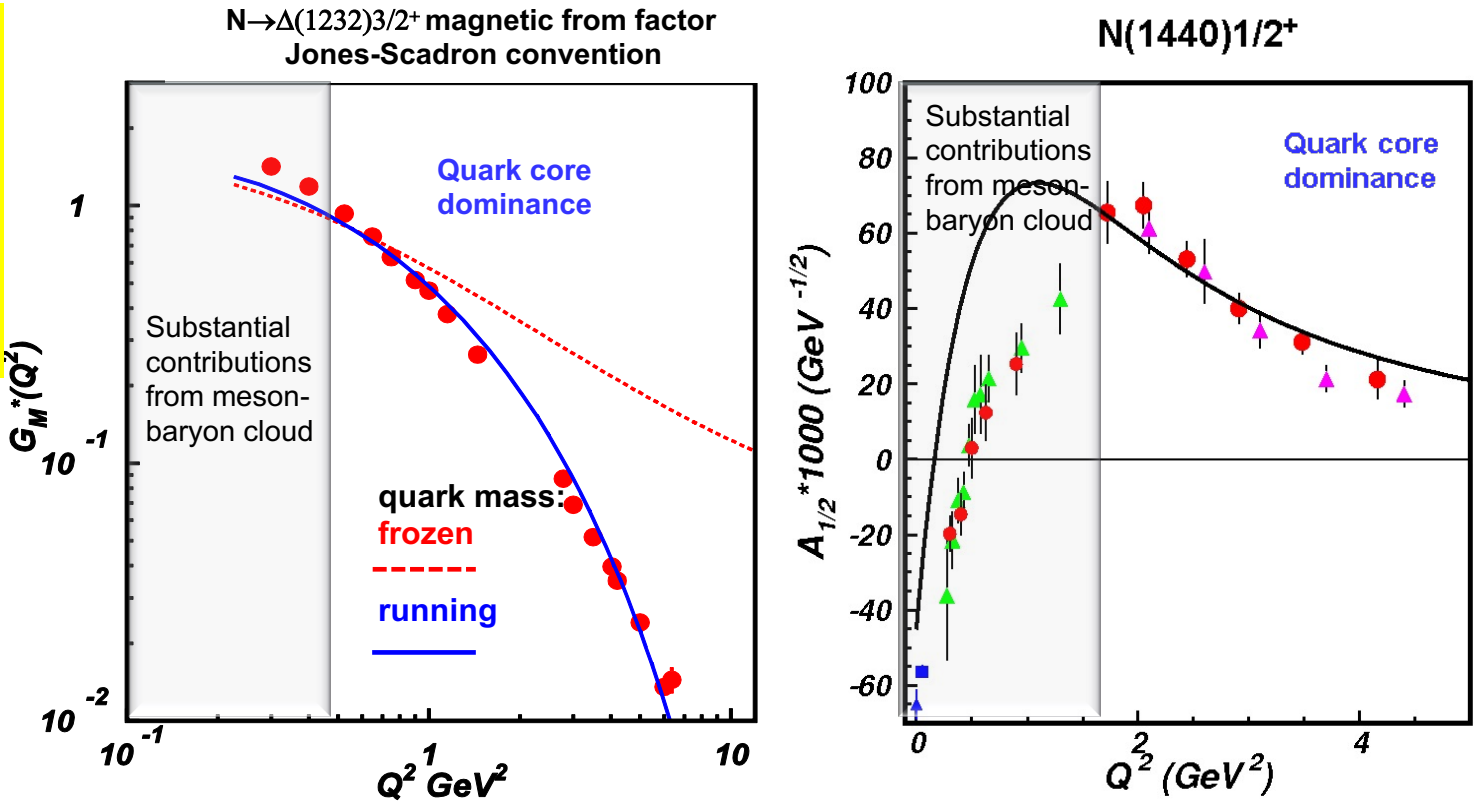


Consistent results on N(1440)1/2$^+$ electrocouplings from independent studies of two major πN and $\pi^+\pi^-$p electroproduction channels with different non-resonant contributions allow us to evaluate the systematic uncertainties of these quantities in a nearly model-independent way

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)



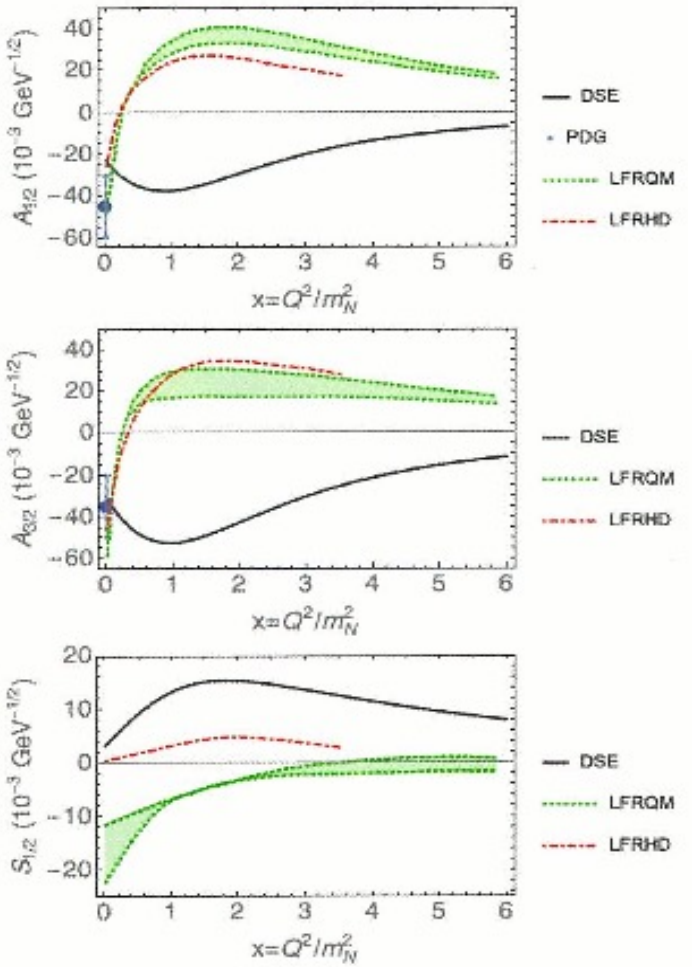
DSE analyses of CLAS data on Δ(1232)3/2⁺ electroexcitation demonstrate that dressed quark mass runs with momentum

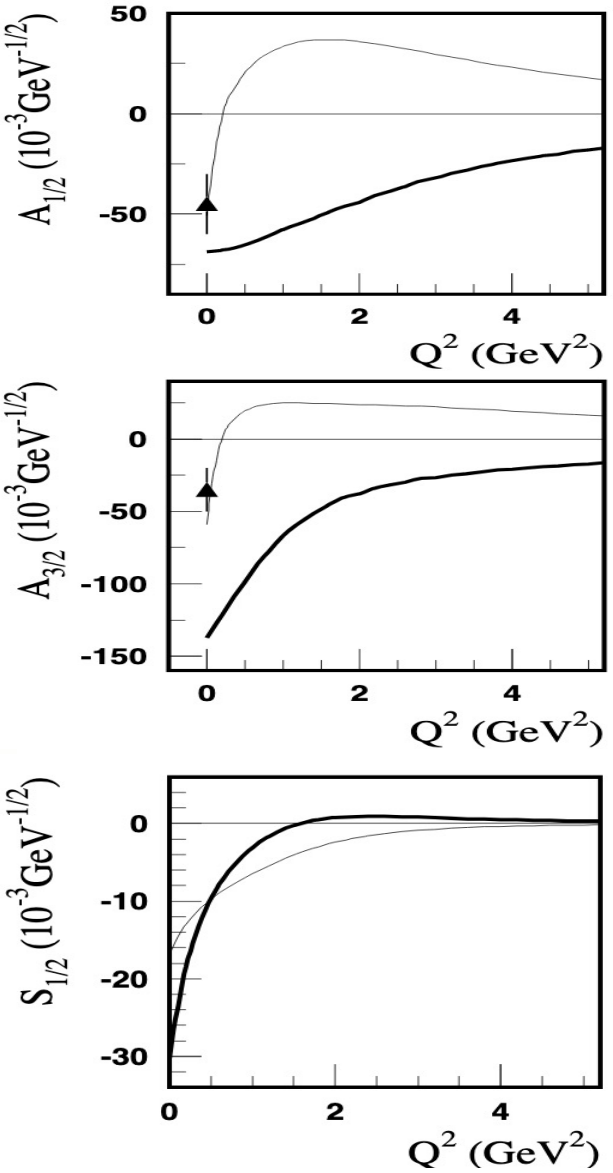
Good data description at Q^2>2.0 GeV^2 achieved with the same dressed quark mass function for the ground and two excited nucleon states of distinctively different structure validates the DSE results on momentum dependence of dressed quark mass. γ_vpN* electrocoupling data offer access to the strong QCD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

Δ(1600)3/2⁺



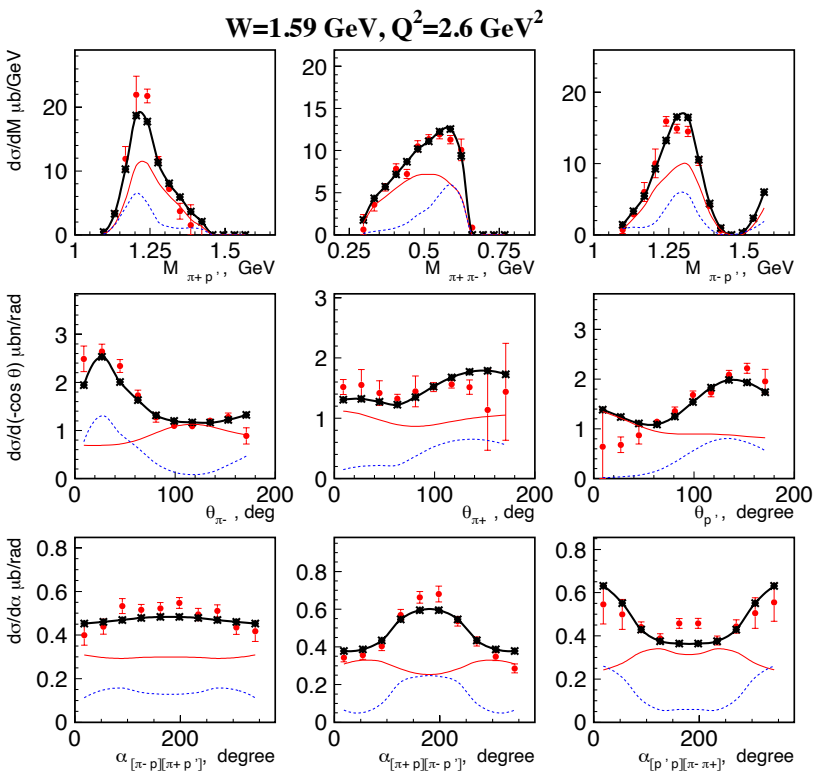


LFRQM accounting for 3-quark configuration mixing : I.G. Aznauryan and V.D. Burkert arXiv: 1603.06692 [nep-ph]

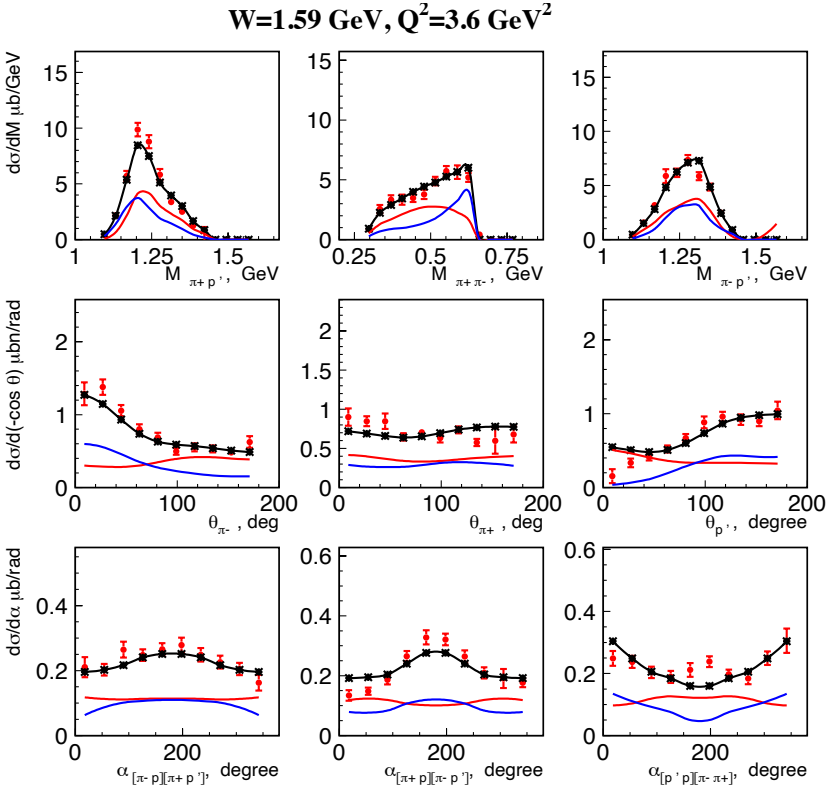
Parameter free continuum QCD (DSE) predictions for Δ(1600)3/2⁺ electrocouplings. Ya Lu et al., Phys. Rev. D100, 034001 (2019)

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



Full.

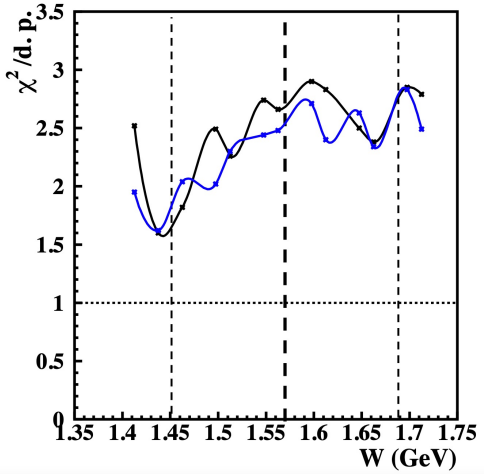
Resonances

Background

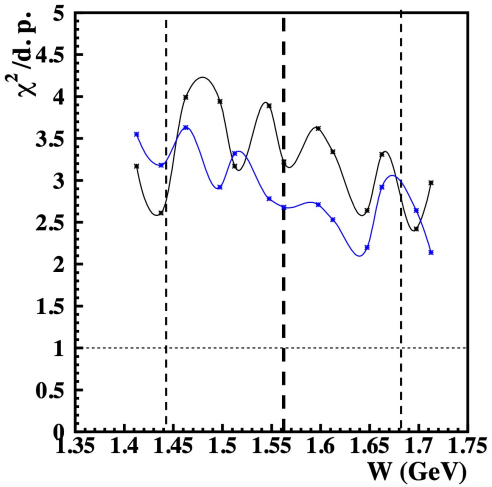
- Reasonable data description and pronounced differences in the resonant/background contributions offer a good prospect for extraction of $\Delta(1600)3/2^+$ electrocouplings from the $\pi^+\pi^-p$ electroproduction data
- Confirmation of the continuum QCD expectations on $\Delta(1600)3/2^+$ electrocouplings 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 $\Delta(1600)3/2^+$

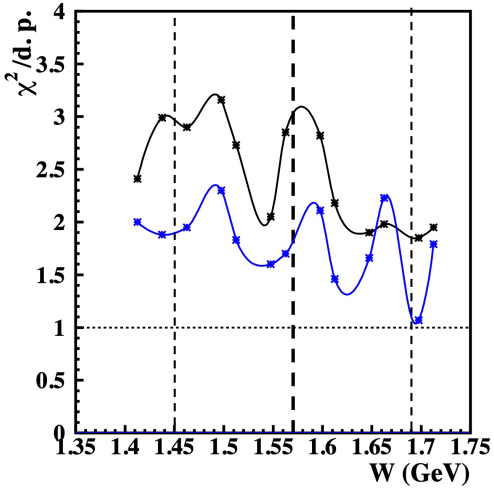
$2.0\ GeV^2<Q^2<2.4\ GeV^2$



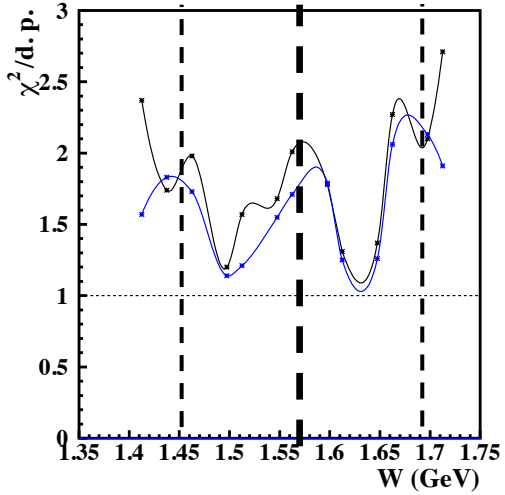
$2.4\ GeV^2<Q^2<3.0\ GeV^2$



$3.0\ GeV^2<Q^2<3.5\ GeV^2$



$4.2\ GeV^2<Q^2<5.0\ GeV^2$



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**

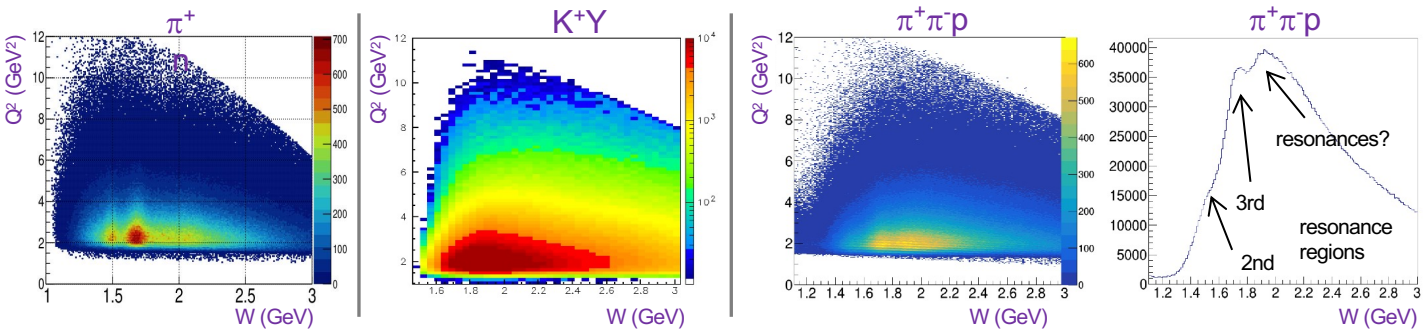
——— **$\Delta(1600)3/2^+$ resonance is included with electro-couplings predicted within continuum QCD (slide #11)**

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 $2.0<Q^2<5.0\ GeV^2$

N* Electroexcitation to High Q^2 with CLAS12

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

kinematic coverage for RG-A data @ 10.6 GeV



Expected events per Q^2/W bin for full RG-A dataset

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

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

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

Emergence of Hadron Mass and Quark-Gluon Confinement

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

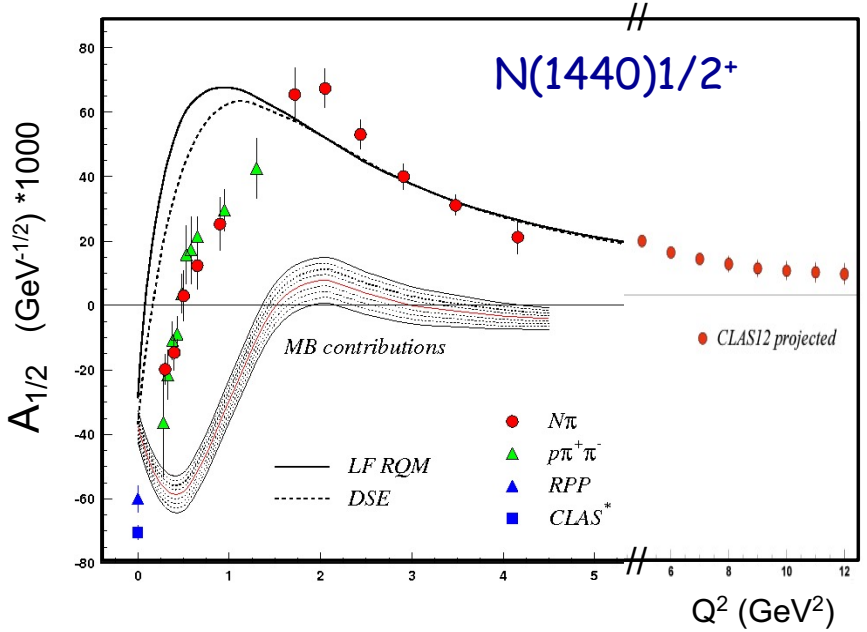
How is >98% of visible mass generated?

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?

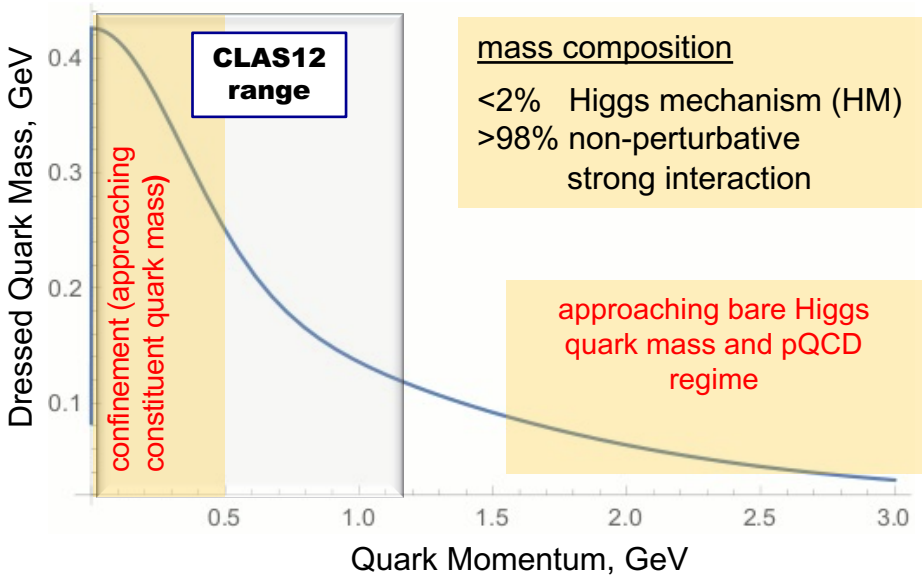
(S.J, Brodsky et al., Int. J. Mod. Phys. Rev. E29, 2030006 (2020))

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



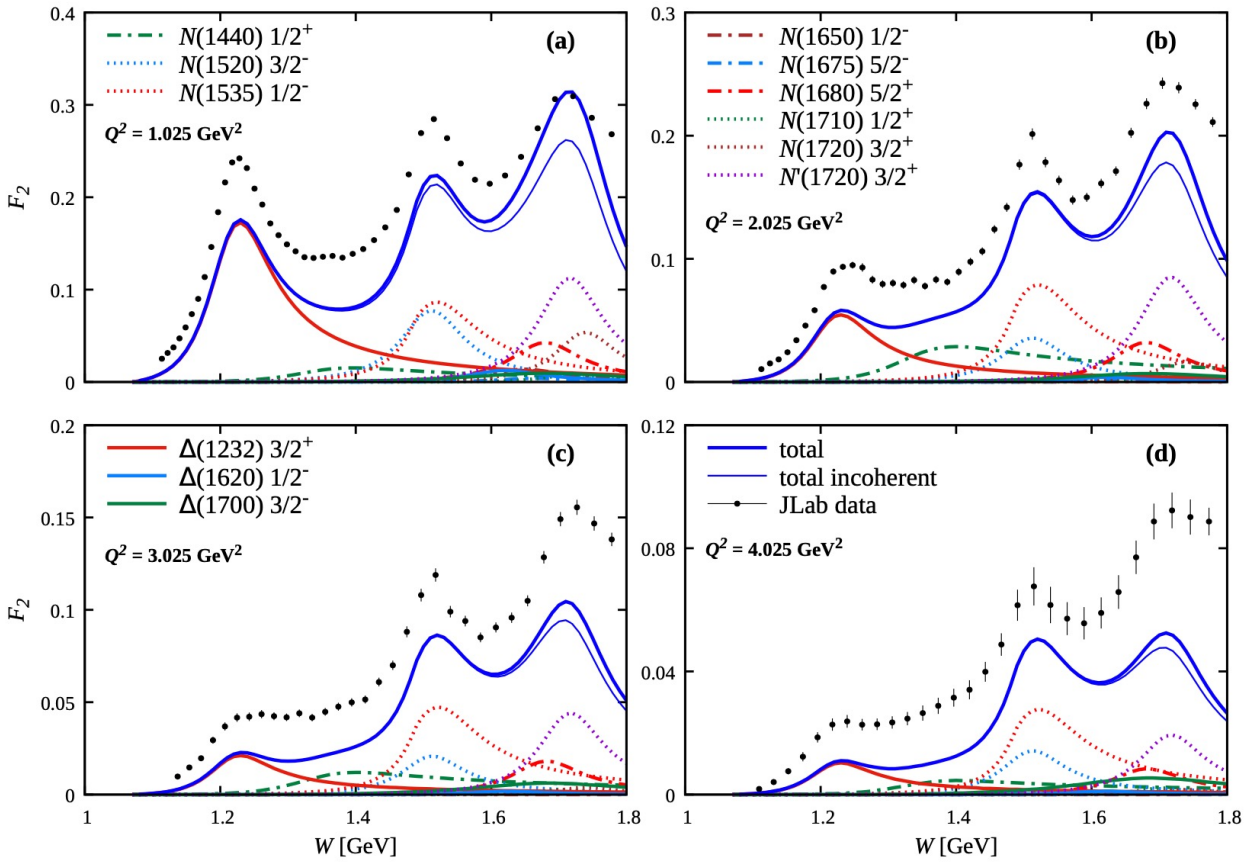
Resonant Contributions into Inclusive $F_2(W,Q^2)$ Structure Functions

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, PhD thesis of American University (2003)

N* contributions computed with γ_vpN* electrocouplings from the CLAS data:
A.N. Hiller Blin et al, Phys. Rev. C100, 035201 (2019)



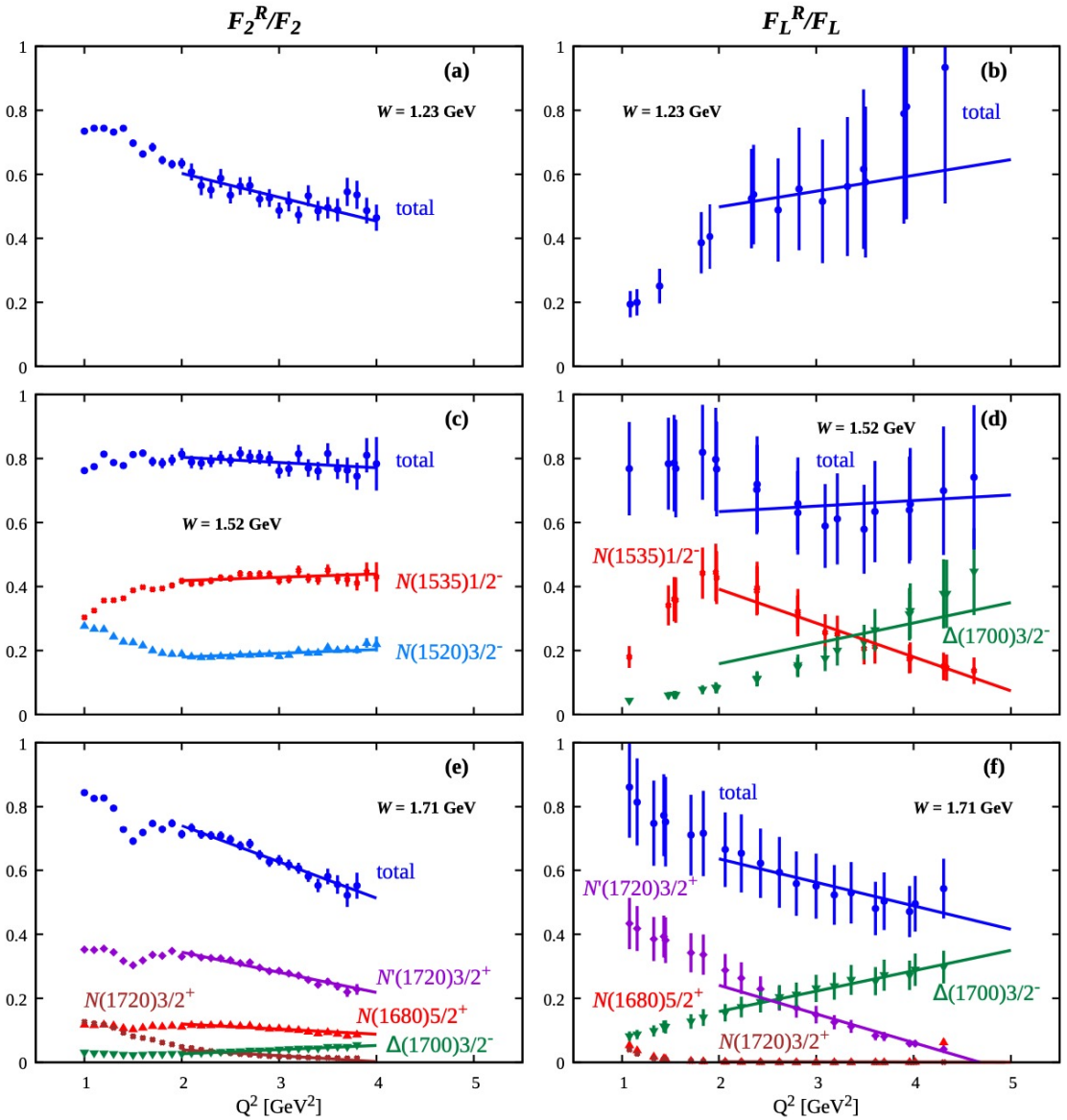
- **Insight into EHM: The non-resonant parts of F_2 structure function can be computed with the dressed quark mass function supported by the results on pion and nucleon elastic FFs, and on γ_vpN* electro-couplings. Estimated from the resonant/non-resonant contributions, full F_2 structure function will be confronted to the data.**
- **CLAS12 data on the structure function moments in a broad range of $Q^2<10$ GeV^2 may shed light on momentum dependence of dressed gluon mass**

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. If those predictions will be confirmed by the data on pseudo-scalar meson structure, then the prediction it makes for the N/N* structure are worth testing so that the one can gain the insights and understanding it promises.**

- **The Hall A/C data on nucleon elastic form factors provided constraints on the transition rate from fully dressed constituent quark in infrared ($p<0.5$ GeV) towards almost bare QCD quark in ultraviolet ($p>2.0$ GeV).**

- **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.**

- **Expected from the experiments in Halls B and D at Jlab, new results on spectrum of mesons and baryons with strange quarks will be confronted with the outcome from independent studies at AMBER. Analyses of the spectra of the mesons and baryons with s-quarks, combined, will shed light on EHM in the bound systems of quarks of different flavors.**

Conclusions and Outlook

- **The expected results from AMBER@CERN and JLab in the 12 GeV era on the pion, kaon, ground and excited nucleon structure will probe many facets of the running coupling and masses within hadrons, especially their impact on momentum distributions allowing us to map out the dressed quark mass function at the distances where the dominant part of hadron mass is generated and to address the most challenging problem of the Standard Model on the nature hadron mass.**

- **Collaborative AMBER@CERN/Jlab efforts are of key importance for an insight into EHM from the data on both the meson and baryon structure analyzed within the common framework of continuum QCD approach.**

Back Up

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 5.0 GeV^2 for most excited proton states through analyzing major meson electroproduction channels from CLAS data
- extend accessible Q^2 range within 5.0 $GeV^2 < Q^2 < 12$ GeV^2 and down to 0.05 GeV^2 from CLAS12 data
- explore hadron mass emergence by mapping out running quark mass in the transition from almost massless pQCD quarks to fully dressed constituent quarks

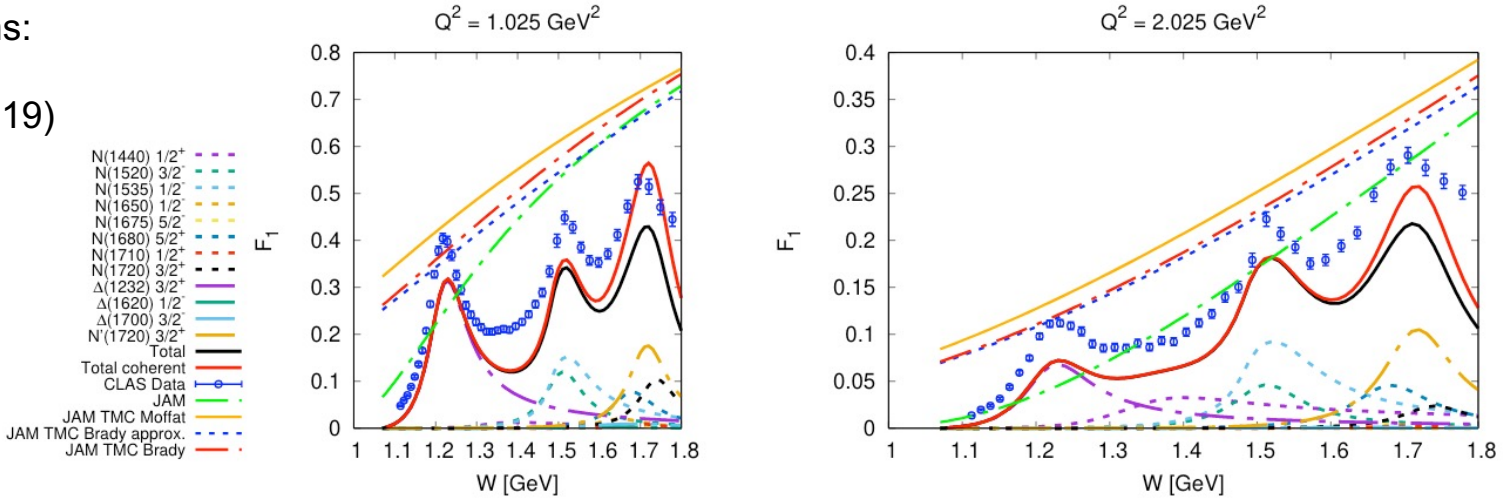
- **A unique source of information on many facets of strong QCD in generating N* states with different structural features**
- **Allow evaluation of the resonant contributions to inclusive F_1, F_2, and F_L structure functions from experimental results on $\gamma_v pN^*$ electrocouplings**

References:

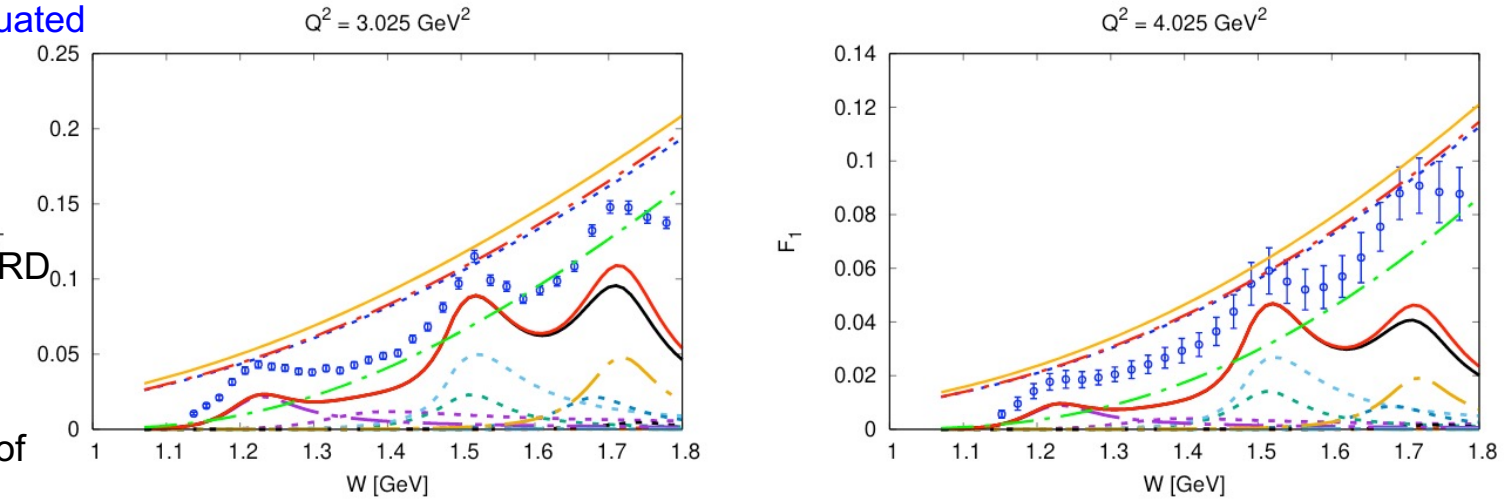
1. I.G. Aznauryan and V.D. Burkert, Prog. Part. Nucl. Phys. 67, 1 (2012)
2. V.D. Burkert and C.D. Roberts, Rev. Mod. Phys. 91, 011003 (2019)
3. D.S. Carman, K. Joo, and V.I. Mokeev, Few Body Syst. 61, 29 (2020)
4. A.N. Hiller Blin et al., Phys. Rev. C100, 035201 (2019)

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

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



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



CLAS data:
M. Osipenko et al., PRD 67, 092001 (2003)

Hall C data:
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

N* studies at 0.05 GeV^2 < Q^2 < 7.0 GeV^2 with CLAS12

Hybrid Baryons E12-16-010	Search for hybrid baryons (qqqg) focusing on 0.05 GeV^2 < Q^2 < 2.0 GeV^2 in mass range from 1.8 to 3 GeV in KΛ, Nππ, Nπ *(A. D'Angelo, et al.)*
KY Electroproduction E12-16-010A	Study N* structure for states that couple to KY through measurements of cross sections and polarization observables that will yield Q^2 evolution of electrocoupling amplitudes at Q^2<7.0 GeV^2 *(D. Carman, et al.)*

Approved by PAC44

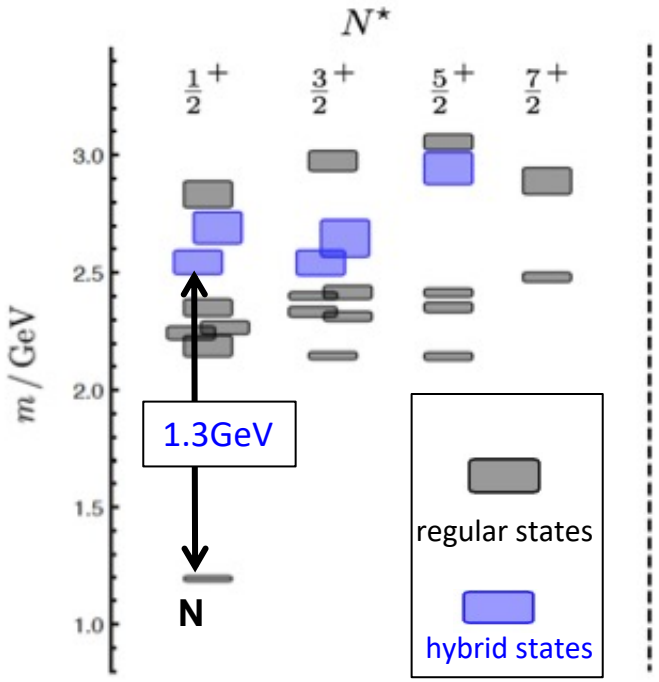
Run Group conditions:
E_b = 6.6 GeV, 50 days
E_b = 8.8 GeV, 50 days

- Polarized electrons, unpolarized LH_2 target
- L = 1x10^{35} cm^{-2}s^{-1}

Hunting for Glue in Excited Baryons with CLAS12

Can glue be a structural component to generate hybrid q^3g baryon states?

Predictions of the N* spectrum from QCD show both regular q^3 *and* hybrid q^3g states



JLab LQCD group results

Search for hybrid baryons with CLAS12 in exclusive KY and $\pi^+\pi^-$p electroproduction

LQCD and/or QM predictions on Q^2 evolution of the hybrid-baryon electroexcitation amplitudes are critical in order to establish the nature of a baryon state