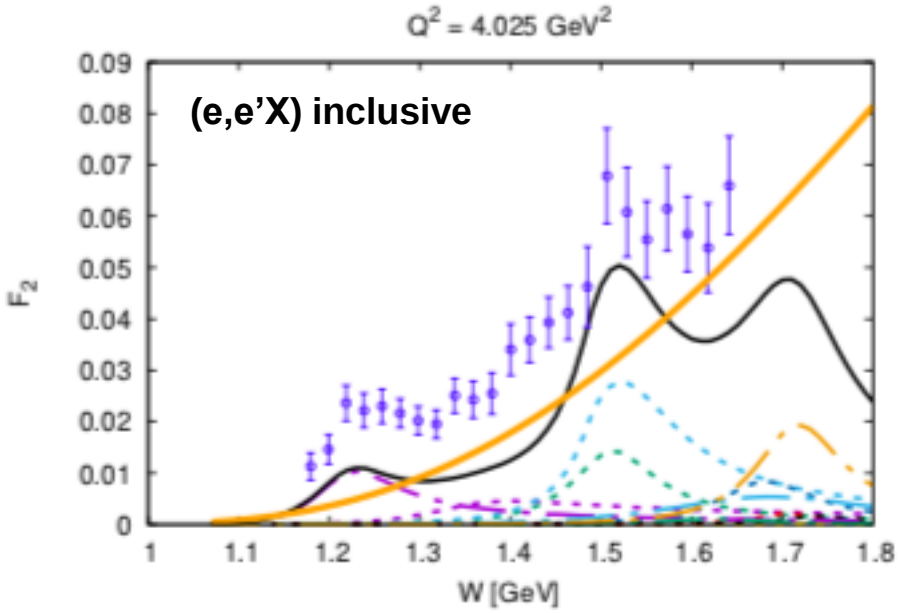
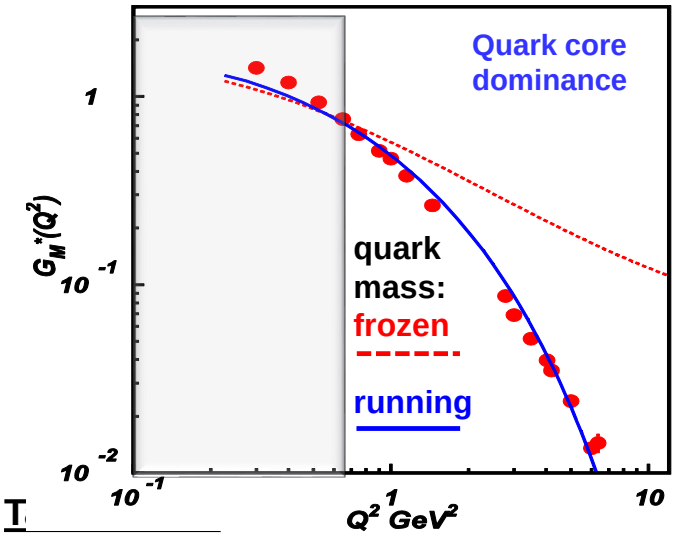
EHM from Baryon Structure Studies with Electromagnetic Probes



$N \to \Delta(1232)3/2^+$ magnetic from factor
Jones-Scadron convention



V.I. Mokeev, A.N. Hiller Blin
Jefferson Laboratory

- Insight into EHM from the exploration of ground and excited nucleon states
- The results on $\gamma_v pN^*$ electrocouplings from CLAS
- Resonant contributions into inclusive (e,e'X) scattering
- Mapping dressed quark mass function from combined studies of $\gamma_v pN^*$ electrocoupling and inclusive structure functions
- Conclusions and outlook

Office of Science

Perceiving the Origin of Hadron Mass through AMBER @ CERN, November 30 – December 4, 2020, Geneva, Switzerland

EHM from Studies of Nucleon and N* Structure

Composition of the Nucleon Mass:

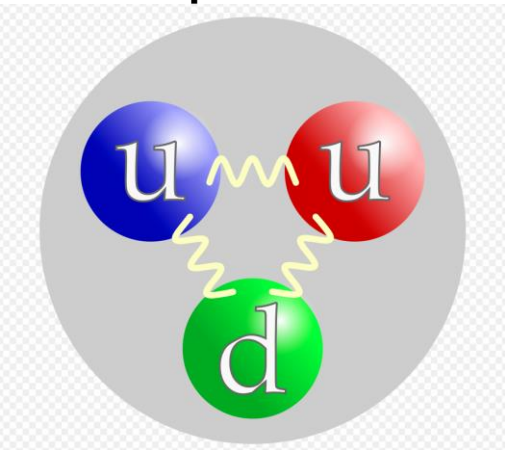
M_p, MeV (PDG20)

938.2720813
±0.0000058

Sum of bare quark masses, MeV

2.16+2.16+4.67
=8.99 or < 1.0%

proton



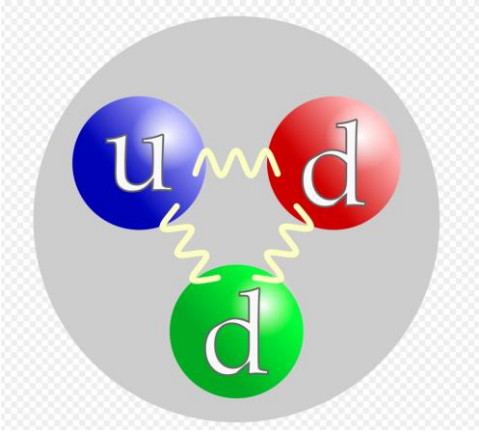
M_n, MeV (PDG20)

939.5654133
±0.0000058

Sum of bare quark masses, MeV

4.67+4.67+2.16
=11.50 or < 1.1%

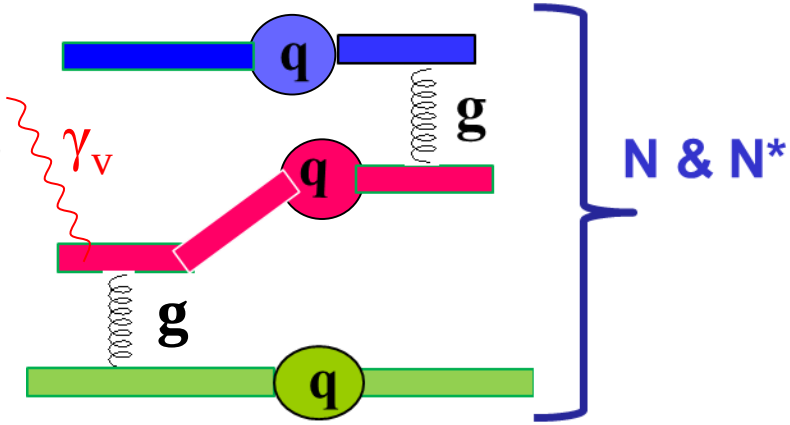
neutron



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

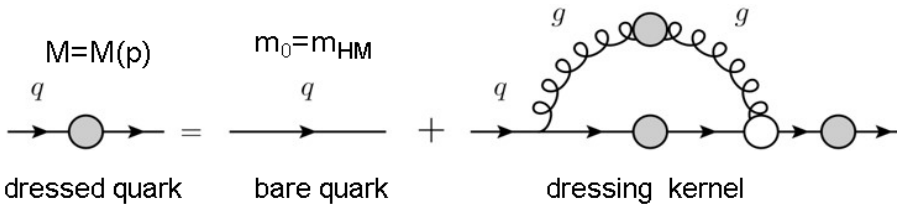
- Elastic/resonance electroexcitation amplitudes are sensitive to dressed quark propagator allowing us to map-out momentum dependence of dressed quark mass

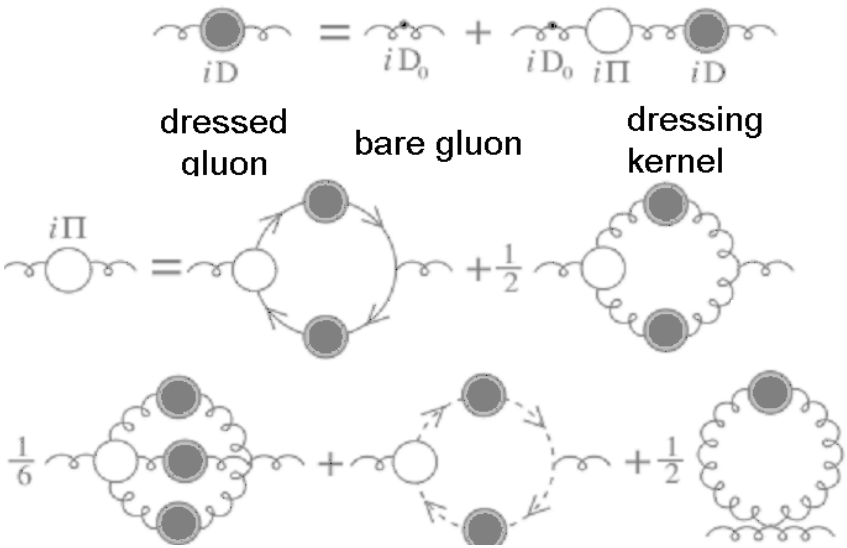
- Consistent results on momentum dependence of dressed quark mass from independent studies of elastic and transition N→N* FF validate credible insight into the hadron mass generation dynamics



Basics for Insight into EHM

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

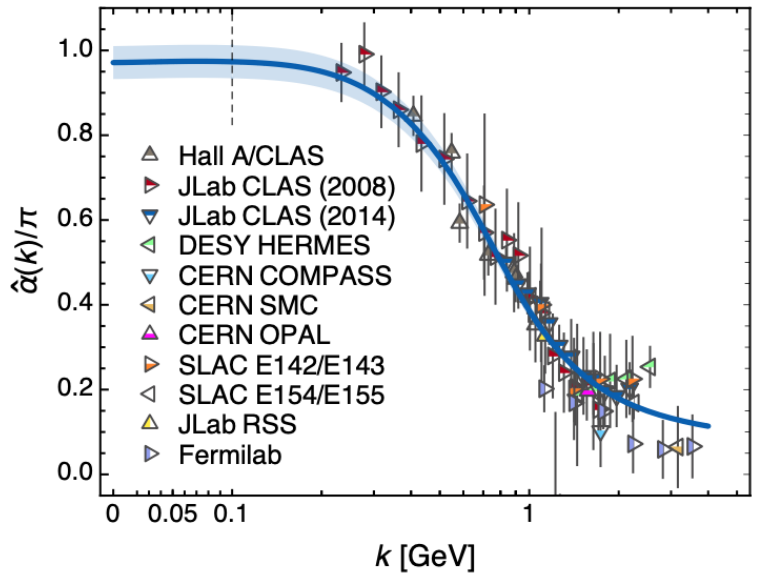


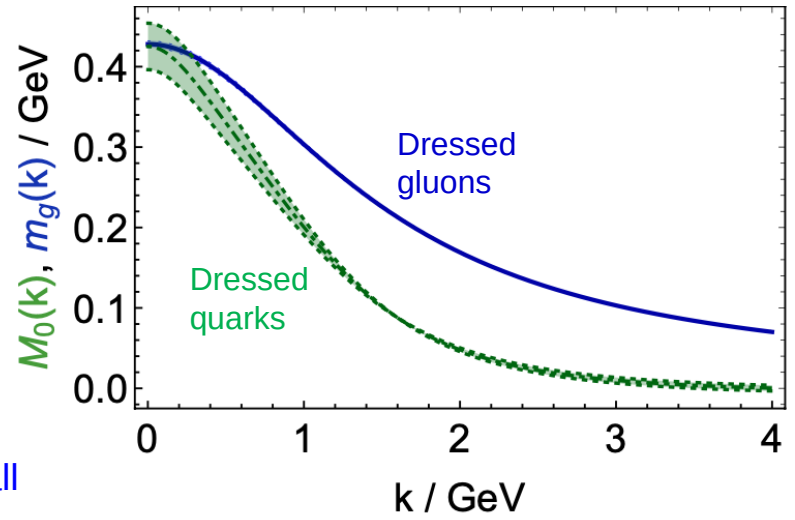


- Dressed quark/gluon masses converge at the complete QCD mass scale of 0.43(1) GeV

- Momentum-dependent quark/gluon masses shape the ground/ excited hadron structure and constrain the behavior of $\alpha(k)$, making QCD well-defined theory at all distance scales

QCD Running Coupling $\alpha(k)$ & Dressed Quark/Gluon Gasses
C.D. Roberts, NJU-INP 029/20

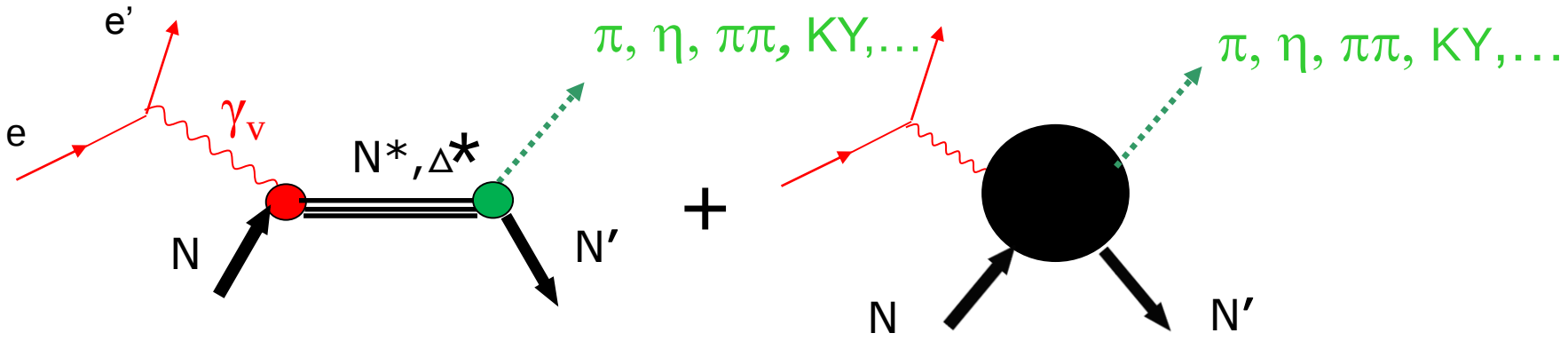




Inferred from QCD Lagrangian with only the Λ_{QCD} parameter

N* Electroexcitation Amplitudes (γ_vpN* Electrocouplings) and Their Extraction from Exclusive Electroproduction Data

Resonant amplitudes | **Non-resonant amplitudes**



- Real $A_{1/2}(Q^2)$, $A_{3/2}(Q^2)$, $S_{1/2}(Q^2)$

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

Definition of N* photo-/electrocouplings employed in CLAS data analyses:

$$\Gamma_\gamma = \frac{k^2_{\gamma_{N^*}}}{\pi} \frac{2M_N}{(2J_r+1)M_{N^*}} \left[|A_{1/2}|^2 + |A_{3/2}|^2 \right]$$

- **Consistent results on γ_vpN* electrocouplings from different meson electroproduction channels are critical in order to validate reliable extraction of these quantities**

Summary of Published CLAS Data on Exclusive Meson Electroproduction off Protons in N* Excitation Region

Hadronic final state	Covered W-range, GeV	Covered Q^2-range, GeV^2	Measured observables
π^+n	**1.1-1.38** **1.1-1.55** **1.1-1.7** **1.6-2.0**	**0.16-0.36** **0.3-0.6** **1.7-4.5** **1.8-4.5**	**$d\sigma/d\Omega$** **$d\sigma/d\Omega$** **$d\sigma/d\Omega$, A_b** **$d\sigma/d\Omega$**
π^0p	**1.1-1.38** **1.1-1.68** **1.1-1.39** **1.1-1.8**	**0.16-0.36** **0.4-1.8** **3.0.0-6.0** **0.4-1.0**	**$d\sigma/d\Omega$** **$d\sigma/d\Omega$, A_b,A_t,A_{bt}** **$d\sigma/d\Omega$** **$d\sigma/d\Omega$**
ηp	**1.5-2.3**	**0.2-3.1**	**$d\sigma/d\Omega$**
$K^+\Lambda$	**thresh-2.6**	**1.40-3.90** **0.70-5.40**	**$d\sigma/d\Omega$** **P^0, P'**
$K^+\Sigma^0$	**thresh-2.6**	**1.40-3.90** **0.70-5.4**	**$d\sigma/d\Omega$** **P'**
$\pi^+\pi^-p$	**1.3-1.6** **1.4-2.1** **1.4-2.0**	**0.2-0.6** **0.5-1.5** **2.0-5.0**	**Nine 1-fold differential cross sections**

- $d\sigma/d\Omega$–CM angular distributions
- A_b,A_t,A_{bt}-longitudinal beam, target, and beam-target asym-metries
- P^0, P' – recoil and transferred polarization of strange baryon

Over 150,000 data points!

Almost full coverage of the final state hadron phase space

The measured observables from CLAS are stored in the CLAS Physics Database http://clas.sinp.msu.ru/cgi-bin/jlab/db.cgi

Approaches for Extraction of $\gamma_v pN^*$ Electrocouplings

Independent analyses of different meson electroproduction channels:

- **$\pi^+ n$ and $\pi^0 p$ channels:**
  Unitary Isobar Model (UIM) and Fixed-t Dispersion Relations (DR)
  I.G. Aznauryan, Phys. Rev. C67, 015209 (2003)
  I.G. Aznauryan et al. (CLAS), Phys. Rev. C80, 055203 (2009)
  I.G. Aznauryan et al. (CLAS), Phys. Rev. C91, 045203 (2015)
- **ηp channel:**
  Extension of UIM and DR
  I.G. Aznauryan, Phys. Rev. C68, 065204 (2003)
  Data fit at W<1.6 GeV, assuming N(1535)1/2$^-$ dominance
  H. Denizli et al. (CLAS), Phys. Rev. C76, 015204 (2007)
- **$\pi^+\pi^- p$ channel:**
  Data driven JLab-MSU meson-baryon model (JM)
  V.I. Mokeev, V.D. Burkert et al., Phys. Rev. C80, 045212 (2009)
  V.I. Mokeev et al. (CLAS), Phys. Rev. C86, 035203 (2012)
  V.I. Mokeev, V.D. Burkert et al., Phys. Rev. C93, 054016 (2016)
  E. Golovatch et al., Phys. Lett. B788. 371 (2019).

Global coupled-channel analysis of $\gamma_{r,v}N$, πN, ηN, $\pi\pi N$, $K\Lambda$, $K\Sigma$ exclusive channels:

H. Kamano, Few Body Syst. 59, 24 (2018)
H. Kamano, JPS Conf. Proc. 13, 010012 (2017)
H. Kamano, arXiv:1909.11935 [nucl-th]

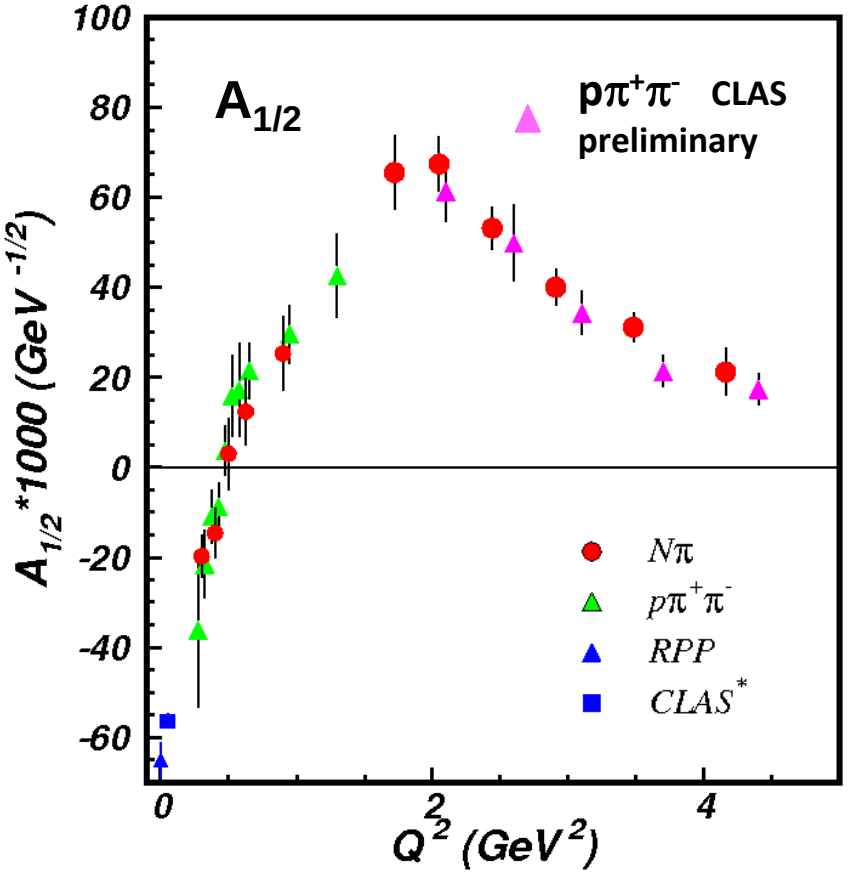
Nucleon Resonance Electrocouplings from Data On Exclusive Meson Electroproduction with CLAS

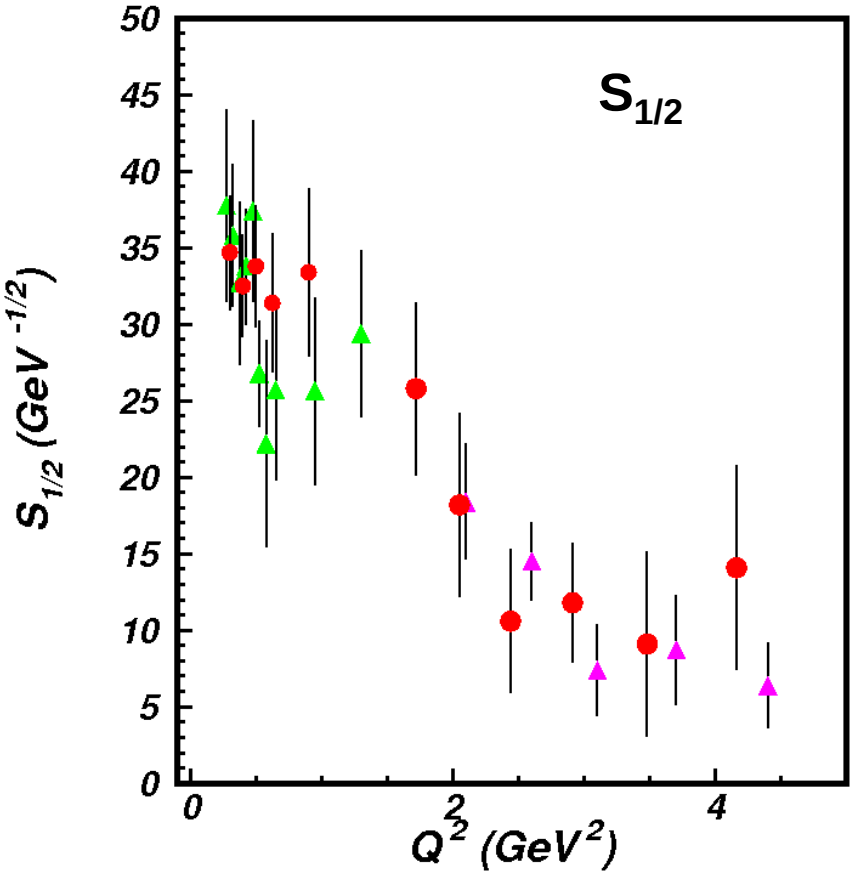
Exclusive meson electroproduction channels	Excited proton states	Q^2-ranges for extracted $\gamma_v pN^*$ electrocouplings, GeV^2
$\pi^0 p$, $\pi^+ n$	$\Delta(1232)3/2^+$ $N(1440)1/2^+$,$N(1520)3/2^-$, $N(1535)1/2^-$	0.16-6.0 0.30-4.16
$\pi^+ n$	$N(1675)5/2^-$, $N(1680)5/2^+$ $N(1710)1/2^+$	1.6-4.5
ηp	$N(1535)1/2^-$	0.2-2.9
$\pi^+\pi^- p$	$N(1440)1/2^+$, $N(1520)3/2^-$ $\Delta(1620)1/2^-$, $N(1650)1/2^-$, $N(1680)5/2^+$, $\Delta(1700)3/2^-$, $N(1720)3/2^+$, $N'(1720)3/2^+$	0.25-1.50 2.0-5.0 (preliminary) 0.5-1.5

Website with numerical results and references:
https://userweb.jlab.org/~mokeev/resonance_electrocouplings/

Interpolation at $0.5\ GeV^2<Q^2<7.0\ GeV^2$ for resonances in the mass range of $W<1.8$ GeV is available in: A.N. Hiller Blin et al., Phys. Rev. C 100, 035201 (2019), userweb.jlab.org/~isupov/couplings/.

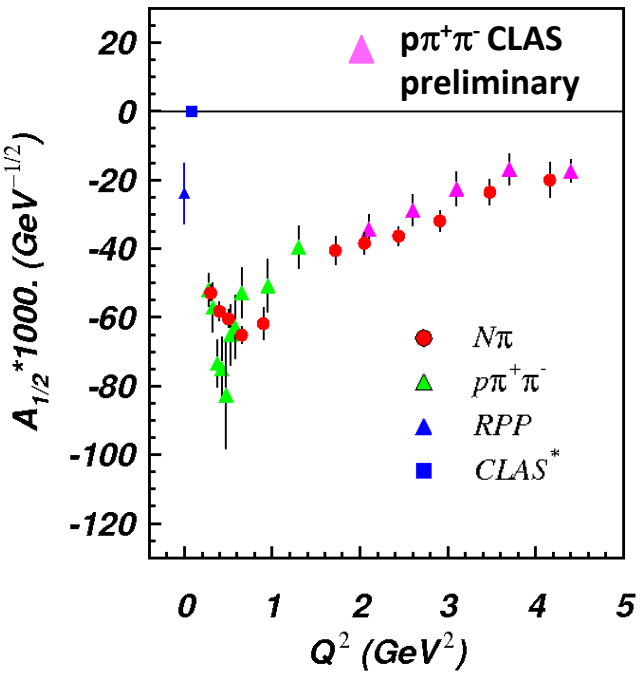
Electrocouplings of N(1440)1/2$^+$ from πN and $\pi^+\pi^-$p Electroproduction off Proton Data

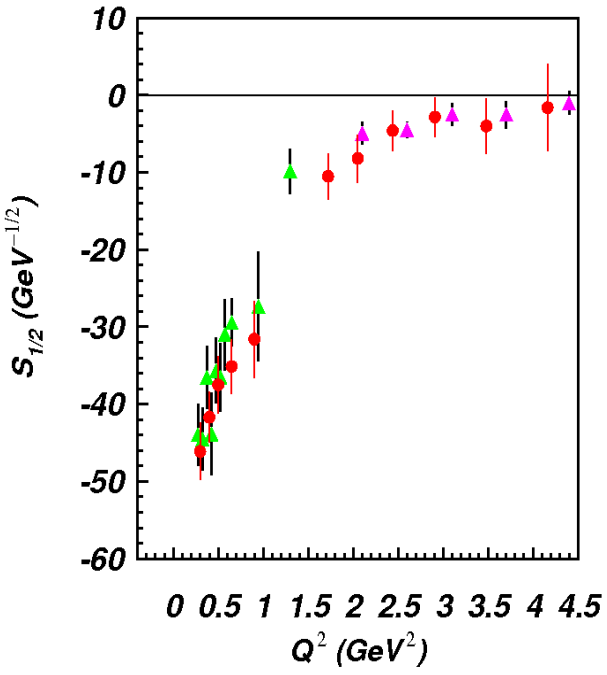


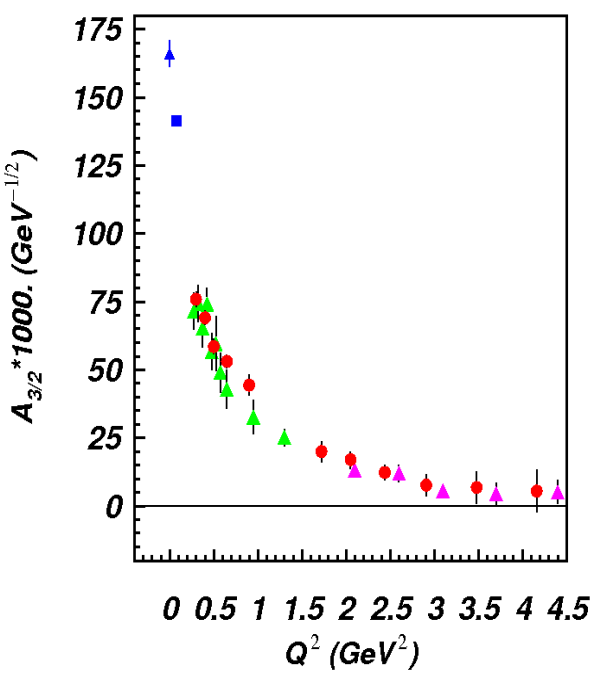


Consistent results on N(1440)1/2$^+$ electrocouplings from independent studies of two major πN and $\pi^+\pi^-$p electroproduction channels with different non-resonant contributions allow us to evaluate the systematic uncertainties of these quantities in a nearly model-independent way

Electrocouplings of N(1520)3/2$^-$ from πN and $\pi^+\pi^-$p Electroproduction off Proton Data





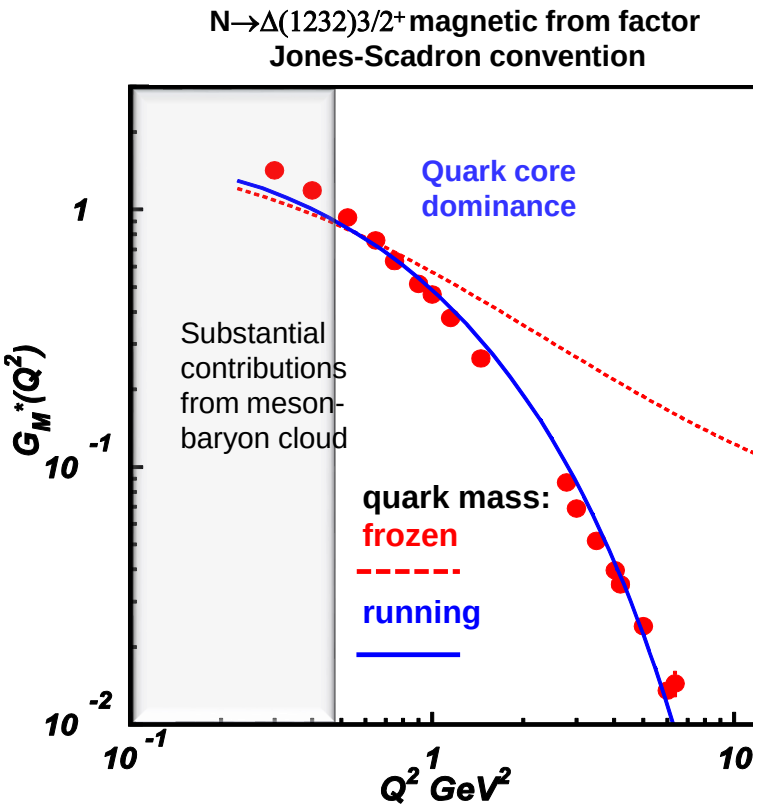


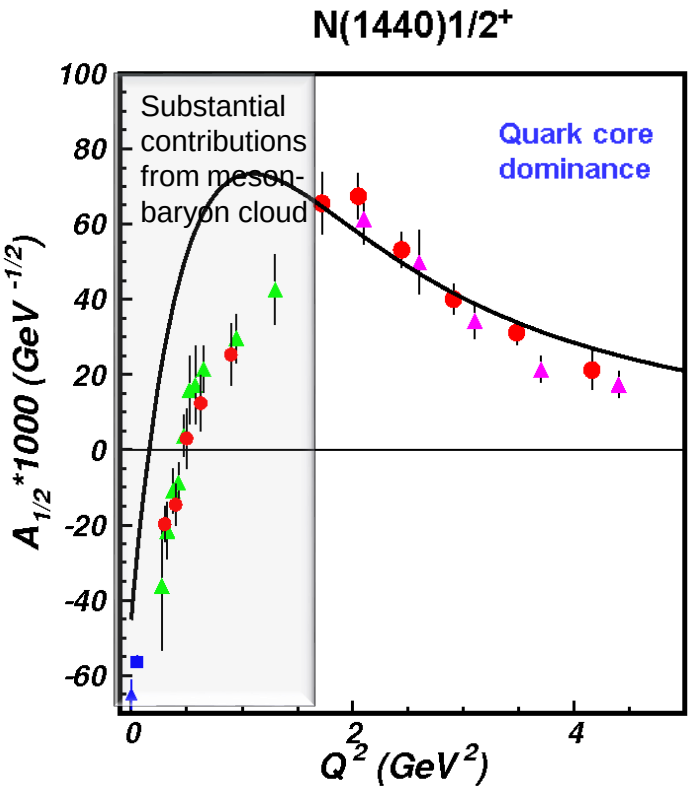
Consistent results from πN and $\pi^+\pi^-$p electroproduction off proton data on electrocouplings of N(1440)1/2$^+$ and N(1520)3/2$^-$ resonances with the biggest combined contribution into the resonant parts of both channels at W<1.55 GeV strongly support the capabilities of the developed reaction models for credible extraction of resonance electrocouplings from independent analyses of both πN and $\pi^+\pi^-$p electroproduction

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)**





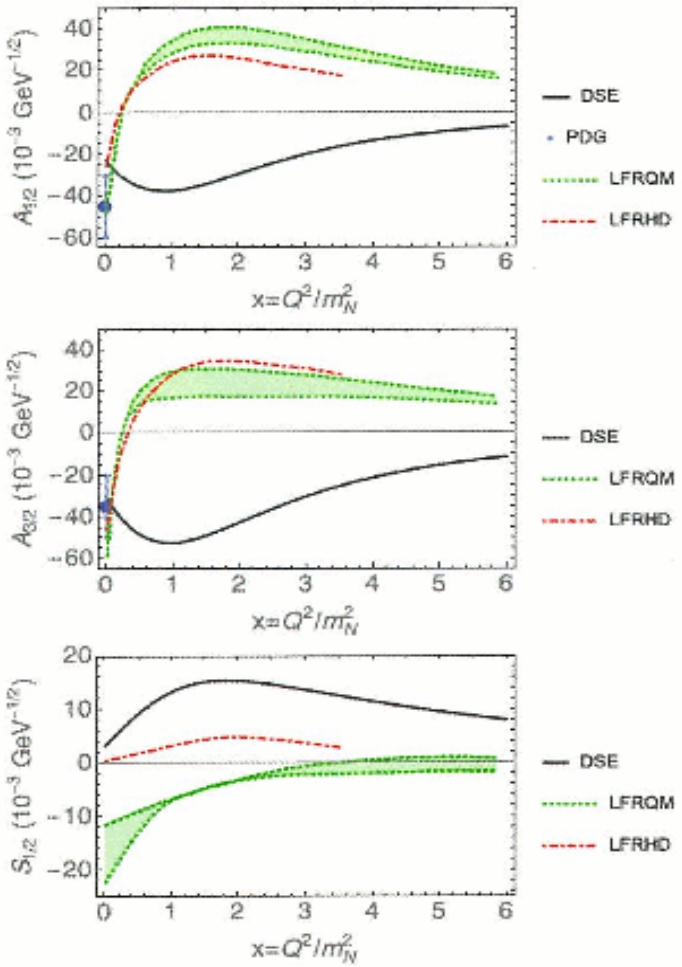
DSE analyses of CLAS data on Δ(1232)3/2+ electroexcitation demonstrate that dressed quark mass runs with momentum

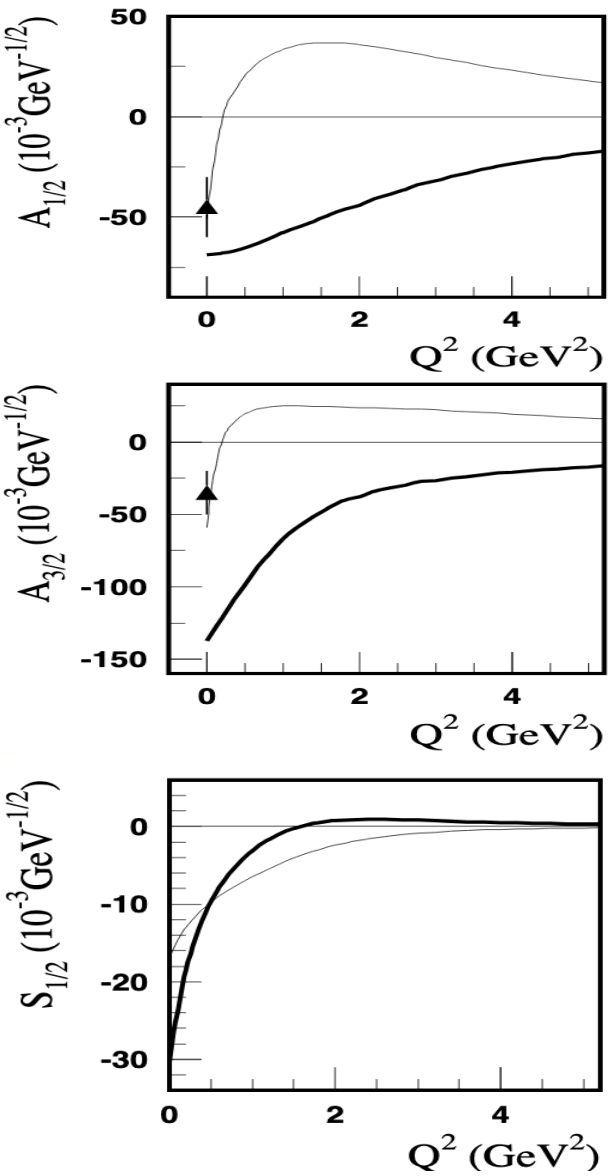
Good data description at Q^2>2.0 GeV^2 achieved with the same dressed quark mass function for the ground and two excited nucleon states of distinctively different structure validates the DSE results on momentum dependence of dressed quark mass. $\gamma_v pN^*$ electrocoupling data offer access to the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

Δ(1600)3/2⁺



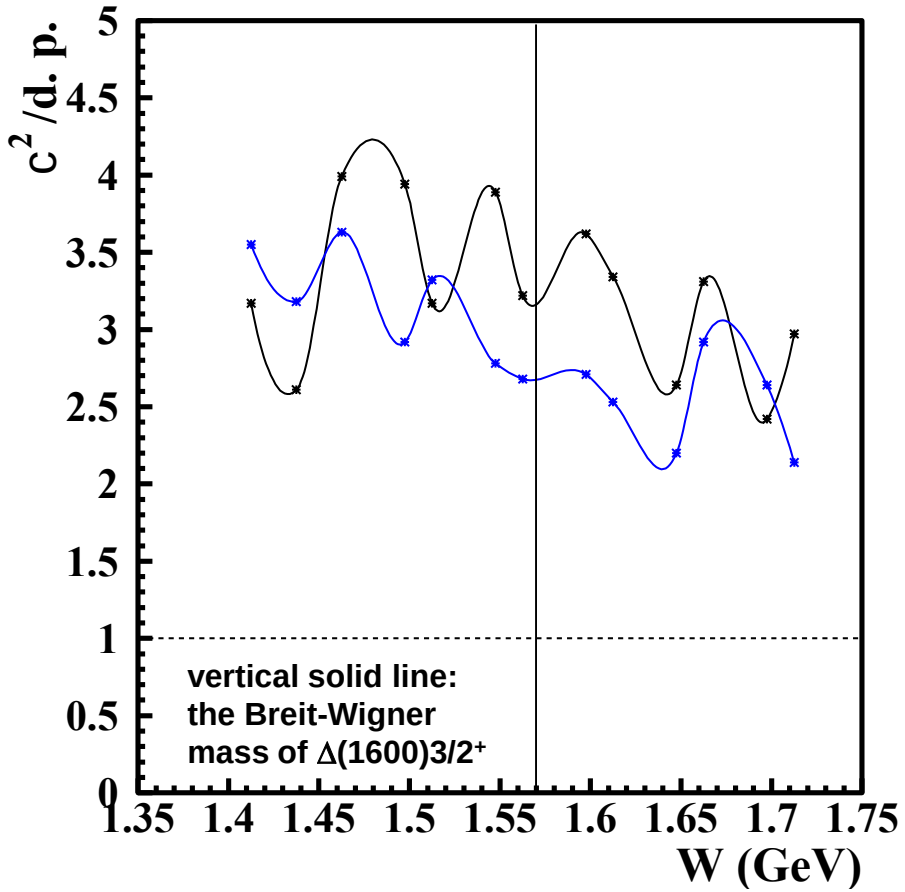


LFRQM accounting for 3-quark configuration mixing: I.G. Aznauryan and V.D. Burkert arXiv: 1603.06692 [hep-ph]

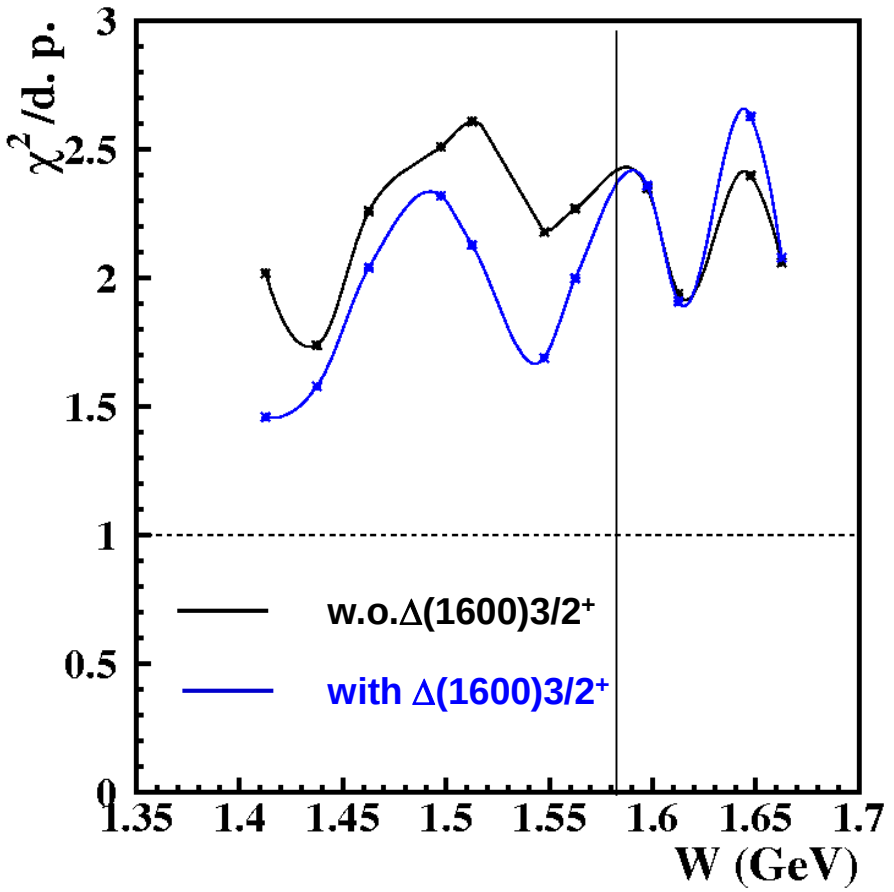
Parameter free continuum QCD (DSE) predictions for Δ(1600)3/2⁺ electrocouplings Ya Lu et al, Phys. Rev. D100, 034001 (2019)

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

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



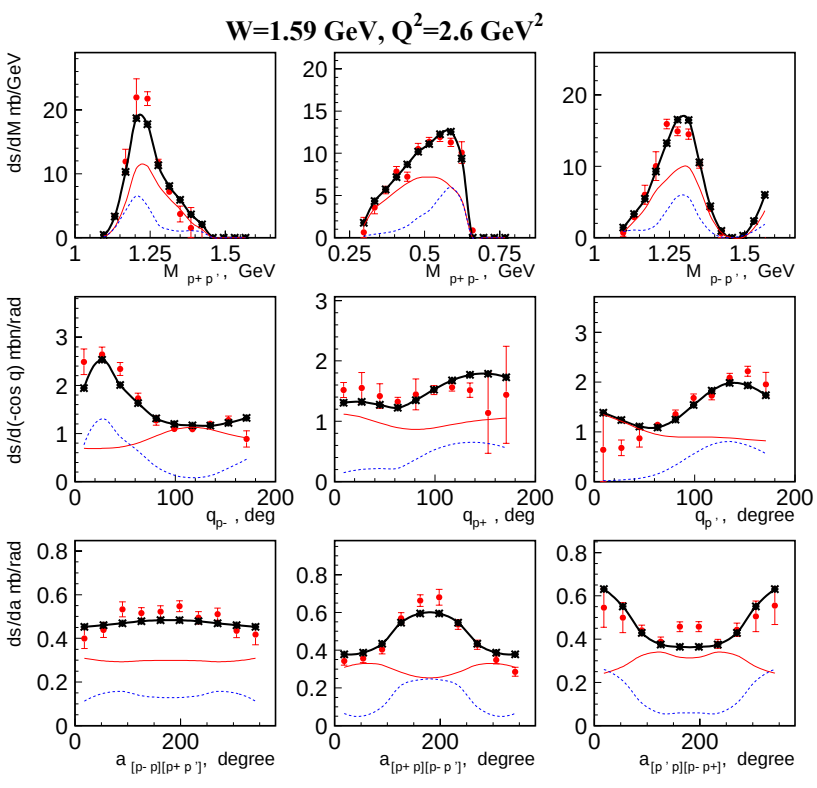
3.5 GeV^2<Q^2<4.2 GeV^2



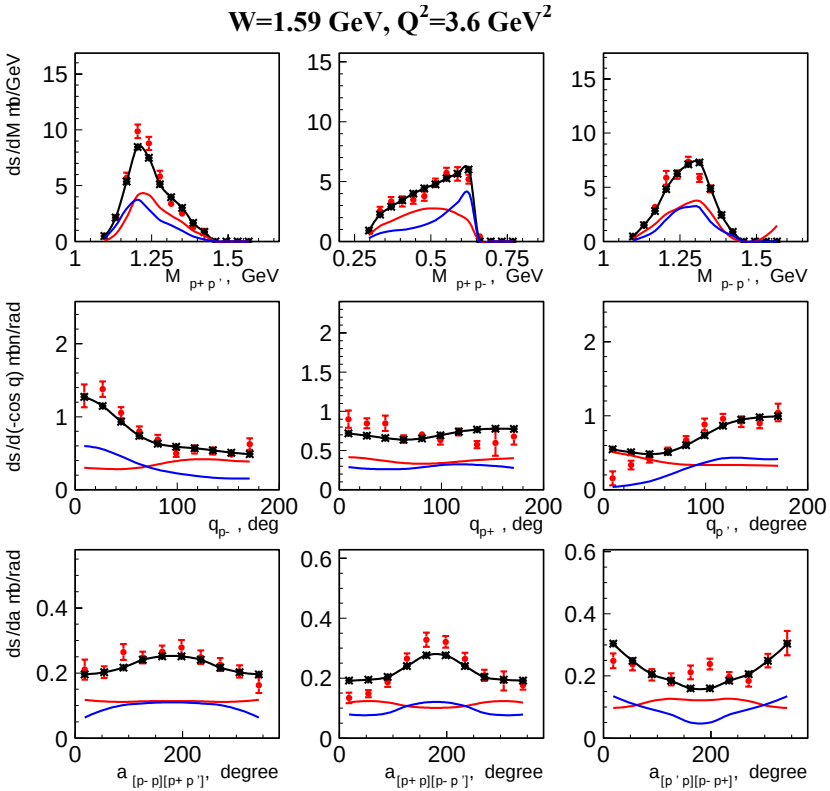
The contribution from $\Delta(1600)3/2^+$ state with electrocouplings from the continuum QCD approach are consistent with the data on $\pi^+\pi^-p$ electroproduction at Q^2>2.0 GeV^2

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 d-quarks at momenta <0.5 GeV.

Insight into EHM from the Data on F_1 and F_2 Inclusive Structure Functions

- **Data on inclusive F_1 and F_2 structure functions in the resonance region can be described by the sum of the non-resonant part which will be predicted within continuum QCD approach by employing the dressed quark mass function used in the description of pion/nucleon elastic and transition form factors and the resonant contributions from the experimental results on $\gamma_v pN^*$ electrocouplings.**

- **Successful description of F_1 and F_2 inclusive structure functions achieved with the same dressed quark mass function as used for description $\gamma_v pN^*$ electrocouplngs will solidify the evidence for credible insight into the baryon mass generation dynamics.**

Evaluation of the Resonant Contributions (Incoherent)

- The experimental results on $\gamma_v pN^*$ electrocouplings from CLAS for most resonances in the mass range W<1.75 GeV make it possible to evaluate the resonant contribution into inclusive cross sections/structure functions from the data on N* electroexcitation amplitudes for the first time.

Transverse and longitudinal resonant cross sections are described by sum of the cross sections from all relevant resonances computed within the Breit-Wigner ansatz.

Resonant contributions to inclusive virtual photon-proton cross sections:

$$\sigma^R_{T,L}(W,Q^2) = \frac{\pi}{q_\gamma K}\sum_{N^*}(2J_r+1)\frac{M_r^2\Gamma_{\rm tot}(W)\Gamma_\gamma{}^{T,L}(M_r,Q^2)}{(M_r^2-W^2)^2+M_r^2\Gamma^2_{\rm tot}(W)},$$

$$q_\gamma = \sqrt{Q^2+E_\gamma^2}, \quad E_\gamma = \frac{W^2-Q^2-M_N^2}{2W}, \quad K = \frac{W^2-M_N^2}{2W}.$$

The electrocouplings $A_{1/2}(Q^2)$, $A_{3/2}(Q^2)$ and $S_{1/2}(Q^2)$ are taken from CLAS electroproduction data and enter the electromagnetic widths as

$$\Gamma^T_\gamma(W=M_r,Q^2) = \frac{q^2_{\gamma,r}(Q^2)}{\pi}\frac{2M_N}{(2J_r+1)M_r}\left(|A_{1/2}(Q^2)|^2+|A_{3/2}(Q^2)|^2\right),$$

$$\Gamma^L_\gamma(W=M_r,Q^2) = 2\frac{q^2_{\gamma,r}(Q^2)}{\pi}\frac{2M_N}{(2J_r+1)M_r}|S_{1/2}(Q^2)|^2, \quad q_{\gamma,r} = q_\gamma|_{W=M_r}.$$

A.N. Hiller Blin et al, Phys. Rev. C 100, 035201 (2019)

Evaluation of the Resonant Contributions (coherent)

Resonant contribution into inclusive structure functions evaluated from amplitudes G_i (i=+,-,0) computed as coherent sum of Breit-Wigner amplitudes from all relevant resonances of spin J, isospin I and parity η:

$$F_1^R = M_N^2 \sum_{I,J,\eta} \left[\left| \sum_{R^{IJ\eta}} G_+^{R^{IJ\eta}} \right|^2 + \left| \sum_{R^{IJ\eta}} G_-^{R^{IJ\eta}} \right|^2 \right],$$

$$\left(1 + \frac{\nu^2}{Q^2}\right) F_2^R = M_N \nu \sum_{I,J,\eta} \left[\left| \sum_{R^{IJ\eta}} G_+^{R^{IJ\eta}} \right|^2 + 2 \left| \sum_{R^{IJ\eta}} G_0^{R^{IJ\eta}} \right|^2 + \left| \sum_{R^{IJ\eta}} G_-^{R^{IJ\eta}} \right|^2 \right]$$

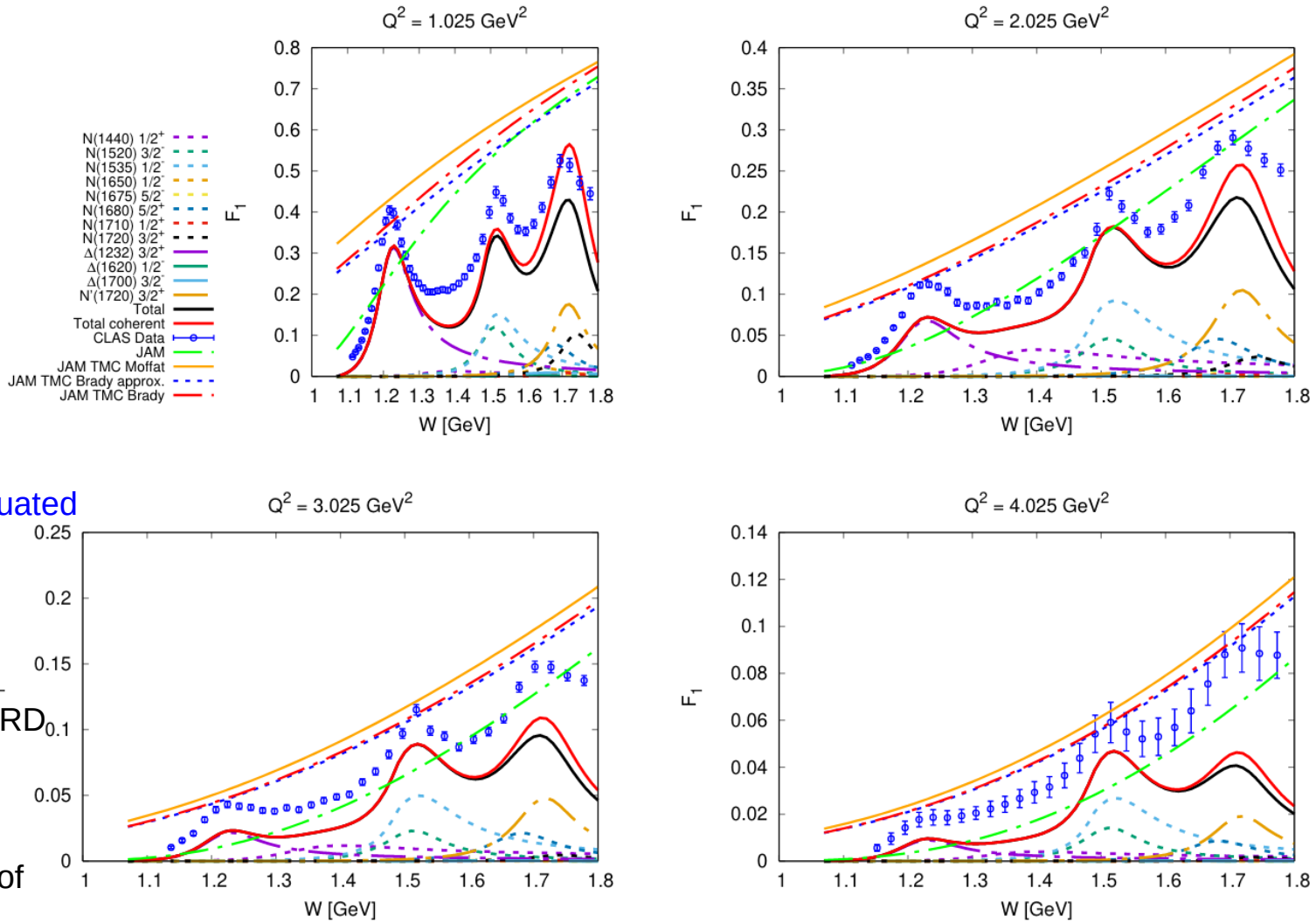
$$G_+^R = \frac{1}{4\pi} \sqrt{\frac{W^2 - M_N^2}{\alpha M_N}} \frac{q_\gamma|_{W=M_R}}{q_\gamma} \frac{\sqrt{M_R \Gamma_R^{\rm tot}(W)}}{M_R^2 - W^2 - {\rm i}\Gamma_R^{\rm tot}(W) M_R} A_{1/2}^R(Q^2),$$

$$G_-^R = \frac{1}{4\pi} \sqrt{\frac{W^2 - M_N^2}{\alpha M_N}} \frac{q_\gamma|_{W=M_R}}{q_\gamma} \frac{\sqrt{M_R \Gamma_R^{\rm tot}(W)}}{M_R^2 - W^2 - {\rm i}\Gamma_R^{\rm tot}(W) M_R} A_{3/2}^R(Q^2)(-1)^\eta,$$

$$G_0^R = \frac{1}{4\pi} \sqrt{\frac{W^2 - M_N^2}{\alpha M_N}} \frac{q_\gamma|_{W=M_R}}{q_\gamma} \frac{\sqrt{M_R \Gamma_R^{\rm tot}(W)}}{M_R^2 - W^2 - {\rm i}\Gamma_R^{\rm tot}(W) M_R} S_{1/2}^R(Q^2)(-1)^\eta,$$

After integration over the final hadron CM angle and adding up the final state isospin projections, only the interference terms from the resonances of the same I, J, and h contribute. Other intereference terms vanish due to orthogonality of the angular momenta eigenfunction and isospin Clebsch-Gordon coefficients.

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



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

- The dressed quark mass function checked against the data on pion/nucleon elastic form factors and $\gamma_v pN^*$ electrocouplings can be used in order to predict the pion PDF and compare with the results expected from pion induced Drell-Yan processes at COMPASS++/AMBER and from Sullivan processes at JLab12.

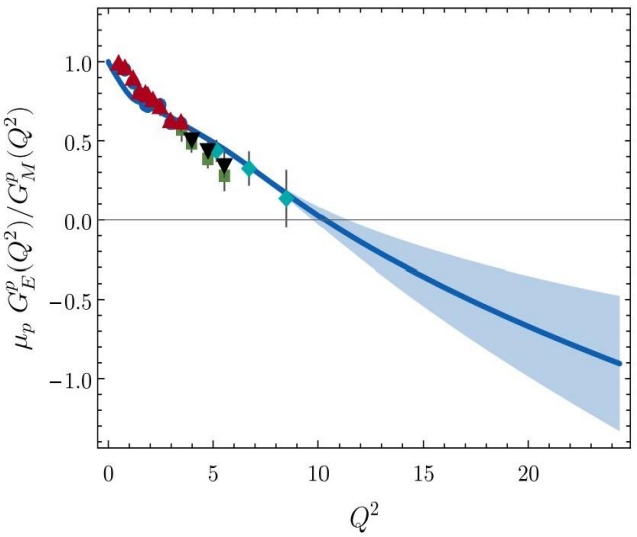
$$f_\pi E_\pi(p^2) = B(p^2)$$

- Studies of pion structure determined essentially by $E_\pi(p^2)$ offer the most straightforward way to map-out the dressed quark mass function related to $B(p^2)$ in the equation above.

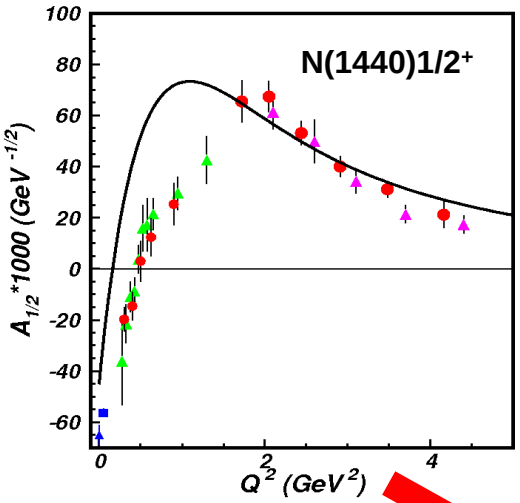
- Combined studies of the structure of the ground and excited states of the nucleon allow us to validate insight into the momentum dependence of the dressed quark mass by observing universality or evolution of this quantity in the structure of the ground and different excited states of the nucleon.

EHM from the Global Hadron Structure Analysis

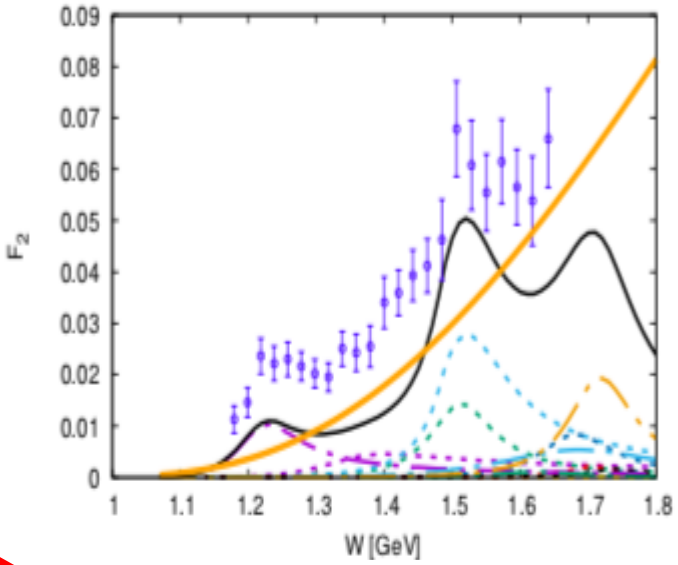
Nucleon Elastic FF



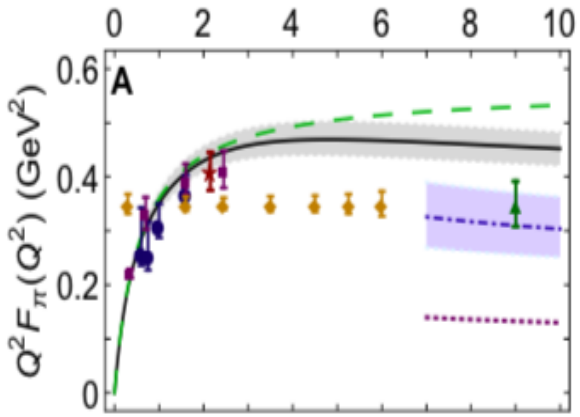
$\gamma_v pN^*$ Electrocouplings



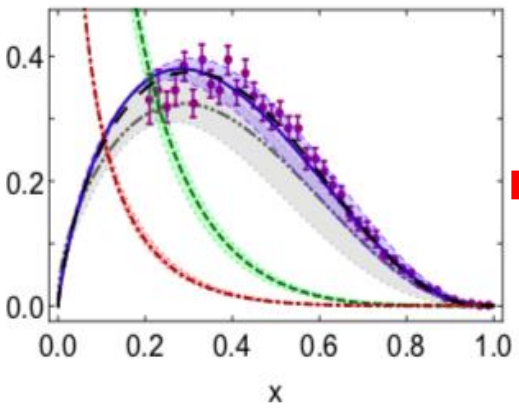
(e,e'X) Inclusive Scattering



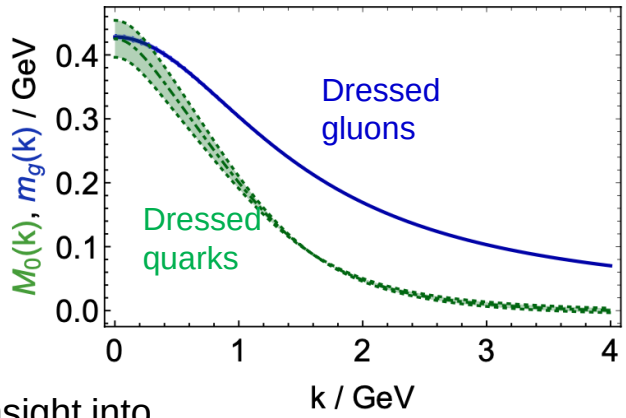
Pion Elastic FF



Pion PDF



Dressed Quark/Gluon Running Masses

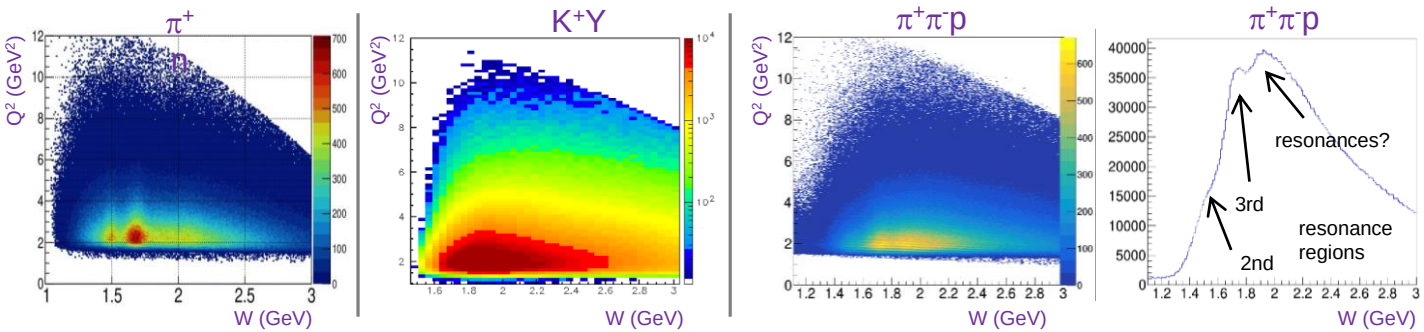


Continuum QCD approach has demonstrated the capability of gaining insight into the dressed quark/gluon running masses from all of the experimental results above!

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:

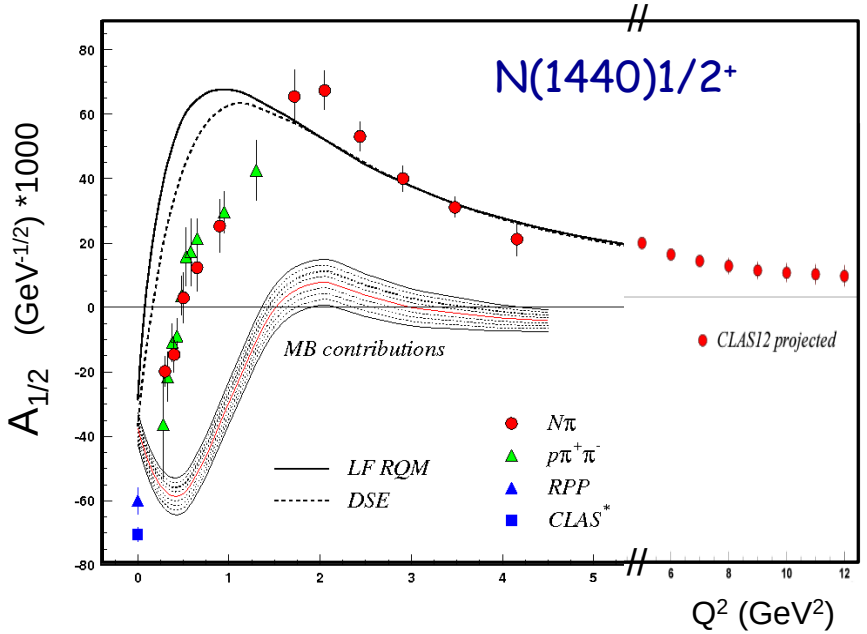
How is >98% of visible mass generated?

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?

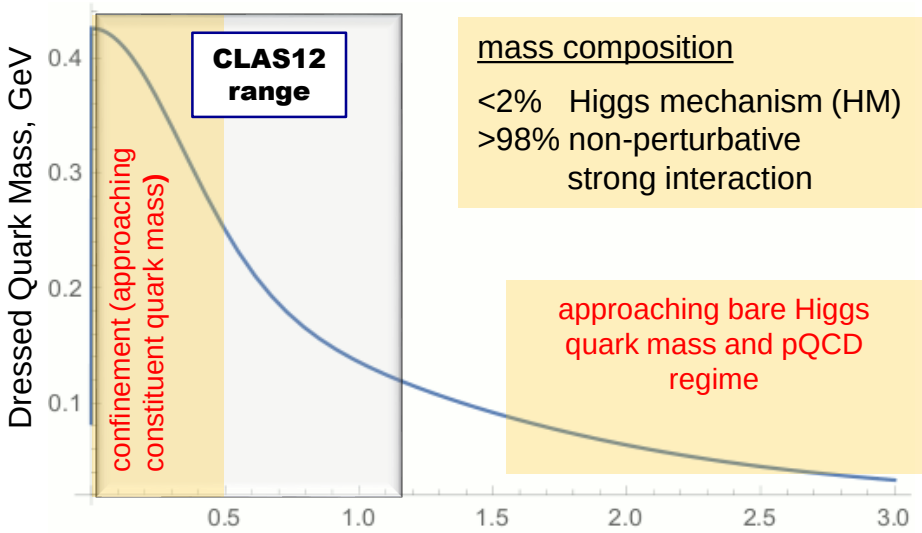
(D. Binosi et al., Phys. Rev. D96, 054026 (2017))

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 versus theory expectations with running quark mass

Access to the dressed quark/hadron mass generation



mass composition

<2% Higgs mechanism (HM)
>98% non-perturbative strong interaction

Conclusions and Outlook

- **High quality meson electroproduction data from CLAS have allowed us to determine the electrocouplings of most resonances in the mass range up to 1.8 GeV with consistent results from analyses of π^+n, π^0p, ηp, and $\pi^+\pi^-p$ electroproduction channels. Resonance electrocouplngs will become available for the N* in the mass range <2.0 GeV and at Q^2<5.0 GeV^2 (CLAS) and at Q^2<12 GeV^2 (CLAS12)**

- **<u>Profound impact on the exploration of the hadron mass generation:</u>**
  A good description of CLAS results on $\Delta(1232)3/2^+$ and $N(1440)1/2^+$ electroexcitation amplitudes *<u>achieved with the same dressed quark mass function</u>* as used previously in successful evaluations of the elastic ground nucleon and pion form factors, validate insight to the dressed quark mass function in a nearly model-independent way. The experimental results on $\Delta(1600)3/2^+$ electrocouplings will allow us to check parameter free continuum QCD prediction and solidify (or question) insight into EHM.

- **The extension of the continuum QCD predictions for electrocouplings of N*s in $[70,1^-]$ SU(6)-supermultiplet is of particular importance in order to explore universality of the baryon mass generation dynamics.**

- **The resonant contributions into inclusive $F_1(W,Q^2)$ and $F_2(W,Q^2)$ structure functions were evaluated by employing the experimental results on $\gamma_v pN^*$ electrocouplings for the first time. Knowledge on the resonant contribution considerably extend the capabilities for the insight into the PDFs in the ground states of the nucleon at large x_B in the resonance region.**

- **The continuum QCD evaluation of the ground nucleon PDF is needed. The successful description of the experimental data from two different areas: a) on unpolarized inclusive structure functions and b) on $\gamma_v pN^*$ electrocouplings achieved with a common dressed quark mass function will solidify the evidence for credible insight into the baryon mass generation.**

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 and F_2 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. V.I. Mokeev, Few Body Syst. 59, 46 (2018)
4. A.N. Hiller Blin et al., Phys. Rev. C100, 035201 (2019)

Approaches for Extraction of $\gamma_v NN^*$ Electrocouplings from the CLAS Exclusive Meson Electroproduction Data

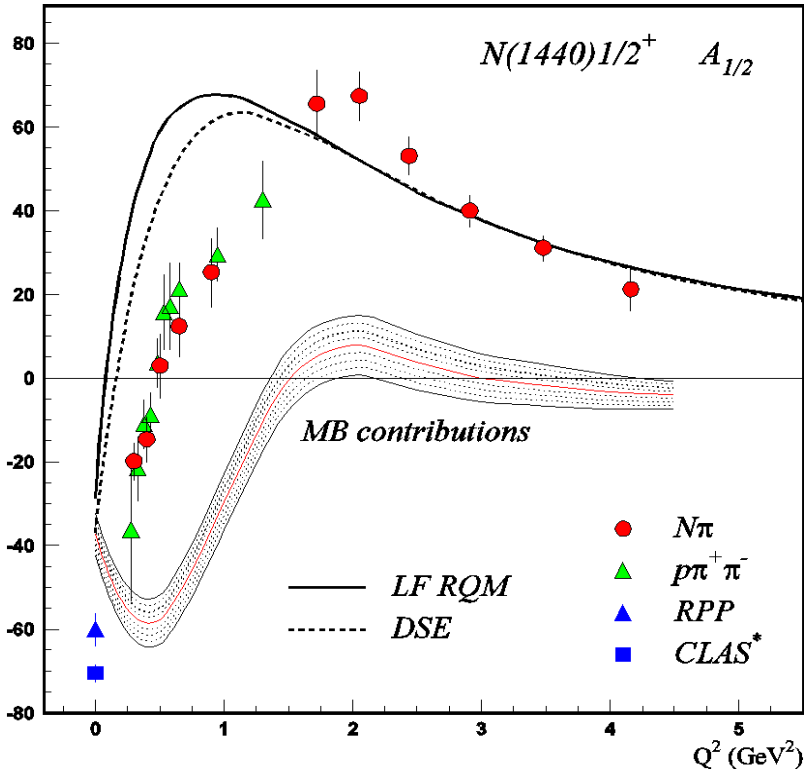
Independent analyses of different meson electroproduction channels:

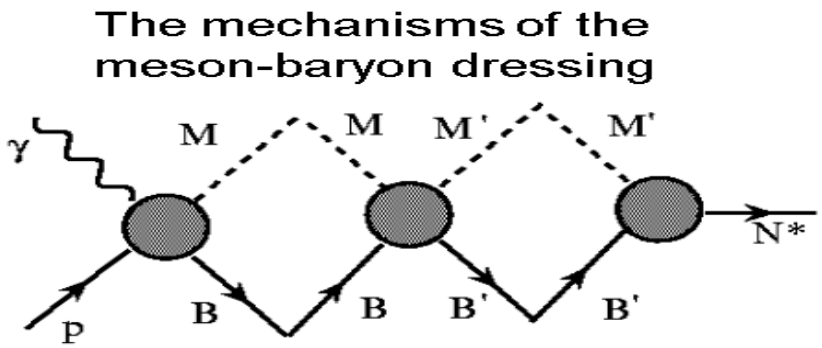
- **$\pi^+ n$ and $\pi^0 p$ channels:**
  Unitary Isobar Model (UIM) and Fixed-t Dispersion Relations (DR)
  I.G. Aznauryan, Phys. Rev. C67, 015209 (2003)
  I.G. Aznauryan et al. (CLAS), Phys. Rev. C80, 055203 (2009)
  I.G. Aznauryan et al. (CLAS), Phys. Rev. C91, 045203 (2015)
- **ηp channel:**
  Extension of UIM and DR
  I.G. Aznauryan, Phys. Rev. C68, 065204 (2003)
  Data fit at W<1.6 GeV, assuming N(1535)1/2$^-$ dominance
  H. Denizli et al. (CLAS), Phys. Rev. C76, 015204 (2007)
- **$\pi^+\pi^- p$ channel:**
  Data driven JLab-MSU meson-baryon model (JM)
  V.I. Mokeev, V.D. Burkert et al., Phys. Rev. C80, 045212 (2009)
  V.I. Mokeev et al. (CLAS), Phys. Rev. C86, 035203 (2012)
  V.I. Mokeev, V.D. Burkert et al., Phys. Rev. C93, 054016 (2016)

Global coupled-channel analysis of $\gamma_{r,v}N$, πN, ηN, $\pi\pi N$, $K\Lambda$, $K\Sigma$ exclusive channels:

H. Kamano, Few Body Syst. 59, 24 (2018)
H. Kamano, JPS Conf. Proc. 13, 010012 (2017)

Resolving Puzzle of the Roper Structure





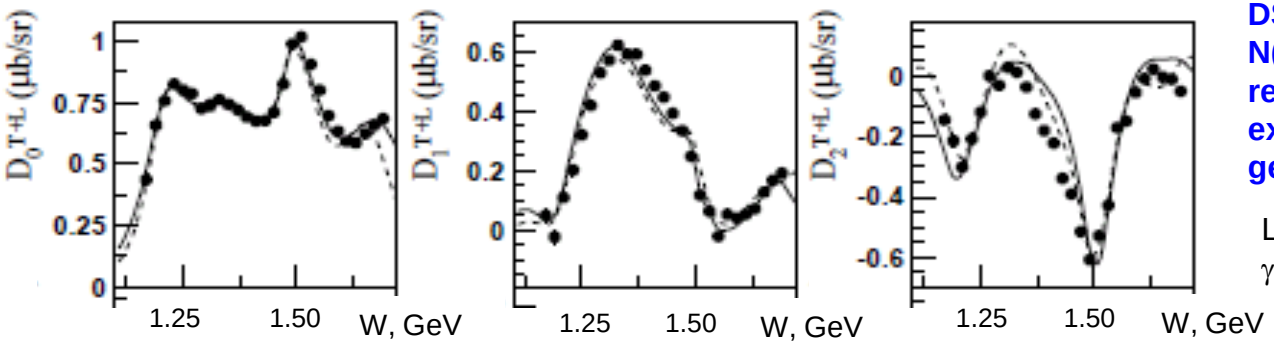
CLAS data in the range of Q^2<5.0 GeV^2 reveal the structure of N(1440)1/2$^+$ as a complex interplay between inner core of three dressed quarks in the first radial excitation and external meson-baron (MB) cloud

LF RQM-Light Front Relativistic Quark Model: V.D. Burkert, I.G. Aznauryan, Phys . Rev. C85, 055202 (2012); Phys. Rev. C95, 065207 (2017)

Quark core description within LF RQM and DSE is consistent

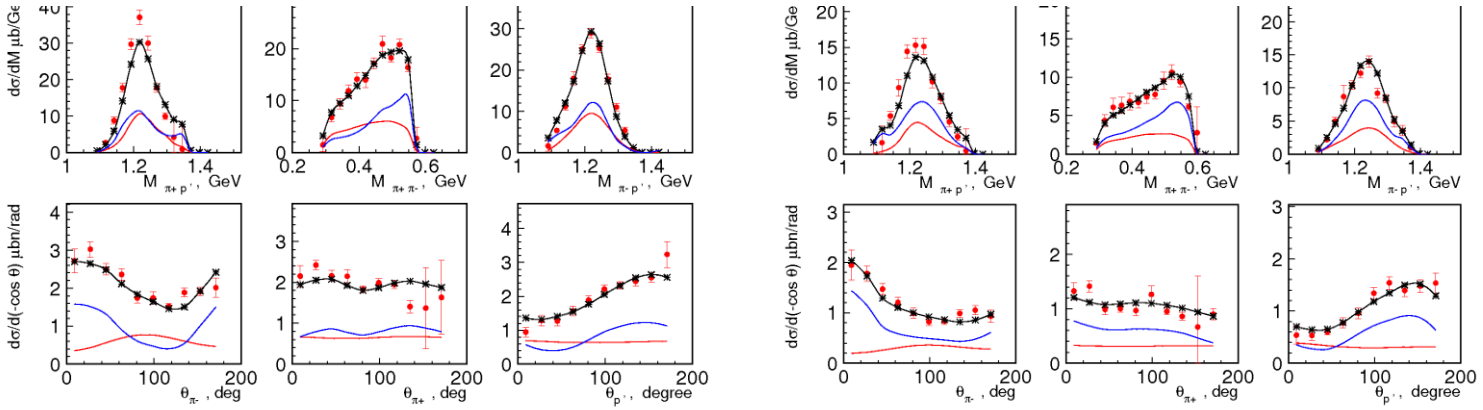
For more details on resolving Roper puzzle see:
V. D. Burkert and C.D. Roberts, Rev. Mod. Phys. 91, 011003 (2019)

Dressed Quark Mass Function from Exclusive Meson Electroproduction off Protons Data



DSE evaluations of N(1520)3/2$^-$ and N(1535)1/2$^-$ electrocouplings represent the next step needed for exploration of hadron mass generation

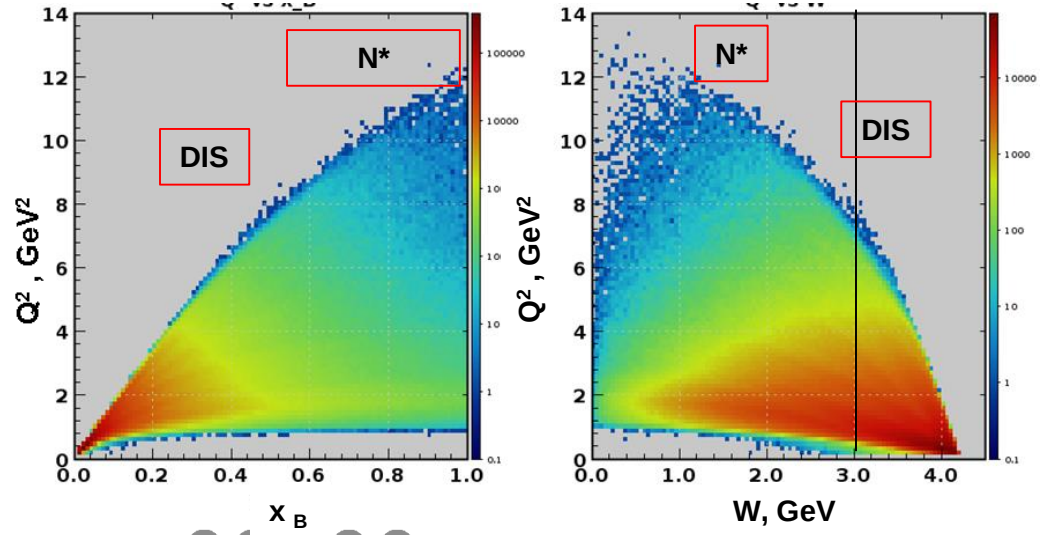
Legendre moments of unpolarized $\gamma_v p \to \pi^+ n$ cross sections at Q^2=2.44 GeV^2



- **The observables of Nπ and $\pi^+\pi^-$p exclusive channels at W<1.55 GeV and 2.0 GeV^2<Q^2< 5.0 GeV^2 will be computed with electrocouplings of four relevant Δ(1232)3/2$^+$, N(1440)1/2$^+$, N(1520)3/2$^-$, and N(1535)1/2$^-$ resonances obtained within DSE by employing a common dressed quark mass function. Mass function parameters will be fit to the data.**

- **Insight to the dressed quark mass function from the Nπ and and $\pi^+\pi^-$p electroproduction observables. The correlations between different resonance electrocouplings imposed by the common quark mass function will be checked against the data for the first time. Successful data description will unambiguously validate credible access to the quark mass function.**

12 GeV Era with the CLAS12 Detector



Physics run started successfully in February 2018

CLAS12 N* Program at High Q^2

E12-09-003	E12-06-108A
Nucleon Resonance Studies with CLAS12	KY Electroproduction with CLAS12
Gothe, Mokeev, Burkert, Cole, Joo, Stoler	*Carman, Gothe, Mokeev*

- Measure exclusive electroproduction cross sections from an unpolarized proton target with polarized electron beam for $N\pi$, $N\eta$, $N\pi\pi$, KY:

  E_b = 11 GeV, Q^2 = 3 → 12 GeV^2, W → 3.0 GeV with nearly complete coverage of the final state phase space

- Key Motivation

  Study the structure of all prominent N states in the mass range up to 2.0 GeV vs. Q^2 up to 12 GeV^2.*

  CLAS12 is the only facility to map-out the N quark with minimal meson-baryon cloud contributions.*

The experiments already started in February 2018!

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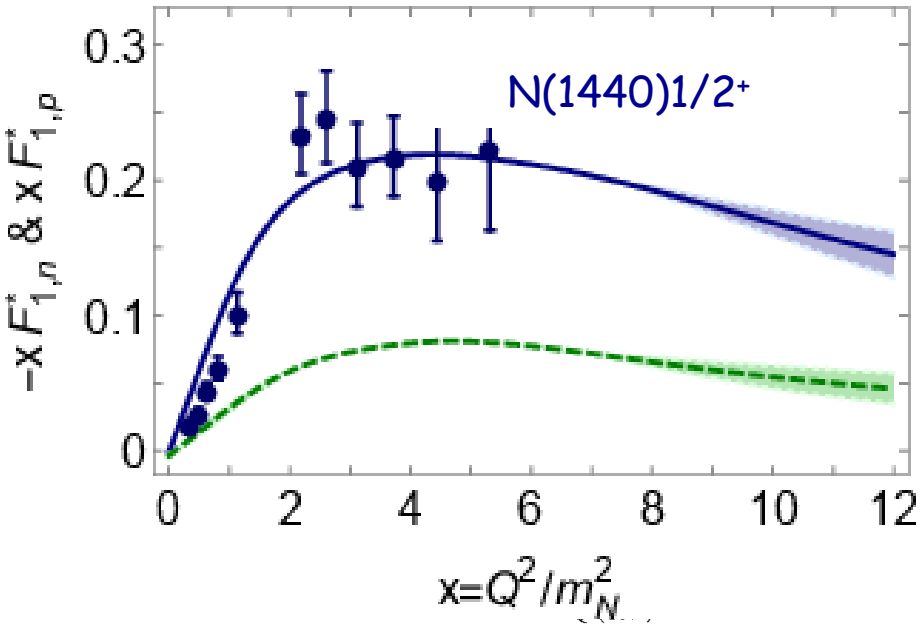
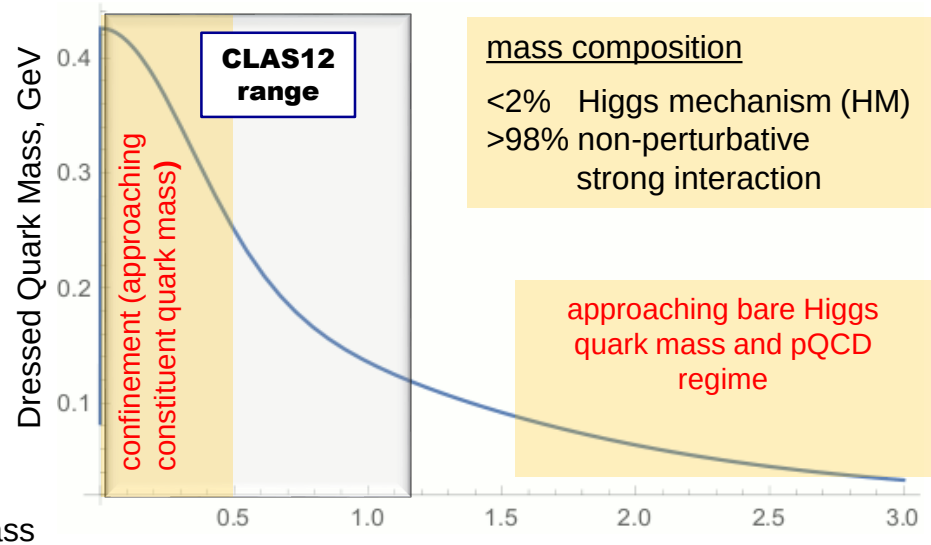
Ch. Chen et al, Phys.Rev. D99, 034013 (2019)



CLAS results versus theory expectations with running quark mass

Access to the dressed quark/hadron mass generation



mass composition

<2% Higgs mechanism (HM)
>98% non-perturbative strong interaction

approaching bare Higgs quark mass and pQCD regime

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

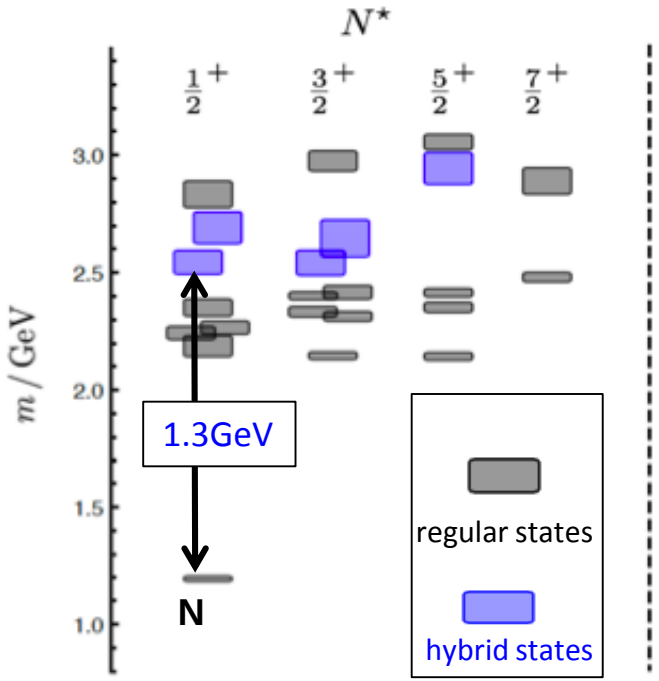
Run Group conditions:
E_b = 6.6 GeV, 50 days
E_b = 8.8 GeV, 50 days

- 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?

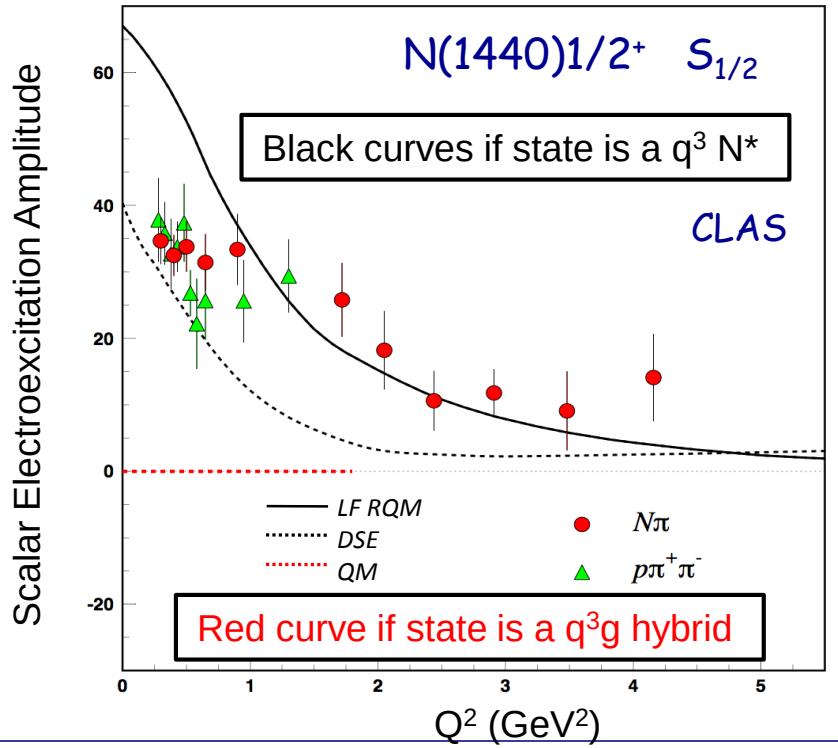
Predictions of the N* spectrum from QCD show both regular q^3 *and* hybrid q^3g states



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



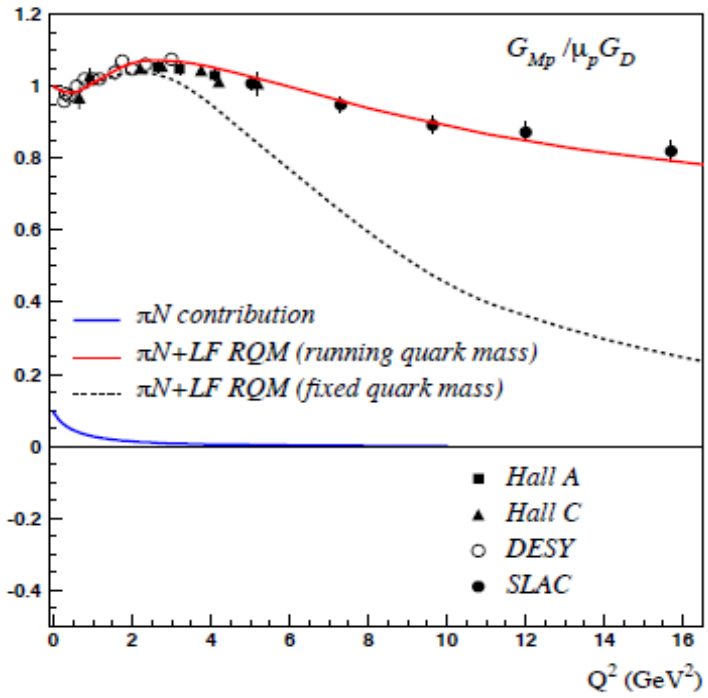
Quark Model with Input from QCD-based Approaches

Light Front QM by I.G. Aznauryan and V.D. Burkert: PRC 85, 055202 (2012).

The approach discussed here is purely phenomenological, and addresses a few topics that have some importance for the direction of the field, in particular:

- obtain a better understanding of the expected meson-baryon contributions
- study the sensitivity of the resonance transition amplitudes to the running quark mass, which is a result of the DSE approach and of LQCD calculations.

Proton Magnetic Form Factor



- Nucleon electromagnetic form factors
  → $q^3 + \pi N$ loops contributions in light-front dynamics
  → running quark mass
- Electroexcitation of $\Delta(1232)\frac{3}{2}^+$, $N(1440)\frac{1}{2}^+$, $N(1520)\frac{3}{2}^-$, and $N(1535)\frac{1}{2}^-$
  → q^3 contribution in a LF RQM with running quark mass
  → inferred MB contributions

Implementation of momentum-dependent quark mass is needed in order to reproduce elastic magnetic form factor of proton at Q^2>3.0 GeV^2