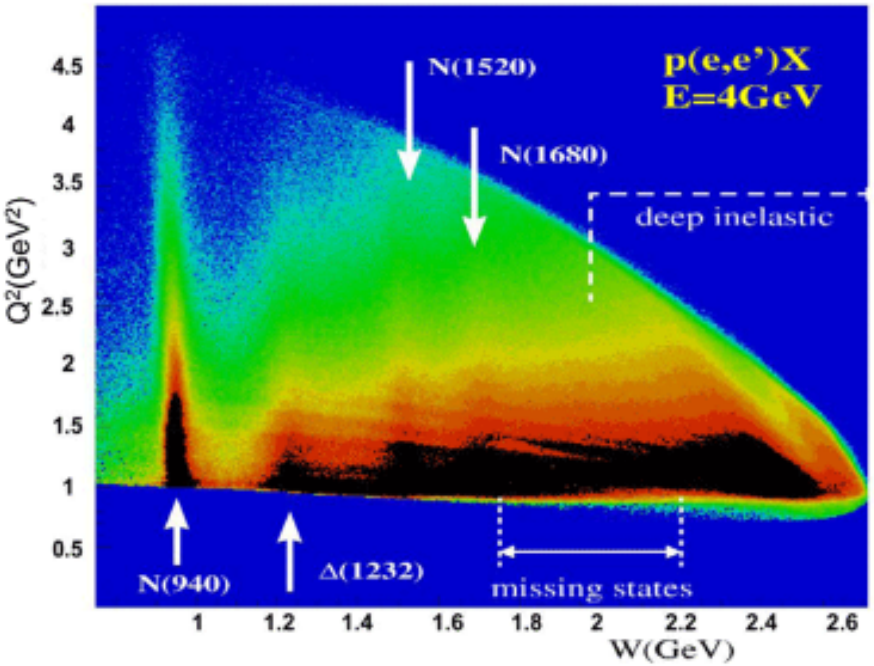
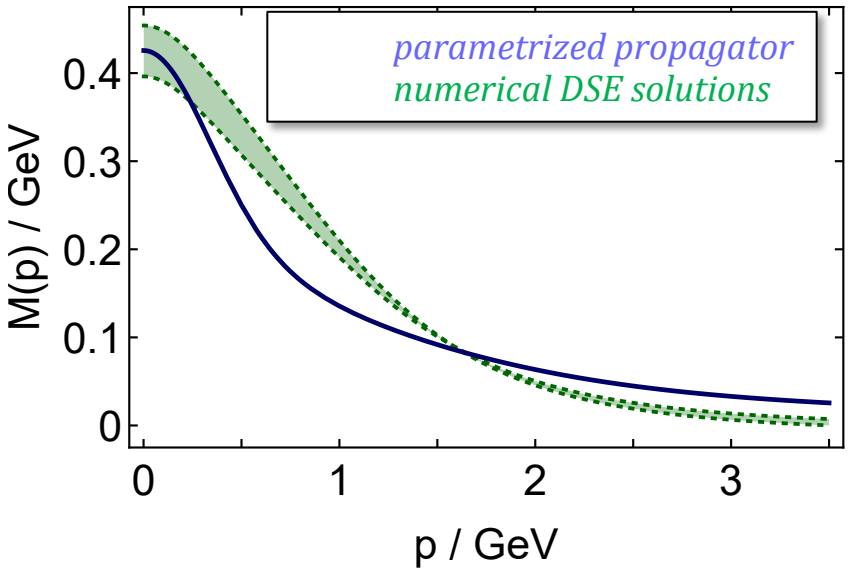
Insight to EHM from the Data on Nucleon Resonance Electroexcitation and the Meson Structure Studies





V.I. Mokeev,
Jefferson Laboratory

Talk outline:

- N* structure as a window into hadron mass generation;
- Resonance photo-/electrocouplings from meson electroproduction data;
- Relating resonance electrocouplings to hadron mass generation;
- Mapping dressed quark mass from the data on meson and N* structure;
- Conclusion and outlook

Office of Science

Perceiving the Origin of Hadron Mass through AMBER @ CERN, March 31 – April 3, 2020, Geneva, Switzerland

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 of excited proton states through analyzing major meson electroproduction channels from CLAS data
- extend accessible Q^2 range up to 12 GeV^2 and down to 0.05 GeV^2 from CLAS12 data and explore N* structure evolution in the transition from the strong to the pQCD regimes
- explore hadron mass emergence by mapping out running quark mass in the transition from almost massless pQCD quarks to fully dressed constituent quarks

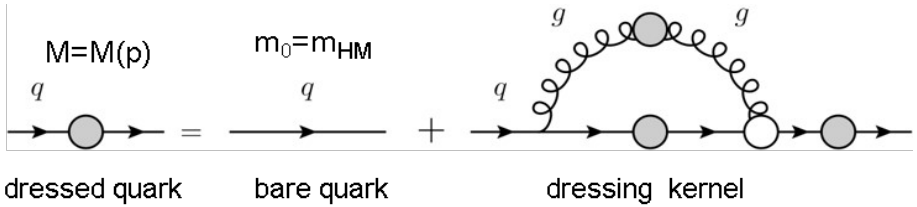
- **A unique source of information on many facets of strong QCD in generating N* states with different structural features**
- **Consistent results on dressed quark mass function from independent studies of different N* electroexcitations validate insight to EHM**

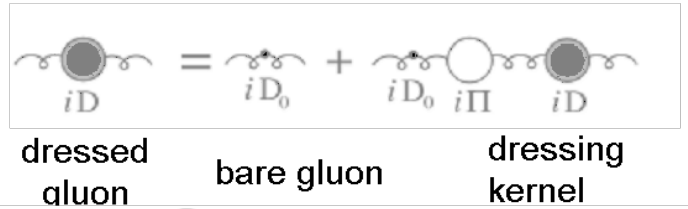
Review papers:

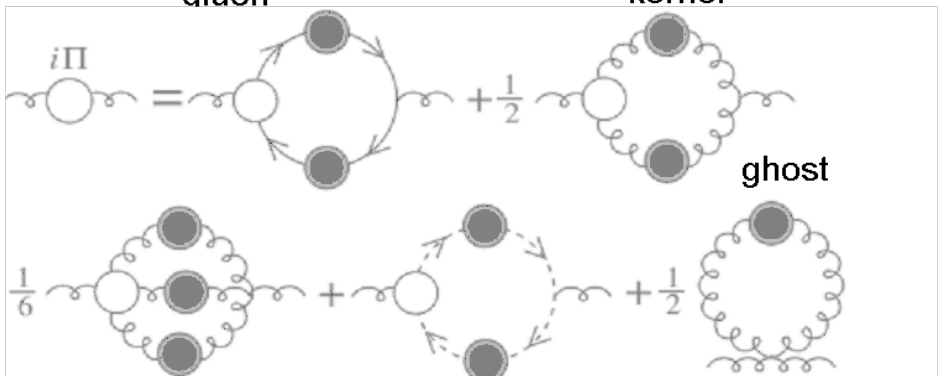
1. **I.G. Aznauryan and V.D. Burkert, Prog. Part. Nucl. Phys. 67, 1 (2012)**
2. **V.D. Burkert and C.D. Roberts, Rev. Mod. Phys. 91, 011003 (2019)**
3. **C.D. Roberts, Few Body Syst. 59, 72 (2018)**
4. **V.I. Mokeev, Few Body Syst. 59, 46 (2018)**

Basics for Insight into EHM from Data on N* Electrocouplings

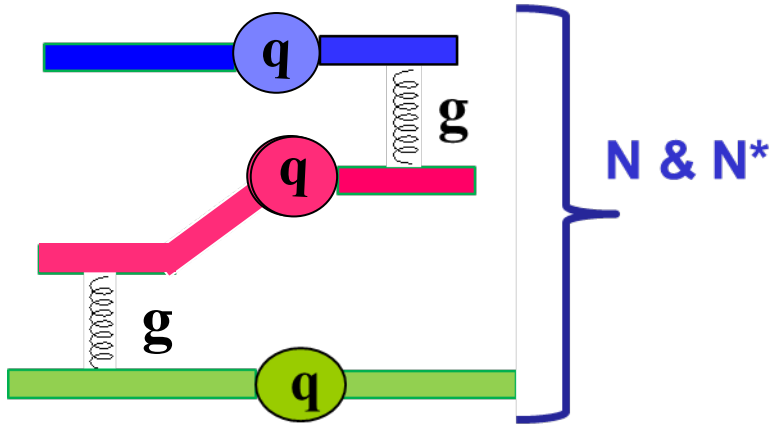
Emergence of Dressed Quarks and Gluons
D. Binosi et al, Phys. Rev. D 95, 031501 (2017)



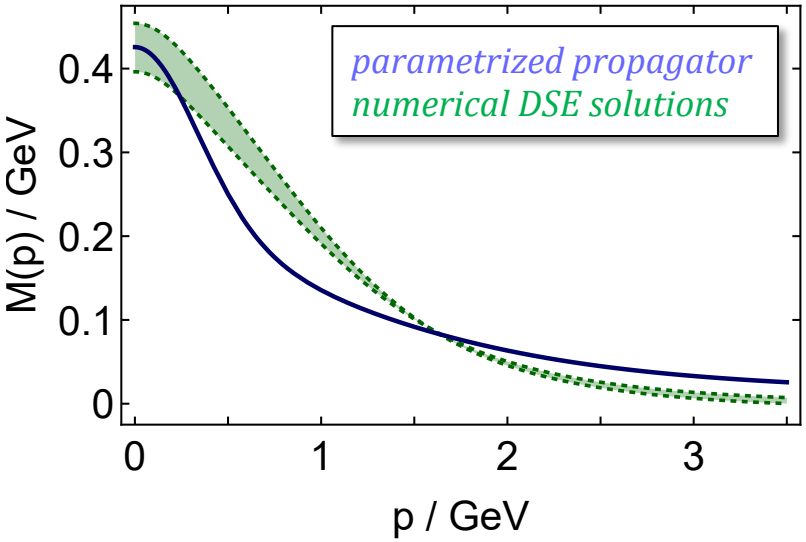




Dressed Quark Borromeo Binding in N/N*
J. Segovia et al., arXiv:1908:0572 [nucl-th]



Dressed Quark Mass Function
C.D. Roberts, Few Body Syst. 58, 5 (2017)



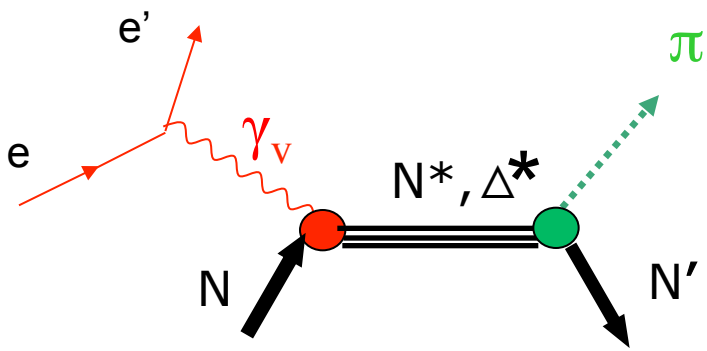
Data on N* electrocoupling are sensitive to the quark propagators and allow us to:

- **Map out quark mass function**
- **Constrain the ground nucleon and meson form factors, PDA, & PDF**

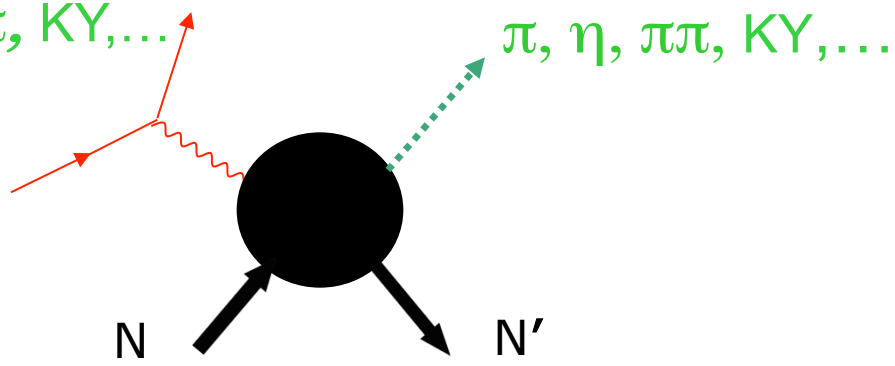
Inferred from QCD Lagrangian with only the Λ_{QCD} parameter

N* Electroexcitation Amplitudes (γ_vNN* 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!

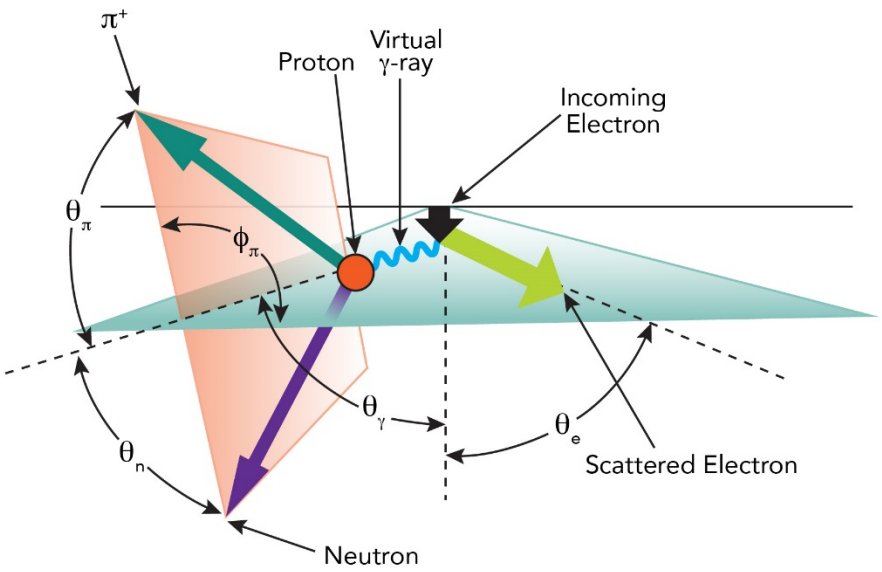
Almost full coverage of the final hadron phase space

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

Accessing Resonance Electrocouplings from the π^+n Differential Electroproduction Cross Sections off Protons

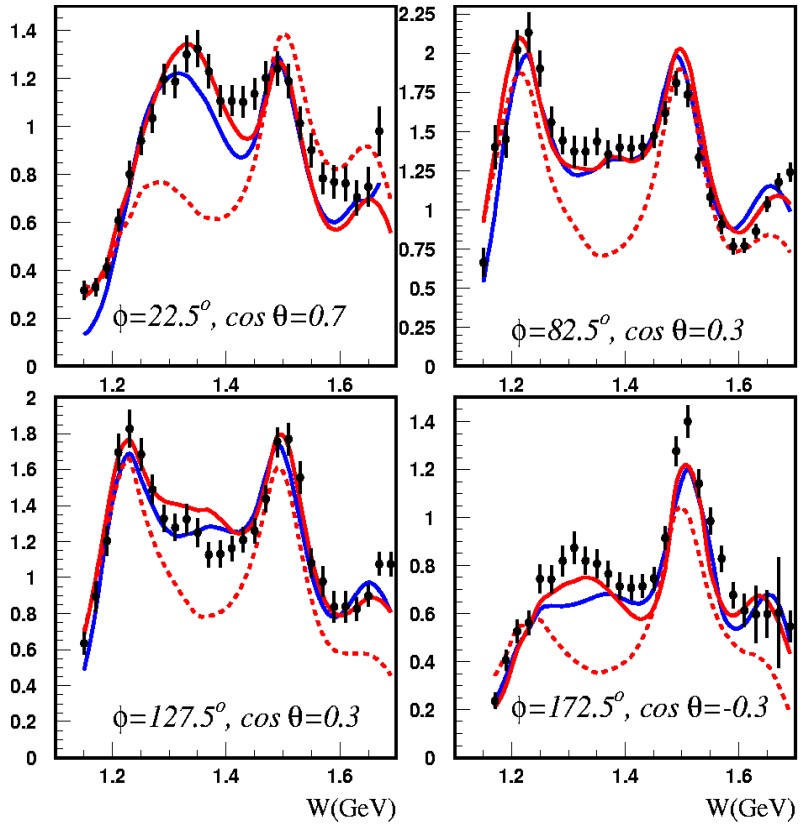
I.G. Aznauryan et al, PR C67, 015209 (2003), PR C80, 055203 (2009).

Kinematics of exclusive π^+n electroproduction off protons (lab frame)



Q^2=2.05 GeV^2

DR
DR w/o P11
UIM

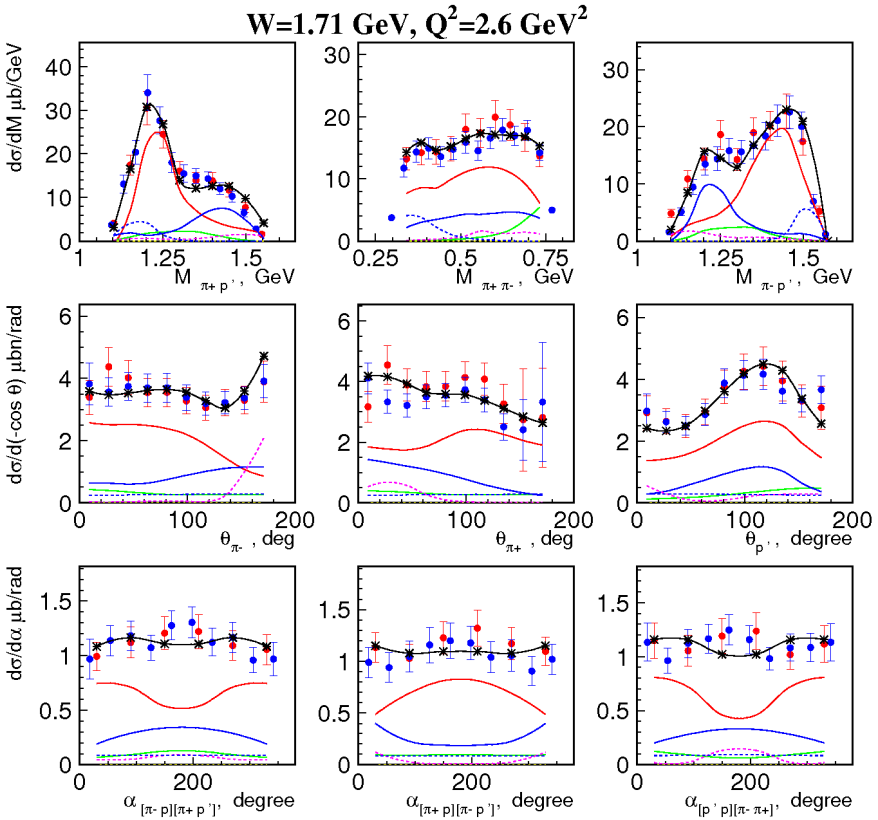


The final pion angles are in the CM-frame of the final hadrons

Accessing Resonance Electrocouplings from the $\pi^+\pi^-p$ Differential Electroproduction off Protons Cross Sections

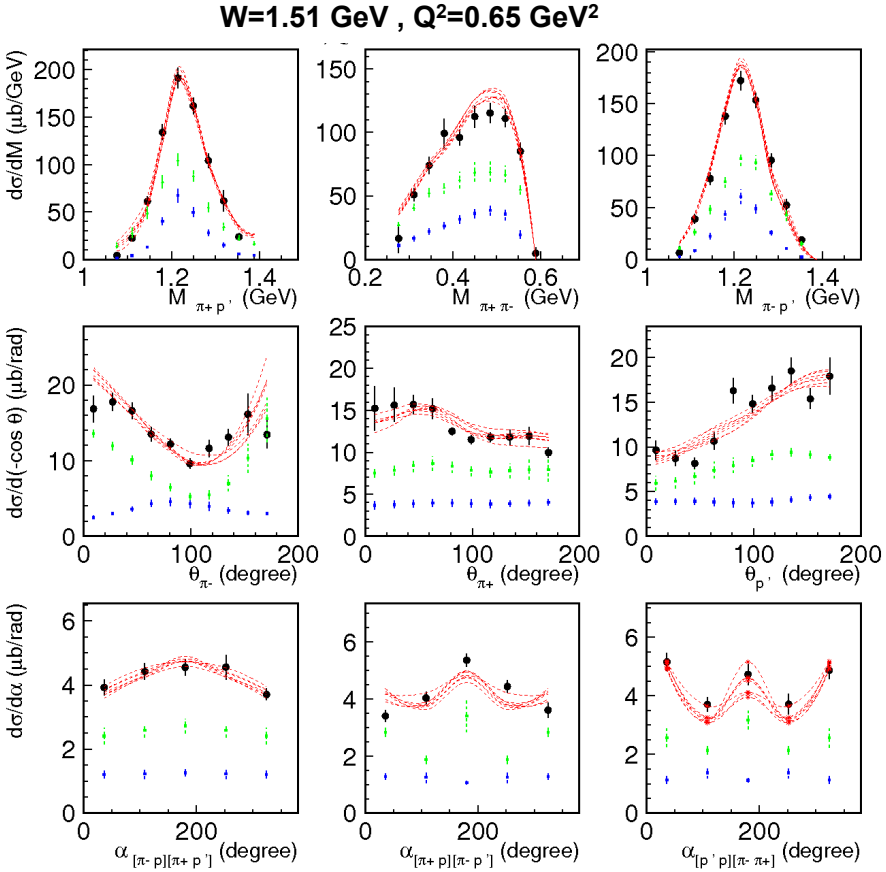
Contributing mechanisms seen in the data

E. Isupov et al. (CLAS), Phys. Rev. C96, 025209 (2017)
A.Trivedi, Few Body Syst. 60, 5 (2019)



Resonant and non-resonant contributions

V.I. Mokeev, V.D. Burkert et al., Phys. Rev. C93, 054016 (2016).



full JM — ρp — π^+ N(1520)3/2$^-$

$\pi^-\Delta^{++}$ — $\pi^+\Delta^0$ ------- π^+ N(1680)5/2$^+$

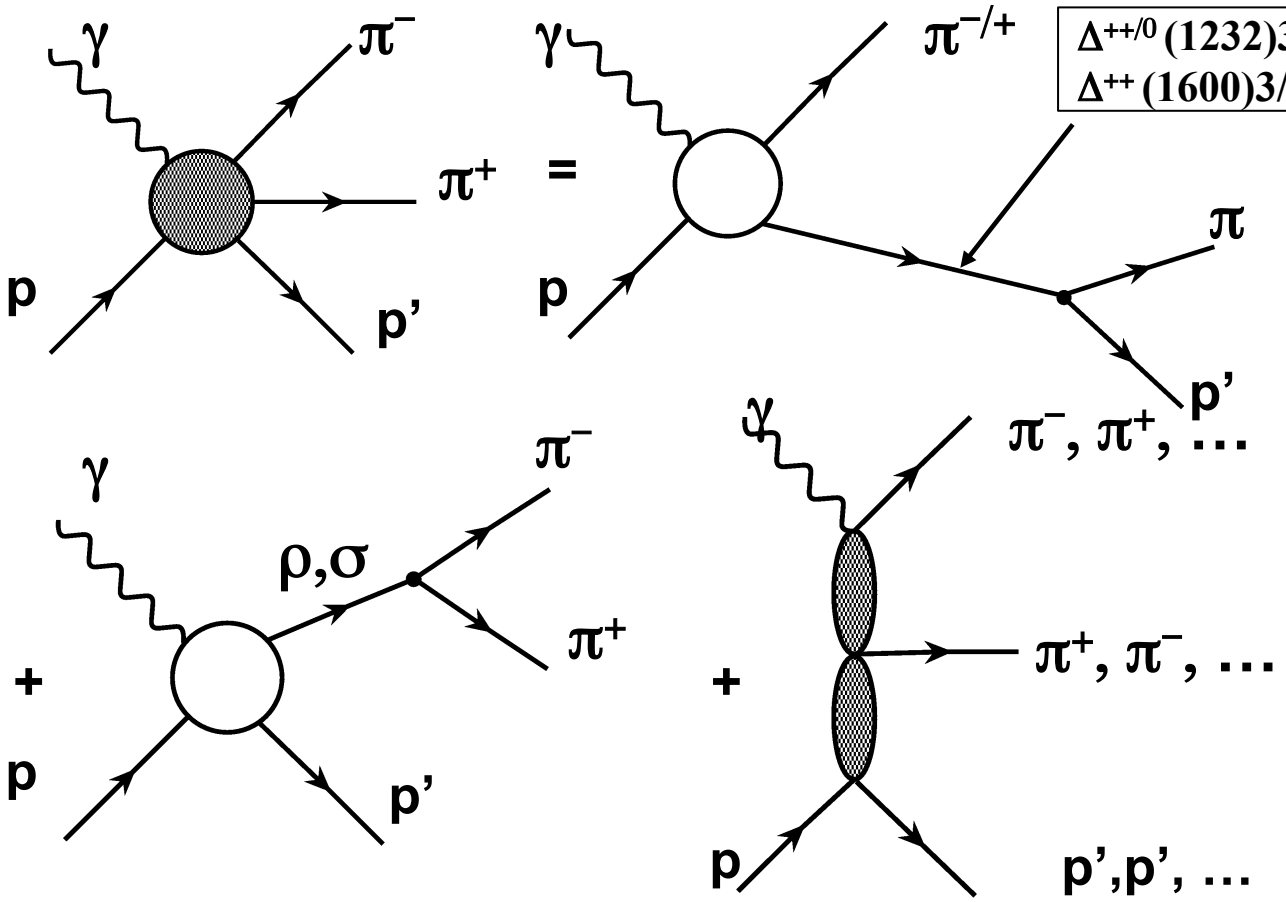
--------- data fit within JM under variations of both resonant and background parameters

background cross sections

resonant cross sections

JM Model for Analysis of $\pi^+\pi^-$p Photo-/Electroproduction

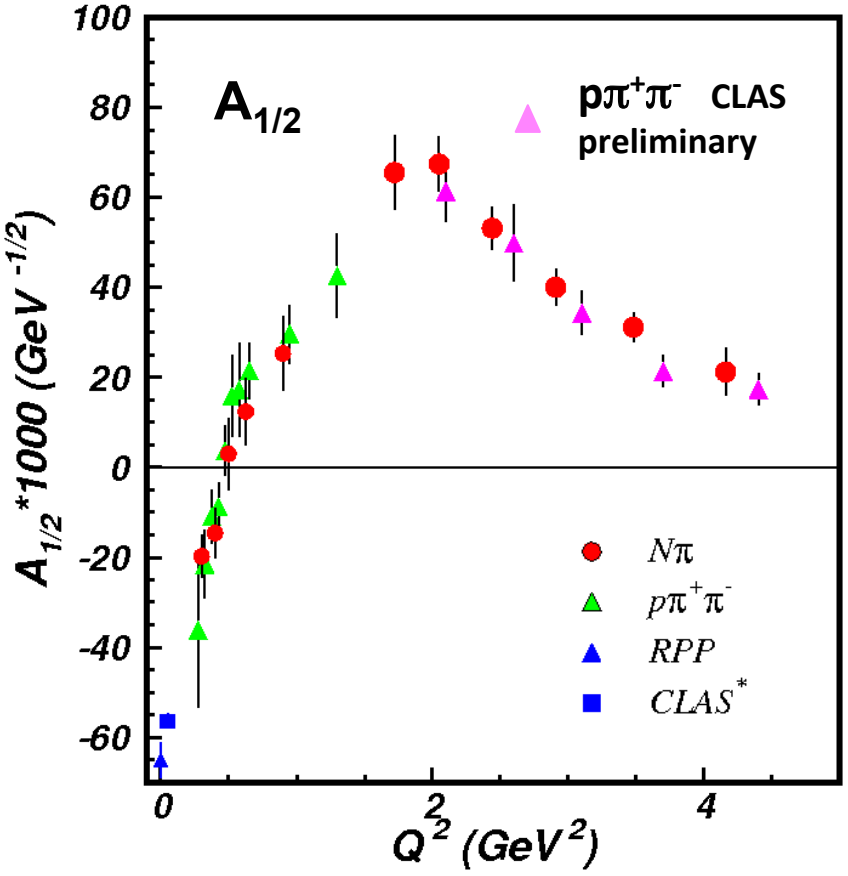
Major objectives: extraction of $\gamma_{r,v}$pN* photo-/electrocouplings and $\pi\Delta$, ρp decay widths (V.I. Mokeev et al, PR C80, 045212 (2009), PR C86,035203 (2012).

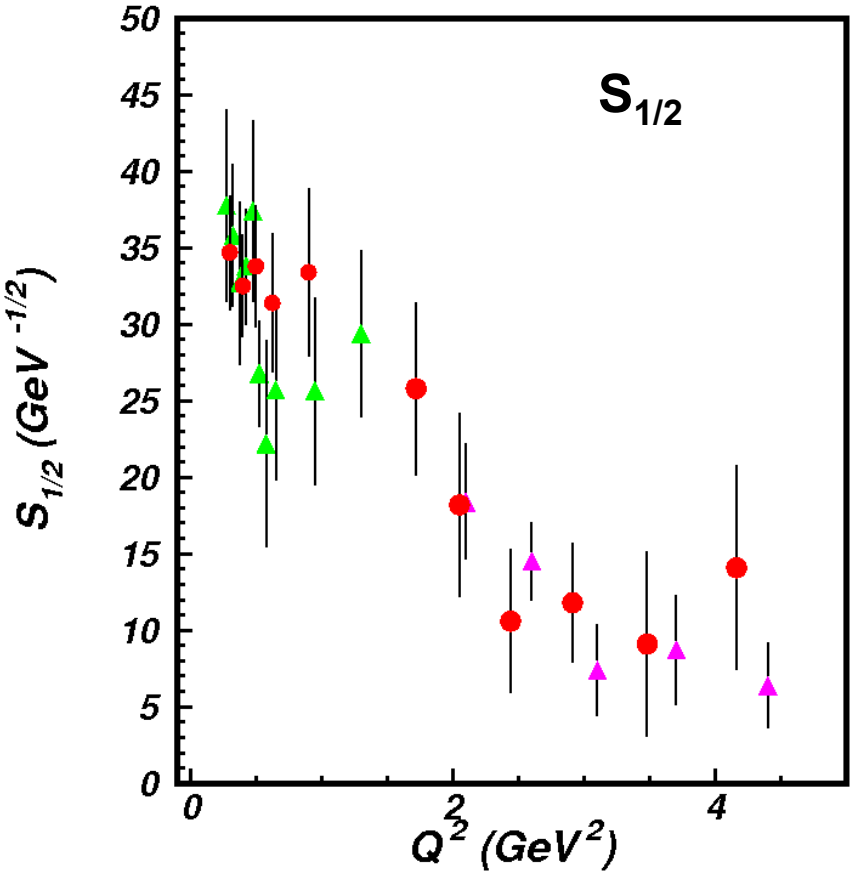


- five channels with unstable intermediate meson/baryon and direct $\pi^+\pi^-$p production;
- N* contribute to $\pi\Delta$ and ρp channels only;
- unitarized Breit-Wigner ansatz for resonant amplitudes;
- phenomenological parameterization of the other meson-baryon channel amplitudes

Good description of $\pi^+\pi^-$p photo-/electroproduction cross sections off protons for 1.4 GeV < W < 2.0 GeV and 0 GeV^2 < Q^2 < 5.0 GeV^2

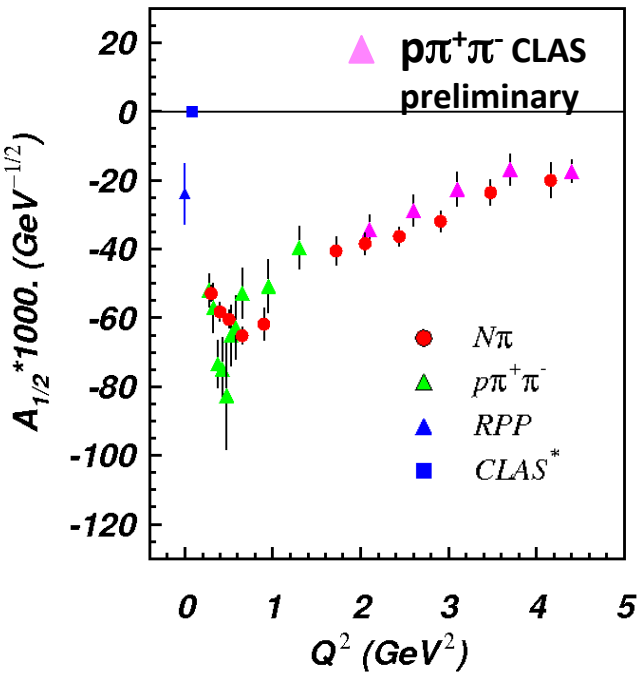
Electrocouplings of N(1440)1/2$^+$ from πN and $\pi^+\pi^-$p Electroproduction off Proton Data

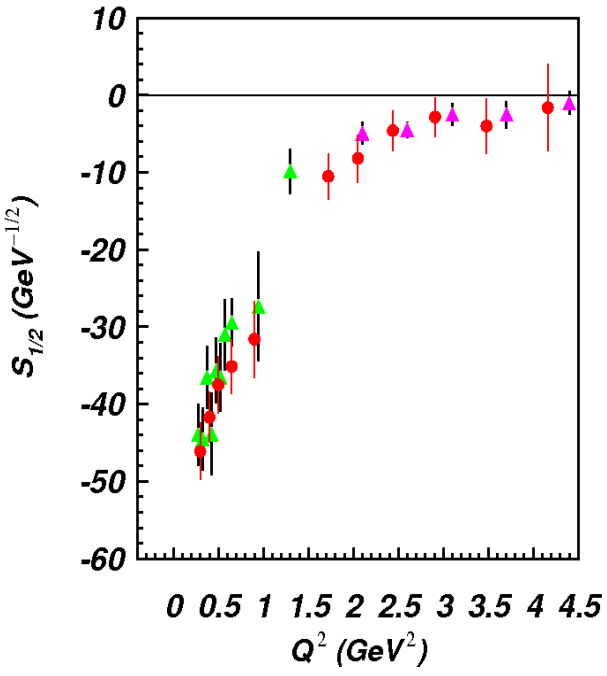


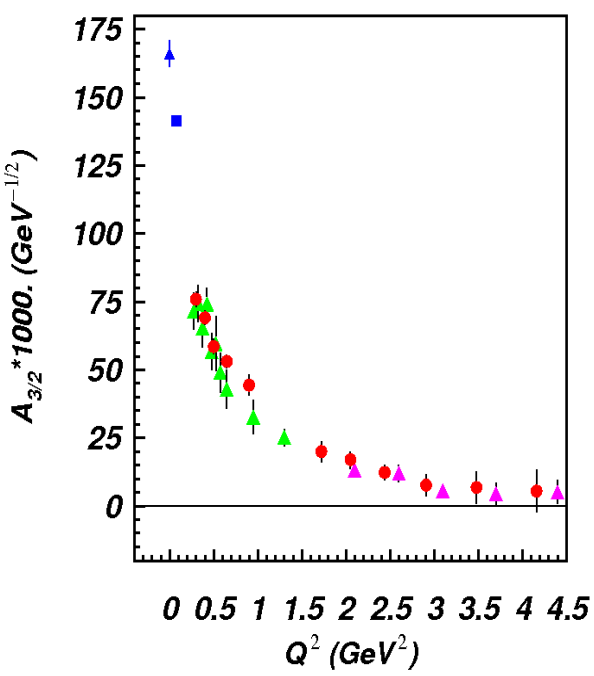


Consistent results on N(1440)1/2$^+$ electrocouplings from independent studies of two major πN and $\pi^+\pi^-$p electroproduction off proton channels with different non-resonant contributions strongly support credible extraction of these quantities in a nearly model-independent way.

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





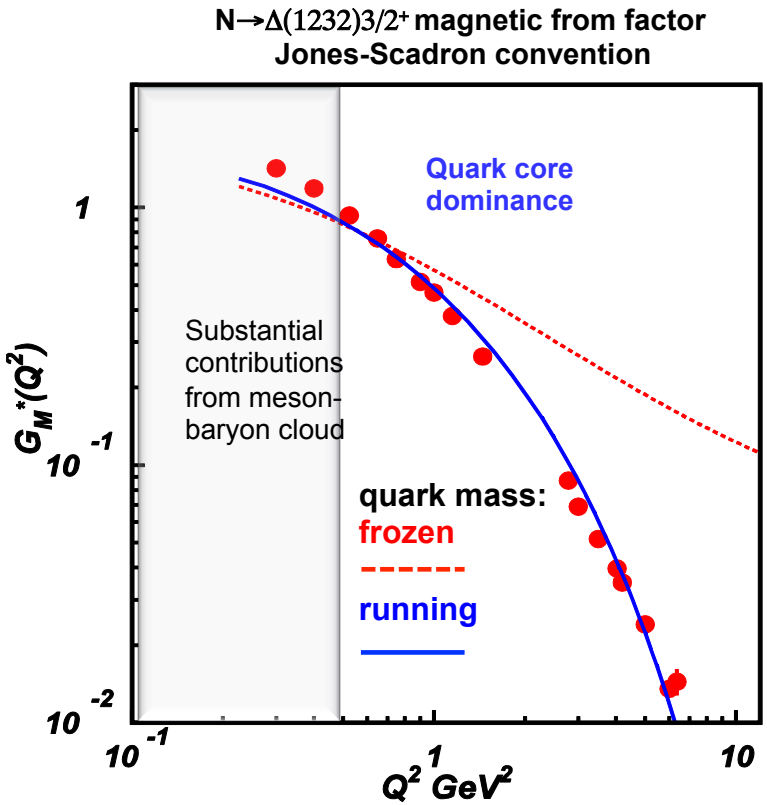


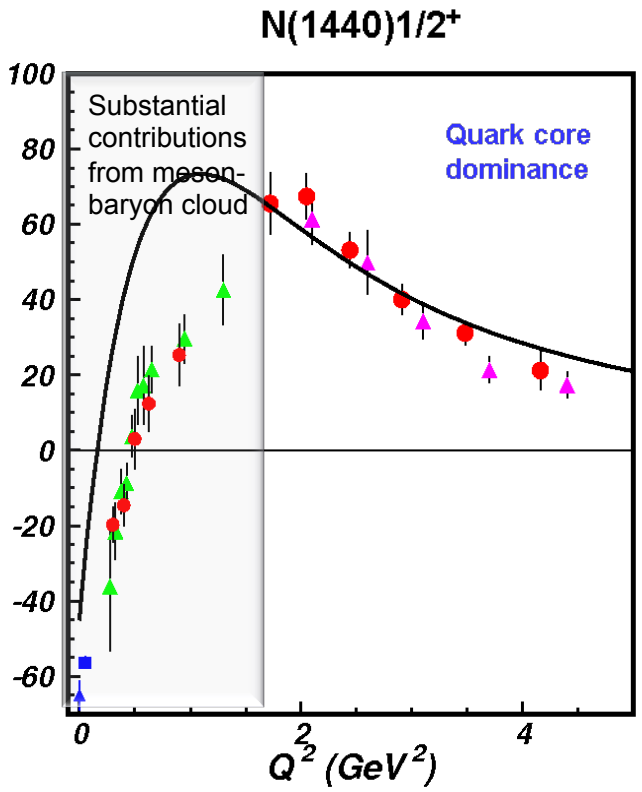
Consistent results from Nπ and $\pi^+\pi^-$p electroproduction off proton data on electrocouplings of N(1440)1/2$^+$ and N(1520)3/2$^-$ resonances with the biggest combined contribution into the resonant parts of both channels at W<1.55 GeV strongly support the capabilities of the developed reaction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





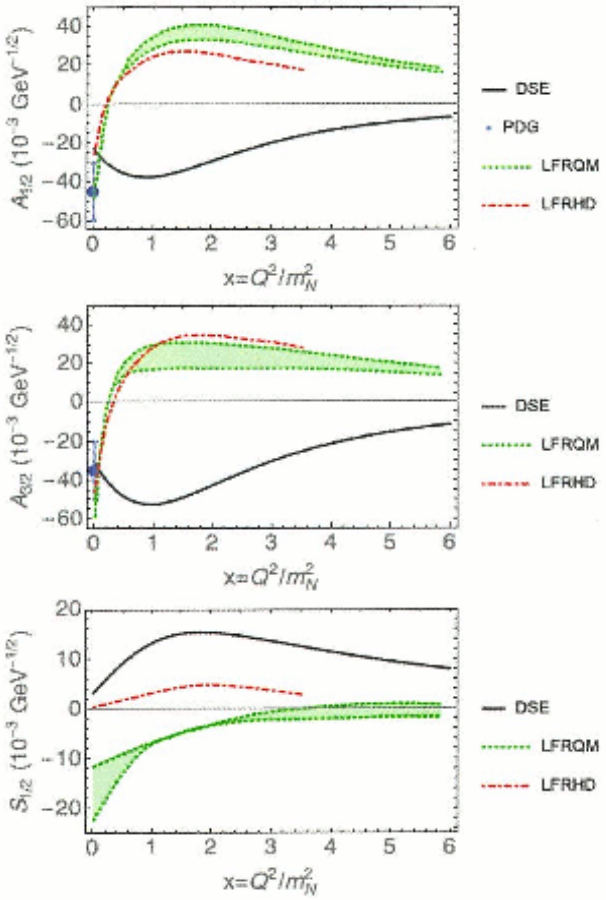
DSE analyses of CLAS data on Δ(1232)3/2⁺ electroexcitation demonstrate that dressed quark mass is running with momentum.

Good data description at Q^2>2.0 GeV² achieved with the same dressed quark mass function for the ground and two excited nucleon states of distinctively different structure validate 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.

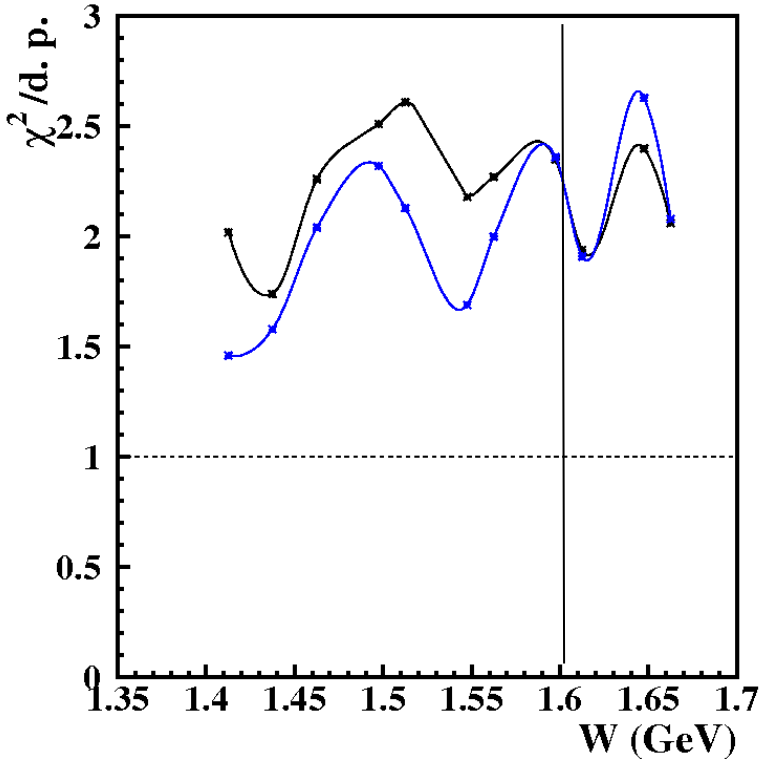
Dressed Quark Mass Function from Electrocouplings of Radial Δ-Excitation

Δ(1600)3/2⁺



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

χ^2/d.p. in all W bin covered by the data at Q^2=3.6 GeV^2



No Δ(1600)3/2⁺

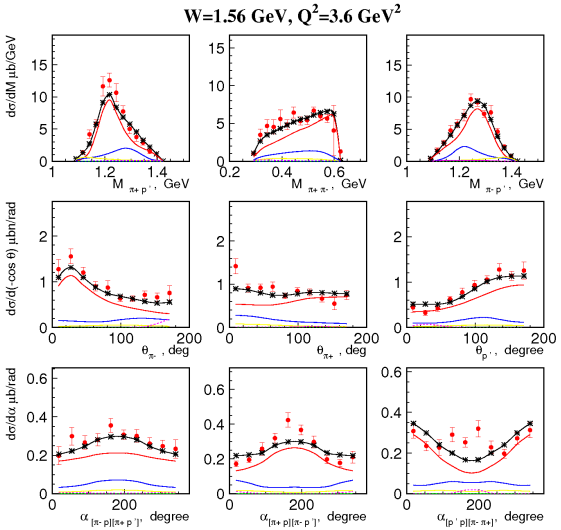
Δ(1600)3/2⁺ included

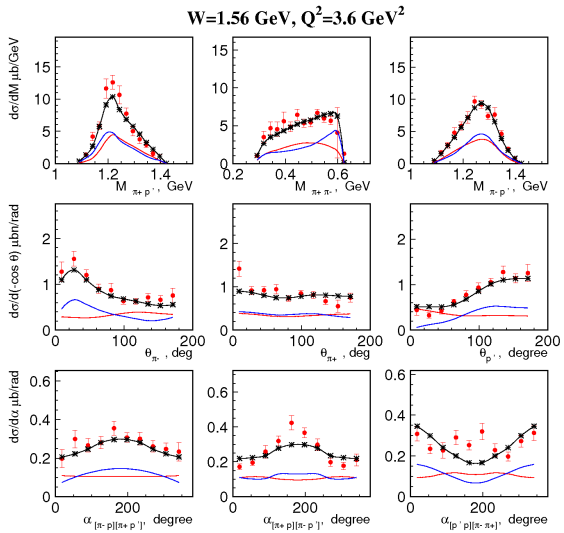
- **CLAS $\pi^+\pi^-$p electroproduction off protons data at 1.4 GeV < W < 2.0 GeV and 2.0 GeV^2 < Q^2 < 5.0 GeV^2 are consistent with the D(1600)3/2⁺ contribution with electrocouplings predicted by DSE**
- **Δ(1600)3/2⁺ electrocouplings will be extracted soon**
- **Confirmation of the DSE expectations will prove the reliable access to the dressed quark mass function**
- **Studies of [70.1-] orbital excitations is the next step**

Description of the CLAS $\pi^+\pi^-p$ Electroproduction Data at W Near Mass of $\Delta(1600)3/2^+$

Preliminary CLAS $\pi^+\pi^-p$ electroproduction data, A.Trivedi, Few Body Syst. 60, 1 (2019)

PDG18 parameters of of $\Delta(1600)3/2^+$: M=1.50-1.64 GeV (1.57 GeV central); Γ = 200-300 MeV (250 MeV central); BF($N\pi\pi$)= 73-83 %





full

$\pi^-\Delta^{++}$

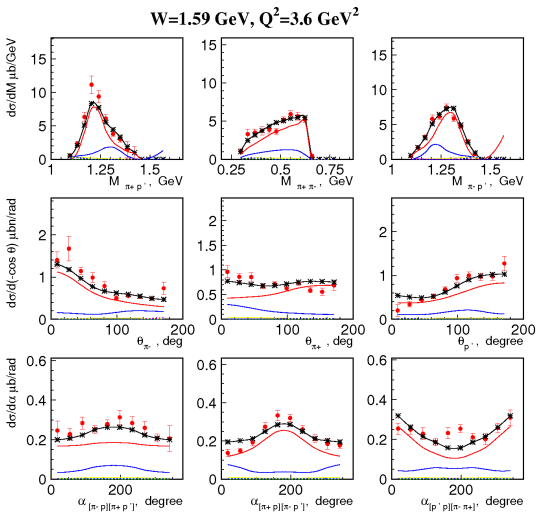
$\pi^+\Delta^0$

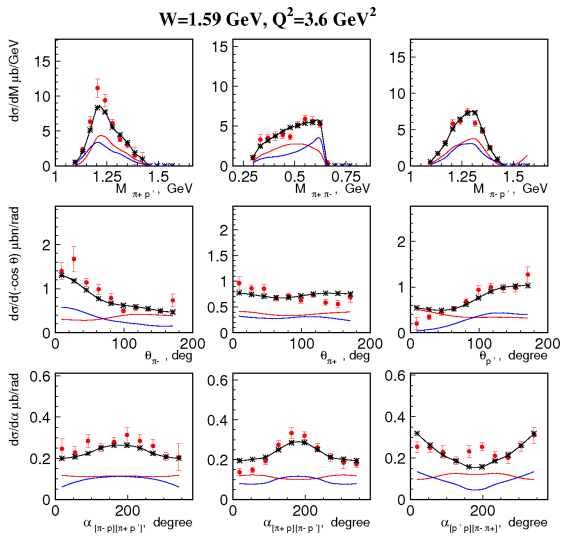
2π direct

$\pi^+D_{13}(1520)$

π^+F_{15}

ρp





Full.

Resonances

background

Insight to EHM from the Combined Studies of Meson and N* Structure

Model, gauge and renormalization scheme independent GT relation between a scalar part of dressed quark propagator $B(p^2)$ and the biggest part of the pion BS amplitude $E_\pi(p^2)$ in chiral limit:

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

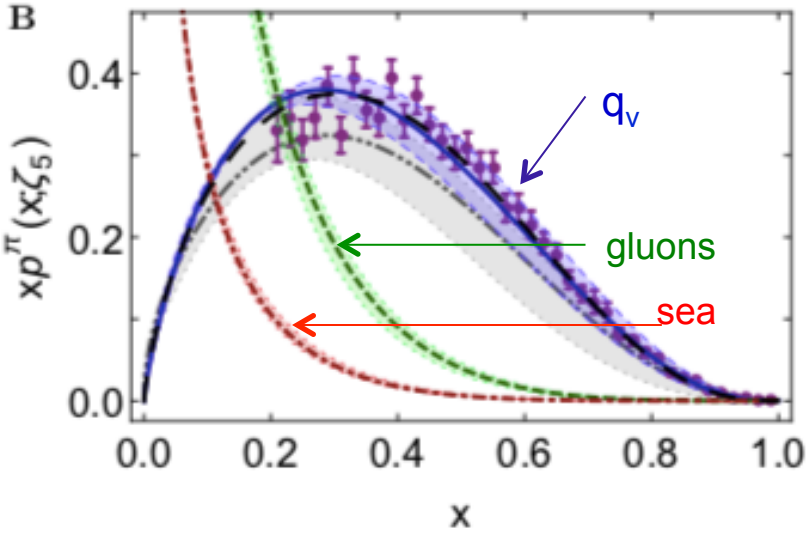
- **Consistency between $B(p^2)$ from the dressed quark mass function mapped out from the results on $\gamma_v pN^*$ electrocouplings and the $E_\pi(p^2)$ part of pion BS amplitudes available from the data on pion structure (e.m. form factor & PDF) are critical in order to validate reliable insight into EHM.**

- **Comparison between the data kaon e.m. form factor with the continuum QCD evaluation with light quark mass function from the results on N* electrocouplings will enhance capability to map out strange quark mass function shedding light on the EHM evolution with quark flavor and on the interplay between DCSB and Higgs mechanisms in hadron mass generation.**

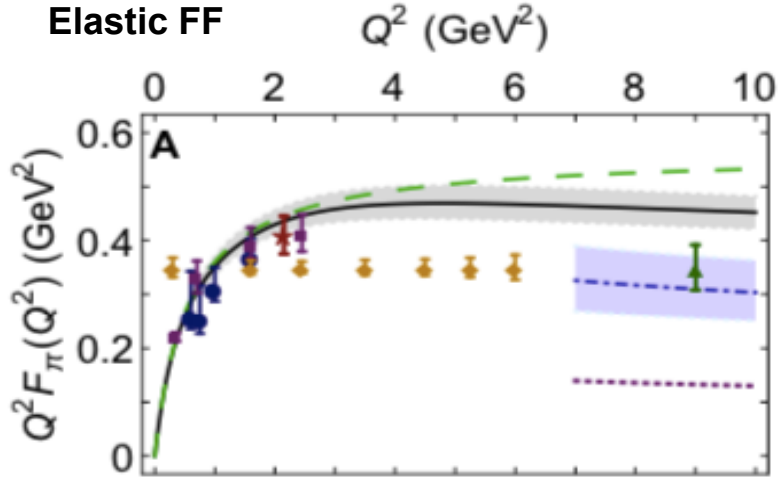
Hadron Mass Generation from the Combined Studies of Pion and N* Structure

A.C. Aguliar et al., Eur. Phys. J A55, 190 (2019)

PDF



Elastic FF



Pion elastic FF and PDF can be computed with exactly the same quark mass function as established from $\gamma_v pN^*$ electrocoupling results and confronted to the data

Strong sensitivity to momentum dependence of dressed quark mass

Pion PDF would be x-independent for frozen quark mass

Essential difference for computed pion elastic form factor with frozen/running quark mass

DSEQCD:
Full ———

Hard*soft part factorization with PDF:
for pQCD frozen quark mass
----
for running quark mass
- · - · - · -

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.**

- **<u>Profound impact on the exploration of the hadron mass generation:</u>**
  a) first continuum QCD evaluations of $\Delta(1232)3/2^+$, $N(1440)1/2^+$, and $\Delta(1600)3/2^+$ electroexcitation amplitudes with the same dressed quark mass function computed starting from the QCD Lagrangian;
  b) 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 structure of mesons in terms of elastic/transition form factors, PDF, and PDA can be predicted within continuum QCD approaches by employing the dressed quark mass function available from the studies of the ground nucleon/N* structure. These predictions can tested in experiments on meson structure studies, bridging the efforts between meson and baryon sectors in addressing the EHM problem.**

Back Up

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

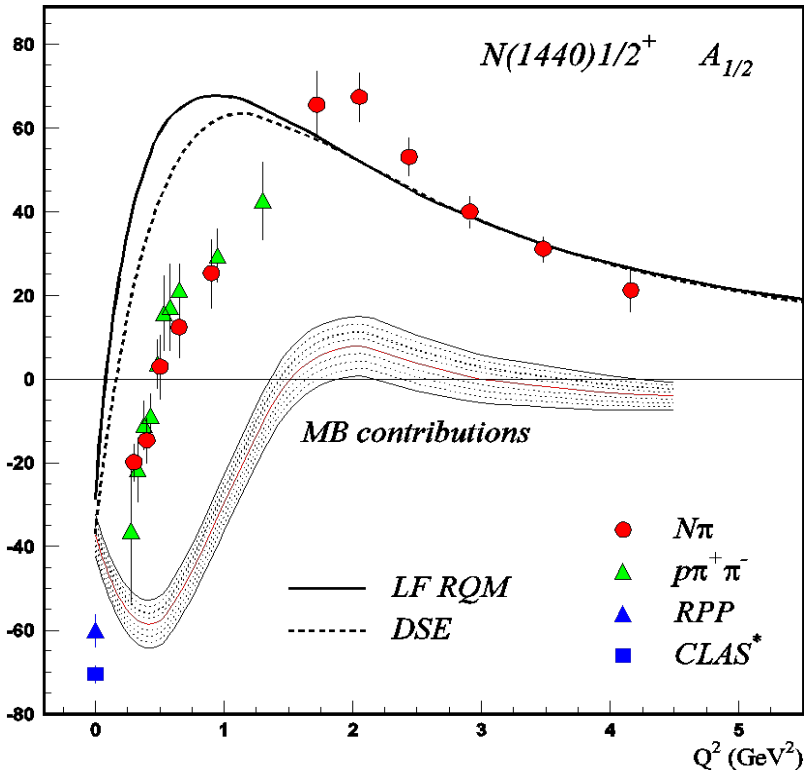
Independent analyses of different meson electroproduction channels:

- **$\pi^+ n$ 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)

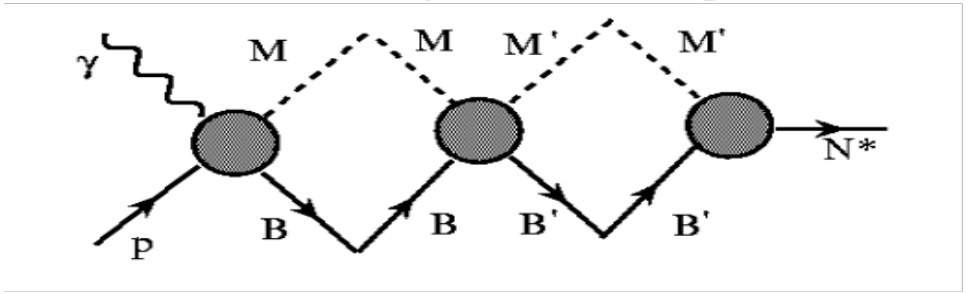
Global coupled-channel analysis of $\gamma_{r,v}N$, πN, ηN, $\pi\pi N$, $K\Lambda$, $K\Sigma$ exclusive channels:

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

Resolving Puzzle of the Roper Structure



The mechanisms of the meson-baryon dressing



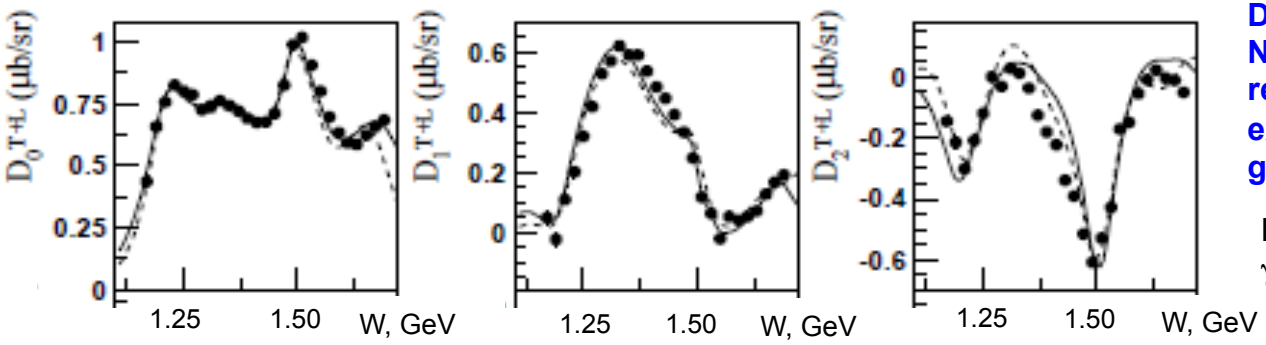
CLAS data in the range of Q^2<5.0 GeV^2 reveal the structure of N(1440)1/2$^+$ as a complex interplay between inner core of three dressed quarks in the first radial excitation and external meson-baron (MB) cloud

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

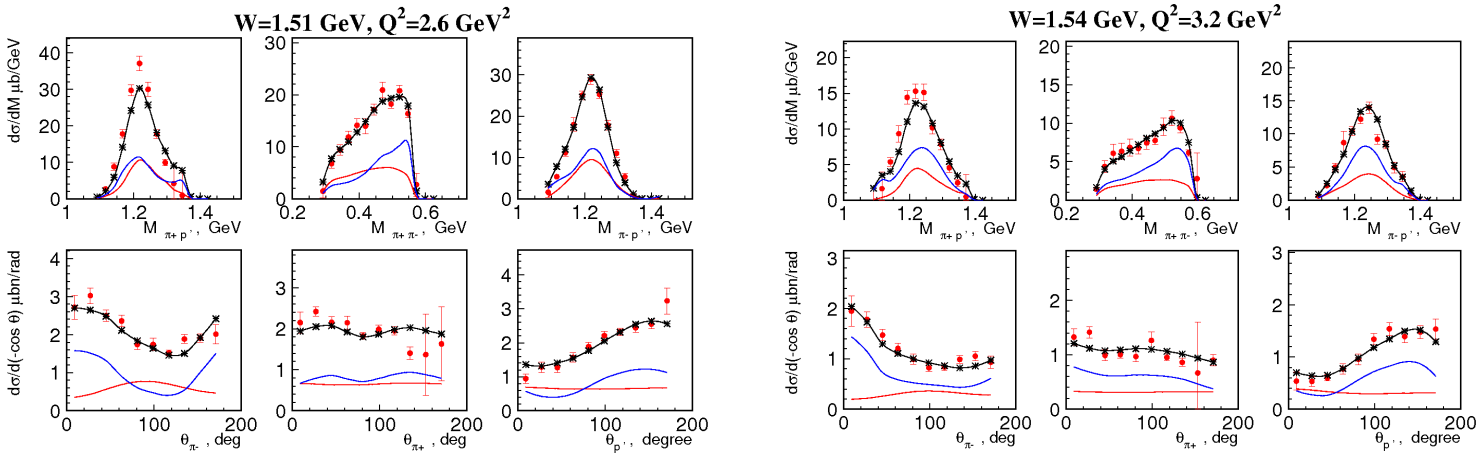
For more details on resolving Roper puzzle see:
V. D. Burkert and C.D. Roberts, Rev. Mod. Phys. 91, 011003 (2019)

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



$\gamma_v p \to \pi^+ \pi^- p$

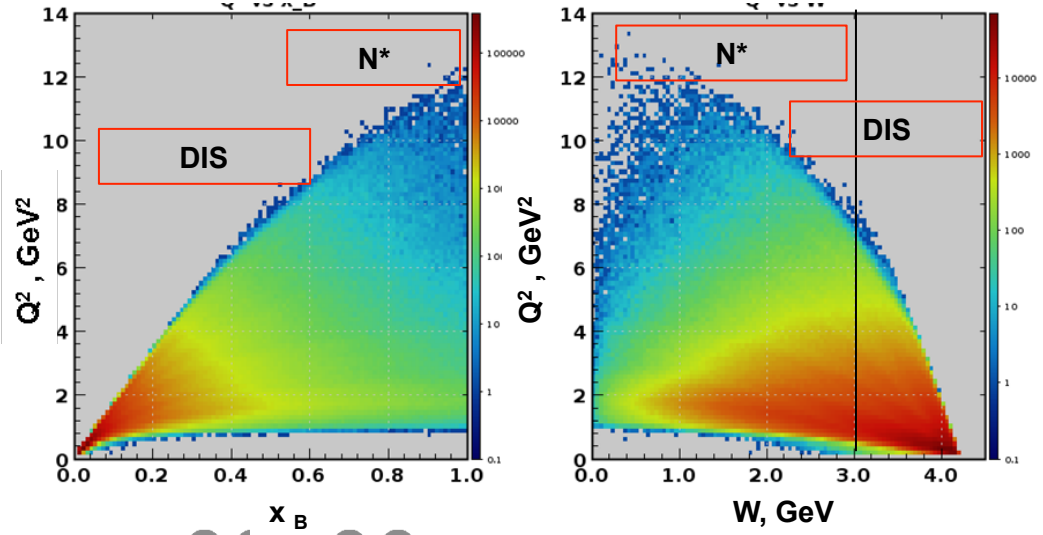
Resonant contributions

Non-resonant contributions

- **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!

Emergence of Hadron Mass and Quark-Gluon Confinement

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

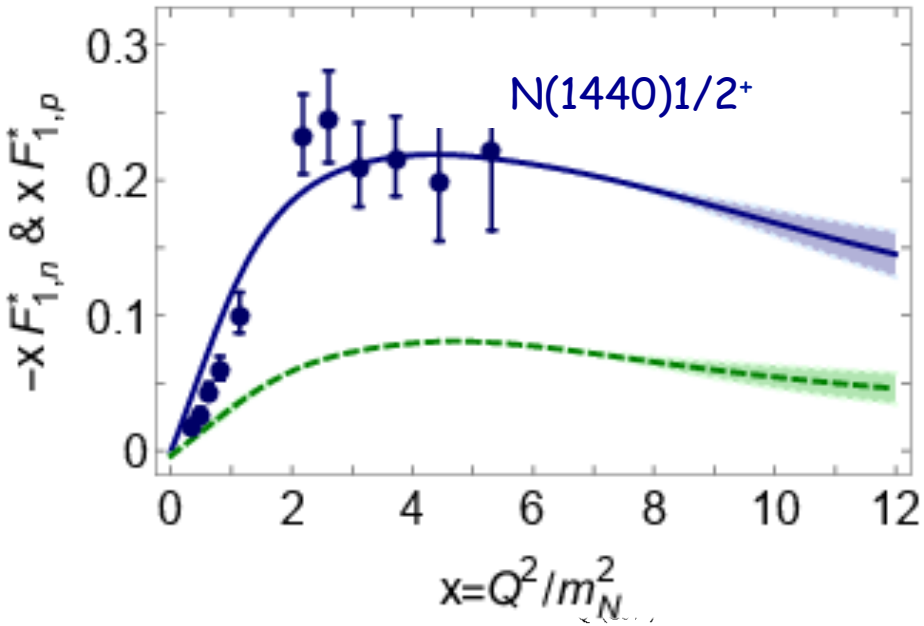
How is >98% of visible mass generated?

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?

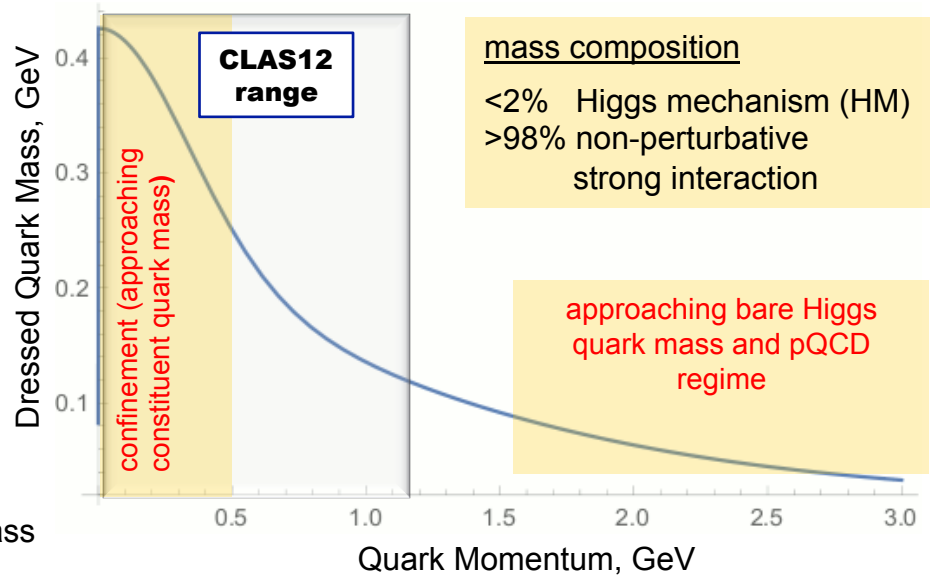
Mapping-out quark mass function from the CLAS12 results on $\gamma_v pN^*$ electrocouplings of spin-isospin flip, radial, and orbital excited nucleon resonances at $5<Q^2<12$ GeV^2 will allow us to explore the transition from strong QCD to pQCD regimes

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

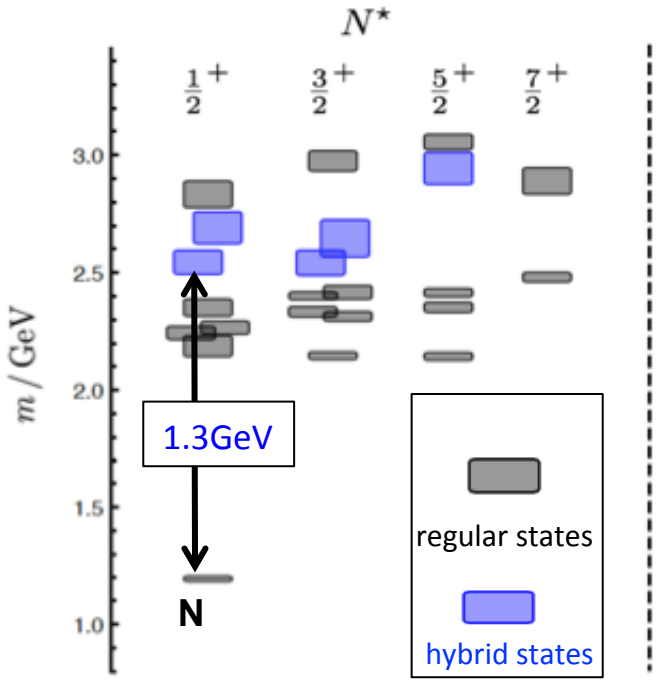
Run Group conditions:
E_b = 6.6 GeV, 50 days
E_b = 8.8 GeV, 50 days

- 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?

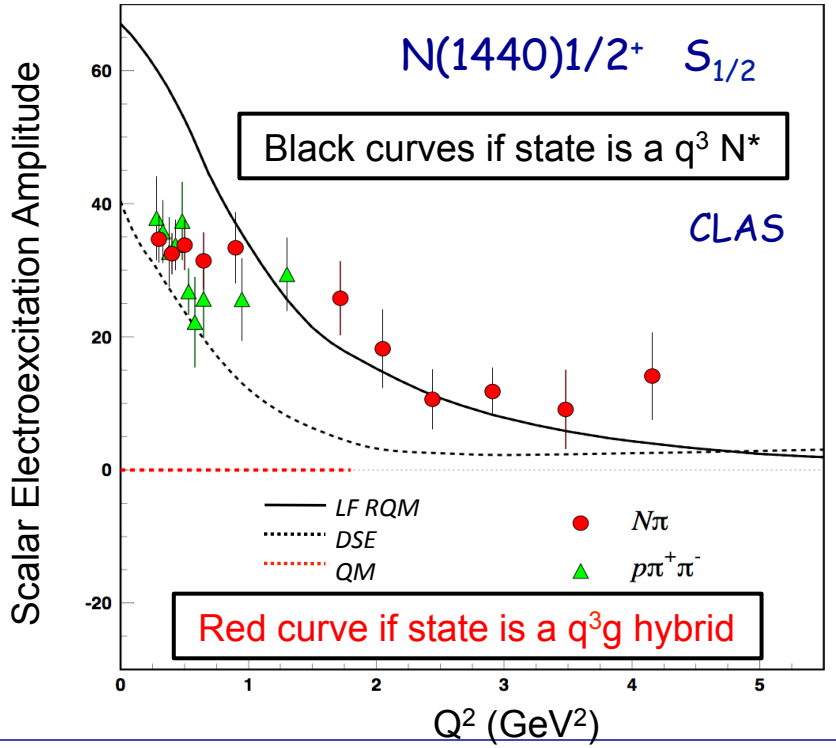
Predictions of the N* spectrum from QCD show both regular q^3 *and* hybrid q^3g states



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



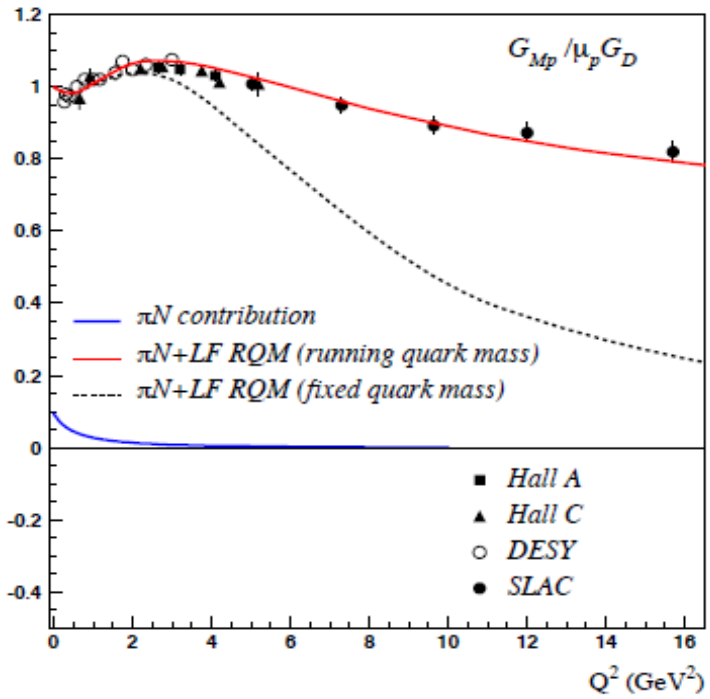
Quark Model with Input from QCD-based Approaches

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