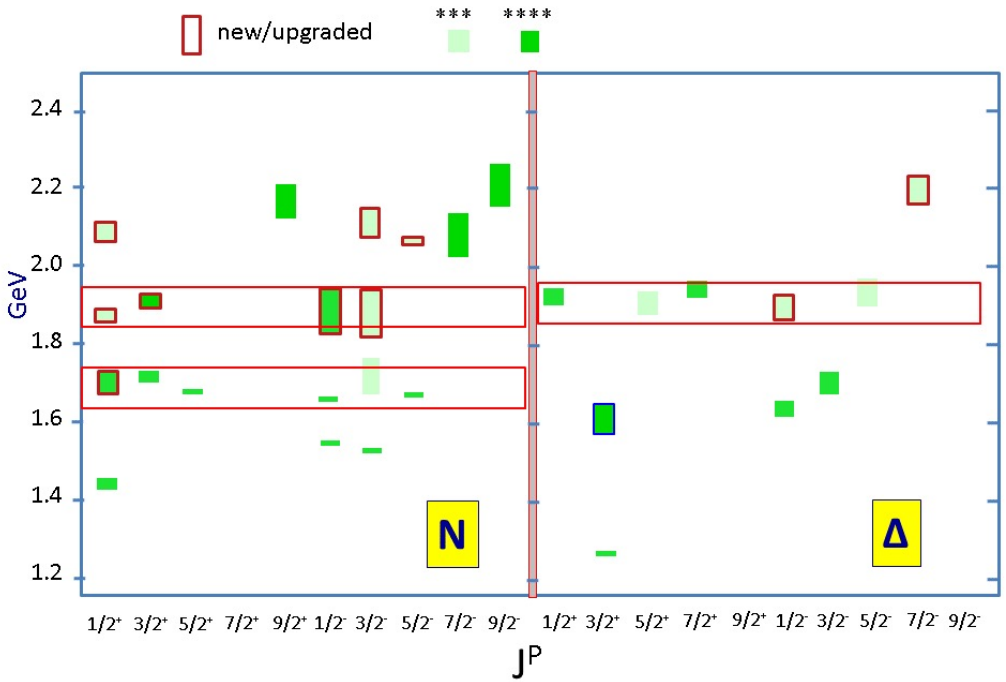
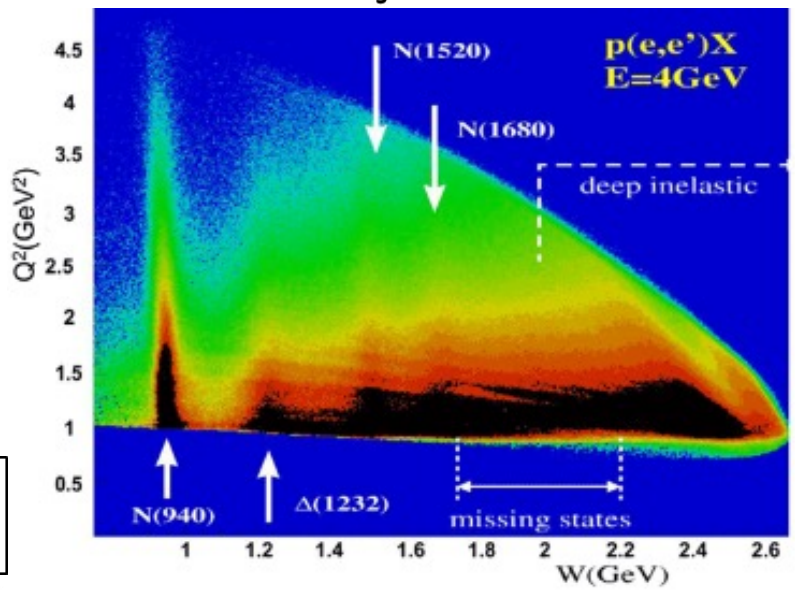
Advances in Exploration of the Nucleon Resonance Spectrum and Structure





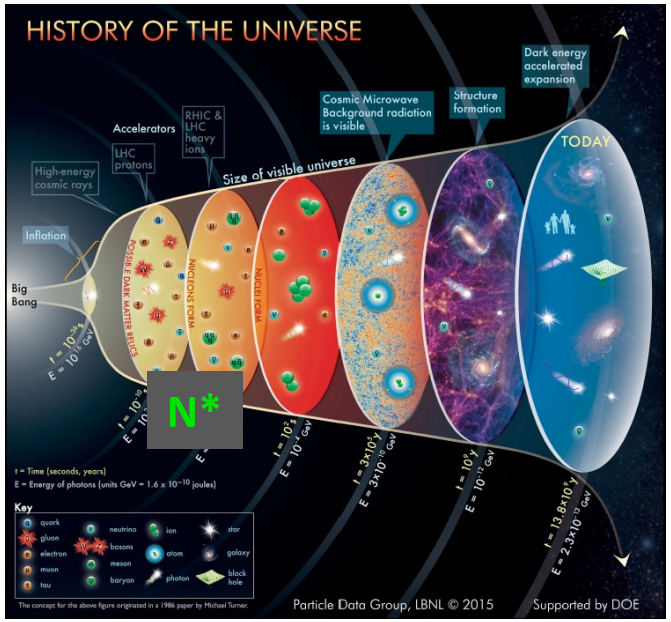
V.I. Mokeev
Jefferson Lab

Talk outline:

- **Nucleon resonances and evolution of hadron matter**
- **Discovery of new baryon states**
- **Insight into N* structure and strong QCD from $\gamma_v pN^*$ electrocouplings**
- **Shedding light on emergence of hadron mass**
- **Prospects with CLAS12 and beyond**

Office of Science

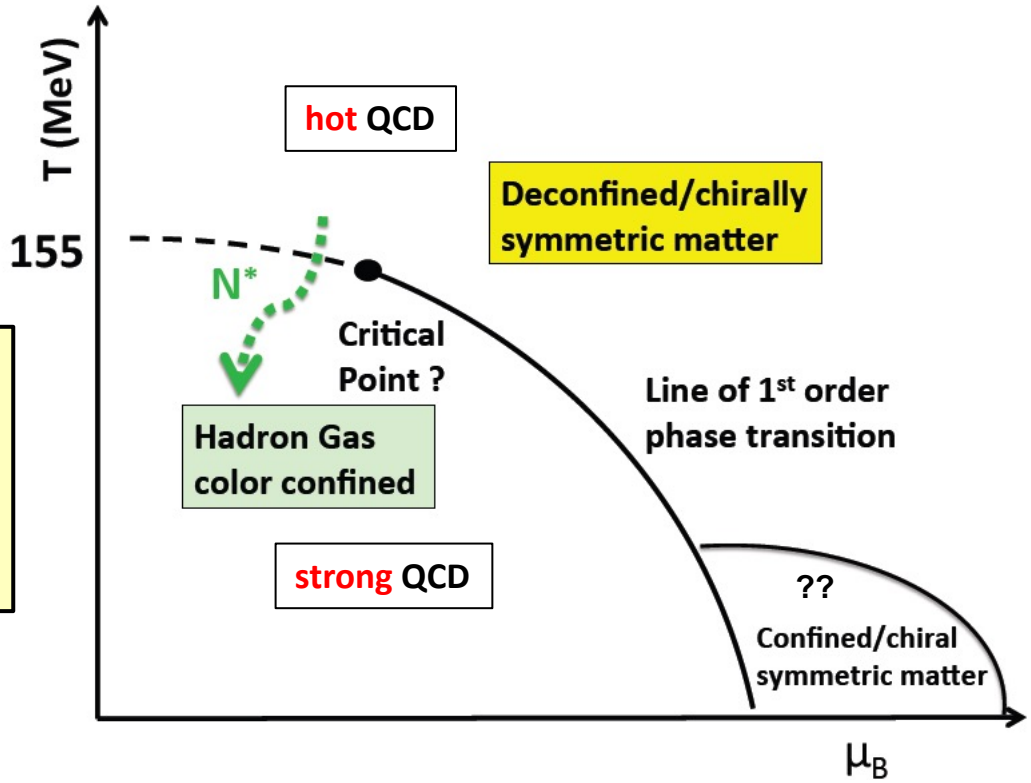
Nucleon Resonances in the Emergence of Hadronic Matter



Dramatic events occurred in the micro-second old universe during the transition from the deconfined quark and gluon phase to the hadron phase.

- Quark-gluon confinement emerges
- Chiral symmetry of QCD broken
- Quarks and gluons acquire mass
- Baryon resonances form

This transition was shaped by the full meson and baryon spectra



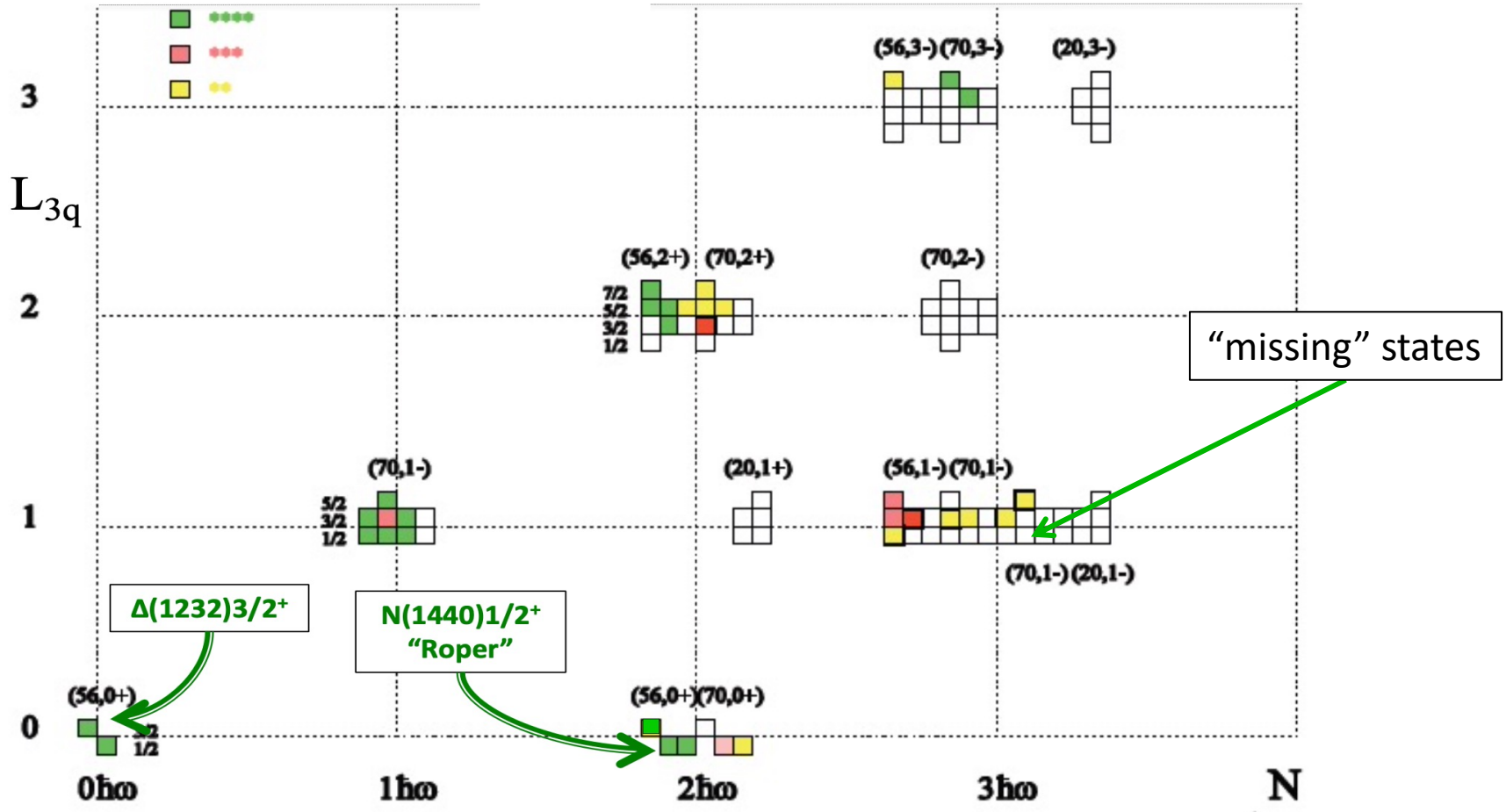
SU(6)xO(3) Spin-Flavor Symmetry and ``Missing" Resonances

PDG2012 status

SU(6)×O(3)

Continuum QCD: C. Chen et al., PRD 100 (2019) 054009; Si-xue Qin et al., FBS 60 (2019) 26

Lattice QCD: R. Edwards et al., PRD 84 (2011) 074508

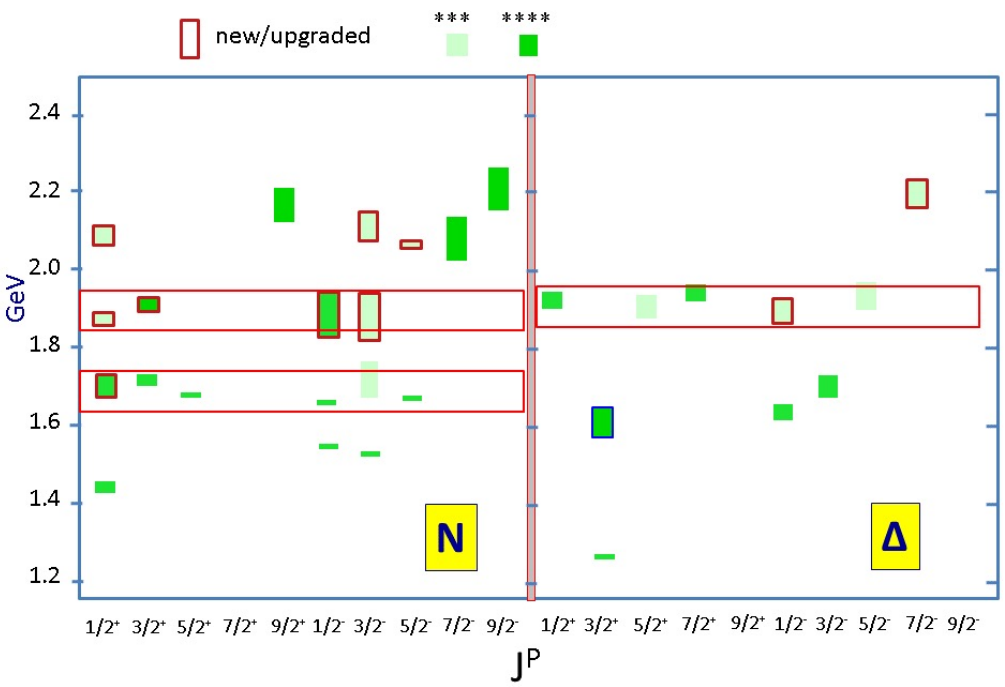


Studies of the N*-spectrum were driven by a guess for the ``missing" baryon states expected from underlying SU(6)xO(3) symmetry and supported by continuum and lattice QCD results on the N*-spectrum

Advances in the Exploration of the N* Spectrum in Photoproduction

Several new nucleon resonances were established in a global multi-channel analysis of exclusive photoproduction data

N^*/Δ^* Spectrum 2020



Nucleon resonances listed in Particle Data Group (PDG) tables

State N(mass)J^P	PDG pre 2012	PDG 2020*
N(1710)1/2+	***	****
N(1880)1/2+		***
N(1895)1/2-		****
N(1900)3/2+	**	****
N(1875)3/2-		***
N(2100)1/2+	*	***
N(2120)3/2-		***
N(2000)5/2+	*	**
N(2060)5/2-		***
Δ(1600)3/2+	***	****
Δ(1900)1/2-	**	***
Δ(2200)7/2-	*	***

Description of the exclusive electroproduction data off the proton with the same masses and hadronic decay widths as in photoproduction will validate the existence of new baryon states.

Combined studies of the CLAS $\pi^+\pi^-p$ photo-/electroproduction off proton data allow us to observe a new N'(1720)3/2+ baryon state in addition to those listed above.

Interpretation of the Structure at W~1.7 GeV in $\pi^+\pi^-$p Electroproduction

M. Ripani et al., CLAS Collaboration
Phys. Rev. Lett. 91, 022002 (2003)

..... *conventional states only, consistent with PDG 02*

——— *implementing N'(1720)3/2⁺ candidate or only conventional states with different N(1720)3/2⁺ Nππ decays than in PDG 02*

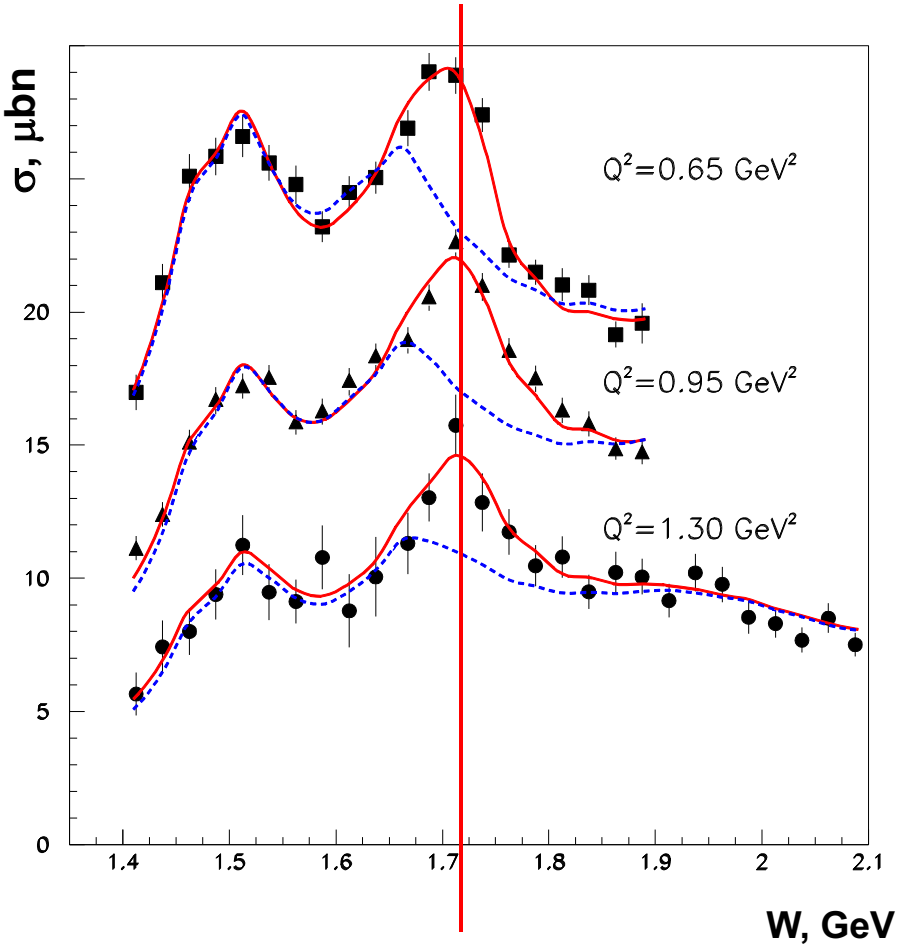
Two equally successful ways for the data description:

No new states, different than in PDG 02'
N(1720)3/2⁺ Nππ hadronic decay widths:

	$\Gamma_{tot,}$ MeV	BF(πΔ) %	BF(ρp) %
N(1720)3/2⁺ decays fit to the CLAS Nππ data	**126±14**	**64-100**	**<5**
N(1720)3/2⁺ PDG 02'	**150-300**	**<20**	**70-85**

new N'(1720)3/2⁺ and regular N(1720)3/2⁺:

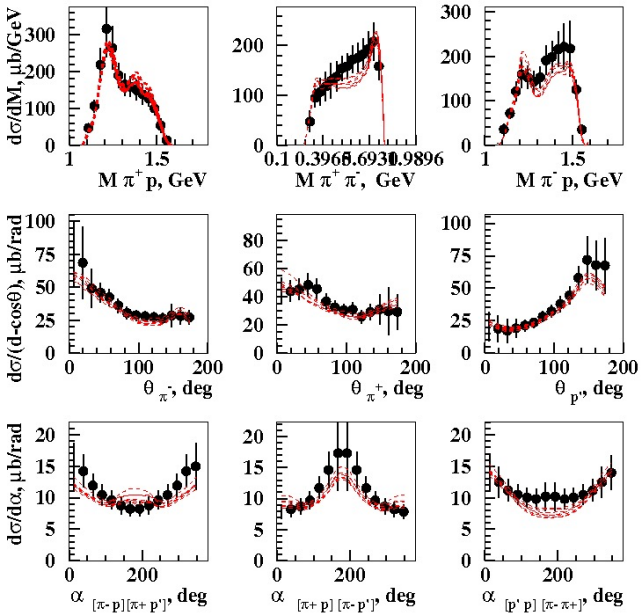
	$\Gamma_{tot,}$ MeV	BF(πΔ) %	BF(ρp) %
N'(1720)3/2⁺ New	**119±6**	**47-64**	**3-10.**
N(1720)3/2⁺ Conventional	**112±8**	**39-55**	**23-49**



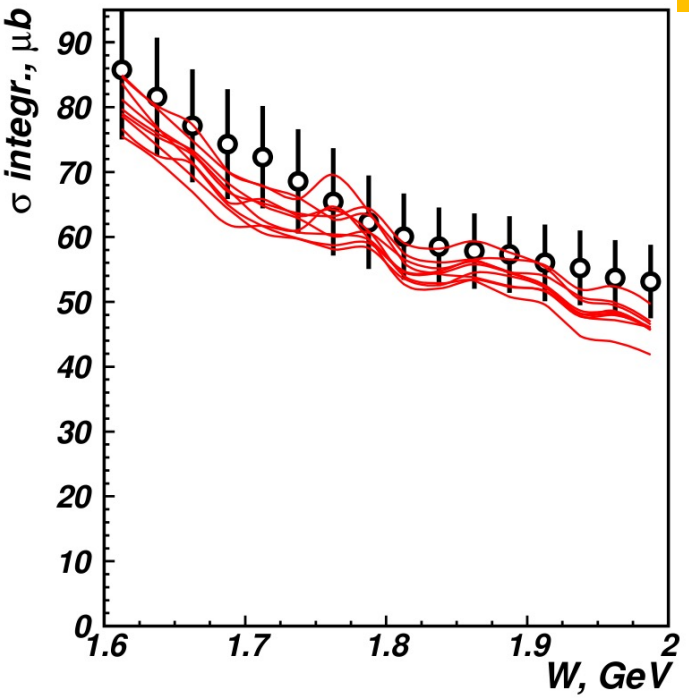
Description of the CLAS $\pi^+\pi^-p$ Photoproduction off Protons Data with/without the New State N'(1720)3/2$^+$

One-fold differential cross sections

W=1.71 GeV



Fully integrated cross sections



E.N. Golovach et al., CLAS Collaboration, Phys. Lett. B 788, 371 (2019).

Almost the same quality of description of the photoproduction data was achieved with and without the new N'(1720)3/2$^+$ state:

N(1720)3/2$^+$ and N'(1720)3/2$^+$ ⟶ 1.19 < χ^2/d.p. < 1.28

N(1720)3/2$^+$ only ⟶ 1.08 < χ^2/d.p. < 1.26

Would it be possible to describe the photo- and electroproduction data with Q^2-independent resonance masses and total and partial hadron decay widths?

Evidence for the Existence of the New State N'(1720)3/2$^+$ from Combined $\pi^+\pi^-$p Analyses in both Photo- and Electroproduction

V.I. Mokeev et al., Phys. Lett. B 805, 135457 (2020)

N(1720)3/2$^+$ hadronic decays from the CLAS data fit with conventional resonances only

	BF($\pi\Delta$), %	BF(ρp), %
electroproduction	64-100	<5
photoproduction	14-60	19-69

The contradictory BF values for N(1720)3/2$^+$ decays to the $\pi\Delta$ and ρp final states deduced from photo- and electroproduction data make it impossible to describe the data with only conventional states.

N* hadronic decays from the data fit that incorporates the new N'(1720)3/2$^+$ state

Resonance	BF($\pi\Delta$), %	BF(ρp), %
N'(1720)3/2$^+$		
electroproduction	47-64	3-10
photoproduction	46-62	4-13
N(1720)3/2$^+$		
electroproduction	39-55	23-49
photoproduction	38-53	31-46
Δ(1700)3/2$^-$		
electroproduction	77-95	3-5
photoproduction	78-93	3-6

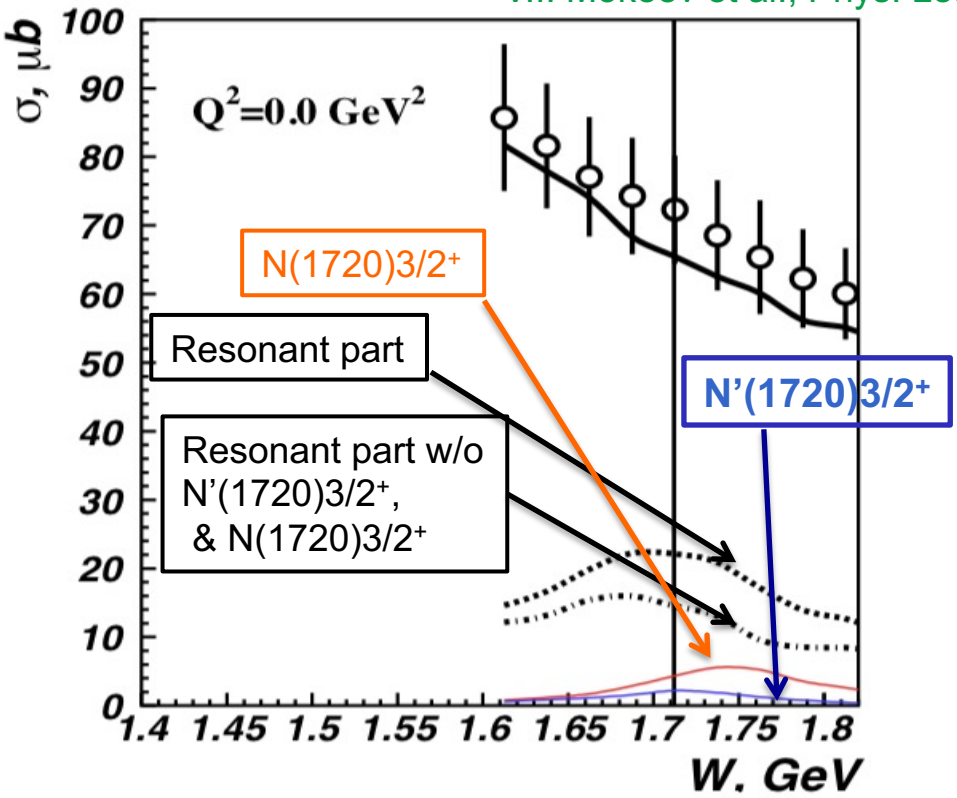
The successful description of the $\pi^+\pi^-$p photo- and electroproduction data achieved by implementing the new N'(1720)3/2$^+$ state with Q^2-independent hadronic decay widths of all resonances contributing at W~1.7 GeV provides strong evidence for the existence of the new N'(1720)3/2$^+$ state.

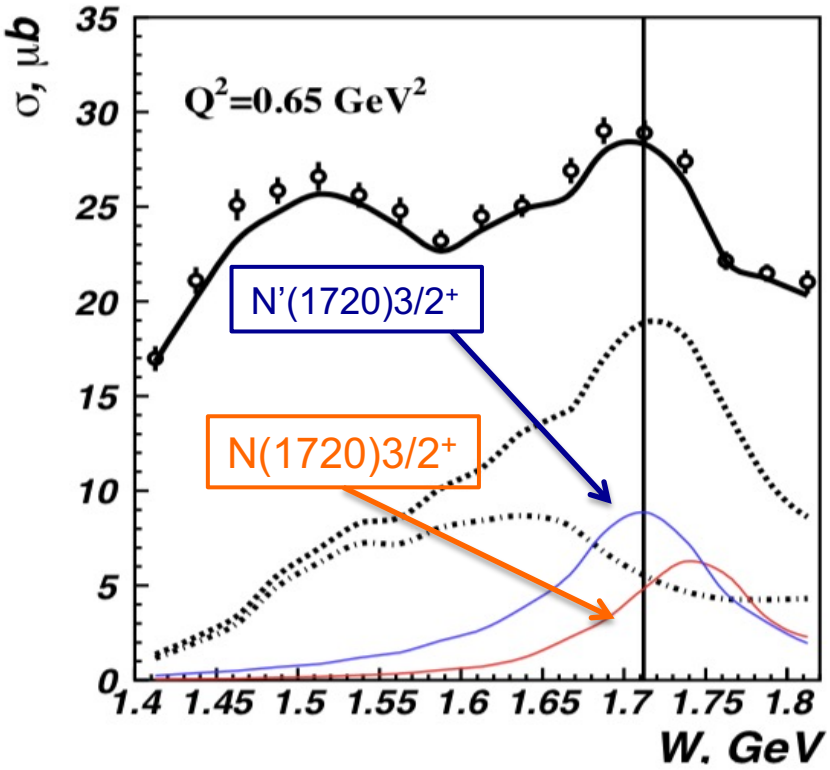
Newly Discovered N'(1720)3/2$^+$

$\pi^+\pi^-$p photoproduction

$\pi^+\pi^-$p electroproduction

V.I. Mokeev et al., Phys. Lett. B 805, 135457 (2020)

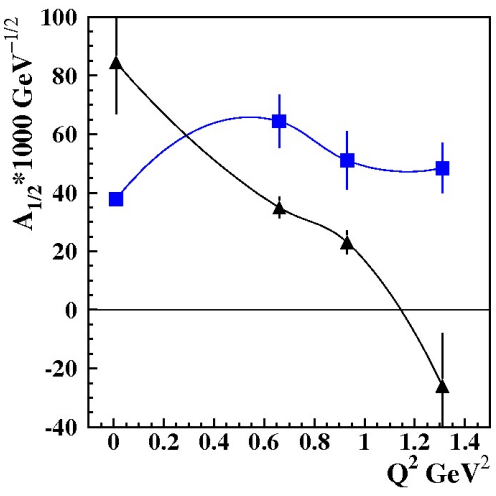


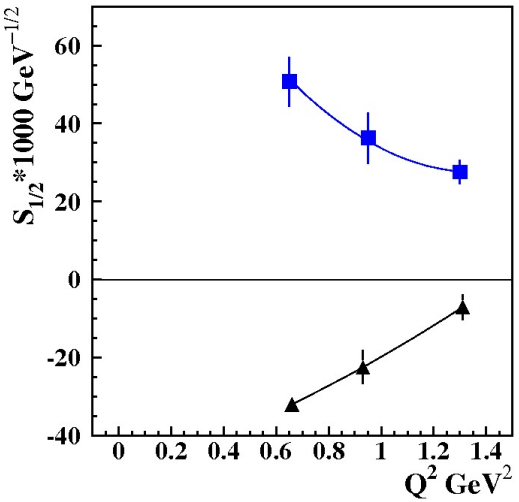


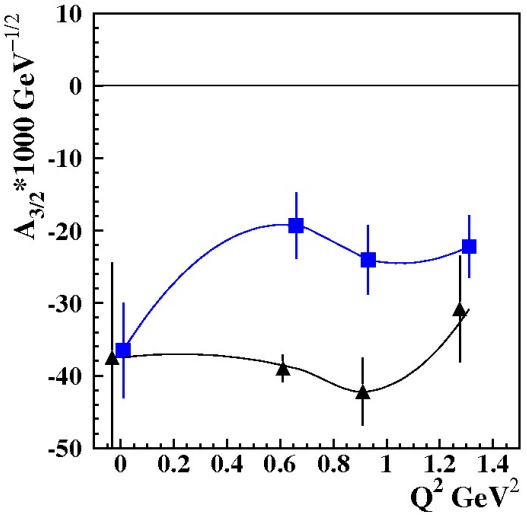
- Evidence of a new N'(1720) 3/2$^+$ resonance in the photo- and electroproduction of the $\pi^+\pi^-$p channel

The Parameters of the New N'(1720)3/2$^+$ State from the CLAS Data Fit

The photo-/electrocouplings of the N'(1720)3/2$^+$ and conventional N(1720)3/2$^+$ states







N'(1720)3/2$^+$

N(1720)3/2$^+$

Resonance	Mass, GeV	Total width, MeV
N'(1720)3/2$^+$	1.715-1.735	120±6
N(1720)3/2$^+$	1.743-1.753	112±8

- The N'(1720)3/2$^+$ is the only new resonance for which data on electroexcitation amplitudes have become available.
- Gaining insight into the ``missing" resonance structure will shed light on their peculiar structural features that have made them so elusive, as well as on the emergence of new resonances from QCD.

SU(6)-Assignment for N'(1720)3/2$^+$ and N(1720)3/2$^+$

New resonances discovered from exclusive meson photoproduction data revealed the following pattern of the high-lying resonance spectrum under approximate SU(6)xO(3) symmetry

[70,2$^+$] multiplet

S_q=3/2 N(1880)1/2$^+$ N(1900)3/2$^+$ N(2000)5/2$^+$ N(2000)7/2$^+$

$M_{avg}(S_q=3/2)$=1.96 GeV $\Delta M(S_q=3/2)$ = 0.075 GeV

S_q=1/2 N'(1720)3/2$^+$ N(1860)5/2$^+$

$\Delta M(S_q=3/2\text{-}S_q=1/2)[70,2^+] = \Delta M(S_q=3/2\text{-}S_q=1/2)[70,1^-]$ = 0.16 GeV

$M_{avg}(S_q=1/2) = M_{avg}(S_q=3/2) - \Delta M(S_q=3/2\text{-}S_q=1/2)[70,2^+]$ = 1.96-0.16 = 1.80 GeV
$M(N'(1720)3/2^{+)} = M_{avg}(S_q=1/2) - \Delta M(S_q=3/2)$ = 1.80-0.075 =1.73 GeV consistent with the mass of N'(1720)3/2$^+$ inferred from the $\pi^+\pi^-$p photo-/electroproduction data

N'(1720)3/2$^+$: three constituent quarks of total spin S_q=1/2 and orbital momentum L=2 in [70,2$^+$] multiplet, double orbital excitation

N(1720)3/2$^+$: three constituent quarks of total spin S_q=1/2 and orbital momentum L=2 in [56,2$^+$] multiplet

Quark model evaluation of γ_vpN* electrocouplings under the aforementioned assignments for N(1720)3/2$^+$ and N'(1720)3/2$^+$ states will shed light on peculiar features in N'(1720)3/2$^+$ structure

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 up to 10 GeV^2 for most excited proton states through analyzing major meson electroproduction channels from CLAS/CLAS12 data.
- Explore hadron mass emergence (EHM) and elucidate the trace anomaly by mapping out the dynamical quark mass in the transition from almost massless pQCD quarks to fully dressed constituent quarks.

An important part of the efforts on the exploration of strong QCD from data of the experiments with the electromagnetic probes:

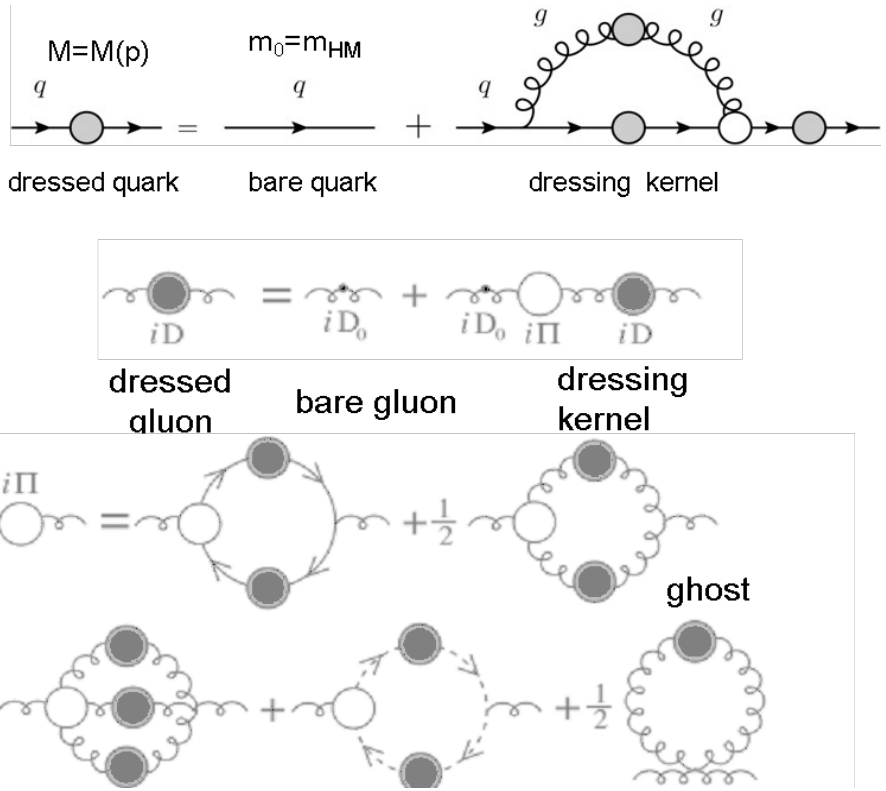
1. S.J. Brodsky et al., Int. J. Mod. Phys. E29, 203006 (2020).
2. C.D. Roberts, Symmetry 12, 1468 (2020).
3. M. Barabanov et al., Prog. Part. Nucl. Phys. 103835 (2021).

A unique source of information on many facets of strong QCD in generating excited nucleon states with different structural features:

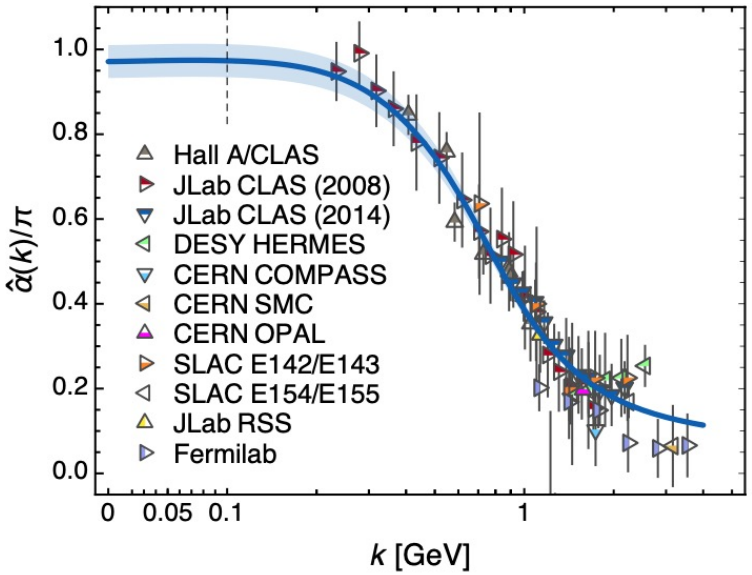
1. I.G. Aznauryan and V.D. Burkert, Prog. Part. Nucl. Phys. 67, 1 (2012).
2. D.S. Carman, K. Joo, and V.I. Mokeev, Few Body Syst. 61, 29 (2020).
3. V.D. Burkert and C.D. Roberts, Rev. Mod. Phys. 91, 011003 (2019).

Basics for Insight into EHM: Continuum and Lattice QCD Synergy

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



QCD Running Coupling α(k)
Zh-F. Cui et al., Chin. Phys. C 44, 083102 (2020)

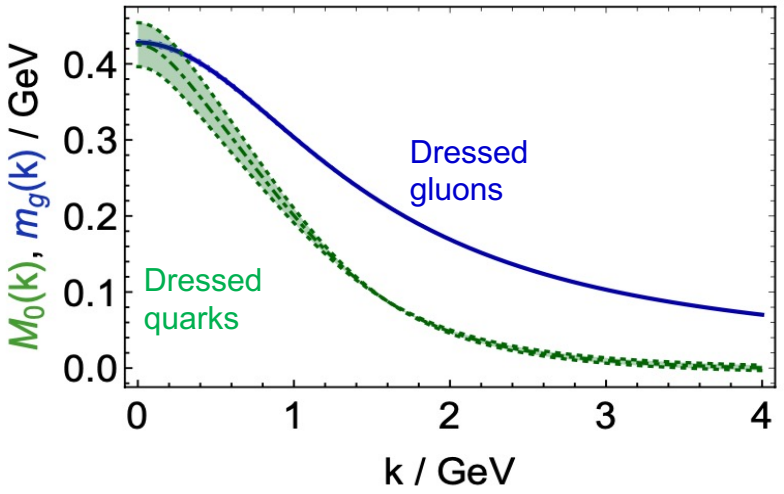


In the regime of the QCD running coupling comparable with unity, the dressed quarks and gluons with distance (momentum) dependent masses emerge from QCD, as follows from the equation of the motion for the depicted QCD fields.

Basics for Insight into EHM: Continuum and Lattice QCD Synergy

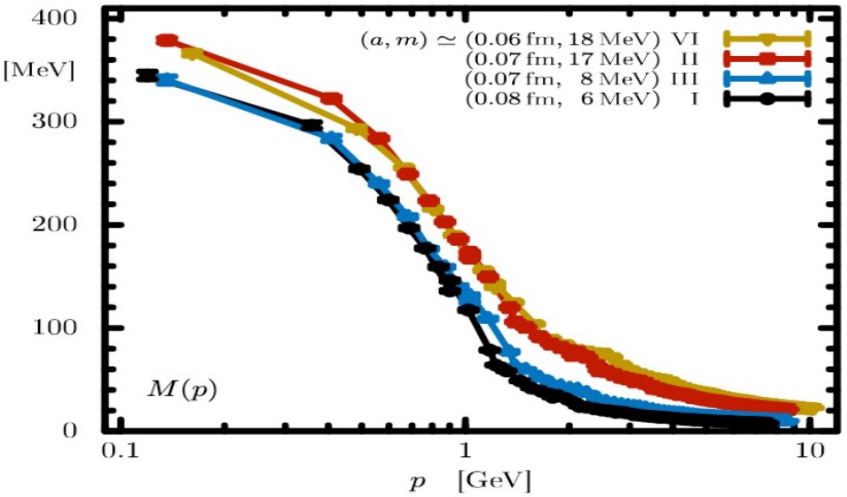
- Dressed quark/gluon masses converge at the complete QCD mass scale of 0.43(1) GeV - value impacted by Higgs mechanism.
- Continuum QCD predictions are confirmed by LQCD simulations.
- Insight into the dressed quark mass function from data on hadron structure represents a challenge for experimental hadron physics.

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

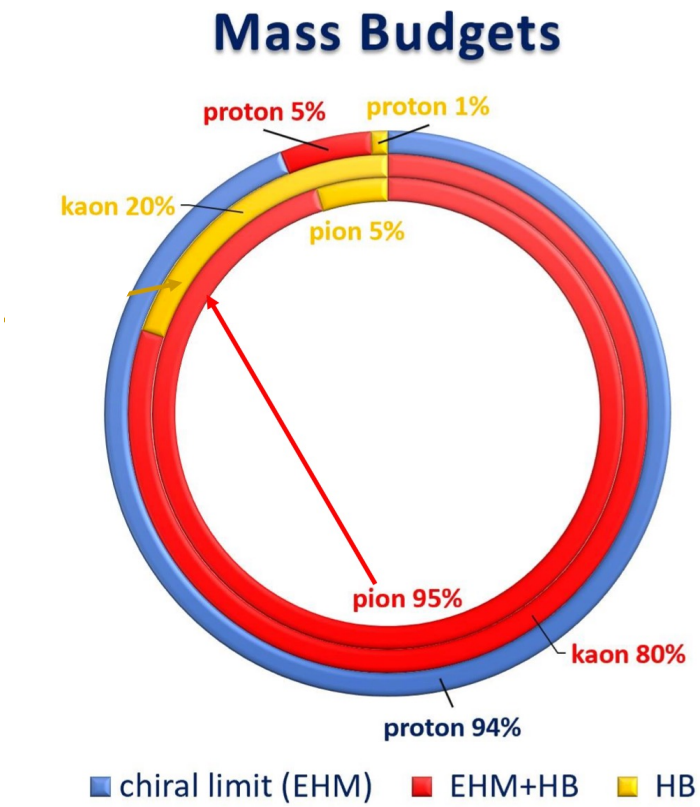


Inferred from QCD Lagrangian with only the Λ_{QCD} parameter

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



Insight into EHM from Data on N/N* Structure



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

- Consistent results on the momentum dependence of the dressed quark mass function from independent studies of the pseudoscalar mesons and the ground and excited state nucleon structure are of particular importance for the validation of insight into EHM.

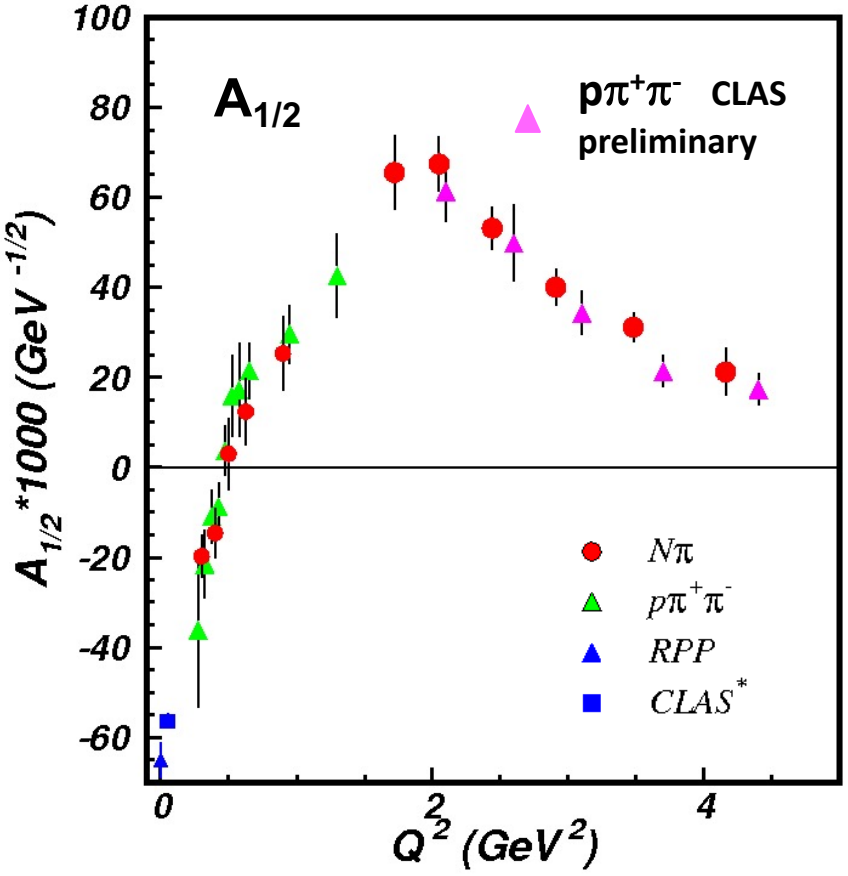
Nucleon Resonance Electrocouplings from Data On Exclusive Meson Electroproduction with CLAS

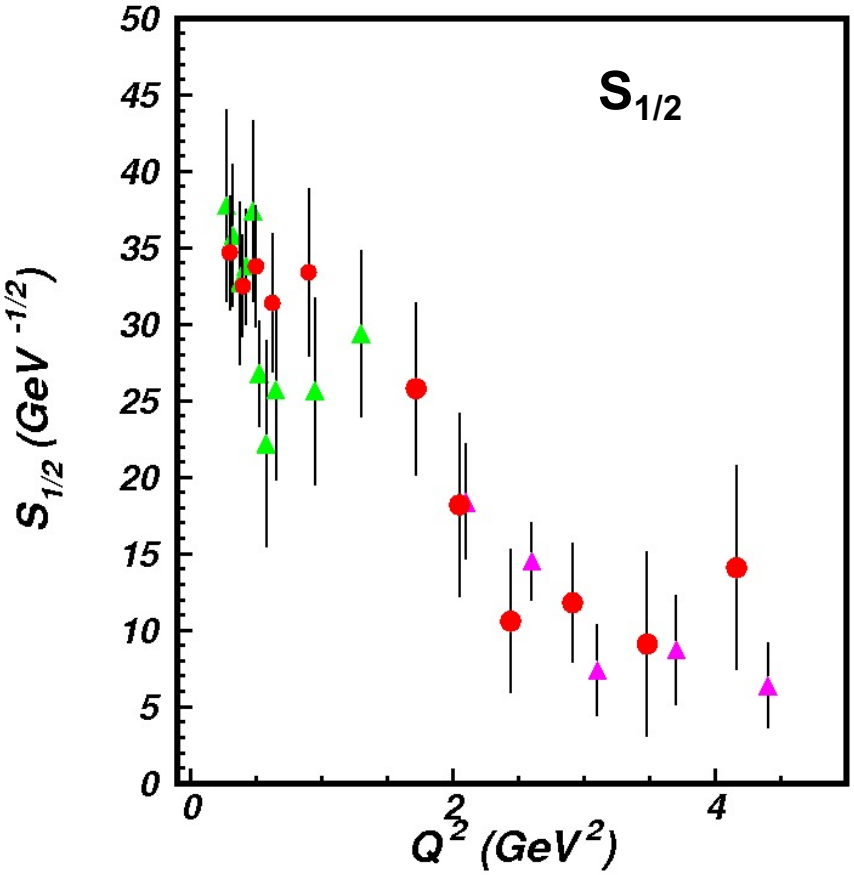
Exclusive meson electroproduction channels	Excited proton states	Q^2-ranges for extracted $\gamma_v pN^*$ electrocouplings, GeV^2
$\pi^0 p$, $\pi^+ n$	$\Delta(1232)3/2^+$ $N(1440)1/2^+$,$N(1520)3/2^-$, $N(1535)1/2^-$	0.16-6.0 0.30-4.16
$\pi^+ n$	$N(1675)5/2^-$, $N(1680)5/2^+$ $N(1710)1/2^+$	1.6-4.5
ηp	$N(1535)1/2^-$	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) have become available in a broad range of $Q^2<5.0$ GeV^2
- In the mass range of W<1.6 GeV the $\gamma_v pN^*$ electrocoupling were obtained from independent studies of πN, ηp, and $\pi^+\pi^- p$ electroproduction

Recent results can be found in: A.N. Hiller Blin et al, PRC100, 035201 (2019)

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



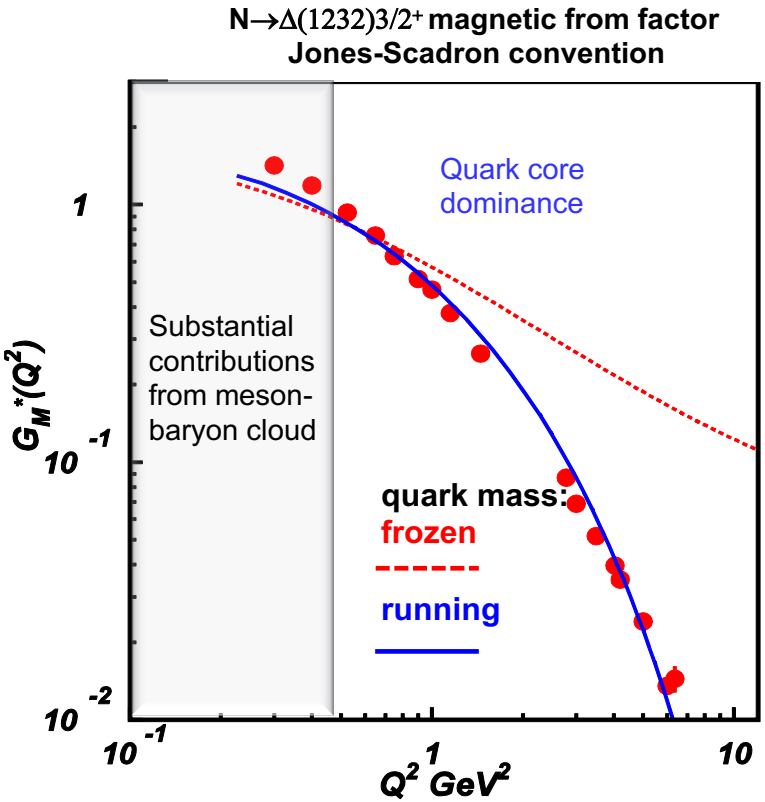


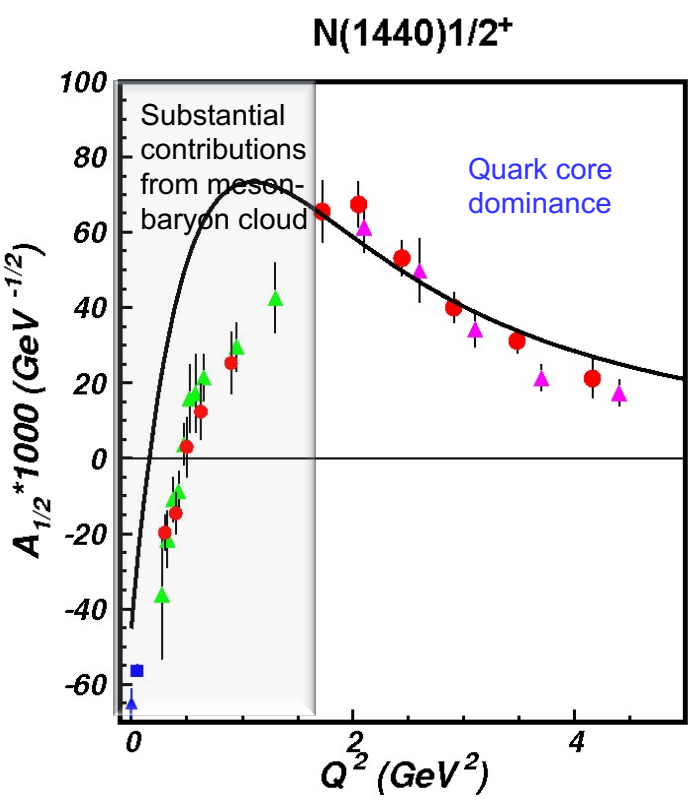
Consistent results on N(1440)1/2$^+$ electrocouplings from independent studies of two major πN and $\pi^+\pi^-$p electroproduction channels with different non-resonant contributions allow us to evaluate the systematic uncertainties of these quantities in a nearly model-independent way.

Insight into EHM From Resonance Electrocouplings

Dyson-Schwinger Equations (DSE):

- **J. Segovia et al., PRL 115, 171801 (2015)**
- **J. Segovia et al., FBS 55, 1185 (2014)**

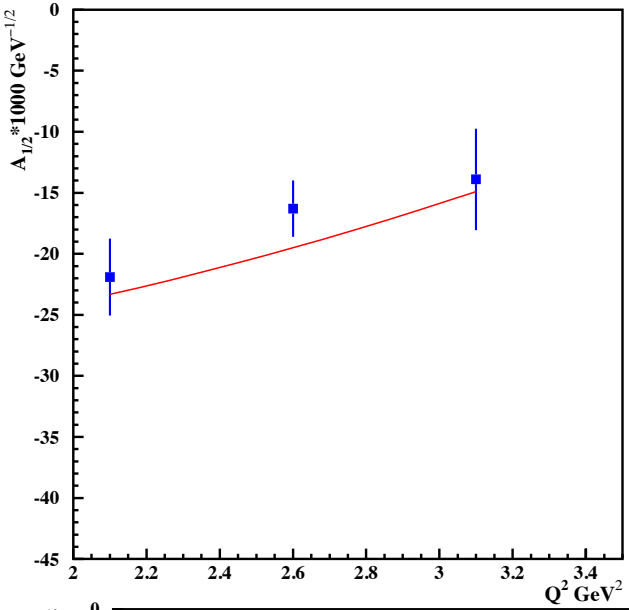


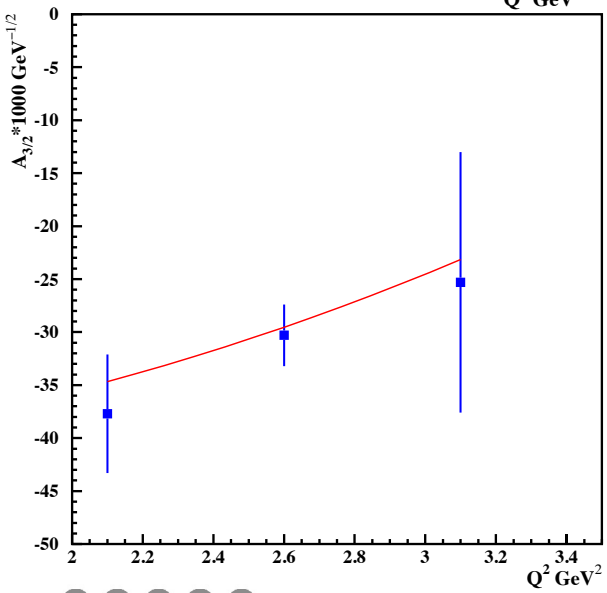


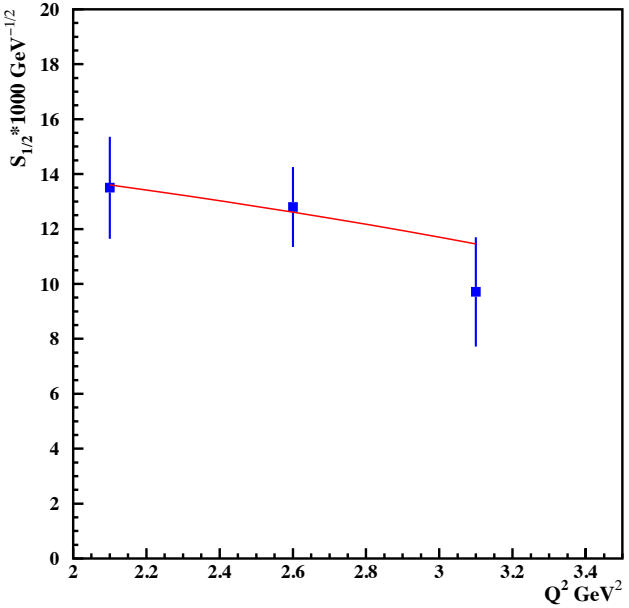
Good data description at Q^2>2.0 GeV^2 achieved with <u>the same dressed quark mass function</u> for the ground and two excited nucleon states of distinctively different structure validates the continuum QCD results on the momentum dependence of the dressed quark mass. γ_vpN* electrocoupling data offer access to the strong QCD dynamics underlying hadron mass generation.

One of the most important achievements in hadron physics of the last decade in synergistic efforts between experimentalists, phenomenologists, and theorists

$\Delta(1600)3/2^+$ Electrocouplings: Continuum QCD Predictions vs. CLAS Data





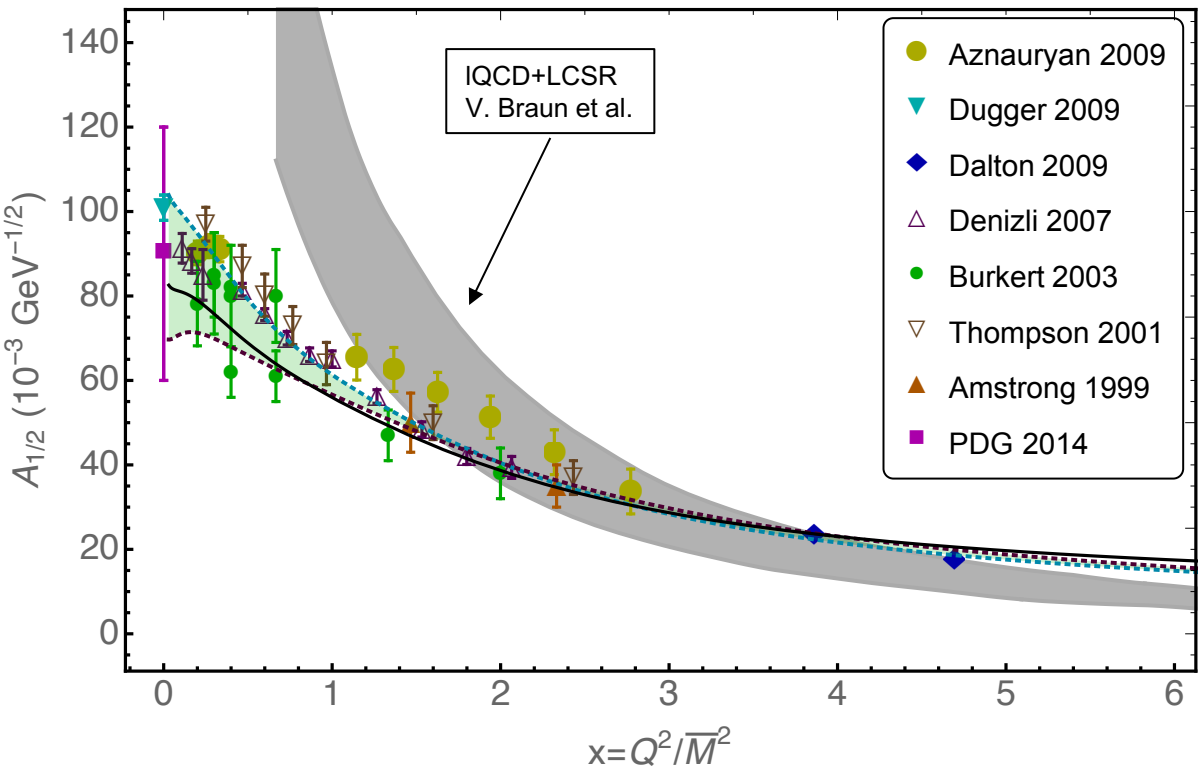


continuum QCD predictions w/o adjustable parameters, Ya Lu et al., Phys. Rev. D100, 034001 (2019)

preliminary results on $\Delta(1600)3/2^+$ electrocouplings from the CLAS $\pi^+\pi^-p$ electroproduction data

CLAS results are consistent with the continuum QCD predications solidifying evidence for reliable insight into the emergence of hadron mass

Toward Exploration of EHM from Orbital Nucleon Excitations



Continuum QCD Breakthrough: $N(1535)1/2^-$ electrocouplings computed under a traceable connection to the QCD Lagrangian (green area). C.D Roberts et al., private communication

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

Studies of electroexcitation amplitudes for the resonances in the second region suggest the universality of the dressed quark mass function for the ground and different excited states of the nucleon, including the first spin-isospin flip, the first radial, and the first orbital (L_{3q}=1) excitations.

Emergence of Hadron Mass and Quark-Gluon Confinement

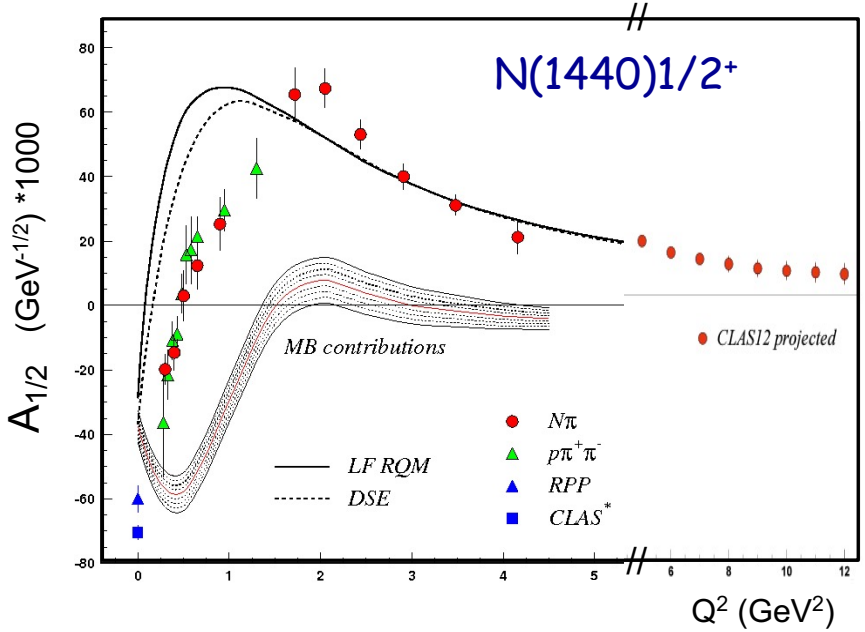
N* electroexcitation studies at JLab during and after 12 GeV era will address the critical questions:

How is >98% of visible mass generated?

How does confinement emerge from QCD and how is it related to Dynamical Chiral Symmetry Breaking?

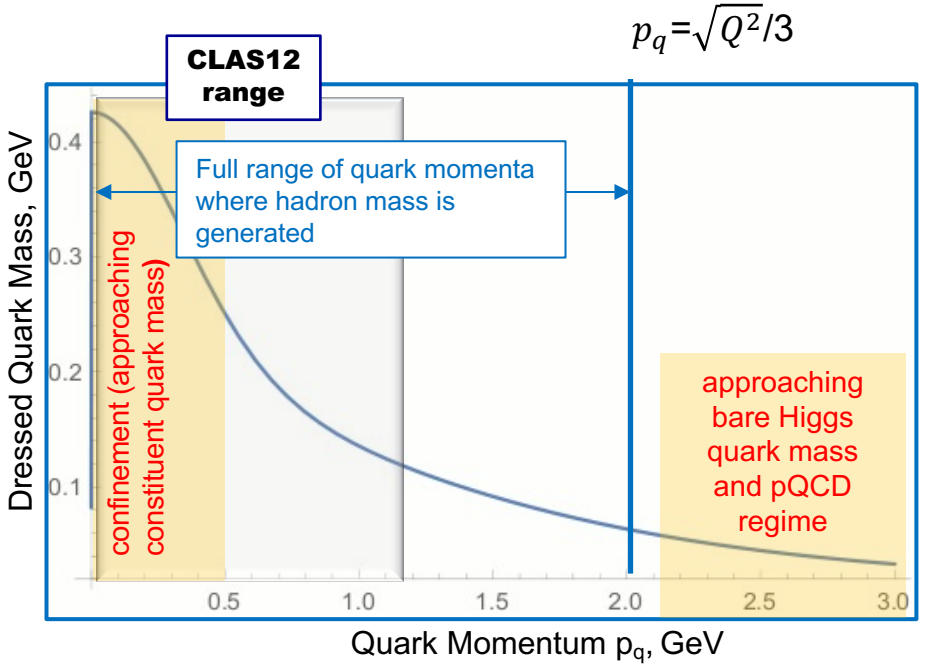
(S.J, Brodsky et al., Int. J. Mod. Phys. Rev. E29, 2030006 (2020))

Mapping-out quark mass function from the results on $\gamma_v pN^*$ electrocouplings of spin-isospin flip, radial, and orbital excited nucleon resonances at $5<Q^2<36$ GeV^2 is needed to explore the full range of distances where the dominant part of hadron mass is generated



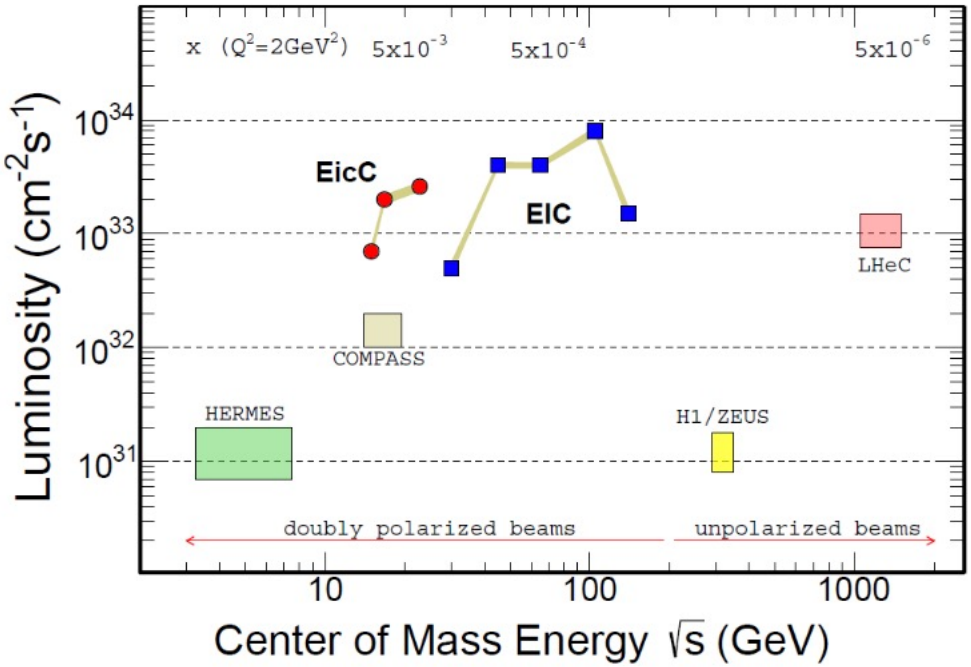
CLAS results vs. theory expectations with running quark mass

Access to the dressed quark/hadron mass generation



Studies of $\gamma_v pN^*$ Electrocouplings at $Q^2 > 10$ GeV^2

Energy and luminosity increase up to $>10^{36}$ cm^{-2}s^{-1} are needed in order to obtain information on the $\gamma_v pN^*$ electrocouplings at $Q^2>10$ GeV^2, allowing us to map out the momentum dependence of the dressed quark mass within the entire range of distances where the dominant part of hadron mass is generated



Both EicC and EIC would need much higher (but likely unfeasible) luminosity

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

- Beam energy at fixed target: 24 GeV
- Nearly 4π coverage
- High luminosity

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

Conclusions and Outlook

- **Several long-awaited new, so-called ``missing" nucleon resonances, have been discovered from global analyses of exclusive meson photo- and hadroproduction data with decisive impact from the KY photoproduction channels measured with CLAS.**

- **New N'(1720)3/2$^+$ resonance has been observed in combined studies of $\pi^+\pi^-$p photo- and electroproduction data. New N'(1720)3/2$^+$ state is the only new resonance for which the results on Q^2-evolution of γ_vpN* electrocouplings have become available. Analyses of the results on the new resonance electrocouplings in collaborative efforts with hadron structure theory will shed light on particular features of the ``missing" resonance structure that have made them so elusive for detection.**

- **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 N* in the mass range <2.0 GeV and at Q^2<5.0 GeV^2 (CLAS) and at Q^2<10 GeV^2 (CLAS12).**

- **A good description of CLAS results on Δ(1232)3/2$^+$, N(1440)1/2$^+$, N(1535)1/2$^-$ and Δ(1600)3/2$^+$, electroexcitation amplitudes *achieved with the same dressed quark mass function* as used previously in successful evaluations of the elastic ground nucleon and pion form factors, pion PDF validate insight to the dynamics that underlie the emergence of hadron mass. Studies of the Δ(1600)3/2$^+$ electrocouplings are in progress with the expected results in the first half of 2022.**

Conclusions and Outlook

- **CLAS12 is the only facility in the world capable of obtaining the electrocouplings of all prominent N* states at still unexplored ranges of highest photon virtualities from 5.0 to 12 GeV^2 from Nπ, $\pi^+\pi^-$p, and KY electroproduction allowing us to map out the dressed quark mass function at quark momenta < 1.3 GeV, addressing the most challenging problems of the Standard Model on the nature of >98% of hadron mass and of quark-gluon confinement.**

- **Extension of the results on γ_vpN* electrocouplings into the Q^2 range from 10 GeV^2 to 36 GeV^2 from the measurements at the future facilities with luminosity >10^{36} cm^{-2}s^{-1} and with detector of nearly 4π acceptance will provide information on dressed quark mass function within full range of distances where the transition from quark-gluon confinement to pQCD regime is expected.**

- **Studies of γ_vpN* electrocouplings and inclusive structure functions in the Q^2 range from 10 GeV^2 to 36 GeV^2 motivate extension of experiments at JLab beyond 12 GeV era paving a way to explore the emergence of hadron mass and structure from QCD.**