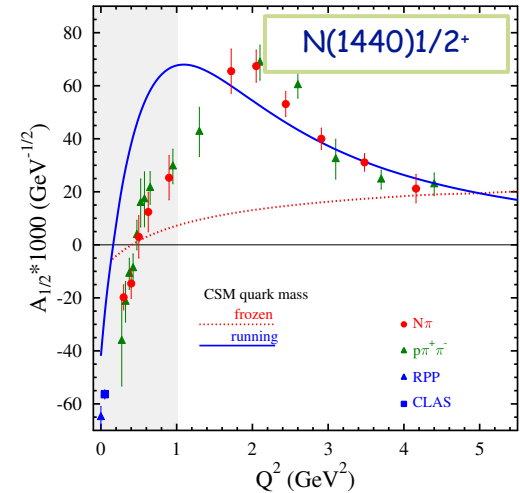
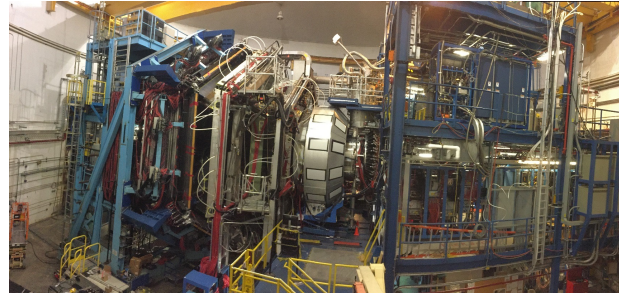
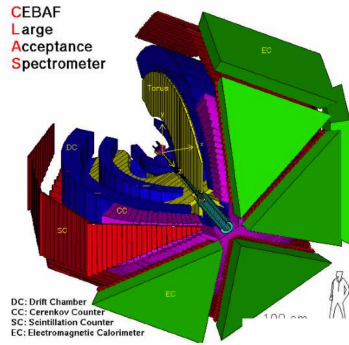


# Nucleon Resonance Electrocouplings and the Emergence of Hadron Mass



- Theory advances in understanding of EHM from QCD
- Complementarity in gaining insight into EHM from the experimental results on pion, kaon,  $N/N^*$  structure
- $\gamma_V p N^*$  electrocouplings from the data of JLab 6 GeV era
- Shedding light on EHM from the CLAS/Hall A/C  $\gamma_V p N^*$  electrocouplings
- Extending insight into EHM from  $N^*$  electroexcitation studies with CLAS12 and beyond



V.I. Mokeev, Jefferson Lab  
(CLAS Collaboration)



Baryons 22 International Conference on the Structure of Baryons



# N\* Structure in Experiments of 6 GeV Era at JLab

The experimental program on the studies of N\* structure in exclusive meson photo-/electroproduction with CLAS/CLAS12 as well as with the spectrometers in Halls A/C seeks to determine:

- $\gamma_{\nu}pN^*$  electrocouplings at photon virtualities  $Q^2$  up to  $10 \text{ GeV}^2$  for most excited proton states through analyzing the major meson electroproduction channels
- Explore hadron mass emergence (EHM) 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 (sQCD) from the experimental data with 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 sQCD in generating excited nucleon states with different structural features:**

1. V.I. Mokeev and D.S. Carman, Few Body Syst. 63, 59 (2022)
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)



# How do the Ground/Excited Nucleon Masses Emerge?

## Composition of the Nucleon Mass:

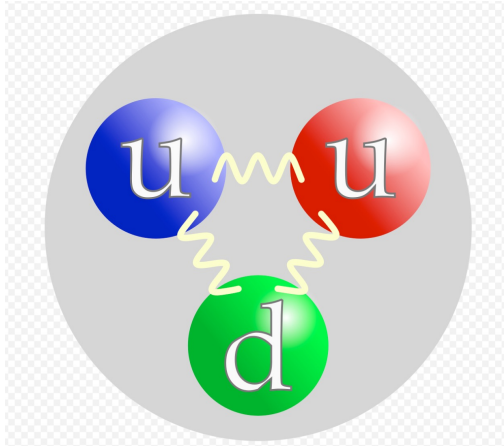
$M_p$ , MeV (PDG20)

938.2720813  
 $\pm 0.0000058$

Sum of bare quark  
masses, MeV

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

proton



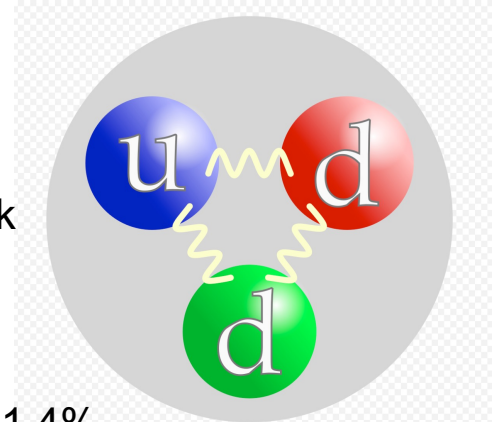
$M_n$ , MeV (PDG20)

939.5654133  
 $\pm 0.0000058$

Sum of bare quark  
masses, MeV

$4.67 + 4.67 + 2.16$   
 $= 11.50_{-0.60}^{+1.45}$  or  $< 1.4\%$

neutron

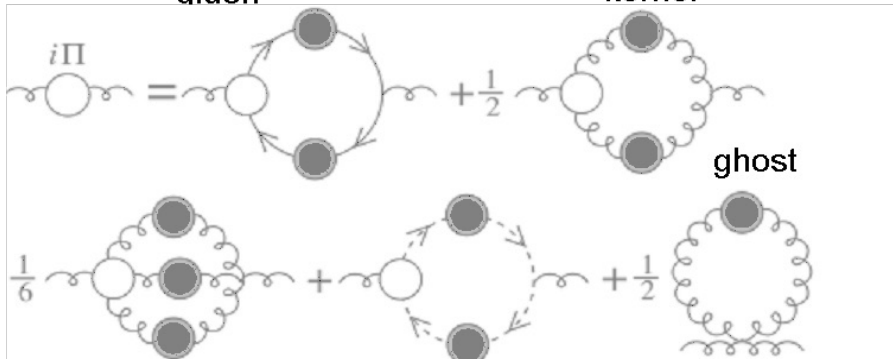
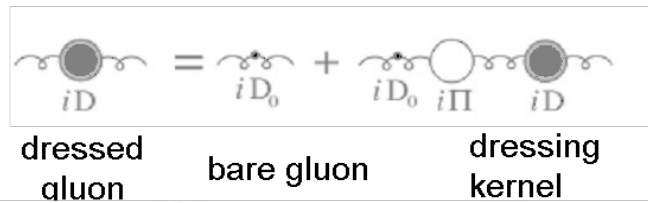
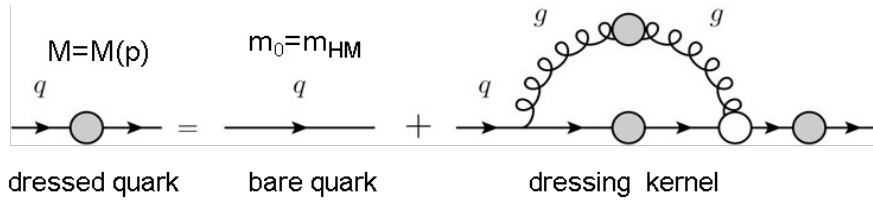


- **Higgs mechanism generates the masses of bare quarks.**
- **Dominant part of nucleon mass is generated in processes other than the Higgs mechanism.**

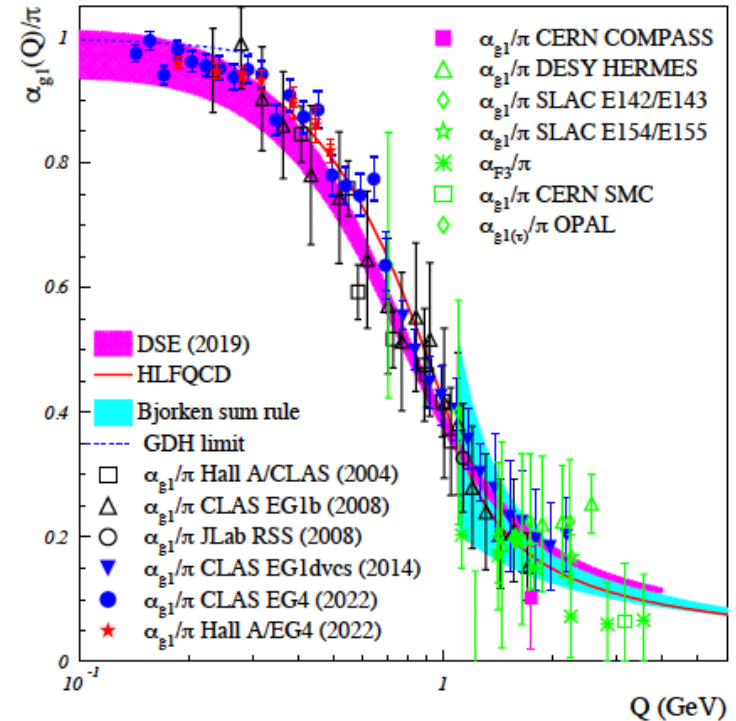
**Studies of nucleon resonance electroexcitation within a broad range of  $Q^2$  shed light on the emergence of the dominant part of hadron mass in the transition from the perturbative to quark-gluon confinement regimes of the strong interaction.**

# 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)



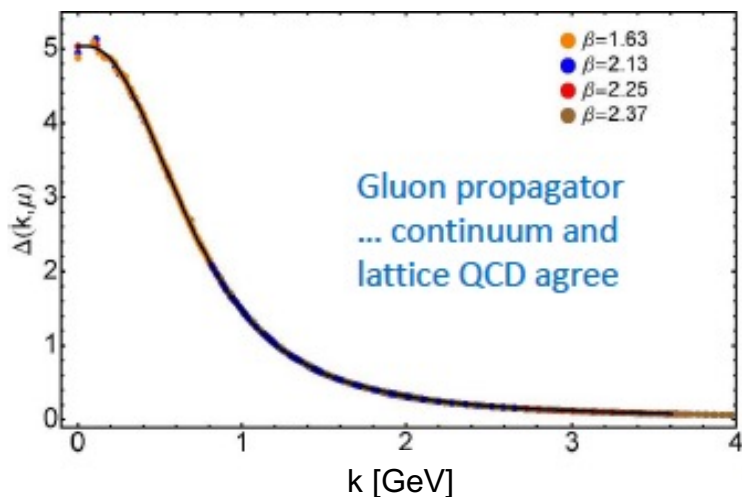
## QCD Running Coupling $\alpha(k)$ Zh-F. Cui et al., Chin. Phys. C44, 083102 (2020) A. Deur et al., Particles 5, 171 (2022)



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

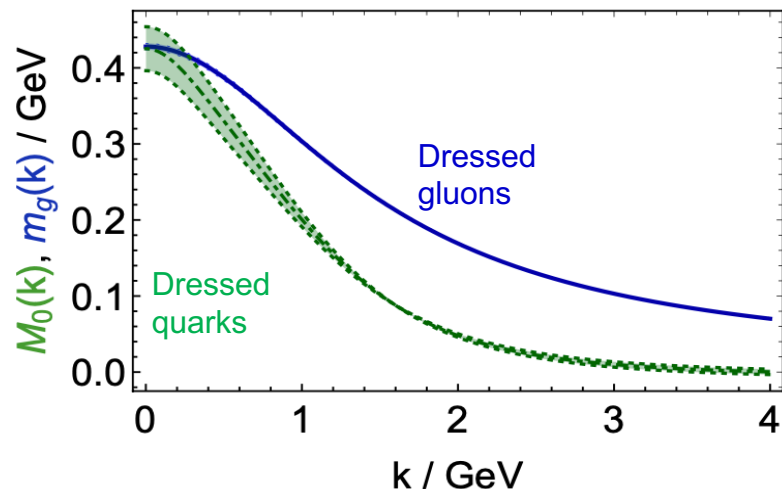
# Basics for Insight into EHM: Continuum and Lattice QCD Synergy

- Dressed quark/gluon masses converge at the complete QCD mass scale of 0.43(1) GeV
- Express the fundamental feature: emergence of the quark and gluon masses even in the case of massless quarks in chiral limit and massless QCD gluons
- Continuum QCD results are confirmed by LQCD



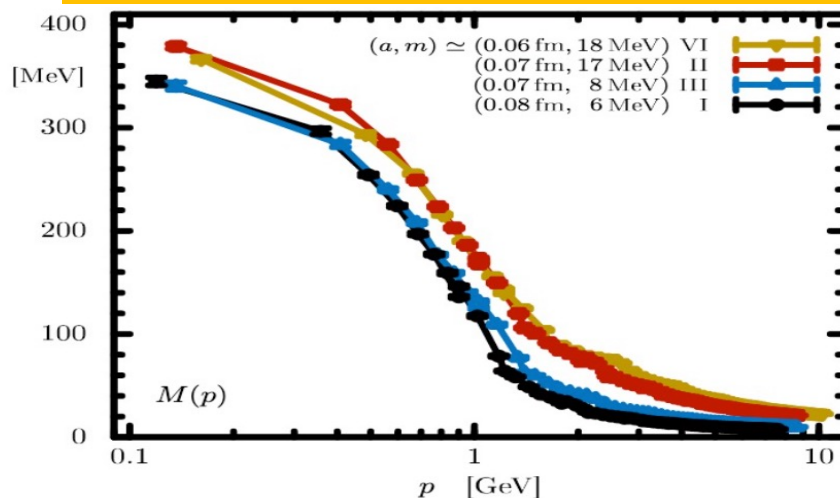
- Insight into dressed quark mass function from data on hadron structure represents a challenge for experimental hadron physics

**Dressed Quark/Gluon Masses (continuum QCD)**  
C.D. Roberts, Symmetry 12, 1468 (2020), AAPS Bull 31, 6 (2021)



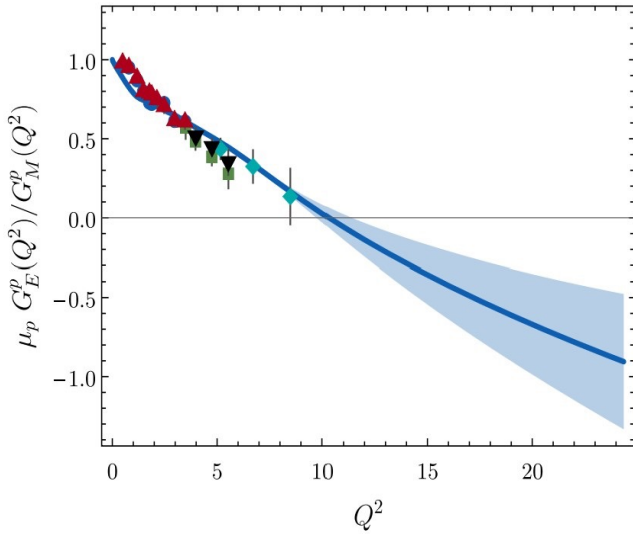
Inferred from QCD Lagrangian with only the  $\Lambda_{\text{QCD}}$  parameter

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

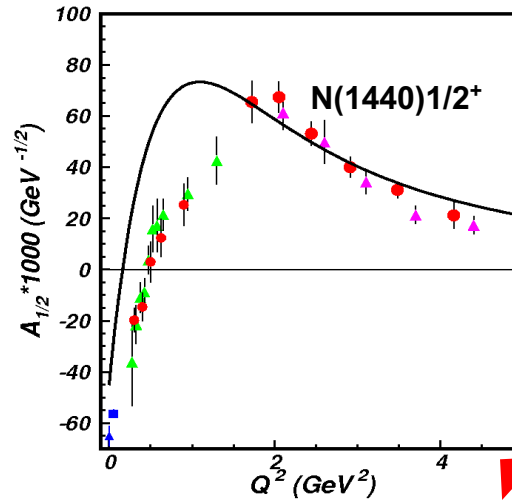


# EHM from Global Hadron Structure Analysis

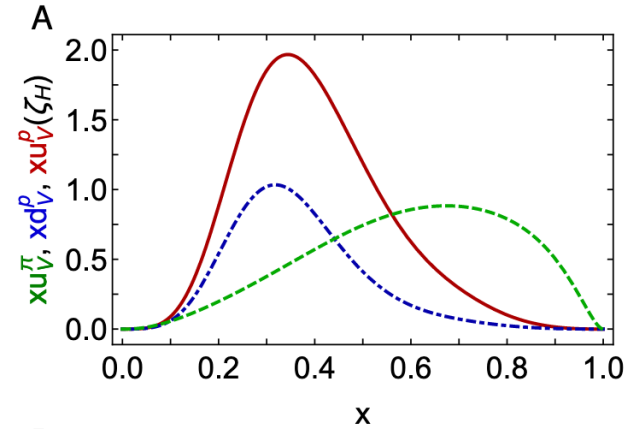
Nucleon Elastic FF



$\gamma_{\nu p N^*}$  Electrocouplings

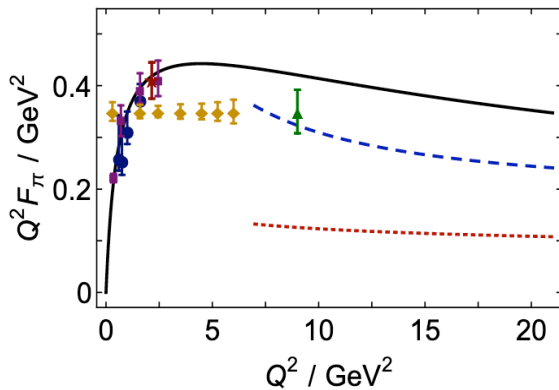


Proton and pion PDF for valence quarks

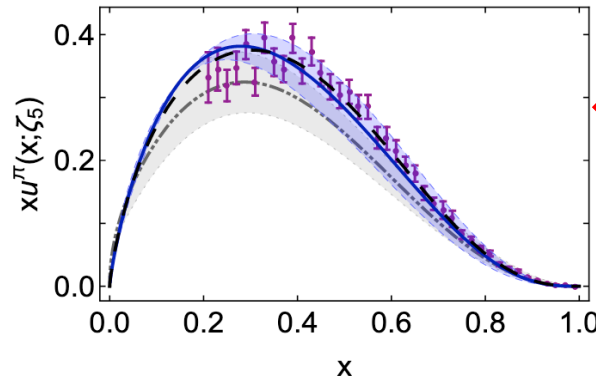


New data from studies of D-Y at AMBER and Sullivan processes at JLab

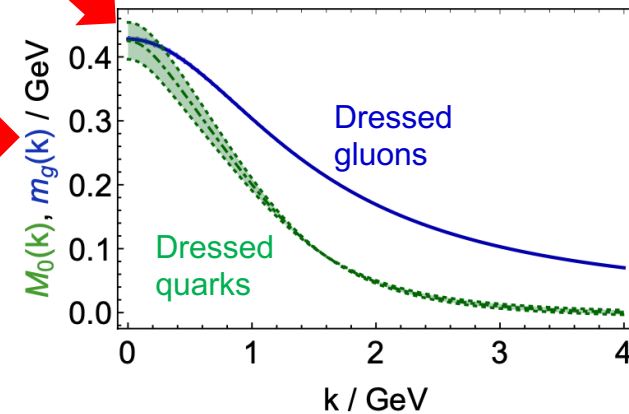
Pion Elastic FF



Pion PDF



Dressed Quark/Gluon Running Masses



- EHM is not expressed simply in the dressed-quark mass function. Instead, the dressed-quark mass function is one of the three pillars of EHM = gluon mass + QCD effective charge + quark mass. These pillars support an enormous array of predictions that go far beyond the quark model and far beyond what lattice QCD will be able to deliver in the foreseeable future.

## Insight into EHM from the Data on Pion/Kaon Structure

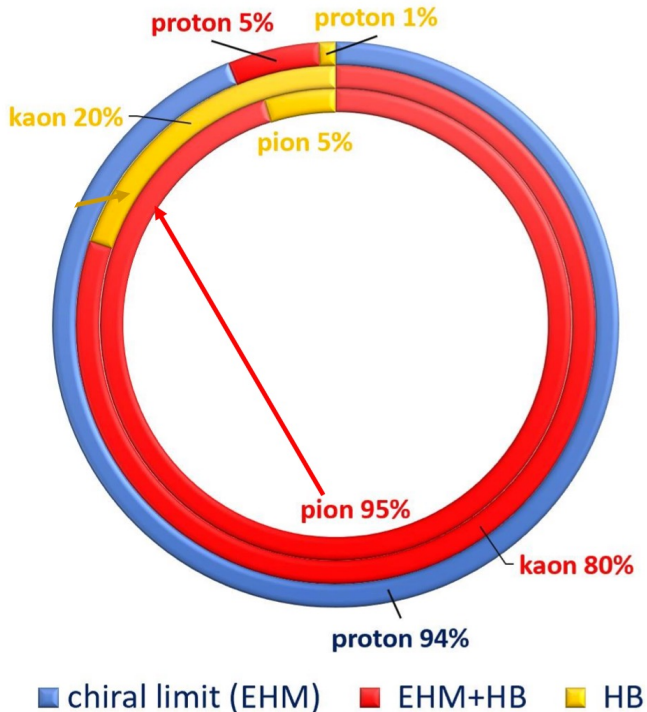
- The model, frame, and renormalization scheme/scale independent Goldberger-Treiman relations connect the momentum dependence of the dressed quark mass to the pion/kaon Bethe-Salpeter amplitudes, making the studies of pion and kaon structure a promising way to map out the momentum dependence of the dressed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

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

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

# Insight into EHM from the Data on N/N\* Structure

## Mass Budgets



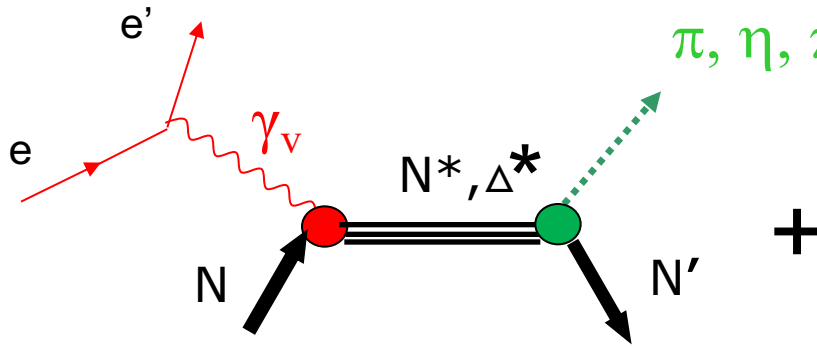
- Studies of  $\pi/K$  structure elucidate the interference between emergent and Higgs mechanisms in EHM
- Studies of ground/excited state nucleon structure allow us to explore the dressed quark mass function in a different environment where the sum of dressed quark masses is the dominant contribution to the physical masses of these states, offering insight into emergent mechanisms

- The successful description of the  $\pi/K$  elastic FF and PDF, nucleon elastic/axial FFs, and the  $\gamma_{\nu p N^*}$  electrocouplings of prominent nucleon resonances of different structure achieved with the *same* dressed quark mass function is of particular importance for the validation of insight into EHM.

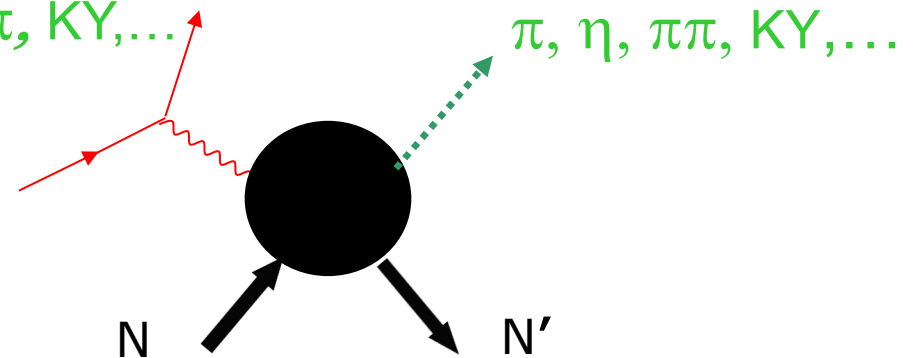


# $N^*$ Photo-/Electroexcitation Amplitudes ( $\gamma_{r,v}pN^*$ Photo-/Electrocouplings) and their Extraction from Exclusive Photo-/Electroproduction Data

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:

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

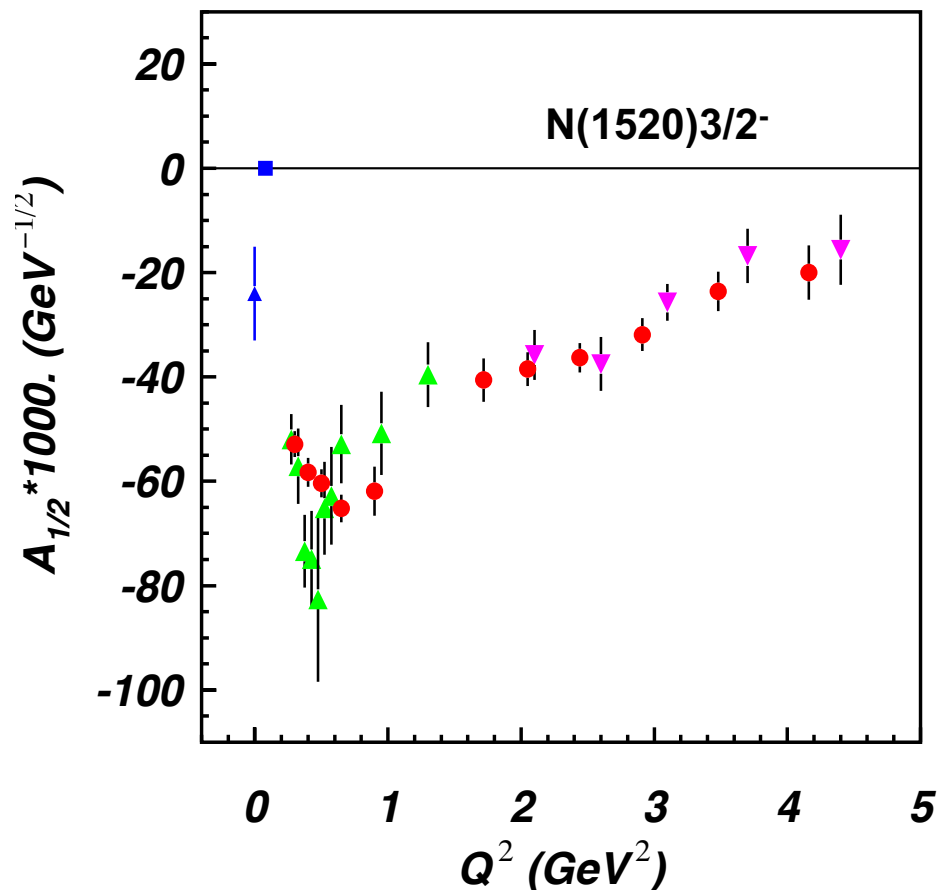
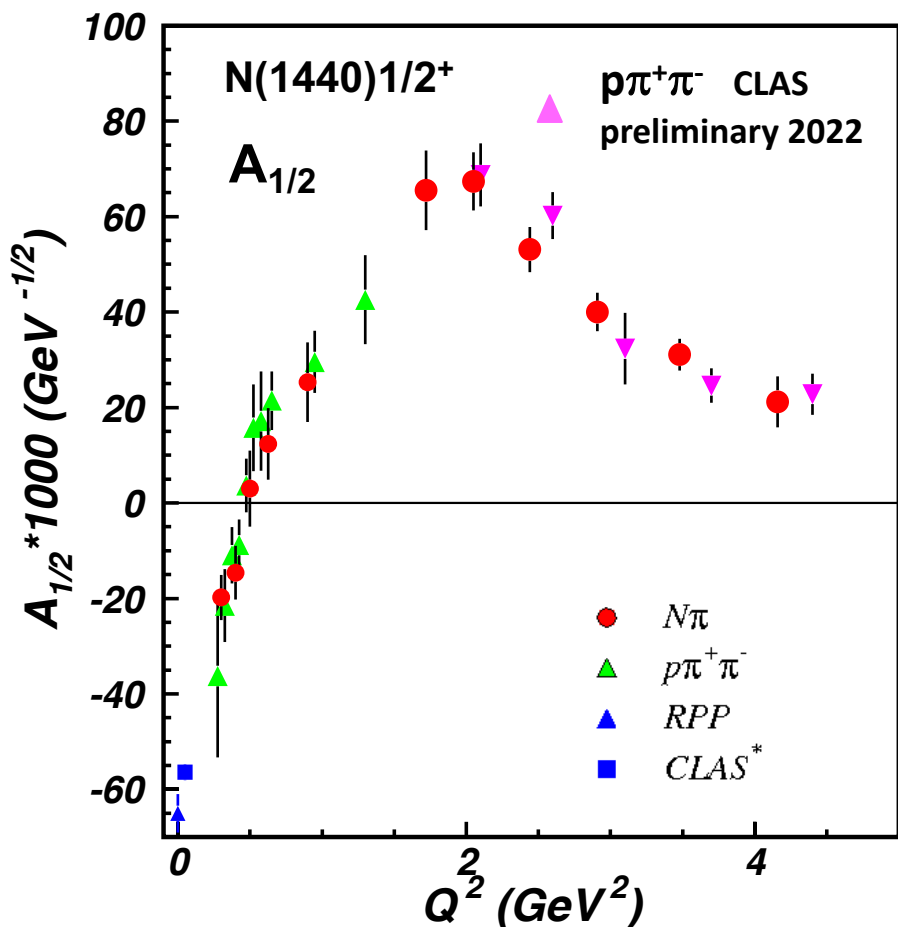
- Consistent results on  $\gamma_{r,v}pN^*$  photo-/electrocouplings from different meson photo-/electro-production channels allow us to validate reliable extraction of these quantities.

# Nucleon Resonance Electrocouplings from Data On Exclusive Meson Electroproduction of 6 GeV Era at JLab

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

- The  $\gamma_{\nu}pN^*$  electrocouplings have become available from analysis of CLAS data for most excited states of the nucleon in the mass range  $<1.8 \text{ GeV}$  and in a broad range of  $Q^2 < 5 \text{ GeV}^2$ .
- The experiments in Halls A/C extended the results on the  $\gamma_{\nu}pN^*$  electrocouplings of  $\Delta(1232)3/2^+$  and  $N(1535)1/2^-$  for  $Q^2 < 7.5 \text{ GeV}^2$
- The recent results can be found in: [A.N. Hiller Blin et al, PRC100, 035201 \(2019\)](#).

# Electrocouplings of $N(1440)1/2^+$ and $N(1520)3/2^-$ Resonances from $\pi N$ and $\pi^+\pi^-p$ Electroproduction off Proton Data

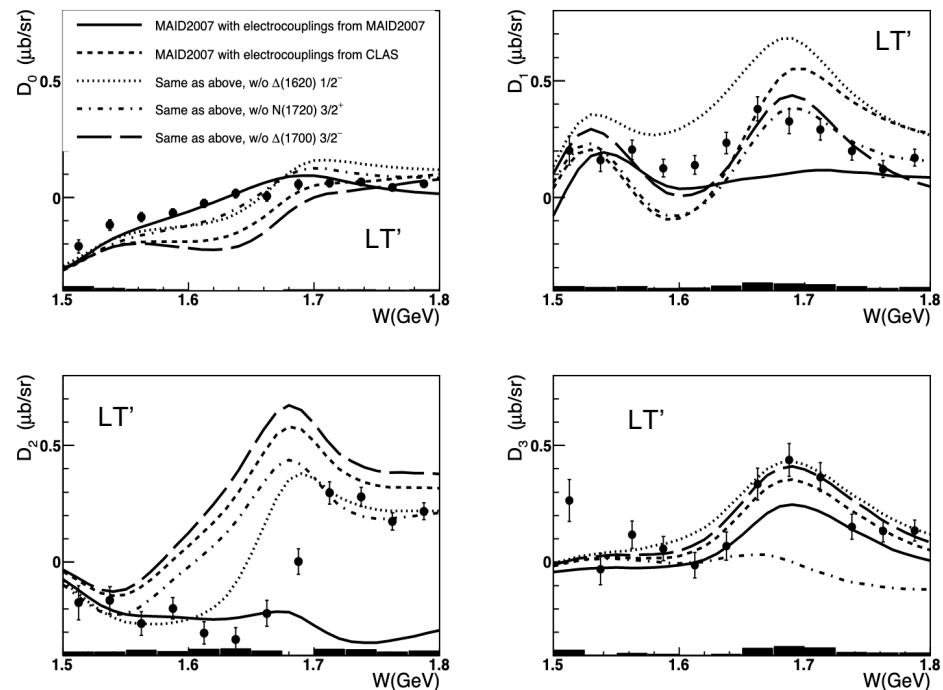
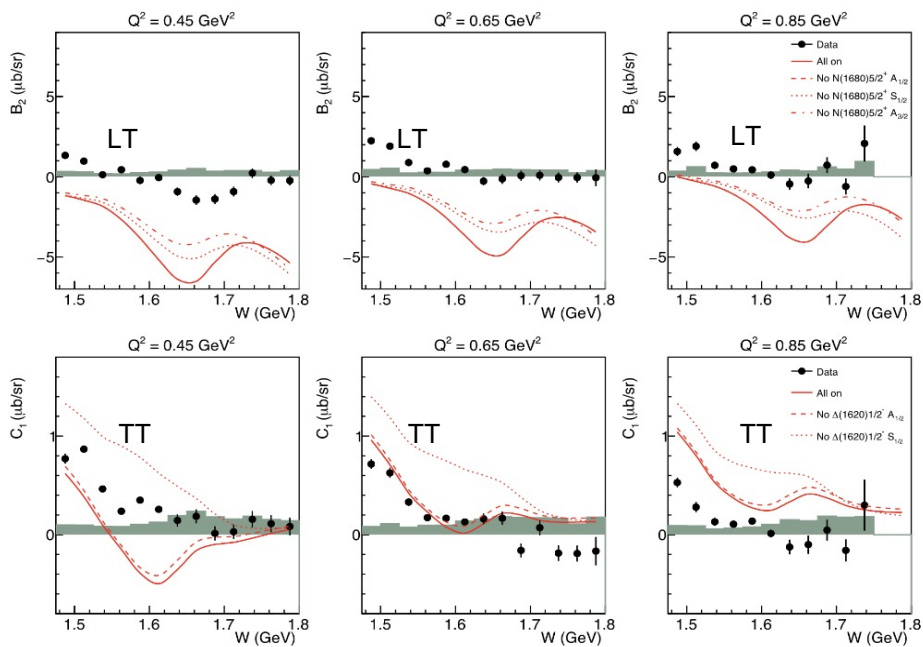


Consistent results on the  $N(1440)1/2^+$  and  $N(1520)3/2^-$  electrocouplings from independent studies of the two major  $\pi N$  and  $\pi^+\pi^-p$  electroproduction channels with different non-resonant contributions allow us to evaluate the systematic uncertainties of these quantities in a nearly model-independent way.

# Extension of the Results on $\pi^0 p$ Electroproduction with CLAS for Extraction of $\gamma_{\nu p N^*}$ Electrocouplings

N.Markov et al, (CLAS Coll.) Phys. Rev. C101, 015208 (2020)

E. L. Isupov et al, (CLAS Coll.) Phys. Rev. C105, L022201 (2021)



Legendre moments from  $\pi^0 p$  electroproduction structure functions measured with CLAS at  $W < 1.8 \text{ GeV}$  and at  $0.4 < Q^2 < 1.0 \text{ GeV}^2$  demonstrate pronounced sensitivity to variation of the  $\gamma_{\nu p N^*}$  electrocouplings for the resonances in mass range from 1.6 GeV to 1.8 GeV offering the good prospects to extend the results on electroexcitation amplitudes for the resonances in the third resonance region..

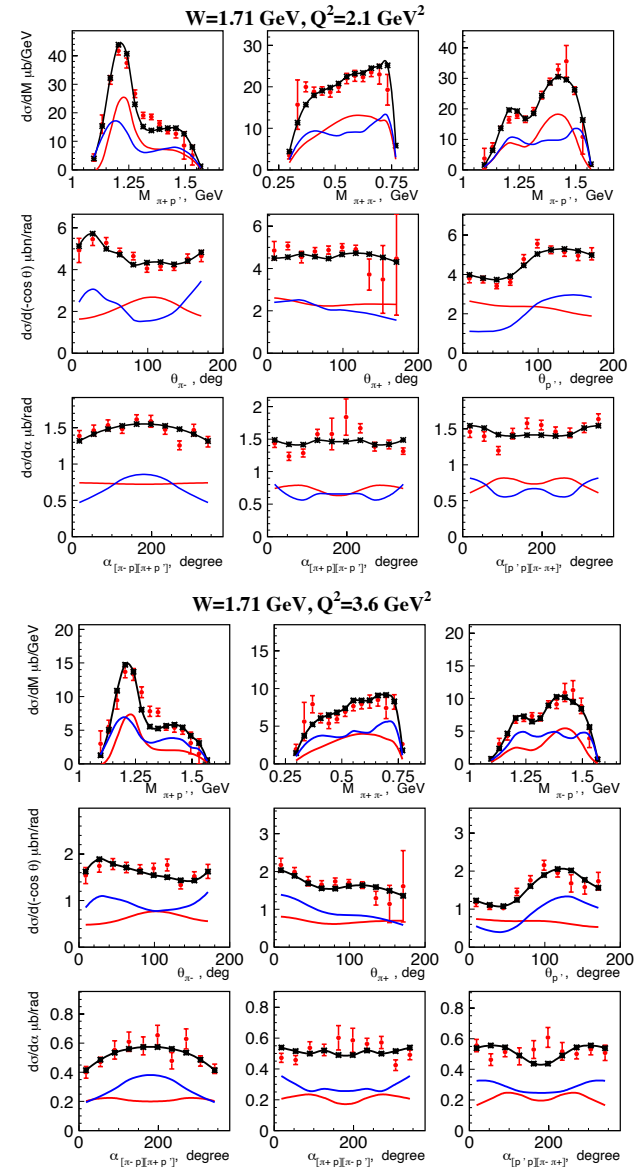
# The Results on $\pi^+\pi^-p$ Electroproduction with CLAS for Extraction of $\gamma_V p N^*$ Electrocouplings

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

V.I. Mokeev, EPJ Web Conf 241, 03003(2020)

— Full  
 — Resonances  
 — Background

In near future, electrocouplings of nucleon resonances in the mass range from to 2 GeV and  $Q^2 < 5 \text{ GeV}^2$  will be determined, concluding the studies of  $N^*$  structure from meson electroproduction data from 6 GeV era at JLab.

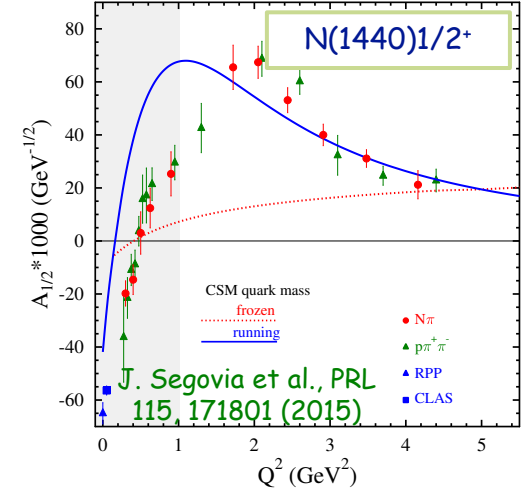
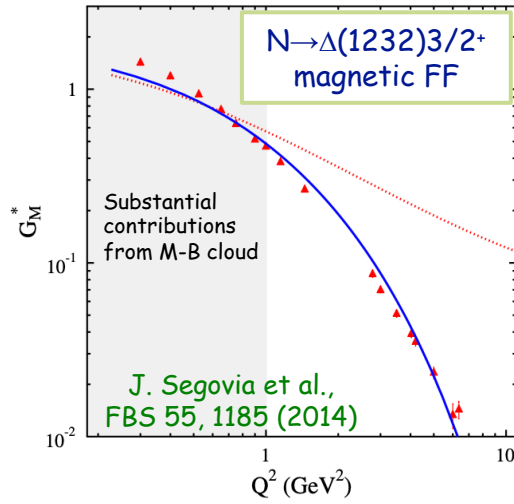


# EHM: Concept from CSM vs. Available Experimental Results

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

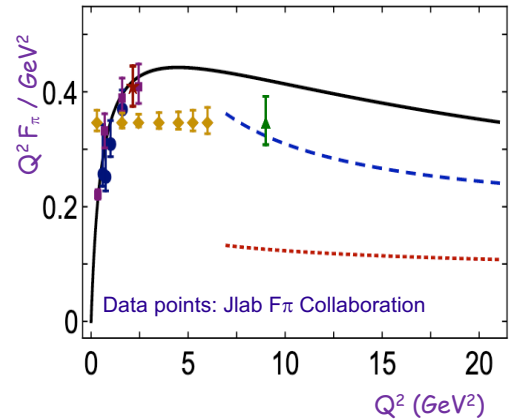
- Dressed quarks with dynamically generated masses represent active degrees of freedom in the structure of the pion, nucleon, and the  $\Delta(1232)3/2^+$ ,  $N(1440)1/2^+$  resonances
- Strong evidence for insight into momentum dependence of dressed quark mass

CLAS/Hall A/C results vs. CSM expectations



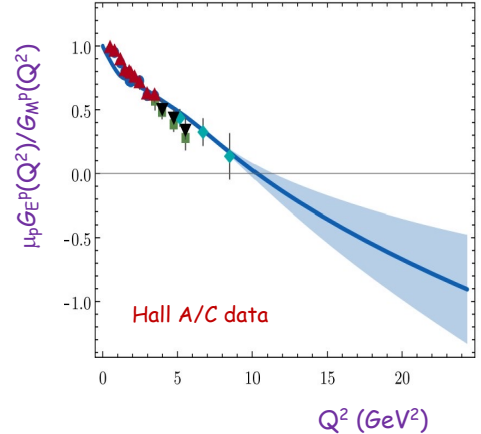
Pion Elastic FF

C.D. Roberts et al., Prog. Part. Nucl Phys. 120, 103883 (2021)



Nucleon Elastic FF

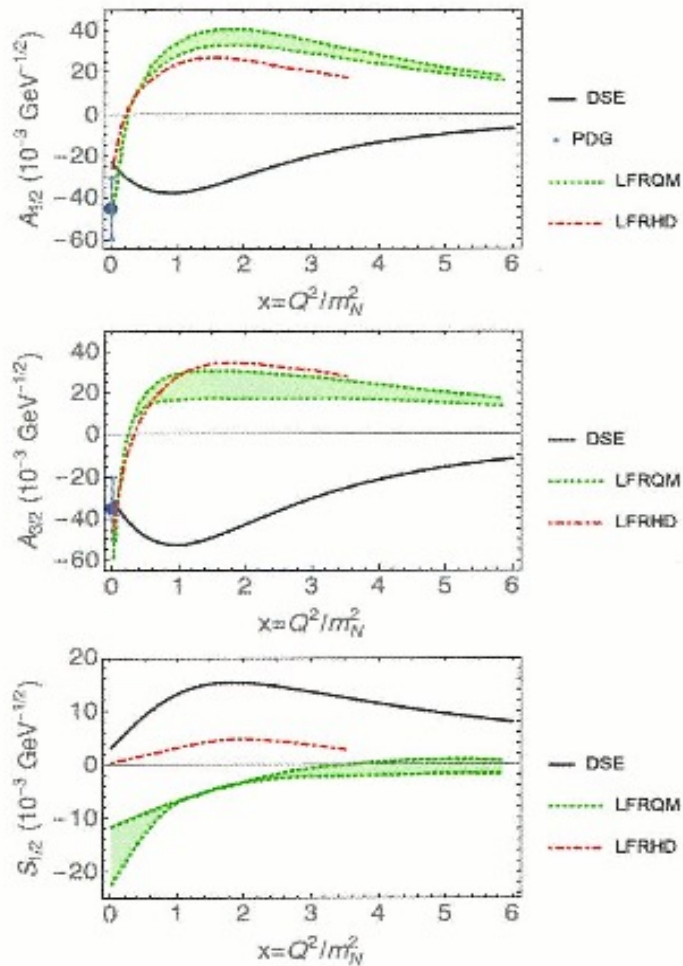
M. Barabanov et al., Prog. Part. Nucl Phys. 103835 (2021)



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

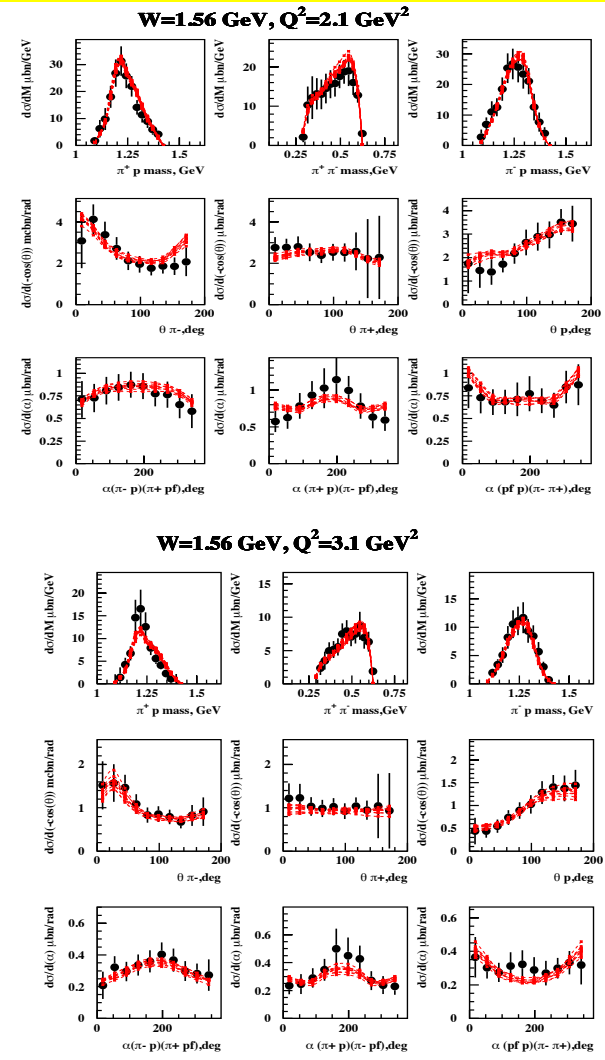


# $\Delta(1600)3/2^+$ Electrocouplings: CSM Prediction vs. Data Determination

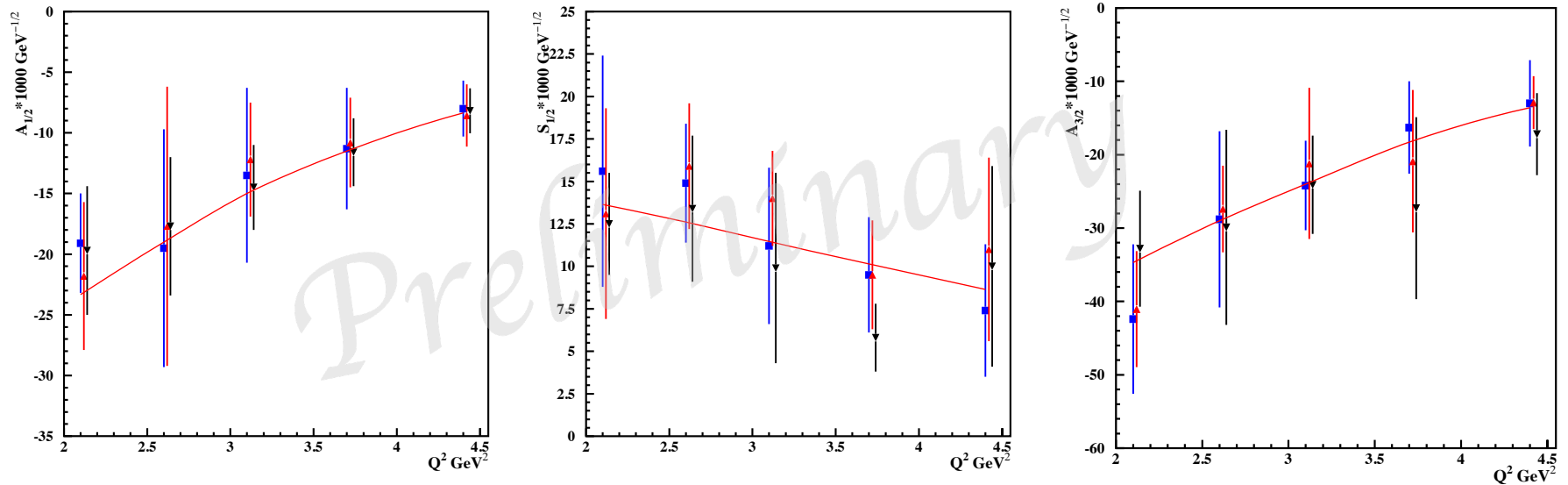


Parameter-free CSM predictions for  $\Delta(1600)3/2^+$  electrocouplings  
 Ya Lu et al., Phys. Rev. D 100, 034001 (2019)

Extraction of  $\Delta(1600)3/2^+$  electrocouplings from the CLAS  $\pi^+\pi^p$  electroproduction data at  $2.0 \text{ GeV}^2 < Q^2 < 5.0 \text{ GeV}^2$  within the JM reaction model, January-March, 2022



# $\Delta(1600)3/2^+$ Electrocouplings : CSM Prediction vs. Data Determination



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

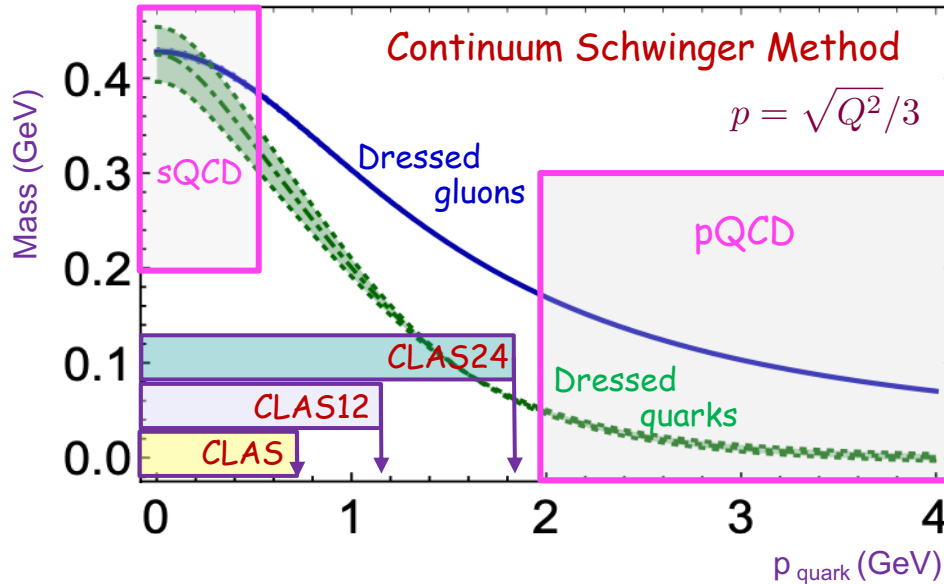
Electrocouplings from independent analyses of  $\pi^+\pi^-p$  differential cross sections within three W-intervals,  $1.46 < W < 1.56$  GeV,  $1.51 < W < 1.61$  GeV, and  $1.56 < W < 1.66$  GeV for  $2.0 < Q^2 < 5.0$  GeV<sup>2</sup>

CLAS results on  $\Delta(1600)3/2^+$  electrocouplings confirmed the CSM prediction, solidifying evidence for gaining insight into dressed quark mass function and, consequently, into EHM from the studies of  $\gamma_V p N^*$  electrocouplings

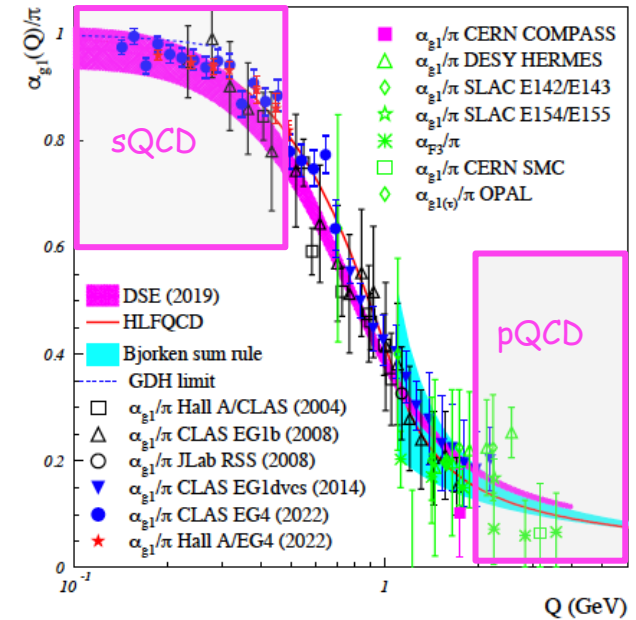


# Unique Opportunities to Understand Emergence of Hadron Mass and $N^*$ Structure from the Measurements with CLAS12 and After CEBAF 20+ GeV Energy Upgrade

Running Dressed Quark/Gluon Masses from CSM  
 C.D. Roberts, Symmetry 12, 1468 (2020), AAPS Bull 31, 6 (2021)



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

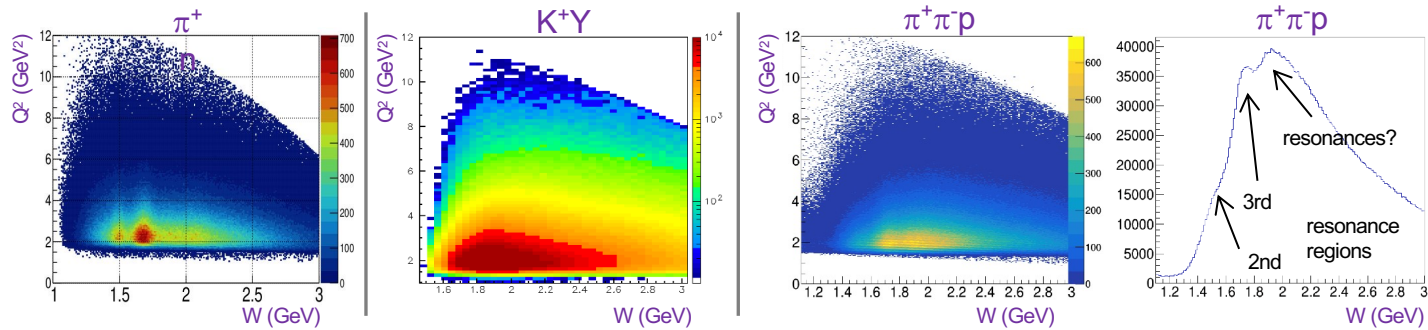


- In order to resolve the challenging open problem in the Standard Model on EHM, the dressed quark mass function  $M_q(p)$  should be mapped out within the entire range of quark momentum to  $\sim 2$  GeV, where the transition from strong to perturbative QCD takes place and where dressed quarks/gluons emerge as  $\alpha_s/\pi \rightarrow 1$ .
- CLAS12 is the only facility in the world capable of obtaining the electrocouplings of all prominent  $N^*$  states in the still unexplored  $Q^2$  range from 5 - 10  $\text{GeV}^2$ , allowing for the mapping of the dressed quark mass function at quark momenta to  $\sim 1.1$  GeV.

# N\* Electroexcitation to High Q<sup>2</sup> with CLAS12

**Expected outcome:** The first results on the  $\gamma_v p N^*$  electrocouplings of most N\* states from data in the range  $W < 2.5$  GeV and  $Q^2 > 5.0$  GeV<sup>2</sup> for exclusive reaction channels:  $\pi N$ ,  $\pi\pi N$ ,  $KY$ ,  $K^*Y$ ,  $KY^*$

kinematic coverage for RG-A data @ 10.6 GeV



Expected events per Q<sup>2</sup>/W bin for full RG-A dataset

$\pi^+n$			$K^*\Lambda$ & $K^*\Sigma^0$				$\pi^+\pi^-p$			
Q <sup>2</sup> [GeV <sup>2</sup> ]	W [GeV] 1.5-1.55	W [GeV] 1.7-1.75	Q <sup>2</sup> [GeV <sup>2</sup> ]	W <sub><math>\Lambda</math></sub> [GeV] 1.7-1.75	W <sub><math>\Sigma</math></sub> [GeV] 1.7-1.75	W <sub><math>\Lambda</math></sub> [GeV] 1.9-1.95	W <sub><math>\Sigma</math></sub> [GeV] 1.9-1.95	Q <sup>2</sup> [GeV <sup>2</sup> ]	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<sup>2</sup> range of the  $\gamma_v p N^*$  electrocouplings to **8-10 GeV<sup>2</sup>** for each of these channels – *the data collected so far will limit us to 6-8 GeV<sup>2</sup>*

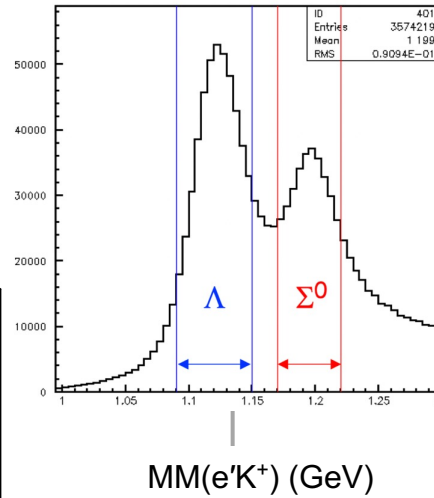


# CLAS12 K<sup>+</sup>Y Transferred Polarization



CLAS12 RG-K @ 6.535 GeV,  
0.3 < Q<sup>2</sup> < 3.5 GeV<sup>2</sup>

CLAS e1-6 @ 5.754 GeV  
0.7 < Q<sup>2</sup> < 5.4 GeV<sup>2</sup>

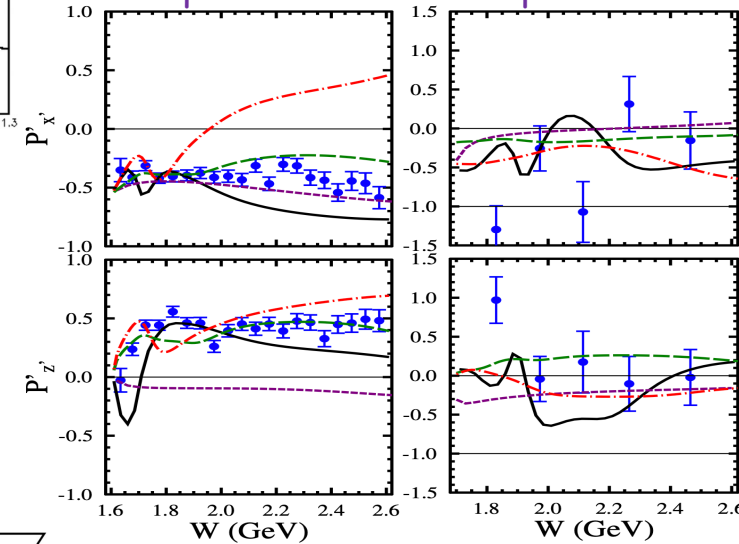
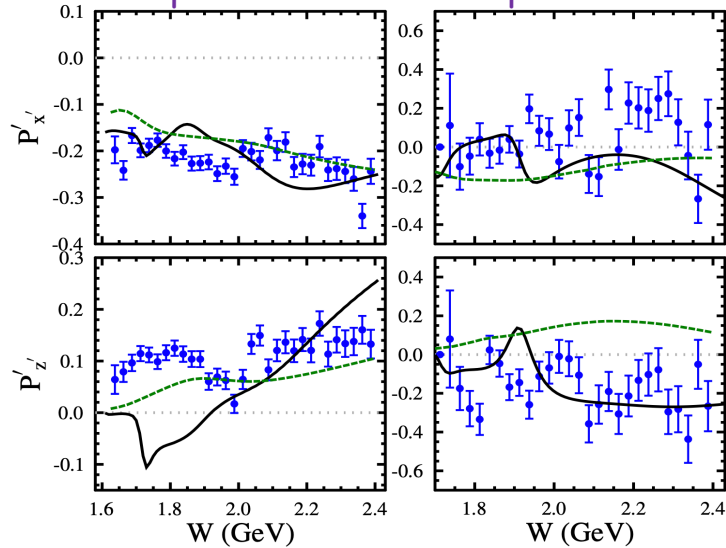


ep → e'K<sup>+</sup>Λ

ep → e'K<sup>+</sup>Σ<sup>0</sup>

ep → e'K<sup>+</sup>Λ

ep → e'K<sup>+</sup>Σ<sup>0</sup>

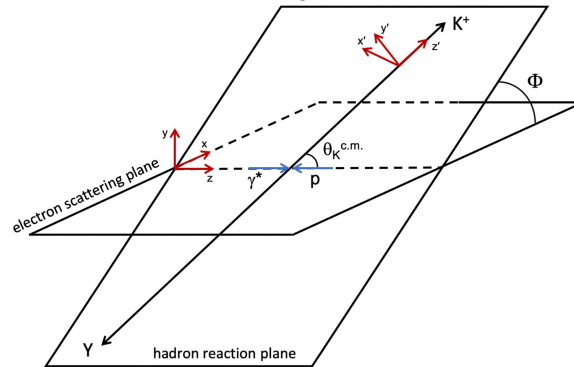


D.S. Carman et al., PRC 105, 065201 (2022)

D.S. Carman et al., PRC 79, 065205 (2009)

KAON-MAID  
RPR

Mart/Bennhold RPR-2  
RPR-1 Regge



# Hadron Structure Studies with CLAS20+

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

**Contribution of the Hadron Structure Group to the Physics Motivation to Increase the Energy and Luminosity of JLab**

It is worth recalling that examination of the ground state of the hydrogen atom did not give us sufficient insight into QCD. It did not even bring us close. Equally, studies of the ground state of the proton alone cannot reveal whether QCD is truly the theory of strong interactions in the Standard Model. The future of hadron physics lies in high-energy, high-luminosity facilities that are capable of moving beyond the 100-year-old focus on the structure of the ground state of the proton to deliver insights that will dramatically expand our store of knowledge concerning the complex array of hadrons in Nature. In this context, studies of the structure of excited nucleon states (N\*) from the data on exclusive meson electroproduction in terms of the Q<sup>2</sup> evolution of their electrocoupling amplitudes, i.e. their  $\gamma_{\nu}pN^*$  electrocouplings, offer a unique opportunity to explore many facets of the strong interaction in the regime of large (comparable with unity) QCD running coupling (i.e. the strong QCD regime) that are evident in the distinctively different structural features of these excited states [1-5]. Data on the  $\gamma_{\nu}pN^*$  electrocouplings over a broad range of Q<sup>2</sup> are critical in order to explore the evolution of the strong interaction in the transition from the strong to the perturbative QCD regime [1,2,6,7]. These electrocouplings provide needed experimental input for the development of the theoretical approaches necessary for the description of the structure of both the ground and excited nucleon states starting from the QCD Lagrangian, as well as within advanced quark models.

The Hadron Structure Group at JLab proposes to extend the studies of the  $\gamma_{\nu}pN^*$  electrocouplings from exclusive meson electroproduction processes initiated with the CLAS2 detector in Hall B at beam energies up to 8 GeV and continued with the CLAS12 detector at beam energies up to 11 GeV, to a proposed CLAS24 configuration at beam energies up to 24 GeV. Such experiments at the highest proton virtualities Q<sup>2</sup> ever achieved (10-36 GeV<sup>2</sup>) in studies of exclusive meson electroproduction will allow for the realization of the goal to improve our understanding of the fundamental underpinnings of the mechanisms for the emergence of hadron mass (CMM) in these strongly interacting N\* baryon states based on description of these data. The proposed experimental program, along with the associated experiments in JLab-Halls A/C and the planned studies at AMBER/CEBN, EIC, and EIC focused on the structure of  $\pi$  and K mesons [2,11], are of particular importance in order to understand the dynamics of the processes that generate the dominant portion of visible hadron mass in the Universe [1,2,8,9,10].

The current quark masses that enter into the QCD Lagrangian are generated by the Higgs mechanism, and account for less than 2% of the mass of the proton and neutron. Therefore, understanding how these bare current quarks evolve into the fully dressed constituent-like quarks relevant for understanding the structure of baryons and mesons is one of the most fundamental and still open problems within the Standard Model. Recent rapid and significant progress in the development of Continuum Schwinger function Methods (CSMs) [8,10], achieved by an international group of physicists and coordinated by the Institute for Nonperturbative Physics at Nanjing University, has provided a concept for understanding EHM, which has been tested in comparisons with other state-magnetic form factors and results of nucleon resonances. Notably, these are practically identical to experiments, a greater range of account for the structure of measured electrocouplings results on the  $\gamma_{\nu}pN^*$  fully confirmed the CSM as the capability to improve pion/nucleon elastic form factors between experiment.

of the mass of any light-quark quark dressing by gluons and of large Q<sup>2</sup> coupling, the dressing with nonrenormalization-dependent form factors shown in Fig. 1 are self-consistent Lagrangian. They show how time fully dressed quarks with is consistent with the measured  $\gamma_{\nu}pN^*$  electrocouplings will each regarding how hadron strongly interacting systems. broad range of Q<sup>2</sup> looks of applicability of different from structure at different

of hadron mass generation. It is critical dressed quark mass over the range of part of hadron mass is generated. This of the  $\gamma_{\nu}pN^*$  electrocouplings into the this kinematic range, the electron beam is a factor of two to ~24 GeV. We are and beam polarization asymmetries of  $\pi^+p$  final states at W=3.0 GeV and within realistic, benchmarked reaction rings for all N\* prominent resonances in  $\sqrt{s} > 10$  GeV<sup>2</sup>, luminosities of at least exclusive electroproduction processes hadron emission angles are required. A bit be necessary for disentangling the

unique to JLab, since the expected two orders of magnitude smaller than that results on the dressed quark mass electrocouplings of resonances with momenta up to 2 GeV where the dominant our understanding of EHM in a nearly identical to JLab, with increased time, capable of addressing the most the Standard Model, i.e. the emergence how the structure of both meson and Standard Model Lagrangian.

20200006 (2020), Phys. 116, 103855 (2021), Body Syst. 61, 29 (2020), Int. J. Mod. Phys. E7, 1 (2012), Phys. 91, 011003 (2019), Rev. D 92, 042018 (2015), 22, 1330015 (2013),

Int. J. Mod. Phys. 12, 121201 (2020), 2022), S.L. Chang, Prog. Part. Nucl. Phys. 1801 (2015), 5 (2014), 2019),

of the dressed quark mass couplings available from the increase of the Lab energy up to 24 GeV and luminosity up to 10<sup>34</sup> cm<sup>-2</sup>s<sup>-1</sup> (up to the right blue vertical line).

## List of Participating Institutions:

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

<https://userweb.jlab.org/~carman/clas24>

- Simulations of  $\pi N$ ,  $KY$ , and  $\pi^+ \pi^- p$  electroproduction with CEBAF@20+ GeV show:

$\gamma_{\nu}pN^*$  electrocouplings can be determined up to  $Q^2 \sim 30 \text{ GeV}^2$  for  $\mathcal{L} \sim 5 \times 10^{35} \text{ cm}^{-2}\text{s}^{-1}$

- Experimental confirmation of CSM predictions of  $\gamma_{\nu}pN^*$  electrocouplings of most prominent N\* states of different structure will provide sound evidence for the understanding how the dominant part of hadron mass and N\* structure emerge from QCD



# Conclusions and Outlook

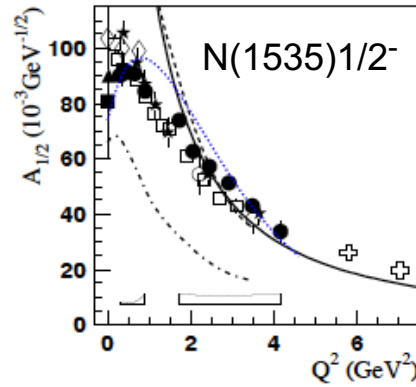
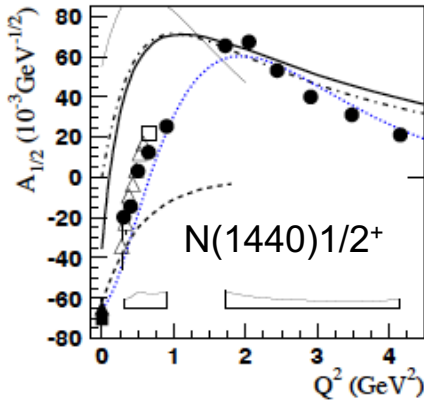
- Baryons are the most fundamental three-body systems in Nature. If we don't understand how QCD builds each of the baryons in the complete spectrum, then we don't understand Nature.
- High-quality meson electroproduction data of 6 GeV era at JLab have allowed for the determination of the electrocouplings of most nucleon resonances in the mass range up to 1.8 GeV for  $Q^2 < 7.5 \text{ GeV}^2$ .
- A good description of the  $\Delta(1232)3/2^+$ ,  $N(1440)1/2^+$ , and  $\Delta(1600)3/2^+$  electroexcitation amplitudes at  $Q^2 < 5.0 \text{ GeV}^2$  achieved within CSM with the same dressed quark mass function inferred from the QCD Lagrangian and used in the successful description of the data on elastic nucleon and pion electromagnetic form factors, offers sound evidence for insight into the momentum dependence of the dressed quark mass.
- CLAS12 is the only facility in the world capable of obtaining the electrocouplings of all prominent  $N^*$  states in the still unexplored  $Q^2$  range from 5 - 10  $\text{GeV}^2$  from measurements of  $N\pi$ ,  $\pi^+\pi^-p$ , and  $KY$  electroproduction, allowing for the mapping of the dressed quark mass function at quark momenta  $< 1.1 \text{ GeV}$  where  $\sim 50\%$  of hadron mass is generated.
- JLab20+ is the only envisaged facility that will enable science to produce a sufficient quantity of precise data on nucleon elastic and transition form factors that can move science toward an understanding of the most fundamental 3-body systems in Nature. JLab20+ will provide the data that will enable science to draw the EHM map. That map will be a key part of the final solution of QCD.
- Extension of the results on the  $\gamma_v p N^*$  electrocouplings into the  $Q^2$  range from 10 - 30  $\text{GeV}^2$  after the increase of the CEBAF energy and pushing the CLAS12 detector capabilities to measure exclusive electroproduction to the highest possible luminosity, will offer the **only foreseen opportunity** to explore how the dominant part of hadron mass and  $N^*$  structure emerge from QCD and will make **CEBAF@20+ GeV unique and the ultimate QCD-facility at the luminosity frontier.**



# Back up



# Facets of Strong QCD from Combined Studies of the Ground/Excited Nucleon State Structure

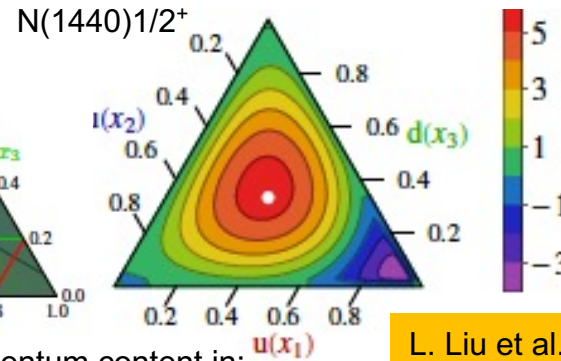
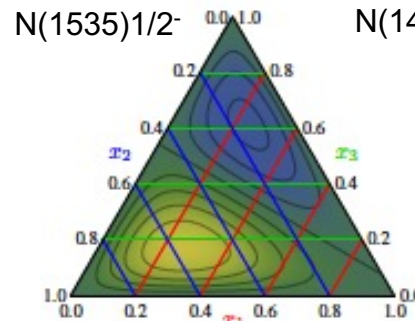
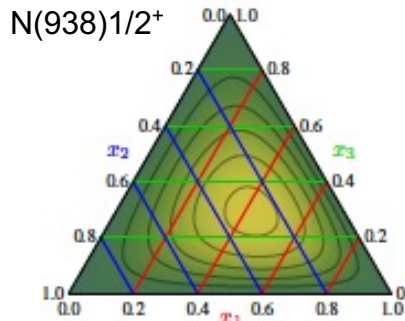


V.D. Burkert and I.G. Aznauryan, Prog. Part Nucl. Phys. 67, 1 (2012)

The results on electroexcitation of different resonances allow us to rigorously test the quark model ingredients for the description of the ground/excited hadron structure

V.M. Braun et al., Phys. Rev. D 89, 094511 (2014)  
C. Mezrag et al., Phys. Rev. Lett. B 783, 263 (2018)

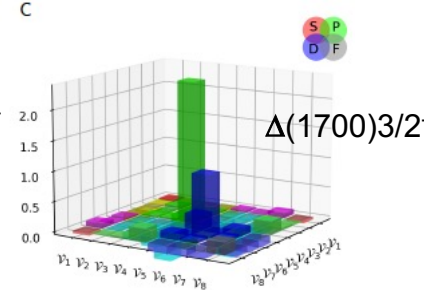
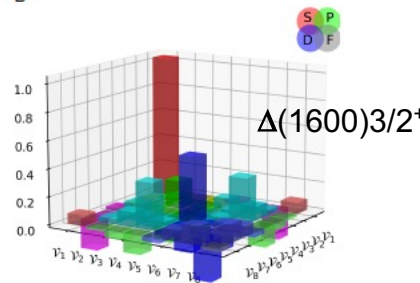
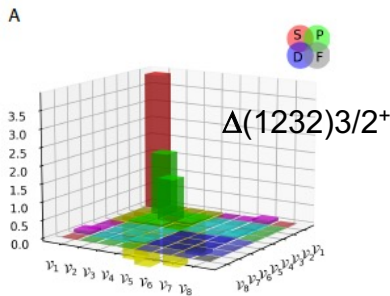
Parton distribution amplitudes (PDA) in:



Pronounced differences predicted for N/N\* PDAs can be explored in N\* electroexcitation, offering insight into the sQCD mechanisms that underlie these differences

Rest frame quark-correlated-di-quark angular momentum content in:

L. Liu et al., e-print: 2203-12083 [hep-ph]



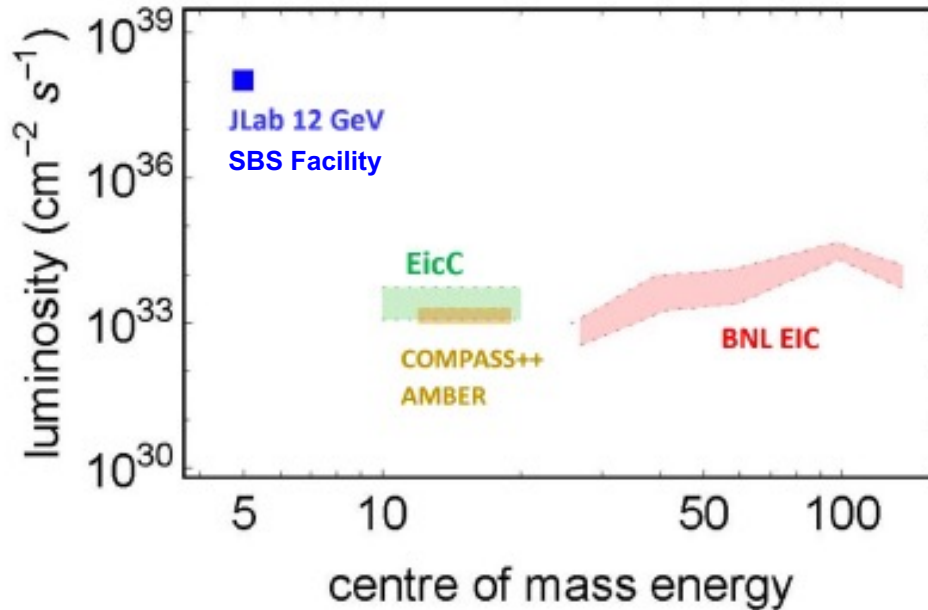
Studies of N\* electroexcitation will contribute to understanding of the nature of spin of the ground and excited states of the nucleon

Exploration of N\* electroexcitations is an important part of efforts aimed to considerably extend knowledge on sQCD



# Studies of $\gamma_{\nu}pN^*$ Electrocouplings at $Q^2 > 10 \text{ GeV}^2$

Energy and luminosity increase up to  $5 \cdot 10^{35} \text{ cm}^{-2}\text{s}^{-1}$  are needed in order to obtain information on the  $\gamma_{\nu}pN^*$  electrocouplings at  $Q^2 > 10 \text{ GeV}^2$ , 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 in the transition from sQCD to pQCD.



Both EicC and EIC would need much higher, unlikely feasible luminosity

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

- Beam energy at fixed target: 24 GeV
- Nearly  $4\pi$  coverage
- High luminosity

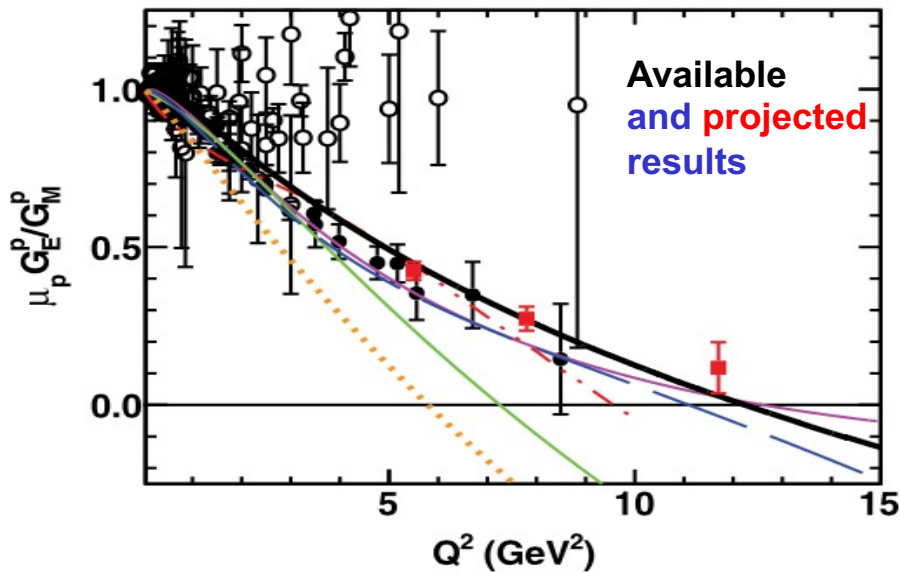


**Offer maximal achievable luminosity for extraction of  $\gamma_{\nu}pN^*$  electrocouplings at  $Q^2 > 10 \text{ GeV}^2$**



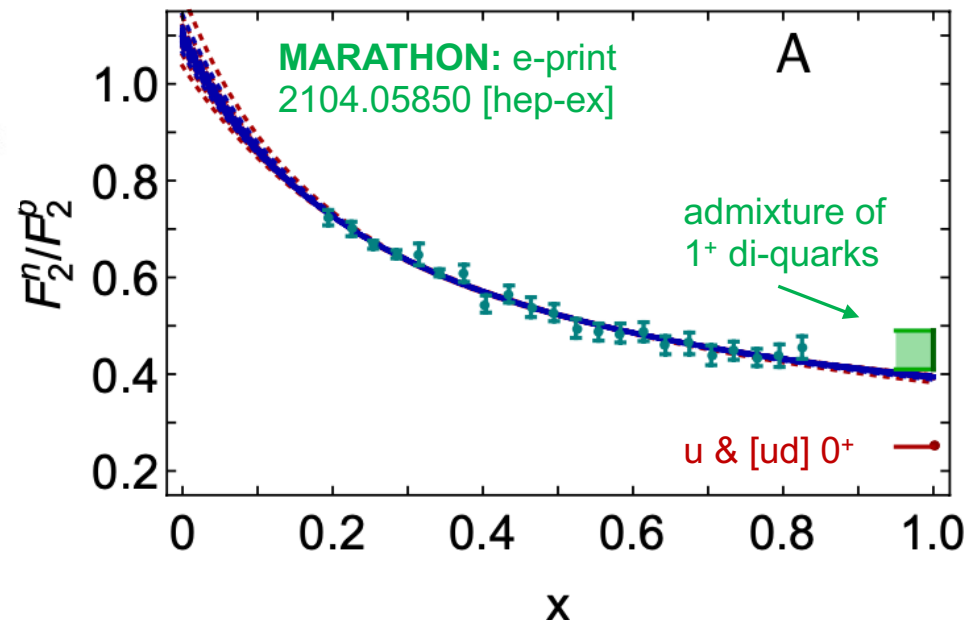
# EHM from the Ground Nucleon Structure Exploration in 12 GeV Era

- A unique combination of high luminosity ( $10^{38} \text{ cm}^{-2}\text{s}^{-1}$ ), 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  $15 \text{ GeV}^2$
- 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  $5.0 \text{ GeV}^2$



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

- 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



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

Hadronic final state	Covered W-range, GeV	Covered Q <sup>2</sup> -range, GeV <sup>2</sup>	Measured observables
$\pi^+n$	1.1-1.38 1.1-1.55 1.1-1.70 1.6-2.00	0.16-0.36 0.3-0.6 1.7-4.5 1.8-4.5	$d\sigma/d\Omega$ $d\sigma/d\Omega$ $d\sigma/d\Omega, A_b$ $d\sigma/d\Omega$
$\pi^0p$	1.1-1.38 1.1-1.68 1.1-1.39 1.1-1.80	0.16-0.36 0.4-1.8 3.0-6.0 0.4-1.0	$d\sigma/d\Omega$ $d\sigma/d\Omega, A_b, A_t, A_{bt}$ $d\sigma/d\Omega$ $d\sigma/d\Omega$
$\eta p$	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 asymmetries
- $P^0, P'$  –recoil and transferred polarization of strange baryon

**Around 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 Data Base <http://clas.sinp.msu.ru/cgi-bin/jlab/db.cgi>



# Approaches for Extraction of $\gamma_{\nu}NN^*$ Electrocouplings from the CLAS Exclusive Meson Electroproduction Data

## Analyses of different meson electroproduction channels independently:

### ➤ $\pi^+n$ and $\pi^0p$ 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)

### ➤ $\eta p$ 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 $\gamma_{r,\nu}N$ , $\pi N$ , $\eta N$ , $\pi\pi N$ , $K\Lambda$ , $K\Sigma$ exclusive channels:

H. Kamano, Few Body Syst. 59, 24 (2018). Argonne-Osaka

H. Kamano, JPS Conf. Proc. 13, 010012 (2017). Argonne-Osaka

M. Mai et al., Phys. Rev. C103, 065204 (2021) Jülich-Bonn-Washington

M. Mai et al., Phys. Rev. C106, 015201 (2022) Jülich-Bonn-Washington

