# Exploration of N\* Electroexcitation at Photon Virtualities Q<sup>2</sup>>10 GeV<sup>2</sup> (Topics for Discussion Session)



# $\Delta$ (1600)3/2<sup>+</sup> electrocouplings: CLAS preliminary results vs. CSM predictions



 $\begin{array}{c} \textbf{4.5} \\ \textbf{Q}^2 \, \textbf{GeV}^2 \end{array}$ 

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#### Emergence of Hadron Mass from N\* Studies with the CLAS12 and Needs for JLab Energy/Luminosity Increase

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

How is >98% of visible mass generated?

How EHM is related to Dynamical Chiral Symmetry Breaking?

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

Mapping-out dressed quark mass function from the results on γ<sub>v</sub>pN\* electrocouplings of different spinisospin flip, radial, and orbital excited states of the nucleon at 5<Q<sup>2</sup><35 GeV<sup>2</sup> <u>is needed</u> to explore the full range of distances where the dominant part of hadron mass is generated



#### V.I. Mokeev, Hadron Spectroscopy Workshop, June 16-17, 2022

#### **Questions for discussion**

- Opportunities for support from the JLab management to develop and build new detector in Hall B to measure exclusive meson electroproduction for Q<sup>2</sup> to ~35 GeV<sup>2</sup> at *L* > 10<sup>36</sup> cm<sup>-2</sup>s<sup>-1</sup> and 4π coverage.
- Theory expectations/constraints on evolution of the resonant/non-resonant ratio with Q<sup>2</sup> at the amplitudes/cross section levels.
- Prospects for development of the reaction models for extraction of nucleon resonance electrocouplings from the data of Nπ, Nη, KΛ, KΣ electroproduction channels at Q<sup>2</sup>>5 GeV<sup>2</sup>.
- Prospects for extension of the continuum Schwinger method framework by other QCD-rooted approaches and quark models, allowing us to relate the results on nucleon resonance electrocouplings at Q<sup>2</sup>>5 GeV<sup>2</sup> to the dynamics of strong interaction that underlies the generation of the structure of excited states of the nucleon.
- Can LQCD provide *ab initio* predictions on the Q<sup>2</sup> evolution of nucleon resonance electrocouplings at Q<sup>2</sup>>5 GeV<sup>2</sup>? Predict A<sub>g</sub>(t), B<sub>g</sub>(t), C<sub>g</sub>(t), and D<sub>g</sub>(t) form factors of the proton energy-momentum tensor ?







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



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

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- Dressed quarks with dynamically generated masses represent active degrees of freedom in the structure of the pion, nucleon, and the Δ(1232)3/2<sup>+</sup>, N(1440)1/2<sup>+</sup> resonances
- Strong evidence for insight into EHM

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

- Express the fundamental feature: emergence of the quark and gluon masses even in the case of massless quarks in the 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)



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



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# **Basics for Insight into EHM: CSM and Lattice QCD Synergy**



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 QCD fields depicted above.



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

 The model 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.



 Pions and kaons are simultaneously qq
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.





#### **Mass Budgets**

 Studies of the ground and 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 into 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 pseudo-scalar mesons and the ground and excited state nucleon structure are of particular importance for the validation of insight into EHM.



#### **Toward Exploration of EHM from Orbital Nucleon Excitations**



Continuum QCD Breakthrough: N(1535)1/2<sup>-</sup> 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 electroexcitation amplitudes of the [70,1<sup>-</sup>] 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.

