Electrocouplings of Nucleon Resonances

- Resonance electroexcitation and insight into strong QCD
- Extraction of resonance electrocouplings
- Resonance electrocouplings and emergence of hadron mass
- Resonant contributions into (e,e′X) scattering in the N* region
- N* structure and strong QCD from experiments with CLAS12

\[ \Delta(1600)_{3/2}^+ \text{ electrocouplings:}
\]

CLAS preliminary results vs. CSM predictions

V.I. Mokeev
Jefferson Lab
(CLAS Collaboration)

2022 JLUO Annual Meeting
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:

- $\gamma_vpN^*$ electrocouplings at photon virtualities $Q^2$ up to 10 GeV$^2$ for most of the excited proton states through analyzing the major meson electroproduction channels from CLAS/CLAS12 data
- 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 data of the experiments with electromagnetic probes:

1. S.J. Brodsky et al., Int. J. Mod. Phys. E29, 203006 (2020)
2. C.D. Roberts, Symmetry 12, 1468 (2020)

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

2. D.S. Carman, K. Joo, and V.I. Mokeev, Few Body Syst. 61, 29 (2020)
Many Facets of Strong QCD from Combined Studies of the Ground/Excited Nucleon State Structure

Parton distribution amplitudes (PDA) in:

\[ N(938)1/2^+ \]

\[ N(1535)1/2^- \]

\[ N(1440)1/2^+ \]

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

\[ \Delta(1232)3/2^+ \]

\[ \Delta(1600)3/2^+ \]

\[ \Delta(1700)3/2^- \]

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

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

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


L. Liu et al., e-print: 2203-12083 [hep-ph]
N\* Photo-/Electroexcitation Amplitudes ($\gamma_{r,v} pN*$ Photo-/Electrocouplings) and their Extraction from Exclusive Photo-/Electroproduction Data

Resonant amplitudes

Non-resonant amplitudes

$\pi, \eta, \pi\pi, KY,\ldots$

$\pi, \eta, \pi\pi, KY,\ldots$

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

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


- Consistent results on the $\gamma_{r,v} pN*$ photo-/electrocouplings from different meson photo-/electroproduction channels allow us to validate reliable extraction of these quantities.
**Summary of Published CLAS Data on Exclusive Meson Electroproduction off Protons in N* Excitation Region**

<table>
<thead>
<tr>
<th>Hadronic final state</th>
<th>Covered W-range, GeV</th>
<th>Covered Q^2-range, GeV^2</th>
<th>Measured observables</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \pi^+n )</td>
<td>1.1-1.38</td>
<td>0.16-0.36</td>
<td>( d\sigma/d\Omega ), ( d\sigma/d\Omega ), ( A_b ), ( d\sigma/d\Omega ), ( A_t ), ( A_{bt} )</td>
</tr>
<tr>
<td></td>
<td>1.1-1.55</td>
<td>0.3-0.6</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.1-1.70</td>
<td>1.7-4.5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.6-2.00</td>
<td>1.8-4.5</td>
<td></td>
</tr>
<tr>
<td>( \pi^0 p )</td>
<td>1.1-1.38</td>
<td>0.16-0.36</td>
<td>( d\sigma/d\Omega ), ( d\sigma/d\Omega ), ( A_b ), ( A_t ), ( A_{bt} )</td>
</tr>
<tr>
<td></td>
<td>1.1-1.68</td>
<td>0.4-1.8</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.1-1.39</td>
<td>3.0-6.0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.1-1.80</td>
<td>0.4-1.0</td>
<td></td>
</tr>
<tr>
<td>( \eta p )</td>
<td>1.5-2.3</td>
<td>0.2-3.1</td>
<td>( d\sigma/d\Omega )</td>
</tr>
<tr>
<td>( K^+\Lambda )</td>
<td>thresh-2.6</td>
<td>1.40-3.90</td>
<td>( d\sigma/d\Omega ), ( P^0 ), ( P' )</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.70-5.40</td>
<td></td>
</tr>
<tr>
<td>( K^+\Sigma^0 )</td>
<td>thresh-2.6</td>
<td>1.40-3.90</td>
<td>( d\sigma/d\Omega ), ( P' )</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.70-5.4</td>
<td></td>
</tr>
<tr>
<td>( \pi^+\pi^-p )</td>
<td>1.3-1.6</td>
<td>0.2-0.6</td>
<td>Nine 1-fold differential cross sections</td>
</tr>
<tr>
<td></td>
<td>1.4-2.1</td>
<td>0.5-1.5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.4-2.0</td>
<td>2.0-5.0</td>
<td></td>
</tr>
</tbody>
</table>

The measured observables from CLAS are stored in the CLAS Physics Data Base [http://clas.sinp.msu.ru/cgi-bin/jlab/db.cgi](http://clas.sinp.msu.ru/cgi-bin/jlab/db.cgi)

- \( d\sigma/d\Omega \)–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

Almost full coverage of the final state hadron phase space

Around 150,000 data points!
Independent analyses of different meson electroproduction channels:

- $\pi^+n$ and $\pi^0p$ channels:
  - Unitary Isobar Model (UIM) and Fixed-t Dispersion Relations (DR)

- $\eta p$ channel:
  - Extension of UIM and DR
  - Data fit at $W<1.6$ GeV, assuming $N(1535)1/2$ dominance

- $\pi^+\pi^-p$ channel:
  - Data driven JLab-MSU meson-baryon model (JM)

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

- M. Mai et al., e-print: 2111.04774 [nucl-th]
### Nucleon Resonance Electrocouplings from Data On Exclusive Meson Electroproduction with CLAS

<table>
<thead>
<tr>
<th>Exclusive meson electroproduction channels</th>
<th>Excited proton states</th>
<th>$Q^2$-ranges for extracted $\gamma_\nu pN^*$ electrocouplings, GeV$^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\pi^0 p, \pi^+ n$</td>
<td>$\Delta(1232)3/2^+$</td>
<td>0.16-6.0</td>
</tr>
<tr>
<td></td>
<td>N(1440)1/2$^+$, N(1520)3/2$^-$, N(1535)1/2$^-$</td>
<td>0.30-4.16</td>
</tr>
<tr>
<td>$\pi^+ n$</td>
<td>N(1675)5/2$^-$, N(1680)5/2$^+$, N(1710)1/2$^+$</td>
<td>1.6-4.5</td>
</tr>
<tr>
<td>$\eta p$</td>
<td>N(1535)1/2$^-$</td>
<td>0.2-2.9</td>
</tr>
<tr>
<td>$\pi^+\pi^- p$</td>
<td>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$^+$</td>
<td>0.25-1.50 2.0-5.0 (preliminary)</td>
</tr>
</tbody>
</table>

- The $N^*$ electroexcitation amplitudes ($\gamma_\nu pN^*$ electrocouplings) have become available in a broad range of $Q^2<5.0$ GeV$^2$
- In the mass range $W<1.6$ GeV the $\gamma_\nu pN^*$ electrocoupling were obtained from independent studies of $\pi N$, $\eta p$, and $\pi^+\pi^- p$ electroproduction

Most 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 πN and π⁺π⁻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 πN and π⁺π⁻p electroproduction channels with different non-resonant contributions allow us to evaluate the systematic uncertainties of these quantities in a nearly model-independent way.
How do the Ground/Excited State Nucleon Masses Emerge?

Composition of the Nucleon Mass:

<table>
<thead>
<tr>
<th></th>
<th>Proton</th>
<th>Neutron</th>
</tr>
</thead>
<tbody>
<tr>
<td>$M_p$, MeV (PDG20)</td>
<td>938.2720813 ±0.0000058</td>
<td>939.5654133 ±0.0000058</td>
</tr>
</tbody>
</table>

Sum of bare quark masses, MeV

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

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

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

The Continuum Schwinger method (CSM) has conclusively demonstrated that the dominant part of hadron mass is generated by the strong interaction in the regime where the QCD running coupling becomes comparable with unity - the so-called strong QCD regime.
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.
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

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

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

Dressed Quark Mass (Lattice QCD)
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 EHM
Electrocouplings of the $\Delta(1600)3/2^+$: CSM Prediction vs. Data Determination

Parameter-free CSM predictions for $\Delta(1600)3/2^+$ electrocouplings

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
Electrocouplings of the $\Delta(1600)3/2^+$: CSM prediction vs. Data Determination

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$^2$

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

Resonant Contributions into Inclusive $F_1(W,Q^2)$ Structure Functions & the Contributions from the PDF in the Ground State of the Nucleon Evaluated from the Data in DIS Region

Resonant contributions:
A.N. Hiller Blin et al.,
PRC 100, 035201 (2019)
A.N. Hiller Blin et al.,
PRC 104, 025201 (2021)

Data points are from interpolation of the CLAS results re-evaluated with the $\sigma_L/\sigma_T$ ratio from Hall A/C data

CLAS data:
M. Osipenko et al., PRD 67, 092001 (2003)

Hall C data:

Green dot-dashed lines: $F_1$ from JAM PDF
Other smooth curves: $F_1$ from JAM PDF after target mass corrections within different prescriptions
Resonant contributions into the $F_2$, $F_L$ structure functions are in the range of 40-60%, suggesting good prospects for the extraction of the $\gamma_vpN^*$ electrocouplings at $Q^2>4.0$ GeV$^2$. 
Emergence of Hadron Mass from N* Studies with the CLAS12

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 $\gamma_v pN^*$ electrocouplings of different spin-isospin flip, radial, and orbital excited states of the nucleon at 5<$Q^2$<12 GeV$^2$ is needed to explore the essential part of the range of distances where the dominant part of hadron mass is generated.

Full range of quark momenta where hadron mass is generated

approaching bare Higgs quark mass and pQCD regime
Conclusions and Outlook

• The CLAS detector has provided the dominant part of the world data on most exclusive meson electroproduction channels in the resonance region, allowing us to determine the electrocouplings of most resonances in the mass range up to 1.8 GeV and at $Q^2 < 5.0$ GeV$^2$. In the near future, the electrocouplings of all prominent nucleon resonances in the mass range <2.0 GeV will be determined from the CLAS data.

• A good description of the $\Delta(1232)3/2^+$ and N(1440)1/2+ electroexcitation amplitudes achieved within CSM approach starting from the QCD Lagrangian with the same dressed quark mass function as used in the successful evaluations of the elastic ground nucleon and pion form factors, and the pion PDF validates insight into EHM.

• The CSM parameter-free predictions on the $\Delta(1600)3/2^+$ electrocouplings have been confirmed by the first results on the electrocouplings of this state obtained from $\pi^+\pi^-p$ electroproduction data offering strong evidence in support of the CSM concept for EHM.

• The first estimates of the resonant contributions into inclusive (e,e'X) scattering computed with resonance electrocouplings from experimental data open up new opportunities to extend knowledge on PDF in the ground states of the nucleon towards large fractional parton momenta x in the resonance region and to explore quark-hadron duality.

• CLAS12 is the only facility in the world that is capable of obtaining the electrocouplings of all prominent N* states at the still unexplored ranges of $Q^2$ from 5.0 GeV$^2$ to 12 GeV$^2$, allowing us to map out the dressed quark mass function at quark momenta < 1.3 GeV, where a substantial part of hadron mass is generated.

• The CLAS/CLAS12 results on the $\gamma_vpN^*$ electrocouplings will address the most challenging problems of the Standard Model on the nature of hadron mass and emergence of the N* structure from QCD.
Back up
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.

- 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 get support from LQCD.

- Insight into dressed quark mass function from data on hadron structure represents a challenge for experimental hadron physics.
Insight into EHM from the Data on N/N* Structure

- 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.

- 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.
Toward Exploration of EHM from Orbital Nucleon Excitations

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.

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 electroexcitation amplitudes of the [70,1−] supermultiplet resonances ($L_{3q}=1$) with the same dressed quark mass function as used for the resonances with $L_{3q}=0$.
Insight to EHM From Resonance Electrocouplings

**Dyson-Schwinger Equations (DSE):**
- J. Segovia et al., PRL 115, 171801 (2015)
- J. Segovia et al., Few Body Syst. 55, 1185 (2014)

Good data description at $Q^2 > 2.0$ GeV$^2$ achieved with the same dressed quark mass function for the ground pion/nucleon and two excited nucleon states of distinctively different structure validates the continuum QCD results on the momentum dependence of the dressed quark mass. $\gamma_v pN^*$ electrocoupling data shed light on 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.
Studies of $\gamma vpN^*$ 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 $\gamma vpN^*$ 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, 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 $\gamma vpN^*$ electrocouplings at $Q^2 > 10$ GeV$^2$
**EHM from Global Hadron Structure Analysis**

Will be extended by the future data from JLab in the 12 GeV era

**Nucleon Elastic FF**

**γpN\(^*\) Electrocouplings**

\(N(1440)\frac{1}{2}^+\)

\(A_{2\,1000}(\text{GeV}^{-1/2})\)

\(Q^2\) (GeV\(^2\))

**Pion Elastic FF**

**Pion PDF**

**(e,e'X) Inclusive Scattering**

\(Q^2 = 3.025\text{ GeV}^2\)

\(W \text{ [GeV]}\)

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

- Insight into the dressed quark/gluon running masses from all the above experimental results within continuum QCD approach

Dressed Quark/Gluon Running Masses

- Dressed gluons
- Dressed quarks

\(M_0(k), m_q(k) \text{ [GeV]}\)

\(k \text{ [GeV]}\)
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.

\[ f_\pi E_\pi(p^2) = B(p^2) \]

• 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.