Excited Nucleon Structure and Strong QCD from Experiments with Electromagnetic Probes

Talk outline:

- N* electrocouplings as a window into strong QCD
- Extraction of $\gamma_p N^*$ electrocouplings from exclusive meson electroproduction data
- From $\gamma_p N^*$ electrocouplings to strong QCD dynamics
- Future prospects with CLAS12 and N*/DIS synergy
The experimental program on the studies of N* structure in exclusive meson electroproduction with CLAS/CLAS12 seeks to determine:

- $\gamma\nu pN^*$ electrocouplings at photon virtualities up to 5.0 GeV$^2$ for most of the excited proton states through analyzing major meson electroproduction channels from the CLAS data
- extend accessible $Q^2$ range up to 12 GeV$^2$ from the CLAS12 data and explore N* structure evolution in the transition from the strong and pQCD regimes
- search for hybrid baryons at $2.0 \text{ GeV} < W < 2.5 \text{ GeV}$ and $Q^2<2.0 \text{ GeV}^2$; completion of the N*-spectrum exploration from exclusive meson photo- and electroproduction off proton data

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

**Review papers:**

Excited Nucleon States and Insight into Strong QCD Dynamics

Emergence of Dressed Quarks and Gluons

N* structure studies address:
• Nature of > 98% of hadron mass
• Confinement and color charge emergence from QCD

Inferred from QCD Lagrangian with only the $\Lambda_{QCD}$ parameter
Extraction of $\gamma_vNN^*$ Electrocouplings from Exclusive Meson Electroproduction off Nucleons

Resonant amplitudes

Non-resonant amplitudes

Definition of $N^*$ photo-/electrocouplings employed in the CLAS data analyses:

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


- Consistent results on $\gamma_vpN^*$ electrocouplings from different meson electroproduction channels are critical in order to validate reliable extraction of these quantities.
### Summary of Published/Submitted 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 )</td>
</tr>
<tr>
<td></td>
<td>1.1-1.55</td>
<td>0.3-0.6</td>
<td>( d\sigma/d\Omega )</td>
</tr>
<tr>
<td></td>
<td>1.1-1.7</td>
<td>1.7-4.5</td>
<td>( d\sigma/d\Omega ), ( A_b )</td>
</tr>
<tr>
<td></td>
<td>1.6-2.0</td>
<td>1.8-4.5</td>
<td>( d\sigma/d\Omega )</td>
</tr>
<tr>
<td>( \pi^0\rho )</td>
<td>1.1-1.38</td>
<td>0.16-0.36</td>
<td>( d\sigma/d\Omega )</td>
</tr>
<tr>
<td></td>
<td>1.1-1.68</td>
<td>0.4-1.8</td>
<td>( d\sigma/d\Omega ), ( A_b, A_t, A_{bt} )</td>
</tr>
<tr>
<td></td>
<td>1.1-1.39</td>
<td>3.0-6.0</td>
<td>( d\sigma/d\Omega )</td>
</tr>
<tr>
<td>( \eta\rho )</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 )</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.70-5.40</td>
<td>( P^0, P' )</td>
</tr>
<tr>
<td>( K^+\Sigma^0 )</td>
<td>thresh-2.6</td>
<td>1.40-3.90</td>
<td>( d\sigma/d\Omega )</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.70-5.40</td>
<td>( P' )</td>
</tr>
<tr>
<td>( \pi^+\pi^0\rho )</td>
<td>1.3-1.60</td>
<td>0.2-0.6</td>
<td>Nine 1-fold differential cross sections</td>
</tr>
<tr>
<td></td>
<td>1.4-2.10</td>
<td>0.5-1.5</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.4-2.00</td>
<td>2.0-5.0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.3-1.83</td>
<td>0.4-1.0</td>
<td></td>
</tr>
</tbody>
</table>

- \( d\sigma/d\Omega \) – 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

**Over 140,000 data points!**

Almost full coverage of the final 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](http://clas.sinp.msu.ru/cgi-bin/jlab/db.cgi).
Approaches for Extraction of $\gamma_{v}NN^{*}$ Electrocouplings

Analyses of different meson electroproduction channels independently:

- $\pi^{+}n$ and $\pi^{0}p$ 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:

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

**Kinematics of exclusive $\pi^+n$ electroproduction off protons (lab frame)**

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

**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 Cross Sections off Protons

Contributing mechanisms seen in the data
E. Isupov et al. (CLAS), Phys. Rev. C96, 025209 (2017)

Resonant and non-resonant contributions

E. Isupov et al. (CLAS), Phys. Rev. C96, 025209 (2017)

Roper Resonance in 2002 & 2018

V. D. Burkert, Baryons 2002

V. D. Burkert, Baryons 2016
## Summary of Results on $\gamma_vpN^*$ Electrocouplings from CLAS

<table>
<thead>
<tr>
<th>Exclusive meson electroproduction channels</th>
<th>Excited proton states</th>
<th>$Q^2$-ranges for extracted $\gamma_vpN^*$ electrocouplings, GeV$^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\pi^0p$, $\pi^+n$</td>
<td>$\Delta(1232)3/2^+$, N(1440)1/2$^+$, N(1520)3/2$^-$, N(1535)1/2$^-$</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>$\pi^+\pi^0p$</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</td>
</tr>
</tbody>
</table>

The website with numerical results and references:
https://userweb.jlab.org/~mokeev/resonance_electrocouplings/

The interpolated/extra[polated CLAS results on $\gamma_vpN^*$ electrocouplings in the mass range <1.8 GeV and $Q^2$<5.0 GeV$^2$:

userweb.jlab.org/~isupov/couplings/.
$\gamma_{\nu}pN^*$ Electrocouplings from $N\pi$, $N\eta$, and $\pi^+\pi^-p$ Electroproduction

Consistent values of resonance electrocouplings from $N\pi$, $N\eta$, and $\pi^+\pi^-p$ electroproduction strongly support their reliable extraction.

The structure of all resonances studied with CLAS represents a complex interplay between the inner quark core and external meson-baryon cloud.
Δ- Electrocouplings: Global Multi-Channel Analysis vs $N\pi$ Electroproduction off Protons Analysis

Argonne-Osaka (AO) eight-channel coupled channel approach. H.Kamano, Few Body Syst. 59, 24 (2018)

CLAS results at the resonant point ($W=M_{N^*}$) from analysis of $N\pi$ electroproduction

real electro-coupling values

Other lines/symbols:
Previous AO analyses

at the pole position
Dyson-Schwinger Equations (DSE):
- J. Segovia et al., Few Body Syst. 55, 1185 (2014).

From Resonance Electrocouplings to Hadron Mass Generation

• **Dressed quark mass is running with momentum.**
• Good data description at $Q^2 > 2.0 \text{ GeV}^2$ with the same dressed quark mass function for the ground and different excited nucleon states validate the DSE results on generation of dressed quarks as the relevant degree of freedom in the structure of the ground and excited nucleons.
• $\gamma_v p N^*$ electrocoupling data offer access to the strong QCD dynamics underlying the hadron mass generation.

One of the most important achievements in hadron physics of the last decade in synergistic efforts between experimentalists and theorists.
Resolving Roper Puzzle

CLAS data in the range of $Q^2 < 5.0 \text{ GeV}^2$ revealed 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.

**For more details on resolving Roper puzzle see:**

**Quark core description within LF RQM and DSE is consistent**
Electrocouplings of the Orbital Excited Resonances from the CLAS $\pi^+\pi^-p$ Electroproduction Data


V.I. Mokeev et al.,
PRC 93, 054016 (2016)

Independent fits in different $W$-intervals:
- green: $1.51 < W < 1.61$ GeV
- red: $1.61 < W < 1.71$ GeV
- black: $1.71 < W < 1.81$ GeV
- magenta: $1.56 < W < 1.66$ GeV
- blue: $1.66 < W < 1.76$ GeV

The $\pi^+\pi^-p$ electroproduction is the major source of information on electrocouplings of the $\Delta(1620)1/2^-$, $\Delta(1700)3/2^-$, and $N(1720)3/2^+$ resonances that decay preferentially to the $N\pi\pi$ final states.
Extending the Kinematical Coverage of $\pi^+\pi^-p$ Electroproduction off Proton Data

Two data sets at $1.40 \text{ GeV} < W < 2.0 \text{ GeV}$ and $2.0 \text{ GeV}^2 < Q^2 < 5.0 \text{ GeV}^2$:
- blue - preliminary, A. Trivedi, R.W. Gothe, USC.

The JM18 model offers a good description of both $\pi^+\pi^-p$ electroproduction off protons data sets.
Future Extension of the Results on $\gamma_NpN^*$ Electrocouplings

In the near term future electrocouplings of most excited nucleon states in the mass range up to 2.0 GeV will become available from these data sets at $2.0 \text{ GeV}^2 < Q^2 < 5.0 \text{ GeV}^2$
• The $\gamma_vpN^*$ electrocouplings of most resonances in the mass range of $W<2.0$ GeV will become available in the near term future at $Q^2<5.0$ GeV$^2$ from the $N\pi$ and $\pi^+\pi^-p$ electro-production off protons data.

• Offer an excellent opportunity to map out dressed quark mass function at the distances corresponded strong QCD regime.

• Theoretical framework for the combined studies of the $N^*$ and ground nucleon structure in one- and three-dimensions:
  - common quark mass function for $N/N^*\leftrightarrow$ light front ground nucleon wave function $\leftrightarrow$ GPDs, TMDs

• The JM model estimates of the $\gamma_vp\rightarrow\pi^-\Delta^{++}, \pi^+\Delta^0, \rho p$ cross sections and amplitudes are of potential interest for $\pi X$ semi-inclusive studies, allowing us to account for the processes beyond those described within the factorization framework.

• Access to the ground nucleon parton distributions at large $x_B$ in the resonance region.
Accessing Parton Distributions in the Resonance Region

Interpolation of the CLAS data on $F_2(x,Q^2)$ structure function, M. Osipenko et al. (CLAS Coll), Phys. Rev. D67, 092001 (2003).

Resonant contributions from the CLAS results on $\gamma pN^*$ electrocouplings stored in: userweb.jlab.org/~mokeev/resonance_electrocouplings, userweb.jlab.org/~isupov/couplings/

The CLAS results on electrocouplings of most $N^*$ in the mass range $W < 1.8$ GeV and at $Q^2 < 5.0$ GeV makes it possible to evaluate the resonant contributions to the inclusive electron scattering offering access to the parton distributions at large $x_B$ in the resonance region.

See details in the talk: A.N. Hiller Blin  "Constraints from Finite-Energy Sum Rules on Inclusive Electron and Virtual Compton Scattering"
CLAS12 in Hall B

Physics run started successfully in February 2018.
CLAS12 N* Program at High $Q^2$

Measure exclusive electroproduction cross sections from an unpolarized proton target with polarized electron beam for $N\pi$, $N\eta$, $N\pi\pi$, KY:

$$E_b = 11 \text{ GeV}, \quad Q^2 = 3 \rightarrow 12 \text{ GeV}^2, \quad W \rightarrow 3.0 \text{ GeV}$$

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*.

*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 $\gamma_vpN^*$ 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.

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

CLAS results versus theory expectations with running quark mass

CLAS12 range

mass composition

<2% Higgs mechanism (HM)

>98% non-perturbative strong interaction

approaching bare Higgs quark mass and pQCD regime
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 $\pi^+n$, $\pi^0p$, $\eta p$, and $\pi^+\pi^-p$ electroproduction channels.

• Physics analyses of the $\gamma\nu pN^*$ electroexcitation amplitudes have revealed the structure of excited nucleons as a complex interplay between the inner core of three dressed quarks and the external meson-baryon cloud.

• **Profound impact on the exploration of strong QCD dynamics:**
  a) first DSE evaluations of $\Delta(1232)3/2^+$ and $N(1440)1/2^+$ electroexcitation amplitudes with a traceable connection to the QCD Lagrangian;
  b) synergistic efforts between the experimental studies of $\gamma\nu pN^*$ electrocouplings in Hall B at JLab and the continuum QCD theory have demonstrated the capability for reliable access to the mechanisms underlying hadron mass generation.

• Electrocouplings of most resonances in the mass range up to 2.0 GeV will become available at $Q^2<5.0$ GeV$^2$ from the new CLAS data on $N\pi$ and $\pi^+\pi^-p$ electroproduction in the near term future.

• Resonant contributions to the inclusive structure functions computed with $\gamma\nu pN^*$ electrocouplings inferred from the CLAS exclusive meson electroproduction off protons data offer an opportunity to explore the ground nucleon parton distributions at large $x_B$ in the resonance region.
Conclusions and Outlook

- CLAS12 is the only facility in the world capable of obtaining electrocouplings of all prominent N* states at still unexplored ranges of low photon virtualities down to 0.05 GeV² and highest photon virtualities for exclusive reactions from 5.0 GeV² to 12 GeV² from measurements of Nπ, π⁺π⁻p, and KY electroproduction.

- The expected results will allow us:
  a) to search for hybrid-baryons and complete the N*-spectrum exploration;
  b) to map out the dressed quark mass function at the distances where the transition from quark-gluon confinement to pQCD regime is expected, addressing the most challenging problems of the Standard Model on the nature of >98% of hadron mass and of quark-gluon confinement.

- Success of the N* program will be very beneficial for the hadron physics community. Synergistic effort between experimentalists, phenomenologists, and theorists on the combined studies of γpN* electrocouplings, elastic form factors, and the results on the 3D ground nucleon structure is required.

- The QCD-rooted theory framework for the unified description of the ground and excited nucleon state structure offering a description and predictions of the parameters extracted from experiment is of particular importance.
Back up
Dramatic events occur in the micro-second old universe during the transition from the QGP phase to hadron phase.

- Chiral symmetry is broken
- Quarks acquire mass
- Baryon resonances occur
- Quark-gluon confinement emerges

Full baryon spectrum shaped this transition
### Hybrid Baryons

**E12-16-010**

Search for hybrid baryons (qqqqg) focusing on $0.05 \text{ GeV}^2 < Q^2 < 2.0 \text{ GeV}^2$ in mass range from 1.8 to 3 GeV in $K\Lambda, N\pi\pi, N\pi$  

*(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 $Q^2 < 7.0 \text{ GeV}^2$  

*(D. Carman, et al.)*

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**Approved by PAC44**

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**Run Group conditions:**

<table>
<thead>
<tr>
<th>Energy (GeV)</th>
<th>Days</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.6</td>
<td>50</td>
</tr>
<tr>
<td>8.8</td>
<td>50</td>
</tr>
</tbody>
</table>

- Polarized electrons, unpolarized LH$_2$ target
- $L = 1 \times 10^{35} \text{ cm}^{-2}\text{s}^{-1}$
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.

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.

JLab LQCD group results:

- $N(1440)1/2^+$ $S_{1/2}$
- Black curves if state is a $q^3 N^*$
- Red curve if state is a $q^3g$ hybrid

Scalar Electroexcitation Amplitude

$Q^2 (\text{GeV}^2)$
Quark Model with Input from QCD-based Approaches


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 $\Delta(1232)^{3\frac{3}{2}^+}$, $N(1440)^{1\frac{1}{2}^+}$, $N(1520)^{3\frac{3}{2}^-}$, and $N(1535)^{1\frac{1}{2}^-}$
  → $q^3$ 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 $Q^2 > 3.0 \text{ GeV}^2$