$\gamma_{\nu}NN^*$ Electrocouplings: from the CLAS to the CLAS12 Data

V.I. Mokeev

The 6 GeV era came to successful close in May 12’ after fifteen years of running many productive world-class experiments. We are poised to continue our very successful experimental program with CLAS12. CLAS12 will be a unique worldwide facility for exploring strong interaction in the non-perturbative regime.
The studies of nucleon resonance (N*) structure: motivation and objectives

Our experimental program seeks to determine

\[ \gamma_{\mathrm{v}NN^*} \] transition helicity amplitudes (electrocouplings) at photon virtualities \( 0.2 < Q^2 < 6.0 \text{ GeV}^2 \) with CLAS and at \( 4.0 < Q^2 < 12.0 \text{ GeV}^2 \) with CLAS12 detectors for most of the excited proton states through analyzing major meson electroproduction channels independently and in a global multi-channel analyses.

This information is absolutely needed to study the non-perturbative strong interaction which generates \( N^* \) states as the bound systems of quarks and gluons.

The non-perturbative strong interaction represents the most important part of the Standard Model that we have yet to explore. The non-perturbative strong interaction is far more complex than the electromagnetic and weak interactions; and very different in nature.
Dynamical mass and structure of dressed quarks

- > 98% of dressed quark and N* masses and their dynamical structure are generated non-perturbatively through dynamical chiral symmetry breaking (DCSB). The Higgs mechanism accounts for less than 2% of the nucleon & N* mass.

- the data from CLAS/CLAS12 will allow us to explore the nature of the dominant part of hadron mass.

- the momentum dependence of the dressed quark mass reflects the transition from quark/gluon confinement to pQCD.
**$\gamma_vNN^*$ electrocouplings as a window to strong interactions in non-perturbative region**

**Quark core contribution to $\gamma_vNN^*$ electrocouplings**

- Quark propagators are sensitive to the quark running mass $M(q)$;

- Dressed quark e.m. current is sensitive to the quark anomalous electromagnetic moment (AEM);

- Quark interaction vertices $\Gamma$ and $X$ are sensitive to the quark anomalous chromomagnetic moment (ACM).

Studies of $\gamma_vNN^*$ electrocouplings at different photon virtualities $Q^2$ provide access to the quark mass function, structure, and $qq$-interactions, which are responsible for $N^*$ formation. Our studies will offer a unique way to explore quark/gluon confinement and DCSB in baryons.
Extraction of $\gamma_{v}NN^{*}$ electrocouplings from the data on exclusive meson electroproduction off protons

N*’s photo-/electrocouplings $\gamma_{v}NN^{*}$ are defined at $W=M_{N^{*}}$ through the N* electromagnetic decay width $\Gamma_{\gamma}$:

$$\Gamma_{\gamma} = \frac{Q_{\gamma r}^{2}}{\pi} \frac{2M^{N}}{(2J_{r} + 1)M_{N^{*}}} \left[A_{1/2}^{2} + A_{3/2}^{2}\right]$$

- Separation of resonant/non-resonant contributions within the framework of reaction models; Breit Wigner ansatz for parameterization of resonant amplitudes; fit of $\gamma_{v}NN^{*}$ electrocouplings and hadronic parameters to the data.

- Consistent results on $\gamma_{v}NN^{*}$ electrocouplings from different meson electroproduction channels demonstrate reliable extraction of N* parameters.
**N* electroexcitation in meson electroproduction off protons**

<table>
<thead>
<tr>
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<tbody>
<tr>
<td>Δ(1232) P_33</td>
<td>0.995</td>
<td></td>
<td></td>
</tr>
<tr>
<td>N(1440) P_11</td>
<td>0.55-0.75</td>
<td></td>
<td>0.3-0.4</td>
</tr>
<tr>
<td>N(1520) D_13</td>
<td>0.55-0.65</td>
<td></td>
<td>0.4-0.5</td>
</tr>
<tr>
<td>N(1535) S_11</td>
<td>0.48±0.03</td>
<td>0.46±0.02</td>
<td></td>
</tr>
<tr>
<td>Δ(1620) S_31</td>
<td>0.20-0.30</td>
<td></td>
<td>0.70-0.80</td>
</tr>
<tr>
<td>N(1650) S_11</td>
<td>0.60-0.95</td>
<td>0.03-0.11</td>
<td>0.1-0.2</td>
</tr>
<tr>
<td>N(1685) F_15</td>
<td>0.65-0.70</td>
<td></td>
<td>0.30-0.40</td>
</tr>
<tr>
<td>Δ(1700) D_33</td>
<td>0.1-0.2</td>
<td></td>
<td>0.8-0.9</td>
</tr>
<tr>
<td>N(1720) P_13</td>
<td>0.1-0.2</td>
<td></td>
<td>&gt;0.7</td>
</tr>
</tbody>
</table>

Hadronic decays of prominent N*'s for \(W<1.8\) GeV.

**CLAS data on yields of meson electroproduction reactions at \(Q^2<4\) GeV^2**

For \(W<1.8\) GeV, the \(\Delta(1232)\) and \(N(1440)\) are prominent hadronic decays of N* states.

\(N_\pi//N_\pi\pi\) channels are sensitive to N* states. They are major contributors to meson exclusive electroproduction in the N* excitation region.
Summary of the CLAS data on single-pion electroproduction off protons

Number of data points >125000, $W<1.7$ GeV, $0.15<Q^2<6.0$ GeV$^2$, almost complete coverage of the final state phase space. **Extended toward $W<3.0$ GeV $Q^2<5. GeV^2**

### Observables

<table>
<thead>
<tr>
<th>Observables</th>
<th>$Q^2$ area, GeV$^2$</th>
<th>Number of data points</th>
</tr>
</thead>
<tbody>
<tr>
<td>$d\sigma/d\Omega(\pi^0)$</td>
<td>0.16-1.45, 3.0-6.0</td>
<td>39830, 9000</td>
</tr>
<tr>
<td>$d\sigma/d\Omega(\pi^+)$</td>
<td>0.25-0.60, 1.7-4.3</td>
<td>25588, 30849</td>
</tr>
<tr>
<td>$A_{e}(\pi^0)$, $A_{t}(\pi^0)$</td>
<td>0.25-0.65</td>
<td>3981</td>
</tr>
<tr>
<td>$A_{e}(\pi^+)$, $A_{t}(\pi^+)$</td>
<td>0.40-0.65, 1.7 - 3.5</td>
<td>1730, 3535</td>
</tr>
<tr>
<td>$A_{et}(\pi^0)$</td>
<td>0.25-0.61</td>
<td>1521</td>
</tr>
</tbody>
</table>

**Low $Q^2$ results:**

I. Aznauryan et al., PRC 71, 015201 (2005); PRC 72, 045201 (2005).

**High $Q^2$ results on Roper:**

I. Aznauryan et al., PRC 78, 045209 (2008).

**Final analysis:**

The CLAS data on $\pi^+\pi^-p$ differential cross sections and their fit within the framework of meson-baryon reaction model JM

G.V. Fedotov et al, PRC 79 (2009), 015204
$1.30 < W < 1.56$ GeV; $0.2 < Q^2 < 0.6$ GeV$^2$

M. Ripani et al, PRL 91 (2003), 022002
$1.40 < W < 2.30$ GeV; $0.5 < Q^2 < 1.5$ GeV$^2$

$W = 1.5125$ GeV, $Q^2 = 0.375$ GeV$^2$

$W = 1.71$ GeV, $Q^2 = 0.65$ GeV$^2$

$1.30 < W < 1.56$ GeV; $0.2 < Q^2 < 0.6$ GeV$^2$

$1.40 < W < 2.30$ GeV; $0.5 < Q^2 < 1.5$ GeV$^2$

$\pi^+\Delta^0$

$\pi^-\Delta^{++}$

$\rho p$

$\pi^+D^0_{13}(1520)$

$\pi^+F^0_{15}(1685)$
Summary of the CLAS/Hall-C data on $\eta p$ electroproduction off protons

<table>
<thead>
<tr>
<th>Observables</th>
<th>Coverage over $Q^2$, GeV$^2$</th>
<th>Coverage over $W$, GeV</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>$d\sigma/d\Omega$</td>
<td>2.4, 3.6</td>
<td>1.48-1.62</td>
<td>[1]</td>
</tr>
<tr>
<td>$d\sigma/d\Omega$</td>
<td>0.38-2.5</td>
<td>1.50-1.86</td>
<td>[2]</td>
</tr>
<tr>
<td>$d\sigma/d\Omega$</td>
<td>0.13-3.3</td>
<td>1.50-2.30</td>
<td>[3]</td>
</tr>
<tr>
<td>$d\sigma/d\Omega$</td>
<td>5.7,7.0</td>
<td>1.50-2.30</td>
<td>[4]</td>
</tr>
</tbody>
</table>


Summary of the CLAS data on KY electroproduction off protons

<table>
<thead>
<tr>
<th>Observables</th>
<th>Channel</th>
<th>Coverage over $Q^2$, GeV$^2$</th>
<th>Coverage over $W$, GeV</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>$P_{x,y,z}$</td>
<td>$K\Lambda, K\Sigma^0$</td>
<td>0.7-5.4</td>
<td>1.60-2.60</td>
<td>[1]</td>
</tr>
<tr>
<td>$A_e$</td>
<td>$K\Lambda$</td>
<td>0.65-1.0</td>
<td>1.60-2.05</td>
<td>[2]</td>
</tr>
<tr>
<td>$d\sigma/d\Omega$</td>
<td>$K\Lambda, K\Sigma^0$</td>
<td>0.5-2.8</td>
<td>1.60-2.40</td>
<td>[3]</td>
</tr>
<tr>
<td>$P_{x,y,z}$</td>
<td>$K\Lambda$</td>
<td>0.3-1.5</td>
<td>1.60-2.15</td>
<td>[4]</td>
</tr>
</tbody>
</table>


More than 85% of meson electroproduction data worldwide were obtained in experiments with the CLAS detector and available in the CLAS Physics Data Base: http://clasweb.jlab.org/physicsdb/
• Analyses of different meson electroproduction channels independently:
  
  - $\pi^+n$ 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 $S_{11}(1535)$ dominance
  
  - $\pi^+\pi^-p$ channel:
    
    **Data driven JLAB-MSU meson-baryon model (JM)**
    
    V.I.Mokeev et al., CLAS Coll., arXiv:1205.3948 [nucl-ex], accepted by PRC.

• Global coupled-channel analyses of the CLAS/world data of $\pi N$, $\gamma_N N \rightarrow \pi N$, $\eta N, \eta \pi N$, $K\Lambda, K\Sigma$ exclusive channels:
  

Talk by T.Sato, Tuesday, August 14.
Fit of the Legendre Moments of Unpolarized Structure Functions


\[ Q^2 = 2.05 \text{GeV}^2 \]

Two conceptually different approaches DR and UIM are consistent. CLAS data provide rigid constraints for checking validity of the approaches.

\[ \sigma_T + \varepsilon \sigma_L = \sum_{l=0}^{n} D_l^{T+L} P_l(\cos \theta^*_\pi) \]

I. Aznauryan  
DR fit  
I. Aznauryan  
DR fit w/o \( P_{11} \)  
I. Aznauryan  
UIM fit
JM Model Analysis of the $\pi^+\pi^- p$ Electroproduction


**Major objectives:**
- Extraction of $g\nu NN^*$ electrocouplings and $\pi\Delta$, $\rho p$ decay widths.

$N^*$ contribute to $\pi\Delta$ and $\rho p$ channels only. Resonant amplitudes are parametrized within the framework of an updated BW ansatz, which imposes the constraint of unitarity.
Resonant /non-resonant contributions from the fit of $\pi^+\pi^- p$ electroproduction cross sections within the JM model

W=1.51 GeV, $Q^2=0.38$ GeV$^2$

W=1.51 GeV, $Q^2=0.43$ GeV$^2$

Full cross sections within the JM model

Reliable isolation of the resonant cross sections is achieved

resonant part

non-resonant part
One third of $G_M^*$ at low $Q^2$ is due to contributions from meson-baryon (MB) dressing:

Within the framework of relativistic QM [B. Julia-Diaz et al., PRC 69, 035212 (2004)], the bare-core contribution is very well described by the three-quark component of wave function

The transition to pQCD at photon at $Q^2$ up to 14 GeV$^2$?
The $P_{11}(1440)$ Electrocouplings from the CLAS Data

LF quark models:


Consistent values of $P_{11}(1440)$ electrocouplings determined in independent analyses of $N\pi$ and $\pi^+\pi^-p$ exclusive channels strongly support reliable electrocoupling extraction.

The physics analyses of these results revealed the $P_{11}(1440)$ structure as a combined contribution of: a) quark core as a first radial excitation of the nucleon $\bar{3}$-quark ground state and b) meson-baryon dressing.
Evaluation of $P_{11}(1440)$ electrocouplings within Dyson-Schwinger Equation of QCD (DSEQCD)

Evidence for substantial contributions from meson-baryon cloud.

Subject for our Workshop: Prospects for DSEQCD evaluations $P_{11}(1440)$ electrocoupings within a realistic quark-quark interaction through the DSEQCD approach and extension for another $N^*$ states see talk by C.D.Roberts at this Workshop

\[ g^2 D_{\mu\nu} (p-q) \Rightarrow \delta_{\mu\nu} \frac{4\pi \alpha_{IR}}{m_G^2} \]

\[ \frac{\alpha_{IR}}{4\pi} = 0.93 \quad m_G = 0.8 \text{GeV} \]

\[ m_q^{\text{bare}} = 0.007 \text{GeV} \Rightarrow m_q^{\text{dressed}} = 0.368 \text{GeV} \]
The \( D_{13}(1520) \) electrocouplings from the CLAS data

- A reasonable agreement between the results from \( N \pi \) and \( \pi^+ \pi^- p \) exclusive channels.
- Contributions from 3 dressed quarks in the first orbital excitation and MB cloud combined.
- Direct access from experimental data on \( A_{1/2} \) electrocoupling at \( Q^2 > 2.0 \, \text{GeV}^2 \) to quark core with negligible contribution from MB cloud.

Subject for our Workshop:
Prospects for evaluation of \( D_{13}(1520) \) electrocouplings within the framework of approaches which are explicitly related to QCD at photon virtualities up to 12 \( \text{GeV}^2 \)
S_{11} (1535) electrocouplings and their interpretation

Analysis of p\eta channel assumes S_{1/2}=0
Branching ratios: \beta_{N\pi} = \beta_{N\eta} = 0.45

- A_{1/2} (Q^2) from N\pi and p\eta are consistent
- First extraction of S_{1/2}(Q^2) amplitude

• LQCD & LCSR calculations (black solid lines) by Regensburg Univ. Group reproduces

Subject for our Workshop:
Prospects for evaluation of \gamma_v NN^* electrocouplings for other pairs of N^* parity partners; access to quark distribution amplitudes in N^* states of different quantum numbers.
High lying resonance electrocouplings from the $\pi^+\pi^-p$ CLAS data analysis

$N_{\pi\pi}$ CLAS preliminary.

$N_\pi$ world

$N_{\pi}$ $Q^2=0$, PDG.

$N_{\pi}$ $Q^2=0$, CLAS

- the $\pi^+\pi^-p$ electroproduction channel provided first preliminary results on $S_{31}(1620)$, $S_{11}(1650)$, $F_{15}(1685)$, $D_{33}(1700)$, and $P_{13}(1720)$ electrocouplings of a good accuracy.

Information on electrocouplings of most $N^*$ with $M_{N^*}<1.8$ GeV is available and will be extended in few years up to $Q^2=5.0$ GeV$^2$ and at $W<3.0$ GeV. This considerably extend the scope on baryon structure theory.
Impact of the Recent LQCD studies of N* Spectrum and Structure on the N* Program with CLAS/CLAS12


- each N* state with $M_{N^*} < 1.8$ GeV has partner in computed LQCD spectrum, but level ordering is not always consistent to the data.

- wave functions of the low-lying N* states dominate by 1-2 SU(6) configurations, while the wave function of high lying N*’s may contain many SU(6) configurations.

- presence of hybrid-N*’s with dominant contribution of hybrid components at $M_{N^*>1.9$ GeV marked by ♠️ ➔ Should be verified by experiment!

New direction in N* studies proposed in V.D.Burkert, arXiv:1203.2373 [nucl-ex]:
Search for hybrid N*-states looking for:
- overpopulation of SU(6)-multiplet;
- particular behavior of $\gamma_vNN^*$ electrocouplings, which reflects presence of the hybrid component.
Signals from \( N^* \) states in the CLAS KY electroproduction data

D. Carman, private communication

\[
C_l = \int \left\{ \frac{d\sigma}{d\theta_{K_T}} + \epsilon \frac{d\sigma}{d\theta_{KL}} \right\} P_l(z) d(-z)
\]

\[z = \cos(\theta_K)\]

the structures in \( W \)-dependencies of \( C_l \) – moments at the same \( W \)-values in all \( Q^2 \)-bins are consistent with the contributions from resonances of spin-parities listed in the plots

reaction model(s) are needed for extraction of \( N^* \) parameters from KY electroproduction
CLAS12 supports a broad program in hadronic physics.

Plans to study excited baryons and mesons:
- Search for hybrid mesons
- Spectroscopy of $\Xi^*$, $\Omega^-$
- $N^*$ Transition form factors at high $Q^2$.
Anticipated N* Electrocouplings from data on Nπ & Nππ electroproduction

- Open circles represent projections and all other markers the available results with the 6-GeV electron beam.

- Examples of published and projected results obtained within 60d for three prominent excited proton states from analyses of Nπ and Nππ electroproduction channels. Similar results are expected for many other resonances at higher masses, e.g. S_{11}(1650), F_{15}(1685), D_{33}(1700), P_{13}(1720), …

- This experiment will – for the foreseeable future – be the only experiment that can provide data on γvNN* electrocouplings for almost all well established excited proton states at the highest photon virtualities ever achieved in N* studies up to Q^2 of 12 GeV^2.
$\gamma N^*_{NN}$ Electrocouplings: A Unique Window into the Quark Structure

Meson-Baryon Dressing

$D_{13}(1520)$

$P_{11}(1440)$

--- absolute meson-baryon cloud amplitudes (EBAC)

quark core contributions (constituent quark models)

Data on $\gamma_{NN^*}$ electrocouplings from E12-09-003 experiment ($Q^2 > 5$ GeV$^2$) will afford for the first time direct access to the non-perturbative strong interaction among dressed quarks, their emergence from QCD, and the subsequent $N^*$ formation.
Electromagnetic form factors are sensitive to the running quark masses and their dynamical structure.

12 GeV experiment E12-09-003 will extend access to transition FF for all prominent N* states in the range up to $Q^2=12\text{GeV}^2$.

Prove the transition from confinement to pQCD regimes, allowing us to explore how confinement in baryons emerge from QCD and how >98% of baryon masses are generated non-perturbatively via dynamical chiral symmetry breaking.
Electrocoupling Sensitivity to Momentum Dependent Quark Mass & Structure

- Colored point with error bars: available CLAS results on $A_{1/2}$ electrocoupling of $P_{11}(1440)$
- CLAS12 projected quark core contribution estimated within:
  - LF quark model which employs momentum dependent mass of pointlike quark ($F_1=1$, $F_2=0$)
  - See the talk by V.D. Burkert at this Workshop

- DSE with contact $qq$-interaction and momentum independent mass function
- DSE expectation for QCD $qq$-interaction and momentum dependent mass function

$\gamma_v^*NN^*$ electrocouplings measured at the $Q^2 > 5.0\text{GeV}^2$ are sensitive to momentum dependence of dressed quark mass and structure.
Reaction Models for Extraction of $\gamma_{v}NN^*$ Electrocoupling at $Q^2>5.0$ GeV$^2$

• All current reaction models for extraction of $\gamma_{v}NN^*$ electrocouplings employ meson-baryon degrees of freedom. They can be applied at $Q^2<5.0$ GeV$^2$, where meson-baryon mechanisms are most relevant.

• The models explicitly account for the transition from meson-baryon to quark degrees of freedom are needed for extracting of $\gamma_{v}NN^*$ electrocouplings from $N\pi$ and $N\pi\pi$ electroproduction data at $5.0<Q^2<12.0$ GeV$^2$ and $W<2.0$ GeV.

The starting point:

- Description of non-resonant mechanisms in $\pi^+n$, $\pi^0p$, $\pi\Delta$, and $\rho p$ electroproduction channels with the full coverage of reaction phase, including:
  - hand-bag diagrams with GPD’s structure function from DIS studies;
  - reggeized meson-baryon amplitudes;
  - color dipole
  - others………. 

Most urgent need for $\gamma_{v}NN^*$ electrocoupling studies with the CLAS12!

Time scale:
Should be ready by 2015, when E-12-09-003 experiment is scheduled to start the collection of $N\pi$ and $N\pi\pi$ electroproduction data
Conclusions and outlook

• Data on $\gamma_{\nu}NN^*$ electrocouplings of most of the excited proton states in mass range $M_{N^*} < 1.8$ GeV are available from analyses of the CLAS meson electroproduction data at photon virtualities $Q^2 < 5.0$ GeV$^2$ for single meson and at $Q^2 < 1.5$ GeV$^2$ for double pion electroproduction. The files with numerical results can be requested from V.Mokeev (mokeev@jlab.org).

• $\gamma_{\nu}NN^*$ electrocoupling of most excited proton states in mass range up to 2.0-3.0 GeV will become available in future from analyses of both single and double pion electroproduction off protons at photon virtualities up to 5.0 GeV$^2$.

• CLAS data on KY electroproduction are important for the studies high-lying N* electrocouplings. Reaction models for KY channels are needed.

• **The CLAS12 detector is key for the N* Program.** Reaction models for extraction of $\gamma_{\nu}NN^*$ electrocoupling from $N\pi$ & $N\pi\pi$ electroproduction off protons at $5.0 < Q^2 < 12.0$ GeV$^2$ should be ready by 2015.

• Discussions at our Workshop will help on focusing on the where we need to go from here.
Major features of strong interaction in non-perturbative regime

\[ \alpha_s(Q^2) = \frac{12\pi}{(33 - 2n_f) \ln \frac{Q^2}{\Lambda^2}} \]

- Quark-gluon running coupling \( \alpha_s \) increases with distance
- Anti-screening (b) prevails over screening (a)
- \( \alpha_s \approx 1 \) as \( Q^2 \to \text{few GeV}^2 \)

Generation of dressed quarks and gluons

Dressed quarks and gluons acquire dynamical, momentum (distance) dependent masses, structure, and quark-gluon interaction amplitudes

- Quark/Gluon Confinement
- Dynamical Chiral Symmetry Breaking

Dressing contribution \( \sim (\alpha_s)^{N/2} \) (N stands for the number of interaction vertices).
Becomes dominant for the light u and d quarks and gluons as \( \alpha_s \approx 1 \).