Nucleon Resonance Studies from the data on Charged Double Pion Electroproduction with CLAS & CLAS12

Victor I. Mokeev
Jefferson Lab

• Introduction.

• Recent developments in analysis method for extraction of N* electrocouplings from Nππ electroproduction data

• New insights into the N* structure from our studies on the Nπ & Nππ CLAS data

• N* studies at high Q² with CLAS12

• Conclusions and outlook
Primary objectives in the studies of N* structure with CLAS & prospects with CLAS12

Our experimental program seeks to determine

- N-N* transition helicity amplitudes (electrocouplings) at photon virtualities $0.2 < Q^2 < 5.0 \text{ GeV}^2$ for almost all excited proton states from analyzing various meson electroproduction channels combined
- extend this studies with the CLAS12 detector toward still fully unexplored area of highest photon virtualities ever achieved $5.0 < Q^2 < 14.0 \text{ GeV}^2$.

This comprehensive information on $Q^2$ evolution of the N-N* electrocouplings will allow us to:

- determine the active degrees of freedom in N* structure at various distances;
- for the first time access dressed quarks;
- study the nonperturbative strong interactions which are responsible for
  - the ground and excited nucleon state formation,
  - and how they emerge from QCD.
How N* electrocouplings can be accessed

- Isolate the resonant part of production amplitudes by fitting the measured observables within the framework of reaction models, which are rigorously tested against data.
- N* electrocouplings can then be determined from resonant amplitudes under minimal model assumptions.

Consistent results on N* electrocouplings obtained in analyses of various meson channels (e.g. $\pi N$, $\eta p$, $\pi\pi N$) with entirely different non-resonant amplitudes will show that they are determined reliably.

Advanced coupled-channel analysis methods are being developing at EBAC: B.Julia-Diaz, T-S.H.Lee et al., PRC76, 065201 (2007); B.Julia-Diaz, et al., arXiv:0904.1918[nucl-th]
Why $N\pi/N\pi\pi$ electroproduction channels are important

- $N\pi/N\pi\pi$ channels are the two major contributors in $N^*$ excitation region;
- these two channels combined are sensitive to almost all excited proton states;
- they are strongly coupled by $\pi N \rightarrow \pi \pi N$ final state interaction;
- may substantially affect exclusive channels having smaller cross sections, such as $\eta p, K\Lambda$, and $K\Sigma$.

Therefore knowledge on $N\pi/N\pi\pi$ electroproduction mechanisms is key for the entire $N^*$ Program
**Nππ electroproduction data from CLAS**

The measurements with an unpolarized e⁻ beam onto a proton target offer nine differential cross sections in each $(W,Q^2)$ bin.

Number data points > 17500
1.3 < W < 2.1 GeV ;
0.25 < Q^2 < 1.5 GeV^2
prelim. 2.0 < Q^2 < 5.0 GeV^2

M. Ripani et al., PRL, 91, 022002 (2003);
G. Fedotov et al., PRC 79, 015204 (2009).
E. Isupov analysis at 2.<Q2<5.GeV^2
JLAB-MSU meson-baryon model (JM) for $N\pi\pi$ electroproduction.

Isobar channels included:

- All well established $N^*$s with $\pi\Delta$ decays and $3/2^+(1725)$ candidate, seen in CLAS $N\pi\pi$ data.
- Reggeized Born terms with effective FSI & ISI treatment.
- Extra $\pi\Delta$ contact term.

- All well established $N^*$s with $\rho p$ decays and $3/2^+(1725)$ candidate.
- Diffractive ansatz for non-resonant part and $\rho$-line shrinkage in $N^*$ region.
continued

3-body processes:

Isobar channels included:

- $\pi^+D_{13}^0(1520)$,
- $\pi^+F_{15}^0(1685)$,
- $\pi^-P_{13}^{++}(1640)$

isobar channels; observed for the first time in the CLAS data at $W > 1.5$ GeV.

Direct $2\pi$ production

Most relevant at $W<1.65$ GeV

V. Mokeev, V.Burkert, J. Phys. 69, 012019 (2007);
Description of the CLAS $N\pi\pi$ differential cross sections within the framework of JM model

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

$W=1.71$ GeV, $Q^2=0.65$ GeV$^2$
Resonant & non-resonant parts of $N\pi\pi$ cross sections as determined from the CLAS data fit within the framework of JM model.
**P_{11}(1440) electrocouplings from the CLAS data on Nπ/Nππ electroproduction**

**Nππ preliminary**

**Nπ**

Light front models:
- I. Aznauryan
- S. Capstick
- hybrid P_{11}(1440)

- **Good agreement** between the electrocouplings obtained from the Nπ and Nππ channels: Reliable measure of the electrocouplings.
- The electrocouplings for Q^2 > 2.0 GeV^2 are consistent with P_{11}(1440) structure as a 3-quark radial excitation of the nucleon.
- **Zero crossing for the A_{1/2} amplitude** has been observed for the first time, indicating the importance of light-front dynamics.
Fully integrated $\gamma p \rightarrow \pi^+\pi^- p$ cross sections: first observation of the structure at $W \sim 1.7$ GeV

- Full calculation
- $\pi^- \Delta^{++}$
- $\pi^+ \Delta^0$
- $\pi^+ D_{13}(1520)$
- $\pi^+ F_{15}(1685)$
- $p\ p$
- $\pi^+ P_{33}(1640)$
- Direct $2\pi$ production

$Q^2 = 0.95$ GeV$^2$
Fully integrated $\gamma p \to \pi^+\pi^- p$ cross sections at $2.0 < Q^2 < 5.0$ GeV$^2$

Resonant structures are clearly seen in entire $Q^2$ area covered by CLAS detector with 5.75 GeV/$e^-$ beam. The structure at $W \sim 1.7$ GeV becomes dominant as $Q^2$ increases.

![Graph showing cross sections for different $Q^2$ values](image)

- $Q^2 = 2.4$ GeV$^2$
- $Q^2 = 2.7$ GeV$^2$
- $Q^2 = 3.3$ GeV$^2$
- $Q^2 = 3.9$ GeV$^2$
- $Q^2 = 4.6$ GeV$^2$

- $D13(1520)$
- $P11(1440)$
- $D33(1700), P13(1720)$
- $3/2^+(1725), F15(1685)$
P_{13}(1720) state with hadronic decays fit to the CLAS data - 2.94<\chi^2/d.p.<3.15

<table>
<thead>
<tr>
<th></th>
<th>M, GeV</th>
<th>\Gamma_{tot}, MeV</th>
<th>BF(\pi\Delta)</th>
<th>BF(\rho p)</th>
</tr>
</thead>
<tbody>
<tr>
<td>P_{13}(1720) CLAS</td>
<td>1.728\pm 0.005</td>
<td>133\pm 19</td>
<td>66\pm 26</td>
<td>16\pm 11</td>
</tr>
<tr>
<td>P_{13}(1720) PDG</td>
<td>1.70 - 1.75</td>
<td>150-300</td>
<td>comp. with 0.</td>
<td>70-85</td>
</tr>
</tbody>
</table>

Precise data on \pi\Delta & \rho p hadronic decays of P_{13}(1720) are needed in order to understand origin of the structure at W\sim 1.7 GeV. This information can be obtained from analysis of \pi N\rightarrow \pi\pi N channel at JPARC and from the CLAS \pi^+\pi^- p photo and electroproduction data.
High lying resonance electrocouplings from $N\pi\pi$ CLAS data analysis

$N\pi\pi$ CLAS preliminary

$N^*$ decay widths to $\pi\Delta$, $\rho p$ final
States are inside the PDG uncertainties

$N\pi$ world

$N\pi$ CLAS $Q^2=0$
Electrocouplings of $[70,1-]$ SU$_{sf}(6)$-plet states from N$\pi$/N$\pi\pi$ CLAS data in comparison with quark model expectations

N$\pi$ preliminary

N$\pi$

Light front models:

S.Capstick:
each N$^*$ state is described by single h.o. 3q configuration

S.Simula:
Mass operator is diagonalized, utilizing a large h.o. basis for 3q configurations
The CLAS data on N* electrocouplings are sensitive to 3q configuration mixing, which is determined by dynamics of qq interactions.

The CLAS data on Q^2 evolution of electrocouplings for almost all N* states with M<1.8 GeV open up a promising opportunity to explore binding potential and qq interactions fitting their parameters to N* electrocouplings within the framework of constituent quark models and taking into account the contributions from meson-baryon (MB) cloud.
Meson-baryon dressing / Quark core contributions in the $A_{1/2}$ electrocouplings of the $P_{11}(1440)$ & $D_{13}(1520)$ states.

Estimates from EBAC for the MB dressing (absolute values): B.Julia-Diaz et al., PRC 76, 5201 (2007).

Light Front quark model by I.Aznauryan

MB contributions to $N^*$ electrocouplings are substantial at $Q^2<1.0$ GeV$^2$ and gradually decrease with $Q^2$;

Contribution from dressed quarks are expected to be dominant at $Q^2>5.0$ GeV$^2$. This area will be studied for the first time with CLAS12 detector after 12 GeV Upgrade.
Nucleon Resonance Studies with CLAS12


JLab PAC 34, January 26-30, 2009
Approved for 60 days beamtime

http://www.physics.sc.edu/~gothe/research/pub/nstar12-12-08.pdf

Argonne National Laboratory (IL,USA), Excited Baryon Analysis Center (VA,USA), Fairfield University (CT, USA), George Washington University (DC, USA), Idaho State University (ID, USA), Jefferson Lab (VA, USA), Moscow State University (Russia), Rensselaer Polytechnic Institute (NY, USA), University of Connecticut (CT, USA), University of South Carolina (SC, USA), and Yerevan Physics Institute (Armenia)

Spokesperson
Contact Person*
For the foreseeable future, CLAS12 will be the only facility worldwide, which will be able to access the N* electrocouplings in the $Q^2$ regime of $5 \text{ GeV}^2$ to $10 \text{ GeV}^2$, where the quark degrees of freedom are expected to dominate.
Physics objectives in the N* studies with CLAS12

- explore the interactions between the dressed quarks, which are responsible for the formation of ground and excited nucleon states.

- probe the mechanisms of light current quark dressing, which are responsible for >97% of nucleon mass.

- explore the transition between dressed and almost undressed quarks.

- constrain QCD’s $\beta$-function in the infrared.

Central direction in the studies of light quark confinement in baryons.

\[ Q^2 = 10 \text{ GeV}^2 \]

\[ \cdot (\text{p times number of quarks})^2 = 10 \text{ GeV}^2 \rightarrow p = 1.05 \text{ GeV} \]
Theory Support Group
I.Aznauryan⁹, V.M. Braun⁸, S.Capstick³, I.Cloët¹⁰, R. Edwards⁶, M.M. Giannini⁵,⁷, B. Julia-Diaz², H. Kamano², T.-S.H. Lee¹,², A. Lenz⁸, H.W. Lin⁶, A. Matsuyama², C.D. Roberts¹, E. Santopinto⁵,⁷, T. Sato², G. Schierholz⁸, N. Suzuki², Q. Zhao⁴, and B.-S. Zou⁴

Argonne National Laboratory (IL,USA)¹, Excited Baryon Analysis Center (VA,USA)², Florida State University(FL,USA)³ Institute of High Energy Physics (China)⁴, Istituto Nazionale di Fisica Nucleare (Italy)⁵, Jefferson Lab (VA, USA)⁶, University of Genova (Italy)⁷,University of Regensburg (Germany)⁸, Yerevan Physics Institute (Armenia)⁹ and University of Washington (WA, USA)¹⁰

Open invitation.
List is open to any and all who wish to participate!

Approaches for extraction and theoretical interpretation of N* electrocouplings are presented in the White Paper:
N* electrocouplings from LQCD

Current calculations with $m_\pi \sim 0.5$ GeV and limited operator basis are close to the data at $Q^2 > 1.0$ GeV$^2$, but failed at $Q^2 < 1.0$ GeV$^2$.

Prospects:
- approaching physical pion mass with full operator basis, take under control meson-baryon dressing;
- provide evaluations in $Q^2$ area up to 4.0 GeV$^2$, utilizing anisotropic lattice;
- by the time of 12 GeV Upgrade with updated computer power to extend evaluations of $\gamma_N N^*$ electrocouplings toward $Q^2 \sim 10$ GeV$^2$ at least for all $N^*$ states of minimal masses in each partial wave.

(All details are in the Section II of the White Paper)

F$_{1,2}$ form factors for P-PP$_{11}(1440)$ transition (exploratory calculations)

LQCD & Light Cone Sum Rule (LCSR) Approach

Theory group in Univ. of Regensburg

- LQCD is used to determine the moments of N* distribution amplitudes (DA)
- N* electrocouplings are determined from the respective DA’s within the LCSR framework.


Central question: How different are short distance quark DA’s for ground and excited nucleon states of various quantum numbers?

Evaluation of chiral parity partner electrocouplings (elastic & $\gamma pS_{11}(1535)S_{11}$) are already available (shadowed bands on the plot).

Near term prospects: a) approach phys. pion mass; b) advance LCSR to NLO

By the time of the 12 GeV Upgrade:
- electrocouplings of others N* doublets will be evaluated (e.g. P33(1232)&S31(1620));
- the data on N* electrocouplings at high $Q^2$, will allow us to constrain their light-cone DA’s, applying LCSR.

see White Paper Sec. iV
DSE provides an avenue to relate N* electrocouplings at high $Q^2$ to QCD and to test the theory’s capability to describe the N* formation based on QCD.

DSE approaches provide a link between dressed quark propagators, qq-scattering amplitudes and QCD.

N* electrocouplings can be determined by applying Faddeev equations with particular kernel to 3 dressed quarks while their propagators and interactions are derived from QCD.

By the time of the upgrade DSE evaluations for electrocouplings of several excited nucleon states will be available, offering an access to dynamical masses of dressed quarks.

see White Paper Sec. III
Conclusions and outlook

- Analysis of the CLAS data on $\pi^+\pi^-p$ electroproduction within the framework of JM model allowed us to establish all essential contributing mechanisms at $W < 1.8$ GeV and $0.25 < Q^2 < 1.50$ GeV$^2$. A good description of these data have been achieved, affording us to access the resonant parts of cross sections, which are directly related to $N^*$ electrocouplings.

- The $P_{11}(1440)$ and $D_{13}(1520)$ electrocouplings have been determined for the first time from both the $N\pi$ & $N\pi\pi$ datasets. The consistent results extracted from these two channels indicate a reliable electrocoupling measurement.

- A full set of the CLAS $N\pi\pi$ electroproduction data inside the structure at $W \sim 1.7$ GeV can be equally well described under two assumptions: a) manifestation of $3/2^+(1725)$ candidate state; b) an evidence for entirely different $P_{13}(1720)$ hadronic decays than reported in PDG. Precise data on $P_{13}(1720)\pi\Delta$ and $\rho p$ decays are needed in order to understand origin of this structure.

- Preliminary results on electrocouplings of $S_{31}(1620)$, $S_{11}(1650)$, $F_{15}(1685)$, $D_{33}(1700)$, and $P_{13}(1720)$ resonances were obtained from analysis of the $N\pi\pi$ CLAS data. The studies of $N\pi\pi$ electroproduction are vital in order to determine electrocouplings of high lying $N^*$’s that preferably decay to $N\pi\pi$ final states.

- Available CLAS data on $Q^2$ evolution of $N^*$ electrocouplings for the first time offer an opportunity to explore binding potential and qq interactions, that are responsible for $N^*$ formation within the framework of constituent quark models. MB dressing should be incorporated, in particular at $Q^2 < 1$ GeV$^2$. 
Conclusions and outlook

- Comparison of the data on electrocouplings of low lying N*’s with quark model expectations and with EBAC evaluations for MB cloud show that for $Q^2<1.0 \text{ GeV}^2$ both the MB cloud and quark core play an important role in the N* structure, while at $Q^2>5.0 \text{ GeV}^2$ quark degrees of freedom are expected to dominate. This new regime in N* electroexcitation will be studied for the first time after 12 GeV Upgrade.

- Electrocouplings of all prominent N*’s will be determined with the CLAS12 detector from $N_\pi$ & $N_{\pi\pi}$ electroproduction at fully unexplored photon virtualities from 5.0 to 14 GeV$^2$. Direct access to quark degrees of freedom in N*’s will enhance considerably our opportunities to explore dressed quark interactions, that are responsible for N* formation, quark DA’s in N* quark cores; for the first time will allow us to study their emergence from QCD and to explore generation of >97% of nucleon mass by strong interactions in nonperturbative regime.

- Strong theoretical support is needed in the following areas:
  a) development of reaction models for description of nonresonant mechanisms at high $Q^2$ accounting for quark degrees of freedom;
  b) development of approaches that are capable to relate $Q^2$ evolution of N* electrocouplings to the mechanisms that are responsible for N* formation (see www.jlab.org/~mokeev/react_models_high2/highq2.html).

Everybody willing to contribute are strongly encouraged to contact to Spoke/Contact Persons of the CLAS Collaboration Proposal on N* studies with CLAS12 Ralf Gothe (gothe@sc.edu) or Victor Mokeev (mokeev@jlab.org)
Back-up
Electrocouplings of $[70,1-]$ SU$_{sf}(6)$-plet states from N$\pi$/N$\pi\pi$ CLAS data and their description in SQTM approach

- SU(6) spin-flavor symmetry for quark binding interactions
- Dominant contribution from single quark transition operator:

$$A L_+ + B L_0 \sigma_+ + C \sigma_0 L_+ + D \sigma_- L_+ L_+$$

World data before CLAS measurements on transverse electrocouplings of $D_{13}(1520)$ and $S_{11}(1535)$ states (the areas between solid lines) allowed us to predict transverse electrocouplings for others $[70,1-]$ states (the areas between solid lines on the next slide), utilizing SU(6) symmetry relations.

Electrocouplings of $[70,1-]$ SU$_{sf}(6)$-plet states from N$\pi$/N$\pi\pi$ CLAS data and their description in SQTM approach

SQTM predictions are consistent with major features in the CLAS data, offering an indication for:

• relevance of quark degrees of freedom;

• substantial contribution to quark binding from interactions that poses SU(6) spin-flavor symmetry;

• considerable contribution from single quark transition operator to N-N* transition e.m. current.
D_{13}(1520) electrocouplings from the CLAS data on Nπ/Nππ electroproduction

- electrocouplings as determined from the Nπ & Nππ channels are in good agreement overall
- *but* the apparent discrepancies for the $A_{1/2}$ amplitude at $Q^2 \sim 0.4$ GeV$^2$ will be further investigated in a combined Nπ/Nππ analysis
- hypercentric Consituent Quark Model calculations reasonably describe electrocouplings at $Q^2 > 2.5$ GeV$^2$, suggesting that the 3-quark component is the primary contribution to the structure of this state at high $Q^2$. 

M.Giannini/E.Santopinto hyper-centric CQM
**Nπ CLAS data at low & high Q²**

Number of data points > 119,000, W < 1.7 GeV

<table>
<thead>
<tr>
<th>Observable</th>
<th>$Q^2$ [GeV²]</th>
<th>Number of Data points</th>
</tr>
</thead>
<tbody>
<tr>
<td>$d\sigma/d\Omega(\pi^0)$</td>
<td>0.35-1.6</td>
<td>31 018</td>
</tr>
<tr>
<td>$d\sigma/d\Omega(\pi^+)$</td>
<td>0.25-0.65</td>
<td>13 264</td>
</tr>
<tr>
<td></td>
<td>1.7-4.3</td>
<td>33 000</td>
</tr>
<tr>
<td>$A_e(\pi^0)$</td>
<td>0.40</td>
<td>956</td>
</tr>
<tr>
<td></td>
<td>0.65</td>
<td>805</td>
</tr>
<tr>
<td>$A_e(\pi^+)$</td>
<td>0.40</td>
<td>918</td>
</tr>
<tr>
<td></td>
<td>0.65</td>
<td>812</td>
</tr>
<tr>
<td></td>
<td>1.7 - 4.3</td>
<td>3 300</td>
</tr>
<tr>
<td>$d\sigma/d\Omega(\eta)$</td>
<td>0.375</td>
<td>172</td>
</tr>
<tr>
<td></td>
<td>0.750</td>
<td>412</td>
</tr>
</tbody>
</table>

**Low Q² results:**
I. Aznauryan et al., PRC 71, 015201 (2005); PRC 72, 045201 (2005);

**High Q² results on Roper:**
I. Aznauryan et al., PRC 78, 045209 (2008).

**Prelim. high Q² results on D_{13}(1520), S_{11}(1535):**

**Summary paper:**
I.G.Aznauryan, V.D.Burkert et al. (CLAS Collaboration) arXiv:0909.2349[nucl-ex]

full data set in: [http://clasweb.jlab.org/physicsdb/]
Input for $N\pi/N\pi\pi$ coupled channel analysis: partial waves of total spin $J$ for non-resonant helicity amplitudes in $\pi^-\Delta^{++}$ isobar channel.

$$\langle \lambda_f | T^J | \lambda_r \lambda_p \rangle =$$

$$\int \frac{2J + 1}{2} \langle \lambda_f | T | \lambda_r \lambda_p \rangle \sin \theta_f d\theta_f$$

Will be used for $N^*$ studies in coupled channel approach developing by EBAC.