Excited States of the Nucleon and New Resonance Structures from Two-Pion Electroproduction Data

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JAEA Hadron Group Seminar 6/13/2017
Hadron Physics and QCD

• High-energy physics has evolved to search for physics beyond the standard model
  – But the standard model is still evolving!

• A goal of hadron physics is to study the strong force in the standard model, QCD.
  – Solving QCD at non-perturbative energies is a difficult problem.
  – To test our understanding, we need improved theoretical calculations and better data.
Spectroscopy: positronium

\[
\begin{align*}
(10^{-10} \text{ MeV}) & \\
51026.0 & \\
51026.3 & 1^- \\
51026.0 & 2^{++} \\
51025.8 & 1^{++} \\
51025.9 & 1^{+-} \\
51025.6 & 0^{++} \\
51018 & \\
8.4 & 1^- \\
0^{+-} & \\
1.022 \times 10^{10} = 0 & \\
\end{align*}
\]

\[
\begin{align*}
^1S_0 & \\
^3S_1 & \\
^3P_{0,1,2} & \\
^1P_1 & \\
\end{align*}
\]
Spectrum of $c\bar{c}$ mesons

- $\eta_c(630)$
- $\psi'(699)$
- $\chi_2(577)$
- $\chi_1(525)$
- $\chi_0(430)$
- $J/\psi(112)$
- $\eta_c(0)$
- $\chi_c(541)$

Energy levels in MeV:
- $1^S_0$
- $3^S_1$
- $3^P_{0,1,2}$
- $1^P_1$

0 MeV
100 MeV
600 MeV
2986 MeV

CHARMONIUM
Group Theory: Flavor SU(3)

OCTET

DECUPLET
### Quark Model: Baryons (qqq)

<table>
<thead>
<tr>
<th>$N$</th>
<th>$sym$</th>
<th>$L^P$</th>
<th>$S$</th>
<th>$N(I = 1/2)$</th>
<th>$\Delta(I = 3/2)$</th>
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<td>$P_{11}(938)$</td>
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### PDG: Known Octet States

<table>
<thead>
<tr>
<th>$J^P$</th>
<th>$(D, L^P_N)$</th>
<th>Octet members</th>
<th>Singlets</th>
</tr>
</thead>
<tbody>
<tr>
<td>$1/2^+$</td>
<td>(56, $0^+_0$)</td>
<td>$1/2 \Lambda(939) \Lambda(1116)$</td>
<td>$\Sigma(1193)$, $\Xi(1318)$</td>
</tr>
<tr>
<td>$1/2^+$</td>
<td>(56, $0^+_2$)</td>
<td>$1/2 \Lambda(1440) \Lambda(1600)$</td>
<td>$\Sigma(1660)$, $\Xi(1690)^\dagger$</td>
</tr>
<tr>
<td>$1/2^-$</td>
<td>(70, $1^-_1$)</td>
<td>$1/2 \Lambda(1535) \Lambda(1670)$</td>
<td>$\Sigma(1620)$, $\Xi(1560)^\dagger$, $\Lambda(1405)$</td>
</tr>
<tr>
<td>$3/2^-$</td>
<td>(70, $1^-_1$)</td>
<td>$3/2 \Lambda(1520) \Lambda(1690)$</td>
<td>$\Sigma(1670)$, $\Xi(1820)$, $\Lambda(1520)$</td>
</tr>
<tr>
<td>$1/2^-$</td>
<td>(70, $1^-_1$)</td>
<td>$3/2 \Lambda(1650) \Lambda(1800)$</td>
<td>$\Sigma(1750)$, $\Xi(?)$</td>
</tr>
<tr>
<td>$3/2^-$</td>
<td>(70, $1^-_1$)</td>
<td>$3/2 \Lambda(1700) \Lambda(?)$</td>
<td>$\Sigma(1940)^\dagger$, $\Xi(?)$</td>
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<td>$5/2^-$</td>
<td>(70, $1^-_1$)</td>
<td>$3/2 \Lambda(1675) \Lambda(1830)$</td>
<td>$\Sigma(1775)$, $\Xi(1950)^\dagger$</td>
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<tr>
<td>$1/2^+$</td>
<td>(70, $0^+_2$)</td>
<td>$1/2 \Lambda(1710) \Lambda(1810)$</td>
<td>$\Sigma(1880)$, $\Xi(?)$, $\Lambda(1810)^\dagger$</td>
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<tr>
<td>$3/2^+$</td>
<td>(56, $2^+_2$)</td>
<td>$1/2 \Lambda(1720) \Lambda(1890)$</td>
<td>$\Sigma(?)$, $\Xi(?)$</td>
</tr>
<tr>
<td>$5/2^+$</td>
<td>(56, $2^+_2$)</td>
<td>$1/2 \Lambda(1680) \Lambda(1820)$</td>
<td>$\Sigma(1915)$, $\Xi(2030)$</td>
</tr>
<tr>
<td>$7/2^-$</td>
<td>(70, $3^-_3$)</td>
<td>$1/2 \Lambda(2190) \Lambda(?)$</td>
<td>$\Sigma(?)$, $\Xi(?)$, $\Lambda(2100)$</td>
</tr>
<tr>
<td>$9/2^-$</td>
<td>(70, $3^-_3$)</td>
<td>$3/2 \Lambda(2250) \Lambda(?)$</td>
<td>$\Sigma(?)$, $\Xi(?)$</td>
</tr>
<tr>
<td>$9/2^+$</td>
<td>(56, $4^+_4$)</td>
<td>$1/2 \Lambda(2220) \Lambda(2350)$</td>
<td>$\Sigma(?)$, $\Xi(?)$</td>
</tr>
</tbody>
</table>
Compare: Exp. to Quark Model

![Diagram showing comparison between experimental and quark model results for isospin (I) = 1/2 and 3/2 states, with mass in MeV/c^2.](image-url)
What have we learned?

• The quark model works well for the ground states with $L=0$.

• When $L>0$, the predictions of the quark model seem to break down.

• This may be because the energy required to excite a quark into higher orbitals is greater than the pion mass.
  – Is it more efficient to create pions than baryon resonances?
Some Theoretical Tools

• Lattice QCD: direct calculations of QCD using the concept of Feynman path integrals.
  – With advances in computers, these calculations are finally possible to predict hadron resonances.
  – One difference from the quark model is that gluon excitations can also form “hybrid” resonances.

• QCD sum rules: fundamental calculations, using the operator product expansion.
  – Oka-san is the expert in this area.
Lattice Gauge Theory
Lattice: heavy meson spectrum
Lattice Predictions: $N^*$ and $\Delta^*$

Hybrids

$m / \text{GeV}$

$m_\pi = 396 \text{ MeV}$
Empty/Yellow boxes are missing/uncertain baryon states.
Empty/Yellow boxes are missing/uncertain baryon states.
Do the new states fit into LQCD?

Ignoring the mass scale, new candidate states fit with the $J^P$ values predicted from LQCD.

Slide borrowed from V. Burkert.
Excited baryons are at the transition between the quark-gluon liquid, described in **hot QCD**, and the confinement of quarks and gluons in nucleons, described in **strong QCD**. This period lasted $\sim 10^{-6}$ seconds.

Do we understand this transition?

Slide borrowed from V. Burkert.
Heavy-ion collisions: a sketch

\[ \sqrt{s} \]

- **initial state**
- **pre-equilibrium**
- **QGP, hydro. expansion**
- **hadronization**
- **freeze-out**

**Temperature**

**Time**

- **freezing-out stage**
- "observed" in HIC

**detectors: hadrons**

Slide borrowed from S. Mukherjee.
The experimental program on the studies of N* structure in exclusive meson photo-/electroproduction with CLAS seeks to determine:

- $\gamma_v NN^*$ electrocouplings at photon virtualities up to 5.0 GeV$^2$ for most of the excited proton states from meson electroproduction.
- extend knowledge on the N*-spectrum and from the data for photo- and electroproduction reactions.

This provides a unique source of information on non-perturbative QCD that generates excited nucleon states (N*’s).
Excited Nucleon States and Insight to Strong QCD Dynamics

Emergence of Dressed Quarks and Gluons

Dressed Quark Borromeo Binding in Baryons

Dressed Quark Mass Function

Dressed Quark Mass, GeV

mass composition
<2% Higgs mechanism (HM)
>98% non-perturbative strong interaction

approaching bare HM mass

confinement (approaching constituent quark mass)

CLAS12 range

Excited Nucleon States and Insight to Strong QCD Dynamics

Emergence of Dressed Quarks and Gluons

Dressed Quark Borromeo Binding in Baryons

Dressed Quark Mass Function

Dressed Quark Mass, GeV

mass composition
<2% Higgs mechanism (HM)
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approaching bare HM mass

confinement (approaching constituent quark mass)
Extraction of $\gamma_v NN^*$ Electrocouplings from the Exclusive Meson Electroproduction off Nucleons


- Consistent results on $\gamma_v NN^*$ electrocouplings from different meson electroproduction channels and different analysis approaches demonstrate the reliable extraction of these quantities.

Resonant amplitudes

Non-resonant amplitudes

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

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

$\Gamma_\gamma$ stands for $N^*$ electromagnetic decay widths and $W=M_{N^*}$ on the real energy axis.
### Summary of the 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 1.1-1.55 1.1-1.7 1.6-2.0</td>
<td>0.16-0.36 0.3-0.6 1.7-4.5 1.8-4.5</td>
<td>( d\sigma/d\Omega ) ( d\sigma/d\Omega, A_b )</td>
</tr>
<tr>
<td>( \pi^0p )</td>
<td>1.1-1.38 1.1-1.68 1.1-1.39</td>
<td>0.16-0.36 0.4-1.8 3.0-6.0</td>
<td>( d\sigma/d\Omega ) ( d\sigma/d\Omega, A_b, A_t, A_{bt} )</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 0.70-5.40</td>
<td>( d\sigma/d\Omega ) ( P^0, P' )</td>
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<tr>
<td>( K^+\Sigma^0 )</td>
<td>thresh-2.6</td>
<td>1.40-3.90 0.70-5.40</td>
<td>( d\sigma/d\Omega ) ( P' )</td>
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<tr>
<td>( \pi^+\pi^-p )</td>
<td>1.3-1.6 1.4-2.1</td>
<td>0.2-0.6 0.5-1.5</td>
<td>Nine 1-fold differential cross sections</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

Almost full coverage of the final hadron phase space in \( \pi N, \pi^+\pi^-p, \eta p, KY \) electroproduction
Approaches for Extraction of $\gamma^*_{\nu}NN$ Electrocouplings from the CLAS Exclusive Meson Electroproduction Data

• Analyses of different pion 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 $N(1535)1/2^-$ dominance
  - $\pi^+\pi^-p$ channel:
    Data driven JLAB-MSU meson-baryon model (JM)

• Global coupled-channel analyses of the CLAS/world data of $\gamma^*_{\nu}N$, $\pi N$, $\eta N$, $\pi\pi N$, $K\Lambda$, $K\Sigma$ exclusive channels:
Fits to $\gamma p \rightarrow \pi^+ n$ Differential Cross Sections and Structure Functions

$Q^2 = 2.05 \text{ GeV}^2$

- DR
- DR w/o P11
- UIM

$Q^2 = 2.44 \text{ GeV}^2$

Legendre moments $D_l \ (l=0,1,2)$ from various structure functions
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$^2$

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

M. Ripani et al, PRL 91 (2003), 022002

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

$W = 1.71$ GeV, $Q^2 = 0.65$ GeV$^2$
Summary of the Results on $\gamma_v pN^*$ Electrocouplings from CLAS

<table>
<thead>
<tr>
<th>Exclusive meson electroproduction channels</th>
<th>Excited proton states</th>
<th>$Q^2$-ranges for extracted $\gamma_v NN^*$ 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^-$</td>
<td>0.30-4.16</td>
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<tr>
<td>$\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^-$</td>
<td>0.25-1.50</td>
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<tr>
<td></td>
<td>$\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>0.5-1.5</td>
</tr>
</tbody>
</table>

The values of resonance electrocouplings can be found in: https://userweb.jlab.org/~mokeev/resonance_electrocouplings/

The CLAS results on $\gamma_v pN^*$ electrocouplings for the excited states in mass range up to 1.8 GeV were interpolated/extrapolated in $Q^2$-range up to 5.0 GeV$^2$. 
Electrocouplings of $\Delta(1232)3/2^+$, $N(1440)1/2^+$, $N(1520)3/2^-$, $N(1535)1/2^-$, $N(1675)5/2^-$, $N(1680)5/2^+$, $N(1710)1/2^+$ were published in the recent edition of the PDG, Chin. Phys. C40, 100001 (2016).
Elucidating the Running Dressed Quark Mass

Data on $\Delta(1232)3/2^+$ electroexcitation from CLAS for the first time demonstrated that dressed quark mass is running with momentum.
Validating the Access to the Quark Mass Function

Dyson-Schwinger Equations (DSE):
- 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 and excited nucleon states of distinctively different structure.

One of the most important achievement in hadron physics of the last decade obtained in synergistic efforts between experimentalists and theorists.
Accessing Quark Mass Function from the $N\pi/\pi^+\pi^-p$ Electroproduction off Protons Data

Resonant/Non-resonant contributions from the fit of the CLAS $\pi^+\pi^-p$ electroproduction off protons cross sections (V.I.Mokeev, et al., PRC 93 025206 (2016))

CLAS data

JM model analysis:
- fit to the data computed cross sections
- resonant part of the computed cross sections
- non-resonant part of the computed cross sections

• non-resonant contributions are determined from the data fit
Meson-Baryon Cloud and Quark Core in the N* Structure

First estimates for meson-baryon cloud amplitudes from the CLAS data on resonance electrocouplings and DSE/LF RQM evaluations for the quark core

- MB cloud is relevant at $Q^2<1.5$ GeV$^2$
- MB cloud dominates at $Q^2<4.5$ GeV$^2$

The structure of all studied resonances is determined by a complex interplay between inner core of dressed quarks and external meson-baryon cloud.
Peculiarities in the Structure of $\Delta(1620)_{1/2}^-$

- Only known resonance with dominant longitudinal electroexcitation at $Q^2 > 0.5 \text{ GeV}^2$.
- QM with three quarks only failed in describing the resonance electrocoupings.

Hadron decays from the CLAS $\pi^+\pi^-p$ electroproduction data

<table>
<thead>
<tr>
<th>Channel</th>
<th>Branching Fraction, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\pi\Delta$</td>
<td>27-64</td>
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<tr>
<td>$\rho p$</td>
<td>31-63</td>
</tr>
</tbody>
</table>

Large $\rho p$ decay in the sub-threshold region

Suggestive for a substantial contribution from $\rho p$ loops:
- either to the MB-cloud or as
- penta-quark admixture in the quark core

Evaluation of $\Delta(1620)_{1/2}^-$ electrocoupings at $Q^2 > 2.0 \text{ GeV}^2$ (in progress).
New CLAS Results on $\pi^0 p$ electroproduction

1.10GeV<$W<$1.80 GeV,
0.3 GeV$^2<$Q$^2<$1.0 GeV$^2$

Fully integrated cross sections

Fit of the structure functions within the framework of UIM/DR (slide#6,7) will provide electrocouplings of the resonances in mass range up to 1.8 GeV with substantial decays to the $N\pi$ final state.

The structure functions

Preliminary
Sensitivity of the $\pi^0 p$ Electroproduction off Protons Data to Electrocouplings of the Excited Nucleon States in the 3-rd Resonance Region

- Structure functions were evaluated within the UIM (see slide #7)
- $\gamma_vpN^*$ electrocouplings and hadronic decay widths were taken from previous analyses of the CLAS $N\pi$ and $\pi^+\pi^-p$ electroproduction off protons data.
- The data on unpolarised structure functions are compared with the UIM expectations accounting for all relevant resonances and when particular $\gamma_vpN^*$ amplitudes were switched off.

Sensitivity to electrocouplings of $N(1680)^{5/2}^-$

Sensitivity to electrocouplings of $\Delta(1700)^{3/2}^-$
\[\frac{d\sigma}{d\Omega^*} = \sigma_T + \varepsilon\sigma_L + \varepsilon\sigma_{TT}\cos2\phi + \sqrt{2\varepsilon(\varepsilon+1)}\sigma_{LT}\cos\phi\]

\[\sigma_L + \varepsilon\sigma_T = a\]

\[\sigma_{LT} = \frac{b}{\sin\theta\sqrt{2\varepsilon(\varepsilon+1)}}\]

\[\sigma_{TT} = \frac{c}{\sin^2\theta\varepsilon_T}\]

**M. Ungaro, talk at INT N* Workshop 2016**
Electrocouplings of the Orbital Excited Resonances from the CLAS $\pi^+\pi^-p$ Electroproduction Data


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 data are the major source of the information on electrocouplings of the $\Delta(1620)1/2^-$, $\Delta(1700)3/2^-$, and $N(1720)3/2^+$ resonances which decay preferentially to the $N\pi\pi$ final states.

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

- Extraction of $\gamma pN^*$ electrocouplings for most $N^*$s in mass range up to 2.0 GeV and $2.0 < Q^2 < 5.0$ GeV$^2$.

- Search for new baryon states through their manifestations in exclusive $\pi^+\pi^-p$ electroproduction with $Q^2$-independent masses and decay widths.

The CLAS $\pi^+\pi^-p$ Electroproduction Data at High Photon Virtualities

Fully integrated $\pi^+\pi^-p$ electroproduction cross sections off protons

1.40 GeV$<W<2.00$ GeV, $2.00$ GeV$^2<Q^2<5.0$ GeV$^2$

- $N(1440)\frac{1}{2}^+$
- $N(1520)\frac{3}{2}^-$
- $N(1685)\frac{5}{2}^+$, $\Delta(1700)\frac{3}{2}^+$
- $N(1720)\frac{3}{2}^+$, $N'(1720)\frac{3}{2}^+$

Mass range where the signals from new baryon states were reported, A.V. Anisovich et al., Eur. Phys. J. A48, 15 (2012).
Q²-Evolution of the Resonant Contributions to the $\pi^+\pi^-p$ Electro-production off Protons Cross sections at $2.0 \text{ GeV}^2 < Q^2 < 5.0 \text{ GeV}^2$

Resonant cross sections:
- Central values
- Uncertainty range
- Data point error bars show the stat. uncertainty
- Bands on the bottom are the data syst. uncertainties

- Resonant contributions were computed within the framework of unitarized Breit-Wigner ansatz successfully used for extraction of the resonance electrocouplings.

- $\gamma_vpN^*$ electrocouplings and $\pi\Delta/\rho p$ decay widths were taken from the CLAS results

Growth of the relative resonant contributions with $Q^2$ suggests good prospects for extraction of $\gamma_vpN^*$ electrocouplings in the entire range of $2.0 \text{ GeV}^2 < Q^2 < 5.0 \text{ GeV}^2$. 
Description of the Differential $\gamma_vp\rightarrow\pi^+\pi^p$ Cross Sections at 2.0 GeV$^2$$<Q^2<5.0$ GeV$^2$
within the Updated JM17 model

- A good description of data at 1.4 GeV $< W < 2.0$ GeV and 2.0 GeV$^2$ $< Q^2 < 4.2$ GeV$^2$ was achieved with $\chi^2$/d.f. $< 1.4$.

JM17 model;
- no new mechanisms in comparison with JM15 (slide #6).
- modifications for the non-resonant amplitudes of the $\pi\Delta$, $\rho p$, and $\pi^+ N(1680)5/2^+$ meson-baryon channels.
Extension of the Experimental Results on $\gamma_v p N^*$ Electrocouplings and the Need for the Theory Support

- $\gamma_v p N^*$ electrocouplings of all prominent nucleon resonances in mass range $M_{N^*} < 2.0$ GeV and at $0.3 < Q^2 < 5.0$ GeV$^2$ will be determined from independent analyses of $N\pi$, $N\pi\pi$, channels measured with the CLAS.

- The information on the structure of orbital excited $N^*$ with total orbital momenta of dressed quarks $L=1$ and $L=2$ will become available for the first time.

- DSE evaluations of the $[70,1^-], [56,2^+]$ $SU_{sf}(6)$-multiplet electrocouplings will extend the access to the strong QCD dynamics allowing us to address:
  a) environmental sensitivity of the quark mass function to orbital excitations of three dressed quarks;
  b) complexity of quark-gluon vertex dressing beyond rainbow-ladder truncation;
  c) first studies of pseudoscalar and vector di-quark correlations.

- New data on $\gamma_v p N^*$ electrocouplings will shed light on dynamical Chiral Symmetry Breaking (DCSB) and its evolution with distance from studies of the chiral partners $\Delta(1232)3/2^+/\Delta(1700)3/2^-$ as the first step.
Simplest rainbow-ladder (RL) truncation:
All structures $L_{i\mu}$ are equal to zero except $L_{1\mu}$.

Far from reality, but a reasonable approximation for the states with orbital momentum of quarks $L=0$.

Dressing of quark-gluon vertex beyond RL-truncation produces nonzero quark orbital angular momenta.

Electrocouplings of $N^*$ states with nonzero quark orbital angular momentum extend the capabilities for access to the complexity of quark-gluon vertex dressing beyond the simplest rainbow-ladder truncation.
Evidence for the New State $N'(1720)3/2^+$ from Combined Analyses of $\pi^+\pi^-p$ Photo- and Electroproduction off Protons

The structure at $W\approx 1.7$ GeV represents the major feature for $W$-dependencies of fully integrated cross sections at $0.5 \text{ GeV}^2 < Q^2 < 5.0 \text{ GeV}^2$ (see also slide #20).

<table>
<thead>
<tr>
<th>Resonance</th>
<th>$\text{BF(}\pi\Delta), %$</th>
<th>$\text{BF(}\rho p), %$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N'(1720)3/2^+$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>electroproduction</td>
<td>64-100</td>
<td>&lt;5</td>
</tr>
<tr>
<td>photoproduction</td>
<td>14-60</td>
<td>19-69</td>
</tr>
<tr>
<td>$\Delta(1700)3/2^-$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>electroproduction</td>
<td>77-95</td>
<td>3-5</td>
</tr>
<tr>
<td>photoproduction</td>
<td>78-93</td>
<td>3-6</td>
</tr>
</tbody>
</table>

Successful description of $\pi^+\pi^-p$ photo- and electroproduction data achieved by implementing new $N'(1720)3/2^+$ state with $Q^2$-independent hadronic decay widths of all resonances contributing at $W\approx 1.7$ GeV provides strong evidence for the existence of new $N'(1720)3/2^+$ state.

The contradictory Branching Fraction (BF) for $N(1720)3/2^+$ decays to the $\pi\Delta$ and $\rho p$ final states deduced from photo- and electroproduction data make it impossible to describe the data with conventional states only.
The parameters of $N'(1720)^{3/2}$ and $N(1740)^{3/2}$ from the CLAS Data Fit

The photo-/electrocouplings of $N'(1720)^{3/2}$ and conventional $N(1740)^{3/2}$ states:

<table>
<thead>
<tr>
<th>Resonance</th>
<th>Mass, GeV</th>
<th>Total width, MeV</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N'(1720)^{3/2}$</td>
<td>1.715-1.735</td>
<td>120±6</td>
</tr>
<tr>
<td>$N(1720)^{3/2}$</td>
<td>1.743-1.753</td>
<td>112±8</td>
</tr>
</tbody>
</table>
**N* at 0.05 GeV² < Q² < 7.0 GeV² with the CLAS12**

<table>
<thead>
<tr>
<th>Hybrid Baryons PR12-16-010</th>
<th>Search for hybrid baryons (qqqg) focusing on 0.05 GeV² &lt; Q² &lt; 2.0 GeV² in mass range from 1.8 to 3 GeV in KΛ, Nπππ, Nπ (A. D’Angelo, et al.)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>KY Electroproduction PR12-16-010A</strong></td>
<td>Study N* structure for states that couple to KY through measurements of cross sections and polarization observables that will yield Q² evolution of electrocoupling amplitudes at Q²&lt;7.0 GeV² (D. Carman, et al.)</td>
</tr>
</tbody>
</table>

**Approved by PAC44**

<table>
<thead>
<tr>
<th>Run Group conditions:</th>
</tr>
</thead>
<tbody>
<tr>
<td>E_b = 6.6 GeV, 50 days</td>
</tr>
<tr>
<td>E_b = 8.8 GeV, 50 days</td>
</tr>
</tbody>
</table>

- Polarized electrons, unpolarized LH₂ 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.

The only way to establish the nature of a baryon state as $q^3$ or $q^3g$ is from the $Q^2$ evolution of its electroexcitation amplitudes.
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 the almost 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 GeV².*

CLAS12 is the only facility foreseen in the world capable to map-out $N^*$ quark core under almost negligible contributions from meson-baryon cloud.

The experiments will start at the end of 2017!
Emergence of Hadron Mass and Quark-Gluon Confinement

N* electroexcitation studies with CLAS12 in Hall B at JLab will address the critical open questions:

- How is >98% of visible mass generated?
- How confinement emerges from QCD and how it is related to DCSB?

Mapping-out quark mass function from the CLAS12 results on $\gamma_vpN^*$ electrocouplings of spin-flavor 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 with a traceable connection to the QCD Lagrangian.

CLAS results versus theory expectations with running quark mass

Access to the dressed quark mass function

- mass composition
  - <2% Higgs mechanism (HM)
  - >98% non-perturbative strong interaction

approaching bare Higgs mass and pQCD regime
Conclusions and Outlook

• High quality meson electroproduction data from CLAS allowed us to determine the electrocouplings of most well-established resonances in mass range up to 1.8 GeV from analyses of $\pi^+n$, $\pi^0p$, $\eta p$ and $\pi^+\pi^-p$ electroproduction channels.

• 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 DSE theory and the experimental studies of $\gamma vpN^*$ electroproduction couplings at JLAB revealed access to quark mass function for the first time.
  c) reaction model developments pave a way to relating quark mass function to the measured observables of $N\pi$ and $\pi^+\pi^-p$ electroproduction channels based on DSE input for the low-mass $N^*$ electrocouplings.

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

• Future analyses the CLAS results on electrocouplings of $N^*$ resonances within the QCD-based framework will extend insight to the strong QCD dynamics addressing:
  a) the environmental sensitivity/ universality of dressed quark mass function,
  b) complexity of the dressed quark-gluon vertex and qq-interaction kernel,
  c) shed light on the DCSB manifestation in the structure of chiral partners $\Delta(1232) 3/2^+$ and $\Delta(1700)3/2^-$. 
Conclusions and Outlook

• After 12 GeV Upgrade, CLAS12 will be only available worldwide facility capable to obtain electrocouplings of all prominent N* states at still unexplored ranges of low photon virtualities down to 0.05 GeV$^2$ and highest photo virtualities ever achieved for exclusive reactions from 5.0 GeV$^2$ to 12 GeV$^2$ from the measurements of exclusive N$\pi$, π+π$^-p$, and KY electroproduction.

• The expected results will allow us:
  a) search for hybrid-baryons and other new states of baryon matter;
  b) to map out the dressed quark mass function at the distance scales 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 quark-gluon confinement.

• Success of N* Program with the CLAS12 detector at Jefferson Lab will be very beneficial for hadron physics community. It requires close collaborative efforts between experiment, phenomenology and the QCD-based hadron structure theory.
Back up
Analysis of the $\gamma p/ep \rightarrow \pi^+\pi^- p$ CLAS data at $W \sim 1.7$ GeV in the JM15 model

### Photoproduction

1.17$<\chi^2/d.p.<1.31$ (1.66 GeV$<W<1.76$ GeV)

- Fit of $\theta_{\pi^-}$, $\theta_{\pi^+}$, $\theta_p$ angular distributions requires essential contribution(s) from $J^\pi=3/2^+$ resonances
- Accounting for the known resonances only results in contradictory values for the N(1720)3/2+ BF to the $\rho p$ final state inferred from the photo- and the electroproduction data
Data description in the JM17 model:

- full
- no $N'(1720)_{3/2}^+$
- difference with/without $N'(1720)_{3/2}^+$

CLAS data will elucidate the $N'(1720)_{3/2}^+$ structure at $0.0<Q^2<5.0$ GeV$^2$ for the first time.
γγpN* Electrocouplings from Nπ, π⁺π⁻p, and ηp Electroproduction

Consistent values of resonance electrocouplings from analyses of Nπ/π⁺π⁻p and Nπ/Nη electroproduction off protons demonstrate the capabilities of the developed reaction models to obtain resonance electrocouplings in independent analyses of these exclusive channels.

Electrocouplings of Δ(1232)3/2⁺, N(1440)1/2⁺, N(1520)3/2⁻, N(1535)1/2⁻, N(1675)5/2⁻, N(1680)5/2⁺, N(1710)1/2⁺ were published in the recent edition of the PDG, Chin. Phys. C40, 100001 (2016).
Nature of the Hadron Mass from N* Electroexcitation

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

Common dressed quark mass function employed for description of elastic, N→Δ G\textsubscript{M} form factors and N(1440)1/2\textsuperscript{+} electrocouplings/form factors

- **Good CLAS data description** at the distances where quark core is the biggest contributor (Q\textsuperscript{2}>0.8 GeV\textsuperscript{2}), was achieved with realistic qq-interaction that generates momentum dependent quark mass.

- **Data on Δ(1232)3/2\textsuperscript{+} electroexcitation** from CLAS for the first time demonstrated that dressed quark mass which is running with momentum.