Electroexcitation of Nucleon Resonances

Ralf W. Gothe

Baryon 2016, Mai 16-20                      FSU, Tallahassee, FL

• γNN* Vertexcouplings: A unique exploration of baryon and quark structure?
• Analysis and New Results: Phenomenological but consistent!
• Outlook: New experiments with extended scope and kinematics!
• QCD based Theory: Can we solve non-perturbative QCD and confinement?

This work is supported in parts by the National Science Foundation under Grant PHY 1505615.
Spectroscopy
Build your Mesons and Baryons …

Three Generations of Matter (Fermions)

<table>
<thead>
<tr>
<th>Quarks</th>
<th>Mass/Charge/Spin/Name</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>U</strong></td>
<td>2.4 MeV, 2/3, 1/2, up</td>
</tr>
<tr>
<td><strong>C</strong></td>
<td>1.27 GeV, 2/3, 1/2, charm</td>
</tr>
<tr>
<td><strong>T</strong></td>
<td>171.2 GeV, 2/3, 1/2, top</td>
</tr>
<tr>
<td><strong>Y</strong></td>
<td>0, 0, 1, photon</td>
</tr>
<tr>
<td><strong>d</strong></td>
<td>4.8 MeV, -1/3, 1/2, down</td>
</tr>
<tr>
<td><strong>s</strong></td>
<td>104 MeV, -1/3, 1/2, strange</td>
</tr>
<tr>
<td><strong>b</strong></td>
<td>4.2 GeV, -1/3, 1/2, bottom</td>
</tr>
<tr>
<td><strong>g</strong></td>
<td>0, 0, 1, gluon</td>
</tr>
</tbody>
</table>

Leptons

<table>
<thead>
<tr>
<th>Leptons</th>
<th>Mass/Charge/Spin/Name</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>e</strong></td>
<td>0.511 MeV, -1/2, 1/2, electron</td>
</tr>
<tr>
<td><strong>μ</strong></td>
<td>105.7 MeV, -1, 1/2, muon</td>
</tr>
<tr>
<td><strong>τ</strong></td>
<td>1.777 GeV, -1, 1/2, tau</td>
</tr>
<tr>
<td><strong>W</strong></td>
<td>80.4 GeV, ±1, 1, weak force</td>
</tr>
</tbody>
</table>

Bosons (Forces)

<table>
<thead>
<tr>
<th>Bosons</th>
<th>Mass/Charge/Spin/Name</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Ve</strong></td>
<td>&lt;2.2 eV, 1/2, electron neutrino</td>
</tr>
<tr>
<td><strong>Vμ</strong></td>
<td>&lt;0.17 MeV, 1/2, muon neutrino</td>
</tr>
<tr>
<td><strong>Vτ</strong></td>
<td>&lt;15.5 MeV, 1/2, tau neutrino</td>
</tr>
<tr>
<td><strong>Z</strong></td>
<td>91.2 GeV, 0, 1, weak force</td>
</tr>
</tbody>
</table>
N and $\Delta$ Excited Baryon States ...

- Orbital excitations (two distinct kinds in contrast to mesons)

- Radial excitations (also two kinds in contrast to mesons)
Quark Model Classification of N*

Lowest Baryon Supermultiplets

SU(6)xO(3) Symmetry

Particle Data Group

- ****
- ***
- **

L_{3q}

Δ(1232)

D_{13}(1520)
S_{11}(1535)

Roper P_{11}(1440)

- q²g
- q³g
- q³q\overline{q}
+ N-Meson
+ ...

- q²q
- ...

0 \hbar\omega
1 \hbar\omega
2 \hbar\omega
3 \hbar\omega

1135 MeV
1545 MeV
1839 MeV
2130 MeV

N

Mass

Dietmar Menze

Particle Data Group:
- ****
- ***
- **

Mass:
- 1135 MeV
- 1545 MeV
- 1839 MeV
- 2130 MeV

Δ(1232) (56,0+)
D_{13}(1520) (56,2+)
S_{11}(1535) (56,2+)(70,0+)(70,1-)(20,1+)
Roper P_{11}(1440) (56,3-) (70,3-) (20,1-)

Dietmar Menze
Quark Model Classification of N*

BnGa energy-dependent coupled-channel PWA of CLAS K⁺Λ and other data

<table>
<thead>
<tr>
<th>L_{3q}</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>(56,0+)</td>
<td>(56,0+)</td>
<td>(56,0+)</td>
<td>(56,0+)</td>
</tr>
<tr>
<td>1</td>
<td>(70,1-)</td>
<td>(70,1+)</td>
<td>(70,2+)</td>
<td>(70,3-)</td>
</tr>
<tr>
<td>2</td>
<td>(70,2-), (70,2+), (56,2+)</td>
<td>(70,2-), (70,2+), (56,2+)</td>
<td>(20,1+), (56,1-), (70,1-)</td>
<td>(20,3-)</td>
</tr>
<tr>
<td>3</td>
<td>(56,3-), (70,3-), (20,3-)</td>
<td>(56,3-), (70,3-), (20,3-)</td>
<td>(56,3-), (70,3-), (20,3-)</td>
<td>(56,3-), (70,3-), (20,3-)</td>
</tr>
</tbody>
</table>

Particle Data Group
- ****
- ***
- **

Mass
- 1135 MeV
- 1545 MeV
- 1839 MeV
- 2130 MeV

Dietmar Menze

naive q²q model

Lowest Baryon Supermultiplets

SU(6)xO(3) Symmetry
## N/Δ Spectrum in RPP 2012

<table>
<thead>
<tr>
<th>$N^*$</th>
<th>$J^P$ ($L_{2f,2j}$)</th>
<th>2010</th>
<th>2012</th>
<th>Δ</th>
<th>$J^P$ ($L_{2f,2j}$)</th>
<th>2010</th>
<th>2012</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p$</td>
<td>$1/2^+$ ($P_{11}$)</td>
<td>******</td>
<td>******</td>
<td></td>
<td>$1/2^+$ ($P_{11}$)</td>
<td>******</td>
<td>******</td>
</tr>
<tr>
<td>$n$</td>
<td>$1/2^+$ ($P_{11}$)</td>
<td>******</td>
<td>******</td>
<td></td>
<td>$1/2^+$ ($P_{11}$)</td>
<td>******</td>
<td>******</td>
</tr>
<tr>
<td>N(1440)</td>
<td>$1/2^+$ ($P_{11}$)</td>
<td>******</td>
<td>******</td>
<td></td>
<td>$1/2^+$ ($P_{11}$)</td>
<td>******</td>
<td>******</td>
</tr>
<tr>
<td>N(1520)</td>
<td>$3/2^-$ ($D_{13}$)</td>
<td>******</td>
<td>******</td>
<td></td>
<td>$3/2^+$ ($P_{33}$)</td>
<td>******</td>
<td>******</td>
</tr>
<tr>
<td>N(1535)</td>
<td>$1/2^-$ ($S_{11}$)</td>
<td>******</td>
<td>******</td>
<td></td>
<td>$1/2^-$ ($S_{31}$)</td>
<td>******</td>
<td>******</td>
</tr>
<tr>
<td>N(1650)</td>
<td>$1/2^-$ ($S_{11}$)</td>
<td>******</td>
<td>******</td>
<td></td>
<td>$1/2^-$ ($S_{31}$)</td>
<td>******</td>
<td>******</td>
</tr>
<tr>
<td>N(1675)</td>
<td>$5/2^-$ ($D_{15}$)</td>
<td>******</td>
<td>******</td>
<td></td>
<td>$5/2^+$ ($F_{35}$)</td>
<td>******</td>
<td>******</td>
</tr>
<tr>
<td>N(1680)</td>
<td>$5/2^+$ ($F_{15}$)</td>
<td>******</td>
<td>******</td>
<td></td>
<td>$1/2^+$ ($P_{31}$)</td>
<td>******</td>
<td>******</td>
</tr>
<tr>
<td>N(1685)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$1/2^+$ ($P_{31}$)</td>
<td>******</td>
<td>******</td>
</tr>
<tr>
<td>N(1700)</td>
<td>$3/2^-$ ($D_{13}$)</td>
<td>******</td>
<td>******</td>
<td></td>
<td>$3/2^+$ ($P_{33}$)</td>
<td>******</td>
<td>******</td>
</tr>
<tr>
<td>N(1710)</td>
<td>$1/2^+$ ($P_{11}$)</td>
<td>******</td>
<td>******</td>
<td></td>
<td>$1/2^-$ ($S_{31}$)</td>
<td>******</td>
<td>******</td>
</tr>
<tr>
<td>N(1720)</td>
<td>$3/2^+$ ($P_{13}$)</td>
<td>******</td>
<td>******</td>
<td></td>
<td>$3/2^-$ ($D_{33}$)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>N(1860)</td>
<td>$5/2^+$</td>
<td></td>
<td></td>
<td></td>
<td>$5/2^+$ ($F_{35}$)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>N(1875)</td>
<td>$3/2^-$</td>
<td></td>
<td></td>
<td></td>
<td>$1/2^-$ ($S_{31}$)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>N(1890)</td>
<td>$3/2^+$</td>
<td></td>
<td></td>
<td></td>
<td>$1/2^-$ ($S_{31}$)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>N(1900)</td>
<td>$3/2^+$ ($P_{13}$)</td>
<td></td>
<td></td>
<td></td>
<td>$3/2^-$ ($D_{33}$)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>N(1990)</td>
<td>$1/2^+$ ($F_{17}$)</td>
<td></td>
<td></td>
<td></td>
<td>$1/2^+$ ($F_{17}$)</td>
<td></td>
<td>**</td>
</tr>
<tr>
<td>N(2000)</td>
<td>$5/2^+$ ($F_{15}$)</td>
<td></td>
<td></td>
<td></td>
<td>$5/2^+$ ($F_{15}$)</td>
<td></td>
<td>**</td>
</tr>
<tr>
<td>N(2080)</td>
<td>$D_{13}$</td>
<td></td>
<td></td>
<td></td>
<td>$D_{13}$</td>
<td></td>
<td>**</td>
</tr>
<tr>
<td>N(2090)</td>
<td>$S_{11}$</td>
<td></td>
<td></td>
<td></td>
<td>$S_{11}$</td>
<td></td>
<td>**</td>
</tr>
<tr>
<td>N(2040)</td>
<td>$3/2^+$</td>
<td></td>
<td></td>
<td></td>
<td>$3/2^+$</td>
<td></td>
<td>**</td>
</tr>
<tr>
<td>N(2060)</td>
<td>$5/2^-$</td>
<td></td>
<td></td>
<td></td>
<td>$5/2^-$</td>
<td></td>
<td>**</td>
</tr>
<tr>
<td>N(2100)</td>
<td>$1/2^+$ ($P_{11}$)</td>
<td></td>
<td></td>
<td></td>
<td>$1/2^+$ ($P_{11}$)</td>
<td></td>
<td>**</td>
</tr>
<tr>
<td>N(2120)</td>
<td>$3/2^-$</td>
<td></td>
<td></td>
<td></td>
<td>$3/2^-$</td>
<td></td>
<td>**</td>
</tr>
<tr>
<td>N(2190)</td>
<td>$7/2^-$ ($G_{17}$)</td>
<td></td>
<td></td>
<td></td>
<td>$7/2^-$ ($G_{17}$)</td>
<td></td>
<td>**</td>
</tr>
<tr>
<td>N(2200)</td>
<td>$D_{15}$</td>
<td></td>
<td></td>
<td></td>
<td>$D_{15}$</td>
<td></td>
<td>**</td>
</tr>
<tr>
<td>N(2220)</td>
<td>$9/2^+$ ($H_{19}$)</td>
<td></td>
<td></td>
<td></td>
<td>$9/2^+$ ($H_{19}$)</td>
<td></td>
<td>**</td>
</tr>
<tr>
<td>N(2250)</td>
<td>$9/2^-$ ($G_{19}$)</td>
<td></td>
<td></td>
<td></td>
<td>$9/2^-$ ($G_{19}$)</td>
<td></td>
<td>**</td>
</tr>
<tr>
<td>N(2600)</td>
<td>$11/2^-$ ($I_{11}$)</td>
<td></td>
<td></td>
<td></td>
<td>$11/2^-$ ($I_{11}$)</td>
<td></td>
<td>**</td>
</tr>
<tr>
<td>N(2700)</td>
<td>$13/2^+$ ($K_{13}$)</td>
<td></td>
<td></td>
<td></td>
<td>$13/2^+$ ($K_{13}$)</td>
<td></td>
<td>**</td>
</tr>
</tbody>
</table>

Are we observing parity doublets with the new states or not?

FROST experiment produced 900 data points of the double-polarization observable $E$ in $\pi^+\gamma p \rightarrow \pi^+ n$ photoproduction with circularly polarized beam on longitudinally polarized protons for $W = 1240 - 2260$ MeV.

Significant improvements of the description of the data in SAID, Jülich, and BnGa partial-wave analyses after fitting.

New evidence found in this data for a $\Delta(2200)\frac{7}{2}^-$ resonance (BnGa analysis).

The strong interaction physics is encoded in the nucleon excitation spectrum that spans the degrees of freedom from meson-baryon and dressed quarks to elementary quarks and gluons.

LQCD predicts states with the same quantum numbers as CQMs with underlying SU(6)xO(3) symmetry.

R. Edwards et al.,
arXiv:1104.5152, 1201.2349
Transition Form Factors
Hadron Structure with Electromagnetic Probes

- Study the structure of the nucleon spectrum in the domain where dressed quarks are the major active degree of freedom.
- Explore the formation of excited nucleon states in interactions of dressed quarks and their emergence from QCD.

\[ Q^2 = -K_\mu^2 \]
Hadron Structure with Electromagnetic Probes

- Study the structure of the nucleon spectrum in the domain where dressed quarks are the major active degree of freedom.
- Explore the formation of excited nucleon states in interactions of dressed quarks and their emergence from QCD.

\[ \pi, \rho, \omega \ldots \]

\[ Q^2 \]

\[ \text{low} \]

\[ q \]

\[ \text{3q-core+MB-cloud} \]

\[ \text{3q-core} \]

\[ \text{pQCD} \]

\[ \text{high} \]

\[ \text{meson dressed quark} \]

\[ \text{LQCD, DSE and …} \]

\[ \text{confinement} \]

\[ \text{current quark} \]

\[ \text{e.m. probe} \]

\[ \text{quark mass (GeV)} \]

\[ q (\text{GeV}) \]
Baryon Excitations and Quasi-Elastic Scattering

Deep Inelastic Scattering
S. Stein et al., PR D22 (1975) 1884
Structure Analysis of the Baryon

Demolition of a chimney at the "Henninger Brewery" in Frankfurt am Main, Germany, on 2 December 2006

hard and confined

hard and soft

quasi-elastic
$\gamma_{\nu NN}^*$

Extraction
Data-Driven Data Analyses

Consistent Results

- Single meson production:
  Unitary Isobar Model (UIM)
  Fixed-\( t \) Dispersion Relations (DR)
- Double pion production:
  Unitarized Isobar Model (JM)
- Coupled-Channel Approach:
  EBAC \(\Rightarrow\) Argonne-Osaka
  JAW \(\Rightarrow\) Jülich-Athens-Washington
  BoGa \(\Rightarrow\) Bonn-Gatchina

Electrocouplings of N(1440)P_{11} from CLAS Data

Consistent results obtained in the low-lying resonance region by independent analyses in the exclusive Nπ and pπ^+π^- final-state channels – that have fundamentally different mechanisms for the nonresonant background – underscore the capability of the reaction models to extract reliable resonance electrocouplings.

Transition Form Factors and QCD Models

Roper resonance $P_{11}(1440)$

- $A_{1/2}$ has zero-crossing near $Q^2=0.5$ and becomes dominant amplitude at high $Q^2$.
- Consistent with radial excitation at high $Q^2$ and large meson-baryon coupling at small $Q^2$.
- Eliminates gluonic excitation ($q^3G$) as a dominant contribution.

Nick Tyler closes the 1-2 GeV$^2$ gap for single pion production.
Transition Form Factors and QCD Models

Roper resonance $P_{11}(1440)$

- $A_{1/2}$ has zero-crossing near $Q^2=0.5$ and becomes dominant amplitude at high $Q^2$.
- Consistent with radial excitation at high $Q^2$ and large meson-baryon coupling at small $Q^2$.
- Eliminates gluonic excitation ($q^3G$) as a dominant contribution.

New proposal on electroexcited gluon hybrids to be submitted to PAC44
N* Spectrum in LQCD

The strong interaction physics is encoded in the nucleon excitation spectrum that spans the degrees of freedom from meson-baryon and dressed quarks to elementary quarks and gluons.

LQCD predicts hybrid baryon states replicating the negative parity multiplet structure.

New proposal on electroexcited gluon hybrids submitted to PAC44
Evidence for the Onset of Precocious Scaling?

- $A_{1/2} \propto 1/Q^3$
- $A_{3/2} \propto 1/Q^5$

Evidence for the Onset of Precocious Scaling?

V. Mokeev, userweb.jlab.org/~mokeev/resonance_electrocouplings/ (2016)
Evidence for the Onset of Precocious Scaling?

V. Mokeev, userweb.jlab.org/~mokeev/resonance_electrocouplings/ (2016)

V. Mokeev, userweb.jlab.org/~mokeev/resonance_electrocouplings/ (2016)
Electrocouplings of N(1520)D_{13} and N(1535)S_{11}

\[ A_{1/2} \]

\[ A_{3/2} \]

Argonne Osaka / EBAC DCC MB dressing (absolute values)

E. Santopinto, M. Giannini, hCQM
PRC 86, 065202 (2012)

S. Capstick, B.D. Keister (rCQM)
PRD51, 3598 (1995)

\[ \pi^+\pi^- p \] 2012
\[ \pi^+\pi^- p \] 2010
\[ N\pi \] 2009

\[ \eta p \] CLAS/Hall-C
Evidence for the Onset of Precocious Scaling?


- $A_{1/2} \propto 1/Q^3$
- $A_{3/2} \propto 1/Q^5$
- $G^*_M \propto 1/Q^4$

$$q^2q$$

$$Q^2 (\text{GeV}^2)$$

$S_{11} Q^3 A_{1/2}$
$F_{15} Q^5 A_{3/2}$
$P_{11} Q^3 A_{1/2}$
$D_{13} Q^5 A_{3/2}$
\[ N \to \Delta \] Multipole Ratios \( R_{\text{EM}}, R_{\text{SM}} \)

- New trend towards pQCD behavior does not show up
- \( R_{\text{EM}} \to +1 \) \( R_{\text{SM}} \to \text{const} \)
- \( G_{M,\text{J.-S.}}^* \to 1/Q^4 \) \( G_{M,\text{Ash}}^* \to 1/Q^5 \)
- CLAS12 can measure \( G_M^* \), \( R_{\text{EM}} \), and \( R_{\text{SM}} \) up to \( Q^2 \approx 12 \text{ GeV}^2 \)
$N(1520)D_{13}$ Helicity Asymmetry

$A_\text{hel} = \frac{A_{1/2}^2 - A_{3/2}^2}{A_{1/2}^2 + A_{3/2}^2}$

L. Tiator

$A_{1/2}$

$S_{1/2}$

$A_{3/2}$

$Q^2(\text{GeV}/c)^2$

$D_{13}(1520)$

$F_{15}(1680)$

$P_{33}(1232)$

$10^{-3}\text{GeV}^{-1/2}$

$A_{1/2}$ vs. $Q^2$

$S_{1/2}$ vs. $Q^2$

$A_{3/2}$ vs. $Q^2$

PDG estimation

N$\pi$ (UIM, DR)

World data

$A_\text{hel} = \frac{A_{1/2}^2 - A_{3/2}^2}{A_{1/2}^2 + A_{3/2}^2}$
\( \gamma N N* \) Helicity Asymmetries

V. Mokeev, userweb.jlab.org/~mokeev/resonance_electrocouplings/ (2016)
The almost direct access to
• quark core from the data on N(1520)3/2-
• meson-baryon cloud from the data on N(1675)5/2-
sheds light on the transition from the confined quark to the colorless meson-baryon structure and its dependents on the N* quantum numbers.
New Experimental Results & Approaches
Higher-Lying Resonance Electrocouplings

N(1680)F_{15}


- - - - D. Merten, U. Löring et al.

- - - - Z. Lee and F. Close

- - - - E. Santopinto and M.M. Gianini


Nππ: V. Mokeev (JM)

Nπ: I.G. Aznauryan (UIM & DR)
Higher-Lying Resonance Electrocouplings

N(1675)D_{15}

Kijun Park

N\pi: I.G. Aznauryan (UIM & DR)

D. Merten, U. Löring et al.
B. Julia-Diaz, T.-S.H. Lee et al.
E. Santopinto and M.M. Gianini
Independent fits in different W-intervals

- green: 1.46<W<1.56 GeV
- magenta: 1.56<W<1.66 GeV
- red: 1.61<W<1.71 GeV
- blue: 1.66<W<1.76 GeV
- black: 1.71<W<1.81 GeV

result in consistent electrocouplings and hence offer sound evidence for their reliable extraction.

The $\pi^+\pi^-p$ electroproduction channel provides first preliminary results on the $\Delta(1620)1/2^-$, $N(1650)1/2^-$, $N(1680)5/2^+$, $\Delta(1700)3/2^-$, and $N(1720)3/2^+$ electrocouplings with good accuracy.

V. Mokeev et al., Phys. Rev. C 93, 025206
New $N'(1720)3/2^+$ State and its Properties

A successful description of $\pi^+\pi^-p$ photo- and electro-production cross sections at $Q^2=0$, 0.65, 0.95, and 1.30 GeV$^2$ has been achieved by implementing a new $N'(1720)3/2^+$ state with $Q^2$-independent hadronic decay widths of all resonances that contribute at $W\sim1.7$ GeV, that allows us to claim the existence of a new $N'(1720)3/2^+$ state.

<table>
<thead>
<tr>
<th>Resonance</th>
<th>BF($\pi\Delta$), %</th>
<th>BF($pp$), %</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N'(1720)3/2^+$ electroproduction</td>
<td>47-64</td>
<td>3-10</td>
</tr>
<tr>
<td>photoproduction</td>
<td>46-62</td>
<td>4-13</td>
</tr>
<tr>
<td>$N(1720)3/2^+$ electroproduction</td>
<td>39-55</td>
<td>23-49</td>
</tr>
<tr>
<td>photoproduction</td>
<td>38-53</td>
<td>31-46</td>
</tr>
<tr>
<td>$\Delta(1700)3/2^-$ 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>

Mass: 1.715-1.735 GeV
Width: 120 6 MeV

Mass: 1.743-1.753 GeV
Width: 112 8 MeV
\[ \left( \frac{d^2\sigma}{dX_{ij} d\phi_j} \right) = R_{2T} X_{ij} + R_{2L} X_{ij} \cos \phi_j + R_{2TT} X_{ij} \cos 2\phi_j \]

Chris McLauchlin extracts the beam helicity dependent differential cross sections.

\( Q^2, W \text{ bin } = [1.25, 1.75) \text{GeV}^2, [1.625, 1.650) \text{GeV} \)
\( Q^2, W \text{ bin } = [1.25, 1.75) \text{GeV}^2, [1.625, 1.650) \text{GeV} \)
Single $\pi$ Electroproduction off the Deuteron

Ye Tian
Single $\pi$ Electroproduction off the Deuteron

Below a missing momentum of 0.2 GeV the measured data coincides with the resolution smeared theoretical Fermi momentum distribution.
Single $\pi$ Electroproduction off the Deuteron

Gary Hollis inclusive of the proton in the Deuteron with correction of Fermi smearing.
**FSI for $\gamma n \rightarrow \pi^- p$**

[V. Tarasov, A. Kudryavtsev, W. Briscoe, H. Gao, IS, Phys Rev C 84, 035203 (2011)]

\[ R_{FSI} = \frac{(d\sigma/d\Omega_{\pi p})}{(d\sigma^{TA}/d\Omega_{\pi p})} \]

**Cuts:**
- $p_s > 200$ MeV/c
- $p_t > 200$ MeV/c

**CLAS data:**
- $E > 1$ GeV
- $\theta > 32$ deg

- There is no large sensitivity to cuts.

- Our estimation of the Glauber FSI corrections gives the value of 5%.

- Previous estimations gave the order of 15-30%.

- For CLAS data
  - The FSI correction factor $R < 1$.
  - The behavior is smooth vs. $\theta$.
  - The effect $\Delta\sigma/\sigma \leq 10\%$.

- There is a sizeable FSI effect from S-wave part of pp-FSI at small angles.

- This region narrows as the $E_t$ increases.

\[ W = 1350 \text{ MeV} \quad W = 1662 \text{ MeV} \]
\[ W = 1924 \text{ MeV} \quad W = 2154 \text{ MeV} \]
\[ W = 2362 \text{ MeV} \quad W = 2441 \text{ MeV} \]
Single $\pi$ Electroproduction off the Deuteron

$W=1.3625, Q^2=0.7$

$R_{\text{yield (quasi-free/full)}}$

$\theta_\pi$

Very Preliminary

Ye Tian
Single $\pi$ Electroproduction off the Deuteron

$W = 1125$ MeV
$\Delta W = 25$ MeV

$W = 1685$ MeV
$\Delta W = 25$ MeV

$Q^2 = 0.7$ GeV$^2$
$\Delta Q^2 = 0.2$ GeV$^2$

Ye Tian

Very Preliminary
Single $\pi$ Electroproduction off the Deuteron

$W = 1125$ MeV
$\Delta W = 25$ MeV
$W = 1685$ MeV

$Q^2 = 0.5$ GeV$^2$

$Q^2 = 0.7$ GeV$^2$
$\Delta Q^2 = 0.2$ GeV$^2$

Kinematic FSI Corrections

Ye Tian
Single $\pi^-$ Electroproduction off the Deuteron

$W = 1212$ MeV
$\Delta W = 25$ MeV

$Q^2 = 0.5$ GeV$^2$
$\Delta Q^2 = 0.2$ GeV$^2$

$\cos(\theta) = -0.7$
$\Delta \cos(\theta) = 0.2$
$\cos(\theta) = 0.7$

$\phi = 15^\circ$
$\Delta \phi = 30^\circ$
$\phi = 345^\circ$
Double $\pi$ Electroproduction off the Deuteron

$Iuliia\ Skorodomina$

$P_x$ of $ep(n) \rightarrow e'p'(n)\pi^+\pi^-$

**Normalized yield**

**Very Preliminary**

FSU, Tallahassee, FL

Baryon 2016, Mai 16-20

Ralf W. Gothe
Double $\pi$ Electroproduction off the Deuteron

Iuliia Skorodomina

$P_x$ of $e p(n) \rightarrow e' p'(n)\pi^+\pi^-$

Normalized yield

$P_x$, GeV

Very Preliminary
QCD-Based Models and Theory

For some highlighted examples see posted presentation or Int. J. Mod. Phys. E, Vol. 22, 1330015 (2013)
DSE and EBAC/ANL-Osaka Approaches

Semi-quantitative agreement with the first DSE 3-dressed-quark core radial excitation

Two poles associated with the Roper resonance and one with the next higher $P_{11}$ resonance are all seeded by the same bare 3-dressed-quark state.

DSE approaches provide links between dressed quark propagators, form factors, scattering amplitudes, and QCD.

N* electrocouplings can be determined by applying Bethe-Salpeter / Faddeev equations to 3 dressed quarks while the properties and interactions are derived from QCD.

DSE calculations of elastic and transition form factors are very sensitive to the momentum dependence of the dressed-quark propagator.


DSE electrocouplings of several excited nucleon states will become available as part of the commitment of the Argonne NL.

DSE approaches provide links between dressed quark propagators, form factors, scattering amplitudes, and QCD.

N* electrocouplings can be determined by applying Bethe-Salpeter / Faddeev equations to 3 dressed quarks while the properties and interactions are derived from QCD.

Impact of a modified momentum dependence of the dressed-quark propagator.

DSE electrocouplings of several excited nucleon states will become available as part of the commitment of the Argonne NL.

Anomalous Magnetic Moment in DSE Approach

The DSE calculation of $R_{EM}$ zero crossing is sensitive to the momentum dependent anomalous magnetic moment of the dressed-quark.

J. Segovia et al., FBS 55 (2014) 1185-1222
Roper Transition Form Factors in DSE Approach

N(1440)P$_{11}$

\[ x = \frac{Q^2}{m_N^2} \]

J. Segovia et al., Phys. Rev. Lett. 115, 171801

DSE Contact
DSE Realistic
Inferred meson-cloud contribution
Anticipated complete result

Importantly, the existence of a zero in $F_2$ is not influenced by meson-cloud effects, although its precise location is.

Radial excitation …
longer tail … $r_R/r_p = 1.8$
… color must be screened … greater need for a meson-baryon cloud!
Lattice QCD calculations of the p(1440)P_{11} transition form factors have been carried out with various pion masses, m_π = 390, 450, and 875 MeV. Particularly remarkable is the zero crossing in F_2 that appears at the current statistics in the unquenched but not in the quenched calculations. This might suggest that at low Q^2 the pion-cloud dynamics are significant in full QCD.

LQCD calculations of N* electrocouplings will be extended to Q^2 = 10 GeV^2 near the physical π-mass as part of the commitment of the JLab LQCD and EBAC groups in support of this proposal.

LQCD & Light Cone Sum Rule (LCSR) Approach

LQCD is used to determine the moments of $N^*$ distribution amplitudes (DA) and the $N^*$ electrocouplings are determined from the respective DAs within the LCSR framework.

Calculations of $N(1535)S_{11}$ electrocouplings at $Q^2$ up to 12 GeV$^2$ are already available and shown by shadowed bands on the plot.

LQCD & LCSR electrocouplings of others $N^*$ resonances will be evaluated as part of the commitment of the University of Regensburg group.

CLAS12
- Luminosity > $10^{35}$ cm$^{-2}$s$^{-1}$
- Hermeticity
- Polarization

- Baryon Spectroscopy
- Elastic Form Factors
- N to N* Form Factors
- GPDs and TMDs
- DIS and SIDIS
- Nucleon Spin Structure
- Color Transparency
- …
New Forward Time of Flight Detector for CLAS12
Torus, LTCC, and FTOF Fully Installed
Anticipated N* Electrocouplings from Combined Analyses of Nπ/Nππ

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), …

The approved CLAS12 experiments E12-09-003 (NM, Nππ) and E12-06-108A (KY) are currently the only experiments that can provide data on γνNN* 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, see http://boson.physics.sc.edu/~gothe/research/pub/whitepaper-9-14.pdf.
Summary

- First high precision photo- and electroproduction data have become available and led to a new wave of significant developments in reaction and QCD-based theories.

- New high precision hadro-, photo-, and electroproduction data off the proton and the neutron will stabilize coupled channel analyses and expand the validity of reaction models, allowing us to
  - investigate and search for baryon hybrids,
  - establish a repertoire of high precision spectroscopy parameters, and
  - measure light-quark-flavor separated electrocouplings over an extended $Q^2$-range, both to lower and higher $Q^2$, for a wide variety of $N^*$ states.

- Comparing these results with DSE, LQCD, LCSR, and rCQM will build further insights into
  - the strong interaction of dressed quarks and their confinement,
  - the emergence of bare quark dressing and dressed quark interactions from QCD, and
  - the QCD $\beta$-function and the origin of 98% of nucleon mass.

- A close collaboration of experimentalists and theorists has formed and is needed to push these goals, see Review Article Int. J. Mod. Phys. E, Vol. 22, 1330015 (2013) 1-99, that shall lead to a QCD theory that describes the strong interaction from current quarks to nuclei. **ECT*2015 and INT2016.**