Review of light baryon spectroscopy

Stefan Diehl

Justus Liebig University Giessen
University of Connecticut

August 21, 2019
Evolution of the Universe

Time after the Big Bang

\( T \sim 10^{-8} \text{ s}: \) QGP

\( T \sim 10^{-6} \text{ s}: N^*, B^* \)

\( \rightarrow \) confinement emerges

\( \rightarrow \) light quarks acquire mass

\( \rightarrow \) chiral symmetry is broken

\( T \sim 10^{-4} \text{ s}: \) Nucleons

\( \rightarrow \) only protons and neutrons remain

\( T \sim 10^2 \text{ s}: \) Nuclei

\( T \sim 300,000 \text{ yrs}: \) Atoms
How do light quarks acquire mass?

As the temperature drops, quarks couple to gluons, become massive and form resonances with other quarks before freezing out as stable nucleons.

=> Measure observables that are sensitive to the quark mass.
QCD and Confinement – Open Questions

What is the origin of confinement?

How are confinement and chiral symmetry breaking connected?

How does QCD give rise to hadrons?
Interaction between quarks unknown throughout > 98 % of a hadron’s volume

Baryons in PDG insufficient to explain transition
=> missing states!

Explaining the excitation spectrum of hadrons is the key to our understanding of QCD in the low-energy regime (Hadron Models, Lattice QCD, ...)

→ Complementary to Deep Inelastic Scattering (DIS) where information on collective degrees of freedom is lost

With a few GeV electron machine, explore events to unravel mechanisms of confinement
Build your Mesons and Baryons ...

Three Generations of Matter (Fermions)

<table>
<thead>
<tr>
<th>Quarks</th>
<th>Mass</th>
<th>Charge</th>
<th>Spin</th>
<th>Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>u</td>
<td>2.4 MeV</td>
<td>$\frac{2}{3}$</td>
<td>$\frac{1}{2}$</td>
<td>up</td>
</tr>
<tr>
<td>c</td>
<td>1.27 GeV</td>
<td>$\frac{2}{3}$</td>
<td>$\frac{1}{2}$</td>
<td>charm</td>
</tr>
<tr>
<td>t</td>
<td>171.2 GeV</td>
<td>$\frac{2}{3}$</td>
<td>$\frac{1}{2}$</td>
<td>top</td>
</tr>
<tr>
<td>y</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>photon</td>
</tr>
<tr>
<td>d</td>
<td>4.8 MeV</td>
<td>$-\frac{1}{3}$</td>
<td>$\frac{1}{2}$</td>
<td>down</td>
</tr>
<tr>
<td>s</td>
<td>104 MeV</td>
<td>$-\frac{1}{3}$</td>
<td>$\frac{1}{2}$</td>
<td>strange</td>
</tr>
<tr>
<td>b</td>
<td>4.2 GeV</td>
<td>$-\frac{1}{3}$</td>
<td>$\frac{1}{2}$</td>
<td>bottom</td>
</tr>
<tr>
<td>g</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>gluon</td>
</tr>
</tbody>
</table>

Leptons

<table>
<thead>
<tr>
<th>Leptons</th>
<th>Mass</th>
<th>Charge</th>
<th>Spin</th>
<th>Name</th>
</tr>
</thead>
<tbody>
<tr>
<td>e</td>
<td>0.511 MeV</td>
<td>-1</td>
<td>$\frac{1}{2}$</td>
<td>electron</td>
</tr>
<tr>
<td>µ</td>
<td>105.7 MeV</td>
<td>-1</td>
<td>$\frac{1}{2}$</td>
<td>muon</td>
</tr>
<tr>
<td>τ</td>
<td>1.777 GeV</td>
<td>-1</td>
<td>$\frac{1}{2}$</td>
<td>tau</td>
</tr>
<tr>
<td>ν_e</td>
<td>&lt;2.2 eV</td>
<td>0</td>
<td>$\frac{1}{2}$</td>
<td>electron neutrino</td>
</tr>
<tr>
<td>ν_µ</td>
<td>&lt;0.17 MeV</td>
<td>0</td>
<td>$\frac{1}{2}$</td>
<td>muon neutrino</td>
</tr>
<tr>
<td>ν_τ</td>
<td>&lt;15.5 MeV</td>
<td>0</td>
<td>$\frac{1}{2}$</td>
<td>tau neutrino</td>
</tr>
</tbody>
</table>

Bosons (Forces)

<table>
<thead>
<tr>
<th>Bosons</th>
<th>Mass</th>
<th>Charge</th>
<th>Spin</th>
</tr>
</thead>
<tbody>
<tr>
<td>Z</td>
<td>91.2 GeV</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>W</td>
<td>80.4 GeV</td>
<td>±1</td>
<td>1</td>
</tr>
</tbody>
</table>

Frank Wilczek, Physics Today, August 2000
N and $\Delta$ Excited Baryon States …

- Orbital excitations (two distinct kinds in contrast to mesons)
- Radial excitations (also two kinds in contrast to mesons)
Experimental questions related to hadrons

Baryons

What are the fundamental degrees of freedom inside a proton or a neutron? How do they change with varying quark masses?

Mesons

What is the role of glue in a quark-antiquark system and how is this related to the confinement of QCD?

What are the properties of predicted states beyond simple quark-antiquark systems (hybrids, glueballs, multi-quark states, ...)?
Goals of the N* program

1. **Spectroscopy** (mainly driven by real photon scattering)
   - Search for previously unobserved or so-called *missing resonances*
   - Measure the N* spectrum more precisely
   - Provides information on the nature of the effective degrees of freedom in strong QCD

2. **Structure of excited baryons** (mainly driven by electron scattering)
   - Electron beams are ideal to measure resonance form factors and their $Q^2$ dependence
   - Provides information on the confining (effective) forces of the 3-quark system.
   - Studying underlying symmetries of hadron system
   - Understanding the effective degrees of freedom
Experiments to explore excited baryons
Thomas Jefferson National Accelerator Facility (Jefferson Lab)

- CEBAF Upgrade completed in September 2017
  - electron beam
  - $E_{\text{max}} = 12 \text{ GeV}$
  - $I_{\text{max}} = 90 \mu\text{A}$
  - $\text{Pol}_{\text{max}} \sim 90\%$

Physics Operation

- 4 halls running simultaneously since January 2018
- Highest intensity tagged photon beam at 9 GeV
- World-record polarized electron beams
- Nuclear experiments at ultra-high luminosities, up to $10^{39} \text{ electrons-nucleons /cm}^2/\text{s}$
$\mathcal{L} = 1 \times 10^{35} \text{ cm}^{-2}\text{s}^{-1}$

- Inclusive electron trigger (all calibration reactions will be analyzed in parallel)
- Electrons in the forward detector
- Protons in the central detector and forward detector
- Photons in the forward detector and forward tagger
Establishing the N* spectrum: The N(1900) 3/2+ state

- First baryon resonance observed and fully established with multiple confirmations in electromagnetic meson production.
- State confirmed in an effective Langrangian resonance model analysis of $\gamma p \rightarrow K^+\Lambda$.
  
  O. V. Maxwell, PRC85, 034611, 2012

- State confirmed in a covariant isobar model single channel analysis of $\gamma p \rightarrow K^+\Lambda$.
  
  T. Mart, M. J. Kholili, PRC86, 022201, 2012

A more detailed analysis is required!
Establishing the N* and Δ* Spectrum

Precision data require accurate analysis procedures to establish the baryon spectrum

QCD
LQCD
DSE, RQM

N*, Δ*, F*, F*

Reaction Theory Dispersion Relations

Data

Amplitude analysis

Hadronic production
Electromagnetic production

V.B., T.S.-H. Lee
Establishing the N* spectrum

Hyperon photoproduction $\gamma p \rightarrow K^{+}\Lambda \rightarrow K^{+}p\pi^-$

$d\sigma/d\Omega, \mu b/sr$

$\Lambda$ recoil polarisation

$M.\ Mc\ Cracken\ et\ al.\ (CLAS),\ Phys.RevC81,\ 025201\ (2010)$

Example of CB-ELSA and MAMI-CB Data

Differential $p\pi^0$ cross section at MAMI-CB fitted with $L = 4$ Legendre expansion.

Target Asymmetry in $\pi^0$ production off protons.
Including additional polarization observables has let to the discovery of new states?

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Final State</th>
<th>W range (GeV)</th>
<th>$\Sigma$</th>
<th>$P$</th>
<th>$C_x$</th>
<th>$C_z$</th>
<th>$T$</th>
<th>$O_x$</th>
<th>$O_z$</th>
</tr>
</thead>
<tbody>
<tr>
<td>CLAS g11</td>
<td>$K\Lambda$</td>
<td>1.62–2.84</td>
<td></td>
<td></td>
<td>*</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$K\Sigma^0$</td>
<td>1.69–2.84</td>
<td></td>
<td></td>
<td>*</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CLAS g1c</td>
<td>$K\Lambda$</td>
<td>1.68–2.74</td>
<td>*</td>
<td>*</td>
<td>*</td>
<td></td>
<td>*</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$K\Sigma^0$</td>
<td>1.79–2.74</td>
<td></td>
<td></td>
<td>*</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LEPS</td>
<td>$K\Lambda$</td>
<td>1.94–2.30</td>
<td></td>
<td>*</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$K\Sigma^0$</td>
<td>1.94–2.30</td>
<td>*</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>GRAAL</td>
<td>$K\Lambda$</td>
<td>1.64–1.92</td>
<td>*</td>
<td></td>
<td>*</td>
<td></td>
<td></td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td></td>
<td>$K\Sigma^0$</td>
<td>1.74–1.92</td>
<td>*</td>
<td></td>
<td>*</td>
<td></td>
<td></td>
<td>*</td>
<td>*</td>
</tr>
<tr>
<td>CLAS g8</td>
<td>$K\Lambda$</td>
<td>1.71–2.19</td>
<td>*</td>
<td></td>
<td>*</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$K\Sigma^0$</td>
<td>1.75–2.19</td>
<td>*</td>
<td></td>
<td>*</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Target $T$ and beam-target $E$ spin asymmetries

$\gamma p \rightarrow p\omega$

**transverse target**

**longitudinal target**

- CLAS
- CBELSA

Fit: Bonn-Gatchina

$P. \text{Roy et al. PRC97 (2018) no.5, 055202}$
More N*’s from polarized K+Λ production?

\[ \gamma p \rightarrow K^+\Lambda \]

C.A. Paterson et al., PRC93 (2016) 065201

Beam Asymmetry, $\Sigma$

- 0.75 < cos $\theta_K$ < 0.55
- 0.55 < cos $\theta_K$ < 0.35
- 0.35 < cos $\theta_K$ < 0.15
- 0.15 < cos $\theta_K$ < 0.05

Beam Recoil, $O_1$

- 0.75 < cos $\theta_K$ < 0.55
- 0.55 < cos $\theta_K$ < 0.35
- 0.35 < cos $\theta_K$ < 0.15
- 0.15 < cos $\theta_K$ < 0.05

Target, $T$

- 0.05 < cos $\theta_K$ < 0.25
- 0.25 < cos $\theta_K$ < 0.45
- 0.45 < cos $\theta_K$ < 0.65
- 0.65 < cos $\theta_K$ < 0.85

$W$ (GeV)

- 14 < 15 < 16 < 17
- 18 < 19 < 20 < 21

ANL-Osaka, BnGa 2014, BnGa 2014 refit
Search for the $\Delta(2200)7/2^-$ resonance


Use all available $p\pi^0$, $n\pi^+$ data, $\sigma$ and single and double polarization data on $T$, $\Sigma$, $E$

Analysis verifies the strong $4^* \Delta(1950) 7/2^+$ state and finds evidence for $\Delta(2200) 7/2^-$

$M = 2176 (40)$ MeV
$\Gamma = 210 (70)$ MeV
$BR(N\pi) = 3.5(1.5)%$
New evidence for excited nucleons

<table>
<thead>
<tr>
<th>State $N((\text{mass})^J_P)$</th>
<th>PDG pre 2012</th>
<th>PDG 2018 evidence</th>
<th>Mass (Pole)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$N(1710)_{1/2}^+$</td>
<td>***</td>
<td>****</td>
<td>1700</td>
</tr>
<tr>
<td>$N(1880)_{1/2}^+$</td>
<td>***</td>
<td>***</td>
<td>1860</td>
</tr>
<tr>
<td>$N(2100)_{1/2}^+$</td>
<td>*</td>
<td>***</td>
<td>2100</td>
</tr>
<tr>
<td>$N(1895)_{1/2}^-$</td>
<td></td>
<td>****</td>
<td>1910</td>
</tr>
<tr>
<td>$N(1900)_{3/2}^+$</td>
<td>**</td>
<td>****</td>
<td>1920</td>
</tr>
<tr>
<td>$N(1875)_{3/2}^-$</td>
<td></td>
<td>***</td>
<td>1900</td>
</tr>
<tr>
<td>$N(2120)_{3/2}^-$</td>
<td>***</td>
<td>***</td>
<td>2100</td>
</tr>
<tr>
<td>$N(2060)_{5/2}^-$</td>
<td>***</td>
<td>***</td>
<td>2070</td>
</tr>
<tr>
<td>$\Delta(2200)_{7/2}^-$</td>
<td>*</td>
<td>***</td>
<td>2150</td>
</tr>
</tbody>
</table>

**** - existence is certain  
***  - existence is likely  
**   - evidence of existence is fair  
*    - evidence of existence is poor

The most recent photoproduction data led to the discovery of new states and fully established poorly known states up to 2200 MeV.

The N/Δ spectrum in PDG 2018

The parity partners $\Delta(1950)7/2^+$ and $\Delta(2200)7/2^-$ show no mass degeneracy.
Do the new states agree with the LQCD predictions?


\[ m_\Omega = 1672 \text{ MeV} \]

\[ m_\pi = 396 \text{ MeV} \]

**Fit needed**
- N(1900)3/2^+ 
- N(2100)1/2^+ 
- N(1880)1/2^+

**Lowest J^+ states** 500-700 MeV high

**Lowest J^- states** 200-300 MeV high

*Ignoring the absolute mass scale, new states correlate with the J^p values predicted from LQCD. We need LQCD projections at or near the physical pion mass*
Search for missing excited states

How many exited baryon states exist in nature?

strangeness / baryon chemical potential

Sandeep Chatterjee et al, PRC 96, 054907 (2017)

The transition near the cross over temperature is not described with accounting for only the currently established excited baryon states.

not included:

<table>
<thead>
<tr>
<th>PDG 2016 with *, **</th>
</tr>
</thead>
<tbody>
<tr>
<td>( N(1860) )</td>
</tr>
<tr>
<td>( N(1895) )</td>
</tr>
<tr>
<td>( N(2000) )</td>
</tr>
<tr>
<td>( N(2060) )</td>
</tr>
<tr>
<td>( N(2120) )</td>
</tr>
<tr>
<td>( N(2570) )</td>
</tr>
<tr>
<td>( \Delta(1750) )</td>
</tr>
<tr>
<td>( \Delta(1940) )</td>
</tr>
<tr>
<td>( \Delta(2150) )</td>
</tr>
<tr>
<td>( \Delta(2300) )</td>
</tr>
<tr>
<td>( \Delta(2390) )</td>
</tr>
<tr>
<td>( \Delta(2750) )</td>
</tr>
<tr>
<td>( N(1875) )</td>
</tr>
</tbody>
</table>

PDG 2018 with ***, ****

We get closer

Stefan Diehl, JLU + UConn
HADRON 2019, Guilin, China
08/21/2019
## Search for excited baryons in 2-body channels

- **data acquired**
- **analyzed/published**

<table>
<thead>
<tr>
<th>Observable</th>
<th>c</th>
<th>s</th>
<th>T</th>
<th>P</th>
<th>E</th>
<th>F</th>
<th>G</th>
<th>H</th>
<th>T_1</th>
<th>T_2</th>
<th>L_1</th>
<th>L_2</th>
<th>O_1</th>
<th>O_2</th>
<th>C_1</th>
<th>C_2</th>
</tr>
</thead>
<tbody>
<tr>
<td>η_π^0</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>η_π^+</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>η_η</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>η_η'</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Σ^0</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Σ^+</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Λ</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Λ_0</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Λ_0^*S</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Λ_1</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Λ_1^*</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>

2018

**γ_π → X**

**γ_η → X**
Meson photoproduction very effective in searching for and identifying new resonances.

To probe the internal structure and relevant degrees of freedom versus distance scale, a hard scale is needed, which is provided in electron scattering.

- 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.

- Reveal the nature of the $N^*$ states
Integrated cross section at W < 2GeV

$\gamma^* p \rightarrow \pi^+ n$

K. Park et al., PR C77 (2008) 015208; PR C91 (2015) 045203

Why study more than one resonance, aren’t they all the same?

States with different quantum numbers respond differently to increase in $Q^2$

→ States with different quantum numbers respond differently to increase in $Q^2$
\[ \frac{d\sigma}{d\Omega} = \left( \frac{d\sigma}{d\Omega} \right)_{\text{Mott}} \cdot \frac{\epsilon G_E^2(Q^2) + \tau G_M^2(Q^2)}{\epsilon (1 + \tau)} \]


- \( G_M \) shows dominance of \( q^3 \) contribution at \( Q^2 > 3 \text{ GeV}^2 \)
- \( R_{EM} = -2\% \) consistent with MB, no trend towards asymptotic behavior (\( R_{EM} \rightarrow +100\% \))
- \( R_{SM} \sim \) consistent with \( q^3 \) dominance, DSE has different trend at high \( Q^2 \)
Solving the Roper N(1440)1/2+ Puzzle

The 1\textsuperscript{st} radial excitation of the 3-quark core seen when the probe penetrates the MB cloud.

“Nature” of the Roper – is consistent with the 1\textsuperscript{st} radial excitation of its quark core surrounded by a meson-baryon “cloud”

• Quark core contributions dominate at $Q^2 > 2 \text{ GeV}^2$
• Non-quark contributions are significant at $Q^2 < 2.0 \text{ GeV}^2$
• The behavior at $Q^2 < 0.5$ can be modeled in EFT

V. Burkert, C. Roberts, Rev.Mod.Phys. 91 (2019) no.1, 011003

\textbf{LF RQM:} I. Aznauryan, V.B., 1603.06692

\textbf{DSE:} J. Segovia et al., PRL 115 (2015); 1504.04386

\textbf{EFT:} T. Bauer, S. Scherer, L. Tiator, PRC90 (2014) 015201

Stefan Diehl, JLU + UConn

HADRON 2019, Guilin, China

08/21/2019
N(1535)1/2- – Parity partner of the nucleon

**light front RQM (LF RQM):** I. Aznauryan, V. Burkert, arXiv:1603.06692

**light cone sum rule (LC SR):** I. Anikin, V. Braun, N. Offen, PRD92 (2015) 014018

- LF RQM describes data at $Q^2 > 1.0 \text{ GeV}^2$
- LC SR with direct link to sQCD describe transition at $Q^2 > 1.5 \text{ GeV}^2$
- Non-quark contributions concentrated at $Q^2 < 1.0 \text{ GeV}^2$

N(1535)1/2- quark core excitation is consistent with the 1st orbital excitation of the nucleon
Electrocoupling Amplitudes for $\gamma p \to N(1520) D_{13}$ Transition

- $A_{1/2}$ amplitude dominant at $Q^2 > 1$ GeV$^2$
- $A_{3/2}$ is only significant contributor at $Q^2 < 3$ GeV$^2$
- There is clear evidence for a helicity switch from $\lambda = 3/2$ (at photon point) to $\lambda = 1/2$ at high $Q^2$:
  - Rapid change in helicity structure when going from photo- to electroproduction of a nucleon resonance
  - Stringent prediction of the chiral QM!
**N^+(1675)5/2- photo/electrocoupling amplitudes**

**proton target**: $q^3$ transverse amplitudes are suppressed due to a selection rule  

$\Rightarrow$ Expect MB contributions to dominate at all $Q^2$

$\Rightarrow$ Meson-baryon contributions significant  

$\Rightarrow$ State is not a MB resonance

K. Park et al.; PRC 91 (2015) 045203
**Neutron Target:** $q^3$ transverse amplitudes are not suppressed

$\Rightarrow$ Expect $q^3$ contributions to dominate at all $Q^2$

- LF RQM predicts large amplitudes on neutrons
- Effect has been observed at the photon point
- Meson-baryon contributions significant, not dominant (~25%)
Evidence for the Onset of Precocious Scaling?


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

Stefan Diehl, JLU + UConn
HADRON 2019, Guilin, China 08/21/2019
Outlook

- The search for new N* states continues with the precision data from CBELSA, MAMI, JLAB, LEPS, J-PARC, ..

**CLAS12 N* program has just started ...**

- Extend the $Q^2$ to a higher range
- Study the hyper-baryon spectrum
- Map out the transition of strong QCD to perturbative QCD
- Probe the running quark mass
• First high precision photo- and electroproduction data have become available and led to a new wave of significant developments in N* program.

• Large amounts of high precision data and multi-channel PWA have been essential in the discovery of new N* resonances.

• So far there is only qualitative agreement of the measured spectrum with LQCD predictions.

• Electroexcitation of nucleon resonances are sensitive to the effective degrees of freedom versus distance scale.

• The N* experimental program at higher energies gives access to domains where the transition from dressed to elementary quarks should occur.
Evidence for the Onset of Precocious Scaling?

V. Mokeev, userweb.jlab.org/~mokeev/resonance_electrocoupings/ (2016)    Ye Tian

Stefan Diehl, JLU + UConn
HADRON 2019, Guilin, China 08/21/2019