Hadron Spectroscopy at CLAS:
The Evolution of Strong Degrees of Freedom

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- Introduction
- $N \rightarrow \Delta$, $N \rightarrow \text{Roper}$, and other $N \rightarrow N^*$ Transitions
- $1\pi$, $2\pi$ Production, and Polarization
Physics Goals

- Understand QCD in the full strong coupling regime
- transition form factors to nucleon excited states allow us to study
- relevant degrees-of-freedom
- wave function and interaction of the constituents
Quark mass extrapolated to the chiral limit, where $q$ is the momentum variable of the tree-level quark propagator using the Asquatl action.
The 6 GeV CW Electron Accelerator at JLab

- $E_{\text{max}} \sim 6$ GeV
- $I_{\text{max}} \sim 200$ µA
- Duty Factor $\sim 100\%$
- $\sigma_{E/E} \sim 2.5 \times 10^{-5}$
- Beam P $\sim 85\%$
- $E_{\gamma}$ (tagged) $\sim 0.8 - 5.5$ GeV
Resonances cannot be uniquely separated in inclusive scattering
CLAS for Exclusive $e^p \rightarrow e'pX$ at 4 GeV
Lattice QCD indicates a small oblate deformation of the $\Delta(1232)$ and that the pion cloud makes $E_{1+}/M_{1+}$ more negative at small $Q^2$. Data at low $Q^2$ needed to study effects of the pion cloud.
Low-$Q^2$ Multipole Ratios for $R_{EM}$, $R_{SM}$

Quenched LQCD describes $R_{EM}$ within error bars, but shows discrepancies with $R_{SM}$ at low $Q^2$. Pion cloud effects?

C. Alexandrou et al., PRL, 94, 021601 (2005)

Need data at low $Q^2$
Low-$Q^2$ Multipole Ratios for $R_{EM}, R_{SM}$

C. Smith

C. Alexandrou et al., PRL, 94, 021601 (2005)

- Significant discrepancy between CLAS and Bates/MAMI results for $R_{SM}$.
- Quenched LQCD describes $R_{EM}$ within error bars, but shows discrepancies with $R_{SM}$ at low $Q^2$. Pion cloud effects?
Constituent Counting Rule

- $A_{1/2} \propto 1/Q^3$
- $A_{3/2} \propto 1/Q^5$
- $G^*_M \propto 1/Q^4$
**N → Δ  Multipole Ratios $R_{EM}$, $R_{SM}$**

- New trend towards pQCD behavior does not show up.
  - $R_{EM} \rightarrow +1$
  - $G_M^* \rightarrow 1/Q^4$
- CLAS12 can measure $R_{EM}$ and $R_{SM}$ up to $Q^2 \sim 12$ GeV$^2$.
\[N \rightarrow \Delta \text{ Multipole Ratios } R_{EM}, R_{SM}\]

\[\vec{e}p \rightarrow e'p\pi^0\]

A. Villano

…… but the trend that \(R_{SM}\) becomes constant in the limit of \(Q^2 \rightarrow \infty\) seems to show up in the latest MAID analysis of the high \(Q^2\) data.
The asymmetries are integrated over $\theta^*$ and $\phi^*$ in the $Q^2$ range from 0.187 to 0.770 GeV$^2$ and will further reduce the model dependence of the extracted resonance parameters.
Roper Electro-Coupling Amplitudes $A_{1/2}$, $S_{1/2}$

- PDG estimation
- $\pi$ electro-production (UIM, DR)
- $\pi$, $2\pi$ combined analysis
- K. Park (Data)
  I. Aznauryan (UIM)
Energy-Dependence of $\pi^+$ Multipoles for $P_{11}, S_{11}$

I. Aznauryan (UIM)

The study of some baryon resonances becomes easier at higher $Q^2$. 

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figs}
\end{figure}
The dominating final state multipole amplitude $M_{1\ell}$ of the $P_{11}(1440)$ resonance is at high $Q^2$ are much more prominent than at small $Q^2$. 

$$\sigma_T + \epsilon \sigma_L = \sum_{l=0}^{n} D_{l}^{T+L} P_l(\cos \theta_\pi^*)$$

I. Aznauryan  
--- DR fit

I. Aznauryan  
--- DR fit w/o P11

I. Aznauryan  
--- UIM fit
\[ J/\psi \rightarrow p\pi^- n \quad \text{and} \quad J/\psi \rightarrow p\pi^+ n \]

\[ \pi N \text{ invariant mass / MC phase space} \]


N*(1440): \( M = 1358 \pm 17 \)
\( \Gamma = 179 \pm 56 \)

N*(2050): \( M = 2068 \pm 15 - 40 \)
\( \Gamma = 165 \pm 42 \)
Fermion Helicity Conservation

Helicity Conservation
\( \lambda = \lambda' \) for \( q \gg M \)

Quark mass extrapolated to the chiral limit, where \( q \) is the momentum variable of the tree-level quark propagator using the Asquat action.

Bowman et al. (LQCD)
$D_{13}(1520)$ Helicity Asymmetry

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

$A_{1/2}$

$\lambda = +1/2 \quad \lambda' = +1/2$

$A_{3/2}$

$\lambda = -1/2 \quad \lambda' = +1/2$

$\lambda' = +3/2$
Nucleon Resonances in $2\pi$ Electroproduction

- $2\pi$ channel is sensitive to N*'s heavier than 1.4 GeV
- Provides complementary information to the $1\pi$ channel
- Many higher lying N*'s decay preferably to $\pi\pi$N final states

Trigger:
- $p(e,e')X$
- $p(e,e'p)\pi^0$
- $p(e,e'\pi^+)n$
- $p(e,e'p\pi^+)\pi^-$

$Q^2 < 4.0\text{GeV}^2$
Contributing Mechanisms to $\gamma^{(*)}p \rightarrow p\pi^+\pi^-$

Isobar Model JM05

- Full calculations
- $\gamma\pi \rightarrow \pi^-\Delta^{++}$
- $\gamma\pi \rightarrow \pi^+\Delta^0$
- $\gamma\pi \rightarrow \pi^+D_{13}(1520)$
- $\gamma\pi \rightarrow \rho p$
- $\gamma\pi \rightarrow \pi^-\Delta^{++}(1600)$
- $\gamma\pi \rightarrow \pi^+F^0_{15}(1685)$
- direct $2\pi$ production

The combined fit of nine single differential cross sections allowed to establish all significant mechanisms.
Fit of the CLAS $N\pi\pi$ Data within JM-Model

**JM**

- full cross sections
- resonant part
- non-resonant part

The reliable resonant/non-resonant cross section separation allows to isolate the $N^*$ contribution and demonstrates the degree of model independence.
Roper Electro-Coupling Amplitudes $A_{1/2}$, $S_{1/2}$

- PDG at $Q^2=0$
- $1\pi$ analysis (UIM)
- $1\pi-2\pi$ combined at $Q^2=0.65$ GeV$^2$
- Newest $2\pi$ analysis at low $Q^2$ (JM 06)
Combined $1\pi-2\pi$ Analysis of CLAS Data

- PDG at $Q^2=0$
- Previous world data
- $2\pi$ analysis
- $1\pi-2\pi$ combined at $Q^2=0.65$ GeV$^2$
- Many more examples: $P_{11}(1440)$, $D_{13}(1520)$, $S_{31}(1650)$, $S_{11}(1650)$, $F_{15}(1685)$, $D_{13}(1700)$, ...
- EBAC at JLab: Full coupled channel analysis
Combined $1\pi-2\pi$ Analysis of CLAS Data

- PDG at $Q^2=0$
- $2\pi$ analysis
- $1\pi-2\pi$ combined at $Q^2=0.65$ GeV$^2$
- Previous world data
Kinematical Coverage of CLAS12

60 days

L = 10^{35} \text{ cm}^{-2} \text{ sec}^{-1}, \Delta W = 0.025 \text{ GeV}, \Delta Q^2 = 0.5 \text{ GeV}^2

Genova-EG

(e', p\pi^+\pi^-) detected
Conclusion: Do Exclusive Electron Scattering

... to

Learn QCD!
The main objectives of the workshop are:

- review the status of the N-N* transition form factors extracted from meson electro-production data.
- call for the theoretical interpretations of the extracted N-N* transition form factors, that enable access to the mechanisms responsible for the N* formation and to their emergence from fundamental QCD.

Since the general development in N* physics had been well discussed in several meetings in 2007 and certainly will be covered by the N* workshop to be held April 19-22, 2009 in Beijing, the emphasis of this meeting will be specifically on the theoretical interpretations of N-N* form factors. We hope to have very concentrated discussions on the predictions from various hadron structure models and Lattice QCD. The meeting will have invited talks and shorter selected contributions. We hope these presentations can be the input to a White Paper on the N* Physics with 12 GeV upgrade of CEBAF.

Preliminary scientific program will be posted soon http://conferences.jlab.org/EmNN/ … or ask me.