Exclusive $\pi^0$ and $\eta$ electro-production at high $Q^2$ in the resonance region

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Baryon form factors

- Knowledge of $N^*$ form factors complements nucleon FF
  - $P_{33}(1232) \ I = 3/2 \ J = 3/2$ Decays to $\pi N$ with 99% BR
    - Can be excited by M1, E2 and S1 multipoles
    - M1 dominates
  - $S_{11}(1535)$ Negative parity partner $I = 1/2 \ J = 1/2$ Decays to $\eta N$ with 55% BR
    - $A_{1/2}$ helicity amplitude dominates over $S_{1/2}$

- Measure $Q^2$ dependence of baryon form factor data
  - Map out the spatial densities of the nucleon
  - Address the role of meson cloud
  - Study the transition from meson/baryon degrees of freedom to the asymptotic regime
Previous Experiments

Magnetic FF, $G^*_M$, for $P_{33}(1232)$

E2/M1 for $P_{33}(1232)$

Two frameworks used to extract multipoles from experimental data
- Fixed-$t$ dispersion relations
- Unitary Isobar Model (UIM)

Previous Experiments

Magnetic FF, $G^*_M$, for $P_{33}(1232)$

$\frac{p(e, e' p) \pi^0}{p(e, e' p)} = \pm \frac{E^2}{M_1}$ for $P_{33}(1232)$

New Hall C data

- Cross sections for $W = 1.08$ to $1.4$ GeV
- Full $\theta^*$ and $\phi^*$ at $Q^2 = 6.4$ GeV$^2$, partial at $Q^2 = 7.7$ GeV$^2$
Helicity Amplitude $A_{1/2}$ for $S_{11}(1535)$

Previous Experiments

New Hall C data
- cross sections for $W = 1.50$ to $1.59$ GeV
- Full $\theta^*$ and $\phi^*$ at $Q^2 = 5.7$ GeV$^2$,
- Partial coverage at $Q^2 = 7.0$ GeV$^2$

At very large $Q^2$ expect $Q^3A_{1/2}$ to be a constant.
Hall C Experiment 00-102

SOS detected electrons
$Q^2 = 6.4 \ \Theta_{SOS} = 47.5$
$Q^2 = 7.7 \ \Theta_{SOS} = 70.0$

<table>
<thead>
<tr>
<th>$Q^2$</th>
<th>$\Theta_{HMS}$</th>
<th>$P_{HMS}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.4</td>
<td>11.2 to 24</td>
<td>2.3 to 4.7</td>
</tr>
<tr>
<td>7.7</td>
<td>11.2 to 14</td>
<td>3.2 to 4.7</td>
</tr>
</tbody>
</table>

HMS detected proton

Angular acceptance
3° in-plane
6° out-of-plane

5.5 GeV $e^-$ Beam
Identifying exclusive channels

Eliminate radiated elastic events with cut on $\phi_{cm} = 180$
Identifying exclusive channels
Identifying exclusive channels

\[ e' \xrightarrow{\Theta_e} e, \quad \gamma^* \xrightarrow{W} q, \quad P' \xrightarrow{\Theta_{pq}} q, \quad M_x \]

\[ \Delta, \quad S_{11}, \quad \pi^0, \quad \eta \]

\[ W(\text{GeV}) \quad M_x^2 \]
Meson Production in $\gamma p$ center of mass

At $Q^2 = 6.4$ GeV$^2$

$\Theta_{cm} = 90^\circ$  $\Theta_{pq} = 3.7^\circ$

\[
\frac{d\sigma}{d\mathbf{q}^*} = \sigma_T + \epsilon\sigma_L + \epsilon\sigma_{TT} \cos 2\phi^* + \sqrt{2\epsilon(1 + \epsilon)}\sigma_{LT} \cos \phi^*
\]
Elimination of elastic radiated process

\[ Q^2 = 6.4 \text{ GeV}^2 \]
Elimination of elastic radiated process

$Q^2 = 6.4 \text{ GeV}^2$

Simulation of elastic radiated events

Data

$0.25 < \cos \theta^* < 1 \quad -0.4 < \cos \theta^* < 0.25 \quad -1 < \cos \theta^* < -0.4$
Elimination of elastic radiated process

\[ Q^2 = 6.4 \text{ GeV}^2 \]
\( \pi^0 \) production c.m. cross section

\[ \frac{d\sigma}{d\cos(\theta^*)} = A_o + A_1 \cos \theta^* + A_2 \cos^2 \theta^* + \epsilon B_o \cos 2\phi^* \sin^2 \theta^* + \sqrt{2\epsilon(1+\epsilon)} \cos \phi^* (C_o + C_1 \cos \theta^*) \sin \theta^* \]
$Q^2 = 6.4 \text{ GeV}^2$

- Large M1- and E0+ so M1 dominance is not viable
- Need to use cross section data in global analysis framework like UIM to reliably extract multipoles
ArXiv:0906.2839v2 has UIM analysis results
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Multipion subtraction in $\eta$ production

$W = 1.5$ GeV

$\cos \theta^*_\eta = -0.92$

$\cos \theta^*_\eta = 0.42$
**η production cross section**

\[
\frac{d\sigma}{d\Omega^*} = A + B \cos^* + C \cos^2\theta^* + D \sin\theta^* \cos\phi^* + E \cos\theta^* \sin\theta^* \cos\phi^* + F \sin^2\theta^* \cos 2\phi^*
\]
$Q^2 = 7.0$ data
Fit with

$$\frac{d\sigma}{d\Phi^*} = A_o + A_1 \cos \theta^*$$
Fit Coefficients
Fit Coefficients

\[ \frac{d\sigma}{d\Omega^*} = A + B \cos\theta^* + C \cos^2\theta^* + D \sin\theta^* \cos\phi^* + E \cos\theta^* \sin\theta^* \cos\phi^* + F \sin^2\theta^* \cos 2\phi^* \]
Simultaneous fit both data sets with relativistic Breit-Wigner.
Q^2 dependence of A_{1/2} for S_{11}
Summary

- Measured $p(e, e'p)\pi^0$
  - Full $\Theta_{cm}$ and $\phi_{cm}$ for $W = 1.08$ to $1.4$ GeV at $Q^2 = 6.4$ GeV$^2$
  - Partial $\Theta_{cm}$ and $\phi_{cm}$ for $W = 1.08$ to $1.4$ GeV $Q^2 = 7.7$ GeV$^2$
  - Determine $G^*_M$, $E2/M1$ in global UIM analysis
    ArXiv:0906.2839v2 has UIM analysis results

- Measured $p(e, e'p)\eta$
  - Full $\Theta_{cm}$ and $\phi_{cm}$ for $W = 1.50$ to $1.59$ GeV at $Q^2 = 5.7$ GeV$^2$
  - Partial $\Theta_{cm}$ and $\phi_{cm}$ for $W = 1.50$ to $1.59$ GeV at $Q^2 = 7.0$ GeV$^2$
  - Determine $A_{1/2}$ for $S_{11}$
Backup slides
Fit total cross section with Breit-Wigner + background
Assume M1 dominance and extract $G_M$
Comparison to UIM extraction

\[ \frac{G_M}{3G_D} \]

\[ Q^2 \left[ \left( \text{GeV/c}^2 \right)^2 \right] \]
Comparison to UIM extraction

![Graph showing data points and markers for different experiments]

- CLAS (2000)
- CLAS (2006)
- Hall C (1999)
- M1 dominance
- Aznauryan fit

Parameters:
- $R_{EM}$ (%)
- $Q^2 \left[ \text{(GeV/c}^2\right)^2\right]$
Comparison to UIM extraction

\[ R_{SM} (%) \]

\[ Q^2 \left( \text{[GeV/c}^2\text{]}^2 \right) \]
Magnetic FF, $G^*_M$, for $P_{33}(1232)$

In Large $N_c$ limit with GPDs $E^u$ and $E^d$ from fits to proton and neutron data

$$G^*_M(t) = \frac{G^*_M(0)}{\kappa_V} \int_{-1}^{+1} dx \left\{ E^u(x, \xi, t) - E^d(x, \xi, t) \right\} = \frac{G^*_M(0)}{\kappa_V} \left\{ F_2^p(t) - F_2^n(t) \right\}$$