Electroproduction of $\eta$ mesons in the $S_{11}(1535)$ resonance region at high momentum transfer

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Nuclear Response vs $Q^2$

$$Q^2 = \vec{q}^2 - \nu^2$$

$$\nu = (E - E')$$
Increasing $Q^2$: increasing resolving power of probe (virtual photon)

- Long photon wavelength cannot resolve internal structure of baryon.
- Photon resolves three quark-like objects and chromomagnetically flips one baryon resolved into a complicated picture of actual quarks and gluons.

Asymptotic freedom, strong coupling small, only lowest order diagrams contribute.

Hadronic models
Constituent Quark Model
non-perturbative QCD, handbag model, GPD's
perturbative QCD

Motivation (1)
Study the transition from low $Q^2$ to high $Q^2$ and search for definitive signals of the onset of perturbative Quantum Chromodynamics (pQCD).
Investigate the transverse distributions of parton spin and momentum within the framework of Generalised Parton Distributions (GPD's). Link this experiment to other high $t$ physics including elastic and transition form factors and wide angle Compton scattering.
Electroproduction of $S_{11}(1535)$

2 hadrons in final state:
exclusive measurement since reaction is kinematically complete.
Can reconstruct one undetected particle in the final state.

$e(p,e'p)X$

incident electron
$k_i = (E, \vec{k}_i)$

scattered electron
$k_f = (E', \vec{k}_f)$

free proton
$p_i = (m_p, \vec{0})$

virtual $\gamma$
$q = (\nu, \vec{q})$

$\gamma$ undetected particle(s)
$p_x = (E_x, \vec{p}_x)$

recoil proton
$p_f = (E'_p, \vec{p}_f)$

$\gamma$ detect in coincidence

> 2 hadrons in final state:
continuous background since not kinematically complete.
Commonly Used Quantities

**$Q^2$**
Momentum transfer of photon

$Q^2 \equiv -q^2 = (k - k')^2 \sim m_\gamma^2$

Virtuality or mass or ‘size’ of the virtual photon

**$W$**
Mass of resonant state

$W^2 = (p + q)^2$

≡ Mandelstam $s$ in the proton-photon system

**$M_x$**
Missing mass

$M_x^2 = (k + p - k' - p')^2$

$\Delta$ resonance studied via $p(e,e'p)\pi_0$

$S_{11}$ resonance studied via $p(e,e'p)\eta$

$x = \pi_0, \eta, \omega$

$k_i = (E, \vec{k_i})$

$q = (\nu, \vec{q})$

$p_i = (m_p, \vec{0})$

$k_f = (E', \vec{k_f})$

$p_x = (E_x, \vec{p_x})$

$p_f = (E'_p, \vec{p_f})$
Spin $\frac{1}{2}$, isospin $\frac{1}{2}$, negative parity – i.e. negative parity partner of the proton.

Strongly excited over all $Q^2$;

Well isolated in $e^p \rightarrow e' \eta p$ channel:
- only isospin $\frac{1}{2}$ contribute;
- large branching fraction to $\eta$ (45%-60%) c.f. few percent for others;

Strong energy dependence at threshold since $W_{\text{thr}} = m_p + m_\eta = 1486$ MeV;

strong S-wave character
Experiment

Data taken at JLab in Hall C
Two spectrometer coincidence configuration

\[ \theta_0 > 11.2^\circ \quad P_0 < 5 \text{ GeV/c} \]

\[ \theta_0 \sim 47.5^\circ \quad P_0 \sim 1.7 \text{ GeV/c} \]

\[ \theta_0 \sim 70^\circ \quad P_0 \sim 1.0 \text{ GeV/c} \]

\[ Q^2 \sim 5.7 \text{ GeV}^2 \]

\[ Q^2 \sim 7.0 \text{ GeV}^2 \]

2 points in \( Q^2 \) measured

Undetected \( \eta \) identified by missing mass reconstruction.

Kinematic focusing at higher \( Q^2 \) – proton recoils in narrow cone allowing detection of full centre of mass angles for \( W < 1550 \text{ MeV} \).
Centre of mass angular acceptance of spectrometers – kinematic focusing

Combine spectrometer settings to get good coverage of centre-of-mass solid angle.

Contours of constant $W$, lab frame.
Continuous Electron Beam Accelerator Facility (CEBAF) at Jefferson Lab

- $E_{\text{max}} \sim 6$ GeV
- $I_{\text{max}} \sim 200 \mu A$
- Duty Factor $\sim 100\%$
- $\sigma_{E/E} \sim 2.5 \times 10^{-5}$
- Beam $P \sim 80\%$
Hall C configuration
Detector Telescope

Magnet is a momentum selector
Detector Elements

calorimeter: total energy

scintillators: good timing

Cherenkov counter: sensitive to speed

drift chambers: good position
Particle Identification

Electron Arm

Proton Arm

- and p easily separated from $\pi$.
Very small backgrounds and good resolution.
Particle Identification Cont.

$M_{x}^{2} = P_{e} + P_{p} - P_{e}^{'} - P_{p}^{'}$

Diagram showing $m_{x}^{2}$ in [GeV$^{2}$] with peaks at $\pi^{0}$, $\eta$, and $\omega$ in the multipion background.
Raw data set binned in W and missing mass squared and the correlation of the two.

The $M_x^2$ peaks can be used to constrain the reaction or resonance.
Angular Distribution of Data

\[ Q^2 \sim 7.7 \text{ GeV}^2/c^2 \text{ (for } \Delta) \]

5 weeks beam time, 128 C total charge, total reconstructed \( \Delta \sim 25 \text{ k}; \ S_{11} \sim 25 \text{ k} \)

\[ Q^2 \sim 6.3 \text{ GeV}^2/c^2 \text{ (for } \Delta) \]

1 week beam time, 30 C total charge, total reconstructed \( \Delta \sim 1.5 \text{ k}; \ S_{11} \sim 1 \text{ k} \)
$p(e,e'p)\eta$ cross section
angular parameters

\[
\frac{d\sigma}{d\Omega^*} = A + B \cos\theta^* + C \cos^2\theta^* + D \sin\theta^* \cos\phi^* 
+ E \cos\theta^* \sin\theta^* \cos\phi^* + F \sin^2\theta^* \cos2\phi^*
\]
Breit-Wigner fit to total cross section
$S_{11}(1535)$ resonance parameters

![Graph showing resonance parameters with legends for simultaneous fit and lower-$Q^2$ fit. The graph plots $I_R(S_{11})$ [GeV] against $W_R$ of $S_{11}$ [GeV]. The lines represent different values of $b_{\eta}$: $b_{\eta}=0.45$, $b_{\eta}=0.50$, and $b_{\eta}=0.55$. The simultaneous fit line is solid, and the lower-$Q^2$ fit line is dashed.]
Helicity conserving amplitude $A_{1/2}$

- Brasse (DESY) 1984
- Armstrong (JLab Hall C) 1999
- Denizli (JLab Hall B) 2007
- This work (JLab Hall C) 2007

- Aiello, Giannini and Santopinto
- Capstick and Keister, non-rel
- Capstick and Keister, rel
- Konen and Weber
- Li and Close
- Pace, Salme and Simula
Test for pQCD type scaling