$\pi^-/\pi^+$ Separated Response Function Ratios in Forward Pion Electroproduction

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Jefferson Lab $F_\pi$ Collaboration

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Motivation

\[ 2H(e, e'_\pi^+)nn, \ 2H(e, e'_\pi^-)pp \] reactions

• Testing the t-pole dominance – key factor in the extraction of the pion form factor \( F_\pi \).

• Pion \( \pi^\pm \) electroproduction can proceed via isovector and isoscalar photons.

• The experimental ratio

\[ R = \frac{\sigma(\gamma_vp \rightarrow \pi^+n)}{\sigma(\gamma_vn \rightarrow \pi^-p)} = \left| \frac{A_V - A_S}{A_V + A_S} \right|^2 \]

- \( t \) gives a good indication of the presence of isoscalar processes.

• Separated ratios \( R_L \) and \( R_T \) tests the t-pole contribution to \( \sigma_L \).
Previous Studies

Exclusive $\pi^-/\pi^+$ ratio vs $-t$

- $W = 2.19$, $120^\circ \leq \phi \leq 240^\circ$

- $Q^2 = 0.70$
- $Q^2 = 1.35$

- Quark model limit
- Isovector limit

**At low $-t$**

\[
R \rightarrow R_L = \frac{Q^2_{\pi^-}}{Q^2_{\pi^+}} = 1
\]

**At high $-t$**

\[
R \rightarrow R_T = \frac{2Q^2_d}{2Q^2_u} = 1/4
\]


Unseparated cross section ratios
Experimental Setup

- **Hall C spectrometers:**
  - Coincidence measurement.
  - SOS detects e⁻.
  - HMS detects π⁺ and π⁻.

- **Targets:**
  - Liquid 4-cm H/D cells.
  - Al (dummy) target for background measurement.
  - \(^{12}\)C solid targets for optics calibration.

| Exp \(F_\pi\) | \(Q^2\) (GeV/c)² | \(W\) (GeV) | \(|t_{\text{min}}|\) (GeV/c)² | \(E_e\) (GeV) |
|------------|-----------------|---------|-----------------|---------|
| \(F_\pi-1\) | 0.6-1.6         | 1.95    | 0.03-0.150      | 2.445-4.045 |
| \(F_\pi-2\) | 1.6, 2.5        | 2.22    | 0.093, 0.189    | 3.779-5.246 |
Event selection

Electron-pion coincidences

Pions detected in HMS - Cerenkov & Coincidence time for PID
Electrons detected in SOS - Cerenkov & Lead Glass Calorimeter

Random coincidences

Exclusivity assured via $0.875 < M_{\text{MM}} < 1.05$ GeV cut

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Kinematics Coverage

Take data at three angles:
\[ \theta_{\pi q} = 0^\circ, +4^\circ, -4^\circ. \]

Diamond cuts define common 
\((W, Q^2)\) coverage at both \(\epsilon\).

Extract \(\sigma_L\) by simultaneous fit of \(L, T, LT, TT\)

\[
2\pi \frac{d\sigma}{dt d\phi} = \epsilon \frac{d\sigma_L}{dt} + \frac{d\sigma_T}{dt} + \sqrt{2\epsilon(\epsilon+1)} \frac{d\sigma_{LT}}{dt} \cos \phi + \epsilon \frac{d\sigma_{TT}}{dt} \cos 2\phi
\]
Data Analysis

- Magnetic Calibrations
  
  Over-constrained $p(e,e'p)$ and elastic $e + ^{12}C$ reactions were used to calibrate spectrometer acceptances, momenta and angular offsets. SOS & HMS Delta/xpfp correlations were corrected with a linear dependent function of form $\delta' = \delta + C_\delta \cdot x_{fp}'$.

- Corrections to the high rate $\pi^-$ data set
  
  $\pi^-$ data were taken at high rates while $\pi^+$ data were taken at low rates. Understanding the rate dependent corrections is very important with respect to the final $\sigma_{\pi^-}/\sigma_{\pi^+}$ ratios.
  - New high rate tracking algorithm.
  - Better high rate tracking efficiencies (2-9%).
  - $\pi^-$ HMS Cerenkov blocking correction (2-20%).
  - High current ($\pi^+$ data set) target boiling correction (2-13%).
EXISTING MODELS (VGG & VGL)

VGL Regge Model

Pion electroproduction in terms of exchange of $\pi$ and $\rho$ Regge trajectories.

[VGL, PRC 57(1998)1454]

Model parameters fixed from pion photoproduction.

Free parameters: $\Lambda_{\pi}^2$ and $\Lambda_{\rho}^2$
(from $^2H$ data).

$$F_{\pi,\rho}(Q^2) = \left[1 + Q^2/\Lambda_{\pi,\rho}^2\right]^{-1}$$

$\rho$ exchange does not significantly influence $\sigma_L$ at small $-t$.

VGG GPD Model

Pion electroproduction in terms of generalized skewed quark distributions (OFPD).

[VGG, PRD 60(1999)094017]

Include power corrections due to:

- intrinsic transverse momentum of the active quark
- soft overlap type contributions (no gluon exchange)

Free parameters: $\Lambda_{\pi}^2$ and $\Lambda_{\rho}^2$
(from $^2H$ data).
Separated Response Functions

$^2\text{H}(e,e'\pi^-)pp$

- $\Lambda_{\pi}^2$, $\Lambda_{\rho}^2$ - 0.410, 1.5
- $\Lambda_{\pi}^2$, $\Lambda_{\rho}^2$ - 0.503, 1.5
- $\Lambda_{\pi}^2$, $\Lambda_{\rho}^2$ - 0.428, 1.5
- $\Lambda_{\pi}^2$, $\Lambda_{\rho}^2$ - 0.428, 1.5

$^2\text{H}(e,e'\pi^+)nn$

- $\Lambda_{\pi}^2$, $\Lambda_{\rho}^2$ - 0.418, 1.5
- $\Lambda_{\pi}^2$, $\Lambda_{\rho}^2$ - 0.494, 1.5
- $\Lambda_{\pi}^2$, $\Lambda_{\rho}^2$ - 0.397, 1.5
- $\Lambda_{\pi}^2$, $\Lambda_{\rho}^2$ - 0.397, 1.5

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Separated Response Functions Ratios

$Q^2 = 0.6 \text{ GeV}^2$
$Q^2 = 1.0 \text{ GeV}^2$
$Q^2 = 1.6 \text{ GeV}^2$

$W = 1.95 \text{ GeV}$

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Summary

- Separated $\sigma_L$, $\sigma_T$, $\sigma_{LT}$, $\sigma_{TT}$ cross sections were extracted using Rosenbluth L/T separation technique.

- Ratios $R = \frac{\sigma_{\pi^-}}{\sigma_{\pi^+}}$ were extracted as a function of $-t$.

- Preliminary results show that $R_L$ is consistent with 1 over the whole range in $-t$ indicating a dominance of isovector processes at low $-t$ in the longitudinal response function $\sigma_L$.

- These findings confirm the expectation that $\sigma_L$ is indeed dominated by the $t$-pole term.

- In the kinematic region studied here both ratios $R_L$ and $R_T$ present a very slight dependence of $Q^2$.

- The evolution of $R_T$ with $-t$ shows a rapid fall off which is consistent with earlier theoretical predictions, expected to approach $\frac{1}{4}$, the square of the ratio of the quark charges involved.

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HMS Q3 Corrections

Old Q3/Dipole ratio

\[ \delta_{\text{HMS}} = \delta_{\text{HMS}} + C_\delta \times f_p \]

\[ \bar{\delta}_{\text{HMS}} = \frac{P - P_{\text{HMS}}}{P_{\text{HMS}}} \times 100 \]

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SOS Optics Calibration

For low momentum (<1.6 GeV/c) we used the Fpi1 (1999) optics matrix & delta/xpfp correction.

For high momentum (>1.6 GeV/c) we used the Fpi2 (2003) new optics matrix & delta/xpfp correction.
HMS Cerenkov Blocking

- Used data taken with open trigger (el. & pions) to fit the effective time window.

- The TDC time window in Fpi1 is 23% larger than in Fpi2.

- Used the Fpi2 data to fit the effective TDC gate (for the same CC cut).

- For a CC cut of npe<1.5 the effective TDC gate for Fpi1 set is ~184 ns.

- Implies a larger correction for Fpi1 data (18-20 % at 1MHz).

- Significant impact in pi- (high rate) data.

\[ \varepsilon_{CC} = 1 - R_e \cdot \tau_{CC} \]

\[ \tau_{CC} = 184 \pm 5 \text{ ns} \]

- Uncertainties associated with this correction are of the order of 1.6% at 1MHz.
Corrected Tracking Efficiencies

A \sim 8\% correction to the tracking efficiencies at 1.4MHz was applied to the high rate data (pi-).

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Simulations vs Experimental data

LD$_2$, $Q^2=1.6$, $E=0.27$, $\phi_p=-0^\circ$, $\pi^+$

$^2$H, $Q^2=1.6$ GeV$^2$, $E=0.27$, $\phi_p=-0^\circ$, $\pi^+$

Simulated Missing Mass spectrum was improved by implementing pions that were penetrating the collimator.

Pion Punchthrough Implementation resulted in an overall improved simulated kinematic variables ($W, Q^2, -t$).

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HMS Q3 corrections

Using central HMS kinematics and detected proton momentum we reconstruct the invariant mass $W$ (electron mass).

The $W$ vs $X'$ distribution was fitted with 1 degree polynomial.

DNP Meeting, NN, Virginia, 13 October 2007
SOS Q3 Corrections

2003 SOS optics matrix

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Tracking efficiency

Two issues:

1. The Fpi1 version of the Trk. Eff. algorithm used a "cleaner" data sample by removing the multiple hits events resulting in overevaluated trk. eff.

2. The Fpi2 version used a "dirty" data sample by including the multiple hits events resulting in subevaluated trk. eff.

- The high rate data (pi-) is the most sensitive to the tracking efficiency correction (~10% at 1.4 MHz).
- A linear correction dependent of event rate was applied to the tracking efficiencies of pi- data.
SOS Q3 Corrections

Low momentum (<1.6 GeV/c) - old settings & corrections works fine.

High momentum (>1.6 GeV/c) - use of new SOS optic matrix & new delta/xpfp correction.
Tracking Efficiency

\[ \varepsilon_{\text{tracking}} = P_1 \cdot \varepsilon_1 + P_2 \cdot \varepsilon_2 \]

\[ P_2 \approx R \cdot T_{\text{DC}} \]

\[ P_1 = 1 - P_2 \]

\[ \varepsilon_1 = 0.984 \]

\[ \varepsilon_2 = 0.71 \]

\[ T_{\text{DC}} \] - DC gate width

\[ R \] - DC rate

\[ P_1 \] - single hit probability

\[ P_2 \] - multiple hits probability

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Using data taken with open trigger (el. & pions).

The TDC time window in Fpi1 is 23% larger than in Fpi2.

Use the Fpi2 data to fit the effective gate (same CC cut).

For npe<2.0 gate width – 190 ns.

Implies a larger correction in Fpi1 (18–20 % at 1MHz).

Significant impact in π- (high rate) data.

\[ \varepsilon = 1 - R_e \cdot T_{CC} \]

HMS Cerenkov TDC spectrum for e as identified by the HMS CC ADC

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Kinematic Variables

\[ t \equiv (\gamma_v - \pi)^2 = -Q^2 + m_{\pi}^2 - 2\nu E_{\pi} + 2\nu p_{\pi} \cos \theta_{q\pi} \]

\[ \frac{d\sigma}{dt} = \sigma_T + \epsilon \sigma_L + \epsilon \cos 2\phi \sigma_{TT} + \sqrt{2\epsilon(1 + \epsilon)} \cos \phi \sigma_{LT} \]

\[ \sigma_L \propto \frac{-2tQ^2}{(t - m_{\pi}^2)^2} \cdot g_{\pi NN}^2(t) \cdot F_{\pi}^2 \]

\[ R \simeq \frac{2Q_d^2}{2Q_u^2} = \frac{(-1/3)^2}{(+2/3)^2} = 1/4 \]

\[ R_L \simeq \frac{Q_{\pi^-}^2}{Q_{\pi^+}^2} = 1 \]
Separated Response Functions
Separated Response Functions

\[ \frac{d\sigma}{dt} (\text{ubarn/GeV}^2) \]

\[ \begin{align*}
\Delta_\pi^2, & \quad \Lambda_\pi^2 - 0.410, 1.5 \\
\Delta_p^2, & \quad \Lambda_p^2 - 0.503, 1.5 \\
\Delta_\rho^2, & \quad \Lambda_\rho^2 - 0.428, 1.5 \\
Q^2 = & \ 0.5 \ \text{GeV}^2 \\
Q^2 = & \ 1.0 \ \text{GeV}^2 \\
Q^2 = & \ 1.6 \ \text{GeV}^2
\end{align*} \]

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\[ \begin{align*}
\Delta_\pi^2, & \quad \Lambda_\pi^2 - 0.418, 1.5 \\
\Delta_p^2, & \quad \Lambda_p^2 - 0.494, 1.5 \\
\Delta_\rho^2, & \quad \Lambda_\rho^2 - 0.397, 1.5 \\
\sigma_L & \ \bullet \ \sigma_T
\end{align*} \]

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\Delta_\pi^2, & \quad \Lambda_\pi^2 - 0.410, 1.5 \\
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\sigma_L & \ \bullet \ \sigma_T
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Separated Response Functions Ratios

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$Q^2 = 1.6 \text{ GeV}^2$

$R_L = \frac{\sigma_L(\pi^+)}{\sigma_L(\pi^-)}$
$R_T = \frac{\sigma_T(\pi^+)}{\sigma_T(\pi^-)}$

Preliminary

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