π⁻/π⁺ Exclusive Pion Electroproduction Results from Jefferson Lab

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Jefferson Lab $F_\pi$ Collaboration

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Deep Exclusive Meson Production

- Single $\pi^+$ produced from proton, or $\pi^-$ from neutron at high momentum transfer.
- Probes the relevant degrees of freedom within nucleon at different distance scales.
- Use the virtual photon’s longitudinal and transverse polarizations to act as a filter on the details of the probing interaction.

$R_T = \frac{\gamma^*_T n \rightarrow \pi^- p}{\gamma^*_T p \rightarrow \pi^+ n} \bigg|_{\text{high } -t} \frac{2Q^2_d}{2Q^2_u} = \frac{(-1/3)^2}{(+2/3)^2} = \frac{1}{4}$


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At low $-t$, Meson-Nucleon Degrees of Freedom

- $\pi^\pm$ $t$-channel diagram is purely isovector (G-parity conservation).

\[ R_L = \frac{\sigma_L[n(e, e'\pi^-)p]}{\sigma_L[p(e, e'\pi^+)n]} = \frac{|A_V - A_S|^2}{|A_V + A_S|^2} \]

- A significant deviation of $R_L$ from unity would indicate the presence of Isoscalar backgrounds (such as $b_1(1235)$ contributions to $t$-channel).

- Relevant for the extraction of the pion form factor from $p(e, e'\pi^+)n$ data, which uses a model including some isoscalar background.
2\pi \frac{d\sigma}{dtd\phi} = \varepsilon \frac{d\sigma_L}{dt} + \frac{d\sigma_T}{dt} + \sqrt{2\varepsilon (\varepsilon + 1)} \frac{d\sigma_{LT}}{dt} \cos\phi + \varepsilon \frac{d\sigma_{TT}}{dt} \cos 2\phi

1. At small $-t$, $\sigma_L$ has maximum contribution from the $\pi$ pole.
   - $t = (p_{\text{target}} - p_{\text{recoil}})^2$ used in this analysis.
   - not necessarily equivalent to $t = (p_\gamma - p_\pi)^2$ due to Fermi momentum and radiation.

2. Only three of $Q^2$, $W$, $t$, $\theta_\pi$ are independent.
   - Vary $\theta_\pi$ to measure $t$ dependence.
   - Since non-parallel data needed, LT and TT must also be determined.
**Jefferson Lab Hall C Experimental Setup**

**Hall C spectrometers:**
- Coincidence measurement.
- SOS detects $e^-$.  
- HMS detects $\pi^+$ and $\pi^-$.  

**Targets:**
- Liquid 4-cm H/D cells.  
- Al target for empty cell measurement.  
- $^{12}$C solid targets for optics calibration.

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| Exp | $Q^2$ (GeV/c$^2$) | W (GeV) | $|t_{min}|$ (GeV/c$^2$) | $E_e$ (GeV) |
|-----|-----------------|---------|-------------------|-------------|
| Fπ-1 | 0.6 - 1.6 | 1.95   | 0.03 - 0.150      | 2.445 - 4.045 |
| Fπ-2 | 2.45  | 2.22   | 0.189             | 4.210 - 5.246  |

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$^2\text{H(e,e'π^±)NN Event selection}$

Pions detected in HMS
- Cerenkov &
Coincidence time for PID
Electrons detected in SOS –Cerenkov & Lead
Glass Calorimeter
Coincidence time
resolution ~200-230 ps.
Cut value ±1 ns.

After PID & MM
cuts, almost no random
coincidences remain.

Exclusivity assured via
$0.875 < \text{MM} < 1.03 \text{ GeV cut}$

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

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**Corrections to $\pi^-$, $\pi^+$ Data**

- **Negative polarity of HMS field for $^2\text{H}(e,e'\pi^-)\text{pp}$ means these runs have high electron rates not shared by $^2\text{H}(e,e'\pi^+)\text{nn}$ runs.**

- **Understanding rate dependent corrections very important with respect to final $\pi^-/\pi^+$ ratios.**
  - Improved high rate HMS tracking algorithm.
  - More accurate high rate tracking efficiencies (91-98%).
  - HMS $\pi$ misidentification correction due to $e^-$ pileup in Cerenkov (13%/MHz $e^-$).
  - High current $^2\text{H}$ target boiling correction (4.7%/100μA).

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**$Q^2$**

$0.60, 0.75, 1.0, 1.6$ GeV$^2$
Extract response functions through iterative procedure

Improve $\varphi$ coverage by taking data at multiple $\pi$ (HMS) angles, $-4^\circ < \theta_{\pi q} < 4^\circ$.

For each $\pi$ HMS setting, form ratio:

$$R = \frac{Y_{\text{EXP}}}{Y_{\text{SIMC}}}$$

Combine ratios for $\pi$ settings together, propagating errors accordingly.

Extract via simultaneous fit of $L, T, LT, TT$

$$2\pi \frac{d\sigma}{dt d\phi} = \varepsilon \frac{d\sigma_L}{dt} + \frac{d\sigma_T}{dt} + \sqrt{2\varepsilon (\varepsilon + 1)} \frac{d\sigma_{LT}}{dt} \cos \phi + \varepsilon \frac{d\sigma_{TT}}{dt} \cos 2\phi$$
$^2$H(e,e'π±)NN Separated $d\sigma/dt$

- Data points have slightly different $\overline{W}, Q^2$.
- All data scaled to $W=2.0$ GeV assuming $1/\overline{W}^2$ dependence, $M$=free nucleon mass.
- No scaling applied in $Q^2$.

- **Longitudinal cross-section shows steep rise due to $\pi$ pole at small $-t$.**
- **Transverse cross-section much flatter, generally smaller for $\pi^-$**.
- **Both follow nearly universal curves vs $-t$, with only a weak $Q^2$-dependence.**

Error bars indicate statistical and pt-pt systematic uncertainties in quadrature.
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\( \pi^-/\pi^+ \) Separated Response Function Ratios

VGL Regge Model:

- \( \pi \) electroproduction in terms of exchange of \( \pi \) and \( \rho \) Regge trajectories.

[PRC 57(1998)1454]

- Model parameters fixed from pion photoproduction.

- Free parameters: \( \Lambda_{\pi}^2 \) and \( \Lambda_{\rho}^2 \) (from \( ^1H \) data).

\[ R_L = 0.8 \text{ consistent with } |A_S/A_V| < 6\% \]

- Transverse Ratios tend to \( 1/4 \) as \(-t\) increases:
  
  \( \rightarrow \) Is this an indication of Nachtmann’s quark charge scaling?

- \(-t = 0.3 \text{ GeV}^2 \) seems too low for this to apply. Might indicate the partial cancellation of soft QCD corrections in the formation of the ratio.

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Summary

- Separated $\sigma_L$, $\sigma_T$, $\sigma_{LT}$, $\sigma_{TT}$ cross sections for the $^2\text{H}(e, e'\pi^\pm)\text{NN}$ reactions were extracted using the Rosenbluth L/T separation technique.
  - $F_{\pi}$-1: $W=1.95\ \text{GeV}$: $Q^2=0.6,\ 1.0,\ 1.6\ \text{GeV}^2$.
  - $F_{\pi}$-2: $W=2.2\ \text{GeV}$: $Q^2=2.45\ \text{GeV}^2$.

- $\pi^-/\pi^+$ ratios for $\sigma_L$, $\sigma_T$ extracted as a function of $-t$.
  - $R_L \approx 0.8$, trending towards unity at low $-t$.
    - Indicates the dominance of isovector processes at low $-t$ in the longitudinal response function.
  - The evolution of $R_T$ with $-t$ shows rapid fall off consistent with earlier theoretical predictions, expected to approach $\frac{1}{4}$, the square of the ratio of the quark charges involved.
    - Further theoretical work needed re. alternate explanations.