Exclusive Charged Pion Electroproduction with Nucleon Tagging

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Exploring Hadron Structure with Tagged Structure Functions
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JLab $F_\pi$ Program – 6 and 12 GeV

JLab 6 GeV – 2 experiments extracted the elastic pion form factor

$F_{\pi^{-1}}$: $Q^2 = 0.6, 0.75 1.6$ GeV$^2$
$F_{\pi^{-2}}$: $Q^2 = 1.6, 2.5$ GeV$^2$

JLab 12 GeV upgrade will allow measurement of $F_\pi$ up to $Q^2=6$ GeV$^2$

Primary constraint on maximum value of $Q^2$ accessible is the need to measure the cross section close to the pole
Measurement of $\pi^+$ Form Factor – Low $Q^2$

At low $Q^2$, $F_{\pi}$ can be measured directly via high energy elastic $\pi^-$ scattering from atomic electrons

→ CERN SPS used 300 GeV pions to measure form factor up to $Q^2 = 0.25$ GeV$^2$ [Amendolia et al, NPB277, 168 (1986)]

→ Data used to extract pion charge radius

$r_{\pi} = 0.657 \pm 0.012$ fm

Maximum accessible $Q^2$ roughly proportional to pion beam energy

$Q^2=1$ GeV$^2$ requires 1000 GeV pion beam
Measurement of $\pi^+$ Form Factor – Larger $Q^2$

At larger $Q^2$, $F_\pi$ must be measured indirectly using the “pion cloud” of the proton via pion $p(e,e'\pi^+)n$

$\rightarrow |p> = |p>_0 + |n \pi^+> + \ldots$.

$\rightarrow$ At small $-t$, the pion pole process dominates the longitudinal cross section, $\sigma_L$

$\rightarrow$ In Born term model, $F_\pi^2$ appears as,

$$\frac{d\sigma_L}{dt} \propto \frac{-tQ^2}{(t - m_{\pi}^2)} g_{\pi NN}^2(t) F_\pi^2(Q^2, t)$$

Drawbacks of this technique

1. Isolating $\sigma_L$ experimentally challenging
2. Theoretical uncertainty in form factor extraction
Extraction of $\pi^+$ Form Factor in $p(e,e'\pi^+)n$

$\pi^+$ electroproduction can only access $t<0$ (away from pole)

Early experiments used “Chew-Low” technique
1. Measured $-t$ dependence
2. Extrapolated to physical pole

Chew-Low extrapolation unreliable\(^1\) – FF depends on fit form

Fitting/constraining a \textit{model} incorporating FF is a more robust technique
$\rightarrow$ \textit{t-pole} “extrapolation” is implicit, but one is only fitting data in physical region

\(^1\)see PRC 78, 045203 (2008) for more details on this
JLab $F_\pi$ Experiment Details

Reaction:

\[ e + p \rightarrow e' + \pi^+ + n \]

Electron ID in SOS:
- Threshold gas Cerenkov detector
- Lead-glass detector ($E/p_{\text{reconstructed}}$)

Pion ID in HMS:
- Aerogel Cerenkov detector
\( p(e, e' \pi^+) n \) Event Selection

1. Select electrons in SOS and pions in HMS
2. Reconstruct undetected neutron mass
   \[ M_n^2 = (P_{e-\text{beam}}^\mu + P_p^\mu - P_{e'}^\mu - P_\pi^\mu)^2 \]
3. Identify events that arrived simultaneously in HMS and SOS
Pion Structure Function vs. Pion Form Factor

Both $F_2^\pi(x)$ and $F_\pi(Q^2)$ measurements use pion cloud of nucleon to provide “virtual pion” target.

Pion structure function – “inclusive” final state
→ Hadron detection needed to “tag” virtual pion
→ Kinematic constraint: $-t > x_\pi^2 M_N^2/(1-x_\pi)$

Pion form factor – real pion in final state tags the virtual pion
→ Similar constraint for $-t_{\text{min}}$
→ Hadron tagging not useful for getting closer to pole

$$t = (p_{N'} - p_N)^2 = m_N^2 + m_{N'}^2 - 2m_N E_{N'}$$
Kinematic Constraints on $-t_{\min}$

Minimum value of $-t$ reached when pion emitted in direction of virtual photon

Require $-t_{\min}<0.2$ for form factor extraction

$F_\pi^{-1/2}$ will reach $Q^2=6$ GeV$^2$ detecting scattered electron and pion

Note: $F_\pi^{-1/2}$ reach also constrained by requirements to detect forward pion
Kinematic Constraints on $-t_{\text{min}}$

Beam energy = 11 GeV

Ultimate $Q^2$ reach of pion form factor program at JLab dictated by beam energy, and minimum accessible pion angle.
Separated $\pi^-/\pi^+$ Ratios

• $F_{\pi}^{-1}$ and $F_{\pi}^{-2}$ measured $\pi^-/\pi^+$ cross sections and ratios in the $D(e, e'\pi^+)nn$ and $D(e, e'\pi^-)pp$ reactions

• Longitudinal ratios:
  – Pole dominance implies $\sigma_L(\pi^-)/\sigma_L(\pi^+) \sim 1$
  – Deviation from 1 suggests non-pole backgrounds $\rightarrow$ complications for pion form factor extraction

• Transverse ratios
  – As $-t$ increases, $\sigma_T(\pi^-)/\sigma_T(\pi^+)$ approaches $\frac{1}{4}$ $\rightarrow$ implies scattering from quarks in nucleon

• Extraction of ratios from deuterium $\rightarrow$ assumes that nuclear effects are either small or largely cancel in the ratio
  – Example: proton-proton, neutron-neutron final state interactions known not to exactly cancel at very small relative momentum
  – Any issues due to nucleon virtuality?
Separated $\pi^-/\pi^+$ Ratios

$\pi^-/\pi^+$ ratios from $F_{\pi^-1}$ and $F_{\pi^-2}$

$R_L \sim 1 \rightarrow$ pion pole dominance

$R_T \rightarrow 1/4$ at large $-t$, scattering from quarks (?)

To appear soon.
Quasifree D(e,e’π)

Missing mass not fixed to one value for pion production from deuterium – nucleon momentum distribution broadens distribution

Momentum distribution can also impact effective kinematics at the virtual photon-nucleon vertex

\[ W = \text{total center of mass energy} = W_{\text{stationary}} \]

\[ W < W_{\text{stationary}} \]

\[ W > W_{\text{stationary}} \]
Event generation uses deuteron momentum distribution

→ Pion kinematics from “struck” nucleon energy assuming spectator on-shell

\[ E_{\text{struck}} = M_D - \sqrt{m_{\text{spec}}^2 + p_{\text{spec}}^2} \]

As \(-t\) increases, so does average value of struck nucleon momentum
Event generation uses deuteron momentum distribution

→ Pion kinematics from “struck” nucleon energy assuming spectator on-shell

\[ E_{\text{struck}} = M_D - \sqrt{m_{\text{spec}}^2 + p_{\text{spec}}^2} \]

As \(-t\) increases, so does average value of struck nucleon momentum

→ Tagging the low momentum nucleon removes this correlation
Tagged D(e,e'\pi\pm)

Test for nuclear effects in exclusive pion production in deuterium

\[
\frac{D(e, e'\pi^- p_s p)}{D(e, e'\pi^-)}
\]

1. Examine tagged cross section integrated up to \(p_s = 100\) MeV
2. Bin in \(p_s\) up to largest accessible momentum

Comparison of tagged protons to tagged neutrons would be most directly applicable to F-\(\pi\) program, but technically challenging
At an electron-ion collider (EIC), tagging of recoil hadron crucial
\[ \rightarrow \] Higher energies, detector resolutions mean missing mass technique can’t be used to guarantee exclusivity

\[ H(e,e' \pi^+n) \rightarrow \] detect recoil neutron at small angles

\[ D(e,e'\pi^-pp) \rightarrow \] detect recoil and spectator proton?
Extracting $F_{\pi}$ at an EIC

Three potential approaches to extracting the pion form-factor at EIC

1. Use the “fact” that as $Q^2$ gets very large, $\sigma_L$ should dominate the unseparated cross section
   - Rely on measurements at JLab 12 GeV to proves whether this assumption is validated (may not be)
   - Form-factor has more model dependence

2. Perform explicit L-T separation similar JLab fixed target program
   - Requires low energies protons (5-15 GeV) to get sufficient epsilon lever arm

3. Use polarization degrees of freedom
Extract $\sigma_L$ with no L-T separation?

In principle possible to extract $R = \sigma_L / \sigma_T$ using polarization degrees of freedom

In parallel kinematics (outgoing meson along $\vec{q}$)

$$\frac{R_L}{R_T} = \frac{1}{\epsilon} \left( \frac{1}{\chi_z} - 1 \right)$$

$$\chi_z = \frac{1}{P_e \sqrt{1 - \epsilon^2}} P_z$$

$\chi_z$ = z-component of proton

"reduced" recoil polarization in $H(e,e'p)\pi^0$


A similar relation holds for pion production from a polarized target if we re-define $\chi_z$

$$\chi_z = \frac{1}{2P_e P_T \sqrt{1 - \epsilon^2}} A_z$$

$A_z$ = target double-spin asymmetry
Isolating $\sigma_L$ with Polarization D.O.F

$$\sigma_{pol} \sim P_e P_p \sqrt{(1 - \varepsilon^2)} A_z$$

Nominal, high energies, $\varepsilon$ very close to 1.0 $\rightarrow$ destroys figure of merit for this technique
$\rightarrow$ If we can adjust $\varepsilon$ to 0.9 then $\sqrt{1 - \varepsilon^2} \rightarrow 0.44$
$\rightarrow \varepsilon = 0.95$
$\sqrt{1 - \varepsilon^2} \rightarrow 0.31$

Example: At $Q^2 = 5$, lowest $s$ of 3 GeV $e^-$ on 20 GeV $p$ results in the smallest $\varepsilon = 0.947$ (for which neutron is still easily detectable)

Additional issue: $A_z =$ component of $p$ polarization parallel to $q \rightarrow$ proton polarization direction ideally tunable at IP
Pion Form Factor at EIC – LT separation

Assumptions:
- High $\varepsilon$: 5(e⁻) on 50(p).
- Low $\varepsilon$ proton energies as noted.
- $\Delta \varepsilon \sim 0.22$.
- Scattered electron detection over $4\pi$.
- Recoil neutrons detected at $\theta < 0.35^\circ$ with high efficiency.
- Statistical unc: $\Delta \sigma_L/\sigma_L \sim 5\%$.
- Systematic unc: 6%/ $\Delta \varepsilon$.
- Approximately one year at $L = 10^{34}$.

Excellent potential to study the QCD transition nearly over the whole range from the strong QCD regime to the hard QCD regime.
Summary

• Tagging not helpful for extraction of the pion form factor for JLab fixed target program
  – Missing mass can cleanly identify exclusive final state
  – Cannot get any closer to the pion pole $\rightarrow$ detecting produced pion is already sufficient for reaching $-t_{\min}$

• Spectator tagging may be helpful for $D(e,e'\pi)pp$
  – $-t$ at the vertex correlated with momentum of struck nucleon $\rightarrow$ off-shellness introduces odd effects in charge ratios?
    – $D(e,e'\pi p_s p)$ could allow constraints on these effects

• Pion form factor (and all exclusive charged pion measurements) will require some kind of hadron tagging for measurements at EIC
$F_\pi$ Extraction from JLab data

VGL Regge Model

Feynman propagator replaced by $p$ and $r$ Regge propagators

→ Represents the exchange of a series of particles, compared to a single particle

Model parameters fixed from pion photoproduction

Free parameters: $\Lambda_\pi, \Lambda_\rho$

(trajectory cutoff)

$F_\pi(Q^2) = \frac{1}{1 + Q^2 / \Lambda_\pi^2}$

$\Lambda_\pi^2 = 0.513, 0.491$ GeV$^2$, $\Lambda_\rho^2 = 1.7$ GeV$^2$
In addition to Born terms, pQCD processes can also contribute to $\pi^+$ production.

Carlson and Milana [PRL 65, 1717 (1990)] calculated these contributions for Cornell kinematics:

→ Asymptotic form for $F_\pi$ → King-Sachrajda nucleon distribution

For $-t > 0.2 \text{ GeV}^2$, pQCD contributions grow rapidly:

→ This helps set the constraint on maximum accessible $Q^2$

(fixed $W$, $-t_{\min}$ grows with $Q^2$)

<table>
<thead>
<tr>
<th>$Q^2$ (GeV$^2$)</th>
<th>$W$ (GeV)</th>
<th>$-t$ (GeV$^2$)</th>
<th>$M_{\text{pQCD}}/M_{\text{pole}}$</th>
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<td>1.94</td>
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<td>9.77</td>
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</table>
\[ H(e,e'\pi^+) \] in GPD framework

Non-pole backgrounds can also be calculated in a GPD framework

\[ \rightarrow M_{\pi^+} \] proportional to linear combination of:

\[
\begin{align*}
H(x, \xi, t) &= H - H \\
E(x, \xi, t) &= E - E
\end{align*}
\]

VGG\*/GPD

VGG model [PRD 60, 094017 (1990)] calculation of non-pole backgrounds shows different \(-t\) dependence than C&M calculation

*Not authorized or endorsed by V,G, or G
Parallel Kinematics

Polarization relation for extracting $s_L/s_T$ only applies in parallel kinematics – how quickly does this relation break down away from $q_{CM} = 0$?

$Q^2 = 5$ GeV$^2$

$W = 1.95$ GeV

MAID2007

\[ R = \frac{\sigma_L}{\sigma_T} \]

\[ (\frac{1}{\chi - 1})/\varepsilon \]
L/T Extraction

Extraction via this technique requires strict cuts on $\theta_{\text{CM}}$

$Q^2 = 5 \text{ GeV}^2$, *(3 on 20)*:
- 1 degree CM cut corresponds to ~ 30 mrad in the lab

$Q^2 = 25 \text{ GeV}^2$, *(5 on 50)*:
- 1 degree CM cut corresponds to 20 mrad in the lab

At 1 degree, polarization observable already ~ 15% different from true value
- very tight cuts will be needed (0.1 degrees?)