Semi-inclusive Pion Electroproduction in Deep Inelastic Scattering.

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Overview

- We are measuring Pion Electroproduction in Semi-inclusive Deep Inelastic Scattering (SIDIS) using the CLAS detector at Jefferson Lab.

- The current talk details progress at measuring three moments of the SIDIS cross section. Two unpolarized terms are measured for positive and negative pions, and the term sensitive to beam helicity is measured in all three pion channels.
Semi-inclusive Pion Production

\[ ep \rightarrow e \pi^+ X \]
\[ ep \rightarrow e \pi^- X \]
\[ ep \rightarrow e \pi^0 X \]

Requires:

- \( W > 2 \)
- \( Q^2 > 1 \)
- \( MM_\pi > 1.2 \)
- \( 0.4 < z < 0.7 \)

Kinematic Variables:

- \( \nu = E - E' \)
- \( Q^2 = -q^2 = -(k - k')^2 \)
- \( x = \frac{Q^2}{2M\nu} \)
- \( z = \frac{E_h}{\nu} \)
- \( W^2 = (q + P)^2 \)
The primary goal of my analysis is to measure these three moments of the SIDIS cross-section:

\[ d\sigma = (1 + A_{UU}^{\cos\phi} \cos\phi + A_{UU}^{\cos^2\phi} \cos 2\phi + \lambda_e A_{LU}^{\sin\phi} \sin\phi) \quad \lambda_e = \pm 1 \]

- Each moment is directly related to a structure function, providing access to TMD’s. (A. Bacchetta, M. Diehl, K. Goeke, P. Mulders, & M. Schlegel, hep-ph/0611265v2, 2007)

- Of particular interest is the Boer-Mulders function, a TMD describing the distribution of transversely polarized quarks in an unpolarized nucleon. It is contained in all three structure functions, but most easily accessed from the \( \cos^2\phi \) moment. (D. Boer and P. J. Mulders, hep-ph/9711485 (1998))

- Both the \( \cos^2\phi \) and \( \cos\phi \) moments are sensitive to the Cahn effect, which is a purely kinematic effect due to the intrinsic momentum of quarks in the nucleon. (R. N. Cahn, Phys. Lett. B78 (1978) 269)

- The \( \sin\phi \) moment is measured from the beam-spin asymmetry. It is a twist-3 object that provides access to information on quark-gluon-quark correlations.
Jefferson Lab

- National Lab supported by DOE in Newport News, Virginia.
- Home of the CEBAF accelerator.
- 6 GeV polarized electron beam.
- Achieved by passing the electron beam through five passes in two linear accelerators.
- CLAS is in Hall-B.
- Very high luminosity $\sim 0.5 \times 10^{34} (\text{cm}^2\text{s})^{-1}$
Drift Chambers: Used for particle tracking.


Cerenkov Counter and Electromagnetic Calorimeter: Used for Electron Detection

Torus: Produces magnetic field used to bend charged particles.
Data taken between April and July of 2003.
Unpolarized liquid hydrogen target.
Torus magnet reduced to 60% of full current to maximize acceptance of charged pions.
Longitudinally polarized electron beam with energy 5.498 GeV and polarization of 75.1±0.2%.
Measuring the following three semi-inclusive reactions:
\[ ep \rightarrow e\pi^+ X \quad 6.2\text{M Events} \]
\[ ep \rightarrow e\pi^- X \quad 1.1\text{M Events} \]
\[ ep \rightarrow e\pi^0 X \quad 0.9\text{M Events} \]
Kinematic Coverage

$Q^2$ vs $x$

$\pi^+$

$Q^2$ vs $x$

$\pi^-$

$Q^2$ vs $x$

$\pi^0$

$z$ vs $P_T$

$z$ vs $P_T$

$z$ vs $P_T$
Beam-spin Asymmetries

- BSA is fit in $\phi$ for each bin in $z$, $P_T$, $x$, and $Q^2$, after integration over other variables.

$$BSA = \frac{1}{P_e} \frac{N^+ - N^-}{N^+ + N^-}$$

- Semi-inclusive range is expected to be $0.4<z<0.7$ for CLAS kinematics.

- Error bars are statistical only.

- Fit with:

$$A_{LU}^{\sin \phi} \sin \phi \over 1 + B \cos \phi + C \cos 2\phi$$

$$\chi^2 / \text{ndf} = 23.71 / 21$$

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p_0$</td>
<td>$0.03046 \pm 0.002908$</td>
</tr>
<tr>
<td>$p_1$</td>
<td>$-0.08351 \pm 0.1425$</td>
</tr>
<tr>
<td>$p_2$</td>
<td>$-0.2517 \pm 0.1415$</td>
</tr>
</tbody>
</table>

$\pi^+, P_T: 0.50-0.60$
Sinφ Moment

Errors are statistical only.
Monte Carlo Simulation

- Acceptance represents the percentage of events that are seen by the CLAS detector.
- Acceptance is calculated by taking the ratio of reconstructed to generated events for each kinematic bin for each pion channel.
- Events are generated using the clasDIS program, which is a LUND-based event generator including the Cahn effect and a recent set of PDFs.
- A GEANT based Monte Carlo (GSim) is used to simulate the CLAS detector.

Acceptance In One $\pi^+$ Kinematic Bin

- $0.3 < x < 0.4$
- $0.4 < P_T < 0.6$
- $0.6 < z < 0.7$
- $1.5 < Q^2 < 2.0$
The acceptance-corrected $\phi$ distribution is fit with the following function in each kinematic bin (after integrating over other kinematic variables):

$$A_0 (1 + A_{UU}^{\cos 2\phi} \cos 2\phi + A_{UU}^{\cos \phi} \cos \phi)$$

\begin{table}[h]
\centering
\begin{tabular}{|c|c|}
\hline
\multicolumn{2}{|c|}{p0*(1+p1*\cos(2\phi)+p2*\cos(\phi))} \\
\hline
$\chi^2$/ndf & 36.4/32 \\
Prob & 0.2712 \\
p0 & 4.096e+04 \pm 541.7 \\
p1 & -0.03813 \pm 0.01538 \\
p2 & -0.9077 \pm 0.01649 \\
\hline
\end{tabular}
\end{table}

$\pi$, $P_T$: 0.60-0.80
Cos$\phi$ Moment

Errors are statistical only.
Radiative corrections are not included.
Other kinematics integrated over 0.4<$z$<0.7.
\[ \cos^2\varphi \text{ Moment} \]

Errors are statistical only. Radiative corrections are not included. Other kinematics integrated over \(0.4<z<0.7\).
Outlook & Conclusion

- Preliminary measurements have been shown for all three moments of the SIDIS cross-section with good statistics in multiple pion channels.

- Currently improving simulation to refine acceptance calculation, computing radiative corrections, and calculating systematic uncertainties.

- These measurements will serve as an important precursor for experiments that will take place at CLAS12.

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SIDIS Cross Section: \( \cos \phi \)

The primary goal of my analysis is to measure these three moments of the SIDIS cross-section:

\[
d\sigma = (1 + A^{\cos \phi}_{UU} \cos \phi + A^{\cos 2\phi}_{UU} \cos 2\phi + \lambda_e A^{\sin \phi}_{LU} \sin \phi) \quad \lambda_e = \pm 1
\]

Each moment is related to a corresponding structure function.

\[
A^{\cos \phi}_{UU} = \frac{F^{\cos \phi}_{UU}}{F_{UU,T}}
\]

\[
F^{\cos \phi}_{UU} = \frac{2M}{Q} C \left[ - \frac{\hat{h} \cdot k_T}{M_h} (x h_1 \frac{D_1}{z} + M_h \frac{D_1}{z}) - \frac{h \cdot p_T}{M} (x f_1 D_1 + M h_1 \frac{\tilde{H}}{z}) \right]
\]

The \( \cos \phi \) moment is associated with the Cahn effect.

The Cahn effect is a kinematic effect due to the intrinsic momentum of quarks in the nucleon.
SIDIS Cross Section: $\cos 2\phi$

The primary goal of my analysis is to measure these three moments of the SIDIS cross-section:

$$d\sigma = (1 + A_{UU}^{\cos \phi} \cos \phi + A_{UU}^{\cos 2\phi} \cos 2\phi + \lambda_e A_{LU}^{\sin \phi} \sin \phi) \quad \lambda_e = \pm 1$$

$$A_{UU}^{\cos 2\phi} = \frac{F_{UU}^{\cos 2\phi}}{F_{UU,T}} \quad F_{UU}^{\cos 2\phi} = C\left[-\frac{2(\hat{h} \cdot k_T)(\hat{h} \cdot p_T) - k_T \cdot p_T}{MM_h} h_t^\perp H_1^\perp \right]$$

The $\cos 2\phi$ moment can provide direct access to the Boer-Mulders function and the Collins function. Also a possible contribution by the Cahn effect. Some models predict this contribution to be of comparable size to that of the Boer-Mulders TMD.

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\[ d\sigma = (1 + A_{UU}^{\cos \phi} \cos \phi + A_{UU}^{\cos 2\phi} \cos 2\phi + \lambda_e A_{LU}^{\sin \phi} \sin \phi) \quad \lambda_e = \pm 1 \]

\[ F_{LU}^{\sin \phi} = \sqrt{2\varepsilon(\varepsilon+1)} \frac{2M}{Q} C[\frac{\hat{h} \cdot k_T}{M_h} (xeH_1^\perp + \frac{M_h}{M} f_1 \frac{\tilde{G}}{z}) + \frac{\hat{h} \cdot p_\perp}{M} (xg_1^\perp D_1 + \frac{M_h}{M} h_1^\perp \frac{\tilde{E}}{z})] \]

The LU term is due to the imaginary part of the interference between longitudinal and transverse photon amplitudes.

The BSA is twist-3, providing access to information on quark-gluon-quark correlations.

These higher-twist effects can partly be related to the average transverse force acting on quarks just after interaction with the virtual photon in the collision (M. Burkardt, 2008, 0807.2599)
Boer-Mulders Function $h_{1\perp}(x, p_T^2)$

- TMD describing the distribution of transversely polarized quarks in an unpolarized hadron.

- Final state interactions expected to convert position-space asymmetry into momentum-space asymmetry.

- One of the two leading-twist time-reversal-odd (T-odd) structures.

- Will vanish if there is no quark orbital angular momentum.

- Models show that $h_{1u}^{\perp} = h_{1d}^{\perp} + O(\frac{1}{N_C})$, implying an opposite sign for $\pi^-$ and $\pi^+$.

- The opposite sign for $\pi^-$ and $\pi^+$ lead to a larger $\cos 2\varphi$ moment for $\pi^-$ than for $\pi^+$.
Fits for $\pi^+$

$$p0 \times 10^3 \times \cos(2\phi) + p2 \times \cos(\phi)$$

$\chi^2 / \text{ndf} = 351.5 / 32$

Prob = 0

- $p0 = 8.173 \pm 574.3$
- $p1 = -0.02565 \pm 0.008322$
- $p2 = -0.4915 \pm 0.008647$

$\pi^+, P_T: 0.60-0.80$