Correlations in Partonic and Hadronic Interactions

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SIDIS Single Pion Beam Spin Asymmetry Measurements with CLAS 12

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Physics Motivation

- The 3D nucleon structure in momentum space can be described by TMDs
- A way to access these properties is the semi inclusive deep inelastic scattering

**SIDIS cross section for an unpolarized target:**

\[
\frac{d\sigma}{dx_B dQ^2 dz d\phi_h dp_{h\perp}^2} = K(x, y, Q^2) \left\{ F_{UU,T} + \varepsilon F_{UU,L} + \sqrt{2 \varepsilon(1 + \varepsilon)} \cos \phi_h F_{UU}^{\cos \phi_h} + \varepsilon \cos(2\phi_h) F_{UU}^{\cos 2\phi_h} + \lambda \varepsilon \sqrt{2(1 - \varepsilon)} \sin \phi_h F_{LU}^{\sin \phi_h} \right\}
\]

\[
F_{LU}^{\sin \phi} = \frac{2M}{Q} C \left( -\frac{\hat{n} \cdot k_T}{M_h} \left( xeH_1^+ + \frac{M_h}{M} f_1 \tilde{G}_\perp^+ \right) + \frac{\hat{n} \cdot p_T}{M} \left( xg_1^+ D_1 + \frac{M_h}{M} h_1^+ \tilde{E}_\perp \right) \right)
\]

- Collins FF
- unpolarized dist. function
- twist-3 pdf
- Boer-Mulders
- twist-3 t-odd dist. function

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A convolution of 4 TMDs and 4 fragmentation functions

Each term contains a twist 3 component

The results can be used in a global fit to constrain the TMDs and FF

**Additional constraints:** i.e. from unpolarized structure functions
and also from di-hadron SIDIS (Timothys talk)

\[ F_{LU}^{\sin \phi_R} = -x \frac{|\vec{R}| \sin \theta}{Q} \left[ \frac{M}{M_{\pi \pi}} x e^q(x) H_1^{\pi \pi}(z, \cos \theta, M_{\pi \pi}) + \frac{1}{z} f_1^q(x) \tilde{G}(z, \cos \theta, M_{\pi \pi}) \right] \]


+ constraints from other experiments (SIDIS + Drell-Yan)

⇒ A global fit is needed for a reliable extraction

What can we learn from the extracted TMDs?

i.e. \( e(x) \) ⇒ Recent publication by Chien-Yeh Seng (PRL 122)

⇒ The chiral-odd, twist 3 distr. function \( e(x) \) is related to the nucleon sigma terms of the quark chromo magnetic dipole moment

⇒ Essential inputs for the CP-odd pion-nucleon couplings

⇒ Main contributors of long range CP-odd nuclear forces

\[ Q^2 = 1.5 \text{ GeV}^2 \]

\[ \sigma_c^0 = (0.08 - 0.34) \text{GeV}^2 \]
Physics Motivation

Goal of this study: Extract $F_{LU}^{\sin \phi}$ from single pion beam spin asymmetries

$$d\sigma = d\sigma_0 (1 + A_{UU}^{\cos \phi} \cos \phi + A_{UU}^{\cos 2\phi} \cos 2\phi + \lambda_e A_{LU}^{\sin \phi} \sin \phi)$$

$$BSA = \frac{d\sigma^+ - d\sigma^-}{d\sigma^+ + d\sigma^-} = \frac{A_{LU}^{\sin \phi} \sin \phi}{1 + A_{UU}^{\cos \phi} \cos \phi + A_{UU}^{\cos (2\phi)} \cos (2\phi)}$$

$$A_{LU}^{\sin \phi} = \sqrt{2\varepsilon (1 - \varepsilon)} \frac{F_{LU}^{\sin \phi}}{F_{UU}}$$

Past: Measurements have been performed with CLAS, HERMES and COMPASS

Advantages of CLAS12
- Significantly higher statistics
- Extended kinematic coverage ($Q^2, P_T$)

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Experimental Setup

- Data recorded with CLAS12 during fall of 2018
- 10.6 GeV electron beam
- 85% average polarization
- Liquid H₂ target
- Analysed data ~ 3% of the approved RG-A beam time
Particle ID

Electron ID → Based on the electromagnetic calorimeter and the cherenkov counters

Hadron ID → Based on $\beta$ vs momentum correlation from TOF

→ Maximum likelihood particle ID

$$P(\beta) = \frac{1}{\sqrt{2\pi}\sigma} \exp\left( -\frac{1}{2} \left( \frac{\beta - \mu}{\sigma} \right)^2 \right)$$

→ Assign particle to species with the highest probability

→ Check if particle is within a certain confidence level

→ Provides a cleaner particle ID for inclusive measurements
Event selection and kinematic cuts

**π⁰ selection:**

\[ E_γ > 0.6 \text{ GeV} \quad \alpha(e^{-}γ) > 8^{°} \]

all 2γ pairs

→ 2.2 σ cut around the peak positions

→ sidebands are used to estimate the asymmetry of the background

→ A sideband subtraction has been done

**Kinematic cuts for all pions:**

minimal electron energy: 2.0 GeV  
minimal pion energy: 1.25 GeV

**DIS cut:**  
\[ Q^2 > 1 \text{ GeV}^2 \quad W > 2 \text{ GeV} \]

**Additionally:** Cut on the final state hadron momentum fraction \( z \)

\[ 0.3 < z < 0.7 \]

→ \( z > 0.3 \) removes the "target fragmentation region"

→ \( z < 0.7 \) removes contamination by pions from exclusive channels
Kinematic coverage for \( \pi^+ \) (similar for \( \pi^- \) and \( \pi^0 \))

\[
Q^2 \quad [\text{GeV}^2] \\
\begin{array}{c|c|c|c|c|c|c}
\hline
\text{DIS} & \text{Counts} & \text{Counts} & \text{Counts} \\
0 & 1 & 2 & 3 & 4 & 5 & 6 \\
\hline
1 & 2 & 3 & 4 & 5 & 6 & 7 \\
\hline
2 & 3 & 4 & 5 & 6 & 7 & 8 \\
\hline
3 & 4 & 5 & 6 & 7 & 8 & 9 \\
\hline
4 & 5 & 6 & 7 & 8 & 9 & 10 \\
\hline
\end{array}
\]

- Experimental
- GEANT based Monte Carlo

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Beam spin asymmetry

\[ BSA_i = \frac{1}{P_e} \cdot \frac{N_i^+ - N_i^-}{N_i^+ + N_i^-} \]

\[ P_e = 85 \% : \text{average e}^- \text{ beam polarisation} \]

**Φ dependence without kinematic bins**

\[ \langle Q^2 \rangle \sim 3.0 \text{ GeV}^2 \quad \langle x_B \rangle \sim 0.27 \quad \langle z \rangle \sim 0.42 \quad \langle P_T \rangle \sim 0.45 \]

**Extraction of the moments:**

a) A simple \( \chi^2 \) fit of the \( \phi \) dependence

b) Statistical extraction by minimizing

\[ P = -\prod_{i=1}^{N} \left( 1 + h \cdot P_e \cdot \frac{\text{gauss}(A_{LU}^{\sin(\phi)} , \sigma_1) \cdot \sin(\phi)}{1 + \text{gauss}(A_{UU}^{\cos(\phi)} , \sigma_2) \cdot \cos(\phi) + \text{gauss}(A_{UU}^{\cos(2\phi)} , \sigma_3) \cdot \cos(2\phi)} \right) \]
$F_{LU}^{\sin \phi} / F_{UU}$ for a $z$ and $x_B$ binning
\[ \frac{F_{LU}^{\sin \phi}}{F_{UU}} \] for a \( P_T \) and \( Q^2 \) binning

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**\( \pi^+ \)**

**\( \pi^- \)**

**\( \pi^0 \)**

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**CLAS12**  **CLAS** [W. Gohn et al. PRD 98 (2014)]

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How do things change with a multidimensional binning?

**Step 1:** A two dimensional binning

\[ 0.3 < z < 0.7 \]

\[ 0.0 \text{ GeV} < P_T < 1.4 \text{ GeV} \]

\[ 1.0 \text{ GeV}^2 < Q^2 < 12 \text{ GeV}^2 \]
How do things change with a multidimensional binning?

Step 2: A multidimensional binning in $z$, $x_B$, $P_T$ and $Q^2$

$\Pi^+ \quad 0.3 < z < 0.4$

$x_B = 0.17$

$x_B = 0.24$

$x_B = 0.40$

1 dimensional
Comparison to theoretical predictions

A first theoretical model for single pion SIDIS was introduced in


Simplifying assumption:

• only contribution from $e(x) \otimes H_1^\perp$

$F_{LU}^{\sin \phi} = \frac{2M}{Q} C \left( \frac{\hat{h} \cdot k_T}{M_h} \left( xeH_1^\perp + \frac{M_h}{M} f_1 \frac{\tilde{G}^\perp}{z} \right) + \frac{\hat{h} \cdot p_T}{M} \left( xg_1^\perp D_1 + \frac{M_h}{M} h_1^\perp \frac{\tilde{E}}{z} \right) \right)$

• signs are correctly reproduced
• ratio between $\pi^+$ and $\pi^0$ not
• magnitude at large $x$ is too low
Recent global fits show that the other terms can not be neglected

Some of the TMDs and FF got better constrained

Updated calculations, including all terms and the most recent TMDs and FF are in progress by P. Schweitzer et al.

A multidimensional binning will enable a much better comparability with the calculations
Conclusion and Outlook

• CLAS12 enables the extraction of SIDIS pion BSA moments with high accuracy in an extended kinematic range.

• \( F_{LU}^{\sin \phi} / F_{UU} \) is positive for \( \pi^+ \) and \( \pi^0 \) and close to zero or slightly negative for \( \pi^- \).

• The presented analysis is based on only ~ 3% of the approved RGA beam time.

• The statistics provided by the pass 1 cooking this spring will enable a precise multidimensional analysis over an extended kinematic region.