Azimuthal Single-Spin Asymmetries on a Transversely Polarized Hydrogen Target at HERMES

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For the HERMES Collaboration
Why worry about unintegrated distribution and fragmentation functions if we don’t even understand the integrated ones?

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Leading Twist

Quark Distribution Functions

\[ f_l^q = \bullet \]
\[ g_l^q = \bullet \rightarrow - \bullet \]
\[ h_l^q = \bullet - \bullet \]

Unpolarized quarks and nucleons

Longitudinally polarized quarks and nucleons

Transversely polarized quarks and nucleons

\( q(x) \): spin averaged (well known)

\( \Delta q(x) \): helicity difference (known)

\( \delta q(x) \): helicity flip (unmeasured!)

⇒ Vector Charge

⇒ Axial Charge

⇒ Tensor Charge

HERMES 1995-2000

HERMES 2002...
Leading Twist
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How can one measure transversity?

Need another chiral-odd object! ⇒ Semi-Inclusive DIS

\[ \sigma^{ep\rightarrow ehX} = \sum_{q} \delta q \otimes \sigma^{eq\rightarrow eq} \otimes FF^{q\rightarrow h} \]

\[ \downarrow \]

chiral-odd

DF

chiral-odd

FF

CHIRAL EVEN
How can one measure transversity?

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\[ \sigma^{ep \rightarrow ehX} = \sum_q \delta q \otimes \sigma^{eq \rightarrow eq} \otimes \text{DF FF}^{q \rightarrow h} \]

\[ \Downarrow \]

chiral-odd

\[ \Downarrow \]

chiral-odd

\[ \text{CHIRAL EVEN} \]

→ use Chiral-odd and T-odd **Collins FF**: Correlation between \( P_{h\perp} \) and transverse spin of nucleon
How can one measure transversity?

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\[ \sigma^{ep \rightarrow ehX} = \sum_q \delta_q \otimes \sigma^{eq \rightarrow eq \chi} \]

↓

chiral-odd

DF FF

↓

chiral-odd

CHIRAL EVEN

→ use Chiral-odd and T-odd Collins FF:

Correlation between \( P_{h\perp} \) and transverse spin of nucleon
Collins Fragmentation Function

- Collins function $H_1^\perp$ describes left-right asymmetry in the direction of outgoing hadron
- Originally proposed by Collins (1993)
- $T$-odd $\Rightarrow$ need interference of amplitudes
- basically unknown (estimates from DELPHI data and model calculations exist)
Caution!

Other Spin-Momentum-Correlations exist!
Unintegrated Quark Distributions

Functions surviving integration over intrinsic transverse momentum

- $f_1 = \circ$
- $g_{1L} = \rightarrow - \rightarrow$
- $h_{1T} = \uparrow - \uparrow$
- $g_{1T} = \circ - \circ$
- $f_{1T} = \circ - \circ$
- $h_{1} = \circ - \circ$
- $h_{1L} = \rightarrow - \rightarrow$
- $h_{1T} = \circ - \circ$
Unintegrated Quark Distributions

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\[ f_{1T} = \]
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Sivers Function
Some words about Sivers Effect

Thanks to Brodsky, Hwang, Schmidt:

- quark rescattering via soft gluon exchange
- correlates transverse spin with direction of outgoing hadron
- requires $L_z$ of quarks
Some words about Sivers Effect

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- requires $L_z$ of quarks

Thanks to Collins, Ji, Yuan, Belitzky ...:

- Soft gluon is model for gauge link needed for gauge invariance
- Gauge links provide necessary complex phase for interference
- T-Symmetry of QCD requires opposite sign of Sivers function in DIS and DY
- slightly different approach by Burkardt using impact parameter dependent PDF’s ("chromodynamic lensing")
$ep \rightarrow e'hX$ – study azimuthal distribution of hadrons:
(Unpolarized beam & Transversely polarized target)

$$A_{UT}(\phi, \phi_S) = \frac{1}{\langle S_\perp \rangle} \frac{N^+(\phi, \phi_S) - N^-(\phi, \phi_S)}{N^+(\phi, \phi_S) + N^-(\phi, \phi_S)}$$

$$\sim \sin(\phi + \phi_S) \sum_q e_q^2 \mathcal{I} \left[ h_{1T}^q(x, p_T^2) H_{1}^{\perp q}(z, k_T^2) \right]$$

$$+ \sin(\phi - \phi_S) \sum_q e_q^2 \mathcal{I} \left[ f_{1T}^{\perp q}(x, q_T^2) D_{1}^{q}(z, k_T^2) \right]$$

$$+ \ldots$$

$\mathcal{I}[\ldots]$: convolution integral over initial ($p_T$) and final ($k_T$) quark transverse momenta
Sine Moments of Countrate Asymmetries

Fit

\[ A(\phi, \phi_S) = A_C \frac{B(<y>)}{A(<x>,<y>)} \sin(\phi + \phi_S) + A_S \sin(\phi - \phi_S) \]

(Virtual Photon Asymmetries)

A. Airapetian et al, hep-ex/0408013 (submitted to PRL)
Sine Moments of Countrate Asymmetries

Collins Asymmetry: \( A_C \propto -h_1(x, p_T^2)H_1^+(z, z^2 k_T^2) \)

- positive for \( \pi^+ \) and negative for \( \pi^- \) as maybe expected (expectation for transversity gives positive \( \delta u \) and negative \( \delta d \))
- unexpected large \( \pi^- \) asymmetry
- averaged over acceptance:
  
  \[ A_C^{\pi^+} = 0.042 \pm 0.014 \] and
  
  \[ A_C^{\pi^-} = -0.076 \pm 0.016 \]

- overall scale uncertainty of 8%
- contribution to pion sample from exclusively produced vector mesons (VM) (from PYTHIA MC)
Sivers Asymmetry: \( A_S \propto -f_{1T}^\perp(x, p_T^2)D_1(z, z^2k_T^2) \)

- significantly positive for \( \pi^+ \)
- first hint of T-odd distribution function from DIS
- \( \pi^- \) asymmetry consistent with zero
- averaged over acceptance:
  \[ A_{S}^{\pi^+} = 0.034 \pm 0.008 \] and
  \[ A_{S}^{\pi^-} = 0.004 \pm 0.010 \]
- overall scale uncertainty of 8%
- systematic error due to VM contribution unknown because VM asymmetry itself unknown
Resolving the Convolution Integral

Weight with transverse hadron momentum $P_{h\perp}$ to resolve convolution:

$$\tilde{A}_{UT}(\phi, \phi_S) = \frac{1}{\langle S_\perp \rangle} \sum_{i=1}^{N^+} P_{h\perp,i} - \sum_{i=1}^{N^-} P_{h\perp,i} \frac{N^+ + N^-}{N^+ + N^-}$$

$$\sim \sin(\phi + \phi_C) \cdot \sum_q e_q^2 \delta q(x) \ z \ H_1^{(1),q}(z) \quad (1): \ p_T^2/k_T^2\text{-moment of distribution / fragmentation function}$$

$$- \sin(\phi - \phi_S) \cdot \sum_q e_q^2 f_{1T}^{(1),q}(x) \ z \ D_1^q(z)$$

$$+ \ldots$$

$\Rightarrow$ 2D-fit of $\tilde{A}_{UT}$ to get Collins and Sivers asymmetries:

$$\tilde{A}_{UT}(\phi, \phi_S) = M_\pi \tilde{A}_C(x, z) \sin(\phi + \phi_s) + M_p \tilde{A}_S(x, z) \sin(\phi - \phi_s)$$
\[ \tilde{A}_{UT}^{\sin \Phi} \propto \delta q(x) \cdot z H_1^{(1)}(z) \]

\[ \tilde{A}_{UT}^{\sin \Phi} \propto -f_{1T}^{(1)}(x) \cdot z D_1(z) \]

Preliminary Results (\(P_{h\perp}\) weighted)
rewrite asymmetries in terms of favored and disfavored fragmentation:

- use $P_{h \perp}$ weighted asymmetries
- neglect strange quarks
- employ symmetry among fragmentation functions, i.e.

$$
D_f \equiv D(u \to \pi^+) \simeq D(d \to \pi^-) \simeq D(\bar{d} \to \pi^+) \simeq D(\bar{u} \to \pi^-) \\
D_d \equiv D(d \to \pi^+) \simeq D(u \to \pi^-) \simeq D(\bar{u} \to \pi^+) \simeq D(\bar{d} \to \pi^-) \\
\frac{1}{2}(D_f + D_d) \simeq D(u \to \pi^0) \simeq D(d \to \pi^0) \simeq D(\bar{d} \to \pi^0) \simeq D(\bar{u} \to \pi^0)
$$

$$
\leftrightarrow \begin{align*}
\tilde{A}_{C}^{\pi^+} \simeq & \frac{(4\delta u + \delta \bar{d})H_{f/d} + (4\delta \bar{u} + \delta d)H_{d/f}}{(4u + \bar{d})D_{f/d} + (4\bar{u} + d)D_{d/f}} \\
\tilde{A}_{C}^{\pi^0} \simeq & \frac{4(\delta u + \delta \bar{u}) + \delta d + \delta \bar{d}}{4(u + \bar{u}) + d + \bar{d}} (H_f + H_d)
\end{align*}
$$
express asymmetries in terms of flavor ratios:

\[
\begin{align*}
\tilde{A}_C^{\pi^+} & = \kappa(x, z) \frac{4 + \delta r \mathcal{H}}{4 + r \mathcal{D}} \\
\tilde{A}_C^{\pi^-} & = \kappa(x, z) \frac{4 \mathcal{H} + \delta r}{4 \mathcal{D} + r} \\
\tilde{A}_C^{\pi^0} & = \kappa(x, z) \frac{(4 + \delta r)(1 + \mathcal{H})}{(4 + r)(1 + \mathcal{D})}
\end{align*}
\]

### Polarized Objects

- \( \mathcal{H} = \frac{H_d}{H_f} \)
- \( \delta r = \frac{\delta d + 4 \delta \bar{u}}{\delta u + \frac{1}{4} \delta \bar{d}} \)

### Unpolarized Objects

- \( \mathcal{D} = \frac{D_d}{D_f} \)
- \( r = \frac{d + 4 \bar{u}}{u + \frac{1}{4} \bar{d}} \)

### Mixed

- \( \kappa = \frac{(\delta u + \frac{1}{4} \delta \bar{d}) z H_f}{(u + \frac{1}{4} d) D_f} \)

i.e. CTEQ6,R1990 and Kretzer et al.

\[\Rightarrow 3 \text{ constraints and 3 unknowns!}\]
express asymmetries in terms of flavor ratios:

\[
\tilde{A}_C^+ = \mathcal{K}(x, z) \frac{4 + \delta r \mathcal{H}}{4 + r \mathcal{D}}
\]

\[
\tilde{A}_C^- = \mathcal{K}(x, z) \frac{4 \mathcal{H} + \delta r}{4 \mathcal{D} + r}
\]

\[
\tilde{A}_C^0 = \mathcal{K}(x, z) \frac{(4 + \delta r)(1 + \mathcal{H})}{(4 + r)(1 + \mathcal{D})}
\]

The three asymmetries are not independent \((C(x, z) \equiv \frac{r(x) + 4 \mathcal{D}(z)}{r(x) \mathcal{D}(z) + 4})\):

\[
\tilde{A}_C^+ (x, z) + C(x, z) \tilde{A}_C^- (x, z) - (1 + C(x, z)) \tilde{A}_C^0 (x, z) = 0
\]

for measured asymmetries: \(0.17 \pm 0.36 \text{ (stat.)}\)

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express asymmetries in terms of flavor ratios:

\[
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\tilde{A}_{C}^{+} & = \mathcal{K}(x, z) \frac{4 + \delta r H}{4 + r D} \\
\tilde{A}_{C}^{-} & = \mathcal{K}(x, z) \frac{4H + \delta r}{4D + r} \\
\tilde{A}_{C}^{0} & = \mathcal{K}(x, z) \frac{(4 + \delta r)(1 + H)}{(4 + r)(1 + D)}
\end{align*}
\]

Polarized Objects  Unpolarized Objects  Mixed

\[
\begin{align*}
\mathcal{H} & = \frac{H_d}{H_f} \\
\delta r & = \frac{\delta d + 4\delta \bar{u}}{\delta u + \frac{1}{4}\delta \bar{d}}
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\[
\begin{align*}
\mathcal{D} & = \frac{D_d}{D_f} \\
r & = \frac{d + 4\bar{u}}{u + \frac{1}{4}d}
\end{align*}
\]

\[
\mathcal{K} = \frac{(\delta u + \frac{1}{4}\delta \bar{d})zH_f}{(u + \frac{1}{4}d)D_f}
\]

i.e. CTEQ6,R1990 and Kretzer et al.

\[\Rightarrow 2 \text{ constraints and 3 unknowns!}\]
eliminate $\mathcal{K}$ and relate $\mathcal{H}$ to $\delta r$

$\Rightarrow$ scan solution space for $\mathcal{H}$ and $\delta r$ by sampling set of $(\tilde{A}_C^{\pi^+}, \tilde{A}_C^{\pi^-}, \tilde{A}_C^0)$

(around measured values according to statistical uncertainty)
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Limits on Transversity and Collins FF

probability distribution for $H_d/H_f$ vs. $\delta r$

![Graph showing probability distribution for $H_d/H_f$ vs. $\delta r$.]
\[ \delta r \approx \delta d / \delta u \text{ from } \chi_{\text{QSM}} \]

look at slice of distribution in \( \delta r \):

strong hint for \( H_d / H_f \) negative
Summary and Outlook

- Non-zero Collins effect observed with $H_d/H_f < 0$
- First evidence of T-odd Sivers distribution in DIS?
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• First evidence of $T$-odd Sivers distribution in DIS?
• More data taking since fall of 2003
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⇒ Additional statistics allows analysis of different channels to access transversity:
  - 2-Meson-Correlations ⇒ Interference FF
  - Spin-1 Fragmentation
  - Spin-1/2 Fragmentation (transverse $\Lambda$ polarization)
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- polarized beam
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  - Spin-1/2 Fragmentation (transverse $\Lambda$ polarization)

- polarized beam ⇒ $A_{LT}$ in $\pi$ production (measurement of twist-3 fragmentation function and transversity)
Kinematic Cuts

- $0.023 < x < 0.4 \quad \Rightarrow \langle x \rangle = 0.09$
- $0.2 < z < 0.7 \quad \Rightarrow \langle z \rangle = 0.36$
- $0.1 < y < 0.85 \quad \Rightarrow \langle y \rangle = 0.54$
- $Q^2 > 1 \text{ GeV}^2 \quad \Rightarrow \langle Q^2 \rangle = 2.41 \text{ GeV}^2$
- $W^2 > 10 \text{ GeV}^2$
- $\theta_{\gamma^*h} > 0.02 \text{ rad} \quad \Rightarrow \langle P_{h\perp} \rangle = 0.41 \text{ GeV}$