Probing Quark Distributions in Semi-Inclusive Single Spin Asymmetries

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For the HERMES Collaboration
Polarized Beam at HERA

- 27.5 GeV $e^+/e^-$ beam
- Self-polarizing through Sokolov-Ternov-Effect
- Average beam polarization of about 55%

Comparison of rise time curves

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LightCone 2002 – Los Alamos, August 6th, 2002
• Internal storage cell: pure gas target
• Forward acceptance spectrometer: $40 \text{ mrad} \leq \Theta \leq 220 \text{ mrad}$
• Tracking: 57 tracking planes: $\delta P/P = (0.7 - 1.3)\%$, $\delta \Theta \leq 0.6 \text{ mrad}$
• PID: Cherenkov (RICH after 1997), TRD, Preshower, Calorimeter
Excellent $e^+/e^-$ identification:

- Efficiency $\geq 99\%$
- Hadron contamination $\leq 1\%$

Until 1997 only used Threshold Cherenkov
Excellent $e^+ / e^-$ identification:
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After 1997 use dual radiator Ring Imaging CHERENKOV
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After 1997 use dual radiator

**Ring Imaging CHERENKOV**

$\rightarrow$ very good hadron identification in the range $2 \text{ GeV} \leq P_h \leq 15 \text{ GeV}$
HERMES Internal Gas Target

- Storage cell with atomic beam source
- Pure target (NO dilution)
- Polarized or unpolarized targets possible
- Different gas targets available (H, D, He, N, Kr ...)

\[ <P_T > \approx 0.90 \]

(movable) collimators against synchrotron radiation

source for polarized gas \(10^{17}\) atoms/sec

solenoid 0.35 Tesla

storage cell
\(29 \times 9.8 \times 400\) mm\(^3\)
\(d < 0.1\) mm Al
\(n = 1-3.5 \times 10^{14}\) atoms/cm\(^2\)

polarimeter 3%

10 atoms/sec

d  < 0.1 mm Al
\(n = 1-3.5 \times 10^{14}\) atoms/cm\(^2\)
Twist-2 Quark Distribution Functions

Functions Surviving on Integration over Transverse Momenta

- The others are sensitive to intrinsic $<k_t>$ in the nucleon & in the fragmentation process.

Distribution Functions

- $f_1 = \ldots$
- $g_{1L} = \ldots$
- $h_{1T} = \ldots$
- $f_{1T}^1 = \ldots$
- $h_1^1 = \ldots$
- $h_{1L} = \ldots$
- $g_{1T} = \ldots$

Fragmentation Functions

- $D_1 = \ldots$
- $G_{1L} = \ldots$
- $H_{1T} = \ldots$
- $D_{1T}^1 = \ldots$
- $H_1^1 = \ldots$
- $H_{1L} = \ldots$
- $G_{1T} = \ldots$
- $H_{1T}^1 = \ldots$

Typeset by Foil TEX

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... surviving $k_\perp$ integration

**Unpolarized quarks and nucleons**

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

**Longitudinally polarized quarks and nucleons**

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

**Transversely polarized quarks and nucleons**

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

**HERMES 1995-2000**
Non-relativistic quarks: $\Delta q(x) = \delta q(x)$

$\Rightarrow$ $\delta q$ probes relativistic nature of quarks

obvious bound: $|\delta q(x)| \leq q(x)$

Soffer bound: $|\delta q(x)| \leq \frac{1}{2}[q(x) + \Delta q(x)]$

Sum Rule: first moment $\rightarrow$ tensor charge reliably calculable in lattice QCD (i.e. at $Q^2 = 2 GeV^2$):

$\delta \Sigma = \sum_f \int_0^1 dx (\delta q_f - \delta \bar{q}_f) = 0.562 \pm 0.088$

transversity distribution CHIRAL ODD

$\leftrightarrow$ No Access In Inclusive DIS
• ∃ a number of model calculation (facing a lack of experimental data)
• $h_1$ must satisfy Soffer inequality
• in common: $h_1$ behaves more valence-like

Quark-Diquark (solid), pQCD based model (dashed) (B.Q. Ma et al)
How can one measure transversity?

Need another chiral-odd object!

Semi-Inclusive DIS $\rightarrow$ HERMES with transversely polarized target

$$\sigma^{ep\rightarrow ehX} = \sum_{q} f^{H \rightarrow q} \otimes \sigma^{eq \rightarrow eq} \otimes D^{q \rightarrow h}$$

\[ \downarrow \quad \downarrow \]

chiral-odd

chiral-odd

DF

FF
Candidates for Fragmentation

Want to measure polarization of outgoing quark various “polarimeters” proposed in the literature possible at HERMES:

1. $e p \uparrow \rightarrow e' \pi (k_\perp) X \iff$ Favoured Process $\Rightarrow$ Signature: Single-Spin Azimuthal Asymmetry
2. $e p \uparrow \rightarrow e' \Lambda \uparrow X$
3. $e p \uparrow \rightarrow e' \pi \pi X$

1. Collins, 93, Kotzinian, 95, Mulders et al, 96
2. Baldracchini, 82, Jaffe, 96
3. Jaffe et al, 97
Single Spin Asymmetries

\[ e p^\uparrow \rightarrow e' \pi X \]

study azimuthal distribution of \( \pi \)'s:

\[ A_{\sin}\Phi \propto \frac{\sum_{i=1}^{N^+} \sin \Phi_i - \sum_{i=1}^{N^-} \sin \Phi_i}{\frac{1}{2}(N^+ + N^-)} \]

with transversely polarized target:

\[ A_{T\sin}\Phi \propto \frac{\sum_q e_q^2 \delta q(x) H_{1^+}^q(z)}{\sum_q e_q^2 q(x) D_1^q(z)} \]

\( \Phi = \phi + \phi^l_s \) Collins angle

\( \phi^l_s \ldots \) angle between target spin vector and scattering plane

\( H_{1^+}^q(z) \) Collins fragmentation function

(T-odd, chiral odd)
HERMES 1996/97: longitudinal polarized proton target

transverse component $S_T$

of target spin (w.r.t. virtual photon):

$$S_T \propto \sin \Theta \gamma \approx \frac{2Mx}{Q} \sqrt{1 - y} \sim 0.15$$

⇒ glimpse on transversity?!

Longitudinal target SSA:

$$A_{UL}(\phi) = \frac{1}{\langle P \rangle} \cdot \frac{N^+(\phi) - N^-(\phi)}{N^+(\phi) + N^-(\phi)}$$
• HERMES 1998-2000: longitudinal polarized deuteron target
• High statistics: \ (~8 Million DIS)
• Very good hadron identification due to RICH
• First measurement of Kaon SSA

\[ e \bar{d} \rightarrow e \pi^+ X \]
\[ P_1 = 0.012 \pm 0.002 \]
\[ P_2 = 0.004 \pm 0.002 \]

\[ e \bar{d} \rightarrow e \pi^0 X \]
\[ P_1 = 0.021 \pm 0.005 \]
\[ P_2 = 0.009 \pm 0.005 \]

\[ e \bar{d} \rightarrow e \pi^- X \]
\[ P_1 = 0.006 \pm 0.003 \]
\[ P_2 = 0.001 \pm 0.003 \]

\[ e \bar{d} \rightarrow e K^+ X \]
\[ P_1 = 0.013 \pm 0.006 \]
\[ P_2 = -0.005 \pm 0.006 \]
Attempt of Interpretation

- observe non-vanishing \( \langle \sin \phi \rangle \)-moments
- \( \langle \sin 2\phi \rangle \)-moment small (consistent with zero)

Attribute asymmetry to Collins fragmentation and transversity:

\[
A^{\sin \phi}_{UL} \sim S_L \langle \sin \phi \rangle_{UL} - S_T \langle \sin \phi \rangle_{UT}
\]

- Longitudinally polarized in experiment (along beam direction)
- \( L/T \) polarized in theory (along virtual gamma direction)
Attempt of Interpretation

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Attribute asymmetry to Collins fragmentation and transversity:

$$A_{UL}^{\sin \phi} \sim S_L \langle \sin \phi \rangle_{UL} - S_T \langle \sin \phi \rangle_{UT}$$

$$\langle \sin \phi \rangle_{UL} \sim \frac{1}{Q} \sum_q e_q^2 (h_{1L}^q(x) H_{1}^{(1),q}(z) - \frac{1}{z} h_{1L}^{(1),q}(x) \tilde{H}(z))$$
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$$\langle \sin \phi \rangle_{UT} \sim \sum_q e_q^2 x h_1^q(x) H_1^{\perp(1),q}(z) \quad \text{but } S_T \sim \frac{1}{Q} \text{ like twist-3}$$
**Attempt of Interpretation**

- observe non-vanishing \( \langle \sin \phi \rangle \)-moments
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Attribute asymmetry to **Collins fragmentation and transversity**:

\[
A_{UL}^{\sin \phi} \sim S_L \langle \sin \phi \rangle_{UL} - S_T \langle \sin \phi \rangle_{UT}
\]

\[
\langle \sin \phi \rangle_{UL} \sim \frac{1}{Q} \sum_q e_q^2 (h_q^L(x) H_{1,1,1}^{L,(1),q}(z) - \frac{1}{z} h_{1L}^{\perp,(1),q}(x) \tilde{H}(z))
\]

\[
\langle \sin \phi \rangle_{UT} \sim \sum_q e_q^2 x h_1^q(x) H_1^{\perp,(1),q}(z) \quad \text{but } S_T \sim \frac{1}{Q} \text{ like twist-3}
\]

\[
\langle \sin 2\phi \rangle_{UL} \sim \sum_q e_q^2 x h_{1L}^{\perp,(1),q}(x) H_1^{\perp,(1),q}(z)
\]
What about Twist-3?

distribution functions are related:

\[ h_L(x) = \frac{m_q}{M} \frac{h_1(x)}{x} - \frac{2}{x} h_{1L}^{(1)}(x) + \tilde{h}_L(x) \]

Lorentz covariance \( \Rightarrow h_L(x) = h_1(x) - \frac{d}{dx} h_{1L}^{(1)}(x) \)

\[ \leftrightarrow h_L(x) = \tilde{h}_L(x) + 2x \int_{x}^{1} \frac{dy}{y^2} [h_1(y) - \tilde{h}_L(y)] \]

set \( \tilde{h}_L = 0 \) \( \Rightarrow h_L(x) = -\frac{2}{x} h_{1L}^{(1)}(x) \)

“Reduced Twist-3”

\[ = 2x \int_{x}^{1} \frac{dy}{y^2} h_1(y) \]
Attribute asymmetry to Sivers effect:

- Final state interactions (Brodsky et al.)
- Sivers function (Sivers, Mulders et al)

\[
\langle \sin \phi \rangle_{UL} \sim f_{1T}^{(1)} D_1
\]

Longitudinally polarized target $\Rightarrow$ Sivers effect indistinguishable from Collins effect

Transversely polarized target

\[
\langle \sin (\phi_h^T - \phi_s^T) \rangle \text{ moment} \quad \langle \sin (\phi_h^T + \phi_s^T) \rangle \text{ moment}
\]
Let's assume Collins

Original predictions by Collins (here: proton target):

- Larger for $\pi^+$, $\pi^0$ than for $\pi^-$ ($u$-quark dominance in case of proton target)
- Peak around $x = 0.3$ (valence quark dominance)
- Grow with $p_\perp$ and peak around 1 GeV ($\frac{H_1}{D_1} \propto \frac{M_c M_b}{M_c^2 + p_\perp^2}$ with $M_c \simeq 1$ GeV)
Model Predictions for Deuteron

- **deuteron target**
- $h_1$ from $\chi$QSM, quark-diquark and pQCD model
- assume reduced twist-3
- $H_1^\perp$: Collins Ansatz or fit to DELPHI data
- $\sin 2\phi$ using $\chi$QSM model
New Target Magnet for HERMES

- Transverse target \((B = 0.295T)\)
- High uniformity along beam direction:
  \[\Delta B \leq 4.5 \cdot 10^{-5}T\]
- Transversely polarized hydrogen
- Target polarization above 80%

\[
\langle \sin \phi \rangle_{UT} \text{ becomes dominant}
\]

\[
\leftrightarrow h_1 \text{ and } H_1^\perp \text{ as well as } f_{1T}^\perp \text{ accessible}
\]