Transversity Measurements at HERMES

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For the HERMES Collaboration
use well-known probe to study hadronic structure

\[ Q^2_{\text{lab}} = 4EE' \sin^2\left(\frac{\Theta}{2}\right) \]

\[ \nu_{\text{lab}} = E - E' \]

\[ W^2_{\text{lab}} = M^2 + 2M\nu - Q^2 \]

\[ y_{\text{lab}} = \frac{\nu}{E} \]

\[ x_{\text{lab}} = \frac{Q^2}{2M\nu} \]
Deep Inelastic Scattering

use well-known probe to study hadronic structure

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\[ z \overset{\text{lab}}{=} \frac{E_h}{\nu} \]
Deep Inelastic Scattering

use well-known probe to study hadronic structure

\[ Q^2 \equiv 4EE' \sin^2 \left( \frac{\Theta}{2} \right) \]
\[ \nu \equiv E - E' \]
\[ W^2 \equiv M^2 + 2M\nu - Q^2 \]
\[ y \equiv \frac{\nu}{E} \]
\[ x \equiv \frac{Q^2}{2M\nu} \]
\[ z \equiv \frac{E_h}{\nu} \]

Factorization \[ \Rightarrow \sigma^{ep\rightarrow ehX} = \sum_q f^{p\rightarrow q} \otimes \sigma^{eq\rightarrow eq} \otimes D^{q\rightarrow h} \]
Quark Distribution Functions

\[ f_1^q = \quad g_1^q = \quad h_1^q = \]

\[ \downarrow \quad \downarrow \quad \downarrow \]

Unpolarized quarks and nucleons
Longitudinally polarized quarks and nucleons
Transversely polarized quarks and nucleons

\[ q(x): \text{spin averaged} \quad \Delta q(x): \text{helicity difference} \quad \delta q(x): \text{helicity flip} \]
(well known) (known) (unmeasured!)

⇒ Vector Charge
⇒ Axial Charge
⇒ Tensor Charge

HERMES 1995-2000
HERMES 2002...
Transversity

- 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 $Q^2 = 2GeV^2$):
  
  $\delta \Sigma = \sum_f \int_0^1 dx (\delta q_f - \delta \bar{q}_f) = 0.562 \pm 0.088$

- no “gluon transversity”
- transversity distribution CHIRAL ODD
  
  No Access In Inclusive DIS
Transversity Measurements

How can one measure transversity?
Need another chiral-odd object!

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

\[ \sigma^{ep\rightarrow ehX} = \sum_q f^{H\rightarrow q} \otimes \sigma^{eq\rightarrow eq} \otimes D^{q\rightarrow h} \]

↓
chiral-odd DF

↓
chiral-odd FF
Twist-2 Quark Distribution Functions

Functions surviving integration over intrinsic transverse momentum

$$f_1 = \begin{array}{c}
\end{array}$$

$$g_{1L} = \begin{array}{c}
\end{array}$$

$$h_{1T} = \begin{array}{c}
\end{array}$$

$$g_{1T} = \begin{array}{c}
\end{array}$$

$$f_{1T} = \begin{array}{c}
\end{array}$$

$$h_1 = \begin{array}{c}
\end{array}$$

$$h_{1L} = \begin{array}{c}
\end{array}$$

$$h_{1T} = \begin{array}{c}
\end{array}$$
Twist-2 Quark Distribution Functions

Functions surviving integration over intrinsic transverse momentum

\[ f_1 = \quad \]
\[ g_{1L} = \quad - \]
\[ h_{1T} = \quad - \]

\[ g_{1T} = \quad - \]

\[ f_{1T}^\perp = \quad - \]
\[ h_1^\perp = \quad - \]
\[ h_{1L}^\perp = \quad - \]

Sivers Function
Functions surviving integration over intrinsic transverse momentum

\[ D_1 = \]
\[ G_{1L} = \]
\[ H_{1T} = \]
\[ G_{1T} = \]
\[ D_{1T} = \]
\[ H_{1} = \]
\[ H_{1L} = \]
\[ H_{1T} = \]
**Twist-2 Fragmentation Functions**

Functions surviving integration over intrinsic transverse momentum:

- $D_1$
- $G_{1L}$
- $H_{1T}$
- $G_{1T}$
- $D_{1T}$
- $H_1$
- $H_{1L}$
- $H_{1T}$

Collins Function
The Need for Semi-Inclusive Measurements

- $h_1$ chiral odd
  ⇒ not accessible in inclusive DIS
  ⇒ need some sort of quark polarimetry
    ⇒ Collins Effect: transverse spin of quark $\rightsquigarrow$ transverse motion of produced hadron

- $k_\perp$-dependent distribution functions
  (besides $f_1$, $g_1$, $h_1$)
  ⇒ vanish when integrating over $k_\perp$
    (i.e. inclusive DIS)
  ⇒ need to access $k_\perp$-dependence

Azimuthal Single Spin Asymmetries in Semi-Inclusive DIS
Single Spin Asymmetries

$e p \rightarrow e' \pi X$

study azimuthal distribution of $\pi$'s:

$$A(\Phi) = \frac{1}{\langle P \rangle} \cdot \frac{N^+(\Phi) - N^-(\Phi)}{N^+(\Phi) + N^-(\Phi)}$$

with transversely polarized target:
(unpolarized beam)

$$A_{UT}^{\sin \Phi} \propto \sum_q e_q^2 h_1^q(x) H_1^{\perp q}(z)$$
$$\sum_q e_q^2 f_1^q(x) D_1^q(z)$$

$\Phi = \phi + \phi_S$ Collins angle
\[
e^p \rightarrow e^' \pi X
\]

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

\[
A(\Phi) = \frac{1}{\langle P \rangle} \cdot \frac{N^+(\Phi) - N^-(\Phi)}{N^+(\Phi) + N^-(\Phi)}
\]

with transversely polarized target:
(unpolarized beam)

\[
A^{\sin \Phi}_{UT} \propto \sum_q e_q^2 h_1^q(x) H_{1,q}^1(z)
\]

\[
A^{\sin \Phi}_{UL} \propto \ldots
\]

\( \Phi = \phi \) Collins angle
Single Spin Asymmetries at HERMES

HERMES 1996/97: longitudinally polarized proton target

Longitudinal target SSA:

\[ A_{UL}(\phi) = \frac{1}{\langle P \rangle} \cdot \frac{N^+(\phi) - N^-(\phi)}{N^+(\phi) + N^-(\phi)} \]

(green band: model calculation)
HERMES Results on Deuteron Target

- HERMES 1998-2000: longitudinally polarized deuteron target
- High statistics: \( \sim 8 \) Million DIS
- Good hadron identification due to RICH
- First measurement of Kaon SSA

\[
P_1 = 0.012 \pm 0.002 \\
P_2 = 0.004 \pm 0.002
\]

\[
P_1 = 0.021 \pm 0.005 \\
P_2 = 0.009 \pm 0.005
\]

\[
P_1 = 0.006 \pm 0.003 \\
P_2 = 0.001 \pm 0.003
\]

\[
P_1 = 0.013 \pm 0.006 \\
P_2 = -0.005 \pm 0.006
\]
HERMES Results on Longitudinally Polarized Deuteron

$$\sin(\phi)$$-moment ⇒

$$\sin(2\phi)$$-moment \sim h_{1L}^+ H_1^+$$
Longitudinally Polarized Target

Transverse component $S_T$ of target spin (w.r.t. virtual photon):

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

$$A^\sin \phi_{UL} L \sim S_L \langle \sin \phi \rangle_{UL} - S_T \langle \sin \phi \rangle_{UT}$$

$L/T$ polarized in theory (along virtual gamma direction)
Longitudinally polarized in experiment (along beam direction)
Longitudinally Polarized Target

Transverse component $S_T$ of target spin (w.r.t. virtual photon):

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$$\langle \sin \phi \rangle_{UL} \sim \frac{1}{Q} \sum_q e_q^2 (h_{1L}^q(x) H_1^{(1),q}(z) - \frac{1}{z} h_{1L}^{(1),q}(x) \tilde{H}(z))$$
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$$\langle \sin \phi \rangle_{UL} \sim \frac{1}{Q} \sum_q e_q^2 (h^q_L(x) H_{1}^{(1),q}(z) - \frac{1}{z} h^{\perp (1),q}_{1L}(x) \tilde{H}(z))$$

$$\langle \sin \phi \rangle_{UT} \sim \sum_q e_q^2 h^q_1(x) H_{1}^{\perp (1),q}(z) \quad \text{(but } S_T \sim \frac{1}{Q} \text{ like twist-3)}$$
Longitudinally Polarized Target

Transverse component $S_T$ of target spin (w.r.t. virtual photon):

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$$\langle \sin \phi \rangle_{UT} \sim \sum_q e_q^2 h_1^q(x) H_{1T}^{(1),q}(z)$$

Collins

$$\langle \sin \phi \rangle_{UT} \sim \sum_q e_q^2 f_{1T}^{(1),q} D_1^q(z)$$

Sivers

Contributions to $A_{UL}^{\sin \phi}$ hard to disentangle
Some words about Sivers Effect

thanks to Brodsky, Hwang, Schmidt:

- quark rescattering
- can generate SSA
- leading twist effect
- requires $L_z$ of quarks
Some words about **Sivers Effect**

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different approach by Burkardt:

spatial distortion of q-distribution

(consequence of anom. magn. moments & impact parameter dependent PDFs)
Some words about Sivers Effect

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different approach by Burkardt:
- spatial distortion of q-distribution
- + attractive QCD potential
  (gluon exchange)
Some words about Sivers Effect

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different approach by Burkardt:
- spatial distortion of q-distribution
- + attractive QCD potential
  $\Rightarrow$ transverse asymmetries
Longitudinally polarized target $\Rightarrow$ Sivers and Collins effects indistinguishable

Transversely polarized target

Sivers

$\langle \sin(\phi - \phi_s) \rangle$ moment

$\downarrow$

$f_{1T}^\perp(x)$

Collins

$\langle \sin(\phi + \phi_s) \rangle$ moment

$\downarrow$

$h_1(x), H_1^\perp(z)$

Additionally: $\langle \sin(3\phi - \phi_s) \rangle$ moment $\Rightarrow h_{1T}^\perp(x), H_1^\perp(z)$

and others
What do theorists expect?

Not much is known about the Collins FF:

$$\left| \frac{\langle H_1 \rangle}{\langle D_1 \rangle} \right| = 6.3\%$$
What do theorists expect?

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\[ \left| \frac{<H_1^+>}{<D_1>} \right| = 6.3\%, \ 12.5\% \]
What do theorists expect?

Not much is known about the Collins FF:

$$| \frac{<H^\perp_1>}{<D_1>} | = 6.3\%, \ 12.5\%, \sim 4\% \ldots ???$$
What do theorists expect?

Not much is known about the Collins FF:
\[ |\frac{\langle H_{1}^{+} \rangle}{\langle D_{1} \rangle}| = 6.3\%, 12.5\%, \sim 4\% \ldots ??? \]

Even less for the Sivers DF:
\[ f_{1T}^{\perp;u} \neq 0 \]
What do theorists expect?

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Gamberg et al. HEP-PH/0301018
New Transverse Target HERMES

- Transverse target magnet ($B = 0.295T$)
- High uniformity along beam direction: $\Delta B \leq 4.5 \cdot 10^{-5} T$
- Transversely polarized hydrogen
- Target polarization around 75%
Data Taking in 2002/03

Integrated Luminosity 2002/03 (before data quality cuts)

Transverse Asymmetry $A_{UT}(\phi, \phi_S)$
Data Taking in 2002/03

Expected precision in comparison with model calculations for Collins Asymmetry

- After data quality: $\sim 600K$ DIS events
- charged and neutral $\pi$ asymmetries
- statistics good enough to (dis)favour various model calculation
Future Data Taking

- additional data taking starting fall of 2003
- detector upgrade ($\Lambda$-Wheels)

⇒ additional statistics allows analysis of different channels to access transversity:
  - 2-Meson-Correlations ⇒ Interference FF
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  - 2-Meson-Correlations ⇒ Interference FF
  - Spin-1 Fragmentation
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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)
Future Data Taking

- additional data taking starting 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 Λ polarization)

- polarized beam ⇒ $A_{LT}$ in $\pi$ production
  (measurement of twist-3 fragmentation function and transversity)
Extracting Quark Distributions – Purity Formalism

\[ A_{UT}^{\sin(\phi - \phi_S), h}(x) = \frac{\int dy S_T \frac{1+(1-y)^2}{2}}{\int dy \frac{1+(1-y)^2}{2}} \sum_q e_q^2 f_{1T}^q(x) \int dz D_1^{q,h}(z) A(x, z) }{ \sum_{q'} e_{q'}^2 f_{1}^{q'}(x) \int dz D_1^{q',h}(z) A(x, z) } \]

\[ = C \cdot \sum_q e_q^2 f_{1}^q(x) \frac{D_1^{q,h}(x)}{\sum_{q'} e_{q'}^2 f_{1}^{q'}(x) \frac{D_1^{q',h}(x)}{f_{1}^{q}(x)} } \cdot \frac{f_{1T}^{q}}{f_{1}^{q}}(x) \]

\[ = C \cdot \sum_q P^h_q(x) \cdot \frac{f_{1T}^{q}}{f_{1}^{q}}(x) \]

- **purities** are completely **unpolarized** objects → present Monte Carlo-tunes can be used
- **probabilistic interpretation** of purities possible
- “easy”: Sivers ← fragmentation function \((D_1)\) known
**Extracting Quark Distributions – Purity Formalism**

- **purities** are completely unpolared objects $\rightarrow$ present
- Monte Carlo-tunes can be used
- probabilistic interpretation of purities possible
- “easy”: Sivers $\leftarrow$ fragmentation function ($D_1$) known
Extracting Quark Distributions –

Purity Formalism

\[
A_{UT}^{\sin(\phi + \phi_S), h}(x) = \frac{\int dy S_T(1 - y) \sum_q e_q^2 h_1^q(x) \int dz H_1^{\perp,q,h}(z) A(x, z)}{\int dy \frac{1+(1-y)^2}{2}} \sum_{q'} e_{q'}^2 f_1^{q'}(x) \int dz D_1^{q',h}(z) A(x, z)
\]

\[
= C \cdot \sum_q \frac{e_q^2 f_1^q(x) H_1^{\perp,q,h}(x)}{\sum_{q'} e_{q'}^2 f_1^{q'}(x) D_1^{q',h}(x)} \cdot \frac{h_1^q}{f_1^q}(x)
\]

\[
= C \cdot \sum_q P_h^q(x) \cdot \frac{h_1^q}{f_1^q}(x)
\]

- **purities** are completely **unpolarized** objects → present Monte Carlo-tunes can be used
- probabilistic interpretation of purities possible
- "easy": Sivers \(\leftarrow\) fragmentation function \((D_1)\) known
- Collins: these purities still depend on parametrization of Collins FF function
Summary

- HERMES measured SSA on longitudinally polarized hydrogen and deuterium targets.
- HERMES has taken data with a transversely polarized hydrogen target.
- Presently more than 600k DIS events after data quality cuts.
- Transverse Asymmetries $\Rightarrow$ disentangle Sivers and Collins contributions.
- Purity formalism $\Rightarrow$ extraction of quark distributions $f_{1T}^q$ and $h_1^q$ ($q = u, d$).
- IFF on longitudinal/transversely polarized target.
- ...