Transversity results from HERMES

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DIS2006 — Tsukuba City (Japan) — 20-24 April 2006
Outline

• The leading-twist distribution functions of the nucleon
• The chiral-odd transversity distribution
• The SIDIS cross section and the Collins and Sivers effects
• The HERMES experiment at HERA
• The Single Spin Asymmetry
• HERMES results on Collins and Sivers moments for $\pi^\pm$ and $K^\pm$
• Conclusions and outlook
The inner spin distribution of the nucleon

Spin distribution of the nucleon → polarised DIS (polarised beam and/or target)

The relevant kinematical variables:

\[ Q^2 = -q^2 = 2E'E' (1-\cos \theta) \]

\[ x = \frac{Q^2}{2Mv} \quad y = \frac{v}{E} \quad v = E - E' \]

- Virtual photon can only couple to quarks of opposite spin
- Different targets give sensitivity to different quark flavors

experiments at CERN, SLAC, DESY, JLAB
The three leading-twist distribution functions

All equally important for a complete description of momentum and spin distribution of the nucleon at leading-twist.

- **unpolarised DF**
  \[ q(x, Q^2) \]
  
  - well known

- **Helicity**
  \[ \Delta q(x, Q^2) \]
  
  - known

- **Transversity**
  \[ \delta q(x, Q^2) \]
  
  - unknown

**Positivity limit**
\[ |\delta q(x)| < q(x) \]

**Soffer bound**
\[ |\delta q(x)| < \frac{1}{2} (q(x) + \Delta q(x)) \]

\[ \begin{cases} 
\delta q(x) = \Delta q(x) & \text{non-relativistic regime} \\
\delta q(x) \neq \Delta q(x) & \text{relativistic regime}
\end{cases} \]

- Probes relativistic nature of quarks
\[ \Delta q(x, Q^2) \]
Helicity basis: \( |+\rangle, |-\rangle \)

\[ \delta q(x, Q^2) \]
Transverse spin basis: \( |\uparrow\rangle, |\downarrow\rangle \)

\[ \int dx (\delta q(x) - \delta \bar{q}(x)) = \langle PS | \bar{\psi} \sigma^{\mu\nu} \gamma_5 \psi | PS \rangle \]

\( \delta q \) is chiral-odd object
associated with a helicity flip of the struck quark

EM interactions cannot flip the chirality of the probed quark

Transversity Distribution is not measurable in inclusive DIS
How can one measure transversity?

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

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

one hadron in the initial state and at least one in the final state (semi-inclusive leptoproduction)
The "Collins effect"

Collins fragmentation function \( H_1^\perp(z, k_T^2) \) carries out the correlation between the transverse spin of the fragmenting quark and \( P_{h\perp} \).

Chiral – odd & naïve T – odd

produces left-right asymmetry in the direction of the outgoing hadron
The “Sivers effect”

Correlation between $p_T$ and transverse spin of the nucleon

Sivers distribution function $f_{1T}^{q}(x, p_T^2)$ describes the probability to find an unpolarized quark with transverse momentum $p_T$ in a transversely polarized nucleon

Chiral – even & naïve T – odd

Non-zero Sivers function requires non-vanishing orbital angular momentum in the nucleon wave function (can contribute to nucleon spin!)

requires a quark rescattering via soft gluon exchange (gauge link)

(Brodsky, Hwang, Schmidt)
The SIDIS cross-section at leading order in $1/Q$

$$d\sigma = d\sigma_0 + \cos 2\phi \, d\sigma_1 + S_L \{\sin 2\phi \, d\sigma_2 + \lambda_e d\sigma_3\} + \lambda_e \cos(\phi - \phi_S) \, d\sigma_{LT}$$

$$+ S_T \left\{ \sin(\phi + \phi_S) \, d\sigma_{UT}^5 + \sin(\phi - \phi_S) \, d\sigma_{UT}^6 + \sin(3\phi - \phi_S) \, d\sigma_{UT}^7 + \sin\phi_S \, d\sigma_{UT}^8 \right\}$$

Collins

Sivers

$$d\sigma_{UT}^{Collins} \propto |S_T| \sin(\phi + \phi_S) \sum_q e_q^2 I \left[ \frac{\vec{k}_T \cdot \hat{P}_h}{M_h} \delta q(x, p_T^2) \otimes H^{1_q}(z, k_T^2) \right]$$

$$d\sigma_{UT}^{Sivers} \propto |S_T| \sin(\phi - \phi_S) \sum_q e_q^2 I \left[ \frac{\vec{p}_T \cdot \hat{P}_h}{M_h} f_{1T}^{1_q}(x, p_T^2) \otimes D_q^q(z, k_T^2) \right]$$

$I[...] = \text{convolution integral over initial } (\vec{p}_T) \text{ and final } (\vec{k}_T) \text{ quark transverse momenta}$
The HERA storage ring (DESY)

The HERMES Spectrometer

- Fixed target experiment
- Forward spectrometer symmetric above and below the beampipe
- Polarized internal gas target
- Relatively large acceptance

- 27.5 GeV $e^+/e^-$ beam
- Self-polarizing through Sokolov-Ternov-Effect
- Average beam polarization of about 55%
Angular acceptance: \( 40 \text{ mrad} < |\theta_y| < 140 \text{ mrad} \quad |\theta_x| < 170 \text{ mrad} \)

Resolution: \( \delta p \leq 2.6\% \); \( \delta\theta \leq 1 \text{ mrad} \)

Particle Identification:

TRD, Calorimeter, preshower, RICH:
lepton-hadron > 98%

RICH:
Hadron: \( \pi \sim 98\% \), K \sim 88\% \), P \sim 85\%
Data from running period 2002-2004 (transversely polarized hydrogen target)

\[Q^2 > 1 \ \text{GeV}^2\]
\[0.2 < z = \frac{E_h}{\nu} < 0.7\]
\[0.023 < x < 0.4\]
\[2 \ \text{GeV} < P_h < 15 \ \text{GeV}\]
\[W^2 > 10 \ \text{GeV}^2\]
\[0.1 < y \leq 0.85\]

**The Single Spin Asymmetry of the SIDIS cross-section**

\[A^h_{UT}(\phi, \phi_S) = \frac{1}{|S_T|} \frac{N^\uparrow_h(\phi, \phi_S) - N^\downarrow_h(\phi, \phi_S)}{N^\uparrow_h(\phi, \phi_S) + N^\downarrow_h(\phi, \phi_S)}\]

\[\approx 2\langle \sin(\phi + \phi_S) \rangle^h_{UT} \sin(\phi + \phi_S) + 2\langle \sin(\phi - \phi_S) \rangle^h_{UT} \sin(\phi - \phi_S) + \cdots\]

Collins moment

\[\propto \delta q(x) H_1^q(z)\]

Sivers moment

\[\propto f_{1T}^q(x) D_1^q(z)\]

The Collins and Sivers moments are then extracted by fitting the asymmetry with:

\[A^{Fit}_{UT}(\phi, \phi_S) = P(1)\sin(\phi + \phi_S) + P(2)\sin(\phi - \phi_S) + P(3)\sin(\phi_S) + P(4)\sin(2\phi + \phi_S) + P(5)\]
Collins moments for $\pi^+/-$ (2002-2004)

- $\propto \delta q(x) H_1^{\perp q}(z)$
- First evidence for non-zero Collins function
- Collins moment is positive for $\pi^+$
- Collins moment negative for $\pi^-$
- the large negative $\pi^-$ amplitude suggests disfavored Collins function with opposite sign
- systematic errors (shaded bands) include acceptance and smearing effects and contributions from unpolarised $\langle \cos(2\varphi) \rangle$ and $\langle \cos(\varphi) \rangle$ moments
Collins moments for $\pi^+/-$ and $K^+/-$ (2002-2004)

HERMES PRELIMINARY 2002-2004

Virtual photon asymmetry amplitudes
6.6% scale uncertainty

$2 \langle \sin(\phi + \phi_S) \rangle_{\delta T}$

$P_{h_{\perp}}$ [GeV]

$z$

$VM$ fraction

$\pi^+$

$\pi^-$

$K^+$

$K^-$

PYTHIA 6 modified by HERMES

$\langle \sin(\phi + \phi_S) \rangle_{\delta T}$

$P_{h_{\perp}}$ [GeV]
Sivers moments for $\pi^{+/−}$ (2002-2004)

- $\propto f_{1T}^q(x)D_1^q(z)$
- Sivers moment is positive for $\pi^+$
- First evidence for non-zero Sivers function $\Rightarrow$ non-vanishing orbital angular momentum $L_z$
- Sivers moment consistent with zero for $\pi^-$
- Systematic errors (shaded bands) include acceptance and smearing effects and contributions from unpolarised $\langle \cos(2\phi) \rangle$ and $\langle \cos(\phi) \rangle$ moments
Sivers moments for $\pi^+/-$ and $K^+/-$ (2002-2004)
Conclusions

- Transverse Spin physics fast evolving (experimental and theoretical) field
- Single Spin Asymmetries powerful tool to access transversity at HERMES.
- Preliminary HERMES results on semi-inclusive pion and kaon leptoproduction support the existence of non-zero chiral-odd and T-odd structures that describe the transverse structures the nucleon.
- First measurements for kaons suggest that sea quarks may provide an important contribution to the Sivers function

Outlook

- 2005 data will double current statistics
- $P_{h\perp}$-weighted asymmetries are under study
- Sivers function likely to be extracted within the next few years at HERMES
- Collins function estimation will allow extraction of the Transversity distribution (first data from Belle supports a non-zero $H_1\perp$)
Backup slides
The SIDIS cross-section (up to subleading order in $1/Q$)

\[ d\sigma = d\sigma_{UU}^0 + \cos 2\phi \, d\sigma_{UU}^1 + \frac{1}{Q} \cos \phi \, d\sigma_{UU}^2 + \lambda_e \frac{1}{Q} \sin \phi \, d\sigma_{LU}^3 \]

\[ + S_L \left\{ \sin 2\phi \, d\sigma_{UL}^4 + \frac{1}{Q} \sin \phi \, d\sigma_{UL}^5 + \lambda_e \left[ d\sigma_{LL}^6 + \frac{1}{Q} \cos \phi \, d\sigma_{LL}^7 \right] \right\} \]

\[ + S_T \left\{ \sin(\phi - \phi_S) \, d\sigma_{UT}^8 + \sin(\phi + \phi_S) \, d\sigma_{UT}^9 + \sin(3\phi - \phi_S) \, d\sigma_{UT}^{10} \right. \]

\[ + \frac{1}{Q} \left( \sin(2\phi - \phi_S) \, d\sigma_{UT}^{11} + \sin \phi_S \, d\sigma_{UT}^{12} \right) \]

\[ + \lambda e \left[ \cos(\phi - \phi_S) \, d\sigma_{LT}^{13} + \frac{1}{Q} \left( \cos \phi_S \, d\sigma_{LT}^{14} + \cos(2\phi - \phi_S) \, d\sigma_{LT}^{15} \right) \right] \right\} \]

\[
\sigma_{XX, YY} \quad \text{Beam Target Polarization}
\]

\[
(d^6\sigma_{UT})_{\text{Collins}} \propto |S_T| \sin(\phi + \phi_S) \cdot \sum_q e_q^2 I \left[ \frac{\vec{k}_T \cdot \hat{P}_{h_1^q}}{M_h} \right] \left[ h_1^q(x, p_T^2) \otimes H_{1q}^1(z, k_T^2) \right]
\]

\[
(d^6\sigma_{UT})_{\text{Sivers}} \propto |S_T| \sin(\phi - \phi_S) \cdot \sum_q e_q^2 I \left[ \frac{\vec{P}_T \cdot \hat{P}_{h_1^q}}{M_h} \right] \left[ f_{1T}^q(x, p_T^2) \otimes D_1^q(z, k_T^2) \right]
\]
Once the convolution integral over the intrinsic momenta is solved (e.g. gaussian ansatz)

\[
\langle \sin(\phi + \phi_s) \rangle_{UT}^h \propto \frac{|\tilde{S}_T|}{\sqrt{1 + z^2 \langle p_T^2 \rangle / \langle K_T^2 \rangle}} \sum_{q,\bar{q}} e_q^2 \delta q(x) H_{1,q} (z) \sum_{q,\bar{q}} e_{\bar{q}}^2 \cdot q(x) \cdot D_{1,q}^q (z)
\]

\[
\langle \sin(\phi - \phi_s) \rangle_{UT}^h \propto \frac{|\tilde{S}_T|}{\sqrt{1 + \langle K_T^2 \rangle / \langle p_T^2 \rangle}} \sum_{q,\bar{q}} e_q^2 f_{VT}^{\perp q} (x) D_{1,q}^q (z) \sum_{q,\bar{q}} e_{\bar{q}}^2 \cdot q(x) \cdot D_{1,q}^q (z)
\]

\[P_{h_\perp}\text{-weighted moments (no assumption on intrinsic transverse momenta distributions)}\]

\[
\left\langle \frac{P_{h_\perp}}{z M_h} \sin(\phi + \phi_s) \right\rangle_{UT}^h \propto |\tilde{S}_T| \sum_{q,\bar{q}} e_q^2 \delta q(x) H_{1,q} (z) \sum_{q,\bar{q}} e_{\bar{q}}^2 \cdot q(x) \cdot D_{1,q}^q (z)
\]

\[
\left\langle \frac{P_{h_\perp}}{z M_h} \sin(\phi - \phi_s) \right\rangle_{UT}^h \propto -|\tilde{S}_T| \sum_{q,\bar{q}} e_q^2 f_{VT}^{\perp q} (x) D_{1,q}^q (z) \sum_{q,\bar{q}} e_{\bar{q}}^2 \cdot q(x) \cdot D_{1,q}^q (z)
\]
The Maximum Likelihood unbinned fit

(Un)binned Maximum-Likelihood fits to azimuthal Fourier amplitudes are significantly superior to least-$\chi^2$ fits for data sets with few events

The polarised event distribution and PDF for each target spin state is:

\[
C \, N_{\uparrow(\downarrow)}(x,y,z,P_t,\phi,\phi_S) = \mathcal{E}(x,y,z,P_{h\perp},\phi,\phi_S) \, \sigma_{UU}(x,y,z,P_t) \times
\]

\[
\frac{1}{2} \left[ 1 + A_{UU}^{\cos \phi}(x,y,z,P_t) \cos \phi + A_{UU}^{\cos 2\phi}(x,y,z,P_t) \cos(2\phi) 
\right.
\]

\[
\left. + (-) \, A_C(\lambda_1,x,y,z,P_t) \sin(\phi + \phi_S) + (-) \, A_S(\lambda_2,x,y,z,P_t) \sin(\phi - \phi_S) \right]
\]

\[
\equiv F_{\uparrow(\downarrow)}(\lambda_1,\lambda_2,x,y,z,P_t,\phi,\phi_S) \quad \text{(Probability Density Fun.)}
\]

Acceptance $\mathcal{E}$ and azimuthally averaged cross section $\sigma_{uu}$ do not depend on the fitting parameter sets $\lambda_1$ and $\lambda_2$

Normalization integral

\[
\mathcal{N}_{\uparrow(\downarrow)}(\lambda_1,\lambda_2) = \sum_{i=1}^{N_1+N_\downarrow} \left[ 1 + \frac{(-) \, A_C(\lambda_1,x_i,y_i,z_i,P_{ti}) \sin(\phi_i + \phi_{Si}) + (-) \, A_S(\lambda_2,x_i,y_i,z_i,P_{ti}) \sin(\phi_i - \phi_{Si})}{1 + A_{UU}^{\cos \phi}(x_i,y_i,z_i,P_{ti}) \cos \phi + A_{UU}^{\cos 2\phi}(x_i,y_i,z_i,P_{ti}) \cos(2\phi)} \right]
\]

Likelihood function

\[
L(\lambda_1,\lambda_2) = \prod_{i=1}^{N_1} F_{\uparrow}(\lambda_1,\lambda_2,x_i,y_i,z_i,P_{ti},\phi_i,\phi_{Si}) \prod_{i=1}^{N_\downarrow} F_{\downarrow}(\lambda_1,\lambda_2,x_i,y_i,z_i,P_{ti},\phi_i,\phi_{Si}) \frac{\mathcal{N}_{\uparrow}^{N_1}(\lambda_1,\lambda_2) \mathcal{N}_{\downarrow}^{N_\downarrow}(\lambda_1,\lambda_2)}{\mathcal{N}_{\uparrow(\downarrow)}(\lambda_1,\lambda_2)}
\]

(to be maximized with respect to the parameter sets: $\lambda_1, \lambda_2$)