Spin Structure Results from HERMES

Wolf-Dieter Nowak
DESY Zeuthen

on behalf of the hermes collaboration

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Contemporary Hierarchy of Partonic Distributions

GTMD
\[ X(x, \xi, \Delta_\perp, k_T, k_T \cdot t) \]

WD
\[ X(x, \xi, b_\perp, k_T, k_T \cdot b_\perp) \]

Integrate over \( k_T \)
\[ \xi = 0 \]
Integrate over Impact Parameter Space
\[ \Delta_\perp / b_\perp \]

TMD
\[ h_1(x, k_T) \]
Integrate over \( k_T \)
Take limit \( \xi = x = 0 \)

Integrate over \( k_T \)
\[ \Delta_\perp / b_\perp \]

GPD
\[ H(x, \xi, t) \]
Integrate over \( x \)
\[ \Delta_\perp / b_\perp \]

PDF

Spin Densities

FF
Charge Densities

Courtesy M. Murray, Glasgow
Unique Experimental Conditions at HERMES

- Running 1996-2007 in 27.5 GeV HERA lepton beam line
- Both beam charges available (positrons, electrons)
- Longitudinal beam polarization (both helicities)
- Various internal gas targets were installed (no dilution)
- Forward spectrometer: tracking and PID (RICH since 1998)
- Recoil detector around target region: 2006-07

\[
\phi \quad \text{- angle between lepton scattering and real photon (hadron) production planes}
\]
\[
\phi_S \quad \text{- angle between (transverse) target spin direction and lepton scattering plane}
\]
Internal gas targets:
- Longitudinally polarized $H, D$
- Transversely polarized $H$
- Unpolarized $H, D, ^4He, N, Ne, Kr, Xe$

Forward magnetic spectrometer
- Momentum resolution 1-2%
- Particle identification: $RICH, TRD, H(odo)2, calorimeter$
HERMES Recoil Detector

1 Tesla superconducting solenoid

Photon Detector (PD)
- detect gammas
- p/π PID for momentum > 600 MeV/c

Scintillating Fiber Tracker (SFT)
Momentum reconstruction by bending in magnetic field

Silicon Strip Detector (SSD)
- Inside the HERA vacuum
- 5 cm close to the beam
- Momentum reconstruction by energy deposit for protons and deuterons

Target cell
- Unpolarized hydrogen and deuterium targets
Exclusive Processes: Access to GPDs

Generalized Parton Distributions (GPDs):

- For spin-1/2 target 4 chiral-even leading-twist quark GPDs: $H, E, \tilde{H}, \tilde{E}$

- $H, \tilde{H}$ conserve nucleon helicity, $E, \tilde{E}$ involve nucleon helicity flip

- Different final states are sensitive to different (combinations of) GPDs:
  - DVCS ($\gamma$) $\rightarrow$ $H, E, \tilde{H}, \tilde{E}$
  - Vector mesons ($\rho, \omega, \phi$) $\rightarrow$ $H, E$
  - Pseudoscalar mesons ($\pi, \eta$) $\rightarrow$ $\tilde{H}, \tilde{E}$

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Interpretation of GPDs

GPDs include Form Factors and Parton Distribution Functions as moments and forward limits, resp.

GPDs yield a multidimensional description of nucleon structure (longitudinal momentum vs. transverse position)

$\rightarrow$ NUCLEON TOMOGRAPHY

GPDs offer access to quark total angular momentum through the Ji relation (in principle also for gluons):

$$J_q = \lim_{t \to 0} i \int dx \, x [H_q(x, \xi, \xi) + E_q(x, \xi, \xi)]$$

Principle of Extraction of Asymmetry Amplitudes

- Distribution in expectation value of measured yield \( (A_{UL}, A_{LL} \text{ missing}) \):

\[
\langle N(e_i, P_i, S_i, \phi, \phi_S) \rangle \propto \sigma_{UU}(\phi)[1 + e_i A_C + P_i A_{LU}^{DVCS} + e_i P_i A_{UL}^I + S_i A_{UT}^{DVCS} + e_i S_i A_{UT}^I + P_i S_i A_{LT}^{BH+DVCS} + e_i P_i S_i A_{LT}^I]
\]

- Examples of Fourier expansion of measured (X-section) asymmetries:

\[
A_C \approx \sum_{n=0}^{3} A_C^{\cos(n\phi)} \cos(n\phi) \quad \left[ \begin{array}{l} A_{LU} \approx \sum_{n=1}^{2} A_{LU}^{\sin(n\phi)} \sin(n\phi) \end{array} \right]
\]

- Simultaneous extraction of asymmetry amplitudes with Maximum Likelihood Method

- Asymmetry amplitudes provide information about Compton Form Factors (CFFs): convolution of GPDs with hard scattering amplitudes

\[
F(\xi, t) = \sum_{q} \int_{-1}^{1} dx C_q^{\pm}(\xi, x) F^q(x, \xi, t)
\]
HERMES DVCS results on proton & deuteron targets

Access to GPD H, H̅, E

- JHEP 11 (2009) 083
- Nucl. Phys. B829

sensitive to J_u

- JHEP 06 (2008) 066


- JHEP 06 (2010) 019
- Nucl. Phys. B 842

Amplitude Value

Re(H)

Im(H)

Im(H - E)

Re(H - E)

Im(H̅)

Re(H̅)

HERMES DVCS

- Hydrogen
- Deuteron
- Hydrogen̅
Kinematic event fitting technique used for DVCS events:
- All 3 particles in final state detected → 4 constraints from energy-momentum conservation
- Selection of `pure' BH/DVCS ($ep \rightarrow epy$) with high efficiency (~84%)
- Allows to suppress background from associated and semi-inclusive processes to a negligible level (~0.1%)
- Makes even PID (Particle Identification) unnecessary

DVCS missing-mass distribution:
- No requirement for Recoil
- Positively charged Recoil track
- Kinematic fit probability > 1%
- Kinematic fit probability < 1%
`Traditional’ and `Recoil-detector’ DVCS samples

Without Recoil Detector (`traditional’ or `unresolved’) 
In Recoil Detector acceptance (`unresolved reference’)
With Recoil Detector (`pure’ sample)

- Similar background
- Background-free
- Similar kinematics
Comparison of traditional & recoil-detector (\(A_{LU}\)) samples

- Indication that the leading amplitude for pure BH/DVCS (background < 0.1%) is slightly larger in magnitude than the one in Recoil Detector acceptance.
- Extraction of asymmetry amplitudes for associated processes is a subject of ongoing dedicated analysis.

**HERMES PRELIMINARY 2006/07 data**

| \(A_{LU}^{\sin \phi}\) | \(A_{LU}^{\sin (2\phi)}\) |
|------------------------|--|--------------------------------------------------|
| Overall                | \(t [\text{GeV}^2]\) | \(x_B\) | \(Q^2 [\text{GeV}^2]\) |

**\(e^+ p \rightarrow e^+ p \gamma\)**

- 3.4% scale uncertainty
- Green: without Recoil Det.
- Red: with Recoil Det.
- Blue: In Recoil Det. accept.

New
NEW!!
Charge-difference double Spin LT Asymmetry

- Sensitive to Re (H+E)
- All consistent with zero. Still: useful input for global GPD fits!

see poster A. Movsisyan
Single-charge double Spin LL Asymmetry

- Sensitive to $\tilde{H}$, non-zero Hydrogen asymmetry amplitudes
- Useful input for global fits. (Deuterium data are rare!)

Deuterium

\[
A_{LL}^{\cos(0\phi)} = \pi r 
\]

Hydrogen

\[
A_{LL}^{\cos(\phi)} = \pi r 
\]

\[
A_{LL}^{\cos(2\phi)} = \pi r 
\]

Deuterium

Hydrogen

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Semi-inclusive deep inelastic scattering

Leading Twist PDFs

Leading Twist TMDs

Intrinsic $k_T$ quark distribution

**Distribution Functions (DF)**

<table>
<thead>
<tr>
<th>N/q</th>
<th>U</th>
<th>L</th>
<th>T</th>
</tr>
</thead>
<tbody>
<tr>
<td>U</td>
<td>$f_1$ number density</td>
<td></td>
<td></td>
</tr>
<tr>
<td>L</td>
<td>$g_1$ helicity</td>
<td></td>
<td></td>
</tr>
<tr>
<td>T</td>
<td>$h_1$ transversity</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Fragmentation Functions (FF)**

<table>
<thead>
<tr>
<th>N/q</th>
<th>U</th>
<th>L</th>
<th>T</th>
</tr>
</thead>
<tbody>
<tr>
<td>U</td>
<td>$D_1$ unpolarized</td>
<td></td>
<td></td>
</tr>
<tr>
<td>T</td>
<td>$H_1$ Collins</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Off-diagonal elements are important objects:

Interference between wave functions with different angular momenta: contains info about parton orbital angular momenta

Testing QCD at the amplitude level

see poster
E. Avetisyan
1-hadron production cross section

\[
d\sigma = d\sigma_{UU}^0 + \cos(2\phi)d\sigma_{UU}^1 + \frac{1}{Q}\cos(\phi)d\sigma_{UU}^2 + P_l\frac{1}{Q}\sin(\phi)d\sigma_{LU}^3 \\
+ S_L\left[\sin(2\phi)d\sigma_{UL}^4 + \frac{1}{Q}\sin(\phi)d\sigma_{UL}^5 + P_l\left(d\sigma_{LL}^6 + \frac{1}{Q}\cos(\phi)d\sigma_{LL}^7\right)\right] \\
+ S_T\left[\sin(\phi - \phi_s)d\sigma_{UT}^8 + \sin(\phi + \phi_s)d\sigma_{UT}^9 + \sin(3\phi - \phi_s)d\sigma_{UT}^{10} + \frac{1}{Q}\sin(2\phi - \phi_s)d\sigma_{UT}^{11} + \frac{1}{Q}\sin(\phi_s)d\sigma_{UT}^{12}\right] \\
P_l\left(\cos(\phi - \phi_s)d\sigma_{LT}^{13} + \frac{1}{Q}\cos(\phi_s)d\sigma_{LT}^{14} + \frac{1}{Q}\cos(2\phi - \phi_s)d\sigma_{LT}^{15}\right)
\]

**Disentangling the contributions:**
- experiments with beam and target polarization states \((U, L, T)\)
- extract the relevant Fourier amplitudes based on their azimuthal dependences

**If no perfect detection efficiency:**

\[
N(\phi, \phi_s) = \epsilon(\phi, \phi_s)\sigma_{UU}^0\left\{1 + 2\langle\cos\phi\rangle_{UU}\cos\phi + 2\langle\cos2\phi\rangle_{UU}\cos2\phi\right. \\
+ S_T\left(2\langle\sin(\phi - \phi_s)\rangle_{UT}\sin(\phi - \phi_s) + 2\langle\sin(\phi + \phi_s)\rangle_{UT}\sin(\phi + \phi_s) + \left.2\langle\sin(3\phi - \phi_s)\rangle_{UT}\sin(\phi + \phi_s) + \ldots\right) \right. \\
+ S_T P_l\left(2\langle\cos(\phi - \phi_s)\rangle_{UT}\cos(\phi - \phi_s) + 2\langle\cos\phi_s\rangle_{UT}\cos\phi_s + \left.2\langle\cos(2\phi - \phi_s)\rangle_{UT}\cos(\phi - \phi_s)\right)\right\}
\]

**Fit the cross section asymmetry for opposite spin states**
Overview on HERMES activities in SIDIS sector

\[ d\sigma = d\sigma^0_{UU} + \cos(2\phi)d\sigma^1_{UU} + \frac{1}{Q}\cos(\phi)d\sigma^2_{UU} + P_t\left(\frac{1}{Q}\sin(\phi)d\sigma^3_{LU}\right) + S_L\left[\sin(2\phi)d\sigma^4_{UL} + \frac{1}{Q}\sin(\phi)d\sigma^5_{UL}\right] + P_t\left(\frac{1}{Q}\sin(\phi)d\sigma^6_{LL} + \sin(2\phi)d\sigma^7_{LL}\right) \]

- Published
- Paper coming out soon
- Published
- Published
- Ongoing analysis

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Cahn and Boer-Mulders effect

$$\frac{d\sigma}{dx dy d\phi_d dz d\phi_P} = \frac{\alpha^2 \gamma^2}{x y Q^2 2 (1-\epsilon)} \left( 1 + \frac{\gamma^2}{2x} \right)$$

$$\left\{ \begin{array}{l}
F_{UUU} + \epsilon F_{ULL} \\
\sqrt{2} (1+\epsilon) \cos(\phi) F_{UUU}^{\cos(\phi)} + \epsilon \cos(2\phi) F_{UUU}^{\cos(2\phi)}
\end{array} \right\} + \lambda$$

+ $S_L$

+ $S_L \lambda$

+ $S_T$

+ $S_T \lambda$

\[ \sigma^{\cos(\phi)}_{UU} \propto \left[ f_1 \otimes D_1 + h_1^\perp \otimes H_1^\perp + \ldots \right] / Q \]

\[ \sigma^{\cos(2\phi)}_{UU} \propto h_1^\perp \otimes H_1^\perp + \left[ f_1 \otimes D_1 + \ldots \right] / Q^2 \]

- **Cahn effect:**

  Cahn Effect
  kinematical effect due to transv. mom-entum of partons in the nucleon

- **Boer-Mulders effect:** Boer-Mulders TMD

  Boer-Mulders $h_1^\perp$:
  correlation of parton transv. momentum and transv. polarization in an unpolarized nucleon

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Phi modulations in unpolarized SIDIS pion X-section

$\cos\phi$ large and negative!

Increasing with $z$ and $P_h$

Large difference in hadron charge!

Larger in magnitude for $\pi^+$

$\cos2\phi$ non-zero!

Difference in hadron charge!

Positive for $\pi^-$

Negative for $\pi^+$
Proton vs. deuteron data: u- vs d-quark Boer-Mulders fct

Quark d vs u contribution?
DATA support Boer-Mulders of same sign for u and d
Boer-Mulders: kaons vs pions

The kaon puzzle

Already found in $A_{UT}$: Collins+Transversity

Role of the sea in distribution and fragmentation functions

NEW!!

Striking difference versus pions!

$\sigma^{\cos(2\phi)}_{UU} \propto h_1^\perp \otimes H_1^\perp + [f_1 \otimes D_1 + \ldots]/Q^2$

$\sigma^{\sin(\phi+\phi_s)}_{UT} \propto h_1 H_1^\perp$

`Pretzelosity’ DF from transversely polarized proton

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

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

\[ + S_T\left[\sin(\phi - \phi_s)d\sigma_{UT}^8 + \sin(\phi + \phi_s)d\sigma_{UT}^9 + \sin(3\phi - \phi_s)d\sigma_{UT}^{10} + \frac{1}{Q}\sin(2\phi - \phi_s)d\sigma_{UT}^{11} + \frac{1}{Q}\sin(\phi_s)d\sigma_{UT}^{12}\right] \]

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

“pretzelosity” DF \( h_{1T}^{q,q}(x, p_T^2) \) gives a measure of the deviation of the nucleon shape from a sphere.

- correlation between parton transverse momentum and parton transverse polarization in a transversely polarized nucleon.

- it is expected to be suppressed at small and large \( x \) w.r.t. \( f_1^q, g_1^q, h_1^q \)

- envolve quark and nucleon helicity flips; is related to chiral-odd GPD

\[ h_{1T}^{q,q}(x, p_T^2) = \frac{3}{(1-x)^2}\widetilde{H}_T^q(x, 0, 0) \]

- gives the measure of ‘relativistic effects’ in the nucleon:

\[ \frac{p_T^2}{2M^2} h_{1T}^{q,q}(x, p_T^2) = g_1^q(x, p_T^2) - h_1^q(x, p_T^2) \]
Result on pretzelosity

\[ 2\langle \sin(3\phi - \phi_s) \rangle_{UT} \propto \frac{\sum_q e_q^2 x h_{1T}^{(1),q}(x) \otimes_w H_{1q}^{(1/2)} q(z)}{\sum_q e_q^2 f_1^{q}(x) \otimes D_{1}^{q}(z)} \]

\[ 2\langle \sin(3\phi - \phi_s) \rangle_{UT} \]

suppressed by two powers of \( P_{h\perp} \) compared to Collins and Sivers amplitudes

compatible with zero within uncertainties

pretzelosity might be non-zero at higher \( P_{h\perp} \)
`Worm-gear' DFs from transversely polarized proton

\[
\begin{align*}
\sigma &= \sigma_{UU}^0 + \cos(2\phi)\sigma_{UU}^1 + \frac{1}{Q}\cos(\phi)\sigma_{UU}^2 + P_t\frac{1}{Q}\sin(\phi)\sigma_{UU}^3 \\
&+ S_L\left[\sin(2\phi)\sigma_{UL}^4 + \frac{1}{Q}\sin(\phi)\sigma_{UL}^5 + P_t\left(\sigma_{LL}^6 + \frac{1}{Q}\cos(\phi)\sigma_{LL}^7\right)\right] \\
&+ S_T\left[\sin(\phi - \phi_s)\sigma_{UT}^8 + \sin(\phi + \phi_s)\sigma_{UT}^9 + \sin(3\phi - \phi_s)\sigma_{UT}^{10} + \frac{1}{Q}\sin(2\phi - \phi_s)\sigma_{UT}^{11} + \frac{1}{Q}\sin(\phi_s)\sigma_{UT}^{12}\right] \\
&+ P_t\left(\cos(\phi - \phi_s)\sigma_{LT}^{13} + \frac{1}{Q}\cos(\phi_s)\sigma_{LT}^{14} + \frac{1}{Q}\cos(2\phi - \phi_s)\sigma_{LT}^{15}\right)
\end{align*}
\]

Worm-gear DFs \( g_{1T}^q(x, p_T^2) \) and \( h_{1L}^{-1}^q(x, p_T^2) \) describe the probability to find a longitudinally/transversely polarized quark in a transversely/longitudinally polarized nucleon.

On a transversely target \( h_{1L}^{-1}^q(x, p_T^2) \) accessible in the measurements through \( \sin(2\phi + \phi_s) \)

Fourier component

Gives correlation between parton transverse momentum and parton longitudinal / transverse polarization in a longitudinal / transversely polarized nucleon

Model dependent relations:

\[
\begin{align*}
g_{1T}^q(x, p_T^2) &\approx x \int_x^1 \frac{1}{y} g_1^q(y, p_T^2)\,dy \\
h_{1L}^{-1}^q(x, p_T^2) &= -g_{1T}^q(x, p_T^2) \\
h_{1L}^{-1}^q(x, p_T^2) &\approx -x \int_x^1 \frac{1}{y} h_1^q(y, p_T^2)\,dy
\end{align*}
\]
Worm-gear DF from long.pol. beam/transv.pol.target

\[
2 \langle \cos(\phi - \phi_s) \rangle_{LT} \propto \frac{C[-\frac{P_{h\perp}p_T}{M_h} g_{1T}^q(x, p_T^2) D_1^q(z, k_T^2)]}{C[f_1^q(x, p_T^2) D_1^q(z, k_T^2)]}
\]

Uncertainties are larger than in single-spin asymmetries scaled by the beam polarization value.

- $\pi^+$ slightly positive
- $\pi^0$ compatible with zero
- $\pi^-$ positive, evidence for non-zero worm-gear distribution
- $K^+$ slightly positive
- $K^-$ compatible with zero

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Subleading-twist amplitudes for pions & kaons

\[ P_{T}A_{U\perp}(\phi, \phi_{s}) = S_{T}A_{UT}(\phi, \phi_{s}) + S_{L}A_{UL} \]

- longitudinal component of the target spin <15\%
- expected to scale as \( \sin \theta_{l} \cdot \langle \sin(2\phi)_{UL} \rangle \)
- related to worm-gear DF \( h_{1L}^{+}q \)
- \( \sin(2\phi+\phi_{s}) \) amplitude is suppressed by one
  powers of \( P_{h\perp} \) compared to Collins and Sivers amplitudes
- compatible with zero within uncertainties except maybe \( K^{+} \)
Subleading-twist amplitudes for pions & kaons

The subleading-twist amplitudes arise solely from longitudinal component of the target spin:

\[ P_{T}A_{UL}(\phi, \phi_{s}) = S_{T}A_{UT}(\phi, \phi_{s}) + S_{L}A_{UL} \]

- Longitudinal component of the target spin <15%.
- Expected to scale as \( \sin \theta_{y} \cdot \langle \sin(2\phi)_{UL} \rangle \).
- Related to worm-gear DF \( h_{1L}^{L_{q}} \).
- \( \sin(2\phi + \phi_{s}) \) amplitude is suppressed by one power of \( P_{h_{1L}} \) compared to Collins and Sivers amplitudes.
- Compatible with zero within uncertainties except maybe \( K^{+} \).
Conclusions and Outlook

HERMES has been pioneering the experimental study of the spin structure of the nucleon towards GPDs and TMDs.

HERMES will stay unique (for a while) offering exclusive and semi-inclusive data taken with both beam charges and undiluted Hydrogen and Deuterium targets.

HERMES has been publishing an almost full spectrum of asymmetries in DVCS and intends to publish more on exclusive meson production (Rho, Phi, Omega, Eta, Pi0).

HERMES intends to soon have published results on a wide variety of (flavor-separated) SIDIS asymmetries.

Spin results not addressed in this talk: Exclusive VM production (see poster B. Marianski).

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