Overview of recent HERMES results

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Outline

- Experiment HERMES
- Inclusive DIS
  - $F_2(x)$
  - $A_2, g_2(x)$
- Semi-Inclusive DIS
  - Double-Spin Asymmetry $A_1^h$
  - Azimuthal Asymmetries in Unpolarized SIDIS
  - Azimuthal Asymmetries in Transversely polarized SIDIS
  - $A_N$ asymmetry for the inclusive hadron production $lp^+ \rightarrow h + X$
- Exclusive Reactions
  - DVCS
- Summary
**Experiment HERMES**

27.5 GeV polarized $e^+ / e^-$ beam of HERA

- Internal gas Target: polarized - $H^\uparrow$
- Angular acceptance: $40 < \theta < 220$ mrad
- RICH: $\pi / K / p$

- $e/h$ rejection: TRD, Preshower, Calorimeter, RICH
- $m$agnetic spectrometer: $\Delta p/p < 2.5\%$ and $\Delta \theta < 0.6$ mrad
HERMES Running History

- **1995:** longitudinally polarized $^3\text{He}$
- **1996 - 2000:** longitudinally polarized hydrogen/deuteron; unpolarized nuclei from Hydrogen to Xenon.
- **2002 - 2005:** transversally polarized hydrogen; unpolarized nuclei from Hydrogen to Xenon;
- **2006 - 2007:** recoil detector with unpolarized target.
- **30.06.2007 -** End of HERA running.
Deep-Inelastic Scattering

\( Q^2 = -q^2 = -(k - k')^2 \)
\( x_B = \frac{Q^2}{2 P \cdot q} \)
\( y = \frac{P \cdot q}{P \cdot k} \)
\( W^2 = (P + q)^2 \)
\( z = \frac{P \cdot P_h}{P \cdot q} \)

inclusive DIS: detect scattered lepton
semi-inclusive DIS: detect scattered lepton and some fragments

\( W^2 > 10 \text{ GeV}^2, \ 0.1 < y < 0.85, \ Q^2 > 1 \text{ GeV}^2, \ 0.2 < z < 0.7 \)

\( < Q^2 > = 2.4 \text{ GeV}^2, \ < x > = 0.09, \ < y > = 0.54, \ < z > = 0.36, \ P_{h\perp} = 0.41 \text{ GeV}^2 \)
Inclusive DIS
Inclusive DIS

\[
\frac{d^2 \sigma(s, S)}{dxdQ^2} = \frac{2\pi \alpha^2 y^2}{Q^6} L_{\mu\nu} (s) W_{\mu\nu} (S)
\]

Hadron Tensor \( W_{\mu\nu} \) parametrized in terms of Structure Functions

\[
\frac{d^3 \sigma}{dxdyd\phi} \propto \frac{y}{2} F_1 (x, Q^2) + \frac{1 - y - \gamma^2 y^2/4}{2xy} F_2 (x, Q^2)
\]

\[
- P_T P_T \cos \alpha \left[ \left( 1 - \frac{y}{2} - \frac{\gamma^2 y^2}{4} \right) g_1 (x, Q^2) - \frac{\gamma^2 y^2}{2} g_2 (x, Q^2) \right]
\]

\[
+ P_T P_T \sin \alpha \cos \phi \gamma \sqrt{1 - y - \frac{\gamma^2 y^2}{4}} \left( \frac{y}{2} g_1 (x, Q^2) + g_2 (x, Q^2) \right)
\]
\( F_2(x) \), Proton, Deuteron

\[ F_2^p \times c \]

- New region covered by HERMES: \( 0.006 < x < 0.9, \quad 0.1 \text{ GeV}^2 < Q^2 < 20 \text{ GeV}^2 \)
- Agreement with world data in the overlap region
\( A_2, g_2(x) \) (Presented by A. Ivanilov)

\[
e^\leftrightarrow + p^\uparrow \rightarrow e' + X
\]

\[
\langle P_T \rangle \simeq 71\%
\]

\[
\langle P_b \rangle \simeq 34\% \text{ (HERA Run 1 } \langle P_b \rangle \geq 50\% \text{)}
\]

\[
ge_2(x, Q^2) = g_2^{WW}(x, Q^2) + \bar{g}_2(x, Q^2), \quad g_2^{WW}(x, Q^2) = -g_1(x, Q^2) + \int_x^1 \frac{dy}{y} g_1(x, Q^2)
\]

Final publication: extended kinematic region; evaluation of \( d_2 = 3 \int_0^1 x^2 \bar{g}_2(x) \, dx \); evaluation of the BC integral \( \int g_2(x, Q^2) \, dx \) in the measured region.
Semi-Inclusive DIS
SIDIS: Double-Spin Asymmetry $A^h_1$

Charge conjugation symmetry for FF: $D_{q^+}^{h^+} = D_{q^-}^{h^-}$

$$A_1^{h^+ - h^-} = \frac{(\sigma_{\uparrow\downarrow}^{h^+} - \sigma_{\downarrow\uparrow}^{h^-}) - (\sigma_{\uparrow\uparrow}^{h^+} - \sigma_{\downarrow\downarrow}^{h^-})}{(\sigma_{\uparrow\downarrow}^{h^+} - \sigma_{\downarrow\uparrow}^{h^-}) + (\sigma_{\uparrow\uparrow}^{h^+} - \sigma_{\downarrow\downarrow}^{h^-})}$$

For isoscalar target and $\Delta s = \bar{\Delta}s$:

$$A_{1,p}^{\pi^+ - \pi^-} = \frac{4\Delta u_v - \Delta d_v}{4u_v - d_v}$$

$$A_{1,d}^{K^+ - K^-} = \frac{\Delta u_v + \Delta d_v}{u_v + d_v}$$

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Overview of recent HERMES results
• Nucleon structure described in leading-twist by 8 transverse-momentum dependent quark distributions (TMDs)
• HERMES has access to all of them through specific azimuthal modulations ($\phi, \phi_S$) of the cross-section due to the polarized beam and target.
Azimuthal Asymmetries in Unpolarized SIDIS

\[ \frac{d^5 \sigma_{UU}}{dx dy dz dP_{h\perp} d\phi_h} \propto \left\{ \mathcal{I} \left[ R f_1 D_1 \right] + \cos 2\phi_h \mathcal{I} \left[ S h_1^\perp H_1^\perp \right] + \cos \phi_h \frac{2M}{Q} \mathcal{I} \left[ T h_1^\perp H_1^\perp + U f_1 D_1 + \ldots \right] \right\} \]

\[ \mathcal{I} \left[ w f D \right] \] - convolution integral over initial (\( P_T^2 \)) and final (\( k_T^2 \)) quark transverse momenta.

\( \cos 2\phi_h \) - solely due to Boer-Mulders \( \otimes \) Collins term at twist-2. Cahn effect (a kinematic effect due to non-zero transverse quark momentum) contributes at twist-4.

\( \cos \phi_h \) - due to the contributions from the Boer-Mulders and the Cahn effects at twist-3.

\[ \langle \cos n\phi \rangle_{UU} = \frac{\int_0^{2\pi} \cos n\phi \, d\sigma_{UU} \, d\phi}{\int_0^{2\pi} d\sigma_{UU} \, d\phi} \]

To account for the experimental smearing and the QED radiative effects, the 5D unfolding procedure was applied.

Finally, the 4D cosine moments in bins of \( x, y, z, \) and \( P_{h\perp} \) were obtained.
Azimuthal Asymmetries in Unpolarized SIDIS

\[ \sigma_{UU}^{\cos 2\phi} \propto h^1_{\perp,q} \otimes H^1_{\perp,q\to h} \]

\[ 2 \left\langle \cos(2\phi^h) \right\rangle_{UU} \]

\[ e p \to e h^- X \]

\[ e p \to e h^+ X \]

HERMES preliminary
Azimuthal Asymmetries in Unpolarized SIDIS

\[ \propto \cos \phi_h \frac{2m}{Q} \mathcal{I} \left[ T h_1^{+} H_1^{+} + U f_1 D_1 + \ldots \right] \]
SIDIS: Extraction of the amplitudes, $UT$

For each kinematic bin, the probability density function for hadron type $h$:

\[ F(2 < \sin(\phi + \phi_S) >_{UT}^h, 2 < \sin(\phi - \phi_S) >_{UT}^h, \ldots, S_\perp, \phi, \phi_S) = \]

\[ 1 + S_\perp \cdot \left( 2 < \sin(\phi + \phi_S) >_{UT}^h \cdot \sin(\phi + \phi_S) + \\
2 < \sin(\phi - \phi_S) >_{UT}^h \cdot \sin(\phi - \phi_S) + \\
2 < \sin(3\phi - \phi_S) >_{UT}^h \cdot \sin(3\phi - \phi_S) + \\
2 < \sin(2\phi - \phi_S) >_{UT}^h \cdot \sin(2\phi - \phi_S) + \\
2 < \sin(2\phi + \phi_S) >_{UT}^h \cdot \sin(2\phi + \phi_S) + \\
2 < \sin(\phi_S) >_{UT}^h \cdot \sin(\phi_S) \right) \]

\[ < \sin(\phi + \phi_S) >_{UT}^h \] — signal for the Collins FF $H_1^\perp$ and the transversity DF $h_1$

\[ < \sin(\phi - \phi_S) >_{UT}^h \] — signal for the Sivers DF $f_{1T}^{\perp, q}$

\[ < \sin(3\phi - \phi_S) >_{UT}^h \] — signal for the pretzelosity DF $h_{1T}^{\perp, q}$
SIDIS: $\sigma_{UT}^{\sin(\phi - \phi_S)}$, $\sigma_{UT}^{\sin(\phi + \phi_S)}$
SIDIS: $\sigma_{UT} \sin(3\phi - \phi_S)$

Consistent with zero.
Negative for $\pi^-$
Positive for $\pi^+$
$\pi^0$, $K^+,-$ consistent with zero.
SIDIS: $\sigma_{UT} \sin(2\phi - \phi_S)$

Consistent with zero.
SIDIS: $\sigma_{UT}^{\sin(2\phi+\phi_S)}$

Consistent with zero.
SIDIS: Extraction of the amplitudes, $LT$

$$F(2 < \sin(\phi + \phi_S) >^h_U, 2 < \sin(\phi - \phi_S) >^h_U, \ldots, \lambda_I, S_\perp, \phi, \phi_S) =$$

$$1 + S_\perp \cdot \left( 2 < \sin(\phi + \phi_S) >^h_U \cdot \sin(\phi + \phi_S) +
 2 < \sin(\phi - \phi_S) >^h_U \cdot \sin(\phi - \phi_S) +
 2 < \sin(3\phi - \phi_S) >^h_U \cdot \sin(3\phi - \phi_S) +
 2 < \sin(2\phi - \phi_S) >^h_U \cdot \sin(2\phi - \phi_S) +
 2 < \sin(2\phi + \phi_S) >^h_U \cdot \sin(2\phi + \phi_S) +
 2 < \sin(\phi_S) >^h_U \cdot \sin(\phi_S) \right) +$$

$$1 + \lambda_I S_\perp \cdot \left( 2 < \cos(\phi - \phi_S) >^h_L \cdot \cos(\phi - \phi_S) +
 2 < \cos(\phi_S) >^h_L \cdot \cos(\phi_S) +
 2 < \cos(2\phi - \phi_S) >^h_L \cdot \cos(2\phi - \phi_S) \right)$$

$$< \cos(\phi - \phi_S) >^h_L \text{ — signal for the worm-gear DF} \ g_{1T}^{\perp,q}$$
SIDIS: $\sigma_{LT}^{\cos(\phi-\phi_S)}$

$\sigma_{LT}^{\cos(\phi-\phi_S)} \propto g_{1T}^{q,} \otimes D_{1}^{q \rightarrow h}$

Worm-gear function: longitudinally polarized quarks in a transversely polarized nucleon

Positive amplitude for $\pi^-$

Hint of a positive signal for $\pi^+$ and $K^+$

Consistent with zero for $\pi^0$ and $K^-$
SIDIS: $\sigma_{LT}^{\cos(\phi_S)}$

Compatible with zero.

The amplitude involve a mixture of either twist-2 DF and twist-3 FF or twist-3 DF and twist-2 FF.
SIDIS: $\sigma_{LT}^{\cos(2\phi-\phi_S)}$

Compatible with zero.

The amplitude involve a mixture of either twist-2 DF and twist-3 FF or twist-3 DF and twist-2 FF.
### SIDIS: Leading-twist TMDs. Summary

**Table: Quark Polarisation**

<table>
<thead>
<tr>
<th>N/q</th>
<th>U</th>
<th>L</th>
<th>T</th>
</tr>
</thead>
<tbody>
<tr>
<td>U</td>
<td>$f_1$</td>
<td>$h_{i\perp}$</td>
<td>Boer-Mulders</td>
</tr>
<tr>
<td></td>
<td>Number Density</td>
<td></td>
<td></td>
</tr>
<tr>
<td>L</td>
<td>$g_1$</td>
<td>$h_{IL\perp}$</td>
<td>Mulders-Kotzinian</td>
</tr>
<tr>
<td></td>
<td>Helicity</td>
<td></td>
<td></td>
</tr>
<tr>
<td>T</td>
<td>$g_{1T\perp}$</td>
<td>$h_i$</td>
<td>Transversity</td>
</tr>
<tr>
<td></td>
<td>Sivers</td>
<td>$h_{1T\perp}$</td>
<td>Pretzelosity</td>
</tr>
</tbody>
</table>

- **Indication to be non-zero!** Preliminary result
- Consistent with zero
  - PLB 562 (2003) 182
  - PRL 84 (2000) 4047
- Different from zero
  - PRL 94 (2005) 012002
  - PLB 693 (2010) 11
- Consistent with zero Preliminary result
- Small Preliminary result

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Overview of recent HERMES results
Non-zero left-right asymmetries $A_N$ were observed in $p^\uparrow p \rightarrow hX$. $A_N$ increased in magnitude with increasing of $x_F$.

It was suggested to investigate such asymmetry in inclusive electroproduction of hadrons $lp^\uparrow \rightarrow hX$. (M. Anselmino et al., 2009)

This would allow a test of the validity of the TMD factorization for processes with only one large scale ($p_T$).

HERMES obtained first data on such single-spin asymmetries.

The following hadron variables were used:
$p_T^h$ and $x_F \approx 2p_L/\sqrt{s}$.

The asymmetry was defined as:

$$A_{UT}(p_T, x_F, \phi) = \frac{N^\uparrow / L_p^\uparrow - N^\downarrow / L_p^\downarrow}{N^\uparrow / L_p^\uparrow + N^\downarrow / L_p^\downarrow}$$

$A_{UT}^{\sin \phi}$ amplitudes were extracted with a fit of the form $p_1 \sin \phi + p_2$ to the measured asymmetry.
Variables $p_T^h$ and $x_F$ are correlated in the HERMES acceptance.

One need study 2D dependencies.
The data are in a good qualitative agreement with predictions of M. Anselmino et al. The $P_T$ dependence is very similar to the HERMES results for the Sivers asymmetry measured in SIDIS.
Exclusive Reactions
Motivation: Total Angular Momentum of Quarks

Ji’s relation (1996):

\[ J_{q,g} = \frac{1}{2} \int_{-1}^{1} dx \cdot x[H_{q,g}(x, \xi, 0) + E_{q,g}(x, \xi, 0)] \]

A measurement of Generalized Parton Distributions (GPD) \( H \) and \( E \) is required. \( \implies \) Hard Exclusive reactions, e.g. DVCS, meson production.
Motivation: Total Angular Momentum of Quarks

- twist-2 GPDs $H, E, \tilde{H}, \tilde{E} (x, \xi, t)$ for spin 1/2 hadron
  - $x \pm \xi$: longitudinal momentum fractions of the partons,
  - $\xi$: fraction of the momentum transfer, $\xi \approx \frac{x_B}{2-x_B}$,
  - $t$: invariant momentum transfer, $t \equiv (p - p')^2$.

**GPDs ⇒ Form Factors:**
\[
\int_{-1}^{1} dx \cdot H_q (x, \xi, t) = F_1^q (t),
\]
\[
\int_{-1}^{1} dx \cdot E_q (x, \xi, t) = F_2^q (t),
\]
\[
\int_{-1}^{1} dx \cdot \tilde{H}_q (x, \xi, t) = G_A^q (t),
\]
\[
\int_{-1}^{1} dx \cdot \tilde{E}_q (x, \xi, t) = G_P^q (t).
\]

**GPDs ⇒ PDFs:**
\[
H_q (x, 0, 0) = q (x)
\]
\[
\tilde{H}_q (x, 0, 0) = \Delta q (x)
\]
\[
H_g (x, 0, 0) = g (x)
\]
\[
\tilde{H}_g (x, 0, 0) = \Delta g (x).
\]

DVCS depends on four GPDs $H, E, \tilde{H}, \tilde{E}$.
DVCS TTSA provides an access to GPD $E$ without a kinematic suppression.

Exclusive production of vector mesons ($\rho, \omega, \phi$) depends on two GPDs, $H$ and $E$. 

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Overview of recent HERMES results
Deeply Virtual Compton Scattering

\[ d\sigma \propto |T_{BH}|^2 + |T_{DVCS}|^2 + T_{BH}T^{*}_{DVCS} + T^{*}_{BH}T_{DVCS} \]

- \( T_{BH} \) depends on known Dirac and Pauli FFs \( F_1, F_2 \)
- \( T_{DVCS} \) depends on Compton FFs \( \mathcal{H}, \mathcal{E}, \tilde{\mathcal{H}}, \) and \( \tilde{\mathcal{E}} \), which are convolutions of respective GPDs with hard-scattering kernels.

At HERMES, \( |T_{BH}| \gg |T_{DVCS}| \).

\( \mathcal{I} \) contains an information on the amplitudes and phases of the Compton FFs.
DVCS: Beam-Charge Asymmetry

\[ A_C(\phi) \sim \sum_{n=0}^{3} A_C^{\cos(n\phi)} \cos(n\phi) \]

\[ A_{LU,I}(\phi) \approx \sum_{n=1}^{2} A_{LU,I}^{\sin(n\phi)} \sin(n\phi) \]

\[ \propto \text{Im}(\mathcal{H}) \]

- VGG overestimates the magnitude of the asymmetry amplitude
New results are in agreement with published (JHEP 11 (2009) 083)
$A_{UT}(\phi, \phi_S) = A_{UT}^{\sin(\phi - \phi_S)} \sin(\phi - \phi_S) + A_{UT}^{\sin(\phi - \phi_S) \cos(\phi)} \sin(\phi - \phi_S) \cos(\phi) + \ldots$

JHEP 06 (2008) 066

\[ \propto \text{Im}(F_2^H - F_1^E) \]

- $A_{UT}^{\sin(\phi - \phi_S) \cos(\phi)}$ sensitive to $J_u$, allows a model-dependent constraint
DVCS: Double-Spin Asymmetry

\[ A_{LT}^I(\phi, \phi_S) = A_{LT, l}^{\sin(\phi - \phi_S)} \cos(\phi - \phi_S) + A_{LT, l}^{\cos(\phi - \phi_S)} \cos(\phi - \phi_S) \cos(\phi) + \ldots \]

- Sensitivity to \( J_\perp \) suppressed by kinematic pre-factor


\[ \propto \text{Re}(F_2 \mathcal{H} - (F_1 + \xi F_2) \mathcal{E}) \]
DVCS: LTSA, Proton

\[ A_{UL}(\phi) = \sum_{n=1}^{2} A_{UL}^{\sin(n\phi)} \sin(n\phi) \]

- Unexpectedly large \( A_{UL}^{\sin(2\phi)} \) asymmetry amplitude

\[ \propto \text{Im}(\tilde{\mathcal{H}}) \]

JHEP 06 (2010) 019
DVCS: LTSA, Deuteron

\[ A_{UL}(\phi) = \sum_{n=1}^{2} A_{UL}^{\sin(n\phi)} \sin(n\phi) \]

- Results for \textit{deuteron} are compatible with that for proton for leading amplitudes
- Different results for \( A_{UL}^{\sin(2\phi)} \): compatible with zero for deuteron

9 chiral-even GPDs in case of spin-1 target: \( H_1, \ldots, H_5, \tilde{H}_1, \ldots, \tilde{H}_4 \)

Search for coherent signature


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Overview of recent HERMES results
DVCS: Recoil Detector

Overall Process fractions

Elastic Assoc.
- with Recoil Det.
- in Recoil Det. accept.
- without Recoil Det.

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Overview of recent HERMES results
Indication that leading amplitude for pure elastic process is slightly larger than for unresolved signal (elastic + associated)

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Overview of recent HERMES results
DVCS: Summary

- Beam charge asymmetry
  - GPD $H$ PRD 75 (2007) 011103
  - JHEP 11 (2009) 083

- Beam helicity asymmetry
  - GPD $H$ JHEP 11 (2009) 083

- Transverse target-spin asymmetry
  - GPD $E$ JHEP 06 (2008) 066

- Transverse double-spin asymmetry
  - GPD $E$ arXiv:1106.2990

- Longitudinal target-spin asymmetry
  - GPD $H$ JHEP 06 (2010) 019

- Longitudinal double-spin asymmetry
HERA was switched off more than 4 years ago, HERMES community still produces new interesting results.

Structure functions $F_2(x, Q^2)$ and $g_2(x)$ are measured in new kinematic region.

The Fourier amplitudes of various azimuthal asymmetries for pion/kaon production on the unpolarized and transversely polarized targets are extracted.

Collins and Sivers amplitudes are well studied and the data have been published.

Contributions from other leading twist DF are investigated.

Boer-Mulders DF is likely to be non-zero.

Contributon from the pretzelosity DF $h_{1T}^⊥ q$ is compatible with zero.

Amplitude $σ_{LT}^{\cos(φ−φ_S)}$ is found to be positive for $\pi^-$. Hint of a positive signal for $\pi^+$ and $K^+$.

Amplitude $σ_{UT}^{\sin(φ_S)}$ is found to be non-zero for $\pi^-$ and $\pi^+$.

First results were obtained for hadron asymmetry $A_N$ in process $lp^↑ → h + X$.

HERMES has obtained the most complete data set of various DVCS asymmetries.

First results on the DVCS asymmetries using data from the recoil detector are obtained. Its using allows essentially increase the purity of the DVCS sample.