Recent HERMES Results on Inclusive Scattering and Exclusive Reactions

⇒ Spin Asymmetries in Semi-inclusive Meson Production
⇒ Measurement of $b_1^d$ Structure Function
⇒ Deeply Virtual Compton Scattering
⇒ Exclusive $\pi^+$ Production
⇒ Exclusive Vector Meson Production
⇒ Hard Exclusive $\pi^+\pi^-$ Pair Production

Michael Tytgat
University of Gent
on behalf of the HERMES Collaboration
The HERMES Experiment @ DESY

- 27.6 GeV HERA e^{-} beam
- Internal, pure gas target: \( ^{\text{He}}, \ ^{\text{H}}, \ ^{\text{D}}, \ ^{\text{H}} \uparrow \);
  unpol: \( ^{\text{H}}_2, ^{\text{D}}_2, \ ^{\text{He}}, \ ^{\text{N}}, \ ^{\text{Ne}}, \ ^{\text{Kr}}, \ ^{\text{Xe}} \)
- Resolution: \( \Delta \rho / \rho = 1.4 - 2.5 \% \), \( \Delta \theta < 0.6 \text{ mrad} \)
- Lepton/hadron separation: TRD, Preshower, Calorimeter, Cherenkov (1995-97)
- Target polarization: longitudinal (1996-2000) \( \langle P_{t} \rangle \approx 85 \% \) & transverse (2002-2005) \( \langle P_{t} \rangle \approx 75 \% \); flipping every 90s
- HERA beam polarization \( \langle P_{b} \rangle = 53 \% \) longitudinal
Semi-inclusive Deep Inelastic Scattering

HERMES → study nucleon spin structure in terms of quarks and gluons through polarized deep-inelastic scattering

⇒ HERMES-II (2002-2005) : transversely polarized target

\[
Q^2 = -q^2 = -(k - k')^2
\]
\[
\nu_{\text{lab}} = E - E'
\]
\[
x = \frac{Q^2}{2 M \nu}
\]
\[
z_{\text{lab}} = \frac{E_h}{\nu}
\]

⇒ Cross section contains quark distribution and fragmentation functions

\[
\sigma^{eN \rightarrow ehX} \sim \sum_q f^{N \rightarrow q} \otimes \sigma^{eq \rightarrow eq} \otimes D^{q \rightarrow h}
\]
Distribution Functions

In leading twist, integrating over quark transverse momenta, 3 DFs:

\[ f_1 = \begin{array}{c} \bullet \\ \text{: unpolarized quarks in unpolarized nucleons} \end{array} \]

\[ g_1 = \begin{array}{c} \bullet \rightarrow - \bullet \rightarrow \\ \text{: longitudinally polarized quarks in longitudinal nucleons} \end{array} \]

\[ h_1 = \begin{array}{c} \bullet \rightarrow \uparrow \rightarrow \downarrow - \rightarrow \bullet \rightarrow \downarrow \rightarrow \uparrow \\ \text{: transversely polarized quarks in transverse nucleons} \end{array} \]

\[ \Rightarrow \text{Unpolarized DF } q(x) : \text{spin averaged, very well known} \]

\[ \Rightarrow \text{Helicity DF } \Delta q(x) \equiv q^\uparrow \downarrow(x) - q^\downarrow \uparrow(x) : \text{helicity difference, well known (HERMES-I)} \]

\[ \Rightarrow \text{Tranversity } \delta q = q^{\uparrow \uparrow} - q^{\uparrow \downarrow} : \text{helicity flip, unknown (HERMES-II)} \]
HERMES-I: longitudinal (semi)-inclusive double spin asymmetries

\[ A_h^1(x) = \sum_q P_q^h(x) \frac{\Delta q(x)}{q(x)} \]

with purity \( P_q^h(x) = \frac{e_q^2 q(x) \int_{0.2}^{0.8} D_q^h(z) dz}{\sum_{q'} e_{q'}^2 q'(x) \int_{0.2}^{0.8} D_{q'}^h(z) dz} \)

\[ \mathbf{Q} \] Solve matrix equation:

\[ \mathbf{A}_1(x) = \mathbf{P}(x) \cdot \mathbf{Q}(x) \]

with

\[ \mathbf{A}_1(x) = (A_{1p}, A_{1p}^{\pi^+}, A_{1p}^{\pi^-}, A_{1d}, A_{1d}^{\pi^+}, A_{1d}^{\pi^-}, A_{1d}^{K^+}, A_{1d}^{K^-}) \]
Strange Quark Polarization

Expect significant negative strange quark polarization

Extract \([\Delta Q/Q](x)\) and \([\Delta S/S](x)\) from \(A_D(x, Q^2)\) and \(A_D^{K^+K^-}\); assume only charge conjugation invariance for purities

\[
\begin{pmatrix}
A_d(x) \\
A^K_d(x)
\end{pmatrix}
= C_R \begin{pmatrix}
P_q(x) & P_S(x) \\
P^K_q(x) & P^K_S(x)
\end{pmatrix}
\begin{pmatrix}
\Delta Q(x)/Q(x) \\
\Delta S(x)/S(x)
\end{pmatrix}
\]

with \(Q(x) \equiv u(x) + \bar{u}(x) + d(x) + \bar{d}(x)\) and \(S(x) \equiv s(x) + \bar{s}(x)\)

Determine \(K\) fragmentation functions from measured multiplicities

\[
\frac{\Delta S(x)}{S(x)} = s(x) + \bar{s}(x) - \int_{x} \Delta S(x)
\]

\[
\frac{\Delta Q(x)}{Q(x)} = u(x) + \bar{u}(x) + d(x) + \bar{d}(x) - \int_{x} \Delta Q(x)
\]
Transversity

- $f_1(x)$ and $g_1(x)$ can be measured in inclusive DIS; $h_1(x)$ is chiral-odd → need another chiral-odd object to access transversity

⇒ Consider quark transverse momentum in distribution and fragmentation functions and measure transversity via single-spin azimuthal asymmetries in $e + p \rightarrow e + h + X$ on a polarized target

Collins effect: \[ A \sim h_1(x) \ H_1^\perp(z) \]

→ Influence of quark’s polarization on transverse momentum acquired in fragmentation process orthogonal to its transverse polarization

Sivers effect: \[ A \sim f_{1T}^\perp(x) \ D_1(z) \]

→ Struck quark “remembers” transverse momentum it had in the target and influences transverse momentum of produced hadrons; implies non-vanishing quark orbital angular momentum
Extracting Transverse Target Asymmetries

\[ A_{UT}^h(\phi, \phi_S) = \frac{1}{\langle P_z \rangle} \frac{N^\dagger_h(\phi, \phi_S) - N^\dagger_h(\phi, \phi_S)}{N^\dagger_h(\phi, \phi_S) + N^\dagger_h(\phi, \phi_S)} \]

\[ = 2 \cdot \langle \sin(\phi - \phi_S) \rangle_{UT}^h \cdot \sin(\phi - \phi_S) \]

\[ + 2 \cdot \langle \sin(\phi + \phi_S) \rangle_{UT}^h \cdot \frac{B(\langle y \rangle)}{A(\langle x \rangle, \langle y \rangle)} \cdot \sin(\phi + \phi_S) \]

\[ \propto \sin(\phi + \phi_S) \frac{\sum_q e^2_q \delta q(x) H_1^+(z)}{\sum_q e^2_q q(x) D_1(z)} \]

\[ + \sin(\phi - \phi_S) \frac{\sum_q e^2_q f_{1T}^+(x) D_1(z)}{\sum_q e^2_q q(x) D_1(z)} \]

⇒ Extract Collins moment \( \langle \sin(\phi + \phi_S) \rangle_{UT}^h \) and Sivers moment \( \langle \sin(\phi - \phi_S) \rangle_{UT}^h \) by 2-dimensional fit to \( A_{UT}^h(\phi, \phi_S) \)
Extracted Collins Moments

- Collins moment positive for $\pi^+$; negative for $\pi^-$
- Expect $\delta u > 0$ and $\delta d < 0$
- Unexpected large absolute value for $\pi^-$; role of unfavoured FF?
- Additional information on Collins FF needed to extract transversity distribution

Sivers moments significantly positive for $\pi^+$; requires a non-vanishing quark orbital angular momentum

Sivers moment consistent with zero for $\pi^-$

Extraction of Sivers function in principle possible (known unpolarized fragmentation function)
Interference Fragmentation on Transverse Target

- Accessing transversity \( h_1(x) \) in 2-pion production
- \( A_{UT} \propto \sin(\phi_{R\perp} + \phi_S) \sin \theta h_1 H_1^\perp \) with interference FF

\[
H_1^\perp(z, \cos \theta, M_{\pi\pi}^2) = H_1^{\perp,sp}(z, M_{\pi\pi}^2) + \cos \theta H_1^{\perp,pp}(z, M_{\pi\pi}^2)
\]

Jaffe et al., PRL80 (1998) : predicted sign change around \( \rho^0 \) mass

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Evidence for non-zero interference fragmentation function;
positive asymmetry vs. \( M_{\pi\pi} \), no sign change observed
Leading-twist structure functions in DIS:

\[ F_1 = \frac{1}{2} \sum_q e_q^2 [q^\perp_1 + q^\perp_2] \]

\[ g_1 = \frac{1}{2} \sum_q e_q^2 [q^\perp_1 - q^\perp_2] \]

\[ b_1 = \frac{1}{2} \sum_q e_q^2 [2q^0_1 - (q^\perp_1 + q^\perp_1)] \]

\( b_1(x) \) measures difference between parton densities in \( m = 1 \) and \( m = 0 \) deuteron states; vanishes in absence of nuclear effects

\[
\frac{d\sigma_{\text{pol}}}{d\Omega} = \frac{d\sigma_{\text{unpol}}}{d\Omega} \left[ 1 - \frac{1}{2} P_z P_B D A_1^d + \frac{1}{2} P_{zz} A_{zz}^d \right]
\]

with \( A_1^d \sim \frac{g_1^d}{F_1^d} \) and \( b_1^d = -\frac{3}{2} A_{zz}^d F_1^d \)

\( 0.01 < \langle x \rangle < 0.45 \) and \( 0.5 \, \text{GeV}^2 < \langle Q^2 \rangle < 5 \, \text{GeV}^2 \)
Generalized Parton Distributions

- For $Q^2 \gg$ and $t << Q^2$, factorization for longitudinal photons in meson production
- 4 GPDs in leading twist:
  $H^q(x, \xi, t), E^q(x, \xi, t)$ unpolarized;
  $\tilde{H}^q(x, \xi, t), \tilde{E}^q(x, \xi, t)$ polarized

$H^q, \tilde{H}^q$ conserve nucleon helicity;
$E^q, \tilde{E}^q$ flip nucleon helicity

⇒ New observables in hard exclusive scattering; related to standard PDF and form factors:

$$H^q(x, 0, 0) = q(x), \quad \tilde{H}^q(x, 0, 0) = \Delta q(x),$$
$$\int_{-1}^{+1} dx \, H^q(x, \chi, t) = F_1^q(t), \quad \int_{-1}^{+1} dx \, E^q(x, \chi, t) = F_2^q(t), \quad \ldots$$

- Ji’s sum rule: $J_q = \frac{1}{2} \Delta q + L_q = \frac{1}{2} \int_{-1}^{+1} dx \, x \, [H^q + E^q]$

⇒ access to orbital angular momentum

- Unpolarized cross section contain quadratic combinations of GPDs; new information from polarized measurements
Accessing Generalized Parton Distributions

Final state quantum numbers select different GPDs:

- **Deeply Virtual Compton Scattering**: $H, E, \tilde{H}, \tilde{E}$
  - Beam charge asymmetry ($e^+ \leftrightarrow e^-$): $H$
  - Transverse Target Spin Asymmetry: $E, J_q$

- **Pseudoscalar meson** production ($\pi, \eta \ldots$): $\tilde{H}, \tilde{E}$
  - Cross section exclusive $\pi^+$ production
  - Transverse single spin asymmetries

- **Vector meson** production ($\rho, \omega, \phi \ldots$): $H, E$
  - Cross section exclusive $\rho^0$ ($\omega, \phi$) production \[A. Airapetian et al., Eur. Phys. J. C17 (2000) 389]\n  - Transverse single spin asymmetries

- **Pion pair** production: $H, E$
Deeply Virtual Compton Scattering

\[ \frac{d\sigma (eN \rightarrow eN\gamma)}{d\Omega} \propto |T_{BH}|^2 + |T_{DVCS}|^2 + T_{BH}T_{DVCS}^* + T_{BH}^*T_{DVCS} \]

Interference term gives rise to azimuthal asymmetries

\[ A(\phi) = \frac{N^+(\phi) - N^-(\phi)}{N^+(\phi) + N^-(\phi)} \]
Deeply Virtual Compton Scattering

- \( ep \rightarrow e\gamma p \) : no recoil detection so far; only \( e \) and \( \gamma \) detected

- Select exclusive events via missing mass cut

\[
M_X^2 = (p + g - p_\gamma)^2
\]

- No separation between elastic and associated DVCS; SIDIS background contamination estimated using Monte Carlo
DVCS: Beam Spin and Charge Asymmetry

Beam Spin Asymmetry $A_{LU}$:
\[
d\sigma(\vec{e}, \phi) - d\sigma(-\vec{e}, \phi) \\
\propto \sin \phi \cdot \text{Im}(T_{BH}T_{DVCS})
\]

Beam Charge Asymmetry $A_C$:
\[
d\sigma(e^+, \phi) - d\sigma(e^-, \phi) \\
\propto \cos \phi \cdot \text{Re}(T_{BH}T_{DVCS})
\]

Only @ HERA

\begin{align*}
A_{LU} &\propto \text{Im}(F_1 H) \cdot \sin \phi \\
A_C &\propto \text{Re}(F_1 H) \cdot \cos \phi
\end{align*}
DVCS : Beam Charge Asymmetry $t$-Dependence

HERMES PRELIMINARY
$e^+ p/d \rightarrow e^\pm, \gamma X$ \hspace{1cm} ($M_X < 1.7$ GeV)
(in HERMES acceptance)

- $\propto$ proton
- $\propto$ deuteron

Regge, D-term
Regge, no D-term
fac., D-term
fac., no D-term

$t$-dependence of BCA may constrain GPD models

GPD model : M. Vanderhaeghen et al., PRD 60 (1999) 094017

Proton $\leftrightarrow$ Deuteron

- Coherent contribution at low $-t \sim 40\%$
- Increasing neutron form factor at high $-t$

Tiny $e^-$ data sample (only $\sim 10$ pb$^{-1}$), but all 2005 with $e^-$!
\[ A_{UL} : d\sigma(\vec{p}, \phi) - d\sigma(\vec{p}, \phi) \propto A_{UL}^{\sin \phi} \sin \phi + A_{UL}^{\sin 2\phi} \sin 2\phi \]

\[ A_{UL}^{\sin \phi} \propto \text{Im}(\bar{F}_1 \bar{H}); \]
compatible with theory model

\[ A_{UL}^{\sin 2\phi} \] larger than theory expectation
\rightarrow \text{twist-3 GPD ?}
DVCS: Transverse Target Spin Asymmetry

\[ A_{UT}(\phi, \phi_s) : d\sigma(p^\uparrow, \phi, \phi_s) - d\sigma(p^\uparrow, \phi, \phi_s) \propto \text{Im}(F_2 H - F_1 E) \cdot \sin(\phi - \phi_s) \cos\phi + \text{Im}(F_2 \tilde{H} - F_1 \xi \tilde{E}) \cdot \cos(\phi - \phi_s) \sin\phi \]

\[ A_{UT}^{(\phi - \phi_s)} \cos\phi \] sensitive to \( J_u \), not to GPD model parameters

\( \text{Im}(F_2 H - F_1 E) \)

\( \text{Im}(F_2 \tilde{H} - F_1 \xi \tilde{E}) \)

\( A_{UT}^{(\phi - \phi_s)} \cos\phi \) sensitive to \( J_u \), not to GPD model parameters

(F. Ellinghaus et al., hep-ph/0506264)
Exclusive Pion Production

\[ e + p \rightarrow e + n + \pi^+ \]

\[ \pi^+/\pi^- = 1.77 \]

\[ \chi^2/\text{ndf} = 21.88/17 \]

\[ \text{Constant} = 341.9 \pm 18.9 \]

\[ \text{Mean} = 0.87 \pm 0.05 \]

\[ \text{Sigma} = 0.677 \pm 0.036 \]

- Use missing mass for \( e + p \rightarrow e + \pi^+ + X \);

- Subtract non-exclusive background via \( \pi^- \) production;

- method cross-checked with GPD based Monte Carlo
\( \pi^+ \) Cross Section Measurement

- GPD model: Vanderhaeghen, Guichon, Guidal
- \( \sigma_{\text{tot}} = \sigma_T + \epsilon \sigma_L \)
- no LT-separation, but \( \sigma_T \) suppressed by \( 1/Q^2 \) and \( 0.80 < \epsilon < 0.96 \) for HERMES
- \( Q^2 \) dependence consistent with LO expectations; power corrections (\( k_\perp \) and soft overlap) overestimate data
- \( \sigma_{\text{reduced}} \rightarrow 1/Q^2 \) in agreement with data [\( \sigma_L = K(x, Q^2) \cdot \sigma_{\text{reduced}} \) with \( K \propto 1/Q^4 \)]
Target Single Spin Asymmetry in $\rho^0$ Production

\[ e + p \rightarrow e + p + \rho^0 \]

- Exclusivity through $\Delta E = \frac{(M_X^2 - M_p^2)}{2M_p}$ cut
- $A_{UT}$ sensitive to interference of $H$ and $E$
  and to total angular momentum of $u$-quarks

Data consistent with theory expectations
Hard Exclusive $\pi^+\pi^-$ Pair Production

- Pion pairs are formed by gluon exchange (isovector pairs) or quark exchange (isovector + isoscalar pairs)
  ⇒ study interference between $I = 1$ ($\rho$-family) and $I = 0$ ($f$-family) channels to get information on small isoscalar channel
  ⇒ new constraints on certain combinations of GPDs

- HERMES: $ep \rightarrow ep\pi^+\pi^-$ and $ed \rightarrow ed\pi^+\pi^-$

- Intensity densities (Legendre moments):

$$< P_l(\cos \theta) >^{\pi\pi} = \frac{\int_{-1}^{+1} d\cos \theta P_l(\cos \theta) \frac{d\sigma^{\pi\pi}}{d\cos \theta}}{\int_{-1}^{+1} d\cos \theta \frac{d\sigma^{\pi\pi}}{d\cos \theta}}$$
Hard Exclusive $\pi^+\pi^-$ Pair Production

$\langle P_1 \rangle$ sensitive to interference of $P$-wave with $S$ and $D$-waves

$\Rightarrow$ Interference of $\rho^0$ $P$-wave with non-resonant $\pi\pi$ $S$-wave, $f_0(980)$ $S$-wave and $f_2(1270)$ $D$-wave

$\langle P_3 \rangle$ sensitive to interference of $P$-wave with $D$-wave

GPD model : B. Lehmann-Dronke et al.
Summary & Outlook

- First measurements of transverse target asymmetries in DIS; first observation of Sivers effect; large Collins asymmetry for $\pi^+$ and $\pi^-$; evidence for non-zero interference fragmentation function in $\pi\pi$ production

Expect double statistics for full transverse data set; with Belle Collins and interference FF extraction of $h_1$ could become feasible

- First measurement of $b_1^d$ structure function

- Access to GPDs in deeply virtual Compton scattering and hard exclusive pseudo-scalar and vector meson production

Installation of Recoil Detector end of this year; HERMES will focus on exclusive reactions during running for 2 years with high density unpolarized target