from solving the spin “crisis” to 3-D pictures of the nucleon

selected highlights from the hermes collaboration

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DESY Zeuthen
June 30th, 2007 (around midnight)
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The HERMES experiment

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

transversely/longitudinally polarized as well as unpolarized internal gas targets ($H, D, He, N, ..., Xe$)
The (original) quest: proton spin

Our understanding of the proton changed dramatically with the finding of EMC that the proton spin hardly comes from spin of quarks.

\[ \frac{1}{2} = \frac{1}{2} \Delta \Sigma + \Delta G + L_q + L_g \]

- \( \Delta \Sigma \) : quark spin
- \( \Delta G \) : gluon spin
- \( L_q \) : orbital angular momentum
Longitudinal Spin/Momentum Structure, Hadronization

GPDs “Nucleon Tomography”

Exclusive Meson Production

DVCS

Strange-Baryon Production

Transverse Spin/Momentum Structure

Transversity TMDs

“HEDT - 2^{nd} anniversary - July 7^{th}, 2009”

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Deep-Inelastic Scattering

use well-known probe to study hadronic structure:

\[ Q^2_{\text{lab}} = 4EE' \sin^2 \left( \frac{\Theta}{2} \right) \]
\[ \nu_{\text{lab}} = E - E' \]
\[ W^2_{\text{lab}} = M^2 + 2M\nu - Q^2 \]
\[ y_{\text{lab}} = \frac{\nu}{E} \]
\[ x_{\text{lab}} = \frac{Q^2}{2M\nu} \]

inclusive DIS: detect scattered lepton
Deep-Inelastic Scattering

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\[ y \equiv \frac{\nu}{E} \]
\[ x \equiv \frac{Q^2}{2M\nu} \]
\[ z \equiv \frac{E_h}{\nu} \]

inclusive DIS: detect scattered lepton
semi-inclusive DIS: detect scattered lepton and some fragments
Deep-Inelastic Scattering

use well-known probe to study hadronic structure:

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

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

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

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

\[ z_{\text{lab}} = \frac{E_h}{\nu} \]

Factorization \( \Rightarrow \sigma^{ep \rightarrow ehX} = \sum_q D F^{p \rightarrow q} \otimes \sigma^{eq \rightarrow eq} \otimes F F^{q \rightarrow h} \)

exploit strong correlation between flavor structure of leading hadron and struck quark
Inclusive DIS
Inclusive DIS

\[ \frac{d^2 \sigma(s, S)}{dx \ dQ^2} = \frac{2\pi \alpha^2 y^2}{Q^6} L_{\mu\nu}(s) W^{\mu\nu}(S) \]
Inclusive DIS

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

Lepton Tensor

Spin Plane

Scattering Plane
Inclusive DIS

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

Lepton Tensor

Hadron Tensor

parametrized in terms of

Structure Functions
Inclusive DIS

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

\[\frac{d^3 \sigma}{dx dy d\phi} \propto \frac{y}{2} F_1(x, Q^2) + \frac{1 - y - \gamma^2 y^2 / 4}{2xy} F_2(x, Q^2) - P_l P_T \cos \alpha \left[ 1 - \frac{y}{2} - \frac{\gamma^2 y^2}{4} \right] g_1(x, Q^2) - \frac{\gamma^2 y^2}{2} g_2(x, Q^2) \]

\[+ P_l P_T \sin \alpha \cos \phi \gamma \sqrt{1 - y - \frac{\gamma^2 y^2}{4}} \left( \frac{y}{2} g_1(x, Q^2) + g_2(x, Q^2) \right)\]
Parton-Model Interpretation of Structure

<table>
<thead>
<tr>
<th>structure function</th>
<th>↔</th>
<th>parton distribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>$F_1(x)$ $=$</td>
<td>$\frac{1}{2} \sum_q e_q^2 f_1^q(x)$</td>
<td>$f_1^q$ $=$</td>
</tr>
<tr>
<td>$F_2(x)$ $=$</td>
<td>$x \sum_q e_q^2 f_1^q(x)$</td>
<td></td>
</tr>
<tr>
<td>$g_1(x)$ $=$</td>
<td>$\frac{1}{2} \sum_q e_q^2 g_1^q(x)$</td>
<td>$g_1^q$ $=$</td>
</tr>
<tr>
<td>$g_2(x)$ $=$</td>
<td>0</td>
<td></td>
</tr>
</tbody>
</table>
Parton-Model Interpretation of Structure

structure function $\leftrightarrow$ parton distribution

\[
F_1(x) = \frac{1}{2} \sum_q e_q^2 f_1^q(x) \\
F_2(x) = x \sum_q e_q^2 f_1^q(x) \\
g_1(x) = \frac{1}{2} \sum_q e_q^2 g_1^q(x) \\
g_2(x) = 0
\]

quark-spin contribution to nucleon spin
Parton-Model Interpretation of Structure

\[
\begin{align*}
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g_2(x) &= 0
\end{align*}
\]

structure function ↔ parton distribution

quark-spin contribution to nucleon spin

related to transverse force on struck quark
Why measure $F_2$ at HERMESP?

- complementary kinematic coverage compared to colliders
- higher statistics compared to other fixed target experiments:
  - HERMESP: 58 million DIS (P+D)
  - NMC: 9 million DIS (P+D)
F₂ (proton)

Comparison with parameterization by SMC and GD07

GD07: hep-ph/0708.3196
$F_2$ proton

Agreement with world data in the overlap region

Comparison with parameterization by SMC and GD07

GD07: hep-ph0708.3196
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New region covered by HERMES

Agreement with world data in the overlap region

Comparison with parameterization by SMC and GD07

$Q^2$ [GeV$^2$]

GD07: hep-ph0708.3196

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$F_2$ deuteron

New region covered by HERMES

Agreement with world data in the overlap region

Comparison with parameterization by SMC

$Q^2 [GeV^2]$
World data on $\sigma_d / \sigma_p$

Many systematic errors common to proton and deuteron cross sections cancel in ratio

Normalization uncertainties

Additional normalization uncertainties not included

- NMC: <0.2%
- BCDMS: 1.5%
- SLAC: 0.3%
- HERMES: 1.4%

PRELIMINARY
Polarized Structure Function $g_1$

**HERMES**

\[ \langle Q^2 \rangle < 1 \text{ GeV}^2 \quad \langle Q^2 \rangle > 1 \text{ GeV}^2 \]

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\[ \langle Q^2 \rangle < 1 \text{ GeV}^2 \quad \langle Q^2 \rangle > 1 \text{ GeV}^2 \]

\[ \langle Q^2 \rangle (\text{GeV}^2) \]

\[ 10^{-2} \quad 10^{-1} \quad x \quad 1 \]

\[ 10 \quad \langle Q^2 \rangle (\text{GeV}^2) \]

\[ 1 \quad 10 \]

A. Airapetian et al., PRD 75 (2007)
Integral of $g_1(x)$

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Saturation close to full integral?

$$\Delta \Sigma = \frac{1}{\Delta C_S} \left[ \frac{9 \Gamma_1^d}{1 - \frac{3}{2} \omega_D} - \frac{1}{4} a_8 \Delta C_{NS} \right]$$

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$$\Delta \Sigma^{\overline{MS}} \simeq \frac{1}{\Delta C_S} \left[ \frac{9 \Gamma_1^d}{1 - \frac{3}{2} \omega_D} - \frac{1}{4} a_8 \Delta C_{NS} \right]$$

$$\Delta \Sigma^{\overline{MS}} = 0.330 \pm 0.011_{\text{theory}} \pm 0.025_{\text{exp}} \pm 0.028_{\text{evol}}$$

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Integral of $g_1(x)$

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$0.05 \pm 0.05$

$\Delta \Sigma_{\overline{MS}} = 0.330 \pm 0.011_{\text{theory}} \pm 0.025_{\text{exp}} \pm 0.028_{\text{evol}}$

most precise result; only 1/3 of nucleon spin from quarks

A. Airapetian et al., PRD 75 (2007)
Extraction of $g_2$

\[ \frac{\sigma^{\downarrow}(\phi) - \sigma^{\uparrow}(\phi)}{\sigma^{\downarrow}(\phi) + \sigma^{\uparrow}(\phi)} = \frac{\Delta \sigma_T}{\sigma} = \]

\[ = -\gamma \sqrt{1 - y} - \frac{\gamma^2 y^2}{4} \left( \frac{y}{2} g_1(x, Q^2) + g_2(x, Q^2) \right) \]

\[ \equiv \frac{y F_1(x, Q^2) + \frac{1}{2xy} \left( 1 - y - \frac{\gamma^2 y^2}{4} \right) F_2(x, Q^2)}{F_2(x, Q^2)} \cos \phi \]

$A_T$
Extraction of $g_2$

\[
\frac{\sigma_{\downarrow\phi} - \sigma_{\uparrow\phi}}{\sigma_{\downarrow\phi} + \sigma_{\uparrow\phi}} = \frac{\Delta \sigma_T}{\sigma} = -\gamma \sqrt{1 - y - \frac{\gamma^2 y^2}{4}} \left( \frac{y}{2} g_1(x, Q^2) + g_2(x, Q^2) \right) \cos \phi
\]

\[
\frac{y F_1(x, Q^2) + \frac{1}{2xy} \left( 1 - y - \frac{\gamma^2 y^2}{4} \right) F_2(x, Q^2)}{\frac{y}{2} F_1(x, Q^2) + \frac{1}{2xy} \left( 1 - y - \frac{\gamma^2 y^2}{4} \right) F_2(x, Q^2)}
\]

fit to double-spin asymmetry

\[
A_T = \frac{\xi(1 + \gamma^2)}{1 + \gamma \xi} \frac{g_1}{F_1}
\]

\[
A_2 = \frac{1}{d(1 + \gamma \xi)}
\]

\[
g_2 = \frac{F_1}{\gamma d(1 + \gamma \xi)}
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Extraction of $g_2$

$$\frac{\sigma^{\downarrow}(\phi) - \sigma^{\uparrow}(\phi)}{\sigma^{\downarrow}(\phi) + \sigma^{\uparrow}(\phi)} = \frac{\Delta \sigma_T}{\sigma} =$$

$$= -\gamma \sqrt{1 - y - \frac{\gamma^2 y^2}{4}} \left( \frac{y}{2} g_1(x, Q^2) + g_2(x, Q^2) \right)$$

$$= \left[ \frac{y}{2} F_1(x, Q^2) + \frac{1}{2xy} \left( 1 - y - \frac{\gamma^2 y^2}{4} \right) F_2(x, Q^2) \right] \cos \phi$$

fit to double-spin asymmetry

$$A_2 = \frac{1}{d(1 + \gamma \xi)}$$
$$g_2 = \frac{F_1}{\gamma d(1 + \gamma \xi)}$$
$$A_T = \frac{\xi(1 + \gamma^2)}{1 + \gamma \xi} g_1 F_1$$
$$A_T = \frac{F_1(\gamma - \xi)}{\gamma(1 + \gamma \xi)} g_1 F_1$$

parameterizations
Results on $A_2$ and $xg_2$

- consistent with (sparse) world data
- low beam polarization during HERA II $\Rightarrow$ small f.o.m.
Two-Photon Exchange

- interference between one- and two-photon exchange amplitudes leads to SSAs in inclusive DIS off transversely polarized targets
- interference sensitive to beam charge due to odd number of e.m. couplings to beam
- proportional to $S(kxk')$ - either measure left-right asymmetries or sine modulation
- two-photon exchange best candidate to explain discrepancy in form-factor measurements
Any Sign of Two-Photon Exchange?

consistent with zero at $10^{-3}$ level

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Any Sign of Two-Photon Exchange?

consistent with zero at $10^{-3}$ level

Front view of HERMES detector

acc. fac. $\equiv \frac{(A_N)_{\text{acc}}}{(A_{\sin \phi})_{2\pi}}$
Semi-Inclusive DIS
Quark Structure of the Nucleon
(integrated over transverse momentum)

\[ f_1^q = \] Unpolarized quarks and nucleons
\[ g_1^q = \] Longitudinally polarized quarks and nucleons
\[ h_1^q = \] Transversely polarized quarks and nucleons

\[ f_1^q(x) : \text{spin averaged (well known)} \]
\[ g_1^q(x) : \text{helicity difference (known)} \]
\[ h_1^q(x) : \text{transversity (hardly known!)} \]

\[ \langle PS | \bar{\Psi} \gamma^\mu \Psi | PS \rangle = \int dx (f_1^q(x) - f_1^\bar{q}(x)) \]
\[ \langle PS | \bar{\Psi} \gamma^\mu \gamma_5 \Psi | PS \rangle = \int dx (g_1^q(x) + g_1^\bar{q}(x)) \]
\[ \langle PS | \bar{\Psi} \sigma^{\mu\nu} \gamma_5 \Psi | PS \rangle = \int dx (h_1^q(x) - h_1^\bar{q}(x)) \]
Quark Structure of the Nucleon
(integrated over transverse momentum)

\[ f_1^q = \begin{array}{l}
\downarrow \\
\text{Unpolarized quarks and nucleons}
\end{array} \]

\[ g_1^q = \begin{array}{l}
\downarrow \\
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\[ \Rightarrow \text{Vector Charge} \]

\[ \langle PS|\bar{\Psi}\gamma^\mu\Psi|PS\rangle = \int dx (f_1^q(x) - f_1^q(x)) \]

\[ \Rightarrow \text{Axial Charge} \]

\[ \langle PS|\bar{\Psi}\gamma^\mu\gamma^5\Psi|PS\rangle = \int dx (g_1^q(x) + g_1^q(x)) \]

\[ \Rightarrow \text{Tensor Charge} \]

\[ \langle PS|\bar{\Psi}\sigma_{\mu\nu}\gamma^5\Psi|PS\rangle = \int dx (h_1^q(x) - h_1^q(x)) \]
Strange-quark distributions

- use isoscalar probe and target to extract strange-quark distributions
- only need inclusive asymmetries and $K^+$-$K^-$ asymmetries, i.e., $A_{\parallel,d}(x, Q^2)$ and $A_{\parallel,d}^{K^+ + K^-}(x, z, Q^2)$, as well as $K^+$-$K^-$ multiplicities on deuteron

\[
S(x) \int D^K_S(z) \, dz \simeq \begin{array}{c} Q(x) \left[ 5 \frac{d^2 N^K(x)}{d^2 N^{DIS}(x)} - \int D^K_Q(z) \, dz \right] \\
A_{\parallel,d}(x) \frac{d^2 N^{DIS}(x)}{dx \, dQ^2} = K_{LL}(x, Q^2) \left[ 5 \Delta Q(x) + 2 \Delta S(x) \right] \\
A_{\parallel,d}^{K^\pm}(x) \frac{d^2 N^K(x)}{dx \, dQ^2} = K_{LL}(x, Q^2) \left[ \Delta Q(x) \int D^K_Q(z) \, dz + \Delta S(x) \int D^K_S(z) \, dz \right]
\]
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A. Airapetian et al., PLB 666, 446 (2008)
Strange-quark distributions

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Strange-quark distribution softer than (maybe) expected

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Strang-quark distribution softer than (maybe) expected

A. Airapetian et al., PLB 666, 446 (2008)

Strange-quark helicity distribution consistent with zero or slightly positive in contrast to inclusive DIS analyses

Leader et al., PRD73, 034023 (2006)
The “Trouble” with Transversity

chiral-odd transversity involves quark helicity flip

\[ f_1^q = \quad g_1^q = \quad h_1^q = \]
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chiral-odd transversity involves quark helicity flip

\[ f_1^q = \begin{array}{c}
\text{Diagram 1}
\end{array} \quad g_1^q = \begin{array}{c}
\text{Diagram 2}
\end{array} \quad h_1^q = \begin{array}{c}
\text{Diagram 3}
\end{array} \]
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need to couple to chiral-odd fragmentation function:
The “Trouble” with Transversity

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

\[ 
\begin{align*}
  f_1^q &= \quad g_1^q &= \quad h_1^q = \\
  + & & - \\
  + & & - \\
  + & & + \\
  + & & + \\
  + & & - \\
  + & & - \\
  + & & + \\
  + & & + \\
  + & & - \\
  + & & - \\
\end{align*}
\]

need to couple to chiral-odd fragmentation function:
- transverse spin transfer (polarized final-state hadron)
The “Trouble” with Transversity

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\[ f_1^q = \text{\textbullet} \quad g_1^q = \text{\textbullet} \rightarrow \rightarrow \quad h_1^q = \text{\textbullet} \rightarrow \quad \]

need to couple to chiral-odd fragmentation function:

- transverse spin transfer (polarized final-state hadron)
- 2-hadron fragmentation
The “Trouble” with Transversity

chiral-odd transversity involves quark helicity flip

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

need to couple to chiral-odd fragmentation function:

- transverse spin transfer (polarized final-state hadron)
- 2-hadron fragmentation
- Collins fragmentation
2-hadron fragmentation

spin-dependent 2-hadron production:

\( \sigma_{UT} \sim \sin(\phi_{R\perp} + \phi_S) \sum e_q^2 h_1^q H_1^< \)

\( H_1^< = H_1^< (z, \zeta, M_{\pi\pi}) \)

(\( \zeta \sim z_1/(z_1 + z_2) \))
2-hadron fragmentation

spin-dependent 2-hadron production:

(Unpolarized beam, Transversely pol. target)

$$\sigma_{UT} \sim \sin(\phi_{R\perp} + \phi_S) \sum e_q^2 h_1^q H_{1}^\perp$$

$$H_1^\perp = H_1^\perp(z, \zeta, M_{\pi\pi}^2)$$

$$\left(\zeta \sim z_1/(z_1 + z_2)\right)$$

😊 only relative momentum of hadron pair relevant

⇒ integration over transverse momentum of hadron pair simplifies factorization and $Q^2$ evolution
2-hadron fragmentation

spin-dependent 2-hadron production:

(Unpolarized beam, Transversely pol. target)

\[
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\]

\[
H_1^< = H_1^<(z, \zeta, M_{\pi\pi}^2)
\]

\((\zeta \sim z_1/(z_1 + z_2))\)

only relative momentum of hadron pair relevant

\(\Rightarrow\) integration over transverse momentum of hadron pair simplifies factorization and \(Q^2\) evolution

however, cross section becomes quite complex (differential in 9 variables)
Model for two-pion fragmentation

\[ A_{UT} \sim \sin(\phi_{R\perp} + \phi_S) \sin \theta h_1 H_1^{\triangleleft} \]

Expansion of \( H_1^{\triangleleft} \) in Legendre moments:

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

about \( H_1^{\triangleleft, sp} \):

Jaffe et al. [hep-ph/9709322]:

\[ H_1^{\triangleleft, sp}(z, M_{\pi\pi}^2) - \sin \delta_0 \sin \delta_1 \sin(\delta_0 - \delta_1) H_1^{\triangleleft, sp'}(z) \]

\[ \delta_0 (\delta_1) \rightarrow \text{S(P)-wave phase shifts} \]

\[ = \mathcal{P}(M_{\pi\pi}^2) H_1^{\triangleleft, sp'}(z) \]

\( \Rightarrow A_{UT} \) might depend strongly on \( M_{\pi\pi} \)
HERMES results (complete data)

A. Airapetian et al., JHEP 0806:017, 2008

G. Schnell - DESY Zeuthen
HERMES results (complete data)

first evidence for T-odd 2-hadron fragmentation function in semi-inclusive DIS!

A. Airapetian et al., JHEP 0806:017, 2008
HERMES results (complete data)

- First evidence for T-odd 2-hadron fragmentation function in semi-inclusive DIS!
- Invariant-mass dependence rules out Jaffe model

A. Airapetian et al., JHEP 0806:017, 2008
Collins fragmentation function

\[ \sum \int \mathrm{d}z H_{\perp, h} = \delta \text{at} \]

quark

\[ P_{h \perp} \]

\[ \pi \]

\[ P_{h \perp} \]

\[ \pi \]
Collins fragmentation function

\[ \sum_{h} \int dz H_{\perp, h} = 0 \]

provides a correlation between spin of quark and transverse momentum of produced hadron.
Collins fragmentation function

- Provides a correlation between spin of quark and transverse momentum of produced hadron.
- Example of transverse-momentum-dependent ("unintegrated") parton distribution/fragmentation functions.
Unintegrated PDFs

- Nucleon with transverse or longitudinal spin
- Parton with transverse or longitudinal spin
- Parton transverse momentum

\[ f_{1T} = \]

\[ h_{1}^{\perp} = \]

\[ g_{1T} = \]

\[ h_{1L}^{\perp} = \]

\[ h_{1T}^{\perp} = \]

Courtesy of A. Bacchetta
G. Schnell - DESY Zeuthen

HEDT - 2nd anniversary - July 7th, 2009
1-hadron production (ep→ehX)

\[
d\sigma = d\sigma_{UU}^0 + \cos 2\phi d\sigma_{UU}^1 + \frac{1}{Q} \cos \phi d\sigma_{UU}^2 + \lambda_1 \frac{1}{Q} \sin \phi d\sigma_{LU}^3 \\
+ S_L \left\{ \sin 2\phi d\sigma_{UL}^4 + \frac{1}{Q} \sin \phi d\sigma_{UL}^5 + \lambda_2 \left[ d\sigma_{LL}^6 + \frac{1}{Q} \cos \phi d\sigma_{LL}^7 \right] \right\} \\
+ S_T \left\{ \sin(\phi - \phi_S) d\sigma_{UT}^8 + \sin(\phi + \phi_S) d\sigma_{UT}^9 + \sin(3\phi - \phi_S) d\sigma_{UT}^{10} \frac{1}{Q} \\
+ \frac{1}{Q} \left( \sin(2\phi - \phi_S) d\sigma_{UT}^{11} + \sin \phi_S d\sigma_{UT}^{12} \right) \\
+ \lambda_3 \left[ \cos(\phi - \phi_S) d\sigma_{LT}^{13} + \frac{1}{Q} \left( \cos \phi_S d\sigma_{LT}^{14} + \cos(2\phi - \phi_S) d\sigma_{LT}^{15} \right) \right] \right\}
\]

Bacchetta et al., JHEP 0702 (2007) 093
1-hadron production (ep→ehX)

\[
d\sigma = d\sigma^0_{UU} + \cos 2\phi d\sigma^1_{UU} + \frac{1}{Q} \cos \phi d\sigma^2_{UU} + \lambda_e \frac{1}{Q} \sin \phi d\sigma^3_{LU} \\
+ S_L \left\{ \sin 2\phi d\sigma^4_{UL} + \frac{1}{Q} \sin \phi d\sigma^5_{UL} + \lambda_e \left[ d\sigma^6_{LL} + \frac{1}{Q} \cos \phi d\sigma^7_{LL} \right] \right\} \\
+ S_T \left\{ \sin(\phi - \phi_S) d\sigma^8_{UT} + \sin(\phi + \phi_S) d\sigma^9_{UT} + \sin(3\phi - \phi_S) d\sigma^{10}_{UT} \frac{1}{Q} \cos(\phi - \phi_S) \right\}
\]

Collins Effect:
sensitive to quark transverse spin
1-hadron production (ep→ehX)

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

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

\[
+ S_T \left\{ \sin(\phi - \phi_S) d\sigma_{UT}^8 + \sin(\phi + \phi_S) d\sigma_{UT}^9 + \sin(3\phi - \phi_S) d\sigma_{UT}^{10} \right. \\
\left. + \cos(2\phi - \phi_S) d\sigma_{LT}^{15} \right\}
\]

**Sivers Effect:**
- correlates hadron’s transverse momentum with nucleon spin
- requires orbital angular momentum

Bacchetta et al., JHEP 0702 (2007) 093
1-hadron production (ep → ehX)

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

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

\[ + S_T \left\{ \sin(\phi - \phi_S) \, d\sigma^8_{UT} + \sin(\phi + \phi_S) \, d\sigma^9_{UT} + \sin(3\phi - \phi_S) \, d\sigma^{10}_{UT} \frac{1}{Q} \right. \]

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

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

Bacchetta et al., JHEP 0702 (2007) 093
The HERMES Collins amplitudes

\[ 2\langle \sin(\phi + \phi_s) \rangle_{UT} = -\frac{\sum_q e^2 q h_1^q(x, p_T^2) \otimes H_1^\perp q(z, K_T^2)}{\sum_q e^2 q f_1^q(x) D_1^q(z)} \]

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The HERMES Collins amplitudes

\[ 2\langle \sin(\phi + \phi_S) \rangle_{UT} = -\frac{\sum e_q^2 h_1^q(x, p_T^2) \otimes H_1^\perp q(z, K_T^2)}{\sum e_q^2 f_1^q(x) D_1^q(z)} \]

non-zero Collins effect observed!
The HERMES Collins amplitudes

\[ 2\langle \sin (\phi + \phi_S) \rangle_{UT} = -\frac{\sum_q e_q^2 h_1^q(x, p_T^2) \otimes H_1^{\perp q}(z, K_T^2)}{\sum_q e_q^2 f_1^q(x) D_1^q(z)} \]

- ✔ non-zero Collins effect observed!
- ✔ both Collins FF and transversity sizeable

HERMES PRELIMINARY 2002-2005
lepton beam asymmetry, Collins amplitudes
8.1% scale uncertainty
The HERMES Collins amplitudes

$$2 \langle \sin (\phi + \phi_S) \rangle_{UT} = - \frac{\sum_q e_q^2 h_1^q(x, p_T^2) \otimes H_1^\perp, q(z, K_T^2)}{\sum_q e_q^2 f_1^q(x) D_1^q(z)}$$

- published results confirmed with much higher statistical precision
- overall scale uncertainty of 8.1%
- positive for $\pi^+$ and negative for $\pi^-$ as maybe expected ($\delta u \equiv h_1^u > 0$, $\delta d \equiv h_1^d < 0$)
- unexpected large $\pi^-$ asymmetry
  ⇒ role of disfavored Collins FF
  most likely: $H_1^{\perp, disf} \approx -H_1^{\perp, fav}$
- isospin symmetry among charged and neutral pions fulfilled

[Published results: A. Airapetian et al, Phys. Rev. Lett. 94 (2005) 012002]
First glimpse at transversity

Combined analysis of data from:

- HERMES
- COMPASS
- BELLE
First glimpse at transversity

Anselmino et al., PRD75 (2007)

$Q^2 = 2.5 \text{ GeV}^2$

$\Delta T u(x)$

$\Delta T d(x)$

$\Delta T s(x)$

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Sivers amplitudes for pions

[7.3% scale uncertainty]

$2 \langle \sin(\phi_{FS}) \rangle_{\text{UT}}$

[π⁺]

[π⁰]

[π⁻]

[A. Airapetian et al., arXiv:0906.3918]
Sivers amplitudes for pions

[7.3% scale uncertainty]

[A. Airapetian et al., arXiv:0906.3918]

- Clear observation of T-odd Sivers effect in SIDIS!
- u-quark dominance suggests sizeable u-quark orbital motion
“Chromodynamic Lensing”

approach by M. Burkardt:

spatial distortion of q-distribution
(obtained using anom. magn. moments & impact parameter dependent PDFs)

\[ u_X(x, b_\perp) \]
\[ d_X(x, b_\perp) \]
“Chromodynamic Lensing”

approach by M. Burkardt:

spatial distortion of q-distribution
(obtained using anom. magn. moments & impact parameter dependent PDFs)

+ attractive QCD potential
(gluon exchange)

⇒ transverse asymmetries

[hep-ph/0309269]
“Chromodynamic Lensing”

approach by M. Burkardt:

spatial distortion of q-distribution
(obtained using anom. magn. moments
& impact parameter dependent PDFs)

+ attractive QCD potential
(gluon exchange)

⇒ transverse asymmetries

\[ L^u_z > 0 \]
Sivers amplitudes for pions

\[ 2\langle \sin (\phi - \phi_S) \rangle_{UT} = -\frac{\sum_q e_q^2 f_{1T}^+, q(x, p_T^2) \otimes D_1^q(z, K_T^2)}{\sum_q e_q^2 f_1^+(x) D_1^q(z)} \]

7.3% scale uncertainty

\[ \sum x, p_T, z, f_{1T}^+, u \rightarrow \pi^+ \]

[\text{A. Airapetian et al., arXiv:0906.3918}]
Sivers amplitudes for pions

\[
2\langle \sin (\phi - \phi_S) \rangle_{UT} = -\frac{\sum_q e_q^2 f_{1T}^q(x, p_T^2) \otimes D_1^q(z, K_T^2)}{\sum_q e_q^2 f_1^q(x) D_1^q(z)}
\]

\[\pi^+\] dominated by u-quark scattering:

\[\simeq - \frac{f_{1T,u}^1(x, p_T^2) \otimes D_{1\to\pi^+}^u(z, K_T^2)}{f_1^u(x) D_{1\to\pi^+}^u(z)}\]

监督检查 u-quark Sivers DF < 0

[A. Airapetian et al., arXiv:0906.3918]
Sivers amplitudes for pions

\[ 2\langle \sin (\phi - \phi_S) \rangle_{UT} = -\frac{\sum_q e_q^2 f_{1T}^q(x, p_T^2) \otimes D_1^q(z, K_T^2)}{\sum_q e_q^2 f_1^q(x) D_1^q(z)} \]

\[ \pi^+ \text{ dominated by } u\text{-quark scattering:} \]

\[ \approx -\frac{f_{1T}^u(x, p_T^2) \otimes D_1^{u\rightarrow\pi^+}(z, K_T^2)}{f_1^u(x) D_1^{u\rightarrow\pi^+}(z)} \]

\[ u\text{-quark Sivers DF } < 0 \]

\[ d\text{-quark Sivers DF } > 0 \]

(cancellation for \( \pi^- \))

[A. Airapetian et al., arXiv:0906.3918]
Sivers amplitudes for kaons

2 \langle \sin(\phi_S - \Phi) \rangle \mu_T

7.3% scale uncertainty

[A. Airapetian et al., arXiv:0906.3918]
Sivers amplitudes for kaons

![Graph showing Sivers amplitudes for K^+ and K^- kaons with large and positive values.]

7.3% scale uncertainty

[large & positive]

[A. Airapetian et al., arXiv:0906.3918]
Sivers amplitudes for kaons

[2 \langle \sin(\phi_{\perp}/x) \rangle]_{UT}

7.3% scale uncertainty

large & positive

Slightly positive

[A. Airapetian et al., arXiv:0906.3918]
The "Kaon Challenge"

\[ \frac{\pi^+}{K^+} \text{ production dominated by scattering off } u\text{-quarks: } \approx - \frac{f_{1T,u}^T(x, p_T^2) \otimes D_{1u \rightarrow \pi^+/K^+}(z, K_T^2) }{f_u^u(x) D_{1u \rightarrow \pi^+/K^+}(z)} \]
The “Kaon Challenge”

\[ \frac{\pi^+}{K^+} \] production dominated by scattering off u-quarks: 

\[ \simeq - \frac{f_{1T,u}(x, p_T^2) \otimes D_1^{u\rightarrow \pi^+/K^+}(z, K_T^2)}{f_1^u(x) D_1^{u\rightarrow \pi^+/K^+}(z)} \]
The “Kaon Challenge”

$\pi^+/K^+$ production dominated by scattering off $u$-quarks: $\simeq - \frac{f_{1T}^u(x, p_T^2) \otimes D_1^{u \rightarrow \pi^+/K^+}(z, K_T^2)}{f_1^u(x) D_1^{u \rightarrow \pi^+/K^+}(z)}$

$K^+ = |u\bar{s}\rangle$ & $\pi^+ = |u\bar{d}\rangle$ \textup{non-trivial role of sea quarks}
The “Kaon Challenge”

$\pi^+ / K^+$ production dominated by scattering off $u$-quarks: $\sim - f_{1T}^{u}(x, p_T^2) \otimes D_1^{u \rightarrow \pi^+ / K^+}(z, K_T^2)$

- $K^+ = |u\bar{s}\rangle$ & $\pi^+ = |u\bar{d}\rangle$ → non-trivial role of sea quarks
- convolution integral in numerator depends on $K_T$ dependence of FFs
The “Kaon Challenge”

$\pi^+/K^+$ production dominated by scattering off $u$-quarks: $\approx - \frac{f_{1T}^{u}(x, p_T^2) \otimes D_1^{u\rightarrow\pi^+/K^+}(z, K_T^2)}{f_1^u(x) \ D_1^{u\rightarrow\pi^+/K^+}(z)}$

- $K^+ = |u\bar{s}\rangle$ & $\pi^+ = |u\bar{d}\rangle$ $\Rightarrow$ non-trivial role of sea quarks
- convolution integral in numerator depends on $K_T$ dependence of FFs
- difference in dependences on kinematics integrated over
Exclusive Reactions
Probing GPDs in Exclusive

Generalized Parton Distributions

Form factors
Transverse distribution of quarks in space coordinates
\[ \int dx H^q(x, \xi, t) = F_1^q(t) \]
\[ \int dx E^q(x, \xi, t) = F_2^q(t) \]
\[ H^q(x, \xi = 0, t = 0) = q(x) \]
\[ \tilde{H}^q(x, \xi = 0, t = 0) = \Delta q(x) \]

Parton Distribution Functions
Quark longitudinal momentum fraction distribution in the nucleon

GPDs
Correlation between transverse position and longitudinal momentum fraction of quark in the nucleon

<table>
<thead>
<tr>
<th></th>
<th>unpolarized</th>
<th>polarized</th>
</tr>
</thead>
<tbody>
<tr>
<td>no nucleon hel. flip</td>
<td>( H )</td>
<td>( \tilde{H} )</td>
</tr>
<tr>
<td>nucleon hel. flip</td>
<td>( E )</td>
<td>( \tilde{E} )</td>
</tr>
</tbody>
</table>

(\(+ 4 \) more chiral-odd functions)
Probing GPDs in Exclusive

Ji relation (1996)

\[ J_q = \lim_{t \to 0} \int_{-1}^{1} dx x (H_q(x, \xi, t) + E_q(x, \xi, t)) \]

Moments of certain GPDs relate directly to the total angular

<table>
<thead>
<tr>
<th>Form factors</th>
<th>Transverse distribution of quarks in space coordinates</th>
<th>Quark longitudinal momentum fraction distribution in the nucleon</th>
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<td>unpolarized</td>
<td>$H_1(x)$</td>
<td>$H_1(x, \xi = 0, t = 0) = q(x)$</td>
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<td>$\tilde{H}_1(x)$</td>
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<td>$E$</td>
<td>$\tilde{E}$</td>
<td></td>
</tr>
</tbody>
</table>

$J_1$ relation (1996)

\[ J_1 = \lim_{t \to 0} \int_{-1}^{1} dx x (H_1(x, \xi, t) + E_1(x, \xi, t)) \]

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HEDT - 2nd anniversary - July 7th, 2009
ρ^0 SDMEs from HERMES

[A. Airapetian et al., arXiv:0901.0701]

target-polarization independent SDMEs
$\rho^0$ SDMEs from HERMES

[A. Airapetian et al., arXiv:0901.0701]

target-polarization independent SDMEs

helicity non-flip much larger than helicity-flip and double helicity-flip

G. Schnell - DESY Zeuthen
Finally, we can compare the measured SDMEs from HERMES with the predicted values. The agreement is very good, with the SDME values from HERMES lying within the error bars of the predictions.

In summary, we have shown that the SDME values from HERMES are consistent with the predictions of the QCD model, and that the target-polarization independent SDMEs can be accurately measured using polarized electron-proton collisions. This provides a powerful tool for probing the structure of the nucleon and testing the predictions of QCD.
ρ⁰ SDMEs from HERMES

[A. Airapetian et al., arXiv:0901.0701]

target-polarization independent SDMEs

G. Schnell - DESY Zeuthen

ρ⁰ SDMEs from HERMES

[A. Airapetian et al., arXiv:0906.5160]

scaled SDME

proton

deuteron

“transverse” SDMEs

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$\rho^0$ SDMEs from HERMES

[A. Airapetian et al., arXiv:0906.5160]

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HEDT - 2nd anniversary - July 7th, 2009
$\rho^0$ SDMEs from HERMES

[\textit{A. Airapetian et al., arXiv:0906.5160}]

\begin{center}
\begin{tikzpicture}
\path (0,0) -- (5,0) node[midway,above]{$e$} -- (5,5) node[midway,above]{$e'$} -- (0,5) node[midway,above]{$\gamma^*$} -- cycle;
\draw[->] (5,5) -- (5,4) node[midway,above]{$S_T$} -- (5,0) node[midway,above]{$\rho^0$};
\draw[->] (5,5) -- (4.5,4.5) node[midway,above]{$\phi_S$} -- (5,0) node[midway,above]{$\phi$};
\end{tikzpicture}
\end{center}

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HEDT - 2nd anniversary - July 7th, 2009
\( \rho^0 \) SDMEs from HERMES

[A. Airapetian et al., arXiv:0906.5160]

G. Schnell - DESY Zeuthen

HEDT - 2nd anniversary - July 7th, 2009
DVCS/Bethe-Heitler interference

\[
\frac{d^4 \sigma}{dQ^2 \, dx_B \, dt \, d\phi} = \frac{y^2}{32(2\pi)^4} \sqrt{1 + \frac{4M^2x_B^2}{Q^2}} \left( |T_{DVCS}|^2 + |T_{BH}|^2 + \mathcal{I} \right)
\]

G. Schnell - DESY Zeuthen
Azimuthal asymmetries in DVCS

Cross section:
\[
\sigma(\phi, \phi_S, P_B, C_B, P_T) = \sigma_{UU}(\phi) \cdot [1 + P_B A_{LU}^{DVCS}(\phi) + C_B P_B A_{LU}^T(\phi) + C_B A_C(\phi) \\
+ P_T A_{UT}^{DVCS}(\phi, \phi_S) + C_B P_T A_{UT}^T(\phi, \phi_S)]
\]

Azimuthal asymmetries:

- **Beam-charge asymmetry** \(A_C(\Phi)\):
  \[
d\sigma(e^+, \phi) - d\sigma(e^-, \phi) \propto \text{Re}[F_1 \mathcal{H}] \cdot \cos \phi
\]

- **Beam-helicity asymmetry** \(A_{LU}^I(\Phi)\):
  \[
d\sigma(e^-, \phi) - d\sigma(e^-, \phi) \propto \text{Im}[F_1 \mathcal{H}] \cdot \sin \phi
\]

- **Transverse target-spin asymmetry** \(A_{UT}^I(\Phi)\):
  \[
d\sigma(\phi, \phi_S) - d\sigma(\phi, \phi_S + \pi) \propto \text{Im}[F_2 \mathcal{H} - F_1 \mathcal{E}] \cdot \sin(\phi - \phi_S) \cos \phi \\
+ \text{Im}[F_2 \tilde{\mathcal{H}} - F_1 \xi \tilde{\mathcal{E}}] \cdot \cos(\phi - \phi_S) \sin \phi
\]

\((F_1, F_2\text{ are the Dirac and Pauli form factors})\)
\((\mathcal{H}, \mathcal{E} \ldots \text{ Compton form factors involving GPDs } H, E, \ldots)\)
Beam-charge asymmetry

\begin{align*}
\text{constant term} & \propto -A_C^{\cos \phi} \\
& \propto \text{Re}[F_1 \mathcal{H}] \\
\text{[higher twist]} & \\
\text{[gluon leading twist]} & \\
\text{Resonant fraction:} & \\
ep & \rightarrow e\Delta^+\gamma
\end{align*}

GPD model: “VGG”  \cite{vvg}

All data 1996-2005
Beam-spin asymmetry

HERMES PRELIMINARY
\( e^+ p \rightarrow e^+ p + \gamma \)

3.4 \% scale uncertainty
Accep & smear \rightarrow sys error

\( A_{LU,I} \)

\( A_{LU,I} \)

\( A_{LU,I} \)

Resonant fraction:
\( e p \rightarrow e \Delta^+ \gamma \)

GPD model: “VGG”

\( \propto \text{Im}[F_1 \mathcal{H}] \)

[higher twist]

\( B_x \)

3.4 \% scale uncertainty
Accep & smear \rightarrow sys error

\( A_{LU,I} \)

\( A_{LU,I} \)

\( A_{LU,I} \)

Res. frac

overall

\( -t[\text{GeV}^2] \)

\( x_B \)

\( Q^2[\text{GeV}^2] \)

\( t[\text{GeV}^2] \)

\( Q^2[\text{GeV}^2] \)

\( x_B \)

\( -t[\text{GeV}^2] \)

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Transverse target-spin asymmetry

A. Airapetian et al., JHEP 0806:066, 2008


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Transverse target-spin asymmetry

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\[ \alpha = A_{UT} \sin(\phi - \phi_S) \cos \phi \]

\[ \propto \text{Im}[F_2 \mathcal{H} - F_1 \mathcal{E}] \]

\[ \propto \text{Im}[F_2 \tilde{\mathcal{H}} - F_1 \xi \tilde{\mathcal{E}}] \]

GPD model: “VGG”  

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HEDT - 2nd anniversary - July 7th, 2009
Outlook
HERMES detector (2006/07)

detection of recoiling proton

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DVCS event selection

Missing $\phi$: $\Delta \phi = \phi_{\text{meas}} - \phi_{\text{calc}}$

Missing $p$: $\Delta p = p_{\text{meas}} - p_{\text{calc}}$

Missing Mass ($\approx M_P^2$):

$M_X^2 = (p + p_{\gamma^*} - p_{\gamma})^2$

Hermes 2007 data

Traditional DVCS analysis ($E_\gamma > 5$ GeV)

- $|\Delta p| < 1$ GeV/c
- $|\Delta p| > 1$ GeV/c

Counts

Hermes 2007 data

DVCS candidates

Measured with RD

Inferred from forward spectrometer

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Exclusive VM event selection

**HERMES 2007 data**

- $|\Delta p| < 0.8\text{GeV/c}$
- Rho candidates

**HERMES Data 2007**

- Traditional $\rho_0$ analysis
- Recoil momentum cut
- Proton in Recoil acceptance

**HERMES Data 2007**

- Traditional $\omega$ analysis
- Recoil momentum cut

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