The spin-momentum structure of the nucleon

--highlights from the hermes collaboration--
20 years ago ...
20 years ago ...

- first DIS events at H1 and Zeus
20 years ago ... 

- first DIS events at H1 and Zeus
- a tiny and asymmetric spin-flip amplitude in synchrotron radiation opens door for polarized DIS at HERA
20 years ago ...

- first DIS events at H1 and Zeus
- a tiny and asymmetric spin-flip amplitude in synchrotron radiation opens door for polarized DIS at HERA
- demonstration of lepton polarization at HERA under realistic running conditions
October 1992, PRC:

“Recommend the DESY directorate to approve HERMES”
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9 October 1992

(conditional) approval of the HERMES experiment
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(conditional) approval of the HERMES experiment

November 1992, Scientific Council

“Parallel running of ep and HERMES?”

June 15, 1993

full approval of HERMES

March 31, 1995

HERMES interlock set
The HERMES experiment

pure gas targets:

- internal to lepton ring
- unpolarized (\(^1\)H ... Xe)
- longitudinally polarized: \(^1\)H, \(^2\)H
- transversely polarized: \(^1\)H
The HERA-I harvest

\[ \frac{1}{2} = \frac{1}{2} \Delta \Sigma \]

\[ + \Delta G \]

\[ + L_q + L_g \]

quark spin

gluon spin

orbital angular momentum
The HERA-I harvest

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

Quark spin

Gluon spin

Orbital angular momentum

Inclusive DIS from longitudinally polarized Deuterium target:

\[ \Delta \Sigma = 0.330 \pm 0.025 \text{ (exp.)} \pm 0.011 \text{ (theory)} \pm 0.028 \text{ (evol.)} \]

PRD 75 (2007) 012007
The HERA-I harvest

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- High-\( p_T \) hadrons at HERMES:

\[ \frac{\Delta G}{G} = 0.071 \pm 0.034^{(\text{stat})} \pm 0.010 \] (sys-exp) \[ +0.127 \] -0.105 (sys-model)

**PRD 75 (2007) 012007**

**JHEP 1008 (2010) 130**
The HERA-I harvest

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\[ + L_q + L_g \]

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... during the same time

- HERMES measures non-vanishing $A_{UL}$ in semi-inclusive DIS [1]
- naive-T-odd - not expected from collinear pQCD
- transversity?
- disguised Sivers effect → orbital angular momentum?

... during the same time

- HERMES measures non-vanishing $A_{UL}$ in semi-inclusive DIS [1]
- naive-T-odd - not expected from collinear pQCD
- transversity?
- disguised Sivers effect $\rightarrow$ orbital angular momentum?
- Ji (1997): relates moments of GPDs*) to total angular momentum
- accessible in DVCS
- HERMES measures $A_{LU}$ in DVCS [2]


*) GPDs=generalized parton distributions
HERA II: transverse-target program
HERA II: transverse-target program

- confirm existence of Sivers effect -> asymmetry in transverse-momentum distribution of partons in nucleon

[Airapetian et al., PRL 103 (2009) 152002]

\[ \sin(\phi_s) \]

\[ \begin{align*}
\pi^+ & \quad 0.1 \\
\pi^0 & \quad 0.1 \\
\pi^- & \quad 0.1 \\
\end{align*} \]

\[ 2 \sin(\phi_s) \]

\[ x, z, P_{h\perp} \text{[GeV]} \]

HERA II: transverse-target program

- confirm existence of Sivers effect -> asymmetry in transverse-momentum distribution of partons in nucleon
- demonstrate spin-dependence in fragmentation (Collins effect, 2-hadron fragmentation)
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- first attempts to constrain (in very model-dependent way) angular momentum of quarks via DVCS

![Diagram](image)
HERA II: transverse-target program

- confirm existence of Sivers effect -> asymmetry in transverse-momentum distribution of partons in nucleon
- demonstrate spin-dependence in fragmentation (Collins effect, 2-hadron fragmentation)
- first attempts to constrain (in very model-dependent way) angular momentum of quarks via DVCS
- add one more piece to the structure-function landscape: $g_2$
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
\[
\frac{d^2\sigma(s, S)}{dx \, dQ^2} = \frac{2\pi\alpha^2 y^2}{Q^6} L_{\mu\nu}(s) W^{\mu\nu}(S)
\]

**Lepton Tensor**

**Hadron Tensor**

**Structure Functions**

\[
\frac{d^3\sigma}{dx dy d\phi} \propto \frac{y}{2} F_1(x, Q^2) + \frac{1 - y - \gamma^2 y^2 / 4}{2xy} F_2(x, Q^2) - S_i S_N \cos \alpha \left[ \left( 1 - \frac{y}{2} - \frac{\gamma^2 y^2}{4} \right) g_1(x, Q^2) - \frac{\gamma^2 y^2}{2} g_2(x, Q^2) \right] + S_i S_N \sin \alpha \cos \phi \gamma \sqrt{1 - y - \frac{\gamma^2 y^2}{4}} \left( \frac{y}{2} g_1(x, Q^2) + g_2(x, Q^2) \right)
\]
Results on $A_2$ and $xg_2$

$\int_{0.023}^{0.9} g_2(x, Q^2) \, dx = 0.006 \pm 0.024_{\text{stat}} \pm 0.017_{\text{syst}}$

$d_2(Q^2) \equiv 3 \int_{0}^{1} x^2 \bar{g}_2(x, Q^2) \, dx = 0.0148 \pm 0.0096_{\text{stat}} \pm 0.0048_{\text{syst}}$

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... going 3D
Spin-Momentum Structure of the Nucleon

\[
\frac{1}{2} \text{Tr} \left[ (\gamma^+ + \lambda \gamma^5) \Phi \right] = \frac{1}{2} \left[ f_1 + S^i \epsilon^{ij} k^j \frac{1}{m} f_{1T} + \lambda \Lambda g_1 + \lambda S^i k^i \frac{1}{m} g_{1T} \right]
\]

\[
\frac{1}{2} \text{Tr} \left[ (\gamma^+ - s^j i \sigma^{+j} \gamma_5) \Phi \right] = \frac{1}{2} \left[ f_1 + S^i \epsilon^{ij} k^j \frac{1}{m} f_{1T} + s^i \epsilon^{ij} k^j \frac{1}{m} h^\perp_1 + s^i S^i h_1 + s^i (2k^i k^j - k^2 \delta^{ij}) S^j \frac{1}{2m^2} h_{1T} + \Lambda s^i k^i \frac{1}{m} h_{1L} \right]
\]

- Each TMD describes a particular spin-momentum correlation
- Functions in black survive integration over transverse momentum
- Functions in green box are chirally odd
- Functions in red are naive T-odd

---

**Table:**

<table>
<thead>
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quark pol.
Spin-Momentum Structure of the Nucleon

\[ \frac{1}{2} \text{Tr} \left[ (\gamma^+ + \lambda \gamma^+ \gamma_5) \Phi \right] = \frac{1}{2} \left[ f_1 + S^i \epsilon^{ij} k^j \frac{1}{m} f_{1T}^\perp + \lambda \Lambda g_1 + \lambda S^i k^i \frac{1}{m} g_{1T} \right] \]

\[ \frac{1}{2} \text{Tr} \left[ (\gamma^+ - s^j i \sigma^{+j} \gamma_5) \Phi \right] = \frac{1}{2} \left[ f_1 + S^i \epsilon^{ij} k^j \frac{1}{m} f_{1T}^\perp + s^i \epsilon^{ij} k^j \frac{1}{m} h_1^\perp + s^i S^i h_1 + s^i (2k^i k^j - k^2 \delta^{ij}) S^j \frac{1}{2m^2} h_{1T}^\perp + \Lambda s^i k^i \frac{1}{m} h_{1L}^\perp \right] \]

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- Each TMD describes a particular spin-momentum correlation.
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**Boer-Mulders**

**Sivers**

**wurm-gear**

**transversity**

**helicity**

**quark pol.**
Probabilistic interpretation

Proton goes out of the screen / photon goes into the screen

\[ f_1 = \]

\[ g_1 = \]

\[ h_1 = \]

[nucleon with transverse or longitudinal spin]

[parton transverse or longitudinal spin]

[parton transverse momentum]

[courtesy of A. Bacchetta, Pavia]
Probabilistic interpretation

Proton goes out of the screen/
photon goes into the screen

\[
f_1 = \quad \bullet \quad \text{nucleon with transverse or longitudinal spin}
\]

\[
g_1 = \quad \bullet \quad - \quad \text{parton with transverse or longitudinal spin}
\]

\[
h_1 = \quad \bullet \quad - \quad \text{parton transverse momentum}
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[courtesy of A. Bacchetta, Pavia]
Probabilistic interpretation

Proton goes out of the screen/
photon goes into the screen

\[ f_1 = \]

\[ g_1 = \]

\[ h_1 = \]

\[ f_{1T} = \]

correlates transverse momentum & spin

nucleon with transverse or longitudinal spin

parton with transverse or longitudinal spin

parton transverse momentum

[courtesy of A. Bacchetta, Pavia]
\[ f_{1T}^\perp = \text{Diagram} - \text{Diagram} \]

Sivers function
\[ f_{1T}^{\perp} = - \] 

- Sivers function
correlates transverse momentum of quarks with transv. mom. of hadron
candidate for large (30-50\%) asymmetries in \( p^+ p \rightarrow h X \)
Sivers function

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- candidate for large (30-50%) asymmetries in $p^+p\to hX$
- HERMES: u-quark Sivers$<0$ and d-quark Sivers$>0$

$\frac{1}{T}$

[courtesy of A. Bacchetta]
Sivers function

- correlates transverse momentum of quarks with transv. mom. of hadron
- candidate for large (30-50%) asymmetries in $p^+p \rightarrow hX$
- HERMES: u-quark Sivers<0 and d-quark Sivers>0
- (naive) T-odd structure: $S_N \cdot (p_\perp \times P_N)$ -- requires ISI/FSI
- leads to peculiar calculable universality breaking (DIS vs. Drell-Yan)

$$f_{1T}^\perp = \rightarrow \rightarrow$$

[courtesy of A. Bacchetta]
Process dependence

simple QED example

\[ \gamma^* \rightarrow + \rightarrow - \]

DIS: attractive

\[ \gamma^* \rightarrow - \rightarrow + \]

Drell-Yan: repulsive
Process dependence

simple QED example

DIS: attractive

Drell-Yan: repulsive

add color: QCD

result: $\text{Sivers}_{\text{DIS}} = - \text{Sivers}_{\text{DY}}$
Process dependence

simple QED example

add color: QCD

rigorous QCD prediction not tested!! - need Drell-Yan data

DIS: attractive

Drell-Yan: repulsive

result: $\text{Sivers}_{\text{DIS}} = - \text{Sivers}_{\text{DY}}$
naively T-odd distributions
“Wilson-line physics”
naively T-odd distributions
“Wilson-line physics”
Unpolarized Drell-Yan

\[
\left( \frac{1}{\sigma} \right) \left( \frac{d\sigma}{d\Omega} \right) = \left[ \frac{3}{4\pi} \right] \left[ 1 + \lambda \cos^2 \theta + \mu \sin 2\theta \cos \phi + \frac{\nu}{2} \sin^2 \theta \cos 2\phi \right]
\]

\[
1 - \lambda - 2\nu = 0
\]

Large deviations from Lam-Tung relation observed in DY
[NA10 ('86/'88) & E615 ('89)]
Unpolarized Drell-Yan

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Large deviations from Lam-Tung relation observed in DY
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\[ 1 - \lambda - 2\nu = 0 \]

- failure of collinear pQCD
Unpolarized Drell-Yan

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\]

Large deviations from Lam-Tung relation observed in DY
[NA10 ('86/'88) & E615 ('89)]

- failure of collinear pQCD
- possible source: Boer-Mulders effect
Sivers effect:
\[ f_{1T}^\perp = \mathbf{S}_N \cdot (\mathbf{p}_\perp \times \mathbf{p}_N) \]

Boer-Mulders effect:
\[ h_{1}^\perp = \mathbf{S}_q \cdot (\mathbf{p}_\perp \times \mathbf{p}_N) \]
Sivers effect:

\[ f_{1T}^{\perp} = S_N \cdot (p_\perp \times P_N) \]

Boer-Mulders effect:

\[ h_1^{\perp} = S_q \cdot (p_\perp \times P_N) \]

**spin-effect in unpolarized reactions**
Boer-Mulders effect

Sivers effect:

\[ f_{1T}^{\perp} = S_N \cdot (p_{\perp} \times P_N) \]

- spin-effect in unpolarized reactions

"QCD Sokolov-Ternov effect" - transverse polarization of "orbiting" quarks

Boer-Mulders effect:

\[ h_1^{\perp} = S_q \cdot (p_{\perp} \times P_N) \]
Boer-Mulders effect

Sivers effect:

$$f_{1T} = S_N \cdot (p_\perp \times P_N)$$

Boer-Mulders effect:

$$h_1 = S_q \cdot (p_\perp \times P_N)$$

- spin-effect in **unpolarized** reactions
- "QCD Sokolov-Ternov effect" - transverse polarization of "orbiting" quarks
- QCD: sign change for DIS vs. Drell-Yan
Boer-Mulders effect

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- spin-effect in \textit{unpolarized} reactions
- “QCD Sokolov-Ternov effect” - transverse polarization of “orbiting” quarks
- QCD: sign change for DIS vs. Drell-Yan
- up to now little data from DIS

⇒ HERMES with most comprehensive data set
Cross section without polarization

\[
\frac{d^5 \sigma}{dxdydzd\phi_h dP_{h\perp}^2} \propto \left( 1 + \frac{\gamma^2}{2x} \right) \left\{ F_{UU,T} + \epsilon F_{UU,L} \right\} \\
+ \sqrt{2\epsilon(1-\epsilon)} F_{UU}^{\cos \phi_h} \cos \phi_h + \epsilon F_{UU}^{\cos 2\phi_h} \cos 2\phi_h
\]

\[
\gamma = \frac{2Mx}{Q} \\
\epsilon = \frac{1 - y - \frac{1}{4} \gamma^2 y^2}{1 - y + \frac{1}{2} y^2 + \frac{1}{4} \gamma^2 y^2}
\]

[see, e.g., Bacchetta et al., JHEP 0702 (2007) 093]
Cross section without polarization

\[
\frac{d^5 \sigma}{dx dy dz d\phi_h dP_{h\perp}^2} \propto \left(1 + \frac{\gamma^2}{2x}\right) \left\{ F_{UU,T} + \varepsilon F_{UU,L} + \sqrt{2\varepsilon(1 - \varepsilon)} F_{UU}^{\cos \phi_h} \cos \phi_h + \varepsilon F_{UU}^{\cos 2\phi_h} \cos 2\phi_h \right\}
\]

leading twist

\[F_{UU}^{\cos 2\phi_h} \propto C \left[ -\frac{2(\vec{P}_{h\perp} \cdot \vec{k}_T)(\vec{P}_{h\perp} \cdot \vec{p}_T) - \vec{k}_T \cdot \vec{p}_T}{MM_h} \right] h_1^\perp H_1^\perp\]

next to leading twist

\[F_{UU}^{\cos \phi_h} \propto \frac{2M}{Q} C \left[ -\frac{\vec{P}_{h\perp} \cdot \vec{p}_T}{M_h} x h_1^\perp H_1^\perp - \frac{\vec{P}_{h\perp} \cdot \vec{k}_T}{M} x f_1 D_1 + \ldots \right]\]

Interaction dependent terms neglected

BOER-MULDER'S EFFECT

CAHN EFFECT

[see, e.g., Bacchetta et al., JHEP 0702 (2007) 093]
Extraction of cosine modulations

- **Fully differential analysis** in \((x, y, z, P_{h\perp}, \phi)\)

- **Multi-dimensional unfolding**: correction for finite acceptance, QED radiation, kinematic smearing, detector resolution

\[
\begin{align*}
\text{probability that an event generated with a certain kinematics is measured with a different kinematics}\\
\begin{align*}
n_{\text{EXP}} &= S \cdot n_{\text{BORN}} + n_{\text{Bg}} \\
n_{\text{BORN}} &= S^{-1} \left[ n_{\text{EXP}} - n_{\text{Bg}} \right] \\
\end{align*}
\end{align*}
\]
Signs of Boer-Mulders

\[ 2 \cos(2\phi)_{uu} \]

\[ \pi^- \]
\[ \pi^+ \]

\[ e^+ p \rightarrow e^- \pi^+ X \]

\[ p_{h \perp} \text{ [GeV]} \]

\[ x \quad 0.4 \quad 0.6 \quad 0.8 \]
\[ y \quad 0.4 \quad 0.6 \]
\[ z \quad 0.2 \quad 0.4 \quad 0.6 \quad 0.8 \]


\[ [\text{Airapetian et al., arXiv:1204.4161}] \]

\[ \text{Cahn effect only does not describe data} \]

\[ \text{HERMES preliminary} \]

\[ \text{All contributions} \]
\[ \text{Boer-Mulders} \]
\[ \text{Cahn (twist 4)} \]
Signs of Boer-Mulders

- Cahn effect only does not describe data
- opposite sign for charged pions with larger magnitude for $\pi^-$ (as expected)
- $\rightarrow$ same-sign BM-function for valence quarks


[Airapetian et al., arXiv:1204.4161]
Cahn effect only does not describe data

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**Signs of Boer-Mulders**


[Airapetian et al., arXiv:1204.4161]

[M. Burkardt and B. Hannfious, PLB658 (2008) 130]

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20 years of DIS@HERA - June 19th, 2012
no dependence on hadron charge expected for Cahn effect

→ flavor dependence of transverse momentum

→ sign of Boer-Mulders in \( \cos\phi \) modulation
  (indeed, overall pattern resembles B-M modulations)

→ additional “genuine” twist-3?

[Airapetian et al., arXiv:1204.4161]
“Strange” results

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<td>f₁</td>
<td>U</td>
<td>h₁⁺</td>
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<tr>
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<td>h₁⁺L</td>
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intriguing behavior for kaons

[Airapetian et al., arXiv:1204.4161]
"strange" results

intriguing behavior for kaons

[Airapetian et al., arXiv:1204.4161]
“strange” results

intriguing behavior for kaons

different pattern for kaon Collins function? (cf. BRAHMS $A_N$ and SIDIS Collins)

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$2\langle \cos(\phi_R)_u \rangle_{uu}$

$2\langle \cos(2\phi_R)_u \rangle_{uu}$

$\langle Q^2 \rangle_{[GeV^2]}$

[Airapetian et al., arXiv:1204.4161]
Another 3D picture of the nucleon

Form factors:
transverse distribution of partons

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Another 3D picture of the nucleon

Form factors:
transverse distribution of partons

Parton distributions:
longitudinal momentum of partons
Another 3D picture of the nucleon

Form factors:
transverse distribution of partons

Nucleon Tomography
correlated info on transverse position and longitudinal momentum

Parton distributions:
longitudinal momentum of partons
Probing GPDs in Exclusive Reactions

\( \cdot \): average longitudinal momentum fraction of active quark (usually not observed & \( x \neq x_B \))

\( \xi \): half the longitudinal momentum change \( \approx x_B/(2-x_B) \)

\( b_y \)

\( b_x \)

\( z \)

\( xP_z \)

\( P_z \)

\( e \rightarrow e' \)

\( \gamma^* \rightarrow \gamma, \rho, \omega, \phi, \pi, \eta \)

\( p \rightarrow p' \)

\( t \)

Probing GPDs in Exclusive Reactions

\( \cdot \): average longitudinal momentum fraction of active quark (usually not observed & \( x \neq x_B \))

\( \xi \): half the longitudinal momentum change \( \approx x_B/(2-x_B) \)
Probing GPDs in Exclusive Reactions

Finally, the tensor GPDs for transversely polarized quarks. The density in Eq. (65). The first moment, charge density. Similarly, the tensor GPD in particular with respect to lattice QCD calculations it is [B\[05\]], as well as for transverse polarizations \[DH05\], as well as for transversely polarized quarks in a (longitudinally or transversely) polarized and tensor/transversity polarized quarks in the pion give an example, the corresponding

Similar expressions hold for the quadrupole distortion given by the last term in Eq. (65). The dipole-like distortions of the form \( \tilde{\mathcal{H}} \) is responsible for dipole-like distortions, as illustrated in Fig. 1. Probability density interpretation of the nucleon GPDs, according to Eqs. (54),(56). All

where the nucleon states are integrated density of quarks minus the density of anti-quark density for transverse polarization is given by

\[
\tilde{\mathcal{H}}(x, t, b, s) \propto \int_{-\infty}^{\infty} d\xi \left[ x^2 \rho_{1}(x, b, s) + x^2 \phi_{1}(x, b, s) \right] e^{-i b \cdot s} e^{i \xi \cdot P_z}
\]

and

\[
\tilde{\mathcal{E}}(x, t, b, s) \propto \int_{-\infty}^{\infty} d\xi \left[ x^2 \rho_{2}(x, b, s) + x^2 \phi_{2}(x, b, s) \right] e^{-i b \cdot s} e^{i \xi \cdot P_z}
\]

\( + \) 4 more chiral-odd functions

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Probing GPDs in Exclusive Reactions

\[
\int dx H^q(x, \xi, t) = F_1^q(t)
\]
\[
\int dx E^q(x, \xi, t) = F_2^q(t)
\]

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

\[ \int dx H^q(x, \xi, t) = F_1^q(t) \]
\[ \int dx E^q(x, \xi, t) = F_2^q(t) \]

\[ H^q(x, \xi = 0, t = 0) = q(x) \]
\[ \tilde{H}^q(x, \xi = 0, t = 0) = \Delta q(x) \]

\begin{table}
\begin{tabular}{|c|c|}
\hline
no quark helicity flip & quark helicity flip \\
\hline
no nucleon helicity flip & \( H \) & \( \tilde{H} \) \\
\hline
nucleon helicity flip & \( E \) & \( \tilde{E} \) \\
\hline
\end{tabular}
\end{table}

(+ 4 more chiral-odd functions)
Finally, the tensor GPDs for transversely polarized quarks. Charge distribution, the GPD in Eq. (65). The first moment, charge density. Similarly, the tensor GPD in longitudinal polarizations \( [DH05] \), as well as for transverse polarizations, as for the PDFs discussed above, also hold for, e.g., transverse or longitudinal polarizations of momentum of the parent hadron. 

To Eqs. (54), (56). All different GPDs become now very clear: While the nucleon states are based on probability densities of (longitudinally or transversely) polarized nucleon \( [DH05] \). To give an example, the corresponding nucleon GPD \( \tilde{H} \) and \( \tilde{E} \) relate directly to the total angular momentum of quarks.

\[
J_q = \frac{1}{2} \lim_{t \to 0} \int_{-1}^{1} dx x \left( H_q(x, \xi, t) + E_q(x, \xi, t) \right)
\]

Moment of GPD \( H \) and \( E \) relate directly to the total angular momentum of quarks.

\[
\int dx H^q(x, \xi, t) = F^q_1(t)
\]

\[
\int dx E^q(x, \xi, t) = F^q_2(t)
\]

\[
H^q(x, \xi = 0, t = 0) = q(x)
\]

\[
\tilde{H}^q(x, \xi = 0, t = 0) = \Delta q(x)
\]

\[
\pm 4 \text{ more chiral-odd functions}
\]
Real-photon production

DVCS

$e' \gamma^* \gamma \quad GPDs(x,\xi,t)$

$p' \quad t \quad p$
Real-photon production

**DVCS**

\[
e \rightarrow \gamma^* \rightarrow e', \\
x^+ \xi \rightarrow x^+ x, t \\
p \rightarrow GPDs(x, \xi, t) \rightarrow p'
\]

**Bethe-Heitler**

\[
e \rightarrow \gamma \rightarrow e', \\
x^+ \xi \rightarrow x^+ x, t \\
p \rightarrow GPDs(x, \xi, t) \rightarrow p'
\]
Real-photon production

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

- beam polarization $P_B$
- beam charge $C_B$
- here: unpolarized target

Fourier expansion for $\phi$:

$$|\mathcal{T}_{BH}|^2 = \frac{K_{BH}}{P_1(\phi)P_2(\phi)} \sum_{n=0}^{2} c_n^{BH} \cos(n\phi)$$

Calculable in QED (using FF measurements)
Azimuthal dependences in DVCS/BH

- beam polarization $P_B$
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$$|T_{BH}|^2 = \frac{K_{BH}}{P_1(\phi)P_2(\phi)} \sum_{n=0}^{2} c_n^{BH} \cos(n\phi)$$

$$|T_{DVCS}|^2 = K_{DVCS} \left[ \sum_{n=0}^{2} c_n^{DVCS} \cos(n\phi) + P_B \sum_{n=1}^{1} s_n^{DVCS} \sin(n\phi) \right]$$
Azimuthal dependences in DVCS/BH

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$$ |\mathcal{T}_{DVCS}|^2 = K_{DVCS} \left[ \sum_{n=0}^{2} c_{DVCS}^{n} \cos(n\phi) + P_B \sum_{n=1}^{1} s_{DVCS}^{n} \sin(n\phi) \right] $$

$$ I = \frac{C_B K_I}{P_1(\phi)P_2(\phi)} \left[ \sum_{n=0}^{3} c_{\mathcal{I}}^{n} \cos(n\phi) + P_B \sum_{n=1}^{2} s_{\mathcal{I}}^{n} \sin(n\phi) \right] $$

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Azimuthal dependences in DVCS/BH

- beam polarization $P_B$
- beam charge $C_B$
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$$|\mathcal{T}_{BH}|^2 = \frac{K_{BH}}{P_1(\phi)P_2(\phi)} \sum_{n=0}^{2} c_n^{BH} \cos(n\phi)$$

$$|\mathcal{T}_{DVCS}|^2 = K_{DVCS} \left[ \sum_{n=0}^{2} c_n^{DVCS} \cos(n\phi) + P_B \sum_{n=1}^{1} s_n^{DVCS} \sin(n\phi) \right]$$

$$I = \frac{C_B K_I}{P_1(\phi)P_2(\phi)} \left[ \sum_{n=0}^{3} c_n^I \cos(n\phi) + P_B \sum_{n=1}^{2} s_n^I \sin(n\phi) \right]$$

bilinear ("DVCS") or linear in GPDs
Exclusivity: missing-mass technique

- e⁺ data
- e⁻ data
- MC sum
- elastic BH
- associated BH
- semi-inclusive
Exclusivity: missing-mass technique

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

- e^+ data
- e^- data
- MC sum
- elastic BH
- associated BH
- semi-inclusive

X=p

... and the future?
Exclusivity: missing-mass technique

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

- \( X = p \)
- \( X = \Delta^+ \)

Data points and curves for various processes:
- \( e^+ \) data
- \( e^- \) data
- MC sum
- Elastic BH
- Associated BH
- Semi-inclusive
Exclusivity: missing-mass technique

**X=p**

**X=Δ⁺**

**X=π⁰+...**

The graph shows the distribution of missing mass squared ($M_x^2$) in GeV², normalized by $N_{DIS}$, for different particle combinations:

- $e^+$ data
- $e^-$ data
- MC sum
- Elastic BH
- Associated BH
- Semi-inclusive

The plot is labeled with the HERMES logo and includes an email address: gunar.schnell@desy.de.

The diagram is from the HERMES conference in 2012.
A wealth of azimuthal amplitudes

HERMES DVCS

Beam-charge asymmetry:
GPD $H$

Beam-helicity asymmetry:
GPD $H$

Transverse target spin asymmetries:
GPD $E$ from proton target

Longitudinal target spin asymmetry:
GPD $\tilde{A}$

Double-spin asymmetry:
GPD $\tilde{A}$

Amplitude Value

-0.3 -0.2 -0.1 0 0.1 0.2 0.3

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A wealth of azimuthal amplitudes

**HERMES DVCS**

<table>
<thead>
<tr>
<th>Amplitude</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_C^{\cos(0)}$</td>
<td>-0.3</td>
</tr>
<tr>
<td>$A_C^{\cos(\phi)}$</td>
<td>-0.2</td>
</tr>
<tr>
<td>$A_C^{\cos(2\phi)}$</td>
<td>-0.1</td>
</tr>
<tr>
<td>$A_C^{\cos(3\phi)}$</td>
<td>0</td>
</tr>
<tr>
<td>$A_L^{\sin(\phi)}$</td>
<td>0.1</td>
</tr>
<tr>
<td>$A_L^{\sin(2\phi)}$</td>
<td>0.2</td>
</tr>
<tr>
<td>$A_L^{\sin(3\phi)}$</td>
<td>0.3</td>
</tr>
</tbody>
</table>

**Beam-charge asymmetry:**

GPD $H$

**Beam-helicity asymmetry:**

GPD $H$

**Transverse target spin asymmetries:**

GPD $E$ from proton target

**Longitudinal target spin asymmetry:**

GPD $\tilde{H}$

**Double-spin asymmetry:**

GPD $\tilde{H}$

---

Beam-charge asymmetry:  
GPD $H$

Beam-helicity asymmetry:  
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Transverse target spin asymmetries:  
GPD $E$ from proton target

Longitudinal target spin asymmetry:  
GPD $\tilde{H}$

Double-spin asymmetry:  
GPD $\tilde{H}$

---

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20 years of DIS@HERA - June 19th, 2012
Beam-charge asymmetry

constant term:
\( \propto -A_C^{\cos \phi} \)

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

[higer twist]

[gluon leading twist]

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

complete data set!
A wealth of azimuthal amplitudes

**HERMES DVCS**

- $A_C^{\cos(0)}$
- $A_C^{\cos\phi}$
- $A_C^{\cos(2\phi)}$
- $A_C^{\cos(3\phi)}$
- $A_{LU, I}^{\sin\phi}$
- $A_{LU, DVCS}^{\sin\phi}$
- $A_{LU, I}^{\sin(2\phi)}$
- $A_{LU, DVCS}^{\sin(2\phi)}$
- $A_{LU, I}^{\sin(\phi-\phi_t)}$
- $A_{LU, DVCS}^{\sin(\phi-\phi_t)}$
- $A_{LT, I}^{\cos(\phi-\phi_t)\sin\phi}$
- $A_{LT, DVCS}^{\cos(\phi-\phi_t)\sin\phi}$
- $A_{LT, I}^{\cos(\phi-\phi_t)\cos\phi}$
- $A_{LT, BH+DVCS}^{\cos(\phi-\phi_t)\cos\phi}$
- $A_{UL}^{\sin\phi}$
- $A_{UL}^{\sin(2\phi)}$
- $A_{UL}^{\cos(0\phi)}$
- $A_{UL}^{\cos\phi}$
- $A_{UL}^{\cos(2\phi)}$

**Beam-charge asymmetry:**

- **GPD H**

**Beam-helicity asymmetry:**

- **GPD H**

**Transverse target spin asymmetries:**

- **GPD E** from proton target

**Longitudinal target spin asymmetry:**

- **GPD $\tilde{A}$**

**Double-spin asymmetry:**

- **GPD $\tilde{A}$**

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**References:**

- PRD 75 (2007) 011103
- NPB 829 (2010) 1
- JHEP 11 (2009) 083
- PRC 81 (2010) 035202
- PRL 87 (2001) 182001
- JHEP 06 (2008) 066
- PLB 704 (2011) 15
- JHEP 06 (2010) 019
- NPB 842 (2011) 265
Beam-spin asymmetry

\[ \alpha \text{ Im}[F_1 H] \]

Resonant fraction:
\[ ep \rightarrow e\Delta^+ \gamma \]

complete data set!

[Airapetian et al., accept. by JHEP; arXiv:1203.6287]
Beam-spin asymmetry

Combined analysis of charge & polarisation observables unique to HERA!

Airapetian et al., accept. by JHEP, arXiv:1203.6287

Complete data set!
HERMES detector (2006/07)

detection of recoiling proton

detection of recoiling proton

HERMES detector (2006/07)
HERMES detector (2006/07)

- All particles in final state detected → 4 constraints from energy-momentum conservation
- Selection of pure BH/DVCS ($e^+p \rightarrow e^+p \gamma$) with high efficiency (~83%)
- Allows to suppress background from associated and semi-inclusive processes to a negligible level (<0.2%)

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DVCS with recoil detector

indication of larger amplitudes for pure sample
(→ assoc. in trad. analysis mainly dilution)

basically no contamination
(→ clear interpretation)

A. Airapetian et al., DESY 12-095
DVCS with recoil detector

A. Airapetian et al., DESY 12-095

good agreement with models


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Associated DVCS with recoil detector

- asymmetry amplitudes consistent with zero
- consistent with pure DVCS results (e.g., dilution in traditional analysis)

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Exclusive meson production

\[ A \propto F(x, \xi, t; \mu^2) \otimes K(x, \xi, z; \log(Q^2/\mu^2)) \otimes \Phi(z, k_{\perp}; \mu^2) \]

at leading-twist:

- \( H, E, \tilde{H}, \tilde{E} \)
- \( H \) and \( E \) conserve the nucleon helicity
- \( E \) and \( \tilde{E} \) describe the nucleon helicity flip
- quantum numbers of final state selects different GPDs

- vector mesons (\( \gamma^* \rightarrow \rho_L, \omega_L, \phi_L \)):
  - \( H \), \( E \)

- pseudoscalar mesons (\( \gamma^* \rightarrow \pi, \eta \)):
  - \( e_H \), \( e_E \)

factorization for \( \sigma_L \) (and \( \rho_L, \omega_L, \phi_L \)) only

\[ \sigma_L - \sigma_T \] suppressed by \( 1/Q \)

\[ \sigma_T \] suppressed by \( 1/Q^2 \)

power corrections:

- \( k_{\perp} \) is not neglected

regulate the singularity in the transverse amplitude

\[ \gamma^*_L \rightarrow \rho_0 \] transitions can be calculated (model dependent)

- Ami Rostomyan - p. 2
SDMEs for phi production

- (decay) angular distributions reveal helicity transitions
- similar to rho production: helicity-conserving SDMEs dominate
- hardly any violation of SCHC observed for phi
If you want to understand the proton, look at it from various perspectives!

The relationships between TMDs and GPDs are nicely depicted by Cédric Lorcé: