Recent results from

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(for the HERMES Collaboration)
HERMES main research topics:

✓ origin of nucleon spin
   ➡️ longitudinal spin/momentum structure
   ➡️ transverse spin/momentum structure

✓ hadronization/fragmentation

✓ nucleon properties (mass, charge, momentum, magnetic moment, spin...) should be explained by its constituents
   ➡️ momentum: quarks carry ~ 50% of the proton momentum
   ➡️ spin: total quark spin contribution only ~30%
Ideally: obtain a quantum phase-space distribution (like the Wigner function)

mission: exploring the 3-dimensional phase-space structure of the nucleon

\[ \hat{O}(x, p) \times = \int dx \, dp \, W(x, p) O(x, p) \]

in 1-dimensional QM:

\[ dp \, W(x, p) = |(x)|^2 \]

\[ dx \, W(x, p) = |(p)|^2 \]

spin-\(k\) correlations? orbiting quarks? intrinsic motion

Wigner functions: \( W^q(k, b) \)

probability to find a quark in a nucleon with a certain polarization in a position \(b\) and momentum \(k\)
probability to find a quark in a nucleon with a certain polarization in a position \( b \) and momentum \( k \)

\[
q(x, k_T) = \int d^3b \ W^q(k, b)
\]

Transverse Momentum Dependent (TMDs) distribution functions (DF)
quantum phase–space “tomography” of the nucleon

Wigner functions: \( W^q(k, b) \)

probability to find a quark in a nucleon with a certain polarization in a position \( b \) and momentum \( k \)

\( q(x, k_T) \)

Transverse Momentum Dependent (TMDs) distribution functions (DF)

center of momentum

\( R_\perp = \sum x_i r_\perp i \)

\( q(x, b_T) \)

transverse position dependent distribution functions
quantum phase-space “tomography” of the nucleon

Wigner functions: $W^q(k, b)$

probability to find a quark in a nucleon with a certain polarization in a position $b$ and momentum $k$

Transverse Momentum Dependent (TMDs) distribution functions (DF)

$q(x, k_T)$

center of momentum
$R_\perp = \sum x_i r_\perp i$

Generalized Parton Distributions (GPDs)

$q(x, b_T)$

transverse position dependent distribution functions

$H(x, \xi, t)$
quantum phase-space “tomography” of the nucleon

Wigner functions: \( W^q(k, b) \)

probability to find a quark in a nucleon with a certain polarization in a position \( b \) and momentum \( k \)

\[ q(x, k_T) \]

Transverse Momentum Dependent (TMDs) distribution functions (DF)

\[ f^q(x) \]

\( \xi = 0, t = 0 \)

Generalized Parton Distributions (GPDs)

Parton Distribution Functions (PDFs)
quantum phase–space “tomography” of the nucleon

Wigner functions: \( W^q(k, b) \)

probability to find a quark in a nucleon with a certain polarization in a position \( b \) and momentum \( k \)

Transverse Momentum Dependent (TMDs) distribution functions (DF)

semi-inclusive measurements

Parton Distribution Functions (PDFs)

inclusive measurements

\( q(x, k_T) \)

\( f^q(x) \)

\( H(x, \xi, t) \)

\( q(x, b_T) \)

transverse position dependent distribution functions

Generalized Parton Distributions (GPDs)

exclusive measurements
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✓ nucleon properties (mass, charge, momentum, magnetic moment, spin...) should be explained by its constituents
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  ☛ spin: total quark spin contribution only ~30%
  ➡ study of TMD DFs and GPDs
HERMES main research topics:

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✓ nucleon properties (mass, charge, momentum, magnetic moment, spin...) should be explained by its constituents
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  ➡ study of TMD DFs and GPDs

✓ isolated quarks have never been observed in nature

✓ fragmentation functions were introduced to describe the hadronization
  ★ non-pQCD objects
  ★ universal but not well known functions
  ➡ advantage of lepton-nucleon scattering data ➔ flavour separation of fragmentation functions (FFs)
The HERMES experiment, located at HERA, with its pure gas targets and advanced particle identification ($\pi$, K, p) is well suited for TMD and GPD measurements.

- **longitudinal** target polarization (H, D, $^3$He)
- **transverse** target polarization (H)
- **unpolarized** targets: H, D, $^4$He, $^{14}$N, $^{20}$Ne, $^{84}$Kr, $^{131}$Xe
- **unpolarized** H, D targets with recoil detector

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**self-polarized $e^+/e^-$ beam**

![Graph showing polarization vs. time for transverse and longitudinal polarimeters.]

**hadron identification with RICH detector**

![Graph showing $\theta_C$ vs. p for $\pi$, K, p.]

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DSPIN 2013
semi-inclusive measurements (probing TMDs)
semi-inclusive DIS cross section and TMDs

\[
\frac{d^4 \sigma}{dx \, dy \, dz \, d\phi_s} \propto F_{UU} + S_{||} \lambda_e \sqrt{1 - \epsilon^2} F_{LL} + S_\perp \left\{ \ldots \right\}
\]

\[ f_1 \otimes D_1 \]
semi-inclusive DIS cross section and TMDs

\[ \frac{d^4 \sigma}{dx \, dy \, dz \, d\phi_s} \propto F_{UU} + S_{\parallel} \lambda_e \sqrt{1 - \epsilon^2} \cos^2 \theta_{LL} + S_{\perp} \{ \ldots \} \]

\[ \int \frac{d^6 \sigma}{dx \, dy \, dz \, dP_{h_{\perp}}^2 \, d\phi \, d\phi_s} \]

\[ \propto \left\{ F_{UU} + \sqrt{2\epsilon(1 + \epsilon)} F_{UU}^{\cos \phi} \cos \phi + \epsilon F_{UU}^{\cos 2\phi} \cos 2\phi \right\} + \lambda_e \left\{ \sqrt{2(1 - \epsilon)} F_{LU}^{\sin \phi} \sin \phi \right\} + S_{\parallel} \{ \ldots \} + S_{\perp} \{ \ldots \} \]
semi-inclusive DIS cross section and TMDs

\[
\frac{d^6 \sigma}{dx \, dy \, d z \, d P_{h \perp}^2 \, d \phi \, d \phi_s} \propto \left\{ F_{UU} + \sqrt{2 \epsilon (1 + \epsilon)} F_{UU}^{\cos \phi} \cos \phi + \epsilon F_{UU}^{\cos 2 \phi} \cos 2 \phi \right\}
+ \lambda_e \left\{ \sqrt{2 \epsilon (1 - \epsilon)} F_{UL}^{\sin \phi} \sin \phi \right\} + S_{||}\left\{ \ldots \right\} + S_{\perp}\left\{ \ldots \right\} + \ldots
\]

**leading twist TMD DF:**
parameterize the quark-flavor structure of the nucleon
semi-inclusive DIS cross section and TMDs

\[
\frac{d^6\sigma}{dx\,dy\,dz\,dP_{h\perp}^2\,d\phi\,d\phi_s} \propto \left\{ F_{UU} + \sqrt{2\epsilon(1+\epsilon)}F_{UU}^{\cos\phi}\cos\phi + \epsilon F_{UU}^{\cos2\phi}\cos2\phi \right\} \\
+ \lambda_e \left\{ \sqrt{2\epsilon(1-\epsilon)}F_{UL}^{\sin\phi}\sin\phi \right\} + S_{\parallel}\left\{ \ldots \right\} + S_{\perp}\left\{ \ldots \right\} + \ldots
\]

**leading twist TMD DF:**
parameterize the quark-flavor structure of the nucleon

**leading twist TMD FF:**
number densities for the conversion of a quark of a certain type to a specific hadron
semi-inclusive DIS cross section and TMDs

\[
\frac{d^6\sigma}{dx \, dy \, dz \, dP_{h \perp}^2 \, d\phi \, d\phi_s} \propto \left\{ F_{UU} + \sqrt{2\epsilon(1 + \epsilon)} F_{UU}^{\cos \phi} \cos \phi + \epsilon F_{UU}^{\cos 2\phi} \cos 2\phi \right\} + \lambda_e \left\{ \sqrt{2\epsilon(1 - \epsilon)} F_{UL}^{\sin \phi} \sin \phi \right\} + S_{\parallel} \left\{ \ldots \right\} + S_{\perp} \left\{ \ldots \right\} + \ldots
\]

leading twist TMD DF:
parameterize the quark-flavor structure of the nucleon

HERMES: access to all TMDs thanks to polarized beam and target
semi-inclusive DIS cross section and TMDs

\[ \frac{d^6 \sigma}{dx
dy
dz
dP_{h \perp}^2
d\phi
d\phi_s} \propto \left\{ F_{UU} + \sqrt{2\epsilon(1+\epsilon)}F_{UU}^{\cos \phi} \cos \phi + \epsilon F_{UU}^{\cos 2\phi} \cos 2\phi \right\} \\
+ \lambda_e \left\{ \sqrt{2\epsilon(1-\epsilon)}F_{UL}^{\sin \phi} \sin \phi \right\} + S_{\parallel} \left\{ \ldots \right\} + S_{\perp} \left\{ \ldots \right\} + \ldots \]

leading twist TMD DF:
parameterize the quark-flavor structure of the nucleon

leading twist TMD FF:
number densities for the conversion of a quark of a certain type to a specific hadron

HERMES: access to all TMDs thanks to polarized beam and target

DSPIN 2013
unpolarized quarks

\[ \sigma_{UU} \propto f_1 \otimes D_1 \]

\[ f_1 = \text{diagram} \]
unpolarized quarks

$$\sigma_{UU} \propto f_1 \otimes D_1$$

$$f_1 = \frac{d\sigma^h_{SIDIS}(x, Q^2, z, P_{h\perp})}{d\sigma_{DIS}(x, Q^2)}$$

$$M^h = \frac{d\sigma^h_{SIDIS}(x, Q^2, z, P_{h\perp})}{d\sigma_{DIS}(x, Q^2)}$$
unpolarized quarks

LO interpretation of multiplicity results (integrated over $P_{h\perp}$):

\[
M^h \propto \sum_q e_q^2 \int dx \ f_{1q}(x, Q^2) D_{1q}^h(z, Q^2) \sum_q e_q^2 \int dx \ f_{1q}(x, Q^2)
\]

✓ charge-separated multiplicities of pions and kaons sensitive to the individual quark and antiquark flavours in the fragmentation process
unpolarized quarks

LO interpretation of multiplicity results (integrated over $P_{h\perp}$):

$$M^h \propto \frac{\sum_q e_q^2 \int dx \ f_1q(x, Q^2) D^h_{1q}(z, Q^2)}{\sum_q e_q^2 \int dx \ f_1q(x, Q^2)}$$

✓ charge-separated multiplicities of pions and kaons sensitive to the individual quark and antiquark flavours in the fragmentation process

$\pi^+$ and $K^+$:

- favoured fragmentation on proton

$\pi^-$:

- increased number of $d$-quarks in $D$ target and favoured fragmentation on neutron

$K^-$:

- cannot be produced through favoured fragmentation from the nucleon valence quarks

$\sigma_{UU} \propto f_1 \otimes D_1$

$M^h = \frac{d\sigma^h_{SIDIS}(x, Q^2, z, P_{h\perp})}{d\sigma_{DIS}(x, Q^2)}$

- HERMES Collaboration

unpolarized quarks

- HERMES Collaboration -

σUU ∝ f_1 ⊗ D_1

✓ calculations using DSS, HNKS and Kretzer FF fits together with CTEQ6L PDFs
proton:
  - fair agreement for positive hadrons
  - disagreement for negative hadrons
deuteron:
  - results are in general in better agreement with the various predictions
 multiplicities measured for deuteron: HNKS and Kretzer FF fits together with CTEQ6L PDFs
 proton: fair agreement for positive hadrons
               disagreement for negative hadrons
dep: results are in general in better agreement with the various predictions

\( \sigma_{UU} \propto f_1 \otimes D_1 \)
in the absence of experimental constraints, many global QCD fits of PDFs assume

\[ s(x) = \bar{s}(x) = r[\bar{u}(x) + \bar{d}(x)]/2 \]

✅ isoscalar extraction of \( S(x)D^K_S \) based on the multiplicity data of \( K^+ \) and \( K^- \) on D

\[
S(x) \int D^K_S(z)dz \simeq Q(x) \left[ 5 \frac{d^2N^K(x)}{d^2NDIS(x)} - \int D^K_Q(z)dz \right]
\]

\[
\begin{align*}
S(x) & = s(x) + \bar{s}(x) \\
Q(x) & = u(x) + \bar{u}(x) + d(x) + \bar{d}(x) \\
D^K_S & = D^{s\rightarrow K^+}_1 + D^{\bar{s}\rightarrow K^+}_1 + D^{s\rightarrow K^-}_1 + D^{\bar{s}\rightarrow K^-}_1 \\
D^K_Q & = D^{u\rightarrow K^+}_1 + D^{\bar{u}\rightarrow K^+}_1 + D^{d\rightarrow K^+}_1 + D^{\bar{d}\rightarrow K^+}_1 + \ldots
\end{align*}
\]
in the absence of experimental constraints, many global QCD fits of PDFs assume
\[ s(x) = \bar{s}(x) = r[\bar{u}(x) + \bar{d}(x)]/2 \]

isoscalar extraction of \( S(x)D^K_S \) based on the multiplicity data of \( K^+ \) and \( K^- \) on \( D \)
\[ S(x) \int D^K_S(z) dz \simeq Q(x) \left[ 5 \frac{d^2N^K(x)}{d^2NDIS(x)} - \int D^K_Q(z) dz \right] \]

\[ S(x) = s(x) + \bar{s}(x) \]
\[ Q(x) = u(x) + \bar{u}(x) + d(x) + \bar{d}(x) \]
\[ D^K_S = D^s_{1 \to K^+} + D^s_{1 \to K^+} + D^s_{1 \to K^-} + D^s_{1 \to K^-} \]
\[ D^K_Q = D^u_{1 \to K^+} + D^\bar{u}_{1 \to K^+} + D^d_{1 \to K^+} + D^\bar{d}_{1 \to K^+} \ldots \]

the distribution of \( S(x) \) is obtained for a certain value of \( D^K_S \)
the normalization of the data is given by that value
whatever the normalization, the shape is incompatible with the predictions
multi-dimensional analysis allows exploration of new kinematic dependences

broader $P_{h\perp}$ distribution for $K^-$
quark’s transverse degrees of freedom

\[ \sigma_{UU} \propto h_{1}^{\perp} \otimes H_{1}^{\perp} \]

\[ h_{1}^{\perp} = \]
quark’s transverse degrees of freedom

\[ \sigma_{UU} \propto h_1^\perp \otimes H_1^\perp \]

\[ h_1^\perp = \]

- HERMES Collaboration-

✓ negative asymmetry for \( \pi^+ \) and positive for \( \pi^- \)

▷ from previous publications (\ PRL 94 (2005) 012002, PLB 693 (2010) 11-16 \):

\[ H_1^\perp, u \rightarrow \pi^+ = - H_1^\perp, u \rightarrow \pi^- \]

◁ data support Boer-Mulders DF \( h_1^\perp \) of same sign for u and d quarks

✓ \( K^- \) and \( K^+ \): striking differences w.r.t. pions

▷ role of the sea in DF and FF
Beyond the leading twist

\[
\frac{d^6 \sigma}{dx \ dy \ dz \ dP_{h\perp}^2 \ d\phi \ d\phi_s} \propto \left\{ F_{UU} + \ldots + \lambda_e \left\{ \sqrt{2\epsilon(1-\epsilon)} F_{LU}^{\sin \phi} \sin \phi \right\} \right\} + \ldots
\]

Convolutions of twist-2 and twist-3 functions.
beyond the leading twist

\[
\frac{d^6 \sigma}{dx \, dy \, dz \, dP_{h \perp}^2 \, d\phi \, d\phi_s} \propto \left\{ F_{UU} + \ldots + \lambda_e \left\{ \sqrt{2} \epsilon (1 - \epsilon) F_{LU}^{\sin \phi} \sin \phi \right\} + \ldots \right\}
\]

convolutions of twist-2 and twist-3 functions
Beyond the leading twist

\[
\frac{d^6 \sigma}{dx \, dy \, dz \, dP_{h\perp}^2 \, d\phi \, d\phi_s} \propto \left\{ F_{UU} + \ldots + \lambda_e \left\{ \sqrt{2\epsilon (1 - \epsilon)} F_{LU}^{\sin \phi} \sin \phi \right\} \right\} + \ldots
\]

Convolutions of twist-2 and twist-3 functions

\[\pi^+ \quad \text{and} \quad \pi^-\]

The role of the twist-3 DF or FF is sizeable
\[ d\sigma = d\sigma^0_{UU} + \cos(2\phi)d\sigma^1_{UU} + \frac{1}{Q}\cos(\phi)d\sigma^2_{UU} + P_l \frac{1}{Q}\sin(\phi)d\sigma^3_{LU} + S_L \left[ \sin(2\phi)d\sigma^4_{UL} + \frac{1}{Q}\sin(\phi)d\sigma^5_{UL} + P_l \left( d\sigma^6_{LL} + \frac{1}{Q}\cos(\phi)d\sigma^7_{LL} \right) \right] + S_T \left[ \sin(\phi - \phi_s)d\sigma^8_{UT} + \sin(\phi + \phi_s)d\sigma^9_{UT} + \sin(3\phi - \phi_s)d\sigma^{10}_{UT} + \frac{1}{Q}\sin(2\phi - \phi_s)d\sigma^{11}_{UT} + \frac{1}{Q}\sin(\phi_s)d\sigma^{12}_{UT} \right] + P_l \left( \cos(\phi - \phi_s)d\sigma^{13}_{LT} + \frac{1}{Q}\cos(\phi_s)d\sigma^{14}_{LT} + \frac{1}{Q}\cos(2\phi - \phi_s)d\sigma^{15}_{LT} \right) \]
Collins amplitudes for pions

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

\[
2 \langle \sin(\phi + \phi_s) \rangle_{UT} \propto \frac{C \left[ - \frac{\vec{p}_{h_{\perp}} \cdot k_T}{M_h} h_1^q(x, p_T^2) H_{1_{q \rightarrow h}}(z, k_T^2) \right]}{C \left[ f_1^q(x, p_T^2) D_{1_{q \rightarrow h}}(z, k_T^2) \right]}
\]
Collins amplitudes for pions

- non-zero Collins effect observed!
- both Collins FF and transversity sizeable
- positive amplitude for $\pi^+$
- compatible with zero amplitude for $\pi^0$
- large negative amplitude for $\pi^-$
- increase in magnitude with $x$
- transversity mainly receives contribution from valence quarks
- increase with $z$
- in qualitative agreement with BELLE results

\[
2\langle \sin(\phi + \phi_s) \rangle_{UT} \propto \frac{C\left[ -\frac{\mathbf{P}_h \cdot k_T}{M_h} h_1^q(x, p_T^2) H_1^{q\rightarrow h}(z, k_T^2) \right]}{C\left[ f_1^q(x, p_T^2) D_1^{q\rightarrow h}(z, k_T^2) \right]}
\]
Collins amplitudes for pions

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

\[
2 \langle \sin(\phi + \phi_s) \rangle_{UT} \propto \frac{C \left[ -\frac{P_{h \perp \cdot k_{T}}}{M_{h}} h_1^q(x, p_T^2) H_{1 \rightarrow h}^{-q}(z, k_T^2) \right]}{C \left[ f_1^q(x, p_T^2) D_{1 \rightarrow h}^q(z, k_T^2) \right]}
\]

- positive amplitude for \( \pi^+ \)
- compatible with zero amplitude for \( \pi^0 \)
- large negative amplitude for \( \pi^- \)
- increase in magnitude with \( x \)
- transversity mainly receives contribution from valence quarks
- increase with \( z \)
- in qualitative agreement with BELLE results
- positive for \( \pi^+ \) and negative for \( \pi^- \)

role of disfavored Collins FF:

\[
H_{1,\text{disfav}}^\perp \approx -H_{1,\text{fav}}^\perp
\]

\[
u \Rightarrow \pi^+; \quad d \Rightarrow \pi^- (\text{fav})
\]

\[
u \Rightarrow \pi^-; \quad d \Rightarrow \pi^+ (\text{disfav})
\]

\[
h_1^u > 0
\]

\[
h_1^d < 0
\]
Collins amplitudes for kaons

\[ 2\langle \sin(\phi + \phi_s) \rangle_{UT} \propto \frac{C\left[-\hat{P}_{h+} \cdot \mathbf{k_T} h_1^q(x, p_T^2) H_1^q \rightarrow_h(z, k_T^2)\right]}{C\left[f_1^q(x, p_T^2) D_1^q \rightarrow_h(z, k_T^2)\right]} \]

**K⁺**

- K⁺ amplitudes are similar to π⁺ as expected from the u-quark dominance
- K⁺ are larger than π⁺

**K⁻**

- consistent with zero amplitudes
- K⁻(ūs) is all see object
Collins amplitudes for kaons

\[ 2 \langle \sin(\phi + \phi_s) \rangle_{UT} \propto \frac{C[-\hat{P}_{h+\cdot k_T} h_1^q(x, p_T^2) H_{1q}^{\perp h}(z, k_T^2)]}{C[f_1^q(x, p_T^2) D_{1q}^{\perp h}(z, k_T^2)]} \]

**K**

- **K**$^+$ amplitudes are similar to $\pi^+$ as expected from the u-quark dominance
- **K**$^+$ are larger than $\pi^+$

**K**$^-$

- consistent with zero amplitudes
- **K**$^-$(\(\bar{u}s\)) is all see object
Collins amplitudes for kaons

\[ 2 \langle \sin(\phi + \phi_s) \rangle_{UT} \propto \frac{C \left[ -\frac{\hat{P}_{h+} \cdot p_T}{M_h} h_1^q(x, p_T^2) H_1^{\perp q \rightarrow h} (z, k_T^2) \right]}{C \left[ f_1^q(x, p_T^2) D_1^{q \rightarrow h} (z, k_T^2) \right]} \]

\( K^+ \)
- \( K^+ \) amplitudes are similar to \( \pi^+ \) as expected from the u-quark dominance
- \( K^+ \) amplitudes are larger than \( \pi^+ \)

\( K^- \)
- consistent with zero amplitudes
- \( K^- (\bar{u}s) \) is all see object

Differences between \( K^+ \) and \( \pi^+ \) amplitudes
- role of sea quarks in conjunction with possibly large FF
- various contributions from decay of seminclusively produced vector-mesons
- the \( k_T \) dependences of the fragmentation functions
inclusive hadron measurements
Inclusive transverse target spin asymmetries

semi-inclusive DIS $l p^\uparrow \rightarrow l' h X$

inclusive hadrons $l p^\uparrow \rightarrow h X$

inclusive transverse target spin asymmetry

$$d\sigma = d\sigma_{UU}[1 + S_\perp A_{UT}^{\sin(\psi)} \sin(\psi)]$$

- no info on $Q^2$
- data dominated by $Q^2 \approx 0$

SIDIS only small subsample
Inclusive transverse target spin asymmetries

\[ x_F \text{ dependence} \]

\[ \pi^+ \] positive, increase nearly linearly with \( x_F \)

\[ \pi^- \] negative, decrease nearly linearly with \( x_F \)

\[ K^+ \] positive, approximately constant with \( x_F \)

\[ K^- \] compatible with zero, with small variation over \( x_F \)

\[ \langle P_T \rangle \text{ (GeV)} \]

\[ A_{UT} \sin \psi \]
Inclusive transverse target spin asymmetries

$p_T$ dependence

- $\pi^+$: positive, increase to approximately 0.06, and then decrease with $p_T$
- $\pi^-$: small, varyingly positive and negative
- $K^+$: positive, increase to approximately 0.08, and then decrease with $p_T$
- $K^-$: small, positive
Inclusive transverse target spin asymmetries

- $p_T$ dependence

- $\pi^+$ positive, increase to approximately 0.06, and then decrease with $p_T$

- $\pi^-$ small, varying positive and negative

- $K^+$ positive, increase to approximately 0.08, and then decrease with $p_T$

- $K^-$ small, positive

- disentangling of $x_F - p_T$ correlation: 2D asymmetries

- disentangling of different data samples: with and without scattered-electron tagging, and different kinematic regions

- to appear very soon on the arXiv!
exclusive measurements
(probing GPDs)
theoretically the cleanest probe of GPDs

\[ \gamma^* N \rightarrow \gamma N : H, E, \bar{H}, \bar{E} \]
theoretically the cleanest probe of GPDs

\[ \gamma^* N \rightarrow \gamma N : H, E, \bar{H}, \bar{E} \]
theoretically the cleanest probe of GPDs

\[ \gamma^* N \rightarrow \gamma N : H, E, \bar{H}, \bar{E} \]
theoretically the cleanest probe of GPDs

\[ \gamma^* N \rightarrow \gamma N : H, E, \tilde{H}, \tilde{E} \]

\[ d\sigma \sim d\sigma_{HH}^{BH} + e_\ell d\sigma_{UU}^{I} + d\sigma_{UU}^{DVCS} + e_\ell \lambda d\sigma_{LU}^{I} + \lambda d\sigma_{LU}^{DVCS} + e_\ell S_{||} d\sigma_{UL}^{I} + S_{||} d\sigma_{UL}^{DVCS} + e_\ell S_{\perp} d\sigma_{UT} + S_{\perp} d\sigma_{UT}^{DVCS} + \lambda S_{||} d\sigma_{LU}^{DVCS} + \lambda S_{||} d\sigma_{LU}^{DVCS} + \lambda S_{\perp} d\sigma_{LT} + \lambda S_{\perp} d\sigma_{LT}^{DVCS} \]
HERMES measured complete set of beam helicity, beam charge and target polarization asymmetries.

\[ \gamma^* N \rightarrow \gamma N : H, E, \tilde{H}, \tilde{E} \]

**Theoretically the cleanest probe of GPDs**
theoretically the cleanest probe of GPDs
\[ \gamma^* N \rightarrow \gamma N : H, E, \tilde{H}, \tilde{E} \]

\[
d\sigma \sim d\sigma^{BH}_{UU} + e_\ell d\sigma^I_{UU} + d\sigma^{DVCS}_{UU} + e_\ell \lambda_\ell d\sigma^I_{LU} + \lambda_\ell d\sigma^{DVCS}_{LU} + e_\ell S_{||} d\sigma^I_{UL} + S_{||} d\sigma^{DVCS}_{UL} + e_\ell S_{\perp} d\sigma^I_{UT} + S_{\perp} d\sigma^{DVCS}_{UT} + \lambda_\ell S_{||} d\sigma^I_{LL} + \lambda_\ell S_{||} d\sigma^{DVCS}_{LL} + e_\ell \lambda_\ell S_{\perp} d\sigma^I_{LT} + \lambda_\ell S_{\perp} d\sigma^{DVCS}_{LT}
\]

✓ HERMES measured complete set of beam helicity, beam charge and target polarization asymmetries

unpolarized target
\[
F(\mathcal{H}) + \frac{x_B}{2 - x_B} (F_1 + F_2) \tilde{\mathcal{H}} - \frac{t}{4M^2} F_2 \mathcal{E}
\]

longitudinally polarized target
\[
\frac{x_B}{2 - x_B} (F_1 + F_2) (\mathcal{H} + \frac{x_B}{2} \mathcal{E}) + F_1 \tilde{\mathcal{H}} - \frac{x_B}{2 - x_B} \left( \frac{x_B}{2} F_1 + \frac{t}{4M^2} F_2 \right) \tilde{\mathcal{E}}
\]

transversely polarized target
\[
\frac{t}{4M^2} \left[ (2 - x_B) F(\mathcal{E}) - 4 \frac{1 - x_B}{2 - x_B} F_2 \mathcal{H} \right]
\]
\[ ep \rightarrow e' \gamma X \]

(without recoil detector)

\[ M_X^2 = (p + e - e' - \gamma)^2 \]

missing mass technique

\[ M_X^2 \]
$ep \rightarrow e' \gamma X$

(without recoil detector)

$ep \rightarrow e' \gamma p'$

(with recoil detector)

\[ M_X^2 = (p + e - e' - \gamma)^2 \]

\textbf{DVCS measurements}

\textbf{missing mass technique}

Resonant excitation: $X = \Delta^+$

$X = \pi^0 + \ldots$
**DVCS measurements**

**ep → e'γX**

(without recoil detector)

**ep → e'γp'**

(with recoil detector)

\[ M_X^2 = (p + e - e' - \gamma)^2 \]

- missing mass technique

- Resonant excitation: \( X = \Delta^+ \)

- X = π^0 + ...

Graphs showing distributions for different processes and regions.
$ep \rightarrow e'\gamma X$

(without recoil detector)

$ep \rightarrow e'\gamma p'$

(with recoil detector)

issing mass technique

$M_X^2 = (p + e - e' - \gamma)^2$

✓ unresolved and unresolved-reference samples: $ep \rightarrow e'\gamma X$

use missing mass technique

for comparison only
**DVCS measurements**

- **Without recoil detector:**
  - $ep \to e'\gamma X$
  - Missing mass technique: $M_X^2 = (p + e - e' - \gamma)^2$

- **Pure sample:** $ep \to e'\gamma p'$
  - All particles in the final state are detected
  - Kinematic event fit
  - BH/DVCS events with 83% efficiency
  - Background contamination from semi-inclusive and associated processes less than 0.2%

- **Unresolved and unresolved-reference samples:** $ep \to e'\gamma X$
  - Use missing mass technique
  - For comparison only

- **With recoil detector:**
  - $ep \to e'\gamma p'$

**Graphs:**
- **Left graph:**
  - Missing mass technique
  - $M_X^2 = (p + e - e' - \gamma)^2$

- **Right graph:**
  - Pure sample $ep \to e'\gamma p'$
  - Unresolved and unresolved-reference samples $ep \to e'\gamma X$
  - Missing mass technique
  - Resonant excitation: $X = \Delta^+$
  - $X = \pi^2 + \ldots$
\[ \sigma(\phi, P_\ell, e_\ell) = \sigma_{UU}(\phi) \times \left[ 1 + P_\ell A_{LU}^{DVCS}(\phi) + e_\ell P_\ell A_{LU}^I(\phi) + e_\ell A_C(\phi) \right] \]

- full hydrogen dataset used (incl. 2006/2007 data)
- sensitivity to Re and Im parts of CFF H

\[ A_C^{\cos \phi} \propto \text{Re}[F_1^H] \quad A_{LU,I}^{\sin \phi} \propto \text{Im}[F_1^H] \]

GPD H: unpolarized hydrogen target

charge-difference beam helicity asymmetry
- large overall value
- no kin. dependencies

beam charge asymmetry
- strong t-dependence
- no \( x_B \) or \( Q^2 \) dependences
GPD H: unpolarized hydrogen target
(recoil data)

\[ \sigma(\phi, P_\ell, e_\ell) = \sigma_{UU}(\phi) \times \left[ 1 + P_\ell A^{DVCS}_{LU}(\phi) + e_\ell P_\ell A^I_{LU}(\phi) + e_\ell A_C(\phi) \right] \]

- HERMES Collaboration -
JHEP 10 (2012) 042

- extraction of single-charge beam-helicity asymmetry amplitudes for elastic (pure) data sample
- no separate access to DVCS and interference terms

indication for slightly larger magnitude of the leading amplitude for elastic process compared to the one in the recoil detector acceptance (unresolved-reference)
associated DVCS

Fractional purity
Associated: DVCS/BH - 85.7 ± 1.8
Elastic DVCS/BH (ep→eγp): 1.1 ± 0.1
SIDIS: 13.2 ± 1.9

Fractional purity
Associated DVCS/BH: 75.6 ± 2.6
Elastic DVCS/BH (ep→eγp): 0.1 ± 0.1
SIDIS: 24.4 ± 3.4

consistent with zero result for both channels
associated DVCS is mainly dilution in the analysis using the missing mass technique
in agreement with the DVCS results on pure sample
vector meson production

\[
\frac{d\sigma}{dx_B dQ^2 dt d\phi_s d\phi d\cos \theta d\varphi} \sim \frac{d\sigma}{dx_B dQ^2 dt} W(x_B, Q^2, t, \phi_s, \phi, \cos \theta, \varphi)
\]

production and decay angular distributions \( W \) decomposed:

\[
W = W_{UU} + P_l W_{LU} + S_L W_{UL} + P_l S_L W_{LL} + S_T W_{UT} + P_l S_T W_{LT}
\]

parametrized by helicity amplitudes

or alternatively by SDMEs:

parametrized by helicity amplitudes or SDMEs describe

\[ T_{\lambda\lambda} \]

\[ \rho^0 \]

\[ \gamma^* \]

\[ r^{\alpha}_{\lambda_Y \lambda_Y'} \]

\[ \rho^0 \]

-Schilling, Wolf (1973)-

helicity amplitudes or SDMEs describe

- the helicity transfer from virtual photon to the vector meson
- the parity of the diffractive exchange process
  - natural parity is related to \( H \) and \( E \)
  - unnatural parity is related to \( \tilde{H} \) and \( \tilde{E} \)
SDMEs on unpolarized H and D targets

\[ ep \to e' \rho^0 p' \]

\[ T^\lambda_\lambda \]

\[ \rho^0 \quad \gamma^* \]

\[ |T_{00}|^2 \sim |T_{11}|^2 \gg |T_{01}|^2 > |T_{10}|^2 \sim |T_{-11}|^2 \]

\[ ep \to e' \omega p' \]

23 SDMEs in 5 classes

The SDMEs for hydrogen and deuteron are similar

✓ class A: different sign of \( \omega \) leading twist SDMEs compared to \( \rho^0 \)

- indication of unnatural parity exchange!

\[ r_{1-1}^1 = \frac{1}{2} \sum \{|T_{11}|^2 + |T_{1-1}|^2 - |U_{11}|^2 - |U_{1-1}|^2\}/N \]

\[ \text{Im} \{r_{1-1}^2\} = \frac{1}{2} \sum \{-|T_{11}|^2 + |T_{1-1}|^2 + |U_{11}|^2 - |U_{1-1}|^2\}/N \]

\[ |U_{11}|^2 + |U_{1-1}|^2 > |T_{11}|^2 + |T_{1-1}|^2 \quad \text{for} \ \omega \ \text{meson} \]

\[ |T_{1-1}|^2 + |U_{11}|^2 > |T_{11}|^2 + |U_{1-1}|^2 \quad \text{for} \ \omega \ \text{meson} \]

Assuming \( |T_{1-1}|^2 \approx |U_{1-1}|^2 \) we get \( |U_{11}|^2 > |T_{11}|^2 \)

✓ class D: Some SDMEs indicate SCHC violation

\[ r_{11}^5 + r_{1-1}^5 - \text{Im}\{r_{1-1}^6\} = -0.14 \pm 0.02 \pm 0.04 \text{ for hydrogen} \]

\[ r_{11}^5 + r_{1-1}^5 - \text{Im}\{r_{1-1}^6\} = -0.10 \pm 0.03 \pm 0.03 \text{ for deuterium} \]
At large $Q^2$ and $W$ the **unnatural** parity exchange should be suppressed by $M_v/Q$

The combinations of SDMEs expected to be zero in case of natural parity exchange dominance:

\[ u_1 = 1 - r_{00}^{04} + 2r_{1-1}^{04} - 2r_{11}^1 - 2r_{1-1}^1 \]
\[ u_2 = r_{11}^5 + r_{1-1}^5 \]
\[ u_3 = r_{11}^8 + r_{1-1}^8 \]

$\rho^0$: non-zero UPE signal (3σ)  

$\omega$: dominant UPE signal!

Possible access to GPD $\widetilde{H}$!
HERMES has been the pioneering collaboration in TMD and GPD fields
still very important player in the field of nucleon (spin) structure
polarized $e^+/-$ beams
good particle identification
pure gas target
recoil detector