Recent results from HERMES

Hadron Structure '13

Ami Rostomyan (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

$$\hat{O}(x, p) \rightarrow \int dx \, dp \, W(x, p) O(x, p)$$

in 1-dimensional QM:

$$dp \, W(x, p) = \left|\psi(x)\right|^2$$

$$dx \, W(x, p) = \left|\psi(p)\right|^2$$

$S$ 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 $k$
quantum phase-space “tomography” of the nucleon

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

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

\[ q(x, k_T) \]

Transverse Momentum Dependent (TMDs) distribution functions (DF)
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)

$$W^q(k, b)$$

Wigner functions:

$$q(x, b_T)$$

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)

Generalized Parton Distributions (GPDs)
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)

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)

\[ q(x, k_T) \]

semi-inclusive measurements

\[ f^q(x) \]

inclusive measurements

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

exclusive measurements

Generalized Parton Distributions (GPDs)

center of momentum

\[ R_\perp = \sum x_i r_{\perp i} \]

transverse position dependent distribution functions

\[ q(x, b_T) \]

FT
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  ➡ study of TMD DFs and GPDs
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✓ 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%

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

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

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

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

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

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

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

\[ \frac{d^6σ}{dx \, dy \, dz \, dP_{h⊥}^2 \, dφ \, dφ_s} \propto \left\{ F_{UU} + \sqrt{2ε(1 + ε)} F_{UU}^{\cos φ} \cos φ + ε F_{UU}^{\cos 2φ} \cos 2φ \right\} \\
+ \lambda_e \left\{ \sqrt{2ε(1 - ε)} F_{UL}^{\sin φ} \sin φ \right\} + S_{||}\{\ldots\} + S_⊥\{\ldots\} + \ldots \]

**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

\[ D_1^q(z, P_{h⊥}^2) \]

\[ H_1^{q⊥}(z, P_{h⊥}^2) \]
semi-inclusive DIS cross section and TMDs

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

**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 the polarized beam and target
semi-inclusive DIS cross section and TMDs

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

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 the polarized beam and target

\[
D^q_1(z, P^2_{h_\perp})
\]

\[
H^q_1(z, P^2_{h_\perp})
\]
unpolarized quarks

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

$$f_1 = \text{image of quarks}$$
unpolarized quarks

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

\[ f_1 = \]

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

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

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

✓ 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 $P_{h\perp}$):

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

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

\[ \pi^+ \text{ and } K^+ : \]

✓ 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

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

- HERMES Collaboration-

unpolarized quarks

- HERMES Collaboration-

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

\( \checkmark \) 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

Ami Rostomyan

Hadron structure 2013
unpolarized quarks

- HERMES Collaboration-

σUU ∝ f_1 ⊗ D_1

✓ calculations using DSS, HKNS and Kretzer FF fits together with CTEQ6L PDFs

proton:
- fair agreement for positive hadrons
- poor agreement for negative hadrons

deuteron:
- results are in general in better agreement with the various predictions

Ami Rostomyan
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 \( S(x)D_S^K(x) \) based on the multiplicity data of \( K^+ \) and \( K^- \) on D

\[ S(x) \int D_S^K(z)dz \simeq Q(x) \left[ 5 \frac{d^2N_K(x)}{d^2N_{DIS}(x)} - \int D_Q^K(z)dz \right] \]

- \( S(x) = s(x) + \bar{s}(x) \)
- \( Q(x) = u(x) + \bar{u}(x) + d(x) + \bar{d}(x) \)
- \( D_S^K = D_1^{s\rightarrow K^+} + D_1^{\bar{s}\rightarrow K^+} + D_1^{s\rightarrow K^-} + D_1^{\bar{s}\rightarrow K^-} \)
- \( D_Q^K = D_1^u\rightarrow K^+ + D_1^{\bar{u}\rightarrow K^+} + D_1^d\rightarrow K^+ + D_1^{\bar{d}\rightarrow K^+} + \ldots \)
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 $S(x)\mathcal{D}_S^K$ based on the multiplicity data of $K^+$ and $K^-$ on D

$$S(x)\int \mathcal{D}_S^K(z)dz \simeq Q(x)\left[5\frac{d^2N_{K}(x)}{d^2N_{DIS}(x)} - \int \mathcal{D}_Q^K(z)dz\right]$$

$$S(x) = s(x) + \bar{s}(x)$$
$$Q(x) = u(x) + \bar{u}(x) + d(x) + \bar{d}(x)$$
$$\mathcal{D}_S^K = D_1^{s\rightarrow K^+} + D_1^{\bar{s}\rightarrow K^+} + D_1^{s\rightarrow K^-} + D_1^{\bar{s}\rightarrow K^-}$$
$$\mathcal{D}_Q^K = D_1^{u\rightarrow K^+} + D_1^{\bar{u}\rightarrow K^+} + D_1^{d\rightarrow K^+} + D_1^{\bar{d}\rightarrow K^+} + \ldots$$

the distribution of $S(x)$ is obtained for a certain value of $\mathcal{D}_S^K$
the normalization of the data is given by that value
whatever the normalization, the shape is incompatible with the predictions
beyond the collinear factorization

-multi-dimensional analysis allows exploration of new kinematic dependences

-broader $P_{h\perp}$ distribution for $K^{-}$
Collins effect

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

The transversity DF $h_1^q(x)$ is sensitive to the difference of the number densities of transversely polarized quarks aligned along or opposite to the polarization of the nucleon.

“Collins-effect” accounts for the correlation between the transverse spin of the fragmenting quark and the transverse momentum of the produced unpolarized hadron.

generates left-right (azimuthal) asymmetries.
Collins amplitudes for pions

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

\[ 2 \langle \sin(\phi + \phi_s) \rangle_{UT} \propto \frac{C \left[ -\frac{\vec{P}_{h\perp} \cdot \vec{k}_T}{M_h} h^q_1(x, p_T^2) H_1^{q\rightarrow h}(z, k_T^2) \right]}{C \left[ f^q_1(x, p_T^2) D_1^{q\rightarrow h}(z, k_T^2) \right]} \]
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

\[ 2\langle \sin(\phi + \phi_s) \rangle_{UT} \propto \frac{C[-\hat{P}_{h^+} \cdot \hat{k_T} h^q_1(x, p_T^2) H_1^{\perp q \to h}(z, k_T^2)]}{C[q_1^q(x, p_T^2) D_1^{\perp q \to h}(z, k_T^2)]} \]
non-zero Collins effect observed!
both Collins FF and transversity sizeable

\begin{align*}
\left< \sin(\phi + \phi_s) \right>_{UT} &\propto C \left[ \frac{-\hat{P}_{h\perp} \cdot \mathbf{k}_T}{M_h} h_1^q(x, p_T^2) H_1^{q\rightarrow h}(z, k_T^2) \right] \\
&\cdot \frac{C \left[ f_1^q(x, p_T^2) D_1^{q\rightarrow h}(z, k_T^2) \right]}{
onumber}
\end{align*}

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

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

\( K^+ \)

- \( K^+ \) amplitudes are similar to \( \pi^+ \) 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

\[ 2 \langle \sin(\phi + \phi_s) \rangle_{UT} \propto \frac{C \left[ -\hat{P}_{h_{11}} \cdot \mathbf{k_T} \right] h_1^q(x, p_T^2) H_{1}^{q \rightarrow h}(z, k_T^2)}{C \left[ f_1^q(x, p_T^2) D_1^{q \rightarrow h}(z, k_T^2) \right]} \]

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

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

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

**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

Differences between K^+ and \(\pi^+\) amplitudes

- role of sea quarks in conjunction with possibly large FF
- various contributions from decay of semi-inclusively produced vector-mesons
- the \(k_T\) dependences of the fragmentation functions
quark’s transverse degrees of freedom

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

\[ h_1^\perp = \text{Diagram} \]
quark's transverse degrees of freedom

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

\[ h_1^\perp = \]

\[ -\text{HERMES Collaboration-} \\
\text{Phys.Rev. D87 (2013) 012010} \]

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

✓ from previous publications (\( \text{PRL 94 (2005) 012002, PLB 693 (2010) 11-16} \)):

\[ H_{1, u \rightarrow \pi^+}^\perp = -H_{1, u \rightarrow \pi^-}^\perp \]

✓ 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

\[ \text{Ami Rostomyan} \]
beyond the leading twist

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

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

\[
d^6 \sigma \propto \left\{ F_{UU} + \ldots + \lambda_e \left\{ \sqrt{2\epsilon(1 - \epsilon)} F_{LU}^{\sin \phi} \sin \phi \right\} + \ldots \right\}
\]

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

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

The role of the twist-3 DF or FF is sizeable.

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

\[ \begin{array}{c}
\pi^+ \\
K^+ \\
p \\
\pi^- \\
K^- \\
\bar{p}
\end{array} \]

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Scale uncertainty 2.4%  

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

\[
+ S_T \left[ \sin(\phi - \phi_s)d\sigma^8_{UT} + \sin(\phi + \phi_s)d\sigma^9_{UT} + \sin(3\phi - \phi_s)d\sigma^{10}_{UT} + \frac{1}{Q} \sin(2\phi - \phi_s)d\sigma^{11}_{UT} + \frac{1}{Q} \sin(\phi_s)d\sigma^{12}_{UT} \right] + P_l \left( \cos(\phi - \phi_s)d\sigma^{13}_{LT} + \frac{1}{Q} \cos(\phi_s)d\sigma^{14}_{LT} + \frac{1}{Q} \cos(2\phi - \phi_s)d\sigma^{15}_{LT} \right) \]
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

$$\gamma^* N \rightarrow \gamma N : H, E, \bar{H}, \bar{E}$$

$$d\sigma \sim d\sigma_{U U}^{BH} + e_\ell d\sigma_{U U}^{I} + \lambda_\ell e_\ell d\sigma_{U U}^{LU} + e_\ell S_{||} d\sigma_{U L}^{I} + e_\ell S_{\perp} d\sigma_{U T}^{I} + \lambda_\ell S_{||} d\sigma_{U U}^{LU} + e_\ell \lambda_\ell S_{||} d\sigma_{L L}^{I} + \lambda_\ell S_{||} d\sigma_{L L}^{LU} + e_\ell \lambda_\ell S_{\perp} d\sigma_{L T}^{I} + \lambda_\ell S_{\perp} d\sigma_{L T}^{LU} + e_\ell \lambda_\ell S_{\perp} d\sigma_{L T}^{LU} + \lambda_\ell S_{\perp} d\sigma_{L T}^{LU}$$
theoretically the cleanest probe of GPDs
\[ \gamma^* N \rightarrow \gamma N : H, E, \bar{H}, \bar{E} \]

\[
\begin{align*}
\sigma_{xy} & = d\sigma^{BH}_{UV} + e_\ell d\sigma^I_{UU} + d\sigma^{DVCS}_{UU} \\
& + e_\ell \lambda d\sigma^I_{LU} + \lambda d\sigma^{DVCS}_{LU} \\
& + e_\ell S_{\parallel} d\sigma^I_{UL} + S_{\parallel} d\sigma^{DVCS}_{UL} \\
& + e_\ell S_{\perp} d\sigma^I_{UT} + S_{\perp} d\sigma^{DVCS}_{UT} \\
+ \lambda_\ell S_{\parallel} d\sigma^{BH}_{LU} & + e_\ell \lambda_\ell S_{\parallel} d\sigma^I_{LL} + \lambda_\ell S_{\parallel} d\sigma^{DVCS}_{LL} \\
+ \lambda_\ell S_{\perp} d\sigma^{BH}_{LT} & + e_\ell \lambda_\ell S_{\perp} d\sigma^I_{LT} + \lambda_\ell S_{\perp} d\sigma^{DVCS}_{LT}
\end{align*}
\]

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

Ami Rostomyan
theoretically the cleanest probe of GPDs

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

\[
\begin{aligned}
&d\sigma \sim d\sigma_{UU}^{BH} + e_\ell d\sigma_{UU}^I + d\sigma_{UU}^{DVCS} \\
&+ e_\ell \lambda_d \sigma_{LU}^I + \lambda_d d\sigma_{LU}^{DVCS} + e_\ell S_{||} d\sigma_{UL}^I + \lambda_{||} d\sigma_{UL}^{DVCS} \\
&+ e_\ell S_{\perp} d\sigma_{UT}^I + \lambda_{\perp} d\sigma_{UT}^{DVCS} + \lambda_{\perp} S_{\perp} d\sigma_{LU}^{DVCS} \\
&+ \lambda_{\perp} S_{\perp} d\sigma_{LT}^{BH} + e_\ell S_{\perp} d\sigma_{LT}^I + \lambda_{\perp} S_{\perp} d\sigma_{LT}^{DVCS} \\
&+ \lambda_{\perp} S_{\perp} d\sigma_{LT}^{BH} + e_\ell S_{\perp} d\sigma_{LT}^I + \lambda_{\perp} S_{\perp} d\sigma_{LT}^{DVCS}
\end{aligned}
\]

\[ F(\mathcal{H}) + \frac{x_B}{2-x_B} (F_1 + F_2)(\mathcal{H} + \frac{x_B}{2} \mathcal{E}) \]

unpolarized target

longitudinally polarized target

transversely polarized target

\[ \frac{x_B}{2-x_B} (F_1 + F_2)(\mathcal{H} + \frac{x_B}{2} \mathcal{E}) \]

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

\[ \frac{t}{4M^2} \left[ (2-x_B) F_1 \mathcal{E} - 4 \frac{1-x_B}{2-x_B} F_2 \mathcal{H} \right] \]

HERMES measured complete set of beam helicity, beam charge and target polarization asymmetries
$ep \rightarrow e' \gamma X$

(without recoil detector)

missing mass technique

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

(without recoil detector)

\[ ep \rightarrow e' \gamma X \]

(with recoil detector)

\[ ep \rightarrow e' \gamma p' \]

missing mass technique

\[ M^2_X = (p + e - e' - \gamma)^2 \]
DVCS measurements

\( ep \rightarrow e' \gamma X \) (without recoil detector)

\( ep \rightarrow e' \gamma p' \) (with recoil detector)

**missing mass technique**

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

\[ ep \rightarrow e' \gamma X \]

(without recoil detector)

\[ ep \rightarrow e' \gamma p' \]

(with recoil detector)

- Missing 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

\[ ep \rightarrow e' \gamma X \]
(without recoil detector)

\[ ep \rightarrow e' \gamma p' \]
(with recoil detector)

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

- pure sample: \( ep \rightarrow e' \gamma p' \)
  - 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: \( ep \rightarrow e' \gamma X \)
  - use missing mass technique
  - for comparison only

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

X = π^2 + ...

\[ 1000 \times \frac{N_{\text{obs}}}{N_{\text{DIS}}} \]

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

\[ 0 \quad 0.1 \quad 0.2 \quad 0.3 \]

\[ 1000 \times \frac{N_{\text{obs}}}{N_{\text{DIS}}} \]

\[ 0 \quad 0.05 \quad 0.1 \quad 0.15 \]

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

\[ 0 \quad 5 \quad 10 \quad 15 \]
\[ \sigma(\phi, P_\ell, e_\ell) = \sigma_{UU}(\phi) \times [1 + P_\ell A_{LU}^{DVCS}(\phi) + e_\ell P_\ell A_{LU}^I(\phi) + e_\ell A_C(\phi)] \]

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

\[ A_{LU}^I(\phi) = \sum_{n=1}^{2} A_{LU,I}^{\sin(n\phi)} \sin(n\phi) \]
\[ \sigma(\phi, P_\ell, e_\ell) = \sigma_{UU}(\phi) \times \left[ 1 + P_\ell A_{LU}^{DVCS}(\phi) + e_\ell P_\ell A_{LU}^{I}(\phi) + e_\ell A_{C}(\phi) \right] \]

\[ A_{C}(\phi) = \frac{(\sigma^{+\rightarrow} + \sigma^{\rightarrow+}) - (\sigma^{\rightarrow-} + \sigma^{+\leftarrow})}{(\sigma^{+\rightarrow} + \sigma^{\leftarrow+}) + (\sigma^{\rightarrow-} + \sigma^{+\leftarrow})} \]

\[ A_{C}^{\cos \phi} \propto \text{Re}[F_{1\mathcal{H}}] \]

Beam charge asymmetry
- strong t-dependence
- no \( x_B \) or \( Q^2 \) dependences

GPD H: unpolarized hydrogen target


ep \rightarrow e'\gamma X

(pre-recoil data)
$ep \rightarrow e'\gamma X$

(pre-recoil data)

GPD H: unpolarized hydrogen target


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

\[ A_C(\phi) = \frac{(\sigma^{++} + \sigma^{+-}) - (\sigma^{--} + \sigma^{-+})}{(\sigma^{++} + \sigma^{+-}) + (\sigma^{--} + \sigma^{-+})} \]

$A_C^{\cos \phi} \propto \text{Re}[F_1 H]$ 

beam charge asymmetry

- strong t-dependence
- no $x_B$ or $Q^2$ dependences

$A^{I,DVCS}_{LU}(\phi) = \frac{(\sigma^{++} - \sigma^{+-})^\dagger (\sigma^{--} - \sigma^{-+})}{(\sigma^{++} + \sigma^{+-}) + (\sigma^{--} + \sigma^{-+})}$

$A^{\sin \phi}_{LU,I} \propto \text{Im}[F_1 H]$ 

charge-difference beam helicity asymmetry

- large overall value
- no kin. dependencies

charge-averaged beam helicity asymmetry

- consistent with zero

$A^{\sin \phi}_{LU,DVCS} \propto \text{Im}[\mathcal{H} \mathcal{H}^* - \tilde{\mathcal{H}} \tilde{\mathcal{H}}^*]$
GPD H: unpolarized hydrogen target

\[
\sigma(\phi, P_\ell, e_\ell) = \sigma_{UU}(\phi) \times [1 + P_\ell A_{LU}^{DVCS}(\phi) + e_\ell P_\ell A_{LU}^I(\phi) + e_\ell A_C(\phi)]
\]

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)
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
$ ep \rightarrow e' \gamma X $  
(pre-recoil data)

GPD $ \tilde{H} $: longitudinally polarized hydrogen target

\[ \sigma(P_\ell, P_z, \phi, e_\ell) = \sigma_{UU}(\phi, e_\ell) [1 + P_z A_{UL}(\phi) + P_\ell P_z A_{LL}(\phi) + P_\ell A_{LU}(\phi)] \]

- no separate access to DVCS and interference terms

\[ A_{UL}(\phi) \simeq \sum_{n=1}^{3} A_{UL}^{\sin(n\phi)} \sin(n\phi) \]

\[ A_{LL}(\phi) = \sum_{n=0}^{2} A_{LL}^{\cos(n\phi)} \cos(n\phi) . \]
\[ \sigma(P_{\ell}, P_z, \phi, e_\ell) = \sigma_{UU}(\phi, e_\ell) [1 + P_z A_{UL}(\phi) + P_\ell P_z A_{LL}(\phi) + P_\ell A_{LU}(\phi)] \]

- no separate access to DVCS and interference terms

\[ A_{UL}(\phi) \approx \sum_{n=1}^{3} A_{UL}^{\sin(n\phi)} \sin(n\phi) \]

\[ A_{LL}(\phi) = \sum_{n=0}^{2} A_{LL}^{\cos(n\phi)} \cos(n\phi) \]

\[ A_{UL}^{\sin \phi} \propto \begin{cases} 
\text{DVCS : twist } - 3 \\
I : \text{twist } - 2
\end{cases} \]

\[ A_{UL}^{\sin \phi} \propto F_1 \text{Im} \tilde{H} \]
\[ \sigma (P_\ell, P_z, \phi, e_\ell) = \sigma_{UU}(\phi, e_\ell) [1 + P_z A_{UL}(\phi) + P_\ell P_z A_{LL}(\phi) + P_\ell A_{LU}(\phi)] \]

- no separate access to DVCS and interference terms

\[ A_{UL}(\phi) \approx \sum_{n=1}^{3} A_{UL}^{\sin(n\phi)} \sin(n\phi) \]

\[ A_{LL}(\phi) = \sum_{n=0}^{2} A_{LL}^{\cos(n\phi)} \cos(n\phi). \]

\[ A_{UL}^{\sin \phi} \propto \begin{cases} 
\text{DVCS : twist } - 3 \\
I : \text{twist } - 2
\end{cases} \]

\[ A_{UL}^{\sin 2\phi} \propto \begin{cases} 
I : \text{quark twist } - 3 \\
or gluon twist } - 2
\end{cases} \]

DVCS : twist \(-4\)

\[ A_{UL} \] unexpected large value

**GPD \( \tilde{H} \): longitudinally polarized hydrogen target**


**Ami Rostomyan**

**Hadron structure 2013**
\( ep \rightarrow e' \gamma X \) (pre-recoil data) 

GPD \( \tilde{H} \): longitundinally polarized hydrogen target

\[ \sigma(P_\ell, P_z, \phi, e_\ell) = \sigma_{UU}(\phi, e_\ell) \left[ 1 + P_z A_{UL}(\phi) + P_\ell P_z A_{LL}(\phi) + P_\ell A_{LU}(\phi) \right] \]

No separate access to DVCS and interference terms

\[ A_{UL}(\phi) \approx \sum_{n=1}^{3} A_{UL}^{\sin(n\phi)} \sin(n\phi) \]

\[ A_{LL}(\phi) = \sum_{n=0}^{2} A_{LL}^{\cos(n\phi)} \cos(n\phi) \]

\[ A_{UL}^{\sin \phi} \propto \begin{cases} 
& \text{DVCS : twist} - 3 \\
& \text{I : twist} - 2 \\
& A_{UL}^{\sin \phi} \propto F_1 \text{Im} \tilde{H} 
\end{cases} \]

\[ A_{UL}^{\sin 2\phi} \propto \begin{cases} 
& \text{I : quark twist} - 3 \\
& \text{or gluon twist} - 2 \\
& \text{DVCS : twist} - 4 \\
& \text{unexpected large value} 
\end{cases} \]

\[ A_{LL}^{\cos 0\phi} \propto \begin{cases} 
& \text{DVCS : twist} - 2 \\
& \text{I : twist} - 2 \\
& A_{LL}^{\cos 0\phi} \propto F_1 \text{Re} \tilde{H} 
\end{cases} \]

Ami Rostomyan

Hadron structure 2013
\[ ep \rightarrow e' \gamma X \] (pre-recoil data)

**GPD E: transversely polarized hydrogen target**

\[
\sigma(\phi, \phi_s, e_\ell, S_\perp, \lambda) = \sigma_{UU}(\phi) \left\{ 1 + e_\ell A_C(\phi) + \lambda A^{DVCS}_{LU}(\phi) + e_\ell \lambda A^I_{LU}(\phi) + S_\perp A^{DVCS}_{UT}(\phi, \phi_s) + e_\ell S_\perp A^I_{UT}(\phi, \phi_s) + \lambda S_\perp A^{BH+DVCS}_{LT}(\phi, \phi_s) + e_\ell \lambda S_\perp A^I_{LT}(\phi, \phi_s) \right\}
\]

\[ ep \to e' \gamma X \]
(pre-recoil data)

GPD E: transversely polarized hydrogen target


\[
\sigma(\phi, \phi_s, \ell, S_\perp, \lambda) = \sigma_{UU}(\phi) \left\{ 1 + e_\ell A_C(\phi) + \lambda A_{LU}^{DVCS}(\phi) + e_\ell \lambda A_{LU}^I(\phi) \\
+ S_\perp A_{LU}^{DVCS}(\phi, \phi_s) + e_\ell S_\perp A_{LT}^I(\phi, \phi_s) \\
+ \lambda S_\perp A_{LT}^{DVCS}(\phi, \phi_s) + e_\ell \lambda S_\perp A_{LT}^I(\phi, \phi_s) \right\}
\]

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

\[ A_{UT,I}(\phi-\phi_s) \cos \phi \]

found much more sensitive to GPD E than others, and thus to \( J_u \)

with a good model, allows a model-dependent constraint
\[ ep \rightarrow e'\gamma X \] (pre-recoil data)

GPD E: transversely polarized hydrogen target

\[
\begin{align*}
\sigma(\phi, \phi_s, e_\ell, S_\perp, \lambda) &= \sigma_{UU}(\phi) \left\{ 1 + e_\ell A_C(\phi) + \lambda A_{LU}^{DVCS}(\phi) + e_\ell \lambda A_{LU}^I(\phi) \right. \\
& \quad + S_\perp A_{UT}^{DVCS}(\phi, \phi_S) + e_\ell S_\perp A_{UT}^I(\phi, \phi_S) \\
& \quad + \lambda S_\perp A_{LT}^{BH+DVCS}(\phi, \phi_S) + e_\ell \lambda S_\perp A_{LT}^I(\phi, \phi_S) \left. \right\}
\end{align*}
\]

\[ \propto \text{Im}[F_2H - F_1E] \]

Equation (2.6) shows that this amplitude is sensitive to the different values for the asymmetry amplitudes describing the dependence of the squar...

\[ \propto \text{Re}[F_2H - F_1E] \]

The error bars represent the statistical uncertainty, while the top (bottom) bands denote the systematic uncertainties.
given channel probes specific GPD flavour
given channel probes specific GPD flavour

✓ see the talk by W. Augustyniak
HERMES DVCS

\[ A_C^{cos(0)} \]
\[ A_C^{cos \phi} \]
\[ A_C^{cos(2\phi)} \]
\[ A_C^{cos(3\phi)} \]
\[ A_L^{sin \phi} \]
\[ A_L^{sin(2\phi)} \]
\[ A_L^{sin(2\phi)} \]
\[ A_L^{sin \phi, I} \]
\[ A_L^{sin \phi, DVC} \]
\[ A_L^{sin(\phi + \phi)} \]
\[ A_L^{sin(\phi - \phi)} \]
\[ A_{LT}^{cos \phi} \sin \phi \]
\[ A_{LT}^{cos(\phi - \phi)} \sin \phi \]
\[ A_{LT}^{cos(\phi + \phi)} cos \phi \]
\[ A_{LT}^{cos(\phi - \phi)} cos \phi \]
\[ A_{UL}^{sin \phi} \]
\[ A_{UL}^{sin(2\phi)} \]
\[ A_{UL}^{cos(0)} \]
\[ A_{UL}^{cos \phi} \]
\[ A_{UL}^{cos(2\phi)} \]

Re \( \mathcal{H} \)

Im \( \mathcal{H} \)

Re \( \mathcal{H} - \varepsilon \)

Im \( \mathcal{H} - \varepsilon \)

Im \( \tilde{\mathcal{H}} \)

Re \( \tilde{\mathcal{H}} \)

\[ \mathcal{H} \]
\[ \tilde{\mathcal{H}} \]
\[ \tilde{\mathcal{E}} \]

Amplitude Value

-0.4 -0.3 -0.2 -0.1 0 0.1 0.2 0.3

\( \gamma \)

Hydrogen
Deuterium
Hydrogen Pure

hadron structure 2013
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