Study of GPDs at HERMES

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(on behalf of the HERMES Collaboration)

Correlations in Partonic and Hadronic Interactions 2020 (CPHI-20)
CERN, Geneva, Switzerland, Feb. 3-7, 2020

- HERMES experiment at HERA
- Exclusive reactions and GPDs
- DVCS: measurement of azimuthal asymmetries at HERMES
- Measurements of BSAs: use of Recoil Detector information
- Exclusive meson production and GPDs
- Summary
Self-polarized e$^+$ and e$^-$ beams
27.6 GeV
Helicity switched every few months

Polarized hydrogen (Long., Trans.), deuterium (Long.)
Polarization flipped at 60-180 s time interval
Unpolarized $He, N, Ne, Kr, Xe$

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3D picture of the nucleon

Wigner distributions $W(x, \vec{k}_T, \vec{b}_\perp)$

$\int d^2 \vec{b}_\perp$

TMD PDFs: $f_p^q(x, k_T),...$

Semi-inclusive measurements
Direct info about momentum distribution

$\int d^2 \vec{k}_T$

GPDs: $H_p^q(x, \xi, t),...$

Exclusive Measurements
Direct info about spatial distribution

$\int d^2 \vec{k}_T$

$\xi=0, t=0$

PDFs $f_p^q(x),...$

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**Exclusive reactions & GPDs**

**Ji sum rule**: access OAM

\[
\begin{align*}
J_q &= \lim_{t \to 0} \frac{1}{2} \int dx x \left[ H^q(x, \xi, t) + E^q(x, \xi, t) \right] \\
\frac{1}{2} &= \frac{1}{2} \Delta \Sigma + L_\Delta + J_q
\end{align*}
\]

Correlated information about **longitudinal momentum** \(x_p\) and **transverse spatial position** \(r_{\perp}\)

**\(H^q\) and \(E^q\): quark **Generalized Parton Distributions (GPDs)**

- **Spin-\(\frac{1}{2}\) target**: 4 chiral-even leading-twist quark GPDs \(H, E, \tilde{H}, \tilde{E}\)

- Final state sensitive to different GPDs

- **DVCS (\(\gamma\))**: \(H, E, \tilde{H}, \tilde{E}\)

- **Vector mesons (\(\rho, \omega, \phi\))**: \(H, E\)

- **Pseudoscalar mesons (\(\pi, \eta\))**: \(\tilde{H}, \tilde{E}\)

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Deeply virtual Compton scattering & GPDs

- Theoretically cleanest way to access GPDs
- Interference between DVCS and Bethe-Heitler amplitude
- $|\tau_{\text{DVCS}}| \ll |\tau_{\text{BH}}|$ at HERMES

Access to GPD combinations through azimuthal asymmetries

**HERMES**: Complete set of asymmetries

- Both beam charges
- Both beam helicities
- Unpolarized $^1H$, $^2H$, and also nuclear targets
- Longitudinally polarized $^1H$ and $^2H$ targets
- Transversely polarized $^1H$ target
- Recoil detector: unpolarized $^1H$ and $^2H$

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Accessing GPDs in DVCS

Beam-Charge Asymmetry
\[ \sigma(e^+, \phi) - \sigma(e^-, \phi) \propto \text{Re}[F_1H] \]

Beam-Spin Asymmetry
\[ \sigma(\bar{e}, \phi) - \sigma(\bar{e}, \phi) \propto \text{Im}[F_1H] \]

Longitudinal Target-Spin Asymmetry
\[ \Rightarrow \sigma(P, \phi) - \sigma(P, \phi) \propto \text{Im}[F_1\tilde{H}] \]

Longitudinal Double-Spin Asymmetry
\[ \Rightarrow \sigma(P, \bar{e}, \phi) - \sigma(P, \bar{e}, \phi) \propto \text{Re}[F_1\tilde{H}] \]

Transverse Target-Spin Asymmetry
\[ \sigma(\phi, \phi_S) - \sigma(\phi, \phi_S + \pi) \propto \text{Im}[F_2H - F_1E] \]

Transverse Double-Spin Asymmetry
\[ \sigma(\bar{e}, \phi, \phi_S) - \sigma(\bar{e}, \phi, \phi_S + \pi) \propto \text{Re}[F_2H - F_1E] \]

Compton Form Factors: convolutions of GPDs with hard scattering kernels
\[ F(\xi, t) = \sum_q^{1 \text{ to } 1} \int dxC_q^+ (\xi, x) F^q (x, \xi, t) \]

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DVCS without recoil detector

• Event with exactly one DIS–lepton and exactly one trackless cluster in the calorimeter.
• No recoil detection

\[ 5 \ < \ \Theta_{\gamma^*\gamma} \ < \ 45 \ \text{mrad} \]
\[ -t \ < \ 0.7 \ \text{GeV}^2, \ E_{\gamma} \ > \ 5 \ \text{GeV} \]
\[ 0.03 \ < \ x_B \ < \ 0.35, \ 1 \ < \ Q^2 \ < \ 10 \ \text{GeV}^2 \]
\[ W \ > \ 3 \ \text{GeV}, \ \nu \ < \ 22 \ \text{GeV} \]

Exclusivity via missing mass:
\[ M_{X^2} = (q + P - q')^2 \]

MC for background and cuts, systematic uncertainty

\[ e^+ p \rightarrow e' X \ \gamma \]

\[ e^+ p \rightarrow e' p \ \gamma; \ \text{elastic BH} \]
\[ e^+ p \rightarrow e' \Delta^+ \gamma; \ \text{associated BH} \]
\[ e^+ p \rightarrow e' \pi^0 X; \ \text{semi-inclusive} \]

Correction; \[ \pi^0 \] background \((\approx 3\%)\);
Associated \((\approx 12\%); \ \text{part of signal} \)

Exclusive bin \((- (1.5)^2 \ < \ M_{X^2} \ < \ (1.7)^2 \ \text{GeV}^2)\)
DVCS asymmetries at HERMES

**Beam-charge asymmetry**

GPD $H$

- PRL 87 (2001) 182001
- PRD 75 (2007) 011103
- JHEP 11 (2009) 083

**Beam-spin asymmetry**

GPD $H$

**Transverse target-spin asymmetry**

GPD $E$

- H: JHEP 06 (2008) 066

**Transverse double-spin asymmetry**

GPD $E$


**Longitudinal target spin asymmetry**

GPD $\tilde{H}$

- H: JHEP 06 (2010) 019

**Longitudinal double spin asymmetry**

GPD $\tilde{H}$


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Beam-charge asymmetry $A_C$

$A_C \propto \cos(\phi)$

$A_C \propto \text{Re} \left[ F_1 \mathcal{H} \right]$

Highers twist

Gluon leading twist

Fractions of associated process from MC

$e p \rightarrow e \Delta^+ \gamma$

**KM09:** Global fit Including data from HERA HERMES and Jlab K. Kumerički, D. Müller Nucl. Phys. B 84 (2010) 1


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Beam-charge-separated asymmetries $A_{LU,I}$ & $A_{LU,DVCS}$

$\Im m \left[ F_1 H \right]$

$\Im m \left[ H H^* + \tilde{H} \tilde{H}^* \right]$

Fractions of associated process from MC

Higher twist

$e p \rightarrow e \Delta^+ \gamma$

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Longitudinal single- and double-spin asymmetries $A_{UL(L)}$


$\propto \Im m \left[ F_1 \tilde{H} \right]$

Relatively large BH contribution to these asymmetries

$\propto \Re e \left[ F_1 \tilde{H} \right]$

VGG: model calculation
M. Vanderhaeghen, P. Guichon, M. Guidal

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DVCS: Transverse target-spin asymmetry $A_{UT}$

Sensitive to GPD $E$


$\propto \Im m \left[ F_2 \mathcal{H} - F_1 \mathcal{E} \right]$

Model: VGG with variation of $J_u$, while $J_d=0$

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DVCS with recoil detector

Recoil Detector to tag exclusivity

A. Airapetian et al., JINST B (2013) P05012

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The leading amplitude for pure elastic process is well described by recent fits to previously published data and by KMS model fit to exclusive meson data.
CFFs are extracted from experimental measurements

- VGG model:
  GPD H in this model is not consistent with experimental results.


Curves:
- K. Kumericki, D. Muller
Results of different fits

Exclusive meson production

- Probes various types of GPDs with different sensitivity and different flavour combinations
- Complementary to DVCS process
- Unpolarized target:
  - nucleon-helicity-non-flip GPDs $H, \tilde{H}$ and $\tilde{E}_T = 2\tilde{H}_T + E_T$.
- Transversely polarized target:
  - nucleon-helicity-flip GPDs $E, \tilde{E}$ and $H_T$.

**NPE** ($J^P = 0^+, 1^-, 2^+ \ldots$) (two-gluon exchange = pomeron, $\rho, \omega, f_2, a_2, \ldots$ reggeons = $\bar{q}q$ exchange):
  - GPDs $H$ and $E$

**UPE** ($J^P = 0^-, 1^+, \ldots$) ($\pi, a_1, b_1, \ldots$ reggeons = $\bar{q}q$ exchange):
  - GPDs $\tilde{H}$ and $\tilde{E}$

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Angular distribution and extraction of SDMEs

Three-dimensional angular distribution \( W^{U+L}(\Phi, \phi, \cos \Theta) \) depends linearly on SDMEs \( r_{\lambda_v \lambda_v'}^\alpha \) and beam polarization \( P_b \):

\[
r_{\lambda_v \lambda_v'}^\alpha \sim \rho_{\lambda_v \lambda_v'} = \frac{1}{2N} \sum_{\lambda, \lambda'} F_{\lambda_v \lambda_v'} \sum_{\lambda, \lambda'} F_{\lambda_v' \lambda_N \lambda_N'} \sum_{\lambda, \lambda'} F_{\lambda_v' \lambda_N' \lambda_N'}
\]

Helicity amplitudes are the fundamental quantities to be compared with theory.

- **Helicity amplitudes** form a basis for the SDMEs.
- For longitudinally polarized beam and unpolarized target there are 23 SDMEs: 15 unpolarized and 8 polarized.
- The SDMEs are extracted by fitting the angular distribution \( W^{U+L}(\Phi, \phi, \cos \Theta) \) to the experimental angular distribution of pions from \( \omega \)-decay using unbinned Maximum Likelihood method.

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Extraction of SDMEs and helicity amplitude ratios at HERMES for $\rho^0$ – mesons challenges GPD-based calculations (giving small values).
5 classes of SDMEs

Unpolarized and polarized SDMEs

Similar magnitudes of SDMEs on proton & deuteron

SCHC (S-Channel Helicity Conservation):
holds for class – A & class – B SDMEs:

\[
\begin{align*}
\text{Re } r_{1-1}^5 &= -\text{Im } r_{1-1}^2 \\
\text{Im } r_{10}^7 &= \text{Re } r_{10}^8
\end{align*}
\]

SCHC: slightly violated for class – C

\[ r_{00}^5 \neq 0 \text{ by 3(2) } \sigma \text{ for } p(d) \]

SCHC: slightly violated for class – D

\[ r_{11}^5 + r_{1-1}^5 - \text{Im } r_{1-1}^6 \neq 0 \text{ by 3(2.5) } \sigma \text{ for } p(d) \]
Extraction of $\pi\omega$ transition form factor

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


The solid line show the calculation of the GK model with pion-pole contribution.
Dashed line are the model results without the pion-pole.

The pion-pole contribution seems to account completely for UPE.

Only the magnitude of the $\pi\omega$ transition form factor (not the sign) can be evaluated.

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Exclusive $\omega$ - meson production: $A_{UT}$ asymmetry

$$e(k) + N(p) \rightarrow e(k') + N(p') + \omega$$
$$\omega \rightarrow \pi^+ \pi^- \pi^0, \quad \pi^0 \rightarrow 2 \gamma$$

Angular dependent part

$$w(\phi, \phi_S) = 1 + A_{UU}^{\cos(\phi)} \cos(\phi) + A_{UU}^{\cos(2\phi)} \cos(2\phi)$$
$$+ S_\perp \left[ A_{UT}^{\sin(\phi+\phi_S)} \sin(\phi+\phi_S) + A_{UT}^{\sin(\phi-\phi_S)} \sin(\phi-\phi_S) \right.$$ $$+ A_{UT}^{\sin(\phi_S)} \sin(\phi_S) + A_{UT}^{\sin(2\phi-\phi_S)} \sin(2\phi-\phi_S) + A_{UT}^{\sin(3\phi-\phi_S)} \sin(3\phi-\phi_S) \left. \right]$$

$$w(\phi, \phi_S, \theta) = \frac{3}{2} r_{00}^{04} \cos^2(\theta) w_L(\phi, \phi_S) + \frac{3}{4} \left( 1 - r_{00}^{04} \right) \sin^2(\theta) w_T(\phi, \phi_S)$$

$$w_L(\phi, \phi_S) = 1 + A_{UU,L}(\phi) + S_\perp A_{UT,L}(\phi, \phi_S)$$
$$w_T(\phi, \phi_S) = 1 + A_{UU,T}(\phi) + S_\perp A_{UT,T}(\phi, \phi_S)$$

Fit angular distributions of $\omega$–decay pions

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The solid (dash-dotted) lines show the calculation of the GK model for a positive (negative) $\pi\omega$ transition form factor. Dashed lines are the model results without the pion pole.

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Exclusive $\rho^0$ – meson production: helicity ratios

$$e(k) + N(p) \rightarrow e(k') + N(p') + \rho^0$$

$$\rho^0 \rightarrow \pi^+ \pi^-$$

$$\gamma^* (\lambda^\gamma) + N (\lambda_N) \rightarrow V(\lambda_V) + N(\lambda'_N)$$

Helicity amplitude ratios:

$$t^{(n)}_{\lambda_V \lambda_N} = T^{(n)}_{\lambda_V \lambda_N} / T_{0^\frac{1}{2}0^\frac{1}{2}}$$

$$u^{(n)}_{\lambda_V \lambda_N} = U^{(n)}_{\lambda_V \lambda_N} / T_{0^\frac{1}{2}0^\frac{1}{2}}$$

$$n=1 \quad \lambda_N = \lambda'_N$$

$$n=2 \quad \lambda_N \neq \lambda'_N$$

$$F_{\lambda_V \lambda'_N \lambda_N \lambda_N} = T_{\lambda_V \lambda'_N \lambda_N \lambda_N} + U_{\lambda_V \lambda'_N \lambda_N \lambda_N}$$

$$T^{(n)}_{\lambda_V \lambda_N} - \text{NPE Amplitude}$$

$$U^{(n)}_{\lambda_V \lambda_N} - \text{UPE Amplitude}$$
Exclusive $\rho^0$ – meson production: helicity ratios

Data clearly favors positive sign

Comparison with GK model:

Where missing, set to zero in GK model

Two set of calculations using opposite signs for the $\pi\rho$ transition form factors

Data clearly favors positive sign

Good agreement for most ratios, but clearly off for some

Problem with phases known already

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Summary

3D picture of the nucleon:

- HERMES measured “full set” of DVCS-related asymmetries on proton and nuclear targets.
- Data with recoil-proton detection allows clean separation of DVCS/BH contribution in a signal.
- Indication of larger amplitude for pure sample.
- Associated DVCS results consistent with zero and also with model prediction.

- Measurement of $\rho^0/\omega$ –meson SDMEs & $A_{UT}$ asymmetry amplitudes from exclusive DIS: good model description based on GPDs with inclusion of pion pole.
  - The sign of the $\pi\omega$ transition form factor
- Measurement of helicity ratios from exclusive $\rho^0$ –meson production in DIS: model description with inclusion of pion pole.

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Azimuthal dependences in DVCS

Unpolarized proton target

\[
\frac{d^4 \sigma}{dQ^2 dx_B dt d\phi} \propto \left( |\tau_{\text{BH}}|^2 + |\tau_{\text{DVCS}}|^2 + I \right)
\]

\[
|\tau_{\text{BH}}|^2 = \frac{K_{\text{BH}}}{P_1(\phi) P_2(\phi)} \sum_{n=0}^{2} C_n^{\text{BH}} \cos(n\phi)
\]

\[
|\tau_{\text{DVCS}}|^2 = K_{\text{DVCS}} \left\{ \sum_{n=0}^{2} C_n^{\text{DVCS}} \cos(n\phi) + \sum_{n=1}^{2} S_n^{\text{DVCS}} \sin(n\phi) \right\}
\]

\[
I = -\frac{e_i K_I}{P_1(\phi) P_2(\phi)} \left\{ \sum_{n=0}^{3} C_n \cos(n\phi) + \sum_{n=1}^{3} S_n \sin(n\phi) \right\}
\]

Fourier coefficients are related to certain linear or bi-linear combinations of Compton Form Factors (CFFs):

\[
F(\xi, t) = \sum_{q} \int_{-1}^{1} dx C_q^{\mp}(\xi, x) F_q^q(x, \xi, t)
\]

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Azimuthal asymmetries in DVCS off unpolarized targets

\[
\sigma_{LU}(\phi, P_l, e_l) = \sigma_{UU}[1 + e_l A_C(\phi) + e_l P_l A_{LU}^I(\phi) + P_l A_{LU}^{DVCS}(\phi)]
\]

Charge-difference beam-helicity asymmetry:

\[
A_{LU}^I(\phi) = \frac{\left(\sigma^{+\rightarrow} - \sigma^{+\leftarrow}\right) - \left(\sigma^{-\rightarrow} - \sigma^{-\leftarrow}\right)}{\left(\sigma^{+\rightarrow} + \sigma^{+\leftarrow}\right) + \left(\sigma^{-\rightarrow} + \sigma^{-\leftarrow}\right)} = -\frac{1}{D(\phi)} \frac{x_B}{y} \sum_{n=1}^{2} S_n^I \sin(n\phi)
\]

Charge-averaged beam-helicity asymmetry:

\[
A_{LU}^{DVCS}(\phi) = \frac{\left(\sigma^{+\rightarrow} - \sigma^{+\leftarrow}\right) + \left(\sigma^{-\rightarrow} - \sigma^{-\leftarrow}\right)}{\left(\sigma^{+\rightarrow} + \sigma^{+\leftarrow}\right) + \left(\sigma^{-\rightarrow} + \sigma^{-\leftarrow}\right)} = \frac{1}{D(\phi)} \frac{x_B^2 t P_1(\phi) P_2(\phi)}{Q^2} S_1^{DVCS} \sin(\phi)
\]

Beam-Charge asymmetry:

\[
A_C(\phi) = \frac{\left(\sigma^{+\rightarrow} + \sigma^{+\leftarrow}\right) - \left(\sigma^{-\rightarrow} + \sigma^{-\leftarrow}\right)}{\left(\sigma^{+\rightarrow} + \sigma^{+\leftarrow}\right) + \left(\sigma^{-\rightarrow} + \sigma^{-\leftarrow}\right)} = -\frac{1}{D(\phi)} \frac{x_B}{y} \sum_{n=0}^{3} C_n^I \cos(n\phi)
\]

- **Measurement with** both beam helicity and both beam charges
  - separate contributions from DVCS and Interference term
- **This separation is impossible** in measurements of single-charge beam-helicity asymmetry \(A_{LU}(\phi) = (\sigma^{-\rightarrow} - \sigma^{-\leftarrow})/(\sigma^{-\rightarrow} + \sigma^{-\leftarrow})\)

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Asymmetries on longitudinally polarized targets

Single-charge target-spin asymmetry (Hydrogen/Deuterium):

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

Single-charge double-spin asymmetry (Hydrogen/Deuterium):

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

Single-charge beam-helicity asymmetry (Deuterium):

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

Single-helicity (←) beam-charge asymmetry (Deuterium):

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

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DVCS: Transverse double-spin asymmetry $A_{LT}$

Consistent with zero, cancellations between $E$ and $H$

Sensitivity to $J_u$ is suppressed by kinematic factors

Full set of data: $e^+/e^-$ beams; both helicities; target polarization - positive/negative.

$A_{LT} \cos(\phi-\phi_S)\cos(\phi)$

$\Re \left[ F_2\tilde{H} - (F_1 + \xi F_2)\tilde{E} \right]$

$\Re \left[ \tilde{H}E^* - \tilde{E}H^* - \xi \left( \tilde{H}\tilde{E}^* - \tilde{E}\tilde{H}^* \right) \right]$

$\Re \left[ F_2H - F_1E \right]$

$\Re \left[ -\tilde{H}E^* - \tilde{H}^*E + \xi \left( \tilde{H}\tilde{E}^* + \tilde{E}\tilde{H}^* \right) \right]$

Sensitive to both GPDs entering the $J_i$ sum rule

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Deuterium (Hydrogen): unpolarized target

JHEP 11 (2009) 083

$\Im m(H)$
$\Im m(H_1)$

$\Re e(H)$
$\Re e(H_1)$

- $A_{\sin \phi}^{LU,L,Coh} = -0.29 \pm 0.18 \text{ (stat)} \pm 0.03 \text{ (syst)}$
- $A_{\cos \phi}^{C,Coh} = 0.11 \pm 0.07 \text{ (stat)} \pm 0.03 \text{ (syst)}$

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Deuterium (Hydrogen): target-spin asymmetry

JHEP 11 (2009) 083


\[ \tilde{m}(\tilde{H}) \]

\[ \tilde{m}(\tilde{H}_1) \]

VGG:
&

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Deuterium (Hydrogen): double-spin asymmetry

JHEP 11 (2009) 083

∞ (BH)

VGG:
&

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$A_C (A_C \leftrightarrow )$ on (un)polarized Deuterium

For coherent scattering

$Re(H_1)$

$Re(H_1 - \frac{1}{3}H_5)$

$Im(H_5)$

$A_{LZZ}$ sin $\phi$ amplitude:

$0.074 \pm 0.196 \pm 0.022$

(-$t < 0.06$ GeV$^2$, 40% coherent)

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### Beam-charge /spin asymmetries on heavier nuclei


<table>
<thead>
<tr>
<th>Target</th>
<th>Spin</th>
<th>L (pb(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>(^1)H</td>
<td>1/2</td>
<td>227</td>
</tr>
<tr>
<td>He</td>
<td>0</td>
<td>32</td>
</tr>
<tr>
<td>N</td>
<td>1</td>
<td>51</td>
</tr>
<tr>
<td>Ne</td>
<td>0</td>
<td>86</td>
</tr>
<tr>
<td>Kr</td>
<td>0</td>
<td>77</td>
</tr>
<tr>
<td>Xe</td>
<td>0, 1/2, 3/2</td>
<td>47</td>
</tr>
</tbody>
</table>

- Separation of coherent-enriched and incoherent-enriched data samples by \(t\)-cutoffs: similar average kinematics
- Coherent-enriched samples: \(\approx 65\%\)
- Incoherent enriched samples: \(\approx 60\%\)

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Leading amplitudes of asymmetries on nuclei

Leading amplitude of Beam-charge asymmetry

Leading amplitudes of Beam-helicity asymmetry

- Two beam charges available

- Only one beam charge available: single-charge asymmetry without entanglement of squared DVCS and Interference terms

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Nuclear-mass dependence of asymmetries

$A_C^{\cos \phi}$ vs. $A$

$A_L^{\sin \phi}$ vs. $A$

$A_{LU}^A / A_{LU}^H$

Coherent-enriched: $0.91 \pm 0.19$

Incoherent-enriched: $0.93 \pm 0.23$

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DVCS with recoil detector

Kinematic event fitting technique: all 3 particles in the final state detected should satisfy 4-constraints on energy-momentum conservation:
- No requirement for Recoil
- Charged recoil track in acceptance
- Kinematic fit probability > 1 %
- Kinematic fit probability < 1 %

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Missing mass distribution: exclusivity with RD

Without Recoil Detector

In Recoil Detector acceptance

With Recoil Detector

Similar background

Background-free

Similar kinematics

Associated processes (e p → e' γ Δ^+)

Pure e p → e' γ p

Missing mass: \( M_X^2 = (q + P - q')^2 = M^2 + 2M (\nu - E_\gamma + t) \)

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- Practically no contamination of associated process.
- Indication that leading amplitude for pure elastic process is larger \(0.054 \pm 0.016\) than for unresolved signal (elastic+associated).

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Beam-spin asymmetry in „associated“ DVCS: $e^+p \rightarrow e^+\gamma n\pi^+$

- Associated DVCS/BH: $(77 \pm 2\%$ for $n\pi^+ \ & 85 \pm 1\%$ for $p\pi^0)$
- Correction: $\pi^0$ SIDIS background: $(23 \pm 3\%$ for $p\pi^0 \ & 11 \pm 1\%$ for $n\pi^+ \text{ channel})$
- Elastic: $(0.2 \pm 0.1\%$ for $n\pi^+ \ & 4.6 \pm 0.1\%$ for $p\pi^0)$

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P. Guichon et al., PRD 68 (2003) 034018
Exclusive $\omega$ - meson production at HERMES

**e(k) + N(p) \rightarrow e(k') + N(p') + \omega**

$\omega \rightarrow \pi^+ \pi^- \pi^0$, $\pi^0 \rightarrow 2\gamma$

**Kinematic conditions:**
- $1 \text{ GeV}^2 < Q^2 < 10 \text{ GeV}^2$
- $0.01 < x_B < 0.35$
- $3.0 \text{ GeV} < W < 6.3 \text{ GeV}$
- $0 \leq -t' = -(t - t_{\text{min}}) < 0.2 \text{ GeV}^2$

**Two photon invariant mass:**
- $0.11 \text{ GeV} < M(\gamma\gamma) < 0.16 \text{ GeV}$

**Three-pion invariant mass:**
- $0.71 \text{ GeV} < M(\pi^+ \pi^- \pi^0) < 0.87 \text{ GeV}$

**Missing energy:**
\[ \Delta E = \frac{M_x^2 - M_p^2}{2M_p} \]

Exclusive region: $-1.0 \text{ GeV} < \Delta E < 0.8 \text{ GeV}$

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Exclusive $\rho^0$ – meson production: helicity ratios

- Dominant amplitude: NPE nucleon-helicity non-flip $t_{11}^{(1)} \neq 0$ by > 5$\sigma$
- UPE nucleon-helicity non-flip $u_{11}^{(1)} \neq 0$ by > 4$\sigma$
- Nucleon-helicity flip $\text{Im} t_{01}^{(2)}$, $\text{Im} u_{11}^{(2)}$, $\text{Im} u_{10}^{(2)} \neq 0$ by 2$\sigma$
- Significant nucleon-helicity non-flip $\text{Re} t_{01}^{(1)} \neq 0$ by > 5$\sigma$

Overall good agreement between direct extraction of SDMEs (Eur. Phys. J. C 71 (2011) 1609) and SDMEs via helicity amplitude ratios (not shown here).