Target single- and double-spin asymmetries in DVCS off a longitudinal polarised hydrogen target at HERMES

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DIS 2010 - Florence, Italy
• Generalised Parton Distributions
• Deeply Virtual Compton Scattering
• Longitudinally-Polarised Target Asymmetries
• The HERMES Experiment @ DESY
• Data Selection and Extraction of Asymmetries
• Systematic Uncertainties
• Final Results and Theory Comparison
Generalised Parton Distributions
A multi-dimensional representation of the nucleon

Form Factors
Parton Distribution Functions
Generalised Parton Distributions

At leading twist and for a proton target there are 4 quark GPDs:

\[
\begin{align*}
\int_{-1}^{1} H(x, \xi, t) \, dx &= F_1(t) \\
\int_{-1}^{1} E(x, \xi, t) \, dx &= F_2(t) \\
\int_{-1}^{1} \tilde{H}(x, \xi, t) \, dx &= G_A(t) \\
\int_{-1}^{1} \tilde{E}(x, \xi, t) \, dx &= G_P(t)
\end{align*}
\]

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

\[H, E, \tilde{H}, \tilde{E}\]
The four-fold differential cross-section (neglecting transverse components) can be expressed as

\[
\frac{d\sigma}{dx_B \, dQ^2 \, dt \, d\phi} = \frac{x_B \, e_\ell^6 \, |\tau|^2}{32 (2\pi)^4 \, Q^4 \, \sqrt{1 + \epsilon^2}}
\]

where \( \epsilon = 2x_B \frac{M_p}{Q} \).

As the DVCS and BH processes have the same initial and final states, their scattering amplitudes interfere, \( i.e. \)

\[
|\tau|^2 = |\tau_{BH}|^2 + |\tau_{DVCS}|^2 + \tau_{BH}^* \tau_{DVCS}^* + \tau_{BH}^* \tau_{DVCS}
\]
The DVCS interaction is **suppressed** with respect to BH at HERMES kinematics and in the analysed $\theta_{y^*y}$ range.

Important GPD-related information can be accessed via the Interference and squared-DVCS terms which are Fourier expanded in $\phi$ to twist-3 level as

$$\mathcal{I} = \frac{-e_\ell K_I}{P(\phi)} \left( P_\ell P_L \sum_{n=0}^{2} c_{n,LP}^{I} \cos(n\phi) + P_L \sum_{n=1}^{3} s_{n,LP}^{I} \sin(n\phi) \right)$$

$$\left| \tau_{DVCS} \right|^2 = K_{DVCS} \left( P_\ell P_L \sum_{n=0}^{1} c_{n,LP}^{DVCS} \cos(n\phi) + P_L \sum_{n=1}^{2} s_{n,LP}^{DVCS} \sin(n\phi) \right)$$

The Fourier coefficients relate to combinations of **Compton Form Factors** (CFFs) which are convolutions of the corresponding GPD with a hard-scattering kernel.

The squared-BH terms are exactly calculable in terms of the Dirac and Pauli FFs and known kinematic conditions.
Two asymmetries in the distribution of real photons with respect to the azimuthal angle $\phi$ are extracted:

\[ A_{UL}(\phi) = \frac{\sigma_{\rightarrow \rightarrow} (\phi + \sigma_{\leftarrow \leftarrow} (\phi)) - [\sigma_{\rightarrow \leftarrow} (\phi) + \sigma_{\leftarrow \rightarrow} (\phi)]}{[\sigma_{\rightarrow \rightarrow} (\phi) + \sigma_{\leftarrow \leftarrow} (\phi)] + [\sigma_{\rightarrow \leftarrow} (\phi) + \sigma_{\leftarrow \rightarrow} (\phi)]} \]

\[ = \frac{K_{DVCS}}{D_{unp} (\phi)} \sum_{n=1}^{2} s_{n,LP}^{DVCS} \sin(n\phi) \frac{e_{\ell} K_{I}}{D_{unp} (\phi) P(\phi)} \sum_{n=1}^{3} s_{n,LP}^{I} \sin(n\phi) \]

The single-spin target asymmetry is sensitive to the imaginary part of CFF $\tilde{H}$

\[ A_{LL}(\phi) = \frac{\sigma_{\rightarrow \rightarrow} (\phi + \sigma_{\leftarrow \leftarrow} (\phi)) - [\sigma_{\rightarrow \leftarrow} (\phi) + \sigma_{\leftarrow \rightarrow} (\phi)]}{[\sigma_{\rightarrow \rightarrow} (\phi) + \sigma_{\leftarrow \leftarrow} (\phi)] + [\sigma_{\rightarrow \leftarrow} (\phi) + \sigma_{\leftarrow \rightarrow} (\phi)]} \]

\[ = \frac{K_{BH}}{D_{unp} (\phi)} \sum_{n=0}^{1} c_{n,LP}^{BH} \cos(n\phi) + \frac{K_{DVCS}}{D_{unp} (\phi)} \sum_{n=0}^{1} c_{n,LP}^{DVCS} \cos(n\phi) \frac{e_{\ell} K_{I}}{D_{unp} (\phi) P(\phi)} \sum_{n=0}^{2} c_{n,LP}^{I} \cos(n\phi) \]

The double-spin asymmetry is sensitive to the real part of CFF $\tilde{H}$

\[ A_{LU}(\phi) \equiv \frac{[\sigma_{\rightarrow \leftarrow} (\phi) + \sigma_{\leftarrow \rightarrow} (\phi)] - [\sigma_{\leftarrow \leftarrow} (\phi) + \sigma_{\rightarrow \rightarrow} (\phi)]}{[\sigma_{\rightarrow \leftarrow} (\phi) + \sigma_{\leftarrow \rightarrow} (\phi)] + [\sigma_{\leftarrow \leftarrow} (\phi) + \sigma_{\rightarrow \rightarrow} (\phi)]} \propto \Im \tilde{m} \tilde{H} \]

The beam-helicity asymmetry has been extracted at HERMES from a larger superset of data. *JHEP* 11 (2009) 083
The HERMES Experiment: The Long. Pol. Proton Data Set

- Situated on the HERA ring at DESY
- Fixed Gas Target Experiment
- Data taken in 1996 – 1997
- Long. pol. (~80%) Hydrogen gas
- 27.57GeV long. pol. (~50%) e^+ beam
- Luminosity ~50pb^{-1}

\( \gamma \) detected in the calorimeter

Charged track identified as an \( e^+ \) detected in the calorimeter and tracked through the spectrometer

\( p \) is not detected. This data was taken pre-Recoil Detector

Data Selection Criteria

One positron, fully tracked through the spectrometer and one photon, identified as a single signal cluster with no track, must be detected with:

\[
1 \text{ GeV}^2 \leq Q^2 \leq 10 \text{ GeV}^2, \ 0.03 \leq x_B \leq 0.35, \ W > 3 \text{ GeV}, \ \nu < 22 \text{ GeV}, \ -t < 0.7 \text{ GeV}^2
\]

Pre-Recoil 'exclusive' data sample is selected by constraining the missing mass:

\[-2.08 \text{ GeV}^2 \leq M_X^2 \leq 2.81 \text{ GeV}^2\]

MC studies show that the final sample contains contributions from:

- \text{DVCS/BH} – 84%
- \text{Resonance production} – 13%
- \text{Semi-Inclusive } M^0 \text{ production} – 3%
- \text{Exclusive } \pi^0 \text{ production} < 1\%
The resultant yield is written for each beam and target polarisation state as:

\[
\langle \mathcal{N}(P_\ell, P_L, \phi) \rangle = L(P_\ell)\eta(\phi)\sigma_{UU}(\phi)[1 + P_LA_{UL}(\phi) + P_\ell P_LA_{LL}(\phi)]
\]

The asymmetries are simultaneously extracted using the Maximum Likelihood fitting formalism as:

\[
- \ln \mathcal{L}_{EML}(\theta) = - \sum_i^{N} \ln[1 + P_LA_{UL}(x_i; \theta) + P_\ell P_LA_{LL}(x_i; \theta)] + \mathcal{N}(\theta)
\]

where \(x_i \in \{\phi, -t, x_B, Q^2\}\) are variables for an event \(i\) and \(\theta\) are the most likely set of asymmetry amplitudes.

The extracted asymmetry amplitudes are:

\[
A_{UL}(\phi) \approx A_{UL}^{\cos(0\phi)} + \sum_{n=1}^{3} A_{UL}^{\sin(n\phi)} \sin(n\phi) \quad A_{LL}(\phi) \approx \sum_{n=0}^{2} A_{LL}^{\cos(n\phi)} \cos(n\phi).
\]

These amplitudes relate to Fourier coefficients appearing in the expansion of \(|\tau|^2\).
These asymmetry amplitudes relate to the Fourier coefficients which depend on $C$-functions – functions of real or imaginary parts of CFFs.

Unlike other HERMES analyses using both beam charges, the contributions from the interference and squared-DVCS terms cannot be disentangled.

The leading-twist amplitudes $A_{UL}^{\sin \phi}$ and $A_{LL}^{\cos \phi}$ offer the best opportunity to access information on the real and imaginary parts of CFF $\tilde{H}$ via $C_{LP}^T$ which is linear in CFFs:

$$C_{LP}^T = \frac{x_B}{2 - x_B} (F_1 + F_2) \left( H + \frac{x_B}{2} \mathcal{E} \right) + F_1 \tilde{H} - \frac{x_B}{2 - x_B} \left( \frac{x_B}{2} F_1 + \frac{t}{4M^2 F_2} \right) \tilde{E}.$$
Several sources of systematic uncertainty affect the results shown:

- $\delta_{M_x^2}$ - introduced by accounting for shifts in the mean of the $M_x^2$ distributions between data taking years
- $\delta_{Bg}$ - accounts for the effect of corrections made to the asymmetries to remove contributions from background processes
- $\delta_{4in1}$ - correlated effects of detector smearing, misalignment and acceptance, and finite bin-width effects
- Scale uncertainties in the measurement of the beam and target polarisations of 3.4% and 4.2% respectively
\( \pi^0 \) Background Correction

- Semi-inclusive DIS background dominated by \( \pi^0 \)
- Same data selection as for exclusive sample but with two photons required in the final state
- Corrected amplitudes determined as

\[
A_{\text{corrected}} = \frac{1}{1 - f_{\text{sidis}} - f_{\text{excl}}}(A_{\text{measured}} - f_{\text{sidis}}A_{\text{sidis}} - f_{\text{excl}}A_{\text{excl}})
\]

- \( \delta_{\text{Bg}} \) is evaluated as half the magnitude of the correction in each bin

Missing-Mass Shift Correction

Shifts were discovered between data years.

New year-dependent regions were calculated

\( \delta_{M_X^2} = \frac{1}{4} \) of the effect the new year-dependent regions have on the extracted amplitudes
Correlated uncertainty from the effects of detector misalignment, smearing, acceptance and finite bin-widths in -$t$, $x_B$ and $Q^2$.

• Amplitudes 'reconstructed' from MC simulation using each model at the same average kinematics of each bin.

• Uncertainty from each model determined as

$$\delta_{4\text{-in-1}} = |A_{\text{generated}} - A_{\text{reconstructed}}|$$

• Overall 4-in-1 uncertainty is determined as the RMS of all 5 models
Results of the Single-Spin Target Asymmetry
Results of the Double-Spin Asymmetry
• Two azimuthal asymmetries in the distribution of real photons from the $\vec{e}p \rightarrow ep\gamma$ interaction were extracted arXiv:1004.0177
  • The single-spin asymmetry $A_{UL}$
  • The double-spin asymmetry $A_{LL}$
• These provide information of the imaginary and real parts of CFF $\tilde{\mathcal{H}}$
• Non-zero $\sin\phi$ and unexpectedly large $\sin(2\phi)$ amplitude were observed for the single-spin asymmetry
• Non-zero $\cos(0\phi)$ amplitudes observed for the double-spin

• It is foreseen these results will be used in future extractions of CFF $\tilde{\mathcal{H}}$ leading to a better understanding of GPD $\mathcal{H}$
BACKUP SLIDES
• Results shown are compared with theoretical calculations from the GPV model implementation of Radyushkin's Double Distribution formalism from VGG (Vanderhaeghen, Guichon and Guidal) \textit{Phys. Rev. D60} (1999) 094017

• Regge-inspired t-dependent ansatz used
• Predicts GPD information up to twist-3 level
• Width of theory bands arises from varying the skewness parameters between unity and infinity
• The 'D term' has not been included for these plots
Overview of HERMES DVCS Results

HERMES DVCS

\[ \propto \text{Re} \mathcal{H} \]

\[ \propto \Im \mathcal{H} \]

\[ \text{sensitive to } \bar{E} \]

\[ \propto \Im \bar{\mathcal{H}} \]

\[ \propto \text{Re} \bar{\mathcal{H}} \]

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**JHEP 11** (2009) 083


**JHEP 06** (2008) 066


Submission to *Nucl. Phys. B* (later in 2010)