Deeply Virtual Compton Scattering off Polarized and Unpolarized Protons at Hermes

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Abstract. HERMES has measured asymmetries in hard exclusive leptoproduction of real photons from unpolarized and from longitudinally and transversely polarized hydrogen targets in the years 1996-2007. Data on the combined dependence of the cross section on beam helicity and beam charge were analyzed. Sizable asymmetries arise from the Bethe-Heitler process and from the interference with deeply virtual Compton scattering. The measured azimuthal asymmetries are Fourier decomposed and compared to predictions from models of Generalized Parton Distributions. The HERMES recoil detector that was installed in 2006-07 is used to separate exclusive DVCS processes from semi-inclusive processes and from associated DVCS processes.

1. Generalized Parton Distributions

1.1. Wigner distributions in quantum mechanical phase-space

When in 1932 Eugene P. Wigner found a way to express quantum mechanical correlations in the language of classical statistical mechanics he certainly did not think that this concept would be used one day to describe quarks and gluons in modern quantum field theory. The Wigner function, defined as

\[ W(x, p) = \int \psi^*(x - \eta/2)\psi(x + \eta/2)e^{ip\eta} d\eta \]

contains the most complete (one-body) information about a quantum system [1]. In contrast to a wave-function \( \psi \) the Wigner distribution is a real function and does not have any unphysical phase ambiguity. The expectation value of any dynamical observable \( O(x, p) \) can be calculated from the Wigner distribution according to

\[ \langle O(x, p) \rangle = \int_{-\infty}^{\infty} dx \int dp O(x, p)W(x, p). \]

This way, a quantum mechanical system is completely described and well defined in phase-space despite the uncertainty principle which apparently smears out any phase-space distribution. Wigner’s concept can be generalized in quantum field theory and can be used to describe partons in the nucleon. The Wigner distribution \( W_T(\vec{r}, k) \) becomes a 7-dimensional density distribution for quarks having a position \( \vec{r} \) and an off-shell 4-momentum \( k^\mu \):

\[ W_T(\vec{r}, k) = \frac{1}{2M} \int \frac{d^3q}{(2\pi)^3} e^{-i\vec{q}\cdot\vec{r}} \langle \hat{W} | -\vec{q}/2 > \]
with $\hat{W}$ being a Wigner distribution operator [2]. It is clear that a complete 7-dimensional evaluation of the quark distributions is beyond the scope of any experiment, especially as flavor and spin degrees of freedom come in addition. By applying symmetry arguments and by integrating out certain variables the number of degrees of freedom is reduced. Double distributions (DDs), Generalized Parton Distributions (GPDs) and transverse momentum dependent parton distributions (TMDs) are examples for distributions that are related to such reduced Wigner functions.

1.2. Quantum phase-space tomography by GPDs

The proton is described by four independent leading twist GPDs: $E, \tilde{E}, H, \tilde{H}$. All of them are functions of the longitudinal parton momentum $x$, of the squared momentum transfer $t$ and of the skewness parameter $\xi$ that is related to $x$-Bjorken $x_B$: $\xi = x_B/(2 - x_B)$. The generalized functions contain the ordinary polarized and unpolarized parton distribution functions (PDFs) for a flavor $q$ as a limiting case:

$$\lim_{t, \xi \to 0} H^q(x, \xi, t) = q(x); \quad \lim_{t, \xi \to 0} \tilde{H}^q(x, \xi, t) = \Delta q(x).$$

The first moments of GPDs are identical to the ordinary form factors (FFs) of the nucleon

$$F_1^q(t) = \int H^q(x, \xi, t) \, dx; \quad F_2^q(t) = \int E^q(x, \xi, t) \, dx.$$  (5)

While FFs and PDFs separately contain information about the (transverse) position of partons and about the longitudinal momentum of partons in the nucleon, Burkardt could show that GPDs in addition contain correlated information of partons in position and momentum [4]. This follows naturally from the picture of Wigner functions as distributions in phase space. Another natural but important implication of this picture is that also the orbital angular momentum of partons can be calculated from GPDs as being a correlated quantity in phase space (classically $\vec{L} = \vec{r} \times \vec{p}$). It has been proven by X. Ji that the total angular momentum of partons is [3]

$$J^q = \lim_{t \to 0} \int dx \, x \left( H^q(x, \xi, t) + E^q(x, \xi, t) \right).$$  (6)

This finding offers for the first time the possibility to measure the total angular momentum and – in combination with the measurement of the spin contribution $\Delta q$ – also the contribution of the orbital angular momentum of quarks $L^q = J^q - \Delta q$.

1.3. Are GPDs/GDAs universal?

GPDs are a new concept in theory and only very incomplete data exist from experiments. The concept applies to a large range of energies, from form factor data of the nucleon at lowest energies to the description of double gluon exchange in diffractive Higgs production at LHC energies. The GPD concept can be applied to scattering data but also to annihilation processes in the time-like region in certain kinematic domains where the proton-antiproton annihilation is kinematically dominated by the annihilation of a single hard quark-antiquark pair. The latter process is described by Generalized Distribution Amplitudes (GDAs) [5] and experiments will have to show if these time-like GDAs can be related to the space-like GPDs.

1.4. Deeply Virtual Compton Scattering (DVCS)

From the theory point of view, the cleanest way to access GPDs is deeply virtual Compton scattering (DVCS) which is the exclusive production of a real photon in $ep$ scattering: $ep \to ep\gamma$ where the photon is produced from a quark in the proton. The proton stays intact after the
scattering process. Fig. 1 shows the QCD handbag diagram of DVCS. It has been proven that the process factorizes into a hard part that is parameterized by perturbative QCD and QED and into a soft part that is described by GPDs. The GPDs describe the correlated probabilities that a quark with momentum $x + \xi$ is emitted from the proton and reabsorbed at a momentum $x - \xi$ without breaking up the proton. A competing and experimentally indistinguishable process of DVCS is the Bethe Heitler process where the real photon is generated by the incoming or scattered electron.

![Figure 1. The DVCS process is described by the QCD handbag diagram. The hard process above the dashed line is described by perturbative QCD and QED. The non-perturbative processes below the dashed line are parameterized by GPDs.](image)

### 2. HERMES: A Pioneering Experiment

#### 2.1. From Ellis-Jaffe to Ji et al.

The HERMES experiment is a fixed target experiment at the HERA 27.6 GeV polarized electron/positron beam at DESY in Hamburg. It was operational from 1995-2007 and used pure polarized H, D and $^3$He target gas and various unpolarized target gases. The HERMES detector is an open spectrometer with an angular acceptance of 40-270 mrad and good particle identification properties [6].

The HERMES experiment has been planned in the late 1980s as a follow-up experiment of the EMC experiment NA2' at CERN that has discovered the failure of the Ellis-Jaffe sum rule [7]. At that time the HERMES experiment was designed to measure the inclusive and semi-inclusive double spin asymmetries of the proton and neutron to investigate the spin structure of the nucleon. In its 12 years of running a large amount of precise data have been taken and it could be shown that the "spin crisis" was no danger for QCD, the violation of the Ellis-Jaffe sum rule is confirmed but the Bjorken sum rule stays valid [8]. One conclusion from the EJ sum rule violation, based on SU(3) flavor symmetry was disproven: HERMES showed that there is no significant polarization of the strange sea. The other conclusion, that the spin of the quarks is not the main contribution of the spin of the proton was confirmed [9].

Besides fulfilling its core business, HERMES made pioneering measurements in two fields: first it measured significant single spin asymmetries off transversely polarized protons, being the first experiment that showed that the leading twist transversity distribution is non-zero and that the Sivers function is non-zero [10]. This lead to an emerging of a new class of so far neglected unintegrated and transverse spin dependent parton distribution functions.

The second pioneering field of HERMES is the subject of this paper. HERMES showed for the first time that there are significant, non-zero azimuthal single spin asymmetries appearing in deeply virtual Compton scattering and other exclusive processes. Motivation for
the investigation of exclusive processes in HERMES are the above described GPDs and the possibility to access to the orbital angular momentum of quarks. Today we know that also the gluon spin seems to contribute little to the spin of the proton. Therefore the measurement of the orbital momentum of the partons seems to be the only possibility to solve the spin puzzle.

To improve the capability of HERMES to select exclusive processes, HERMES was upgraded by a recoil detector to be able to explicitly measure and identify the recoiling proton. The recoil detector was successfully operated in the data period 2006-2007. Finally, HERMES had become the experiment with the most complete access for measuring the spin structure of the nucleon. It has data with

- charge reversal ($e^-$ and $e^+$ beams),
- beam spin reversal (left and right handed beam polarization),
- target spin reversal (parallel, transverse and unpolarized target gas),
- target mass variation (H, D, He, N, Ne, Kr, Xe),
- and recoil and spectator proton detection.

2.2. Exclusive $ep \rightarrow ep\gamma$ cross section at HERMES

At HERMES energies, the exclusive $ep \rightarrow ep\gamma$ cross section is dominated by the Bethe Heitler contribution whereas the DVCS cross section is very small. However, despite the dominance of the BH diagram, the interference term $I$ (see Fig. 2) contributes significantly as its cross section is much larger than the quadratic DVCS term and generates specific non-zero azimuthal asymmetries which can be used to access the DVCS matrix elements at amplitude level:

$$\frac{d\sigma}{dx_B dQ^2 dt d\phi} = \frac{x_B e^6}{32(2\pi)^4 Q^4 \sqrt{1 + \epsilon^2}} \left( |\tau_{BH}|^2 + |\tau_{DVCS}|^2 + \frac{\tau_{DVCS}^* \tau_{BH} + \tau_{BH}^* \tau_{DVCS}}{I} \right).$$  \hspace{1cm} (7)

Here, $x_B$, $Q^2$ and $t$ are the usual kinematic variables, $\epsilon$ is a kinematic factor, $\tau$ denotes the reaction amplitudes and $\phi$ is the azimuthal angle between the lepton scattering plane and the plane defined by the real and the virtual photon as shown in Fig. 3 [11].

![Figure 2](image)

Figure 2. At HERMES energies the Bethe Heitler process (left) dominates, the DVCS process (middle) has a small cross section. The interference term (right) has interesting properties. Its contribution is larger than the pure DVCS process and it gives direct experimental access to DVCS matrix elements.
2.3. Separation of amplitudes

HERMES is in the unique situation that it can reverse the charge (+/−) and the helicity (→/←) of the lepton beam separately, which leads to 4 independent measurements that are combined to two clever double difference asymmetries, which HERMES can use to separate the contribution of the interference term from the one of the DCVS term:

\[ A_{ILU}^I(\phi) = \frac{(d\sigma^+−−d\sigma^−−)−(d\sigma^−−−d\sigma^+−)}{(d\sigma^+−+d\sigma^−−) + (d\sigma^−−+d\sigma^+−)} \]  \tag{8} \\
\[ A_{ILU}^{DVCS}(\phi) = \frac{(d\sigma^+−−d\sigma^−−) + (d\sigma^−−−d\sigma^+−)}{(d\sigma^+−+d\sigma^−−) + (d\sigma^−−+d\sigma^+−)} \]  \tag{9} 

The notation \( A_{ILU}^I \) denotes the azimuthal asymmetry \( A \) of the interference term \( I \) for a longitudinally polarized beam (L) and an unpolarized target (U). In a second step, each of these azimuthal asymmetries is then Fourier decomposed into the appropriate sine \( (s_n) \) and cosine \( (c_n) \) coefficients for each of the three contributions \( I, DVCS \) and \( BH \), as shown here for the example \( A_{ILU}^I \)

\[ A_{ILU}^I(\phi) = \frac{-K_I}{P_1(0)P_2(0)} \left( \sum_{n=1}^{2} s_n \sin(n\phi) \right) + \frac{1}{Q^2} \left( \sum_{n=0}^{2} c_n^{DVCS} \cos(n\phi) \right). \]  \tag{10} 

\( P_1, P_2 \) denote lepton propagators and \( K_I, K_{BH} \) are kinematical factors. The \( BH \) contributions can be calculated in QED from the known form factors.

3. Experimental Results

3.1. Access to Compton Form Factors and GPDs

Fig. 4 summarizes the experimental results of the HERMES DVCS proton data. The upper panel shows the Fourier coefficients of the beam charge asymmetry. The already published data from 1996-2005 [11] agree with the preliminary data from the data period 2006-07. The 2006-07 data analysis does not yet include the information from the recoil detector of HERMES as described in the contribution from S. Yaschenko in this volume. Figure 5 shows the kinematic dependences of the beam charge asymmetry coefficients as function of the kinematic variables \( −t, x_B \) and \( Q^2 \). The \( \cos \phi \) data show non-zero values for \( i = 0, 1 \) which are related to the real part of the Compton Form Factor (CFF) \( H \) that is related to the GPD \( H \). The new data on the \( \cos \phi \) coefficient do not confirm the strong rise at large \( −t \) as the previous data suggested.

The second panel in Fig. 4 shows the result of the beam spin asymmetry that has been separated into Fourier contributions from the interference term and the pure DVCS term. A large negative amplitude is observed for the interference term \( A_{ILU,I}^{\sin \phi}(\phi) \) that is related to the imaginary part of the CFF \( H \).
**Figure 4.** The amplitudes of the Fourier decomposition in \( \sin(i\phi) \) and \( \cos(i\phi) \) for the azimuthal asymmetries of the HERMES proton data. The indices \( X/Y \) in \( A_{XY} \) denote the properties of the beam/target. \( C \) means charge conjugation of the beam, and \( L,U,T \) denote the asymmetry with respect to longitudinal, transverse and unpolarized beam/target conditions for the DVCS (DVCS) and the Interference (I) term. The measured amplitudes give information about the real and imaginary parts of certain Compton Form factors \( \tilde{H},E,\tilde{H} \) that are related to the corresponding GPDs \( H,E,H \).

The two panels below show the single and double spin asymmetries for a longitudinally polarized proton target [12]. Again non-zero Fourier coefficients are observed. They correspond to the imaginary and real part of the CFFs \( \tilde{H} \).

### 3.2. Access to orbital angular momentum

The lowest panel of Fig. 4 shows asymmetries obtained from the DVCS-BH interference term at a transversely polarized proton target [13]. The measured non-zero Fourier coefficients have the important property that they give access to the CFF \( E \) which is related to the GPD \( E \) that is part of the Ji sum rule. Therefore the transversely polarized data are essential to gain...
Figure 5. The beam charge asymmetry is shown as a function of the kinematic variables $-t$, $x_B$ and $Q^2$ for the published data taken in 1996-2005 and for the new data set 2006-2007. The data basically agree, but the new data of the beam charge asymmetry $A^\psi$ do not confirm the strong rise at large $-t$. The lowest row of panels shows an estimate of the fraction of associated DVCS production $ep \rightarrow e^\pm p \gamma$.

4. Conclusion and Outlook
HERMES has the most complete data set of various DVCS asymmetries. They give first insights on GPDs. More data are being analyzed, especially data that include the recoil detector. As HERA was switched off in 2007, the data will remain statistics limited and new experiments with high luminosity will have to follow up this interesting new way to study the internal structure of the nucleon.

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Figure 6. The asymmetry $A_{UT}$ measured with unpolarized lepton beam off a transversely polarized target depends on two azimuthal angles that are related to the direction of the target polarization and to the angle of the real photon. This asymmetry is of special importance as it is sensitive to the total angular momentum $J_u$ of (up-)quarks. The different lines illustrate the sensitivity of a given model on the value of $J_u$.

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