Deeply virtual Compton scattering: results & future

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Abstract. Access to Generalised Parton Distributions (GPDs) through Deeply Virtual Compton Scattering (DVCS) is briefly described. Presently available experimental results on DVCS are summarized in conjunction with plans for future measurements.

1 Introduction

For more than two decades the momentum and spin composition of the nucleon and other hadrons has been investigated by now, preferentially using charged leptons as probes. A great variety of measurements was performed in order to study the underlying structure of quarks and gluons that constitute the fundamental degrees of freedom in Quantum Chromodynamics (QCD). Their momenta and angular momenta cannot yet be calculated from first principles, they are encoded in universal distribution functions whose determination is a central topic that embraces particle physics and hadron physics.

The longitudinal momenta and polarisations carried by quarks, antiquarks and gluons within a fast moving hadron are encoded in universal Parton Distribution Functions (PDFs). They are conveniently introduced in the description of the inclusive deep inelastic scattering (DIS) process, \( e p \rightarrow e X \). The exchange of one virtual photon dominates this reaction at fixed-target kinematics with center-of-mass energies \( \sqrt{s} = O(10 \text{ GeV}) \), and it is still the major contribution at collider kinematics with \( \sqrt{s} = O(300 \text{ GeV}) \). In the Bjorken limit of high virtuality \( Q^2 \) and large energy \( \nu \) of the photon in the target rest frame, at a finite ratio \( x_B = \frac{Q^2}{2m\nu} \) (m being the nucleon mass), the cross section factorises into that of a hard partonic subprocess and (a certain combination of) PDFs. For a parton of a given species, the unpolarised PDF represents the probability of finding it at a given fraction \( x_B \) of the nucleon momentum, while the polarised one describes the imbalance of probabilities between oppositely polarised partons. PDFs are called ‘forward’ distributions, as the inclusive \( \gamma^* p \) cross section can be expressed through the optical theorem by the imaginary part of the forward Compton amplitude \( \gamma^* p \rightarrow \gamma^* p \).

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2 Generalised Parton Distributions

The theoretical framework of Generalised Parton Distributions (Dittes et al. 1988; Müller et al. 1994; Radyushkin 1996; Ji 1997; Blümlein et al. 1999) is capable of simultaneously treating several types of processes ranging from inclusive to hard exclusive lepton-nucleon scattering. Exclusive scattering is ‘non-forward’ in nature since the photon initiating the process is virtual and the final-state particle is usually real, forcing a small but finite $t$, the squared momentum transfer between initial and final nucleon states. GPDs depend on $t$ and on $Q^2$, the hard scale of the process, and also on two longitudinal momentum variables. Through these dependences they carry information on two-parton correlations and on quark transverse spatial distributions (Burkardt 2000; Ralston and Pire 2002; Diehl 2002; Belitsky and Müller 2002, Burkardt 2003). A recent comprehensive theoretical review can be found in (Diehl 2003).

Presently the most intensely discussed GPDs are the chirally-even, or quark-helicity conserving GPDs $F^q (F = H, \tilde{H}, E, \tilde{E}$ and $q = u, d$). In order to constrain their non-forward behaviour, measurements can be performed of hard exclusive leptonproduction of a photon or meson, in processes leaving the target intact. The production of a real photon, ie, Deeply Virtual Compton Scattering (DVCS) $e p \rightarrow e p \gamma$, has two benefits:

i) it is considered to be the theoretically cleanest process that can be accessed experimentally in the foreseeable future and

ii) effects of next-to-leading order (Belitsky and Müller 1998; Ji and Osborne 1998; Mankiewicz et al. 1998) and sub-leading twist (see eg Anikin et al. 2000; Radyushkin and Weiss 2000; Belitsky et al. 2002) are under theoretical control.

In the generalised Bjorken limit of large photon virtuality $Q^2$ at fixed $x_B$ and $t$ the dominant pQCD subprocess of DVCS is described by the ‘handbag’ diagram shown in the left panel of Figure 1. The internal variable $x$ and the skewedness parameter $\xi$, with

\[ \xi \simeq \frac{x - x_B}{2x_B} \]

in the Bjorken limit, describe the longitudinal momentum transfer between two partons: the parton (of flavour $q$) taken out of the proton carries the longitudinal momentum fraction $x + \xi$ and the one put back into the proton carries the fraction $x - \xi$. The GPD $F^q(x, \xi, t, Q^2)$ can then be considered as describing the correlation between these two partons at the given values of $t$ and $Q^2$.

![Figure 1. Left: Deeply Virtual Compton Scattering. Right: Bethe-Heitler process (photon radiated by incoming or outgoing lepton).](image-url)
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Figure 2. Visualisation of (most of) the relevant Generalised Parton Distributions and their limiting cases, forward Parton Distributions and Nucleon Form Factors. Different colours illustrate the status of their experimental access (see legend). For explanations see text. The Figure has been taken from (Nowak 2003).

GPDs reduce to ordinary PDFs in the forward limit, i.e., at vanishing momentum transfer. The first x-moments of GPDs are related to certain form factors measured in elastic lepton-nucleon scattering which describe the difference of the electromagnetic nucleon structure from that of a point-like spin-1/2 particle. A particular second moment of GPDs, for a given parton species \( f = (u, d, g) \), is in the limit of vanishing \( t \) connected to the total angular momentum carried by these partons (see Equation 5). The latter finding (Ji 1997) stimulated strong interest in GPDs, as the total angular momenta carried by quarks and gluons in the nucleon constitute the hitherto missing pieces in the puzzle representing the momentum and spin structure of the nucleon.
Generalised Parton Distributions, as phenomenological functions, have to be parameterised. Two ansätze are most customary at present:

i) originally, the ‘factorised ansatz’ uses uncorrelated dependences on $t$ and $(x, \xi)$. The former is written in accordance with proton elastic formfactors and the latter is based on double distributions (Radyushkin 1999) plus additional D-term (Polyakov and Weiss 1999). Double distributions are constructed from ordinary PDFs complemented with a profile function that characterises the strength of the $\xi$-dependence; in the limit $b \to \infty$ of the profile parameter $b$ the GPD is independent on $\xi$. Note that $b$ is a free parameter to be determined by experiment, separately for valence and sea quarks.

ii) measurements of elastic diffractive processes and, more recently, phenomenological considerations (Diehl et al. 2005; Guidal et al. 2004) suggest that the $t$-dependence of the $\gamma^* p$ cross section is entangled with its $x_B$-dependence. The ‘Regge ansatz’ for GPDs hence uses for the $t$-dependence of double distributions a soft Regge-type parameterisation $\sim |x|^{-\alpha'_t}$ with $\alpha'_t = 0.8...0.9$ GeV$^2$ for quarks.

The scheme presented in Figure 1 visualises the present experimental knowledge on the above mentioned functions. As main ingredients, GPDs are placed in the middle of three concentric rings. Their forward limits and moments are situated in the adjacent rings: PDFs in the outermost and nucleon form factors in the innermost one. Today’s experimental knowledge of the different functions is illustrated in different colours from light (no data exist) to dark (well known). The emphasis in Figure 1 is placed on the physics message and not on completeness; some GPDs have been omitted. Empty sectors mean that the function does not exist, decouples from observables in the forward limit, or no strategy is known for its measurement. More details can be found in (Nowak 2003).

3 Deeply Virtual Compton Scattering

3.1 Compton Form Factors

The Bethe-Heitler (BH) process, or radiative elastic scattering, is illustrated in the right panel of Figure 1. Its final state is indistinguishable from that of the DVCS process, hence both mechanisms have to be added on the amplitude level. The differential real-photon leptoproduction cross section is given as

$$\frac{d\sigma}{dx_B dQ^2 dt d\phi} \propto |\tau_{BH}|^2 + |\tau_{DVCS}|^2 + \tau_{DVCS}^* \tau_{BH} + \tau_{DVCS} \tau_{BH}^*. \quad (1)$$

Here $\phi$ is the azimuthal angle between the scattering plane, spanned by the incoming and outgoing leptons, and the production plane spanned by the virtual photon and the produced real photon (cf. Figure 3). The BH amplitude $\tau_{BH}$ is exactly calculable using the knowledge of the elastic nucleon form factors. The DVCS contribution $|\tau_{DVCS}|^2$ can then be extracted by integrating over the azimuthal dependence of the cross section. In this case the interference term $I$ vanishes to leading order in $1/Q$; its total contribution at collider kinematics was estimated to be at the percent level (Belitsky et al. 2002).

The twist-2 DVCS amplitudes can be represented in the convention of (Belitsky et al. 2002) as linear combinations of $F_1$ and $F_2$, the Dirac and Pauli elastic nucleon form
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These complex CFFs are flavour sums of convolutions of the corresponding leading-twist GPDs with the hard scattering kernels $C_{q}^\pm$ that are available up to NLO in pQCD (Belitsky and Müller 1998; Ji and Osborne 1998; Mankiewicz et al. 1998):

$$F(q, t, Q^2) = \sum_q \int_{-1}^{1} dx \ C_{q}^\pm(\xi, x) \ F^q(x, \xi, t, Q^2). \quad (2)$$

Here the $- (+)$ sign in the superscript applies to the CFFs $F^q = H^q, E^q$, corresponding to the GPDs $F^q = H^q, E^q$.

The real and imaginary parts of a CFF have different relationships to (the flavour sum over) the respective quark GPDs which are embodied. Taking Equation (2) at leading order in $\alpha_s$ (Belitsky et al. 2002), the imaginary part

$$\text{Im} \{F\} = \pi \sum_q e_q^2 \left( F^q(\xi, \xi, t, Q^2) \mp F^q(-\xi, \xi, t, Q^2) \right) \quad (3)$$

directly probes the respective GPDs along the line $x = \pm \xi$. In contrast, through the real part of the CFF,

$$\text{Re} \{F\} = -\sum_q e_q^2 \left[ P \int_{-1}^{1} dx \ F^q(x, \xi, t, Q^2) \left( \frac{1}{x - \xi} \mp \frac{1}{x + \xi} \right) \right], \quad (4)$$

the integral over the respective GPDs is accessed, whereby the weighting by the propagators $1/(x \mp \xi)$ strongly enhances the contribution close to the line $x = \pm \xi$. The sign convention is the same as for Equation (2) and $P$ denotes Cauchy’s principal value.

Equations (3) and (4) show that in DVCS a GPD, at given values of $t$ and $Q^2$, is essentially probed along the line $x = \pm \xi$, i.e., a complete mapping of a GPD in the $(x, \xi)$-plane is impossible and models of GPDs are to be constructed to calculate observables that have to be compared to corresponding experimental results in an iterative procedure.

Full $(x, \xi)$-mapping of GPDs is still possible, at least in principle:
i) once a large enough dynamic range in $Q^2$ is available in DVCS measurements, the known $Q^2$-evolution of GPDs can be used to constrain their $x$-dependence, similar as for the extraction of ordinary PDFs in DIS.

ii) in hard exclusive leptoproduction of a virtual photon (double DVCS or DDVCS) its virtuality, ie the effective mass of the produced lepton pair, is an additional variable that facilitates a complete mapping of GPDs. However, the DDVCS cross section is suppressed by an additional factor $\alpha_{em}^2$, thereby making this reaction practically inaccessible in the foreseeable future (Guidal 2002).

The $t$-dependence of GPDs is directly accessible in DVCS although high experimental precision, ie, high statistical accuracy in conjunction with sufficient resolution is required to extrapolate to the limes $t \to 0$. The latter is of particular importance for the evaluation of the 2nd $x$-moment of the two ‘unpolarised’ GPDs $H^f + E^f$, which is related to the total angular momentum $J^f$ of the parton species $f = \{u, d, g\}$, at a given value of $Q^2$ (Ji 1997):

$$J^f(Q^2) = \lim_{t \to 0} \frac{1}{2} \int_{-1}^{1} dx \: x \left[ H^f(x, \xi, t, Q^2) + E^f(x, \xi, t, Q^2) \right]. \quad (5)$$

### 3.2 The Interference Term

The interference term $I$ is of special interest, as the measurement of its azimuthal dependence opens experimental access to the complex DVCS amplitudes, ie, to both their magnitude and phase (Diehl et al. 1997). This method of using the BH process as an ‘amplifier’ to study DVCS can be compared to holography (Belitsky and Müller 2002) in the sense that the phase of the Compton amplitude is measured against the known ‘reference phase’ of the BH process.

The full interference term can be filtered out by forming a cross section asymmetry, or difference, w.r.t. the charge of the lepton beam (Brodsky et al. 1972). The imaginary part of the interference term can be accessed by forming single-spin asymmetries, or differences, w.r.t. the spin of the lepton beam (Kroll et al. 1996) or of the target (Belitsky et al. 2002; Diehl 2003). Note that the measurement of cross section differences is favoured by theorists over that of asymmetries (Diehl 2003). Differences are free from azimuthal dependences of BH, DVCS and interference terms appearing in the denominator of an asymmetry and thereby complicating the separation of the relevant terms in the numerator. They allow easier separation of higher harmonics when compared to the evaluation of an asymmetry, while larger experimental systematic uncertainties may appear.

Each of the three terms in Equation 1 can be expressed as a Fourier series in $\phi$ (Diehl et al. 1997; Belitsky et al. 2002). For an unpolarised target, the interference term $I$ can be written as

$$I = -\frac{K_I e_l}{P_1(\cos \phi) P_2(\cos \phi)} \times$$

$$\{c_0' + c_1' \cos(\phi) + c_2' \cos(2\phi) + c_3' \cos(3\phi) + P_l \left[ s'_I \sin(\phi) + s'_I \sin(2\phi) \right] \},$$

where $K_I$ is a kinematic factor and $e_l = \pm 1$ is the charge of the lepton beam with longitudinal polarisation $P_l$. The virtual-lepton propagators $P_{1,2}(\phi)$ of the BH process intro-
duce an extra $\cos \phi$-dependence. The Fourier coefficient $c^I_1(s^I_1)$ is proportional to the real (imaginary) part of a certain linear combination of the four twist-2 CFFs $\mathcal{H}, \mathcal{E}, \tilde{\mathcal{H}}, \tilde{\mathcal{E}}$, the detailed expression depending on the target polarisation (cf. Equations 11, 14, 15, 16). The coefficient $c^I_0$ is related to approximately the same combination of CFFs as $c^I_1$, but it is kinematically suppressed by $1/Q$ (Belitsky et al. 2002; Diehl 2003). The coefficient $c^I_1$ is sensitive to the D-term that was mentioned in Section 2 (Polyakov and Weiss 1999). The coefficients $c^I_2$ and $s^I_2$ describe twist-3 amplitudes and scale as $1/Q$, whereas $c^I_3$ is $\alpha_S$-suppressed at leading twist (Diehl 1997). In case of a polarised target, additional sums with analogous structure appear in Equation 6 (Diehl and Sapeta 2005). In particular, terms $s^I_3 \sin(3\phi)$ appear where $s^I_3$ is sensitive to contributions from gluon transversity, as in the case of $c^I_3$.

4 Azimuthal Cross Section Asymmetries

4.1 Unpolarised Target

The beam-spin asymmetry (BSA) for a longitudinally ($L$) polarised beam and an unpolarised ($U$) proton target is defined as

$$A_{LU}(\phi) = \frac{d\sigma^- - d\sigma^-(\phi)}{d\sigma^- + d\sigma^-(\phi)},$$

(7)

where $\rightarrow \leftarrow$ denotes beam spin parallel (antiparallel) to the beam direction. Similarly, the beam-charge asymmetry (BCA) for an unpolarised beam of charge $C$ scattering from an unpolarised proton target is defined as:

$$A_C(\phi) = \frac{d\sigma^+ - d\sigma^-(\phi)}{d\sigma^+ + d\sigma^-(\phi)},$$

(8)

where the superscripts + and − denote the lepton beam charge.

Evaluating these asymmetries using Equations 1 and 6 to leading power in $1/Q$ in each contribution, and to leading order in $\alpha_S$, only the $\sin \phi \, (\cos \phi)$ term remains in the numerator of the beam-spin (beam-charge) asymmetry. To the extent that the leading BH-term $c^{BH}_0$ dominates the denominator, the products of the virtual-lepton propagators, $\mathcal{P}_1(\cos \phi)\mathcal{P}_2(\cos \phi)$, cancel. In this approximation, the azimuthal dependence of the beam-spin (beam-charge) asymmetry is reduced to $\sin \phi \, (\cos \phi)$:

$$A_{LU}(\phi) \propto \frac{1}{c^{BH}_0} s^I_{1,U} \sin \phi \propto \text{Im} \, \mathcal{M} \sin \phi,$$

(9)

$$A_C(\phi) \propto \frac{1}{c^{BH}_0} c^I_{1,U} \cos \phi \propto \text{Re} \, \mathcal{M} \cos \phi,$$

(10)

where the additional subscript (U) of the Fourier coefficients denotes the unpolarised target. It appears that both beam-charge and beam-spin asymmetries are sensitive to the same linear combination $\mathcal{M}$ of CFFs which describes an unpolarised proton target (Belitsky et al. 2002):

$$\mathcal{M} = \frac{\sqrt{t_0 - t}}{2m} \left[ F_1 \mathcal{H} + \xi (F_1 + F_2) \tilde{\mathcal{H}} - \frac{t}{4m^2} F_2 \mathcal{E} \right].$$

(11)
Here $-t_0 = 4\xi^2 m^2/(1 - \xi^2)$ is the minimum possible value of $-t$ at a given $\xi$.

Note that, almost independently on details of GPD models, the GPDs $H^q$ are expected to dominate this expression, because i) the second term is suppressed by at least a factor of 10, as $\xi$ is usually not larger than 0.2 even in fixed-target kinematics (cf. Figure 11) and the unpolarised contribution $\mathcal{H}$ is expected to dominate the polarised one $\tilde{\mathcal{H}}$, in analogy to the forward case; ii) the third term is $t$-suppressed, by about a factor of 25 for typical $t$-values of about 0.15 GeV$^2$. For scattering on the proton, the GPD $H^u$ will yield the major contribution to $\tilde{M}$ because of $u$-quark dominance.

4.2 Polarised Target

In case of a polarised proton target further sums appear in Equation (6) as mentioned above. They contain other linear combinations than $\tilde{M}$, so that measurements of target-spin asymmetries deliver valuable additional experimental information.

The single-spin asymmetry w.r.t. to the polarisation of a longitudinally (L) polarised target (LTSA) is defined as

$$A_{UL}(\phi) = \frac{d\sigma^{-\phi}(\phi) - d\sigma^{\phi}(\phi)}{d\sigma^{-\phi}(\phi) + d\sigma^{\phi}(\phi)}$$

where $\leftarrow (\Rightarrow)$ denotes target spin antiparallel (parallel) to the beam direction. In the above introduced approximation and for ‘balanced’ beam polarisation ($\langle P_I \rangle \approx 0$), its azimuthal dependence is also purely sinusoidal:

$$A_{UL}(\phi) \propto \frac{1}{c_{0,L}^{I_1}} s_{1,L}^{I_1} \sin(\phi).$$

Neglecting terms of $O(\xi^2)$ and higher, the Fourier coefficient $s_{1,L}^{I_1}$ is sensitive to a linear combination of CFFs different from Equation (11) (Belitsky et al. 2002; Diehl 2003):

$$s_{1,L}^{I_1} \propto \frac{\sqrt{t_0 - t}}{2m} \text{Im} \left[ F_1 \tilde{\mathcal{H}} + \xi (F_1 + F_2) \left( \mathcal{H} + \frac{\xi}{1 + \xi} \mathcal{E} \right) \right. - \left. \left( \frac{\xi}{1 + \xi} F_1 + \frac{t}{4m^2} F_2 \right) (\xi \bar{E}) \right].$$

$A_{UL}$ is expected to be most sensitive to a combination of $H^q$ and $\tilde{H}^q$, because the kinematic suppression of the second term in Equation (14) as compared to the first one, may approximately compensate the expected dominance of the unpolarised GPDs $H^q$ over their polarised counterparts $\tilde{H}^q$. Hence both should become separable by combining this measurement with asymmetries measured on an unpolarised target. For not too small values of $t$ there exists also some sensitivity to $(\xi \mathcal{E})$, which is written in this way as $\mathcal{E}$ itself is inversely proportional to $\xi$ (Goeke et al. 2001; Diehl 2003).

For a transversely (T) polarised target, the definition of the single-spin asymmetry (TTSA) $A_{UT}$ is more complicated. The additional dependence on the azimuthal angle $\phi_S$ of the spin vector creates ‘normal’ (N) and ‘sideways’ (S) components. In the approximation used for Equation (14) the corresponding Fourier coefficients contain yet further
combinations of CFFs (Diehl and Sapeta 2005). The normal component reads:

\[ s_{1,N}^I \propto -\frac{t}{4m^2} \text{Im} \left[ F_2 \mathcal{H} - F_1 \mathcal{E} + \xi(F_1 + F_2) (\xi \tilde{\mathcal{E}}) \right]. \]  (15)

This is known to be the only combination of CFFs where the GPDs \( E^q \) are not kinematically suppressed as compared to \( H^q \). Hence DVCS measurements on a transversely polarised proton target, in particular of the normal contribution, appear to be indispensable for the evaluation of the total quark angular momentum through the Ji relation (5). An inherent complication for the measurement of this relation lies in the fact that both the GPDs \( H^q \) and \( E^q \) need to be measured towards lowest possible values of \( t \), while the \( \phi \)-dependence of the cross section disappears in the limit \( t \to 0 \); the relevant asymmetry is suppressed by a factor of \( \sqrt{-t/2m} \) when extracting the GPDs \( H^q \) and even by a factor of \( t/4m^2 \) when extracting the GPDs \( E^q \), as can be seen from a comparison of Equations 11 and 15.

The sideways component, written in the above used approximation, undergoes the same kinematic suppression as the normal component:

\[ s_{1,S}^I \propto -\frac{t}{4m^2} \text{Im} \left[ F_2 \tilde{\mathcal{H}} + \xi(F_1 + F_2) \tilde{\mathcal{E}} - (F_1 + \xi F_2) (\xi \tilde{\mathcal{E}}) \right]. \]  (16)

It offers access to the imaginary part of a combination of both polarised CFFs, \( \tilde{\mathcal{H}} \) and \( (\xi \tilde{\mathcal{E}}) \), although accompanied by the unpolarised CFF \( \mathcal{E} \) whose \( \xi \)-suppression will presumably be compensated by its larger size.

### 4.3 Beyond DVCS

i) Similar as for differently polarised targets in DVCS, for hard exclusive processes other than DVCS, as eg meson production, the involved amplitudes embody other subsets of proton GPDs that are linearly combined by different kinematic suppression factors. In other words, a certain process is more sensitive to an individual GPD than another and hence a complete as possible determination of GPDs requires measurements of several hard exclusive reactions and/or final states.

ii) Every experiment covers a peculiar subspace of the \((x_B, t, Q^2)\) phase space, with certain overlap regions between experiments as will be detailed at the beginning of section 6. Hence a certain GPD combination accessible through a certain cross section, cross section difference or cross section asymmetry will be surveyed by different experiments in partly overlapping subspaces only.

iii) In ‘associated’ DVCS, where the proton target does not stay intact, the formalism of angular analysis remains the same, while the accessible GPDs are different from those of the proton (Diehl 2003).

iv) Hard exclusive leptoproduction on nuclear targets proceeds either coherently, \( ie \), by scattering on the nucleus as a whole, or incoherently, \( ie \) on a single proton or neutron. Coherent scattering proceeds preferentially at (very) small values of \( t \). For small and medium values of \( t \), the electromagnetic form factor of the neutron is small, leading to a small Bethe-Heitler cross section, as compared to DVCS. Hence in this \( t \)-region the interference term \( I \) is suppressed for scattering on the neutron and incoherent nuclear DVCS is expected to behave similarly to DVCS on the proton.
v) Gluon GPDs can be accessed in DVCS and vector meson production (Diehl 2003; Goloskokov and Kroll 2005), in particular at small $\xi$, *ie* at collider kinematics, but also in $\phi$-production at fixed-target kinematics (Diehl and Vinnikov 2004).

5 Experimental Results on DVCS

5.1 Collider Experiments

The DVCS cross section has been measured in hard exclusive photon electroproduction at the HERA collider by the experiments H1 and ZEUS. It becomes accessible by integrating Equation 1 over its azimuthal dependence (see section 3.1). For the $x_B$-range accessible at collider kinematics ($10^{-2} ... 10^{-4}$), two-gluon exchange plays a major role besides the above discussed quark-exchange handbag diagram, *ie*, both gluon and quark GPDs are probed simultaneously but only for very small skewedness values below $10^{-2}$.

The analysis method used is similar in both experiments due to their similar geometry. As the outgoing proton remains undetected in the beam pipe, the event topology is defined by two electromagnetic clusters, the outgoing lepton and the produced real photon, and at most one associated track. Two events samples are selected:

i) in the ‘DVCS-enriched’ sample a hard, *ie* centrally produced real photon is required, while the outgoing lepton is measured under a small scattering angle w.r.t. the incoming one; still a high enough virtuality $Q^2 > 4 \text{ GeV}^2$ is ensured by requiring a large energy of the scattered lepton (> 15 GeV).

ii) in the Bethe-Heitler dominated ‘reference sample’ the radiatively produced photon is emitted under a small angle w.r.t. the incoming lepton, and the outgoing lepton is measured in the central region.

A Monte Carlo simulation of the completely known BH process, which describes the reference sample, is used to subtract the BH contribution from the DVCS-enriched sample. The remainder of the spectrum is due to DVCS and possible additional background; no contribution from the interference term exists at leading twist, as the data are integrated over the azimuthal angle. The $Q^2$-dependence of the differential $\gamma^* p \rightarrow \gamma p$ cross section is illustrated in Figure 4. The data shown are from H1, both earlier published (Adloff et al. 2001) and recent preliminary (Favart 2004), and from ZEUS (Chekanov et al. 2003), the latter based on substantially higher statistics. The solid curve shows a NLO pQCD calculation (Freund and McDermott 2002) using a GPD parameterisation based on MRST2001 PDFs and a $Q^2$-dependent $t$-slope $b(Q^2)$ describing the factorised $t$-dependence (Freund et al. 2003). Using instead CTEQ6 PDFs with the same $t$-slope (not shown) yields a very similar $Q^2$-dependence, but a different normalisation. For comparison a Colour Dipole model calculation (Donnachie and Dosch 2001) is also shown in the Figure. Agreement between all data sets and models can be seen in the log-scale representation of the $Q^2$-dependence, although there seem to be discrepancies at lower values of $Q^2$.

The corresponding $W$-dependence is displayed in Figure 5 for the same data sets and models, where $W$ is the center-of-mass energy of the system of virtual photon and proton. The virtuality appears high enough to assign the observed steep rise with $W$ to the nature
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Figure 4. $Q^2$-dependence of the differential $\gamma^* p \rightarrow \gamma p$ cross section measured by H1 and ZEUS in comparison to a GPD-based NLO pQCD calculation. For comparison, a prediction of a Colour Dipole model is also shown. The Figure is taken from (Favart 2004).

Figure 5. $W$-dependence of the differential $\gamma^* p \rightarrow \gamma p$ cross section measured by H1 and ZEUS, compared to a GPD-based NLO pQCD calculation. For comparison, a prediction of a Colour Dipole model is also shown. The Figure is taken from (Favart 2004).

of DVCS as a hard process, as increasing $W$ implies decreasing $x_B$, where the parton densities in the proton show a fast rise. Most data reside at lower $Q^2$ ($\langle Q^2 \rangle = 8$ GeV$^2$), the region of possible discrepancies between data sets. Presently a $2\sigma$ difference exists between ZEUS and H1 data in the medium $W$-range. Differences of similar size exist between different model calculations. Note that, since the slope of the $t$-dependence of GPDs is still unknown, the normalisation of the GPD-based curves shown above remains arbitrary to some extent. Future measurements of the $t$-dependence of the DVCS cross section are therefore of high importance.
5.2 Fixed-target Experiments

In sections 3 and 4 it was shown that in hard exclusive real-photon leptoproduction the interference of the Bethe-Heitler and Deeply Virtual Compton Scattering processes is a rich source for extracting a wealth of information on GPDs. In fact, the first published GPD-related experimental results were beam-spin asymmetries measured in DVCS on the proton by the fixed-target experiments HERMES at HERA (Airapetian et al. 2001) with a positron beam and by CLAS at Jefferson Laboratory (Stepanyan et al. 2001) with an electron beam.

Figure 6. CLAS: Azimuthal dependence of the beam-spin asymmetry. Left: earlier data at 4.25 GeV. Right: recent preliminary data at 5.75 GeV. Only statistical errors are shown.

Figure 7. HERMES: Azimuthal dependence of the beam-spin asymmetry on proton (left) and deuteron (right), measured at 27.6 GeV. Only statistical errors are shown.
Note that opposite beam charges mean opposite signs of the measured BSAs, a fact that is not apparent when comparing Figures 6 and 7 due to different \( \phi \)-ranges chosen. Meanwhile, more precise (preliminary) BSA measurements were presented by both experiments.

The average beam polarisation at CLAS (HERMES) was 70\% (55\%). Both experiments use the missing-mass technique to compensate for present incompletenesses of their detectors; at CLAS (HERMES) the real photon (recoiling proton) remains undetected. At CLAS, the missing-mass resolution cannot cleanly separate the \( epn^0 \) from \( ep\gamma \) reactions. The electromagnetic calorimeter detects only photons above 8°, ie, it misses most of the DVCS photons but detects usually one of the two \( \pi^0 \) decay photons. In the analysis of the 5.75 GeV data, background from \( \pi^0 \) decay is reduced by applying a corresponding veto. A cut \( \theta_{\gamma\gamma^{*}} < 120 \text{ mrad} \) is used to select data at low \( t \). The missing mass squared for the undetected real photon is restricted to \( M_{X}^2 < 0.025 \text{ GeV}^2 \). The kinematics coverage for \( W > 2 \text{ GeV} \) is \( 1.2 < Q^2 < 4 \text{ GeV}^2 \) and \( 0.1 < x_B < 0.5 \), and the analysis is restricted to \( -t < 0.5 \text{ GeV}^2 \). At HERMES, to account for the limited resolution of the spectrometer, an asymmetric missing-mass interval around the proton mass is chosen (called ‘exclusive bin’: \( -1.5 < M_X < 1.7 \text{ GeV} \)), based on signal-to-background studies using a Monte Carlo simulation. Kinematic requirements to the outgoing lepton are \( 1 < Q^2 < 10 \text{ GeV}^2 \), \( W^2 > 9 \text{ GeV}^2 \) and \( \nu < 22 \text{ GeV} \), implying \( 0.03 < x_B < 0.35 \). For the results shown in Figure 7 (Ellinghaus et al. 2002b), the polar angle between virtual and produced real photon obeys \( 2 < \theta_{\gamma\gamma^{*}} < 70 \text{ mrad} \). Monte Carlo studies show that the exclusive sample contains about 10\% associated events, where the nucleon doesn’t stay intact, and about 5\% events from DIS fragmentation. Note that for the exclusive sample the variable \( t \) is calculated assuming the 3-particle final state \( ep\gamma \), thereby considerably improving the \( t \)-resolution, and the analysis is restricted to \( -t < 0.7 \text{ GeV}^2 \).

CLAS proton data for average kinematics ( \( \langle Q^2 \rangle = 1.25 \text{ GeV}^2 \), \( \langle x_B \rangle = 0.19 \), \( \langle -t \rangle = 0.19 \text{ GeV}^2 \)) are shown in Figure 6, the earlier (Stepanyan et al. 2001) BSA result in the left panel and the more recent preliminary result (Smith 2003) in the right one. The most recent (preliminary) BSA results from HERMES, on both proton and deuteron (Ellinghaus et al. 2002b), are shown in Figure 7. The average kinematics are \( \langle Q^2 \rangle = 2.5 \text{ GeV}^2 \), \( \langle x_B \rangle \approx 0.10 \) and \( \langle -t \rangle \approx 0.20 \text{ GeV}^2 \). All BSA data exhibit substantial sinusoidal asymmetries in accordance with the expectation given in Equation 9. The magnitude of the sin \( \phi \) component was fitted as \( 0.202 \pm 0.028_{\text{stat}} \pm 0.013_{\text{sys}} \) and \( -0.23 \pm 0.04_{\text{stat}} \pm 0.03_{\text{sys}} \) for the published data from CLAS and HERMES, respectively, while \( 0.202 \) and \( -0.18 \pm 0.03_{\text{stat}} \) were obtained from their recent preliminary data. The next-higher harmonic (sin(2\( \phi \))), see Equation 6 is found to be compatible with zero within the total experimental uncertainty in both experiments. No difference is seen when comparing the HERMES BSA results for proton and deuteron, which is not surprising when recalling the argument made in Note iv) of section 4.4. No published data exist yet for kinematic dependences of BSAs. Unpublished HERMES data (Ellinghaus 2004a) do not show any clear dependence on \( t \), \( x_B \) or \( Q^2 \) within experimental uncertainties.

A beam-charge asymmetry measurement requires data for both beam charges. HERA is presently the only GeV-range accelerator that provides both electron and positron beams. It offers the additional flexibility of switching from time to time, for the same charge of the beam, the direction of its polarisation to reduce systematic effects.

In Figure 8 preliminary BCA results from HERMES are shown (Ellinghaus 2004c),
Figure 8. HERMES: Azimuthal dependence of the beam-charge asymmetry on proton (left) and on unpolarised and vector-polarisation-balanced deuteron (right). Only statistical errors are shown.

Figure 9. HERMES: $t$-dependence of the $\cos \phi$ component of the beam-charge asymmetry on proton and deuteron. Statistical (systematic) uncertainties are indicated by error bars (bands). The curves represent LO pQCD calculations using different GPD ansätze, see text.

which were obtained from the same analysis as described above using $5 < \theta_{\gamma \gamma} < 45$ mrad. Both proton and deuteron data exhibit the expected $\cos \phi$-dependence with a similar sizeable magnitude, $0.059 \pm 0.028_{\text{stat}}$ and $0.061 \pm 0.018_{\text{stat}}$, again not a surprising agreement. The proton BCA also contains a significant $\sin \phi$-component that is caused by average beam polarisation values not vanishing individually for each beam charge. For clarity it has to be noted that an about twice as large deuteron BCA (not shown here)
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was reported earlier (Ellinghaus 2002a), obtained by discarding the low-\(t\) region with the requirement \(15 < \theta_{\gamma\gamma^*} < 70\) which led to a larger average value of \(\langle -t \rangle \simeq 0.27\) GeV\(^2\). Both results are consistent because the BCA decreases with decreasing \(-t\), as will be shown below.

Kinematic dependences are obtained by subdividing the data set into several bins, depending on the statistics for a given variable at a time. In each bin a fit of the azimuthal dependence is performed, including the same harmonics as indicated in the panels of Figure 8. The \(t\)-dependence of proton and deuteron BCA is shown in Figure 9, also obtained for \(5 < \theta_{\gamma\gamma^*} < 45\) mrad (Ellinghaus 2004c). As expected, the signal becomes only sizeable from medium values of \(-t\) on. Here proton and deuteron data agree, as discussed in Note iv) of section 4.3. Incoherent scattering on the neutron may become a substantial contribution at larger \(-t\)-values, \(ie\) in the last \(t\)-bin, and compensate a further increase of the deuteron asymmetry. No effects are seen from coherent scattering on the deuteron bound state which would be present in the lowest \(-t\)-bin only. Superimposed to the experimental data are curves representing theoretical calculations (Vanderhaeghen et al. 2001) based on different GPD models (Vanderhaeghen et al. 1999). They are calculated at HERMES kinematics, separately for the average kinematics in each individual bin (Ellinghaus 2004a). On the basis of the available statistics, the data seem to favour the model with the Regge ansatz and no D-term contribution. From Figure 9 it can already be concluded, and it will be discussed in more detail in section 6.3, that BCA measurements possess a considerable discriminative power against different ansätze and parameterisations in GPD models. Note that no dependence on \(x_B\) or \(Q^2\) is seen in unpublished BCA results (Ellinghaus 2004a).

![Figure 10. HERMES: The \(\sin(\phi)\)-component of the beam-spin asymmetry on Neon and Krypton, shown in dependence on missing mass. Only statistical errors are given.](image)

By measuring DVCS on a longitudinally polarised deuteron target, HERMES obtained a preliminary result on the longitudinal target-spin asymmetry (LTSA, cf. Equations 12-14). Fits as explained above, including \(\sin \phi\) and \(\sin(2\phi)\) harmonics, yield asymmetries compatible with zero; both components are found to be smaller than 0.03 with the total experimental uncertainty being of the same order.
DVCS on nuclear targets was briefly mentioned in Note iv) of section 4.3. Both experimental and theoretical information is scarce, especially for targets with an atomic number higher than that of deuterium. In Figure 10, preliminary BSA results of HERMES using Neon and Krypton targets are shown in dependence on the missing mass, using the proton mass to calculate the kinematic variables. The average kinematics are indicated in the panels, based on $2 < \theta_{\gamma\gamma^*} < 70$ mrad. As for all HERMES results discussed above, sizeable asymmetries appear only in the exclusive bin around the target (proton) mass, while they generally vanish at higher masses. It is clearly seen for both Neon and Krypton that already without separation of coherent and incoherent processes significant BSAs exist in the exclusive bin, while their interpretation can be attempted only after the separation. The fitted size of the $\sin \phi$-component is $-0.22 \pm 0.03 (-0.17 \pm 0.07)$ for Neon (Krypton), without significant higher harmonics (Ellinghaus et al. 2002b). For the case of coherent hard exclusive processes on nuclei it was pointed out that information about the energy, pressure, and shear forces distributions inside nuclei will become accessible (Polyakov 2003).

6 Future DVCS Measurements

In Figure 11 kinematics coverages are compared for DVCS measurements by existing or planned fixed-target experiments at CERN, HERA and JLAB. The kinematic limits are taken from (d’Hose 2002), (Ellinghaus 2004a and 2004b) and (Cardman et al. 2001).

Figure 11. Kinematics coverage for fixed-target experiments: i) COMPASS at 190 GeV; ii) HERMES at 27.6 GeV, dotted line for existing data ($\leq 2005$), solid line for future (2005-2007) data with an integrated luminosity higher by about one order of magnitude; iii) JLAB experiments at 6 GeV (now), and at 11 GeV (after upgrade).
As can be seen, the \((x_B, Q^2)\)-regions of these fixed-target experiments do partly overlap, while in comparison to the collider experiments at HERA there is no overlap in \(x_B\) (fixed-target above 0.03, collider below 0.01) and only very little overlap in \(Q^2\) (1...8 GeV\(^2\) vs. 5...100 GeV\(^2\)). Higher \(x_B\)-values (> 0.3) can only be accessed at JLAB, an advantage of their relatively low beam energy. At moderate \(x_B\), higher \(Q^2\)-values (≈ 8 GeV\(^2\)) are reachable in the short-term at HERMES only. Later on, the upgraded JLAB will be able to also reach this region, by compensating their lower beam energy by a huge luminosity planned to be several orders of magnitude higher than that at other facilities.

6.1 HERA Collider Experiments

No published projections exist, to what extent the recent detector upgrades of the HERA collider experiments H1 and ZEUS will be beneficial to the ongoing and future measurements of DVCS, until the foreseen shutdown of the HERA accelerator in the middle of 2007. The newly installed spin rotators make the polarised beam also available to H1 and ZEUS. In both experiments microvertex detectors have been installed which will allow the precise measurement of the outgoing lepton track, and hence of the event vertex, so that the azimuthal angle of the photon can be determined with higher precision. Altogether, these upgrades will make it possible to also measure the azimuthal dependence of beam-spin and beam-charge asymmetry at collider kinematics. It remains to be shown, to what extent these future data sets will allow the determination of quark or gluon GPDs in the region of very small \(\xi\).

6.2 Experiments at Jefferson Lab

Jefferson National Laboratory (JLAB) has approved two dedicated DVCS experiments to run at the 6 GeV longitudinally polarised electron beam with high luminosity. The first one, the high-resolution arm spectrometer E00-110 in Hall A (Bertin et al. 2000) is using both hydrogen and deuterium targets and finished data taking at the end of 2004. It aims at a precise check of the \(Q^2\)-dependence of cross section differences in the reaction \(e p \rightarrow e p \gamma\), for different beam helicities. The second experiment, E01-113 using the CLAS spectrometer in Hall B (Burkert et al. 2001), measures in early 2005 the kinematic dependence of the beam-spin asymmetry on \(t\), \(\phi\), and \(x_B\), for several fixed \(Q^2\)-bins. Also cross-section differences will be measured. As demonstrated in Figure 12, these dependences will be measured with a precision that will allow for a discrimination between certain parameter sets of GPD models.

Precision studies of hard exclusive scattering processes at fixed-target kinematics are among the main research programs driving the 12 GeV upgrade of the Continuous Electron Beam Accelerator at JLab (Cardman et al. 2001). The high-duty-cycle and high-intensity beam (electrons only) will facilitate more accurate measurements of cross sections and single-spin asymmetries w.r.t. beam helicity and target spin. Running, eg, 500 hours with the upgraded CLAS detector at a luminosity of \(10^{35}\) cm\(^{-2}\)s\(^{-1}\) will yield a BSA with a precision about twice better than that for E01-113 (cf. Figure 13), so that kinematic dependences can be studied in more detail. Projections (not shown) demonstrate (Cardman et al. 2001) that using, eg, 8 bins in the range \(0.2 < -t < 0.8\) in each of 3x3 cells in the \((2 < Q^2 < 5\) GeV\(^2\), \(0.2 < x_B < 0.6\))-plane, the beam-spin asymmetry may be
Figure 12. CLAS: Projections for beam-spin asymmetries at 6 GeV: $t$-dependence at $\phi = 90^o$ (left) and $\phi$-dependence at $-t = 0.325 \text{ GeV}^2$ (right). Projected statistical errors are given at $Q^2 = 2 \pm 0.5 \text{ GeV}^2$ and $x_B = 0.35 \pm 0.05$, for which the solid (dashed) curve shows a calculation (Vanderhaeghen et al. 2001) with $\xi$-(in)dependent GPDs (Vanderhaeghen et al. 1999). The long-dashed curve shows a calculation including twist-3 effects. Other curves are for other kinematics. The Figure is taken from (Elouadrhiri 2002).

Figure 13. CLAS: Projected statistical accuracy for a high-statistics BSA measurement at 11 GeV with an upgraded detector. Bins of $Q^2 = (3 \pm 0.1) \text{ GeV}^2$, $W = (2.8 \pm 0.15)$ GeV, and $-t = 0.3 \pm 0.1 \text{ GeV}^2$ are used. GPD calculations (Vanderhaeghen et al. 2001) are shown for different combinations of profile parameters (Vanderhaeghen et al. 1999). The Figure is taken from (Mecking 2002).

measured with good statistical precision in most of the cells.

No plans are published to also install a positron beam at JLAB, so that no high-precision measurements of beam-charge asymmetries can be expected.
6.3 New Results Expected from HERMES

Between 2002 and the middle of 2005, HERMES data are taken with a transversely polarised hydrogen target, allowing the evaluation of transverse target-spin asymmetries (cf. Equations 15,16). Based on an anticipated data sample of about 0.15 fb−1, a first attempt was made to evaluate the sensitivity to GPDs, in DVCS and hard exclusive $\rho^0$-production on the proton (Ellinghaus et al. 2005). Assuming $u$-quark dominance, the sensitivity to the GPD $E_u$ was studied and, through a model for it, also to the total angular momentum $J^u$ (cf. Equation 5). For both reactions, the projected total experimental $1\sigma$-uncertainty is equivalent to a range of about 0.12 in $J^u$, so that a significant result can be expected.

Figure 14. Left (right) panel: Existing data and projections on beam-charge (beam-spin) asymmetry on the proton, shown as $\cos \phi$ ($\sin \phi$) component. For explanations see text. Notes: i) the more recent $t$-dependence shown in Figure 9 is not included here; ii) HERMES average kinematics are used for the displayed model calculations, the average CLAS kinematics are lower (higher) in $Q^2$ ($x_B$) by about a factor of two, as it can also be seen in the Figure. The Figure is taken from (Ellinghaus 2004b).
The newly built HERMES recoil detector (HERMES Collaboration 2001) will surround the (unpolarised) internal gas target. By measuring the hitherto undetected recoil proton and/or other low-momentum particles, it will serve several purposes:

i) the slow recoil proton can be identified measuring its large energy deposition in the (diamond-shaped) double-layer double-sided Silicon strip detector.

ii) in conjunction with a double (stereo)-layer scintillating fiber detector possible additional tracks will be identified, so that the exclusivity of the reaction can be established and contaminations from DIS fragmentation and associated (resonance) production will both be reduced to \(<1\%\).

For 2005-2007, HERMES recoil detector operation is planned with an unpolarised hydrogen target, sharing about equally the running time between both beam charges. In Figure 14 projected accuracies are shown for beam-charge and beam-spin asymmetries, confronted to different GPD model predictions that are explained in Table 1.

| Model | D–Term | \(b_{val}\) | \(b_{sea}\) | Ansatz \(t\)–dependence |
|-------|---------|------------|-------------|----------------------|
| A     | Yes     | 1          | \(\infty\)  | Regge                |
| B     | No      | 1          | \(\infty\)  | Regge                |
| C     | Yes     | 1          | \(\infty\)  | factorised           |
| D     | No      | 1          | \(\infty\)  | factorised           |
| E     | Yes/No  | 1          | 1           | factorised           |

**Table 1.** Parameter sets for GPD model predictions calculated (Vanderhaeghen et al. 2001) on the basis of (Vanderhaeghen et al. 1999) in (Ellinghaus 2004a).

Error bars shown are total experimental uncertainties, i.e., statistical and systematic uncertainty added in quadrature. The statistical accuracy at a given point in one of the variables \((-t, x_B, Q^2)\) includes integration over the other two variables. Existing data already discussed above, included for completeness, are shown at average kinematics: Preliminary HERMES data are represented by closed triangles for BCA (Ellinghaus 2002a) and 2000 BSA (Ellinghaus 2002b), but open triangles for 96/97 BSA (Airapetian et al. 2001); open crosses show BSA data from CLAS (Stepanyan et al. 2001). Projected total experimental uncertainties for future BCA and BSA results from HERMES are shown in dependence on \(-t, x_B, and Q^2\) (Ellinghaus 2004b): Black squares show the precision of the soon expected final results from 1996-2000 proton data and red circles show the projected precision for 1 fb\(^{-1}\) of data from recoil detector running in 2005-2007. Clearly, in the last case a finer binning will be possible for lower values of the respective variables.

Somewhat earlier (Korotkov and Nowak 2002a) the azimuthal dependence of the beam-charge asymmetry was studied for a certain class of GPD models (Vanderhaeghen et al. 1999; Goeke et al. 2001); projections for larger values of \(x_B\) are shown in Figure 15. For the models chosen, there seems to be a clear sensitivity to the existence of the D-term, although it was also shown that the D-term contribution can be replaced by equivalent tuning of other model parameters (Belitsky et al. 2002). The right panel of the same figure indicates that from the anticipated data set even 2-dimensional dependences can be mapped to some extent, here showing the \(t\)-dependence of the beam-spin asymmetry for two distinct regions in \(x_B\) (Korotkov 2001).
When measuring a beam-spin asymmetry at HERMES kinematics, the imaginary part of $\tilde{M}$ (cf. Equation 11 and text thereafter) will be dominated by $\text{Im} \mathcal{H}$, ie by the GPDs $H^q$. This suggests a possible way for a first measurement of the quantity

**Figure 15.** HERMES: Projections for 2005-07 running with a recoil detector, based on $2 \text{ fb}^{-1}$. Left: $\phi$-dependence of beam-charge asymmetry in the region $x_B > 0.20$. GPDs calculated without D-term, where dashed-dotted means $\xi$-independent and long-dotted (long-dashed) means $\xi$-dependent with profile parameter $b = 1 \ (b = 3)$, are confronted to those including a D-term, denoted by dotted (dashed) instead. Right: $t$-dependence of the $\sin \phi$-component of the beam-spin asymmetry, for two distinct regions in $x_B$. The figures are taken from (Korotkov and Nowak 2002a) and (Korotkov 2001).

**Figure 16.** HERMES: Projected extraction of $\text{Im} \mathcal{H}$, measuring DVCS at HERMES with a Recoil Detector in 2005-07, based on $2 \text{ fb}^{-1}$. The projection B (A) is calculated using a $\xi$-(in)dependent GPD, corresponding to the dash-dotted (long-dotted) line in the left panel of the previous figure. Solid lines enclose the projected fully correlated $1 \sigma$ error band in the region $-t \leq 0.15 \text{ GeV}^2$. The shaded area outside of a band indicates a possible systematic uncertainty of the extraction method used. The figure is taken from (Korotkov and Nowak 2002b).
\[ \sum q e_q^2 (H^q(\xi, \xi, t) - H^q(-\xi, \xi, t)). \] Its dependence on the skewedness variable \( \xi \) is shown in Figure 16 (Korotkov and Nowak 2002b) for two different GPD parameterisations (see caption). Measuring on a proton target, \( u \)-quark dominance can be used to obtain a coarse mapping of the function \((H^u(\xi, \xi, t) - H^u(-\xi, \xi, t))\) as a function of \( t \) and \( \xi \), ie \( x_B \). This function is sometimes referred to as ‘singlet’ combination, as in the forward limit of vanishing \( t \) (and \( \xi \)) it reduces to the unpolarised singlet quark PDF \( u(x_B) + \bar{u}(x_B) \).

Altogether, the new data set expected from HERMES running in 2005-2007 with a recoil detector will have greatly improved capabilities to discriminate between different GPD models.

### 6.4 Future DVCS Results from COMPASS

When considering leptoproduction by muons instead of electrons, the strength of radiative elastic scattering is reduced by the squared ratio of the beam particle masses, \((m_e/m_\mu)^2\) (Mo and Tsai 1969). The relative contributions of Bethe-Heitler and DVCS processes to real photon leptoproduction vary strongly with beam energy, the former dominates the latter at electron beam energies of 27.5 GeV (Korotkov and Nowak 2002a) and below. Hence at HERMES and CLAS the DVCS cross section contribution is very hard to access experimentally. Instead, for a muon beam the DVCS process is already dominant over the BH one at an energy of 200 GeV, making COMPASS at CERN the only

**Figure 17.** COMPASS: Projected statistical accuracy for the beam-charge asymmetry from 100 GeV running, 3 months each per beam charge, with an upgraded apparatus. The statistical uncertainty shown is for the bin \( 0.03 < x_B < 0.07, 1.5 < Q^2 < 2.5 \text{GeV}^2 \) while integrating over \( 0.06 < -t < 0.3 \text{GeV}^2 \). Solid and dotted curve show a non-factorised and a Regge-type GPD ansatz. The Figure is taken from (d’Hose et al. 2002).

set-up that is able to measure \( |\tau_{\text{DVCS}}|^2 \) at moderate values of \( x_B \). At 100 GeV, DVCS and BH contribution are of comparable size, suggesting this lower energy for a measurement of the beam-charge asymmetry. Like in the case of the HERA electron or positron
beam, the CERN SPS muon beam can be produced with either charge. Unlike the former case, its helicity is fixed and hence always non-zero for individual beam charges. The resulting non-zero $\sin \phi$-component in the beam-charge asymmetry drops out when symmetrising the BCA, ie, when calculating it only over a range of $\pi$.

A possible GPD experiment at COMPASS (Burtin et al. 2003) would use a 2.5 meter long liquid hydrogen target to achieve a luminosity comparable to that of HERMES, ie, approximately $10^{32}$ s$^{-1}$ cm$^{-2}$. Several detector upgrades are necessary to reduce photon background from $\pi^0$ and to detect the recoil proton. The anticipated accuracy of a DVCS cross section measurement at $E_\mu = 190$ GeV amounts to a few % (Burtin et al. 2003). Running at 100 GeV will allow to measure the azimuthal dependence of the beam-charge asymmetry in bins of $x_B$ and $Q^2$ with good statistical accuracy, as can be inferred from Figure 17 (d’Hose et al. 2002), with the two curves representing two different GPD ansätze, see caption.

7 Conclusions

Deeply Virtual Compton Scattering appears to be the presently best tool to pursue the in-depth study of the angular momentum structure of the nucleon. Interpreting the rich body of present and future data within the theoretical framework of generalised parton distributions, it can be expected that severe constraints to different ansätze and parameterisations will emerge.

Final analysis results from existing JLAB and HERMES data sets are expected soon to give a first glimpse on kinematic dependences of beam-spin and beam-charge (HERMES only) asymmetries on proton and deuteron (HERMES only). Final data on proton and deuteron longitudinal target-spin asymmetries can be expected from HERMES, as well as on the $A$-dependence of BSAs measured on several nuclei.

HERMES data taking with a transversely polarised hydrogen target in 2003-2005 is expected to yield information on transverse target-spin asymmetries, which may be capable of giving first experimental hints on the total angular momentum of the $u$-quark.

JLAB experiments running in 2004 and 2005 and HERMES running with a recoil detector in 2005-2007 are expected to deliver quite accurate kinematic dependences of asymmetries and cross section differences. This data will presumably allow a first look to the $\xi$-dependence of the unpolarised ‘valence’ $u$-quark GPD.

Independent information is expected from possible COMPASS running in the last quarter of the decade, in particular beam-charge asymmetry and DVCS cross section will be measured with good precision at moderate values of $x_B$.

The collider experiments H1 and ZEUS are measuring DVCS at very small values of $x_B$. They have obtained the $Q^2$ and $W$-dependence of the DVCS cross section and will attempt to measure its $t$-dependence, as well. Based on recent upgrades they will attempt to obtain results on beam-spin and beam-charge asymmetries from data taking in 2005-2007.

The extraction of firm information on GPDs from experimental data will continue to constitute a complicated task. As can be judged from today, a major step in precision towards multi-dimensional mapping of generalised parton distributions can be made once
the 12 GeV upgrade of the JLab electron beam facility will have become reality. This data will then allow to perform a global fit based on high-precision beam-spin (and target-spin) asymmetries, aiming at a simultaneous determination of several accessible GPDs in dependence on $t, x_B,$ and $Q^2$. Note that a considerable model-dependence will remain for the (internal) $x$-dependence of GPDs, as it can be accessed only via beam-charge asymmetry measurements that are not possible at JLAB. Nevertheless, eventually completely new knowledge may become available on the 3-dimensional angular momentum structure of the nucleon.

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