Eur. Phys. J. A **18**, 429–432 (2003)
DOI 10.1140/epja/i2002-10252-0

THE EUROPEAN
PHYSICAL JOURNAL A

Generalized parton distributions

M. Vanderhaeghen[a]

Institut für Kernphysik, Johannes Gutenberg-Universität, D-55099 Mainz, Germany

Received: 30 September 2002 /
Published online: 22 October 2003 –

Abstract. We discuss how generalized parton distributions (GPDs) enter in a variety of hard exclusive processes such as deeply virtual Compton scattering (DVCS) and hard meson electroproduction reactions on the nucleon. We show some key observables which are sensitive to the various hadron structure aspects of the GPDs, and discuss their experimental status.

PACS. 13.60.Fz Elastic and Compton scattering – 13.60.Le Meson production – 12.38.Bx Perturbative calculations

1 Introduction

Generalized parton distributions (GPDs), are universal non-perturbative objects entering the description of hard exclusive electroproduction processes (see refs. [1–3] for reviews and references). In leading twist there are four GPDs for the nucleon, *i.e.* H, E, $\tilde{H}$ and $\tilde{E}$, which are defined for each quark flavor (u, d, s). These GPDs depend upon the different longitudinal momentum fractions $x + \xi$ $(x - \xi)$ of the initial (final) quark and upon the overall momentum transfer $t = \Delta^2$ to the nucleon (see fig. 1). As the momentum fractions of initial and final quarks are different, one accesses quark momentum correlations in the nucleon. Furthermore, if one of the quark momentum fractions is negative, it represents an antiquark and, consequently, one may investigate $q\bar{q}$ configurations in the nucleon. Therefore, these functions contain a wealth of new nucleon structure information, generalizing the information obtained in inclusive deep inelastic scattering.

In particular, the GPDs allow to access the fraction of the nucleon spin carried by the quark total angular momentum (J^u, J^d, etc.), $\bar{q}q$ components of the nucleon wave function (in particular the D-term [4]), the strength of the skewedness effects in the GPDs (encoded in their ξ-dependence), the quark structure of $N \to N^*$, Δ transitions, flavor $SU(3)$ breaking effects, and others. Furthermore, it has been shown that by a Fourier transform of the t-dependence of GPDs, it is conceivable to access the distributions of parton in the transverse plane [5,6].

[a] e-mail: marcvdh@kph.uni-mainz.de

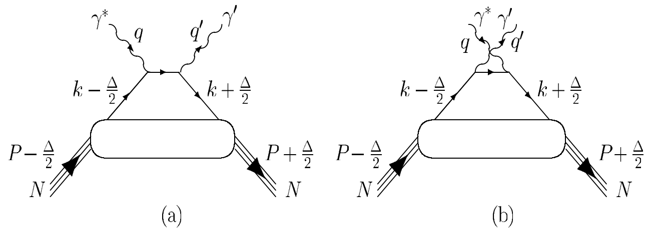

Fig. 1. "Handbag" diagrams for the DVCS process, containing the GPDs.

2 DVCS beam-helicity asymmetry

We first turn to the DVCS observables and their dependence on the GPDs. At intermediate lepton beam energies, one can extract the imaginary part of the DVCS amplitude through the $ep \to ep\gamma$ reaction with a polarized lepton beam, by measuring the out-of-plane angular dependence (in the angle ϕ) of the produced photon [7]. It was found in refs. [8,9] that the resulting electron single spin asymmetry (SSA)

$$\mathcal{A}^{\rm SSA} = \frac{\sigma_{e,h=+1/2} - \sigma_{e,h=-1/2}}{\sigma_{e,h=+1/2} + \sigma_{e,h=-1/2}}\,, \qquad (1)$$

with $\sigma_{e,h}$ the cross-section for an electron of helicity h, can be sizeable for HERMES ($E_e = 27\,\mathrm{GeV}$) and JLab ($E_e =$ 4–11 GeV) beam energies. The SSA for the $\boldsymbol{ep} \to ep\gamma$ reaction has recently been measured in pioneering experiments at HERMES [10] and JLab/CLAS [11], as shown in fig. 2. They display already at the accessible values of $Q^2 \simeq$ 1–2.5 GeV^2 predominantly a $\sin\phi$-dependence, indicating a dominance of the twist-2 DVCS amplitude. Furthermore, the observed magnitude is in good agreement with the

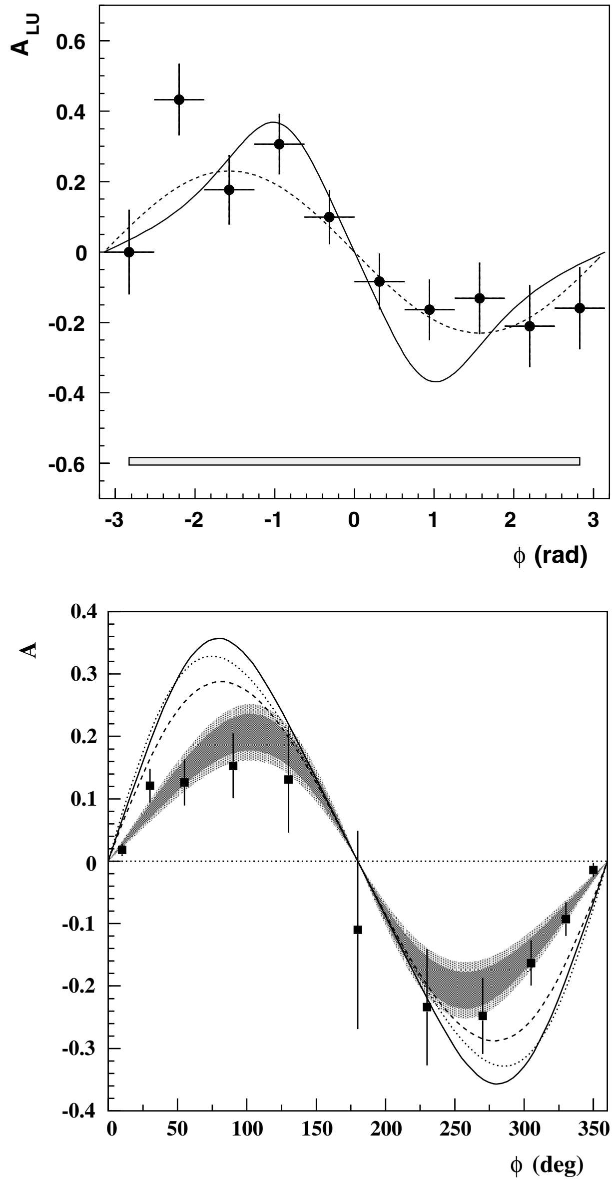

Fig. 2. The DVCS beam helicity asymmetry as measured at HERMES [10] (upper panel) and JLab/CLAS [11] (lower panel). Full curves: twist-2 + twist-3 predictions of ref. [12].

theoretical calculations [12,13] in terms of GPDs. Once the leading-order mechanism is confirmed by experiment, the measured helicity difference is directly proportional to the GPDs along the line $x = \xi$.

Dedicated experiments to measure the SSA with improved accuracy in a large kinematic range are already planned and underway both at JLab and HERMES.

Recently, the double deeply virtual Compton scattering (DDVCS) process has been studied [14] through the scattering of a spacelike virtual photon with large virtuality resulting in the production of a timelike virtual photon, decaying into an e^+e^- pair. For DDVCS, by varying the virtualities of both incoming and outgoing virtual photons, one can vary independently the variables ξ and ξ', where $-2\xi'$ is the longitudinal momentum fraction of the

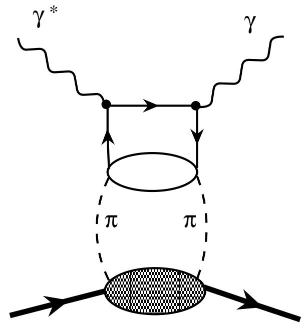

Fig. 3. Model contribution to the D-term entering the GPDs H and E.

incoming virtual photon. In contrast, in DVCS, only one variable can be varied as $\xi \approx \xi'$. It was then shown in ref. [14] that the imaginary part of the DDVCS amplitude (which can be directly measured through the beam helicity asymmetry as discussed for the DVCS process above) will access, in a concise notation, the GPD$(2\xi' - \xi, \xi, t)$, and allows to map out the GPDs as a function of its three arguments independently. In particular, in this way one can access the domain $x < \xi$ of the GPD(x, ξ, t), where one is sensitive to $q\bar{q}$ correlations in the nucleon. Although the cross-sections for the DDVCS process are small, their measurement seems feasible with a dedicated experiment at JLab and at a future high-energy, high-luminosity lepton facility.

3 DVCS beam-charge asymmetry

Besides the beam-helicity asymmetry for the $\boldsymbol{e}p \to ep\gamma$ reaction, which accesses the imaginary part of the DVCS amplitude, one gets access to the real part of the DVCS amplitude by measuring both $e^+p \to e^+p\gamma$ and $e^-p \to e^-p\gamma$ processes. In those reactions, besides the mechanism where the photon originates from a quark (handbag diagrams of fig. 1), the photon can also be emitted by the lepton lines, in the so-called Bethe-Heitler (BH) process. However, in the difference $\sigma_{e^+} - \sigma_{e^-}$, the BH drops out, and one measures the real part of the BH-DVCS interference [15],

$$\sigma_{e^+} - \sigma_{e^-} \sim \Re\Big[T^{\mathrm{BH}} T^{\mathrm{DVCS}*}\Big], \qquad (2)$$

which is sensitive to (a convolution integral of) GPDs away from the line $x = \xi$.

It has been shown in [12] that this beam-charge asymmetry (BCA) gets a sizeable contribution from the D-term. The latter encodes $q\bar{q}$ scalar-isoscalar correlations in the nucleon as shown in fig. 3, and has been estimated in the chiral quark soliton model [16].

The DVCS BCA has been accessed experimentally at HERMES [17], and the preliminary data are shown in fig. 4, together with the theoretical predictions. The measured asymmetry shows a $\cos\phi$-dependence with magnitude $\sim$ 0.10–0.15, and favors the calculations which include the D-term. This opens up the perspective to study

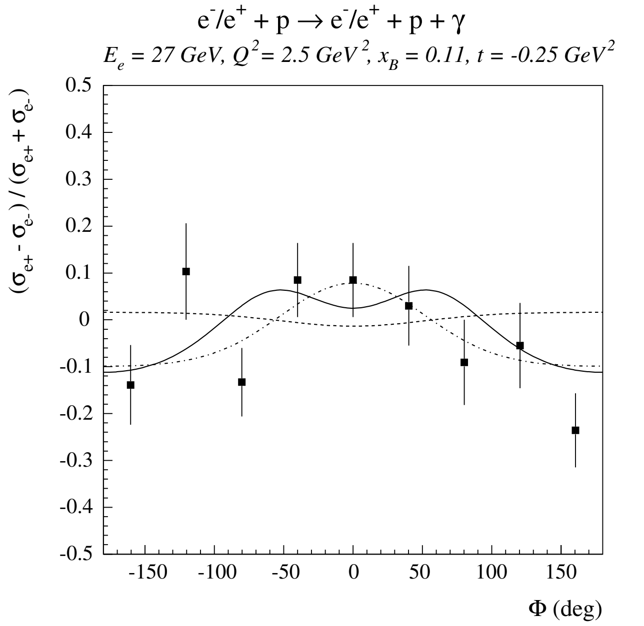

Fig. 4. The DVCS beam-charge asymmetry with preliminary HERMES data [17]. Theoretical predictions from [12]. Dashed-dotted (dashed) curves: twist-2 DVCS with (without) D-term. Full curve: twist-3 effects in addition to the D-term.

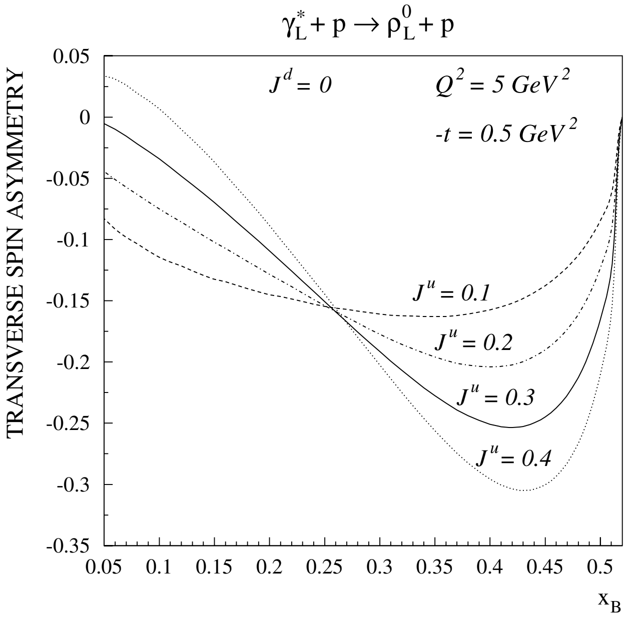

Fig. 5. x_B-dependence of the transverse target spin asymmetry for the $\gamma^*_L p \to \rho^0_L p$ reaction. The estimates are given using the model of ref. [3] for the GPDs E^u and E^d. The sensitivity is shown to different values of J^u (for a value $J^d = 0$).

systematically (mesonic) $q\bar{q}$ components in the nucleon. Further measurements, with improved statistics, of the DVCS BCA are planned at HERMES.

4 Hard meson electroproduction

The GPDs reflect the structure of the nucleon independently of the reaction which probes the nucleon. In this sense, they are universal quantities and can also be accessed, in different flavor combinations, through the hard exclusive electroproduction of mesons, for which a QCD factorization proof was given [18]. This factorization theorem applies when the virtual photon is longitudinally polarized, which corresponds to a small-size configuration compared to a transversely polarized photon.

For the longitudinal vector meson (V_L) electroproduction processes $\gamma^*_L + N \to V_L + N$ at large Q^2, the GPDs enter in different isospin combinations for $V_L = \rho^0_L, \rho^+_L, \omega_L$, allowing for a flavor decomposition of GDPs.

An $\gamma^*_L + N \to V_L + N$ observable of particular interest is the transverse spin asymmetry (TSA) for a nucleon polarized perpendicular to the reaction plane [3]. The TSA is proportional to the imaginary part of the *interference* of the amplitudes which contain the GPDs H and E, respectively. Therefore, the TSA provides a unique observable to extract the GPD E. Besides, one may expect that the theoretical uncertainties for the meson electroproduction cross-sections largely disappear for the TSA, as it involves a ratio of cross-sections, suggesting that the leading-order expression is already accurate at accessible values of Q^2 (of a few GeV^2). Due to its linear dependence on the GPD E, the TSA for longitudinally polarized vector mesons opens up the perspective to get information on the total angular momentum contributions J^u and J^d of the u- and d-quarks to the proton spin. Due to the different u- and d-quark content of the vector mesons, the asymmetries for the ρ^0_L, ω_L and ρ^+_L channels are sensitive to different combinations of J^u and J^d, with ρ^0_L production sensitive to $2J^u + J^d$, ω_L to $2J^u - J^d$, and ρ^+_L to $J^u - J^d$.

In fig. 5, the TSA for ρ^0_L production is shown. One observes that it displays a pronounced sensitivity to J^u. It will therefore be very interesting to provide a first measurement of this asymmetry in the near future, for a transversely polarized target, such as is currently available at HERMES.

5 Outlook

We have seen some very promising first glimpses of GPDs entering hard exclusive reactions at existing facilities. A dedicated program aiming at the extraction of the full physics potential contained in the GPDs will require a dedicated facility combining high luminosity and a good resolution.

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