IL NUOVO CIMENTO Vol. 36 C, N. 5 Settembre-Ottobre 2013
DOI 10.1393/ncc/i2013-11580-8

Colloquia: QCDN12

Constraining GPDs at Jefferson Lab

H. S. Jo
Institut de Physique Nucléaire d'Orsay - 91406 Orsay, France

ricevuto il 18 Aprile 2013

Summary. — Generalized parton distributions (GPDs) are nowadays the object of an intense effort of research. Among other aspects, they allow to unravel the correlation between the longitudinal momentum fraction and the transverse spatial distributions of quarks and gluons inside the nucleon, with the prospect of accessing the angular momentum contribution of the partons to the nucleon's spin. The Hall A and CLAS Collaborations of Jefferson Lab, or JLab, play a key role in the extraction of GPDs from deeply virtual Compton scattering (DVCS) and from deeply virtual meson production (DVMP). This topic is at the heart of the physics program for the upcoming JLab machine upgrade to 12 GeV. This report presents an overview (with a large focus on DVCS) of published results and ongoing analyses from JLab 6 GeV data, and future experiments planned at JLab 12 GeV, in Hall A and with the future CLAS12 detector in Hall B.

PACS 13.60.Fz – Elastic and Compton scattering.
PACS 13.60.Le – Meson production.
PACS 14.20.Dh – Protons and neutrons.
PACS 24.85.+p – Quarks, gluons, and QCD in nuclear reactions.

1. – Introduction

Generalized parton distributions (GPDs) take the description of the complex internal structure of the nucleon to a new level by providing access to, among other things, the correlations between the transverse position and longitudinal momentum distributions of the partons in the nucleon. They also give access to the orbital momentum contribution of partons to the spin of the nucleon.

GPDs can be accessed via deeply virtual Compton scattering (DVCS) and deeply virtual meson electroproduction (DVMP), processes where an electron interacts with a parton from the nucleon by the exchange of a virtual photon, and that parton radiates a real photon (in the case of DVCS) or hadronizes into a meson (in the case of DVMP). The amplitude of the process can be factorized into a hard-scattering part, exactly calculable in pQCD or QED, and a non-perturbative part, representing the soft structure of the nucleon, parametrized by the GPDs. At leading twist and leading order, there are four independent quark helicity conserving GPDs for the nucleon: H, E, $\tilde{H}$ and $\tilde{E}$. These

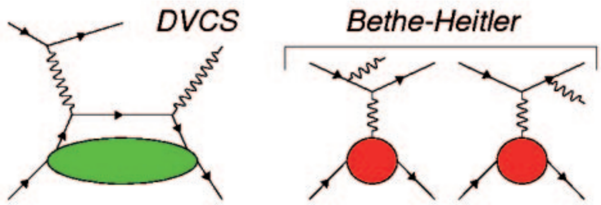

Fig. 1. – One of the two handbag diagrams for DVCS (left) and diagrams for Bethe-Heitler (right). These two processes contribute to the amplitude of the $eN \to eN\gamma$ reaction.

GPDs are functions depending on three variables x, ξ and t, among which only ξ and t are experimentally accessible. The quantities $x + \xi$ and $x - \xi$ represent respectively the longitudinal momentum fractions carried by the initial and final parton. The variable ξ is linked to the Bjorken variable x_B through the asymptotic formula: $\xi = \frac{x_B}{2-x_B}$. The variable t is the squared momentum transfer between the initial and final nucleon. Since the variable x is not experimentally accessible, only Compton form factors (CFFs), $\mathcal{H}$, $\mathcal{E}$, $\tilde{\mathcal{H}}$ and $\tilde{\mathcal{E}}$, whose real parts are weighted integrals of GPDs over x and whose imaginary parts are combinations of GPDs at $x = \pm\xi$, can be extracted:

$$\mathrm{Re}\,\mathcal{F} \equiv P \int_0^1 \mathrm{d}x[F(x,\xi,t) \mp F(-x,\xi,t)]C^{\pm}(x,\xi), \tag{1}$$

$$\mathrm{Im}\,\mathcal{F} \equiv F(\xi,\xi,t) \mp F(-\xi,\xi,t), \tag{2}$$

where $\mathcal{F}$ is a CFF, F is a GPD, and $C^{\pm}(x,\xi) = \frac{1}{x-\xi} \pm \frac{1}{x+\xi}$. The top signs correspond to the unpolarized (H, E) GPDs and the bottom signs to the polarized ($\tilde{H}$, $\tilde{E}$) GPDs. Proton and neutron GPDs that are respectively accessed through the proton and neutron CFFs are linked to the u- and d-quark GPDs in the following way for the GPD H:

$$H_p(\xi,\xi,t) = \frac{4}{9}H_u(\xi,\xi,t) + \frac{1}{9}H_d(\xi,\xi,t), \tag{3}$$

$$H_n(\xi,\xi,t) = \frac{4}{9}H_d(\xi,\xi,t) + \frac{1}{9}H_u(\xi,\xi,t), \tag{4}$$

and similarly for the other GPDs.

The reader is referred to refs. [1-10] for detailed reviews on the GPDs and the theoretical formalism.

2. – Deeply virtual Compton scattering (DVCS)

Among the exclusive reactions allowing access to GPDs, DVCS, which corresponds to the electroproduction of a real photon off a nucleon $eN \to eN\gamma$, is the key reaction since it offers the simplest theoretical interpretation in terms of GPDs. The DVCS amplitude interferes with the amplitude of the Bethe-Heitler (BH) process which leads to the exact same final state. In the BH process, the real photon is emitted by either the incoming or the scattered electron while in the case of DVCS, it is emitted by the target nucleon (see fig. 1). Although these two processes are experimentally indistinguishable, the BH process is well-known and exactly calculable in QED. At current JLab energies (6 GeV), the BH process is dominant in most of the phase space but the DVCS process can be accessed via the interference term arising from the two processes.

With a polarized beam or/and a polarized target, different types of asymmetries can be extracted: beam-spin asymmetry (A_{LU}), longitudinally polarized target-spin asymmetry (A_{UL}), transversely polarized target-spin asymmetry (A_{UT}), and double-spin (beam-target) asymmetries (A_{LL}, A_{LT}). Each type of asymmetry gives access to a different combination of CFFs, and is mostly sensitive to one or two particular CFF(s). Single-spin asymmetries give access to the imaginary part of the CFFs and double-spin asymmetries to their real part. The DVCS/BH $eN \to eN\gamma$ unpolarized cross section is sensitive to both the real part and the imaginary part of the CFFs. The beam-polarized cross section difference is linearly proportional to the imaginary part of the CFFs.

For the past few years, DVCS has been the subject of several experiments carried out by the Hall A and CLAS Collaborations, using JLab's 6 GeV polarized electron beam. The high resolution spectrometers (HRS) of Hall A [11] allow high accuracy measurements while Hall B's "4π" CLAS detector [12] provides a very large kinematic coverage.

2·1. *Hall A at 6 GeV*. – Using a 5.75 GeV polarized electron beam and a LH_2 target (E00-110 experiment), the Hall A Collaboration measured the $ep \to ep\gamma$ reaction [13]. The scattered electron and the produced photon were detected respectively with one of the HRSs and a dedicated PbF_2 electromagnetic calorimeter. The high resolution allowed a precise selection of the exclusive reaction by cutting on the missing mass of the proton. DVCS unpolarized 4-fold cross sections were extracted at $Q^2 = 2.3\,\mathrm{GeV}^2$ and $x_B = 0.36$, for four different values of $-t$ (0.17, 0.23, 0.28, and $0.33\,\mathrm{GeV}^2$). DVCS beam-polarized cross sections, mostly sensitive to the imaginary part of the proton CFF $\mathcal{H}_p$, were not only extracted at the same kinematics but also at $Q^2 = 1.5\,\mathrm{GeV}^2$ and $Q^2 = 1.9\,\mathrm{GeV}^2$. At leading twist, the GPDs and CFFs are expected to be independent of Q^2. The Hall A results do not show a Q^2 dependence, which is a strong indication of the handbag dominance, already at those relatively low Q^2 values, although it is on a quite limited Q^2 range. The Hall A Collaboration also measured the $en \to en\gamma$ reaction [14] by using a LD_2 target (E03-106 experiment). DVCS beam-polarized cross sections on the neutron, mostly sensitive to the imaginary part of the neutron CFF $\mathcal{E}_n$, were extracted at $Q^2 = 1.9\,\mathrm{GeV}^2$ and $x_B = 0.36$, for different values of $-t$ (from 0.1 to $0.5\,\mathrm{GeV}^2$), and were found to be compatible with zero.

Two experiments, E07-007 (proton) and E08-025 (neutron), were carried out in 2010, using different beam energies to attempt a Rosenbluth-like separation of the BH-DVCS interference term and the pure DVCS term. Analyses are in progress.

2·2. *Hall B (CLAS) at 6 GeV*. – The e1-DVCS experiment was carried out in Hall B of JLab using a 5.75 GeV polarized electron beam and a LH_2 target, aiming to measure the $ep \to ep\gamma$ reaction. The setup allowed a fully exclusive measurement, using a dedicated $PbWO_4$ electromagnetic calorimeter located at the forward angles, where the DVCS/BH photons are mostly emitted, to extend the acceptance of the CLAS spectrometer. The e1-DVCS data cover the following ranges: $1 < Q^2 < 4.6\,\mathrm{GeV}^2$, $0.1 < x_B < 0.58$, and $0.09 < -t < 2\,\mathrm{GeV}^2$. From these data, the CLAS Collaboration published the largest set of DVCS A_{LU} asymmetries ever measured in the valence quark region [15]. The asymmetries were extracted as a function of $-t$ for different bins in (Q^2, x_B). The predictions from the VGG GPD model [9,10] overestimate the asymmetries at low $|-t|$, especially for small values of Q^2 which can be expected since the GPD mechanism is supposed to be valid at high Q^2.

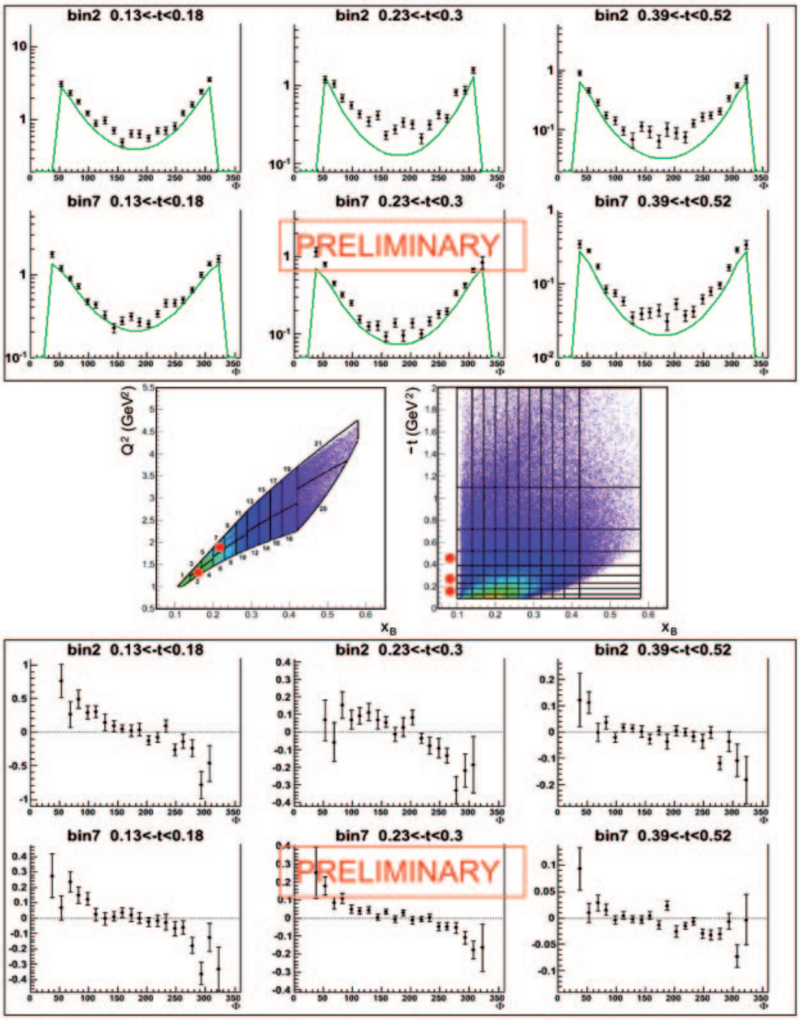

Fig. 2. – Sample of preliminary results for the DVCS unpolarized (top six plots) and beam-polarized (bottom six plots) 4-fold cross sections, in nb/GeV^4, as a function of Φ, for three bins in $-t$ (corresponding to the three columns) and for two different sets of values of Q^2 and x_B (corresponding to the two rows). These selected kinematics are highlighted with red full circles on the Q^2 vs x_B (bins 2 and 7, out of 21 bins) and $-t$ vs x_B (bins in $-t$) distributions from the middle part of the figure which shows the large kinematic coverage of the e1-DVCS data. The curves on the unpolarized cross sections plots represent the BH calculation, integrated over each 4-dimensional bin.

We are in the process of extracting, from the e1-DVCS data, DVCS unpolarized and beam-polarized 4-fold cross sections on the proton [16]: $\frac{\mathrm{d}^4\sigma}{\mathrm{d}Q^2\,\mathrm{d}x_B\,\mathrm{d}t\,\mathrm{d}\Phi}$ in bins in $(Q^2, x_B, -t, \Phi)$, with Φ the angle between the leptonic and hadronic planes. Figure 2 shows a sample of preliminary results. The top six plots show DVCS unpolarized cross sections as a function of Φ for three bins in $-t$ (corresponding to the three columns), for two different sets of values of Q^2 and x_B (bins 2 and 7, corresponding to the two rows). The curves represent the BH calculation integrated over each 4-dimensional bin.

The difference between the curves and the data can thus be attributed to the DVCS process and the interference term, which are therefore a significant contribution. The bottom six plots show DVCS beam-polarized cross sections as a function of Φ for the same kinematics. The middle part of the figure shows the large kinematic coverage of the e1-DVCS data, with Q^2 and $-t$ as a function of x_B, with red full circles indicating the bins for which preliminary results are shown. These new results will provide strong constraints on both the real and imaginary parts of the proton CFF $\mathcal{H}_p$ over a wide kinematic domain.

The eg1-DVCS experiment was carried out with CLAS upgraded with the same $PbWO_4$ calorimeter that was used for the e1-DVCS experiment and using successively two longitudinally polarized NH_3 and ND_3 targets. The eg1-DVCS data cover the following ranges: $1 < Q^2 < 3.5\,\mathrm{GeV}^2$, $0.15 < x_B < 0.42$, and $0.1 < -t < 0.6\,\mathrm{GeV}^2$. Two thirds of the duration of the experiment were dedicated to DVCS on the proton (NH_3 target), and the last third to DVCS on the neutron (ND_3 target). Preliminary results on the proton for DVCS A_{UL} (mostly sensitive to the imaginary parts of the proton CFFs $\mathcal{H}_p$ and $\tilde{\mathcal{H}}_p$) and A_{LL} (mostly sensitive to the real parts of $\mathcal{H}_p$ and $\tilde{\mathcal{H}}_p$) asymmetries, as well as a preliminary extraction of DVCS A_{LU} asymmetry on the neutron (mostly sensitive to the imaginary part of the neutron CFF $\mathcal{E}_n$) are shown and described in [17].

See [18] for a review on the constraints provided by the JLab (Hall A and CLAS) 6 GeV data to GPD models (comparison of the data with models, as well as CFF fits).

3. – Deeply virtual meson production (DVMP)

Using the E00-110 data, the Hall A Collaboration measured the $ep \rightarrow ep\pi^0$ cross sections at two values of Q^2 (1.9 and $2.3\,\mathrm{GeV}^2$) [19].

The CLAS Collaboration recently measured cross sections of pseudoscalar meson electroproduction (π^0 [20], π^+ [21]), with hints of the possibility of accessing transversity GPDs. CLAS published cross-section measurements for the following vector mesons: ρ^0 [22, 23], ω [24] and ϕ [25, 26], contributing significantly to the world data on vector mesons with measurements in the valence quark region.

4. – GPD program at JLab 12 GeV

JLab's CEBAF accelerator is going through an upgrade to reach a beam energy of 12 GeV and GPD studies is one of the highest priorities of the 12 GeV program.

In Hall A, the E12-06-114 experiment [27] will run with different beam energies (6.6, 8.8, and 11 GeV), with a luminosity of $10^{38}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$. Measurements of DVCS unpolarized and beam-polarized cross sections on the proton will allow, among others, to study the Q^2 dependence of the CFFs on a larger Q^2 range and check the handbag dominance.

With the 12 GeV upgrade, CLAS will be replaced in Hall B by the future CLAS12 detector. There are so far three DVCS experiments planned with CLAS12. DVCS A_{LU} and A_{UL} asymmetries on the proton will be measured by running with a LH_2 target and a longitudinally polarized NH_3 target, respectively, with a luminosity of $10^{35}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ [28]. The precision and large kinematic coverage of the data will provide strong constraints for global fits aiming to extract the imaginary parts of the CFFs $\mathcal{H}_p$ and $\tilde{\mathcal{H}}_p$. A second experiment will aim to measure the DVCS A_{UT} and A_{LT} asymmetries on the proton, mostly sensitive to the GPD E_p, by running with a transversely polarized HD target, with a lower luminosity ($5 \times 10^{33}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$) [29]. A third experiment will aim to measure the DVCS A_{LU} asymmetries on the neutron, over a wide kinematic range for the first time, by running with a deuterium target, with a luminosity of $10^{35}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$ [30]. The DVCS A_{LU} on the neutron is a key observable to constrain the GPD E_n and to progress towards a flavor separation of the GPDs.

Examples of CFF fits obtained using proton pseudo-data can be found in [18], illustrating what we can expect in terms of extraction of CFFs from the CLAS12 data.

5. – Conclusions

The JLab 6 GeV results from Hall A and CLAS on DVCS and DVMP provided strong constraints to GPD models. There are still exciting things to come from ongoing analyses. JLab 12 GeV will allow to obtain even more precise measurements, on an even wider kinematic domain, with a unique role in the valence quark region.

* * *

Thanks go to the organizing committee of the QCD-N'12 conference for the opportunity to give this presentation.

REFERENCES

[1] Mueller D., Robaschik D., Geyer B., Dittes F. M. and Horejsi J., *Fortschr. Phys.*, **42** (1994) 101.
[2] Ji X., *Phys. Rev. Lett.*, **78** (1997) 610; *Phys. Rev. D*, **55** (1997) 7114.
[3] Radyushkin A. V., *Phys. Lett. B*, **380** (1996) 417; *Phys. Rev. D*, **56** (1997) 5524.
[4] Collins J. C., Frankfurt L. and Strikman M., *Phys. Rev. D*, **56** (1997) 2982.
[5] Goeke K., Polyakov M. V. and Vanderhaeghen M., *Prog. Part. Nucl. Phys.*, **47** (2001) 401.
[6] Diehl M., *Phys. Rep.*, **388** (2003) 41.
[7] Belitsky A. V. and Radyushkin A. V., *Phys. Rep.*, **418** (2005) 1.
[8] Belitsky A. V., Mueller D. and Kirchner A., *Nucl. Phys. B*, **629** (2002) 323.
[9] Vanderhaeghen M., Guichon P. A. M. and Guidal M., *Phys. Rev. D*, **60** (1999) 094017.
[10] Guidal M., Polyakov M. V., Radyushkin A. V. and Vanderhaeghen M., *Phys. Rev. D*, **72** (2005) 054013.
[11] Alcorn J. *et al.* (JLab Hall A Collaboration), *Nucl. Instrum. Methods A*, **522** (2004) 294.
[12] Mecking B. *et al.* (CLAS Collaboration), *Nucl. Instrum. Methods A*, **503** (2003) 513.
[13] Muñoz Camacho C. *et al.* (JLab Hall A Collaboration), *Phys. Rev. Lett.*, **97** (2006) 262002.
[14] Mazouz M. *et al.* (JLab Hall A Collaboration), *Phys. Rev. Lett.*, **99** (2007) 242501.
[15] Girod F. X. *et al.* (CLAS Collaboration), *Phys. Rev. Lett.*, **100** (2008) 162002.
[16] Jo H. S., PoS QNP2012 (2012) 052.
[17] Niccolai S., PoS QNP2012 (2012) 053.
[18] Guidal M., Moutarde H. and Vanderhaeghen M., preprint arXiv:1303.6600 [hep-ph].
[19] Fuchey E. *et al.* (JLab Hall A Collaboration), *Phys.Rev. C*, **83** (2011) 025201.
[20] Bedlinskiy I. *et al.* (CLAS Collaboration), *Phys. Rev. Lett.*, **109** (2012) 112001.
[21] Park K. *et al.* (CLAS Collaboration), *Eur. Phys. J. A*, **49** (2013) 16.
[22] Hadjidakis C. *et al.* (CLAS Collaboration), *Phys. Lett. B*, **605** (2005) 256.
[23] Morrow S. *et al.* (CLAS Collaboration), *Eur. Phys. J. A*, **39** (2009) 5.
[24] Morand L. *et al.* (CLAS Collaboration), *Eur. Phys. J. A*, **24** (2005) 445.
[25] Lukashinet K. *et al.* (CLAS Collaboration), *Phys. Rev. C*, **63** (2001) 065205.
[26] Santoro J. *et al.* (CLAS Collaboration), *Phys. Rev. C*, **78** (2008) 025210.
[27] Hyde C. *et al.* (JLab Hall A Collaboration), JLab proposal E12-06-114.
[28] Sabatié F. *et al.* (CLAS Collaboration), JLab proposal E12-06-119.
[29] Elouadrhiri L. *et al.* (CLAS Collaboration), JLab proposal E12-12-010.
[30] Niccolai S. *et al.* (CLAS Collaboration), JLab proposal E12-11-003.