Generalized Parton Distributions with CLAS and CLAS12

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Abstract

Recent promising results obtained with the Jefferson Lab CLAS detector on deeply virtual exclusive processes and their link to the Generalized Parton Distributions, along with the experimental program to study GPDs at the 12-GeV upgraded JLab using the CLAS12 detector, are here discussed. With its wide acceptance, high luminosity, good resolution and particle identification capabilities, large Q^2 and x_B coverage ($1 < Q^2 < 10$ GeV^2, $0.1 < x_B < 0.8$), CLAS12 will be the ideal facility to pursue the research on the 3-dimensional structure of the nucleon in the valence region.

1 GPDs in deeply exclusive processes

The Generalized Parton Distributions, introduced nearly a decade ago, have emerged as a universal tool to describe hadrons, and nucleons in particular, in terms of their elementary consituents, the quarks and the gluons [1, 2, 3, 4]. The GPDs, which generalize the features of form factors and ordinary parton distributions, describe the correlations between partons in quantum states of different (or same) helicity, longitudinal momentum, and transverse position. They also can give access, via the Ji's sum rule [3], to the contribution to the nucleon spin coming from the orbital angular momentum of the quarks. There are four different GPDs for the nucleon: H, E (the two spin-independent GPDs), $\tilde{H}$, $\tilde{E}$ (the two spin-dependent GPDs), and they can be measured in exclusive hard reactions.

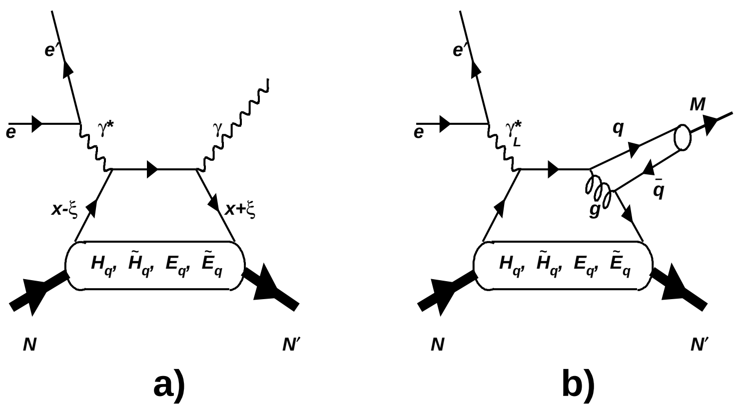

Figure 1: Leading-order "handbag diagram" for DVCS (a) and DVMP (b). x is the average longitudinal momentum fraction of the active quark in the initial and final states, while 2ξ is their difference ($\xi \simeq x_B/(2 - x_B)$, where x_B is the Bjorken scaling variable). The third variable on which the GPDs depend is $t = (p' - p)^2$, the squared four-momentum transferred to the target.

Deeply Virtual Compton scattering (DVCS) on the proton, $ep \to e'p'\gamma$, is the simplest process to access GPDs. In the Bjorken regime (high γ^* virtuality Q^2, small squared momentum transferred to the nucleon t) and at leading twist, this mechanism (Fig. 1a) corresponds to the absorption of a virtual photon by a quark carrying the longitudinal momentum fraction $x + \xi$. The struck quark emits a real photon and goes back into the nucleon with the longitudinal momentum fraction $x - \xi$. The amplitude for DVCS is factorized [5] into a hard-scattering part (exactly calculable in pQCD) and a non-perturbative part, representing the soft structure of the nucleon, parametrized by the GPDs, which will depend on the three kinematic variables x, ξ and t. The DVCS amplitude interferes with the amplitude for Bethe-Heitler (BH), the process where the real photon is emitted either by the incoming or the scattered electron. Although these two reactions are experimentally indistinguishable, the BH is known and exactly calculable via the electromagnetic form factors. Furthermore, their different sensitivity to the polarization of the beam or of the target can also be positively exploited. In fact, the DVCS-BH interference gives rise to spin asymmetries, which can be connected to combinations of GPDs. For instance, the beam-spin asymmetry (BSA), which depends on Q^2, x_B, t and ϕ (the angle between the leptonic and the hadronic planes), is particularly sensitive to the GPD H, while the contribution of the other GPDs are expected to be negligible [6]. The target-spin asymmetry (TSA), for a longitudinally polarized proton target, can instead give access to a combination of the GPDs H and $\tilde{H}$. Disposing of a transversely polarized proton target and measuring TSA for DVCS would allow one to extract both H and the less known and constrained GPD E, and therefore be sensitive to the possible different combinations of values for the orbital angular momentum of the quarks. Information about the flavor decomposition of the GPDs via DVCS requires measurements with both proton and neutron targets.

Deeply virtual exclusive meson production (DVMP), Fig. 1b, also allows access to GPDs. By measuring the longitudinal part of the cross section (the factorization hypothesis not being proven for the transverse part) for different mesonic final states one can, as in the case of proton/neutron DVCS, operate a flavor decomposition of the GPDs. Compared to DVCS, however, due to the additional exchange of a gluon, the scaling regime for DVMP is expected to be reached at higher Q^2.

2 Recent CLAS results on GPDs

After the first pioneering observation of $\sin\phi$ behavior — hinting to handbag dominance — on the DVCS beam-spin asymmetry obtained with non-dedicated data [7] taken with the CLAS detector [8], various DVCS- and GPDs-focused experiments have been performed at Jefferson Lab. As of today, the results of DVCS-dedicated experiments performed in Hall A (polarized and unpolarized cross sections [9]) and in Hall B with CLAS (BSA [10] – Fig. 2 – and TSA with longitudinally polarized target [11]) suggest that the handbag mechanism dominates already at relatively low Q^2 (~ 2 GeV^2).

More CLAS data taken at 6 GeV with unpolarized [12] and longitudinally polarized proton and deuteron targets [13] are currently under analysis, and new results for proton-DVCS cross sections [14], TSAs [15] and also the yet-unmeasured double-spin (beam-target) asymmetry [16] will be soon released. An exploratory analysis of DVCS on the neutron using a polarized ND_3 target is also underway [17].

Cross section measurements for DVMP (for ρ^0 [18] — Fig. 3 —, ω [19], and π^0 [20]) obtained with CLAS at 6 GeV hint that either the scaling regime cannot be reached for values of Q^2 as low as for DVCS or that something is otherwise missing in the existing GPD parametrizations [18].

More data are needed for both DVCS and DVMP:

- at a higher Q^2, to verify the scaling for DVCS on a wider range, and to approach the handbag regime for DVMP;
- on a wide x_B ($\simeq \xi$) coverage;
- with high accuracy on measured observables to test models (this requires high luminosity);

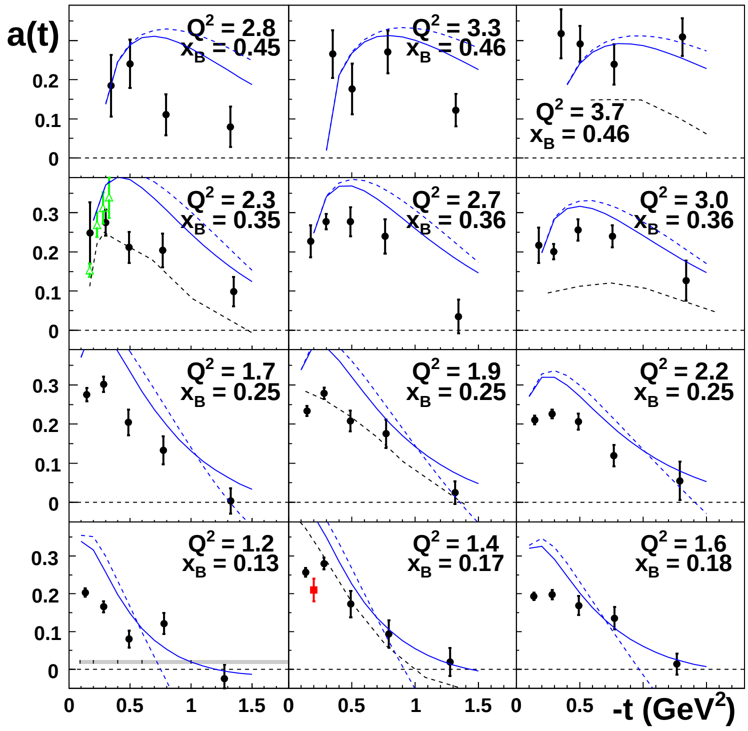

Figure 2: t dependence of the $sin\phi$ amplitude of the DVCS beam-spin asymmetry, for different $Q^2 - x_B$ bins, extracted from CLAS data at 6 GeV [10]. The blue curves are GPD model predictions [6], the black curves are Regge-based model calculations [27].

- performing measurements of various kinds of spin asymmetries (beam, longitudinal and transverse target, single- and double-spin asymmetries) and of cross sections, thus providing constraints for the recently developed model-independent GPD fits [26].

The CLAS12 setup will fulfill these requirements, providing unprecedented capabilities for exploring nucleon structure via the measurement of GPDs in the valence quark region.

3 The JLab 12-GeV upgrade and the CLAS12 detector

The CEBAF (Continuous Electron Beam Facility) accelerator has been delivering up to 6 GeV of high-duty-factor electron beam for hadronic physics research to the three experimental Halls (A, B, and C) of the Jefferson Laboratory since 1995. As of today, more than a hundred experiments have been completed, deepening our understanding of the strong interaction and making JLab a world-leading facility in the experimental study of hadronic matter. An energy upgrade of CEBAF to 12 GeV is underway in order to pursue the experimental study of the confinement of quarks (via the search for hybrid mesons) and of the 3-dimensional quark-gluon structure of the nucleons. The CEBAF upgrade to 12 GeV, which will be completed in 2014, will be achieved via 5.5 recirculations through its two existing linacs, in which 10 new high-gradient cryomodules will be added. A new experimental hall, Hall D, devoted to the hybrid mesons studies, will be built, while the capabilities of the detectors in the other three existing halls will be enhanced to suit the new experimental program.

In particular, the Hall-B CLAS12 detector (Fig. 4) will be composed of two parts: a Forward Detector (FD) and a Central Detector (CD). The FD will have similar characteristics as the current CLAS [8] but with improved resolution. A toroidal magnetic field will segment the detector into six

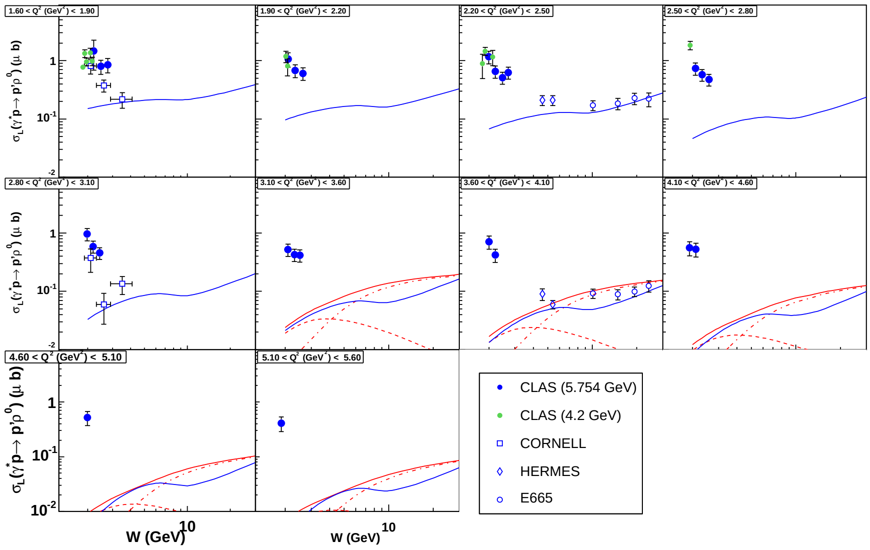

Figure 3: World data (CLAS at 4.2 GeV [21] and 5.754 GeV [18], CORNELL [22], HERMES [23] and E665 [24]) for the reduced cross sections of the $\gamma^*_L p \to p\rho^0_L$ reaction, as a function of W for constant Q^2 bins. The blue curve is the prediction of the VGG model [6] while the red curves show the results of calculations by Goloskokov and Kroll [25] (solid line: full model; dashed line: valence quarks only; dashed-dotted line: sea quarks and gluons only).

azimuthal sectors, each of which will be equipped for tracking and for identification of charged and neutral particles. Its acceptance will cover the polar angles between 5° and 40° for charged particles and between 2° and 40° for photons. The CD, equipped for the identification and tracking of backwards-recoiling charged particles, will cover polar angles between 40° and 135°, with full azimuthal coverage. All of its detector components will be housed in a compact superconducting solenoid magnet, which will serve the functions of shielding the tracking detectors from electromagnetic backgrounds and of providing the uniform magnetic field necessary for both the momentum analysis of charged particles at large angles and the operation of a dynamically polarized target.

With its large acceptance, good particle identification capability and high luminosity ($L \sim 10^{35}$ cm^{-2}s^{-1}), CLAS12 will be the optimal detector to study nucleon structure at high x_B.

4 Planned GPDs experiments with CLAS12

The experimental program for the first 5 years of operation of CLAS12 will be particularly focused on measurements of Generalized Parton Distributions in exclusive processes. Figure 5 shows the projections for the DVCS BSA that will be obtained running CLAS12 for 80 days on a proton target at its nominal (10^{35} cm^{-2}s^{-1}) luminosity. Measurements of unpolarized and polarized DVCS cross sections, as well as TSA (Fig. 6) and DSA with longitudinally polarized target are also planned [28]. The statistical precision of the data and their wide kinematical coverage will provide strong constraints for model-independent fits aiming to extract the imaginary parts of the GPDs H and $\tilde{H}$ [26]. R&D studies are currently underway for the construction of a transversely polarized target for CLAS12, which will allow the extraction of transverse-target single-spin asymmetries, observables particularly sensitive to the values of the orbital angular momentum of the quarks. The construction of a neutron detector for the CD is also ongoing. It will be necessary to ensure exclusivity in the measurement of DVCS on the neutron – a key reaction to constrain the GPD E and to progress towards flavor separation of GPDs [29]. Beam-spin asymmetries for neutron-DVCS will be extracted for the first time over a wide

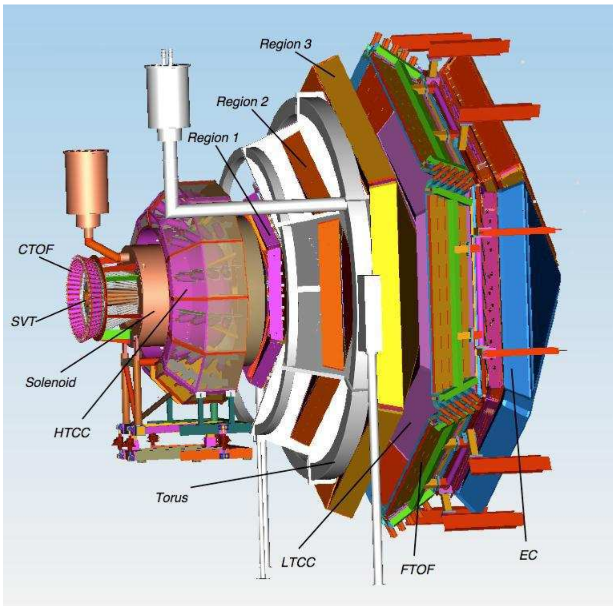

Figure 4: The CLAS12 detector. Its forward part will include: a superconducting toroidal magnet, high- and low-threshold Cerenkov counters (HTCC and LTCC), 3 regions of drift chambers, forward time-of-flight counters (FTOF), electromagnetic calorimeters (EC), and a low-angle inner calorimeter (IC, not visible) for the detection of high-energy photons; the backward part will be composed of a superconducting solenoid magnet containing a silicon vertex tracker (SVT) and time-of-flight counters (CTOF).

phase space taking data for 80 days on a liquid deuterium target with luminosity of 10^{35} cm^{-2}s^{-1} per nucleon. Figure 7 shows the expected sensitivity of the asymmetry to different values of the GPD E (parameterized, in the VGG model [6], by the quarks' total angular momenta J_u and J_d), for one of the 49 Q^2-x_B-t bins for which we will extract the ϕ dependence (in 12 ϕ bins) of the BSA. The size of the error bars will be such to allow us to discriminate between the different hypotheses.

5 Conclusions

The recent results obtained with CLAS on DVCS and DVMP point to the necessity to pursue the study of GPDs via the measurement of exclusive reactions at high Q^2 and over a wide phase space. The JLab 12-GeV upgrade will be essential for the study of the structure of the nucleon in 3D in the valence region with high precision, allowing the measurement of deeply virtual exclusive processes with polarized beam and targets. CLAS12 will be the only full acceptance, general purpose detector for high-luminosity electron scattering experiments, and it will be perfectly suited for the GPD program. The first 11-GeV electron beam will hit the CLAS12 target at the end of 2014.

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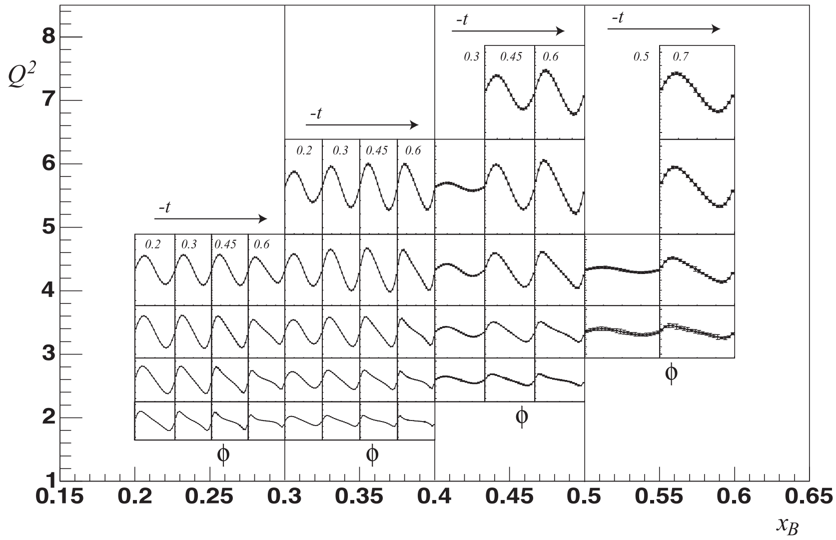

Figure 5: Expected statistical accuracy for the DVCS BSA, obtainable with CLAS12 after 80 days of beam time on a liquid hydrogen target, as a function of ϕ, for the various Q^2, x_B and t bins that the CLAS12 acceptance will access.

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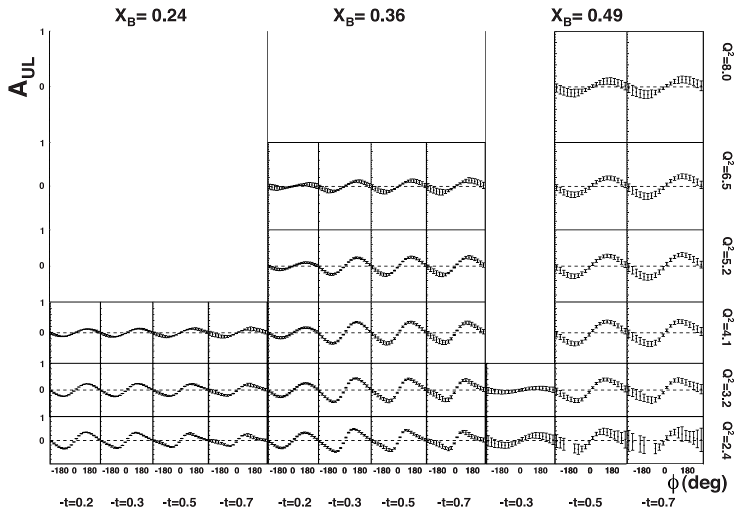

Figure 6: Expected statistical accuracy for the DVCS TSA, obtainable with CLAS12 after 80 days of beam time on a longitudinally polarized NH3 target, as a function of ϕ, for the various Q^2, x_B and t bins that the CLAS12 acceptance will access.

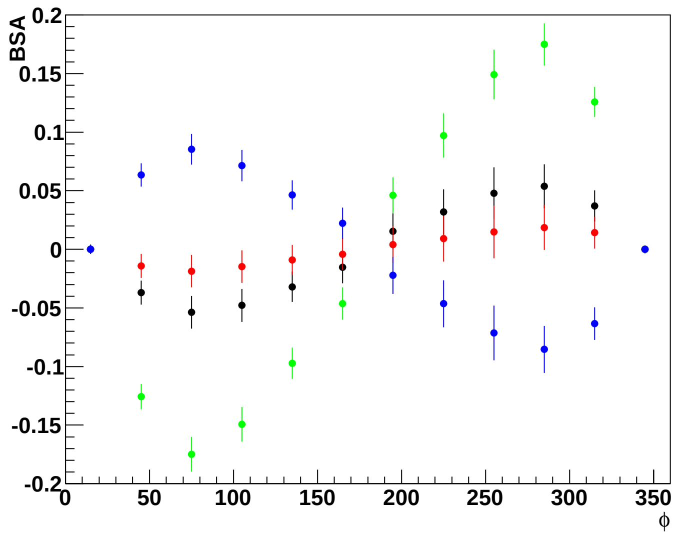

Figure 7: Projected results for the ϕ dependence (for $Q^2 = 2.75$ GeV^2, $x_B = 0.225$, $-t = 0.35$ GeV^2) of the beam-spin asymmetry for DVCS on the neutron, for 80 days of running on a deuterium target with CLAS12, equipped with a neutron detector in its central part. The four colours of the points correspond to different combinations of values for the angular momentum of the u and d quarks (black: $J_u = 0.3$, $J_d = 0.1$; red: $J_u = 0.1$, $J_d = 0.1$; green: $J_u = 0.3$, $J_d = 0.3$; blue: $J_u = 0.3$, $J_d = -0.1$).