

## The DVCS program in Hall A at JLab

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The DVCS Hall A/JLab experiments aim at providing data relevant to the “3-D structure of the nucleon” exploration by measuring precise absolute cross sections in the Deep Exclusive domain. Deeply Virtual Compton Scattering off the nucleon ( $\gamma^*N \rightarrow \gamma N$ ) is the simplest process which is sensitive to the Generalized Parton Distribution functions. Currently, the DVCS in Hall A program is articulated in three steps. The first generation of experiments showed the power of precise measurement of absolute cross sections to test factorization of the DVCS amplitude. The second generation of experiments (data under analysis) will separate (at twist-2 order) all of the terms making up the unpolarized cross section. And the third generation of experiments (data to be taken with the 12 GeV beam at JLab) will provide measurements over an extended kinematic range. In this conference proceeding, the status of the DVCS in Hall A/JLab program is reviewed.

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## 1. Deeply Virtual Compton Scattering and Generalized Parton Distribution functions

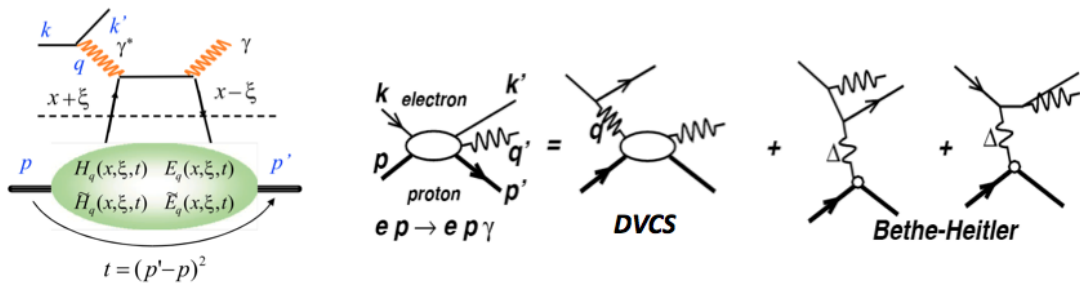
Deeply Virtual Compton Scattering (DVCS) off the nucleon ( $\gamma^* N \rightarrow \gamma N$ ) is the simplest process which is sensitive to the Generalized Parton Distribution (GPD) functions [1, 2, 3]. In the Bjorken limit, similarly to DIS, factorization theorems separate the reaction amplitude into the convolution of a known perturbative ( $\gamma^* q \rightarrow \gamma q$ ) kernel with an unknown soft matrix element describing the nucleon structure which can be described by the GPDs (Fig. 1). GPDs are universal objects entering in the description of a wide range of hard scattering exclusive processes; they provide a unified tool for describing many observables of hadron structure from form factors to parton distributions and to the total quark contribution to the nucleon spin. The key feature of the GPDs is that they provide a link between the spatial and momentum distributions of the partons within the nucleon; this gives access to build a spatial distribution of the partons as a function of their wavelength. Experimentally (Fig. 1), the DVCS process can only be measured at the same time as the Bethe-Heitler process (BH) where the real photon is emitted by either the incoming or scattered electrons. As a result, the unpolarized  $ep \rightarrow ep\gamma$  cross section has the form

$$d^5\sigma \propto |T_{BH}|^2 + \text{Re}(T_{BH} \cdot T_{VCS}^\dagger) + |T_{VCS}|^2 \quad (1.1)$$

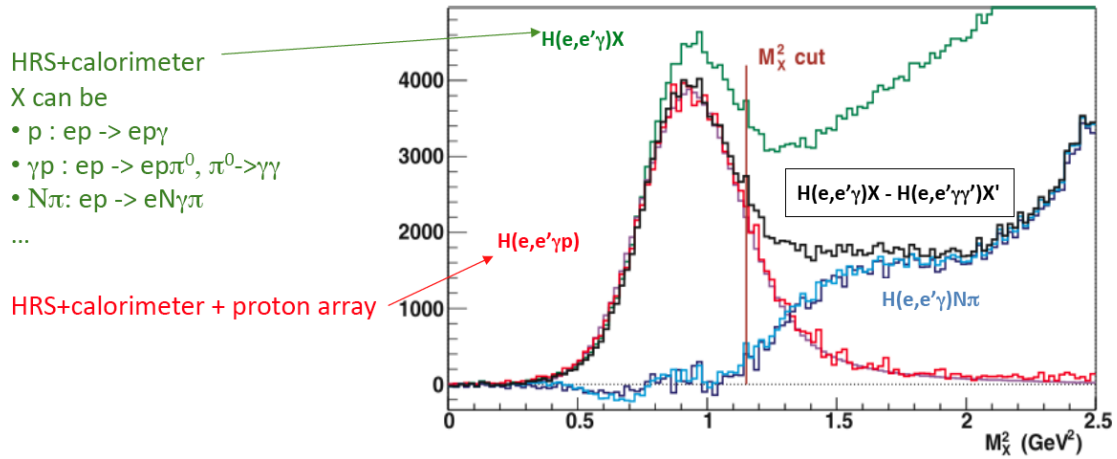
and the beam helicity dependent cross section difference is

$$d^5\sigma_L - d^5\sigma_R \propto \text{Im}(T_{BH} \cdot T_{VCS}^\dagger) \quad (1.2)$$

where  $d^5\sigma_L$  is the cross section for the beam with Left helicity. The pure BH term  $|T_{BH}|^2$  is calculable in term of the nucleon form factors. The azimuthal analysis of the interference terms gives access to Compton Form Factors (CFF) that are the integration of the GPDs over the quark loop of figure 1. The DVCS program in Hall A at JLab aims at a full decomposition of each of the terms of equation 1.1 and 1.2 and the extraction of the Compton Form Factors combinations it can access.



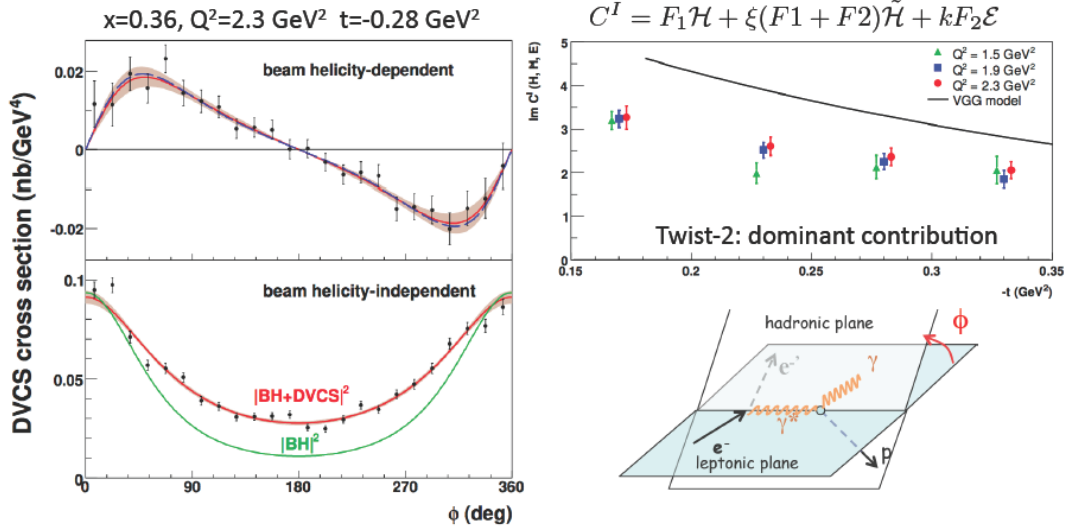
**Figure 1:** Left: Leading twist of the Deeply Virtual Compton Scattering amplitude. In the Bjorken limit, the factorization theorems separate the hard scattering part (top) from the soft one (bottom). The GPDs ( $H, E, \tilde{H}, \tilde{E}$ ) describe the emission and the absorption of a single quark by the nucleon. Right: Lowest order QED amplitude for the  $ep \rightarrow ep\gamma$  reaction. Electro-production of photon results from the interference between the DVCS and Bethe-Heitler processes.



**Figure 2:** Missing mass squared distribution of the  $H(e, e'\gamma)X$  reaction measured in experiment E00-110. For this first experiment, a recoil proton array detector was used in addition to the electron spectrometer and the EM calorimeter. Triple coincidence events are used to check the exclusivity of the base system (spectrometer-calorimeter). Within the missing mass selection (shown by the vertical line) and with the base system only, the  $N\pi$  continuum contamination to the DVCS data set is 1.7%.

## 2. First generation of DVCS Hall A experiment (2004)

The DVCS Hall A program started with experiment E00-110[4] and experiment E03-106[5]. The DVCS Hall A group used a simple experimental apparatus with well understood acceptance: the scattered electron is detected in a high resolution spectrometer[6] while the radiated photon is detected in a square-shaped electro-magnetic calorimeter. The calorimeter is made up of 132  $\text{PbF}_2$  blocks and covers  $\sim 0.1$  sr. Each block is read out by a 1 GHz digitizer with a 128 ns long buffer[7]. This setup and the halo-free CW beam at JLab allow to take data at a luminosity of the order of  $1 - 4 \cdot 10^{37}$  Hz/cm<sup>2</sup> per nucleon in a non magnetic environment while maintaining excellent exclusivity (Fig. 2). Experiment E00-110 measured DVCS off the proton at  $Q^2=1.5, 1.9$  and  $2.3$  GeV<sup>2</sup>. The absolute helicity-independent cross section revealed a significant contribution from the DVCS amplitude beyond the pure BH cross section (Fig. 3-bottom). As a result, subsequent analyses world-wide of relative asymmetries  $(\sigma_L - \sigma_R)/\sigma$  include the full DVCS term in both the numerator and the denominator. The helicity dependent cross section was fitted to a (popular at the time) azimuthal parametrization whose parameters are the Compton Form Factors[8]. The effective twist-2 interference  $\text{Im}C^l$  extracted that way, showed no variation as a function of  $Q^2$ , supporting the conjuncture of leading twist dominance (Fig. 3-top). In his QNP2012 presentation [2], Sabatié showed the unpublished results of an analysis using an update of this parametrization: the hint of scaling remains. This experiment also yielded results on Exclusive Neutral Pion Electroproduction in the Deeply Virtual Regime[9]. Experiment E03-106 measured helicity dependent cross sections on deuterium,  $D(\vec{e}, e')X$  at  $Q^2=1.9$  GeV<sup>2</sup>. The analysis provided constraints on the neutron and deuteron DVCS-BH interference[5]. From this interference, a model dependent extraction of total up and down quark contribution to the spin of the nucleon was extracted.

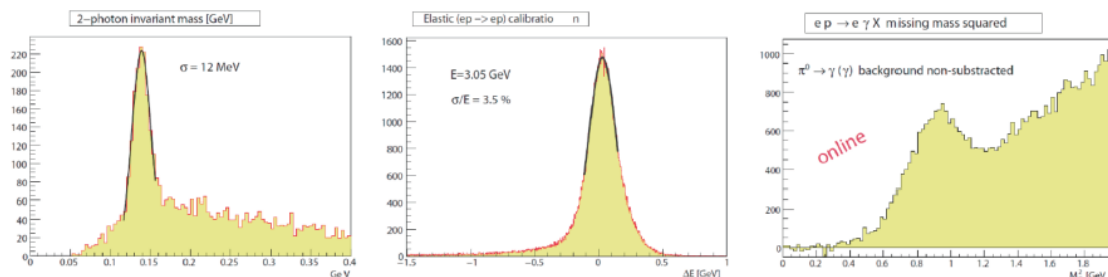


**Figure 3:** Typical results from the first generation proton experiment E00-110. Left: helicity dependent (top) and independent (bottom) cross sections. The cross sections are fitted by twist-2 parametrization of the BH·DVCS term (red), twist-2 and twist-3 (blue-dashed) and pure BH (green). Right-top: from the parametrization of the helicity dependent cross sections difference, one can extract the effective Compton Form Factor  $Im C^I$  at various  $Q^2$  and momentum transfer  $t$ . The VGG model is described in [11]. Right-bottom: the cross sections are analyzed as a function of the angle  $\phi$  between the hadronic and leptonic plane.

### 3. Second generation of DVCS Hall A experiments (2010)

AN important result of the first generation of the DVCS in Hall A experiments, was to show that the contribution from the calculable BH process accounts for only 50% of the total cross section. The goal of the second generation of experiments is to provide a complete separation of the two other components (Eq. 1.1) using a Rosenbluth-like separation: cross sections at a given  $Q^2$  are measured at two different beam energies. Experiment E07-007[10] off the hydrogen target will provide this separation at three different values of  $Q^2$  (1.5, 1.75 and 2.0 GeV<sup>2</sup>), while E08-025[12] will provide the separation at one  $Q^2$  (1.75 GeV<sup>2</sup>) on deuterium. E07-007 also aims at measuring the 5 response functions of the exclusive deep virtual  $\pi^0$  channel, in particular  $d\sigma_L$  and  $d\sigma_T$  by a conventional Rosenbluth separation. Both experiments took data in the Fall of 2010, 80% of the proposed data were collected. Data were collected in all kinematic settings proposed. The proposals assumed a 6 GeV beam while the maximum that could be delivered to accommodate an experiment running in parallel in Hall C was only 5.5 GeV. This resulted in a reduced lever arm in  $Q^2$  (1.5-2.0 GeV<sup>2</sup> instead of 1.5-2.3), data being taken closer to the nucleon resonance region for the lowest  $Q^2$  setting ( $W^2 = 3.55$  instead of 3.78 GeV<sup>2</sup>) and overall larger background noise. The experimental setup featured an expanded calorimeter<sup>1</sup> and an improved trigger; both modifications will improve the neutral pion background rejection. The online analysis showed that the data quality was good (Fig. 4). The analysis is on-going.

<sup>1</sup>208 PbF<sub>2</sub> blocks instead of 132.



**Figure 4:** Online distributions measured during the second generation experiments of DVCS in Hall A/JLab. The left plot shows the invariant mass of events for which two photons are detected in coincidence in the calorimeter. Photons resulting from  $\pi^0$  decays peak at  $\sim 0.135$  GeV. The plot in the middle shows the distribution for elastically scattered electrons measured energy compared to the expected energy. For these measurements, the elastically recoiling proton is measured in the spectrometer. The right plot shows the  $ep \rightarrow e\gamma X$  missing mass squared distribution. In each case, the location and resolution of the peaks matched expectations.

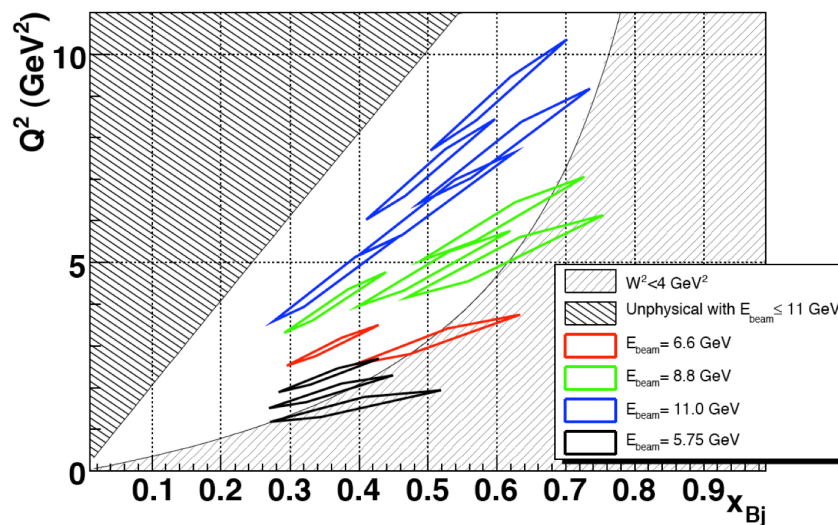
#### 4. Third generation of DVCS Hall A experiment (post JLab 12 GeV upgrade)

The upgrade of the JLab beam started during the spring of 2012. Doubling the energy of the electron beam (up to 12 GeV) offers a prime opportunity for the study of deep exclusive scattering. The DVCS Hall A experiment E12-06-114[13] takes advantage of the increased energy while maintaining the strengths of its experimental method. Namely: (i) Measurement of accurate cross sections using high luminosity (up to  $10^{38} \text{ cm}^{-2}\text{s}^{-1}$ ) and a well understood acceptance, (ii) High angular resolution which allows to bin data in small bins and therefore capture the rapidly varying Bethe-Heitler section and (iii) Equal statistic in every bins even at high  $Q^2$ . Figure 5 shows the kinematics that will be measured in that experiment. The goals for E12-06-114 are to measure absolute cross sections with a 3-5% statistical precision and a 4% systematic precision. These data will allow a test the scaling of the DVCS cross section, to extract the Real and Imaginary parts of the DVCS amplitude as well as to perform their azimuthal analysis. The experiment has been approved by the JLab PAC with A rating for 100 days of running. Because the experimental apparatus is the same as the one used in the second generation of experiment, data taking can begin immediately after the 12 GeV beam is established.

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**Figure 5:** Projected kinematics for the 12 GeV DVCS Hall A experiment. With polarized 6.6, 8.8 and 11 GeV electron beam, the experiment covers almost the entire kinematic range accessible at the facility. The 5.57 GeV data already exist [4].

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