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DVCS and associated processes at HERMES

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Abstract. Deeply virtual Compton scattering provides information about the structure of nucleon in the framework of generalized parton distributions. During the last 13 years, DVCS was extensively studied at the HERMES experiment through measurement of various cross-section asymmetries. Due to unique experimental conditions, HERMES has collected a wealth of data on scattering polarized electron and positron beams off unpolarized and longitudinally polarized hydrogen and deuterium targets, as well as off transversely polarized hydrogen targets. The variety of measured asymmetries provides sensitivity to real and/or imaginary parts of different combination of Compton form factors, and thus related GPDs. The HERMES recoil detector is used to separate pure DVCS from associated DVCS processes involving resonance production.

1. Are generalized parton distributions universal?

Generalized Parton Distributions (GPDs) and their counterpart in timelike processes, the Generalized Distribution Amplitudes (GDAs), describe non-pertubative phase-space distributions of quarks and gluons in the nucleon [1]. GPDs and GDAs can be regarded as reduced Wigner functions [2] that contain information about correlations of a parton in space and momentum, and hence also of its orbital angular momentum [3]. GPDs and GDAs appear in various processes at different kinematics and different energies. Figure 1 shows some examples ranging from well-known form factors to polarized and unpolarized parton distributions in Deep Inelastic Scattering (DIS), to exclusive pion-photon production in proton-antiproton annihilation in PANDA [4] and diffractive Higgs production at LHC [5]. Many of the GPD/GDA-related processes are exclusive processes with very low cross sections, and thus it will be a challenge for experimentalists to measure these multi-dimensional distributions and to find analogies between the space- and time-like functions and to prove their universality at low and high energies. One of the theoretically and experimentally cleanest processes to measure GPDs is Deeply Virtual Compton Scattering (DVCS). As depicted in Fig. 1, the DVCS handbag diagram depends on a correlation function of the nucleon where a quark with momentum $x + \xi$ is taken out of the nucleon and brought back with momentum $x - \xi$, where the skewness parameter ξ is experimentally accessible.

2. HERMES, a pioneering experiment of DVCS

The HERMES experiment was designed at the time of the spin crisis to measure spin structure functions and flavor dependent quark spin distributions [6]. It started data taking in 1995. More than 13 years ago,

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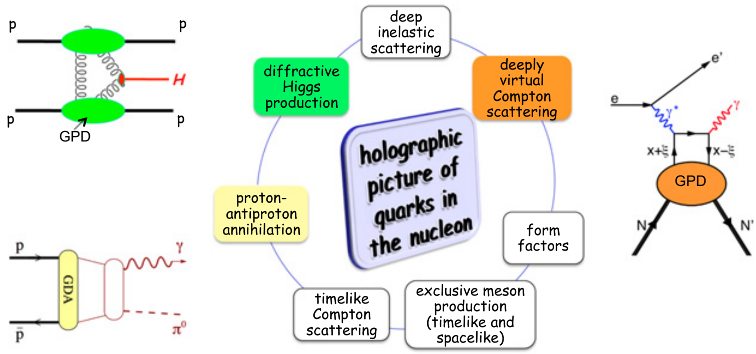

Figure 1. A large variety of processes at low and high energies can be described by the framework of GPDs and GDAs, like the diffractive Higgs production (green), some exclusive processes in $p\bar{p}$-annihilation (yellow), and especially the handbag diagram of DVCS (orange).

HERMES realized that the experiment was sensitive to DVCS processes, and in 2000 it published a pioneering result of a non-zero, single-spin azimuthal asymmetry in DVCS [8]. In 2006, HERMES added a recoil detector around its internal storage cell target to measure the recoiling proton and low energy pions from resonance decays [9]. In 2007, data taking stopped when HERA was shut down. HERMES had the most complete experimental access to DVCS due to its flexibility with regard to

- charge reversal (e^+ and e^- beams)
- beam spin reversal (both beam helicities)
- target spin variation (parallel, transverse, unpolarized)
- target mass variation (H, D, He, N, Ne, Kr, Xe)
- recoil and spectator proton detection.

It is beyond the scope of this paper to describe the analysis in details [7]. The basic concept is to measure the interference term between the Bethe-Heitler process and the DVCS amplitude. This interference term has a non-zero azimuthal asymmetry which is sensitive to charge and spin reversal. Fourier coefficients can be extracted that are related to Compton Form Factors (CFFs). The real and imaginary parts and the square of the CFFs are related to the GPDs. Figure 2 gives an overview of the main asymmetry coefficients that were extracted by HERMES using various beam and target configurations for hydrogen and deuterium targets [7, 10–15]. Not included are HERMES data on nuclear DVCS of heavier targets [16].

3. The HERMES recoil detector and associated DVCS production

The HERMES forward spectrometer measures the scattered electron and the photon in the exclusive process $ep \to ep\gamma$. The BH and DVCS processes are selected by using the missing mass technique with a mass window of -2.25 GeV$< M_X^2 < 2.89$ GeV^2 around the final state proton mass. As shown in figure 3 (left) the mass peak contains in addition to a background of semi-inclusive DIS scattering a significant contribution of about 12% of associated DVCS production: $ep \to e\Delta^+\gamma$. In 2006 HERMES installed a recoil proton detector to measure the final state proton or pion from resonance decay. The BH and DVCS processes could now be completely measured and a kinematic fit allows the refinement of the kinematics. Figure 3 (right) shows the DVCS peak of a pure recoil sample with complete event reconstruction. The contributions from semi-inclusive and associated production are negligible. The green points in Fig. 2 are extracted using this method [15].

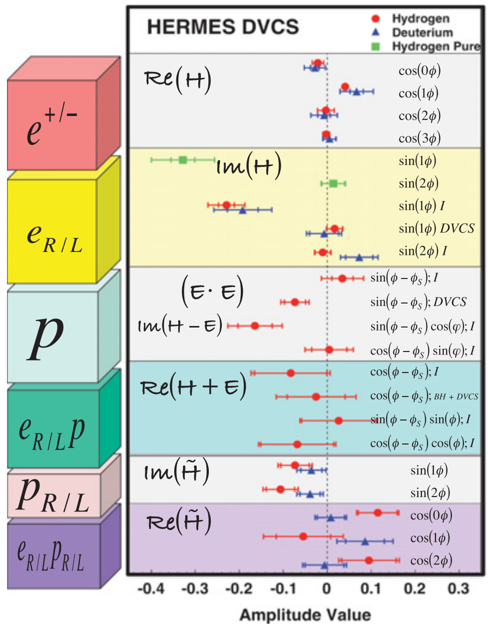

Figure 2. Measured DVCS amplitude values given for various beam and target conditions as follows: beam charge asymmetry ($e^{+/-}$); longitudinal beam spin asymmetry ($e_{R/L}$); longitudinal target spin asymmetry ($p_{R/L}$); transverse target spin asymmetry ($p_\perp$); double spin asymmetries ($e_{R/L}\, p_\perp$) and ($e_{R/L}\, p_{L/R}$). On the right of the measured points is indicated which Fourier coefficient ($\sin(n\phi)$, $\cos(n\phi)$) is measured. Only the most relevant coefficients are shown. ϕ and ϕ_S denote azimuthal angles of the scattering plane and the target polarization. $I/BH/DVCS$ indicate the Interference/ Bethe-Heitler/DVCS term. The separation of some of the coefficients requires a common fit of beam-spin and beam-charge asymmetries. HERMES is currently the only experiment who can do that. On the left of the points it is indicated which of the measurements is sensitive to the real or imaginary part or square of a CFF related to the GPDs H or E or $\tilde{H}$. The red (blue) points denote the hydrogen (deuterium) target. The green points are measured with the recoil detector as explained in Sect. 3. Details of the notations can be found in [7].

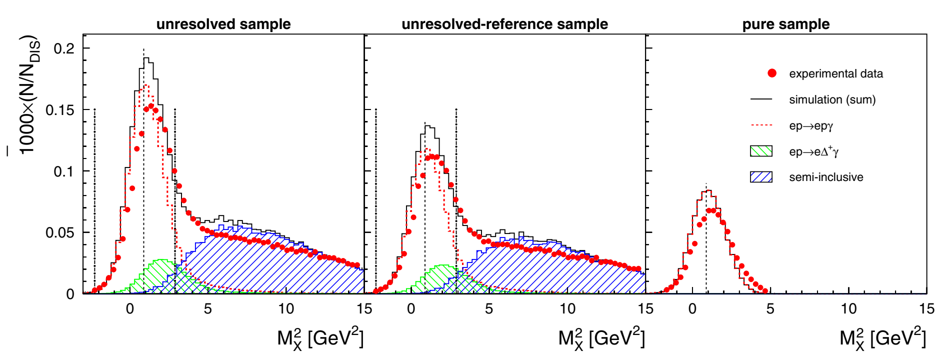

Figure 3. Left: the invariant mass spectrum of the reaction $ep \rightarrow eX\gamma$ shows a peak at the proton mass. From Monte Carlo simulations the contributions of semi-inclusive DIS and associated production $ep \rightarrow e\Delta^+\gamma$ are extracted as blue and green shaded areas. Middle: the "reference" sample contains the events where the calculated final state proton is in the acceptance of the recoil detector. Right: by detecting the final state proton in the recoil detector, the background disappears and a pure DVCS/BH sample is selected.

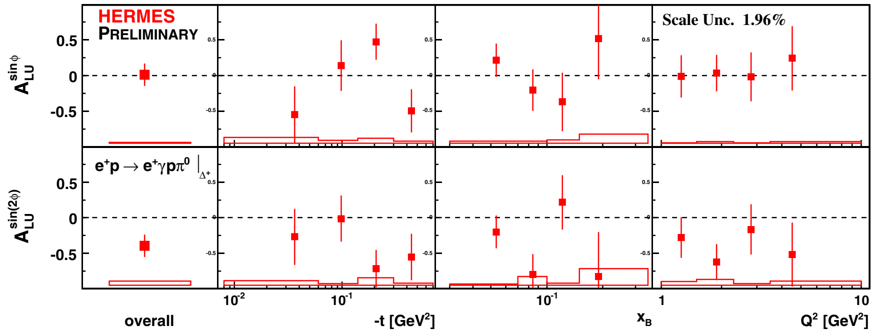

Figure 4. Measured amplitudes of associated DVCS production of the decay channel $ep \to e\Delta^+\gamma \to ep\pi^0\gamma$ for the longitudinal beam spin asymmetry ($e_{R/L}$) with unpolarized target. The Fourier coefficients $\sin(\phi)$ and $\sin(2\phi)$ are plotted (from left to right) as average, as function of the mandelstam variable $-t$, as function of the Bjorken variable x_B, and as function of the invariant mass squared of the virtual photon Q^2. The $\sin(2\phi)$-value is non-zero.

The recoil detector is not only useful for selecting pure BH/DVCS events but also for the selection of associated DVCS production: $ep \to e\Delta^+\gamma$, where the resonance decays into a pion and a nucleon according to: $\Delta^+ \to p\pi^0$ or $\Delta^+ \to n\pi^+$. As the π^0 and the n is normally not detected in the recoil detector, a kinematic fit is used to select a sample with enhanced associated DVCS production. Figure 4 shows the results of the azimuthal asymmetry amplitude values for the $ep \to e\Delta^+\gamma \to ep\pi^0\gamma$ channel [17, 18].

To conclude, HERMES was a pioneering experiment in DVCS and had unique conditions that allowed the extraction of a variety of DVCS amplitudes.

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