

Study of DVCS and DVMP processes at COMPASS

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Abstract. The study of DVCS and DVMP processes over a wide range in x_B is an outstanding part of the scientific proposal for the COMPASS program after 2011. The measurement of the double-differential DVCS cross-section will provide information on the transverse size of the nucleon as function of x_B , often referred to as “nucleon tomography”. Also, the combination of data samples collected with opposite beam charge and polarization will allow to single out terms related to the GPD H . The physics goals of the COMPASS GPD program will be discussed in detail, and projections on the achievable statistical and systematic accuracies will be given. The sensitivity of the COMPASS experimental apparatus to the DVCS signal has been investigated during dedicated pilot measurements in the years 2008 and 2009. Preliminary results on the observed DVCS and Bethe-Heitler signals are presented, and the comparison with Monte-Carlo simulations is discussed.

1. Introduction

In recent years, very significant theoretical progress has been achieved in the field of Generalized Parton Distributions (GPDs) [1, 2, 3, 4, 5], which provide information on the transverse localisation of a parton as function of the fraction it carries of the nucleon’s longitudinal momentum. The interest in the GPD formalism has risen after it has been shown [2] that the total angular momenta of quarks or gluons is related to the second moment of the sum of the GPDs H and E . Generally speaking, the GPDs contain the hitherto most complete information on the nucleon structure.

The study of exclusive reactions like Deeply Virtual Compton Scattering (DVCS) and Deeply Virtual Meson Production (DVMP) is one of the most promising ways to experimentally constrain the GPDs. Measurements of those processes have been performed or are planned at JLab [6, 7, 8], DESY (HERMES, H1 and ZEUS) [9, 10, 11, 12, 13] and CERN (COMPASS) [14]. Each experiment is exploring a different region in the x-Bjorken (or x_B) scaling variable, so that the available and future data sets will play a complementary role. In this context, COMPASS will cover the kinematics domain ranging from $x_B \sim 5 \times 10^{-3}$ to about 0.1, which cannot be explored by any other existing or planned facility in the near future (see figure 1). The DVCS and DVMP measurements are an outstanding part of the physics program for the second phase of the COMPASS experiment (COMPASS-II), which has been recently approved by the CERN SPS scientific committee [14].

COMPASS uses the high-energy muon beam delivered by the M2 secondary beam line of the SPS accelerator complex at CERN. The beam is naturally polarized in the longitudinal direction, with a typical polarization of $\sim 80\%$ at 160 GeV; the momentum can be chosen between 60 and 190 GeV/ c . Both positive and negative muon beams (which have opposite polarization) are available.

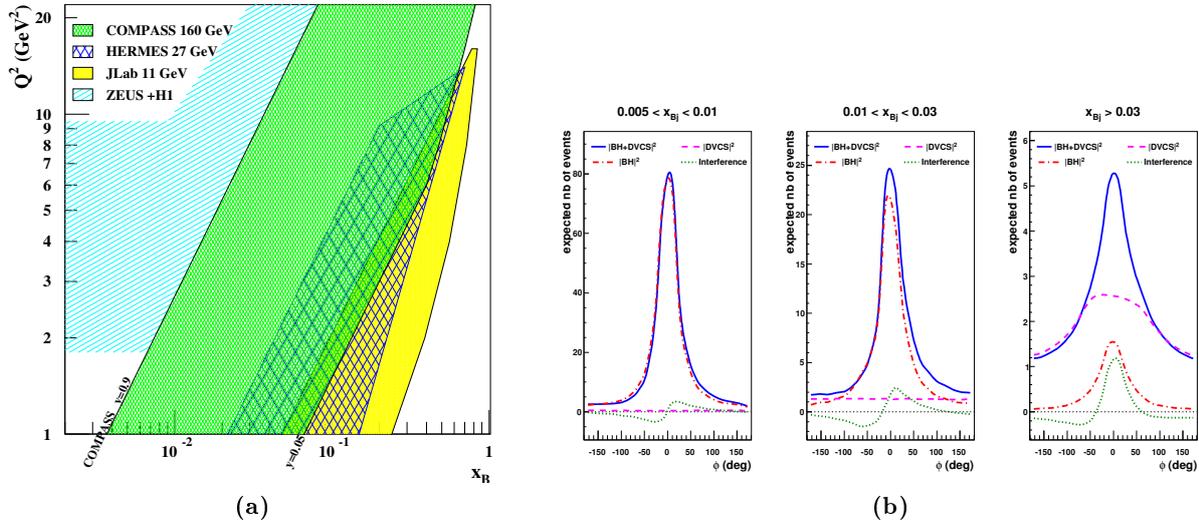


Figure 1: Left: kinematic domains for measurements of hard exclusive processes shown for the COMPASS (green area enclosed by the lines $y = 0.9$ and $y = 0.05$), HERMES and JLab fixed-target experiments, and the HERA collider experiments H1 and ZEUS.

Right: MonteCarlo simulation of the exclusive muonproduction of single hard photons. The plots show the ϕ angle distribution of reconstructed events for three bins in x_B and for $Q^2 > 1 \text{ GeV}^2$. The event yield is normalized to the integrated luminosity of the 2009 test run, as described in sec. 3.

The experimental apparatus will be upgraded with a new electromagnetic calorimeter (ECAL0) and a recoil proton detector (RPD) surrounding a 2.5 m-long liquid-hydrogen target. The ECAL0 will extend the angular acceptance for exclusive photons and increase the accessible x_B domain to substantially higher values compared to the present set-up. The RPD on the other end will ensure the exclusivity of DVCS and DVMP by detecting the recoil protons. See reference [15] for a more detailed description of the COMPASS experimental apparatus.

2. Measurement of DVCS at COMPASS

DVCS is presently the theoretically cleanest approach to GPDs, because effects of next-to-leading order and subleading twist are under theoretical control [16]. In DVCS, a virtual photon emitted by the incoming lepton scatters off a nucleon and emerges as a real photon in the final state, while the target nucleon recoils without being destroyed. DVCS competes with the Bethe-Heitler (BH) process, which is elastic lepton-nucleon scattering with a hard photon emitted by either the incoming or outgoing lepton. As the two processes have identical initial and final states, they interfere at the level of amplitudes. Hence, the differential cross-section for hard exclusive leptonproduction of a single photon off an unpolarised proton target can be written as

$$\frac{d^4\sigma(\mu p \rightarrow \mu p \gamma)}{dx_B dQ^2 dt |d\phi} = d\sigma^{BH} + (d\sigma_{unpol}^{DVCS} + P_\mu d\sigma_{pol}^{DVCS}) + e_\mu (\text{Re } I + P_\mu \text{Im } I), \quad (1)$$

where ϕ is the angle between the lepton scattering plane and the photon production plane, e_μ and P_μ are, respectively, the charge and the polarization of the lepton beam, and I represents the DVCS - BH interference term. The broad kinematics domain covered in COMPASS allows to explore regions where either the BH or the DVCS processes dominate (see figure 1).

The almost pure BH sample at small x_B will provide a precise reference yield to accurately control the global efficiency of the experiment. At large x_B , where the DVCS contribution

becomes dominant, the known BH contribution can be subtracted and the pure DVCS cross-section studied as function of x_B and t . In the intermediate region, the DVCS contribution is “boosted” by the BH process through the interference term. It has to be noted that the ϕ -dependence of the DVCS cross-section in figure 1 is not flat at large x_B due to acceptance effects in the set-up used for this simulation, which did not include the large-angle calorimeter ECAL0.

COMPASS is presently the only facility able to perform measurements with opposite beam charges. Moreover, the polarization of the COMPASS muon beam changes sign when the charge is reversed. This allows to isolate various terms in equation 1 by summing or subtracting measurements obtained with both beam charges. In particular:

- the **difference** (\mathcal{D}) of cross-sections with opposite beam **charge** (C) and **spin** (S) and for **unpolarized** (U) protons can be written as:

$$\begin{aligned} \mathcal{D}_{CS,U} &\equiv d\sigma^{\leftarrow} - d\sigma^{\rightarrow} = 2 \left[P_\mu d\sigma_{pol}^{DVCS} + e_\mu \text{Re} I \right] \\ &\propto \left(\left\{ s_1^{DVCS} \sin \phi \right\} \right) + \left(c_0^I + c_1^I \cos \phi + \left\{ c_2^I \cos 2\phi + c_3^I \cos 3\phi \right\} \right). \end{aligned} \quad (2)$$

In this combination the BH contribution *cancels out*, as it is independent of the sign and the polarisation of the beam, and only the polarised DVCS cross-section and the *real part* of the interference term remain.

- the **sum** (\mathcal{S}) of cross-sections with opposite beam **charge** (C) and **spin** (S) and for **unpolarized** (U) protons can instead be written as:

$$\begin{aligned} \mathcal{S}_{CS,U} &\equiv d\sigma^{\leftarrow} + d\sigma^{\rightarrow} = 2 \left[d\sigma^{BH} + d\sigma_{unpol}^{DVCS} + e_\mu P_\mu \text{Im} I \right] \\ &\propto 2 \left[d\sigma^{BH} \right] + \left(c_0^{DVCS} + \left\{ c_1^{DVCS} \cos \phi + c_2^{DVCS} \cos 2\phi \right\} \right) + \left(s_1^I \sin \phi + \left\{ s_2^I \sin 2\phi \right\} \right). \end{aligned} \quad (3)$$

This other combination allows to single out the *imaginary part* of the interference term; on the other hand, the BH contribution *does not cancel out*, and needs to be subtracted (and this can only be done in the kinematical regions where it is not too large).

The c_n and s_n coefficients in equation 2 and 3 are related to given combinations of Compton Form Factors (CFFs), defined as the sum over flavors f of the respective GPDs F^f with a perturbatively calculable kernel describing the hard γ^*q interaction. The terms enclosed in curly braces correspond to higher-twist or higher-order effects.

2.1. Determination of the real and imaginary parts of the Compton Form Factor \mathcal{H}

The analysis of the ϕ -dependence of equation 2 will provide the two leading twist-2 expansion coefficients c_0^I and c_1^I that, in the kinematics domain of COMPASS, are mainly related to the real part of the CFF \mathcal{H} . This quantity was found to be positive at H1 and Zeus and negative at HERMES and JLab; hence, the COMPASS kinematic domain is expected to provide the node of this amplitude, which is an essential input for any global fit analysis.

The expected statistical (error bars) and systematic (grey band) accuracy for the measurement of the ϕ -dependence of $\mathcal{D}_{CS,U}$ in a particular (x_B, Q^2) bin is shown in figure 2. Two of the curves are calculated using the “VGG” GPD model [17] using either a “reggeized” parametrization of the correlated x, t dependence or a “factorized” x, t dependence of the GPDs; here x represents the average between the initial and final longitudinal momentum fractions of the nucleon, carried by the parton throughout the process. The other two curves are the result of a fitting procedure [18, 19], including next-to-next-to leading order (NNLO) corrections, which was developed and successfully applied to describe DVCS observables from both very small x_B (HERA) and large x_B (HERMES and JLab).

In a similar manner, the analysis of the ϕ -dependence of equation 3 will provide information on the imaginary part of the CFF \mathcal{H} via the leading twist-2 coefficient s_1^I .

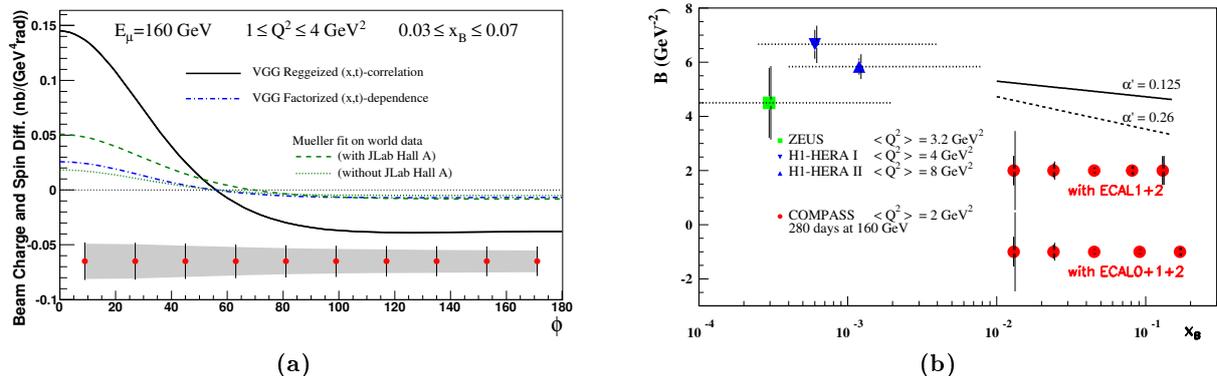


Figure 2: Left: expected statistical (error bars) and systematic (grey band) accuracy for the measurement of the ϕ -dependence of $\mathcal{D}_{CS,U}$ for $1 \leq Q^2 \leq 4 \text{ GeV}^2$ and $0.03 \leq x_B \leq 0.07$. A running time of 280 days with a 2.5 m long liquid H_2 target has been assumed for the estimate. The solid and dash-dotted curves correspond to different variants of the “VGG” model [17], while the other two curves show predictions based on fits to existing HERA, HERMES and JLab data [18, 19].

Right: projections for the measurement of the t -slope parameter $B(x_B)$ for various bins in x_B . The bars on the red data points show the expected statistical (left bar) and total (right bar) errors assuming a running time of 280 days with a 2.5 m long liquid H_2 target. The first row of data points was estimated only the existing calorimeters ECAL1 and ECAL2, while for the lower row the new large-angle calorimeter ECAL0 was also included. The solid and dashed lines show the results of two parametrizations corresponding to $\alpha' = 0.125 \text{ GeV}^{-2}$ and $\alpha' = 0.26 \text{ GeV}^{-2}$.

2.2. t -slope of the pure DVCS cross-section to study nucleon tomography

The unpolarized DVCS cross-section $\frac{d\sigma}{dt} \propto \exp(-B(x_B)|t|)$ can be isolated in equation 3 after integration over ϕ and subtraction of the known BH contribution. At small x_B , where amplitudes are predominantly imaginary, the t -slope parameter $B(x_B)$ is related to the total transverse size r_\perp of the nucleon via the relation $\langle r_\perp^2(x_B) \rangle \approx 2 \cdot B(x_B)$. In the simple ansatz $B(x_B) = B_0 + 2\alpha' \log(\frac{x_0}{x_B})$ the expected decrease of the nucleon size with increasing x_B is described by the parameter α' . Data on $B(x_B)$ have only been provided by the HERA collider experiments in the low x_B range from 10^{-4} to 0.01, and no significant evolution with x_B was observed; a first value of the transverse proton radius $\langle r_\perp^2 \rangle = 0.65 \pm 0.02 \text{ fm}$ has been determined using H1 data [11, 12].

The study of the x_B and t -dependence of the DVCS cross-section will allow us to draw conclusions on the x_B evolution of the transverse size of the nucleon (often referred as “Nucleon Tomography”) in the so far unmeasured region $0.01 < x_B < 0.1$ accessible to COMPASS. The corresponding projected statistical accuracy is shown in figure 2; values of α' down to 0.125 (corresponding to half of the value for Pomeron exchange in soft scattering processes) can be determined with an accuracy better than 2.5σ with the upgraded set-up that includes the large-angle calorimeter ECAL0.

3. First Observation of DVCS and BH Processes at COMPASS

The feasibility of the DVCS measurement at COMPASS has been studied during dedicated test runs in 2008 and 2009, using a 40 cm long liquid H_2 target surrounded by a Recoil Proton Detector (RPD). Apart from the reduced target length and the lack of the ECAL0 calorimeter, the experimental set-up presented all the relevant features of the one foreseen for the GPD program. The test measurements have been performed using both μ^+ and μ^- beams of 160 GeV

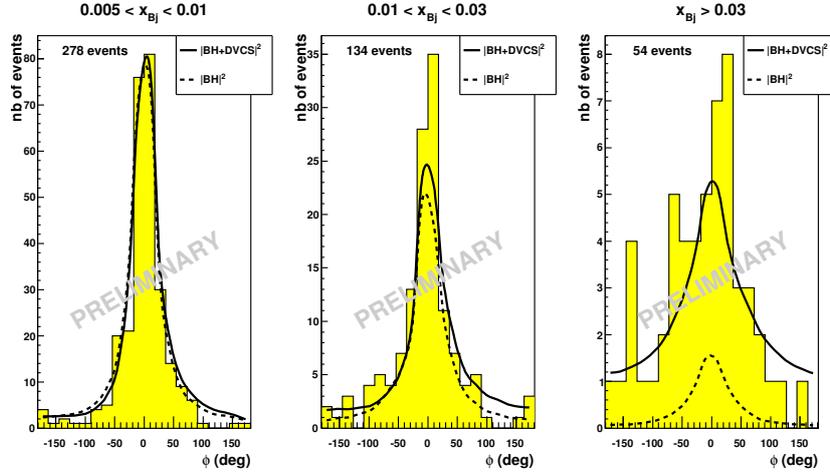


Figure 3: Distributions in the azimuthal angle ϕ for exclusive single-photon events at $Q^2 > 1 \text{ GeV}^2$, measured in the 2009 test DVCS run at COMPASS. The solid and dashed curves correspond to the total and BH-only event yields from figure 2.

of energy, at an intensity close to the nominal value in 2009 and about three times lower in 2008. The collected data allowed to perform a first estimate of the global efficiency of the experiment, which was found to be of about 10% (including SPS beam and spectrometer availabilities as well as trigger and DAQ efficiencies and dead times). The ϕ -dependence of the observed exclusive single-photon production has been analyzed for three different x_B ranges using the 2009 test data (see figure 3), providing a first direct measurement of the relative contributions of BH and DVCS in the x_B region covered at COMPASS.

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