

## Hard Exclusive Processes at COMPASS and COMPASS-II

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**Summary.** — A major part of the future COMPASS program is dedicated to the study of Deeply Virtual Compton Scattering (DVCS) and Meson Production (DVMP) to investigate nucleon structure through Generalised Parton Distributions (GPD). The high energy of the muon beam allows us to measure the  $x_B$ -dependence of the  $t$ -slope of the pure DVCS cross section and to study nucleon tomography. In a first phase the use of positive and negative polarised muon beams and of an unpolarised proton target allow measurements of the Beam Charge and Spin Difference of the DVCS cross sections to access the Compton form factor related to the dominant GPD H. In a second phase we consider to use a transversely polarized proton target to constrain the GPD E.

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### 1. – Introduction for GPD studies at COMPASS

Generalised Parton Distributions provide [1] a comprehensive description of the partonic structure of the nucleon and contain a wealth of new information. They embody both, form factors observed in elastic scattering and parton distribution functions measured in deep inelastic scattering. A GPD can be considered as a momentum-dissected form factor providing information on the transverse localisation of a parton as a function of the fraction it carries of the nucleon's longitudinal momentum. Thus one obtains a "3D picture" of the nucleon which is often referred to as "nucleon tomography" (one main goal of COMPASS-II phase 1 [2]). GPDs also allow access to such a fundamental property of the nucleon as the orbital angular momentum of partons (goal of COMPASS-II phase 2 in a future addendum to the present proposal).

The COMPASS experiment is situated at the CERN SPS M2 beam line. It provides high-energy (50–280 GeV) muon beams of either charges. The muons are produced in pion and kaon decays. Hence they are naturally longitudinally polarized and the helicity is charge dependent. As will be discussed later this is an important and unique feature of

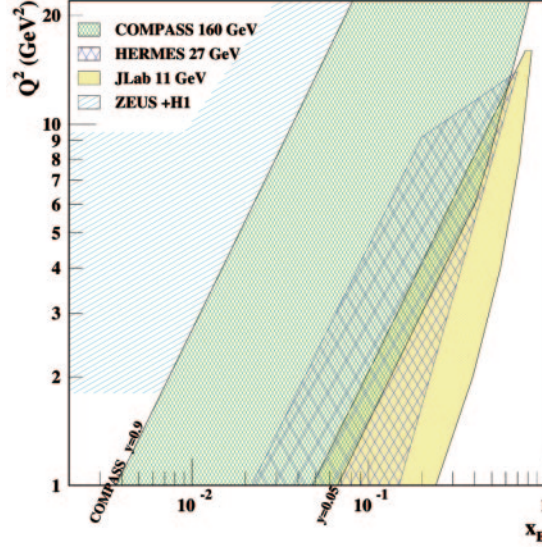


Fig. 1. – Kinematic domains for measurements of hard exclusive processes.

COMPASS-II to access GPDs via DVCS and DVMP. The existing COMPASS set-up [3] equipped with a 2.5 m long liquid-hydrogen target will be used. In order to accomplish the detection of exclusive events a 4 m long recoil proton detector (CAMERA) will be installed around the target. For the DVCS channel the photon detection assured at small angle by the two existing electromagnetic calorimeter (ECAL1 and ECAL2) will be completed at larger angle by a new electromagnetic calorimeter (ECAL0) placed just downstream of the target. This will increase significantly the acceptance of the DVCS photon detection. Hence COMPASS-II will become a facility measuring exclusive reactions within a kinematic Bjorken variable ranging from  $x_B \sim 0.01$  to about 0.1 and a photon virtuality  $Q^2$  from 1 to 10 GeV<sup>2</sup>, which cannot be explored by any other existing or planned facility in the near future (fig. 1). COMPASS-II will thus explore the uncharted  $x_B$  domain between the HERA collider experiments H1 and ZEUS and the fixed-target experiments as HERMES and the planned 12 GeV extension of the JLab [4].

## 2. – Study of the GPD H through DVCS with high-energy polarised $\mu^+$ and $\mu^-$ beams and an unpolarized proton target and with recoil proton detection in COMPASS-II phase 1

DVCS which is the golden channel to study GPDs, has the same final state as the competing Bethe-Heitler (BH) process, which is elastic lepton-nucleon scattering with a hard photon emitted by either the incoming or outgoing lepton. The two processes interfere at the amplitude level and the differential cross section for hard exclusive muoproduction of a single real photon off an unpolarised proton target can be written as<sup>(1)</sup>

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

<sup>(1)</sup> For simplicity  $d\sigma$  is used in the following instead of  $\frac{d^4\sigma(\mu p \rightarrow \mu p \gamma)}{dx_B dQ^2 d|t| d\phi}$ .

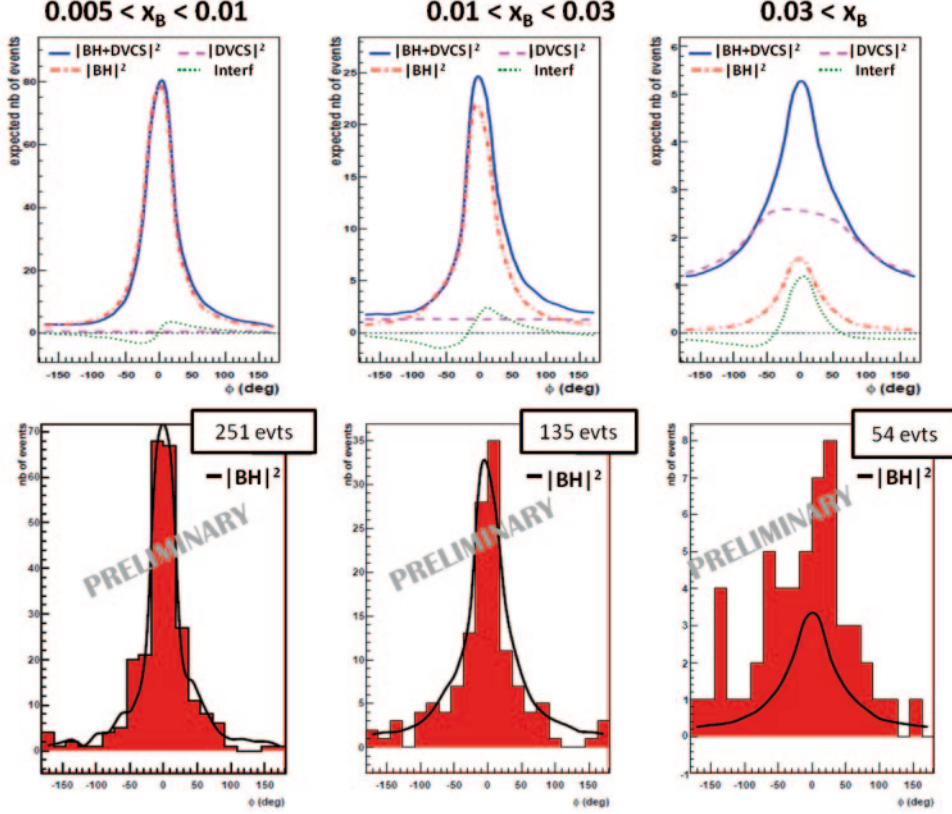


Fig. 2. – Top: Monte Carlo simulation of the exclusive muoproduction of a single real photon at COMPASS-II without ECAL0 showing the  $\phi$  angle distributions of reconstructed events for three bins in  $x_B$  for  $Q^2 > 1 \text{ GeV}^2$ . Bottom:  $\phi$  angle distributions measured in the DVCS 2009 test run at COMPASS and the solid lines represent the expected BH yield.

where  $P_\mu$  and  $e_\mu$  are the polarisation and the charge of the muon beam respectively and  $I$  is the interference term between DVCS and BH.  $t$  is the four-momentum transfer squared between the initial and final nucleon state and  $\phi$  is the angle between the scattering plane and the photon production plane. Due to the high energy beam, COMPASS offers the advantage to provide various kinematic domains where either BH or DVCS dominates. This is illustrated in fig. 2 on the upper part showing a Monte Carlo simulation for  $Q^2 > 1 \text{ GeV}^2$  based on the acceptance of the presently existing COMPASS set-up, *i.e.*, using the calorimeters ECAL1 and ECAL2. For  $x_B < 0.01$  the BH process dominates which provides an excellent reference yield to monitor the detector acceptance and the luminosity measurement. For  $x > 0.03$  DVCS dominates. The distribution for DVCS is not flat in  $\phi$  due to the present limited acceptance at large photon angles. This will be improved by the addition of the new calorimeter ECAL0. The size of the interference term increases with rising  $x_B$  and offers via its characteristic  $\phi$  variation additional possibilities to access real or imaginary part of the complex DVCS amplitude.

In 2008 and 2009 tests measurements were performed using the COMPASS detector in the configuration dedicated to the hadron spectroscopy program. A 40 cm long

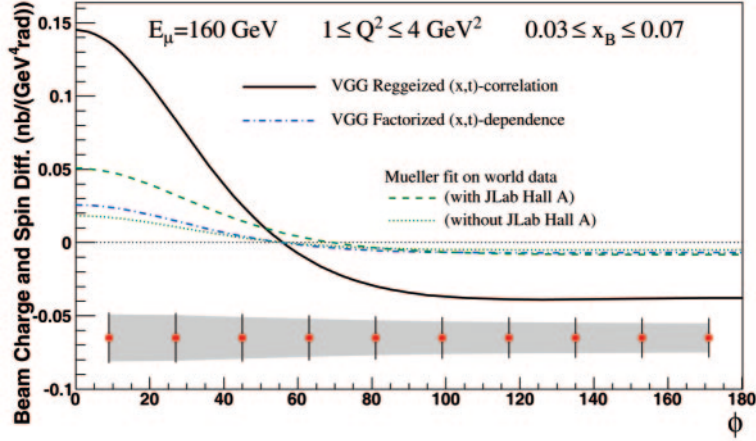


Fig. 3. – Projected statistical (error bars) and systematic (grey band) accuracy for the measurement of the  $\phi$  dependence of  $\mathcal{D}_{CS,U}$  for  $0.03 \leq x \leq 0.07$  and  $1 \leq Q^2 \leq 4 \text{ GeV}^2$  and for 280 days of running time with a 2.5 m LH<sub>2</sub> target, an intensity of  $4.6 \times 10^8 \mu$  in a 48 s SPS spill period and an overall *global efficiency*  $\epsilon_{global} = 0.1$ .

liquid-hydrogen target surrounded by a 1 m long recoil was used. The short run in 2008 proved the capability of the detection and reconstruction of exclusive single photon events. In 2009 approximately 10 times more statistics was collected giving access to the  $\phi$  distributions in three bins in  $x_B$  (see fig. 2 lower part). The solid lines represent the expected BH event yield while the histogram shows the measured single photon yields which include pure DVCS events and also misidentified  $\pi^0$  events.

1. Building the Beam Charge ( $C$ ) and Spin ( $S$ ) Difference of the cross section for Unpolarized ( $U$ ) proton target, BH contribution cancels out:

$$\mathcal{D}_{CS,U} \equiv d\sigma^{\rightarrow} - d\sigma^{\leftarrow} = 2 [P_{\mu} d\sigma_{pol}^{DVCS} + e_{\mu} \text{Re } I] \propto (c_0^I + c_1^I \cos \phi).$$

In the last step the DVCS amplitude is expanded in  $1/Q$  keeping only leading twist-2 terms [5]. The coefficients  $c_0^I$  and  $c_1^I$  are for COMPASS kinematics related to the dominant real part of the Compton Form Factors (CFF)  $\mathcal{H}$  which is in leading order a weighted sum over flavors  $f$  of convolutions of the GPDs  $H^f$  with a kernel describing the hard interaction of virtual photon and quark. The projected statistical accuracy of the measurement of  $\mathcal{D}_{CS,U}$  is shown in fig. 3. It corresponds to a luminosity of  $L = 1222 \text{ pb}^{-1}$ , which is equal to 280 days of data taken over two calendar years. Two of the curves are calculated using the VGG GPD model [6] which is based on a “reggeized” parameterisation of the correlated  $x, t$  dependence of the GPDs. It uses a shrinkage parameter  $\alpha'$  to describe the decrease in nucleon size with increasing  $x$ . As this model is meant to be applied mostly in the valence region, typically a large value  $\alpha' = 0.8$  is used. For comparison, also the model for the “factorised”  $x, t$  dependence is shown, which corresponds to  $\alpha' \approx 0.1$  in the “reggeized” ansatz. The other two curves are predictions based on first fits to world data [7]. These fits which include next-to-next-to leading order (NNLO) corrections were successfully applied to describe DVCS observables from very small

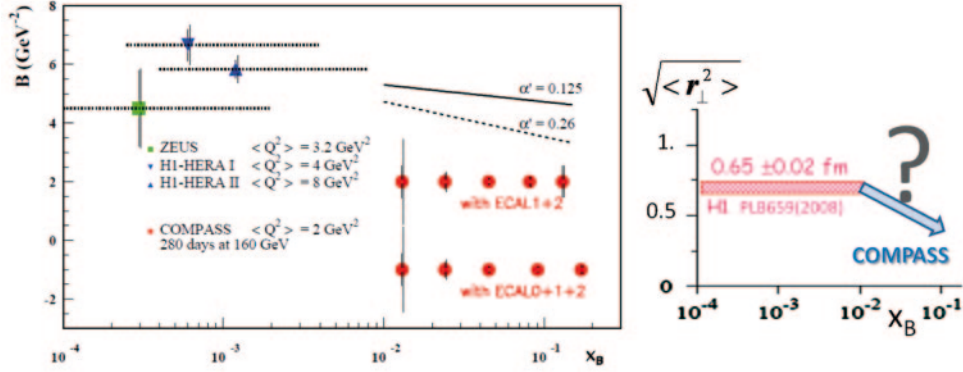


Fig. 4. – Left: Projections for measuring the  $x_B$  dependence of the  $t$ -slope parameter  $B(x_B)$  of the DVCS cross section, calculated for  $1 < Q^2 < 8 \text{ GeV}^2$ . A comparison to HERA results with similar  $\langle Q^2 \rangle$  is shown [8, 9]. The left vertical bar on each data point indicates the statistical error only while the right one includes also the systematic uncertainty, using only ECAL1 and ECAL2 (first row) and also ECAL0 (second row). Two different parameterisations are shown using  $\alpha' = 0.125 \text{ GeV}^{-2}$  and  $0.26 \text{ GeV}^{-2}$ . Right: Transverse proton radius as a function of  $x_B$ . New and significant information will be obtained in the uncharted  $x_B$  region, further elucidating the issue of “nucleon tomography”.

values of  $x_B$ , for the HERA collider to large  $x_B$  for HERMES and JLab. It has to be noted that the real part of the Compton form factor  $\mathcal{H}$  was found positive at H1 and ZEUS and negative at HERMES and JLab. The COMPASS kinematic domain is expected to provide the node of the real part of this amplitude, which is an essential input for any global fit analysis.

- At leading twist the cross section of the Beam Charge ( $C$ ) and Spin ( $S$ ) Sum for Unpolarized ( $U$ ) proton target can be written as:

$$\mathcal{S}_{CS,U} \equiv d\sigma^{\leftarrow} + d\sigma^{\rightarrow} = 2[d\sigma^{BH} + d\sigma_{unpol}^{DVCS} + e_{\mu} P_{\mu} \text{Im } I] \propto 2d\sigma^{BH} + c_0^{DVCS} + s_1^I \sin \phi,$$

in which the BH contribution does not cancel out.

- The analysis of the  $\phi$ -dependence of  $\mathcal{S}_{CS,U}$  will provide via the term  $\text{Im } I$  the leading twist-2 quantity  $s_1^I$ . Its dominant contribution is related to the imaginary part of the Compton form factor  $\mathcal{H}$ , which is proportional to the GPD  $H$ .
- A parallel analysis can be performed subtracting the BH contribution and integrating over  $\phi$  to get rid of the complete interference term. Thus the DVCS leading twist-2 quantity  $c_0^{DVCS}$  can be isolated and its characteristic  $t$ -slope as a function of  $x_B$  can be determined, from which conclusions can be drawn on the evolution of transverse size of the nucleon over the  $x_B$ -range accessible to COMPASS. Such a mapping in  $x_B$  is referred to as “Nucleon Tomography”. Figure 4 shows the projected statistical accuracy for a measurement at COMPASS of the  $x_B$ -dependence of the  $t$ -slope parameter  $B(x_B)$  of the DVCS cross section. In the simple ansatz

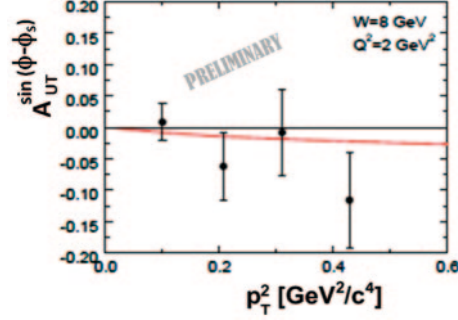


Fig. 5.  $-A_{UT}^{\sin(\phi-\phi_S)}$  using the transversely polarized  $\text{NH}_3$  (proton) COMPASS 2007 data and compared to the predictions of the GPD model [12] at  $\langle Q^2 \rangle = 2 \text{ GeV}^2$  and  $\langle W \rangle = 8 \text{ GeV}$ .

$\frac{d\sigma}{dt} \propto \exp(-B(x_B)|t|)$  with  $B(x_B) = B_0 + 2\alpha' \log(\frac{x_0}{x})$ . At small  $x_B$ , where amplitudes are predominantly imaginary, the overall transverse size of the nucleon  $\langle r_{\perp}^2(x_B) \rangle \approx 2 \cdot B(x_B)$ . Data on  $B$  exist only for the HERA collider  $x_B$ -range from  $10^{-4}$  to 0.01 [8,9], below the COMPASS range  $0.01 < x_B < 0.1$ . No evolution with  $x_B$  was observed and a first transverse proton radius has been determined  $\langle r_{\perp}^2 \rangle = 0.65 \pm 0.02 \text{ fm}$  using H1 data [8]. In the valence region, where no experimental determinations of  $B$  exist, some information comes from fits adjusted to form factor data which give  $\alpha' \simeq 1 \text{ GeV}^2$  [10, 11]. For the simulation two values  $\alpha' = 0.125$  and  $\alpha' = 0.26$  are shown which correspond to the half and the total of the value for Pomeron exchange in soft scattering processes. The largest value can be determined with an accuracy better than  $2.5\sigma$  by using the two existing calorimeters ECAL1 and ECAL2 while the smallest value requires the new calorimeter ECAL0 to get a better precision at large  $x_B$ .

### 3. – Study of the GPD E using transversely polarized protons ( $\text{NH}_3$ target)

A sensitivity to the GPD E requires either the use of a neutron target or a transversely polarized proton target. This second way is investigated at COMPASS for exclusive meson production. It will be still further investigated both for DVCS and DVMP, using a transversely polarized proton target and a recoil detector. This will be the goal of a future addendum to the COMPASS-II proposal for a second phase of GPD measurements.

1. Exclusive rho production from transversely polarized protons has already been studied using the 2007 COMPASS data obtained with a polarized  $\text{NH}_3$  target. The  $\rho^0$  mesons are selected by the detection of two charged pions of invariant mass  $m_{\pi\pi}$  between 0.5 and  $1.1 \text{ GeV}^2$ . Because of this early stage, recoil protons are not detected, a cut is applied on the missing energy  $E_{miss} = (M_X^2 - M_p^2)/2M_p$  where  $M_X$  is the mass of the undetected particle and  $M_p$  the proton mass. The transverse target spin dependent cross section is accessed experimentally by the modulation of the cross section asymmetry  $A_{UT}^{\sin(\phi-\phi_S)}$  as a function of  $\sin(\phi - \phi_S)$  ( $\phi_S$  is the azimuthal angle of the transverse target spin vector relative to the lepton scattering plane). This asymmetry is presented in fig. 5 as a function of  $p_T^2$  the transverse momentum of  $\rho^0$  with respect to the direction of the virtual photon. This



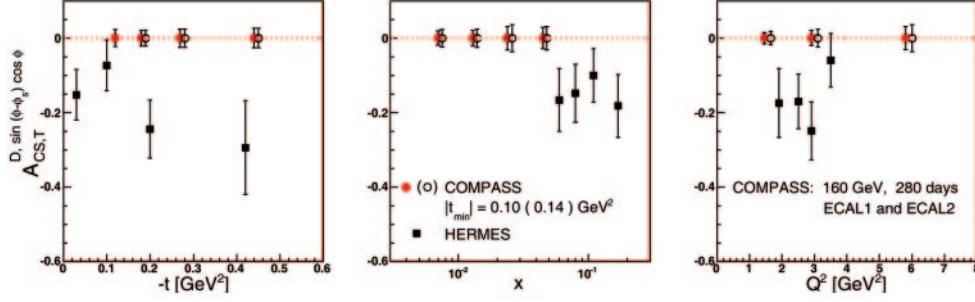


Fig. 6. – Projections for the statistical accuracy of the transverse target asymmetry compared to measurements done at HERMES [13].

asymmetry is proportional to  $p_T$  and to a weighted sum of convolutions of the GPD  $E^{q,g}$  with the distribution amplitude of the produced meson and a hard scattering kernel. The weights depend on the contributions of quarks of various flavours and gluons to the production of a given vector meson. The model [12] explains the small value of the asymmetry as due to an approximate cancellation of two sizable contributions of opposite signs for the GPDs  $E^u$  and  $E^d$  for the valence  $u$  and  $d$  quarks, respectively. In contrast the model predicts larger asymmetry for exclusive production of  $\omega$  meson or  $\rho^+$  meson.

2. DVCS using high-energy polarised  $\mu^+$  and  $\mu^-$  beams with a transverse polarized NH<sub>3</sub> target and recoil proton detection will be proposed at a further stage of COMPASS-II. The modulation of the cross section asymmetry as a function of  $\sin(\phi - \phi_S)$  will provide  $A_{UT}^{\sin(\phi - \phi_S)}$  which involves the quark GPD  $E^f$  unsuppressed relatively to the GPD  $H^f$ . Predictions are given in fig. 6 as a function of  $t$ ,  $x_B$  and  $Q^2$  for a measurement in 280 days using a 160 GeV beam and ECAL1 and ECAL2. The solid and open circles correspond to the simulations for two hypothetical configurations of the polarized target and the recoil proton detector design. The predictions are compared to HERMES results [13] with its statistical errors.

In the next future before new facilities are built, only COMPASS-II using a 160 GeV muon beam and JLab using a 12 GeV electron beam will perform DVCS measurements to access GPDs. JLab has an excellent luminosity to study in details the valence region through the interference between DVCS and BH while COMPASS-II with its high energy  $\mu^+$  and  $\mu^-$  beams will study a complementary domain at smaller  $x_B$  ranging from 0.01 to about 0.1 which has never been investigated so far. COMPASS-II will consider GPD studies both through the BH and DVCS interference and the almost pure DVCS cross section. A first DVCS test using the new recoil detector CAMERA around the long LH<sub>2</sub> target and a new ECAL0 partially equipped will be performed in autumn 2012. The full two years DVCS experiment is foreseen in 2015-16 according a tentative schedule for the full COMPASS-II program comprising also Drell-Yan experiments. Then COMPASS-II will investigate in a complementary approach subtle effects of either intrinsic transverse parton momenta or transverse parton localisation.

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