THE GPD PROGRAM AT COMPASS

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Abstract

The COMPASS proposed program of the Generalised Parton Distribution (GPD) studies is reviewed. Various observables for this program and the expected accuracies are discussed. The necessary developements of the experimental setup and the first results from the test run are also presented.

1 Introduction

Generalised Parton Distributions (GPDs) [1–3] provide a comprehensive description of the nucleon's partonic structure and contain a wealth of new information. In particular, they embody both the nucleon electromagnetic form factors and the parton distribution functions, unpolarised as well as helicity-dependent. But more important, they allow a novel description of the nucleon as an extended object, referred sometimes as 3-dimensional 'nucleon tomography' [4]. GPDs also allow access to such a fundamental property of the nucleon as the orbital momentum of quarks [2]. For reviews of the GPDs see Refs [5–7].

The mapping of the nucleon GPDs requires extensive experimental studies of hard processes, Deeply Virual Compton Scattering (DVCS) and Deeply Virtual Meson Production (DVMP), in a broad kinematic range. The high energies available at the CERN SPS and the availability of both muon beam polarisations make the fixed-target COMPASS set-up a unique place for such studies. In the future program [8] we propose to measure both DVCS and DVMP using an unpolarised proton target during a first period, in order to constrain mainly GPD H, and a transversely polarised ammonia target during another period in order to constrain the GPD E.

2 The proposed setup

The COMPASS apparatus is located at the high-energy (100-200 GeV) and highly-polarized $\mu^{\pm}$ beam line of the CERN SPS. At present it consists of a two stage spectrometer comprising various tracking detectors, electromagnetic and hadron calorimeters, and particle identification detectors grouped around 2 dipole magnets SM1 and SM2 in conjunction with a longitudinally or transversely polarized target. By installing a recoil proton detector around the target to ensure exclusivity of the DVCS and DVMP events, COMPASS could be converted into a facility measuring exclusive reactions within a kinematic domain from $x \sim 0.01$ to ~ 0.1, which cannot be explored at any other existing or planned facility in the near future. Thus COMPASS could explore the uncharted x domain between the HERA collider experiments and the fixed-target experiments as HERMES and the planned 12 GeV extension of the JLAB accelerator. For values of x below 10^{-1}, the outgoing photon (or meson) is emitted at an angle below 10° which corresponds for the photon, to the acceptance of the two existing COMPASS electromagnetic calorimeters ECAL1 and ECAL2 and which for charged particles is within the acceptance of the tracking devices and the RICH detector. To access higher x values a large angular acceptance calorimeter ECAL0 is needed, which is presently under a study. Schematic layout of COMPASS is shown in Fig. 1, with only new or upgraded detectors and the spectrometer magnets indicated.

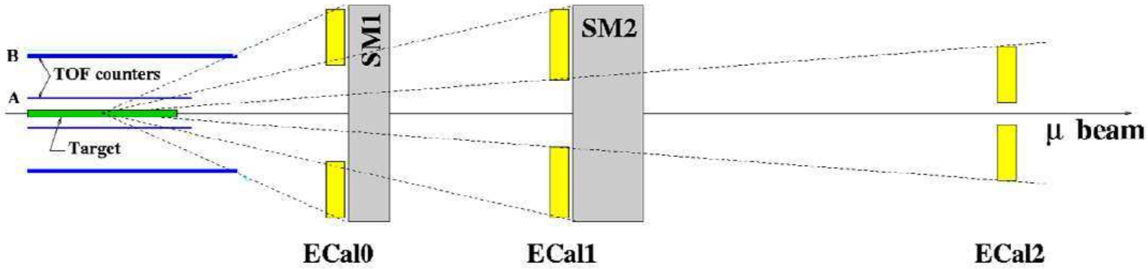

Figure 1: Schematic layout of the proposed setup. Only new and upgraded detectors are shown.

The data will be collected with polarized μ^+ and μ^- beams. Assuming 140 days of data taking and a muon flux of $4.6 \cdot 10^8$ μ per SPS spill, reasonable statistics for the DVCS process can be accumulated for Q^2 values up to 8 GeV^2. It is worth noting that an increase of the number of muons per spill by a factor 4 would result in an increase in the range in Q^2 up to about 12 GeV^2.

3 Foreseen measurements

The complete GPD program at COMPASS will comprise the measurements of DVCS cross section with polarized positive and negative muon beams and at the same time the measurements of a large set of mesons (ρ, ω, ϕ, π, η, ...).

3.1 Deeply Virtual Compton Scattering

DVCS is considered to be the theoretically cleanest of the experimentally accessible processes because effects of next-to-leading order and higher twist contributions are under theoretical control [10]. The competing Bethe-Heitler (BH) process, which is elastic lepton-nucleon scattering with a hard photon emitted by either the incoming or outgoing lepton, has a final state identical to that of DVCS so that both processes interfere at the level of amplitudes.

COMPASS offers the advantage to provide various kinematic domains where either BH or DVCS dominates. The collection of almost pure BH events at small x allows one to get an excellent reference yield and to control accurately the global efficiency of the apparatus. In contrast, the collection of almost pure DVCS sample at larger x will allow the measurement of the x dependence of the t-slope of the cross section, which is related to the tomographic partonic image of the nucleon. In the intermediate domain, the DVCS contribution will be boosted by the BH process through the interference term. The dependence on ϕ, the azimuthal angle between lepton scattering plane and photon production plane, is a characteristic feature of the cross section [10].

COMPASS is presently the only facility to provide polarized leptons with either charge: polarized μ^+ and μ^- beams. Note that with muon beams one naturally reverses both charge and helicity at once. Practically μ^+ are selected with a polarisation of -0.8 and μ^- with a polarization of +0.8. The difference and sum of cross sections for μ^+ and μ^- combined with the analysis of ϕ dependence allow to isolate the real and imaginary parts of the leading twist-2 DVCS amplitude, and of higher twist contributions.

In the following sections we show projections for DVCS measurements with unpolarised proton target (3.1.1 and 3.1.2) and with transversely polarised ammonia target (3.1.3).

3.1.1 x-dependence of the t-slope of DVCS

The t-slope parameter $B(x)$ of the DVCS cross section $\frac{d\sigma}{dt}(x) \propto \exp(-B(x)\,|t|)$ can be obtained from the and charge sum of the cross section after integration over ϕ and BH subtraction. The expected statistical accuracy of measurements of $B(x)$ at COMPASS is shown in Fig. 2. The systematic errors are mainly due to uncertainties involved in the subtraction of the BH contribution. At $x > 0.02$ they are small compared to the statistical errors. For the simulations the simple ansatz $B(x) = B_0 + 2\,\alpha' \log(\frac{x_0}{x})$, was used. As neither B_0 nor α' are known in the COMPASS kinematics, for the simulatations shown in Fig. 2 we chose the values $B_0 = 5.83$ GeV^2, $\alpha' = 0.125$ and $x_0 = 0.0012$. The precise value of the t-slope parameter $B(x)$ in the COMPASS x-range will yield new and significant information in the context of 'nucleon tomography' as it is expected in Ref. [11].

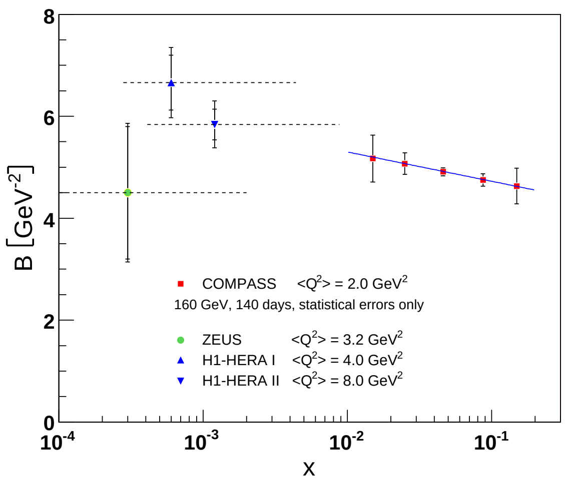

Figure 2: The x dependence of the fitted t-slope parameter B of the DVCS cross section, expressed as $d\sigma/dt \propto e^{-B|t|}$. COMPASS projections are calculated for $1 < Q^2 < 8$ GeV^2 and are compared to some HERA results for which the mean value $< Q^2 >$ is in this range.

3.1.2 Beam charge and spin asymmetry

Fig. 3 shows the projected statistical accuracy if the beam charge and spin asymmetry $A_{CS,U}$ measured as a function of ϕ in a selected (x, Q^2) bin. The asymmetry is defined as

$$\mathcal{A}_{CS,U} = \frac{d\sigma^{\overset{+}{\leftarrow}} - d\sigma^{\overset{-}{\rightarrow}}}{d\sigma^{\overset{+}{\leftarrow}} + d\sigma^{\overset{-}{\rightarrow}}}\,, \tag{1}$$

with arrows indicating the orientations of longitudinal polarisation of beams. This asymmetry is sensitive to the real part of the DVCA amplitude which is a convolution of GPDs with the hard scattering kernel over the whole range of longitudinal momenta of

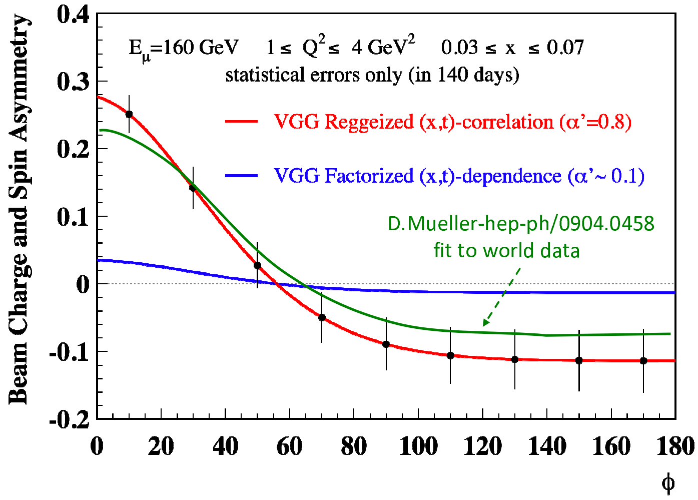

Figure 3: Projections for the Beam Charge and Spin Asymmetry measured at COMPASS in one year for $0.03 \leq x \leq 0.07$ and $1 \leq Q^2 \leq 4$ GeV^2. The red and blue curves correspond to different variants of the VGG model [9] while the green curve shows predictions based on the first fit to the world data [12].

exchanged quarks. Therefore measuements of this asymmymmetry provide strong constrains on the models of GPD. Two of the curves shown in the figure are calculated using the 'VGG' GPD model [9]. As this model is meant to be applied mostly in the valence region, typically the value $\alpha' = 0.8$ is used in the 'reggeized' parameterization of the correlated x, t dependence of GPDs. For comparison also the model result for the 'factorized' x, t dependence is shown, which corresponds to $\alpha' \approx 0.1$ in the reggeized ansatz. A recent theoretical development exploiting dispersion relations for Compton form factors was successfully applied to describe DVCS observables at very small values of x typical for the HERA and extended to include DVCS data from HERMES and JLAB. The prediction for COMPASS from this analysis is shown as an additional curve.

As the overall expected data set from the GPD program for COMPASS will allow 9 bins in x vs. Q^2, each of them expected to contain statistics sufficient for stable fits of the ϕ dependence, a determination of the 2-dimensional x, Q^2 (or x, t) dependence will be possible for the various Fourier expansion coefficients c_n and s_n [10], thereby yielding information on the nucleon structure in terms of GPDs over a range in x. This data is expected to be very useful for future developments of reliable GPD models able to simultaneously describe the *full* x-range.

3.1.3 Predictions for the transverse target spin asymmetry

Transverse target spin asymmetries for exclusive photon production are important observables for studies of the GPD E, and for the determinaton of the role of the orbital momentum of quarks in the spin budget of the nucleon. The sensitivity of these asymmetries to the total angular momentu of u quarks, J_u, was estimated for the transversely polarised protons in a model dependent way in Ref. [13].

The transverse target spin asymmetries for the proton will be measured with the transversely polarised ammonia target, similar to the one used at present by COMPASS. Two options are considered for the contiguration of the target magnet and RPD, each with a different impact on the range of measurable energy of the recoil proton.

The transverse spin dependent part of the cross sections will be obtained by subtracting the data with opposite values of the azimuthal angle ϕ_s, which is the angle between the lepton scattering plane and the target spin vector. In order to disentangle the $|DVCS|^2$ and the interference terms with the same azimuthal dependence, it is necessary to take data with both μ^+ and μ^- beams, because only in the difference and the sum of μ^+ and μ^- cross sections these terms become separated. Both asymmetries for the difference and the sum of μ^+ and μ^- transverse spin dependent cross sections will be analysed. The difference (sum) asymmetry $A^D_{CS,T}$, ($A^S_{CS,T}$) is defined as the ratio of the μ^+ and μ^- cross section difference (sum) divided by the lepton-charge-averaged, unpolarised cross section. Here CS indicates that both lepton charge and lepton spin are reversed between μ^+ and μ^-, and T is for the transverse target polarisation.

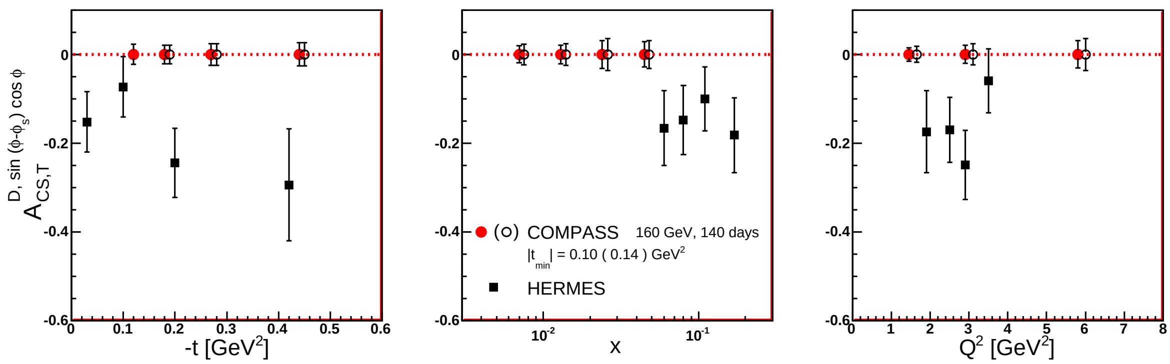

Figure 4: The expected statistical accuracy of $A^{D,\sin(\phi-\phi_s)\cos\phi}_{CS,T}$ as a function of $-t$, x and Q^2. Solid and open circles correspond to the simulations for the two considered configurations of the target region. Also shown is the asymmetry $A^{\sin(\phi-\phi_s)\cos\phi}_{U,T}$ measured by HERMES [13] with its statistical errors.

As an example, the results from the simulations the expected statistical accuracy of the asymmetry $A^{D,\sin(\phi-\phi_s)\cos\phi}_{CS,T}$ is shown in Fig. 4 as a function of $-t$, x and Q^2 for the two considered configurations of the target region. Here $\sin(\phi-\phi_s)\cos\phi$ idicates type of azimuthal modulations. This asymmetry is an analogue of the asymmetry $A^{\sin(\phi-\phi_s)\cos\phi}_{UT}$ measured by HERMES experiment with unpolarised electrons which is also shown in the figure.

Typical values of the statistical errors of $A^{D,\sin(\phi-\phi_s)\cos\phi}_{CS,T}$, as well as of the seven remaining asymmetries related to the twist-2 terms in the cross section, are expected to be ≈ 0.03.

3.2 Deeply Virtual Meson Production

Hard exclusive vector meson production is complementary to DVCS as it provides access to various other combinations of GPDs. For vector meson production only GPDs H and E contribute, while for pseudoscalar mesons GPDs $\tilde{H}$ and $\tilde{E}$ plays a role. We recall that DVCS depends on the four GPDs. Also in contrast to DVCS, where gluon contributions enter only beyond leading order in α_s, in DVMP both quark and gluon

GPDs contribute at the same order. For example

$$H_{\rho^0} = \frac{1}{\sqrt{2}}(\frac{2}{3}H^u + \frac{1}{3}H^d + \frac{3}{8}H^g); \;\; H_\omega = \frac{1}{\sqrt{2}}(\frac{2}{3}H^u - \frac{1}{3}H^d + \frac{1}{8}H^g); \;\; H_\phi = -\frac{1}{3}H^s - \frac{1}{8}H^g.$$

Therefore by combining the results for various mesons the GPDs for various quark flavours and for gluons could be disentangled.

It was pointed out that vector meson production on a transversely polarised target is sensitive to the nucleon helicity-flip GPD E [5, 14]. This GPD offers unique views on the orbital angular momentum carried by partons in the proton [2] and on the correlation between polarisation and spatial distribution of partons [4]. The azimuthal aymmetry $A_{UT}^{\sin(\phi-\phi_s)}$ for exclusive production of a vector meson off the transversely polarised nucleon depends linearly on GPD E and at COMPASS kinematic domain it can be expressed as

$$A_{UT}^{\sin(\phi-\phi_s)} \sim \sqrt{t_0 - t}\frac{\mathrm{Im}(\mathcal{E}^M \mathcal{H}_M^*)}{|\mathcal{H}_M|^2}\,, \tag{2}$$

where t_0 is the minimal momentum transfer. The quantities $\mathcal{H}_M$ and $\mathcal{E}_M$ are weighted sums of integrals over the GPD $H^{q,g}$ and $E^{q,g}$ respectively. The weights depend on the contributions of quarks of various flavours and of gluons to the production of meson M.

We note that the production of ρ, ω, ϕ vector mesons is already being investigated at COMPASS [15]. The recent results from COMPASS on the transverse target spin asymmetries for ρ^0 production off transversely polarised protons and deuterons were presented in Ref. [16]. The spin asymmetry $A_{UT}^{\sin(\phi-\phi_s)}$ for the proton is shown in Fig. 5 as a function of Q^2, x and p_t^2, where p_t is the trasverse momentum of ρ^0 with respect to the virtual photon. The errors shown are statistical ones. Preliminary estimates of systematic errors indicate that they are smaller than the statistical ones. The asymmetry is consistent with zero within the statistical errors.

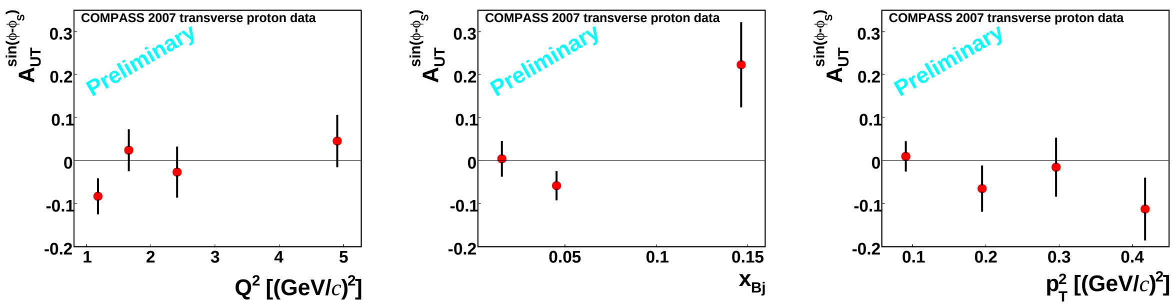

Figure 5: $A_{UT}^{\sin(\phi-\phi_s)}$ for exclusive ρ^0 production off the transversely polarised protons as a function of Q^2, x and p_t^2.

A similar analysis of $A_{UT}^{\sin(\phi-\phi_s)}$ for the deuteron was done using the data taken in 2002-2004 with transversely polarised ^{6}LiD target. Coherent and incoherent contributions to the exclusive production on the deuteron have to be disentangled. The asymmetry for the deuteron is consistent with zero as well. The separation of contributions from longitudinal and transverse virtual photons for both data sets is in progress.

Theoretical calculations of $A_{UT}^{\sin(\phi-\phi_s)}$ for ρ^0 have been performed by Goloskokov and Kroll [17]. At COMPASS kinematics the predicted values for ρ^0 production on the proton are about -0.02, in agreement with the data. The small values of asymmetry are to a large extent due to a cancellation of E^u and E^d for ρ^0 production. Significantly higher asymmetry, about -0.10, is expected for ω production.

4 Validation tests and outlook

The setup used in 2008 and 2009 for the meson spectroscopy measurements with hadron beams happens to be an excellent *prototype* to perform validation measurements for DVCS. A first measurements of exclusive γ production on a 40 cm long LH target, with detection of the slow recoiling proton in the RPD has been performed during a short (< 2 days) test run in 2008 using 160 GeV μ^+ and μ^- beams. The measurements were performed with the present hadron setup, all the standard COMPASS tracking detectors, the ECAL1 and ECAL2 electromagnetic calorimeters for photon detection and appropriate triggers. An efficient selection of single photon events, and suppression of the background is possible by using the combined information from the forward COMPASS detectors and the RPD.

A way to tag the observed process, $\mu + p \rightarrow \mu' + \gamma + p'$, to which both the DVCS and Bethe-Heitler process contribute, is to look at the angle ϕ between the leptonic and hadronic planes. The Bethe-Heitler contribution, which dominates the sample, show a peak at $\phi \simeq 0$. The observed distribution, after applying all cuts and selections and for $Q^2 > 1$ (GeV/c)^2, is displayed in Fig. 6 with the prediction from the Monte Carlo simulation. The shape of the observed distribution is compatible with the dominant Bethe-Heitler process. The overall detection efficiency can be deduced from the relative normalisation of the two distributions. The global efficiency is equal to about 0.13 ± 0.05 .

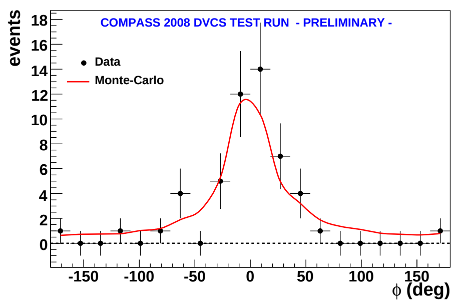

Figure 6: The distribution of the azimuthal angle ϕ for observed exclusive single photon production (points). The line is the Monte Carlo prediction normalised to the data.

In 2009 a two-week DVCS test run was performed with 160 GeV μ^+ and μ^- beams, and with the similar setup as in 2008. In addition the beam momentum station was operational during the test, which allowed momentum measurements of individual beam particles. The main goal for the 2009 DVCS test in 2009 is a better understanding of all backgrounds and a first evaluation of the relevant contributions of DVCS and DVCS-BH interference in a kinematic domain at larger x where BH is not dominant.

A proposal to extend the physics program of COMPASS, including the GPD studies, will be submitted in 2010. A possible start of the GPD program, first with unpolarised proton target, is planned for 2012.

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