THE GPD PROGRAM AT COMPASS

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Abstract

The high energy polarised muon beam available at CERN, with positive or negative charge, makes COMPASS a unique place for GPD studies. The GPD program is a part of 'COMPASS-II proposal', which started to be realised in 2012. The new detectors, the large recoil proton detector and a (part of) large angle electromagnetic calorimeter that are essential for measurements of exclusive processes, were constructed and incorporated into the COMPASS setup. A short DVCS pilot run in 2012 was devoted to the commissioning of these new detectors followed by data taking. The COMPASS program of present and future GPD studies is reviewed and various observables for this program and expected accuracies are discussed.

1 Introduction

Generalised Parton Distributions (GPDs) [1–3] contain a wealth of information on the partonic structure of the nucleon. In particular, they allow a novel description of the nucleon as an extended object, sometimes referred to as 3-dimensional 'nucleon tomography' [4]. GPDs also allow access to such a fundamental property of the nucleon as the orbital angular momentum of quarks [2]. For reviews of the GPDs see Refs [5–7]. The mapping of the nucleon GPDs requires comprehensive experimental studies of hard processes, Deeply Virtual Compton Scattering (DVCS) and Hard Exclusive Meson Production (HEMP), in a broad kinematic range.

2 Brief overview of the program

The COMPASS GPD program encompasses the three following activities.

a) The analysis of exclusive vector meson production on polarised ^{6}LiD and NH_3 targets using the data from 2002-2011. Although no recoil proton detector was included in the used experimental setup, which is a disadvantage for measurements of exclusive processes, the analysis of these data allows to obtain valuable results that are sensitive to GPDs E and chiral-odd GPDs. At the moment these GPDs are still poorly constrained experimentally. This subject is covered at this conference in more detail in another contribution from COMPASS [8] and in a theoretical presentation [9].

b) Data taking and analysis of dedicated short 'DVCS test' runs in 2008 and 2009. The setup used in 2008/2009 for the meson spectroscopy with hadron beams (so called 'hadron setup') happened to be an excellent *prototype* to perform validation measurements for DVCS. First measurements of exclusive γ production on a 40 cm long liquid hydrogen (LH_2) target, with detection of the slow recoiling proton in the recoil proton detector (RPD), have been performed during the test runs using 160 GeV highly polarised μ^+ and μ^- beams from the M2 beam line of the CERN SPS. They were obtained with the 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 was possible by using the combined information from the forward COMPASS detectors and the RPD. One of the results from the DVCS test data is discussed in Sec. 3

c) The GPD program of COMPASS-II. This is a part of new 'COMPASS-II proposal' [10], which has been approved in December of 2010 and started to be realised in 2012. The GPD part will be devoted to measurements of both DVCS and HEMP with polarised μ^+ and μ^- beams and a liquid hydrogen target. The following time lines are assumed for the approved part of the proposal. In 2012 there were already performed measurements of pion and kaon polarisabilities using Primakoff reactions with hadron beam scattering off a nickel target. They were followed, still in 2012, by the commissioning and pilot run for DVCS. After a technical stop of the LHC in 2013 and the most part of 2014, the measurements of the Drell-Yan process in scattering of a pion beam on transversely polarised protons will start in late 2014 and will continue in 2015. They will be followed by two years (2016-2017) of data taking for the GPD program (Phase-1) with unpolarised protons accompanied by semi-inclusive DIS (SIDIS) measurements.

Measurements to be pursued by COMPASS-II after 2017 will be a subject of an addendum to the proposal. They will include the GPD E studies (Phase-2) using a transversely polarised target and a recoil proton detector. Also high statistics SIDIS data will be collected with transversely polarised protons and deuterons. Further, measurements of Drell-Yan on transversely polarised protons and deuterons, as well as on unpolarised protons and nuclear targets are foreseen. Hadron spectroscopy in diffractive and central production will be also performed, with an emphasis on a search for glueballs and exotic states.

3 Validation tests

From the theoretical view point DVCS is considered to be the cleanest process among those investigated experimentally, because effects of next-to-leading order and higher twist contributions are under theoretical control [11]. 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 an 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 [11].

The DVCS test runs in 2008 and 2009 with the 40 cm LH_2 target and the small RPD allowed to demonstrate the feasibility to measure exclusive single γ production at COMPASS. A way to identify 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 observed distributions, after applying all cuts and selections and for $Q^2 > 1$ (GeV/c)^2, are displayed in Fig. 1 and compared to the predictions from the Monte Carlo simulations for the BH event yield. The Bethe-Heitler contribution shows a characteristic peak at $\phi \simeq 0$. The overall

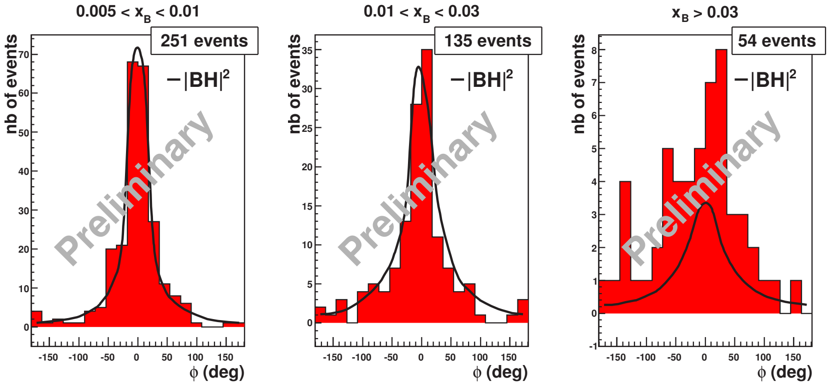

Figure 1: The distribution of the azimuthal angle ϕ for observed exclusive single photon production measured in the 2009 DVCS test run at COMPASS. The lines represent the expected BH event yield.

detection efficiency can be deduced from the relative normalisation of the two distributions for the low x-region dominated by BH. The global efficiency, is equal to 0.14 ± 0.05 in agreement with the value 0.1 assumed for the proposal [10]. It includes the detection efficiency, SPS and COMPASS availabilities, trigger efficiencies and dead time.

4 The proposed setup

The COMPASS apparatus [12] 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 polarised target. By installing a large recoil proton detector around the new 2.5 m long LH_2 target COMPASS has been 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.

The recoil proton detection is based on a ToF measurement between two barrels of 24 scintillator slats read out at both ends. The inner barrel (Ring A) of 2.75 m length with diameter of 50 cm and surrounding directly the target is made of slats of 4 mm thickness to allow low-momentum-proton detection down to about 260 MeV/c. The outer barrel (Ring B) is made of 3.6 m long and 5 cm thick slats and has a diameter of 2.2 m.

Given the time window of about 150 ns dictated by the dispersion in proton momentum, vertex position along the target and light propagation in the scintillators, a high counting rate in all elements of the RPD is expected, in particular in Ring A, where the dominant source is the production of δ-rays in the target material and walls. A line-shape analysis of the PMT signal is used to obtain precise ToF information and improve background rejection. Given the high counting rates, a dedicated readout called GANDALF based on a 1 GHz digitiser has been designed and implemented.

An entirely new calorimeter ECAL0 covering large photon angles is being constructed. Compared to the existing electromagnetic calorimeters, it will increase the accessible domain in x for DVCS and exclusive π^0 production, and therefore it will provide an overlap with HERMES and JLAB experiments. ECAL0 will provide an improved hermeticity for detection of exclusive events and contribute to reduce background to single-photon production that originates from π^0 and other decays. It will also have a significant impact on the uniformity of acceptance as a function of angle ϕ [10].

ECAL0 will be located immediately downstream from the RPD. With the transverse size of 216x216 cm^2 and a 80x64 cm^2 central hole it will cover the polar angle range 0.15 - 0.6 mrad and the energy range from 0.2 GeV to 30 GeV. ECAL0 will consist of about 1700 cells arranged in 9-cell modules. Each cell will contain a stack of lead/scintillator plates that have the sampling 'shashlik' structure. The light collected and transported by WLS fibers will be detected by Multipixel Avalanche PhotoDiode (MAPD) detectors.

The central 56 ECAL0 modules, out of the total number of 194, were already calibrated with the beam and made available for the 2012 DVCS pilot run. The complete ECAL0 will be ready for the restart of the GPD program in 2016.

For the GPD program the data will be collected with polarised μ^+ and μ^- beams. Assuming in total 280 days of data taking, μ^+ beam flux of $4.6 \cdot 10^8$ μ per SPS spill and three times smaller flux for μ^- beam, a reasonable statistics for the DVCS process can be accumulated for Q^2 values up to 8 GeV^2. The upper limit of Q^2-range is driven by the luminosity, and the quoted number corresponds to the present beam intensity and spill structure. In the following sections we show projections for DVCS measurements with an unpolarised proton target (5.1 and 5.2) and with a transversely polarised ammonia target (5.3). For each target the integrated muon flux was taken the same as described above and the value of the global efficiency was assumed to be equal to 0.1.

5 Planned measurements

The complete GPD program at COMPASS-II will comprise the measurements of the DVCS cross section with polarised positive and negative muon beams and at the same time the measurements of exclusive production of a large set of mesons (ρ, ω, ϕ, π, η, ...). In the following we show selected projections for DVCS, while that for exclusive ρ^0 production is given in Ref. [8].

5.1 x-dependence of the t-slope of DVCS

The t-slope parameter $B(x)$ of the DVCS cross section $d\sigma/dt(x) \propto \exp(-B(x)\,|t|)$ can be obtained from the beam charge and spin sum of the cross sections after integration over ϕ and BH subtraction. The expected statistical accuracy of the measurements of $B(x)$ at COMPASS is shown in Fig. 2. The upper set of COMPASS points corresponds to the acceptance of the existing electromagnetic calorimeters, while the lower one is obtained assuming that in addition the new calorimeter ECAL0 is also available. 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 $B(x) = B_0 + 2\,\alpha' \log(x_0/x)$ was used. As neither B_0 nor α' are known in the COMPASS kinematics, for the projections of expected uncertainties 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 the 'nucleon tomography' as it is expected in Ref. [13].

5.2 Beam charge and spin difference of cross sections

COMPASS is presently the only facility to provide polarised leptons with either charge: polarised μ^+ and μ^- beams. Note that with muon beams one naturally reverses both charge

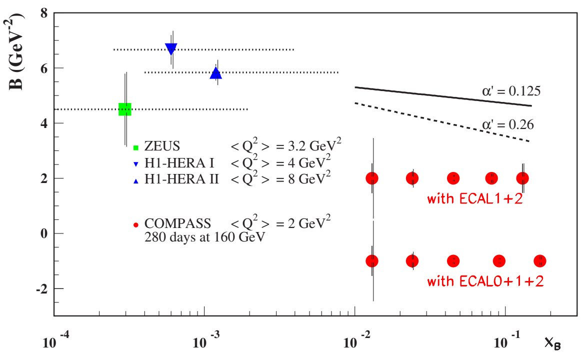

Figure 2: The x dependence of the fitted t-slope parameter B of the DVCS cross section. COMPASS projections for expected uncertainties are calculated for $1 < Q^2 < 8$ GeV^2 and compared to HERA results for which the mean value $< Q^2 >$ is in this range. The two curves in the right part of the figure represent $B(x)$ dependence for different values of α'.

and helicity at once. Practically μ^+ are selected with a polarisation of -0.8 and μ^- with a polarisation of $+0.8$. The difference and sum of cross sections for μ^+ and μ^- combined with the analysis of ϕ dependence allow us to isolate the real and imaginary parts of the leading twist-2 DVCS amplitude, and of higher twist contributions.

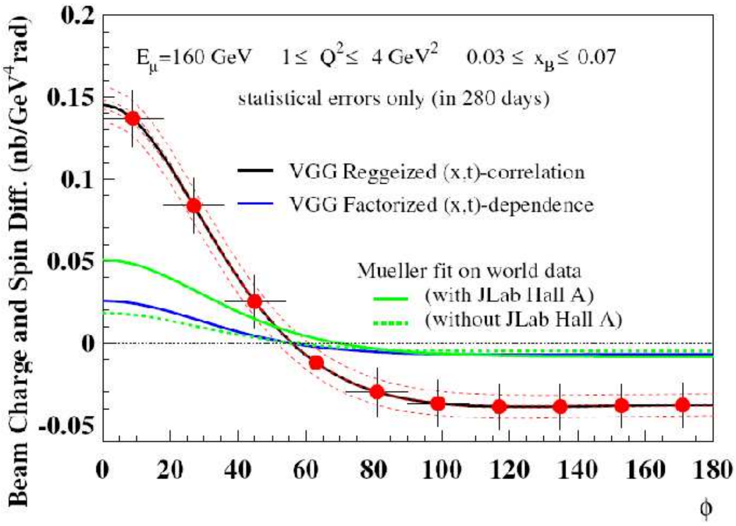

Figure 3: Projections for the beam charge and spin difference of cross sections measured at COMPASS for $0.03 \leq x \leq 0.07$ and $1 \leq Q^2 \leq 4$ GeV^2. The red and blue curves correspond to two variants of the VGG model [14] while the green curves show predictions based on the first fits to the world data [15].

Fig. 3 shows the projected statistical accuracy for the beam charge and spin difference of cross section $\mathcal{D}_{\mathcal{CS},\mathcal{U}}$ measured as a function of ϕ in a selected (x, Q^2) bin. The difference is defined as

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

with arrows indicating the orientations of the longitudinal polarisation of the beams. The difference $\mathcal{D}_{\mathcal{CS},\mathcal{U}}$ is sensitive to the real part of the DVCS amplitude which is a convolution of GPDs with the hard scattering kernel over the whole range of longitudinal momenta of exchanged quarks. Therefore measurements of this asymmetry provide strong constrains on the models of GPD. Two of the curves shown in the figure are calculated using the 'VGG' GPD model [14]. As this model is meant to be applied mostly in the valence region, typically the value $\alpha' = 0.8$ is used in the 'reggeized' parameterisation of the correlated x, t dependence of GPDs. For comparison also the model result for the 'factorised' x, t dependence is shown, which corresponds to $\alpha' \approx 0.1$ in the reggeized ansatz. A theoretical development [15] 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 are shown as additional curves.

As the overall expected data set from the GPD program for COMPASS will allow about 10 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 [11], thereby yielding information on the nucleon structure in terms of GPDs over a range in x. These data are expected to be very useful for future developments of reliable GPD models able to simultaneously describe the *full* x-range.

5.3 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 determination 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 momentum of u quarks, J_u, was estimated for the transversely polarised protons in a model dependent way in Ref. [16].

The transverse target spin asymmetries for the proton will be measured with the transversely polarised ammonia target, similar to the one used in the past by COMPASS. Two options are considered for the configuration of the target magnet and the 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^- of 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.

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

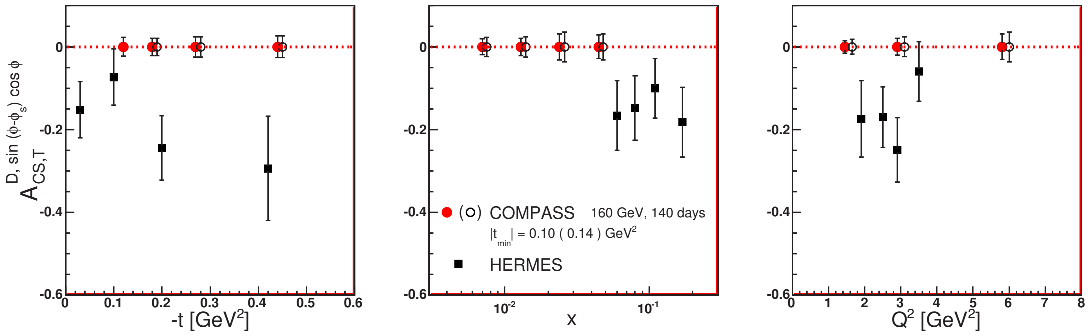

Figure 4: The expected statistical uncertainty of $A_{CS,T}^{D,\sin(\phi-\phi_s)\cos\phi}$ as a function of $-t$, x and Q^2. Solid and open circles correspond to the simulations for the two considered configurations of the target region. Also shown is the asymmetry $A_{U,T}^{\sin(\phi-\phi_s)\cos\phi}$ measured by HERMES [16] with its statistical errors.

6 Summary

COMPASS has a great potential for the GPD physics. It is unique due to the availability of polarised μ^+ and μ^- and a favourable kinematic range in x. The GPD program required major upgrades of the existing apparatus. For measurement with the liquid hydrogen target (Phase-1) the large RPD was build and a part of the large angle electromagnetic calorimeter ECAL0 was already available for the DVCS pilot run in 2012. For measurements with transversely polarised protons (Phase-2), which are planned after 2017, a new recoil proton detector has to be incorporated into a large polarised target.

Investigation of GPDs with DVCS and HEMP on unpolarised protons will allow to determine the x-dependence for t-slopes of the differential cross sections. That is related to the transverse distribution of partons and the 'nucleon tomography'. Measurements of the beam charge and spin sum and difference of single-γ cross sections will give access to the real and imaginary parts of the DVCS amplitude, and will allow to further constrain GPDs H. Studies of exclusive production of vector mesons (ρ, ω, ϕ) will lead to the quark flavour and gluon separation for GPDs H, while that of exclusive π^0 production will provide constrains on the GPD $\tilde{E}$ and on chiral-odd GPDs.

The main goal of future measurements with transversely polarised target is to constrain GPDs E, which are related to the orbital momentum of partons, and also to investigate the role of chiral-odd GPDs in exclusive meson production.

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