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GPD program at COMPASS

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Summary. — A major part of the future COMPASS program is dedicated to investigation of the nucleon structure by studying Generalised Parton Distributions (GPDs) through Deeply Virtual Compton Scattering (DVCS) and Meson Production (DVMP). Already new results of the transverse target spin azimuthal asymmetry $A_{UT}^{\sin(\phi-\phi_s)}$ for hard exclusive ρ^0-meson production on a transversely polarized target have been obtained. Now the realisation of the first DVCS test run with a 2.5 m long liquid hydrogen target surrounded by a new ToF system and an extended calorimetry has been achieved. The availability of muon beams with high energy and opposite charge and polarization will allow to access the Compton form factor related to the dominant GPD H and to measure the x_B-dependence of the t-slope of the pure DVCS cross section to study nucleon tomography. In the future we consider to use a transversely polarized proton target to constrain the GPD E.

PACS 13.60.Fz – Elastic and Compton scattering.
PACS 13.60.Hb – Total and inclusive cross sections (including deep-inelastic processes).
PACS 13.60.Le – Meson production.
PACS 14.20.Dh – Protons and neutrons.

1. – Introduction for GPD studies at COMPASS

Generalised Parton Distributions (GPDs) [1] provide 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. GPDs provide a sort of "3D picture" of the nucleon often referred as "nucleon tomography". GPDs also allow access to such a fundamental property of the nucleon as the orbital angular momentum of partons via the second moment of the sum of the GPDs H and E. The study of exclusive reactions like Deeply Virtual Compton Scattering (DVCS) and

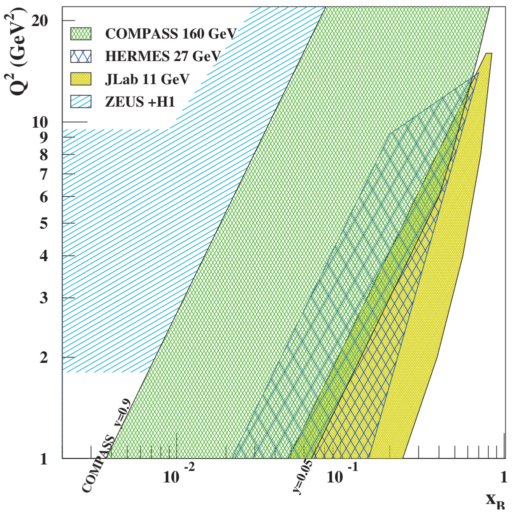

Fig. 1. – Kinematic domains for measurements of hard exclusive processes.

Deeply Virtual Meson Production (DVMP) is one of the most promising ways to experimentally constrain the GPDs. Measurements of these processes and notably of DVCS, the golden channel, have been performed or are planned at JLab [2](1), at DESY with HERMES [3](1), H1 [4](1) and ZEUS [5](1) and at CERN wih COMPASS [6].

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 COMPASS-II to access GPDs via DVCS and DVMP. The existing COMPASS set-up [7] has been equipped with a 2.5 m long liquid hydrogen target. In order to accomplish the detection of exclusive events a 4 m long recoil proton detector (CAMERA) has been installed around the target. For the DVCS channel the photon detection assured at small angle by the two existing electromagnetic calorimeter (ECAL1 and ECAL2) is completed at larger angle by a new electromagnetic calorimeter (ECAL0) placed just downstream of the target. This increases 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^2, which cannot be explored by any other existing or planned facility in the near future (fig. 1). COMPASS-II [6] 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 [8](1).

2. – Study of the GPD H through DVCS with high energy polarised μ^+ and μ^- beams and an unpolarized proton target and with recoil proton detection

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

(1) Only recent or planned DVCS publications are cited.

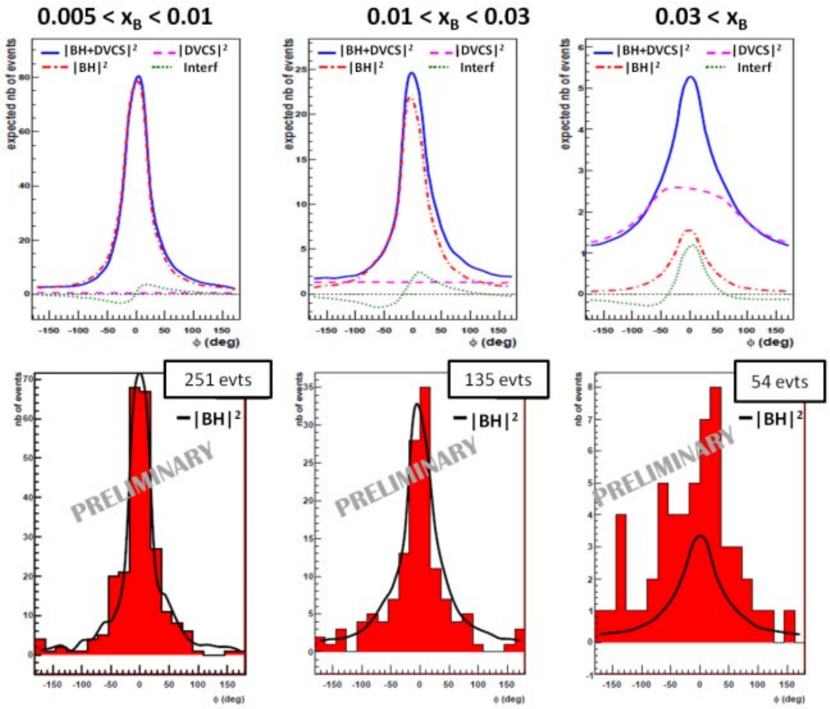

Fig. 2. – Upper: Monte Carlo simulation of the exclusive muoproduction of a single real photon at COMPASS-II without ECAL0 showing the ϕ angle distributions of reconstructed events for three bins in x_B for $Q^2 > 1\,\text{GeV}^2$. Lower: ϕ angle distributions measured in the DVCS 2009 test run at COMPASS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

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([2])

$$\frac{\mathrm{d}^4\sigma(\mu p \to \mu p \gamma)}{\mathrm{d}x_B \mathrm{d}Q^2 \mathrm{d}|t| \mathrm{d}\phi} = \mathrm{d}\sigma^{BH} + \left(\mathrm{d}\sigma^{DVCS}_{unpol} + P_\mu\, \mathrm{d}\sigma^{DVCS}_{pol}\right) + e_\mu \left(\mathrm{Re}\, I + P_\mu\, \mathrm{Im}\, I\right),$$

where P_μ and e_μ 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 ϕ 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 ϕ due to the present limited acceptance at large photon angles. This will be

([2]) For simplicity $\mathrm{d}\sigma$ is used in the following instead of $\frac{\mathrm{d}^4\sigma(\mu p \to \mu p \gamma)}{\mathrm{d}x_B \mathrm{d}Q^2 \mathrm{d}|t| \mathrm{d}\phi}$.

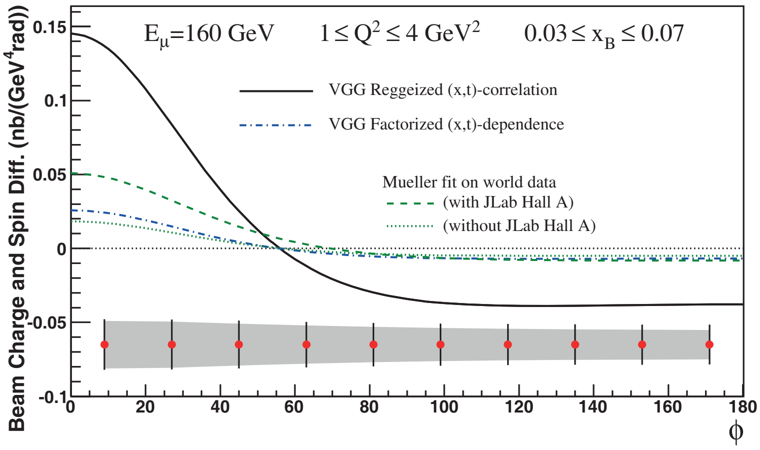

Fig. 3. – Projected statistical (error bars) and systematic (grey band) accuracy for the measurement of the ϕ dependence of $\mathcal{D}_{CS,U}$ for $0.03 \leq x \leq 0.07$ and $1 \leq Q^2 \leq 4\,\mathrm{GeV}^2$ and for 280 days of running time with a 2.5 m LH_2 target, an intensity of $4.6 \times 10^8 \mu$ in a 48 s SPS spill period and an overall *global efficiency* $\epsilon_{global} = 0.1$.

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 ϕ 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 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 approximatively 10 times more statistics was collected giving access to the ϕ distributions in three bins in x_B (see fig. 2 on the 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 π^0 events.

In 2012 we have collected about still 10 times more statistics with the 2.5 m long liquid hydrogen target surrounded by the new 4 m long recoil detector CAMERA and equipped with about one third of the new calorimeter ECAL0. These data will help to confirm the different contributions of BH and DVCS and to settle the crucial background issue. They will provide the first insight of the results of the observables developped in the two next items.

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

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

In the last step the DVCS amplitude is expanded in $1/Q$ keeping only leading twist-2 terms [9]. 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 $L = 1222\,\mathrm{pb}^{-1}$, which is equal to 280 days of data taken over two calendar years. Two of the curves are calculated using the VGG GPD model [10] which is based on a "reggeized" parameterisation of the correlated x, t dependence of the GPDs. It uses a shrinkage parameter α' 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 [11]. These fits which include next-to-next-to leading order (NNLO) corrections were successfully applied to describe DVCS observables from very small 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.

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

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

in which the BH contribution does not cancel out.

- The analysis of the ϕ-dependence of $\mathcal{S}_{CS,U}$ will provide via the term 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 ϕ 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 $\frac{\mathrm{d}\sigma}{\mathrm{d}t} \propto \exp(-B(x_B)\,|t|)$ 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 [4,5], 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 $\langle r_\perp^2\rangle = 0.65 \pm 0.02\,\mathrm{fm}$ using H1 data [4]. In the valence region, where no experimental determinations of B exist, some information comes from fits adjusted to form factor data which give $\alpha' \simeq 1\,\mathrm{GeV}^2$ [12,13]. 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.

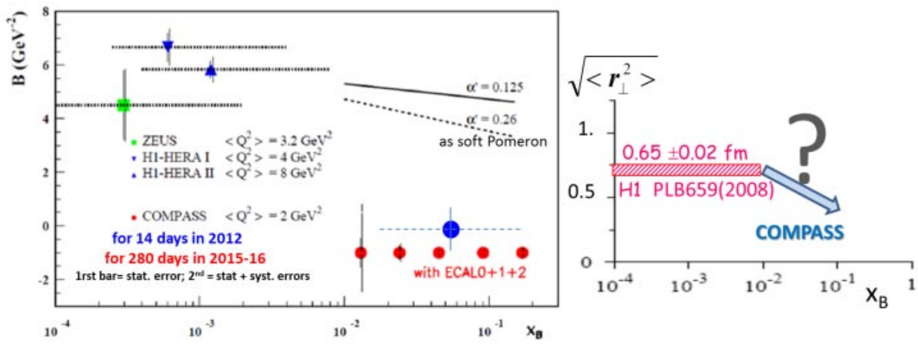

Fig. 4. – Left: Projections for measuring the x_B dependence of the t-slope parameter $B(x_B)$ of the DVCS cross section, calculated for $1 < Q^2 < 8\,\text{GeV}^2$. A comparison to HERA results with similar $\langle Q^2 \rangle$ is shown [4, 5]. The left vertical bar on each data point indicates the statistical error only while the right one includes also the systematic uncertainty, using all the 3 calorimeters ECAL0, ECAL1 and ECAL2. 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".

3. – Study of the GPD E using transversely polarized targets

A sensitivity to the GPD E requires either the use of a neutron target or a transversely polarized proton target. This second way has been investigated at COMPASS for exclusive meson production.

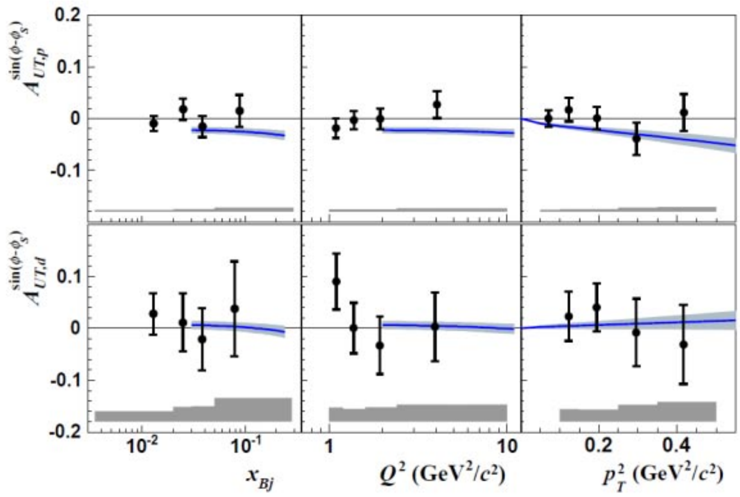

Fig. 5. – Results [14] for $A_{UT}^{\sin(\phi-\phi_S)}$ measured on proton (upper) and deuteron (lower) as a function of x_B, Q^2 and p_T^2. The systematic uncertainties are indicated by grey bands. The curves show the predictions of the GPD model [16] using the set of parameters called "variant 1". The theoretical error bands take into account uncertainties of GPD parameterisations.

Exclusive rho production from transversely polarized protons has already been studied using the 2007 and 2010 COMPASS data obtained with a polarized NH_3 target. The same analysis was done for transversely polarized deuterons using the 2003 and 2004 COMPASS data obtained with the a polarized ^{6}LiD target. The ρ^0 mesons are selected by the detection of two charged pions of invariant mass $m_{\pi\pi}$ between 0.5 and 1.1 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 $\sin(\phi - \phi_S)$ (ϕ_S is the azimuthal angle of the transverse target spin vector relative to the lepton scattering plane). This asymmetry is presented in fig. 5 [14] as a function of x_B, Q^2 and p_T^2 the transverse momentum of ρ^0 with respect to the direction of the virtual photon. For transversely polarised deuterons it is the first measurement. The proton results are compatible with the results measured by HERMES [15]. This 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 [16] 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. For proton the asymmetry is sensitive to $2/3E^u + 1/3E^d$, while for deuteron it is effectively $E^u + E^d$. In contrast the model predicts larger asymmetry for exclusive production of ω meson or ρ^+ meson.

Investigation of both DVCS and DVMP for the quest of the GPD E will be proposed in a future addendum to the COMPASS-II proposal for a second phase of GPD measurements.

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