Possibility to perform DVCS measurement at COMPASS

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The high energies available at CERN and the option of using either positive or negative polarized muon beams make the fixed-target COMPASS set-up a unique place for studying GPDs through Deeply Virtual Compton Scattering (DVCS). The impact of a one-year dedicated run is examined. Preliminary beam test data were analyzed and demonstrated the feasibility of such an experiment. This initiative is part of a Letter of Intent [2] for the Medium and Long Term Plans at COMPASS.

1 Kinematic Domain accessible at COMPASS

The COMPASS experiment is located on the unique high-energy (200 GeV) and highly polarized $\mu^{\pm}$ beam line of the CERN SPS and uses a high resolution forward spectrometer in conjunction with a fixed target (unpolarized or longitudinally or transversely polarized). By installing a recoil proton detector around the target to ensure exclusivity of Deeply Virtual Compton Scattering (DVCS) and Deeply Virtual Meson Production (DVMP) events, it could be converted into a facility measuring exclusive reactions within a kinematic subspace ranging from $x \sim 0.01$ to ~ 0.1, which cannot be explored by any other existing or planned facility in the near future. Figure 1 displays the kinematic domain of the fixed-target experiments COMPASS, HERMES and JLab. These domains are indicated between the dotted lines defined by the maximum energy of the facility and the curve W > 2 GeV, i.e. above the resonance domain. COMPASS would thus explore the uncharted x domain between those of H1 and ZEUS at the HERA collider and of fixed-target experiments as HERMES and the planned 12 GeV extension of the JLab accelerator.

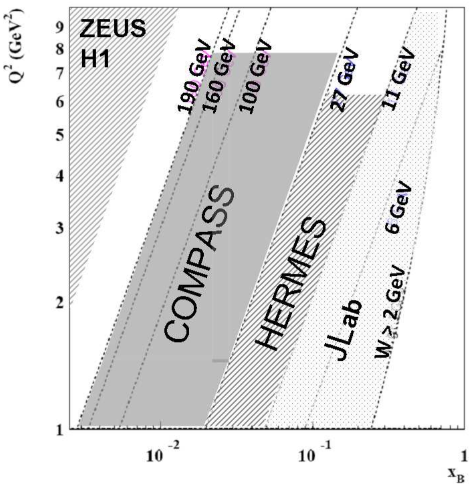

Figure 1: Kinematical domain at various facilities.

2 DVCS Measurement with polarized μ^+ and μ^- beams

DVCS is considered to be the theoretically cleanest of the experimentally accessible processes to measure GPDs because effects of next-to-leading order and subleading twist are under theoretical control [3]. 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 $\mathcal{A}$:

$$d\sigma(\mu\mathrm{N} \to \mu\mathrm{N}\gamma) \propto |\mathcal{A}_{BH}|^2 + |\mathcal{A}_{DVCS}|^2 + \underbrace{\mathcal{A}_{BH}\mathcal{A}^*_{DVCS} + \mathcal{A}^*_{BH}\mathcal{A}_{DVCS}.}_{I} \tag{1}$$

The Bethe-Heitler amplitude can be calculated using QED and elastic form factors measurements. The collection of almost pure BH events at small x allows one to get an excellent reference yield and to control accurately the efficiency of the detection. In contrast the collection of almost pure DVCS events at larger x will allow for 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 enhanced by the BH process through their interference. COMPASS is presently the only facility to provide polarized leptons with either charge: polarized μ^+ and μ^- beams. As the BH is independent of charge and polarization, this contribution can be removed by subtracting 2 separate measurements obtained for the two beam charges. Moreover the *natural* polarization of the muon beam produced from pion decay changes sign when the beam charge is reversed and the different topologies of μ^+ and μ^-, polarized with opposite direction, allow one to select only the real part or the imaginary part of the complex amplitude of DVCS.

For the muo-production of real photons off an *unpolarized proton* target, the differential cross section can be written as :

$$\frac{d^4\sigma(\mu p \to \mu p\gamma)}{dx_B dQ^2 d|t| d\phi} = d\sigma^{BH} + [d\sigma^{DVCS}_{unpol} + P_\mu\, d\sigma^{DVSC}_{pol}] + e_\mu\, [\mathrm{Re}\, I + P_\mu\, \mathrm{Im}\, I]\,, \tag{2}$$

where I is the interference term of Eq. (1), P_μ is the beam polarization and e_μ its charge in units of the elementary charge. The DVCS amplitude can be expanded in $1/Q$ beyond leading twist-2 including all twist-3 contributions [3]. The dependence on ϕ, the azimuthal angle between lepton scattering plane and photon production plane, is a characteristic feature of the cross section. Integration over ϕ and/or analysis of the angular dependence in ϕ allows us to isolate specific contributions that are sensitive to different combinations of quark GPDs. Gluon GPDs enter in DVCS only beyond leading order in α_s (LO), analogous to DIS.

At the CERN SPS M2 beamline, the 'natural' polarization of the muon beam produced from pion decay changes sign when the beam charge is reversed. Hence with the *same* apparatus the COMPASS experiment can perform separate measurements for the two beam charge/polarization states $\overset{+}{\leftarrow}$ and $\overset{-}{\rightarrow}$, which can be used to calculate:
the 'Beam Charge (C) and Spin (S) Difference' (for Unpolarized (U) proton target)

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

in which the pure BH contribution *cancels out.* The coefficients $c_i^{I,DVCS}$ and $s_i^{I,DVCS}$ are related to certain combinations of Compton Form Factors (CFFs). A CFF $\mathcal{F}$ is a sum over flavors f, of convolutions of the respective GPDs F^f with a perturbatively calculable kernel describing the hard $\gamma^* q$ interaction. Note that the contributions shown between a pair of

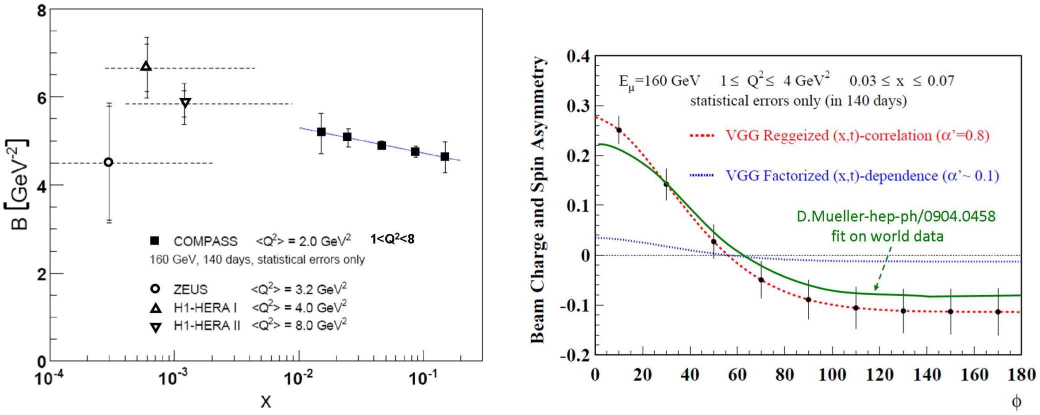

Figure 2: Projection of statistical error bars on the observables described in the txt and for 140 days of running time with a 2.5m LH$_2$ target, an intensity of $4.6 \times 10^8 \mu$ in a 48 s SPS spill period and a global efficiency $\epsilon_{global} = 0.1$ Left : x dependence of the fitted t-slope parameter B of the DVCS cross section. Right : Beam Charge and Spin Asymmetry.

braces corresponds to higher-twist or higher-order effects. The analysis of the ϕ-dependence of the beam charge and spin difference $\mathcal{D}_{U,CS}$ will provide via the term Re I the two leading twist-2 expansion coefficients c_0^I and c_1^I, the dominant contribution to which is related to the *real* part of the Compton form factor $\mathcal{H}$ that is in LO given by a flavor sum of convolutions involving the GPDs H^f.

The 'Beam Charge and Spin Sum' of cross sections can also be evaluated:

$$\begin{aligned}\mathcal{S}_{U,CS} &\equiv d\sigma^{\overleftarrow{+}} + d\sigma^{\overrightarrow{-}} = 2[d\sigma^{BH} + d\sigma^{DVCS}_{unpol} + e_\mu P_\mu \mathrm{Im}\, I] \qquad (4)\\ &\propto 2[d\sigma^{BH}] + \left(c_0^{DVCS} + \left\{c_1^{DVCS}\cos\phi + c_2^{DVCS}\cos 2\phi\right\}\right) + \left(s_1^I \sin\phi + \left\{s_2^I \sin 2\phi\right\}\right)\end{aligned}$$

in which the BH contribution *does not cancel out.* 1) The analysis of the ϕ-dependence of $\mathcal{S}_{U,CS}$ 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 $\mathcal{H}$. 2) A parallel analysis can be performed subtracting the BH contribution when it is not too large, and integrating over ϕ to get rid of the complete interference term and of the ϕ-dependent terms of the DVCS contribution. Thus the DVCS leading twist-2 quantity c_0^{DVCS} can be isolated and its characteristic t-slope can be determined as a function of x, from which conclusions can be drawn on the transverse size of the nucleon over the x-range accessible to COMPASS ('nucleon tomography').

2.1 Shrinkage of the nucleon size

Using the ϕ-integrated beam charge and spin sum after BH subtraction, figure 2 (left) shows the projected statistical accuracy for a measurement at COMPASS of the x-dependence of the t-slope parameter $B(x)$ of the DVCS cross section $\frac{d\sigma}{dt}(x) \propto \exp(-B(x)\,|t|)$. In the simple ansatz $B(x) = B_0 + 2\,\alpha' \log(\frac{x_0}{x})$, the shrinkage parameter α' is known a long time to describe the decrease in nucleon size with increasing x. More recently, this ansatz was also used for the 'reggeized' description of a correlated (x, t) dependence of GPDs. The t-slope of the GPD H^f at a given x was shown [4] to be related to the average impact parameter $\langle (b_\perp^f)^2 \rangle$ in the distribution of partons of flavor f carrying the longitudinal momentum fraction x at a given t: $B^f(x) \sim 1/2\, \langle (b_\perp^f)^2 \rangle (x)$.

Data on B exist only for the HERA collider x-range from 10^{-4} to 0.01 [6, 7], below the COMPASS range $0.01 < x < 0.1$. In Fig. 2 only HERA results are reported for which the mean value $\langle Q^2 \rangle$ is in the investigated domain by COMPASS. In the valence region, where no experimental determinations of B exist, some information comes from fits adjusted to form factor data which give $\alpha' \simeq 1$ GeV^2 [8, 9]. For the low-x sector, H1 results on α' from exclusive J/ψ production [10], which involves the generalized gluon distribution, are smaller by two standard deviations in the total experimental uncertainty than the corresponding value $\alpha' = 0.25$ for Pomeron exchange in soft scattering processes. For the simulation shown in figure 2 we chose the value $\alpha' = 0.125$.

This measurement will yield new and significant information in the context of 'nucleon tomography' as it is expected in chiral-dynamics approach [5]. In this approach, the gluon density is generated by the 'pion cloud' of the nucleon so that a significant increase in the transverse size of the nucleon is predicted for x below the ratio of pion and proton masses, $m_\pi/m_p \approx 0.15$ which lies in the COMPASS domain.

2.2 Beam Charge and Spin Asymmetry and sensitivity to models

Using the beam charge and spin asymmetry $\mathcal{D}_{U,CS}/\mathcal{S}_{U,CS}$, figure 2 (right) shows the projected statistical accuracy in a particular (x, Q^2) bin, for a measurement of its ϕ-dependence. Two of the curves are calculated using the 'VGG' GPD model [11]. 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 exploits dispersion relations for Compton form factors. In this context, the additional curve is the result of a fitting procedure [12] including next-to-next-to leading order (NNLO) corrections which was developed and successfully applied to describe DVCS observables from very small values of x, for the HERA collider to large x for HERMES and JLab.

3 Observation of exclusive photon production in 2008 beam test

At the end of the 2008, we took data with the 160 GeV muon beam impinging on a 40cm-long liquid hydrogen target. The goal was to demonstrate the detectability of the exclusive photon production in the COMPASS conditions. The Recoil Proton Detector developed for the Hadron program of COMPASS was fully operational and the calibration could be taken from previous hadron beam data. The calorimeters ECAL1 and ECAL2 were also operational and could be used in this analysis.

Events were selected according to the topology of the exclusive photon final state. It was required that only one primary vertex with one incoming muon and one scattered muon was found. Calorimeter energy clusters were examined and events with one photon with energy larger than 5 GeV and no other clusters above 1 GeV were kept. Then, it was required that only one proton track could be reconstructed in the recoil proton detector. A clear position and timing correlation between the RPD information and muons information with almost no random hits is observed. From the scattered muon and the photon one can predict the kinematics of the proton and apply further selection criteria. For the transverse momentum a cut at $|\Delta p_\perp| < 0.2$ GeV is applied and for the azimuthal angle a cut at $|\Delta\phi| < 36°$ is applied as shown on the left panel of figure 3.

To identify the process one can look at the angle between the leptonic (μ, μ') and hadronic (γ, p) planes. The distribution of this angle for the events passing all cuts and with $Q^2 > 1$ GeV^2 is displayed in the right panel of figure 3 along with a prediction from a fast Monte-Carlo simulation program. The shape of the observed distribution is compatible with the Bethe-Heitler process. From the comparison, one can extract a detection efficiency for the exclusive photon reaction and obtain values of the order of 30%. Along with factors relevant to the availability of the accelerator and spectrometer, it validates the hypothesis of 10% global efficiency used in the letter of intent.

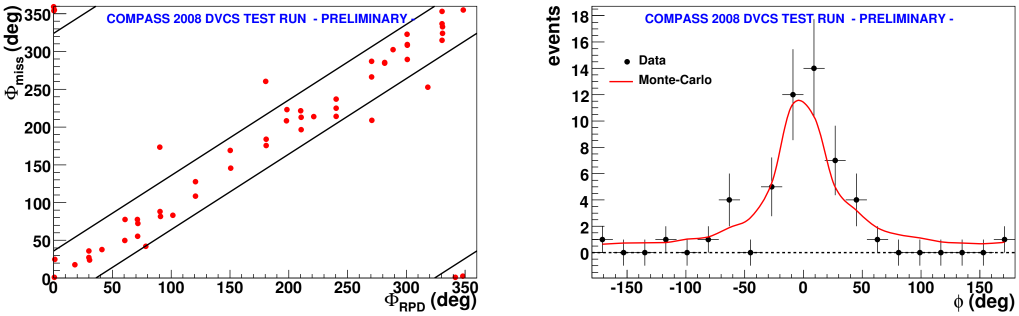

Figure 3: Correlation in azimuthal angle (left). Angle between leptonic an hadronic planes (right).

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