Future Programme of COMPASS at CERN

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COMPASS at CERN is preparing for a new series of measurements on the nucleon structure comprising deep virtual Compton scattering and hard exclusive meson production using muon beams, as well as Drell-Yan reactions using a polarised proton target and a negative pion beam. The former will mainly constrain the generalised parton distribution H and determine the transverse size of the nucleon, while the latter measurements will provide information on transverse-momentum dependent parton distribution functions. The projected results of the programme and the necessary hardware upgrades are discussed.

1 Introduction

The COMPASS Collaboration at CERN proposed in 2010 new measurements on hadron structure [1]. The proposal was approved in December 2010 and experiments will start in 2012 with a pion/kaon polarisability measurement (not discussed here). The future programme starting 2014 after the accelerator shutdown focuses on transverse momentum dependent (TMD) distributions and generalised parton distributions (GPDs). A polarised Drell–Yan experiment will take place in 2014 and in 2015/2016 deeply virtual Compton scattering (DVCS) and hard exclusive meson production will be studied with a 160 GeV muon beam and an unpolarised hydrogen target. A pilot run for the latter experiment is planned already for late 2012. In parallel with the GPD programme, high statistics data for semi-inclusive DIS will be taken.

2 GPD programme

The GPDs are universal distributions which contain as limiting cases nucleon form factors on the one hand and parton distribution functions (PDFs) on the other. The GPDs H^f and $\widetilde{H}^f$ ($f = u, d, s, g$) describe processes where the nucleon helicity is preserved and contain as limiting cases the PDFs f_1 and g_1, respectively. Processes where the nucleon helicity is flipped are described by the GPDs E^f and $\widetilde{E}^f$ for which no such limiting case exists. GPDs correlate transverse spatial and longitudinal momentum and thus provide a kind of 'nucleon tomography'. They depend on four variables x, ξ, t, and Q^2. The cleanest pro-

Figure 1: DVCS process.

cess to assess GPDs is DVCS shown in Fig. 1, in which also the relevant momentum fractions x (not the Bjorken scaling variable) and ξ, and the momentum transfers t and Q^2 are defined.
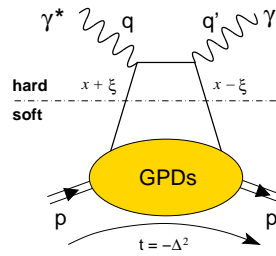
The interest in these distributions was boosted, when X.-D. Ji showed that there is a sum rule for the total angular momentum J^f of a quark or a gluon and the corresponding GPDs [2].

The DVCS process interferes with the Bethe–Heitler (BH) process due to identical final states. The cross-section then contains five terms

$$\mathrm{d}\sigma^{\mu p \to \mu p \gamma} = \mathrm{d}\sigma^{\mathrm{BH}} + \mathrm{d}\sigma_0^{\mathrm{DVCS}} + P_\mu \mathrm{d}\Delta\sigma^{\mathrm{DVCS}} + e_\mu \Re e\, I + P_\mu e_\mu \Im m\, I, \qquad (1)$$

where I denotes the DVCS–BH interference term. An important feature is that the BH contribution can be normalised at small x_B, where it dominates. From Eq. 1 one can build the sum $\mathcal{S}$ and difference $\mathcal{D}$ of the $\mu p \to \mu p \gamma$ cross-section for simultaneous change of lepton charge e_μ and polarisation P_μ of the incoming lepton beam ($+$ to $-$ and $\leftarrow$ to $\rightarrow$)

$$
\begin{aligned}
\mathcal{D} &= \mathrm{d}\sigma^{\overset{+}{\leftarrow}} - \mathrm{d}\sigma^{\overset{-}{\rightarrow}} &= 2(\mathrm{d}\sigma_0^{\mathrm{DVCS}} + \Re e\, I)\\
\mathcal{S} &= \mathrm{d}\sigma^{\overset{+}{\leftarrow}} + \mathrm{d}\sigma^{\overset{-}{\rightarrow}} &= 2(\mathrm{d}\sigma_0^{\mathrm{BH}} + \mathrm{d}\sigma_0^{\mathrm{DVCS}} + \Im m\, I).
\end{aligned}
\qquad (2)
$$

The muon beam used at COMPASS has exactly this behaviour that negative muons have opposite polarisation than positive muons. Upon integration over the azimuthal angle ϕ the interference contribution to $\mathcal{S}$ vanishes [3] and after subtraction of the BH contribution one obtains the DVCS cross-section. This cross-section depends on the squared momentum transfer t from the initial to final nucleon (Fig. 1). At small x_B one has the relation $\langle r_\perp^2(x_B)\rangle \approx 2B(x_B)$ if the exclusive cross-section is parametrised as $\mathrm{d}\sigma/\mathrm{d}t \propto \exp(-B(x_B)|t|)$. The transverse distance $r_\perp$ is measured between the struck quark and the centre of mass of the spectator system. Thus, independent of any GPD parametrisation, one obtains a measure of the transverse nucleon size as a function of x_B. Using a parametrisation of the type $B(x_B) = B_0 + 2\alpha' \log(x_0/x_B)$, one can characterise the t slope of the cross-section by the parameter α'. The projected precision of a t-slope measurement is presented in Fig. 2. A new electromagnetic calorimeter, ECAL0, will improve the precision of the measurement and enlarge the accessible range towards larger x_B. Combined with the HERA data and future JLab data a comprehensive picture of the evolution of the nucleon's transverse size with x_B will be achieved in a model-independent way. For the 2012 pilot DVCS run we project already a significant measurement combining the three central x_B bins of Fig. 2 into one large x_B.

The ϕ dependence of the difference $\mathcal{D}$, the sum $\mathcal{S}$ and the asymmetry $\mathcal{A} = \mathcal{D}/\mathcal{S}$ of the DVCS cross-sections defined in Eq. 2 allow for the extraction of quantities related to Compton form factors (CFF) which in turn depend on the GPDs. With an unpolarised target, COMPASS DVCS results will mainly provide information on the CFF $\mathcal{H}$ and thus constrain the GPD H. Results will be obtained in (x_B, Q^2) bins. An example for the projected precision in such a bin is shown in Fig. 3 for the beam charge-and-spin asymmetry $\mathcal{A}$.

Some handle on the flavour separation of GPDs may be obtained from hard exclusive meson production measured simultaneously with DVCS. Here the meson replaces the real photon. The GPD E can in principle be assessed using a transversely polarised target. Such measurements are under consideration for a later stage of the programme.

Another physics topic pursued in parallel with DVCS, is the study of spin-independent TMD distributions like the Boer–Mulders distribution and of fragmentation functions, in particular for strange quarks. Also the spin-averaged strange quark PDF needs further studies.

A major rearrangement of the spectrometer target region will be necessary for the GPD measurements. The polarised target has to be removed and a recoil proton detector, the Camera detector, will be installed. It consists of two concentric scintillator barrels of 3.6 m
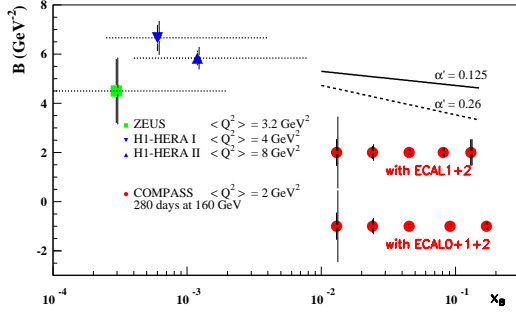
Figure 2: Projected measurements of the x_B dependence of the t-slope parameter $B(x_B)$ (red filled dots) using only ECAL1 and ECAL2 (upper row) and with an additional ECAL0 calorimeter (lower row).
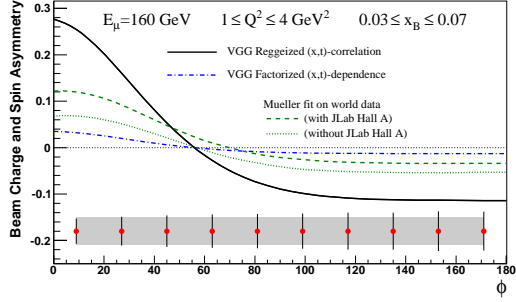

Figure 3: Projected measurements of the dependence of the beam charge-and-spin asymmetry on ϕ. compared to various models from Refs. [4, 5]

length and $2.2\,\mathrm{m}$ diameter for the outer barrel. The photomultiplier signals will be digitised with 1 GHz to cope with the high rate and pile-up. Camera is essential to ensure the exclusivity of the observed reactions. It houses on the central axis a $2.5\,\mathrm{m}$ long liquid hydrogen target. In order to improve the acceptance of real photons, a third electromagnetic calorimeter, ECAL0, will be constructed and placed just downstream of the Camera detector. Multipixel avalanche photodiodes were chosen for the readout to avoid problems due the magnetic field of the close spectrometer magnet SM1. Furthermore the RICH photodetection will be improved.

3 Drell–Yan programme

The second approach to access transverse nucleon structure in the future COMPASS programme is via the Drell–Yan process (Fig. 4) using a $190\,\mathrm{GeV}$ negative pion beam impinging on a transversely polarised proton target (NH_3). The advantage of DY processes is that fragmentation functions are not involved. However, this has to be paid by a convolution of two distribution functions. The DY cross-section is given by $\sigma^{\mathrm{DY}} \propto \sum_f f_{\bar{u}|\pi^-} \otimes f'_{u|p}$,

Figure 4: Sketch of the Drell–Yan process.

where f and f' are generic place holders of PDFs. For $\pi^- p$ scattering the process is dominated by the up quark distributions. Polarised DY experiments can study TMD distributions like the Sivers and Boer–Mulders distributions. Theory predicts that these naive T-odd TMD distributions obey a restricted universality and change sign when observed in SIDIS and DY

$$f_{1T}^\perp\big|_{DY} = -f_{1T}^\perp\big|_{DIS} \qquad \text{and} \qquad h_1^\perp\big|_{DY} = -h_1^\perp\big|_{DIS}. \tag{3}$$

This sign change is due to switching from final-state interaction in SIDIS to initial-state interaction in DY [6]. A violation of this prediction would imply drastic consequences on how cross-sections are calculated. This has generated wide-spread interest in a direct comparison of TMD distributions obtained from SIDIS and DY, respectively. Plans for future polarised DY
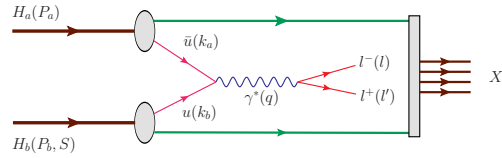
experiments exist at various laboratories, e.g. at RHIC, JPARC, GSI and at JINR. The COMPASS DY experiment is planned and approved for 2014 and primarily assess transversity h_1 and the T-odd Sivers and Boer–Mulders TMD distributions, $f_{1T}^\perp$ and $h_1^\perp$ for up quarks. For all of these COMPASS SIDIS measurements exist, showing non-vanishing asymmetries for the proton.

To avoid the J/ψ region and the region of background from charm decays, the experiments will focus on dimuon masses $4\,\text{GeV} < M_{\mu\mu} < 9\,\text{GeV}$. The azimuthal asymmetries depend on two azimuthal angles, ϕ_S of the target spin with respect to the transverse momentum of the virtual photon in the target rest frame and ϕ between the incoming hadron and outgoing lepton plane in the Collins–Soper frame, a the polar angle θ of the lepton pair (see Ref. [1]), as well as on the Feynman variable $x_F = x_\pi - x_p$. Here x_π and x_p are the momentum fractions carried by the involved quarks in the pion and proton, respectively. The projected $A_T^{\sin \phi_S}$ asymmetry measurement in the high-mass region $4\,\text{GeV} < M_{\mu\mu} < 9\,\text{GeV}$ is compared to predictions in Fig. 5 (top left). The measurement will certainly be able to answer the sign question of T-odd TMD distributions and allow for a comparison of the absolute size of the effects in SIDIS and DY. However, a determination of the shape of the Sivers TMD distribution in DY will only be possible with

Figure 5: Projections for the asymmetries $A_T^{\sin \phi_S}$ (Sivers), $A_U^{2\cos\phi}$ (Boer–Mulders), $A_T^{\sin(2\phi+\phi_S)}$ and $A_T^{\sin(2\phi-\phi_S)}$.

further measurements. The shaded grey area and the central line in Fig. 5 correspond to a calculation based on a TMD PDF fit to data [7]. The Boer–Mulders related asymmetry $A_T \cos 2\phi$ will be determined with high precision.

As the measurement is statistics limited, optimising luminosity is mandatory. A massive hadron absorber downstream of the target reduces radiation and detector occupancy problems. Therefore the polarised target has to be moved upstream by about $3\,\text{m}$. The absorber consists of a tungsten core surrounded by alumina (Al_2O_3), which minimises multiple scattering. This is essential to disentangle the oppositely polarised target cells in the track reconstruction.

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[7] M. Anselmino *et al.*. In Proceedings of *II International Workshop on Transverse Polarization Phenomena in Hard Scattering Processes*, World Scientific, ed. by 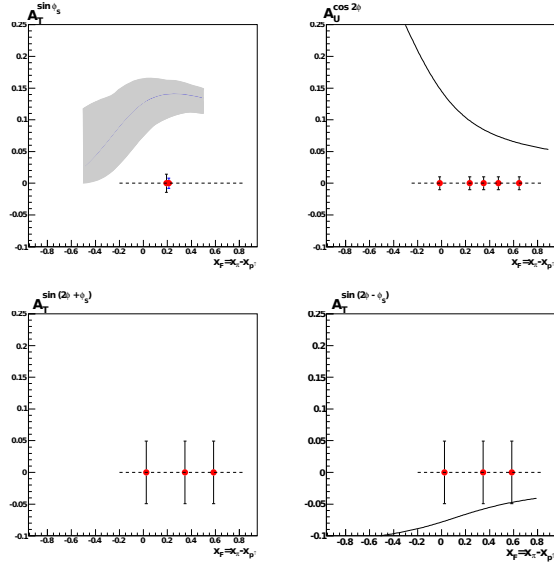G. Ciullo *et al.*, April 2009, p. 138.