Future exploration of the nucleon structure at COMPASS

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Abstract. Up to now, COMPASS experiment [1] essentially focussed, in its program with muon beams, on studying aspects of the longitudinal momentum structure of the nucleon in the collinear approximation, like $\Delta q(x)$ and $\Delta G/G(x)$ [2, 3, 4]. However, quarks can also have intrinsic transverse momentum in the nucleon, which give rise to a new class of Transverse Momentum Distribution (TMD) Parton Distribution Functions. As an example, Sievers function has been measured by both COMPASS and HERMES to be non zero on the proton, paving thus the way for more precise investigations[5, 6].

It is precisely the goal of the new COMPASS phase II proposal [7] to investigate in more detail new transverse description of the nucleon structure. Deeply Virtual Compton Scattering (DVCS) will allow studies in the transverse space via Generalized Parton Distributions (GPDs). Transverse Momenum Dependent PDFs will essentially be studied in Drell-Yan (DY) reaction and SIDIS, and some universality arguments in QCD imply different signs for Sievers and Boer-Mulders functions in DY and SIDIS.

1. Introduction

Parton Distribution Functions (PDFs) describe the structure of the nucleon as a function of the nucleon momentum fraction carried by a parton of a certain species. They are studied primarily in Deeply Inelastic Scattering (DIS) where the longitudinal momentum structure of the nucleon is explored in the collinear approximation, i.e. neglecting transverse degrees of freedom. Up to now, PDFs were investigated independently from nucleon electromagnetic form factors that are related to ratios of the observed elastic electron-nucleon scattering cross section to that predicted for a structureless nucleon. The recently developed theoretical framework of Generalised Parton Distributions (GPDs) embodies both form factors and PDFs, such that GPDs can be considered as momentum- dissected form factors which provide information on the transverse localization of a parton as a function of the fraction it carries of the nucleon's longitudinal momentum. Obtaining such a 3-dimensional picture of the nucleon is sometimes referred to as nucleon tomography.

In a complementary approach, the subtle effects of intrinsic transverse parton momenta are described by Transverse-Momentum-Dependent PDFs (TMDs). These effects become visible in hadronic Drell-Yan and Semi-Inclusive DIS (SIDIS) processes. The structure of hadrons can not yet be calculated in QCD from first principles. However, the deformation of the shape of a hadron in an external electromagnetic field, described by polarizabilities, can be predicted by chiral perturbation theory which is a low-energy expansion of the QCD Lagrangian.

The study of the nucleon transverse structure via GPDs and TMDs, as well as polarizabilities,
will be addressed in COMPASS Phase II proposal [7], by making use of polarized muon beams, as well as pion beams, on unpolarized and transversally polarized targets.

2. TMD via Polarized Drell-Yan measurement

The transverse momentum of partons is a central element in understanding the 3-dimensional structure of the nucleon. At leading twist, if the intrinsic transverse momentum of the quarks $k_T$ is taken into account, 8 parton distribution functions are needed to fully describe the nucleon the so-called transverse momentum dependent (TMD) PDFs [8]. $f_{1T}^+(x,k_T^2)$ (Sivers), $h_{1T}^+(x,k_T^2)$ (Boer-Mulders), and $h_{1T}^+(x,k_T^2)$ (pretzelosity) are examples of such TMD PDFs, which contribute directly to measurable azimuthal asymmetries.

Transverse spin, in fact, couples naturally to intrinsic transverse momentum, and the resulting correlations are encoded in various transverse-momentum-dependent parton distribution and fragmentation functions. The SIDIS cross section contains convolutions of these two types of functions, while the convolutions in the DY cross section comprise only (TMD) PDFs. Thus, a complementary way to access TMD PDFs is from the study of Drell-Yan processes, where a quark from the target annihilates with an anti-quark from the beam. In this case, the spin asymmetry is proportional to a convolution of two PDFs. Of particular interest are the correlations between quark transverse momentum and nucleon transverse spin, and between quark transverse spin and its transverse momentum in an unpolarized nucleon, which are encoded in the so-called Sivers and Boer-Mulders functions. Given the T-odd character of both Sivers and Boer-Mulders functions, the sign of these TMDs is expected to be reversed when observed from SIDIS or from DY. There is a keen interest in the community to test this prediction which is rooted in fundamental aspects of QCD.

![Graph](image)

**Figure 1.** Theoretical predictions [9] and expected statistical errors on the Sivers (left) and Boer-Mulders (right) asymmetries for a DY measurement in the high-mass region $4 \text{ GeV}/c^2 < M_{\mu^+\mu^-} < 9 \text{ GeV}/c^2$

The Sivers function was recently measured by Hermes [6] and Compass [5] in SIDIS off transversely polarized targets and shown to be different from zero and measurable. In order to test the sign change of the Sivers function, DY experiments with transversely polarised hadrons are required, but none were performed so far. The main goal of our DY program is to measure for the first time on a transversely polarized target the process $\pi^- p \rightarrow \mu^+\mu^- X$. This will be a
unique measurement as at Compass energies the virtual photon originates mainly from the fusion
of a $\bar{u}$ quark from the pion and a $u$ quark from the nucleon, both in valence-like kinematics. In
two years of data taking with the 190 GeV $\pi^-$ beam and the Compass spectrometer with the
NH$_3$ transversely polarized target, augmented by an absorber to allow clean detection of $\mu^+\mu^-$
pairs, the fundamental prediction for the sign of the $u$ quark Sivers function and Boer-Mulders
function can be tested for the first time (Fig 1).

3. GPD via DVCS measurement with polarized $\mu^+$ and $\mu^-$ beams

GPDs [10, 11, 12], just like ordinary PDFs, describe the structure of the nucleon independently
of the specific reaction by which the nucleon is probed, i.e. they are expected to be universal
quantities. In particular, they embody both nucleon electromagnetic form factors, i.e. ratios of
the observed elastic electron scattering to that predicted for a point-like nucleon, and Parton
Distribution Functions (PDFs) measured in DIS, i.e. parton number and helicity densities.
Very importantly, GPDs provide a novel description of the nucleon as an extended object,
referred sometimes to as 3-dimensional nucleon tomography [13], which correlates (transverse)
spatial and (longitudinal) momentum degrees of freedom of quarks and gluons. Moreover, the
evaluation of GPDs may for the first time provide an insight into orbital momenta of quarks
and gluons, another fundamental property of the nucleon. The mapping of nucleon GPDs,
which very recently became one of the key objectives of high-energy nuclear physics, requires a
comprehensive programme of measuring various hard exclusive processes in a broad kinematic
range, in particular Deeply Virtual Compton Scattering (DVCS).

![Figure 2. Handbag diagram for the DVCS process at leading twist](image)

The kinematic variables on which GPDs depend can be illustrated using the handbag diagram
shown in Fig. 2 which describes the DVCS process at leading twist in the Bjorken limit
($Q^2 \to \infty$ for fixed $x_B$ and $t$, i.e. $|t|/Q^2$ small). GPDs depend on the photon virtuality $Q^2$,
the total four-momentum squared $t = (p - p')^2 = (q - q')^2$ transferred between initial and fi-
nal nucleon states, and on $x$ and $\xi$. The latter two variables represent respectively average
and half the difference between the initial and final longitudinal momentum fractions of the
nucleon, carried by the parton throughout the process. Based on the factorization theorem [14],
the short-distance information specific to the virtual-photon quark interaction can be separated
from the long-distance information about nucleon structure contained in the GPDs.

DVCS is considered to be the theoretically cleanest of the experimentally accessible processes
to measure GPDs because effects of next-to-leading order and sub-leading twist are under
theoretical control [15]. 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 $\mathcal{A}$:

$$d\sigma(\mu N \rightarrow \mu N\gamma) \propto |\mathcal{A}_{DVCS}|^2 + |\mathcal{A}_{BH}|^2 + \mathcal{A}_{BH}\mathcal{A}_{DVCS}^* + \mathcal{A}_{BH}^*\mathcal{A}_{DVCS}$$

(1)

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.

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

$$\frac{d^4 \sigma(\mu p \rightarrow \mu p\gamma)}{dx_dQ^2 dt d\phi} = d\sigma_{BH} + \left[ d\sigma_{DVCS}^{\text{unpol}} + P_\mu d\sigma_{DVCS}^{\text{pol}} \right] + e_\mu [\text{Re} I + P_\mu \text{Im} I]$$

(2)

where $I$ is the interference term of Eq.(1), $P_\mu$ is the beam polarization and $e_\mu$ its charge in units of the elementary charge. COMPASS is presently the only facility to provide polarized leptons with either charge: polarized $\mu^+$ and $\mu^-$ beams. The natural polarization of the muon beam produced from pion decay changes sign when the beam charge is reversed, so only $\mu^+(P = -1; e = +1)$ and $\mu^-(P = +1; e = -1)$ are possible, leading to two possible combinations:

-Beam charge and Spin difference:

$$\mathcal{D}_{U,CS} \equiv d\sigma^+ - d\sigma^- = 2 \left[ P_\mu d\sigma_{DVCS}^{\text{pol}} + e_\mu \text{Re} I \right]$$

in which the pure BH contribution cancels out. The dependence on $\phi$, the azimuthal angle between lepton scattering plane and photon production plane, is a characteristic feature of the cross section. Integration over $\phi$ and/or analysis of the angular dependence in $\phi$ allows us to isolate specific contributions that are sensitive to different combinations of quark GPDs.

-Beam charge and Spin sum:

$$\mathcal{S}_{U,CS} \equiv d\sigma^+ + d\sigma^- = 2 \left[ d\sigma_{BH} + d\sigma_{DVCS}^{\text{unpol}} + e_\mu P_\mu \text{Im} I \right]$$

Using the $\phi$-integrated beam charge and spin sum after BH subtraction, the $x$ dependence of the t-slope parameter $B(x)$ of the DVCS cross section $d\sigma/dt(x) \propto \exp(-B(x)|t|)$ can be obtained. In the simple ansatz $B(x) = B_0 + 2\alpha'\log(x_0/x)$, the shrinkage parameter $\alpha'$ is known a long time to describe the decrease in nucleon size with increasing $x$ [16].

The present COMPASS forward spectrometer, augmented by both a recoil proton detector around a 2.5m LH$_2$ target to ensure exclusivity of DVCS, and an additional calorimeter ECAL$_0$ at large angle to ensure hermeticity of photon detection, allows precise measurements of both Beam Charge and Spin asymmetry ($\mathcal{D}_{U,CS}/\mathcal{S}_{U,CS}$) and $x$ dependence of the fitted t-slope $B$ of the DVCS cross section within 280 days of data taking (Figs. 3,4). The covered kinematic domain in $x$ lies 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.
3. Estimated statistics for the azimuthal $\phi$ dependence of the Beam Charge and Spin Asymmetry

4. Estimated statistics for $x$ dependence of the fitted t-slope parameter $B$ of the DVCS cross section

4. Conclusion
To summarize, the two main goals of COMPASS Phase II Proposal [7] are:
- measure TMD distribution functions in Drell-Yan reaction, like the T-odd Sievers and Boer-Mulders, and check their sign change as compared to their SIDIS equivalent
- study the transverse size of the nucleon through the $x$ dependence of the slope in $t$ of the DVCS cross section, which dominates over the Bethe-Heitler term in most of COMPASS kinematics. Also, beam charge and spin asymmetry will be obtained.

In order to fulfill this program, equipments will be added to standard COMPASS setup: a thick iron absorber after the target in order to clean up the di-muon detection for the DY program; a 2.5m long hydrogen target surrounded by a plastic scintillator recoil detector, as well as a calorimeter for photon detection at large angles to ensure hermeticity for the DVCS program. This phase II will span over more than 3 years of data taking, starting after 2013.

References
[1] COMPASS, Abbon P et al. 2007 Nucl. Inst. Meth. A 577 455
[2] COMPASS, Alexakhin et al. 2007 Phys. Lett. B 647 330 and refs. therein
[3] COMPASS, Ageev E S et al., 2006 Phys. Lett. B 633 25
[4] COMPASS, Alekseev M et al. 2009 Phys. Lett. B 676 31
[5] COMPASS, Alekseev M et al. 2010 Preprint hep/ex 1005.5609
[6] HERMES, Airapetian A et al. 2005 Phys. Rev. Lett. 94 012002
[7] COMPASS-II Proposal 2010 Report to CERN SPSC CERN-SPSC-2010-014
[8] Bacchetta A et al. 2007 J. High Energy Phys. 02 093
[9] Anselmino et al. 2009 Proc. Workshop on Transverse Polarization Phenomena in Hard Scattering Processes ed Ciullo G et al. (Ferrara: World Scientific) p 138
[10] Mueller D et al., 1994 Fortschr. Phys. 42 101
[11] Ji X D 1997 Phys. Rev. D 55 7114
[12] Radyushkin A V 1997 Phys. Rev. D 56 5524
[13] Burkardt M 2003 Int. J. Mod. Phys. A 18 173
[14] Collins J.C. et al. 1999 Phys. Rev. D 59 074009
[15] Belitsky A V, Mueller D and Kirchner A 2002 Nucl. Phys. B 629 323
[16] Burkardt M 2000 Phys. Rev. D 62 071503; Erratum ibid. 2002 D 66 119903