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Overview of the COMPASS Experimental Programme on TMDs and GPDs

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Abstract The investigation of the recently introduced transverse momentum dependent (TMD) parton distribution functions (PDFs) and generalized parton distributions (GPDs) is an important part of the programme of the COMPASS experiment at CERN. A variety of Semi-inclusive deeply inelastic scattering (SIDIS) measurements on transversely polarized proton and deuteron targets from the 2002–2010 data have allowed to obtain a wealth of results on the transversity distribution and on the TMD PDFs. Further SIDIS measurements are planned in 2016 and 2017 on a pure hydrogen target. In a complementary approach, the first ever Drell–Yan measurement on a transversely polarized proton target is the objective of the 2015 run, still ongoing at the time of this conference, to address the fundamental issue of the change of sign of the Sivers function when measured in the Drell–Yan process as compared to that measured in SIDIS. GPDs are also being investigated. Measurements of the exclusive muon-production of vector mesons, in particular the ρ^0 and the ω, on transversely polarized proton targets have provided information on the GPD E. Preliminary results from a test run on deeply virtual compton scattering of 160 GeV muons on a liquid hydrogen target are also given, as well as plans for a two-year long run in 2016 and 2017 with a suitably modified spectrometer.

1 Introduction

Twenty years ago the COMPASS spectrometer was conceived as "COmmon Muon and Proton apparatus for structure and spectroscopy", capable of addressing a large variety of open problems in both hadron structure and spectroscopy. By now, an impressive list of results has been published. In this review, I will mention only the results which are relevant to the field of TMD PDFs and GPDs.

The description of the nucleon structure in terms of collinear parton distributions, i. e. distributions depending only on Bjorken x and the squared four-momentum transfer Q^2, has recently been generalized to take into account the parton transverse momentum $\mathbf{k}_T$, thus leading to a total of eight TMD PDFs for a complete picture of the nucleon at leading order. After integration over the transverse momentum three of them reduce to the well-known "collinear" PDFs, namely the number density, the helicity and the transversity distributions. The other five TMD PDFs are sensitive to the direction of the quark transverse momentum, they vanish when integrating over $\mathbf{k}_T$, and their measurement provides important information on the dynamics of the partons in the transverse plane in momentum space. In particular the T-odd Sivers and the Boer-Mulders functions are related to the correlations between the transverse momentum of quarks and the nucleon transverse spin and between the transverse momentum and the transverse spin of quarks in unpolarized nucleons, respectively. All these

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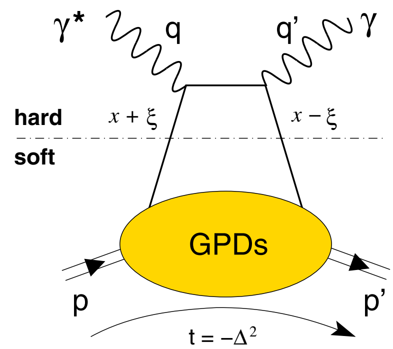

Fig. 1 Handbag diagram for the DVCS at leading twist

PDFs have been investigated by HERMES and COMPASS through measurements of the azimuthal asymmetries of hadrons produced in SIDIS processes [1,2], and are presently being investigated in the Drell–Yan process $\pi p \rightarrow \mu^+\mu^- X$ on transversely polarized protons [3].

In a different approach, PDFs have been generalized to GPDs introducing a transverse spatial dependence. The GPDs constitute a new, three dimensional parametrization of the nucleon structure [4–6]. They correlate the longitudinal momentum distribution of the partons inside the nucleon, parametrized by the PDFs, to the transverse spatial distribution of those partons, parametrized by the form factors. Most important, these objects grant access to the orbital angular momentum of the quarks [7,8]. GPDs can be accessed via exclusive processes such as deeply virtual compton scattering (DVCS, $lp \rightarrow l'p\gamma$) or hard exclusive meson production (HEMP) off the nucleon. In such reactions, the virtual photon (with a high virtuality Q^2) emitted by the lepton selects a quark in the nucleon with a longitudinal momentum fraction ξ^+, which re-emits a photon (in the case of DVCS) or produces a hadron (in the case of meson production), and is reabsorbed in the proton with a longitudinal momentum fraction ξ^-. During the reaction, a four-momentum t is transferred to the nucleon, as schematically shown in Fig. 1.

2 Measurements of TMDs in SIDIS

Impinging 160 GeV muons from the M2 beam line at the CERN SPS on either proton (NH_3) or deuteron (^{6}LiD) transversely polarized targets, the COMPASS collaboration has produced a wealth of results, the most important being the assessment, together with the HERMES Collaboration, that the so-called Collins and Sivers asymmetries on the proton are definitely non-zero and sizable. The fact that these effects are non-vanishing implies that both the transversity and the Sivers PDFs are non-zero and several extractions of these PDFs have already been performed. In particular a non-zero Sivers PDF for a given quark implies non-zero orbital angular momentum for that quark. Results have already been published, both for unidentified and identified hadrons, as function of x, z (the fraction of the available energy taken by the hadron) and p_T (the hadron transverse momentum). As an example, Fig. 2 shows the recently published COMPASS results for the Sivers asymmetries on the proton for π^+ and K^+ [9]: the asymmetries are definitely non-zero and positive, even down to the sea-quark region. A multi-dimensional analysis of the SIDIS data collected, presently in progress, should provide a deeper sensitivity on the kinematic. An example of the binning presently chosen in the $x - Q^2$ domain is shown in Fig. 3. Preliminary results for the x-dependence of the Sivers asymmetries in different Q^2 bins are shown in Fig. 4. Corresponding results have been produced for all the other transverse spin asymmetries. Clear non-zero signals over the whole Q^2 range are also observed in the case of the Collins asymmetry.

Further investigations of the Collins asymmetry as measured on transversely polarized protons in 2010 have led to interesting conclusions [10] about the properties of the Collins fragmentation function (FF) and of the di-hadron FF. In a nutshell, the amplitudes of the Collins-like (CL) asymmetries in a sample of SIDIS events in which at least a h^+h^- pair is detected are well compatible to those of the usual Collins asymmetries of h^+ and h^- in the "standard" SIDIS event sample (i.e. a sample containing at least one charged hadron), i.e. they have the same modulus and opposite sign, as shown in Fig. 5, where they are plotted as a function of $\Delta\phi$, the difference of the azimuthal angles of the two hadrons. Moreover, an analytical calculation allows to compute the di-hadron asymmetry $A_{CL,2h}$ as a function of $\Delta\phi$ from the CL asymmetries, giving convincing evidence that the Collins and the di-hadron asymmetries are driven by a common mechanism, as suggested

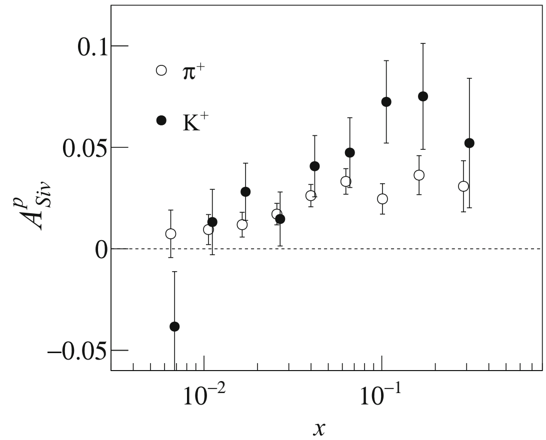

Fig. 2 The Sivers asymmetries for positive pions and kaons, as a function of x (COMPASS results)

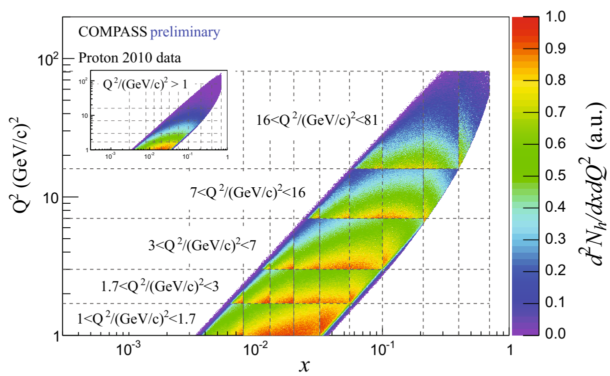

Fig. 3 The $x - Q^2$ grid which has been chosen to evaluate the transverse spin asymmetries. The region with $Q^2 > 16\ (\mathrm{GeV}/c)^2$ is the so-called safe region for the Drell–Yan measurement

by the $^3\mathrm{P}_0$ recursive string fragmentation model [11]. Further studies of SIDIS will be performed in 2016 and 2017, in parallel to the GPD measurement, on a liquid hydrogen target, mainly to extract identified hadron multiplicities, p_T distributions and the azimuthal modulations of the cross-section [3]. These measurements, if precise enough, will allow to extract information on the k_T distribution and the Boer-Mulders PDFs.

3 Measurements of TMDs in Drell–Yan

After the long CERN shutdown of 2013, starting in October 2014 COMPASS had a 2-months test run with a 190 GeV/c momentum π^- beam to commission a modified spectrometer aiming at a first ever measurement of the Drell–Yan process $\pi^- p \rightarrow \mu^+\mu^- X$ on a transversely polarized proton target. In order to keep to a tolerable degree the radiation level in the spectrometer, a sophisticated absorber was inserted between the target and the first trackers to stop most of the beam and the hadrons created in the target. The cross-section for the process can be written as the sum of several azimuthal modulations, whose amplitudes are given by convolutions of different TMD PDFs. Of particular interest is the term $\sin\phi_{CS}$, where ϕ_{CS} is the azimuthal angle between the hadron plane and the lepton plane in the Collins-Sopper frame, whose amplitude depends on the Sivers function of the u quark of the target proton ($f^{\perp}_{1T/p}$) and the number density of the $\bar{u}$ quark in the incident π^- ($f_{1/\pi}$). Knowing $f_{1/\pi}$ it is thus possible to extract the Sivers function of the u quark in the transversely polarized proton, and compare it with the corresponding one measured in SIDIS. Being T-odd, the Sivers function is expected to change sign going from SIDIS to Drell–Yan. Such a prediction is deeply rooted in the present formulation of the theory [12], in particular in the way gauge invariance is guaranteed, and its experimental verification is the main motivation of the COMPASS Drell–Yan programme. After the successful test run of 2014 the measurements have been resumed this year, at the end of April, and data will

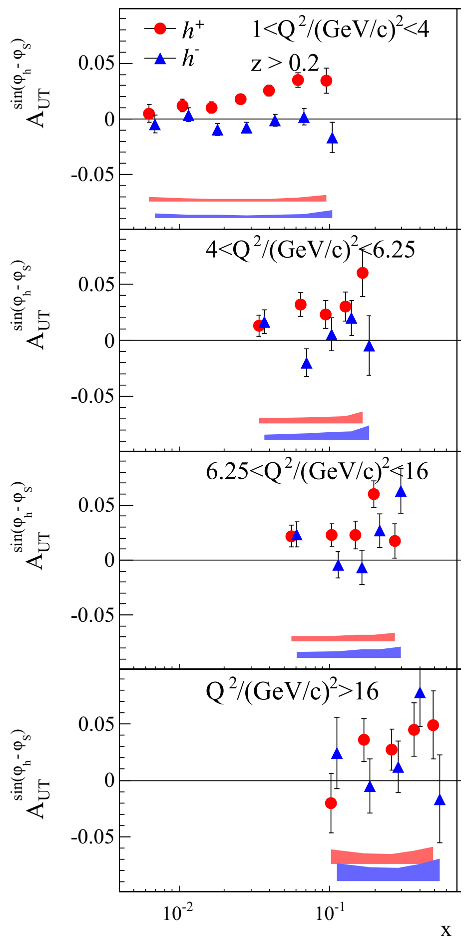

Fig. 4 The proton Sivers asymmetries as a function of x in 5 different Q^2 bins for positive and negative hadrons (COMPASS 2010 data, *preliminary*)

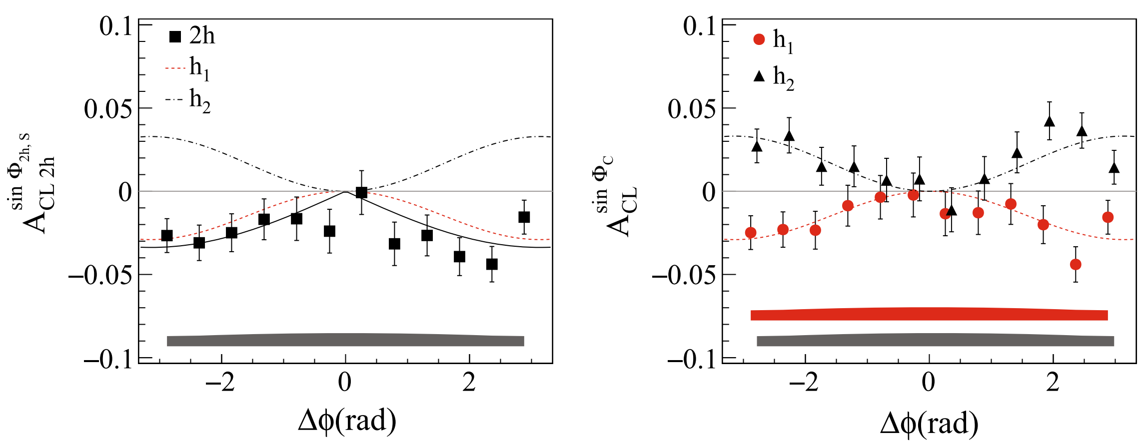

Fig. 5 COMPASS results. *Left* Dihadron asymmetry. *Right* Collins-like asymmetry in h^+h^- sample; h_1 indicates the first hadron of the pair, which is always the positive hadron. As expected from the mirror symmetry of the h^+ and h^- A_{CL}, all the three asymmetries can be fitted with simple functions which depend on only one parameter (see Ref. [10] for details)

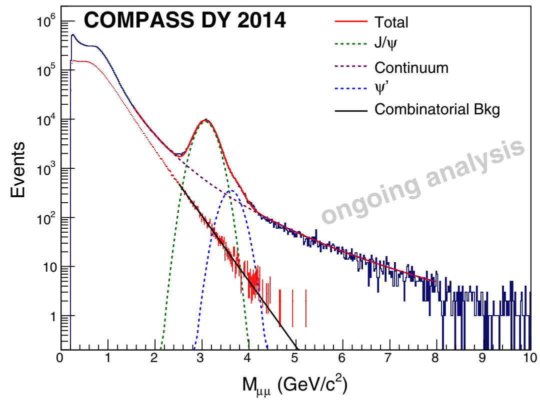

Fig. 6 $\mu^+\mu^-$ pair invariant mass spectrum from the 2014 Drell–Yan test run together with the measured combinatorial background from uncorrelated muons

be taken until middle of November. The $\mu^+\mu^-$ pair invariant mass spectrum measured in 2014 is given in Fig. 6. As shown in Fig. 4, in the "safe" Drell–Yan range $Q^2 > 16\ (\mathrm{GeV}/c)^2$, the Sivers asymmetry measured in SIDIS is clearly different from zero, therefore we should definitely be able to assess the expected change of sign in the Drell–Yan process.

4 Measurements of GPDs: HEMP

The measurements of DVCS and exclusive channels on a polarized proton target give access to the GPD E, which allows for the nucleon spin flip. The exclusive production of ρ^0 mesons on a transversely polarized proton target has been performed with muon data recorded at COMPASS in 2007 and 2010. Since no recoil detector could be used around the polarized target, exclusivity was ensured imposing energy and momentum conservation between the incoming muon and the outgoing muon and the vector meson. Eight target spin asymmetries, depending on ϕ (the azimuthal angle of the vector meson) and ϕ_S (the angle between the muon scattering plane and proton polarization) have been extracted [13] and successfully interpreted in terms of GPDs [14]. From the data collected on a transversely polarized proton target in 2010 it has also been possible to study the exclusive production of the ω meson, with $\omega \rightarrow \pi^+\pi^-\pi^0$ and $\pi^0 \rightarrow \gamma\gamma$ (the two photons were detected in the electromagnetic calorimeters of the COMPASS spectrometer). Due to the different quark combinations in the flavor dependent wave functions of the mesons, certain asymmetries are expected to be larger for ω production than the corresponding ones for ρ^0. Also, certain azimuthal asymmetries for ω production are sensitive to the pion pole contribution and hence allow in principle to determine the sign of the $\omega\pi$ transition form factor. Figure 7 shows the preliminary results on the single transverse spin asymmetries in bins of Q^2, x and p_T^2. The dashed red and dotted blue curves represent the predictions [15] with the positive and negative contributions of the pion pole, respectively, while the solid black curve represents the predictions without the pion pole contribution.

5 Measurements of GPDs: DVCS

In order to ensure exclusivity of DVCS (and also HEMP) events, a new recoil detector has been built, to surround a 2.5 m long liquid hydrogen target [3]. The DVCS cross section will be determined as a function of both the momentum transfer t between initial and final nucleons and the fraction of the longitudinal nucleon momentum carried by the struck parton. A new electromagnetic calorimeter (ECAL0) will provide coverage of substantially higher values of this fraction as compared to the existing calorimeters ECAL1 and ECAL2. With such an apparatus, COMPASS can measure the DVCS process on a wide x range (from 0.005 to 0.3), in a Q^2 range from 1 to 20 $(\mathrm{GeV}/c)^2$ at the expected integrated luminosity. In 2012 a short test run was performed with an almost complete apparatus (the new ECAL0 was only partially available), and data taking is planned in 2016 and 2017. A competing process to DVCS is the Bethe-Heitler (BH) process of elastic lepton-nucleon scattering with a hard Bremsstrahlung photon emitted by either the incoming or the outgoing lepton. It produces the same final state as DVCS so that the two processes interfere at the level of amplitudes.

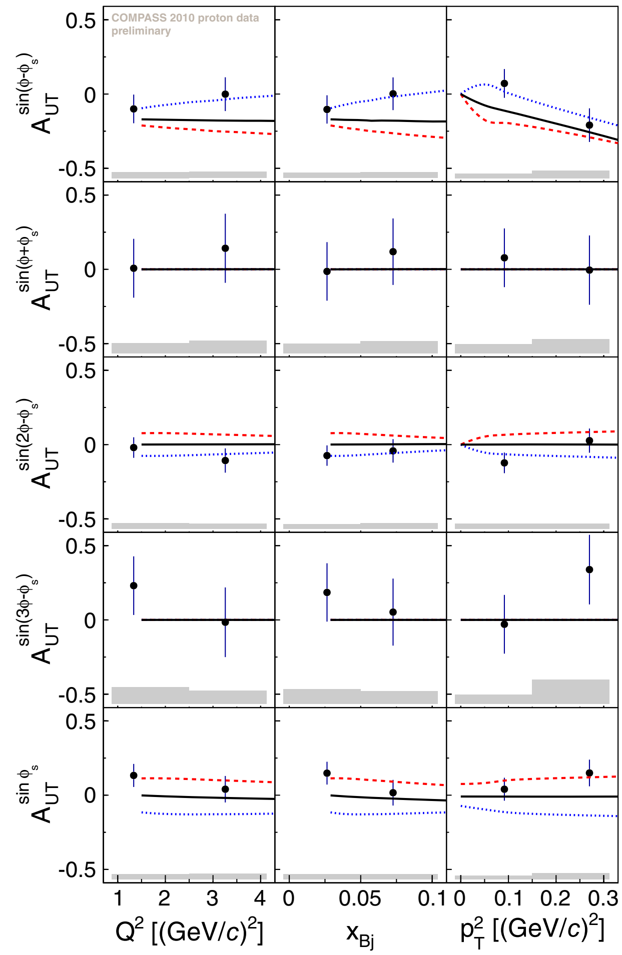

Fig. 7 Preliminary results on the transverse spin asymmetries for ω production in bins of Q^2, x and p_T^2

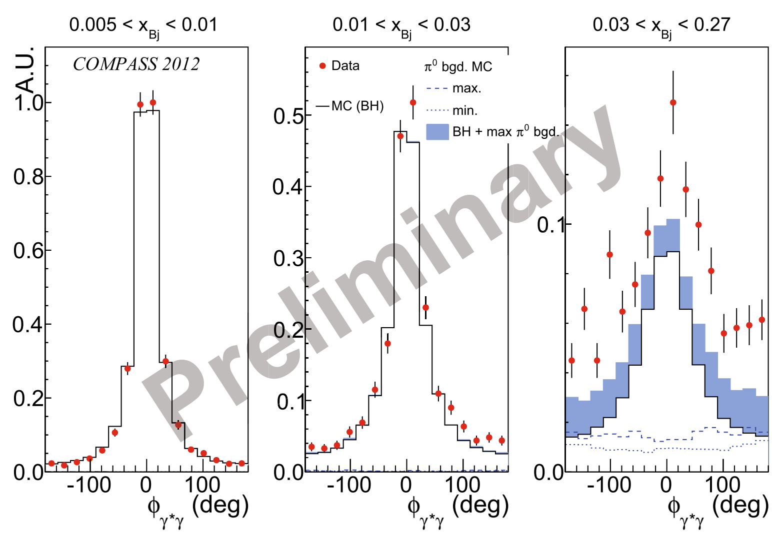

Fig. 8 Preliminary results from the 2012 test run and Monte Carlo (MC) predictions

In the COMPASS experiment, kinematic domains are accessible where either BH or DVCS dominate. At high x almost pure DVCS events will be collected, which will also allow for a measurement of the t dependence of the cross section, related to the tomographic imaging of the nucleon. At low x almost pure BH events are recorded which can be used as an excellent reference yield. In the intermediate domain the DVCS contribution will be enhanced by the BH process through their interference. Some preliminary results from the 2012 test run are shown in Fig. 8, together with Monte Carlo predictions. At large x a clear DVCS signal is visible, and the BH contribution can easily be subtracted. The analysis of these data is still ongoing to improve the estimate of the π^0 background. All COMPASS DVCS measurements will exploit the availability of positive and negative muon beams with opposite polarization. This allows to measure with the same apparatus the beam-charge and beam-spin cross-section sum and difference. From these measurements the real and imaginary part of the Compton form factors can be extracted allowing a detailed study of the GPD H.

6 Outlook

In 2018 COMPASS will take one more year of data. The most likely options are either a second year of Drell–Yan or the continuation of the GPD/SIDIS data taking: both measurements are statistically limited, and the decision will be taken on the basis of the significance of the data collected in 2015, 2016 and 2017. Starting from 2019 all CERN accelerators will stop for a second long shut-down, but our Collaboration has already made plans for a new phase of measurements [16], which include GPD measurements on a transversely polarized proton target and SIDIS measurements on a transversely polarized deuteron target. These plans are presently being revisited.

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