ФИЗИКА ЭЛЕМЕНТАРНЫХ ЧАСТИЦ И АТОМНОГО ЯДРА
2013. Т. 44. ВЫП. 6

COMPASS-II*

M. Chiosso on behalf of the COMPASS Collaboration

INFN, Sezione di Torino and University of Torino, Torino, Italy

On December the 1st, 2010, the proposal of the COMPASS-II experiment [1] has been approved by the CERN Research Board. After almost ten years of important results achieved by the COMPASS Collaboration in both nucleon spin physics, with the use of muon beam, and hadron spectroscopy, using hadron beams, this second phase offers now a unique chance to address in the very near future newly opened QCD-related challenges, at very moderate upgrade cost, thanks to the versatility of the COMPASS apparatus [2]. This implies mainly study of chiral perturbation theory (ChPT), by measuring the pion polarizability through the Primakoff reaction; generalized parton distributions (GPDs), by measuring exclusive deeply virtual Compton scattering (DVCS) and hard exclusive meson production (DVMP); transverse momentum-dependent parton distributions (TMDs) in single-polarized pion-induced Drell–Yan muon production and in SIDIS on a liquid hydrogen target (in parallel to DVCS). An overview of the COMPASS-II proposal is presented here, with a main focus on the new upcoming investigation of the nucleon structure via the Drell–Yan and DVCS processes.

PACS: 14.20.Dh; 13.85.Qk; 13.60.Fz; 75.40.Gb; 12.38.-t

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 of 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 Generalized 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. Such a description of the nucleon as an extended object is sometimes referred to as

*Plenary talk at the 20th International Symposium on Spin Physics (SPIN2012), JINR, Dubna, September 17–22, 2012.

3-dimensional «nucleon tomography». In a complementary approach, the presence of nonzero intrinsic transverse parton momentum described by Transverse-Momentum-Dependent PDFs (TMDs) plays an important role in understanding the 3-dimensional structure of the nucleon. Studying both the Semi-Inclusive DIS (SIDIS) and Drell–Yan (DY) processes with the same apparatus gives an inclusive access to these functions and provides a unique opportunity to test the universality of TMDs and some fundamental QCD predictions.

The COMPASS-II experiment aims to address all these fascinating QCD-related studies of nucleon structure. The future programme starting after the accelerator shutdown focuses on TMDs and GPDs.

A polarized Drell–Yan experiment will take place in 2014; in 2015/2016 deeply virtual Compton scattering and hard exclusive meson production will be studied with a 160 GeV muon beam and an unpolarized hydrogen target. A pilot run for the latter experiment already took place in late 2012, at the end of the pion polarizabilty measurement (which is not discussed here). In parallel with the GPD programme, high statistics data for SIDIS will be taken.

1. GPD PROGRAMME

The GPDs provide a novel and comprehensive description of the nucleon partonic structure [3–5]. First of all, they embody both the nucleon electromagnetic form factors and the parton distribution functions: GPDs H^f and $\tilde{H}^f$ $(f = u, d, s, g)$, describing processes where nucleon helicity is preserved, contain as limiting case the parton density and helicity distributions, respectively. The processes with nucleon helicity flip are described by GPDs E^f and $\tilde{E}^f$, which do not contain such limiting cases.

The GPDs also provide a «3-dimensional picture» of the nucleon [6], which correlates (transverse) spatial and (longitudinal) momentum degrees of freedom of quarks and gluons. Moreover, they may open the way to constrain the quark total angular momentum contributions to the nucleon spin budget [7].

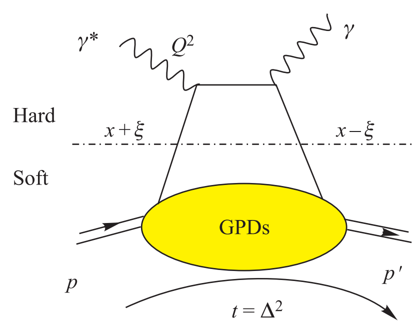

Fig. 1. Handbag diagram for the DVCS process at leading twist

GPDs are expected to be universal quantities. The golden hard exclusive process to access them is the Deeply Virtual Compton Scattering (DVCS), shown in Fig. 1. The DVCS final state is identical to that of the competing Bethe–Heitler (BH) process, interfering on the level of amplitudes. The differential cross section for hard exclusive muoproduction of real photons off an unpolarized proton target can be written as

$$d\sigma^{\mu p\to\mu' p'\gamma} = d\sigma^{\mathrm{BH}} + [d\sigma^{\mathrm{DVCS}}_{\mathrm{unpol}} + P_\mu\, d\sigma^{\mathrm{DVSC}}_{\mathrm{pol}}] + e_\mu\,[\mathrm{Re}\, I + P_\mu\, \mathrm{Im}\, I]\,, \tag{1}$$

where P_μ is the polarization, e_μ is the charge, in units of the elementary charge, of the polarized muon beam and I is the interference term. BH cross section dominates at small x_B where it provides an excellent reference yield, while DVCS dominates at larger x_B (> 0.03). COMPASS is the only facility so far able to measure hard exclusive reactions using both μ^+ and μ^- beams, which are naturally oppositely polarized. Hence with the same apparatus and 160 GeV/c μ^+ and μ^- beams on an unpolarized hydrogen target the COMPASS experiment can perform sum and difference of the cross sections for the two beam charge/polarization states, obtaining, from Eq. (1):

$$S_{\mathrm{CS},U} \equiv d\sigma^{\overset{+}{\leftarrow}} + d\sigma^{\overset{-}{\rightarrow}} = 2[d\sigma^{\mathrm{BH}} + d\sigma^{\mathrm{DVCS}}_{\mathrm{unpol}} + e_\mu P_\mu\, \mathrm{Im}\, I], \tag{2}$$

$$D_{\mathrm{CS},U} \equiv d\sigma^{\overset{+}{\leftarrow}} - d\sigma^{\overset{-}{\rightarrow}} = P_\mu d\sigma^{\mathrm{DVCS}}_{\mathrm{pol}} + e_\mu\, \mathrm{Re}\, I. \tag{3}$$

An analysis of their Φ-dependence (with Φ — the azimuthal angle between lepton scattering plane and photon production plane) will allow us to access certain combinations of the Compton Form Factors (CFFs) related to the respective quark GPDs. With an unpolarized target, COMPASS DVCS results will mainly provide information on the CFF H and thus constrain the GPD H. Some handle on the flavour separation of GPDs may be obtained from hard exclusive meson production measured simulataneously with DVCS. When, in an alternative approach, the Φ-dependence is integrated over, measuring the x_B dependence of the t slope of the cross section, over the full experimentally accessible x_B range, will allow us to obtain a measure of the transverse nucleon size $\langle (r_\perp)^2 \rangle$ in a model-independent way. The projected statistical and systematic accuracy for a measurement at COMPASS of the x_B-dependence of the t-slope parameter $B(x)$ is shown in Fig. 2. 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 new electromagnetic calorimeter, ECAL0, will improve the precision of the measurement and enlarge the accessible range towards larger x_B, where DVCS dominates.

Another major upgrade developed for the GPD programme is the construction and installation of a recoil proton detector, the Camera detector, essential to ensure exclusivity of the measured reactions. The Camera is 4 m long and is made of two ToF barrels of 24 scintillator slats read-out at both ends by photomultipliers. In order to cope with high rate and pile-up, the photomultipliers signal is digitized at 1 GHz by a dedicated read-out module called Gandalf. A 2.5 m long liquid hydrogen target is housed inside the Camera, on the central axis.

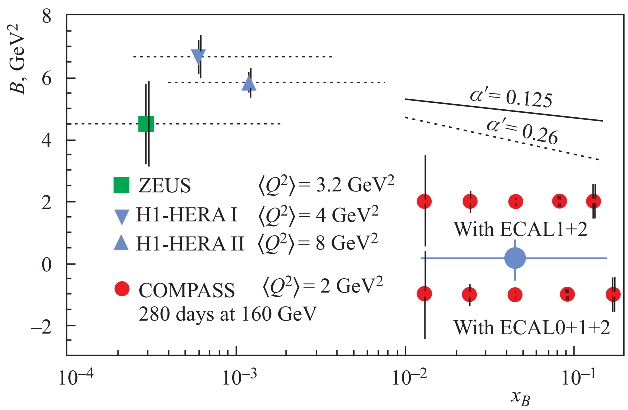

Fig. 2. COMPASS projections for the x dependence of the fitted t-slope parameter $B(x)$ of the DVCS cross section, calculated for $1 < Q^2 < 8$ GeV^2 and compared to some HERA results with similar $\langle Q^2 \rangle$ [8–10]. The first (left) vertical bar on each data point indicates the statistical error only while the second (right) error bar includes also the systematic uncertainty. The upper row presents prediction using only ECAL1 and ECAL2; in the lower row also ECAL0 is included

In parallel with the DVCS and DVMP measurements, high-statistics data on SIDIS on the proton will be recorded using the long liquid hydrogen target. Combined with existing COMPASS SIDIS data on the deuteron taken earlier with the ^{6}LiD target, they will permit quark flavour separation; in particular, the unpolarized strange quark distribution function $s(x)$ will be extracted in a region of x_B where measurements from other experiments are either not available or have limited precision.

2. DRELL–YAN PROGRAMME

A second and complementary approach towards the comprehension of the transverse nucleon structure is the study of TMDs. Of particular interest are the so-called Sivers and Boer–Mulders TMDs which describe the correlations between quark transverse momentum and nucleon transverse spin, and between quark transverse spin and its transverse momentum in an unpolarized nucleon, respectively. Much of the information that exists today about TMDs comes from SIDIS measurements with unpolarized and polarized beams and targets where they appear convoluted with fragmentation functions (FFs). DY measurements are complementary to those by SIDIS experiments, as they allow one to measure convolutions of only PDFs without involving FFs. 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.

Measurements of SIDIS were performed by COMPASS in the period 2002 to 2007 and in 2010, using a naturally polarized μ^+ beam and a solid state target polarized either longitudinally or transversely with respect to the beam direction. Now the opportunity to study TMDs, namely Sivers and Boer–Mulders functions, both from SIDIS and Drell–Yan processes with the same apparatus, will be unique at COMPASS, allowing us to test the sign change prediction for the first time. The main goal of COMPASS DY programme is to measure the process $\pi^- p^\uparrow \to \mu^+\mu^- X$ with a 190 GeV π^- beam on a transversely polarized target (NH_3).

By performing the measurements of target spin (in)dependent asymmetries in DY reaction and by comparing the results with ones measured in SIDIS, we will be able to verify the universality of TMD approach for the description of these reactions; this would be a crucial test of QCD in the nonperturbative regime. We will access four azimuthal asymmetries:

— $A_U^{\cos 2\phi}$ which gives access to the Boer–Mulders functions, $h_1^\perp$, of incoming hadrons;

— $A_T^{\sin \phi_S}$ which gives access to the Sivers function, $f_{1T}^\perp$, of the target nucleon;

— $A_T^{\sin (2\phi+\phi_S)}$ which gives access to the Boer–Mulders functions of beam hadron and to the pretzelosity function, $h_{1T}^\perp$, of the target nucleon;

— $A_T^{\sin (2\phi-\phi_S)}$ which gives access to Boer–Mulders functions of beam hadron and to the transversity function, h_1, of the target nucleon.

Disentangling the PDFs in each of these asymmetries requires certain knowledge of other PDFs. Namely, to access the transversity and pretzelosity of the nucleon, the knowledge of the Boer–Mulders function of the pion is needed. Another topic which will be investigated is the so-called J/ψ-DY duality [11]. In spite of the large amount of experimental data on J/ψ production in various reactions, the production mechanism is still unclear. Since the J/ψ and the γ are both vector particles and the helicity structure of $\bar{q}q(J/\psi)$ and $(\bar{q}q)\gamma^*$ couplings is the same, it is believed that an analogy in the production mechanism might occur at low energies where the $\bar{q}q$ annihilation dominates. The study of the J/ψ production in the dilepton decays channel will allow us to check the duality hipothesis. Moreover, such a possibility of using the J/ψ production for the extraction of PDFs is very attractive because the dilepton production rate in the J/ψ production region is by a factor of 30 higher than in the continuum region above the J/ψ mass.

A full Monte Carlo simulation was performed to evaluate the COMPASS spectrometer acceptance in the invariant mass intervals $4 \leqslant M_{\mu\mu} \leqslant 9$ GeV/c^2 and

$2 \leqslant M_{\mu\mu} \leqslant 2.5$ GeV/c^2. These two regions are considered to be the best mass intervals for Drell–Yan analysis, avoiding the large combinatorial background that shall dominate at lower dimuon masses, and excluding the ϕ, J/ψ and Υ vector-meson resonances. The first (high) mass region certainly provides a cleaner sample of DY events, because of the very small contribution from uncorrelated combinatorial muon background (originating from pion and kaon decays) and open-charm semileptonic decays (i.e., $D\bar{D}$ decays into muons). Moreover, it is particularly interesting, as it covers mostly the region of valence quarks; but the DY cross section for such masses is almost by a factor of 10 smaller than in the second (intermediate) mass region.

The simulation results [1] show that the COMPASS spectrometer acceptance is 35% in the high mass region. In the intermediate mass region, the average acceptance is 43%.

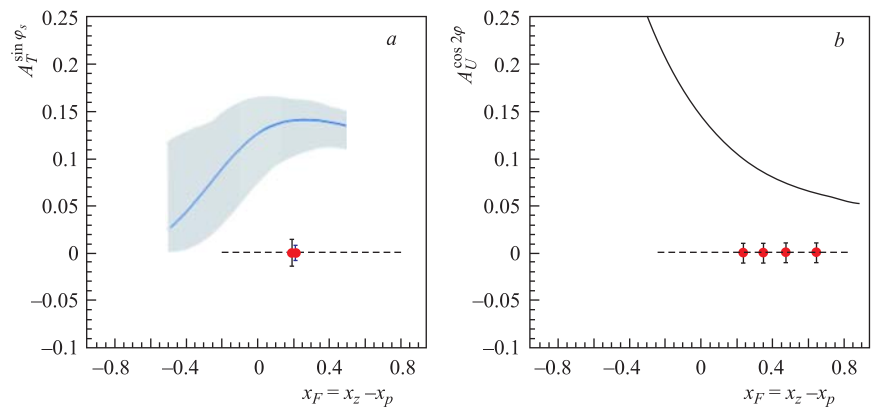

Fig. 3. Expected statistical errors and theoretical predictions [13] on the Sivers (a) and Boer–Mulders (b) asymmetries for a DY measurement in the dimuon mass range $4 \leqslant M_{\mu\mu} \leqslant 9$ GeV/c^2. The smaller error bar in Sivers denotes the statistical error, while the larger corresponds to the quadratic sum of statistical and systematic error

In Fig. 3, projections of the expected statistical error of the Sivers and Boer–Mulders asymmetries, assuming two years of data taking, together with the theory predictions [13], are shown. As the measurement is statistics limited, optimizing luminosity is mandatory. The installation of a hadron absorber downstream of the target will reduce the high secondary particle flux produced by the interaction of the pion beam in the target and, consequently, the tracking detector occupancies. This will make an increase in the intensity of the incident pion beam possible. The absorber consists of a tungsten beam plug surrounded by alumina (Al_2O_3), which minimises multiple scattering; this is essential to disentangle the two oppositely polarized target cells in the track reconstruction.

REFERENCES

1. *Gautheron F. et al. (COMPASS Collab.).* CERN-SPSC-2010-014 SPSC-P-340. 2010.
2. *Abbon P. et al. (COMPASS Collab.)* // Nucl. Instr. Meth. A. 2007. V. 577. P. 455.
3. *Mueller D. et al.* // Fortschr. Phys. 1994. V. 42. P. 101.
4. *Ji X. D.* // Phys. Rev. D. 1997. V. 55. P. 7114.
5. *Radyushkin A. V.* // Ibid. V. 56. P. 5524.
6. *Burkardt M.* // Intern. J. Mod. Phys. A. 2003. V. 18. P. 173.
7. *Ji X.-D.* // Phys. Rev. Lett. 1997. V. 78. P. 610.
8. *Aaron F. D. et al. (H1 Collab.)* // Phys. Lett. B. 2008. V. 659. P. 796.
9. *Aktas A. et al. (H1 Collab.)* // Eur. Phys. J. C. 2005. V. 44. P. 1.
10. *Chekanov S. et al. (ZEUS Collab.)* // JHEP. 2009. V. 05. P. 108.
11. *Collins J. C.* // Phys. Lett. B. 2002. V. 536. P. 43.
12. *Anselmino M. et al.* // Phys. Lett. B. 2004. V. 594. P. 97.
13. *Anselmino M. et al.* // Proc. of Workshop on Transverse Polarization Phenomena in Hard Scattering Processes. Ferrara: World Sci., 2009. P. 138.