COMPASS-II : COMPASS Future Programs

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Abstract. The COMPASS (COmmon Muon and Proton apparatus for Structure and Spectroscopy) experiment started more than 10 years ago and has published many results concerning nucleon structure and hadron spectroscopy. We propose additional measurements for a new fascinating QCD-related studies of nucleon structure and hadron spectroscopy with small modifications of the present apparatus, that includes either an unpolarized or polarized target.

Keywords: Nucleon structre, Hadron spectroscopy, Drell-Yan, GPD, DVCS, Pion polarizability, polarized muon beam, polarized target
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INTRODUCTION

The COMPASS experiment at CERN has been taking data since 2002 using either muon or hadron beams with a longitudinally or transversely polarized solid target, liquid hydrogen or heavy nuclear targets. And many interesting and impressive results on nucleon spin structure and hadron spectroscopy have been published [1, 2]. The COMPASS Collaboration has recently submitted a proposal for additional measurements in the next years. The proposal (COMPASS-II) was approved by the CERN Research Board in December 2010 [3]. It includes studies of polarized Drell-Yan program (for two years), Generalized Parton Distribution (GPD) program (for two years) and pion and kaon polarizabilities program (for one year) for which data taking can be started in 2012.

EXPERIMENTAL SET UP

A variety of beams and targets

CERN SPS M2 beam line delivers hadron or naturally polarized positive and negative muon beams in the energy range between 50 and 280 GeV. The muon beam polarization is about 80 % at 160 GeV. The COMPASS experiment uses those beams with a longitudinally or transversely polarized solid target [4, 5], liquid hydrogen or heavy nuclear targets.

The COMPASS spectrometer

The COMPASS spectrometer consists of two stages of spectrometers, one called Large Angle Spectrometer (LAS) and the other called Small Angle Spectrometer (SAS). Both stages are equipped with spectrometer magnets, tracking, electromagnetic and hadronic calorimeters and muon detectors [6]. The charged particle identification is obtained by a RICH (Ring Imaging CHerenkov) counter, and for the muons by the detection of the tracks after hadron filters. The incoming muons and hadrons are detected by tracking detectors and the energy of the muon beams can be reconstructed by using a beam momentum station which is located along the beam about 100 m before the target. π and K are mixed in the hadron beam, that are identified by CEDAR detectors which are placed about 50 meters before the target.

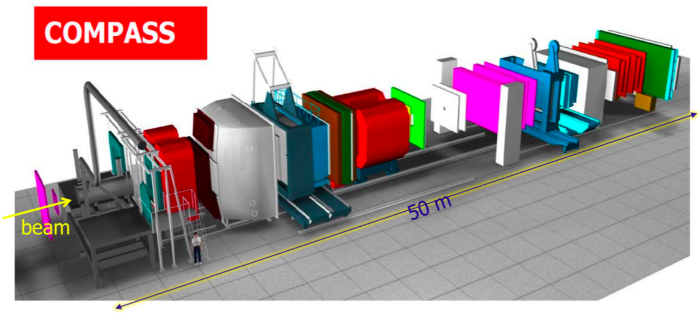

FIGURE 1. COMPASS spectrometer

POLARIZED DRELL-YAN PROGRAM

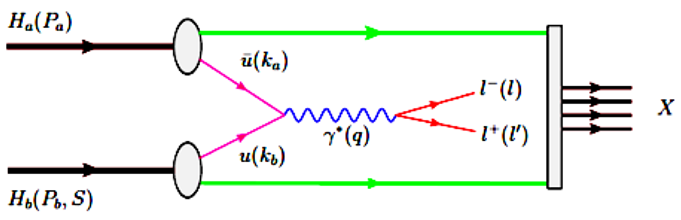

FIGURE 2. Feynman diagram of the Drell-Yan process

The availability of pion beam provides an access to the Drell-Yan physics, i.e. to the process where quark(target)-antiquark(beam) pair annihilates electromagnetically with a production of dilepton pair. Study of angular dependencies of the Drell-Yan process cross-section allows us to access to parton distribution functions (PDFs) or, more precisely, a convolutions of various PDFs. The possibility to use a transversely polarized target together with negative pion beam is an important feature of the future COMPASS Drell-Yan experiment. This experiment will provides us with unique data on transverse momentum dependent (TMD) PDFs.

The leading order expansion of the single polarized Drell-Yan cross section is

$$\begin{aligned} \frac{d\sigma}{d^4qd\Omega} &= \frac{\alpha^2}{Fq^2}\hat{\sigma}_U\Big\{\big(1+D_{[sin^2\theta]}\underline{\underline{A_U^{cos2\phi}}}cos2\phi\big) \\ &+\left|\vec{S}_T\right|\Big[\underline{\underline{A_T^{sin\phi_s}}}sin\phi_s \\ &+D_{[sin^2\theta]}\Big(\underline{\underline{A_T^{sin(2\phi+\phi_s)}}}sin(2\phi+\phi_s) \\ &+\underline{\underline{A_T^{sin(2\phi-\phi_s)}}}sin(2\phi-\phi_s)\Big)\Big]\Big\}, \end{aligned} \quad (1)$$

where D is depolarization factor, S is target spin component, $\hat{\sigma}_U$ is a part of the cross-section surviving integration over ϕ and ϕ_s and $F = 4\sqrt{(P_a\cdot P_b)^2 - M_a^2 M_b^2}$. The azimuthal asymmetries $A_{U,L,T}^{f(\phi,\phi_s)}$ are described with a convolution of two PDFs as

$$\begin{aligned} A_U^{cos2\phi} &: (\mathbf{BM})_\pi \otimes (\mathbf{BM})_p \\ A_T^{sin\phi_s} &: (f_1)_\pi \otimes (\mathbf{Sivers})_p \\ A_T^{sin(2\phi+\phi_s)} &: (\mathbf{BM})_\pi \otimes (\mathbf{Pretzelosity})_p \\ A_T^{sin(2\phi-\phi_s)} &: (\mathbf{BM})_\pi \otimes (\mathbf{Transversity})_p, \end{aligned} \quad (2)$$

where **BM** means Boer-Mulders functions.

One of the main motivations of the program is to study the universality of TMD PDFs. Because Sivers ($f_{1T}^\perp$) and Boer-Mulders ($h_1^\perp$) PDFs are "Time-reversal odd", they are expected to change the sign when measured from SIDIS or from DY as

$$f_{1T}^\perp|_{DY} = -f_{1T}^\perp|_{SIDIS} \qquad h_1^\perp|_{DY} = -h_1^\perp|_{SIDIS}. \quad (3)$$

The Sivers asymmetry in SIDIS was measured in COMPASS in 2007 and 2010 [1, 7]. We have the opportunity to test this sign change using the same spectrometer and the transversely polarized target at COMPASS.

A luminosity of $L = 1.2\times 10^{32} cm^{-2}s^{-1}$ can be obtained with a beam intensity of $I_{beam} = 6\times 10^7/s$, 190 GeV/c π^- beam, and with a 110cm long polarized proton target. Assuming 2 years of data taking, one can obtain the statistical accuracy of 0.0142 in the asymmetry of $A_T^{sin\phi_s}$ at the dimuon mass range of $4 < M_{\mu\mu} < 9GeV/c^2$ where is negligible small of background contamination.

In 2009 we performed a beam test for 3 days with 190 GeV/c π^- beam on a CH_2 target. A hadron absorber and a beam plug were used. The test was to study combinatorial background and event yields of J/ψ and Drell-Yan. the combinatorial background and J/ψ are main background sources. We corrected 3170 J/ψ events which is almost as expected and found the absorber reduced the combinatorial background by a factor 10 at 2.0 GeV/c^2 (Fig. 3).

The Drell-Yan measurement requires a transversely polarized proton target. The present COMPASS polarized target system needs to be modified for this purpose. We will use two cells of 55 cm long with a 4 cm diameter and the distance between the cells is 20 cm because of vertex resolution. Therefore, the microwave cavity and the target cell have to be modified. We have to consider the heat input by energy deposit of hadron beam which produces several secondly hadrons. The heat makes relaxation time of the target polarization shorter. The dilution refrigerator needs to be optimized in order to increase cooling power.

An additional hadron absorber to be placed immediately downstream the polarized target is required. At the beam intensity of $6 \times 10^7/s$ this absorber is mandatory, in order to keep the occupancies in the firrst detector planes at an acceptable level, and to reduce the combinatorial background from pion decays into muons. The choice of material, length and geometry of the absorber must be such that it minimizes the muon multiple scattering, while maximizing the hadron stopping power, and keeping the radiation levels within the allowed limits. A beam plug inside the absorber is also mandatory, in order to stop the beam that did not interact in the target. A possible configuration for the hadron absorber is a length along the beam direction of at least 2 meters, the absorber will be made of aluminum oxide (Al2O3), eventually with a layer of stainless steel in the most downstream part. The beam plug has approximate conical shape, it is built from tungsten disks and is inserted inside the absorber.

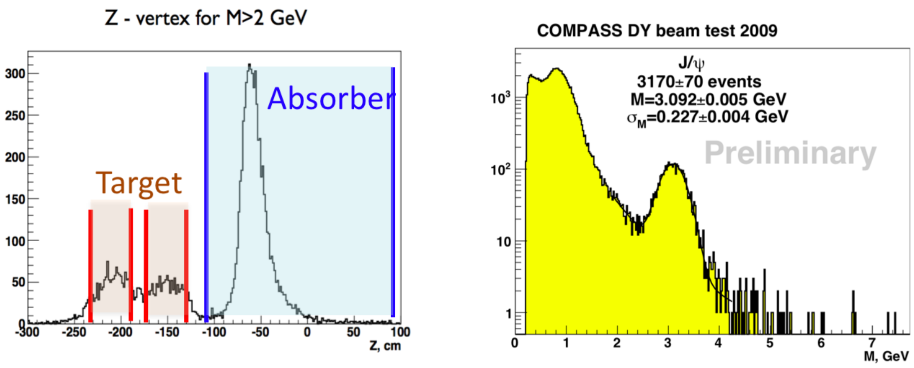

FIGURE 3. Left: Vertex reconstruction distribution on the beam axis for dimuon mass. the 20 cm gap between two targets is reasonable for separation. Right: Dimuon invariant mass. the combinatorial background is dominant at < 2.5 GeV/c^2.

GPD PROGRAM

The high energy polarized muon beam is available at CERN with the option of using positive or negative muons with opposite polarization. It gives us a possibility to study generalized parton distributions (GPDs) via deeply virtual Compton Scattering (DVCS) with a 2.5m long liquid hydrogen target as an unpolarized proton target.

DVCS has the same final state as the competing Bethe-Heitler (BH) process (Fig. 4). The cross section can be written as

$$\begin{aligned} d\sigma_{(\mu p \to \mu p \gamma)} &= d\sigma^{BH} + d\sigma^{DVCS}_{unpol} + P_{\mu} d\sigma^{DVCS}_{pol} \\ &\quad + e_{\mu} a^{BH} Re(I) + e_{\mu} P_{\mu} Im(I), \end{aligned} \tag{4}$$

where P_{μ} is the polarization and e_{μ} the charge of the polarized muon beam. The interference term I arises as the DVCS and BH processes interfere on the level of amplitudes.

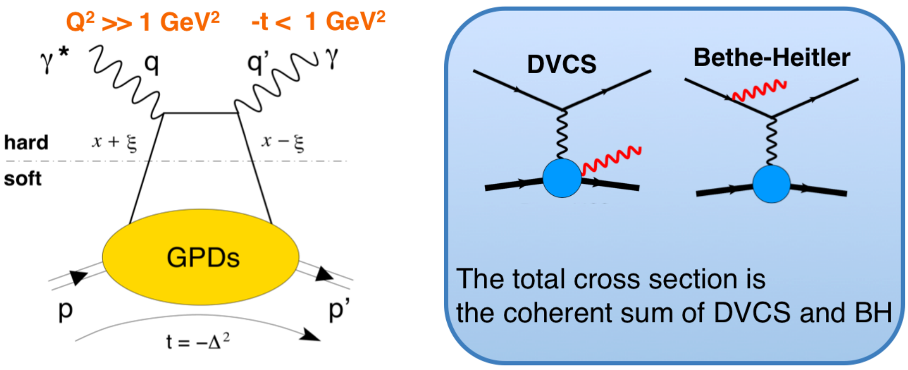

FIGURE 4. *Left: Handbag diagram for the DVCS process at leading twist. Right: DVCS process and BH process.*

The beam charge and spin sum of cross section

$$\begin{aligned} S_{CS,U} &= d\sigma^{+\leftarrow} + d\sigma^{-\rightarrow} \\ &= 2\left(d\sigma^{BH} + d\sigma^{DVCS}_{unpol} + e_{\mu} P_{\mu} Im(I)\right) \end{aligned} \tag{5}$$

contains both the mostly dominant BH contribution and the unpolarized DVCS contribution. $Im(I)$ contains the Compton form factor which is related to the GPD H. An extension of the program is envisaged using a transversely polarized target mainly to constrain the GPD E.

We also propose to study the slope of the t dependence of the differential cross section as a function of x_{Bj} to observe a possible shrinkage of the nucleon with increasing x_{Bj}.

The unpolarized DVCS cross section

$$\frac{d\sigma}{dt} \propto exp(-B(x_B)\,|\,t\,|) \qquad (6)$$

can be isolated in Eq. 5 after integration over ϕ and subtraction of the known BH contribution. At small x_B, where amplitudes are predominantly imaginary, the t-slope parameter $B(x_B)$ is related to the total transverse size $r_\perp$ of the nucleon via the relation $< r_\perp^2(x_B) > \approx 2 \cdot B(x_B)$. In the simple educated guess of $B(x_B) = B_0 + 2\alpha' log(\frac{x_0}{x_B})$ the expected decrease of the nucleon size with increasing x_B is described by the parameter α'.

We performed beam tests for 2 weeks in 2009 with a 40 cm long liquid hydrogen target and 1 m long recoil proton detector in oder to observe BH and DVCS events shown in Fig. 5. The 44 pure DVCS events could be obtained.

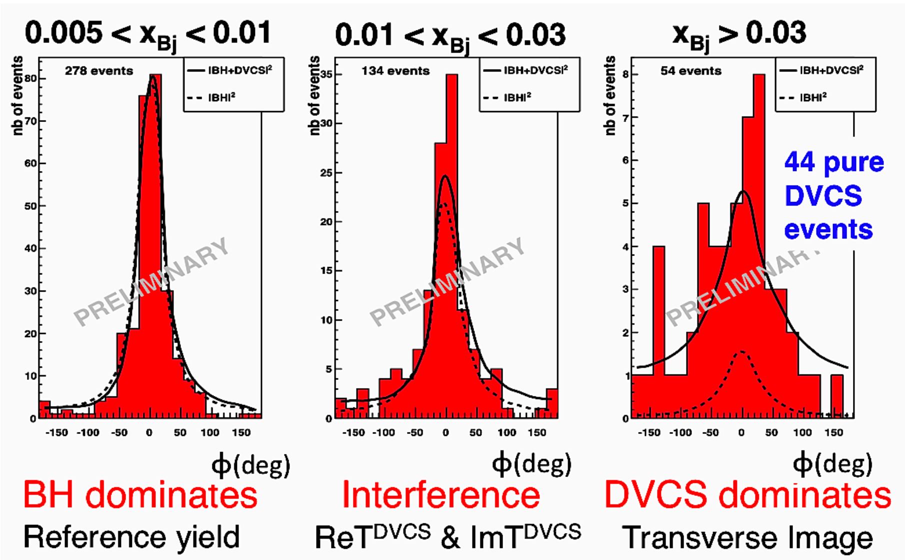

FIGURE 5. Test results of the exclusive process $\mu^+ p \to \mu'^+ p\gamma$ for $Q^2 > 1$ GeV^2, showing the ϕ angle distribution for three bins.

At Compass energies, the evaluation of the missing mass using the energy balance of the incoming and scattered muons and the photon (or meson) has an uncertainty of a few GeV, which is not sufficient to obtain a precise signature of exclusive events. Therefore, the spectrometer will be equipped with a Recoil Proton Detector (RPD) that has a large polar and full azimuthal angular acceptance. The projected uncertainties for the proposed measurements are based on the presently maximum possible muon beam intensities and a liquid hydrogen (LH) target of 2.5 m length, resulting in a luminosity of about $10^{32} cm^{-2} s^{-1}$. In order to match the LH target length, an RPD of about 4 m length is needed. Every possible increase in the maximum positive and negative muon fluxes will increase the statistics correspondingly, thereby also extending the Q^2 range. Therefore all existing or newly designed equipment should stand such an anticipated flux increase.

PION AND KAON POLARIZABILITY

The availability of pion beam as well as a thin nuclear target provide us with the possibility to measure the rigidity of pion's internal structure, described by the electric and the magnetic polarizabilities, via so-called Primakoff reaction

$$\pi^- Z \rightarrow \pi^- Z\gamma \tag{7}$$

embedding the pion Compton scattering reaction as depicted in Fig. 6.

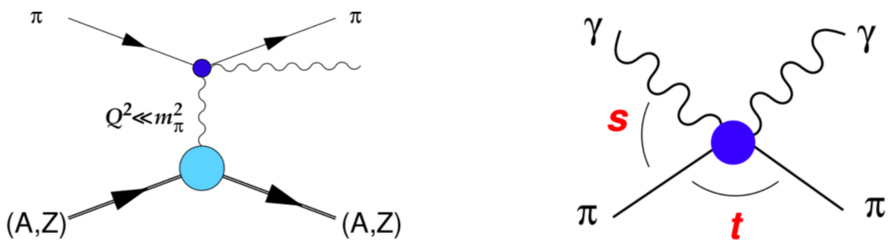

FIGURE 6. *Pion Compton reaction (right graph) embedded in the Primakoff reaction (left graph) on a nucleus of charge Z.*

The differential cross section for the Primakoff reaction is described by

$$\frac{d\sigma_{\pi\gamma}}{d\Omega_{cm}} = \frac{\alpha^2(s^2z_+^2 + m_\pi^4 z_-^2)}{s(sz_+ + m_\pi^2 z_-)^2} - \frac{\alpha m_\pi^3(s-m_\pi^2)^2}{4s^2(sz_+ + m_\pi^2 z_-)} \cdot \mathscr{P} \tag{8}$$

which is given by the pion polarizability term

$$\begin{aligned} \mathscr{P} &= z_-^2(\alpha_\pi - \beta_\pi) + \frac{s^2}{m_\pi^4} z_+^2(\alpha_\pi + \beta_\pi) \\ &\quad - \frac{(s-m_\pi^2)^2}{24s} z_-^3(\alpha_2 - \beta_2) \end{aligned} \tag{9}$$

and $Z_\pm = 1 \pm cos\theta_{cm}$, where θ_{cm} is the scattering angle in CM system, s is the Mandelstam variables, α_π and β_π are the pion electric and magnetic dipole polarizabilities. The last term accounts for the quadrupole polarizability difference $(\alpha_2 - \beta_2)$.

TABLE 1. Theoretical prediction for pion polarizabilities. $\alpha_\pi + \beta_\pi$ predictions are alomost zero in any models. However, the predictions of $\alpha_\pi - \beta_\pi$ are quite different.

Model	Parameter	$[10^{-4} fm^3]$
χPT	$\alpha_\pi - \beta_\pi$ $\alpha_\pi + \beta_\pi$	5.7± 1.0 0.16
NJL	$\alpha_\pi - \beta_\pi$	9.8
QCM	$\alpha_\pi - \beta_\pi$ $\alpha_\pi + \beta_\pi$	7.05 0.23
QCD sum rules	$\alpha_\pi - \beta_\pi$	11.2±1.0
Dispersion sum rules	$\alpha_\pi - \beta_\pi$ $\alpha_\pi + \beta_\pi$	13.60±2.15 0.166±0.024

Different theoretical models predict quite different values of pion polarizabilites shown in Table 1. The experimental measurement will provide a stringent test of the theoretical approaches.

Kaon beam is also available at COMPASS and we can observe Primakoff scattering with charged kaons for the fist time and thus obtain the kaon polarizability.

The expected statistical accuracy of $\alpha_\pi - \beta_\pi$ is ± 0.66 with a proposed running time of 120 days and $\alpha_K - \beta_K$ is ± 0.08 with 90 days.

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