Program of COMPASS-II at CERN

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COMPASS collaboration has started in 2012 a five-year program of new measurements, which are outlined in the 'COMPASS-II' proposal. The two new major projects of the proposal are measurements of polarized Drell-Yan process in π^- scattering off transversely polarized protons and studies of GPDs via measurements of Deeply Virtual Compton Scattering and Hard Exclusive Meson Production in muon scattering off a liquid hydrogen target. In addition, high statistics SISI measurements with muon beams and a study of charged pion and kaon polarizabilities via Primakoff reactions with hadron beams are also foreseen as a part of this program.

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1. Introduction

The description of the partonic structure of the nucleon is one of central problems of hadron physics. The two complementary types of parton distributions, Generalized Parton Distributions (GPDs) and Transverse Momentum Dependent distributions (TMD distributions) provide a 3-dimensional picture of the nucleon, either in a mixed momentum-position representation for the former or in a momentum space for the latter. Moreover, they contain an important information on the orbital motion of partons inside the nucleon. While GPDs appear in the QCD description of hard exclusive processes such as Deeply Virtual Compton Scattering (DVCS) or Hard Exclusive Meson Production (HEMP), TMDs can be accessed either in the Semi-Inclusive Deep Inelastic Scattering (SIDIS) or in the Drell-Yan (DY) process.

COMPASS is a fixed target experiment at the CERN SPS suitable to study the nucleon structure in the framework of GPDs and TMDs. The experiment is situated at the M2 beam line, which can deliver either high-energy hadrons or muons. The range of possible beam energies is 50–280 GeV. The COMPASS spectrometer¹ is

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50 m long two stage spectrometer with variety of tracking detectors that allows to detect charged tracks in a broad angular and momentum range. Each stage is equipped with hadron and electromagnetic calorimeters, and a muon detector. A gas RICH detector is available for particle identification. Transverse spin and transverse momentum dependent effects were extensively studied in COMPASS since 2002 with SIDIS data collected using a 160 GeV muon beam and transversely polarized proton (NH_2) and deuteron (^6LiD) targets (see *e.g.* Refs. [2, 3]). The analyses of exclusive vector meson production on transversely polarized targets⁴ were performed at COMPASS as well. Although no recoil detector was included in the experimental setup, which is a disadvantage for studies of exclusive processes, the measured asymmetries allowed to obtain valuable results that are sensitive to 'elusive' GPDs E and chiral-odd GPDs.

In the following sections we briefly present selected topics of the COMPASS-II program:⁵ measurement of the charged-pion polarizability, the polarized DY process and GPD studies using DVCS and HEMP.

2. Measurement of Charged-pion Polarizability

The electric and magnetic polarizabilities of an extended object describe its rigidity against deformation by external electric and magnetic fields. For a strongly interacting particles, the polarizabilities are of special interest as they are related to the inner forces determining the substructure and thus provide valuable information about quantum chromodynamics (QCD) at low energy. A chiral perturbation theory (ChPT) predicts the value of pion electric polarizability $\alpha_\pi = (2.9 \pm 0.5) \times 10^{-4} \text{ fm}^3$. Although different techniques exists, all previous measurements deviate from ChPT prediction and are affected by large experimental and theoretical uncertainties.

In order to determine pion polarizabilities, the COMPASS collaboration investigates pion Compton scattering, $\pi^- \gamma \rightarrow \pi^- \gamma$, at center-of-mass energy below 3.5 pion masses. The process is embedded in the reaction $\pi^- \text{Ni} \rightarrow \pi^- \gamma \text{Ni}$, which is initiated by 190 GeV pions impinging on a nickel target. The exchange of quasi-real photons is selected by isolating the sharp Coulomb peak observed at smallest momentum transfers, $Q^2 < 0.0015 \text{ (GeV}/c)^2$. The polarizabilities are determined from the deviation of the measured cross section for the reaction $\pi^- \gamma \rightarrow \pi^- \gamma$ with respect to the Born cross section for the point-like particle.

The value of the pion electric polarizability that has been recently reported by COMPASS,⁶ $\alpha_\pi = (2.0 \pm 0.6_{\text{stat}} \pm 0.7_{\text{sys}}) \times 10^{-4} \text{ fm}^3$, is based on the data collected in 2009 using alternatively either hadron or muon beams. The analysis of $\mu^- \gamma \rightarrow \mu^- \gamma$ process, which shares most of the systematics with the analysis of the pion data, provides an excellent tool to verify corrections for systematic effects. The measurements using a muon beam has revealed no significant systematic bias of our method. We find the size of the pion polarizability to be at variance with previous experiments and compatible with the expectation from ChPT. This result

constitutes important progress towards resolving one of the long-standing issues in very low energy QCD.

High statistics data on Primakoff reaction were taken in 2012 and their analysis is ongoing. These data will allow for the first time an independent determination of the pion electric and magnetic dipole polarizabilities, α_π and β_π , as well as the determination of the quadrupole polarizabilities. Because the hadron beam contains a few percent admixture of kaons, which can be tagged using the beam Cerenkov counter, it is expected that also the kaon polarizability will be determined for the first time.

3. Polarized Drell-Yan Process

In addition to SIDIS, the polarized Drell-Yan process provides an alternative access to TMD distributions. The advantage of DY is that it does not depend on the parton fragmentation functions. However, the price to pay is that it depends on convolutions of two parton distribution functions. For pion scattering on transversely polarized protons the azimuthal dependence of the DY cross section is described by four azimuthal asymmetries. They give access to the following convolutions: the pion Boer-Mulders function $h_1^\perp$ with the proton Boer-Mulders function for $A_{UT}^{cos2\phi}$, the pion unpolarized TMD f_1 with the proton Sivers function $f_{1T}^\perp$ for $A_{UT}^{sin\phi_s}$, the pion Boer-Mulders function with the proton transversity function h_1 for $A_{UT}^{sin(2\phi-\phi_s)}$ and the pion Boer-Mulders function with the proton pretzelosity function $h_{1T}^\perp$ for $A_{UT}^{sin(2\phi+\phi_s)}$. Here ϕ is the azimuthal angle defined in the Collins-Soper frame between the plane of incoming hadrons and the plane of outgoing leptons, and ϕ_s is the azimuthal angle of the target spin with respect to the transverse momentum of the virtual photon in the target rest frame.

Of particular interest are the Sivers and Boer-Mulders TMDs. Due to their naive time reversal odd nature they change sign when extracted from either DY or SIDIS.⁷ This change of sign, called restricted universality of TMDs, is due to the contribution of initial-state interactions in DY or final-state interactions in SIDIS. Verifying this prediction is considered to be a crucial test of the TMD approach of non-perturbative QCD.

The COMPASS will start the DY program in October 2014 and continue in 2015. In the anticipated 140 days of data taking a total of 285 000 Drell-Yan events in the di-muon high-mass range, $4 \text{ GeV}/c^2 < M_{\mu^+\mu^-} < 16 \text{ GeV}/c^2$, will be accumulated, which corresponds to a rate of approximately 2000 events per day. These will be the first ever data for polarized DY process.

For measurements of DY di-muon pairs a π^- beam of 190 GeV energy and the polarized target will be used. The target consists of two separate cells filled with ammonia. The protons of NH_3 molecules are transversely polarized with respect to the pion beam direction, with opposite polarizations for the two target cells. In order to minimize systematic errors for the extraction of azimuthal asymmetries, the target spin reversal will be performed every few days. Due to the low cross-section

Fig. 1. The target region and absorber of the COMPASS Drell-Yan experiment.

of the DY process the maximum beam intensity of 10^8 pions/s will be used. The limit is dictated by the allowed radiation dose in the experimental hall and to avoid local heating of the target that could compromise the target polarization.

Several upgrades of the COMPASS setup are necessary for the DY program. In order to keep detectors occupancy at an acceptable level below 5%, a thick hadron absorber made of aluminum and alumina (Al_2O_3) will be placed immediately downstream the polarized target. In its inner part the absorber contains a core of tungsten designed to stop the non-interacting beam. This so called beam plug is a heavy nuclear target useful also for studies of non-polarized DY process. An additional thin Al target will be placed half-way between the target and the beam plug. The data from these two nuclear targets will allow to study the flavor dependence of the EMC effect in DY process. In Fig. 1 the target region of the COMPASS Drell-Yan setup is shown. Due to the presence of hadron absorber the spectrometer will detect mostly muons. The hadron absorber degrades the resolution on vertex position because of increased multiple scattering of muons. Therefore, in order to provide an adequate vertex resolution that is needed for an unambiguous assignment of each DY interaction to a given target cell, a new scintillating fibers vertex detector is inserted in the upstream part of absorber as shown in Fig. 1.

In order to minimize the contribution from J/ψ , charmed meson decays and combinatorial background of muons coming from decays of secondary pions and kaons, the experiment will focus on di-muon high-mass region $4\text{GeV}/c^2 < M_{\mu^+\mu^-} < 16\text{GeV}/c^2$. Given the clear signals measured at COMPASS in SIDIS, the direct comparison of the TMDs obtained in SIDIS with these from DY in the same kinematic domain is of great interest. In Fig. 2 the COMPASS kinematic coverage is shown for SIDIS and DY processes. In the overlap region of high Q^2 the expected statistical uncertainties for DY asymmetries are similar to uncertainties of the already measured SIDIS asymmetries. For instance, the uncertainty of the Sivers asymmetry $A_{UT}^{\sin\phi_s}$ obtained for DY events collected in 140 days of data taking will be about 0.013, while for the Sivers asymmetries for positive or negative hadrons from SIDIS events collected in the corresponding Q^2 range it is about 0.01. The expected

Fig. 2. Phase space coverage of the SIDIS and Drell-Yan COMPASS measurements.

uncertainties of the remaining asymmetries for the DY process are equal to 0.005 for $A_{UU}^{\cos 2\phi}$ (Boer-Mulders) and 0.027 for $A_{UT}^{\sin(2\phi-\phi_s)}$ (transversity) or $A_{UT}^{\sin(2\phi+\phi_s)}$ (pretzelosity).

4. The GPD Program

Generalized Parton Distributions contain a wealth of information on the partonic structure of the nucleon. In particular, they allow a novel description of the nucleon as an extended object, sometimes referred to as 3-dimensional 'nucleon tomography' [8]. GPDs also allow access to such a fundamental property of the nucleon as the orbital angular momentum of quarks.⁹ For reviews of the GPDs see Refs. [10].

The GPD part of COMPASS-II program is devoted to measurements of both DVCS and HEMP with polarized μ^+ and μ^- beams and a liquid hydrogen target. Already in 2012 the commissioning of new detectors and a pilot run for DVCS were performed. The dedicated data taking for the GPD program, accompanied in parallel by SIDIS measurements, is foreseen in 2016-2017 for a total period of 280 days.

From the theoretical view point DVCS is considered to be the cleanest process among exclusive processes, because effects of next-to-leading order and higher twist contributions are under theoretical control.¹¹ The competing Bethe-Heitler (BH) process has a final state identical to that of DVCS so that both processes interfere. COMPASS covers various kinematic domains where either BH or DVCS dominates. The collection of almost pure BH events at small x allows one to get an excellent reference yield and to control accurately the global efficiency of the apparatus. In contrast, the collection of an almost pure DVCS sample at larger x will allow to measure the DVCS cross section and an x -dependence of its t -slope, which is related to the tomographic image of the nucleon. In the intermediate x -domain, the DVCS contribution will be boosted by the BH process through the interference term that allows to investigate DVCS at the amplitude level.

Fig. 3. The distribution of the azimuthal angle ϕ for exclusive single photon production measured in the 2009 DVCS test run at COMPASS. The lines represent the expected BH event yield.

The DVCS test runs in 2008 and 2009 with the 40 cm LH₂ target and the small recoil proton detector proved the feasibility to measure exclusive single γ production at COMPASS. A way to identify the observed process, $\mu + p \rightarrow \mu' + \gamma + p'$, to which both the DVCS and Bethe-Heitler processes contribute, is to look at the angle ϕ between the leptonic and hadronic planes. The observed distributions, after applying all cuts and selections and for $Q^2 > 1 (\text{GeV}/c)^2$, are displayed in Fig. 3 and compared to the predictions from the Monte Carlo simulations for the BH event yield. The Bethe-Heitler contribution shows a characteristic peak at $\phi \simeq 0$. The overall detection efficiency can be deduced from the relative normalization of the two distributions for the low x -region dominated by BH. The global efficiency is equal to 0.14 ± 0.05 , in agreement with the value 0.1 assumed for the proposal.⁵ It includes the detection efficiency, SPS and COMPASS availabilities, trigger efficiencies and dead time.

By installing a large recoil proton detector, built in 2012, around the 2.5 m long LH₂ target the COMPASS setup can be converted into a facility measuring exclusive reactions within a kinematic domain from $x \sim 0.005$ to ~ 0.27 , which cannot be explored at any other existing or planned facility in the near future.

A new calorimeter ECAL0 covering large photon angles is being constructed. Compared to the existing electromagnetic calorimeters, it will increase the accessible domain in x for DVCS and exclusive π^0 production, and therefore it will provide an overlap with HERMES and JLAB experiments. ECAL0 will also improve hermeticity for detection of exclusive events and will contribute to reduce background to single-photon production that originates from π^0 and other decays.

For illustration we present two selected projections for the GPD program observables from the COMPASS-II proposal.⁵

The t -slope parameter $B(x)$ of the DVCS cross section $d\sigma/dt(x) \propto \exp(-B(x)|t|)$ can be obtained from the beam charge and spin sum of the cross

Fig. 4. The x dependence of the fitted t -slope parameter B of the DVCS cross section. COMPASS projections for expected uncertainties are calculated for $1 \text{ (GeV/c)}^2 < Q^2 < 8 \text{ (GeV/c)}^2$ and compared to HERA results for which the mean value $\langle Q^2 \rangle$ is in this range. The two curves in the upper right part of the figure represent $B(x)$ dependence for different values of α' .

Fig. 5. Projections for the beam charge and spin difference of cross section for single photon production measured at COMPASS for $0.03 \leq x \leq 0.07$ and $1 \text{ (GeV/c)}^2 \leq Q^2 \leq 4 \text{ (GeV/c)}^2$. The curves correspond to the predictions described in the text.

sections after integration over ϕ and BH subtraction. The expected accuracy of the measurements of $B(x)$ at COMPASS is shown in Fig. 4. For the simulations the simple ansatz $B(x) = B_0 + 2\alpha' \log(x_0/x)$ was used with the values $B_0 = 5.83 \text{ (GeV/c)}^2$, $\alpha' = 0.125$ and $x_0 = 0.0012$. The knowledge of x -dependence of t -slope parameter $B(x)$ in the COMPASS kinematic range will yield a new important information in the context of the ‘nucleon tomography’.

COMPASS is presently the only facility to provide polarized leptons with either charge, *i.e.* μ^+ and μ^- beams with opposite polarizations. The difference and sum of cross sections for μ^+ and μ^- combined with the analysis of ϕ dependence will allow us to isolate the real and imaginary parts of the leading twist-2 DVCS amplitude and of higher twist contributions.

The projected errors for the beam charge and spin difference of cross section measured as a function of ϕ in a selected (x, Q^2) bin are shown in Fig. 5. This difference is sensitive to the real part of the DVCS amplitude, which is a convolution of GPDs with the hard scattering kernel over the whole range of longitudinal momenta of exchanged quarks. Therefore measurements of this asymmetry provide strong constraints on GPD models. Two of the curves shown are calculated using the ‘VGG’ GPD model.¹² A theoretical development exploiting dispersion relations for Compton form factors was successfully applied¹³ to describe DVCS observables at very small values of x typical for the HERA, and extended to include DVCS data from HERMES and JLAB. The prediction for COMPASS from this analysis are also shown as additional curves.

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