Polarised Drell-Yan physics at COMPASS

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The COMPASS experiment at CERN is one of the leading experiments studying the spin structure of the nucleon. Until now, the Parton Distribution Functions (PDFs) and the Transverse Momentum Dependent Parton Distribution Functions (TMD PDFs) of protons and deuterons have been studied in Semi-Inclusive Deep Inelastic Scattering (SIDIS) measurements. The polarised Drell-Yan (DY) process is a complementary way to access the TMD PDFs, as it allows us to measure convolutions of only PDFs without involving fragmentation functions (FFs). COMPASS aims to perform the first ever polarised DY experiment in the world, which is foreseen to start in late 2014. By detecting dimuons from DY events we will be able to extract azimuthal spin asymmetries, each containing a convolution of two TMD PDFs, one from a negative pion beam with a momentum of 190 GeV/c and the other one from a transversely polarised proton target (NH_3). After their disentangling we can access four of the eight TMD PDFs needed to describe the nucleon structure at leading twist, like the Sivers and the Boer-Mulders functions. The opportunity to study, in the same experiment, the TMD PDFs from both SIDIS and DY processes is unique at COMPASS. Therefore, we are in privileged conditions to confirm or to deny the expected sign change in Sivers and Boer-Mulders functions when accessed via DY or SIDIS processes. An overview of the preparation and future measurements of the polarised DY experiment will be provided.

1. Introduction

The main goal of the DY program of COMPASS is the study of the TMD PDFs of the proton [1]. The DY process consists in an electromagnetic annihilation of a quark-antiquark pair with the production of two leptons in the final state. The COMPASS case is represented in Fig. 1. A negative pion beam is used to study the valence up quarks of the proton. The experiment is focused on the dimuon channel to take advantage of the good muon reconstruction by the existing spectrometer. The idea of using the polarised DY process to study TMD PDFs comes from unpolarised DY experiments. In particular, it was found by two past experiments (NA10 [2] and E615 [3])

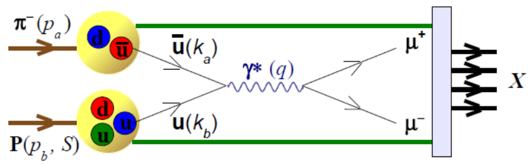

Fig. 1. The Drell-Yan process at COMPASS

that the intrinsic transverse momentum (k_T) of quarks is not a negligible quantity inside the proton. This conclusion was made by studying the angular dependence of the DY cross-section:

$$\frac{1}{\sigma}\frac{d\sigma}{d\Omega} = \frac{3}{4\pi}\frac{1}{\lambda+3}[1+\lambda\cos^2\theta + \eta\sin 2\theta\cos\phi + \frac{\nu}{2}\sin^2\theta\cos 2\phi]\,, \qquad (1)$$

where θ and ϕ are the polar and azimuthal angles of one of the produced leptons in the dilepton rest frame. In the case of $k_T = 0$ no azimuthal modulations are expected. However, the above mentioned experiments measured a $\cos 2\phi$ modulation up to 30%, which without a doubt point to the importance of k_T. Consequentely, instead of 3 collinear PDFs (unpolarised f_1, helicity g_1 and transversity h_1) a total of 8 TMD PDFs are needed to describe the nucleon structure at leading twist.

The key feature of the DY process, when compared with the SIDIS process, is the possibility to study convolutions of two TMD PDFs instead of a TMD PDF convoluted with a quark fragmentation function. Using a transversely polarised proton target and a π^- beam we are able to measure four azimuthal spin asymmetries, each containing a convolution of two TMD PDFs. Therefore, we can access 4 of the 8 leading twist TMD PDFs of the proton: $h_1(x, k_T^2)$ (which leads to transversity after integration over k_T), $h_1^\perp(x, k_T^2)$ (Boer-Mulders), $f_{1T}^\perp(x, k_T^2)$ (Sivers) and $h_{1T}^\perp(x, k_T^2)$ (pretzelosity). Of particular importance are the T-odd Sivers and Boer-Mulders functions. The former describes the transverse motion of quarks induced by the transverse spin of the nucleon and the latter describes the correlations between the transverse spin and transverse momentum of quarks in an unpolarised nucleon. By itself the Sivers function is extremely important because it contains information about the orbital angular momentum (OAM) of quarks. The OAM of quarks is one of the remaining unknowns of the so-called spin-puzzle of the nucleon, a puzzle which the scientific community has been trying to solve over the last 30 years. However, the main motivation to study $h_1^\perp(x, k_T^2)$ and $f_{1T}^\perp(x, k_T^2)$ via DY is the prediction that these two TMD PDFs must change sign when accessed via DY or SIDIS. This prediction is a crucial test of our current understanding of TMD PDFs.

It results from the fact that the re-summation of all soft gluons in a k_T dependent PDF is process dependent. This procedure, which is essential to provide the gauge invariance of a PDF, leads to the existence of the above mentioned T-odd functions. Therefore, the time invariance of the Sivers and Boer-Mulders functions is ensured if and only if they change sign between SIDIS and DY.

Up to now COMPASS has been studying the TMD PDFs of protons and deuterons via SIDIS processes of a polarised muon beam off a transversely polarised target. With our pioneering polarised DY experiment, which basically uses the same spectrometer, we are in privileged conditions to observe the sign change. In Fig. 2 we can confirm the existence of a phase-space overlap between the two COMPASS measurements.

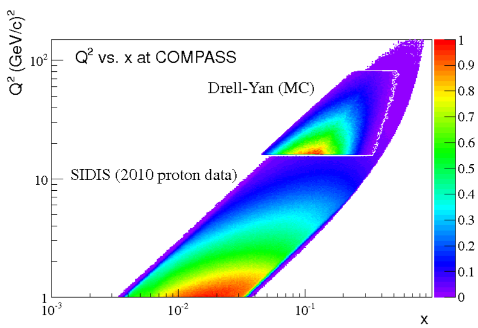

Fig. 2. Phase-space coverage of the SIDIS and DY measurements at COMPASS.

2. The COMPASS experiment

COMPASS is a fixed target experiment located in the CERN North Area, at the end of the M2 beam line of the **S**uper **P**roton **S**ynchrotron (SPS) accelerator. The M2 line provides either muon or hadron beams in a momentum range of 50 to 280 GeV/c. Detailed studies have shown that a π^- beam with 1×10^8 π^-/s and a 190 GeV/c momentum is the best choice for the DY measurement. The high intensity is required to counterbalance the low DY cross-section and it is only limited by the polarised target and by the performance of the M2 beam line. Concerning the target, it will be formed by two cells transversely polarised in opposite directions in order to allow us to measure the needed spin asymmetries for the extraction of the TMD PDFs. Using solid state ammonia as target material one can reach a polarisation of the order of 90%, with a fraction of polarisable material of 0.22.

Since the hadro-production cross section is much larger than the DY one, the use of a hadron absorber is mandatory to prevent the hadronic products to overflood the detectors. The composition of the absorber is chosen to minimise the number of radiation lengths crossed by the muons (for a minimum multiple scattering), while maximising the number of pion interaction lengths. It will be a compound more than 2 meters long made of aluminum oxide, aluminum and stainless steel, placed immediately after the polarised target. A tungsten beam-plug will also be used as a beam-stopper in the central part of the absorber. Together with a vertex detector and a dimuon trigger, formed by two large area hodoscopes with target pointing features, these are the main modifications in the two-stage spectrometer of COMPASS. A complete description of the latter can be found in [4].

3. The extraction of azimuthal asymmetries

The general polarised DY cross-section was derived by Arnold et. al. [5]. For the special case of COMPASS, involving an unpolarised beam and a transversely polarised target, the cross-section can be written in LO as:

$$\begin{aligned}\frac{d\sigma}{d^4q d\Omega} &= \frac{\alpha^2}{Fq^2}\hat{\sigma}_U\{(1 + D_{[\sin^2\theta]}\boxed{A_U^{\cos 2\phi}}\cos 2\phi) + |\vec{S}_T|[\boxed{A_T^{\sin\phi s}}\sin\phi_S \\ &+ D_{[\sin^2\theta]}(\boxed{A_T^{\sin(2\phi+\phi_S)}}\sin(2\phi+\phi_S) + \boxed{A_T^{\sin(2\phi-\phi_S)}}\sin(2\phi-\phi_S))]\}\end{aligned} \tag{2}$$

where the azimuthal and polar angles, ϕ and θ, are defined in the Collins-Soper reference frame and ϕ_S is the angle between the transverse spin of the target and the transverse momentum of the virtual-photon (γ^*):

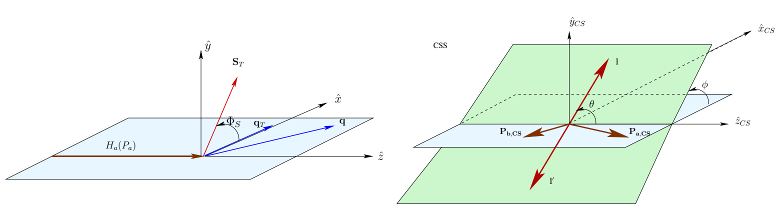

Fig. 3. Left: ϕ_S in the laboratory frame. Right: ϕ and θ in the Collins-Soper frame.

The quantity F is defined by $F = 4\sqrt{(p_\pi \cdot p_P)^2 - M_\pi^2 M_p^2}$, q is the four-momentum of the γ^*, $\hat{\sigma}_U$ is the part of the cross-section surviving the integration over the angles ϕ and θ, $|\vec{S}_T|$ is the target polarisation and $D_{[\sin^2\theta]}$ is the γ^* depolarisation factor.

The four highlighted asymmetries in Eq. 2 can be measured at COMPASS by fitting the corresponding azimuthal modulations of the dimuan pair. In non-perturbative QCD these asymmetries are interpreted as a ratio of 2 convolutions, each one containing 2 TMD PDFs. The TMD PDFs depending on spin appear in the numerator and they completely define the corresponding asymmetries. In this sense, each of the asymmetries is defined by the following convolutions:

- $A_U^{\cos 2\phi}$: the Boer-Mulders function of both hadrons ($h_1^\perp \otimes h_1^\perp$)
- $A_T^{\sin 2\phi}$: the density number function of the beam hadron with the Sivers function of the target nucleon ($f_1 \otimes f_{1T}^\perp$)
- $A_T^{\sin 2\phi+\phi_S}$: the Boer-Mulders function of the beam hadron with the pretzelosity function of the target nucleon ($h_1^\perp \otimes h_{1T}^\perp$)
- $A_T^{\sin 2\phi-\phi_S}$: the Boer-Mulders function of the beam hadron with the transversity function of the target nucleon ($h_1^\perp \otimes h_1$)

The proton's TMD PDFs $h_1^\perp(x,k_T^2)$, $f_{1T}^\perp(x,k_T^2)$, $h_{1T}^\perp(x,k_T^2)$ and $h_1(x,k_T^2)$ can be extracted from the measured asymmetries in global analyses.

4. Event rates and statistical errors

In COMPASS we are interested mostly in the so-called high mass region of the dimuon pair, i.e. $4 \leq M_{\mu\mu} < 9$ GeV/c^2. Despite the DY cross-section being quite low, amounting only to fractions of nanobarn, the main advantage of this mass region is that it is free from both combinatorial and physics backgrounds. The intermediate mass region of $2 \leq M_{\mu\mu} < 2.5$ GeV/c^2 has 5 times larger cross-section but it has also a huge contamination by the combinatorial background, at least as large as the signal, and an open charm contamination at the level of 15%. In addition to the high mass region, the J/Ψ resonance will also be investigated in detail due to the so-called DY-J/Ψ duality. Since the J/Ψ and γ are both vector particles, we can consider an analogous DY and J/Ψ production via quark-antiquark annihilation, which is believed to dominate at the COMPASS energy. In case of duality, we can use the much higher dimuon cross-section in the J/Ψ region to extract the TMD PDFs with much better precision. This can be confirmed in Table 1, where the expected precision is provided for the 4 azimuthal asymmetries. These predictions are based on the use of a π^- beam with a $p = 190$ GeV/c momentum and an intensity of $I_{beam} = 6{\times}10^7 s^{-1}$, which allows us to achieve a luminosity of $L = 1.2{\times}10^{32} cm^{-2} s^{-1}$. With this luminosity we expect about 900 events/day in the high mass region, $4 \leq M_{\mu\mu} < 9$ GeV/c^2, 4300 events/day in $2 \leq M_{\mu\mu} < 2.5$ GeV/c^2 and 22500 events/day in the DY+J/Ψ mass region of $2.9 \leq M_{\mu\mu} < 3.2$ GeV/c^2. A total of 280 days of data taking is foreseen.

Table 1. Statistical uncertainty for the asymmetries in the high mass region.

Asymmetry uncertainty	Dimuon mass (GeV/c^2) $2 < M_{\mu\mu} < 2.5$	$2.9 < M_{\mu\mu} < 3.2$	$4 < M_{\mu\mu} < 9$
$\delta A_U^{cos2\phi}$	0.0026	0.0014	0.0056
$\delta A_T^{sin\phi_S}$	0.0065	0.0036	0.0142
$\delta A_T^{sin(2\phi+\phi_S)}$	0.0131	0.0073	0.0284
$\delta A_T^{sin(2\phi-\phi_S)}$	0.0131	0.0073	0.0284

In Fig. 4 is shown a comparison between the expected precision of the measurements and the theoretical predictions for the azimuthal asymmetries. These predictions point to sizable asymmetries in the valence region of the proton and, as it is clearly seen from Fig 5, COMPASS has a large acceptance in that region.

5. Feasibility of the measurement

The feasibility of the measurement was proved by several beam tests performed in 2007, 2008, 2009 and 2012. In 2007 and 2008 an open spectrometer configuration (without a hadron absorber) was used. Using a π^- beam of 160 GeV/c momentum and an intensity up to $6.5 \times 10^6 \pi/s$, a high occupancy of the detectors closer to the target region was observed. This expected fact confirmed the necessity of using a hadron absorber in the future experiment. These first tests were important to verify the spectrometer response and the level of radiation in the experimental hall.

In 2009 a more important test was performed using a prototype hadron absorber. A π^- beam of 190 GeV/c momentum was used together with two target cells of polyethylene material, each one 40 cm in length and 5 cm in diameter, spaced by 20 cm. The absorber was made of two blocks of concrete and stainless steel, each one 100 cm in length and 80×80 cm^2 in transverse dimension. The beam test had a duration of only three days but it was enough to compare the J/Ψ signal with the expected yield. The obtained mass spectrum can be seen in Fig. 6. Good agreement was found with the expected number of J/Ψ's, which amounts to 3600 ± 600.

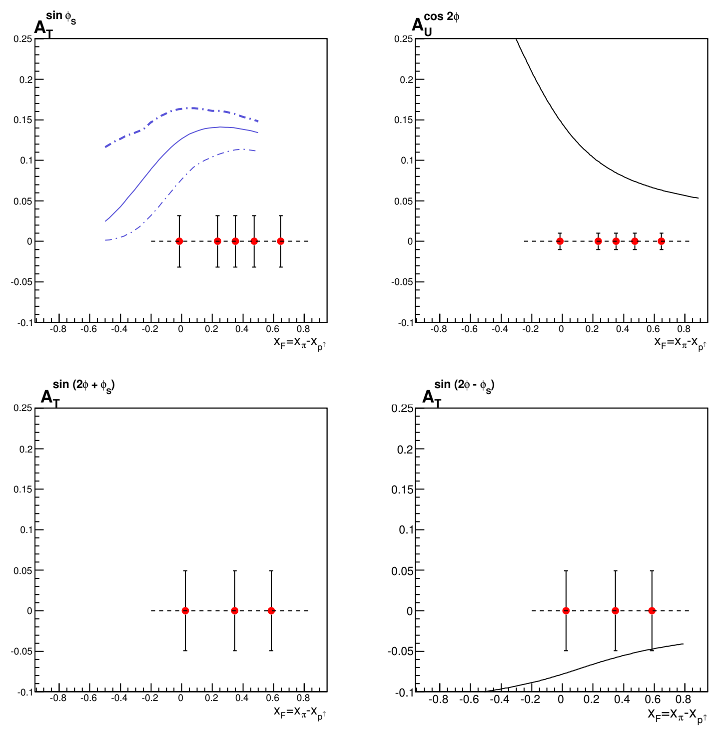

Fig. 4. Comparison between theory predictions and experimental precision for the 4 azimuthal asymmetries accessible at COMPASS.

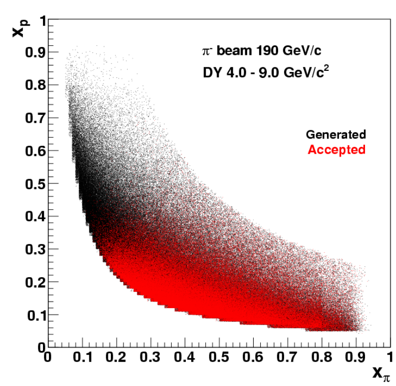

Fig. 5. COMPASS acceptance for DY in the high mass region.

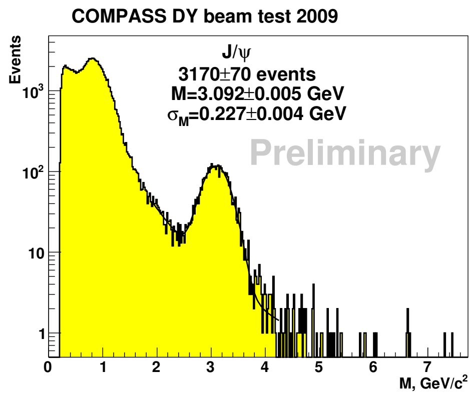

Fig. 6. Invariant mass spectrum of dimuons obtained with the 2009 DY beam test.

6. Summary

The experimental acceptance of COMPASS for DY events covers the valence quarks region, where TMD effects are expected to be sizable. The opportunity to study, with the same spectrometer, the TMD PDFs from both SIDIS and DY processes is unique at COMPASS. In particular, the sign change in the Sivers and Boer-Mulders functions when measuring in DY or in SIDIS will be checked. This verification is crucial for our current understanding of TMD PDFs. The feasibility of the measurement has been proven after a series of beam tests.

The polarised DY measurement is approved and will start by the end of 2014 with a short beam test. The physics run will take place in 2015. A second year of data taking is also planed, possibly in 2018. With 2 years of data we can study the TMD PDFs as a function of x_F and p_T.

Acknowledgments

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References

[1] COMPASS Collaboration, COMPASS-II proposal, CERN-SPSC.2010-014, SPSC-P-340, 17 May 2010.

[2] S. Falciano *et al.* (NA10 Collaboration), Z. Phys. C **31**, 513 (1986).

[3] J.S. Conway *et al.* (E615 Collaboration), Phys. Rev. D **39**, 92 (1989).

[4] P. Abbon *et al.* (COMPASS Collaboration), Nucl. Inst. Meth. A **577**, 455 (2007).

[5] S. Arnold *et al.*, Phys. Rev. D **79**, 034005 (2009).