Future Drell-Yan measurements in COMPASS

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Abstract. The COMPASS experiment at CERN studies the spin structure of the nucleon, using its unique polarized target in both longitudinal and transverse polarization modes. The future Drell-Yan measurement by the COMPASS collaboration proposes to access the transverse momentum dependent parton distribution functions, namely Sivers and Boer-Mulders functions. The Drell-Yan process with unpolarized and with transversely polarized target is a very promising tool for this purpose, complementary to the semi-inclusive deep inelastic scattering measurements available from COMPASS, HERMES and JLab experiments. Also interesting related studies like the J/ψ-Drell-Yan duality are proposed. The physics case, as well as the most important technical aspects of this project will be presented.

1. Introduction

The unpolarized Drell-Yan process allows since some decades to access information on the dynamical structure of the nucleons. This purely electromagnetic process of quark-antiquark annihilation, with the produced virtual photon decaying to a pair of dileptons, has shown important deviations from the collinearity assumption of partons inside the nucleons. Experiments like E615 at Fermilab [2] and NA10 at CERN [1] studied the angular distribution of the Drell-Yan events, that can be written in the form:

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

where θ and ϕ are the polar and azimuthal angles of one of the produced leptons in a dilepton rest frame. Usually the Collins-Soper frame is used for this purpose, as it averages the virtual photon emission angle in the hadrons frame, thus being more adequate for polarization studies. The so-called Lam-Tung sum rule: $1 - \lambda - 2\nu = 0$, relates the modulation amplitudes of the Drell-Yan process [3]. The collinear hypothesis for the partons inside the nucleons is equivalent to $\lambda = 1$ and $\mu = \nu = 0$. This hypothesis was shown to be violated by the NA10 and E615 experiments, with ν increasing up to 30% for increasing dilepton transverse momentum.

These results are nowadays interpreted as resulting from the correlation between the partons spin and their intrinsic transverse momentum. The so-called Boer-Mulders parton distribution function (PDF), that describes this correlation, is one of the transverse momentum dependent (TMD) PDFs. The transversely polarized Drell-Yan process allows to access other TMD PDFs as well, as the Sivers and the pretzelosity functions, thus contributing to a full picture of the nucleon. At leading twist the complete description requires the knowledge of 8 PDFs, dependent on the parton momentum fraction x and on its intrinsic transverse momentum squared k_T^2:

f_1 (density number), g_{1L} (helicity), h_1 (transversity), $f_{1T}^{\perp}$ (Sivers), $h_1^{\perp}$ (Boer-Mulders), $h_{1T}^{\perp}$ (pretzelosity), g_{1T} and $h_{1L}^{\perp}$ (worm-gears). From these, only the first three survive k_T integration. The Sivers and the Boer-Mulders functions are time-reversal odd functions, which leads to the very interesting prediction that they must change sign when accessed from Drell-Yan (DY) or from semi-inclusive deep inelastic scattering (SIDIS). The experimental confirmation of this sign change is considered a crucial test of non-perturbative QCD.

In May 2010 COMPASS has submitted to the CERN SPS scientific committee a proposal for new measurements, that includes a polarized Drell-Yan experiment, having a pion beam and a transversely polarized target [4]. This proposal was recommended for approval in September 2010, and it includes one year of data-taking devoted to the Drell-Yan measurement.

2. Polarized Drell-Yan at COMPASS

The COMPASS experiment at CERN has a multipurpose spectrometer allowing to use both muon and hadron beams. Its high versatility makes it possible to address a vast range of physics topics from the spin structure of the nucleon to hadron spectroscopy. Spin studies have been done in the period 2002 to 2007, and restarted in 2010/2011, using a naturally polarized μ^+ beam and a solid state target polarized either longitudinally or transversely with respect to the direction of the beam. The (semi-inclusive) DIS process has been used to make a direct measurement of the gluon polarization, and access the helicity (in longitudinal mode) and transversity (in transverse polarization mode) PDFs among other topics. The opportunity to study some TMD PDFs, namely Sivers, both from SIDIS and from the Drell-Yan process using the same spectrometer, presents itself as a unique chance to test the sign change prediction.

In a recent paper, Arnold *et al.* [5] derived the full expression of the Drell-Yan cross-section for arbitrarily polarized beam and target. Having an unpolarized beam and a transversely polarized target the Drell-Yan cross-section in leading order (LO) can be written as:

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

In this expression θ and ϕ are the polar and azimuthal angles of the positive lepton in the Collins-Soper reference frame, and ϕ_S is the angle between the transverse spin of the target nucleon and the transverse momentum of the virtual photon. Having a pion beam and a proton target, the factor F is given by $F = 4\sqrt{(P_\pi \cdot P_p)^2 - M_\pi^2 M_p^2}$. The γ^* four-momentum is q, and $\hat{\sigma}_U$ is the part of the cross-section surviving the integration over the azimuthal angles ϕ and ϕ_S. $|\vec{S}_T|$ is the target polarization value; and $D_{[\sin^2\theta]}$ is the virtual photon depolarization factor. The azimuthal asymmetries are the functions A, depending on the target polarization state and the modulation term observed. The expression of each asymmetry contains a convolution of 2 PDFs, one relative to the target and the other to the beam hadrons.

Being observables, the asymmetries must contain an even number of chiral-odd objects. Thus, the chiral-odd transversity PDF for example can only be observed in double-polarized Drell-Yan; or if in single polarized Drell-Yan, convoluted with another chiral-odd PDF, as is the case of the Boer-Mulders TMD PDF. In equation 2, the asymmetry $A_U^{\cos 2\phi}$ accesses the Boer-Mulders functions of both incoming hadrons, $A_T^{\sin\phi_S}$ to the Sivers function of the target nucleon, $A_T^{\sin(2\phi+\phi_S)}$ to the Boer-Mulders function of beam hadron and pretzelosity of target nucleon, and finally $A_T^{\sin(2\phi-\phi_S)}$ gives access to the Boer-Mulders function of beam hadron and to transversity of target nucleon. To disentangle the PDFs in each of these asymmetries requires some input

from other sources. Namely to access the transversity and pretzelosity of the nucleon one needs to know the Boer-Mulders function of pions. For this purpose, several options are available, using directly the existing parametrizations of this PDF (see for example the parametrization given by [6], using data from NA10 on $A_U^{\cos 2\phi}$); or using parametrizations of the nucleon transversity (see for example [7], using data from HERMES, COMPASS and BELLE) and the $A_T^{\sin(2\phi-\phi_S)}$ asymmetry that will be measured in COMPASS.

The COMPASS phase space is favorable for TMD PDF studies as it probes the valence quarks region of the nucleon. The so-called high mass Drell-Yan events with dimuons of masses $4. \leq M_{\mu\mu} \leq 9.$ GeV/c^2 is particularly interesting, as in this region we have all events with x$_{proton} > 0.05$. Figures 1 and 2 present the simulation of the phase space covered by the Drell-Yan experiment in COMPASS. The Drell-Yan events are generated using PYTHIA, and passed in a GEANT simulation of the spectrometer. Two dimuon mass ranges are shown, the intermediate mass region $2. \leq M_{\mu\mu} \leq 2.5$ GeV/c^2 (on the right hand side), and the high mass region already referred (on the left hand side). In black the generated events are presented, while in red the accepted ones in the spectrometer are shown.
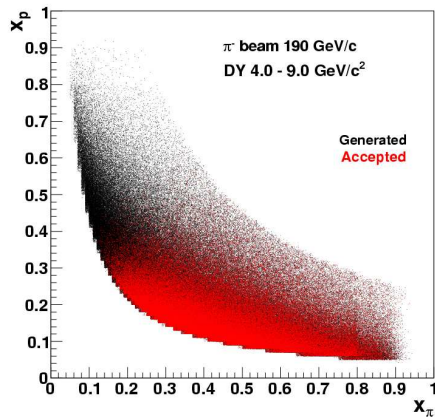

Figure 1. COMPASS phase space in x_p versus x_π. Black: generated; red: accepted events. Drell-Yan events $4. \leq M_{\mu\mu} \leq 9.$ GeV/c^2.
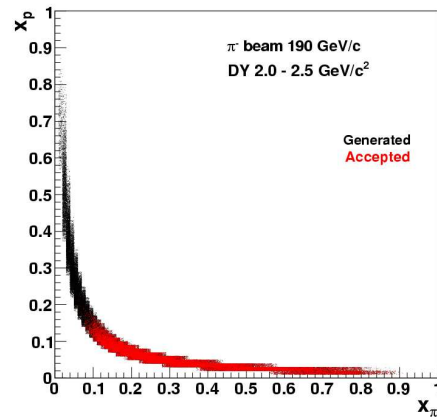
Figure 2. COMPASS phase space in x_p versus x_π. Black: generated; red: accepted events. Drell-Yan events with $2. \leq M_{\mu\mu} \leq 2.5$ GeV/c^2.

The high mass region covers mostly the region of valence quarks, and it has the additional advantage of being a region of pure Drell-Yan events with negligible background contamination. It is limited on the left and right hand sides by the ψ and the Υ resonance families. In the intermediate mass region, on the contrary, the Drell-Yan events compete with a combinatorial background of muons from pion decays, and a physics background of muons from semi-leptonic decays of open-charm mesons (the latter estimated to be 14% of the Drell-Yan signal). The biggest advantage of studying the intermediate mass region is its higher Drell-Yan cross-section, that decreases rapidly with increasing dimuon masses.

The leading order Drell-Yan cross-section obtained from PYTHIA, for a 190 GeV/c incident pion beam in a NH_3 target is 1.3 nanobarn for dimuons in the high mass region $4. \leq M_{\mu\mu} < 9.$ GeV/c^2, and 6.2 nanobarn for dimuons in the intermediate mass region $2. \leq M_{\mu\mu} < 2.5$ GeV/c^2. These cross-sections are calculated for the ammonia target case from a weighted combination of π^--proton and π^--neutron cross-sections.

Another topic that can be explored in a polarized Drell-Yan experiment is the so-called J/ψ-DY duality. The fact that both the charmonium resonance and the photon are vector particles

leads to a possible analogy in the production mechanisms, as at low energies $q\bar{q}$ annihilation is the dominant source of J/ψs. The study of the charmonium mass region in the dilepton decay channel allows to check the duality hypothesis. Its much larger cross-section presents an obvious advantage for the extraction of TMD PDFs. Additionally, by varying the pion beam energy (a possibility that exists in the M2 beam line of the SPS/CERN available for COMPASS, in the approximate energy range of 50 to 200 GeV) the different J/ψ production mechanisms and polarization states can be studied.
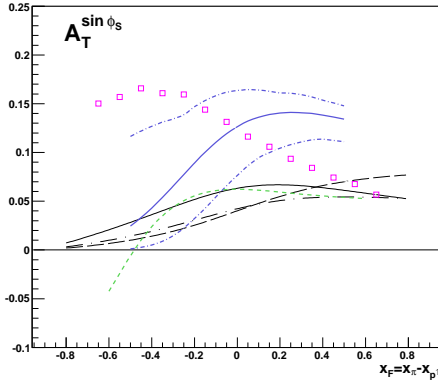
Figure 3. $A_T^{\sin\phi_S}$. ——and − − −: Efremov et al [8]; — · —: Collins et al [9]; blue lines: Anselmino et al [10]; magenta □: Bianconi et al [11]; green line: Bacchetta et al [12].
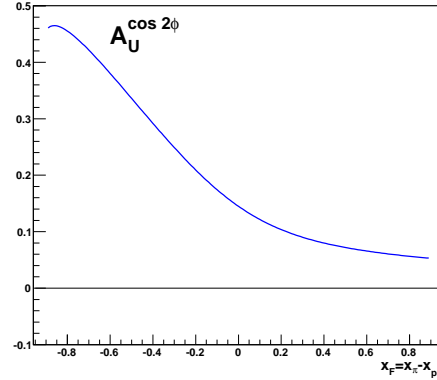

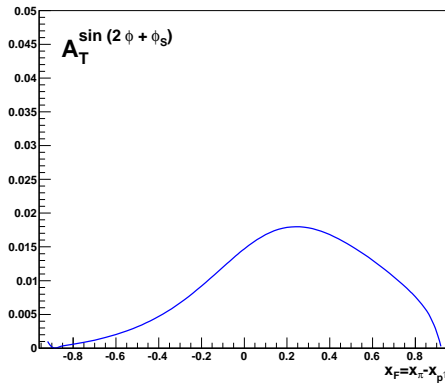**Figure 4.** $A_T^{\cos 2\phi}$. Blue line: B. Zhang et al [13].

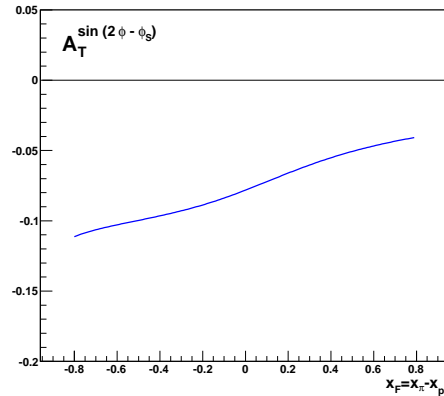**Figure 5.** $A_T^{\sin(2\phi+\phi_S)}$ at $Q^2 = 20$ GeV^2. Blue line: A. Efremov et al [15].

Figure 6. $A_T^{\sin(2\phi-\phi_S)}$. Blue line: A.N. Sissakian et al [14].

The COMPASS future Drell-Yan measurements raised much interest in the theorists community. Theory predictions specific for the COMPASS case, using a pion beam of 190 GeV/c and a proton target have been published recently. The predictions for the azimuthal asymmetries expected in the COMPASS case, in the Drell-Yan high mass range, as a function of the Feynman-x variable ($x_F = x_\pi - x_p$) are compiled in figures 3 to 6.

All the azimuthal asymmetries are expected to be sizable. The smallest one is expected to be $A_T^{\sin(2\phi+\phi_S)}$, giving access to Boer-Mulders of pion convoluted with pretzelosity of nucleon,

that amounts to only 2% at its maximum, thus in the limit of our experimental sensitivity.

3. COMPASS Drell-Yan set-up

COMPASS took data in 2008 and 2009 with positive and negative hadron beams at 190 GeV/c, with the physics goal of hadron spectroscopy studies. The secondary π^- beam has a small contamination of kaons (approximately 3%) and antiprotons ($< 1\%$). The Drell-Yan measurement proposed shall use this hadron beam at 190 GeV/c, incident in a polarized solid state target. The two-cells NH_3 target, installed inside a superconducting solenoid +dipole, allows to make the simultaneous measurement of spin asymmetries in two opposite polarization configurations, thus minimizing the systematic uncertainties. The ammonia target was used by COMPASS in 2007, 2010 and 2011 for DIS measurements and allows to reach 90% polarization with a dilution factor around 15%. The target cells can be polarized longitudinally or transversely to the beam direction. The transverse polarization mode uses the target dipole field (0.6 T) to keep the nucleons spin frozen with a relaxation time around 4000 hours.

COMPASS has a two-stages spectrometer, the first one (LAS) for large angle particles, and the second for particles emitted at small angles (SAS). The set-up includes 2 dipole magnets and approximately 350 tracking planes, covering a large angular acceptance up to 160 mrad. A complete description of the COMPASS set-up can be found in [16].

The Drell-Yan measurement requires an additional hadron absorber to be placed immediately downstream the polarized target. At the beam intensity of the planned measurement 6×10^7 π^-/s this absorber is mandatory, in order to keep the occupancies in the first 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 shown in figures 7 and 8. With transverse dimensions covering the target solenoid acceptance, and a length along the beam direction of at least 2 meters, the absorber will be made of aluminum oxide (Al_2O_3), 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.
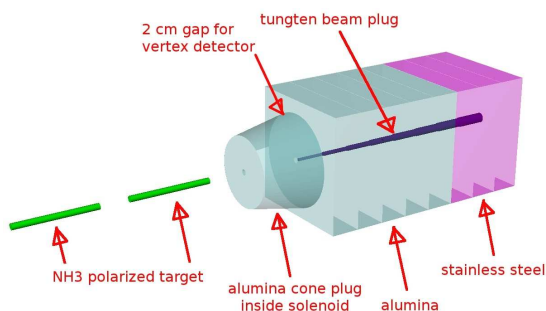

Figure 7. Possible configuration of the hadron absorber and beam plug for the COMPASS Drell-Yan measurement.
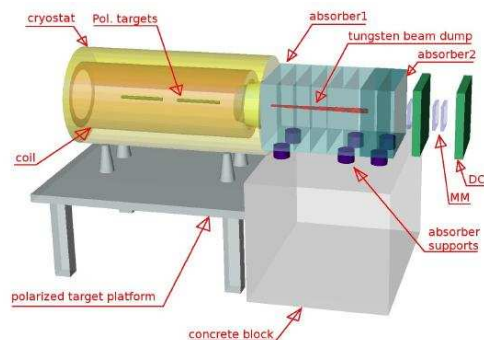

Figure 8. The polarized target region, including the absorber and first detectors.

Adequate shielding of the target and absorber region is needed, to ensure radiation levels within the allowed limits. The shielding will surround that whole area, including below and above. The material used to contain the radiation will most probably be concrete, layered with a plastic compound.

4. Feasibility of the measurement

Several Drell-Yan beam tests were performed in COMPASS in 2007, 2008 and 2009 to check the feasibility of the measurement. The 2007 test was performed with an open spectrometer configuration, that is without the presence of an hadron absorber. It used a π^- beam at 160 GeV/c, and an unpolarized NH$_3$ target. 90000 dimuon events were collected in less than 12 hours. The dimuon mass spectrum obtained, and namely the J/ψ peak, allowed to validate the Drell-Yan event rate calculations. The good response of the spectrometer was verified, and the radiation doses were controlled.

In 2008 a set-up without hadron absorber was once again used, but this time increasing the beam intensity up to 25% of the nominal value for the proposed Drell-Yan experiment. The high occupancy of the detectors located closer to the target region proved that the open spectrometer configuration is not feasible, thus confirming the need to use an hadron absorber.

In 2009 a prototype absorber was installed, made of concrete and stainless steel, 1 meter long each. It contained in its center a tungsten beam plug. A dimuon trigger was built, using two signal thresholds in the first hadronic calorimeter, the one covering the largest angles. Data was collected during approximately 3 days. The presence of the absorber degrades the vertex, mass and angle resolutions. Nevertheless, the two target cells and the absorber are clearly separated in the reconstructed vertexes distribution, as can be seen in figure 9.
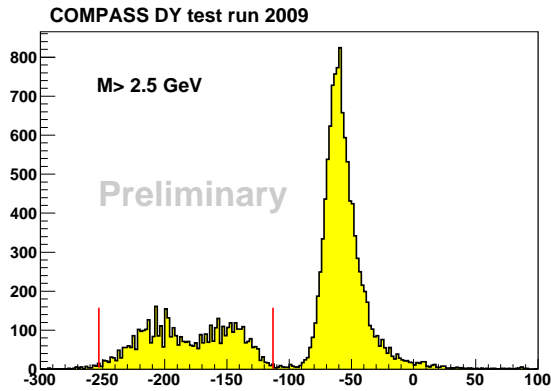

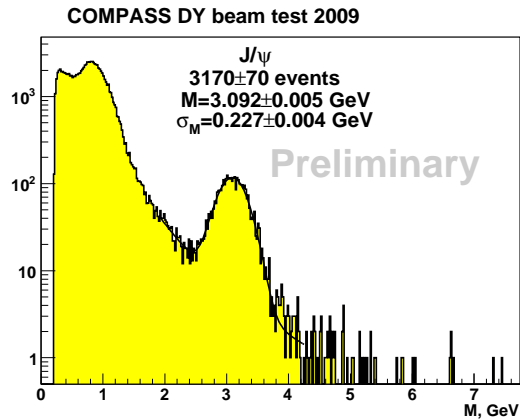**Figure 9.** Reconstructed vertexes, for dimuon masses $M_{\mu\mu} > 2.5$ GeV/c^2.

Figure 10. Reconstructed dimuon mass spectrum.

The dimuon mass spectrum obtained, shown in figure 10 is in agreement with the Monte-Carlo simulations performed. The fact that the mass resolution in the J/ψ peak, $\sigma_M = 227 \pm 4$ MeV/c^2, is worse than in past Drell-Yan experiments is understood, as the reconstruction program needs to be optimized, as well as the positions of some detectors. The resolution can be improved by adding some radiation hard tracking planes close to the target. The presence of the absorber reduces the combinatorial background of uncorrelated μ^+ and μ^- from pion decays by approximately one order of magnitude at $M_{\mu\mu} = 2$ GeV/c^2.

5. Acceptances, event rates and statistical errors

A full Monte-Carlo simulation shows that the COMPASS spectrometer acceptance for dimuons in the mass region $4. \leq M_{\mu\mu} < 9.$ GeV/c^2 is 35%, with 65% of the accepted events being in the large angle spectrometer, and 4% detected in the small angle spectrometer. In 40% of the cases one of the muons is measured in LAS and the other in SAS (note that there is a small overlap in LAS and SAS coverages). In the dimuon intermediate mass region $2. \leq M_{\mu\mu} < 2.5$ GeV/c^2 the average acceptance is 43%.

The proposed Drell-Yan measurement with a π^- beam of 190 GeV/c and a beam intensity of 6×10^7 particles/s can achieve a luminosity of 1.2×10^{32} cm^{-2} s^{-1}, and Drell-Yan rates amounting to 800 events/day for high masses and 4900 events/day in the intermediate mass region. Assuming two years of Drell-Yan data-taking (140 days/year), the expected statistical errors in the azimuthal asymmetries are as given in table 1.

Table 1. Estimated statistical errors in the azimuthal asymmetries assuming two years of data-taking.

Asymmetry	Dimuon mass (GeV/c^2)		
	$2 < M_{\mu\mu} < 2.5$	J/ψ region	$4 < M_{\mu\mu} < 9$
$\delta A_U^{\cos 2\phi}$	0.0020	0.0013	0.0045
$\delta A_T^{\sin \phi_S}$	0.0062	0.0040	0.0142
$\delta A_T^{\sin(2\phi+\phi_S)}$	0.0123	0.008	0.0285
$\delta A_T^{\sin(2\phi-\phi_S)}$	0.0123	0.008	0.0285

Figures 11 and 12 present the expected statistical errors together with the theory predictions for the azimuthal asymmetries for the Drell-Yan high masses and the intermediate mass region, respectively. For the Sivers asymmetry $A_T^{\sin \phi_S}$ only the prediction from [10] is shown.
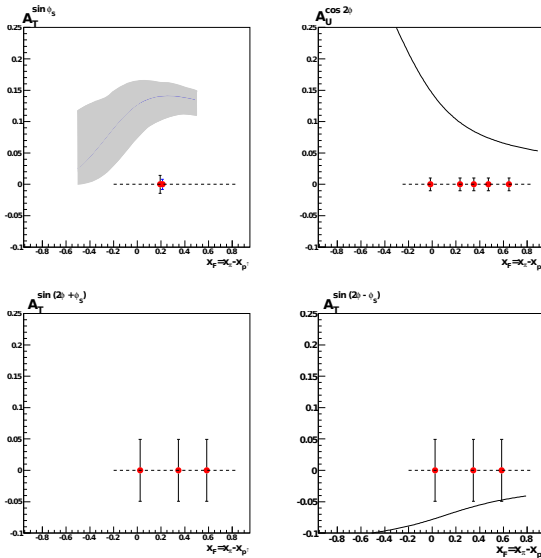

Figure 11. Azimuthal asymmetries for dimuon masses $4. \leq M_{\mu\mu} < 9.$ GeV/c^2. Theory predictions and expected statistical errors assuming 2 years data-taking.
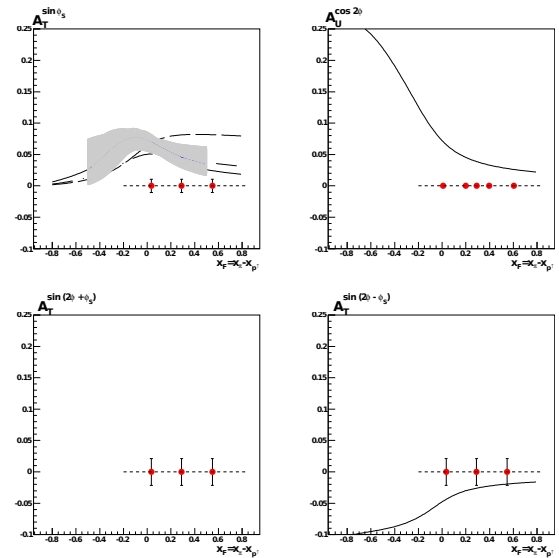
Figure 12. Azimuthal asymmetries for dimuon masses $2. \leq M_{\mu\mu} < 2.5$ GeV/c^2. Theory predictions and expected statistical errors assuming 2 years data-taking.

6. Conclusions

The polarized Drell-Yan process is an ideal tool to study TMD PDFs and improve our present knowledge on the nucleon dynamics. The COMPASS collaboration proposes to do such measurement using a π^- beam of 190 GeV/c momentum incident in a NH$_3$ transversely polarized

target. In these conditions the dimuons produced in the mass range $4. \leq M_{\mu\mu} < 9.$ GeV/c^2 populate a phase-space where the valence quarks of the nucleon are probed. The COMPASS multipurpose spectrometer offers the unique possibility to probe the Sivers TMD PDF via the polarized Drell-Yan process, and via the semi-inclusive deep inelastic scattering, as was done in the first part of the COMPASS physics programme [17]. These two complementary measurements will allow to check the theory prediction of a sign change of the Sivers PDF when accessed from one or the other of these processes.

The COMPASS collaboration proposes to measure unpolarized and transversely polarized Drell-Yan, accessing four azimuthal asymmetries, and from these the transversity PDF as well as the TMD PDFs Sivers, Boer-Mulders and pretzelosity of the nucleon. All four asymmetries are expected to be sizable in the COMPASS case, although pretzelosity seems to be in the limit of the experiment's sensitivity. Assuming two years of data-taking, the expected statistical errors in the asymmetries shall allow a measurement of Sivers, Boer-Mulders and transversity of the nucleon in several bins of x_F, thus providing not only sign information, but also showing the trend of each of these PDFs.

COMPASS has performed since 2007 several beam tests that demonstrated the feasibility of the proposed measurement. The experiment will require a slightly modified set-up, where a long hadron absorber is placed downstream the polarized target, and a selective dimuons trigger based in large area hodoscopes is installed. Eventually some additional radiation hard tracking planes will be added in the region between the target and the absorber, to improve the vertex resolution. The proposed experiment was recommended for approval by the SPS-CERN scientific committee, in September 2010. COMPASS has the potential to become the first ever polarized Drell-Yan experiment, and may start to take data as soon as in 2013.

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