# Future measurements of the transverse spin structure of the nucleon in SIDIS and Drell-Yan at COMPASS

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**Abstract.** COMPASS (COmmon Muon and Proton Apparatus for Structure and Spectroscopy) is a fixed target experiment at the CERN SPS taking data since 2002. The spin nucleon structure has been investigated in the years 2002-2007, by scattering a 160 GeV muon beam off deuteron and proton targets polarised both longitudinally and transversely with respect to the beam direction. After two years of spectroscopy measurements with hadron beams in 2008 and 2009, the measurements with the muon beam and the polarised proton target will be resumed. In 2010 data will be collected with the proton target transversely polarised to further investigate the transverse spin effects in semi-inclusive deep inelastic scattering (SIDIS). On a longer time scale, the Collaboration plans to pursue the study of the transverse spin and momentum structure of the nucleon by measuring the Drell-Yan process on a transversely polarised target. The physics case and the expected outcome of both these measurements are described here.

# **1** Introduction

Transverse spin effects constitute a central issue in understanding the nucleon structure. It is well known since many years that transverse spin asymmetries do not vanish at high energies at variance with a widespread theoretical prejudice, but only recently the transverse spin structure of the nucleon started to be investigated in a systematic way. On the experimental side, a large international effort started in the nineties to measure transverse spin effects both in SIDIS by the HERMES [1] and the COMPASS [2] Collaborations, and in high energy polarised proton-proton scattering [3] at the RHIC collider. The results coming from these experiments confirm the relevance of the transverse spin effects and reveal interesting and new phenomena. In parallel, the theoretical description of the nucleon structure became more and more complete. At leading order a third quark distribution function, the "transversity", has been introduced, and more distribution functions are necessary if the transverse momentum of the quarks is taken into account. In the new theoretical framework several of the present experimental results can be described in this new framework and predictions for specific spin effects are available. Still, this field is at its infancy and the available data set is very limited and not adequate to the complexity of the phenomena under investigation. To progress further, more data are required: some of the observed effects need to be further investigated and new channels have to be measured.

The COMPASS Collaboration will continue the investigation of the transverse spin effects in SIDIS in 2010 and a proposal to measure the Drell-Yan process on a transversely polarised target is in preparation. These two measurements are part of the medium and long term plans of COMPASS [4–6] which also include SIDIS with the longitudinally polarised proton target,

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Deeply Virtual Compton Scattering, and further measurements with hadron beams. This talk only deals with the first two measurements. The current description of the transverse spin and momentum structure of the nucleon is briefly given in section 2, together with the experimental status and some of the recent SIDIS results which have a clear interpretation in the present theoretical framework. Projections of the future SIDIS and Drell-Yan measurements with the transversely polarised target at COMPASS are given in sections 3 and 4 respectively.

#### 2 The transverse spin and momentum structure of the nucleon

To fully specify the quark structure of the nucleon at the twist-two level, the transversity distributions  $\Delta_T q(x)$  (or  $h_1^q(x)$ ) has to be added to the well known spin-averaged parton distribution function (PDF) q(x) (or  $f_1(x)$ ) and to the helicity PDF  $\Delta q(x)$  (or  $g_{1L}^q(x)$ ). The transversity distribution  $\Delta_T q(x)$  gives the correlation between the quark transverse spin in transversely polarised nucleons and the nucleon spin. Its relevance became clearer and clearer in the last years and many interesting properties have been established. Among them, transversity is chiral-odd. As such, it does not contribute to inclusive DIS, which has been and is a fundamental tool to access the nucleon structure, and this explains why it is still very poorly known, at variance with the number and helicity PDFs. Transversity can only be measured via observables in which it is coupled to another chiral-odd quantity. The first suggestion was to access it by measuring double transverse spin observables in the Drell-Yan process, as proposed by the RHIC Spin Collaboration [7]. Unfortunately these are very difficult measurements which have not yet been performed.

Completely new opportunities came up in 1993, when Collins [8] pointed out that the distribution of the hadrons produced in the hadronization of a transversely polarised quark could exhibit a left-right asymmetry with respect to the plane containing the spin and the momentum of the quark. The spin dependent part of the fragmentation function (the Collins FF) is chiral-odd and can couple with the transversity PDF giving a modulation of the type  $sin\Phi_C$  in the azimuthal distribution of the hadrons produced in SIDIS on transversely polarised targets. The Collins angle is defined as  $\Phi_C = \phi_h + \phi_s + \pi$  where  $\phi_h$  and  $\phi_s$  are the azimuthal angles of the components of the hadron momentum and of the target nucleon spin which are orthogonal to the exchanged  $\gamma$  direction as measured in the Gamma-Nucleon System. The amplitude of the modulation, usually called Collins asymmetry, is the convolution of transversity PDF and the Collins FF and its measurement with different targets and for identified hadrons could allow to access the transversity PDFs for each different quark flavour.

More than ten years after, in 2005, the first results on the Collins asymmetry in SIDIS of 28 GeV electrons on a transversely polarised proton target by the HERMES Collaboration [9] showed a clear signal for positive and negative pions, indicating that both the transversity PDF and the Collins FF are different from zero.

At the same time, COMPASS was taking data with the 160 GeV muon beam and a deuteron target polarised both longitudinally and transversely. The choice of starting the experiment using a deuteron target was dictated by the priority given to the measurement of  $\Delta G/G$ , the gluon contribution to the nucleon longitudinal spin. For this measurement the deuteron target (<sup>6</sup>LiD) had a superior figure of merit than the proton target (NH<sub>3</sub>), thus data were collected over the first four years of the experiment (2002, 2003, 2004 and 2006) with the deuteron target. The Collins asymmetries measured on deuteron turned out to be compatible with zero for positive and negative hadrons [10,11], for charged pions, and for charged and neutral kaons [12]. When, in 2005, this result was first obtained, it was interpreted as a cancellation between the u and d quark contributions to the deuteron asymmetry, interpretation which was also in agreement with the HERMES result.

About the Collins FF, independent evidence that the Collins mechanism is real and gives measurable effects came from the analysis of the azimuthal correlations in  $e^+e^- \rightarrow hadrons$  performed by the BELLE Collaboration [13].

A global fit of the HERMES proton results, the COMPASS deuteron results and the BELLE data has already been performed [14]. The agreement with all the data is very good, and for



Fig. 1. COMPASS measurement of the Collins asymmetry on proton for positive (top) and negative (bottom) hadrons as function of x, the relative hadron energy z and the hadron transverse momentum  $p_T$ . The curves are the calculations of Ref. [14].

the first time both the transversity distributions for the u and d quark and the Collins FFs could be extracted. Even if several assumptions had to be used in the fitting procedure and the available data set was very limited, this was a major step forward which gave much confidence in the current description of the transverse spin structure of the nucleon.

New input came in 2008, when COMPASS produced the first results from part of the data collected in 2007 with the transversely polarised proton target and the 160 GeV muon beam [15]. The measured Collins asymmetry turned out to be different from zero in the valence region both for positive and negative hadrons, as can be seen in fig. 1 where the preliminary COMPASS results from all the data collected with the transversely polarised proton target [16] are shown. The size of the signal is about the same as that measured by HERMES and the agreement with the predictions [14] based on the global fit discussed before is very good, as clear from fig. 1. Given the different kinematical domains covered by HERMES and COMPASS, this is an important result which gives a clear indication that the Collins signal seen on a proton target is not due to higher-twist effects, but to real new properties, finally being measured.

The measurement of the Collins asymmetry and the transversity PDF was the main motivation for the HERMES and COMPASS proposals to run with transversely polarised targets. In the mean time, however, a different item rapidly grew, namely the role of the parton transverse momentum and its correlation with the spin. New transverse momentum dependent (TMD) parton distributions have been introduced. Today there are eight leading-order TMD PDFs, five of them vanish when integrating over the intrinsic transverse parton momentum while three of them survive after integration and give q(x),  $\Delta q(x)$ , and  $\Delta_T q(x)$ . Two of the leading order TMD PDFs are T-odd: the Boer-Mulders function  $h_1^{\perp}$  which describes the correlation between the spin and the transverse momentum of the quarks in unpolarised nucleons, and the Sivers function  $\Delta_0^T q$  (or  $f_{1T}^{\perp}$ ) which gives the correlation between the transverse momentum of the quarks and the nucleon transverse spin [17]. The Sivers function is presently the most studied. For several years it was believed to vanish by time-reversal invariance but recently it has been proven that it can be non zero because of final state interactions, and presently it has an important role in fundamental issues of QCD. Moreover, a large theoretical effort is devoted to establish a connection between the Sivers function and the orbital angular momentum of the partons.

The TMD PDFs are expected to contribute to several different processes. In particular the Boer-Mulders function could explain the large asymmetries measured in the high energy  $\pi^-W$  Drell-Yan production [18]. The Sivers function could be responsible for the large transverse spin asymmetries measured in hard pp scattering. In this process, however, it can not be easily disentangled by the contribution due to the transversity PDF. The Sivers function is also expected to contribute to the still unmeasured azimuthal asymmetries in Drell-Yan processes on transversely polarised targets. These points will be further discussed in section 4.

All the eight TMD PDFs enter in the SIDIS cross-section [19]. Their convolutions with the usual FFs or the Collins FFs are the amplitudes of the possible modulations of azimuthal distributions of the final state hadrons. These azimuthal asymmetries either appear for different polarisation of the beam and the target, or are related to the distributions of independent azimuthal angles, and can thus be disentangled and measured from the same data.

The Boer-Mulders PDF, convoluted with the Collins FF, appears in the unpolarised SIDIS cross-section, and contributes to the  $cos2\phi_h$  modulation in the hadron azimuthal distribution. Both the COMPASS [20] and the HERMES experiments have measured it as by-product of the spin dependent asymmetries finding quite interesting results.

About the TMD PDFs appearing in the SIDIS cross-section on transversely polarised nucleons, most of the data are related to the Sivers function. Its convolution with the unpolarised FF is the amplitude of a modulation of the type  $\sin \Phi_S$ ; the Sivers angle is  $\Phi_S = \phi_h - \phi_S$ , i.e. it is the difference of the azimuthal angles of the hadron transverse momentum and of the target spin, and it is orthogonal to the Collins angle. HERMES has measured a non-zero Sivers asymmetry with the proton target for  $\pi^+$  (and  $K^+$ , where Sivers asymmetries larger than 10% have been observed) hinting to a sizable  $\Delta_0^T u$ . For  $\pi^-$  the asymmetry is compatible with zero, suggesting a cancellation between the u and d-quark contributions in the proton. As for the Collins asymmetries, the Sivers asymmetries measured by COMPASS on the deuteron are again compatible with zero, both for positive and negative hadrons [10, 11], pions and kaons [12]. These results are in agreement with a cancellation between the u and d-quark contributions in the deuteron and put stringent constrains on the d-quark Sivers function. Fits of the HERMES proton and COMPASS deuteron data with almost no  $Q^2$  dependence data allowed for the extraction of the Sivers functions for the u and d quarks, finding both of them definitively different from zero, of about the same strength, and of opposite sign [21]. In this situation the preliminary results from the analysis of part of the 2007 COMPASS proton data [15] were completely unexpected. They show small asymmetries, compatible with zero within the statistical errors, both for positive and negative hadrons. For positive hadrons the COMPASS asymmetry data are smaller than the HERMES results, and the probability that the two sets of data are compatible with the present statistical uncertainties is of a few percent. This is an intriguing result since no strong dependence of the Sivers asymmetry on the phase space is presently expected in any model. Given the relevance of the Sivers function in the present theoretical description of the nucleon structure, new precise SIDIS measurements at high energy are urgently needed.

#### 3 Further measurements of transverse spin asymmetries in SIDIS

The COMPASS Collaboration has proposed to resume the SIDIS data taking and to dedicate a full year of run to the measurements with the transversely polarised proton  $(NH_3)$  target and the 160 GeV muon beam. The proposal has been accepted by the CERN Committees and the new data will be collected in 2010. The experimental apparatus will be essentially the same as used in 2007, but we will take advantage of the improvements of the last two years, in particular for the small area trackers, the calorimetry, and the DAQ. A new large angle muon trigger will also be available.

The new data will allow to precisely measure the transverse spin asymmetries in the inclusive hadron production and in several other channels, like the inclusive production of hadron pairs and  $\Lambda$ s, and the exclusive production of  $\rho^0$ . Here, only some points related to the Collins and Sivers asymmetries will be reviewed.

As clear from fig. 1, the Collins asymmetry is different from zero at the COMPASS energies. Still, the statistical errors are large and a new independent measurement is mandatory. In 150



Fig. 2. Parametrisations of the transversity PDF for the u (positive values) and the d (negative values) quarks [22–27].

days of data taking the expected statistical errors will be smaller than those of fig. 1 by a factor of two. The measurement will be quite accurate over all the accessible x range, from x = 0.003 to x = 0.4, and, thanks to the good particle identification available in COMPASS, both for charged pions and kaons. This will also allow to put constrains on the low-x shape of the transversity functions for which several different parametrisation have been proposed, as shown in fig. 2, and to have a much better estimation of its first moments. With the new data, it will also be possible to undertake a multidimensional analysis in x, z, and  $p_T$  and to perform a first preliminary study of the  $Q^2$  evolution of the Collins asymmetry to test the present assumptions.

For the Sivers asymmetry, the new data are needed first of all to clarify the issue of energy dependence suggested by the comparison between the HERMES and the COMPASS preliminary results. In 150 days of data taking the statistical errors are expected to be smaller by a factor of 3 than those of the released results. They are shown in fig. 3 together with the preliminary results from HERMES [28] (stars) and COMPASS [15] (closed squares). As for the Collins asymmetry, the planned measurement will allow a first detailed study of the dependence of the Sivers asymmetry on the various kinematical variables.

The new COMPASS measurements, together with the existing measurements of HERMES and COMPASS, and the future measurements at JLab, will give important information over a



Fig. 3. Sivers asymmetry on proton for positive (left) and negative (right) hadrons. The open circles show the expected statistical errors from the COMPASS measurement in 2010. The stars and the closed squares are respectively the HERMES [28] and COMPASS [15] preliminary results.

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Fig. 4. Schematic view of the Drell-Yan process from ref. [29].

quite large kinematical region and will very likely conclude the exploratory phase of the study of transverse spin effects in SIDIS. In the future, precise measurements at high energies should be possible at the lepton-nucleon colliders which are being proposed. Depending on the time scale of these projects it is not excluded that it might be worthwhile to perform further SIDIS measurements at CERN, presently the only laboratory where SIDIS at high energy can be studied.

#### 4 Drell-Yan measurements with a transversely polarised target

The current knowledge on the partonic structure of the nucleons is mainly coming from DIS and SIDIS experiments. Unique complementary information is also provided by the Drell-Yan process, theoretically a very clean hard hadron-hadron scattering process.

At large invariant mass of the lepton pair, the dilepton production in hadron hadron scattering can be described in the Drell-Yan model in which a quark (or antiquark) from a hadron  $H_a$  and an antiquark (or quark) from a hadron  $H_b$  annihilate into a virtual photon which decays into a lepton pair:

$$q_a + q_b \to \gamma^* \to l^- + l^+$$

as sketched in fig. 4. The Drell-Yan cross-section thus involves the convolution of two PDFs, at variance with SIDIS, where the PDFs are convoluted with FFs.

The general expression of the cross-section in the one photon approximation [29] includes 48 structure functions, 24 of which are non zero at large dilepton invariant mass in leading twist calculations. These structure functions are proportional to the convolutions of the eight leading order TMD PDFs introduced in section 2, and can be measured using unpolarised and polarised hadrons from the azimuthal distributions of the dilepton plane

At leading order the unpolarised cross-section depends on two structure functions and from the measurable azimuthal distribution of the lepton pair one can access the convolution of the quark and the antiquark Boer-Mulders functions  $h_1^{\perp} \bar{h}_1^{\perp}$ . If one of the hadrons is transversely polarised the cross-section depends on three different structure functions and measuring the modulation in the corresponding azimuthal angle distributions one can access  $f_1 \bar{f}_{1T}^{\perp}$ ,  $h_1^{\perp} \bar{h}_{1T}^{\perp}$ and  $h_1^{\perp} \bar{h}_1$ , and get information on the Sivers, the Boer-Mulders, the "pretzelosity"  $h_{1T}^{\perp}$ , and the transversity PDFs. If the two hadrons are both transversely polarised, the azimuthal asymmetry is related to the transversity distributions, and, in the case of transversely polarised proton and antiproton interaction, its measurement would give a clean and direct access to the *u* quark transversity distribution. This interesting experimental program has been proposed at FAIR, the new facility being built at GSI, but it can not start soon since polarised antiproton beams are needed.

Till now, no polarised Drell-Yan measurement has been performed. The COMPASS Collaboration plans to measure the Drell-Yan process using a high energy pion beam and a transversely polarised proton target [4], and this could be the first measurement of transverse spin effects in Drell-Yan.

The Collaboration plans to use a 190 GeV/c  $\pi^-$  beam and the COMPASS apparatus, which has large acceptance muon identification capability. The main modifications to the experimental



Fig. 5. Left: distribution of accepted Drell-Yan events in the  $(x_p, x_\pi)$  plane. Right: expected statistical errors (filled circles at zero) for the asymmetry related to the Sivers function as a function of  $x_F = x_\pi - x_p$  compared with model calculations.

set-up are dictated by the use of a high intensity beam which is needed to achieve a sufficient luminosity with the 120 cm long  $NH_3$  target. To reduce the particle flux in the trackers a hadron absorber has to be placed just downstream of the polarised target. Another important upgrade consists in the setting up of a new dedicated muon trigger based on large area hodoscopes.

The measurement will be done in the safe invariant mass region  $4 < M_{\mu\mu} < 9 \text{ GeV/c}^2$ , higher than the  $J/\Psi$  invariant mass. The x-Bjorken range covered by the measurement is illustrated in fig. 5 (left) where the  $x_{\pi}, x_{p}$  correlation for the dimuon pairs in the COMPASS acceptance is shown. As can be seen, the acceptance is larger in the valence region, where the signals should be higher. An example of the statistical precision achievable in two years of data taking is given in Fig. 5 (right) where the points at zero show the expected statistical errors for the asymmetry related to the Sivers function. The curves are calculations from different models [30–33] based on the preliminary HERMES measurements of the SIDIS Sivers asymmetry. Using a  $\pi^-$  beam, this asymmetry is mainly given by the convolution of the  $\bar{u}$  unpolarised PDF of the pion and the u Sivers function of the proton. Even if the Sivers function would be smaller, as indicated by the COMPASS preliminary results, the expected statistical errors are small, of the order of 1-2%, and the measurement should still be significant and test the change of sign of the Sivers function in Drell-Yan as compared to SIDIS. This sign reversal is a clean prediction of QCD. It is related to the gauge links which are needed in the theory to guarantee gauge invariance and it is also expected for the T-odd Boer-Mulders function, which appears in the amplitude of a different azimuthal modulation measurable from the same data. In addition to the measurement of the structure functions entering in the unpolarised and single polarised Drell-Yan cross-section, other interesting measurements can be performed in parallel, like those to address the " $J/\Psi$  - Drell-Yan duality".

To test the feasibility of the Drell-Yan measurements in the COMPASS environment, short test beam measurements took place in 2007 and in 2008. The main goal of the tests was to check the detector occupancy and the radiation level, a major issue because of the location of the experiment at the ground level. The tests gave encouraging results and indications that the problems related with the high beam flux and interaction rate can be solved. Also, a  $J/\Psi$  signal has been seen in the data collected in those few days, with a number of events in agreement with the expected one. In the third test beam period which will take place in 2009 a prototype of the hadron absorber will be installed, and the radiation level measured at many locations.

Since the required modifications to the experimental set-up are small, the measurement of transverse spin effects in  $\pi^- p^{\uparrow} \rightarrow \mu^+ \mu^- X$  could be performed soon. In a second phase, the measurement of the Drell-Yan processes in  $\bar{p}p^{\uparrow}$  and  $Kp^{\uparrow}$  interactions are envisaged, assuming that adequate beams will be available.

### 5 Conclusions

The COMPASS experiment is giving an important contribution to the study of the transverse spin and transverse momentum structure of the nucleon with the measurement of SIDIS off transversely polarised targets. This contribution will continue in the future, with the 2010 run dedicated to the measurement of SIDIS off transversely polarised protons. The measurement of transverse spin effects in single polarised Drell-Yan is a promising tool to further investigate the nucleon structure in a complementary channel, and it is included in the medium term plans of the COMPASS Collaboration. In the more distant future, new facilities should be available to study the nucleon structure, but, depending on the time line of those projects, further measurements at CERN could also be needed.

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