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Executive summary

As outlined in the proposal for the ongoing COMPASS-II programme, the research fields of hadron spectroscopy and hadron structure are closely connected since their very beginnings, leading to the establishment of Quantum Chromodynamics (QCD) of quarks and gluons as the theory of strong interactions. It explains the observed weakening of the interquark forces at short distances or large momentum transfers. QCD not only describes hard processes through perturbative expansions, but also the non-perturbative dynamics of the strong interaction, down to soft and extremely soft processes which are involved in meson spectroscopy and linked to chiral perturbation theory. Also the finite extension of the hadrons, as encoded in the nucleon form factors, is connected to their inner dynamics and thus a decisive test field for QCD.

The COMPASS-II proposal covers three important processes in that context, namely deeply-virtual Compton scattering, Drell-Yan dimuon production off a polarised target, and Primakoff reactions on nuclei giving access to soft pion-photon reactions. This programme is foreseen to be completed in the end of the year 2018, after the second year of data taking for polarised Drell-Yan processes, before the long shutdown period LS2 in 2019 and 2020.

The impressive scientific output of COMPASS and COMPASS-II and the rapid progress in the fields of our investigation make us consider various future scenarios where we could again make important contributions, further exploiting the capabilities of the M2 beam line and of an upgraded spectrometer. They are currently being collected in a Letter of Intent that is planned to be submitted end of this year. It will contain, beyond the usage of the conventional, by now available beams, longer-term perspectives with radiofrequency-separated (kaon) beams, with a physics programme of about 10 years, and is worked out within the CERN Physics Beyond Colliders initiative.

Since the CERN Research Board has approved in the memorandum DG-Dr-RCS-2017-093 an early post-LS2 fixed-target programme and running, the COMPASS-II collaboration has decided to propose two physics cases of the future programme, as an addendum to the ongoing programme for data taking immediately after LS2.

The first program, semi-inclusive DIS on transversely polarized deuterons, is the "missing piece" in the COMPASS data sets on transverse target spin orientations. In 2010, a dedicated run was taken on a transversely polarised proton (NH3) target, which provided pioneering and unique information on transversity and Sivers functions, underlining the importance of transverse spin in the QCD structure of the nucleon and the correctness of conjectures put forward 25 years ago. On the contrary we provided only a marginal (albeit unique) data set for the isoscalar deuteron target. The older data have been taken only for short periods in the first years of COMPASS running and with the low-aperture SMC target magnet so that the statistical uncertainties of the deuteron transverse spin asymmetries are considerably larger than those of the corresponding proton asymmetries. With one additional year of data taking, which is proposed here, the statistical error of the deuteron measurements will be 0.6 times smaller than those of the corresponding proton data in all the x bins, allowing accurate flavour separation for the new functions and measurements which will stay unique for many years to come.

The second program, elastic muon-proton scattering, represents a new physics case for COMPASS. It was recognized recently that in the context of the currently debated "proton radius puzzle", high-energy muon-proton elastic scattering is a decisive experimental method that is complementary, in part even superior to the manifold of other

proposed or ongoing experiments. With a dedicated hydrogen gas target to be contributed by the St. Petersburg group, who has developed a similar target for an experiment with electron beams at Mainz, COMPASS-II is seen to be the ideal – in fact the only – place to realize this experiment with multi-GeV muon beams. This very appealing perspective includes the incorporation of some new equipment, and also necessitates new developments regarding the readout of the detectors, such that some testing will be indispensable.
In view of these preliminaries, the following running schedule is proposed:

2021 soon after LS2: one year [1] of semi-inclusive DIS data taking with the transversely polarised deuteron target, and at an early stage test measurements for the proton radius measurement

2022: one year of data taking for the proton radius measurement (under the condition of a successful testing phase in 2021)

[1] by one year of data taking we intend 150 days of data taking with 2.5×10^{13} protons delivered to the T6 target of the M2 beam line every 40.8 s. With an accelerator chain efficiency of 90% 6.1×10^{18} protons at T6 are expected.

1 Measurement of semi-inclusive deep inelastic scattering off transversely polarised deuterons

1.1 Introduction

In collinear QCD, when the transverse momentum of the partons is neglected, three parton distribution functions (PDFs) fully describe the nucleon at the twist-two level: the momentum distributions $f_1^q(x)$, the helicity distributions $g_1^q(x)$ and the transversity distributions [1] $h_1^q(x)$, where x is the Bjorken variable. On the other hand, evidence for a sizable transverse momentum of quarks was provided from the measured azimuthal asymmetries of hadrons produced in unpolarised semi-inclusive deep inelastic scattering (SIDIS) and of the lepton pairs produced in Drell-Yan (DY) processes. Taking into account a finite intrinsic transverse momentum k_T, in total eight transverse momentum dependent (TMD) distribution functions are required to fully describe the nucleon at leading twist [2, 3, 4]. Since transverse spin couples naturally to intrinsic transverse momentum, the resulting correlations are encoded in various TMD PDFs. Presently, PDFs that describe non-perturbative properties of hadrons are not calculable in QCD from first principles, but their first moments can already be computed in lattice QCD. In the SIDIS cross-section they appear convoluted with fragmentation functions (FFs) [5, 6], so that they can be extracted from the data.

Particularly interesting is therefore the measurement of the SIDIS cross-section when the target nucleon is transversely polarized. In this case 8 (5 in case of unpolarised lepton beam) different spin-dependent azimuthal modulations are expected, from which information on the TMD PDFs can be extracted [2)]. In this domain the HERMES and the COMPASS collaborations have performed pioneering measurements and shown beyond any possible doubt the correctness of three most interesting recent conjectures:

- The Sivers function: in a nucleon that is polarized transversely to its momentum the quark distribution is not left-right symmetric with respect to the plane defined by the directions of the nucleon spin and momentum. This asymmetry of the distribution function is called the Sivers effect, and the asymmetric function is known as the Sivers PDF [8].
- The Transversity function: the quarks in a transversely polarized nucleon are transversely polarized. Their polarization is described by the h_1 PDFs which a priori are different and have different properties from the helicity PDFs.
- The Collins function: the hadronization of a transversely polarized quark is not left-right symmetric with respect to the plane defined by the direction of the quark momentum and the quark spin [9]. This fact has been confirmed by the e^+e^- measurements at Belle, BeBar and BES and has been exploited to measure the quark transverse polarization in a transversely polarized nucleon, namely the quark transversity PDF.

These effects represent novel and unexpected features, and one still believes that they might explain the very large transverse spin asymmetries observed since more than 40 years in hadron-hadron scattering.

The non zero results for the Collins and the Sivers asymmetries were obtained on proton targets. COMPASS has also measured transverse spin asymmetries using a deuteron target [10]. The accuracy of the data is definitely inferior to that of the proton data, and all the results are compatible with zero, hinting at a possible cancellation

[2)] For a review of the notation we refer to the Appendix A of the memo CERN-SPSC-2009-025 SPSC-M-769, SPSLC-P-297 Add.2 [7], which for completeness is also added to this document as section 1.6.

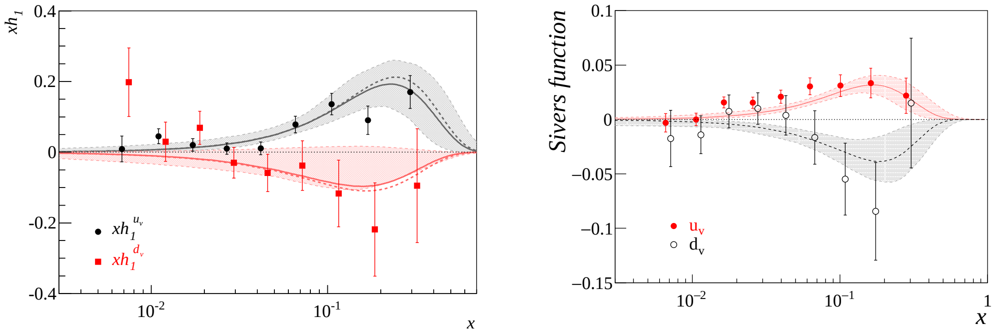

Figure 1: The transversity and Sivers PDFs extracted point-by-point using the existing COMPASS p and d data from Ref. [13, 14]. The curves are the results of fits to the COMPASS and HERMES data and, for transversity, to the Belle data. Note that the uncertainty band for the d-quark transversity would be larger if the Soffer bound was not imposed.

between u and d quarks contributions. More recently data have been collected at much lower energy at JLab on a ^{3}He target, essentially a transversely polarized neutron target: the measured asymmetries [11, 12] are also compatible with zero, but the error bars are fairly large. The COMPASS data are still today the only SIDIS data ever taken on a transversely polarised deuteron target, they are necessary to flavour separate the PDFs, and provide constraints on the d-quark contribution.

From the present data several extractions of the transversity and of the Sivers PDFs have been performed. As an example Fig. 1 shows the results of the point-by-point extractions of the transversity and the Sivers PDFs using all the existing COMPASS p and d data [13, 14] compared to the extractions done using also the HERMES data [15, 16]. More recent extractions [17, 18] did not improved substantially the picture. It is immediately apparent that the accuracy of the d-quark PDFs is considerably inferior to that of the u-quark because of the bad quality of the existing d data and this is the straightforward motivation for this proposal.

We propose to perform a standard one-year (150 days) measurement scattering the M2 muon beam at 160 GeV/c momentum on a transversely polarized deuteron target, as soon as the LS2 will be over, using the COMPASS spectrometer. The polarized target system is being reassembled at the end of the DVCS/SIDIS run, this fall, it will be used for the Drell-Yan run of 2018, and will stay installed in Hall 888 for this new measurement.

Due to the late delivery of the COMPASS polarized target magnet, this precise measurement could not be carried through in the early years of data taking when the low statistics sample was collected. It is a matter of fact, however, that the knowledge gained in the last few years thanks also to the SIDIS results has by now made the physics case very clear and strong, and we regard this measurement as necessary to complete the exploratory COMPASS programme on the transverse spin nucleon structure.

The new SIDIS asymmetry data, combined with the good precision HERMES and COMPASS proton data, and with the future high precision JLab12 data, will allow u and d distribution functions to be extracted with comparable accuracy. The future EIC will possibly superseed the existing and the proposed measurements, but the new COMPASS contribution will stay there for several years.

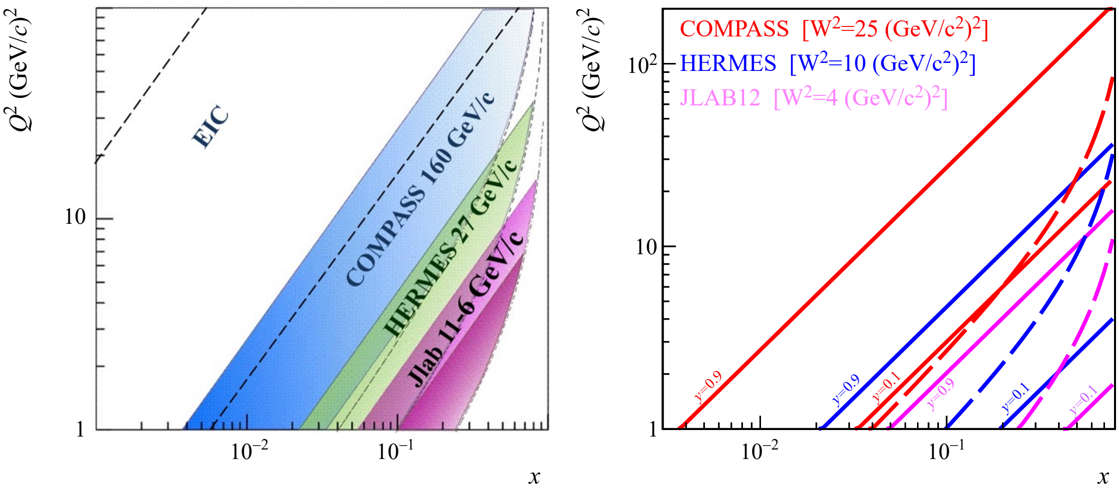

Figure 2: The $x - Q^2$ scatter plot for SIDIS experiments HERMES, COMPASS and JLab12. Left: also indicated are the ($\sqrt{s}$ = 140 GeV , $y = 0.9$) and ($\sqrt{s}$ = 40 GeV, $y = 0.1$) borders for a future EIC. Only the kinematics's ranges are drawn, independently of the luminosity and of the years needed to perform the measurements. Right: the full lines indicate the $y = 0.1$ and $y = 0.9$ boundaries for the three experiments, the dashed lines the corresponding W^2 values.

1.2 The case for muon scattering on transversely polarized deuterons

High energy muon scattering on transversely polarized deuterons will provide in a standard 150 days run a wealth of data and complement the data sample collected in 2007 and 2010 on transversely polarized protons.

The new data will provide large Q^2 results in the x-range covered by JLab12, which is very important to evaluate the size of the Q^2 evolution, and will provide lower-x data (down to $x = 0.003$) which are essential both to perform the integrals necessary to evaluate the tensor charges and to estimate the TMD PDFs of the sea quarks. The phase space covered by the different experiments is shown in Fig. 2. Clearly the experiment we propose is unique and complementary to the JLab12 experiments. In the longer term the planned Electron Ion Collider (EIC) has the potential to carry on a very good program scattering at high $\sqrt{s}$ electrons on transversely polarized protons, but its start is not yet well defined in time, and colliding polarized deuterons is not in the core program: a deuteron measurement st CERN has a considerable chance of staying as an important and unique result for a couple of decades.

The case for the Collins asymmetry will be detailed in the next section. Here we will summarize some of the other measurements which will be performed in parallel using the new deuteron data. Very much as for the Collins asymmetry, all the target transverse spin asymmetries (TSA) are expected to be measured with a statistical uncertainty equal to 0.62 times the statistical uncertainties of the corresponding asymmetries measured in the 2010 proton run which we use as a reference.

1.2.1 The two hadron asymmetries

The transverse polarization of a fragmenting quark can also be assessed from the azimuthal modulation of the plane containing two oppositely charged hadrons of the jet. This di-hadron asymmetry can be expressed as the product of the quark transversity distribution and a chiral-odd di-hadron FF, $H_1^{\sphericalangle}$, which survives after integration over the two hadron momenta, and thus can be analyzed in the framework of collinear factorization. The high energy of the beam and the large acceptance of the COMPASS spectrometer have allowed us to collect in 2010 a large sample of (oppositely charged) hadron pairs. From the measured di-hadron asymmetries and from corresponding Belle data fairly precise estimates of the u-quark transversity distribution could be obtained [13, 19], while the d-quark extraction has considerably larger uncertainties, very much as for the Collins asymmetry case. Also, a unique and original comparison between the single-hadron Collins asymmetry and the di-hadron asymmetry could be performed [20, 21]. The conclusion of this investigation was that both the single hadron and the di-hadron transverse-spin dependent fragmentation functions are driven by the same elementary mechanism, which is very well described in the $^3P_0$ recursive string fragmentation model [22, 23]. A corresponding analysis with the deuteron data was not possible because of the particularly small statistics of the two hadron data sample due to the use of the small acceptance PT magnet used in the first three years of COMPASS running. The new deuteron data therefore will provide more information both on the transversity PDFs and on the di-hadron FF.

1.2.2 The Sivers function

As underlined in Ref. [14], and clear from fig. 1, the d_v Sivers function is poorly determined from the present data, in spite of the fact that it should be constrained by the PID of the final state hadrons. Moreover, the Sivers asymmetry exhibits strong kinematic dependencies [24] which are not easy to be explained. For these reasons, the new deuteron data are badly needed and will allow to measure the Sivers asymmetries with a statistical error 0.62 times smaller than that of the existing COMPASS proton data, very much as in the Collins case.

The assessment of a non-zero Sivers function for the quarks and its possible connection with the orbital angular momentum have stimulated a great interest on a possible non-vanishing Sivers function for the gluon and considerable further theoretical work (see f.i. [25]). A recent analysis of proton-proton data at RHIC has not evidenced a signal [26]. However, an analysis of all the COMPASS data has provided some indication that the gluon Sivers function might be different from zero [27]. The accuracy of the existing deuteron data is worse by a factor of about 2 than that of the proton data and the new data would allow to have a measurement of the gluon Sivers asymmetry with a statistical uncertainty of 0.05, to be compared with the present uncertainty of 0.08.

In a similar analysis the Sivers asymmetry for the J/Ψ has also been determined, which in some models it is related to the gluon Sivers asymmetry [28]. That analysis can also be repeated and improved with the new deuteron data.

1.2.3 The g_2 structure function

In the naive parton model g_2 is expected to be zero, thus its measurement provides information on the quark-gluon interaction. In COMPASS we have started an analysis to extract g_2 from the 2010 proton data, which will be repeated with the new deuteron data. After standard cuts we have slightly more than 10^8 DIS events. Compared to previous measurements done by SLAC on proton and deuteron (E142, E143, E154 and E155) and by HERMES (proton), COMPASS explores a larger kinematic range accessing also the essentially unknown low-x region ($0.003 < x < 0.05$). So far the efforts are concentrated on the extraction of the g_2-related inclusive asymmetry, $A_T^{cos\phi_S}$ (where the angle ϕ_S is defined in the $\gamma^* N$-system as the azimuthal angle between the lepton scattering plane and the target spin direction) and the virtual photon-absorption asymmetry A_2. The estimated statistical uncertainties of the $A_T^{cos\phi_S}$ asymmetry in the different kinematic bins are comparable with the corresponding uncertainties of the Sivers asymmetries extracted from the 2010 proton SIDIS sample.

It is interesting to note that, from constraints imposed by Lorentz invariance relations, g_2 is expected to be linked to the first k_T-moment of the g_{1T} TMD PDF which is being accessed in SIDIS through the measurement of $A_{LT}^{cos(\phi_h-\phi_S)}$ asymmetry. This is yet an other effect we plan to address with the deuteron measurement and another piece of information that can be acquired.

1.2.4 Other SIDIS measurements

COMPASS has performed a multidimensional extraction of the whole set of target transverse spin dependent azimuthal asymmetries using the proton data collected in 2010 [29]. Various multi-differential configurations have been tested exploring the $x - Q^2 - z - p_T$ phase-space. Very interesting correlations have been noticed in particular for the Sivers function. This analysis was not possible with the existing deuteron data, and will be done with the new data.

Finally, COMPASS has recently extracted the "p_T-weighted" Sivers asymmetries from the 2010 proton data [30]. These results allow to directly derive the first moment of the Sivers function [31]. Also this analysis which could not be done with the existing deuteron data, will be performed on the new data set.

1.2.5 Exclusive vector meson production

In exclusive vector meson production COMPASS has produced several interesting results. In a first paper [32] we published the transverse target spin azimuthal asymmetry $A_{UT}^{\sin(\phi-\phi_S)}$ in hard exclusive production of ρ^0 mesons which we measured both on transversely polarized protons and deuterons. The measured asymmetry is sensitive to the nucleon helicity-flip generalized parton distributions E_q, which are related to the orbital angular momentum of quarks in the nucleon. A second publication [33] used the high statistics proton data collected in 2010, and presented results for all 8 possible transverse target spin asymmetries. In particular a specific combination of two of these asymmetries indicates a signal from the so called "transversity GPD" (i.e. GPD with the helicity flip of exchanged quark). Concerning deuterons, only the results on the $A_{UT}^{\sin(\phi-\phi_S)}$ asymmetry are published [32], due to the poor statistics of the existing deuteron COMPASS data. Given the expected small contribution of the gluons and sea quarks [34] very much as for the SIDIS case, a combined analysis of both proton and deuteron data is necessary to disentangle the u and d quark GPDs, thus new accurate deuteron data are essential to carry through this analysis. In parallel, the exclusive production of ω will also be measured. The cross-section is smaller by about a factor 10 than for ρ^0 mesons and the detection of the two photons further reduces the ω event sample with respect to the ρ^0, but a combined analysis of ρ^0 and ω mesons provide strong constrains in disentangling the u and d quark contributions.

1.3 The case for transversity

In this section the impact of the new deuteron measurement for the Collins asymmetry and for the extraction of transversity for the u and d quarks will be detailed. The measurement of the transversity distributions, which are defined in terms of the nucleon

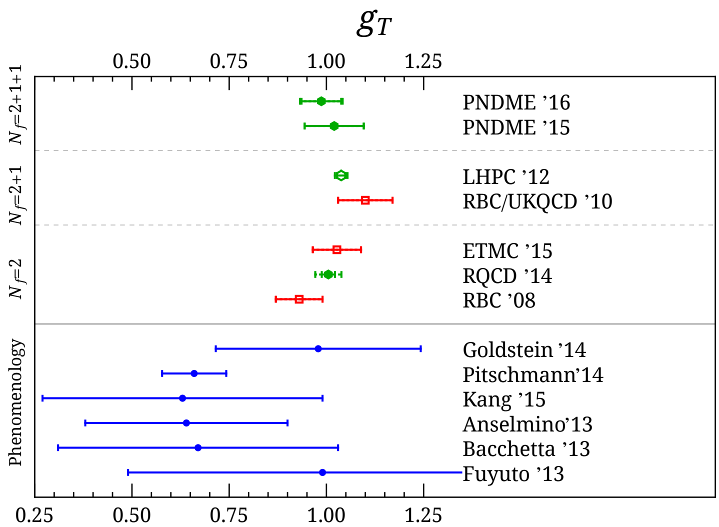

Figure 3: A summary plot showing the current estimates of g_T^{u-d} from Ref. [36].

matrix element of the quark tensor current, is particularly important because it provides access to the tensor charges δq, which are given by the integral

$$\delta q(Q^2) = \int_0^1 dx[h_1^q(x, Q^2) - h_1^{\bar{q}}(x, Q^2)] \tag{1}$$

In a non-relativistic quark model, h_1^q is equal to g_1^q, and δq is equal to the valence quark contribution to the nucleon spin. The difference between h_1^q and g_1^q provides important constraints to any model of the nucleon. Knowing the quark tensor charges one can construct the isovector nucleon tensor charge $g_T = \delta u - \delta d$, a fundamental property of the nucleon which, together with the vector and axial charge, characterizes the nucleon as a whole. Since many years the tensor charge is being calculated with steadily increasing accuracy by lattice QCD [35]. More recently, its connection with possible novel tensor interactions at the TeV scale in neutron and nuclear β-decays and its possible contribution to the neutron electric dipole moment (EDM) have also been investigated [36], and possible constraints on new physics beyond the standard model have also been derived [37].

The present knowledge on g_T is well summarized in Fig. 3, from Ref. [36]. The huge difference between the accuracy of the extractions from the existing data and from the QCD lattice simulations is striking and more experimental data are needed. When evaluating the tensor charge from the transversity data h_1^u and h_1^d have the same weight, so they must be known with a comparable accuracy. In SIDIS off protons, because of the opposite sign of the favored and unfavored Collins FF, the Collins asymmetries of positive and negative pions depend almost on the same linear combination of h_1^u and h_1^d, with weights 4 and 1, so basically to first approximation it is impossible to precisely extract the d-quark transversity without deuteron (or neutron) data. This means that

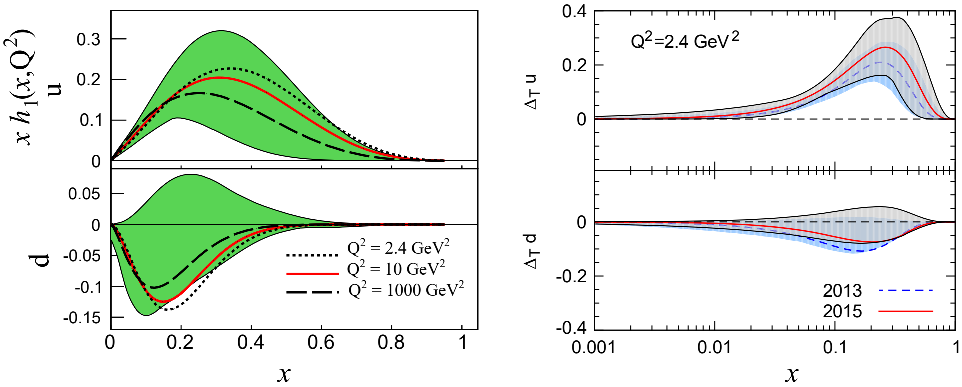

Figure 4: The u and d quark transversity PDFs from recent global fits. The plots are from Ref. [17] (left) and from Ref. [18] (right).

most of the present uncertainty in the tensor charge are due to the poor accuracy of the deuteron data, and that remeasuring the deuteron is a priority issue.

In Fig. 1 we have shown the point-by-point extraction of the u- and d- transversity PDF of Ref. [13] which clearly indicates the inadequacy of the existing data to extract h_1^d. This is the case even for the most recent extractions, which utilize all existing SIDIS data (from COMPASS, HERMES and JLab) and the constraints given by the Soffer bound. Two very recent extractions, from Ref. [17] and from Ref. [18], are shown in Fig. 4, and both give the same message, that new accurate SIDIS data on the deuteron are necessary to improve on the d-quark transversity.

In the near future the only planned and approved experiments will run at JLab12 [38, 39], with both proton and neutron targets, and very good statistics, but only in the region $x > 0.05$ and at relatively small Q^2. The main objective of our proposal is to measure from $x = 0.3$ down to 0.003 and at larger Q^2, improving the accuracy of the extraction of h_1^d and improving also the precision of h_1^u as will be shown in the next sections.

1.3.1 Present COMPASS data and extrapolated errors

The transversity PDF is chiral-odd and thus not directly observable in inclusive deep inelastic lepton-nucleon scattering. In 1993 Collins suggested [9] that it could be measured in SIDIS processes, where it appears coupled with another chiral-odd function, which by now is known as "Collins fragmentation function" $H_{1q}^{\perp h}$. It is the chiral-odd transverse-spin dependent FF that describes the correlation of quark (q) transverse polarization and hadron (h) transverse momentum. This mechanism leads to a left-right asymmetry in the distribution of hadrons produced in the fragmentation of transversely polarized quarks, which in SIDIS shows up as an azimuthal transverse spin asymmetry A_{Coll} (the "Collins asymmetry") in the distribution of produced hadrons. At leading order this asymmetry can be written as

$$A_{Coll} = \frac{\sum_{q,\bar{q}} e_q^2 x h_1^q \otimes H_{1q}^{\perp}}{\sum_{q,\bar{q}} e_q^2 x f_1^q \otimes D_{1q}} \qquad (2)$$

where the sum is over all (anti)quark flavours, D_q^h is the usual FF and $\otimes$ indicates the convolutions (different for numerator and denominator) over the intrinsic transverse momenta. The Collins effect shows up as a modulation $[1 + a_C \sin(\phi_h + \phi_S - \pi)]$ in the hadron

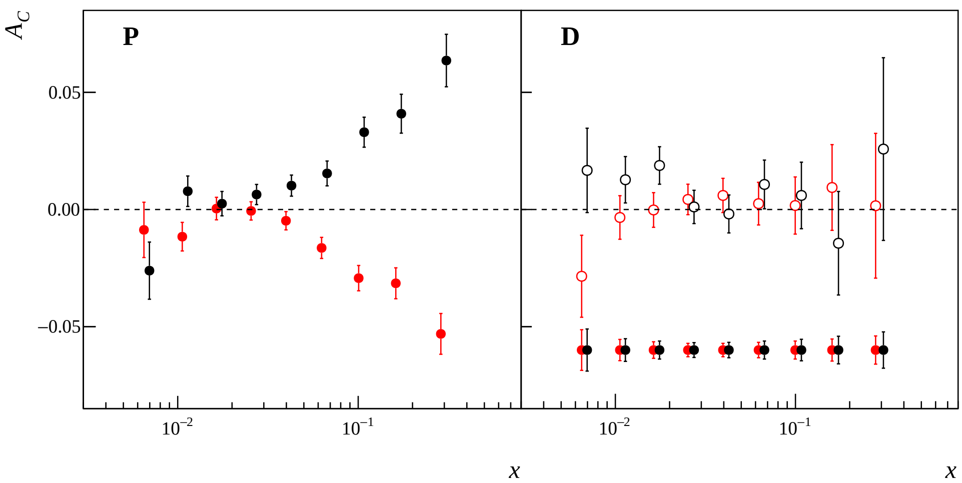

Figure 5: A_{Coll} obtained from the 2010 data with the polarized proton NH_3 target as a function of x (left plot) compared to the results we obtained [10] from the runs of 2002, 2003 and 2004 with polarised deuteron ^{6}LiD target (right plots). The red (black) points refer to positive (negative) hadrons. The full points at -0.06 in the right plot show the extrapolated statistical error from the proposed deuteron run.

azimuthal distribution. Here $\Phi_C = \phi_h + \phi_S - \pi$ is the Collins angle, and ϕ_h and ϕ_S are the azimuthal angles of the hadron transverse momentum $\boldsymbol{P}_{hT}$ and of the spin direction of the target nucleon with respect to the lepton scattering plane, in a reference system in which the z axis is the virtual-photon direction. The amplitude of the modulation is $a_C = D_{NN} f P A_{Coll}$, where D_{NN} is the transverse spin transfer coefficient from target quark to struck quark, f the dilution factor of the target material, and P is the proton (or deuteron) polarization. In Fig. 5 the results [40] for A_{Coll} we have obtained from the 2010 data collected using as target NH_3, a polarized proton target, are shown as a function of x (left panel) and compared to the results we obtained [10] from the deuteron runs of 2002, 2003, and 2004, when as target we used ^{6}LiD (right panel).

It is clear that the accuracy of the data is considerably better for the proton target, in particular at large x, where the Collins asymmetry is large. In order to quantify this fact, it is instructive to look at the ratio of the errors, shown in Fig. 6 as a function of x. In order to understand this plot, one has to remind that, for small asymmetries, the statistical error is given by

$$\sigma_A \simeq \frac{1}{fP}\frac{1}{\sqrt{N}} = \frac{1}{FOM}\frac{1}{\sqrt{N}} \tag{3}$$

where N is the total number of hadrons and FOM is the figure of merit of the polarised target. Using $N_{d,h} = 15.5 \cdot 10^6$ and $N_{p,h} = 80 \cdot 10^6$ for the number of hadrons collected on p and d, and the known FOM values for the two targets, one gets

$$\frac{\sigma_{A_d}}{\sigma_{A_p}} = \frac{0.155 \cdot 0.80}{0.40 \cdot 0.50}\frac{\sqrt{80}}{\sqrt{15.5}} = 0.62 \cdot 2.3 = 1.4, \tag{4}$$

in the hypothesis that the spectrometer acceptance was the same for the proton and the deuteron runs. As a remark, it is interesting to note that in the ratio 4 the better FOM of the deuteron target partly compensates the factor of 5 in statistics in favor of the proton target run. In Fig. 6, at small x, where statistics is largest, the ratio between the statistical

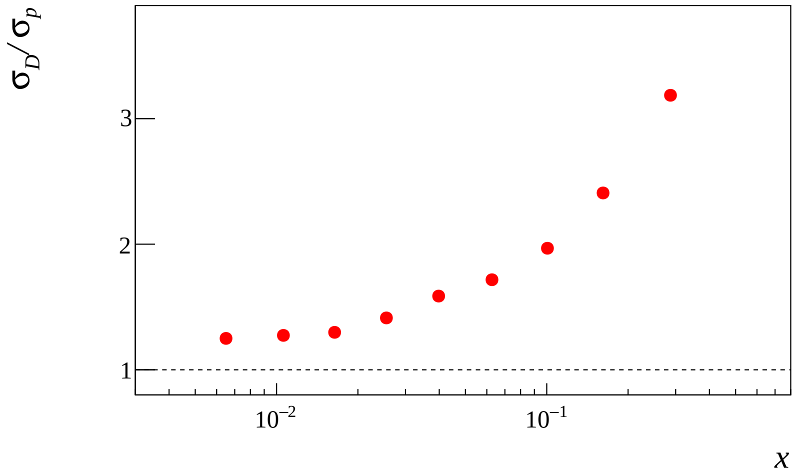

Figure 6: Ratio of the A_{Coll} statistical uncertainties on deuteron and proton as measured by COMPASS.

uncertainties of the deuteron and the proton asymmetries is constant, an indication of the fact that the spectrometer acceptance was essentially the same at small x in the two data taking. The measured value of the ratio is 1.25, which indeed is close to the expected value of 1.4. The 10% difference is due to the fact that the polarised target cells diameter in the deuteron runs was 3 cm while for the proton runs it was 4 cm, which resulted in a 20% larger muon beam acceptance in the proton runs. Our plan is to run in 2021 with 4 cm target cells diameter as long as enough 6LiD material will be available.

The most important information provided by Fig. 6 is however the dramatic increase of the ratio with x. This increase is due to the fact that there is a huge difference between the acceptance of the COMPASS P_T magnet utilized for the proton run and the SMC PT magnet in operation in 2002-2003-2004 for the measurements with the ^{6}LiD target. The COMPASS magnet has a polar acceptance of 200 mrad (as seen from the upstream end of the target) while the SMC magnet has a corresponding polar angle acceptance of 70 mrad. A reduced acceptance in scattering angle mainly translates into a reduced acceptance at large x-Bjorken, thus Fig. 6 essentially gives the square root of the ratio of the two acceptances as a function of x.

1.3.2 Projected errors after 1 year of deuteron run

Since target density and packing factors are essentially identical for ^{6}LiD and NH_3, it can be safely assumed that in one year of deuteron run in the conditions of the 2010 proton run $80 \cdot 10^6$ "good" events will be collected, so that the errors on the new deuteron asymmetries will be equal to the present errors for the 2010 proton asymmetries scaled by the ratio of the FOM, namely they will be smaller by a factor of 0.62. The projected errors for the deuteron asymmetries are also plotted in Fig. 5, together with the existing results for the deuteron and proton asymmetries. We neglect the systematic errors which were estimated to be at most 0.5 times the statistical errors in the 2010 data.

Using the 2010 proton data and the projections of Fig. 5 for the statistical errors of the new deuteron data we have extracted the u- and d-quark transversity, in order to quantify the gain in statistical error in these fundamental PDFs. To carry through this evaluation we have followed the procedure of Ref. [13], for a point by point extraction of transversity directly from the measured SIDIS and $e^+e^- \to hadrons$ asymmetries.

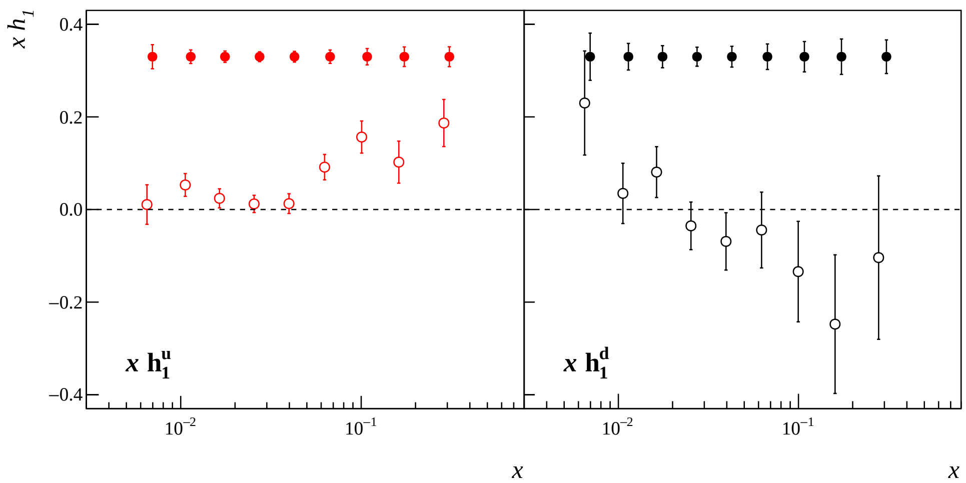

Figure 7: Values of u_v-quark (left) and d_v-quark (right) transversity extracted from the existing p and d data (open points), and the corresponding error bars estimated using the existing p data and the new d data (closed points).

The big advantage of this method is that

- it is simple, it avoids the use of parametrizations for the unknown functions, and the PDFs are calculated algebraically from the asymmetries

but

- it requires asymmetry measurements (p, d or n, identified final state particles) performed at the same x-values and in the same kinematic ranges.

This second point is the reason why we could not utilize all the available data (i.e. the HERMES measurements). A comparison between Fig. 1 and Fig. 3 however shows that the two procedures, i.e using the COMPASS data alone and the point-to-point extraction method, or doing a global analysis on all the existing data, give similar results. Therefore we leave the more complete and global approach to the specialized colleagues and present the result we obtained with the simplified analysis, which is already quite adequate to our purposes. The results are given in Fig. 7, which shows both the values of transversity (open points) extracted from the existing p and d data, and the corresponding error bars (closed points) estimated using the existing p data and the d data, with the projected errors of the new measurement. The impact of the proposed measurement is clearly quantified in fig. 8, which gives the ratio, at each x value, of the present and projected errors on the extracted transversity PDFs. The gain in precision for the d-quark ranges from a factor of 2 at small x to a factor of 5 at large x, and is also important for the u-quark.

1.3.3 Projections for the tensor charge

In order to evaluate the impact of the proposed measurement on the statistical accuracy of the tensor charge one can introduce a functional dependence for h_1^q, to be fixed by fitting the point-to-point extracted values of $xh_1^{u_v}$ and $xh_1^{d_v}$ from the COMPASS data and then integrating the curves over the measured x-range. We neglect the Q^2 dependence of h_1 and take

$$xh_1^q(x) = a_q x^{b_q}(1-x)^{c_q}. \tag{5}$$

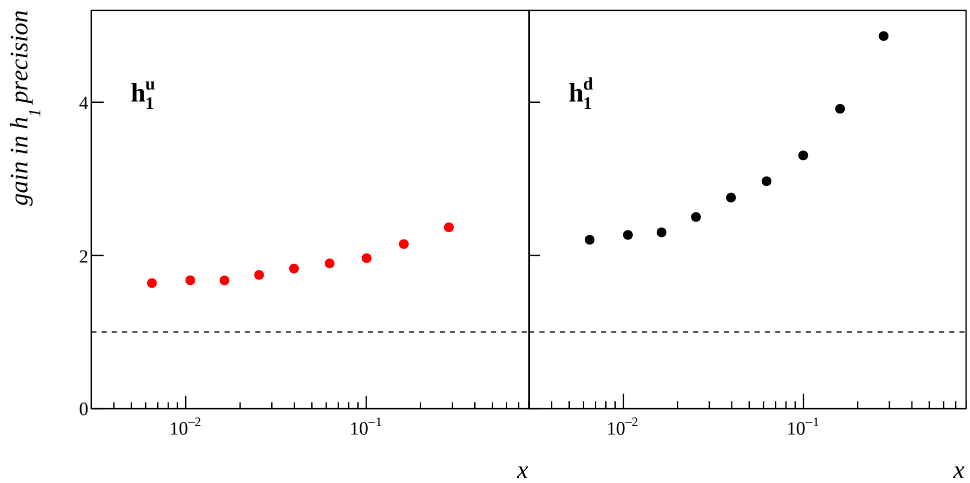

Figure 8: Ratio of the existing uncertainties on the extracted transversity and the projected uncertainties for u_v-quark (left) and d_v-quark (right).

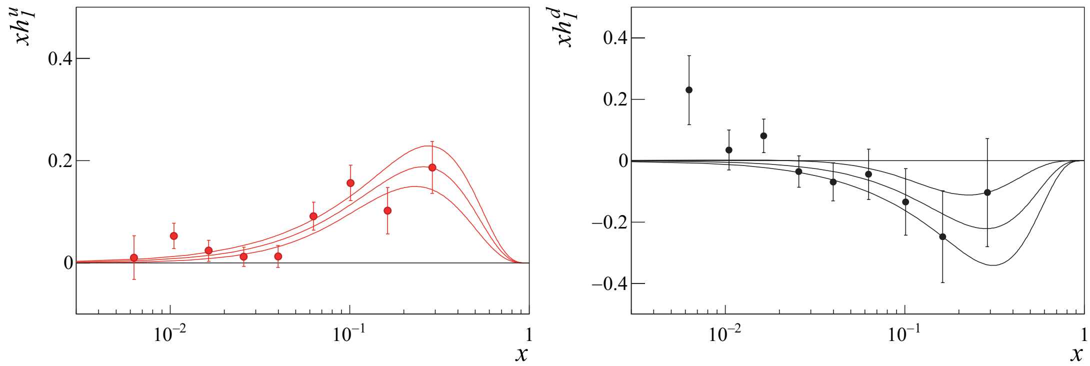

Figure 9: Extracted values of the valence quark transversity distributions $xh_1^{u_v}$ and $xh_1^{d_v}$ [13] with the curves from the fits with the 1σ uncertainty band indicated.

Unfortunately, the present statistical accuracy on xh_1^q with $q = u_v, d_v$ does not allow to safely determine all the parameters a_q, b_q and c_q and in particular their covariance matrix, needed for this exercise. We thus assumed $c_q = 4$, as suggested by the central values given by the fit. For the remaining two free parameters we get

$$a_{u_v} = 3.5 \pm 1.6,\ b_{u_v} = 1.3 \pm 0.2,\ ; a_{d_v} = -5.2 \pm 5.3,\ b_{d_v} = 1.5 \pm 0.5\,. \quad (6)$$

The comparisons between the fitted $xh_1^{u_v}$ and $xh_1^{d_v}$ and the extracted transversity values are shown in Fig. 9, together with the 68% uncertainty bands.

To estimate the impact of the proposed measurement on the extraction of the tensor charge, the curves have been numerically integrated in the range $0.003 < x < 0.21$. The integrated range excludes the last measured x bin, in order to not overlap with the future precise data from JLab12. The exercise has been done twice, the first time assigning to the quark transversity values the errors obtained from the extraction of Ref. [13], shown in Fig. 8, and a second time, reducing the errors by the estimated ratios as given in Fig. 7. Needless to say, the purpose of this exercise is not to give absolute values for the uncertainties on the extractions of the u- and d-quark tensor charges, but only to show the reduction in the statistical error obtained with the new run as compared to the present situation. The results are given in Table 1 together with the corresponding values

Table 1: Integrated values of h_1 and result for g_T from the fits with the present and the projected uncertainties.

	$0.003 < x < 0.21$		
errors	$\int dx h_1^{u_v}(x)$	$\int dx h_1^{d_v}(x)$	g_T
present	0.255 ± 0.043	-0.202 ± 0.112	0.45 ± 0.12
projected	0.211 ± 0.027	-0.212 ± 0.042	0.423 ± 0.050
	$0 < x < 1$		
present	0.59 ± 0.13	-0.61 ± 0.35	1.20 ± 0.37
projected	0.587 ± 0.077	-0.585 ± 0.119	1.172 ± 0.142

of $g_T = \int dx h_1^{u_v}(x) - \int dx h_1^{u_v}(x)$. In the range where we measure ($0.003 < x < 0.21$) the errors become a factor of 2.5 smaller. While the evaluation of the d-quark tensor charge presently has small statistical significance, the new measurement should provide an almost 5σ effect with respect to the presently estimated value, and the extraction of g_T in the x-interval in which COMPASS can measure has a small uncertainty. Only for completeness we have integrated the fitted functions also in the entire domain $0 < x < 1$, to give an idea of the contribution that COMPASS can give to the determination of the tensor charge. Again this estimates are meant only to propagate the statistical uncertainties from the measured PDF to the integrated tensor charges in order to evaluate the impact of the new data, and not to give a value for the tensor charge itself.

We are well aware that making use of a parametrizations for the transversity functions introduces a systematic uncertainty almost impossible to be estimated. This is a common problem with all global fits as clear from f.i. Ref. [41]. To avoid it, we have also estimated the quark tensor charges without any parametrization, integrating numerically the extracted transversity values, over the interval $0.003 < x < 0.13$, which corresponds to the first 7 values measured by COMPASS as a function of x. The data we will collect at $x > 0.13$ will be very important for a comparison with the future JLab data, both to assess compatibility and to investigate the Q^2 dependence. The data we will obtain in the range $0.003 < x < 0.13$ will on the contrary be unique, and they will allow an estimate of the value of the tensor charge in that range fully independent of any model. In this case the statistical errors become ± 0.027 for the u- tensor charge and ± 0.051 for the d-tensor charge, and ± 0.058 for g_T. If indeed SOLID will provide high accuracy measurements for $x > 0.1$ [42], so that the error on the integration in the range $0.13 < x < 1$ can be neglected with respect to the uncertainty of the integration in the COMPASS range, then the overall uncertainty on the tensor charge g_T will be the uncertainty of our future measurement.

To summarize, at large x, JLab will provide very accurate partial measurements for g_T. At smaller x ($0.003 < x < 0.1$) the COMPASS data will provide a contribution to g_T with an uncertainty of ± 0.06. Without the new deuteron data from COMPASS, the evaluation of the tensor charge from the future high precision JLab data would be affected by the error of the integration between 0 and 0.1 difficult to be ascertained, and the result will anyhow be model dependent. With the new COMPASS deuteron data, the uncertainty of the extrapolated contribution of the integration from 0 to 0.003 can reasonably be very small, and the uncertainty of the partial integration of the COMPASS data (± 0.06) will be the resulting uncertainty on the tensor charge g_T.

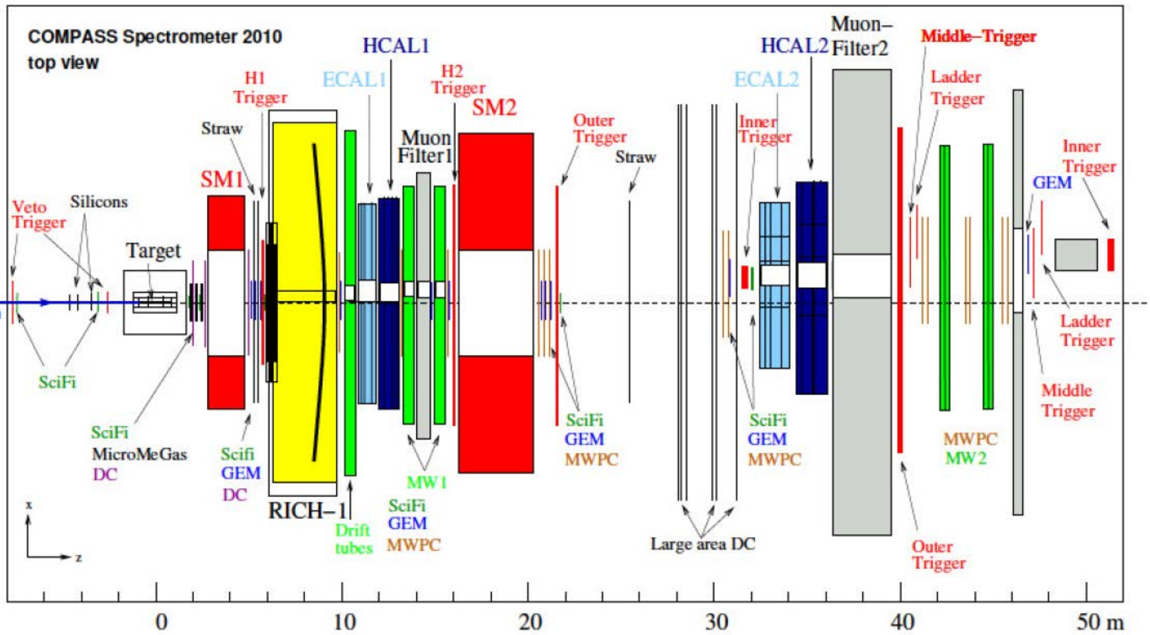

Figure 10: Schematic lay-out of the COMPASS spectrometer (top view) as it was used in 2010 and as it will be reassembled for the 2021 run.

1.4 Experimental Apparatus and Beam request

The apparatus to be used for the deuteron run is basically the COMPASS Spectrometer as it was used in the 2010 muon run, shown schematically in Fig. 10. This implies removing the absorber which will be used for the 2018 Drell-Yan run, moving the polarised target 2 m downstream to the position it had for the SIDIS runs, and reinstalling all the trackers and all the counters which were used in 2010. The polarized target will be housed in the large acceptance COMPASS PT magnet, and the target material will be the same which was used in the years 2002, 2003, 2004 and 2006, namely ^{6}LiD. For a better usage of the muon beam, the target cells diameter will be increased from 3 to 4 cm. The average polarization of the target is expected to be the same as in the past deuteron runs ($\leq 50\%$).

The beam request is the same as for the 2010 proton run, namely 2.5×10^{13} protons delivered to the T6 target of the M2 beam line every 40.8 s. With an accelerator chain efficiency of 90% and a running time of 150 days a total of 6.1×10^{18} protons at T6 is expected. This number of protons is the basis of all the projections presented in this document, which are obtained from the number of reconstructed hadrons in the 2010 run.

The estimated uncertainties have been obtained assuming the COMPASS spectrometer availability and efficiency to be the same as in the 2010 run, but several upgrades have already been implemented over the past years and more upgrades are foreseen for running after 2020. Tracking will profit of the addition of several trackers over the past ten years, in particular the new large area DC5, the pixelized GEMs and Micromegas and several scintillating fiber hodoscopes. At variance with the past deuteron runs, electromagnetic calorimetry will also be available (ECAL1 and ECAL2). Here we consider unidentified hadrons only, but as in 2010, particle identification will be provided by the RICH1 detector, for which the completion of the upgrade done for the 2016 run is foreseen. In addition some increase in the collected data is expected from hardware upgrades of the last years, in particular concerning the DAQ and trigger. Since no major upgrades of the present spectrometer are necessary for this measurement, it can start soon and take place in 2021.

1.5 Summary

We propose to improve our knowledge of the transverse spin structure of the nucleon by measuring 160 GeV muon semi inclusive DIS on a transversely polarized deuteron target. This measurement will complete the exploratory investigation of the transverse spin structure of the nucleon originally proposed by COMPASS 20 years ago. The measurement will be unique in the small x-Bjorken region, and complementary to corresponding measurements already approved at JLab. The proposed measurements will have a profound impact on the field, and their combination with the already taken proton data will allow to further clarify the properties of the up, down and sea quarks in the nucleon. Moreover, a combined analysis of the transversity measurement at CERN and at JLab will allow a determination of the isovector tensor charge with an accuracy of ± 0.06.

Quoting from our last proposal for a polarized SIDIS measurement [7], the high intensity and polarization of the muon beam together with the COMPASS polarized target and spectrometer make CERN a unique place to perform such measurement. This will not change until the construction of a high energy and luminosity polarized electron-ion collider in the longer term future".

1.6 TMD PDFs and SIDIS scattering (for ease of reference reproduced from [7], App. A)

The recent theoretical work on the nucleon structure points out the relevance of its transverse structure. A good knowledge of the transverse intrinsic momentum $\mathbf{k}_T$ carried by the partons and of its connection with the spin is needed to understand the parton orbital motion and to progress towards a more structured picture, beyond the collinear partonic representation.

In the QCD parton model, at leading twist, the nucleon structure is described by eight TMD PDFs: $f_1(x, \mathbf{k}_T^2)$, $g_{1L}(x, \mathbf{k}_T^2)$, $h_1(x, \mathbf{k}_T^2)$, $g_{1T}(x, \mathbf{k}_T^2)$, $h_{1T}^{\perp}(x, \mathbf{k}_T^2)$, $h_{1L}^{\perp}(x, \mathbf{k}_T^2)$, $h_1^{\perp}(x, \mathbf{k}_T^2)$ and $f_{1T}^{\perp}(x, \mathbf{k}_T^2)$, using the so-called Amsterdam notation. After integrating over $\mathbf{k}_T$ only the first three PDFs survive, yielding the number distribution $f_1(x)$ (or $q(x)$), the helicity distribution $g_1(x)$ (or $\Delta q(x)$), and the transversity distribution $h_1(x)$ (or $\Delta_T q(x)$ in the usual COMPASS notation). These three functions fully specify the quark structure of the nucleon at the twist-two level. Today, a lot of attention is put in particular on the TMD functions $f_{1T}^{\perp}$, the Sivers function which gives the correlation between the nucleon transverse spin and the quark intrinsic transverse momentum, $h_1^{\perp}$, the Boer–Mulders function which gives the correlation between the transverse spin and the intrinsic transverse momentum of a quark inside an unpolarised nucleon, and g_{1T}, which is the only chiral-even and T-even leading twist function in addition to f_1 and g_1.

A powerful method to access the poorly known TMD PDF is SIDIS on transversely polarised targets. In fact, on the basis of general principles of quantum field theory in the one photon exchange approximation, the SIDIS cross-section in the COMPASS kinematic range can be written in a model independent way as:

$$
\begin{aligned}
\frac{d\sigma}{dx\,dy\,dz\,d\phi_S\,d\phi_h\,dp_T^h} = \; & \frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\epsilon)}\Big\{F_{UU} + \\
& +\sqrt{2\epsilon(1+\epsilon)}\cos\phi_h F_{UU}^{\cos\phi_h} + \epsilon\,\cos 2\phi_h\, F_{UU}^{\cos 2\phi_h} + \\
& +\lambda\sqrt{2\epsilon(1-\epsilon)}\sin\phi_h F_{LU}^{\sin\phi_h} + \\
& +S_L\Big[\sqrt{2\epsilon(1+\epsilon)}\sin\phi_h F_{UL}^{\sin\phi_h} + \epsilon\sin 2\phi_h F_{UL}^{\sin 2\phi_h} + \\
& \quad + \lambda\left(\sqrt{1-\epsilon^2}F_{LL} + \sqrt{2\epsilon(1-\epsilon)}\cos\phi_h F_{LL}^{\cos\phi_h}\right)\Big] + \\
& +S_T\Big[\sin(\phi_h-\phi_S)F_{UT}^{\sin(\phi_h-\phi_S)} + \epsilon\sin(\phi_h+\phi_S)F_{UT}^{\sin(\phi_h+\phi_S)} + \\
& \quad + \epsilon\sin(3\phi_h-\phi_S)F_{UT}^{\sin(3\phi_h-\phi_S)} + \\
& \quad + \sqrt{2\epsilon(1+\epsilon)}\sin\phi_S F_{UT}^{\sin\phi_S} + \\
& \quad + \sqrt{2\epsilon(1+\epsilon)}\sin(2\phi_h-\phi_S)F_{UT}^{\sin(2\phi_h-\phi_S)} \\
& \quad + \lambda\Big(\sqrt{1-\epsilon^2}\cos(\phi_h-\phi_S)F_{LT}^{\cos(\phi_h-\phi_S)} \\
& \qquad + \sqrt{2\epsilon(1-\epsilon)}\cos\phi_S F_{LT}^{\cos\phi_S} \\
& \qquad + \sqrt{2\epsilon(1-\epsilon)}\cos(2\phi_h-\phi_S)F_{LT}^{\cos(2\phi_h-\phi_S)}\Big)\Big]\Big\}\,. \qquad (7)
\end{aligned}
$$

Here ϕ_S and ϕ_h are the azimuthal angles of the nucleon transverse spin and of the hadron transverse momentum $\boldsymbol{p}_T^h$ in the Gamma–Nucleon System, α is the fine structure constant, λ is the lepton helicity, S_T and S_L are the nucleon transverse and longitudinal polarization. Neglecting the terms in $\gamma^2 = (2Mx/Q)^2$, the quantity ϵ is given by $\epsilon = (1-y)/(1-y+y^2/2)$.

The r.h.s. structure functions F's in general depend on Q^2, x, z and p_T^h. Their superscripts refer to the corresponding azimuthal asymmetries. The subscripts refer to the beam and to the target polarization (U means unpolarised, L longitudinally polarised, and T transversely polarised). Since the modulations which appear in the cross-section for unpolarised, longitudinally polarised and transversely polarised nucleons are independent combinations of the azimuthal angles, all of them can be measured using data taken with unpolarised, longitudinally polarised and transversely polarised targets.

In the S_T-dependent part of the cross-section, only four of the eight structure functions are of leading order. They are:

- $F_{UT}^{\sin(\phi_h+\phi_S)} \propto h_1 \otimes H_1^{\perp}$, where h_1 is the transversity distribution, $H_1^{\perp}$ is the Collins fragmentation function and $\otimes$ indicates the convolution over the quark intrinsic transverse momentum summed over the quark flavours. When divided by F_{UU} it is the Collins asymmetry measured by COMPASS and HERMES;
- $F_{UT}^{\sin(\phi_h-\phi_S)} \propto f_{1T}^{\perp} \otimes D$, where $f_{1T}^{\perp}$ is the Sivers function and D is the unpolarised fragmentation function. When divided by F_{UU} it is the Sivers asymmetry measured by COMPASS and HERMES;
- $F_{UT}^{\sin(3\phi_h-\phi_S)} \propto h_{1T}^{\perp} \otimes H_1^{\perp}$, and
- $F_{LT}^{\cos(\phi_h-\phi_S)} \propto g_{1T} \otimes D$.

A complete list of the TMD PDFs which appear in all the structure functions can be found e.g. in Ref. [6]

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