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Addendum 2 to the COMPASS Proposal

COMPASS Collaboration

Abstract

In this Addendum a request is presented for two years (2×150 days) of muon data taking, one year with a transversely polarised proton target and one year with a longitudinally polarised proton target. The proposed measurements complete the initial data taking with a proton target which took place in 2007. Only minor modifications and improvements of the apparatus with respect to 2007 are planned. The measurements should start in 2010 with the transverse part.

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Contents

1 Introduction

The physics topics addressed 1996 in the original COMPASS Proposal [1] are still of top interest within the hadron physics community. Since then we have achieved many of the goals of the Proposal. In the nucleon structure sector we obtained important results with the polarised deuteron target, in particular the gluon polarisation from open charm and high-p_T hadron pairs, quark helicity distributions from inclusive and semi-inclusive processes as well as transverse single-spin asymmetries.

Both, proton and deuteron data are indispensable to determine the structure functions separately for different quark flavours. Therefore 1.5 years of proton data taking was part of the original COMPASS Proposal and further data taking was proposed in our Letter of Intent [2]. Up to now we took proton data only in 2007. This Addendum to the Proposal presents the case for further data taking with a polarised muon beam and a polarised proton target.

For the transverse part the situation has changed considerably since 1996, when the orginal Proposal was written. Transverse spin effects in semi-inclusive deep inelastic scattering (SIDIS) related to the transversity parton distribution are now well established and to progress further more precise data are needed. In the field of transverse momentum dependent functions, the energy dependence suggested by the COMPASS proton result for the Sivers asymmetry urgently needs to be clarified. The new proton data will bring into reach a reliable determination of the transverse structure of the nucleon. We aim to extend the measured x-Bjorken range with precise data and to match the HERMES statistics in the overlap region at larger x. Already in 2007 we chose to increase the share of data taking with transverse target polarisation from 20% to 50%, reflecting the grown theoretical and experimental interest in transverse spin effects. The first results are intriguing and strengthen the case for further measurements.

In the original Proposal we had asked for 1.5 years of proton data taking, i.e. 1.2 years of longitudinal running and 0.3 years of transverse running. To roughly match the accuracy of the deuteron data an additional year of longitudinal proton data taking is required in line with the original request. Apart from the new proton data in a unique kinematic domain, this would permit us to combine proton and deuteron data of comparable precision and thus to make best use of the deuteron data already taken.

None of proposed measurements does require major hardware upgrades but profit from the major 2006 upgrade and the improvements made for the hadron spectroscopy programme, which started in 2008. The spectrometer is described in detail in Ref. [3].

Another unfinished part of the COMPASS Proposal concerns the measurement of the pion polarisability via the Primakoff reaction. This quantity is a cornerstone in chiral perturbation theory and the experimental results vary far outside their given uncertainties. In 2004 a few days of data were taken and on this basis the feasibility of the measurement has been established. However, another lesson learnt from these data is that systematic uncertainties must be better controlled to obtain a conclusive result. The optimal spectrometer configuration is still under discussion and we will come back on this measurement in the near future. Data on hadron spectroscopy using hadron beams are currently being taken. The key points of this program will be further elaborated in the course of the analysis of the 2008/9 data and additional measurements might be proposed in the future.

This Addendum is organised in the following way. Section 2 is dedicated to the transverse measurements with sub-sections on the physics of transverse spin effects (2.1), the present experimental status of SIDIS (2.2) and the expected physics outcome of the proposed transverse measurements (2.3). Section 3 discusses the case for the proposed longitudinal measurements with sub-sections on the experimental status and motivation (3.1, 3.2), the structure function g_1 (3.3), the non-singlet structure function (3.4) and flavour-separated quark distributions (3.5). The improvements of the COMPASS spectrometer for the proposed data taking and the beam request are described in Section 4. Section 5 contains the summary. Additional information on the transverse momentum dependent functions and highlights of the COMPASS results with the longitudinal target are given in Appendix A and B, respectively.

2 Measurements with a transversely polarised proton target

The study of the transverse spin and transverse momentum structure of the nucleon is today an exciting and rapidly growing field. Remarkable progress has been made since the time of the COMPASS Proposal [1] thanks to the effort of the very active and large international community working in this field. However, in spite of the achievements of the last few years, many questions are still open and urgently require further experimental investigation, as already anticipated in the Letter of Intent [2] submitted by the COMPASS Collaboration in January 2009.

2.1 Transverse spin effects

The relevance of transverse spin effects at high energy in hadronic physics was first suggested by the discovery in 1976 that Λ hyperons produced in pN interactions exhibited a large and unexpected transverse polarisation [4]. In spite of the subsequent observation of large single-spin asymmetries (SSAs) in various hadronic processes (quite remarkable is the left-right asymmetry in pion production measured by E704 [5]), these effects could not easily be explained and for a long time they were just believed to be forbidden at leading twist in QCD [6].

2.1.1 Transversity PDFs

In 1978 a new quark distribution called “transversity”, describing the transverse spin distribution of quarks in a transversely polarised nucleon, was first introduced [7] but there was no simple way to relate the observed SSAs in hadronic processes to the new distribution.

In 1991 a general scheme of all leading twist and higher-twist parton distribution functions was worked out [8]. To fully specify the quark structure of the nucleon at the twist-two level, the transverse spin distributions $\Delta_T q(x)$ (or $\delta q(x)$, or $h_1^q(x)$), introduced 15 years before, had to be added to the better known spin-averaged and helicity parton distribution functions (PDFs), $q(x)$ and $\Delta q(x)$.

Being chiral odd, the transversity PDF does not contribute to inclusive DIS. However, it can be accessed via observables in which it is coupled to another chiral-odd quantity. It was first suggested [7] to measure it via double transverse spin observables in the Drell–Yan process, as proposed by the RHIC Spin Collaboration (BNL). These are very challenging measurements, and 30 years later they have not yet been performed.

An important step forward was done in 1993, when Collins [9] proposed an alternative way to access transversity, namely to measure the azimuthal angular distribution of hadrons inclusively produced in DIS of leptons on transversely polarised nucleons. The distribution would exhibit a modulation of the type $\sin \Phi_C$, where $\Phi_C = \phi_h + \phi_S - \pi$ is the so-called “Collins angle”. The azimuthal angles ϕ_h and ϕ_S are the angles of the hadron transverse momentum $\vec{p}_T^{\,h}$ and of the nucleon spin $\vec{S}_\perp$ with respect to the lepton scattering plane as measured in the Gamma–Nucleon System. The amplitude of the modulation is $\epsilon_C = f \cdot P_T \cdot D_{NN} \cdot A_{Coll}$, where P_T is the target nucleon polarisation and f is its dilution factor. The quantity $D_{NN} = (1-y)/(1-y+y^2/2)$ is the transverse spin transfer coefficient from the target quark to the struck quark. The "Collins asymmetry" is given by

$$A_{Coll} = \frac{\sum_q e_q^2 \cdot \Delta_T q(x) \cdot \Delta_T^0 D_q^h(z, p_T^h)}{\sum_q e_q^2 \cdot q(x) \cdot D_q^h(z, p_T^h)}\,, \tag{1}$$

where e_q is the quark charge, z is the fraction of the available energy carried by the hadron and D_q^h is the usual unpolarised fragmentation function (FF). The Collins asymmetry is thus proportional to the product[1)] of the transversity PDF and the spin-dependent part of the FF for a polarised quark fragmenting into a hadron h (the "Collins FF" $\Delta_T^0 D_q^h$ or $H_1^\perp$). This transverse momentum dependent (TMD) function is the chiral-odd partner which makes SIDIS an important tool to access transversity. It is an interesting quantity by itself, and it was completely unknown until few years ago.

Other independent channels were also proposed to probe transversity in SIDIS, like the polarisation of produced Λ's and azimuthal asymmetries in two hadron production [10, 11]. The advantage of these processes is that they do not involve TMD functions and can be performed in parallel to the measurement of the Collins asymmetry. On the other hand, they are statistically limited and still unknown FFs appear in the observables.

In the past few years clear signals for the Collins asymmetry have been observed in SIDIS by the HERMES (DESY) and the COMPASS experiments, and the BELLE Collaboration has published the first measurements of the convolution of two Collins FFs. In parallel, measurements have been and are being performed with colliding polarised p beams by the RHIC Spin Collaboration at BNL. A summary of these results is given in the next section.

Theoretically the relevance of the transversity PDF is today firmly established and many of its properties have been deduced:

- The evolution of $\Delta_T q(x, Q^2)$ is expected to be quite different from that of the helicity PDF $\Delta q(x, Q^2)$ partly because there is no gluon contribution to transversity; it has already been calculated at NLO in the collinear case [12].
- The Soffer bound [13] $|\Delta_T q(x)| \leq [q(x) + \Delta q(x)]/2$ gives a relation among transversity, helicity and unpolarised PDFs.
- The transversity PDF is the forward limit of the generalised parton distribution H_T [14].
- The tensor charge $g_T^q = \sum_q \int dx[\Delta_T q(x) - \Delta_T \bar{q}(x)]$ is an all-valence object and a fundamental charge, like the electric and the axial charge. Several calculations based on models (see e.g. [15, 16]) as well as lattice calculations [14, 17] already exist and the measurement of transversity is the only known way of accessing it experimentally.
- The first moments of $\Delta_T q$'s are also connected to the spin of the nucleon. Recently, the Bakker–Leader–Trueman angular momentum sum rule [18] for transversity

$$\frac{1}{2} = \frac{1}{2}\sum_q \int dx[\Delta_T q(x) + \Delta_T \bar{q}(x)] + \sum_{q,\bar{q},g} L_T \tag{2}$$

[1)] Taking into account the intrinsic transverse momenta in Eq. (1), the products are replaced by convolution integrals (see Appendix A).

has been proposed. It is free from the gluon PDF contribution, and provides an independent way to access the contribution of the orbital angular momentum of q, $\bar{q}$, and g to the nucleon spin.

It has to be stressed that the experimental investigation of most of the previous points (as well as the validation of any sum rule which could be put forward in the future) requires two basic ingredients, which make SIDIS a unique tool:

- precise measurements over an x range as wide as possible, and
- flavour separation.

As outlined in the next section, much theoretical work on the transversity PDF and the Collins FF has been stimulated by the recent experimental results which became available since 2005.

2.1.2 Transverse momentum dependent PDFs

Since the times of the COMPASS Proposal, a new item has been investigated, namely the role of the parton transverse momentum and its correlation with the spin in describing the nucleon structure. New ("unintegrated") transverse momentum dependent PDFs have been introduced [19] to describe the nucleon structure and it has been established that SIDIS, Drell–Yan processes, and hadron production in e^+e^- annihilation factorise at leading twist thus allowing to access TMD FFs and PDFs. There are eight leading-twist TMD PDFs, three of which survive after integration over the transverse momenta and give $q(x)$, $\Delta q(x)$, and $\Delta_T q(x)$. All the eight TMD PDFs are expected to contribute to the SIDIS cross-section (the general expression of the SIDIS cross-section in the one-photon exchange approximation from [20] is given in the Appendix A). Here we will only quote two of them which are particularly interesting, namely the so-called "Sivers" and "Boer–Mulders" functions.

As suggested by Sivers [21], a mechanism not related to transversity could also be the possible cause of the large transverse spin effects observed in pp scattering, namely the existence of a correlation between the transverse momentum $\vec{k}_T$ of an unpolarised quark in a transversely polarised nucleon and the nucleon polarisation vector. The quark distribution $q(x)$ could thus be written as

$$q_T(x, \vec{k}_T) = q(x, k_T) + |\vec{S}_\perp| \cdot \Delta_0^T q(x, k_T) \cdot \sin\phi' \,. \tag{3}$$

Here $\Delta_0^T q$ (or $f_{1T}^\perp$) is the T-odd Sivers function and ϕ' is the difference of the azimuthal angles of the transverse spin of the nucleon and of $\vec{k}_T$, the quark transverse momentum relative to the nucleon direction.

The existence of the Sivers function requires final state interactions and an interference between Fock states of different helicity. In the absence of interactions the Sivers function would vanish by time-reversal invariance of QCD (see e.g. Ref. [22]) and indeed it was believed for several years that the Sivers function is zero. Recently it was shown however [23, 24, 25] that these interactions are represented naturally by the gauge link that is required for a gauge invariant definition of a TMD parton distribution. Thus the Sivers function has become a very important piece in fundamental issues of QCD. Moreover, it has to be stressed that presently a large theoretical effort is devoted to establish a connection between the Sivers function and the angular momentum of the partons in the nucleon [26].

Very much as in pp scattering, the Sivers mechanism could also be responsible for a spin asymmetry in the cross-section of SIDIS off transversely polarised nucleons, where it could show up as a $\sin \Phi_S$ modulation in the azimuthal distribution of the produced hadrons. The “Sivers angle” $\Phi_S = \phi_h - \phi_S$ is the difference of the azimuthal angles of the hadron transverse momentum and of the target spin in the Gamma–Nucleon System. From the measured amplitude of the modulation $\epsilon_S = f \cdot P_T \cdot A_{Siv}$ one could thus extract the “Sivers asymmetry”

$$A_{Siv} = \frac{\sum_q e_q^2 \cdot \Delta_0^T q(x, p_T^h/z) \cdot D_q^h(z)}{\sum_q e_q^2 \cdot q(x, p_T^h/z) \cdot D_q^h(z)}, \tag{4}$$

which is proportional to the product[2] of the Sivers function and the unpolarised FF D_q^h.

It has to be noted that the Collins and Sivers terms in the transverse spin asymmetry depend on the different angles Φ_C and Φ_S, which are orthogonal combinations of ϕ_h and ϕ_S. Using SIDIS off a transversely polarised target, the corresponding asymmetries can be determined separately and the Collins and the Sivers effects can thus be disentangled from data (at variance with the spin asymmetries in inclusively produced hadrons in polarised *pp* scattering). The same is true for the other structure functions which appear in the SIDIS cross-section. Correlations between the different terms can be introduced by a non-constant acceptance of the apparatus, but they can be precisely estimated from the data. The HERMES and the COMPASS experiments have recently produced results for the Sivers asymmetry which are also presented in the next section.

The Boer–Mulders function describes the correlation between the spin and the intrinsic transverse momentum of a quark inside an unpolarised hadron. This novel TMD function could explain the large angular asymmetries measured in the high energy π^-W Drell–Yan production [27, 28] 20 years ago. The Boer–Mulders function can also be accessed in SIDIS off unpolarised targets (and thus be obtained as a by-product of the transverse spin measurements) where it is expected to contribute to the $\cos 2\phi_h$ modulation [29] recently measured by COMPASS [30].

Transversity, the Sivers function, and the Boer–Mulders function are all expected to contribute to Drell–Yan processes, where they appear in structure functions which are convolution of TMDs in the transverse momentum space [31]. These challenging measurements are complementary to the SIDIS measurements and in particular the investigation of Drell–Yan production in $\pi^- p^\uparrow$ interaction is part of the medium and long term planning of the COMPASS experiment [2].

2.2 Experimental status

On the experimental side a worldwide effort is ongoing in two complementary fields: high energy transversely polarised *pp* scattering and lepton SIDIS off transversely polarised nucleons.

The experiments of the RHIC Spin Collaboration have devoted a significant fraction of their data taking to the measurement of transversely polarised *pp* scattering, and many precise results are being published [32]. In particular, the large asymmetries in inclusive meson production already observed by the E704 experiment are by now measured with high statistics at higher energy. The effects are still there, as large and as intriguing as ever. Both the Collins and the Sivers mechanisms are presently expected to contribute to those asymmetries [33, 34] making the interpretation of the results difficult, and till

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[2] As for the Collins asymmetry, the products in Eq. (4) should be replaced by convolutions over the transverse momenta.

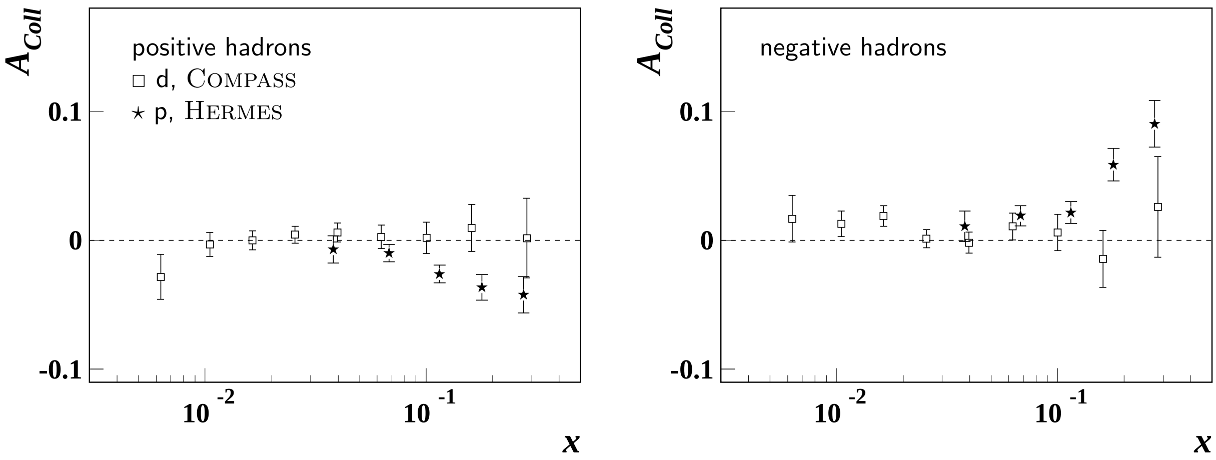

Figure 1: Proton and deuteron Collins asymmetries as a function of x for positive (left) and negative (right) particles. The stars are the preliminary HERMES proton results [36] for charged pions from the 2002–2005 data (see text). The open squares are the COMPASS deuteron results for charged hadrons from the 2002–2004 data [37].

now no measured quantity allows to extract unambiguous information in spite of the huge theoretical effort.

The situation is quite different in the case of the transverse spin asymmetries in SIDIS measured by HERMES and, at higher energy, by COMPASS, which have allowed the first ever extractions of the Sivers and of the transversity functions. The measurements of the Collins and Sivers asymmetries, their phenomenological interpretation and some of the still open points, as well as the expected outcome from other experiments are summarised in the following.

2.2.1 Transversity distribution

The only existing measurements of the Collins asymmetry come from the COMPASS and the HERMES experiments. The Collins modulations have first been shown to be non-zero by the HERMES measurements of pion SSAs in SIDIS of 28 GeV/c electrons on a transversely polarised proton target [35, 36]. The preliminary results from the whole data collected in 2002–2005 are shown as stars in Fig. 1 for positive and negative pions. The data points have been corrected for the D_{nn} factor and the sign has been changed, according to the COMPASS convention for the Collins angle [37]. The measured values show a clear signal both for π^+ and π^- and have provided the first convincing evidence that both the transversity distribution $\Delta_T u(x)$ and the Collins FFs $\Delta_T^0 D_u^h$ are not zero (the contribution to the asymmetry of the up quark is the dominant one). Independent evidence that the Collins mechanism is a real measurable effect has come from the recent analysis of the azimuthal correlations in $e^+e^- \to$ hadrons of the BELLE Collaboration [38, 39].

COMPASS has first measured SIDIS on a transversely polarised deuteron target in the years 2002–2004 using incident muons with 160 GeV/c momentum. Thanks to the larger energy, COMPASS can measure over a considerably wider x range, from $4 \cdot 10^{-3}$ to 0.5. Results for the Collins asymmetries with the deuteron target have been published both for non-identified hadrons [37, 40], and for charged pions and charged and neutral kaons [41]. All the asymmetries turned out to be small, compatible with zero inside the few percent experimental errors, as can be seen from Fig. 1 where the

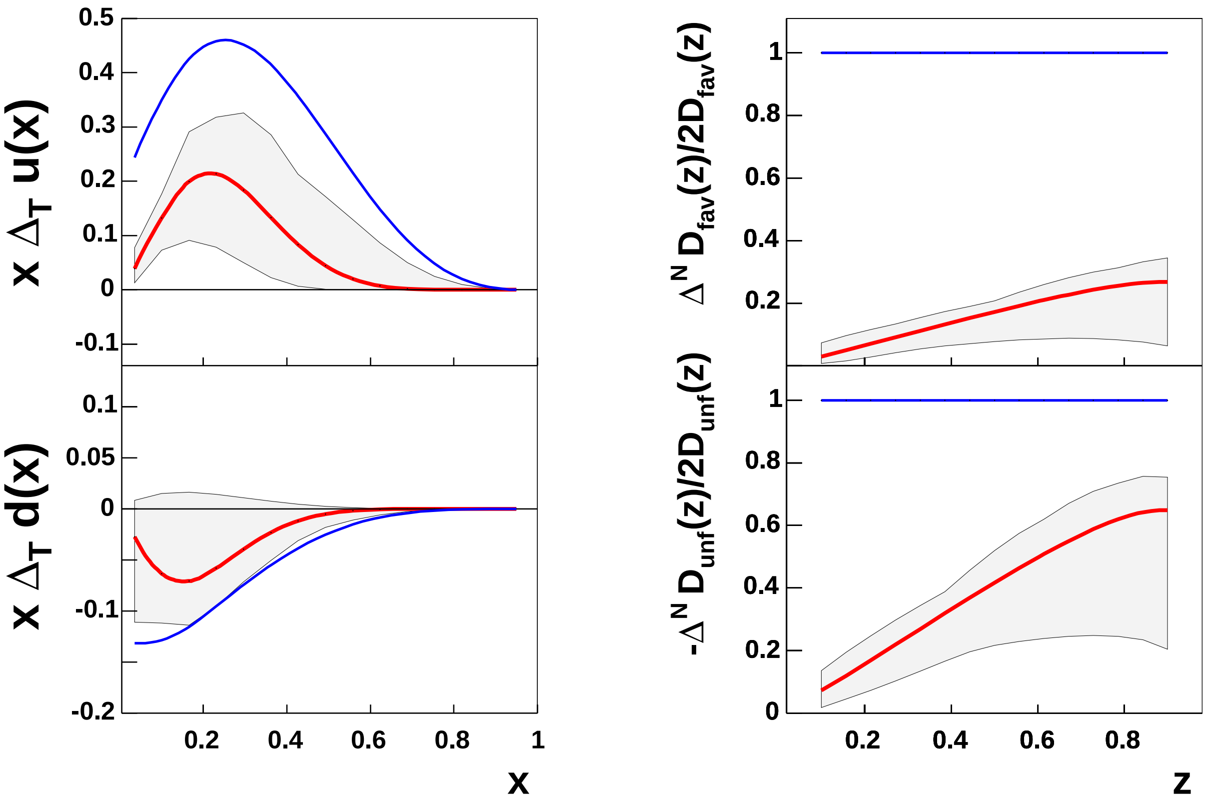

Figure 2: Results of the fit from Ref. [42] to COMPASS deuteron, HERMES proton and BELLE data. Left: the transversity PDFs for the up (top) and down quarks (bottom) vs. x with their uncertainty bands in grey. Also shown are the Soffer bounds as solid line. Right: the favoured (top) and unfavoured (bottom) Collins FFs vs. z.

open squares are the results for charged hadrons. The deuteron asymmetries suggest cancellation between up and down-quark contributions and are very important to assess the transversity distribution of the down quark.

Global fits of all these data and the BELLE data have already allowed for a first extraction [42] of the Collins FFs and of the transversity PDFs. The fit results are in very good agreement with all the existing data, which can thus be described in a consistent picture. This represents a major step forward in the knowledge of the transverse spin structure of the nucleons.

The plots in Fig. 2 show the results from the global fit of M. Anselmino et al. [42]. In the left top and bottom plots the up and down-quark transversity distributions versus x are shown together with the Soffer bound and the statistical uncertainty (grey bands). The transversity distribution is positive for up quarks and negative for down quarks, the magnitude of $\Delta_T u$ is larger than that of $\Delta_T d$, and they are both significantly smaller than the corresponding Soffer bound.

The trend is in substantial agreement with the results obtained in several models, like the Chiral Quark-Soliton Model [43]. At the right, we show the favoured (top) and the unfavoured (bottom) Collins fragmentation functions normalised to twice the corresponding unpolarised fragmentation functions versus z. The favoured and unfavoured Collins FFs have opposite sign and the size of the unfavoured Collins FF is even larger than that

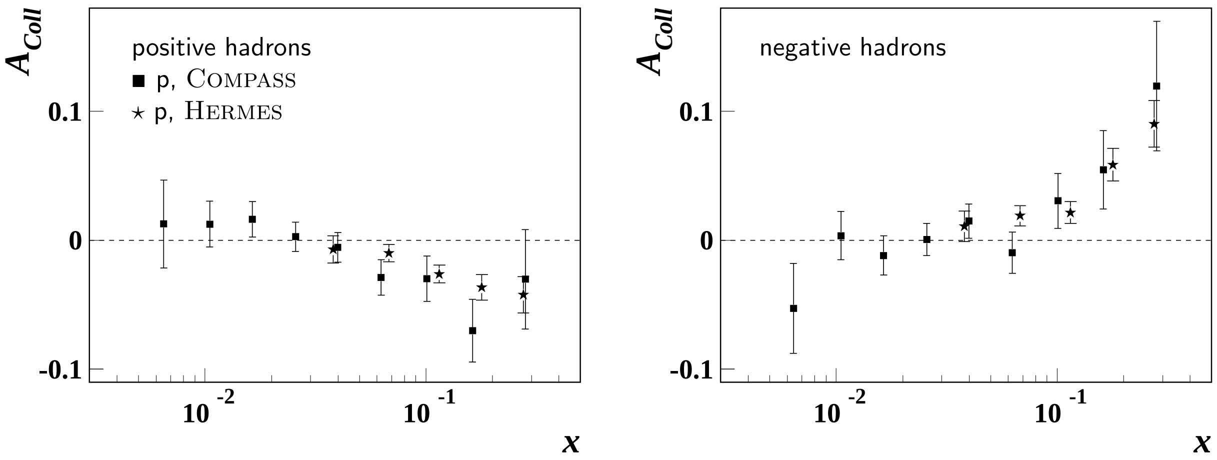

Figure 3: Proton Collins asymmetries as a function of x for positive (left) and negative (right) hadrons. The stars are the preliminary values measured by HERMES from the whole 2002–2005 proton data already shown in Fig. 1. The closed squares are the preliminary COMPASS results on proton [44].

of the favoured one, a quite surprising result.

The extraction of the transversity PDF is an important result which also allowed for the first time for the evaluation of the tensor charge. Still, one has to say that we are just at the beginning of the work and that the available data set is very limited. As stressed by the authors, several assumptions were used in the global fitting procedure, and this first extraction has to be considered as a qualitative result. In particular for the x dependence of the transversity distribution, and for the z and transverse momentum dependence of the Collins functions, simple parameterisations have been used. Also, the fit has been performed at $Q^2 = 2.4$ (GeV/c)^2, assuming that the QCD evolution of the Collins FFs is the same as for the unpolarised FFs. This is an important point, since a stronger Q^2 dependence of the Collins asymmetry could not be excluded.

New input came with the COMPASS measurements on transversely polarised protons at 160 GeV/c performed in 2007. The first preliminary Collins asymmetries from an analysis performed on part of the statistics were presented at the Transversity 2008 Workshop [44]. They are shown in Fig. 3 for positive and negative hadrons together with those from HERMES already shown in Fig. 1. The COMPASS signal is of the same sign and strength as that measured by HERMES. This is not an obvious result, given the different energies of HERMES and COMPASS and consequently the different Q^2 values in the valence region. In particular it suggests that the large Collins asymmetry first measured by HERMES is not due to higher-twist effects, and that mechanisms like the Sudakov suppression are not large in the kinematical region explored in so far.

2.2.2 Sivers function

In parallel to the Collins asymmetry, HERMES and COMPASS have measured the Sivers asymmetry. HERMES has measured a non-zero asymmetry on the proton target for π^+ (and K^+, where Sivers asymmetries larger than 10% have been observed) while for π^- the asymmetry is compatible with zero [35, 36], pointing to a cancellation between the up and down-quark contributions. The preliminary values of the asymmetries for charged pions from the 2002–2005 data are shown in Fig. 4.

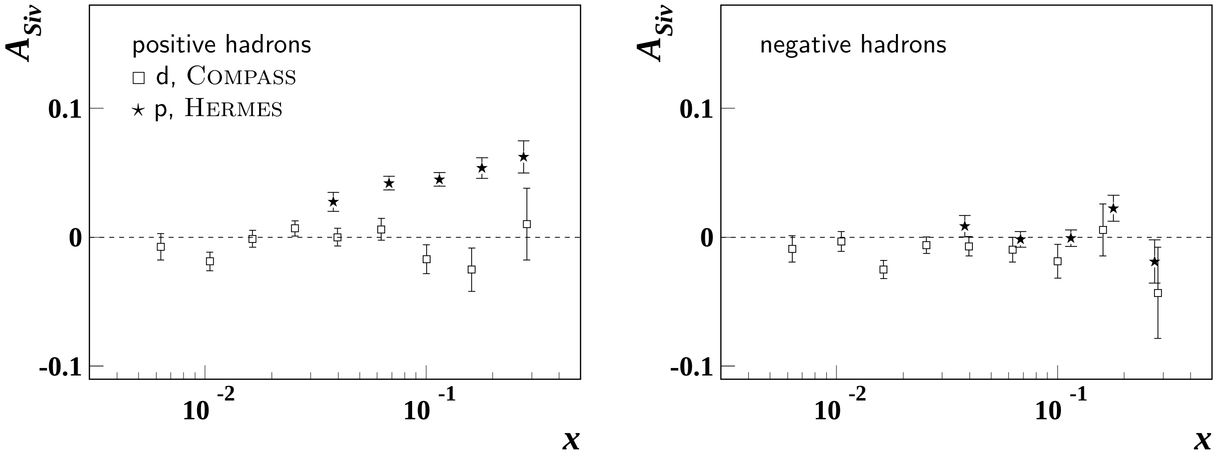

Figure 4: Proton and deuteron Sivers asymmetries as a function of x for positive (left) and negative (right) particles. The stars are the preliminary HERMES proton results for charged pions from the 2002–2005 data. The open squares are the COMPASS deuteron results for charged hadrons from the 2002–2004 data.

The asymmetries measured by COMPASS on the deuteron are again compatible with zero, both for positive and negative hadrons, pions and kaons [40, 37, 41]. These results are in agreement with a cancellation between the up and down-quark contributions and again put more stringent constrains on the down-quark Sivers function. The asymmetries for charged hadrons [37] are shown as open points in Fig. 4.

Fits of the HERMES proton and COMPASS deuteron data [45, 46] allowed for the first time for the extraction of the Sivers functions for the up and down quark, confirming that both of them are definitively different from zero, of about the same strength, and of opposite sign.

The preliminary results from the analysis of part of the 2007 COMPASS proton data [44] for positive and negative hadrons are shown in Fig. 5. The asymmetries are small, compatible with zero within the statistical errors, both for positive and negative hadrons. For negative hadrons the HERMES and the COMPASS data are in agreement. For positive hadrons the COMPASS data are smaller than the HERMES data: a completely unexpected and intriguing result. However, given the present statistical uncertainties of the COMPASS data, there remains a probability of a few percent that the data are compatible. Within the present theoretical framework, neither the difference in beam energy, nor in Q^2, can explain the damping of the HERMES signal in the COMPASS kinematic domain. If at COMPASS energies the Sivers effect would be confirmed to be small compared to HERMES measurement, a profound revision of our understanding of the TMD effects would be required. The scientific community is eagerly awaiting a clarification of the apparent discrepancy and COMPASS is the only experiment where such measurement can be performed.

2.2.3 Information from other experiments

Complementary to SIDIS are the experiments which study spin asymmetries in hadron–hadron scattering. Presently the only running experiments are those of the RHIC Spin Collaboration. The “golden” channel to access transversity, namely Drell–Yan production in transversely polarised pp scattering, allows for a direct measurement of the

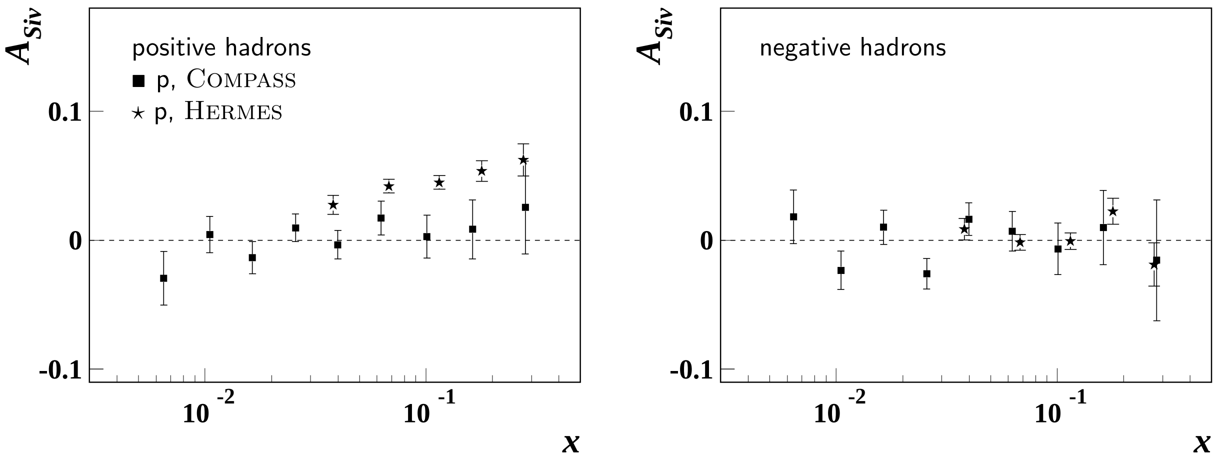

Figure 5: Proton Sivers asymmetries as a function of x for positive (left) and negative (right) particles. The closed squares are the preliminary COMPASS measurements [44] for charged hadrons. The stars are the HERMES results already shown in Fig. 4.

product of quark and antiquark transversity distributions. The latter is expected to be very small, making the measurement difficult and results will not come soon. As already mentioned, a lot of theoretical work is ongoing, but presently there is no definite recipe to extract transversity and Sivers functions without more input from the SIDIS experiments. Drell–Yan measurements in pp scattering are also foreseen in the future at J-PARC.

The measurement of Drell–Yan processes using a high energy pion beam and a transversely polarised target is a very promising (and challenging) opportunity which is part of the long term planning of the COMPASS experiment.

In the future anti-proton beams will be available at GSI. Using polarised p (or $\bar{p}$) the measurement of Drell–Yan processes will give access to the convolutions of different TMD quark distribution functions. If polarised anti-proton beams were available, it would be possible to directly access transversity using those results only. However, flavour separation would still not be possible and the accessible x range would be more limited than at COMPASS-like experiments

All these measurements are complementary and all will give important contributions. However, DIS always had a key role in the study of the nucleon structure and today SIDIS on transversely polarised targets is undoubtedly the best tool to understand the transverse spin structure of the nucleon. Presently, HERMES has completed the data taking and used all the collected statistics for the measurements of the Collins and Sivers asymmetries. The final results for the Collins and Sivers asymmetries from the COMPASS proton run in 2007 will be published soon. The statistical uncertainties are expected to drop for the Collins asymmetry [47] by up to a factor 1.6 with respect to results shown in Section 2.2. The Sivers asymmetry is more sensitive to the instabilities we had in the first part of the data taking and no major error reduction from the 2007 data is expected here. In both cases, the precision is not adequate to answer the most urgent questions.

At low energy, experiments are being performed at JLab at 6 GeV and are planned at 12 GeV. They are complementary from the point of view of kinematics to the experiment proposed here. They can only explore the large x region and are more vulnerable to higher twist effects.

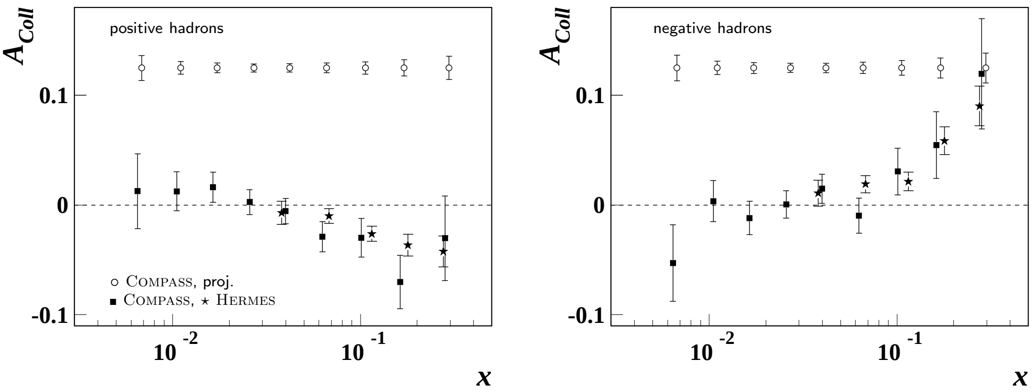

Figure 6: Collins asymmetry on proton for positive (left) and negative (right) hadrons. The open circles show the expected statistical errors from the proposed measurement. The stars and the closed squares are respectively the HERMES and the COMPASS results already shown in Fig. 3.

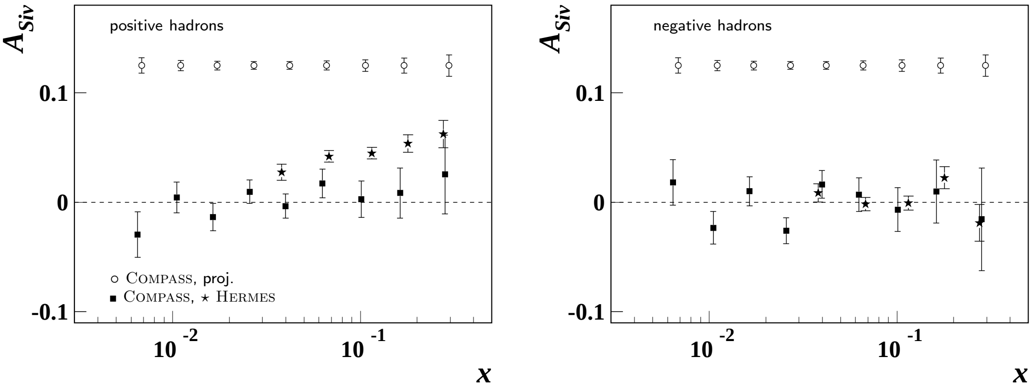

Figure 7: Sivers asymmetry on proton for positive (left) and negative (right) hadrons. The open circles show the expected statistical errors from the proposed measurement. The stars and the closed squares are respectively the HERMES and the COMPASS results already shown in Fig. 5.

For the distant future, new facilities (like EIC or ENC [48]) are being proposed. In the meantime, CERN is the only laboratory where SIDIS at high energy can be measured and COMPASS has the capability to perform precise measurements. As spelled out in the next sections, one year of data taking with the transversely polarised proton target at COMPASS will give more input both for transversity, which now has been shown to be measurable, and for the Sivers asymmetry, whose energy dependence is at the moment not clear.

2.3 Physics outcome

As spelled out in the previous sections, with 150 days of SPS beam and the transversely polarised NH_3 target, the expected statistical errors will be a factor 3 smaller than the statistical errors of the preliminary COMPASS results on proton of Ref. [44]. They are shown as open circles in Fig. 6 and 7 for the Collins and the Sivers asymmetries respectively, together with the HERMES and the COMPASS preliminary results. Precise results are expected over the whole x range, and in the overlap region the projected COMPASS errors are smaller than those of the HERMES data. The systematic uncertainties are related to the available data for statistical tests. For the new measurements, we are confident that the upper limit for the relative size of systematic uncertainties will not exceed that of the 2007 preliminary data, namely 0.3 (0.5) of the expected statistical uncertainties for the Collins (Sivers) asymmetries. Given its accuracy and the wide x range, the new measurement will constitute a major step forward.

For the Collins asymmetry, the new data will be precise enough to perform a first study of the Q^2 evolution to test the present assumptions, to study its z and p_T dependence, and to constrain the x dependence of the transversity PDF in order to get a much better evaluation of its first moments. All these issues are crucial in the present description of the transverse spin structure of the nucleon and of the Collins function.

For the Sivers asymmetry the new data are necessary to clarify the energy dependence suggested by the present COMPASS results and a detailed study of the dependence on the kinematical variables x, z and Q^2 will be possible.

Finally, from the same data, it will be possible to improve considerably on several interesting measurements not quoted here being already performed at COMPASS [49]. This is the case of the two-hadron asymmetries and the transverse polarisation of the inclusively produced Λ's, which are both related to transversity, the kaon Collins and Sivers asymmetries, and the other TMD asymmetries contributing to the SIDIS cross-section. Also, it will be possible to measure the spin dependence of the azimuthal modulation of the decay plane of the exclusively produced ρ^0 which is related to GPDs.

Concerning the deuteron data the only existing results are those from the COMPASS experiment. It is clear from Figs. 1 and 4 that more precise measurements are desirable in the future.

3 Measurements with a longitudinally polarised proton target

Given the wide success of the Quark Parton Model in explaining and predicting the results of the spin-independent deep inelastic scattering experiments, the results of the spin-dependent muon–proton scattering measurements performed by the European Muon Collaboration (EMC) at CERN 20 years ago [50] came as a large surprise. They revealed a surprisingly small quark contribution to the nucleon spin, $\Delta\Sigma \sim 0.1$, compared to predictions from simple quark models. In the context of the Ellis–Jaffe sum rule, the EMC results can also be interpreted as a considerable negative polarisation of the strange sea quarks Δs. These results, named "spin crisis", stirred a huge amount of theoretical efforts [51] to explain the results by the axial anomaly, a violation of the assumptions used in the derivation, experimental problems, etc.

3.1 Experimental status

The EMC measured the first moment of the spin structure function $g_1(x, Q^2)$ of the proton. Combined with the Bjorken sum rule $\Gamma_1^p - \Gamma_1^n = \int_0^1 (g_1^p - g_1^n)\mathrm{d}x$ the result for Γ_1^p implied that the first moment of the neutron spin structure function is sizable. Therefore further spin experiments were launched at SLAC (E142/3 and E154/5) [52], CERN (SMC) [53] and DESY (HERMES [54]) which aimed at an improved helicity structure measurement of the proton and (for the first time) also of the neutron using either polarised ^{3}He or deuteron targets.

The availability of the proton and the neutron data as well as the span in Q^2 between the SLAC and SMC results permitted the first perturbative QCD analyses [55]. The singlet and the two non-singlet quark distributions as well as the gluon helicity distribution were extracted applying quite restrictive assumptions. The results confirmed the earlier measurements of $\Delta\Sigma$ and Δs but it was obvious that the determination of the gluon contribution to the nucleon spin is hardly possible from these inclusive results. It was confirmed that the contribution of quarks to the nucleon spin is indeed smaller than predicted, of the order of 25%. Although the statistical uncertainties were much improved compared to the first measurements, the systematic error to the extrapolation towards $x = 0$ remained non-negligible due to the limited x range especially of the high statistics SLAC data. SMC provided also the first test of the fundamental Bjorken sum rule, which now is verified to a precision of about 10%.

At this time it became clear that there are several contributions to the nucleon spin: from quarks $\Delta\Sigma$, gluons ΔG, and orbital angular momenta ΔL which need to be measured in dedicated experiments. The flavour decomposition of $\Delta\Sigma$ is accessible in semi-inclusive spin dependent deep-inelastic scattering. The gluon contribution ΔG can be measured in photon–gluon fusion processes and the total quark contribution is accessible through deeply virtual Compton scattering [51]. Thus, the next round of experiments at DESY and CERN, focused on measurements of semi-inclusive channels, while improvements at high x also came from inclusive measurements at lower energies at JLAB [56]. An alternative approach to measure the gluon polarisation is pursued at RHIC colliding polarised proton beams [57].

Over the last decade COMPASS and HERMES obtained precise results. With the inclusive data the quark contribution to the nucleon spin is now measured to be $0.33 \pm 0.03\,(\text{stat.})$ [58]. A crucial improvement came from the high precision low-x COMPASS deuteron data. Semi-inclusive results were used to obtain the flavour decomposition of the quark contribution [70]. Here a new puzzle arose: while all the QCD analyses give a negative contribution of the strange quarks to the nucleon spin of the order of 10%, the semi-inclusive results point to a vanishing or even slightly positive polarisation in the x range of the measurements. The gluon polarisation was studied in the production of high-p_T hadron pairs by COMPASS [60, 61], SMC [62] and HERMES [63] and in the open charm production by COMPASS [64, 65]. Together with the recent results from RHIC, the data, all situated around $x \sim 0.1 - 0.2$, point to a small gluon polarisation at that value of x. This makes a large value of ΔG rather unlikely and indicates that the axial anomaly only plays a marginal role in solving the nucleon spin puzzle. In this situation, orbital angular momentum might contribute significantly to the nucleon spin. A more complete summary of our deuteron results is given in Appendix B.

3.2 Motivation

New insight into the nucleon spin structure can only be gained by additional measurements. The attempt to access orbital angular momenta via DVCS measurements will be described in a separate proposal. Here we concentrate on further studies of the helicity contribution, especially that of quarks. For that, measurements of the proton structure function g_1 and of semi-inclusive asymmetries at low x are needed with a precision comparable to the deuteron data.

Between 2002 and 2006, COMPASS has taken very precise data with a polarised deuteron target. In 2007 a first set of the proton data was taken. However, the run was shared between longitudinal and transverse polarisation of the target resulting in only half a year of data taking with longitudinal polarisation. Together with a lower figure of merit due to the properties of the target material, the precision of the proton data lacks far behind that of the deuteron data in a unique kinematic domain only accessible at CERN. Nevertheless, the 2007 proton measurement combined with the previous deuteron data will bring already new physics results, especially in the sector of flavour separation for the polarised quark distributions. It is obvious that statistics of the proton data set should be increased substantially thus giving a better balance between the two data sets. With the proposed measurement of one year (150 days) with a polarised proton target the aim of comparable precision of deuteron and proton data can be achieved.

Such an improvement, especially at low x, would help to pin down the error of the low-x extrapolation of moments, and considerably help in constraining the functional form of the polarised quark distributions in current QCD analyses. An essential ingredient for such analyses is the available Q^2 range above 1 $(\mathrm{GeV}/c)^2$ at a given x value. Due to the beam energy required, more precise data at the high-Q^2 frontier can presently only come from COMPASS. The recent DSSV global analysis [66], which included our precise deuteron g_1 measurements [58], illustrates well the impact of new precise data in the wide COMPASS kinematic range. Also, an improved determination of the Bjorken sum rule will be feasible as its current systematic error has a substantial contribution from the low-x extrapolation. Moreover, the determination of the contribution of the individual quark flavours will benefit from a better balance between the deuteron and proton statistics.

3.3 Measurement of the proton longitudinal spin structure function g_1^p

The latest g_1^p measurement by the SMC was performed in 1996. A new sample of proton data covering x down to 0.003 has been obtained in 2007 by COMPASS.

In Fig. 8 we present the preliminary COMPASS results for $g_1^d(x)$ (2002–2006 data) and $g_1^p(x)$ (2007 data) compared to those from SMC. For the proton also the projected data points including an additional year of data taking at 200 GeV are shown. Compared to SMC, these errors will be about three to five times smaller at low x and about three times smaller at high x.

The contribution to the first moment of g_1^p from the unmeasured low-x region was estimated to be negative by SMC and reduced the total value of the integral by 10%. The COMPASS proton data may completely change this conclusion.

3.4 The non-singlet spin structure function g_1^{NS} and the Bjorken sum rule

The availability of g_1^d and g_1^p data with good and comparable precision at low x will permit a new evaluation of the non-singlet spin structure function

$$g_1^{NS}(x) = g_1^p(x) - g_1^n(x) = 2\Big[g_1^p(x) - \frac{g_1^d(x)}{1-\frac{3}{2}\omega_D}\Big], \tag{5}$$

where ω_D is the probability of the D-state in the deuteron ($\omega_D = 0.05 \pm 0.01$). The first moment Γ_1^{NS} of $g_1^{NS}(x)$ provides a test of the Bjorken sum rule

$$\Gamma_1^{NS} = \Gamma_1^p - \Gamma_1^n = \frac{1}{6}\left|\frac{g_A}{g_V}\right|. \tag{6}$$

This sum rule is a fundamental result of QCD, first derived using current algebra. It relates the first moments of the spin structure functions of the proton and the neutron measured in high energy experiments to the axial charge measured in neutron decay, thus at low energies. Experimental efforts in the past confirmed this relation with a precision of about 10% of the measured value. Our new preliminary results (2002–2007 data) for the non-singlet function $g_1^{NS}(x)$ are shown in Fig. 9 together with the error projection after another year of proton data taking. The new data will determine more precisely the

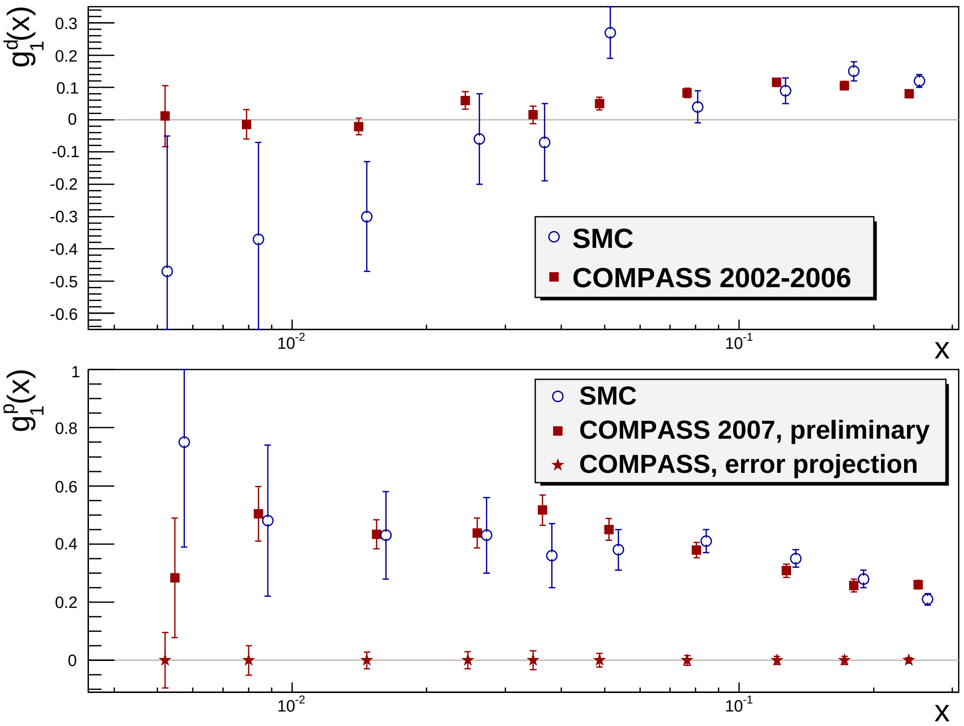

Figure 8: Preliminary results for the spin-dependent structure function of the deuteron $g_1^d(x)$ (2002–2006 data) (top) and of the proton $g_1^p(x)$ (2007 data) (bottom). For comparison also the SMC data are shown. For g_1^p (bottom) the statistical uncertainty expected after another year of data taking are also shown.

shape of $g_1^{NS}(x)$ at low x and provide a much more reliable extrapolation towards $x = 0$, which in turn will reduce the systematic uncertainty in the test of the Bjorken sum rule.

From our g_1^d data (Fig. 8) integrated over the measured range, the first moment Γ_1^d at $Q^2 = 3$ (GeV$/c)^2$ will be determined with a statistical precision of 0.002 (to be compared with 0.003 in our previous publication based on the 2002–2004 data). The statistical error on Γ_1^p, estimated to be 0.004 for the 2007 data, is expected to be reduced to 0.002 for the projected errors shown in Fig. 8. In SMC both Γ_1^p and Γ_1^d were affected by large corrections for the unmeasured region at low x where both g_1^p and g_1^d were assumed to be negative at the reference Q^2 of 10 (GeV$/c)^2$. The recent COMPASS data on g_1^d do not support this assumption and the same may happen for g_1^p. A very precise measurement of g_1^p at low x may thus lead to a significant change in the value of Γ_1^p with respect to the value of SMC. The improvement in the statistical error expected by adding one year of proton data is about 25% (see Table 1).

Our published result on Γ_1^d [58] is dominated by a systematic error of 0.005 (i.e. 10%), which results mainly from the combination of relative errors on the beam and target polarisation and the dilution factor. These errors are expected to be reduced for the proton, e.g. the NH_3 target polarisation measurement from 5% to 2%. The improved values result in the following uncertainties on the Bjorken sum

$$\int_{0.003}^{0.7} g_1^{NS}(x)\mathrm{d}x : \qquad \pm 0.006\,(\text{stat.}) \pm 0.011\,(\text{syst.})$$

to be compared to the SMC result of $0.184 \pm 0.016\,(\text{stat.}) \pm 0.014\,(\text{syst.})$. The unmeasured low-$x$ contribution to Γ_1^{NS} is estimated to 0.008 using QCD fits assuming either positive

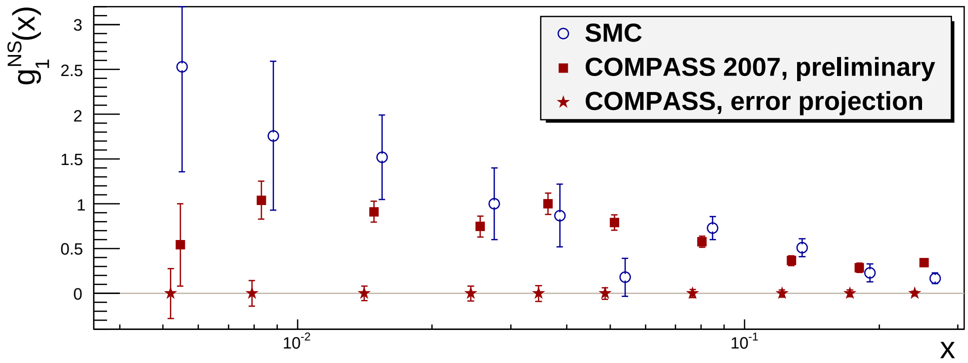

Figure 9: Preliminary results for the non-singlet structure function $g_1^{NS}(x)$. The statistical uncertainties projected for a data set including the proposed new measurements are shown on the zero line. For comparison the SMC measurements are also shown.

Table 1: The statistical uncertainties for the truncated moments of the proton and deuteron structure functions g_1^p and g_1^d and of the non-singlet structure function g_1^{NS}.

	$\delta(\int_{0.003}^{0.7} g_1^p dx)$	$\delta(\int_{0.003}^{0.7} g_1^d dx)$	$\delta(\int_{0.003}^{0.7} g_1^{NS} dx)$
SMC	0.005	0.006	0.016
COMPASS	0.004	0.002	0.008
COMPASS proj.	0.002		0.006

or negative ΔG [58].

3.5 Flavour separation of helicity distributions $\Delta q(x)$

At LO in QCD, under the assumption of independent quark fragmentation function, the double-spin asymmetries for a hadron h produced in the current fragmentation region can be written in terms of quark helicity distributions Δq

$$A_1^h(x, Q^2, z) = \frac{\Sigma_q e_q^2 \Delta q(x, Q^2) D_q^h(z, Q^2)}{\Sigma_q e_q^2 q(x, Q^2) D_q^h(z, Q^2)}.$$

The sums run over $q = u, d, s, \bar{u}, \bar{d}, \bar{s}$. Hadron asymmetries A_p^h (where h can be a charged pion or kaon, or a K^0) are measured in parallel to the inclusive ones. For the extraction of all $\Delta q^f(x)$ the knowledge of the unpolarised quark distributions $q(x)$ and of the fragmentation functions (FF) $D_q^h(z)$ is required. The latter are reasonably known for up and down quarks, but poorly known for the strange quark. This is illustrated in the Appendix B.

Previous analyses determining the quark helicity distributions were performed by the SMC [67] and the HERMES [68, 69] Collaborations using proton and deuteron data. The SMC data cover a similar kinematic range as the COMPASS data, but due to the missing particle identification (PID) the determination of Δs was not possible. HERMES has a high statistics deuteron data set and PID, thus all five quark helicity distributions could be disentangled. On the other hand, the x region accessible to HERMES is limited due to the low incident lepton energy ($0.023 < x < 0.6$) and as a consequence the full first moments of the quark helicity distributions were not presented, but only integrals in the measured range.

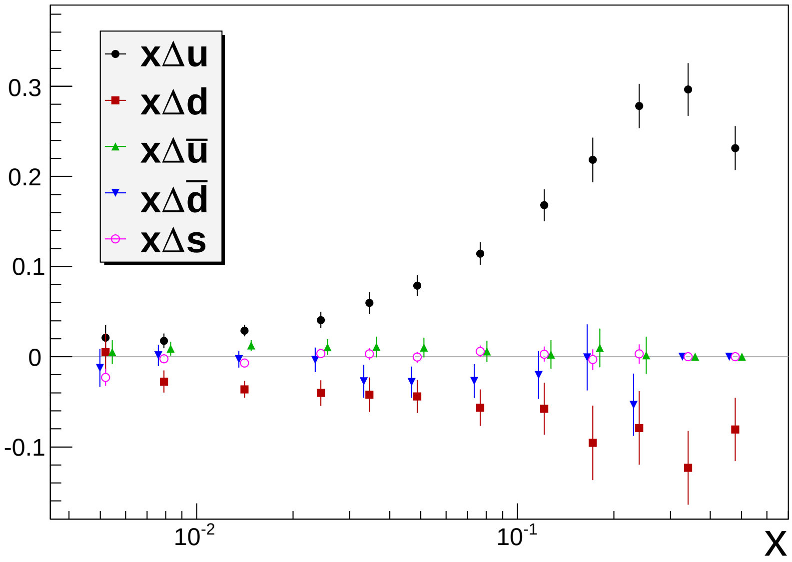

Figure 10: Projected errors on Δu $\Delta\bar{u}$, Δd, $\Delta\bar{d}$ and Δs assuming one additional year of proton data and using DSS [72] fragmentation functions at LO.

At COMPASS, the high energy of the polarised muon beam ensures an x coverage from 0.003 to 0.7 and a good separation between the current and target fragmentation regions. Indeed, working at a much larger W^2 corresponds to higher centre-of-mass rapidity for the same z cut. The large acceptance for hadrons is combined with an excellent particle identification by the RICH.

The COMPASS 2002–2006 deuteron data alone already led to the separate determination of the valence $\Delta u_v + \Delta d_v$, and sea quark $\Delta\bar{u} + \Delta\bar{d}$ polarised distributions [59, 70] (see Appendix B). In particular $\Delta\bar{u} + \Delta\bar{d}$ was measured to be close to zero ($-0.03 \pm 0.03 \pm 0.01$), in contrast to the often assumed fully symmetric scenario $\Delta\bar{u} = \Delta\bar{d} = \Delta\bar{s} = \Delta s$, but in agreement with the latest parametrisation of DNS [71].

The first set of proton data was taken by COMPASS in 2007. Combined with the deuteron data, it leads to a separate extraction of all flavours Δu, $\Delta\bar{u}$, Δd, $\Delta\bar{d}$ and Δs (the latter assumed to be equal to $\Delta\bar{s}$) as a function of x. The projected error bars for COMPASS assuming an additional year with a proton target are shown in Fig. 10 using the DSS [72] fragmentation functions at LO. The statistical uncertainties are reduced by 35% on Δu and $\Delta\bar{u}$, by 15% on Δd and $\Delta\bar{d}$ and by 20% on Δs, compared to the present 2002–2007 error bars (not shown here). More importantly, the COMPASS data reach x values about ten times smaller than HERMES, covering a region where the sea quark distributions are not bound by unpolarised distributions as at higher x.

The determination of the helicity distributions at RHIC via $W^\pm$ exchange is limited to $x > 0.04$ for $\sqrt{s} = 500$ GeV.

3.5.1 Flavor asymmetry of the light sea $\Delta\bar{u} - \Delta\bar{d}$

The sizable flavour asymmetry between the unpolarised up and down sea-quark distributions ($\bar{u}(x)-\bar{d}(x) < 0$) has been a well established experimental fact since more than ten years (see e.g. [73] and references therein). It has inspired a large theoretical activity and led to various non-perturbative models, which also predict a flavour asymmetry for the helicity densities of the light sea ($\Delta\bar{u} - \Delta\bar{d} \neq 0$). Most of the models, like Pauli-blocking models, instanton model, chiral quark–soliton model and statistical models

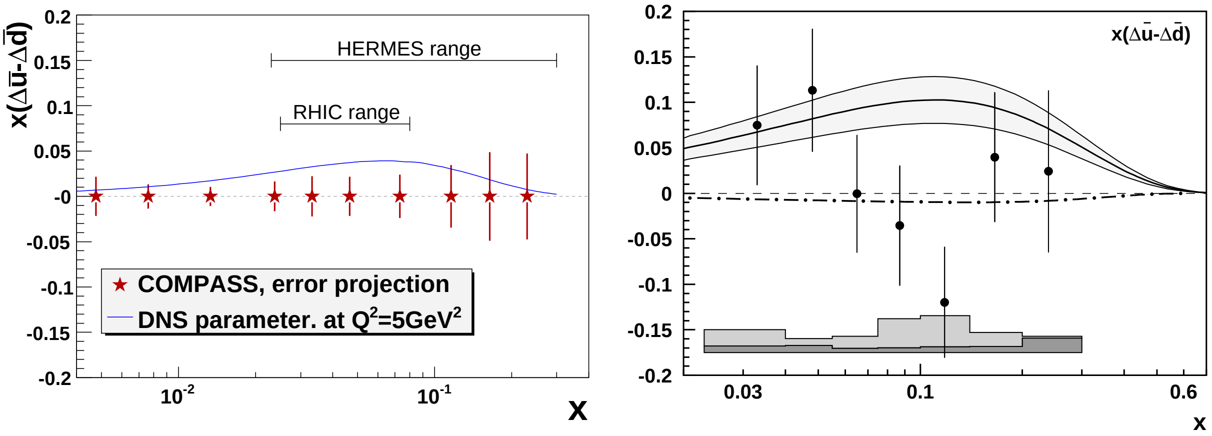

Figure 11: Left: Projected errors for $\Delta\bar{u}-\Delta\bar{d}$ assuming one additional year of proton data and using DSS [72] FF. The curve is taken from the DNS [71] global QCD fit at LO. Right: $\Delta\bar{u}-\Delta\bar{d}$, evaluated by HERMES [68] at $Q_0^2 = 2.5$ GeV^2. The data are compared with predictions from the χQSM (solid line) and from a meson cloud model (dash-dotted line).

(see review [74] and references therein), predict a positive value of $\Delta\bar{u} - \Delta\bar{d}$. The meson cloud models are the only ones which predict a $\Delta\bar{u} - \Delta\bar{d}$ very small in absolute value, but with a negative sign. Only measurements can provide a test of those predictions.

The difference $\Delta\bar{u} - \Delta\bar{d}$ was measured by HERMES [68]. Their results evaluated at $Q^2 = 2.5$ GeV^2 are shown in Fig. 11. For comparison predictions from the chiral quark–soliton model (χQSM) [75] and from a meson cloud model [76] are also shown. These models were chosen because they provide two extreme predictions (largest positive and almost zero, respectively). Within their large uncertainties, the results of HERMES rather favour a symmetric polarised light flavour sea and exclude the χQSM at a 97% confidence level.

Estimates of the statistical precision for the flavour asymmetry in the helicity densities of the light sea, $\Delta\bar{u}(x) - \Delta\bar{d}(x)$, which can be obtained with the proposed measurements are shown in Fig. 11. We use the FF from DSS [72] and make the same assumptions as those described in previous subsections. The curve shows the parameterisation from the global QCD fit at LO from DNS [71]. The x domain covered by HERMES is indicated by the horizontal line. One can see that the precision of COMPASS data permits to distinguish between the two models presented in Fig. 11.

3.5.2 The case for Δs — consistency of DIS and SIDIS data.

The case for $\Delta s(x)$ is of particular interest. It is the only polarised sea quark distribution for which the first moment can be extracted directly from inclusive DIS measurements, assuming SU(3) flavour symmetry and using data from hyperon decay constants. The first moment was found rather large and negative, equal approximately to -0.1 already by EMC. This was confirmed by HERMES [69] and the COMPASS result [59]

$$\int_0^1 (\Delta s + \Delta\bar{s})\mathrm{d}x = -0.09 \pm 0.01\,(\mathrm{stat.}) \pm 0.02\,(\mathrm{syst.}).$$

Hints on the shape of $\Delta s(x)$ cannot be obtained with sufficient accuracy from global fits of $g_1(x, Q^2)$ due to the lack of precise and dense g_1 data.

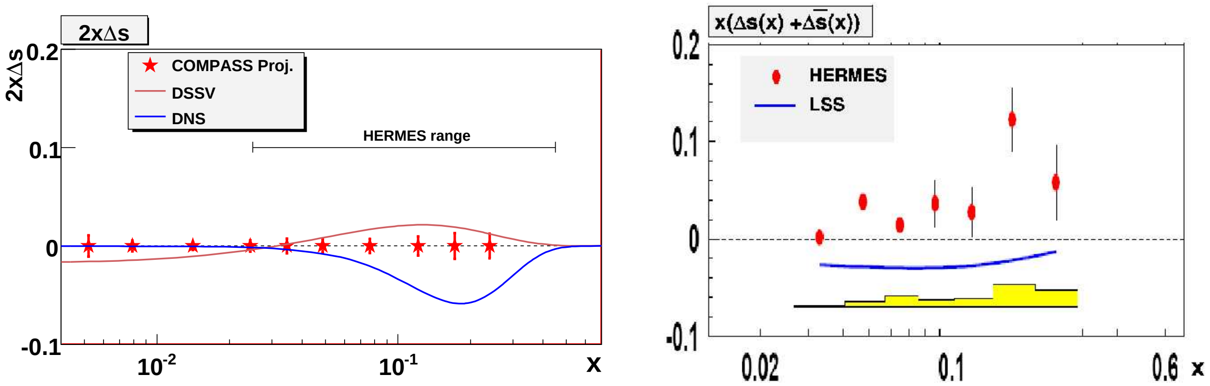

Figure 12: Left: Error projections for the strange quark helicity density $2\Delta s$ with one additional year of proton data. The curves are parameterisations from DSSV [66] (NLO fit using DSS FF) and DNS [71] (LO fit using Kretzer et al. FF). Right: HERMES results [69] for Δs+$\Delta\bar{s}$ at $Q_0^2 = 2.5$ GeV^2 together with parameterisation from LSS [78].

More direct measurements of Δs are accessible through semi-inclusive DIS, and in particular from the production of kaons where interactions with strange quarks are favoured. However, these results extracted at LO, depend strongly on the set of fragmentation functions used. First results from semi-inclusive DIS on the deuteron obtained by HERMES and COMPASS show values of $\Delta s(x)$ compatible with zero, or slightly positive for HERMES. The integrated value in the measured range, down to $x = 0.02$ for HERMES [69] is

$$\int_{0.02}^{0.6} (\Delta s + \Delta\bar{s})\mathrm{d}x = 0.037 \pm 0.019\,(\mathrm{stat.}) \pm 0.027\,(\mathrm{syst.})$$

and down to $x = 0.004$ for COMPASS is

$$\int_{0.004}^{0.7} (\Delta s + \Delta\bar{s})\mathrm{d}x = -0.01 \pm 0.01\,(\mathrm{stat.}) \pm 0.02\,(\mathrm{syst.}).$$

In the recent DSSV global fit [66], which includes HERMES data, the positive values of $\Delta s(x)$ at $x > 0.05$ are compensated by negative ones in the unmeasured low-x region in order to accommodate to the negative value of the first moment of $\Delta s + \Delta\bar{s}$ cited above (≈ -0.10).

Using COMPASS semi-inclusive deuteron data [70] we have shown the strong dependence of Δs on the fragmentation functions and in particular on the ratio of fragmentation functions R_{SF} ($\bar{s}$ and u quark fragmentation functions into K^+: $D_{\bar{s}}^{K^+}/D_u^{K^+}$). This ratio will be determined experimentally from existing COMPASS data (work is in progress). When it is known precisely, and provided it is large enough ($\geq$ 5), the dominant uncertainty on Δs extracted from semi-inclusive asymmetries will be the statistical error. Assuming $R_{SF} = 5 - 6$, the discrepancy between inclusive and semi-inclusive results on Δs, is presently at a two σ level.

The projected errors for $2x\Delta s(x)$, using DSS [72] fragmentation functions (FF), are shown in Fig. 12 together with parameterisations from DSSV [66] (NLO global QCD fit using FF from DSS) and DNS [71] (LO global QCD fit using FF from Kretzer et al. [77]). Results from HERMES for $x(\Delta s(x) + \Delta\bar{s}(x))$, using also DSS FF are shown in Fig. 12 with the same vertical scale. They are compared to the LSS [78] parameterisation.

3.6 Higher energy and higher luminosity

From the above presentations, two kinds of kinematical regions emerged as of particular importance: the low-x region (for g_1^p, g_1^{NS}, $\Delta\bar{q}$ and Δs) and the high-Q^2 region (to increase the lever arm in Q^2 at fixed x for g_1^p evolution in global QCD analyses). This implies that the maximum beam energy and/or the maximum luminosity are vital.

The present simulations for g_1^p (Fig. 8) were obtained assuming a beam energy of 200 GeV and a luminosity comparable to the one used in 2007. We have shown, using a LEPTO simulation, that a further increase in energy, i.e. going to 220 GeV would add 50% more statistics to the present low x bin, or alternatively provide a new low-x bin [79]. As a consequence, we should look at possible substantial improvements in luminosity as well as beam energy.

4 Spectrometer and beam requirements

4.1 Experimental apparatus

The apparatus to be used for the proposed measurements is essentially the same as used during the 2007 muon run. With respect to the 2004 version of the spectrometer, described in detail in Ref. [3], important improvements were made for the 2006 muon run already outlined in the same paper. In particular the polarised target magnet will be the large acceptance COMPASS magnet used in 2006 and 2007, which guarantees about twice more hadrons at large x with respect to the runs of the previous years. The polarised target will be the same used in 2007, namely a NH_3 target divided in 3 cells, a central cell 60 cm long and two 30 cm cells with polarisation opposite to that of the central one. With the RICH photon detector upgrade in 2006 particle identification is excellent also in the central region close to the beam.

The measurement will also benefit from the improvements of the the spectrometer for the 2008 and 2009 hadron runs. These include the use of pixelised GEM detectors at small angles, upgraded electromagnetic calorimetry and a more performing DAQ system. The spectrometer provides good track resolution and particle identification over a wide phase space interval. The high incident energy allows for measurements of polarised deep inelastic scattering (DIS) for x values down to about 0.003 while keeping $Q^2 > 1(\mathrm{GeV}/c)^2$. High polarisation of the incident muons and of the target protons create ideal conditions for spin asymmetry measurements. Excellent identification of the final state particles gives access to semi-inclusive hadron asymmetries in the DIS region.

Smaller upgrades are planned concerning

- the beam intensity monitor. A new beam counter will be installed and tested during the DVCS test beam COMPASS plans to do during the 2009 run. Its use in the 2010 run will permit to further scrutinise the stability of the spectrometer performance;
- the trigger system. A new hodoscope system will be built to trigger in the high-x–high-Q^2 region, replacing the “Calorimetric Trigger” used in the 2007 run. This new trigger, which is needed also for other possible future measurements in COMPASS, will improve the purity and the overall efficiency. Also, the existing hodoscope elements will be rearranged to cover the full azimuthal angular range of the scattered muon;
- the target holder. A new target holder is being constructed, which doesn’t contain free protons. Such protons complicated the polarisation measurement considerably in 2007.

All together, these upgrades will allow for more efficient and stable data taking, and they are expected to give a 30% gain in the number of events over all the x range, and some higher gain in the large-x region. This gain should compensate the loss of muons when going to 200 GeV muon momentum for the longitudinal part of the programme.

4.2 Beam request

For the beam time requests it is assumed that 2.4×10^{13} protons are delivered to the T6 target of the M2 beam line every 40.8 s. With an accelerator chain efficiency of 80% and a running time of 150 days a total of 6×10^{18} protons at T6 is expected. For each of the two proposed measurements we request this number of protons, which is also the basis of all projections presented in this document.

The COMPASS spectrometer availability and efficiency as well as the average polarisation of the NH_3 target ($> 80\%$) are assumed to be the same as in the 2007 run. In addition an increase of 30% in the collected data is expected from hardware upgrades, in particular concerning the DAQ and trigger. The measurements should start 2010 with the transverse part.

Transverse measurements: The measurements will be performed with a 160 GeV/c positive muon beam and transverse target polarisation. The target polarisation will be reversed by irradiation with microwaves about once per week. The running time requirements have been evaluated in order to achieve the necessary accuracy for the first complete mapping of the properties of the new transverse PDFs and fragmentation functions.

We assume a rejection of 20% of the collected events due to stability requirements (the typical value we had for the deuteron runs in 2003 and 2004). Under these conservative assumptions, we expect to collect data from about 8×10^{13} muons, that is 9 times more data compared to what was used for the 2007 preliminary results shown in Section 2.2.

Longitudinal measurements: The measurement will be performed with a 200 GeV/c positive muon beam and longitudinal target polarisation. The higher muon momentum is chosen to enhance the statistics at low x. The loss of intensity at 200 GeV compared to 160 GeV used in 2007 is assumed to be compensated by the upgrades in the hardware. The event rejection rate is much lower in the longitudinal case than in the transverse case due to a daily polarisation reversal by rotation of the magnetic field and an in general lesser sensitivity of the asymmetries to spectrometer efficiency variations.

5 Summary

We have presented an Addendum to the COMPASS Proposal with the aim to progress in the understanding of the transverse spin structure of the proton and to improve the knowledge of its helicity structure, in particular at low x and high Q^2. Both subjects are important issues in QCD and concern basic properties of the nucleon. The proposed measurements will have a significant impact in the field. Moreover, their combination with the already taken deuteron data will permit to further investigate individually the role of up, down and strange quarks in the nucleon.

The high intensity and polarisation of the muon beam together with the COMPASS polarised target and spectrometer make CERN a unique place to perform such measurements. This will not change until the the construction of a high energy and luminosity polarised electron–ion collider in the longer term future.

Appendix

A TMD PDFs and SIDIS scattering

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 kinematical range can be written in a model independent way as:

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

Here ϕ_S and ϕ_h are the azimuthal angles of the nucleon transverse spin and of the hadron transverse momentum $\vec{p}_T^{\,h}$ 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 polarisation.

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 polarisation (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 flavors. 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. [20]

COMPASS has measured the Collins and Sivers asymmetries (see Sec. 2.2) and has produced preliminary results on deuteron for the F_{UT} and F_{LT} structure functions. Preliminary results from the deuteron data have also been obtained for the unpolarised structure functions $F_{UU}^{\cos\phi_h}$ and $F_{UU}^{\cos 2\phi_h}$ which contains $h_1^\perp \otimes H_1^\perp$.

B Highlights from COMPASS measurements with longitudinally polarised deuterons

COMPASS started measurements with the 160 GeV/c polarised muon beam with the measurement of the gluon polarisation as the main goal. Therefore the data taking from 2002 to 2006 used a polarised deuteron (^{6}LiD) target. A polarised proton (NH_3) target was only used in 2007. Here we focus on the measurements with longitudinally polarised ^{6}LiD target.

B.1 Inclusive measurements and moments of polarised PDFs from global QCD analysis

Inclusive asymmetries $A_1^d(x, Q^2)$ were extracted in a wide range of x and Q^2, independently for $Q^2 < 1$ (GeV/c)^2 [80] and $Q^2 > 1$ (GeV/c)^2 [58, 81]. The first results are compared with previous measurements in Fig. 13. It shows that A_1^d is compatible with zero for $x \leq 0.03$ and that the precision at low x, here given for 2002–2003 data only, is already more than tenfold better than previous experiments. The spin structure function g_1^d as obtained in the analysis with $Q^2 > 1$ (GeV/c)^2 is compared to earlier results from SMC in Fig. 14. The negative trend observed by SMC at low x is not confirmed, xg_1^d is consistent with zero for $x \leq 0.03$. The new results lead to a dramatic reduction (from 50% to 2%) of the uncertainty of the low x extrapolation. After evolution to a common Q^2 of 3 (GeV/c)^2 the first moment Γ_1^N of the nucleon was determined as $\Gamma_1^N = 0.050 \pm 0.003\,(\text{stat.}) \pm 0.003\,(\text{evol.}) \pm 0.005\,(\text{syst.})$ with a high statistical precision. Here, the measured region represents 98% of the total value. The first moment gives access to the singlet axial current a_0 using values obtained from neutron decay for a_3 and from hyperons decays for a_8. The values of $a_0 = 0.33 \pm 0.03\,(\text{stat.}) \pm 0.05\,(\text{syst.})$) and $\Delta s + \Delta\bar{s} = \frac{1}{3}(a_0 - a_8) = -0.08 \pm 0.01\,(\text{stat.}) \pm 0.02\,(\text{syst.})$ are obtained when extrapolated to $Q^2 \to \infty$ ($a_0 = \Delta\Sigma$ in the used $\overline{\text{MS}}$ scheme). The new g_1^d results were used in a new NLO pQCD analysis of the data for g_1^p, g_1^d and g_1^n [58] which also provides the extrapolation needed to calculate Γ_1^N. Adding the new COMPASS data led to an increase of $\Delta\Sigma$ from ≈ 25 to 30% and a reduction of its statistical error by 50%. The fit yields two solutions with either $\Delta g(x) > 0$ or $\Delta g(x) < 0$ (see curves in Fig. 14) which equally well describe the data. In both cases, the first moment (ΔG) of $\Delta g(x)$ is of the order of 0.2–0.3 in absolute values, but the shapes of the $\Delta g(x)$ distributions are very different.

B.2 Direct measurement of the gluon helicity distribution

Direct access to the gluon polarisation is obtained using the photon-gluon fusion process (PGF). PGF events can be tagged either by the open charm production or by the high-p_T hadron pairs. In the former case the PGF mechanism yields a $c\bar{c}$ pair which fragments mainly into D mesons [64]. In COMPASS D^0 and $\bar{D}^0$ mesons are reconstructed from the decay channels with a $K\pi$ pair: $D^*(2010)^+ \to D^0\pi^+_\text{slow} \to K^-\pi^+\pi^+_\text{slow}$, $D^*(2010)^+ \to D^0\pi^+_\text{slow} \to K^-\pi^+\pi^0\pi^+_\text{slow}$ and $D^0 \to K^-\pi^+$ and charge conjugates. Using a parametrisation of the analysing power a_LL in LO obtained via a neural net trained on a Monte Carlo simulation with the AROMA generator, a preliminary value of $\langle\Delta G/G\rangle = -0.39 \pm 0.24\,(\text{stat.}) \pm 0.11\,(\text{syst.})$ is obtained at $x_g = 0.11$ and at a QCD scale of ≈ 13 (GeV/c)^2 [65] using all 2002–2006 data. Using the high-p_T hadron pairs a much higher statistical precision of the measurement was obtained. However for this analysis also physical background processes like the QCD Compton process or resolved photon processes contribute to the measured asymmetries. These contributions have to be estimated using Monte Carlo simulations, leading to larger systematic uncertainties of

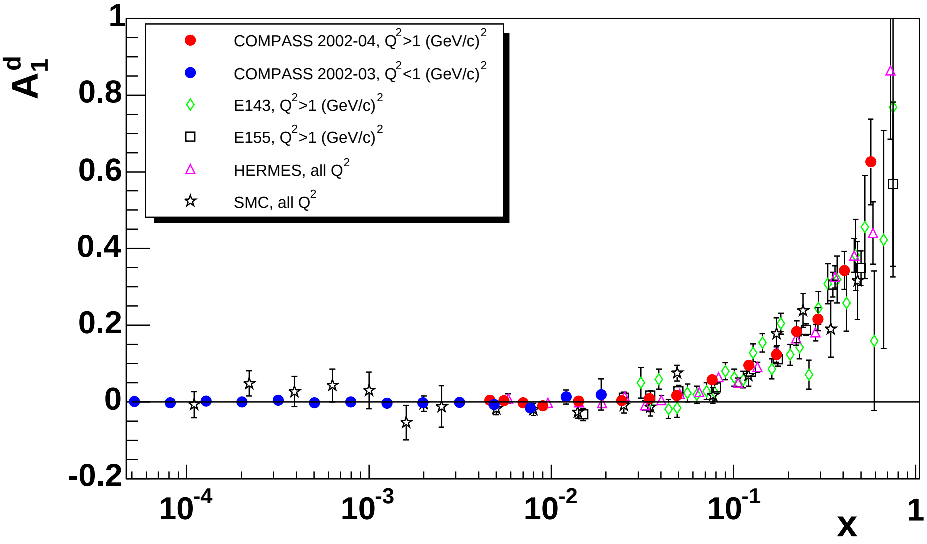

Figure 13: Results from different experiments on $A_1^d(x)$ as a function of x.

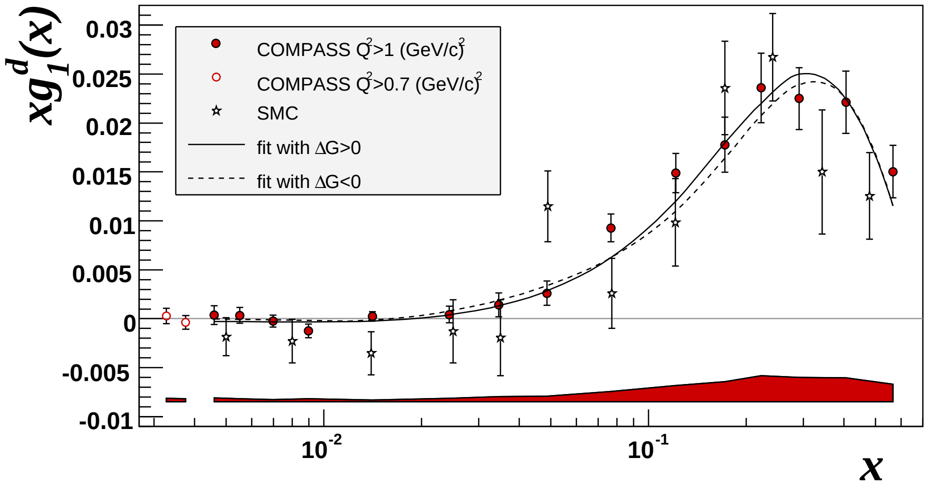

Figure 14: Results for the spin-dependent structure function of deuteron $xg_1^d(x)$ from COMPASS (2002–2004 data) and SMC. The curves are from the COMPASS NLO pQCD fit [58] with a positive or negative gluon distribution.

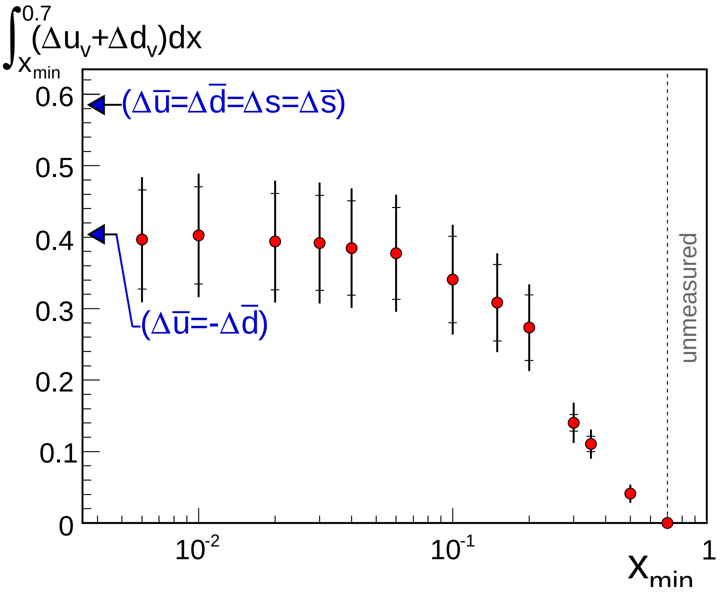

Figure 15: Integral of $\Delta u_v(x) + \Delta d_v(x)$ over the range of $0.006 < x < 0.7$ as a function of the x_{min} limit, evaluated at $Q^2 = 10$ (GeV/c)^2. COMPASS deuteron data (2002–2004).

the results. The high-p_{T} analysis is done independently for $Q^2 < 1$ (GeV/c)^2 [60] where PYTHIA is used as MC generator, and for $Q^2 > 1$ (GeV/c)^2 [61] where resolved photon processes are negligible and the LEPTO generator can be used as MC generator. A value of $\langle \Delta G/G \rangle = 0.02 \pm 0.06\,(\mathrm{stat.}) \pm 0.06\,(\mathrm{syst.})$ is obtained at $\langle x_g \rangle = 0.09$ for $Q^2 < 1$ (GeV/c)^2 data, and $\langle \Delta G/G \rangle = 0.08 \pm 0.10\,(\mathrm{stat.}) \pm 0.05\,(\mathrm{syst.})$ at $\langle x_g \rangle = 0.08$ for $Q^2 > 1$ (GeV/c)^2 data. For both results, the QCD scale is ≈ 3 (GeV/c)^2. All measurements indicate that the gluon polarisation is small or compatible with zero for gluon momentum fractions of $x_g \approx 0.1$.

B.3 Quark helicity distributions from semi-inclusive measurements

Access to the polarisation of the individual quark flavours can be obtained from the measurement of semi-inclusive asymmetries. In a first step COMPASS extracted longitudinal asymmetries for positive and negative hadrons in the range of $0.006 < x < 0.7$ [59]. The difference of these asymmetries can be related to the polarised valence quark distribution and its first moment. Figure 15 illustrates the result for the truncated first moment of $\Delta u_v + \Delta d_v$, $\Gamma_v = 0.40 \pm 0.07\,(\mathrm{stat.}) \pm 0.06\,(\mathrm{syst.})$ in the measured range, which can be used to estimate the contribution of the polarised sea to the nucleon spin. Using Γ_1^N and a_8 in addition, the data indicate that $\Delta\bar{u} + \Delta\bar{d}$ is compatible with zero, thus suggesting a flavour asymmetric polarised light quark sea, similar to the non-polarised case.

More information can be extracted using the semi-inclusive asymmetries for identified pions and kaons [70]. Based on all the COMPASS deuteron statistics, a LO analysis was performed using results for A_1^d, A^{π^+}, A^{π^+}, A^{K^-} and A^{K^+} obtained in the range $0.004 < x < 0.3$ to determine the polarised valence, light quark sea and strange quark sea distributions. Pions and kaons were identified using the RICH in the first spectrometer stage. In this analysis good knowledge of the fragmentation functions (FF) is essential. Whereas the favoured (like $D_u^{\pi^+}$) and unfavoured (like $D_u^{\pi^-}$) fragmentation functions of non-strange quarks are reasonably well known, the fragmentation functions of strange

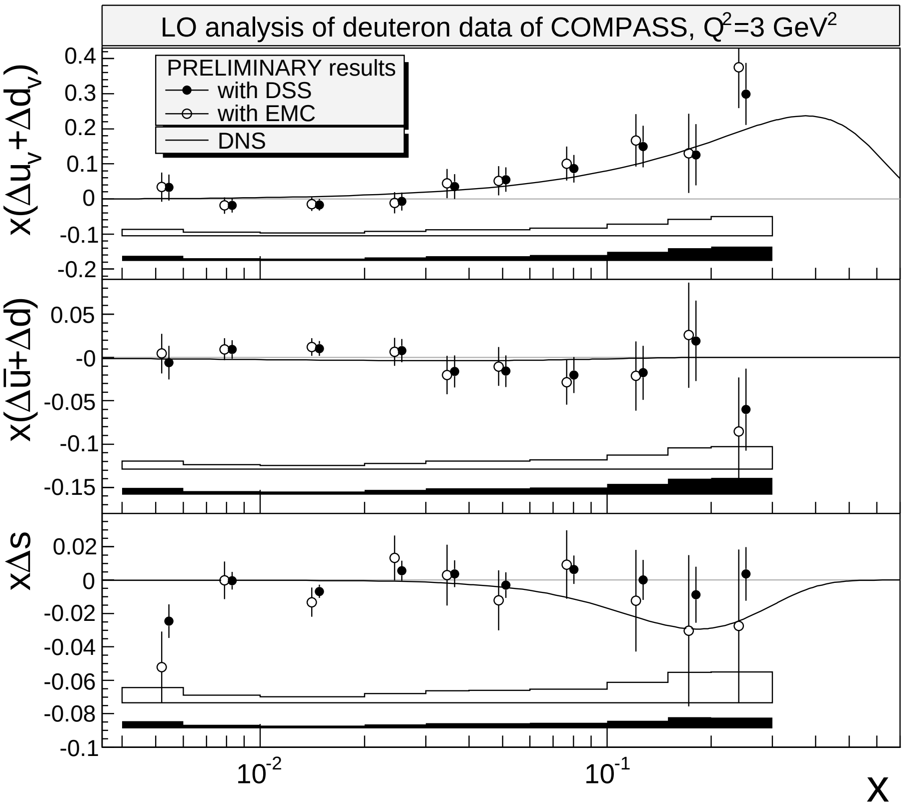

Figure 16: Quark helicity distributions evaluated from COMPASS deuteron data (2002–2006) as a function of x. Values are given for two set of fragmentation functions: DSS[72] and EMC (see text). The curves represent the DNS [71] LO parameterisation of polarised PDF.

quarks have not been measured in the COMPASS kinematic range. They can be taken from global analyses including e^+e^- data, like DSS [72]; polarised PDF extracted in this way are referred to as "with DSS" in Fig. 16. Fragmentation functions for strange quarks can also be estimated using assumptions made by EMC, namely $D_{\bar{s}}^{K^+} = D_u^{\pi^+}$ equal to all favoured FF; corresponding results for polarised PDF are referred to as "with EMC" in Fig. 16. This uncertainty on the FF of strange quarks in COMPASS kinematics introduces a systematic uncertainty in the determination of $\Delta s(x)$. The results for the valence distribution are in good agreement with the determination discussed above for unidentified hadrons. For Δs, values compatible with zero are obtained in contrast to the results of the QCD analyses using inclusive asymmetries only. Thus, the future analysis will concentrate on a determination of the strange quark fragmentation functions which have a direct impact on these results.

B.4 Lambda and rho production

Further results from the deuteron data are available on the production of Λ hyperons and ρ mesons. For the exclusive ρ^0 production the measured asymmetries A_1^ρ are dominated by quasi-real photoproduction and are compatible with zero in the Q^2 range of $3 \cdot 10^{-7}$ (GeV/c)^2 to 7 (GeV/c)^2 and x from $5 \cdot 10^{-5}$ to 0.05 [82]. An analysis of exclusive ρ production to determine the spin density matrix elements is on the way.

The longitudinal spin transfer to Λ and $\bar{\Lambda}$ hyperons was investigated in the region of $Q^2 > 1$ (GeV/c)^2 to shed more light on strange quarks in the nucleon [83]. In a first step, averaging over the target polarisation, sensitivity to the unpolarised strange quark distribution is obtained. The measured Λ spin transfer is compatible with zero whereas sizable effects are observed for $\bar{\Lambda}$. Using a model for the spin structure of the Λ hyperon these results are sensitive mainly to the $\bar{s}$ distribution in the nucleon.

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