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THE SPIN STRUCTURE OF THE NUCLEON: a phenomenological introduction

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Abstract

The investigation of the spin structure of the nucleon via semi-inclusive deep inelastic scattering on polarized nucleons is updated with the most recent results of the JLab, HERMES, and COMPASS experiments. A short description is given of these experiments, which are complementary in phase space and use sophisticated and different techniques to polarize the nucleon targets. The cases of target spin parallel or orthogonal to the direction of the incoming lepton require different experimental techniques, have a different phenomenology and need a different theoretical treatment. After reviewing these differences, the most recent transverse spin advances are presented, and evidence is given that the new data already allow for a rather precise extraction of the transversity and of the Sivers PDFs.

1 Introduction

Always nice to be in Erice, and I am grateful to Amand and Jochen for giving me again the opportunity to come here and talk about the most recent advances of our knowledge of the spin structure of the nucleon.

Since the time the magnetic moment of the proton was first measured by Frisch and Stern in 1933 (the magnetic moment of the deuteron was measured by Rabi and collaborators the following year) it is known that the nucleons are not Dirac particles, and must have an internal structure. With the advent of the quark model, in the 60s, the magnetic moments of the baryons could be explained with a remarkable accuracy and simplicity. In this model, the quarks are in an S-state, they fully account for the nucleon spin, and there is no contribution from either the sea-quarks or the gluons. It is well known that this picture does not correspond to reality, and that in 1988 the EMC Collaboration at CERN [1] showed that the spins of the quarks contribute for only a small fraction to the proton spin. This finding was totally unexpected, and several experiments were proposed and executed to confirm the effect, to extend the result to the neutron, and to improve the accuracy of the measurement. Twenty years later, we know that the quarks contribute only 1/3 of the nucleon spin, a number which is known with a 10% accuracy.

The standard technique to investigate the structure of the nucleon is Deep Inelastic Scattering (DIS), and, using polarised lepton beams and polarised targets the spin structure of the nucleon can be measured. If both the beam and the target spins are aligned along the direction of the incident lepton, one structure function, g_1, can be measured from the cross-section asymmetry of the inclusive scattering. In the quark parton model this structure function can be written as

$$g_1(x) = \frac{1}{2}\Sigma_q e_q^2 \cdot \Delta q(x) \tag{1}$$

where e_q are the quark charges and $\Delta q(x) = \left\{\left(q(x)^{\downarrow\uparrow} + \bar{q}(x)^{\downarrow\uparrow}\right) - \left(q(x)^{\uparrow\uparrow} + \bar{q}(x)^{\uparrow\uparrow}\right)\right\}$ are the differences of the quark densities for quark spin antiparallel or parallel to the target nucleon spin. Adding up over the quark flavours the first moments $\Delta q = \int_0^1 \Delta q(x)\ dx$, one obtains $\Delta\Sigma = \Delta u + \Delta d + \Delta s$, i.e. the contribution of the spin of the quarks to the spin of the nucleon which in general terms can be written as

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + < L_z > \ . \tag{2}$$

In this expression, ΔG is the contribution of the gluons, and $< L_z >$ is a possible contribution from the gluons and quarks angular momentum.

$\Delta\Sigma$ being small, an important effort has been ongoing to measure ΔG, both in semi-inclusive DIS experiments (SIDIS), namely in experiments in which inclusively produced hadrons are detected on top of the incoming and outgoing lepton, and at RHIC, colliding polarized proton beams at high energies. In all these experiments, both the incoming particles and the target nucleons are longitudinally polarized, and ΔG is extracted from a cross-section spin asymmetry. Within the experimental accuracies, all these experiments suggest rather small values, even compatible with zero, for ΔG, so that the missing contribution to the nucleon spin is not likely to be provided by the gluons, but rather by the orbital angular momenta of the quarks and of the gluons. More information on the SIDIS experiments with longitudinal beams and targets can be found in other talks given at this school, thus I will no longer discuss this case and rather switch to the case of transversely polarized nucleon targets.

2 Transverse spin and transverse momentum

Transverse spin phenomena in hard processes have been discovered and investigated theoretically since 40 years but the field was vigorously revisited in the 90s, when a general scheme [2] of all leading twist and higher twist parton distribution functions (PDFs) was worked out.

These studies were originally motivated by the attempt to understand the spectacular transverse spin effects which had been observed in pp reactions [3]. These effects persist even at very large energy, and have been observed again at RHIC, at $\sqrt{s} = 200$ GeV [4]. An ambitious project is ongoing to understand these effects in terms of transverse momentum dependent (TMD) distribution functions and fragmentation functions. Along this line, transverse spin effects have been predicted in SIDIS.

It has been realised that to fully specify the quark structure of the nucleon at the twist-two level, the transverse spin distributions $\Delta_T q(x)$ must be added to the momentum distributions $q(x)$ and the helicity distributions $\Delta q(x)$ [2]. The definition of $\Delta_T q(x)$ is analogous to that of $\Delta q(x)$, but it refers to transversely polarised quarks in a transversely polarised nucleon. The transversity distributions $\Delta_T q$ are difficult to measure, since they are chirally odd and therefore absent in inclusive DIS. They may instead be extracted from measurements of the single-spin asymmetries in SIDIS cross-sections of leptons on transversely polarized nucleons. In these processes the measurable asymmetry, the "Collins asymmetry" A_{Coll}, is due to the combined effect of $\Delta_T q$ and another chirally-odd function, $\Delta_T^0 D_q^h$, which describes the spin-dependent part of the hadronization of a transversely polarized quark q into a hadron h [5]. At leading order A_{Coll} can be written as

$$A_{Coll} = \frac{\sum_q e_q^2 \cdot \Delta_T q \cdot \Delta_T^0 D_q^h}{\sum_q e_q^2 \cdot q \cdot D_q^h}\ , \tag{3}$$

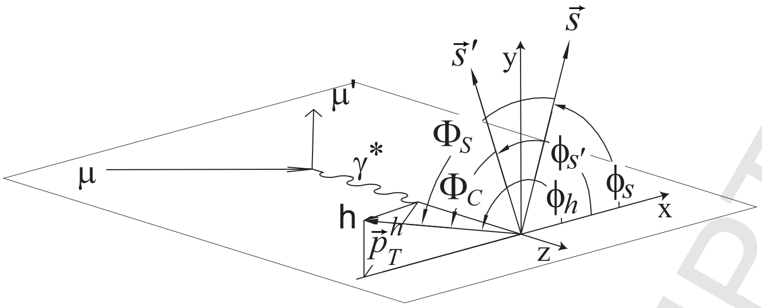

Figure 1: Definition of the Collins and Sivers angles. The vectors $\vec{p}_T^{\,h}$, $\vec{s}$ and $\vec{s'}$ are the hadron transverse momentum and the spin of the initial and struck quarks respectively.

and should show up as the amplitude of a $\sin\Phi_C$ modulation in the hadron azimuthal distribution. The Collins angle $\Phi_C = \phi_h + \phi_s - \pi$ is the sum of the azimuthal angles of the hadron transverse momentum $\vec{p}_T^{\,h}$ (ϕ_h) and of the spin direction of the target nucleon (ϕ_s) with respect to the lepton scattering plane, as measured in the Gamma-Nucleon System. Figure 1 illustrates the choice of the reference system and of the relevant angles. A non-zero Collins asymmetry for the proton was first observed by HERMES [6] implying that the Collins fragmentation and the transversity functions are both non-vanishing. Independent evidence of a non-zero and sizeable Collins function came soon after from the measurements of a correlation between the azimuthal angles of the hadrons in the two jets resulting from the e^+e^- annihilations at high energy as measured by the Belle Collaboration [7].

If the quarks are assumed to be collinear with the parent nucleon (no intrinsic quark transverse momentum $\vec{k}_T$), or after integration over $\vec{k}_T$, the three distributions $q(x)$, $\Delta q(x)$ and $\Delta_T q(x)$ exhaust the information on the internal dynamics of the nucleon. However, admitting a finite $\vec{k}_T$, a total of eight transverse momentum dependent (TMD) distribution functions are needed for a full description of the nucleon [8]. All these functions lead to azimuthal asymmetries in the SIDIS cross-section and can be disentangled measuring their different angular modulations.

In between these TMD PDFs of particular interest is the Sivers function $\Delta_0^T q$ (or f_1^q) which arises from a correlation between the transverse momentum of an unpolarised quark in a transversely polarized nucleon and the nucleon polarization vector [9] . Neglecting the hadron transverse momentum with respect to the fragmenting quark, this $\vec{k}_T$ dependence could cause the “Sivers asymmetry”

$$A_{Siv} = \frac{\sum_q e_q^2 \cdot \Delta_0^T q \cdot D_q^h}{\sum_q e_q^2 \cdot q \cdot D_q^h} \tag{4}$$

in the angular distribution of the hadrons resulting from the quark fragmentation. The Sivers asymmetry is the amplitude of a possible $\sin\Phi_S$ modulation in the number of produced hadrons, where $\Phi_S = \phi_h - \phi_s$ and ϕ_h and ϕ_s are the same azimuthal angles which enter in definition of Φ_C. In SIDIS off a transversely polarized target the Collins and the Sivers effects can to be disentangled, as shown by the COMPASS and the HERMES experiments.

The Sivers function is of particular interest because it is odd under time reversal (T). Due to its T-odd nature and to the T-invariance property of the strong interaction, soon after being proposed it was demonstrated that it had to be zero [10]. Ten years later, however, in an explicit calculation [11] it was proved that final state interactions in SIDIS arising from gluon-exchange between the struck quark and the nucleon remnant, or initial state interactions in Drell-Yan processes, can produce a non-zero Sivers asymmetry. Soon after it was understood [12] that taking correctly into account the gauge links in the TMD distributions, time reversal invariance does not imply a vanishing Sivers function but rather a sign difference between the Sivers function measured in SIDIS and the same distribution measured in Drell-Yan. Clearly the test of this pseudo-universality of the T-odd functions requires their measurement in Drell-Yan process and, first of all, a well established non-zero signal in SIDIS.

Using a 160 GeV μ^+ beam COMPASS has measured SIDIS on a transversely polarized ^{6}LiD target in 2002, 2003 and 2004. In those data no appreciable asymmetries were observed within the accuracy of the measurements [13, 14, 15], a fact which is understood in terms of a cancellation between the u- and d-quark contributions. The COMPASS data are still today the only SIDIS data ever taken on a transversely polarized deuteron target, and provide important constraints to the contribution of the d-quark. The first results from COMPASS from the 2002 data [13], together with the first HERMES data on a transversely polarized proton target [6] and the $e^+e^- \to$ *hadrons* Belle data [7], allowed for the first global analysis and the first extraction of the transversity distributions and of the Sivers functions for the u- and d-quarks [16, 17, 18]. In 2007 COMPASS measured for the first time SIDIS on a transversely polarized proton (NH_3) target [19]. The results for the Collins asymmetry were in nice agreement with those of HERMES [20], while the Sivers asymmetry turned out to be somewhat smaller [21]. Understanding the reasons for this difference was a strong motivation for a new proton run, and the entire 2010 data taking period, from June to November, was dedicated to such a measurement. We have just recently finished the data analysis and I have the great pleasure to present here the new results which have been shown for the first time at Transversity2011 [22].

3 SIDIS experiments

At HERA the HERMES experiment was designed to utilise the circulating electron or positron beam. At the experiment, the stored beam (27.5 GeV and 40 mA) passes through a cell, a tube 60 cm long, coaxial with the beam, in which polarised atoms of hydrogen or deuterium are pumped in from an Atomic Beam Source. Polarisation is achieved in the Atomic Beam Source by Stern-Gerlach filtering followed by radio-frequency transitions to the selected spin state. This target system is particularly attractive when compared to the solid polarised targets because there is no dilution of the target polarisation due to the presence of the unpolarised nucleons bound in the other nuclei present in the material. Target densities of 10^{14} nucleons/cm^2 were regularly achieved. After the target, a large acceptance magnetic spectrometer based on a 1.3 Tm dipole magnet analysed all charged particles up to 170 mrad in the horizontal plane and between 40 and 149 mrad in the vertical plane. Charged particle tracking is provided by several micro-strip counters, multiwire proportional chambers and drift chambers located before, inside and behind the magnet. Charged particle identification is provided by a RICH Cherenkov counter, while electron-hadron discrimination is achieved with a lead-glass calorimeter with a pre-shower hodoscope in front, and by a Transition Radiation detector. At the end of the spectrometer, a muon hodoscope located after an iron absorber helps the muon identification. The experiment took data with polarised targets from 1995 until 2005. After an upgrade to implement the spectrometer with a recoil detector to investigate exclusive channels, it took data on unpolarised targets from 2008 to July 2009, when HERA ceased operation, and it has afterwards been dismantled.

At CERN the COMPASS experiment has been assembled in the Hall 888, where the EMC and afterwards the SMC experiments were installed. Its physics program includes not only the investigation of the spin structure of the nucleon, but also the search of exotic light-quark hadronic states, like glueballs and hybrids. In the following only the configuration which has been used for the study of the spin structure of the nucleon will be described, which uses the high energy muon beam at the CERN SPS. Typical intensities are $2 \cdot 10^8$ muons per spill at 160 GeV, the momentum at which most of the data have been collected, delivered every $20 - 40$ s depending on the accelerators supercycle. The target materials which have been used in so far are ^{6}LiD (ratio of polarizable nucleons to total nucleons $f \simeq 0.4$) as a deuteron target, and NH_3 ($f \simeq 0.15$) as a proton target. The target system uses a solenoidal superconducting magnet, providing a highly homogeneous field of 2.5 T over a length of 130 cm along the axis. About one kg of material is contained in a 4 cm diameter cylinder, coaxial with the beam, over a length of 120 cm, distributed either over two cells (in 2002, 2003, and 2004), or over three cells (since 2006). Nearby cells are oppositely polarised, so that scattering data on the two orientation of the target are taken simultaneously to minimise systematic effects. A cryogenic system allows to keep the target at temperatures of about 0.5 K, and to polarise it with the DNP method. A set of two saddle coils allows to get a transverse field of up to 0.6 T which can be either used to adiabatically rotate the target polarisation from parallel to antiparallel to the beam, or to set it in the transverse mode, orthogonal to the beam direction. At regular intervals, the polarisation orientation of the target cells are reversed by changing the frequency of the microwaves, so that possible effects due to the different acceptances of the different cells can be cancelled in the analysis. The experiment is still running, and more data have been collected with a NH_3 polarised proton target, in the transverse polarisation mode in 2010 and in the longitudinal mode in 2011. Large angular and momentum acceptance is guaranteed by a two-stage magnetic spectrometer, 60 m long, centred around two dipole magnets with 1 Tm and 4.4 Tm bending power respectively. A variety of tracking detectors ensures charged particles tracking from zero to $\sim$200 mrad scattering angle, and charged particle identification is provided by a RICH Cherenkov counter. Two hadronic calorimeters, two electromagnetic calorimeters and two muon filters complement the particle identification and allow the reconstruction of neutral pions.

At Jefferson Lab (JLab) many measurements of electron-nucleon scattering and in particular of DIS have been performed over the past 10 years using the electron beam of CEBAF (Continuous Electron Beam Accelerator Facility), with energies from 0.8 to 6 GeV, and polarised targets. In Hall A, the focus has been on measurements on a neutron target. Thanks to the very high beam current, a polarised ^{3}He gas target could be used as a neutron target. The ^{3}He gas fills a pressurised glass vessel (10 atm, typically) and is mixed with Rubidium vapour whose electrons can be polarised via optical pumping with circularly polarised laser light. The ^{3}He nuclei get polarised through spin exchange collisions with the Rubidium atoms. With a 15 μA electron beam on a 40 cm target at 10 atm a luminosity of 10^{36} cm^{-2}s^{-1} is achieved. A series of high precision experiments have provided invaluable information on the two structure functions g_1 and g_2 for the neutron, particularly at large x values. The measurements have utilised a pair of high resolution magnetic spectrometers to measure the scattered electron, and by changing the angular settings and the momentum settings the structure functions could be precisely measured over a broad $(Q^2 - W)$ plane. On the other hand, no SIDIS measurements were possible, due to the small angular acceptance of the spectrometers.

Complementary measurements, using solid polarised targets (both Ammonia, and Deuterated ammonia) have been carried on in Hall B, using the CEBAF Large Angle Spectrometer (CLAS). The large acceptance of this spectrometer has allowed to detect also hadrons to study SIDIS and exclusive events, but the target geometry did not allow to put the polarisation orthogonal to the beam, so that no transversity measurements have been possible in so far.

Recently, in 2009, the first transversity measurements have been performed at JLab, by the E06-010 collaboration, in Hall A. The experiment has used the High Resolution Spectrometer to detect the hadrons in SIDIS reaction and a new large acceptance (64 msr) spectrometer, the BigBite spectrometer, to measure the electrons. Thus the first ever measurement of SIDIS on a transversely polarised neutron target are now available, to complement the HERMES and COMPASS proton and deuteron data.

4 Results

An impressive amount of data has been produced and analyzed in SIDIS reactions on transversely polarized targets by the HERMES, COMPASS and, more recently, the E06-010 experiment at JLAB, which is complemented by the information coming from the Collaborations working at the e^+e^- machines, BELLE first and very recently also BaBar [23]. In the next years global analyses should allow for new extraction of transversity and of the recently introduced TMD parton distributions and fragmentation functions, and will provide a more detailed picture of the nucleon internal structure and of the hadronization process. For a comprehensive review on the subject I refer the interested reader to Ref. [24]. In this lecture I prefer to concentrate myself on the results which have been obtained for the Collins and the Sivers asymmetries, which, as apparent from Section 2, I regard as particularly important, the first because it is the main door to transversity, the third quark distribution existing at leading order in collinear QCD, and the second because of the long debate about its existence and of its unusual property of “pseudo-universality”. Both distributions have been shown to be different from zero, and in the following I will summarize the experimental evidence for this statement.

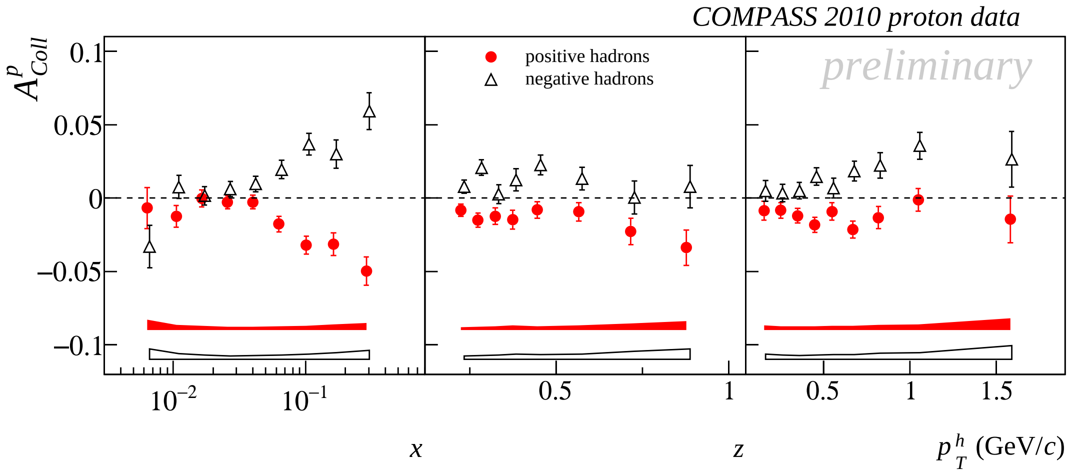

Figure 2: COMPASS results for the Collins asymmetry as function of x, z, and p^h_T, for positive and negative hadrons.

4.1 Results for the proton

The most recent results on single spin asymmetries have been produced by the COMPASS Collaboration [22], which has dedicated the entire 2010 run to a SIDIS measurement with 160 GeV/c muons and a transversely polarized proton target (NH_3). The preliminary results for the Collins asymmetry are given as function of x, z, and p^h_T for positive and negative hadrons, and are shown in fig. 2. The error bars are only statistical, while the bands indicate the size of the systematic errors. The systematic errors have been evaluated as a fraction of the statistical error which is 0.5 for both the Collins and Sivers asymmetries.

As is clear from fig. 2 the Collins asymmetry has a strong x dependence. It is compatible with zero at small x and increases up to 0.05 in the valence region ($x > 0.1$). The values agree both in magnitude and in sign with our previous measurements [19] but the statistical errors have been considerably reduced (a factor of 1.5 to 2, from low x to high x). As can be seen in fig. 3, the values are also in very good agreement with the measurements of HERMES [20], which were performed at a considerably lower electron beam energy. To make the comparison, only the COMPASS data with $x > 0.032$ have been used. Moreover, the published HERMES asymmetries have been rescaled by $1/D$ (HERMES published the beam asymmetries and not the photon asymmetries) and the sign convention of fig. 1 for the Collins angle has been used. Given the fact that in the x-bins at large x, where the signal is large, the mean Q^2

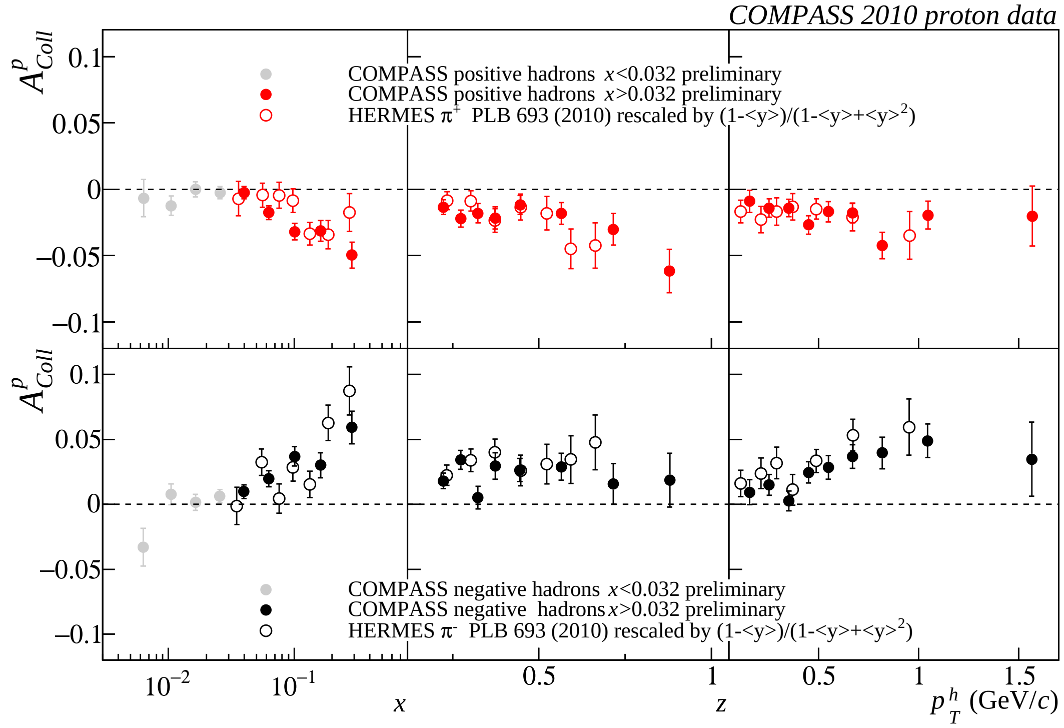

Figure 3: Collins asymmetry as function of x, z, and p^h_T, for positive (top) and negative (bottom) hadrons. The closed points are the COMPASS results for $x > 0.032$ and the open points are the HERMES results. In the first column the COMPASS results for $x < 0.032$ are also plotted as the light-gray close points.

values of COMPASS are a factor 3-4 larger than the corresponding bins of HERMES, the agreement of the two sets of data points at a small Q^2 dependence, as expected for a leading order quantity.

Figure 4 shows the new preliminary COMPASS results for the Sivers asymmetries from the 2010 data. Again, there is an excellent agreement with the published results from the 2007 run, with a considerable reduction of the error bars (more than a factor of two). The asymmetry is definitely positive for positive hadrons and compatible with zero for negative hadrons. At variance with the Collins asymmetry, the Sivers asymmetry stays positive even for very small x-values, in the region of the sea. Moreover, very much as was the case for the 2007 data, the measured asymmetries are definitely smaller than the corresponding ones measured by HERMES. This can be seen in fig. 5, where the COMPASS results from the 2010 data are compared to the published HERMES data. Again, to make the comparison meaningful, only the COMPASS data with $x > 0.032$ have been plotted.

To understand the reason of the difference we have enlarged the kinematic domain, namely we have looked at the events with smaller y values (in the interval $0.05 < y < 0.1$) and at the hadrons with smaller z values ($0.1 < z < 0.2$), as compared with the standard kinematic region in which we accept the events ($0.1 < y < 0.9$ and $z > 0.2$). A clear increase of the Sivers asymmetry has been observed for the low-y data ($0.05 < y < 0.1$) [22]. This strong effect could be associated with the smaller values of Q^2 and/or with the smaller values of W, the invariant mass of the hadronic system. The "standard sample" ($y > 0.1$) corresponds to $W > 5$ GeV, while in the range $0.05 < y < 0.1$ the W values are as low as ∼3 GeV. While a Q^2 dependence is expected and has been calculated [25], no dependence on y (nor on W) is foreseen. A similar correlation, statistically less significant, was already noticed in

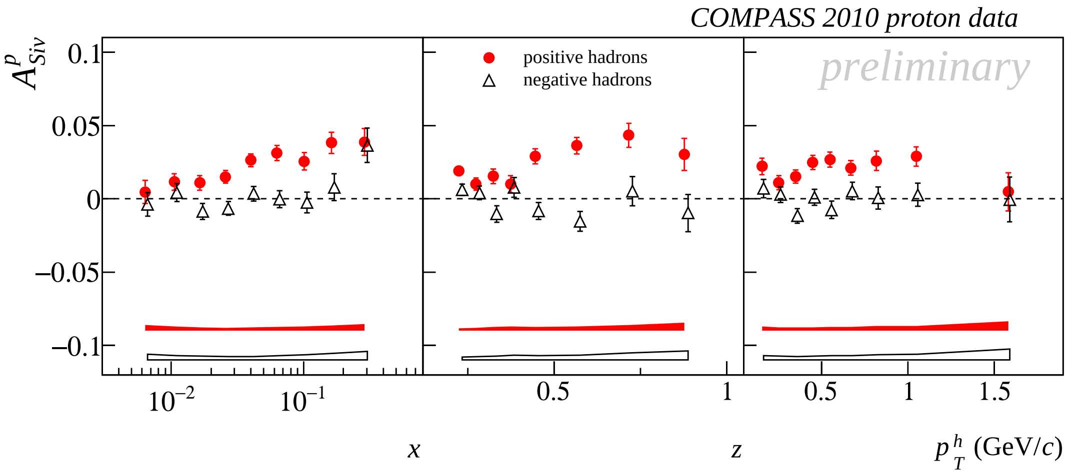

Figure 4: COMPASS results for the Sivers asymmetry as function of x, z, and p_T^h, for positive and negative hadrons.

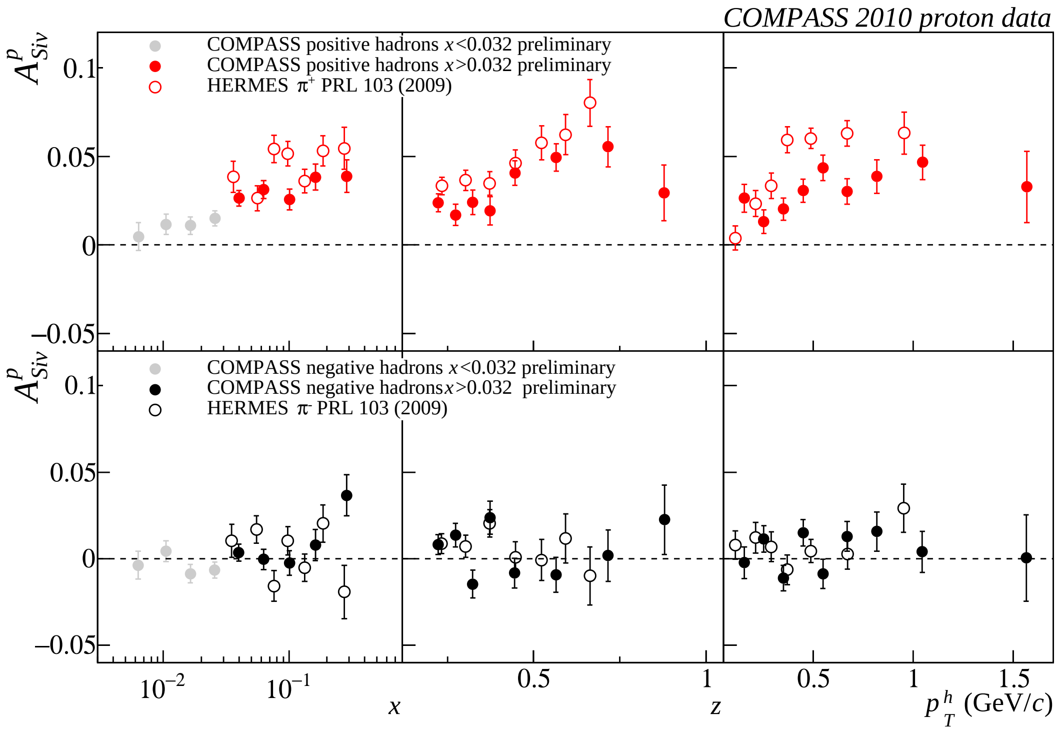

Figure 5: Sivers asymmetry as function of x, z, and p_T^h, for positive (top) and negative (bottom) hadrons. The closed points are the COMPASS results for $x > 0.032$ and the open points are the HERMES results. For completeness in the first column also the COMPASS results for $x < 0.032$ are plotted as the light-gray points.

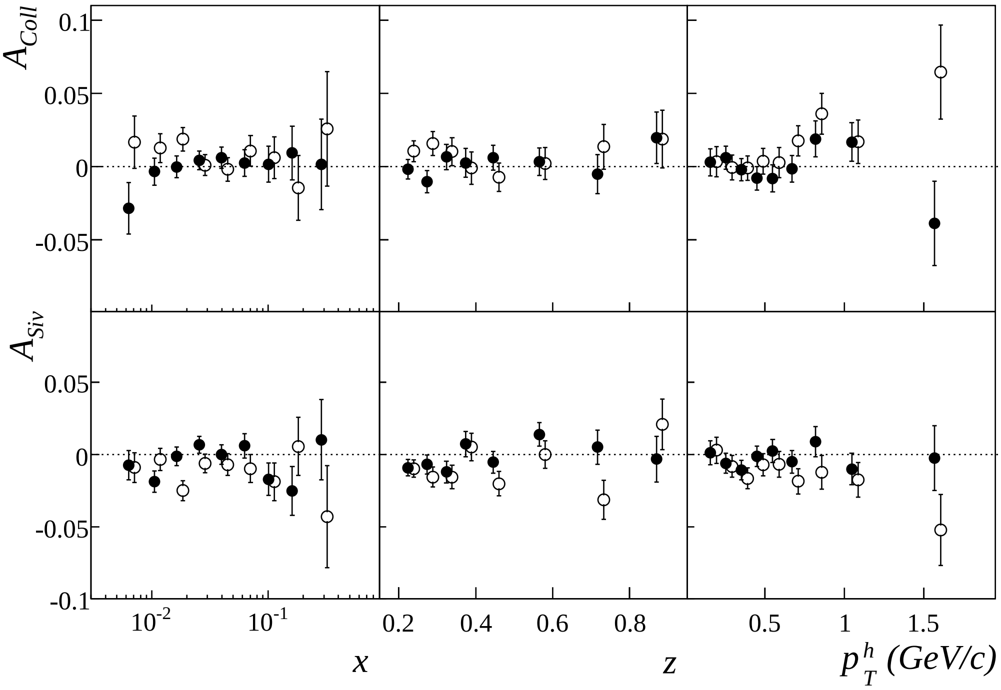

Figure 6: COMPASS results for Collins asymmetry (top) and Sivers asymmetry (bottom) on deuteron against x, z, and p_T^h for all positive (full circles) and all negative hadrons (open circles).

our published 2007 proton data. Clearly this point needs further investigation. No particular trend is observed for the case of the Sivers asymmetry of the negative hadrons, which are compatible with zero for the standard sample and stay compatible with zero at small y.

4.2 Results for the neutron

Only two experiments have measured transverse spin asymmetries on the neutron:

- the COMPASS experiment, which used a deuteron target (^{6}LiD) in the years 2002-2003-2004. This target was polarized at 50%, and having a good ratio ($f \sim 0.4$) between polarizable material (the ^{6}Li nucleus is lightly bound and has spin 1) and total amount of nucleons, it has an excellent figure-of-merit. All the data are published. The main results are reproduced in fig. 6. Both for positive and negative hadrons the Collins and the Sivers asymmetries are compatible with zero, within the boundaries of the accuracy of the measurement. This result was immediately interpreted as cancellation between the u- and d- quark PDFs, both transversity and Sivers. As a comment, however, I'd like to add that the statistical error of the proton data at large x, where the signal is large, is by now a factor 4–5 smaller than the corresponding error of the COMPASS deuteron data, so that for a good extraction of the d-quark PDFs more measurements on a deuteron target are highly desirable.

- the E06-010 collaboration at JLAB has produced first results on transversely polarized neutrons, using a ^{3}He target in Hall A. The results are shown in fig. 7, again for positive and negative hadrons. The kinematic region covered by this experiment, the valence region, is very important, but the statistical significance of this measurement is not very high. As much as in the deuteron case there is cancellation between the u- and d-quark PDFs, therefore the expected asymmetries are very small, as can be seen

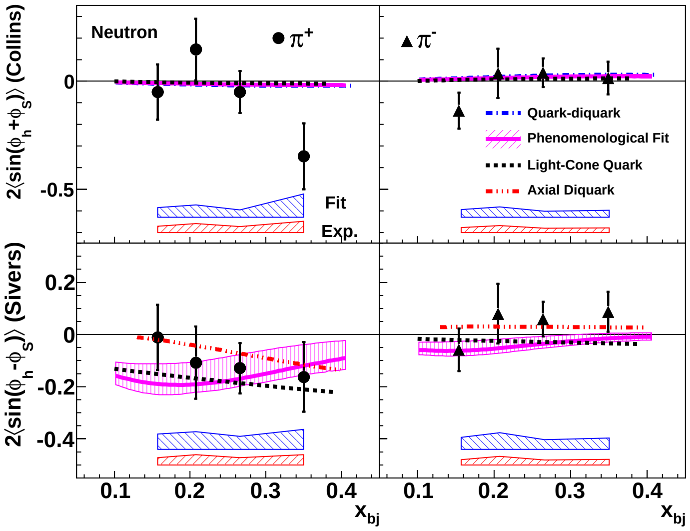

Figure 7: E06-010 results for Collins asymmetry (top) and Sivers asymmetry (bottom) on neutron against x for all positive (left) and all negative (right) hadrons.

from the curves, which correspond both to extrapolations from the phenomenological fit of ref. [17, 18] and to various models calculations. Needless to say, this experiment is expected to run in an upgraded version at JLab12, and the foreseen luminosity is orders of magnitude higher.

5 Conclusions

Transverse spin and transverse momentum effects in lepton nucleon scattering offer new tools to unveil the structure of the nucleon. The proton data are particularly important because of the relatively large Collins and Sivers asymmetries which HERMES and COMPASS have observed for the first time, but probably the next measurement should again address the neutron, because the accuracy of the existing deuteron and ^{3}He data is considerably worse than the accuracy of the proton data. Still, the amount of data which has been produced by now by HERMES, COMPASS, JLab, and Belle is already impressive, and time has come for new phenomenological global analyses.

In the long term the investigation of the spin structure of the nucleon in SIDIS will necessitate a major investment, a high luminosity electron-proton collider in which polarized electrons and polarized proton will collide at high energy. Projects are ongoing since some time at JLAB, at BNL, and, more recently, in Europe, where ideas to use the HESR antiproton storage ring of FAIR at GSI to store polarized protons are being put forward. In the meantime, only JLAB and COMPASS can contribute to this field. JLAB experiments are unbeatable in statistical precision, but the interpretation of the data requires also measurements at high Q^2 which can only be performed using high energy beams. From this point of view, I think COMPASS should stay on the stage for several years, beyond the presently approved Drell-Yan [26] and DVCS [27] measurements, profit of the accelerator complex upgrade which is being carried on at CERN and thus increase its luminosity, and bridge the colleagues who are interested in this field across the time gap from now to the day the future collider(s) will enter into operation.

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