Recent results from COMPASS

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Abstract. The COMPASS experiment at CERN is studying since 2002 the spin structure of the nucleon, both for longitudinal and transverse nucleon spin. In the first case, the measurements of DIS and SIDIS asymmetries, including also high-p_T hadron production and D^0 mesons, allow to access the nucleon longitudinal PDFs, their first moments and the gluon polarization. The LO analysis, performed by COMPASS have shown that $\Delta g/g$ is small around $x_g \simeq 0.1$, and its first moment should not be larger than $0.2 - 0.3$ in absolute value. Transverse spin effects have rised large interest in the last 10 years and the measurements performed have shown evidence for new phenomena, associated with transverse momentum dependent distribution and fragmentation functions. Collins and Sivers asymmetries obtained by COMPASS on a proton target, together with the latest results on unpolarized modulations on the deuterated ^{6}Li target will be shown here.

1. Introduction

Since 2002 the COMPASS (COmmon Muon and Proton Apparatus for Structure and Spectroscopy) experiment at CERN has carried on DIS measurements impinging a 160 GeV/c μ^+ beam on solid polarized deuteron and proton targets to investigate the spin structure of the nucleon. In 2002, 2003, 2004 and 2006 a ^{6}LiD target has been used, mainly for the larger figure of merit as compared to polarized proton targets. In 2007 data have been collected on a NH_3 polarized proton target. In 2008 and in 2009 the COMPASS Collaboration has started measuring central production and diffractive processes, scattering a 190 GeV/c pion beam on a liquid H_2 target and on nuclear targets, to search for exotic hadronic states (glue-balls and hybrids). A selection of the results of the DIS and SIDIS measurements will be given here.

The COMPASS apparatus consists of a two stage magnetic spectrometer detecting both the scattered muon and the produced hadrons. The incoming muons are also detected and the energy of the muons reconstructed on an event-by-event basis, by using a beam momentum station, located along the beam about 100 m before the target. The high energy of the beam (160 GeV) allows to access the low x region, down to 10^{-3} for $Q^2 > 1$ (GeV/c)^2, a key feature of the COMPASS data. The charged particle identification is obtained by a RICH (Ring Imaging CHerenkov) counter, and for the muons by the detection of the tracks after hadron filters. The target material is contained in two 60 cm long cells, polarized by dynamic nuclear polarization in opposite directions, allowing to collect at the same time data from both spin directions. Since 2006, a new target magnet has been used, increasing the acceptance from 70 mrad to 180 mrad. Moreover, the target material has been distributed into three cells, with a length of 30 cm for the outer cells and 60 cm for the inner one, with the advantage of a more uniform overall acceptance for the two spin orientations.

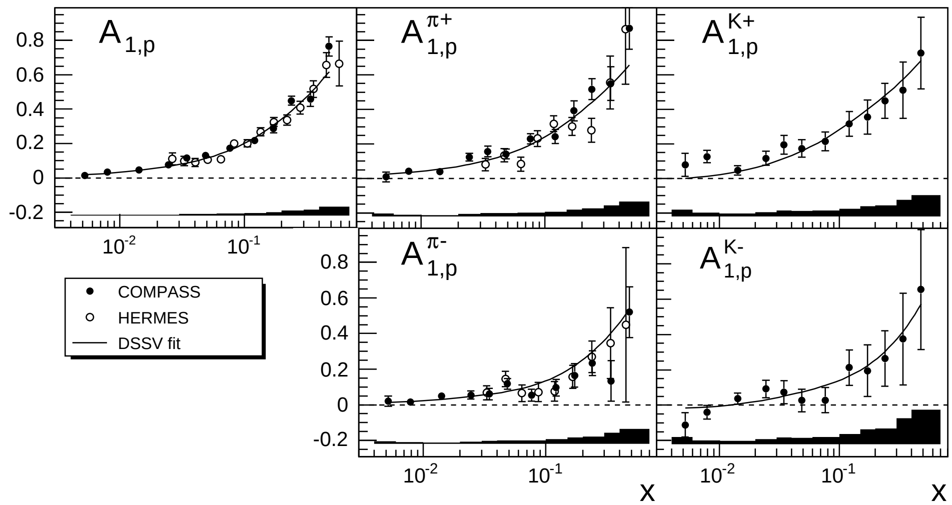

Figure 1. Inclusive, $\pi^{\pm}$ and $k^{\pm}$ asymmetries [1] (closed points); the lower dark bands show the systematic errors. The HERMES measured asymmetries[3] are also shown (open points) for comparison, together with the prediction for COMPASS of the DSSV fit[5].

2. The longitudinal structure of the nucleon

Double spin DIS and SIDIS asymmetries of longitudinally polarized lepton beams scattering off longitudinally polarized nuclear targets provide the main source of information in the study of the longitudinal structure of the nucleon. SIDIS asymmetries where pions and kaons are detected, are sensitive to the individual quark flavor, and, together with the inclusive asymmetries and the proton-proton data are the key ingredient of the QCD fits leading to the extraction of quark helicity distribution. The most recent proton asymmetries measured in 2007 by COMPASS [1, 2] are shown in figure 1, together with the HERMES [3, 4] values and the result of the DSSV prediction for COMPASS proton asymmetries, based of on a global fit of the previously existing data [5, 6]. The agreement with DSSV is good also for the kaon asymmetries were no results were previously available, while the agreement between HERMES and COMPASS at fixed x testify that the Q^2 dependence is small for SIDIS asymmetries.

Semi-inclusive asymmetries, together with inclusive asymmetries on protons and deuterons allow a LO QCD extraction of the polarized PDFs. Assuming an independent quark fragmentation these asymmetries are given by the sums over quark flavors of the products of helicity PDFs and fragmentation functions:

$$A_h^1(x,z) = \frac{\sum_q e_q^2 \left(\Delta q(x) D_q^h(z) + \Delta\bar{q}(x) D_{\bar{q}}^h(z)\right)}{\sum_q e_q^2 \left(q(x) D_q^h(z) + \bar{q}(x) D_{\bar{q}}^h(z)\right)}$$

where h indicates the hadron type and D_q^h and $D_{\bar{q}}^h$ are the fragmentation functions which are taken from the LO parameterization of DSS [7]. The LO unpolarised parton distributions (q and $\bar{q}$) with three quark flavors from the MRST parameterization [8] are used.

The ten inclusive and semi-inclusive asymmetries from proton and deuteron targets provide a system of equations with six unknowns (Δu, Δd, $\Delta\overline{u}$, $\Delta\overline{d}$, Δs and $\Delta\overline{s}$), which are extracted with a least-squares fit to the data, performed independently in each bin of x. The results for Δs and $\Delta\overline{s}$ and for their difference are displayed in figure 2. In the measured x-range both distributions are flat and compatible with zero, and this is true also for their difference, $\Delta s - \Delta\overline{s}$. For this reason the assumption $\Delta s = \Delta\overline{s}$ has been made, thus reducing to five the number of unknowns. The resulting helicity distributions are shown in figure 3. The curves show the results of the DSSV fit at Next-to-Leading Order (NLO) and so the comparison with the experimental results derived at LO is only qualitative. Nevertheless, the curves reproduce fairly well the shape of the data, confirming that a direct extraction at LO provides a good estimate of the shape of the helicity distributions. The anti-quark distributions, $\Delta\overline{u}$ and $\Delta\overline{d}$, do not show any significant variation in the x-range of the data, with $\Delta\overline{u}$ consistent with zero, while $\Delta\overline{d}$ is slightly negative. No significant variation of $\Delta s(x)$ is observed, but the expected behavior from the DSSV fit cannot be excluded at the present precision. The contradiction between Δs from semi-inclusive (the first moment is compatible with zero) and the negative first moment derived [9] from the spin structure function $g_1(x)$, may have different explanations and moreover one has to keep in mind that the semi-inclusive results on $\Delta s(x)$ strongly depend on the choice of a set of fragmentation functions[10].

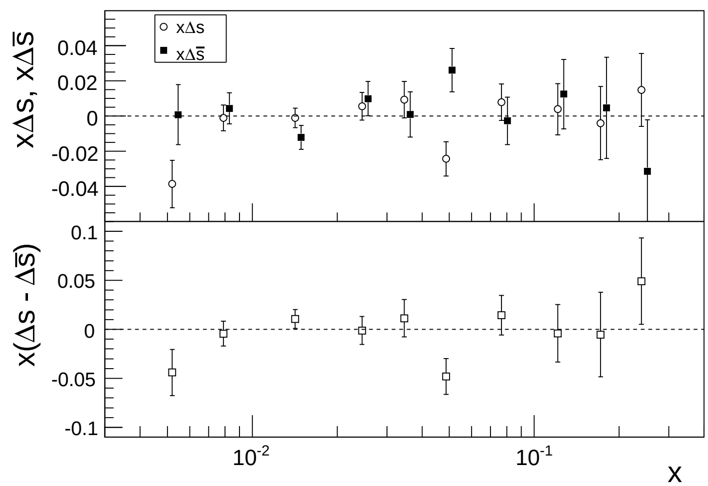

Figure 2. Comparison of $x\,\Delta s$ (open circles) and $x\,\Delta\overline{s}$ (squares) at $Q_0^2 = 3$ $(\mathrm{GeV}/c)^2$ (top) and corresponding values of the difference $x(\Delta s - \Delta\overline{s})$ (bottom).

The flavor asymmetry of the helicity distribution of the sea, $\Delta\overline{u} - \Delta\overline{d}$ has also been extracted from the data and, although compatible with zero, the values indicate a slightly positive distribution. The first moment truncated to the range of the data is found to be $-0.03 \pm 0.03(\mathrm{stat.}) \pm 0.01(\mathrm{syst.})$ and is about one standard deviation smaller than the unpolarised one truncated to the same range (≈ 0.10 for the MRST parameterization[8]). The models prediction $\Delta\overline{u} - \Delta\overline{d} \gg \overline{d} - \overline{u}$ [11, 12] is not confirmed by the data.

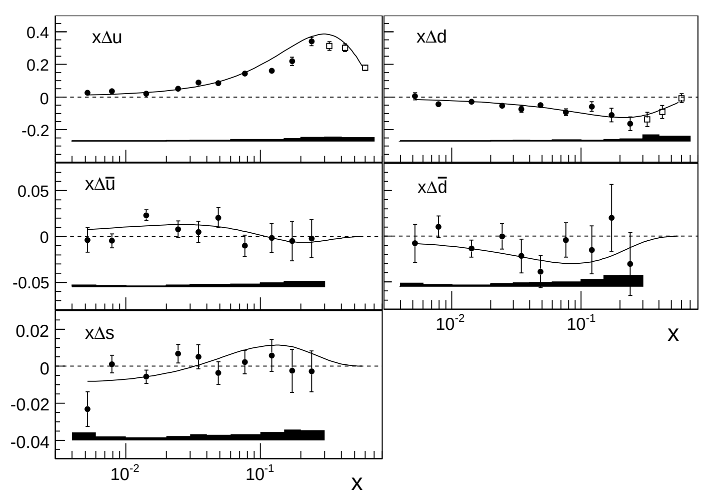

Figure 3. The quark helicity distributions $x\,\Delta u$, $x\,\Delta d$, $x\,\Delta\overline{u}$, $x\,\Delta\overline{d}$ and $x\,\Delta s$ at $Q_0^2 = 3$ $(\mathrm{GeV}/c)^2$ as a function of x. The bands at the bottom of each plot show the systematic errors. The curves show the predictions of the DSSV fit calculated at NLO[5].

In COMPASS the gluon polarization $\Delta g/g$ is accessed by identifying the photon-gluon fusion process, tagged either by open-charm production or by the production of high-p_T hadron pairs. Open-charm events are selected by reconstructing D^0 and D^* mesons from their decay products. For this analysis the whole data collected on the ^{6}LiD (from 2002 to 2006) and NH_3 (2007) have been used. The particle identification is performed by using the RICH. The

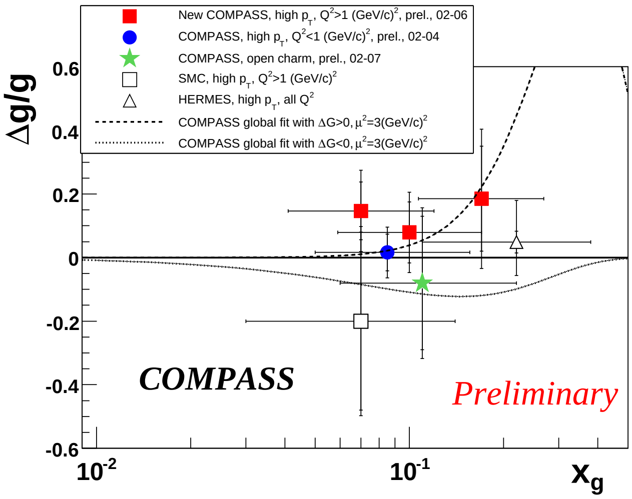

Figure 4. Compilation of the $\Delta g/g$ measurements from open-charm and high-p_T hadron pair production by COMPASS, SMC and HERMES as a function of x. The open charm measurement is at a scale of about 13 $(\mathrm{GeV}/c)^2$, other measurements at 3 $(\mathrm{GeV}/c)^2$. The curves display two parameterizations from the COMPASS QCD analysis at NLO [9], with $\Delta g > 0$ (broken line) and with $\Delta g < 0$ (dotted line).

tagged D^* sample, where the D^0 are tagged by the detection of a low momentum pion from the $\mathrm{D}^* \to \mathrm{D}^0\pi_\mathrm{s}$ decay, resulting in a $\mathrm{S}/(\mathrm{S}+\mathrm{B}) \simeq 1$ (as compared to the 0.1 of the pure D^0 sample) has been enriched adding to the simple $\mathrm{D}^0 \to \mathrm{K}\pi$, three or four body decay channels $\mathrm{D}^0 \to \mathrm{K}\pi\pi^0$, $\to \mathrm{K}\pi\pi\pi$ and decays in $\pi\mathrm{K}$ where the kaon momentum is below the RICH threshold (~ 9 GeV) requesting that is not identified as a pion. For the untagged events, only the 'golden channel' $\mathrm{D}^0 \to \mathrm{K}\pi$ decays have been used. All events have to satisfy a selection on the energy fraction ($\mathrm{z_D} = \mathrm{E_D}/\mathrm{E}_{\gamma^*} > 0.20$); for the D^0 sample, a cut on the kaon direction in the D^0 rest frame ($|\cos(\theta^*_\mathrm{K})| < 0.65$) is applied to reduce the background still dominant. The D^*-tagged D^0 sample is cleaner given the unique kinematics and the cut on the kaon direction has been relaxed considerably ($|\cos(\theta^*_\mathrm{K})| < 0.90$). The total number of D^0 mesons is about 14,000 (9,700) and 46,000 (19000) in the D^* and the D^0 samples collected on ^{6}LiD ($\mathrm{NH_3}$) targets. For the final event samples the mean value of Q^2 is 0.65 $(\mathrm{GeV}/c)^2$, x ranges from 1×10^{-5} to 0.6 with a mean value of 0.04 and y from 0.1 to 1 with a mean value of 0.55. Note that the perturbative scale for the selected events is not given by Q^2, but by the transverse mass of the charmed quarks, $M_T^2 = 4(m_c^2 + p_T^2)$. The final value [13] given by the weighted mean of the results for D^0 and D^* is:

$$\Delta g/g = -0.08 \pm 0.21\ (\mathrm{stat.}) \pm 0.11\ (\mathrm{syst.})$$

in the range $0.06 < x < 0.22$ with $\langle x\rangle = 0.11$ at a scale $\mu^2 \approx 13\ (\mathrm{GeV}/c)^2$.

$\Delta g/g$ from high-p_T hadron pairs has, compared to open charm, the advantage of a larger statistics, even if the extraction of the gluon polarization is more difficult due to the contribution to the asymmetry of competitive processes. Selecting events with $Q^2 > 1\ (\mathrm{GeV}/c)^2$ drastically cuts the contribution from resolved photons, at the price of a factor 10 reduction of the original data sample. The cuts on the hadronic variables are: p_T of the first (second) hadron > 0.7 (> 0.4) GeV/c, $x_F > 0$, $z_1 + z_2 < 0.95$. Selecting events with high-p_T hadrons reduces the contribution from the leading order process $\gamma q \to q$ (LO), and increases the QCD-Compton process $\gamma q \to \gamma q(gq)$, and the photon-gluon fusion (PGF) creation of a light $q\bar{q}$ pair. A neural network is then use to assign for each event a probability for the three processes considered (PGF, QCD-Compton or LO).

The preliminary result for $\Delta g/g$ for high-p_T hadron pairs with $Q^2 > 1\ (\mathrm{GeV}/c)^2$ is

$$\Delta g/g = 0.125 \pm 0.060\ (\mathrm{stat.}) \pm 0.063\ (\mathrm{syst.})$$

at $\langle x_g\rangle = 0.09^{+0.8}_{-0.4}$ with an average scale of the process of 3 $(\mathrm{GeV}/c)^2$. The larger statistics have also allowed to measure Δg in three bins of x_g to check the x dependence of the gluon polarization; the COMPASS results on $\Delta g/g$ compared with other measurements are summarized in figure 4; also shown in the figure are the measurements of SMC [14] and HERMES [15, 16] and the two parameterizations from the COMPASS NLO QCD analysis of the world data [9] which resulted in two curves giving almost the same χ^2, one with $\Delta g > 0$ (broken line) and one with $\Delta g < 0$ (dotted line). The present result is consistent with previous measurements favoring small values of $\Delta g/g$.

3. The transverse structure of the nucleon

Partons are not only collinear moving objects but they may also have a momentum transverse to xP; as a consequence PDFs also depends on $k_\perp$. Only three of these distributions survive the integration over $k_\perp$; these are the spin-averaged distribution $q(x, k_\perp)$, the helicity distribution $\Delta q(x, k_\perp)$ and the transversity distribution $\Delta_\perp q(x, k_\perp)$. Besides these, many other twist-2 distributions can be introduced, correlating e.g. the spin and the transverse momentum, among which the most famous and studied one is the Sivers PDF. These distributions are commonly known as transverse-momentum-dependent parton distributions (TMD-PDFs). Both TMD-PDFs and fragmentation functions (TMD-FF) are today considered an important ingredient of the structure of the nucleon.

The transversity distributions $\Delta_T q(x)$ cannot be measured in inclusive DIS due to their chirally odd nature. They may instead be extracted from measurements of the single-spin azimuthal asymmetries in cross-sections for SIDIS of leptons on transversely polarized nucleons, in which a hadron is also detected in the final state. The measurable asymmetry, the Collins asymmetry $\mathrm{A}_{\mathrm{Coll}}$, is due to the combined effect of $\Delta_T q$ and the chiral-odd Collins TMD-FF $\Delta_T^0 D_q^h$, which describes the spin-dependent part of the hadronization of a transversely polarized quark into a hadron with transverse momentum p_T^h. At leading order, the Collins mechanism [17] leads to a modulation in the azimuthal distribution of the produced hadrons given by:

$$N(\Phi_C) = \alpha(\Phi_C) \cdot N_0 \left(1 + A_{\mathrm{Coll}} \cdot P_T \cdot f \cdot D_{NN} \sin \Phi_C\right),$$

where α contains the apparatus efficiency and acceptance, P_T is the target polarization, D_{NN} is the spin transfer coefficient and f is the fraction of polarizable nuclei in the target; $\Phi_C = \phi_h - \phi_{S'} = \phi_h + \phi_S - \pi$ is the Collins angle, with ϕ_h the hadron azimuthal angle, $\phi_{S'}$ the final azimuthal angle of the quark spin and ϕ_S the azimuthal angle of the nucleon spin in the $\gamma^* N$ system. Finally

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

is the Collins asymmetry, arising from the convolution of the transversity distribution $\Delta_T q$ and the Collins fragmentation function $\Delta_T^0 D_q^h$.

The Sivers PDF, which takes into account a possible deformation in the distribution of the quark intrinsic transverse momentum in a transversely polarised nucleon, can be accessed by looking at the Sivers asymmetry.

$$A_{\mathrm{Siv}} = \frac{\sum_q e_q^2 \cdot \Delta_0^T q(x, k_\perp) \cdot D_q^h(z)}{\sum_q e_q^2 \cdot q(x) \cdot D_q^h(z)}$$

with a modulation expressed in terms of the Sivers angle $\Phi_S = \phi_h - \phi_S$. Since in this case the unpolarized fragmentation functions are known, the measurement of the Sivers asymmetry for both positive and negative produced hadrons allows directly to extract the Sivers functions. The asymmetries have been calculated as a function of x, z and p_T for positive and negative hadrons, respectively. Both the resulting Collins and Sivers asymmetries from the whole deuteron data turned out to be small and compatible with zero [18] (a trend that is also shown by the identified hadron results [19]), a result which was interpreted as a cancellation between the contribution of

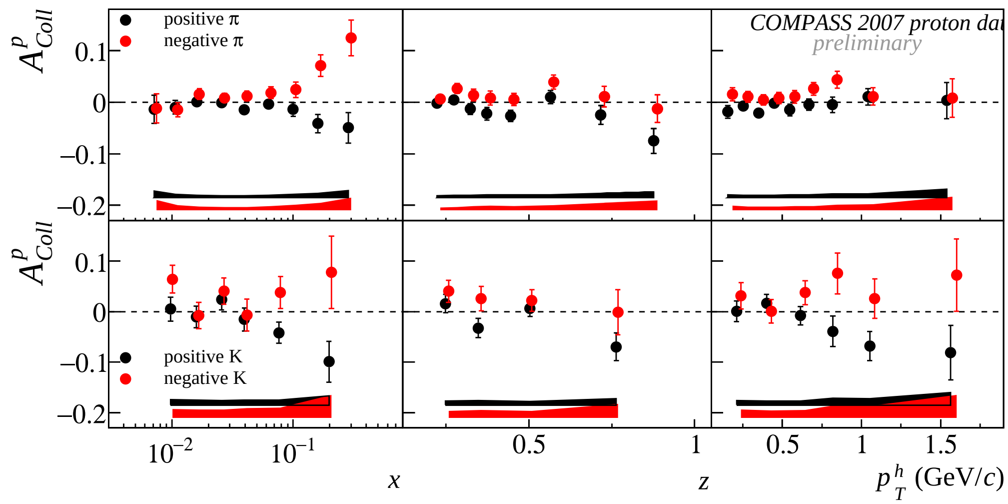

Figure 5. Collins asymmetry for pions (upper row) and kaons (lower row) as a function of x, z and p_T for the proton 2007 data.

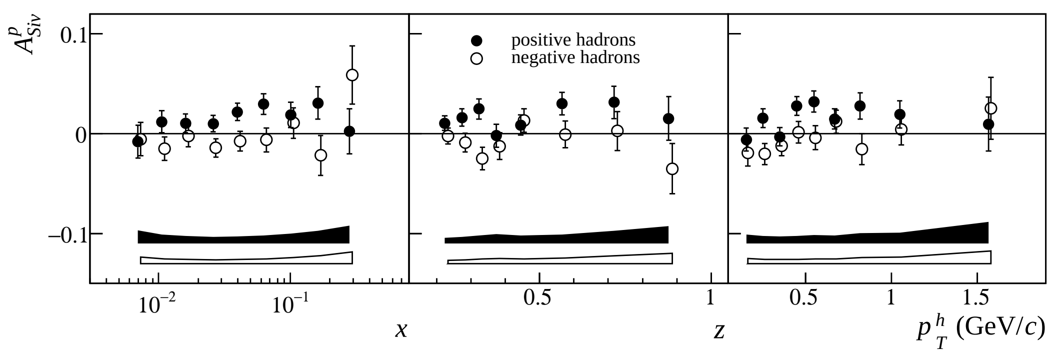

Figure 6. Sivers asymmetry [20] for positive and negative hadrons as a function of x, z and p_T for the proton 2007 data.

the u and d quarks for the isoscalar deuteron target. The new results for the proton NH_3 target and for identified hadrons are shown in figure 5 for the Collins asymmetries. These asymmetries as a function of x are small, compatible with zero, up to $x\ \sim 0.05$, while in the last points a signal appears, and the asymmetries increases up to 10% with opposite sign for the positive and negative pions (upper row). The same trend is exhibited also by the positive and negative kaons (lower row); even if the statistical error is larger, a stronger p_T behavior is present in this case. The results for the Sivers asymmetry (figure 6 for positive and negative hadrons) for negative hadrons exhibit values compatible with zero within the statistical accuracy of the measurement. For positive hadrons, the data indicate small positive values, up to about 3% in the valence region. These values are somewhat smaller than but still compatible with the ones measured by HERMES at smaller Q^2. To check on a possible energy dependence we have evaluated the asymmetries as a function of x with $W \gtrless 7.5\mathrm{GeV}/c^2$ and for W selecting the two regions with $x \gtrless 0.032$ respectively; the results are shown in figure 7. For the positive hadrons, were a Sivers amplitude is present, the signal seems to be concentrated at small W, in the region where HERMES measures, while at large W, which for large x means large Q^2, it tends to zero. So the COMPASS data seem to indicate a possible W dependence of the Sivers asymmetry for positive hadrons. The increase of statistics obtained with the 2010 COMPASS transverse run will allow to draw a definite conclusions on this very interesting observation.

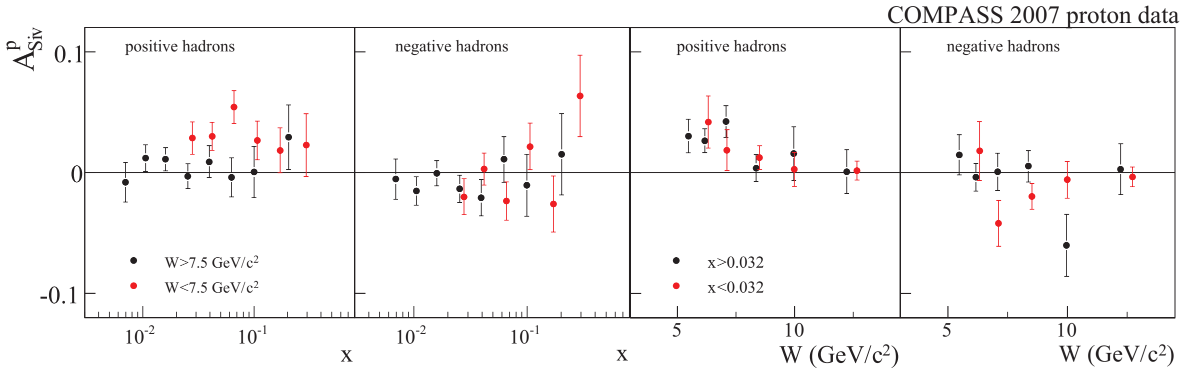

Figure 7. Sivers asymmetry [20] for positive and negative hadrons as a function of x, and W for two specific ranges in W and x for the proton 2007 data.

The cross-section for hadron production in lepton-nucleon DIS $\ell N \to \ell' h X$ for unpolarized beam and targets [21] includes two azimuthal modulations:

$$\frac{d\sigma}{dxdydzd\phi_h dp_{h,T}^2} = \frac{\alpha^2}{xyQ^2}\frac{1+(1-y)^2}{2}\Big[F_{UU,T} + F_{UU,L} + \varepsilon_1 \cos\phi_h F_{UU}^{\cos\phi_h} + \varepsilon_2 \cos(2\phi_h) F_{UU}^{\cos\ 2\phi_h}\Big]$$

where α is the fine structure constant, x, y and Q^2 are the inclusive DIS variables, z is the fraction of the virtual photon energy carried by the detected hadron, ϕ_h is the azimuthal angle of the outgoing hadron in the $\gamma^* N$ system. $F_{UU,T}$, $F_{UU,L}$, $F_{UU}^{\cos\phi_h}$, and $F_{UU}^{\cos\ 2\phi_h}$ are structure functions, with the first and second subscripts which indicate the beam and target polarization, respectively, and the last subscript which indicates the polarization of the virtual photon. Finally $\varepsilon_1 = (2(2-y)\sqrt{1-y})/(1+(1-y)^2)$ and $\varepsilon_2 = (2(1-y))(1+(1-y)^2)$ are depolarization factors.

Particularly interesting is also the so called Boer-Mulders function, describing the transverse parton polarization inside an unpolarized hadron, and generating azimuthal asymmetries in this part of the SIDIS cross-section. The Boer-Mulders PDFs contribute to both the $\cos\phi$ and the $\cos 2\phi$ structure functions, together with the so called Cahn effect [22] which arises from the fact that the kinematics is non collinear when the $k_\perp$ is taken into account (i.e. a kinematical higher twist), and with the perturbative gluon radiation, resulting in order α_s QCD processes. pQCD effects are becoming important for high transverse momenta of the produced hadrons, while they are small for p_T up to 1 GeV/c. For the extraction of unpolarized asymmetries the usual tricks to cancel the experimental acceptance are not applicable and a full acceptance correction is needed in order to extract the amplitude of the azimuthal modulations.

Unpolarized azimuthal asymmetries have been measured by the EMC collaboration [23, 24], with a liquid hydrogen target and a muon beam at a slightly higher energy, but without charge separation for the hadrons, an important aspect since the Boer-Mulders contribution should have opposite sign for opposite charges. These data have been used [25] to extract the average $\langle k_\perp^2 \rangle$. Azimuthal asymmetries have been also measured by E665 [26] and at higher energies by ZEUS [27]. More recent are the COMPASS results first presented at [28], and the measurements done by HERMES, first shown at [29].

In the measurement of unpolarized asymmetries the correction of the azimuthal distribution for acceptance effects is mandatory. This is done by using a full Monte Carlo chain, which starts from the SIDIS event generation performed by Lepto, simulates the particle interactions with the experimental setup and also the detectors response, and ends with the reconstruction of the

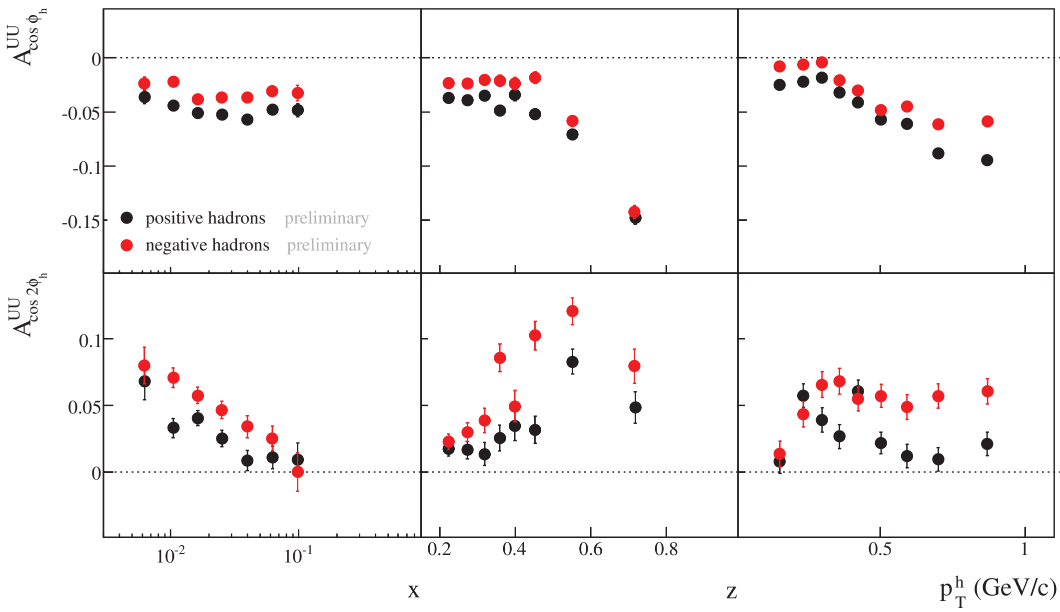

Figure 8. (upper row) $\cos\phi$ asymmetries from COMPASS deuteron data for positive and negative hadrons as a function of x, z and p_T; the asymmetries includes the kinematical factor ε_1 and the bands indicate the size of the systematic errors. (lower row) $\cos 2\phi$ for positive and negative hadrons. The bands indicate size of the systematic errors.

generated events by the same program used to analyze the real data. The quality of this chain is evaluated by comparing distributions of real data and of generated events both for the DIS variables and for the hadronic variables.

The experimental acceptance as a function of the azimuthal angle $A(\phi)$ is then calculated as the ratio of reconstructed over generated events for each bin of x, z and p_T on which the asymmetries are measured. The overall y, z and p_T acceptances are quite constant over the range used in the analysis, so that the effect resulting from the integration over the other variables when the asymmetries in one of the variables are extracted is well within the systematic error.

The amplitude of the $\cos\phi$ modulations extracted from COMPASS deuteron data are shown in figure 8 (upper row) for positive and negative hadrons, as a function of x, z and p_T; the systematic error, not shown on the plots is about two times the statistical error. The asymmetries show the same trend for positive and negative hadrons with a slightly larger values for the positive one. Values as large as 15% are reached in the last point of the z-range. The $\cos\phi$ modulation is dominated by the Cahn effect and the slightly different amplitude for positive and negative produced hadrons need to be understood, since it can be given by the contribution of Boer-Mulders (which enters with an extra $k_\perp/M$ with respect to the pure Cahn effect in the $\cos\phi$) or by other effects.

The $\cos 2\phi$ asymmetries are shown in figure 8. The COMPASS data show a different amplitude for positive and negative hadrons, a trend which confirms the theoretical predictions [30] for a non zero Boer-Mulder PDF, and as allowd a first, even if preliminary, extraction of this PDF [31].

4. Conclusion

COMPASS is adding since 2002 a large amount of information on both the longitudinal and the transverse spin degrees of freedom of the nucleon. The average gluon polarisation around $x_g \approx 0.1$ is small and its first moment is limited to about $0.2 - 0.3$ in absolute value, while the overall contribution of the quark helicities is $\simeq 0.3$, leaving the challenge of measuring the contribution of the total angular momentum for the future. TMD-PDF and FF give rise to various asymmetries in the SIDIS cross-sections, and while only the Collins and Sivers asymmetries have been addressed here, COMPASS has shown at this conference new results for many of them (see e.g. [32, 33]). Completely uncovered here are the future COMPASS-II measurements, recently approved by CERN, and presented at this conference [34, 35]. In 2011 COMPASS will collect data with the longitudinally polarized proton target, doubling the statistics presently available. This run will end the first phase of the COMPASS experiment.

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