Transverse Spin Effects at COMPASS

C. Schill

on behalf of the COMPASS collaboration

Physikalisches Institut der Albert-Ludwigs Universität Freiburg,
Hermann-Herder Str. 3
D-79104 Freiburg, Germany.

The investigation of transverse spin and transverse momentum effects in deep inelastic scattering is one of the key physics programs of the COMPASS collaboration. In the years 2002-2004 COMPASS took data scattering 160 GeV muons on a transversely polarized ^6LiD target. In 2007, a transversely polarized NH_3 target was used. Three different channels to access the transversity distribution function have been analyzed: The azimuthal distribution of single hadrons, involving the Collins fragmentation function, the azimuthal dependence of the plane containing hadron pairs, involving the two-hadron interference fragmentation function, and the measurement of the transverse polarization of Λ hyperons in the final state. Transverse quark momentum effects in a transversely polarized nucleon have been investigated by measuring the Sivers distribution function. Azimuthal asymmetries in unpolarized semi-inclusive deep-inelastic scattering give important information on the inner structure of the nucleon as well, and can be used to estimate both the quark transverse momentum k_T in an unpolarized nucleon and to access the so-far unmeasured Boer-Mulders function. COMPASS has measured these asymmetries using spin-averaged ^6LiD data.

1. Introduction

Most of our knowledge of the inner structure of the nucleon is encoded in parton distribution functions. They are used to describe hard scattering processes involving nucleons. While there has been achieved a lot of understanding concerning the longitudinal structure of a fast moving nucleon, very little is known about its transverse structure [1]. Transverse refers to the direction of motion and concerns both the transverse spin distribution and the parton intrinsic motion, k_T.

Recent data on single spin asymmetries in semi-inclusive deep-inelastic scattering (SIDIS) off transversely polarized nucleon targets [2,3] triggered a lot of interest towards the transverse momentum dependent and spin dependent distribution and fragmentation functions [4]. Correlations between spin and transverse momentum (k_T) induce new spin effects, which would be zero in the absence of intrinsic motion of the quarks in the nucleon [5].

The SIDIS cross-section in the one-photon exchange approximation contains eight transverse-momentum dependent distribution functions [6]. Some of these can be extracted in SIDIS measuring the azimuthal distribution of the hadrons in the final state [7]. Three distribution functions survive upon integration over the transverse momenta: These are the quark momentum distribution $q(x)$, the helicity distribution $\Delta q(x)$, and the transversity distribution $\Delta_T q(x)$ [8]. The latter is defined as the difference in the number density of quarks with momentum fraction x with their transverse spin parallel to the nucleon spin and their transverse spin anti-parallel to the nucleon spin [9].

To access transversity in SIDIS, one has to measure the quark polarization, i.e. use the so-called 'quark polarimetry'. Different techniques have been proposed so far. Three of them are used in COMPASS:

- a measurement of the single-spin asymmetries (SSA) in the azimuthal distribution of

the final state hadrons (the Collins asymmetry)

- a measurement of the SSA in the azimuthal distribution of the plane containing final state hadron pairs (the two-hadron asymmetry)

- a measurement of the polarization of final state hyperons (the Λ-polarimetry)

Of special interest among the transverse-momentum dependent distribution functions are the Sivers function $\Delta_0^T q(x, \overrightarrow{k_T})$ [10], which describes a possible deformation in the distribution of the quark intrinsic transverse momentum in a transversely polarized nucleon [11], and its chiral-odd partner, the Boer-Mulders function [12], describing the transverse parton polarization in an unpolarized hadron.

The Boer-Mulders function generates azimuthal asymmetries in unpolarized SIDIS, together with the so-called Cahn effect [13], which arises from the fact that the kinematics is non-collinear when k_T is taken into account, and with the perturbative gluon radiation, resulting in higher order QCD processes.

In the past, unpolarized azimuthal asymmetries have been measured by the EMC collaboration [14,15], with a liquid hydrogen target and a muon beam, without separating hadrons of different charge. These data have been used [5] to extract the average $\langle k_\perp^2 \rangle$ of quarks in the nucleon. Azimuthal asymmetries have been also measured by E665 [16] and at higher energies by ZEUS [17]. More recent are the measurements done by HERMES [18] and the COMPASS results presented here.

2. The COMPASS experiment

COMPASS is a fixed target experiment at the CERN SPS accelerator with a wide physics program focused on the nucleon spin structure and on hadron spectroscopy. COMPASS investigates transversity and the transverse momentum structure of the nucleon in semi-inclusive deep-inelastic scattering. A 160 GeV muon beam is scattered off a transversely polarized NH_3 or

^6LiD target. The scattered muon and the produced hadrons are detected in a wide-acceptance two-stage spectrometer with excellent particle identification capabilities [19]. In the years 2002, 2003, and 2004, data were collected on a transversely polarized ^6LiD target. In the run 2007, data were taken with a transversely polarized NH_3 target. In the following I will focus on the new results from the data taken on the polarized NH_3 target and on the results for unpolarized azimuthal asymmetries. The latter were obtained by averaging over opposite spin orientations of the ^6LiD target.

3. The Collins asymmetry

In semi-inclusive deep-inelastic scattering the transversity distribution $\Delta_T q(x)$ can be measured in combination with the chiral odd Collins fragmentation function $\Delta_T^0 D_q^h(x)$. According to Collins, the fragmentation of a transversely polarized quark into an unpolarized hadron generates an azimuthal modulation of the hadron distribution with respect to the lepton scattering plane [8]. The hadron yield $N(\Phi_{Coll})$ can be written as:

$$N(\Phi_{Coll}) = N_0 \cdot (1 + f \cdot P_t \cdot D_{NN} \cdot A_{Coll} \cdot \sin \Phi_{Coll}), (1)$$

where N_0 is the average hadron yield, f the fraction of polarized material in the target, P_t the target polarization, $D_{NN} = (1-y)/(1-y+y^2/2)$ the depolarization factor, and y the fractional energy transfer of the muon. The angle Φ_{Coll} is the Collins angle. It is defined as $\Phi_{Coll} = \phi_h + \phi_s - \pi$, the sum of the hadron azimuthal angle ϕ_h and the target spin vector azimuthal angle ϕ_s, both with respect to the lepton scattering plane [9]. The measured Collins asymmetry A_{Coll} can be factorized into a convolution of the transversity distribution $\Delta_T q(x)$ and the Collins fragmentation function $\Delta_T^0 D_q^h(z, p_T)$, summed over all quark flavors q:

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

Here, e_q is the quark charge, $D_q^h(z, p_T)$ the unpolarized fragmentation function, $z = E_h/(E_\mu - E_{\mu'})$ the fraction of available energy carried by

the hadron and p_T the hadron transverse momentum with respect to the virtual photon direction. As can be seen from equation (1), the Collins asymmetry shows as a $\sin \Phi_{Coll}$ modulation in the number of produced hadrons.

4. Two-hadron asymmetry

The chiral-odd transversity distribution $\Delta_T q(x)$ can be measured in combination with the chiral-odd polarized two-hadron interference fragmentation function $H_1^{\triangleleft}(z, M_{inv}^2)$ in SIDIS. M_{inv} is the invariant mass of the $h^+ h^-$ pair. The fragmentation of a transversely polarized quark into two unpolarized hadrons leads to an azimuthal modulation in $\Phi_{RS} = \phi_R + \phi_s - \pi$ in the SIDIS cross section. Here ϕ_R is the azimuthal angle between $\vec{R}_T$ and the lepton scattering plane and $\vec{R}_T$ is the transverse component of $\vec{R}$ defined as:

$$\vec{R} = (z_2 \cdot \vec{p}_1 - z_1 \cdot \vec{p}_2)/(z_1 + z_2). \quad (3)$$

$\vec{p}_1$ and $\vec{p}_2$ are the momenta in the laboratory frame of h^+ and h^- respectively. This definition of $\vec{R}_T$ is invariant under boosts along the virtual photon direction.

The number of produced oppositely charged hadron pairs $N_{h^+ h^-}$ can be written as:

$$N_{h^+ h^-} = N_0 \cdot (1 + f \cdot P_t \cdot D_{NN} \cdot A_{RS} \cdot \sin \Phi_{RS} \cdot \sin \theta). (4)$$

Here, θ is the angle between the momentum vector of h^+ in the center of mass frame of the $h^+ h^-$-pair and the momentum vector of the two hadron system [4].

The measured amplitude A_{RS} is proportional to the product of the transversity distribution and the polarized two-hadron interference fragmentation function

$$A_{RS} \propto \frac{\sum_q e_q^2 \cdot \Delta_T q(x) \cdot H_1^{\triangleleft}(z, M_{inv}^2)}{\sum_q e_q^2 \cdot q(x) \cdot D_q^{2h}(z, M_{inv}^2)}. \quad (5)$$

$D_q^{2h}(z, M_{inv}^2)$ is the unpolarized two-hadron interference fragmentation function. The polarized two-hadron interference fragmentation function can be expanded in the relative partial waves of the hadron pair system, which up to the p-wave level gives [4]:

$$H_1^{\triangleleft} = H_1^{\triangleleft,sp} + \cos \theta H_1^{\triangleleft,pp}. \quad (6)$$
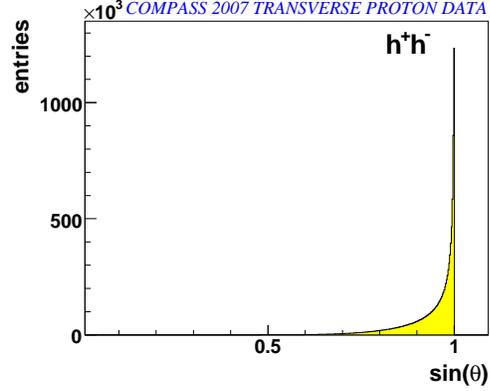
Figure 1. $\sin \theta$ distribution

Where $H_1^{\triangleleft,sp}$ is given by the interference of s and p waves, whereas the function $H_1^{\triangleleft,pp}$ originates from the interference of two p waves with different polarization. For this analysis the results are obtained by integrating over θ, because the $\sin \theta$ distribution shown in Fig. 1 is strongly peaked at one and the $\cos \theta$ distribution is symmetric around zero.

Both the interference fragmentation function $H_1^{\triangleleft}(z, M_{inv}^2)$ and the corresponding spin averaged fragmentation function into two hadrons $D_q^{2h}(z, M_{inv}^2)$ are unknown, and need to be measured in $e^+ e^-$ annihilation or to be evaluated using models [4,20–22].

5. The Sivers asymmetry

Another source of azimuthal asymmetry is related to the Sivers effect. The Sivers asymmetry rises from a coupling of the intrinsic transverse momentum $\overrightarrow{k}_T$ of unpolarized quarks with the spin of a transversely polarized nucleon [10]. The correlation between the transverse nucleon spin and the transverse quark momentum is described by the Sivers distribution function $\Delta_0^T q(x, \overrightarrow{k}_T)$. The Sivers effect leads to an azimuthal modulation of the produced hadron yield:

$$N(\Phi_{Siv}) = N_0 \cdot (1 + f \cdot P_t \cdot A_{Siv} \cdot \sin \Phi_{Siv}). \quad (7)$$

The Sivers angle is defined as $\Phi_{Siv} = \phi_h - \phi_s$. The measured Sivers asymmetry A_{Siv} can be factorized into a product of the Sivers distribution

function and the unpolarized fragmentation function $D_q^h(z)$:

$$A_{Siv} = \frac{\sum_q e_q^2 \cdot \Delta_0^T q(x, \overrightarrow{k}_T) \cdot D_q^h(z)}{\sum_q e_q^2 \cdot q(x) \cdot D_q^h(z)}. \quad (8)$$

In this case the asymmetry A_{Siv} shows up as the amplitude of a $\sin \Phi_{Siv}$ modulation in the number of produced hadrons.

Since the Collins and Sivers asymmetries are independent azimuthal modulations of the cross section for semi-inclusive deep-inelastic scattering [12], both asymmetries can be determined experimentally from the same dataset.

6. Data sample and event selection

The polarized NH_3 target consists of three cells (upstream, central and downstream) of 30, 60 and 30 cm length, respectively. The upstream and downstream cell are polarized in one direction while the middle cell is polarized oppositely. The target material has a high polarization of about 90%. The dilution factor of the ammonia target is constant at 0.15 in z and p_T bins, while it increases with x from 0.14 to 0.17. The direction of the target polarization was reversed every five days. The asymmetries are analyzed using at the same time data from two time periods with opposite polarization and from the different target cells. The data have been selected requiring a good stability of the spectrometer within one and between consecutive periods of data taking.

To select DIS events, kinematic cuts of the squared four momentum transfer $Q^2 > 1$ (GeV/c)^2, the hadronic invariant mass $W > 5$ GeV/c^2 and the fractional energy transfer of the muon $0.1 < y < 0.9$ were applied. The hadron sample on which the single hadron asymmetries are computed consists of all charged hadrons originating from the reaction vertex with $p_T > 0.1$ GeV/c and $z > 0.2$.

The Collins and Sivers asymmetries were evaluated as a function of x, z, and p_T integrating over the other two variables. The extraction of the amplitudes is then performed fitting the expression for the transverse polarization dependent part of the semi-inclusive DIS cross section [12] to the measured count rates in the target cells

by a unbinned extended maximum likelihood fit, taking into account the spectrometer acceptance. The results have been checked by several other methods described in Ref. [2].

The hadron pair sample consists of all oppositely charged hadron pair combinations originating from the reaction vertex. The hadrons used in the analysis have $z > 0.1$ and $x_F > 0.1$. Both cuts ensure that the hadron is not produced in the target fragmentation. To reject exclusively produced ρ^0-mesons, a cut on the sum of the energy fractions of both hadrons was applied $z_1 + z_2 < 0.9$. Finally, in order to have a good definition of the azimuthal angle ϕ_R a cut on $R_T > 0.07$ GeV/c was applied.

7. Transverse target results

In Fig.2 the results for the Collins asymmetry on a proton target are shown as a function of x, z, and p_T for positive and negative hadrons. For small x up to $x = 0.05$ the measured asymmetry is small and statistically compatible with zero, while in the last points an asymmetry different from zero is visible. The asymmetry increases up to about 10% with opposite sign for negative and positive hadrons.

In Fig.3 the results for the Sivers asymmetry are shown as a function of x, z, and p_T. The Sivers asymmetry is small and statistically compatible with zero for both positive and negative hadrons.

The two-hadron asymmetry as a function of x, z and M_{inv} is shown in Fig. 4. A strong asymmetry in the valence x-region can be observed, which implies a non-zero transversity distribution and a non-zero polarized two hadron interference fragmentation function $H_1^{\sphericalangle}$. In the invariant mass binning one observes a strong signal around the ρ^0-mass and the asymmetry is negative over the whole mass range. The lines are predictions from Bacchetta and Radici, which are based on the transversity distribution from Anselmino *et al.* and on a fit to HERMES data [23]. It can be seen that the predictions are by about a factor of 3 smaller than the measured asymmetry.
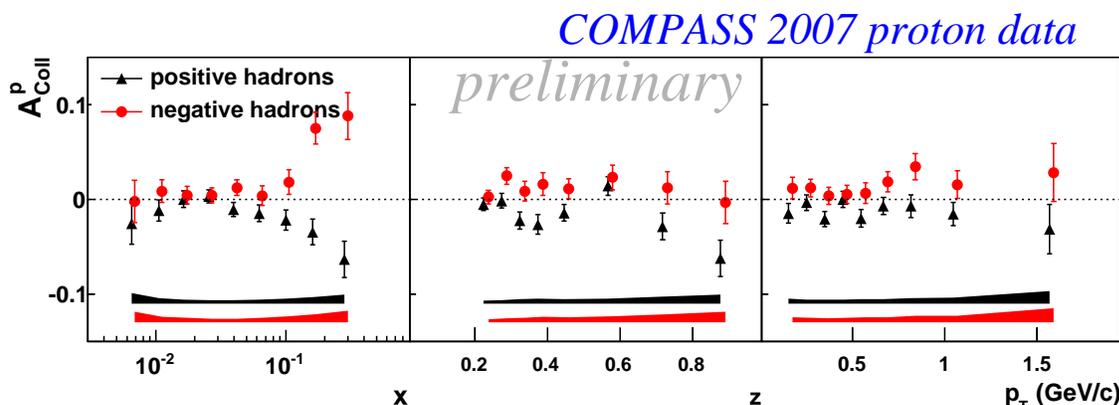
Figure 2. Collins asymmetry on the proton for unidentified positive (triangles) and negative (circles) hadrons as a function of x, z, and p_T. The bands indicate the systematic uncertainty of the measurement.
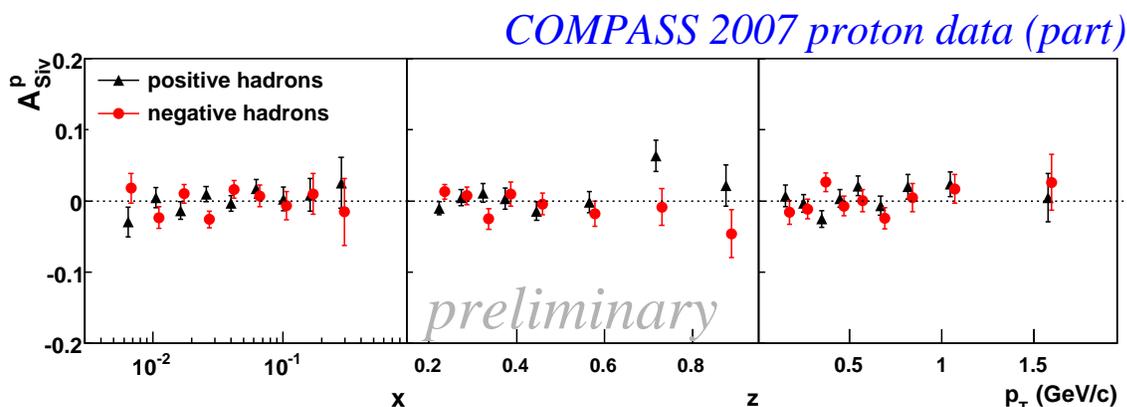
Figure 3. Sivers asymmetry on the proton for unidentified positive (triangles) and negative (circles) hadrons as a function of x, z, and p_T.
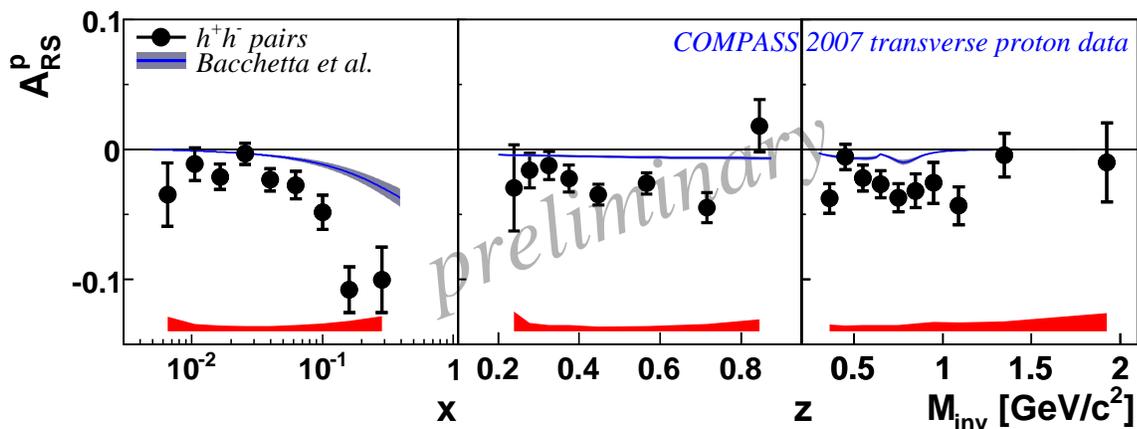
Figure 4. Two-hadron asymmetry A_{RS} as a function of x, z and M_{inv}, compared to predictions of [23]. The lower bands indicate the systematic uncertainty of the measurement.

8. Azimuthal asymmetries in DIS off an unpolarized target

The cross-section for hadron production in lepton-nucleon DIS $\ell N \to \ell' h X$ for unpolarized targets and an unpolarized or longitudinally polarized beam has the following form [24]:

$$\frac{d\sigma}{dxdydzd\phi_h dp^2_{h,T}} = \frac{\alpha^2}{xyQ^2}\frac{1+(1-y)^2}{2}.$$
$$[F_{UU,T} + F_{UU,L} + \varepsilon_1\cos\phi_h F^{\cos\phi_h}_{UU} \qquad (9)$$
$$+\varepsilon_2\cos(2\phi_h)F^{\cos 2\phi_h}_{UU} + \lambda_\mu\varepsilon_3\sin\phi_h F^{\sin\phi_h}_{LU}]$$

where α is the fine structure constant. $F_{UU,T}$, $F_{UU,L}$, $F^{\cos\phi_h}_{UU}$, $F^{\cos 2\phi_h}_{UU}$ and $F^{\sin\phi_h}_{LU}$ are structure functions. Their first and second subscripts indicate the beam and target polarization, respectively, and the last subscript denotes, if present, the polarization of the virtual photon. λ_μ is the longitudinal beam polarization and:

$$\varepsilon_1 = \frac{2(2-y)\sqrt{1-y}}{1+(1-y)^2}$$
$$\varepsilon_2 = \frac{2(1-y)}{1+(1-y)^2} \qquad (10)$$
$$\varepsilon_3 = \frac{2y\sqrt{1-y}}{1+(1-y)^2}$$

are depolarization factors. The Boer-Mulders parton distribution function contributes to the $\cos\phi_h$ and the $\cos 2\phi_h$ moments as well, together with the Cahn effect [13] which arises from the fact that the kinematics is non collinear when the $k_\perp$ is taken into account, and with the perturbative gluon radiation, resulting in order α_s QCD processes. pQCD effects become important for high transverse momenta p_T of the produced hadrons.

9. Analysis of unpolarized asymmetries

The event selection requires standard DIS cuts, i.e. $Q^2 > 1$ (GeV/c)^2, mass of the final hadronic state $W > 5$ GeV/c^2, $0.1 < y < 0.9$, and the detection of at least one hadron in the final state. For the detected hadrons it is also required that:

- the fraction of the virtual photon energy carried by the hadron is $0.2 < z < 0.85$ to select hadrons from the current fragmentation region.

- the hadron transverse momentum is $0.1 < p_T < 1.5$ GeV/c for a better determination of the azimuthal angle ϕ_h.

Data taken with a longitudinally polarized and a transversely polarized target have both been spin-averaged to obtain an unpolarized data sample. The statistics corresponds after all cuts to 5×10^6 positive hadrons and 4×10^6 negative hadrons.

In the measurement of unpolarized asymmetries a Monte Carlo simulation is used to correct for acceptance effects of the detector. The SIDIS event generation is performed by Lepto[25], the experimental setup and the particle interactions in the detectors are simulated by COMGEANT.

The experimental acceptance as a function of the azimuthal angle $A(\phi_h)$ is then calculated as the ratio of reconstructed over generated events for each bin of x, z and p_T in which the asymmetries are measured. The measured distribution, corrected for acceptance, is fitted with the following functional form:

$$N(\phi_h) = N_0\left(1 + A^D_{\cos\phi}\cos\phi_h + A^D_{\cos 2\phi}\cos 2\phi_h + A^D_{\sin\phi}\sin\phi_h\right)$$

The contribution of the acceptance corrections to the systematic error was studied with care. As the asymmetries were extracted from data taken both with longitudinal and transverse target configurations, comparing the two results gives the effect of the acceptance changes due to the different configuration of the target magnet and to the different direction of the incoming beam (for the transverse setup the beam is bent in order to leave the target with the same direction as in the longitudinal case). In order to check the effect of the Monte Carlo simulation parameters, the acceptance was calculated using two different sets of Lepto parameters. All the resulting asymmetries were compared in order to quantify the systematic error in each kinematic bin. Further systematic tests, like splitting the data sample according to the event topology and to the time of the measurement, gave no significant contributions.
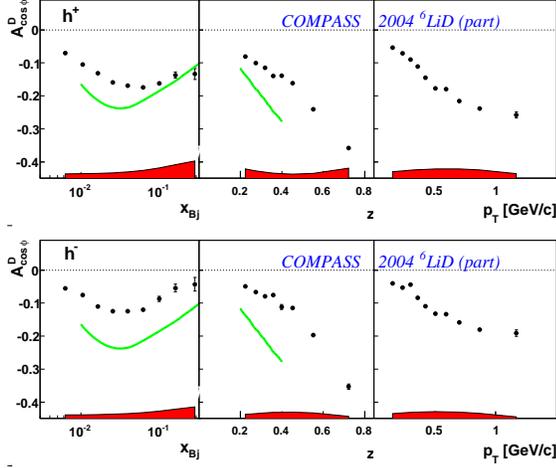
Figure 5. $\cos\phi_h$ asymmetries from COMPASS deuteron data for positive (upper row) and negative (lower raw) hadrons; the asymmetries are divided by the kinematic factor ε_1 and the bands indicate the size of the systematic uncertainty. The superimposed curves are the values predicted by [26] taking into account the Cahn effect only.

Figure 6. $\cos 2\phi_h$ asymmetries from COMPASS deuteron data for positive (upper row) and negative (lower raw) hadrons; the asymmetries are divided by the kinematic factor ε_1 and the bands indicate size of the systematic error.

10. Results for unpolarized asymmetries

The $\sin\phi_h$ asymmetries measured by COMPASS, not shown here, are compatible with zero, at the present level of statistical and systematic errors, over the full range of x, z and p_T covered by the data.

The $\cos\phi_h$ asymmetries extracted from COMPASS deuteron data are shown in Fig. 5 for positive (upper row) and negative (lower row) hadrons, as a function of x, z and p_T. The bands indicate the size of the systematic error. The asymmetries show the same trend for positive and negative hadrons with slightly larger absolute values for positive hadrons. Values as large as $30-40\%$ are reached in the last point of the z range. The theoretical predictions [26] in Fig. 5 takes into account the Cahn effect only, which does not depend on the hadron charge. The Boer-Mulders parton distribution function is not taken into account in this prediction.

The $\cos 2\phi_h$ asymmetries are shown in Fig. 6

together with the theoretical predictions of [27], which take into account the kinematic contribution given by the Cahn effect, first order pQCD (which, as expected, is negligible in the low p_T region), and the Boer-Mulders parton distribution function (coupled to the Collins fragmentation function), which gives a different contribution to positive and negative hadrons. In [27] the Boer-Mulders parton distribution function is assumed to be proportional to the Sivers function as extracted from preliminary HERMES data. The COMPASS data show an amplitude different for positive and negative hadrons, a trend which confirms the theoretical predictions. There is a satisfactory agreement between the data points and the model calculations, which hints to a non-zero Boer-Mulders parton distribution function.

11. Summary

New preliminary results for Collins and Sivers asymmetries measured at COMPASS in semi-

inclusive deep-inelastic scattering off a transversely polarized proton target have been presented. For $x > 0.05$, a Collins asymmetry different from zero and with opposite sign for positive and negative hadrons has been observed. Within statistical precision of the measurement, the Sivers asymmetry is yet compatible with zero, both for negative and positive hadrons. In 2010, COMPASS will continue a full year of data taking with a transversely polarized proton target and largely increase the statistical precision of both the Collins and Sivers results.

The measured unpolarized azimuthal asymmetries on the deuteron target show large $\cos\phi_h$ and $\cos 2\phi_h$ moments which can be qualitatively described in model calculations taking into account the Cahn effect and the intrinsic k_T of the quarks in the nucleon and the Boer-Mulders structure function.

REFERENCES

1. M. Anselmino *et al.*, Phys.Rev. **D74** (2006), 074015.
2. V.Yu. Alexakhin *et al.* [COMPASS collaboration] Phys. Rev. Lett. **94**, 202002 (2005) and E.S. Ageev *et al.* [COMPASS collaboration] Nucl. Phys. **B765**, 31 (2007).
3. A. Airpetian *et al.* [HERMES Collaboration], Phys. Rev. Lett. **94**, 012002 (2005).
4. A. Bacchetta and M. Radici, Phys. Rev. **D67**, 094002 (2003), Phys. Rev. **D69**, 074026 (2004) and Phys. Rev. **D74**, 114007 (2006).
5. M. Anselmino *et al.*, Phys. Rev. **D71** (2005) 074006.
6. A. Bacchetta, hep-ph/0612196, AIP-Conf.Proc. **915** (2007), 517-520.
7. A. Kotzinian, Proc. of **DIS07**, hep-ex/0705.2402.
8. J.C. Collins *et al.*, Nucl. Phys. **B420**, 565 (1994).
9. X. Artru and J.C. Collins, Z. Phys. **C69**, 277 (1996).
10. D.W. Sivers, Phys. Rev. **D41** (1991) 83.
11. A. Bacchetta, hep-ph/0902.7212, AIP-Conf.Proc. **1149** (2007), 447-452.
12. D. Boer and P.J. Mulders, Phys. Rev. **D57** (1998) 5780.
13. R.N. Cahn, Phys. Lett. **B78** (1978), 269.
14. The EMC Collaboration, M. Arneodo *et al.*, Z. Phys. **C34** (1987) 277.
15. The EMC Collaboration, J. Ashman *et al.*, Z. Phys. **C52** (1991) 361.
16. The E665 Collaboration, M.R. Adams *et al.*, Phys. Rev. **D48** (1993) 5057.
17. The ZEUS Collaboration, J. Breitweg *et al.*, Phys. Lett. **B481** (2000) 199.
18. F. Giordano, "Measurements of azimuthal asymmetries of the unpolarized cross-section at HERMES", in the proceedings of 'SPIN2008' and arXiv:0901.2438.
19. P. Abbon *et al.* [COMPASS collaboration], NIM **A577**, 455-518 (2007).
20. R.L. Jaffe *et al.*, Phys. Rev. Lett. **80**, 1166 (1998).
21. A. Bianconi, S. Boffi, R. Jakob and M. Radici, Phys. Rev. **D62**, 034008 (2000).
22. M. Radici, R. Jakob and A. Bianconi, Phys. Rev. Lett **D65**, 074031 (2002).
23. Alessandro Bacchetta *et al.*, Phys. Rev. **D79** (2009) 034029.
24. A. Bacchetta *et al.*, JHEP **0702** (2007) 93.
25. G. Ingelman, A. Edin and J. Rathsman, Comp.Phys.Commun. **101** (1997) 108.
26. M. Anselmino *et al.*, Eur. Phys. J. **A31** (2007) 373.
27. V. Barone, A. Prokudin and B.Q. Ma, Phys. Rev. **D78** (2008) 45022.