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TRANSVERSE SPIN AND TRANSVERSE MOMENTUM EFFECTS AT COMPASS

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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 160 GeV muon scattering data on a transversely polarized ^{6}LiD 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 lambda 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 also give important information on the inner structure of the nucleon, and can be used to estimate both the quark transverse momentum in an unpolarized nucleon and to access the so-far unmeasured Boer-Mulders function. COMPASS has measured these asymmetries in 2004 using spin-averaged ^{6}LiD data.

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1. Introduction

The study of transverse-polarization and transverse-momentum dependent distribution functions was initiated by Ralston and Soper in their study of Drell-Yan processes [1]. In order to understand these effects in a QCD framework, the description of the partonic structure of the nucleon has been extended to include the quark transverse spin and transverse momentum k_T [2 − 4]. Recent data on single spin asymmetries in semi-inclusive deep-inelastic scattering (SIDIS) off transversely polarized nucleon targets [5 – 7] triggered a lot of interest towards the transverse-momentum-dependent and spin-dependent distribution and fragmentation functions [8 – 13].

The SIDIS cross-section in the one-photon exchange approximation contains eight transverse-momentum dependent distribution functions [2]. Some of these can be extracted in SIDIS measuring the azimuthal distribution of the hadrons in the final state [14]. Three distribution functions survive upon integration over the transverse momenta: they are the quark momentum distribution $q(x)$, the helicity distribution $\Delta q(x)$, and the transversity distribution $\Delta_T q(x)$. The last 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 [15].

To access transversity in SIDIS, one has to measure the quark polarization, i.e. use the so-called 'quark polarimetry'. Three complementary approaches are used at 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), and a measurement of the polarization of final state hyperons (the Λ-polarimetry).

The chiral-odd Boer-Mulders function is of special interest among the other transverse-momentum dependent distribution functions [16]. It describes 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 [17], which arises from the fact that the kinematics is non-collinear when k_T is taken into account.

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 ^{6}LiD target. The scattered muon and the produced hadrons are detected in a 50 m long wide-acceptance forward spectrometer with excellent particle identification capabilities [18]. A variety of tracking detectors is used to cope with the different requirements of position accuracy and rate capability at different angles. Particle identification is provided by a large acceptance RICH detector, two electromagnetic and hadronic calorimeters, and muon filters.

The polarized ^{6}LiD target is split into two cylindrical cells along the beam direction. The two cells are polarized in opposite direction. 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 polarization of the ^{6}LiD target is $48\% \pm 5\%$ and of the NH_3 target about 90%. The amount of polarized material in the target, the so called dilution factor, of the ^{6}LiD target is 0.38. The dilution factor of the ammonia target is 0.15 in bins of the hadron fractional energy z and the hadron transverse momentum p_T, while it increases with Bjorken 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.

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 [14]. The hadron yield $N(\Phi_{\rm Coll})$ can be written as

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

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, $A_{\rm Coll}$ the Collins asymmetry, and y the fractional energy transfer of the muon. The angle $\Phi_{\rm Coll}$ is the so called Collins angle. It is defined as $\Phi_{\rm Coll} = \phi_h + \phi_s - \pi$, 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 [15]. The measured Collins asymmetry $A_{\rm Coll}$ 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,

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

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. E_h, E_μ and $E_{\mu'}$ are the energies of the hadron, the muon before and after the scattering, respectively. As can be seen from Eq. (1), the Collins asymmetry appears as a $\sin\Phi_{\rm Coll}$ modulation in the number of produced hadrons. By measuring the Collins asymmetry on a proton and a deuteron target, the contributions from u- and d-quarks can be disentangled [10].

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 asymmetry is 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 [16] 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. [6, 5].

In the upper panel of Fig. 1, the results for the Collins asymmetry on a proton

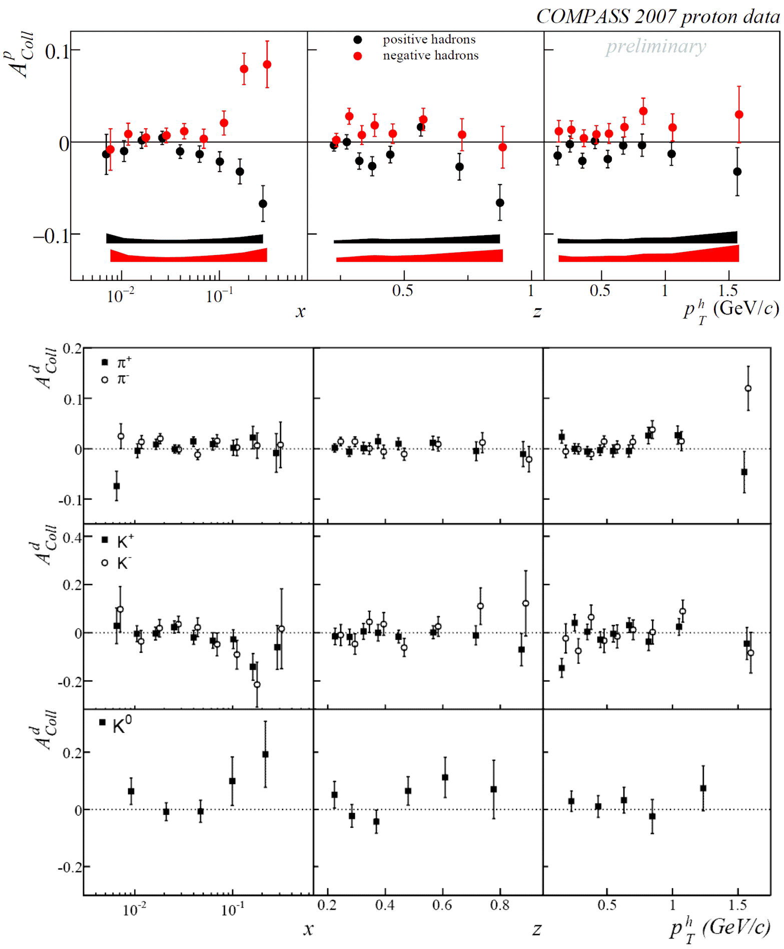

Fig. 1. Upper panel: Collins asymmetry on the proton for unidentified positive (black) and negative (red) hadrons as a function of x, z, and p_T as published in Ref. [5]. The bands indicate the systematic uncertainty of the measurement. Lower panel: Collins asymmetry on the deuteron for positive (filled squares) and negative (open circles) pions and kaons and K^0 as a function of x, z, and p_T as published in Ref. [6].

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 8% with opposite sign for negative and positive hadrons. This result confirms the measurement of a sizable Collins function and transversity distribution. The asymmetry measured on the deuteron target shown in the lower panel of Fig. 1 is small. From this measurement, the opposite sign of u- and d-quark transversity has been derived [6]. Both datasets have been employed in global fits taking into account the Collins fragmentation function from BELLE and the Collins asymmetries from COMPASS and HERMES to obtain constrains to the transversity distribution for u- and d-quarks [10].

4. Two-hadron asymmetry

The chiral-odd transversity distribution $\Delta_T q(x)$ can also be measured in combination with the chiral-odd polarized two-hadron interference fragmentation function $H_1^{\sphericalangle}(z, M_{\rm inv}^2)$ in SIDIS. $M_{\rm inv}$ 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

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

$\vec{p}_1$ 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

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

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 [10].

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

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

$D_q^{2h}(z, M_{\rm inv}^2)$ is the unpolarized two-hadron interference fragmentation function. The polarized two-hadron interference fragmentation function $H_1^{\sphericalangle}$ can be expanded in the relative partial waves of the hadron pair system, which up to the p-wave level gives [10]

$$H_1^{\sphericalangle} = H_1^{\sphericalangle,sp} + \cos\theta \cdot H_1^{\sphericalangle,pp}, \tag{6}$$

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

Both the interference fragmentation function $H_1^{\sphericalangle}(z, M_{\rm inv}^2)$ and the corresponding spin-averaged fragmentation function into two hadrons $D_q^{2h}(z, M_{\rm inv}^2)$ are unknown. The interference fragmentation function $H_1^{\sphericalangle}(z, M_{\rm inv}^2)$ can be measured in e^+e^- annihilation or needs to be evaluated using models [10, 19 − 22].

For data selection, 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 $R_T > 0.07\,\mathrm{GeV/c}$ was applied.

The two-hadron asymmetry on the proton as a function of x, z and $M_{\rm inv}$ is shown in the upper panel of Fig. 2. A strong asymmetry in the valence x-region is 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

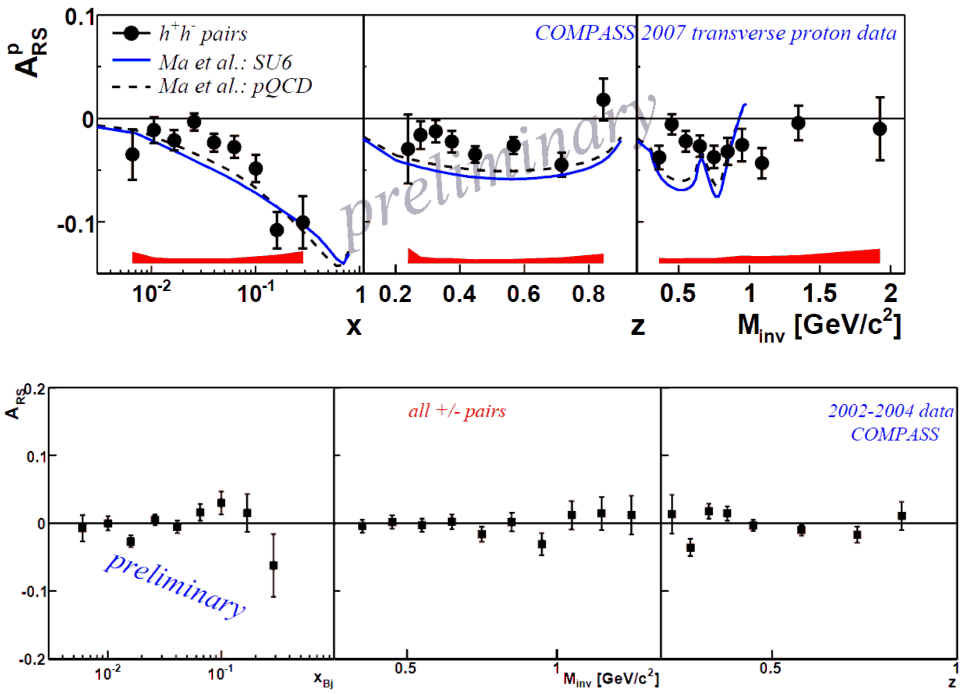

Fig. 2. Upper panel: Two-hadron asymmetry A_{RS} on the proton as a function of x, z and $M_{\rm inv}$, compared to predictions of Ref. [12]. The lower bands indicate the systematic uncertainty of the measurement. Lower panel: Two-hadron asymmetry A_{RS} on the deuteron as a function of x, $M_{\rm inv}$ and z.

whole mass range. The lines are calculations from Ma et al., based on a SU6 and a pQCD model for transversity [12]. The calculations can describe the magnitude and the x-dependence of the measured asymmetry, while there are discrepancies in the M_{inv}-behavior. The two-hadron asymmetry on the deuteron is shown in the lower panel of Fig. 2. The measured asymmetry is small, which shows an opposite sign of the u- and d-quark transversity distribution.

5. *Transverse* Λ *and* $\bar{\Lambda}$ *polarization*

Information on the transversely-polarized quark distributions $\Delta_T q(x)$ in the nucleon can be accessed by measuring the transverse Λ and $\bar{\Lambda}$ polarizations, which refer to a spin correlation between the transversely polarized nucleon and the Λ particle. Λ and $\bar{\Lambda}$ particles are identified from their weak decays $\Lambda \to p\pi^-$ and $\bar{\Lambda} \to \bar{p}\pi^+$ The Λ polarization is measured with respect to the reference axis T, where T is the transverse quark polarization vector after the scattering with respect to the $\mu - \mu$‘ scattering plane. P^Λ is accessible through the angular distribution of the parity-violating weak decay in the Λ rest frame by

$$\frac{\mathrm{d}N}{\mathrm{d}\cos\theta} = \frac{N}{2}(1 \pm \alpha P^\Lambda \cos\theta), \tag{7}$$

where N is the number of produced $\Lambda(\bar{\Lambda})$ hyperons, θ is the decay angle of the proton with respect to the reference axis T. $\alpha = 0.642 \pm 0.013$ is the analyzing power of the parity violating Λ decay. To determine the number of Λ hyperons in each $\cos\theta$ bin, a side-bin subtraction method is used. The data of the target cells with different polarizations and the data taking periods in which the polarization in the cells have been reversed are used in order to cancel acceptance effects and leave only the counting rate asymmetry $\epsilon_T(\theta) = \alpha P_T^\Lambda \cos\theta$. Finally, the transverse Λ and $\bar{\Lambda}$ polarization is extracted from the slope of the $\epsilon_T(\theta)$ distribution.

In analysis, Λs and $\bar{\Lambda}$s are identified from their weak decays $\Lambda \to p\pi^-$ and $\bar{\Lambda} \to \bar{p}\pi^+$. Only tracks with momenta greater than 1 GeV/c are selected, to provide good tracking efficiency. A collinearity angle between the lambda direction calculated by the position of the primary and secondary vertex and the direction of the reconstructed lambda from its decay products has to be within 10 mrad. The contamination from e^+e^- pairs from photon conversion is reduced by requiring a minimal transverse momentum $p_T > 23$ MeV/c of hadrons with respect to the reconstructed $\Lambda(\bar{\Lambda})$ momentum. Information from the RICH detector is used to apply a veto condition on the proton from the hyperon decay to reject electrons, pions and kaons.

The transverse Λ and $\bar{\Lambda}$ polarization as a function of x and z is shown in Fig. 3. Both the Λ and the $\bar{\Lambda}$ polarization show no significant deviation from zero in the whole explored kinematic range $8 \cdot 10^{-3} < x < 0.1$. The measured zero value for P_T^Λ might be due to the smallness of the transversity distribution in the available x-range or to the fact that the polarized fragmentation function into a transverse lambda is small in the COMPASS kinematic range, since the measured asymmetry

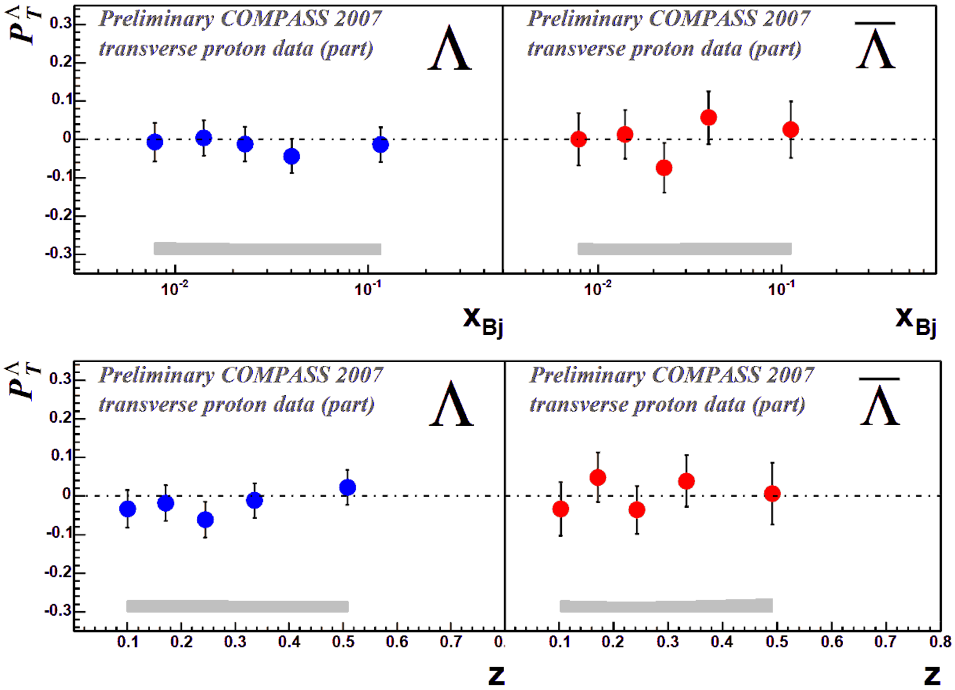

Fig. 3. Transverse Λ and $\bar{\Lambda}$ polarizations scattering off a transversely polarized proton target as a function of x (upper panel) and z (lower panel).

is proportional to the product of $\Delta_T q(x)$ and $\Delta_T D_q^\Lambda(z)$. In order to gain further information from the measurement of transverse $\Lambda(\bar{\Lambda})$ polarization, the limited Λ statistics in the valence quark region, where transversity is sizable, needs to be increased. The new data set from 2010 with a transversely-polarized proton target will contribute to that.

6. 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 $\vec{k}_T$ of unpolarized quarks with the spin of a transversely-polarized nucleon [23]. The correlation between the transverse nucleon spin and the transverse quark momentum is described by the Sivers distribution function $\Delta_0^T q(x, \vec{k}_T)$. The Sivers effect results in an azimuthal modulation of the produced hadron yield

$$N(\Phi_{\rm Siv}) = N_0 \cdot (1 + f \cdot P_t \cdot A_{\rm Siv} \cdot \sin\Phi_{\rm Siv}). \tag{8}$$

The Sivers angle is defined as $\Phi_{\rm Siv} = \phi_h - \phi_S$. The measured Sivers asymmetry $A_{\rm Siv}$ can be factorized into a product of the Sivers distribution function and the unpolarized fragmentation function $D_q^h(z)$,

$$A_{\rm Siv} = \frac{\sum_q e_q^2 \cdot \Delta_0^T q(x, \overrightarrow{k}_T) \cdot D_q^h(z)}{\sum_q e_q^2 \cdot q(x) \cdot D_q^h(z)}. \qquad (9)$$

In this case, the asymmetry $A_{\rm Siv}$ shows up as the amplitude of a $\sin \Phi_{\rm Siv}$ 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 [16], both asymmetries are determined experimentally in a common fit to the same dataset, taking into account the acceptance of the spectrometer.

In the upper panel of Fig. 4, the results for the Sivers asymmetry on the proton are shown as a function of x, z and p_T. The Sivers asymmetry for negative hadrons is small and statistically compatible with zero. For positive hadrons the Sivers asymmetry is positive. Predictions of the Sivers asymmetry for COMPASS kinematics from Ref. [13] are shown as curves. The predictions are obtained using the COMPASS results for the Sivers asymmetry on the deuteron target [6] and the HERMES results on a proton target [7]. The predictions describe well the x-dependence of the measured asymmetries, while there are discrepancies in the z and p_T behavior. The Sivers asymmetry on the deuteron target is shown in the lower panel of Fig. 4. The asymmetry is small, which shows the opposite sign of the $u-$ and $d-$quark Sivers function.

7. *Azimuthal asymmetries in SIDIS off an unpolarized target*

The cross-section for hadron production in lepton-nucleon SIDIS $\ell N \to \ell' h X$ for unpolarized targets and an unpolarized or longitudinally polarized beam has the following form [25]:

$$\frac{{\rm d}\sigma}{{\rm d}x\,{\rm d}y\,{\rm d}z\,{\rm d}\phi_h\,{\rm d}p_{h,T}^2} = \frac{\alpha^2}{xyQ^2}\frac{1+(1-y)^2}{2} \qquad (10)$$

$$\times\Big[F_{UU,T} + \varepsilon F_{UU,L} + \varepsilon_1 \cos\phi_h F_{UU}^{\cos\phi_h} + \varepsilon_2 \cos(2\phi_h) F_{UU}^{\cos\,2\phi_h} + \lambda_\mu \varepsilon_3 \sin\phi_h F_{LU}^{\sin\phi_h}\Big],$$

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

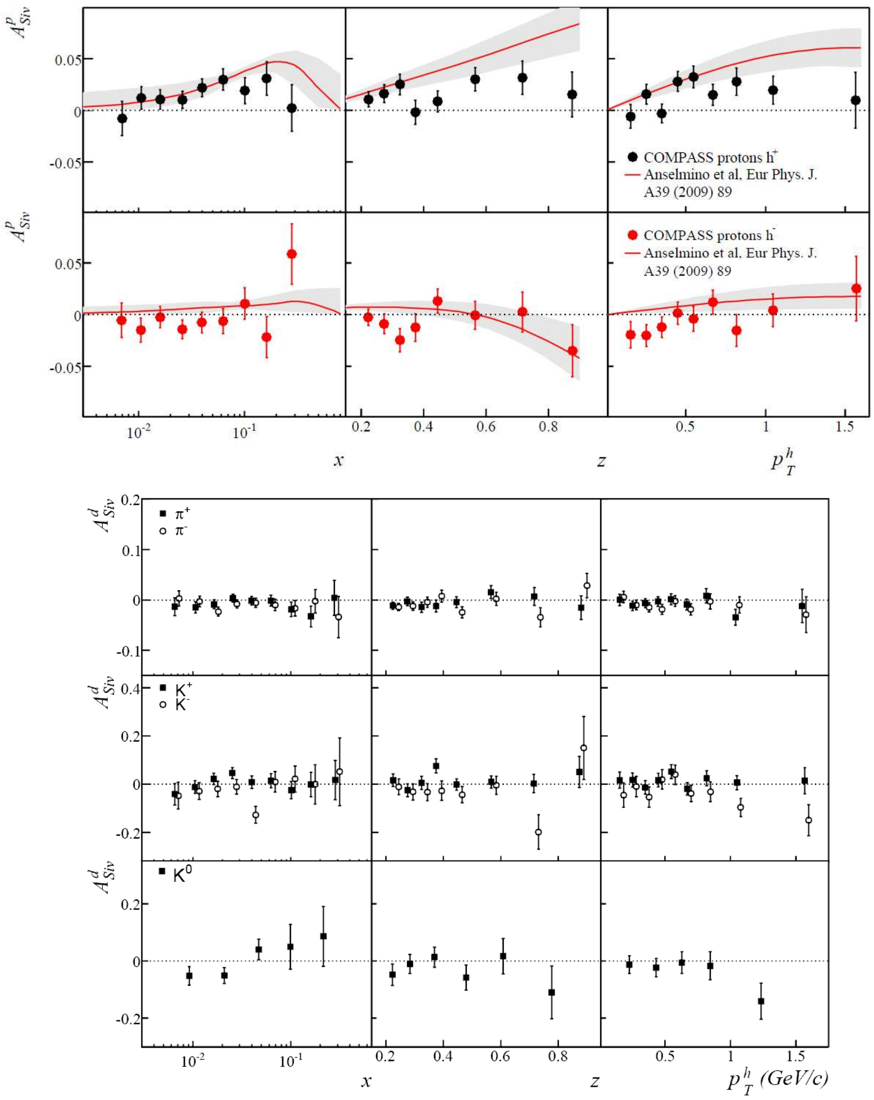

Fig. 4. Upper panel: Sivers asymmetry on the proton for unidentified positive (black) and negative (red) hadrons as a function of x, z, and p_T as published in Ref. [5]. Predictions from Ref. [13] are drawn as curves. Lower panel: Sivers asymmetry on the deuteron for positive (filled squares) and negative (open circles) pions and kaons and K^0 as a function of x, z, and p_T as published in Ref. [6].

polarization of the virtual photon. λ_μ is the longitudinal beam polarization and

$$\varepsilon_1 = \frac{2(2-y)\sqrt{1-y}}{1+(1-y)^2}, \quad \varepsilon_2 = \frac{2(1-y)}{1+(1-y)^2} \quad \varepsilon_3 = \frac{2y\sqrt{1-y}}{1+(1-y)^2} \tag{11}$$

are depolarization factors.

The Boer-Mulders parton distribution function contributes to both the $\cos\phi_h$ and the $\cos 2\phi_h$ moments. Another source of $\cos\phi_h$ and the $\cos 2\phi_h$ moments in unpolarized scattering is the so-called Cahn effect [17] which arises from the fact that the kinematics is non collinear when the transverse momentum $k_\perp$ of the quarks is taken into account. Additionally, perturbative gluon radiation, resulting in higher order α_s QCD processes, contributes to the observed $\cos\phi_h$ and the $\cos 2\phi_h$ moments as well. pQCD effects become important for high transverse momenta p_T of the produced hadrons.

In analysis, data taken with a longitudinally or transversely polarized ^{6}LiD target in the year 2004 has been spin-averaged in order to obtain an unpolarized data sample. A Monte Carlo simulation is used to correct for acceptance effects of the detector. The SIDIS event generation is performed by the LEPTO generator [24], the experimental setup and the particle interactions in the detectors are simulated by the COMPASS Monte Carlo simulation program COMGEANT.

The acceptance of the detector 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:

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

The contribution of the acceptance corrections to the systematic error was studied in detail.

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 prediction [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 considered in this prediction.

The $\cos 2\phi_h$ asymmetries are shown in Fig. 6 together with the theoretical predictions of Ref. [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 Ref. [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,

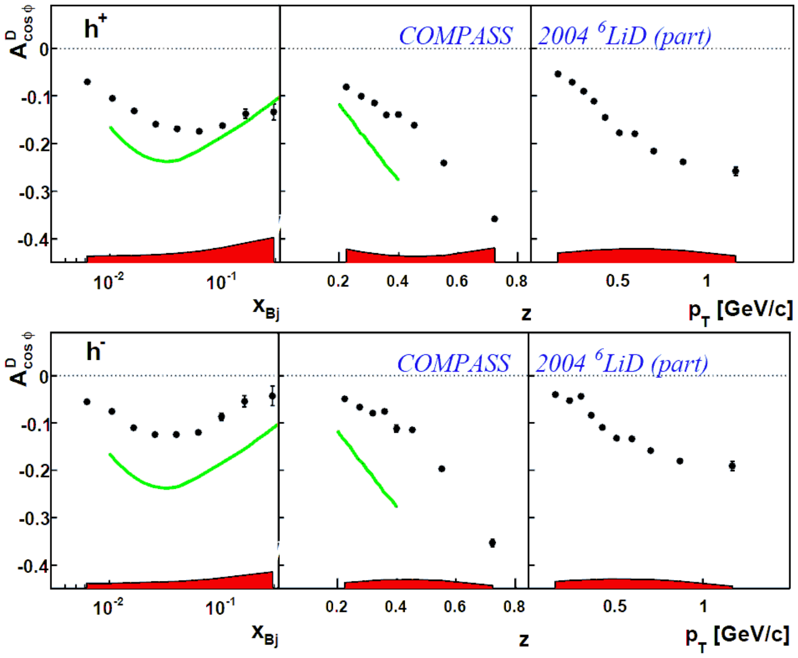

Fig. 5. $\cos\phi_h$ *asymmetries from COMPASS deuteron data for positive (upper row) and negative (lower row) hadrons; the asymmetries are divided by the kinematic factor* ε_1 *and the bands indicate the size of the systematic uncertainty. The superimposed curves are the values predicted in Ref. [26] taking into account the Cahn effect only.*

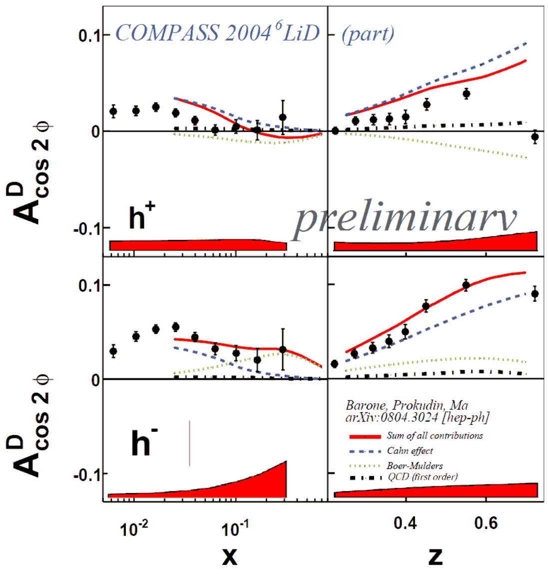

Fig. 6. $\cos 2\phi_h$ *asymmetries from COMPASS deuteron data for positive (upper row) and negative (lower row) hadrons; the bands indicate size of the systematic error.*

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.

8. Summary and Outlook

Results for the Collins and the two-hadron azimuthal asymmetry at COMPASS in semi-inclusive deep-inelastic scattering off transversely polarized proton and deuteron targets have been presented. For $x > 0.05$, a Collins and a two-hadron asymmetry different from zero and increasing magnitude with increasing x-Bjorken have been observed on the proton. The asymmetries on the deuteron are small and compatible with zero. The transverse Λ and the $\bar{\Lambda}$ polarization on the proton were found to be small and compatible with zero within the available kinematic range.

The measured Sivers asymmetry on the proton for negative hadrons is compatible with zero, while a positive asymmetry is observed for positive hadrons. On the deuteron, the Sivers asymmetry is small.

The measured unpolarized azimuthal asymmetries on a 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.

With the data from a full-year transverse-target running completed in 2010, COMPASS will significantly increase its statistical precision in all measurements of transverse-spin dependent asymmetries.

Acknowledgements

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POPREČNI SPINSKI I POPREČNI IMPULSNI UČINCI PRI COMPASSU

Među glavnim istraživačkim programima suradnje COMPASS je proučavanje poprečnih spinskih i poprečnih impulsnih učinaka u duboko-neelastičnom raspršenju. Tijekom 2002. – 2004., COMPASS je sakupio podatke za muonsko raspršenje na 160 GeV na polariziranoj meti ^{6}LiD. U 2007. rabila se polarizirana meta NH_3. Analizirana su tri različita kanala radi dobivanja funkcije raspodjele poprečnosti: azimutalna raspodjela za pojedinačne hadrone koja ovisi o Collinsovoj funkciji lomljenja, azimutalna ovisnost ravnine koja sadrži parove hadrona i u kojoj se javlja interferencija funkcije lomljenja, te poprečna polarizacija lambda hyperona u konačnom stanju. Istraživali su se učinci poprečnih kvarkovskih impulsa u poprečno polarizirnom nukleonu mjerenjem Siversove funkcije. Azimutalne asimetrije u nepolariziranom poluinkluzivnom duboko-neelastičnom raspršenju također daju važne podatke o unutarnjoj strukturi nukleona. Mogu se primijeniti radi procjenjivanja poprečnih impulsa kvarkova u nepolariziranom nukleonu i za određivanje Boer-Muldersove funkcije koja dosada nije mjerena. Te je asimetrije odredio COMPASS u 2004. rabeći prosjeke podataka ^{6}LiD mjerenja.