Transverse Spin Effects and TMDs in SIDIS from the COMPASS Experiment at CERN

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Abstract. The measurement of azimuthal single spin asymmetries in semi-inclusive deep-inelastic scattering (SIDIS) on a transversely polarized target is an important part of the COMPASS program, giving access to the transversity distribution functions as well as transverse momentum dependent distribution functions. After COMPASS took data in the years 2002-2004 by scattering a 160 GeV/c muon beam off a transversely polarized deuteron (^{6}LiD) target, in 2007 and 2010 additional data was collected on a transversely polarized proton (NH_3) target. In this contribution, the results of the 2007 measurements of the Collins and Sivers asymmetries in single hadron production as well as two-hadron asymmetries are presented.

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Over the last years, intense experimental efforts were made to measure the transversity distribution functions $h_1^q(x)$ [1, 2, 3], describing the difference in the number density of quarks with momentum fraction x with their transverse spin parallel and anti-parallel to the nucleon spin. These chiral-odd distribution functions, in addition to the momentum and helicity distribution functions $f_1^q(x)$ and $g_1^q(x)$, complete the full description of the spin structure of the nucleon at twist-two level, when the parton momentum is integrated over. Transversity can be measured in SIDIS, both in single and hadron-pair production, in combination with chiral-odd fragmentation functions regaining a chiral-even process, giving rise to azimuthal single spin asymmetries of the final state hadrons.
On a transversely polarized target, the transversity distribution can be measured convoluted with the Collins fragmentation function $H_1^h(z, p_T^2)$ [2], describing the spin-dependent part of the hadronization of a transversely polarized quark into an unpolarized hadron with transverse momentum p_T. This fragmentation leads to a modulation in the SIDIS cross section [2], so the number of produced hadrons N can be written as

$$N_h \propto \sigma_{UU}\,(1 \pm f(x,y)\,P_T\,D_{nn}(y)\,A_{Coll}\sin\phi_C) \quad \text{with} \quad A_{\text{Coll}} = \frac{\sum_q e_q^2 \cdot h_1^q(x) \otimes H_1^h(z,p_T^2)}{\sum_q e_q^2 \cdot f_1(x) \otimes D_q^h(z,p_T^2)}\,.$$

Here, $\phi_C = \phi_h + \phi_S - \pi$ is the *Collins angle*, defined by ϕ_h, the azimuthal angle of the hadron with respect to the scattering plane, and ϕ_S, the azimuthal angle between the spin of the initial quark and the scattering plane. σ_{UU} is the unpolarized cross section, P_T is the target polarization, $f(x,y)$ is the kinematics dependent target dilution factor and $D_{nn}(y) = (1-y)/(1-y+y^2/2)$ is the transverse spin transfer coefficient. A_{Coll} is the *Collins asymmetry*, proportional to the convolution of the transversity distribution function with the Collins fragmentation function, where $\otimes$ stands for convolution integrals of the parton and hadron transverse momenta k_T and p_T, respectively. The Collins fragmentation functions were independently measured at the KEK e^+e^- collider by the BELLE experiment [4].
As an alternative it was proposed to measure the SIDIS process $l p^\uparrow \to h^+ h^- X$ [2, 3, 5], involving a different chiral-odd fragmentation function, the Interference Fragmentation Function $H_1^\sphericalangle(z, M^2_{h^+h^-}, \cos\theta)$. It describes the fragmentation of transversely polarized quarks into pairs of unpolarized hadrons. Here, the transverse polarization of the fragmenting quark is related to the relative motion of both hadrons, resulting in an azimuthal modulation of the cross section with respect to the virtual photon direction and the lepton scattering plane, depending on the angle $\phi_{RS} = \phi_R + \phi_S - \pi$, where $\mathbf{R}$ is the relative momentum of both hadrons and ϕ_R is the corresponding azimuthal angle of the two hadron plane. The number of oppositely charged hadron pairs on a transversely polarized target can then be written as

$$N_{h^+h^-} \propto \sigma_{UU}\left(1 \pm f(x,y)\,P_T\,D_{nn}(y)\,A_{UT}^{\sin\phi_{RS}}\sin\theta\sin\phi_{RS}\right) \quad \text{with} \quad A_{UT}^{\sin\phi_{RS}} = \frac{|\mathbf{R}|}{M_h}\frac{\sum_q e_q^2 \cdot h_1^q(x) \cdot H_{1,q}^\sphericalangle(z,M_h^2,\cos\theta)}{\sum_q e_q^2 \cdot f_1^q(x) \cdot D_{1,q}(z,M_h^2,\cos\theta)}\,.$$

Here, M_h is the invariant mass of the hadron pair and θ is the polar angle of the positive hadron in the two-hadron center-of-mass frame with respect to the two-hadron boost axis. The measured amplitude A_{RS} is proportional to the product of the transversity distribution and the two hadron interference fragmentation function. The interference fragmentation functions have recently also been measured in e^+e^- reactions by the BELLE collaboration [6].

Allowing for an intrinsic transverse momentum ($\mathbf{k_T}$) dependence of the quark distributions in the nucleon, further azimuthal asymmetries are related to transverse momentum dependent distribution functions. One of these is the Sivers function $f_{1T}^{\perp}(x,\mathbf{k_T})$ [7]. It describes the correlation of the transverse quark momentum to the transverse polarization of the nucleon and is thus related to the quark angular momentum. It leads to an azimuthal modulation of the number of produced hadrons in the *Sivers angle* $\phi_{Siv} = \phi_h - \phi_S$. The measured asymmetry A_{Siv} is proportional to the convolution of the Sivers distribution function $f_{1T}^{\perp}(x,\mathbf{k_T})$ with the well known unpolarized fragmentation function $D_q^h(z,p_T^2)$:

$$N_h \propto \sigma_{UU}\,(1 \pm f(x,y)\,P_T\,A_{Siv}\sin\phi_{Siv}) \quad \text{with} \quad A_{\text{Siv}} = \frac{\sum_q e_q^2 \cdot f_{1T}^{\perp}(x,\mathbf{k_T}) \otimes D_q^h(z,p_T^2)}{\sum_q e_q^2 \cdot q(x) \otimes D_q^h(z,p_T^2)} \,.$$

COMPASS [8] is a fixed target experiment at the CERN SPS accelerator. For SIDIS measurements a -80% longitudinally polarized 160 GeV/c μ^+ beam was scattered off solid state polarized targets, consisting of several cylindrical cells along the beam direction. As target materials ^6LiD and NH_3 were used, giving access to the properties of the deuteron and proton repectively. The target polarization direction could be set either parallel or orthogonal to the beam direction. Within each configuration, it was additionally periodically reversed to reduce systematic effects due to the different acceptances of the cells. Particle tracking and identification are performed in a two-stage spectrometer, covering a wide kinematical range for the full apperture of the polarized target of 180 mrad. A Ring Imaging Cherenkov detector (RICH) covering the complete spectrometer acceptance provides particle identification from threshold up to 50 GeV/c. After data was collected on a transversely polarized deuteron (^{6}LiD) target in 2002–2004 [9, 10, 11]. in 2007 and 2010 COMPASS took data using a transversely polarized proton (NH_3) target [12]. The target was segmented in three cells, with the two outer cells polarized in one direction and the central one polarized oppositely. The polarization was reversed every 4-5 days. A polarization of $P_T \sim 90\%$ with a dilution factor of $f \sim 0.15$ was achieved. The asymmetries presented here, have been extracted from the data collected in 2007. To select DIS events, kinematic cuts on the momentum transfer $Q^2 > 1\,(\text{GeV}/c)^2$, on the fractional energy transfer of the muon $0.1 < y < 0.9$ and the hadronic invariant mass $W > 5\,\text{GeV}/c^2$ were applied. For the single-hadron asymmetries, the sample consists of all charged hadrons from the reaction vertex with transverse momentum $p_T > 0.1\,\text{GeV}/c$ and $z > 0.2$. Particle identification using the RICH detector has been applied to provide samples of pions and kaons. The hadron-pair sample consists of all oppositely charged hadron pair combinations originating from the reaction vertex with a transverse momentum of the hadron pair of $R_T > 0.07$ GeV/c and a missing energy $E_{miss} > 3$ GeV to reject exclusive ρ^0 production. For the individual hadrons the cuts were $z > 0.1$ and $x_F > 0.1$ to exclude target fragmentation. In this case particle identification has not been applied yet. To extract the asymmetries, an unbinned extended likelihood method was used, including the full expression for the transverse polarization dependent part of the SIDIS cross section into the fit. To disentangle acceptance and spin dependent modulations events from target cells with opposite polarization within one data taking period were combined with corresponding samples of a consecutive period with reversed target polarization.

The Collins and Sivers asymmetries were evaluated as functions of x, z, and p_T respectively integrating over the remaining two variables. In Fig. 1 the results for the Collins asymmetries are shown for identified pions (left) and kaons (right). The pion asymmetries, which account for about 70 % of the unidentified data already published in [12] show a strong x dependence, both for positive and negative pions. For $x > 0.05$ the measured asymmetries are clearly non-zero and rising, reaching values of about +10 % for π^- and about -5 % for π^+. No distinct dependence on the other two variables z and p_T are visible. For the kaon sample, the asymmetries for K^+ show a similar behaviour in x, reaching values of up to -10 %. Here, a trend is visible in the dependence on p_T. For K^- the measured asymmetries are smaller reaching about +8 %, most likely because the K^- are pure sea objects, while the K^+ do contain a valence u-quark. The dependence on x and p_T is much less pronounced. The results for the charged pions are in excellent agreement with the predictions of [13], however, no such predictions exist for the kaon asymmetries. The good agreement with the data published by HERMES [14] measured at smaller average Q^2 values indicates only a weak Q^2 dependence.

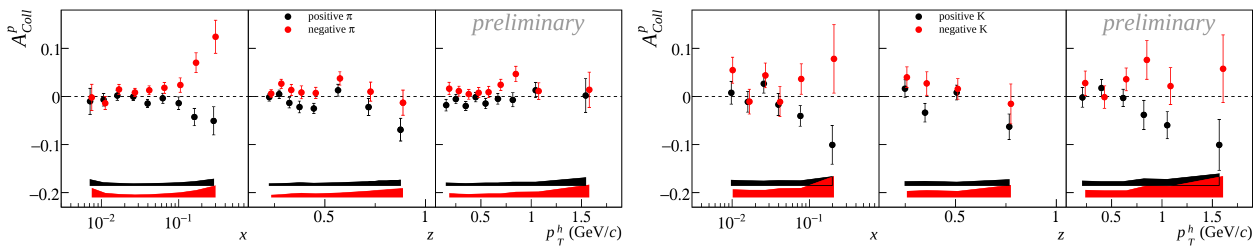

FIGURE 1. Collins asymmetries on the proton target. The error bars show the statistical errors, while the bands indicate the systematic errors. Left: asymmetries of the extracted pion sample, right: kaon asymmetries.

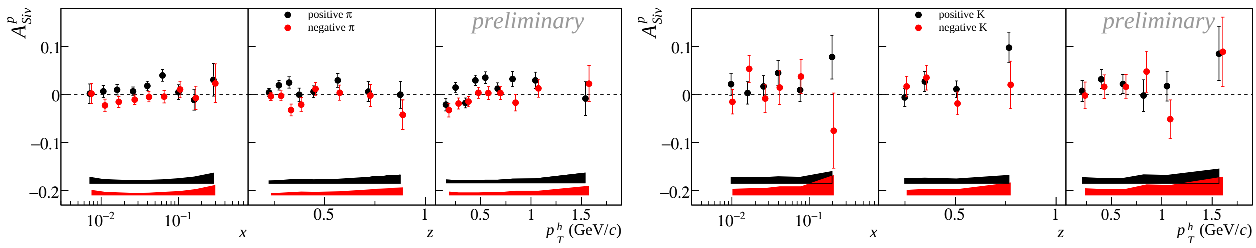

FIGURE 2. Sivers asymmetries on the proton target. The error bars show the statistical errors, while the bands indicate the systematic errors. Left: asymmetries of the extracted pion sample, right: kaon asymmetries.

The Sivers asymmetries are shown in Fig. 2. For negative pions and kaons, the asymmetries are competible with zero over the whole kinematic range. However, both for positive pions and kaons, the asymmetries are positive on average, indicating an increase for $x > 0.05$, while no clear dependence is observed for the other two variables. The asymmetries for K^+ are in the order of the π^+ asymmetries. Within the statistical errors the Sivers asymmetries are in agreement with the predictions in [15] and the results obtained by the HERMES collaboration [16], although the mean values measured by COMPASS are smaller. However, the dip in the asymmetries at $x \approx 0.1$ is not observed there. The nature of this difference will need further investigation, requiring the high statistics data taken by COMPASS in 2010.

For the two-hadron asymmetries the results for $A_{UT}^{\sin\phi_{RS}} \sin\theta$ are shown as a function of x, z and M_{inv} in Fig. 3. Here, $\sin\theta$ is not disentangled from the asymmetry, as it strongly peaks close to one with $\langle \sin\theta \rangle \approx 0.94$. The distributions are all negative for the complete ranges covered in x, z and M_{inv}. Again, like in the case of single hadron production, a strong dependence on x is visible with significant asymmetries for $x > 0.05$ reaching up to 10 %. No obvious structure is visible in z, however, at larger z the asymmetries seem to increase. In the invariant mass a small enhancement at the ρ^0-mass can be observed. In combination with the fragmentation function measured by BELLE, the high statistics of these data, which will even be increased significantly by the analysis of the data taken in 2010, will allow for an independent extraction of the transversity functions in addition to the results extracted from the Collins effect.

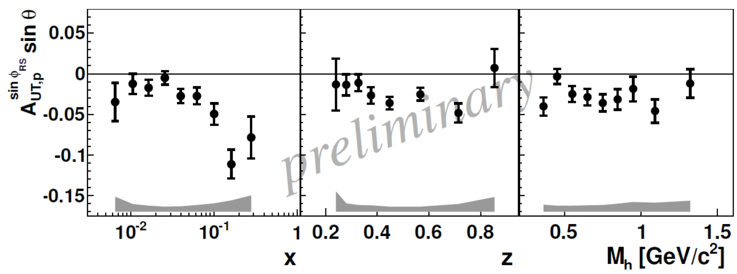

FIGURE 3. Two hadron asymmetries $A_{UT}^{\sin\phi_{RS}} \sin\theta$ *vs.* x, z and M_{inv}. The lower bands represent the systematic errors.

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