Single Spin Asymmetries at COMPASS with transverse target polarization

C. Schill for the COMPASS collaboration

Physikalisches Institut der Universität Freiburg
Hermann-Herder Str. 3
D-79104 Freiburg

Abstract. COMPASS is a fixed target experiment at CERN investigating the spin structure of the nucleon and performing hadron spectroscopy. The transverse spin structure of the nucleon is studied in semi-inclusive deep-inelastic scattering of 160 GeV/c muons off a transversely polarized proton or deuteron target. In 2002-2005, a transversely polarized ^6LiD, and in 2007 a transversely polarized NH_3 target were used. To get access to the transversity distribution, different single-spin asymmetries have been measured: the Collins asymmetry, the hadron-pair asymmetry and the transverse lambda polarization. In addition, transverse momentum effects of quarks have been studied by the Sivers effect. New results for the Collins and the Sivers asymmetries on the proton for identified pions and kaons and for the two hadron interference asymmetry will be presented.

INTRODUCTION

The cross-section for semi-inclusive deep-inelastic scattering (SIDIS) in the one-photon exchange approximation contains eight transverse-momentum dependent distribution functions [1]. Some of these can be extracted measuring the azimuthal distribution of the hadrons in the final state [2]. 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 $\Delta_T q(x)$. The latter is defined as the difference in the number density of quarks with momentum fraction x with their transverse spin parallel to the the transversely polarized target and their spin anti-parallel to the target. [3].

THE COMPASS EXPERIMENT

At COMPASS, the scattered muon and the produced hadrons are detected in a 50 m long wide-acceptance forward spectrometer with excellent particle identification capabilities [4]. A transversely polarized NH_3 target consists of three cells aligned along the muon beam axis. The upstream and downstream cells are polarized in one direction while the middle cell is polarized oppositely. The average polarization of the NH_3 target is about 90%. The direction of the target polarization is reversed every few days to reduce the systematic error. The asymmetries are analyzed using at the same time data from two periods of opposite polarization and from the different target cells. Pions and Kaons are identified in a large scale Ring Imaging Cherenkov Detector (RICH) in a wide momentum range [5].

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 [2]. The hadron yield $N(\Phi_{Coll})$ can be written as $N(\Phi_{Coll}) = N_0 \cdot (1 + f \cdot P_t \cdot D_{NN} \cdot A_{Coll} \cdot \sin\Phi_{Coll})$, where N_0 is the average hadron yield, f the fraction of polarized material in the target, P_t the target polarization, A_{Coll} the Collins asymmetry, $D_{NN} = (1-y)/(1-y+y^2/2)$ the depolarization factor, and y the fractional energy transfer of the muon. The angle Φ_{Coll} is the so called Collins angle. It is defined as $\Phi_{Coll} = \phi_h - \phi_s$, the difference of the hadron azimuthal angle ϕ_h and the quark spin azimuthal angle ϕ_s after the scattering, both with respect to the lepton scattering plane [3]. 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:

$$A_{Coll} = \frac{\sum_q e_q^2 \cdot \Delta_T q(x) \cdot \Delta_T^0 D_q^h(z, p_T)}{\sum_q e_q^2 \cdot q(x) \cdot D_q^h(z, p_T)}. \tag{1}$$

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.

To select DIS events, kinematical cuts on the negative 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 $0.1 < y < 0.9$ are 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 extraction of the amplitudes is then performed fitting the expression for the transverse polarization dependent part of the semi-inclusive DIS cross section [6] 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. [7].

In left panel of Fig.1 the results for the Collins asymmetry on a NH_3 target are shown as a function of x for positive and negative pions. 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 pions. This result confirms the measurement of a sizable Collins function and transversity distribution. The asymmetry for positive and negative kaons is shown in the second panel of Fig.1. At larger x, the asymmetry is different from zero as well and shows opposite signs for positive and negative kaons. The data provide important information for 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-, d- and s-quarks [8, 9, 10, 11].
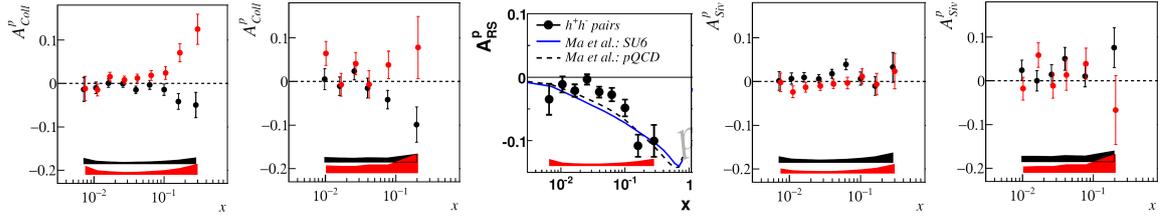
FIGURE 1. Collins asymmetry on the proton for positive (black) and negative (red) pions (first panel on the left) and kaons (second panel) as a function of x. Two-hadron asymmetry A_{RS} on the proton compared to predictions of [12] (third panel). Sivers Asymmetry for positive (black) and negative (red) pions (fourth panel) and kaons (right panel). The bands indicate the systematic uncertainty of the measurements.

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 $H_1^{\triangleleft}(z, M_{inv}^2)$ 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 $\Phi_{RS} = \phi_R - \phi_s$ 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 $\vec{R} = (z_2 \cdot \vec{p}_1 - z_1 \cdot \vec{p}_2)/(z_1 + z_2)$. $\vec{p}_1$ 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 $N_{h^+ h^-} = N_0 \cdot (1 + f \cdot P_t \cdot D_{NN} \cdot A_{RS} \cdot \sin \Phi_{RS} \cdot \sin \theta)$. 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 [9]. The measured amplitude A_{RS} is proportional to the product of the transversity distribution and the polarized two-hadron interference fragmentation function

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

$D_q^{2h}(z, M_{inv}^2)$ is the unpolarized two-hadron interference fragmentation function. 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 $R_T > 0.07\,\text{GeV/c}$ was applied. The two-hadron asymmetry on the proton as a function of x is shown in the third panel of Fig. 1. 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 $H_1^{\triangleleft}$. The lines are calculations from Ma *et al.*, based on a SU6 and a pQCD model for transversity [12] and the di-hadron fragmentation functions from Bacchetta *et al.* [9]. The calculations describe well the magnitude and the x-dependence of the measured asymmetry.

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 [13]. 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 results in an azimuthal modulation of the produced hadron yield: $N(\Phi_{Siv}) = N_0 \cdot (1 + f \cdot P_t \cdot A_{Siv} \cdot \sin \Phi_{Siv})$. The Sivers angle is defined as $\Phi_{Siv} = \phi_h - \phi_S$, where ϕ_S is the azimuthal angle of the target spin vector. The measured Sivers asymmetry A_{Siv} can be factorized into a product of the Sivers distribution function and the unpolarized fragmentation function $D_q^h(z)$:

$$A_{Siv} = \frac{\sum_q e_q^2 \cdot \Delta_0^T q(x, \overrightarrow{k_T}) \cdot D_q^h(z)}{\sum_q e_q^2 \cdot q(x) \cdot D_q^h(z)}. \tag{3}$$

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 [6], both asymmetries are determined experimentally in a common fit to the same dataset, taking into account the acceptance of the spectrometer.

In the fourth panel of Fig.1 the results for the Sivers asymmetry on the proton are shown as a function of x. The Sivers asymmetry for negative pions is small and statistically compatible with zero. For positive pions the Sivers asymmetry is positive. The Sivers asymmetry for kaons is shown in the right panel of Fig.1.

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