PROCEEDINGS OF SCIENCE

Transverse target spin asymmetries on a proton target at COMPASS

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Transversity and transverse momentum-dependent parton distribution functions (TMDs) are been measured in semi-inclusive deep inelastic scattering (SIDIS) by using a transversely polarized target at the COMPASS experiment. COMPASS is a fixed target experiment at the CERN M2 beamline, which provides a 160 GeV/c polarized μ^+ beam. In the years 2002-2004 COMPASS has collected data with a transversely polarized deuteron ^{6}LiD target. In 2007, COMPASS has used for the first time a proton NH_3 target. To access transversity COMPASS has used three different quark polarimeters: the Collins effect, responsible for an azimuthal asymmetry in the single hadron distribution, azimuthal target spin asymmetries of charged hadron pairs and the transverse polarisation of Λ hyperons. Beside this also the Sivers asymmetry arising from the correlation between the transverse nucleon spin and the quark intrinsic transverse momentum was measured.

European Physical Society Europhysics Conference on High Energy Physics, EPS-HEP 2009,
July 16 - 22 2009
Krakow, Poland

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1. Introduction

Three distribution functions are needed to fully describe the nucleon at leading twist: the unpolarized distribution function $q(x)$ describing the probability to find a quark with a fraction x of the nucleon momentum, the helicity distribution function $\Delta q(x)$ describing the probability difference in a longitudinally polarized nucleon (w.r.t. the direction of motion) to find a quark with spin parallel or antiparallel to the nucleon spin and the transversity spin distribution function $\Delta_T q(x)$ describing the probability difference in a transversely polarized nucleon (w.r.t. the direction of motion) to find a quark with spin parallel or antiparallel to the nucleon spin. While the first two are known, transversity is now under intensive examination.
Because the transversity function is chiral-odd, it decouples from inclusive deep inelastic scattering (DIS). A measurement is therefore only possible in combination with another chiral-odd function, as e.g. in semi-inclusive scattering with the Collins fragmentation function $\Delta_T^0 D_q^h$ for single hadron production or the interference fragmentation function $H_1^{\sphericalangle}$ for the production of hadron pairs, which give rise to an azimuthal single spin asymmetry (SSA) in the final state hadrons.
Annother approach to measure $\Delta_T q(x)$ at COMPASS, employs the transverse polarization of Λ hyperons.
A second possible source for an azimuthal asymmetry is the Sivers effect [1]. Here the corresponding SSA are created from the correlation between the nucleon spin and the quark intrinsic transverse momentum k_T. The Sivers effect is described by the product of the so-called Sivers distribution function $\Delta_T^0 q(x, k_T)$ and the unpolarized fragmentation function D_q^h.
COMPASS is a fixed target experiment at the CERN M2 beamline, which provides a 160 GeV/c polarized μ^+ beam [2]. The main goal of the experiments' spin physics program is the study of the spin structure of the nucleon. In the years 2002-2004 COMPASS has collected data with a transversely polarized deuteron ^{6}LiD target for about 20% of its running time to measure transverse spin effects. In 2007, COMPASS has used for the first time a proton NH_3 target with the data taking time equally shared between longitudinal and transverse polarization of the target.

2. One hadron asymmetries

2.1 Collins asymmetry

The Collins mechanism [3] leads to a modulation in the azimuthal distribution of the produced hadrons given by:

$$N = N_0 \cdot (1 + f \cdot P_T \cdot D_{NN} \cdot A_C \cdot \sin(\Phi_{Coll})) \tag{2.1}$$

Here P_T is the target polarization, f the target dilution factor, i.e. the fraction of the target nuclei, which can be polarized and $D_{NN} = (1-y)/\left(1-y+y^2/2\right)$ the spin transfer coefficient. Φ_{Coll} is the Collins angle, defined as $\Phi_h - \Phi_{S'} = \Phi_h + \Phi_S - \pi$, where Φ_h is the azimuthal angle of the hadron momentum, $\Phi_{S'}$ is the azimuthal angle of the quark spin after scattering and Φ_S is the azimuthal angle of the nucleon spin with respect to the sacttering plane.
The Collins asymmetry A_C is given by:

$$A_C = \frac{\sum_q e_q^2 \Delta_T q(x) \Delta_T^0 D_q^h\left(z, p_T^h\right)}{\sum_q e_q^2 q(x) D_q^h\left(z, p_T^h\right)} \tag{2.2}$$

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arising from the product of the transversity distribution $\Delta_T q(x)$ and the Collins fragmentation function $\Delta_T^0 D_q^h$ divided by the momentum distribution $q(x)$ and the unpolarized fragmentation function D_q^h. $z = E_h/(E_l - E_{l'})$ with E_l and $E_{l'}$ as the lepton energy before and after scattering, respectively, is the proportion of the virtual photon energy carried by the hadron and p_T^h is the transverse momentum of the hadron with respect to the virtual photon direction.
To select DIS events cuts on the photon virtuality $Q^2 > 1\,(\mathrm{GeV}/c)^2$, on the fractional energy transfer of the muon $0.1 < y < 0.9$ and on the mass of the final hadronic state $W > 5\,\mathrm{GeV}/c^2$ were applied. Further cuts on charged hadrons were $z > 0.2$ and $p_T^h > 0.1\,\mathrm{GeV}/c$.
The Collins asymmetry on the proton target for the whole data taking are shown in fig. 1 as function of x, z and p_T^h. For large $x > 0.05$ the asymmetries are different from zero and negative in sign for positive hadrons and positive in sign for negative hadrons. For small $x < 0.05$ the values are small and compatible with zero. The agreement with the predictions of Anselmino et al. based on a fit the proton data of HERMES, the deuteron data of COMPASS and the measurement of $\Delta_T^0 D_q^h$ at Belle [4] can be seen.

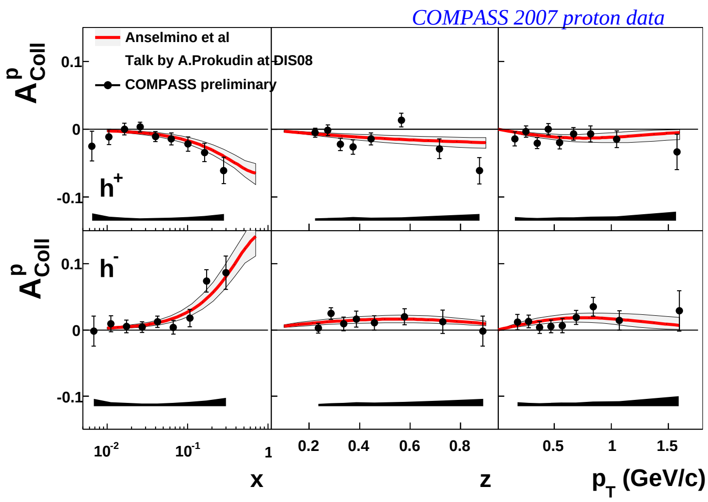

Figure 1: Collins asymmetry for positive (top) and negative (bottom) hadrons as function of x, z and p_T^h for the full 2007 data on a proton target and comparison with the precictions of Anselmino et al. [4].

2.2 Sivers asymmetry

Another possible source for the asymmetry in the distribution of the produced single hadrons is caused by the Sivers effect. This mechanism is sensitive to the correlation of the transverse momentum of an (fragmenting) unpolarized quark inside a transversely polarized nucleon and the transverse polarization of this nucleon. The Sivers effect is described by the so-called Sivers function $\Delta_T^0 q(x, k_T)$, which is the distribution function of unpolarized quarks in a transversely polarised nucleon. It is connected to the orbital angular momenta of the quarks, which also contribute to the nucleon spin.
The Sivers asymmetry gives a modulation in the azimuthal distribution of $\Phi_{Siv} = \Phi_h - \Phi_S$, which is independent of the Collins angle and can therefore be disentangled in SIDIS.

Because the Sivers asymmetries are more sensitive to instabilities of the spectrometer, the extraction of the Sivers asymmetries exhibits larger systematic errors and only a fraction of the data set has been used. The Sivers asymmetries are shown in fig. 2 as function of x, z and p_T^h. The asymmetries are small and compatible with zero within the statistical errors. The comparison with the predictions of Anselmino et al. [5] from the COMPASS deuteron and the HERMES proton data also shown in this figure gives a good agreement for the negative hadrons, while for positive hadrons a signal was expected as it was measured at the HERMES experiment [6].

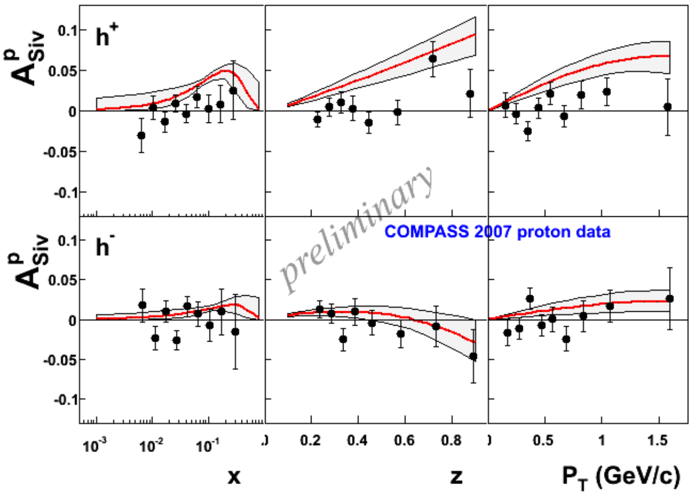

Figure 2: Sivers asymmetry for positive (top) and negative (bottom) hadrons as function of x, z and p_T^h for a part of the 2007 data on a proton target and comparison with the precictions of Anselmino et al. [5].

3. Two hadron asymmetries

An access to transversity is also possible via the production plain of pairs of two unpolarized hadrons[7, 8]. For this process the counting rates are given by:

$$N = N_0 \cdot (1 + f \cdot P_T \cdot D_{NN} \cdot A_{RS} \cdot \sin(\Phi_{RS})) \tag{3.1}$$

where the azimuthal angle Φ_{RS} is defined as $\Phi_{RS} = \Phi_R + \Phi_S - \pi$, with Φ_R as the azimuthal angle of the plane containing the two produced hadrons and Φ_S as the azimuthal angle of the target spin vector with respect to the lepton scattering plane. At COMPASS Φ_R is defined as the azimuthal angle of the transverse component R_T of the vector $\frac{z_2\mathbf{P}_1 - z_1\mathbf{P}_2}{z_1+z_2}$, where the indices 1 and 2 refer to the two final state hadrons.

The resulting asymmetry A_{RS} is proportional to the convolution of the transversity distribution $\Delta_T q(x)$ and the interference fragmentation function $H_1^{\sphericalangle}\left(z, M_h^2\right)$:

$$A_{RS} = \frac{\sum_q e_q^2 \Delta_T q(x) H_1^{\sphericalangle}\left(z, M_h^2\right)}{\sum_q e_q^2 q(x) D_q^h\left(z, M_h^2\right)} \tag{3.2}$$

Here M_h is the invariant mass of the hadron pair and $D_q^h\left(z, M_h^2\right)$ the also unknown unpolarized fragmentation function into two hadrons that can be measured at the Belle experiment.

The event selection is basically analog to the one for the single hadron asymmetries with the exception of the lower cut on z chosen as $z_{1,2} > 0.1$ for each hadron and $z_1 + z_2 < 0.9$ for the sum to remove exclusive production. Furthermore a cut on $x_F > 0.1$ was also applied. The results are shown in fig. 3 as function of x, z and M_{inv}. A strong signal in the valence x-region is visible implying a non-zero transversity distribution function and a non-zero interference fragmentation function $H_1^{\sphericalangle}$. Predictions from Bacchetta et al. [9] based on the transversity distribution extracted by Anselmino et al. [4] and on a fit to the HERMES results [10] are also shown in this figure. It can be seen that our measured asymmetries are larger than the predictions of Bacchetta et al. [9].

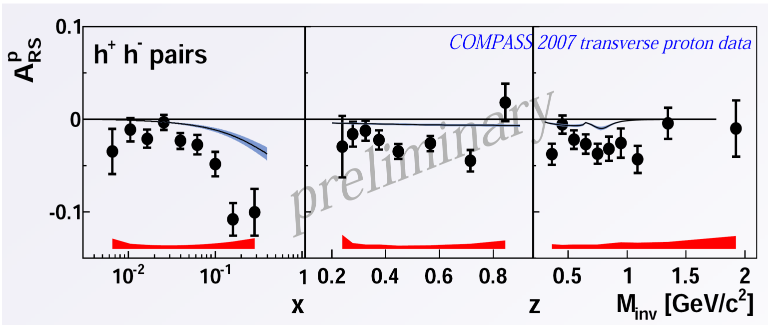

Figure 3: Asymmetries for charged hadron pairs for the full 2007 data on a proton target as function of x, z and M_{inv}.

4. Λ polarimetry

The third channel used at COMPASS to get information about $\Delta_T q(x)$ is to measure the transverse polarization of Λ and $\overline{\Lambda}$ in the reaction $\mu N^{\uparrow} \to \mu' \Lambda^{\uparrow} X$. The polarization of the Λ hyperon produced in this reaction is given by [11, 12]:

$$P^{\Lambda}_{T,exp} = \frac{d\sigma^{\mu N\uparrow \to \mu' \Lambda^{\uparrow} X} - d\sigma^{\mu N^{\downarrow} \to \mu' \Lambda^{\uparrow} X}}{d\sigma^{\mu N^{\uparrow} \to \mu' \Lambda^{\uparrow} X} + d\sigma^{\mu N^{\downarrow} \to \mu' \Lambda^{\uparrow} X}} = f \cdot P_T \cdot D_{NN}(y) \cdot \frac{\sum_q e_q^2 \Delta_T q(x) \Delta_T D_{\Lambda/q}(z)}{\sum_q e_q^2 q(x) D_{\Lambda/q}(z)} \tag{4.1}$$

Analog equations are valid for $\overline{\Lambda}$.

The measured transverse polarizations can be seen in fig. 4 as a function of z. No significant deviation from zero is visible for the whole z range. As the other channels for transversity are non-zero, it seems that the fragmentation function $\Delta_T D_{\Lambda/q}(z)$ as function of z is quite small.

Also no dependance on x for the polarization was seen.

5. Summary

After the measurement on a transversely polarized deuteron target in 2002-04, the COMPASS collaboration in 2007 has measured also single spin asymmetries on a transversely polarized proton target.

The extracted Collins asymmetries are different from zero for $x > 0.05$ implying a non-zero transversity distribution $\Delta_T q(x)$. Together with the COMPASS deuteron data and the Collins fragmentation

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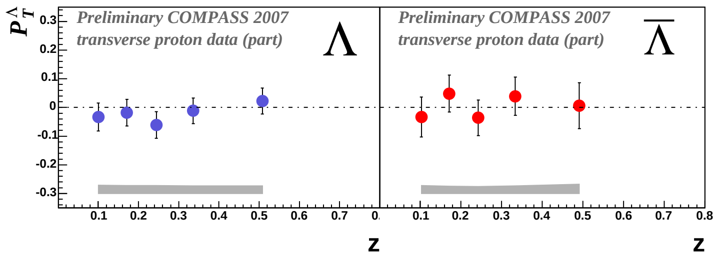

Figure 4: Transverse Λ and $\bar{\Lambda}$ polarization from a part of the 2007 data on a proton target as function of z.

function measured at Belle it is possible to extract the u and d quark transversity. The Sivers asymmetries are compatible with zero within the present statistical errors in difference to the signal seen by HERMES for positive hadrons. Here only further measurements can provide more clarity.

The two hadron asymmetries from charged hadron pairs show a stronger signal than expected. The result means that the interference fragmenatation function and the transversity distribution are both different from zero.

The transverse polarization of Λ and $\bar{\Lambda}$ show no dependance from z meaning that the fragmentation function $\Delta_T D_{\Lambda/q}(z)$ as function of z seems to be quite small.

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