Transverse Spin Physics at COMPASS

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Abstract

The investigation of transverse spin and transverse momentum effects in deep inelastic scattering is one of the key physics programs of the COMPASS collaboration.

Three channels have been analyzed at COMPASS to access the transversity distribution function: 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.

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.

Keywords: polarized deep-inelastic scattering, transversity, azimuthal asymmetries, structure functions.

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 a lot of understanding has been achieved on the longitudinal structure of a fast moving nucleon, very little is known about its transverse structure [1]. 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].

The SIDIS cross-section in the one-photon exchange approximation contains eight transverse-momentum dependent distribution functions [5]. Some of these can be extracted in SIDIS measuring the azimuthal distribution of the hadrons in the final state [6]. 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 $\Delta_T q(x)$ [7]. 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 [8].

To access transversity in SIDIS, one has to measure the quark polarization, i.e. use the so-called 'quark polarimetry'. Several techniques 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). In these proceedings, I will focus on new results for the two-hadron asymmetry, while results for the other channels are shown elsewhere [9].

The chiral-odd Boer-Mulders function is of special interest among the other transverse-momentum dependent distribution functions [10]. 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

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Cahn effect [11], 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 ^6LiD target.

The scattered muon and the produced hadrons are detected in a wide-acceptance two-stage spectrometer with excellent particle identification capabilities [12]. The data with a transversely polarized NH_3 target shown here were taken in the 2007 run.

3. 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 $H_1^{\sphericalangle}(z, M_{inv}^2)$ 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:

$$\vec{R} = (z_2 \cdot \vec{p}_1 - z_1 \cdot \vec{p}_2)/(z_1 + z_2). \qquad (1)$$

$\vec{p}_1$ 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:

$$N_{h^+h^-} = N_0 \cdot (1 + f \cdot P_t \cdot D_{NN} \cdot A_{RS} \cdot \sin\Phi_{RS} \cdot \sin\theta). \quad (2)$$

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

$$A_{RS} \propto \frac{\sum_q e_q^2 \cdot \Delta_T q(x) \cdot H_1^{\sphericalangle}(z, M_{inv}^2)}{\sum_q e_q^2 \cdot q(x) \cdot D_q^{2h}(z, M_{inv}^2)}. \qquad (3)$$

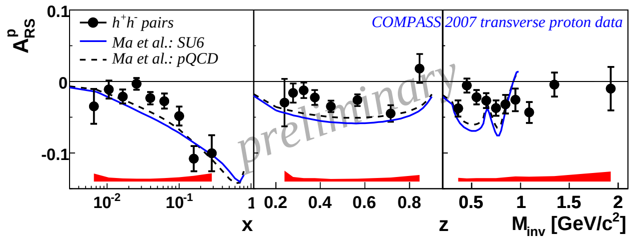

Figure 1: Two-hadron asymmetry A_{RS} as a function of x, z and M_{inv}, compared to predictions of [16]. The lower bands indicate the systematic uncertainty of the measurement.

$D_q^{2h}(z, M_{inv}^2)$ 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 [4]:

$$H_1^{\sphericalangle} = H_1^{\sphericalangle,sp} + \cos\theta \cdot H_1^{\sphericalangle,pp}. \qquad (4)$$

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 $H_1^{\sphericalangle}(z, M_{inv}^2)$ 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, 13–15].

4. Results for hadron pairs

The two-hadron asymmetry as a function of x, z and M_{inv} is shown in 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 $H_1^{\sphericalangle}$. 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 calculations from Ma *et al.*, based on a SU6 and a pQCD model for transversity [16]. The calculations can describe the magnitude and the x-dependence of the measured asymmetry, while there are discrepancies in the M_{inv}-behavior.

5. Azimuthal asymmetries in DIS off an unpolarized target

The cross-section for hadron production in lepton-nucleon DIS $\ell N \rightarrow \ell' hX$ for unpolarized targets and an unpolarized or longitudinally polarized beam has the following form [17]:

$$\frac{d\sigma}{dxdydzd\phi_h dp^2_{h,T}} = \frac{\alpha^2}{xyQ^2}\frac{1+(1-y)^2}{2}\cdot$$
$$[F_{UU,T} + F_{UU,L} + \varepsilon_1 \cos\phi_h F^{\cos\phi_h}_{UU} \qquad (5)$$
$$+\varepsilon_2 \cos(2\phi_h) F^{\cos\ 2\phi_h}_{UU} + \lambda_\mu \varepsilon_3 \sin\phi_h F^{\sin\phi_h}_{LU}]$$

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:

$$\begin{aligned}
\varepsilon_1 &= \frac{2(2-y)\sqrt{1-y}}{1+(1-y)^2} \\
\varepsilon_2 &= \frac{2(1-y)}{1+(1-y)^2} \qquad (6) \\
\varepsilon_3 &= \frac{2y\sqrt{1-y}}{1+(1-y)^2}
\end{aligned}$$

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 [11] 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.

6. Analysis of unpolarized asymmetries

To obtain an unpolarized data sample, data taken with a longitudinally polarized or a transversely polarized ^6LiD target in the year 2004 have both been spin-averaged.

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 the LEPTO generator [18], the experimental setup and the particle interactions in the detectors are simulated by the COMPASS Montecarlo simulation program COMGEANT.

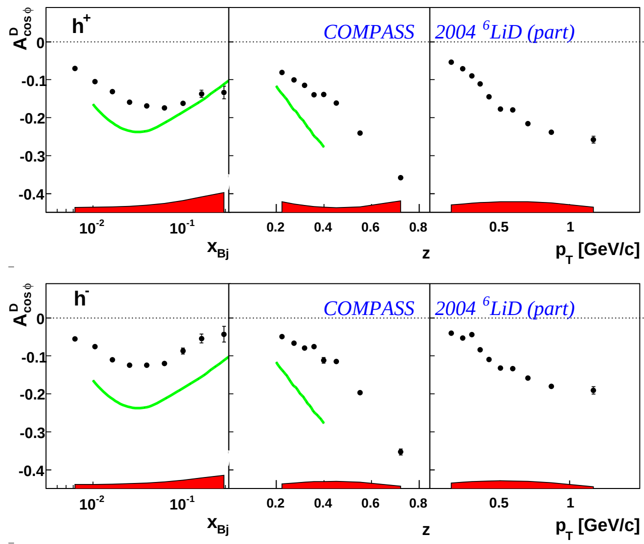

Figure 2: $\cos\phi_h$ asymmetries from COMPASS deuteron data for positive (upper row) and negative (lower raw) hadrons; the asymmetries are divided by the kinematic factor ε_1 and the bands indicate the size of the systematic uncertainty. The superimposed curves are the values predicted by [19] taking into account the Cahn effect only.

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:

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

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

7. 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. 2 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.

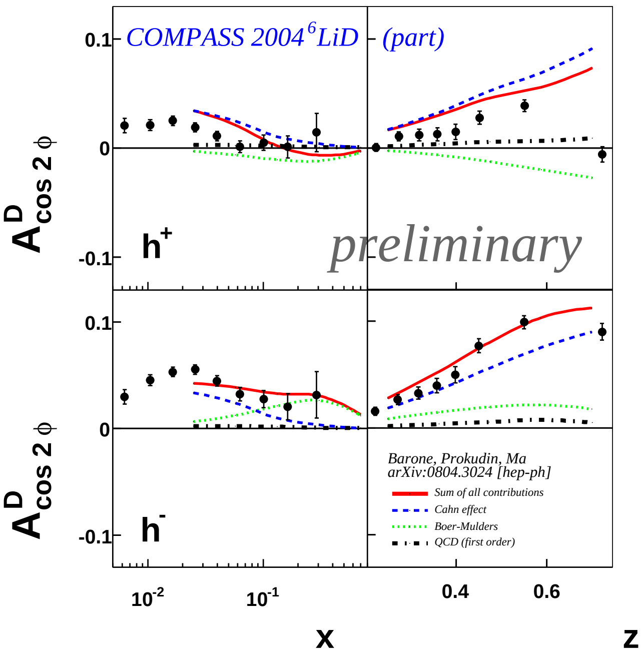

Figure 3: $\cos 2\phi_h$ asymmetries from COMPASS deuteron data for positive (upper row) and negative (lower raw) hadrons; the asymmetries are divided by the kinematic factor ε_1 and the bands indicate size of the systematic error.

The theoretical prediction [19] in Fig. 2 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. 3 together with the theoretical predictions of [20], 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 [20], 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.

8. Summary and Outlook

New preliminary results for the two-hadron azimuthal asymmetry at COMPASS in semi-inclusive deep-inelastic scattering off a transversely polarized proton target have been presented. For $x > 0.05$, an asymmetry different from zero and increasing with increasing x-Bjorken has been observed.

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

Acknowledgments

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