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Work on the Interplay Among h^+, h^- and Hadron Pair Transverse Spin Asymmetries in SIDIS

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In the fragmentation of a transversely polarized quark a left-right asymmetry, the Collins asymmetry, is expected for each hadron produced in the process $\mu N \rightarrow \mu' h^+ h^- X$. Similarly, an asymmetry is also expected for the hadron pair, the dihadron asymmetry. Both asymmetries have been measured to be different from zero on transversely polarised proton targets and have allowed for first extractions of the transversity distributions. From the high statistics COMPASS data we have further investigated these asymmetries getting strong indications that the two mechanisms are driven by a common physical process.

Keywords: Nucleon spin structure; transversity; COMPASS; BELLE.

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It is well known that the description of the partonic structure of the nucleon at leading twist requires the knowledge of three parton distribution functions (PDFs), the number, helicity and transversity PDFs. Being chirally odd, the transversity distribution is difficult to be measured and is still the least known of the three, but in the past ten years both the HERMES and the COMPASS experiments have provided unambiguous evidence that transversity is different from zero.[1] Experimentally, the transversity distribution has been probed in semi-inclusive deeply inelastic scattering (SIDIS) experiments on transversely polarized targets in two different ways. In the first one a target spin dependent azimuthal asymmetry in single-hadron production was measured, which depends on the convolution of transversity and a transverse-momentum dependent chirally odd fragmentation function, $H_1^\perp$, the so-called Collins function.[2] The second process is dihadron production,[3–5] where transversity couples to a dihadron fragmentation function $H_1^{\perp}$. In both cases essential information for the extraction of transversity was provided by the measurements of the azimuthal asymmetries of the hadrons produced in e^+e^- annihilation.[6,7] Recently COMPASS has provided experimental evidence of a close relationship between the Collins and the dihadron asymmetries, hinting at a common physical origin of the two fragmentation functions,[8,9] a conclusion also supported by calculations with a specific Monte Carlo model.[10] That work has been continued and new results are here presented for the first time.

COMPASS (COmmon Muon and Proton Apparatus for Structure and Spectroscopy) is a fixed-target experiment at the CERN SPS taking data since 2002. The COMPASS spectrometer[11] is by now very well known in the scientific community and no description will be given here. The results presented in this paper have been extracted from the data collected with a transversely polarized proton (NH_3) target in 2010, already used to measure the Collins and the dihadron asymmetries.[9,12] In the x-Bjorken region where the Collins asymmetry is different from zero and sizable ($x > 0.032$) the positive and negative hadron asymmetries exhibit a mirror symmetry and the dihadron asymmetry is very close to the Collins asymmetry for positive hadrons. This suggests that the anti-correlation between the azimuthal angles of the positive and negative hadrons, which is present in the multi-hadrons fragmentation of the struck quark due to a local transverse momentum conservation, is also present in the Collins fragmentation function that describes the spin-dependent hadronization of a transversely polarized quark.

The analysis presented here refers to the so called "$2h$ sample", namely SIDIS events where at least one pair of oppositely charged final state hadrons has been reconstructed. The selection of such events is described in detail in Ref. 9. Specific to this analysis is the requirement that a minimum value of 0.1 GeV/c for the hadron transverse momenta $p^h_{T\,(1,2)}$ (the indexes 1 and 2 refer to the positive and negative hadron of the pair respectively) is required to ensure good resolution in the azimuthal angles ϕ_1 and ϕ_2 measured in the standard gamma-nucleon reference system for SIDIS.[13] Also, the two hadrons must carry a fraction $z_{1,2}$ of the virtual-photon energy of at least 0.1 and the results presented here have been obtained in the region $x > 0.032$. For the positive and negative hadrons in the $2h$ sample the Collins-like asymmetries have been extracted, namely the amplitudes $A_{1CL}^{\sin(\phi_1+\phi_S-\pi)}$ and $A_{2CL}^{\sin(\phi_2+\phi_S-\pi)}$ of the $\sin(\phi_{1,2}+\phi_S-\pi)$ modulations in the cross section, where ϕ_S is the azimuthal angle of the transverse spin of the target proton. For this analysis charged hadrons are used as many times as in the hadron pairs. To better investigate the mirror symmetry and the anti-correlation between ϕ_1 and ϕ_2 the Collins asymmetries have been measured as functions of the angle $\Delta\phi = \phi_1 - \phi_2$. The results are shown in the left panel of Fig. 1 . The two asymmetries look like even functions of $\Delta\phi$, are compatible with zero when $\Delta\phi$ tends to zero, and increase in magnitude as $\Delta\phi$ increases. The mirror symmetry between positive and negative hadrons is again a striking feature of the data.

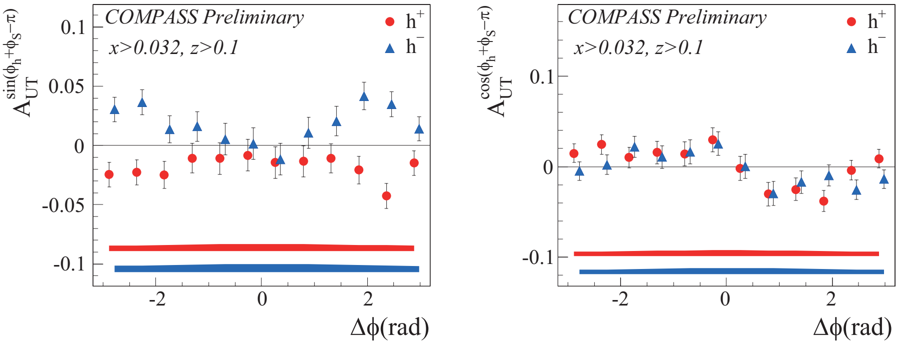

Fig. 1. Left: the $A_{1CL}^{\sin(\phi_1+\phi_S-\pi)}$ (red points) and the $A_{2CL}^{\sin(\phi_2+\phi_S-\pi)}$ (blue points) vs $\Delta\phi$. Right: the $A_{1CL}^{\cos(\phi_1+\phi_S-\pi)}$ (red points) and the $A_{2CL}^{\cos(\phi_2+\phi_S-\pi)}$ (blue points) vs $\Delta\phi$.

The trend of the data can be described rather well starting from the general expression for the transversity induced part of the SIDIS cross-section of Ref. 14. After integration on x, Q^2, z_1, z_2, p_{T1}^2 and p_{T2}^2, the cross-section for the SIDIS process $lN \to l' h^+ h^- X$ can be written as

$$\frac{d\sigma^{h_1h_2}}{d\phi_1 d\phi_2 d\phi_S} = \sigma_U^{h_1h_2} + S_T \left[\sigma_{1C}^{h_1h_2} \sin(\phi_1 + \phi_S - \pi) + \sigma_{2C}^{h_1h_2} \sin(\phi_2 + \phi_S - \pi)\right], \quad (1)$$

where the structure functions $\sigma_{1C}^{h_1h_2}$, $\sigma_{2C}^{h_1h_2}$ and $\sigma_U^{h_1h_2}$ might depend on $\Delta\phi$. It is interesting to rewrite Eq. (1) in terms of ϕ_1 and $\Delta\phi$, or alternatively in terms of ϕ_2 and $\Delta\phi$:

$$\begin{aligned} \frac{d\sigma^{h_1h_2}}{d\phi_1 d\Delta\phi d\phi_S} &= \sigma_U^{h_1h_2} + S_T \Big[\Big(\sigma_{1C}^{h_1h_2} + \sigma_{2C}^{h_1h_2} \cos\Delta\phi\Big) \sin(\phi_1 + \phi_S - \pi) \\ &\quad - \sigma_{2C}^{h_1h_2} \sin\Delta\phi \cos(\phi_1 + \phi_S - \pi)\Big], \\ \frac{d\sigma^{h_1h_2}}{d\phi_2 d\Delta\phi d\phi_S} &= \sigma_U^{h_1h_2} + S_T \Big[\Big(\sigma_{2C}^{h_1h_2} + \sigma_{1C}^{h_1h_2} \cos\Delta\phi\Big) \sin(\phi_2 + \phi_S - \pi) \\ &\quad + \sigma_{1C}^{h_1h_2} \sin\Delta\phi \cos(\phi_2 + \phi_S - \pi)\Big]. \end{aligned} \quad (2)$$

With the change of variables above a new modulation, of the type $\cos(\phi_{1,2}+\phi_S-\pi)$, appears in the cross section, which can then be rewritten alternatively in terms of the sin and cos modulations of only one of the two hadrons. Fig. 1 (right panel) shows the amplitudes $A_{1,2CL}^{\cos(\phi_{1,2}+\phi_S-\pi)}$ of the $\cos(\phi_{1.2}+\phi_S-\pi)$ modulations obtained from our data: the amplitudes are rather similar for positive and negative hadrons, and they seem to be odd-function of $\Delta\phi$.

From Eq. (2) it is possible to write explicit expressions for the four amplitudes shown in Fig. 1:

$$A_{1CL}^{\sin(\phi_1+\phi_S-\pi)}(\Delta\phi) = \frac{\sigma_{1C}^{\sin(\phi_1+\phi_S-\pi)}}{\sigma_U^{h_1h_2}} = \frac{\sigma_{1C}^{h_1h_2}(\Delta\phi) + \sigma_{2C}^{h_1h_2}(\Delta\phi)\cos\Delta\phi}{\sigma_U^{h_1h_2}(\Delta\phi)}$$

$$A_{1CL}^{\cos(\phi_1+\phi_S-\pi)}(\Delta\phi) = \frac{\sigma_{1C}^{\cos(\phi_1+\phi_S-\pi)}}{\sigma_U^{h_1h_2}} = \frac{-\sigma_{2C}^{h_1h_2}(\Delta\phi)\sin\Delta\phi}{\sigma_U^{h_1h_2}(\Delta\phi)}$$

$$A_{2CL}^{\sin(\phi_2+\phi_S-\pi)}(\Delta\phi) = \frac{\sigma_{2C}^{\sin(\phi_2+\phi_S-\pi)}}{\sigma_U^{h_1h_2}} = \frac{\sigma_{2C}^{h_1h_2}(\Delta\phi) + \sigma_{1C}^{h_1h_2}(\Delta\phi)\cos\Delta\phi}{\sigma_U^{h_1h_2}(\Delta\phi)}$$

$$A_{2CL}^{\cos(\phi_2+\phi_S-\pi)}(\Delta\phi) = \frac{\sigma_{2C}^{\cos(\phi_2+\phi_S-\pi)}}{\sigma_U^{h_1h_2}} = \frac{\sigma_{1C}^{h_1h_2}(\Delta\phi)\sin\Delta\phi}{\sigma_U^{h_1h_2}(\Delta\phi)} \quad (3)$$

The quantities $\sigma_1^{h_1h_2}/\sigma_U^{h_1h_2}$ and $\sigma_2^{h_1h_2}/\sigma_U^{h_1h_2}$, which in principle can still be functions of $\Delta\phi$, can be obtained from the measured asymmetries since it is:

$$\frac{\sigma_{1C}^{h_1h_2}(\Delta\phi)}{\sigma_U^{h_1h_2}(\Delta\phi)} = A_{1CL}^{\sin(\phi_1+\phi_S-\pi)}(\Delta\phi) + A_{1CL}^{\cos(\phi_1+\phi_S-\pi)}(\Delta\phi)\cot\Delta\phi$$

$$\frac{\sigma_{2C}^{h_1h_2}(\Delta\phi)}{\sigma_U^{h_1h_2}(\Delta\phi)} = A_{2CL}^{\sin(\phi_1+\phi_S-\pi)}(\Delta\phi) - A_{2CL}^{\cos(\phi_2+\phi_S-\pi)}(\Delta\phi)\cot\Delta\phi \quad (4)$$

The results for the ratios of the cross-sections are given in Fig. 2 and show that within statistical errors $\sigma_{1C}^{h_1h_2}/\sigma_U^{h_1h_2}$ and $\sigma_{2C}^{h_1h_2}/\sigma_U^{h_1h_2}$ are constant, equal in absolute value and of opposite sign. As a consequence, the measured asymmetries can well be fitted with the simple functions $\pm a\cdot(1-\cos\Delta\phi)$ in the case of the sine asymmetries (Fig. 3, left), and $a\sin\Delta\phi$ for the cosine asymmetries (Fig. 3, right), with values for the constant a well compatible for the four asymmetries. As a conclusion, the mirror symmetry between the positive and negative hadron asymmetries is clearly confirmed from these studies and can be summarized by the relation $\sigma_{1C}^{h_1h_2}/\sigma_U^{h_1h_2} = -\sigma_{2C}^{h_1h_2}/\sigma_U^{h_1h_2}$ where the ratios of the structure functions do not depend on $\Delta\phi$.

In Refs. 8, 9 it was shown that the Collins asymmetry of the hadron pair, defined as the amplitude of the modulation $\sin(\phi_{2h}+\phi_S-\pi)$, where $\phi_{2h} = [\phi_1+(\phi_2-\pi)]/2$ (calculated using the unit vectors of the transverse nomenta), is essentially identical to the dihadron asymmetry which is calculated in the standard procedure[9, 15] which

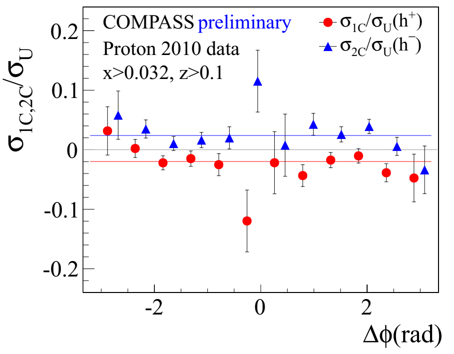

Fig. 2. $\sigma_{1C}^{h_1h_2}/\sigma_U^{h_1h_2}$ and $\sigma_{2C}^{h_1h_2}/\sigma_U^{h_1h_2}$ as extracted from the measured asymmetries.

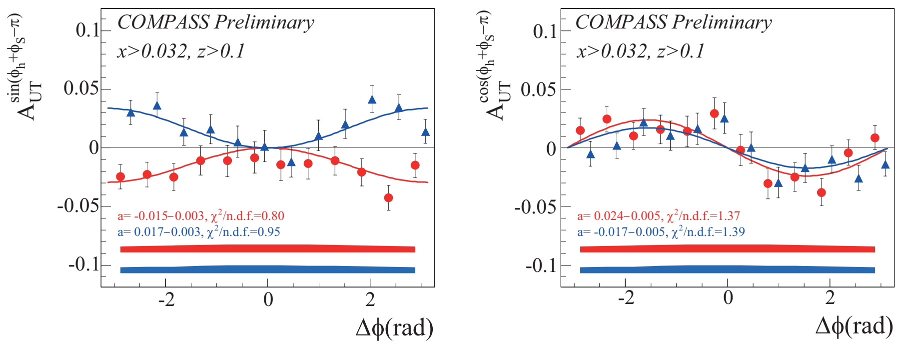

Fig. 3. Same data points as in Fig. 1 with superimposed the fitting functions (see text).

uses the transverse component of the relative momentum between the two hadrons. Starting from the general expression of the cross section given in Eq. (1), it is possible to calculate the amplitude of the modulation $\sin(\phi_{2h} + \phi_S - \pi)$. Changing variables from ϕ_1 and ϕ_2 to ϕ_1 and ϕ_{2h} and using $\sigma_{2C}^{h1h2} = -\sigma_{1C}^{h1h2}$, Eq. (1) can be rewritten as:

$$\sigma^{h1h2} = \sigma_U^{h1h2} + S_T \cdot \sigma_{1C}^{h1h2} \cdot \sqrt{2(1-\cos\Delta\phi)} \cdot \sin(\phi_{2h} + \phi_S - \pi). \tag{5}$$

This cross section implies a sine modulation with the amplitude

$$A_{2h,CL}^{\sin(\phi_{2h}+\phi_S-\pi)} = \frac{\sigma_{1C}^{h1h2}(\Delta\phi)}{\sigma_U^{h1h2}(\Delta\phi)} \cdot \sqrt{2(1-\cos\Delta\phi)} \tag{6}$$

while no $A_{2h,CL}^{\cos(\phi_{2h}+\phi_S-\pi)}$ asymmetry is expected. Our measurements are shown in Fig. 4. As can be seen in the left panel, the $A_{2h,CL}^{\cos(\phi_{2h}+\phi_S-\pi)}$ asymmetry (black points) is indeed compatible with zero. In the right panel of Fig. 4 the $A_{2h,CL}^{\sin(\phi_{2h}+\phi_S-\pi)}$,

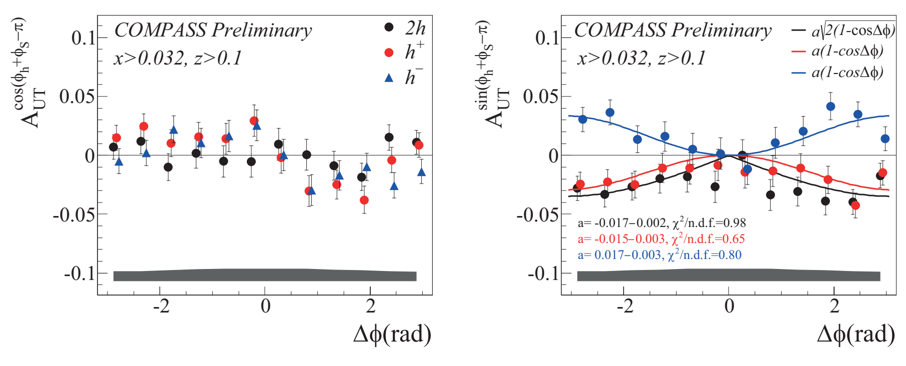

Fig. 4. Left: $A_{1CL}^{\cos(\phi_1+\phi_S-\pi)}$ (red points), $A_{2CL}^{\cos(\phi_2+\phi_S-\pi)}$ (blue points) and $A_{2h,CL}^{\cos(\phi_{2h}+\phi_S-\pi)}$ (black points) vs $\Delta\phi$. Right: $A_{1CL}^{\sin(\phi_1+\phi_S-\pi)}$ (red points), $A_{2CL}^{\sin(\phi_2+\phi_S-\pi)}$ (blue points) and $A_{2h,CL}^{\sin(\phi_{2h}+\phi_S-\pi)}$ (black points) vs $\Delta\phi$.

the $A_{1CL}^{\sin(\phi_1+\phi_S-\pi)}$ and the $A_{2CL}^{\sin(\phi_2+\phi_S-\pi)}$ asymmetries are shown together with the curves $p_{0,1(2)} \cdot (1-\cos(\Delta\phi))$ (red, blue lines) and $p_{0,2h} \cdot \sqrt{2(1-\cos(\Delta\phi))}$ (black line) as obtained by the fits. As can be seen the fits are very good, and the values of the p_{0x} parameters are all compatible, in agreement with the fact that $\sigma_{1C}^{h1h2}/\sigma_U^{h1h2}$ is the same for the three asymmetries. Evaluating the ratio of the integrals of the two-hadron amplitudes over the one-hadron amplitudes one gets a value of $4/\pi$ which is in agreement with our original observation that the dihadron asymmetry is somewhat larger than the Collins asymmetry for positive hadrons.

As a conclusion, we have shown that in the SIDIS process the Collins asymmetries of the positive and negative hadrons are mirror symmetric, in agreement with a $(1-\cos\Delta\phi)$ dependence which is expected from general principles. Most important, the amplitude of the dihadron asymmetry has a very simple relation to that of the single hadron asymmetries, confirming our original observation that the Collins mechanism and the interference fragmentation must have a common physical origin.

A similar analysis has been performed for the Sivers asymmetry, namely for modulations of the type $\sin(\phi_{1,2,2h}-\phi_S)$, but as expected from the h^+ and h^- data[16] and from model calculations[14] no mirror symmetry is observed for positive and negative hadrons, and no simple relationship is extracted for the structure functions.

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