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Transversity distributions from difference asymmetries in semi-inclusive DIS

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Ratios of the u and d quark transversity distributions have been extracted from the COMPASS Collaboration measurements of the Collins asymmetries of positively and negatively charged hadrons produced on transversely polarized proton and deuteron targets. The method we have applied does not require the e^+e^- data. It was proposed long time ago, but this is the first time it is used to extract transverse spin asymmetries. The results for the ratio $h_1^{d_v}/h_1^{u_v}$ compare well to those obtained in a previous point–by–point extraction based both on SIDIS and e^+e^- data.

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1. Introduction

Over the last decade single-spin asymmetries clearly related to the transversity distribution function h_1 have been measured in semi-inclusive deep inelastic scattering (SIDIS) on transversely polarized nucleons, namely in DIS processes in which at least one hadron of the current jet is detected. In these processes the cross-section exhibits a spin-dependent azimuthal modulation which can be expressed in terms of a convolution of h_1 and a fragmentation function (FF) which are both chiral-odd, thus guaranteeing the cross-section to be chirally-even. Two observables have been studied in so far. The first one is single hadron spin asymmetry, namely the amplitude of the target-spin dependent azimuthal modulation of each of the produced hadrons. The second one is the amplitude of the target spin-dependent azimuthal modulation of the plane defined by any two of the oppositely charged hadrons produced in the same SIDIS event. In the first case, the FF is the Collins FF $H_1^{\perp}$ in the second the FF is the dihadron FF $H_1^{\sphericalangle}$ İn the case of transversely polarized proton targets clear non zero azimuthal modulations have been measured for both observables by the HERMES and the COMPASS Collaborations. Corresponding measurements on a transversely polarized deuteron target by the COMPASS Collaboration gave asymmetries compatible with zero, which have been interpreted as evidence of cancellation between h_1^u and h_1^d.

Independent evidence that both the Collins function and the dihadron FF are different from zero came from the measurements of azimuthal asymmetries in hadron inclusive production in e^+e^- annihilation by the Belle, the BaBar and the BESIII Collaborations.

Combining the SIDIS data and the $e^+e^- \rightarrow$ hadrons measurements, extractions of both the transversity functions and of the two transversely polarized quark FFs have been possible [1, 2, 3].

An alternative way to measure transversity from the Collins asymmetries alone is via the so-called "difference asymmetries", which allow extracting combinations of the u and d quark transversity without knowing the Collins FF. This method was proposed a long time ago [4, 5, 6] to access the helicity PDFs, and has been used by the SMC Collaboration [7]. Later on it has been used to measure the helicity PDFs in COMPASS [8], and recently it has been proposed again in the context of the Sivers, Boer-Mulders and transversity distributions [9]. In the present work [10] the difference asymmetries are used for the first time to access transversity using the COMPASS measurements of the Collins asymmetries on p [11] and d targets [12].

2. Cross sections and difference asymmetries

We have extracted the asymmetries of differences from the Collins asymmetries measured by the COMPASS Collaboration scattering a 160 GeV/c momentum muon beam first on a transversely polarized deuteron (^{6}LiD) target [12] and then on a transversely polarized proton (NH_3) target [11].

In order to ensure the DIS regime, only events with photon virtuality $Q^2 > 1$ (GeV/c)^2, fractional energy of the virtual photon $0.1 < y < 0.9$, and mass of the hadronic final state system $W > 5$ GeV/c^2 were considered in the data analysis. All the details of the event selection and of the analysis can be found in [12, 11].

In the following, for simplicity we will write explicitly only the Collins part of the SIDIS transverse spin dependent cross-section, and consider charged pions, even if, at the end, we will use the results for charged hadrons assuming they are all pions, as it was done, for instance, in [3]. The SIDIS cross section can be written as

$$\sigma_t^{\pm}(\Phi_C) = \sigma_{0,t}^{\pm} + f P_T D_{NN} \sigma_{C,t}^{\pm} \sin\Phi_C \tag{2.1}$$

where Φ_C is the Collins angle, f is the target dilution factor, P_T is the nucleon polarization, and D_{NN} is the mean transverse-spin-transfer coefficient not included in σ_C to simplify the expressions used in the following. Only the deuteron (or hydrogen) nuclei in the targets were polarized, and the target dilution factor f is given by the ratio of the absorption cross-sections on the deuteron (or proton) to that of all nuclei in the target. The signs $\pm$ refer to the pion charge and $t = p,\ d$ is the target type. The Collins angle $\Phi_C = \phi_h + \phi_S - \pi$ is the sum of the azimuthal angles ϕ_h of the hadron transverse momentum and of the spin direction ϕ_S of the target nucleon with respect to the lepton scattering plane, in a reference system in which the z axis is the virtual photon direction.

The Collins asymmetry is defined as

$$A_{C,t}^{\pm} = \frac{\sigma_{C,t}^{\pm}}{\sigma_{0,t}^{\pm}} \tag{2.2}$$

In terms of the ordinary PDFs and FFs the unpolarized part of the cross-sections in eq. (2.1) can be written as (omitting a kinematic factor that cancels out when taking the ratios of cross sections):

$$\sigma_{0,p}^{+} \sim x\left[(4f_1^u + f_1^{\bar{d}})D_{1,\mathrm{fav}} + (4f_1^{\bar{u}} + f_1^d)D_{1,\mathrm{unf}} + (f_1^s + f_1^{\bar{s}})D_{1,s}\right] \tag{2.3}$$

$$\sigma_{0,p}^{-} \sim x\left[(4f_1^u + f_1^{\bar{d}})D_{1,\mathrm{unf}} + (4f_1^{\bar{u}} + f_1^d)D_{1,\mathrm{fav}} + (f_1^s + f_1^{\bar{s}})D_{1,s}\right] \tag{2.4}$$

$$\sigma_{0,d}^{+} \sim x\left[(f_1^u + f_1^d)(4D_{1,\mathrm{fav}} + D_{1,\mathrm{unf}}) + (f_1^{\bar{u}} + f_1^{\bar{d}})(D_{1,\mathrm{fav}} + 4D_{1,\mathrm{unf}}) + 2(f_1^s + f_1^{\bar{s}})D_{1,s}\right] \tag{2.5}$$

$$\sigma_{0,d}^{-} \sim x\left[(f_1^u + f_1^d)(D_{1,\mathrm{fav}} + 4D_{1,\mathrm{unf}}) + (f_1^{\bar{u}} + f_1^{\bar{d}})(4D_{1,\mathrm{fav}} + D_{1,\mathrm{unf}}) + 2(f_1^s + f_1^{\bar{s}})D_{1,s}\right] \tag{2.6}$$

where $D_{1,\mathrm{fav}}$ ($D_{1,\mathrm{unf}}$) is the favored (unfavored) unpolarized FF, $D_{1,s}$ is the strange sea unpolarized FF, and f_1^q are the unpolarized PDFs.

Following [3], the corresponding spin–dependent cross sections $\sigma_{C,t}^{+}$ and $\sigma_{C,t}^{-}$ are obtained by replacing f_1^q with the transversity PDFs h_1^q and the FFs D_1 with the "half moments" of the Collins function, $H_1^{\perp(1/2)}$, defined as

$$H_1^{\perp(1/2)}(z, Q^2) \equiv \int \mathrm{d}^2\boldsymbol{p}_T \, \frac{p_T}{zM_h} \, H_1^{\perp}(z, p_T^2, Q^2)\,. \tag{2.7}$$

We now define the difference asymmetries as

$$A_{D,t} = \frac{\sigma_{C,t}^{+} - \sigma_{C,t}^{-}}{\sigma_{0,t}^{+} + \sigma_{0,t}^{-}}. \tag{2.8}$$

In [5] an alternative definition was proposed, namely

$$A'_{D,t} = \frac{\sigma_{C,t}^{+} - \sigma_{C,t}^{-}}{\sigma_{0,t}^{+} - \sigma_{0,t}^{-}}. \tag{2.9}$$

As we will see, the two definitions turn out to give the same results. For the sake of simplicity, our discussion in the following we be centered on the definition (2.8), but we will also briefly summarize the results obtained with eq. (2.9).

Writing explicitly the asymmetries one gets:

$$A_{D,p} = \frac{1}{9}\frac{H_{1,\mathrm{fav}}^{\perp(1/2)} - H_{1,\mathrm{unf}}^{\perp(1/2)}}{\sigma_{0,p}^{+} + \sigma_{0,p}^{-}}(4h_1^{u_v} - h_1^{d_v}) \tag{2.10}$$

$$A_{D,d} = \frac{1}{3}\frac{H_{1,\mathrm{fav}}^{\perp(1/2)} - H_{1,\mathrm{unf}}^{\perp(1/2)}}{\sigma_{0,d}^{+} + \sigma_{0,d}^{-}}(h_1^{u_v} + h_1^{d_v}), \tag{2.11}$$

where we have assumed $H_{1,s}^{\perp(1/2)} = 0$.

When taking the ratios of the asymmetries on deuteron and proton, the Collins FFs cancel out:

$$\frac{A_{D,d}}{A_{D,p}} = 3\left[\frac{(4f_1^u + 4f_1^{\bar{u}} + f_1^d + f_1^{\bar{d}})(D_{1,\mathrm{fav}} + D_{1,\mathrm{unf}}) + 2(f_1^s + f_1^{\bar{s}})D_{1,s}}{5(f_1^u + f_1^d + f_1^{\bar{u}} + f_1^{\bar{d}})(D_{1,\mathrm{fav}} + D_{1,\mathrm{unf}}) + 4(f_1^s + f_1^{\bar{s}})D_{1,s}}\right]\frac{h_1^{u_v} + h_1^{d_v}}{4h_1^{u_v} - h_1^{d_v}}, \tag{2.12}$$

and the only unknowns are the transversity PDFs. Thus, by measuring A_D on p and d, one obtains the ratio $h_1^{d_v}/h_1^{u_v}$ in terms of known quantities. instead instead instead In order to determine $A_{D,t}$, one should in principle fit the quantity

$$\sigma_t^D(\Phi_C) = (\sigma_{0,t}^{+} - \sigma_{0,t}^{-}) + f P_T D_{NN}(\sigma_{C,t}^{+} - \sigma_{C,t}^{-})\sin\Phi_C \tag{2.13}$$

and extract the amplitude of the $\sin\Phi_C$ modulation.

The measurements are much simpler if the Φ_C acceptance for positively charged particles is equal to that for negatively charged ones. In this case it is not necessary to evaluate the difference asymmetries from the amplitude of the modulation, as it is possible to get them from the measured Collins asymmetries. One has in fact

$$A_{D,t} = \frac{\sigma_{0,t}^{+}}{\sigma_{0,t}^{+} + \sigma_{0,t}^{-}}A_{C,t}^{+} - \frac{\sigma_{0,t}^{-}}{\sigma_{0,t}^{+} + \sigma_{0,t}^{-}}A_{C,t}^{-}, \tag{2.14}$$

where the ratios of the cross sections are known.

If instead one uses the definition (2.9), the ratio of the difference asymmetries has the form

$$\frac{A'_{D,d}}{A'_{D,p}} = \frac{4f_1^{u_v} - f_1^{d_v}}{f_1^{u_v} + f_1^{d_v}}\frac{h_1^{u_v} + h_1^{d_v}}{4h_1^{u_v} - h_1^{d_v}} \tag{2.15}$$

and the equivalent of eq. (2.14) is

$$A'_{D,t} = \frac{\sigma_{0,t}^{+}}{\sigma_{0,t}^{+} - \sigma_{0,t}^{-}}A_{C,t}^{+} - \frac{\sigma_{0,t}^{-}}{\sigma_{0,t}^{+} - \sigma_{0,t}^{-}}A_{C,t}^{-}. \tag{2.16}$$

The acceptances of the COMPASS spectrometer for positively charged and negatively charged hadrons have been extensively investigated with Monte Carlo simulations.[1] The acceptances, which include both the geometrical acceptance of the apparatus and the reconstruction efficiency, are essentially the same for positively and negatively charged hadrons, and the small differences are compatible with the statistical fluctuations.

[1]We are grateful to the COMPASS Collaboration for the use of the Monte Carlo chain.

3. Results

On the basis of the Monte Carlo results, the difference asymmetries have been calculated using eq. (2.14) with the Collins asymmetries from the 2010 COMPASS data. Actually, since $\sigma_{0,t}^{\pm} \sim N_t^{\pm}$ and $\mathrm{var}(A_{C,t}^{\pm}) \sim 1/N_t^{\pm}$, where $N_t^{\pm}$ is the total number of hadrons which has been used to extract the Collins asymmetries, in a given x bin, eq. (2.14) can be rewritten as:

$$A_{D,t} = \frac{\mathrm{var}(A_{C,t}^-)}{\mathrm{var}(A_{C,t}^+) + \mathrm{var}(A_{C,t}^-)} A_{C,t}^+ - \frac{\mathrm{var}(A_{C,t}^+)}{\mathrm{var}(A_{C,t}^+) + \mathrm{var}(A_{C,t}^-)} A_{C,t}^- \tag{3.1}$$

The calculation of the difference asymmetries can thus be performed using the published COMPASS data for $A_{C,t}^{\pm}$ and their statistical uncertainties [11].

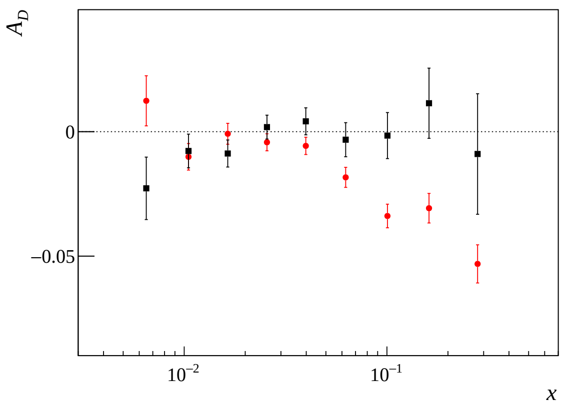

Figure 1: Difference asymmetries $A_{D,p}$ (red points) and $A_{D,d}$ (black points) as function of x.

From the ratios $A_{D,d}/A_{D,p}$ the quantities $(h_1^{u_v} + h_1^{d_v})/(4h_1^{u_v} - h_1^{d_v})$ have been extracted using eq. (2.12) and standard parametrisations and tables for the unpolarized PDFs [13] and FFs [14]. Finally, from the quantities $(h_1^{u_v} + h_1^{d_v})/(4h_1^{u_v} - h_1^{d_v})$ the ratios $h_1^{d_v}/h_1^{u_v}$ are determined. They are shown as closed circles in Fig. 2. The values in the first five x bins have very large uncertainties, are compatible with zero and are not plotted in the figure. At larger x the values are negative, in agreement with previous extractions. The same procedure has been carried through starting from the difference asymmetries $A'_{D,t}$ and using eq. (2.15), getting essentially the same values and the same statistical uncertainties, which are shown as closed squares in Fig. 2. In the same figure we also compare our results with the values of $h_1^{d_v}/h_1^{u_v}$ calculated from the transversity values obtained in [3] (open circles). The results of the three determinations are in very good agreement, but some reduction (up to $\sim 20\%$) of the uncertainties can be observed in the ratios obtained in the present work from the difference asymmetries.

As a conclusion, one can say that the method we applied is interesting and simple, and does not require any knowledge of the Collins fragmentation functions. Hence it strengthens the validity of the methods utilized so far to extract the transversity distributions, based on a combined analysis of SIDIS and e^+e^- data, and can be used as a useful cross-check for more elaborated extractions.

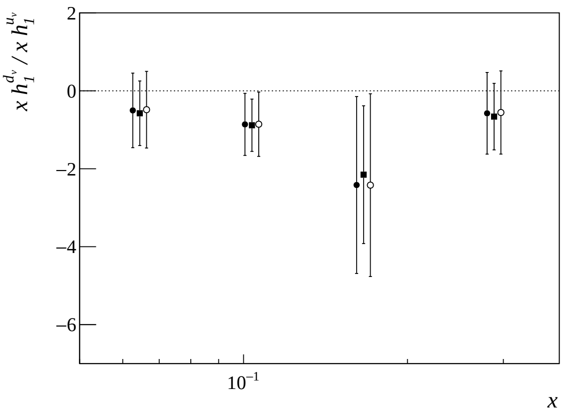

Figure 2: Ratio $h_1^{d_v}/h_1^{u_v}$ from the asymmetries A_D (closed circles), from the asymmetries A'_D (closed squares) and from [3] (open circles).

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