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Further direct extractions of the transversity functions

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The transversity function can be extracted in a direct way using the Collins asymmetries measured in SIDIS and the corresponding asymmetries from e^+e^- annihilation data, provided that SIDIS asymmetries for proton and deuteron (neutron) targets at the same kinematics are available.
The first extractions performed in 2015 using COMPASS and Belle data provided fairly accurate determinations of the u-quark transversity function, but were characterised by large statistical uncertainties on the d-quark transversity functions due to the low statistics measurements with the deuteron data.
The COMPASS Collaboration used the results from the data collected in 2022 with a transversely polarised deuteron target to extract the valence quarks transversity function, showing the impressive impact of the new data.
Here we apply the same procedure to extract the sea quark transversity functions, which turn out to be again compatible with zero, despite the smaller statistical uncertainties.
Also, we use the "difference asymmetries" to evaluate the ratio of the transversity functions of u and d valence quarks without using the Collins fragmentation functions. The ratio turns out to be about -0.5, almost constant over the investigated x-Bjorken range.

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1. Introduction

The investigation of the transverse-spin structure of nucleons has been a very active research area of hadronic physics in the past two decades and it is still a hot topic. Single-spin asymmetries in leptoproduction of hadrons from a transversely polarized target, $lN^{\uparrow} \to l'hX$, have been measured by the HERMES, COMPASS and Jefferon Lab Hall C experiments, and discovered to be different from zero. They represent the primary way to access the transverse-spin distributions of quarks.

One of these asymmetries, the Collins asymmetry, involves the convolution between the transversity distribution h_1 and the Collins fragmentation function (FF) $H_1^{\perp}$. Transversity is a leading-twist and chirally odd distribution function that measures the transverse polarization of quarks inside a transversely polarized nucleon [4]. The Collins FF is a transverse-momentum-dependent chirally odd function, which describes the fragmentation of a transversely polarized quark into a spinless hadron.

The SIDIS Collins asymmetries have been measured by the HERMES [1–3] and the COMPASS [4, 5] experiments on a proton target, and by COMPASS on a deuteron target [6–9]. Independent information on the Collins FF is obtained from $e^+e^- \to hadrons$ measurements performed at Belle [10, 11], BaBar [12] and BESIII [13].

Several phenomenological analyses of these asymmetries have been performed to extract the transversity functions (see [14, 15] and references therein). Most of them extract the quark distributions by fitting the data with a given functional form for their dependence on the Bjorken variable x and the fractional energy z of the final state hadrons.

A more direct approach was adopted in Ref. [16]. It takes advantage of the fact that the COMPASS measurements of the Collins asymmetries with proton and deuteron targets were performed at the same 160 GeV/c muon beam energy, namely at the same kinematics and using the same x binning. This allowed to perform a point by point extraction of the transversity function of the valence and the sea quarks. The same procedure has been used by the COMPASS Collaboration to extract $h_1^{u_v}$ and $h_1^{d_v}$ adding to the data sample the new results from the 2022 deuteron data [8, 9].

Here we present the new point by point extraction of the $\bar{u}$ and $\bar{d}$ quark transversity from all the COMPASS results, showing the remarkable impact of the most recent deuteron measurement. We also present the results for $h_1^{d_v}/h_1^{u_v}$ obtained from the same data set following the procedure of Ref. [17, 18], which uses the "difference asymmetries" to extract the transversity ratio wich does not depend on the Collins FF. The formalism is fully detailed in the quoted papers [16–18], and here we only give the final expressions for the transversity functions, and the results.

2. Sea quark transversity from the Collins asymmetries

By simple general arguments, taking advantage of isospin symmetry and sea flavour symmetry, it was possible in [16, 18] to relate to each other the Collins asymmetries of SIDIS on proton and deuteron targets and combine them in such a way that the transversity distributions of the valence quarks $h_1^{u_v}$ and $h_1^{d_v}$ can be separately extracted point by point in x. The approach is almost model-independent. In fact, although a Gaussian Ansatz is adopted for the transverse-momentum dependence of quark distribution functions and FF in order to solve the convolutions appearing in the structure functions, the Gaussian widths do not appear in the final result. This is true when assuming

$$G(z) = \frac{1}{\sqrt{1 + z^2\langle k_T^2\rangle/\langle p_\perp^2\rangle}} \simeq 1\,. \tag{1}$$

Here z is the fractional energy of the final state hadron, $\vec{k}_T$ is the transverse momentum of the quark inside the nucleon, $\vec{p}_\perp$ is the transverse momentum of the hadron with respect to the direction of the fragmenting quark, and G is the factor coming from the convolution. The assumption $z^2\langle k_T^2\rangle/\langle P_T^2\rangle \ll 1$ is expected to be reasonable, especially at low z, where the statistics is higher.

Under these assumptions, and assuming isospin and flavour symmetry, the transversity functions of the valence quarks are given by

$$xh_1^{u_v} = \frac{1}{5}\frac{1}{a_P(1-\alpha)}\left[(xf_p^+A_p^+ - xf_p^-A_p^-) + \frac{1}{3}(xf_d^+A_d^+ - xf_d^-A_d^-)\right], \tag{2}$$

$$xh_1^{d_v} = \frac{1}{5}\frac{1}{a_P(1-\alpha)}\left[\frac{4}{3}(xf_d^+A_d^+ - xf_d^-A_d^-) - (xf_p^+A_p^+ - xf_p^-A_p^-)\right], \tag{3}$$

where $A_{p,d}^{\pm}$ are the Collins asymmetries for positive and negative pions on transversely polarized protons or deuterons measured in the same x bin. The coefficients $f_{p,d}^{\pm}$ are known being linear combinations of the unpolarised parton distribution functions and of the z-integrated FFs [19, 20]. The last needed ingredients are

$$\alpha(Q^2) = \frac{\widetilde{H}_{1,\mathrm{unf}}^{\perp(1/2)}(Q^2)}{\widetilde{H}_{1,\mathrm{fav}}^{\perp(1/2)}(Q^2)}, \qquad a_P(Q^2) = \frac{\widetilde{H}_{1,\mathrm{fav}}^{\perp(1/2)}(Q^2)}{\widetilde{D}_{1,\mathrm{fav}}(Q^2)}, \tag{4}$$

where $\widetilde{H}_{1,\mathrm{fav(unf)}}^{\perp(1/2)}$ and $\widetilde{D}_{1,\mathrm{fav}}$ are the “half-moments” of the favoured (unfavoured) Collins FF and the favoured unpolarised FF integrated over the useful z range, respectively. They are calculated in Ref. [16] using the Belle data [10] with two different hypotheses ("Scenario 1" and "Scenario 2") on the ratio of the favoured and unfavoured Collins functions. Here we follow Scenario 2, in which

$$\frac{H_{1,\mathrm{fav}}^{\perp(1/2)}(z,Q^2)}{D_{1,\mathrm{fav}}(z,Q^2)} = -\frac{H_{1,\mathrm{unf}}^{\perp(1/2)}(z,Q^2)}{D_{1,\mathrm{unf}}(z,Q^2)}\,. \tag{5}$$

As in Ref. [16], in these extractions the Collins asymmetries for charged hadrons are used assuming that all charged hadrons are pions (about 75% of the sample). The same COMPASS results from the 2002-2004, 2007 and 2010 data [5, 7] have been used, with the addition of the new high precision results from the data collected in 2022 by COMPASS with the transversely polarised deuteron target [8].

The resulting values of $h_1^{u_v}$ and $h_1^{d_v}$ have been shown earlier in this Workshop [9] and will not be shown again here. On the contrary, the same algebra [16] allows the extraction of the sea quark transversity distributions

$$xh_1^{\bar{u}} = \frac{1}{15}\frac{1}{a_P(1-\alpha^2)}\left[(1-4\alpha)\,xf_p^+A_p^+ + (4-\alpha)\,xf_p^-A_p^- - xf_d^+A_d^+ + \alpha\,xf_d^-A_d^-\right], \tag{6}$$

$$xh_1^{\bar{d}} = \frac{1}{15}\frac{1}{a_P(1-\alpha^2)}\left[(4\alpha-1)\,xf_p^+A_p^+ - (4-\alpha)\,xf_p^-A_p^- - 4\alpha\,xf_d^+A_d^+ + 4\,xf_d^-A_d^-\right], \tag{7}$$

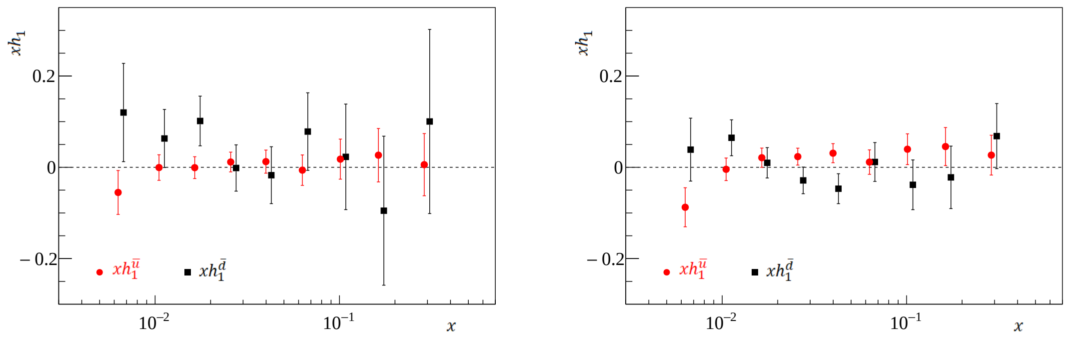

Figure 1: Left: the extracted values of the h_1 distribution for the u and d sea-quarks vs x obtained using all the COMPASS proton [5] data and the old deuteron data [7] from [16]. Right: the same when adding the results from the high statistics deuteron data collected in 2022 [8].

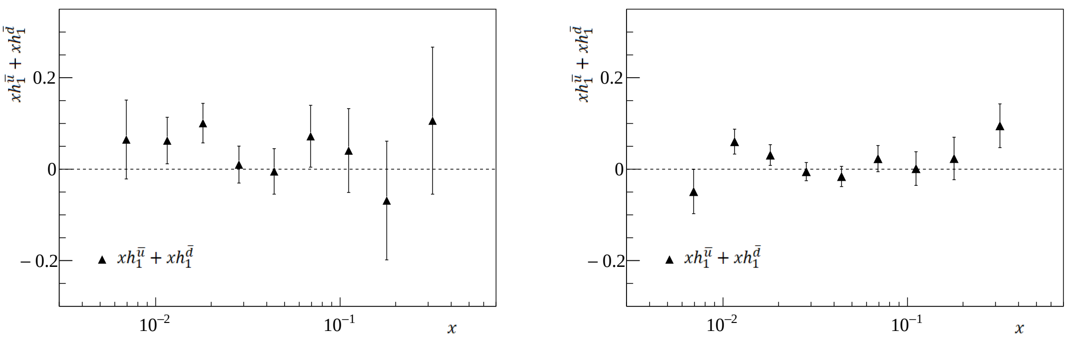

Figure 2: Left: the extracted values of the overall sea transversity $h_1^{\bar{u}} + h_1^{\bar{d}}$ vs x obtained using all the COMPASS proton [5] data and the old deuteron data [7] from [16]. Right: the same when adding the results from the high statistics deuteron data collected in 2022 [8].

and of the overall sea transversity, $h_1^{\bar{u}} + h_1^{\bar{d}}$, determined by the deuteron asymmetries only:

$$x h_1^{\bar{u}} + x h_1^{\bar{d}} = \frac{1}{15} \frac{1}{a_P(1-\alpha^2)} \left[(4+\alpha)\, x f_d^- A_d^- - (4\alpha+1)\, x f_d^+ A_d^+ \right] . \tag{8}$$

The extracted sea-quark transversity distributions can be seen in fig. 1. To the left, the extracted values are shown as obtained using all the COMPASS proton data and the old deuteron data, collected in the years 2002-2004, while to the right the most recent high statistics deuteron data, collected in 2022, have also been used. The new values are still compatible with zero, despite the important gain in accuracy, confirming the idea that transversity is a valence object.

The overall sea transversity, $h_1^{\bar{u}} + h_1^{\bar{d}}$, in the different x bins is shown in fig. 2. Also in this case, the gain in accuracy is remarkable. The values are still compatible with zero, in agreement with predictions from the large-N_c limit [21]. Note that the method used here allows for a direct extraction of $h_1^{\bar{u}} + h_1^{\bar{d}}$, while in phenomenological analysis the condition $h_1^{\bar{u}} = -h_1^{\bar{d}}$ is often imposed (see e.g. [22]) in order to limit the number of free parameters.

3. Extraction of $h_1^{d_v}/h_1^{u_v}$ from the difference asymmetries

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 with no need for independent measurements of the Collins functions. This method was proposed about 30 years ago to access the helicity distributions in SIDIS. It has been used for the first time to access transversity with the COMPASS measurements of the Collins asymmetries on proton [5] and deuteron data [7] in Ref. [17]. To define the difference asymmetries it is useful to write the SIDIS cross section as

$$\sigma_t^{\pm}(\Phi_C) = \sigma_{0,t}^{\pm} + f P_T D_{NN} \sigma_{C,t}^{\pm} \sin\Phi_C + \ldots \tag{9}$$

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 formalism. The difference asymmetries are then defined as

$$A_{D,t} = \frac{\sigma_{C,t}^{+} - \sigma_{C,t}^{-}}{\sigma_{0,t}^{+} + \sigma_{0,t}^{-}}. \tag{10}$$

where $t = p, d$ stays for either proton or deuteron, and $\sigma_C^{\pm}$ is the Collins amplitude in the SIDIS cross section for positive (+) and negative (−) hadrons. When taking the ratios of the difference asymmetries on deuteron and proton, the Collins FFs cancel out:

$$\frac{A_{D,d}}{A_{D,p}} = 3\left[\frac{(4f_1^u + 4f_1^{\bar{u}} + f_1^d + f_1^{\bar{d}})(D_{1,\mathrm{fav}} + D_{1,\mathrm{unf}}) + 2(f_1^s + f_1^{\bar{s}})D_{1,s}}{5(f_1^u + f_1^d + f_1^{\bar{u}} + f_1^{\bar{d}})(D_{1,\mathrm{fav}} + D_{1,\mathrm{unf}}) + 4(f_1^s + f_1^{\bar{s}})D_{1,s}}\right]\frac{h_1^{u_v} + h_1^{d_v}}{4h_1^{u_v} - h_1^{d_v}}, \tag{11}$$

and the only unknowns are the transversity distributions. 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. In Fig. 3 left we show the extraction of $h_1^{d_v}/h_1^{u_v}$ done in [17] using all the COMPASS proton and the old COMPASS deuteron results. Note that the statistical uncertainties explode where the asymmetries are small, outside the valence region. In Fig. 3 right the same quantities are shown (closed points) when the deuteron data include also the new 2022 results. The open circles are the corresponding values from the standard extractions, using the COMPASS Collins asymmetries and the e^+e^- data [16] and in [8]. The improvement in accuracy is striking. Also, it has to be stressed that the agreement with the ratio of "standard" transversities, with the improved precision, provides a strong argument in favour of all the methods used here.

4. Summary

In a simple and direct model-independent way the u and d quark transversity distributions, both valence and sea, have been extracted from all the available COMPASS data and from the Belle data. The ratio $h_1^{d_v}/h_1^{u_v}$ has also been obtained from the difference asymmetries using the new COMPASS asymmetry for deuteron.

Thanks to the new COMPASS results, transversity of the valence d quark turns out to be compatible but smaller than that previously estimated and different from zero. In particular $h_1^{d_v}$

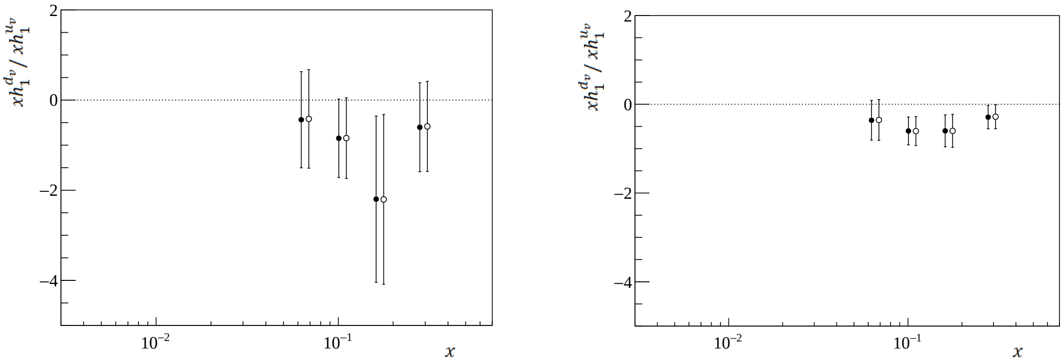

Figure 3: The extracted ratio $h_1^{d_v}/h_1^{u_v}$ from difference asymmetries when the new COMPASS results from the 2022 deuteron data are not used (left; values from Ref. [18]) and when they are included (right). The open circles are the corresponding values calculated from the transversity values obtained in [16] and in [8].

turns out to have opposite sign and a size about one half of $h_1^{u_v}$ over the explored x range. Also, the sea-quark transversity functions are better determined and still compatible with zero.

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