Exploring the transverse spin structure of the nucleon

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Abstract. We discuss our present understanding of the transverse spin structure of the nucleon and of related properties originating from parton transverse motion. Starting from the transversity distribution and the ways to access it, we then address the role played by spin and transverse momentum dependent (TMD) distributions in azimuthal and transverse single spin asymmetries. The latest extractions of the Sivers, Collins and transversity functions are also presented.

Keywords: Transverse spin, inclusive processes, transverse momentum dependent distributions


Transversity and TMD distributions

The study of the nucleon spin structure has made important progress in the last years. Our understanding of the longitudinal degrees of freedom, concerning both motion and spin content of partons inside unpolarized and longitudinally polarized fast moving nucleons, respectively encoded in the unpolarized quark distribution, \( q(x) \), and the helicity distribution, \( \Delta q(x) = q_{+/+} - q_{-/-} \), is quite accurate.

On the other hand the transversity distribution, \( \Delta T q(x) = q_{\uparrow\uparrow} - q_{\downarrow\downarrow} \) (also denoted \( h_1 \)), despite its fundamental importance \(^1\) and the intense theoretical work of the last decade \(^2\), has been accessed experimentally only very recently. The main difficulty in measuring this function is that, being chiral-odd, it decouples from inclusive deep inelastic scattering (DIS), since the so-called handbag diagram cannot flip the chirality of quarks. The only way to access this distribution is by coupling it to another chiral-odd quantity. A further feature of \( h_1 \) is that it has no gluonic counterpart, implying a non-singlet like QCD evolution. Very recently an angular sum rule for the transversity, similar to that for the helicity distribution, has been proposed \(^3\). Despite some controversy it could be extremely useful from a phenomenological point of view in perturbative QCD.

In the usual collinear picture or when all the intrinsic transverse momenta (\( k_\perp \)) are integrated over, the three twist-two parton distribution functions (PDF) \( q, \Delta q, \) and \( \Delta T q \), give a complete description of the structure of a nucleon. On the other hand by taking into account the transverse motion a much richer description can be obtained. At leading twist, the correlations between spin and \( k_\perp \) lead to five new distributions that disappear when the hadronic tensor is integrated over \( k_\perp \). For a detailed classification and relations between different notations for these functions see Refs. \(^4, 5, 6, 7\). Here, by restricting only to transverse spin and transverse momentum correlations, we recall that:

1) two possible TMD distributions may contribute to the spin asymmetry of transversely polarized quarks inside a transversely polarized nucleon (the unintegrated transversity
distribution \( h_1(x,k_{\perp}) \) and a new function, \( h_1^{\perp}(x,k_{\perp}) \); ii) In a transversely polarized nucleon the azimuthal distribution of an unpolarized quark can be asymmetric: this effect is encoded in the chiral-even Sivers function \([8, 9]\), denoted as \( \Delta^N f_{q/p} \) (or \( f_1^T \)); iii) In an unpolarized nucleon a quark can be transversely polarized orthogonally to the plane spanned by the quark and nucleon momenta: this effect is encoded in the chiral-odd Boer-Mulders function \([10]\), denoted as \( \Delta^N f_{q/p} \) (or \( h_{\perp}^1 \)).

Analogously, in the fragmentation process into unpolarized hadrons, besides the unpolarized fragmentation function (FF), \( D_{h/q} \), a new spin and TMD function appears: the chiral-odd Collins function \([11]\), denoted as \( \Delta^N D_{h/q} \) or \( H_{\perp}^1 \). This gives the azimuthal asymmetry in the fragmentation of a transversely polarized quark into an unpolarized hadron.

The Sivers (Boer-Mulders) function is naively T-odd under time reversal and this would imply its vanishing. On the other hand a direct calculation \([12]\) in a quark-spectator model showed that gluon exchange between the struck quark and the target remnants allows a nonzero Sivers mechanism in DIS at leading twist. As shown by Collins in Ref. \([13]\), the gauge link entering the operator definition of PDFs is crucial. Under time reversal a future-pointing Wilson line, as probed in SIDIS, changes into a past-pointing Wilson line, as probed in Drell-Yan (DY), implying: \( \Delta^N f_{q/p} \mid_{\text{DIS}} = - \Delta^N f_{q/p} \mid_{\text{DY}} \) (i.e. a modified universality). Concerning the Collins FF, not forbidden by time reversal, in Ref. \([14]\) it has been shown that the standard universality is preserved. This feature has been crucial in the first extraction of transversity \([15]\).

For completeness we mention another class of functions relevant in our understanding of the nucleon structure, the generalized parton distributions: for their general properties see i.e. Ref. \([16]\), while their connections to TMDs can be found in Ref. \([17]\).

We discuss now how the study of transverse double spin asymmetries (DSA) in the collinear picture and of transverse single spin asymmetries (SSA) in a TMD approach could provide a powerful tool to learn on the transverse spin structure of nucleons.

### Transverse double spin asymmetries

As already pointed out, to access \( h_1 \) in a physical observable we need another chiral-odd partner. The most direct way, as originally proposed in Ref. \([1]\), is via the transverse double spin asymmetry in Drell-Yan processes, \( p^\uparrow p^\uparrow \rightarrow \ell^+ \ell^- X \):

\[
A_{TT} \equiv \frac{d\sigma^{\uparrow\uparrow} - d\sigma^{\uparrow\downarrow}}{d\sigma^{\uparrow\uparrow} + d\sigma^{\uparrow\downarrow}} = \hat{a}_{TT} \frac{\sum_q e_q^2 \left[ h^q_1(x_1,M^2) h^\bar{q}_1(x_2,M^2) + (1 \leftrightarrow 2) \right]}{\sum_q e_q^2 \left[q(x_1,M^2) \bar{q}(x_2,M^2) + (1 \leftrightarrow 2) \right]},
\]

where the last expression refers to leading order (LO) accuracy, in collinear pQCD, and where \( M \) is the invariant mass of the lepton pair and \( \hat{a}_{TT} \) is the elementary DSA for the \( q\bar{q} \rightarrow \ell^+ \ell^- \) process. Here one measures the product of two transversity distributions, one for a quark and one for an anti-quark. At large energies, like those reachable at RHIC, NLO corrections are small and LO expressions can be used. On the other hand as shown in Ref. \([18]\), \( A_{TT}^{p\bar{p}} \) in this kinematical region is of the order of few percents: indeed, \( h_1 \) for antiquarks is expected to be small and at such small \( x \) its non-singlet nature implies a strong suppression compared to \( q(x,M^2) \) entering the denominator of \( A_{TT} \).
A better way to access $h_1$ in DY processes is the transverse double spin asymmetry in the collision of polarized protons and antiprotons (implying a product of two quark transversity distributions) in a kinematical region of intermediate $x$ values (to have a sizeable $h_1^T$). These are the conditions of the experiment proposed by the PAX collaboration [19] at GSI, where one expects $A_{TT}^{p\bar{p}} \simeq 20 - 40\%$. At such moderate energies, NLO corrections, which are significant for the unpolarized cross sections, almost cancel out in $A_{TT}$ [20]. Moreover, to overcome the expected low event rates, Ref. [21] proposed to look at the $J/\psi$ peak, where, gaining up to two orders of magnitude in the yield, by reasonable assumptions one might still have a direct access to $h_1$.

The inclusive production of photons or pions in $p^+p^\dagger$ collisions is another good channel to learn on $h_1$. Here one expects larger rates compared to DY, but, due to the large gluon contribution in the denominator, $A_{TT}$ might be very small.

Still in the collinear factorization, one can look for a chiral-odd partner in the final hadron, like in $\ell p^\dagger \rightarrow \ell' \Lambda^\dagger X$ or $p^\dagger p \rightarrow \Lambda^\dagger X$. In SIDIS, for the $\Lambda$ polarization, we would have $P_{\Lambda} \sim \sum_q h_1^q \otimes \Delta T D_{\Lambda/q}$. The advantage here is the self-analyzing property of $\Lambda$-hyperons through their parity violating decay. The price is twofold: 1) the appearance of a new unknown chiral-odd function, $\Delta T D_{\Lambda/q}$ (giving the probability that a transversely polarized quark fragments into a transversely polarized hadron); 2) the competing dominance of up quarks from the incoming polarized hadron and of strange quarks in the spin transfer to $\Lambda$ via the fragmentation process.

**Azimuthal and transverse single spin asymmetries**

As shown in Ref. [22], in collinear pQCD a transverse SSA appears only as the imaginary part of interference terms between helicity-flip and non-helicity-flip partonic scattering amplitudes. Since at LO these are real and helicity is conserved for massless partons, it was natural to expect (in $p^\dagger p \rightarrow hX$, for instance)

$$A_N \equiv \frac{d\sigma^\dagger - d\sigma^\dagger}{d\sigma^\dagger + d\sigma^\dagger} \simeq \alpha_s m / \sqrt{s}. \quad (2)$$

Contrary to these expectations several experimental observations show sizeable SSAs in the high-energy regime [23, 24, 25, 26]. The TMD approach to $p^\dagger p \rightarrow \pi X$ was indeed introduced to overcome this problem and a rich phenomenology [27, 28, 29, 7] has been successfully developed. An alternative approach to these SSAs, extending the QCD collinear factorization theorems to higher-twist contributions, has been formulated [30, 31]. For an up-to-date overview on SSAs see i.e. Ref. [32].

Before focusing on the phenomenology of TMD distributions, we mention another tool to access the transversity distribution via SSAs, but still in a collinear factorization picture. Refs. [33, 34] proposed to consider two-pion production in transversely polarized DIS: $\ell p^\dagger \rightarrow \ell \pi \pi X$. This allows $h_1$ to be coupled to a new chiral-odd interference (or di-hadron) FF, $\delta q_I$. This SSA has been observed by HERMES [35] and more information on $\delta q_I$ is going to be gathered by Belle from the study of $e^+e^- \rightarrow hhX$.

The TMD approach applies naturally to leading-twist asymmetries, like SSAs in Drell-Yan processes and SIDIS, or azimuthal asymmetries in $e^+e^- \rightarrow h_1h_2X$, at low
transverse momentum. For such processes TMD factorization has been proved \cite{36,37}.
Different groups have performed several phenomenological analyses \cite{38,39,40,15,41,42,43,44,45,46,47} and their results are quite similar and consistent with each others. In the following we will skip unessential details, like assumptions in fitting procedures and experimental cuts, which can be found in the above referred papers.

**Drell-Yan processes:** \( pp \rightarrow \ell^+ \ell^- X \)

This process is a clean tool to learn on TMD distributions. Data on unpolarized cross sections \((d\sigma/d\cos\theta d\phi_\ell)\) show a \(\cos 2\phi\) dependence, that, if puzzling in LO and NLO collinear QCD, might be explained in terms of the convolution of two Boer-Mulders functions \cite{10}. \(\phi\) is the azimuthal angle of the photon momentum in the Collins Soper lepton c.m. frame w.r.t. the perpendicular lepton direction (identified by \(\phi_\ell\)).

For transverse SSAs in DY, two mechanisms could play a role: the Sivers effect and the Boer-Mulders effect (coupled to \(\Delta Tq\)). Again in a schematic way we have

\[
A_N \simeq \sum_q \left[ \Delta N_{fq/p}^\perp \otimes f_{\bar{q}/p} \sin(\phi - \phi_0) + \frac{\sin^2 \theta}{(1 + \cos^2 \theta)} \Delta Tq \otimes \Delta N_{f_{\bar{q}}/p} \sin(\phi + \phi_0) \right].
\]

This means that by proper integration over the lepton-pair angular variables \((\phi_\ell)\) one can have a direct access to the Sivers function \cite{48}, crucial to test the predicted modified universality. At the same time this SSA represents another tool to extract the transversity distribution. Experimental measurements are planned (i.e. RHIC, COMPASS).

**Azimuthal correlations in \(e^+ e^- \rightarrow h_1 h_2 X\)**

This process, even without any polarization, is the clearest way to access the \(k_\perp\)-polarization correlation in the fragmentation mechanism. The spins of the \(q\bar{q}\) pair produced in the lepton annihilation are strongly correlated and in the fragmentation into two nearly back-to-back hadrons via the Collins mechanism a clear azimuthal asymmetry might arise \cite{49}. This effect has been observed by Belle at KEK \cite{50,51}. In particular, two experimental methods have been adopted: 1) by reconstructing the 2-jet thrust axis to look for a \(\cos(\phi_1 + \phi_2)\) modulation (\(\phi_{1,2}\) are the azimuthal angles of the two hadrons w.r.t. the plane spanned by the lepton momenta and the thrust axis); 2) by observing the azimuthal dependence of one hadron w.r.t. the plane spanned by the other hadron and the incoming beam, a \(\cos(2\phi_0)\) dependence arises. In both cases one accesses the product of two Collins functions. By suitable integrations, see Ref. \cite{15}, one gets

\[
d\sigma \simeq \sum_q \left[ (1 + \cos^2 \theta) D_{h_1/q}(z_1) D_{h_2/\bar{q}}(z_2) \right. \\
+ \sin^2 \theta \Delta N_{h_1/q}(z_1) \Delta N_{h_2/\bar{q}}(z_2) \times \cos(\phi_1 + \phi_2) \left. \right] \ [or \times \cos(2\phi_0)].
\]

\(^1\) Notice that the combination \((\phi - \phi_0)\), related to the Sivers effect, does not depend on \(\phi_\ell\).
FIGURE 1. Left: Latest fit [42] of the \(\cos(\phi_1 + \phi_2)\) modulation observed by Belle in \(e^+ e^- \rightarrow \pi\pi X\) [51]. Right: Extracted favoured and unfavoured Collins functions. Shaded areas show the uncertainty on this extraction (wider bands correspond to the fit of Ref. [15]).

In the study of Ref. [15] the first data from Belle [50] were used. New and more accurate data, recently released, have allowed a better extraction of the Collins function. In Fig. [1] we show the preliminary updated fit [42] of the latest high statistics Belle data [51] (left panel) and the corresponding favoured (i.e. \(u \rightarrow \pi^+\)) and unfavoured (i.e. \(d \rightarrow \pi^+\)) Collins functions (right panel). From these results we can conclude that the Collins effect is sizeable, and favoured and unfavoured Collins functions, comparable in magnitude, have opposite sign. Notice that this information has been crucial in the global analysis involving the Collins effect in SIDIS and leading to the extraction of \(h_1\).

**SIDIS processes: \(\ell p \rightarrow \ell' hX\)**

Also in this case the unpolarized cross section exhibits interesting azimuthal dependences that could be explained in terms of TMD distributions. In particular, the convolution of unpolarized \(k_\perp\)-dependent PDFs and FFs gives rise to the so-called Cahn effect [52]. This has been indeed used for the extraction of the \(k_\perp\) behaviour of TMD distributions [53]. Moreover a \(\cos 2\phi_h\) dependence could be ascribed to the convolution of the Boer-Mulders function with the Collins FF [54, 5].

Transverse SSAs in SIDIS have been the gold channel to access for the first time the Sivers function and the transversity distribution (this together with the Collins function by a combined analysis of SIDIS and Belle \(e^+ e^-\) data). This has been possible thanks to dedicated experimental programs by HERMES [55, 56, 57] (with hydrogen target) and COMPASS [58, 59, 60] (with deuteron target) collaborations. In particular, thanks to their latest high statistics data [57, 60] we have been able to improve our knowledge of the Sivers (including sea quarks) [41], Collins and transversity functions [42].

In a schematic form (Unpolarized lepton, Transversely polarized target) we have

\[
A_{UT} \simeq \sum_q \left[ \Delta N_{f/q/p} \otimes D_{h/q} \sin(\phi_h - \phi_S) + \frac{1 - y}{1 + (1 - y)^2} \Delta T_{q} \otimes \Delta N_{h/q} \sin(\phi_h + \phi_S) \right] + \cdots,
\]

where \(\phi_h (\phi_S)\) is the azimuthal angle of the observed hadron momentum (target polarization vector) in the photon-nucleon c.m. frame, measured from the leptonic plane [6].

\[Q^2 < 2.4 \text{ GeV}^2, \quad z \lesssim 0.36, \quad 0.2 < z < 0.5, \quad 0.3 < z < 0.4, \quad 0.6 < z < 0.8.\]
An extra term involving again the Collins function coupled to the \( h_{\perp T} \) distribution and providing a \( \sin(3\phi_h - \phi_S) \) azimuthal modulation has been omitted.

The different azimuthal dependence in Eq. 5 allows the separation of Sivers and Collins effects. It is therefore common to consider the following azimuthal moments

\[
A_{UT}^{\sin(\phi_h \pm \phi_S)} = \frac{2 \int d\phi_h d\phi_s \sin(\phi_h \pm \phi_S) [d\sigma(\phi_S) - d\sigma(\phi_S + \pi)]}{\int d\phi_h d\phi_s [d\sigma(\phi_S) + d\sigma(\phi_S + \pi)]}. \tag{6}
\]

In Fig. 2 (left) we show the latest analysis [41] of Sivers asymmetry data from HERMES [57] and (right) the Sivers function for up and down quarks (solid lines) compared with the results from our previous study (dashed lines) [39].

In Fig. 3 (left) we show the updated fit [42] of Collins asymmetry data from HERMES [57] and (right) the extracted transversity distribution for up and down quarks.

Notice that COMPASS SSA data on deuteron, even if compatible with zero, complement with HERMES results concerning flavour separation of TMDs.

From these analyses we see that: 1) The Sivers functions for valence quarks are sizeable and opposite in sign for up and down quarks; 2) Transversity is different from zero, smaller than its Soffer bound [61], with up quarks carrying a degree of transverse polarization bigger (and opposite in sign) than down quarks.

**SSAs in \( pp \rightarrow hX \)**

Despite a clear experimental evidence and a rich phenomenology in the TMD approach, this case might deserve further theoretical study. Assuming a TMD factorization, both the Sivers [29] and the Collins [62] mechanism might explain the large SSAs observed in \( pp \rightarrow \pi X \). The extension of the universality of the Collins function to \( pp \) collisions is presented in Ref. [63], while, even though at a phenomenological level, Ref. [64] shows the compatibility of the Sivers effect in SIDIS and \( pp \rightarrow \pi X \). For such a process the two mechanisms are not separable and information from less inclusive re-
actions, like $p^\uparrow p \to \gamma \text{jet} \, (\Delta^N f_{q/p})$ [65] or $p^\uparrow p \to \pi \text{jet} \, (h_1 \otimes \Delta^N D_{\pi/q'})$ [63], could help.

The effective investigation of the nucleon transverse spin has definitely started. Much progress has been made and further work is needed both theoretically (a more solid picture of SSAs in the TMD approach, $Q^2$-evolution of TMDs) and experimentally (DSAs and SSAs in DY processes, data at large $x$ and for less inclusive processes).

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