UNDERSTANDING TRANSVERSITY: 
PRESENT AND FUTURE

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I review the present state of knowledge concerning transversity distributions and related observables. In particular, I discuss the phenomenology of transverse asymmetries in $ep$, $pp$, $p+p$ and $\bar{p}+p$ scattering, and the perspectives of ongoing and future research.

1 General properties of transversity

The transverse polarization, or transversity, distribution of quarks $h_1(x)$ – also called $\Delta_T q(x)$ – has been the subject of an intense theoretical work in the last decade (for reviews, see Refs. 1 and 2), and the corresponding observables are now actively investigated in many experiments.

Let us start by recalling the partonic definition of $h_1(x)$. Given a transversely polarized hadron, if we denote by $q_\uparrow(q_\downarrow)$ the number density of quarks with polarization parallel (antiparallel) to that of the hadron, the transversity distribution is the difference $h_1(x) = q_\uparrow(x) - q_\downarrow(x)$. In field-theoretical terms, $h_1(x)$ is given by ($P$ and $S$ are the momentum and the spin of the hadron, respectively)

$$h_1(x) = \int \frac{d\xi^-}{4\pi} e^{ixP^+\xi^-} \langle P, S|\bar{\psi}(0)\gamma^+\gamma_\perp\gamma_5\psi(\xi)|P, S\rangle|_{\xi^+=\xi_\perp=0},$$

(1)

and is a leading-twist quantity, like the number density $f_1(x)$ (also called $q(x)$) and the helicity distribution $g_1(x)$ (more often, and less ambiguously, called $\Delta q(x)$). A Wilson line $W(0, \xi)$ should be inserted between the quark fields in (1), in order to ensure gauge invariance. In the light-cone gauge, $W$ reduces to unity and can be omitted (this is no more true for $k_T$-dependent distributions, see below). The tensor charge $\delta q$ is defined by

$$\langle P, S|\bar{\psi}(0)i\sigma^{\mu\nu}\gamma_5\psi(0)|P, S\rangle = 2\delta q S^{[\mu}P^{\nu]},$$

(2)

and corresponds to the first moment of $h_1 - \bar{h}_1$: $\delta q = \int dx (h_1^q - \bar{h}_1^q)$.

An important peculiarity of $h_1$ is that it has no gluonic counterpart (in spin-1/2 hadrons). Therefore, it does not mix with gluons, and behaves as a

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non-singlet distribution. At low $x$, it turns out to rise slower than $g_1$ by QCD evolution.\(^3\) An angular momentum sum rule for transversity,

\[
\frac{1}{2} = \frac{1}{2} \sum_{a=q,\bar{q}} \int dx h_1^a(x) + \sum_{a=q,\bar{q},g} \langle L_T \rangle^a,
\]

has been recently proven in the framework of the quark-parton model.\(^4\) Since transversity decreases with increasing $Q^2$, the orbital angular momentum $\langle L_T \rangle$ must increase (assuming an initial zero value). Of course, it would be very interesting to study this sum rule in perturbative QCD.

The transversity distributions have been computed in a variety of models (for a review, see Ref. 1). Generally, one finds $h_1 \approx g_1$ at the model scale, i.e. for $Q^2 \lesssim 0.5$ GeV\(^2\) (the difference between the two quantities comes from the lower components of the quark wavefunctions). Tensor charges have been also evaluated in lattice QCD and by QCD sum rules. A summary of all estimates is: $\delta u \sim 0.7 - 1.0$, $\delta d \sim -(0.1 - 0.4)$ at $Q^2 = 10$ GeV\(^2\).

Examining the operator structure in (1) one sees that $h_1(x)$ is chirally-odd. Now, fully inclusive DIS proceeds via the so-called handbag diagram, which cannot flip the chirality of quarks. Thus, transversity distributions are not observable in inclusive DIS. In order to measure $h_1$, the chirality must be flipped twice, so one needs either two hadrons in the initial state (hadron–hadron collisions), or one hadron in the initial state and one - at least - in the final state (semi-inclusive deep inelastic scattering, SIDIS).

### 2 $k_T$-dependent distributions related to transversity

If we ignore (or integrate over) the transverse momenta of quarks, $f_1(x)$, $g_1(x)$ and $h_1(x)$ completely describe the internal dynamics of hadrons. Taking the transverse motion of quarks into account, the number of distribution functions increases. At leading twist there are eight $k_T$-dependent distributions, three of which, upon integration over $k_T^2$, yield $f_1(x)$, $g_1(x)$ and $h_1(x)$. The remaining five distributions are new and disappear when the hadronic tensor is integrated over $k_T$. They are related to various correlations between $k_T$, $S_T$ and $S_{qT}$ (the quark spin). The spin asymmetry of transversely polarized quarks inside a transversely polarized proton is given by

\[
P_{q^+}/p^+(x,k_T) - P_{q^-}/p^-(x,k_T) = (S_T \cdot S_{qT}) h_1(x,k_T^2)
- \frac{1}{M^2} \left( (k_T \cdot S_{qT})(k_T \cdot S_T) + \frac{1}{2} k_T^2 (S_T \cdot S_{qT}) \right) h_{1T}^+(x,k_T^2),
\]

and contains not only the unintegrated transversity distribution $h_1(x,k_T^2)$, but also another distribution function, called $h_{1T}^+(x,k_T^2)$. Both $h_1$ and $h_{1T}^+$...
contribute to single-spin asymmetries in SIDIS (via Collins effect), but with
different angular distributions, \( \sin(\phi_h + \phi_S) \) and \( \sin(3\phi_h - \phi_S) \) respectively
(see below). Consider now unpolarized quarks inside a transversely polarized
proton. They may have an azimuthal asymmetry of the form

\[
\mathcal{P}_{q/p}^\uparrow(x, k_T) - \mathcal{P}_{q/p}^\downarrow(x, k_T) = \frac{(k_T \times \hat{P}) \cdot S_T}{M} f_{1T}^\perp(x, k_T^2),
\]

(5)

where \( f_{1T}^\perp \) is the Sivers distribution function. Specularly, transversely polarized
quarks inside an unpolarized proton admit a possible spin asymmetry of the form

\[
\mathcal{P}_{q/p}^\uparrow(x, k_T) - \mathcal{P}_{q/p}^\downarrow(x, k_T) = \frac{(k_T \times \hat{P}) \cdot S_{qT}}{M} h_{1T}^\perp(x, k_T^2),
\]

(6)

where \( h_{1T}^\perp \) is the so-called Boer–Mulders distribution function. The two distri-
butions \( f_{1T}^\perp \) and \( h_{1T}^\perp \) are associated with the \( T \)-odd
\( (\hat{P} \times k_T) \cdot S_T \) and \( (\hat{P} \times k_T) \cdot S_{qT} \). To see the implications of time-reversal invariance, let us
write the operator definition of the Sivers function:

\[
f_{1T}^\perp(x, k_T^2) \sim \int d\xi^- \int d\xi^- e^{i\hat{P} \cdot \xi^- - ik_T \cdot \xi^-} \times \langle P, S_T | \bar{\psi}(\xi^-) \gamma^+ W(0, \xi^-) \psi(0) | P, S_T \rangle
\]

(7)

If we naively set the Wilson link \( W \) to \( \mathbb{1} \), the matrix element in (7) changes sign
under time reversal \( T \), hence the Sivers function must be zero.9 On the other
hand, a direct calculation10 in a quark-spectator model shows that \( f_{1T}^\perp \) is non
vanishing: gluon exchange between the struck quark and the target remnant
generates a non-zero Sivers asymmetry (the presence of a quark transverse mo-
mentum smaller than \( Q \) ensures that this asymmetry is proportional to \( M/k_T \),
rather than to \( M/Q \), and therefore is a leading-twist observable). The puzzle
is solved by carefully considering the Wilson line in (7).11 For the case at hand
(SIDIS), \( W(0, \xi^-) \) includes a link at \( \infty^- \) which does not reduce to \( \mathbb{1} \) in the
light-cone gauge.12 Time reversal changes a future-pointing Wilson line into a
past-pointing Wilson line and therefore invariance under \( T \), rather than con-
straining \( f_{1T}^\perp \) to zero, gives a relation between processes that probe Wilson lines
pointing in opposite time directions. In particular, since in SIDIS the Sivers asymmetry arises from the interaction between the spectator and the outgoing
quark, whereas in Drell-Yan processes it is due to the interaction between the spectator and an incoming quark, one gets

\[
f_{1T}^\perp(x, k_T^2)_{\text{SIDIS}} = - f_{1T}^\perp(x, k_T^2)_{\text{DY}}.
\]

This is an example of the “time-reversal modified universality” of distribution functions in SIDIS, Drell-Yan production and \( e^+e^- \) annihilation studied by
Collins and Metz. More complicated Wilson link structures in various hard processes have been investigated by Bomhof, Mulders and Pijlman. The issue is not completely settled and more theoretical work seems to be needed in order to fully clarify the universality properties of $k_T$-dependent distributions. Finally, it is known that at twist 3, effective $T$-odd distributions emerge from gluonic poles. The precise connection between $k_T$-dependent and twist-3 distributions is another problem that deserves further study.

3 Probing transversity

3.1 Semi-inclusive deep inelastic scattering

Let us start with the single-spin process $e p^\uparrow \to e^' \pi X$, for which some data are already available. In order to have a non vanishing asymmetry, one must consider the transverse motion of quarks. The non-collinear factorization theorem has been recently proven by Ji, Ma and Yuan for $P_{hT} \ll Q$. A single-spin transverse asymmetry is due either to: i) a spin asymmetry of transversely polarized quarks fragmenting into the unpolarized hadron, the so-called Collins effect involving

$$N_{h/q}^1(z, P_{hT}) - N_{h/q}^\downarrow(z, P_{hT}) = \frac{\hat{k}_T \times \hat{P}_{hT} \cdot S_{qT}^\perp}{zM_h^2} H_1^\perp(z, P_{hT}^2), \quad (8)$$



a $T$-odd function not forbidden by time reversal invariance (due to final-state interactions); or to ii) an azimuthal asymmetry of unpolarized quarks inside the transversely polarized proton, the so-called Sivers effect, involving $f_{1T}^\perp$. The differential cross section for $e p^\uparrow \to e^' \pi X$ is

$$d\sigma \sim A(y) \int \frac{k_T \cdot \hat{P}_{hT}}{M_h} h_1^\perp \sin(\phi_h + \phi_S) + B(y) \int \frac{k_T \cdot \hat{P}_{hT}}{M_h} f_{1T}^\perp D_1 \sin(\phi_h - \phi_S) + C(y) \int \lambda(k_T, k_T, \hat{P}_{hT}) h_1^\perp H_1^\perp \sin(3\phi_h - \phi_S), \quad (9)$$

where $\int[...]$ is a convolution integral over $k_T$ and $\kappa_T$. As one can see, there is a variety of angular distributions which combine in different ways the two physical angles $\phi_h$ and $\phi_S$. In particular, the Collins effect is associated with $\sin(\phi_h + \phi_S)$, and also with $\sin(3\phi_h - \phi_S)$ if the transverse motion of quarks inside the target is not neglected, whereas the Sivers effect is associated with a $\sin(3\phi_h - \phi_S)$ distribution. One can disentangle these angular distributions by
taking the azimuthal moments of the asymmetries. For instance, the Collins moment is

\[
\langle \sin(\phi_h + \phi_S) \rangle = \frac{\int d\phi_h d\phi_S \sin(\phi_h + \phi_S) [d\sigma(\phi_h, \phi_S) - d\sigma(\phi_h, \phi_S + \pi)]}{\int d\phi_h d\phi_S [d\sigma(\phi_h, \phi_S) + d\sigma(\phi_h, \phi_S + \pi)]}.
\]

Recently, the HERMES Collaboration\(^7\) reported the first measurement of the Collins moment \(\langle \sin(\phi_h + \phi_S) \rangle\) and of the Sivers moment \(\langle \sin(\phi_h - \phi_S) \rangle\), in the region \(0.02 < x < 0.4, 0.2 < z < 0.7\), at \(Q^2 = 2.4 \text{ GeV}^2\). The Collins asymmetry \(A_T^+\) is found to be positive, whereas \(A_T^-\) is negative. This is consistent with the fact that \(h_1^u > 0\) and \(h_1^d < 0\). However, \(A_T^+\) is negative and its absolute value \(|A_T^-|\) is larger than \(|A_T^+|\), whereas one expects from models \(|h_1^u| \ll |h_1^d|\). Recalling that \(A_T^+\) and \(A_T^-\) involve the following combinations of distribution and fragmentation functions (‘fav’ = favored, ‘unf’ = unfavored)

\[
A_T^+ : 4 h_1^u H_1^{1\text{ fav}} + h_1^d H_1^{1\text{ unf}}, \quad A_T^- : h_1^d H_1^{1\text{ fav}} + 4 h_1^u H_1^{1\text{ unf}}
\]

one sees that the \(\pi^-\) data seem to require large unfavored Collins functions, with \(H_1^{1\text{ unf}} \approx -H_1^{1\text{ fav}}\). It would be very useful to get some independent information on \(H_1^+\) from other processes: in this respect, the forthcoming extraction of \(H_1^+\) from \(e^+e^-\) annihilation data in the Belle experiment at KEK will be extremely important.\(^8\) There are also preliminary HERMES results on the \(\pi^0\) asymmetry, showing a largely negative \(A_T^{\pi^0}\), similar to \(A_T^-\). This is quite a controversial finding, as it conflicts with expectations based on isospin invariance. The Collins asymmetry has also been measured by the COMPASS Collaboration with a deuteron target.\(^9\) In the \(x \lesssim 0.1\) region, it is found to be compatible with zero for both \(\pi^+\) and \(\pi^-\), as expected quite generally at small \(x\). Concerning Sivers asymmetries, HERMES find \(A_T^{\pi^0} > 0\): this is the first evidence of a non vanishing Sivers function \(f_1^{\perp T}\), although – due to the smallness of \(A_T^{\pi^+}\) and the present uncertainties – more precise data are needed to draw a definite conclusion.

Another access to transversity in the context of SIDIS is offered by the double-spin process \(ep^+ \rightarrow e'\Lambda X\) (transversely polarized \(\Lambda\) production), which probes the fragmentation analog of \(h_1\), i.e. \(H_1(z) = N_{h_1}^{\perp T/q^+}(z) - N_{h_1}^{\perp T/q^+}(z)\). Unfortunately, it is hard to predict the \(\Lambda\) polarization, because \(H_{1\Lambda}\) is unknown (see, however, some attempts in Ref. 20). An analysis of data on transversely polarized \(\Lambda\) production is currently being performed by the COMPASS Collaboration.\(^{21}\)

A third promising process to detect transversity is two-pion production in \(ep^+\) scattering. In this case, after integrating the cross sections over \(P_{hT}\), one finds that the single-spin asymmetry depends on an interference fragmentation
function $I(z, M^2)$, arising from the interference between different partial waves of the two-pion system.\textsuperscript{22} The extraction of this function is under way.\textsuperscript{23}

### 3.2 Pion hadroproduction

Collins and Sivers effects manifest themselves also in pion hadroproduction with a transversely polarized target. A non vanishing asymmetry is generated either by quark transverse momenta or by higher-twist effects. The non-collinear factorization formula is, in this case, only conjectured. Assuming its validity, the Collins asymmetry reads

\[
\frac{d\sigma^\uparrow - d\sigma^\downarrow}{d\sigma^\uparrow + d\sigma^\downarrow} \sim \sum_{abc} [h_1(x_a, k_T^2) + k_T^2 / (M^2) h_1^T(x_a, k_T^2)] \otimes f_1(x_b, k_T^2) \\
\otimes \Delta_{TT} \delta(a^\uparrow b \rightarrow c^\uparrow d) \otimes H_1^\perp(z, \kappa^2_T),
\]

(12)

whereas the Sivers asymmetry is

\[
\frac{d\sigma^\uparrow - d\sigma^\downarrow}{d\sigma^\downarrow} \sim f_{1T}(x_a, k_T^2) \otimes f_1(x_b, k_T^{2\perp}) \otimes \delta(ab \rightarrow cd) \otimes D_1(z, \kappa^2_T).
\]

(13)

An extensive and detailed treatment of single-spin asymmetries in the framework of non-collinear factorization has been presented in Refs. 24 and 25 (for another approach leading to similar conclusions, see Ref. 26). The main finding is that the Collins asymmetry alone is unable to reproduce the E704\textsuperscript{27} and STAR\textsuperscript{28} data: the Collins effect turns out to be suppressed due to kinematic phases occurring in non-collinear partonic subprocesses (this does not imply anything about the magnitude of $H_1^\perp$). On the contrary, the Sivers mechanism is not affected by a similar suppression. A major shortcoming of pion hadroproduction is that it depends on one physical angle only, so that all asymmetry mechanisms are entangled. A possible way to avoid this problem is to study a less inclusive process, such as pion + jet production, as advocated by Teryaev (private communication).

In a recent paper, Bourrely and Soffer\textsuperscript{29} argued that, since collinear pQCD correctly reproduces the large-$\sqrt{s}$ STAR unpolarized cross sections but fails to describe the small-$\sqrt{s}$ E704 data, the single-spin asymmetries measured by these two experiments are actually different phenomena, and in particular the E704 asymmetry “cannot be attributed to pQCD”. Two comments are in order: first of all, higher-twist effects might be important, since $\langle P_{hT} \rangle$ is not so large (typically, around 1-2 GeV). Second, as shown by D’Alesio and Murgia\textsuperscript{25}, quark transverse momenta considerably improve the agreement of the pQCD calculations with the small-$\sqrt{s}$ unpolarized cross sections.
3.3 Drell-Yan processes

Drell-Yan production in $p^\uparrow p^\uparrow$ collisions is the cleanest process that probes transversity. The double-spin asymmetry $A_{TT}^{DY}$, in fact, contains only combinations of the transversity distributions. At leading order, for instance, one has

$$A_{TT}^{DY}(pp) \sim \frac{\sum_q e_q^2 h_q^1(x_1, M^2) \bar{h}_q^1(x_2, M^2) + [1 \leftrightarrow 2]}{\sum_q e_q^2 f_q^1(x_1, M^2) \bar{f}_q^1(x_2, M^2) + [1 \leftrightarrow 2]}.$$  \hspace{1cm} (14)

It turns out, however, that at the energies of RHIC (where this process will be studied\textsuperscript{30}) this asymmetry is rather small\textsuperscript{31,32} (about 1–2%; similar values are found for transverse double-spin asymmetries in prompt photon production\textsuperscript{33}).

The reason is twofold: 1) $A_{TT}^{DY}(pp)$ contains antiquark transversity distributions, which are small; 2) RHIC kinematics ($\sqrt{s} = 200$ GeV, $M < 10$ GeV, $x_1 x_2 = M^2/s \lesssim 3 \times 10^{-3}$) probes the low-$x$ region, where $h_1$ rises slowly.

The problem could be circumvented by considering $\bar{p}^\uparrow p^\uparrow$ scattering at more moderate energies. In this case a much larger asymmetry is expected\textsuperscript{31,34,35} since $A_{TT}^{DY}(\bar{p}p)$ contains products of valence distributions at medium $x$. The PAX Collaboration has proposed to study $\bar{p}^\uparrow p^\uparrow$-initiated Drell-Yan production at the High-Energy Storage Ring of GSI, in the kinematic region $30 \text{ GeV}^2 \lesssim s \lesssim 45 \text{ GeV}^2$, $M \gtrsim 2$ GeV, $x_1 x_2 \gtrsim 0.1$\textsuperscript{36}. Leading-order predictions for the $\bar{p}p$ asymmetry in this regime are shown in Fig. 1 (left). $A_{TT}^{DY}(\bar{p}p)$ is as large as 0.3 at $M = 4$ GeV, but counting rates are small and this makes the measurement arduous. Things become easier if one looks at the $J/\psi$ peak, where the production rate is larger by two orders of magnitude. Assuming the dominance of $q\bar{q}$ fusion (as suggested by a comparison of $pp$ and $\bar{p}p$ cross sections at the CERN SPS), the $J/\psi$ production double transverse asymmetry $A_{TT}^{J/\psi}(\bar{p}p)$ has the same structure as Eq. (14), with the electric charges replaced by the $q\bar{q} - J/\psi$ couplings. These cancel out in the ratio, and hence $A_{TT}^{J/\psi}(\bar{p}p)$, which is dominated by the $u$ sector, becomes

$$A_{TT}^{J/\psi}(\bar{p}p) \sim \frac{h_1^\psi(x_1, M_{J/\psi}^2) \bar{h}_1^\psi(x_2, M_{J/\psi}^2)}{f_1^u(x_1, M_{J/\psi}^2) \bar{f}_1^u(x_2, M_{J/\psi}^2)}.$$  \hspace{1cm} (15)

This asymmetry is also of the order of 0.3 (Fig. 1, right) and, by measuring it, one can directly extract the $u$ transversity distribution.

4 Conclusions and perspectives

Transversity is presently a very hot topic in high-energy spin physics. From the theoretical point of view, a lot of work has been done and $h_1$ is by now rather
well known. On the experimental side, the era of data has at last arrived: single-spin processes are under study and the first results are already matter of phenomenological analyses. Double-spin processes are experimentally more difficult but theoretically cleaner, and their investigation is certainly worth the effort. While we look forward to more - and more precise - data, the main goal of theory is to achieve a solid picture of single-spin transverse asymmetries (sheding further light on $k_T$ and higher-twist effects), in view of future global studies of transversity measurements.

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