Handedness inside the proton

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Abstract. The transversity of quarks inside unpolarized hadrons and its phenomenology are discussed. Several experimental suggestions are proposed that would allow further study of this intrinsic handedness.

INTRODUCTION

As pointed out in Ref. [1] there exists an experimental indication – a cos 2φ azimuthal asymmetry in the Drell-Yan process – for nonzero transversity of quarks inside unpolarized hadrons. The idea is that transverse polarization of a noncollinear quark inside an unpolarized hadron in principle can have a preferred direction and therefore, does not need to average to zero. This preferred direction signals an intrinsic handedness. For example expressed in the infinite momentum frame, the transverse quark polarization is orthogonal to the directions of the proton and the (noncollinear) quark momentum:

\[ S_T^q \propto P_{\text{hadron}} \times p_{\text{quark}}. \] (1)

Clearly, this must be related to orbital angular momentum, but how exactly is still an open question.

Whether there is indeed nonzero intrinsic handedness remains to be tested and here we will discuss ways of how one would be able to pursue this issue. Some theoretical aspects of this quark-transversity distribution function (usually denoted by \( h_1^T \)) [2] will be reviewed and its main experimental signatures will be pointed out. In particular, unpolarized and single spin asymmetries will be discussed for the Drell-Yan (DY) process and semi-inclusive DIS. Important in the latter case are polarized \( \Lambda \) production observables. Special emphasis will be put on how to distinguish the various asymmetries compared to those arising from other mechanisms, like the Sivers effect [3].

"T-ODD" DISTRIBUTION FUNCTIONS

The quark-transversity function \( h_1^T \) is a function of the lightcone momentum fraction \( x \) and transverse momentum \( p_T \) of a quark inside an unpolarized hadron. At first sight, this intrinsic handedness function appears to violate time reversal invariance, when the incoming hadron is treated as a plane-wave state. However, already in a simple gluon-exchange model calculation [4] such so-called “T-odd” distribution functions turn out to

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be nonzero. In recent work \cite{5, 6, 7} it has been demonstrated that the proper gauge
invariant definition of transverse momentum dependent functions does indeed allow
for such seemingly time reversal symmetry violating functions. Therefore, here we
will simply assume that there exists no symmetry argument that forces the intrinsic
handedness to be absent.

A large part of the $h_{T}^{1}$ phenomenology was already presented in Refs. \cite{2, 1}. The func-
tion $h_{T}^{1}$ enters the asymmetries discussed below without suppression by inverse powers
of the hard scale in the process (but the operator associated to the function is not twist-2
in the OPE sense). The other unsuppressed transverse momentum dependent “T-odd”
function is the Sivers effect function, denoted by $f_{1T}^{T}$. It parameterizes the probability of
finding an unpolarized quark (with $x$ and $p_{T}$) inside a transversely polarized hadron.

**UNPOLARIZED DRELL-YAN**

As mentioned, there exists data that is compatible with nonzero $h_{T}^{1}$. A large $\cos 2\phi$
angular dependence in the unpolarized DY process $\pi^{-}N \rightarrow \mu^{+}\mu^{-}X$ was observed, for
deuterium and tungsten and with $\pi$-beam energies ranging between 140 and 286 GeV
\cite{8, 9, 10}. Conventionally, the differential cross section is written as

$$\frac{1}{\sigma} \frac{d\sigma}{d\Omega} \propto \left(1 + \lambda \cos^2 \theta + \mu \sin^2 \theta \cos \phi + \nu \sin^2 \theta \cos 2\phi \right), \quad (2)$$

where $\phi$ is the angle between the lepton and hadron scattering planes in the lepton center
of mass frame (see Fig. 3 of Ref. \cite{1}). The perturbative QCD (pQCD) prediction for
very small transverse momentum ($Q_{T}$) of the muon pair is $\lambda \approx 1, \mu \approx 0, \nu \approx 0$. More
generally, i.e. also for larger $Q_{T}$ values, one expects the Lam-Tung relation $1 - \lambda - 2\nu = 0$
to hold (at order $\alpha_s$). However, the data (with invariant mass $Q$ of the lepton pair in
the range $Q \sim 4 - 12$ GeV) is incompatible with this pQCD relation (and with its $\mathcal{O}(\alpha_s^3)$
modification as well \cite{11}). Several explanations have been put forward in the literature,
but these will not be reviewed here.

In Ref. \cite{1} we have observed that within the framework of transverse momentum
dependent distribution functions, the $\cos 2\phi$ asymmetry can only be accounted for by
the function $h_{T}^{1}$ or else will be $1/Q^2$ suppressed. We obtained $\nu \approx h_{T}^{1} \pi h_{T}^{1,N}$ and this
expression was used to fit the function $h_{T}^{1}$ from the data. This approach has several
aspects in common with earlier work by Brandenburg, Nachtmann and Mirkes \cite{11},
where the large values of $\nu$ were generated from a nonperturbative, nonfactorizing
mechanism that correlates the transverse momenta and spins of the quark and anti-quark
that annihilate into the virtual photon (or $Z$, but not $W$, boson). But the description of
$\nu$ as a product of two $h_{T}^{1}$ functions implies that these correlations are not necessarily
factorization breaking and this type of effects will then not be specific to hadron-hadron
scattering. We also note that since the function $h_{T}^{1}$ is a quark helicity-flip matrix element,
its offers a natural explanation for $\mu \approx 0$.

\footnote{The name “T-odd” is thus a misnomer, since it seems to suggest a violation of time reversal invariance,
which turns out not to be the case. Other names, like naive or artificial T-odd, have been suggested.}
POLARIZED DRELL-YAN

Instead of colliding two unpolarized hadrons, one can also use a polarized hadron to become sensitive to the polarization of quarks inside an unpolarized hadron. In principle, this provides a new way to measure the transversity distribution function $h_1$.

In this case the transverse hadron spin ($S_T$) dependent differential cross section may be parameterized by (choosing $\mu = 0$ and $\lambda = 1$)

$$
\frac{d\sigma(pp^\uparrow \rightarrow \ell\bar{\ell}X)}{d\Omega d\phi_S} \propto 1 + \cos^2 \theta + \sin^2 \theta \left[ \frac{V}{2} \cos 2\phi - \rho |S_T| \sin(\phi + \phi_S) \right] + \ldots,
$$

(3)

where $\phi_S$ is the angle of the transverse spin compared to the lepton plane, cf. Ref. [1].

The analyzing power $\rho$ is (within this framework) proportional to the product $h_1 h_1$ [2, 1]. Hence, the measurement of $\langle \cos 2\phi \rangle$ (e.g. at RHIC in $pp \rightarrow \mu^+\mu^- X$ or at Fermilab in $p\bar{p} \rightarrow \mu^+\mu^- X$) combined with a measurement of the single spin azimuthal asymmetry $\langle \sin(\phi + \phi_S) \rangle$ (also possible at RHIC) could provide information on $h_1$. In other words, a nonzero function $h_1^\perp$ will imply a relation between $\nu$ and $\rho$, which in case of one (dominant) flavor (usually called $u$-quark dominance) and Gaussian transverse momentum dependences, is approximately given by

$$
\rho \approx \frac{1}{2} \sqrt{\frac{\nu}{\nu_{\text{max}}}} h_1 f_1,
$$

(4)

where $\nu_{\text{max}}$ is the maximum value attained by $\nu(Q_T)$. This relation depends on the magnitude of $h_1$ compared to $f_1$ and since $h_1$ is not known experimentally, in Fig. 1 we display two options for $\rho$, using the function $\nu$ which was fitted from the 194 GeV data [1] (which has $\langle Q_T \rangle \lesssim 3$ GeV) and is extrapolated to larger $Q_T$ values (the theoretically expected turn-over of $\nu$ has not yet been seen in experiments).

FIGURE 1. Results for $\rho$ using Eq. (4), for $h_1$ equal to $f_1/2$ and $f_1/10$.

We note that the Sivers function $f_{1T}^\perp$ will generate a different angular single spin asymmetry, namely proportional to $(1 + \cos^2 \theta) |S_T| \sin(\phi - \phi_S) f_{1T}^\perp f_1$. 
HADRON PRODUCTION SINGLE SPIN ASYMMETRIES

Large single transverse spin asymmetries have been observed in the process $p p \uparrow \rightarrow \pi X$ [12]. It has been suggested that these asymmetries can arise from various “T-odd” functions with transverse momentum dependence. There are three options:

$$h_1^\perp \otimes h_1 \otimes D_1; \quad f_1^T \otimes f_1 \otimes D_1; \quad h_1 \otimes f_1 \otimes H_1^\perp.$$  

The first two options are similar to those described in the previous section, now accompanied by the unpolarized fragmentation function $D_1$. The third option contains the Collins effect function $H_1^\perp$ [13], which is the fragmentation function analogue of $h_1^\perp$, but in principle is unrelated in magnitude. The last two options were investigated in [14, 15].

We note that the first two options also occur in jet production asymmetries: $p + p \uparrow \rightarrow \text{jet} + X$ (with only neutral current contributions for the first option). However, as Koike has pointed out, the first option is a double transverse spin asymmetry on the parton level and is thus expected to be small, like the example of Ref. [16] or the double transverse spin asymmetry in DY. It is therefore more likely to obtain information on $h_1^\perp$ from hadron production asymmetries in semi-inclusive DIS (SIDIS).

SEMI-INCLUSIVE DIS

First some comments on unpolarized asymmetries in SIDIS. The $\langle \cos 2\phi \rangle$ in SIDIS at values of $Q^2$ similar to those of the unpolarized DY data, has been measured by the EMC collaboration [17, 18]. No significant asymmetry was observed due to the large errors. But in the present picture of “T-odd” functions the $\langle \cos 2\phi \rangle$ in SIDIS would be $\propto h_1^\perp H_1^\perp$, which thus can be quite different in magnitude. A consistent picture should emerge by also comparing to $\langle \cos 2\phi \rangle \propto H_1^\perp H_1^\perp$ in $e^+ e^-$ annihilation (e.g. doable at BELLE). However, one should keep in mind that there is another source of a $\cos 2\phi$ asymmetry, namely one that stems from double gluon radiation in the hard scattering subprocess. Fortunately, this forms a calculable background which only dominates in the large $Q_T$ region (close to $Q$).

Another test would be to look at $\langle \cos 2\phi \rangle$ for a jet instead of a hadron: $e p \rightarrow e' \text{jet} X$. The contribution from $h_1^\perp$ will then be absent.

Apart from these unpolarized asymmetries, one can also consider polarized hadron production asymmetries in SIDIS, most notably polarized $\Lambda$ production. In that case the intrinsic handedness can lead to the following asymmetries:

- $\sin(\phi_{\Lambda}^p + \phi_{\Sigma_T}^p)$ and $\sin(3\phi_{\Lambda}^p - \phi_{\Sigma_T}^p)$ in $e p \rightarrow e' \Lambda^\uparrow X$ (transverse $\Lambda$ polarization)
- $\sin(2\phi_{\Lambda}^p)$ in $e p \rightarrow e' \bar{\Lambda} X$ (longitudinal $\Lambda$ polarization)

These particular angular dependences should be absent for charged current exchange processes, like $\nu p \rightarrow e \Lambda^\uparrow X$ or $\nu p \rightarrow e \bar{\Lambda} X$ [19].

These asymmetries are distinguishable from other mechanisms via the $y$ and $\phi^e$ dependences. For instance, the first asymmetry for transversely polarized $\Lambda$ production, can be distinguished from the asymmetry due to the so-called polarizing fragmentation func-
tions [20, 21] (also called the Sivers fragmentation function, although it is in principle unrelated in magnitude to the Sivers distribution function). Moreover, the asymmetries should vanish after integration over $Q_T$, leaving only possibly a $\sin(\phi^e_S T)$ asymmetry (which is a twist-3, and hence suppressed, asymmetry) [22, 23].

**CONCLUSIONS**

The chiral-odd, “T-odd” distribution function $h_{T}^{\perp}$ offers an explanation for the large unpolarized $\cos 2\phi$ asymmetry in the $\pi^- N \rightarrow \mu^+ \mu^- X$ data. Nonzero $h_{T}^{\perp}$ would relate unpolarized and polarized observables in a distinct way and thus in principle offers a new way to access $h_{1}$ in $p p \uparrow \rightarrow \mu^+ \mu^- X$.

There are several ways of differentiating $h_{1}^{\perp}$ dependent asymmetries from those due to other mechanisms and the suggestion of nonzero $h_{1}^{\perp}$ can be explored using a host of existing (Fermilab, BELLE) and near-future data (RHIC, COMPASS, HERMES).

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