Mapping the Transverse Nucleon Spin

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The transverse nucleon spin can be transferred to the quarks and gluons in several ways. In the factorizing, hard scattering processes to be considered, these are parameterized at leading twist by the transversity distribution function and at next-to-leading twist by quark-gluon correlation functions. The latter enter the description of the structure function $g_2$ and possibly of single spin asymmetries. It is discussed what is known about these functions and what are the remaining open issues.

1. Introduction

Large single transverse spin asymmetries have been observed experimentally in the process $pp^* \to \pi X$. However, the question of how the direction of the pions is correlated with the transverse spin direction of the nucleon has not been answered yet. Many theoretical studies have been devoted to the possible origin(s) of such asymmetries. One clean approach is to consider the process in a kinematical region where factorization applies and hence, where a description in terms of quark and gluon correlation functions is valid. What are the possibilities in such a description will be the main subject here.

A transverse spin state is an off-diagonal state in the helicity basis. For instance, consider a state of transverse polarization in the (conventional) $\pm \hat{x}$ direction:

$$
|\uparrow\rangle = \left[ |+\rangle + |-\rangle \right]/\sqrt{2},
|\downarrow\rangle = \left[ |+\rangle - |-\rangle \right]/\sqrt{2}
$$

Clearly the r.h.s. is a helicity-flip density matrix element. In factorized hard scattering processes one encounters helicity dependent amplitudes $\Phi = (H, h; H', h')$ (Fig. 1a), where $H, H'$ are nucleon and $h, h'$ are quark helicity labels. In this notation the matrix element $h_1 \equiv (+, +; -, -)$ (called transversity) signals helicity flip. The transversity distribution function $h_1$ (also commonly denoted by $\delta q$) is a measure of how much of the transverse spin of a polarized nucleon is transferred to its quarks. In other words, it is the density of transversely polarized quarks inside a transversely polarized nucleon and is a function of the lightcone momentum fraction $x$ of a quark inside the nucleon.

There is no diagram Fig. 1a for gluons, at least at leading order where the gluons carry $\pm 1$ helicity. Gluons play a subleading role (either $h$ or $h'$ should be helicity 0), i.e. they enter the cross section suppressed by one or more powers of the hard scale. Therefore the transversity distribution does not mix with a gluon distribution function. Under

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evolution, gluons which are radiated off only carry away momentum, but do not affect transverse quark spin (perturbatively gluons couple in a helicity conserving way).

Although gluons play a subleading role, they may be crucial for the single spin asymmetries mentioned above. At subleading order one has two types of gluon dependent matrix elements that play a role: the aforementioned two-gluon correlation function and a quark-gluon-quark correlation. These two matrix elements will in fact mix under evolution and here we will focus attention only on the latter. In Fig. 1b its helicity structure is shown and compared to the transversity function. In the quark-gluon correlation matrix elements, \( g_T \) and \( T(x, S_T) \), the gluon balances the helicity flip of the nucleon state, such that there is no helicity flip required of the quark states. The difference between \( g_T \) and \( T(x, S_T) \) is that in the latter matrix element the gluon has zero momentum fraction, which occurs only in the description of single spin asymmetries.

2. Transversity

As said the transversity distribution function is a helicity flip (so-called chiral-odd) amplitude. Observables involving transversity should therefore be (helicity flip)\(^2\). This is the reason why \( h_1 \) cannot be measured in inclusive Deep Inelastic Scattering (DIS) \( ep \rightarrow e' X \); it enters the cross section suppressed by a factor of order \( m_q/Q \), where \( m_q \) is the mass of the struck quark and \( Q \) is the invariant mass of the virtual photon that probes the nucleon, for which we take a proton from now on. A further complication is that in charged current exchange processes chiral-odd functions like \( h_1 \) cannot be accessed.

To measure transversity there are essentially two options: single or double transverse spin asymmetries in (semi-inclusive, neutral current) \( ep \) and \( pp \) processes. Few such experiments have been performed to date and no (undisputed) experimental information on \( h_1 \) is available thus far. But a number of future experiments (e.g. COMPASS, HERMES, RHIC) are expected to provide detailed information.

2.1. Transversity asymmetries

The Drell-Yan process of two colliding transversely polarized hadrons producing a lepton pair was originally thought to be the best way to access the transversity distribution, for instance at RHIC. This double transverse spin asymmetry \( A_{TT}^{DY} \) is proportional to \( h_1^q(x_1) \overline{T}_1^q(x_2) \). The problem is that \( h_1 \) for antiquarks inside a proton (\( h_1^q = \overline{T}_1^q \)) is presumably much smaller than for quarks and the asymmetry is not expected to be large.
In fact, by using Soffer's inequality ($|h_1(x)| \leq \frac{1}{2} [f_1(x) + g_1(x)]$), $A_{LT}^{DY}$ has been shown [3] to be small at RHIC, probably just beyond the experimental reach (but a future luminosity upgrade will be very promising).

Also the double transverse spin asymmetry in jet production [4] (directly proportional to $h_1(x_1) h_1^\ast(x_2)$ at high $p_T$) poses experimental problems due to small cross sections and asymmetries. In Ref. [5] it is demonstrated that for RHIC statistics is not the problem, but that the systematic errors need to be under extremely good control.

Another possible way to access the transversity distribution function via a double transverse spin asymmetry, involves the transversity fragmentation function $H_1$. It measures the probability of $q^+ \rightarrow h^+ + X$, where $h$ is a spin-1/2 hadron, for instance a $\Lambda$ hyperon. The double transverse spin asymmetry $D_{NN}$–the transverse polarization transfer–involving both $h_1$ and $H_1$, occurs in the processes $e^+ p^+ \rightarrow e' \Lambda^+ X$ and $p^+ p^+ \rightarrow \Lambda^+ X$ [6]. The latter observable has been measured by E704 [7] and found to be sizable, but a conclusion about $h_1$ cannot be drawn due to the low $p_T$ range, which prohibits the use of a factorized expression for the cross section. Furthermore, $H_1$ is also unknown and although it could be extracted from $e^+ e^- \rightarrow \Lambda^+ \Lambda^+ X$ via $H_1$ and $h_1$, this also poses quite a challenge.

In short, double transverse spin asymmetries do not seem promising for extracting the transversity distribution in the near future. This leaves the single spin asymmetry (SSA) options, which all exploit fragmentation functions of some sort. Three options have been considered: 1) measuring the transverse momentum of the final state hadron compared to the jet axis, exploiting the so-called Collins effect; 2) producing final state hadrons with higher spin, e.g. $\rho$ or its decay product: a $\pi^+\pi^-$ pair (related to the interference fragmentation functions); 3) higher twist asymmetries which are suppressed by inverse powers of the hard scale $Q$. The third option will not be discussed here.

3. Collins effect asymmetries

The Collins effect refers to a nonzero correlation between the transverse spin $s_T$ of a fragmenting quark and the distribution of produced hadrons. More specifically, the transversely polarized quark fragments into particles (with nonzero transverse momentum $k_T$) distributed with a $k_T \times s_T$ angular dependence around the jet axis or, equivalently, the quark momentum, see Fig. 1 of Ref. [8]. The Collins effect will be denoted by a fragmentation function $H_1^1(z,k_T)$ and if nonzero, it can lead to SSA in $e^+ p^+ \rightarrow e' \pi X$ and $p^+ p^+ \rightarrow \pi X$. There is some experimental hint in the SMC data [9] (at the 2σ level) that the Collins effect (and hence transversity) is indeed nonzero. Also, HERMES pion asymmetry ($A_{UL}$) data [10] and the left-right asymmetries in $p^+ p^+ \rightarrow \pi X$ [11] can (at least partially) be described in terms of the Collins effect (see e.g. [11,12]). No consensus about the interpretation of these data has been reached though. Another open question is how the Collins effect works precisely, i.e. how the transverse spin of quarks is transformed into orbital angular momentum during the (nonperturbative) fragmentation process. In any case, a correlation between the transverse spin of the fragmenting quark and the transverse momentum of a hadron in the jet is allowed by the symmetries.

3.1. Collins effect in semi-inclusive DIS

Collins considered [13] semi-inclusive DIS (SIDIS) $e^+ p^+ \rightarrow e' \pi X$, where the spin of the proton is orthogonal to the direction of the virtual photon $\gamma^*$. and one observes the pion...
transverse momentum $P_{\perp}^\pi$, which has an angle $\phi_\pi^e$ compared to the lepton scattering plane. He showed that the cross section for this process can have an asymmetry that is proportional to the transversity function: $A_T \propto \sin(\phi_\pi^e + \phi_s^e) \left| S_T \right| h_1 H_1^\perp$. Since the functions $h_1$ and $H_1^\perp$ are chiral-odd and the asymmetry on the parton level is $\hat{a}_{T T}$, this asymmetry depends on the orientation of the lepton scattering plane, i.e. if one integrates over the direction of the back-scattered electron $e'$, then the asymmetry would vanish.

To discuss this SSA further, we will focus on the observable (cf. Refs. [14,8,15])

$$O \equiv \left\langle \frac{\sin(\phi_C) |P_{\perp}^1|}{4\pi \alpha^2_s/Q^2} \right\rangle M_\pi = \left| S_T \right| (1-y) \sum_{a,\bar{a}} e_a^2 x h_{1T}^a(x) z H_{1T}^a(z),$$

where $\phi_C = \phi_\pi^e + \phi_s^e$ and $H_{1T}^a(z) = \int d^2k_T k_T^2 H_{1T}(z, k_T^2)/(2z^2 M_\pi^2)$. At present all phenomenological studies of the Collins effect are performed using tree level expressions like Eq. (2). But the leading order (LO) evolution equations are known for both $h_1$ (NLO even) and $H_{1T}^a$ (at least in the large $N_c$ limit [14]). The LO $Q^2$ behavior of the observable $O$ arises solely from the LO evolution of $h_1$ and $H_{1T}^a$. This is however a nontrivial result, since this semi-inclusive process is not a case where collinear factorization applies. In the differential cross section $d\sigma/d^2P_{\perp}$ itself, beyond tree level soft gluon corrections do not cancel, such that Sudakov factors need to be taken into account and a more complicated factorization theorem applies [17,19]. In fact, the observable $O$ (Eq. (4)) is the only $|P_{\perp}^1|$-moment of the Collins asymmetry in the cross section, that is not sensitive to Sudakov factors. This observable is therefore better suited for a $Q^2$ dependent analysis than the full $|P_{\perp}^1|$-dependent asymmetry.

Another point to note here is that the Collins effect asymmetry is not power suppressed. Since it is not down by $1/Q$, it is sometimes referred to as leading twist, but strictly speaking the Collins function is not related to local operators of twist-2 exclusively (rather one is using Jaffe’s “working redefinition of twist” [19] to indicate the leading power in $1/Q$ at which the contribution appears in the cross section). The reason why the asymmetry is not suppressed by $1/Q$ is that one is dealing with a multi-scale process: the hadronic scale $M_\pi$, the transverse momentum $|P_{\perp}^\pi|$ of the pion compared to the virtual photon (which itself is in the lepton scattering plane) and the hard scale $Q$. The Collins effect is a term $k_T P_{\perp}^\pi H_{1T}(z, k_T^2)/M_\pi^2$ in the fragmentation correlation function $\Delta(z, k_T)$ [20], which indicates that the explicit factor of $k_T$ is not suppressed by an inverse power of the hard scale $Q$, but rather is compensated by a hadronic scale ($M_\pi$ by definition).

The evolution of $H_{1T}^a$ is quite involved since it is not of definite twist. One must perform a full twist-3 evolution calculation [20]. Luckily, in the large $N_c$ limit the evolution simplifies (it becomes DGLAP-like [10]) and should be sufficient for initial comparisons of data which are obtained at different energies.

The effect of Sudakov factors is to decrease the magnitude of the asymmetry and to broaden it as a function of transverse momentum. This decrease can be quite substantial at high energies, estimated to be roughly $1/\sqrt{Q}$ per Collins function when compared to tree level [12]. As said, to avoid such Sudakov suppression one can consider the particular moment in Eq. (2). But one does need to keep in mind that the average transverse momentum of the pion, $\langle |P_{\perp}^\pi| \rangle$, is a function of $Q$, governed by Sudakov factors.
3.2. Collins effect in $e^+ e^- \rightarrow \pi^+ \pi^- X$

In order to obtain the Collins function itself, one can measure a $\cos(2\phi)$ asymmetry in $e^+ e^- \rightarrow \pi^+ \pi^- X$, that has a contribution which is proportional to the Collins function squared [22] (at equal momentum fractions). A first indication of such a nonzero (but small) asymmetry comes from a preliminary analysis [23] of the LEP1 data (DELPHI). A similar study of off-resonance data from the B-factory BELLE at KEK, is under way [24].

Also for this Collins effect observable the tree level asymmetry expression is not sufficient when results from different experiments are to be compared. Beyond tree level Sudakov factors need to be included. Since the Collins function enters twice in this asymmetry the suppression is estimated to be of the order $1/Q_T^2 = 1/\sqrt{s}$ [18], which may well be the reason the DELPHI data indicated a small asymmetry. Therefore, this Collins effect observable is best studied with two jet events at lower $\sqrt{s}$ (a requirement satisfied by BELLE, which operates on and just below the $\Upsilon(4S)$, i.e. around 10.5 GeV).

Nevertheless, the extraction of the Collins function from this asymmetry is not straightforward, since there is asymmetric background from hard gluon radiation (when $Q_T \sim Q$) and from weak decays. The former enters the $Q_T$ dependent asymmetry proportional to $\alpha_s Q_T^2/Q^2$, which at lower values of $Q^2$ need not be small. This contribution could be neglected at LEP energies [22]. Luckily it is calculable and so is the background from weak decays, e.g. $e^+ e^- \rightarrow \pi^+ \pi^- \rightarrow \pi^+ \pi^- X$.

As in the case of the Collins asymmetry in SIDIS, there is one particular $Q_T$ moment of the asymmetry that is not sensitive to Sudakov factors, namely the first $Q_T^2$ moment:

$$\int dQ_T^2 Q_T^2 \rho / dQ_T^2.$$

Unfortunately, it is mostly sensitive to the high $Q_T^2 (\sim Q^2)$ hard gluon radiation. This contribution could in principle be cut off by imposing a maximum $Q_T$ cut, but this introduces a further source of uncertainty. It may therefore be better to calculate its contribution using the known ordinary fragmentation functions $D_1^\pi$.

The main conclusion we can draw about this kind of Collins effect asymmetries is that they are not like ordinary leading twist asymmetries and special care must be taken beyond tree level regarding Sudakov factors.

4. Interference fragmentation functions

Apart from the Collins effect, there may be a correlation between the transverse spin of the fragmenting quark and the orientation of a $\pi^+ \pi^-$ pair inside the jet [25 27], which can also be parameterized by a chiral odd function. Concretely, Jaffe, Jin and Tang [27] considered the two pion final state $|\pi^+ \pi^-\rangle \langle \pi^+ \pi^-|$ and assumed a dependence on the strong phase shifts of the $\pi^+ \pi^-$ system. The interference between different partial waves then gives rise to a nonzero chiral-odd fragmentation function, called the interference fragmentation function (IFF). The IFF would lead to single spin asymmetries in $e p^\uparrow \rightarrow e' (\pi^+ \pi^-) X$ and $p p^\uparrow \rightarrow (\pi^+ \pi^-) X$, both proportional to $h_1$. The SSA expression in terms of the IFF $\delta \hat{q}_I(z)$ is [27]

$$\langle \sin(\phi_{ST} + \phi_{R_T}) \rangle \propto F |S_T||R_T|h_1(x)\delta \hat{q}_I(z),$$

(3)

In Refs. [8,15] the asymmetry Eq. (3) was erroneously written as $\cos(\phi_{ST} + \phi_{R_T})$. 
where \( z = z^+ + z^- \); \( \mathbf{R}_T = (z^+ \mathbf{k}_- - z^- \mathbf{k}_+) / z \); \( F = F(m^2) = \sin \delta_0 \sin \delta_1 \sin(\delta_0 - \delta_1) \), where \( \delta_0, \delta_1 \) are the \( \ell = 0, 1 \) phase shifts and \( m^2 \) is the \( \pi^+\pi^- \) invariant mass. Note again the dependence on the orientation of the lepton scattering plane. Also note the implicit assumption of factorization of \( z \) and \( m^2 \) dependences, which leads to the prediction that on the \( \rho \) resonance the asymmetry is zero (according to the experimentally determined phase shifts). More general \( z, m^2 \) dependences have been considered \([28]\).

Unlike the Collins effect asymmetries, Eq. (3) is based on a collinear factorization theorem (soft gluon contributions cancel, no Sudakov factors appear). This makes an analysis beyond tree level conceptually straightforward. The evolution of \( \delta q_T(z) \) equals that of \( H_1(z) \) (known to NLO \([29]\)) and a NLO analysis is feasible (cf. also Ref. \([30]\)).

For the extraction of the interference fragmentation functions themselves one can study a \( \cos(\phi_{R_{1T}} + \phi_{R_{2T}}) \) asymmetry \([31]\) in \( e^+ e^- \rightarrow (\pi^+ \pi^-)_{\text{jet}1} (\pi^+ \pi^-)_{\text{jet}2} X \) which is proportional to \( (\delta q_T)^2 \). This is again possible at BELLE and this time there is no expected asymmetric background. Combining such a result with for instance the single spin asymmetry in \( pp \rightarrow \pi^+ \pi^- X \) to be measured at RHIC or in \( ep \rightarrow e' \pi^+ \pi^- X \) at COMPASS or HERMES, seems at present to be one of the most realistic ways of obtaining information on the transversity function. However, one does need to have an accurate measurement of the ordinary fragmentation function of a quark into a \( \pi^+ \pi^- \) pair, \( D_{1T}^{\pi^+ \pi^-} \).

5. Quark-gluon correlations

Gluons play a subleading role in the transverse spin of the nucleon, but their effects may be observable nevertheless. But so far not more than a hint comes from the measurement of the structure function \( g_2 \). At tree level the structure function \( g_2(x_B, Q^2) \) is expressed in terms of parton distribution functions as \( g_2(x_B, Q^2) = \sum_{a,\bar{a}} e_a^2 (g_T^a(x_B) - \hat{g}_T^a(x_B)) / 2 \), where \( g_T \) is not a density however. It enters in a power suppressed azimuthal spin asymmetry in the cross section of polarized DIS

\[
\frac{d\sigma(\ell H^+ \rightarrow \ell' X)}{dx_B \, dy} \propto \left\{ \left( \frac{\hat{x}^2}{1-y} \right) x_B f_1^a(x_B) - 2y \sqrt{1-y} \lambda_e |S_T| \cos(\phi_s) \frac{M}{Q} x_B^2 g_T^a(x_B) \right\}.
\]

(4)

The E155 Collaboration at SLAC has successfully measured \( g_2 \) \([32]\). Within errors it is still consistent with the Wandzura-Wilczek part, which is determined by the twist-2 function \( g_1 \). The SLAC data results in \( d_2 = 3 \int_0^1 x^2 g_2(x) |_{\text{twist-3}} dx = 0.0032 \pm 0.0017 \), which is barely \( 2\sigma \) away from zero. A future demonstration of a nonzero \( g_2(x) |_{\text{twist-3}} \) would unambiguously show the role of gluons in the transverse nucleon spin.

The azimuthal angular dependence \( \cos(\phi_s) \) (the angle \( \phi_s \) is between the transverse spin and the lepton scattering plane) in Eq. (3) is the only possible one in fully inclusive DIS \( \ell H^+ \rightarrow \ell' X \). Christ and Lee \([33]\) have shown that a \( \sin(\phi_s) \) dependence would violate time reversal invariance. Since parity forces such a \( \sin(\phi_s) \) asymmetry to be independent of the lepton polarization, one would be dealing with a SSA in fully inclusive polarized DIS. In general, to generate a SSA one needs to have an imaginary part. For instance, a complex-valued (but hermitian) quark-gluon correlation function, parameterized by \( g_T \) and \( f_T \) (called a T-odd distribution function), yields in the cross section a power-suppressed...
\[
\sin(\phi_s) \text{ single transverse spin asymmetry:} \\
\frac{d\sigma(\ell H^+ \rightarrow \ell' X)}{dx_B dy} \propto \left\{ \left( x_B^2 + 1 - y \right) x_B f^a_1(x_B) - 2y\sqrt{1-y} |S_T| \sin(\phi_s) \frac{M}{Q} x_B^2 f^a_T(x_B) \right\}.
\]

As said this would violate time reversal invariance. So far the absence of such an asymmetry has only been confirmed with percent level precision in experiments performed more than 30 years ago \[34\].

To formulate it more precisely, T-odd distribution functions are absent due to time reversal invariance, if the incoming hadron is treated as a plane-wave state \[13\]. This is related to the stable nature of the incoming hadron (stable on strong interaction time scales, since the incoming hadron might be a neutron) and the absence of imaginary parts in its correlation functions.

However, a formal loophole has been pointed out by Anselmino et al. \[35\]. In addition, there may be other ways of generating an imaginary part if the process is not fully inclusive. This is the case for the Efremov-Teryaev and Qiu-Sterman single spin asymmetries \[36,37\]. Qiu and Sterman considered SSA in pion and prompt photon production arising from a so-called soft gluon (or gluonic) pole mechanism. Hammon et al. \[38\] applied this to the Drell-Yan (DY) process. Here the contribution to the SSA comes from a gluon with vanishing lightcone momentum fraction, such that the \( i\epsilon \) part of a fermion propagator is picked up. It yields an effective \( f_T \) function, which means that the effects of the gluonic pole are indistinguishable from those of an \( f_T \) \[39\]. The only reason that one cannot view it as being equivalent to a T-odd distribution function is that the gluonic pole does not contribute to fully inclusive DIS (which is the only exception).

The Qiu-Sterman matrix element \( T(x, S_T) \) has the following operator structure

\[
T(x, S_T) \propto \langle \bar{\psi}(0) \Gamma_\alpha \int d\eta F^+\alpha(\eta n_\perp) \psi(\lambda n_\perp) \rangle.
\]

The lightcone integral over the field strength reflects the fact that the gluon has vanishing lightcone momentum fraction. Since this quantity is like an average gluon field strength inside the ordinary unpolarized quark distribution function, as a first guess one sometimes uses the simplifying Ansatz (due to Qiu and Sterman): \( T^a(x, S_T) \approx \kappa_a \lambda f^a_1(x) \), with \( \kappa_u = 1 = -\kappa_d \), \( \kappa_s = 0 \). Using the parameter value \( \lambda \sim 100 \text{ MeV} \) obtained from a fit to the pion production SSA, the SSA in DY then becomes \( |A_N| \sim 0.7 \lambda/Q \) \[40\]. Hence, just below and above the \( J/\psi \) the asymmetry is of the order of a few percent. This prediction is very different from for instance the one by Boros et al. \[41\], which ranges well above 20%. RHIC experiments should be able to test these predictions in the coming years. In addition, the Collins effect cannot contribute to the SSA in DY, making the latter observable an even more useful tool to distinguish between different mechanisms.

As a final topic, we now look at the almost inclusive DIS process \( e p^\uparrow \rightarrow e' \text{ jet } X \), where one observes the transverse momentum \( P_{\text{jet}}^\perp \) of the jet. Also here the Collins effect (and hence transversity) cannot contribute to a SSA.

Consider the cross section of an unpolarized electron scattering off a transversely polarized hadron, weighted by a function of the transverse momentum of the jet:

\[
\langle W \rangle_{UT} \equiv \int dz \ d^2 P_{\perp}^\text{jet} W \ \frac{d\sigma[e p^\uparrow \rightarrow e' \text{ jet } X]}{dx dy dz d\phi e d\phi_{\text{jet}}|P_{\perp}^\text{jet}|^2}.
\]

I thank A. Drago for pointing out these references.
where \( W = W( |P_\perp^{\text{jet}} |, \phi_e^{\text{jet}}) \), but again restricted to the case \( |P_\perp^{\text{jet}} |^2 \ll Q^2 \).

For \( W = 1 \) one would retrieve the \( 1/Q \) suppressed asymmetry proportional to \( f_T \) [14]:

\[
\langle 1 \rangle_{UT}^{\text{jet}} = -\sin \phi_S |S_T| (2-y) \sqrt{1-y} \frac{M}{Q} \sum_{a,\bar{a}} e_a^2 x^2 f_T^1(x) \ T^{\text{rev}}. \ 0,
\]

forced to be zero by time reversal invariance. As mentioned, the gluonic pole mechanism does not generate it either. However, if one weights with a power of the observed transverse momentum one obtains for instance the following unsuppressed expression (take simply \( D_1(z) = \delta(1-z) \) in the expression given in [14])

\[
\langle \cos \phi_e^{\text{jet}} |P_\perp^{\text{jet}} |/M \rangle_{UT}^{\text{jet}} = -\sin \phi_S |S_T| (1-y+y^2/2) \sum_{a,\bar{a}} e_a^2 x^2 f_T^{1\perp}(x).
\]

This asymmetry depends on the T-odd Sivers function \( f_T^{1\perp}(x, p_{T}^2) \) [12] via

\[
f_T^{1\perp}(x) \equiv \int d^2 p_T \frac{p_T^2}{2M^2} f_T^{1\perp}(x, p_T^2).
\]

There has been much discussion in the literature whether the T-odd distribution function \( f_T^{1\perp} \) is allowed to be nonzero or not. Collins has given a proof that it should be zero [13], but recently he pointed out a loophole [13]. Also, Brodsky, Hwang and Schmidt [14] have shown by an explicit model calculation that there can indeed be a nonzero (and unsuppressed) asymmetry in the process \( eP^1 \rightarrow e'\pi X \). It arises from a gluon having zero lightconee momentum fraction (but nonzero transverse momentum), such that the \( i\epsilon \) from a fermion propagator is picked up, generating the imaginary part required for a SSA. It seems to produce a nonzero Sivers effect and thus is expected to yield an effective \( f_T^{1\perp} \) in the same way as \( T(x, S_T) \) generates an effective \( f_T \). It also leads to a SSA in \( eP^1 \rightarrow e'\pi X \), which is distinguishable from the Collins effect: the latter has a dependence \( (1-y) \sin(\phi_e^{\pi} + \phi_S^{\perp}) \), whereas the former \( (1-y+y^2/2) \sin(\phi_e^{\pi} - \phi_S^{\perp}) \). This is understandable, since the Sivers effect asymmetry has unpolarized quarks in the elementary cross section and therefore, does not depend on the lepton scattering plane and also its \( y \) dependence is characteristic of unpolarized scattering. Thus, recent investigations [13][14] seem to revive the Sivers effect as a possible origin of single transverse spin asymmetries, showing once more that the transverse spin of the nucleon harbors highly nontrivial physics involving the angular momentum of both quarks and gluons.

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