Origins of single transverse spin asymmetries

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Single transverse spin asymmetries in \(p p \rightarrow \pi X\) and \(\ell p \rightarrow \ell \pi X\) processes have been observed; their possible origins and connections are investigated. A phenomenological description within a pQCD generalized factorization scheme is discussed.

1. Introduction and data

Several spin asymmetries in processes involving only one transversely polarized hadron have been observed experimentally; these, when occurring in a kinematical region where pQCD should be applicable, pose a severe challenge to a correct phenomenological description, as single spin asymmetries are negligible in the elementary interactions, due to chirality conservation of QCD and QED dynamics. Single transverse spin asymmetries are related to helicity flip amplitudes and to relative phases, both of which are absent in the perturbative, leading order interactions of quarks, gluons and photons.

Single transverse spin asymmetries are then sensitive to higher twist contributions, or non perturbative effects in the long distance physics, and are expected to vanish in the truly asymptotic, high energy, large \(Q^2\) (or \(p_T\)) regions, where leading twist and parton collinear configurations dominate in the QCD factorization scheme. Most data are not from that region yet, and the investigation of single spin effects, both in experiments and theories, is bound to be rich of unexpected and new results.

We discuss here two kinds of single spin asymmetries, occurring in \(p p \rightarrow \pi X\) and \(\ell p \rightarrow \ell \pi X\) processes with a polarized initial proton; the cross-sections depend on the proton spin orientation, whether \(\uparrow\) or \(\downarrow\) with respect to the production plane, giving origin to an asymmetry,

\[
A_N \equiv \frac{d\sigma^\uparrow - d\sigma^\downarrow}{d\sigma^\uparrow + d\sigma^\downarrow}.
\] (1)

Large values of \(A_N\) for the first process have been measured already several years ago \([1]\); more recently also \(A_N\) for the semi-inclusive DIS process has been found to be different from zero \([2,3]\).

The two asymmetries are interesting in many respects: they might have a common origin – the so called Collins quark fragmentation function \([4]\) – and are going to be measured again very soon, respectively at RHIC and by HERMES collaboration, with an upgraded transversely polarized proton target. It is then appropriate to have a discussion about the possible origins of \(A_N\) and to develop a phenomenological approach towards their description and prediction.

Among the attempted explanations of \(A_N\) observed in E704 experiment there are generalizations of the QCD factorization theorem with the inclusion of higher twist correlation functions \([5–7]\), or with the inclusion of intrinsic \(k_\perp\) and spin dependences in distribution \([3,11]\) and fragmentation \([10]\) functions; there are also some semi-classical approaches based on introduction of quark orbital angular momentum \([13,14]\). A review paper on the subject can be found in Ref. \([15]\). We consider here only the approaches which are based on QCD dynamics, through a generalization of the factorization scheme, accord-
ing to which, at leading twist and with collinear configurations, the cross-section for the process 
\[ pp \rightarrow \pi X \] can be written as the usual convolution,
\[ d\sigma = \sum_{a,b,c} f_{a/p} \otimes f_{b/p} \otimes d\hat{\sigma}^{ab\rightarrow c \ldots} \otimes D_{\pi/c}, \]
in terms of distribution and fragmentation functions and pQCD partonic interactions. This simple approach, however, predicts negligible single spin asymmetries and higher order contributions have to be taken into account.

2. Higher twist parton correlations

In the approach of Ref.\[6\] Eq. (2) is generalized – and proven to hold – with the introduction of higher twist contributions to distribution or fragmentation functions. Schematically it reads:
\[ d\sigma^\uparrow - d\sigma^\downarrow = \sum_{a,b,c} \left\{ \Phi^{(3)}_{a/p} \otimes f_{b/p} \otimes \hat{H} \otimes D_{\pi/c} \right\} \]
\[ + h_1^{a/p} \otimes \Phi^{(3)}_{b/p} \otimes \hat{H}' \otimes D_{\pi/c} \]
\[ + h_1^{a/p} \otimes f_{b/p} \otimes \hat{H}'' \otimes D_{\pi/c}^{(3)} \],
where the \( \Phi^{(3)} \)'s, \( D^{(3)} \)'s, are the higher twist correlations and the \( \hat{H} \)'s denote the elementary interactions. \( h_1 \) is the transversity distribution.

The higher twist contributions are unknown, but some simple models can be introduced, for example
\[ \Phi^{(3)}_{a/p} \sim \int \frac{dy^-}{4\pi} e^{i\phi} y^- (p, s_T) |\bar{\psi}_a(0)\rangle^+ \times \left[ \int dy^+ \epsilon_{\rho\sigma\alpha\beta} s_T^\rho p^\sigma p'^\beta F^{\sigma\tau}(y^2) \right] \psi_a(y^-) |p, s_T\rangle \]
\[ = k_a C \ f_{a/p}. \]

The above contribution depends on the initial nucleon momenta \( p \) and \( p' \), on the transverse proton spin \( s_T \) and on some external gluonic field \( F^{\mu\nu} \); it involves transverse degrees of freedom of the partons and it differs from the usual definition of the distribution functions \( f_{a/p} \) only by the insertion of the term in squared brackets. This is the reason for the last line of Eq. (4), where \( C \) is a dimensional parameter and \( k_a \) is respectively +1 and −1 for \( u \) and \( d \) quarks.

Such a simple model can reproduce the main features of the data \[6\] and some predictions for RHIC energy can be attempted \[6\].

3. Intrinsic \( k_\perp \) in QCD factorization

A somewhat analogous approach has been discussed in Refs. \[8,9,11,12\]; again, one starts from the leading twist, collinear configuration scheme of Eq. (2), and generalizes it with the inclusion of intrinsic transverse motion of partons in distribution functions and hadrons in fragmentation processes.

The introduction of \( k_\perp \) and spin dependences opens up the way to many possible spin effects; these can be summarized by the new functions:
\[ \Delta_{q/p}^{N} \equiv \hat{f}_{q/p}^{N}(x, k_\perp) - \hat{f}_{q/p}^{N}(x, -k_\perp) \]
\[ \Delta_{q/p}^{N} \equiv \hat{f}_{q/p}^{N}(x, k_\perp) - \hat{f}_{q/p}^{N}(x, -k_\perp) \]
\[ \Delta_{q/p}^{N} \equiv \hat{D}_{h/q}^{N}(z, k_\perp) - \hat{D}_{h/q}^{N}(z, -k_\perp) \]
\[ \Delta_{q/p}^{N} \equiv \hat{D}_{h/q}^{N}(z, k_\perp) - \hat{D}_{h/q}^{N}(z, -k_\perp) \],
which have a clear meaning if one pays attention to the arrows denoting the polarized particles. Details can be found, for example, in Ref. \[17\]. All the above functions vanish when \( k_\perp = 0 \) and are naïvely T-odd. The ones in Eqs. (5) and (6) are chiral-odd, while the other two are chiral-even.

Similar functions have been introduced in the literature with different notations; in particular there is a direct correspondence between the above functions and the ones denoted, respectively, by: \( f_{1T}^{u}\), \( h_{1T}^{u}\), \( H_{1T}^{u}\), \( D_{1T}^{1}\), \( 2\), \( 3\), \( 5\), \( 9\). The function in Eq. (5) is the Collins function \( \Phi \), while that in Eq. (6) was first introduced by Sivers \( \Phi \). By inserting the new functions into Eq. (3), and keeping only leading terms in \( k_\perp \), one obtains:
\[ d\sigma^\uparrow - d\sigma^\downarrow = \sum_{a,b,c} \]
\[
\left\{ \Delta^N f_{a/p} (k_\perp) \otimes f_{b/p} \otimes \Delta \bar{\sigma}(k_\perp) \otimes D_{\pi/f} \right. \\
+ h_{1}^N \otimes f_{b/p} \otimes \Delta \bar{\sigma}(k_\perp) \otimes \Delta D_{\pi/f} (k_\perp) \\
+ h_{1}^N \otimes \Delta^N f_{b/p} (k_\perp) \otimes \Delta \bar{\sigma}(k_\perp) \otimes D_{\pi/f} (z),
\]

where the convolution now involves also a \( k_\perp \) integration (we have explicitly shown the \( k_\perp \) dependences). The \( \Delta \bar{\sigma} \)'s denote polarized elementary interactions, computable in pQCD. Notice that in the physical quantity above only products of even numbers of chiral-odd functions appear.

The above expression has been used to successfully fit the E704 data, either with the Sivers effect only \( 3 \) (second line of Eq. \( 3 \)) or the Collins effect only \( 2,13 \) (third line). Some words of caution are necessary concerning the Sivers function \( \Delta^N f_{q/p} \), which is proportional to off-diagonal (in helicity basis) expectation values of quark operators between proton states \( 3 \):

\[
\Delta^N f_{a/p} (p_\perp) \sim \langle p + | u \gamma^+ | p - \rangle.
\]

By exploiting the usual QCD parity and time-reversal properties for free states one can prove the above quantity to be zero \( 3 \). This might eliminate the Sivers function from the possible phenomenological explanations of single spin asymmetries. However, Sivers effect might be rescued by initial state interactions, or by a new and subtle interpretation of time reversal properties, discussed in the talk by A. Drago \( 20 \).

4. Fragmentation of polarized quarks

The Collins function, Eq. \( 6 \), can explain the E704 data on \( pp \to \pi X \) single spin asymmetry \( 12,13 \); are there other ways of accessing it, in order to get independent estimates of its size?

The answer to this question brings us to the azimuthal asymmetry observed by HERMES and SMC collaborations in semi-inclusive DIS \( 23 \), \( \ell p \to \ell \pi X \). Such asymmetries are directly related to the Collins function. In fact Eq. \( 6 \) can be rewritten as:

\[
D_{h/q^\perp} (z, k_\perp) = \hat{D}_{h/q^\perp} (z, k_\perp) \\
+ \frac{1}{2} \Delta^N D_{h/q^\perp} (z, k_\perp) \frac{P_q \cdot (P_q \times k_\perp)}{|P_q \times k_\perp|},
\]

for a quark with momentum \( P_q \) and a transverse polarization vector \( P_q \cdot P_q = 0 \) which fragments into a hadron with momentum \( P_h = zP_q + k_\perp (P_q \cdot k_\perp = 0) \). \( \hat{D}_{h/q^\perp} (z, k_\perp) \) is the unpolarized, \( k_\perp \) dependent, fragmentation function. Parity invariance demands that the only component of the polarization vector which contributes to the spin dependent part of \( D \) is that perpendicular to the \( q - h \) plane; in general one has:

\[
P_q \cdot \frac{P_q \times k_\perp}{|P_q \times k_\perp|} = P_q \sin \Phi_C,
\]

where \( P_q = | P_q | \) and \( \Phi_C \) is the Collins angle. When \( P_q = 1 \) and \( P_q \) is perpendicular to the \( q - h \) plane \( (P_q = \uparrow, -P_q = \downarrow) \) one has \( P_q \sin \Phi_C = 1 \).

Eq. \( 11 \) then implies the existence of a quark analysing power:

\[
A_q^h \equiv \frac{\hat{D}_{h/q^\perp} - \hat{D}_{h/q^\perp}}{\hat{D}_{h/q^\perp} + \hat{D}_{h/q^\perp}} = \frac{\Delta^N D_{h/q^\perp}}{2 \hat{D}_{h/q}}.
\]

The question about the possible size of \( A_q^\pi \), as derived from the experimental data, has been addressed in Ref. \( 21 \).

The asymmetry \( A_N \), Eq. \( 4 \), for the \( \ell p \to \ell \pi X \) process, is given, at leading twist, by:

\[
A_N^{\pi^\pm} = \frac{\frac{4h_{1}^{N/p}}{4f_{a/p} + f_{d/p}} A_q^{\pi^\pm}}{4(1 - y)} \sin \Phi_C
\]

in terms of the usual DIS variables. Similar expressions hold for \( \pi^- \) and \( \pi^0 \). Notice that \( A_N^{\pi^\pm} \) depends on the product of the Collins function and the transversity distribution (as required by chirality conservation): each of them depends on different variables \( (z \ for A_q^{\pi^+} \ and \ x \ for h_{1}^\pi) \) and, in principle, accurate measurements could provide access to both functions.

Eq. \( 4 \) should be compared with data in kinematical regions such that leading twist contributions are dominant; this is not the case for HERMES experiment, as they have protons with a longitudinal (with respect to the lepton direction) polarization, whose transverse (with respect to \( \gamma^\ast \) direction) component is depressed by a \( 1/Q \) factor, making it effectively a higher twist contribution. The situation is better with SMC data, obtained with transversely polarized protons, although their results are still preliminary (and
very likely will remain such); anyway, they have

\[ A_{\pi} \simeq -(0.10 \pm 0.06) \sin \Phi \, . \tag{15} \]

By comparing Eqs. (14) and (15), and assuming for the unknown transversity distribution \( h_1^{u/p} \) its upper value, given by saturation of the Soffer bound [22],

\[ |A_{\pi}^{u} = A_{\pi}^{-} = A_{\pi}^{+} = A_{d}^{-}, \text{etc.}, \text{the amazingly large lower limit} [21]: \]

\[ |A_{\pi}^{x}(z, \langle p_T \rangle) | \gtrsim (0.24 \pm 0.15) \tag{16} \]

\[ \langle z \rangle \simeq 0.45, \quad \langle p_T \rangle \simeq 0.65 \text{ GeV}/c \, . \]

5. Conclusions

Single spin asymmetries offer a unique access to new information on proton structure – like transversity distributions – and quark hadronization – like the quark analysing power; as such they deserve much further experimental and theoretical attention. New data will soon be available and will help in their understanding and interpretation.

Ideally, one should carefully isolate current quark jets, in processes involving transversely polarized protons, and possibly study the \( k_{\perp} \) distribution of pions inside them; this would essentially be a direct observation of Collins effect and might be feasible at RHIC. The separation of \( z \) dependent Collins function from \( x \) dependent transversities should be possible at future or ongoing DIS experiments [23].

From the theoretical point of view, a better understanding of the fundamental properties of the new spin and \( k_{\perp} \) dependent functions is desirable: this includes their universality, QCD evolution, factorizability, classification and relations among them.

Acknowledgments

M.A. would like to thank the organizers, ECT* and BNL, for the invitation to a useful and interesting Workshop.

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