The nucleon is an ideal laboratory to solve QCD in the nonperturbative regime. There are several experimental observations that still lack a rigorous interpretation; they involve the nucleon as a (polarized) target as well as a beam (in collisions and Drell-Yan processes). These data look like big azimuthal and spin asymmetries, related to the transverse polarization and momentum of the nucleon and/or the final detected particles. They suggest internal reaction mechanisms that are suppressed in collinear perturbative QCD but that are “natural” in Nuclear Physics: quark helicity flips, residual final state interactions, etc. In my talk, I will give a brief survey of the main results and I will flash the most recent developments and measurements.

1. Introduction

The spin structure of the nucleon can be best studied by using the so-called spin asymmetry, defined as the ratio between the difference and the sum of differential cross sections obtained by flipping the spin of one of the particles involved in the reaction. Spin asymmetries are known since a long time; historically, the first one was obtained at FERMILAB, where an anomalous large transverse polarization of the $\Lambda$ produced in proton-nucleon annihilations was measured \[1\] surviving even at large values of the $\Lambda$ transverse momentum. More recently, similar anomalously large asymmetries have been observed, for example by the STAR $^2$ collaboration in inclusive pion production from collisions of transversely polarized protons, as well as in Deep-Inelastic Scattering (DIS) of lepton probes on polarized protons by the HERMES $^3$ and CLAS $^4$ collaborations.

Assuming that partons are collinear with their parent hadrons and that
a factorization theorem exists for the process at hand, QCD relates the spin asymmetry for transversely polarized objects to the off-diagonal components of the elementary scattering amplitude in the parton helicity basis; actually, to the imaginary part of products of such components. But with the above assumptions any mechanism flipping the helicity of the parton is suppressed in QCD up to terms proportional to its mass. Since we are considering here mainly protons, which contain only up and down valence quarks, we can assume that deviations to this rule are negligible. Therefore, QCD in collinear approximation is not capable to explain the above mentioned amount of experimental observations.

Indeed, since in polarized DIS the structure function \( g_T = g_1 + g_2 \) (related to the partonic transverse spin distribution) appears at subleading twist, a common prejudice has always driven people to consider transverse spin effects as suppressed because inextricably associated to off-shellness, higher-order quark-gluon interactions, etc.. But in perturbative QCD (pQCD), longitudinal- and transverse-spin effects can be described on the same footing provided that the appropriate helicity and transverse basis are selected, respectively. As a consequence, the spin structure of the proton at leading twist is not fully exploited by just the well known momentum and helicity distributions \( f_1(x) \) and \( g_1(x) \) (or, \( q(x) \) and \( \Delta q(x) \)), in another common notation. A third one, the transversity \( h_1(x) \) (or, \( \delta q(x) \)), is necessary which is basically unknown because it is related to helicity-flip mechanisms, as it should be clear from the above discussion. Since helicity and chirality coincide at leading twist, it is usually referred to as a chiral-odd distribution. Observables, like the cross section, must be chiral-even; hence, the transversity needs another chiral-odd partner to be extracted from a spin asymmetry. This is why, for example, it is suppressed in simple inclusive DIS (for a review on the transversity distribution, see Ref. 7).

From this short introduction, it should hopefully be clear that the standard framework in which pQCD is usually calculated, namely collinear approximation neglecting transverse spin components, is not adequate to interpret the wealth of data collected over the years under the form of spin (azimuthal) asymmetries. In the following, I will review the main flowing ideas about improving such framework.

2. Intrinsic transverse momentum distribution of partons

Let consider the annihilation process \( pp^\uparrow \rightarrow \pi X \), where a pion is semi-in inclusively detected. If a factorization proof holds for the elementary
process, in collinear approximation the differential cross section can be schematically written as
\[
\frac{d\sigma}{d\eta dP_\pi d\phi_S} \propto \sum_{abcd} \int dx_a dx_b dz_c dz_d \phi(x_a, Q^2) \phi(x_b, Q^2) d\sigma(ab^1 \rightarrow c^1d) \\
\times \chi(z_c, Q^2) \delta(z_c - \bar{z}_c) \delta(z_d - 1),
\]
where the functions \(\phi\) are the distributions for the two annihilating partons carrying the fractions \(x_a\) and \(x_b\) of the two corresponding proton momenta, respectively, while \(\chi\) is the fragmentation function for the pion with momentum \(P_\pi\) and carrying a fraction \(z_c\) of the fragmenting parton. Momentum conservation at the partonic level implies that \(z_c\) is constrained to \(\bar{z}_c\), which is a function of \(x_a, x_b, s\) and of the rapidity \(\eta\). The elementary cross section \(d\sigma\) with transversely polarized partons can be deduced from Ref. 8. The angle \(\phi_S\) is formed between the directions of the polarization and of the momentum of the polarized proton.

If this framework is not appropriate to describe experimental observations of spin asymmetries involving transversely polarized objects, a possible generalization consists in assuming (and trying to prove) that the factorization holds also when an explicit dependence upon the parton transverse momenta is introduced in Eq. (1), namely
\[
\frac{d\sigma}{d\eta dP_\pi d\phi_S} \propto \sum_{abcd} \int dx_a dx_b dz_c dz_d dP_T a dP_T b dP_T \pi \delta(z_c - \bar{z}_c) \delta(z_d - 1) \\
\times \phi(x_a, P_T a, Q^2) \phi(x_b, P_T b, Q^2) d\sigma(ab^1 \rightarrow c^1d) \\
\times \chi(z_c, P_T \pi, Q^2) \delta(z_d - 1),
\]
At present, this factorization scheme has been proven only for Drell-Yan and \(e^+ e^-\) processes, as well as for semi-inclusive DIS in some kinematical regions. Therefore, for the considered process Eq. (2) is no more than an assumption, but it leads to several interesting consequences.

When partons have an intrinsic transverse momentum with respect to the direction of the parent hadron momentum, the list of the leading-twist distribution and fragmentation functions is far longer than in the collinear case. Several (chiral-odd) functions appear with a specific number density interpretation, that can originate new interesting spin effects. In the initial state, when the proton is transversely polarized, we have
\[
f(q/p^1) = f_1^q(x, P_T) - f_{1T}^q(x, P_T) \frac{\hat{P} \times P_T \cdot S_T}{M},
\]
where the function \( f_{1T}^\perp(x, p_T) \propto f(q/p^\perp) - f(q/p^\perp) \) describes how the distribution gets distorted by the proton transverse polarization. This is possible because \( f_{1T}^\perp \) appears weighted by the correlation \( \hat{P} \cdot p_T \cdot S_T \) between the momentum \( P \) and transverse spin \( S_T \) of the proton with mass \( M \), and the transverse momentum \( p_T \) of the parton (see Fig. 1-a). As a consequence, the final pion emerging from the fragmentation can be deflected into different directions according to the transverse polarization of the initial proton, the so-called Sivers effect \(^{12}\). From the field-theoretical point of view, \( f_{1T}^\perp \) can be represented as in Fig. 1-a, i.e. it is diagonal in the parton helicity basis but not in the hadron one. As such, it is chiral-even but does not fulfill the constraints of time-reversal invariance (in jargon, it is T-odd); a possible interpretation for the latter feature is that in the considered process \( pp^\uparrow \rightarrow \pi X \), a sort of initial state interaction occurs before the collision \(^{13}\), which prevents the S matrix from being invariant under time-reversal transformations. Interestingly, \( f_{1T}^\perp \) can be linked to the helicity-flip Generalized Parton Distribution (GPD) \( E \), where the correlation between \( S_T \) and \( p_T \) can be directly interpreted as due to the orbital angular momentum of the partons themselves \(^{14}\).

When the proton is not polarized, we can have

\[
f(q^\perp/p) = \frac{1}{2} \left( f_1^q(x, p_T) - h_{1T}^\perp(x, p_T) \frac{\hat{P} \cdot p_T \cdot S_T}{M} \right),
\]

where the function \( h_{1T}^\perp(x, p_T) \propto f(q^\perp/p) - f(q^\perp/p) \) describes the influence of the parton transverse polarization \( S_{qT} \) on its momentum distribution inside an unpolarized proton. Alternatively to the Sivers effect, the final pion can be deflected according to the direction of \( S_{qT} \) entering the correlation factor (see Fig. 1-b). In the corresponding handbag diagram, the function is diagonal in the hadron helicity but not in the parton one, hence it is chiral-odd and it represents a natural partner of transversity for the considered process \(^{15}\). Extraction of \( h_{1T}^\perp \) is of great importance, because it is believed to be responsible for the well known violation of the Lam-Tung sum rule \(^{16}\), an anomalous big azimuthal asymmetry of the unpolarized Drell-Yan \( pp \rightarrow \mu^+\mu^-X \) process, that neither Next-to-Leading Order (NLO) QCD calculations \(^{17}\), nor higher twists or factorization-breaking terms in NLO QCD \(^{18,19,20}\) are able to justify.

In the final state, a transversely polarized/unpolarized parton can fragment into a hadron with mass \( M_h \) and carrying a fraction \( z \) of the momentum. As for the former, since we are considering a semi-inclusive process
with a pion in the final state, we can have
\[ D(h/q^1) = D_1^q(z, P_{hT}) + H_{1T}^1(z, P_{hT}) \frac{\hat{p} \times P_{hT} \cdot S_{hT}}{z M_h}, \]
where \( D_1^q(z, P_{hT}) \) is the probability for a quark \( q \) to fragment into a hadron with transverse momentum \( P_{hT} \), while \( H_{1T}^1(z, P_{hT}) \propto D(h/q^1) - D(h/q^1) \) is the analogue for a quark with transverse polarization \( S_{hT} \), i.e. the Collins function. Again, also the polarization of the fragmenting quark can be responsible for an asymmetric distribution of the detected pion via the correlation \( \hat{p} \times P_{hT} \cdot S_{hT} \) (see Fig. 1(c)). In the same figure, the diagram corresponding to \( H_{1T}^1 \) displays a helicity flip for the fragmenting quark; the Collins function is both chiral-odd and T-odd, and it represents another possible partner for extracting the transversity through the Collins effect.

Several experimental collaborations are pursuing this goal, with the help of theoretical calculations as well.

Finally, the last combination is given by
\[ D(h^1/q) = \frac{1}{2} \left( D_1^q(z, P_{hT}) + D_{1T}^q(z, P_{hT}) \frac{\hat{p} \times P_{hT} \cdot S_{hT}}{z M_h} \right). \]

The function \( D_{1T}^q(z, P_{hT}) \propto D(h^1/q) - D(h^1/q) \) describes the fragmentation of an unpolarized parton into a hadron with polarization \( S_{hT} \), like, e.g., the \( \Lambda \): it is not pertinent to the process we have here selected, but it is anyway important because the correlation \( \hat{p} \times P_{hT} \cdot S_{h} \) is believed to be the mechanism responsible for the observed asymmetric production of \( \Lambda \) in unpolarized proton collisions. (See Fig. 1(d).) From the related diagram, the function \( D_{1T}^q \) is related to a helicity flip of just the polarized hadron; it is then chiral even, but T-odd.

3. Interference fragmentation functions

From previous section, it emerges that in the non-collinear factorized framework of Eq. (2), at least three different interpretations arise at leading twist for the spin asymmetry observed in the \( pp^1 \rightarrow \pi X \) process: the Sivers effect, related to the convolution \( f_1^a \otimes f_{1T}^b \otimes D_1^c \) for the elementary process \( a + b \rightarrow c + d \); the Collins effect, related to the convolution \( f_1^a \otimes h_{1T}^b \otimes H_{1T}^c \) for \( a + b^1 \rightarrow c^1 + d \); the effect related to the convolution \( h_{1T}^a \otimes h_{1T}^b \otimes D_1^c \) for \( a^1 + b^1 \rightarrow c + d \). An intense experimental and theoretical activity is ongoing in this field in order to unravel the physics contained in the asymmetry data, and also in related topics, like for example the new project of extracting transversity from Drell-Yan using (polarized) antiprotons.
But all the above mechanisms require an explicit dependence of the distribution and fragmentation functions upon an intrinsic transverse momentum of partons. We already stressed that in such a non-collinear framework the factorization leading to Eq. (2) has not yet been proven for hadron-hadron collisions. A lot of work is being done also in this specific, though quite general, subject. Nevertheless, it would be desirable to find out a mechanism that leads to a spin asymmetry without invoking an explicit dependence on \( p_T \). Since we are considering here final states made of unpolarized hadrons only, we need an additional 4-vector that can be provided by semi-inclusively detecting a second hadron inside the same jet of the first one. In fact, in this case the system of two unpolarized hadrons with momenta \( P_1 \) and \( P_2 \) is described by two 4-vectors, the cm one, \( P_h = P_1 + P_2 \) and the relative one, \( R = (P_1 - P_2)/2 \), by which we can construct the correlation \( S_{qt} \cdot R \times P_h \) (see Fig. 2).

Indeed, for the DIS lepton-induced production from a transversely polarized proton of two pions with the cm momentum aligned to the jet axis (i.e., with \( P_{hT} = 0 \)), it has been shown that at leading twist the cross section contains a term like \( (S_{qt} \times R_T) h_1(x) H_{1T}^q(z, M_h^2, R_T^2) \), where the chiral-odd (T-odd) \( H_{1T}^q \) is representative of a new class of fragmentation functions, the Interference Fragmentation Functions (IFF). A spin asymmetry can be built by flipping the spin of the transversely polarized proton target, which isolates the transversity \( h_1 \) at leading twist via \( H_{1T}^q \). A thorough analysis of IFF has been carried out up to twist-3, and \( H_{1T}^q \) is the only one surviving at leading twist in the collinear situation, since it is related to the azimuthal position of the plane containing the two pions: the latter ones are differently distributed in the azimuthal angle \( \phi \) of Fig. 2 according to the direction of the transverse polarization of the fragmenting quark. A partial-wave analysis of the two-pion system allows to isolate the main channels, where the two pions are produced in a relative \( s \) or \( p \) wave. Interference between the two or between different components of \( p \) waves is responsible of the T-odd nature of IFF. These functions can be extracted in principle from the process \( e^+e^- \rightarrow (\pi\pi)_{jet1}(\pi\pi)_{jet2}X \). Measurements aiming at the extraction of IFF are under way at HERMES (DIS) and BELLE \((e^+e^-)\) and could be possible at COMPASS and BABAR too. However, it has been recently proposed that a consistent extraction of \( h_1 \) and \( H_{1T}^q \) could be achieved by considering again the collision of (un)polarized protons leading to one or two pion pairs semi-inclusively detected in the final state. For the case \( pp \rightarrow (\pi\pi)X \), the cross section contains the convolution \( f_{1T}^q \otimes h_1^b \otimes H_{1T}^{q*} \) for the elementary process.
\(a + b^\uparrow \rightarrow c^\uparrow d\). On the other hand, for the corresponding unpolarized process 
\(pp \rightarrow (\pi \pi)^{\text{jet}1}(\pi \pi)^{\text{jet}2}X\) the cross section contains 
\(f_1^a \otimes f_1^b \otimes H_1^{\perp} \otimes H_1^{\perp}\) for \(a + b \rightarrow c^\uparrow + d^\uparrow\). By combining the two measurements, information on the two unknowns \(h_1\) and \(H_1^{\perp}\) can be extracted consistently in the same experiment. Finally, the very same formalism offers the possibility of observing for the first time the transverse linear polarization of gluons, even using spin-\(\frac{1}{2}\) targets.  

References

Figure 1. On the left, from top to bottom: a- the nonperturbative correlation giving rise to the Sivers effect; b- the same for transversely polarized quarks in unpolarized protons; c- the same for the Collins effect; d- the same for the polarized fragmentation. On the right, from top to bottom, the corresponding field-theoretical interpretations.
Figure 2. The mechanism leading to a spin asymmetry for a transversely polarized quark fragmenting into two unpolarized hadrons.