TRANSVERSITY AND Λ POLARIZATION

M. Anselmino
Dipartimento di Fisica Teorica, Università di Torino and
INFN, Sezione di Torino, Via P. Giuria 1, I-10125 Torino, Italy

Abstract
Two related issues are discussed, which might be easily explored by present and future COMPASS experiments. The first one deals with the new world of transversity, the fundamental polarized parton distribution so far totally unknown. The second issue concerns Λ production in polarized semi-inclusive processes, with a measurement of the Λ polarization, which might give novel information on distribution and fragmentation properties of polarized partons. In case of transverse polarization the detection of Λ's gives access to a new way of measuring transversities. Also the interesting case of Λ polarization in *unpolarized* processes is discussed.

1. TRANSVERSITY

The transverse polarization of quarks inside a transversely polarized nucleon, denoted by h_1, δq or $\Delta_T q$, is a fundamental twist-2 quantity, as important as the unpolarized distributions q and the helicity distributions Δq. It is given by

$$h_1(x, Q^2) = q_\uparrow^\uparrow(x, Q^2) - q_\downarrow^\uparrow(x, Q^2)\,, \tag{1}$$

that is the difference between the number density of quarks with transverse spin parallel and antiparallel to the nucleon spin [1]. Figure 1 shows the three fundamental quark distributions as seen in Deep Inelastic Scattering.

Transversity is the same as the helicity distribution only in a non relativistic approximation, but is expected to differ from it for a relativistic nucleon. Not much is known about it, apart from the fact that it should obey the Soffer's inequality [2]

$$2\,|h_1| \leq (q + \Delta q)\,, \tag{2}$$

and that its integral is related to the tensor charge

$$a_q^t = \int_0^1 [h_{1q}(x, Q^2) - h_{1\bar{q}}(x, Q^2)]\, dx\,, \tag{3}$$

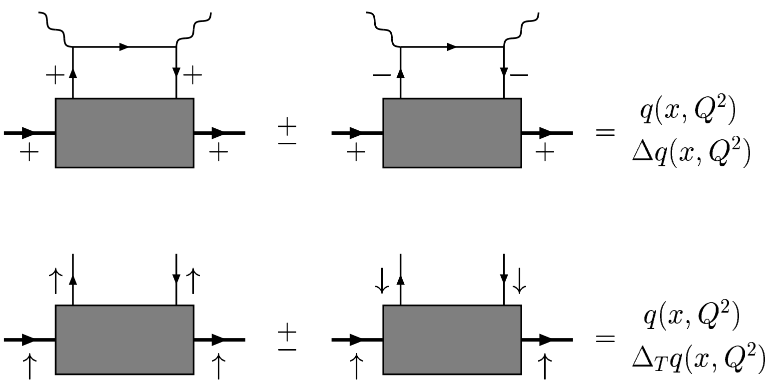

Fig. 1: The three leading twist quark distributions as seen in DIS.

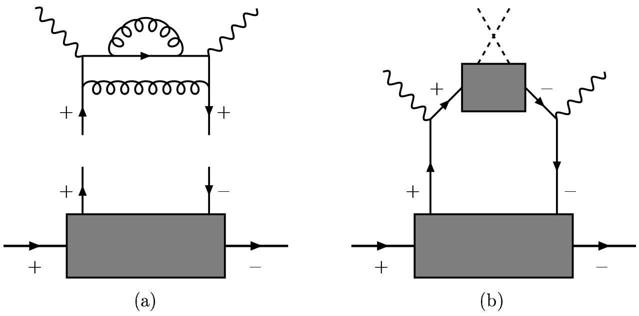

Fig. 2: The chiral-odd function h_1 (lower box) cannot couple to inclusive DIS dynamics, even with QCD corrections; it couples to semi-inclusive DIS, where chiral-odd non perturbative fragmentation functions may appear.

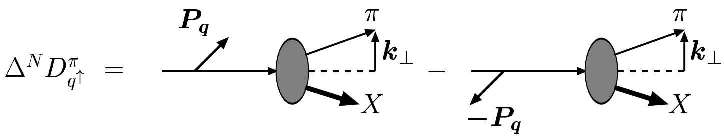

Fig. 3: Pictorial representation of Collins function; notice that a similar function is sometimes denoted by $H_1^\perp$ in the literature.

for which some estimates have been obtained using non perturbative QCD models [1].

When represented in the helicity basis (see Fig. 2) h_1 relates quarks with different helicities, revealing its chiral-odd nature. This is the reason why this important quantity has never been measured in DIS: the electromagnetic or QCD interactions are helicity conserving, there is no perturbative way of flipping helicities and h_1 decouples from inclusive DIS dynamics, as shown in Fig. 2a.

However, it can be accessed in semi-inclusive deep inelastic scatterings (SIDIS), where some non perturbative chiral-odd effects may take place in the non perturbative fragmentation process, Fig. 2b. Similarly, it could be accessed in Drell–Yan polarized processes, $p^\uparrow\, p^\uparrow \,\to\, \mu^+\,\mu^-\,X$, where transverse spin asymmetries

$$A_{TT} = \frac{d\sigma^{\uparrow\uparrow} - d\sigma^{\uparrow\downarrow}}{d\sigma^{\uparrow\uparrow} + d\sigma^{\uparrow\downarrow}} \tag{4}$$

are related to the convolution of two transversity distributions. However, one expects very small numerical values for such asymmetries [3].

2. h_1 IN SIDIS

In order to measure the unknown transversity distribution in semi-inclusive DIS, one needs a chiral-odd partner to associate with h_1; these are usually new fragmentation functions and several suggestions have been made [4], which we shall briefly consider.

2.1 The Collins function

A chiral-odd function which might occur in the fragmentation of a transversely polarized quark into, say, a pion was first introduced by Collins [5] and is schematically represented in Fig. 3; it describes an azimuthal asymmetry in the hadronization process of a transversely polarized quark.

Such a function can give origin to a single spin asymmetry in $\ell\, p^\uparrow \,\to\, \ell\,\pi X$ processes, as indeed observed by HERMES [6], and certainly observable by COMPASS experiments:

$$A_N = \frac{d\sigma^\uparrow - d\sigma^\downarrow}{d\sigma^\uparrow - d\sigma^\downarrow} \cdot \tag{5}$$

At leading twist, this asymmetry, if attributed to the Collins function $\Delta^N D_{\pi/q^\uparrow}$, is given by:

$$A_N^\pi = \frac{\sum_q e_q^2\, h_{1q}(x)\, \Delta^N D_{\pi/q^\uparrow}(z, k_\perp)}{2\sum_q e_q^2\, q(x)\, \hat{D}_{\pi/q}(z, k_\perp)}\, \frac{2(1-y)}{1+(1-y)^2}\, \sin\Phi_C\,, \tag{6}$$

where Φ_C is the azimuthal angle between the fragmenting quark polarization vector $\boldsymbol{P_q}$ and the pion transverse momentum $\boldsymbol{k}_\perp$. Thus, A_N clearly gives access to the transversity distributions h_{1q}, via the (unknown) Collins function: notice that a careful study of the dependence of A_N on the different DIS variables might help in obtaining separate information on h_1 and $\Delta^N D_{\pi/q^\uparrow}$; also, selection of particular kinematical ranges might help in the flavour decomposition [7].

2.2 The Sivers function

A mechanism similar to the Collins fragmentation was suggested for the proton distributions [8, 9], and the corresponding function denoted by $\Delta^N f_{q/p^\uparrow}$ or $f_{1T}^\perp$ [10]; it can again be described by Fig. 3 if one replaces the initial transversely polarized quark with a transversely polarized proton and the final pion with a quark [11]. The Sivers asymmetry was much debated, despite its phenomenological success [9, 12], because of some supposed problems with QCD time-reversal properties: however, very recently, a series of papers [13–15] have clarified the situation and fully promoted the rights of $\Delta^N f_{q/p^\uparrow}$.

When attributing the asymmetry (5) to the Sivers mechanism, at leading twist, one obtains:

$$A_N^\pi = \frac{\sum_q e_q^2\, \Delta^N f_{q/p^\uparrow}(x, k_\perp)\, D_{\pi/q}(z)}{\sum_q e_q^2\, q(x, k_\perp)\, D_{\pi/q}(z)}\, \sin\Phi_S\,, \tag{7}$$

to be compared with Eq. (6). The Sivers asymmetry does not allow access to transversity – it is a chiral-even function – but might contribute to A_N; such a contribution should be separated from that of the Collins asymmetry, if we want to use data on A_N to extract information on h_1. This is in principle possible if one notices that Eq. (7) does not depend on y and that the azimuthal angle dependence is different from the one in Eq. (6); Φ_S is now the angle between the proton polarization vector and the quark $\boldsymbol{k}_\perp$.

2.3 Other ways to approach transversity

Other approaches to elusive transversity have been proposed [4]. For example, within DIS, in Ref. [16] it was suggested to look at final states with two pions, originating from s and p wave states, whose interference might supply the necessary phase for a single spin asymmetry: these are the so-called interference fragmentation functions. They might avoid the danger that, in single inclusive production, the sum over many different channels averages the phases to zero.

Another possibility of measuring h_1 goes via the SIDIS production of spin 1 vector particles [17]; for example, one (measurable) non diagonal element of the helicity density matrix of a spin 1 meson, is related to h_1 and some unknown fragmentation amplitudes [18].

3. Λ POLARIZATION

Let us now turn to the second issue. Λ hyperons have the peculiar feature of revealing their polarization through the angular distribution of their weak decay, $\Lambda \to p\,\pi$; indeed such a feature has allowed many interesting measurements with unexpected and somewhat mysterious results [19].

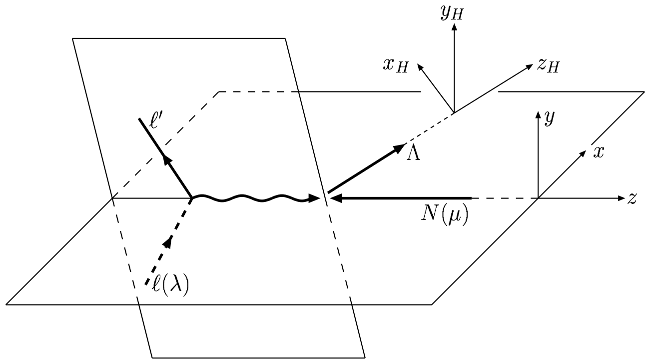

Fig. 4: Λ production in the γ^*-p c.m. frame; the angular decay of the hyperon is measured for the particle at rest in the helicity frame, denoted by the pedices H; λ, μ and h denote, respectively, the initial lepton, nucleon and Λ helicities.

Let us consider the SIDIS processes, $\ell(\lambda)\,p(\mu) \to \ell\,\Lambda(h)\,X$, within the QCD factorization theorem at leading order, with several spin configurations, described by the helicities λ, μ and h; the Λ's are required to be produced in the current quark fragmentation region. The kinematics and our choice of reference frames are explicitly shown in Fig. 4; the Λ decay is observed in the helicity rest frame (x_H, y_H, z_H).

We define

$$\frac{d\sigma^{\ell(\lambda)\,p(\mu)\to\Lambda(h)\,X}}{dx\,dy\,dz} \equiv d\sigma^{\Lambda_h}_{\lambda\mu}\,. \tag{8}$$

Neglecting weak interaction contributions there are four independent helicity observables, which can be chosen and written as:

the unpolarized cross-section

$$d\sigma^{\Lambda} = \frac{2\pi\alpha^2}{sx}\,\frac{1+(1-y)^2}{y^2}\sum_q e_q^2\,q(x)\,D_{\Lambda/q}(z)\,, \tag{9}$$

the double spin asymmetry

$$A_{\parallel} = \frac{d\sigma^{\Lambda}_{++} - d\sigma^{\Lambda}_{+-}}{2\,d\sigma^{\Lambda}} = \frac{y(2-y)}{1+(1-y)^2}\,\frac{\sum_q e_q^2\,\Delta q(x)\,D_{\Lambda/q}(z)}{\sum_q e_q^2\,q(x)\,D_{\Lambda/q}(z)}\,, \tag{10}$$

the spin transfer from ℓ to Λ (with an unpolarized nucleon)

$$P_{+0} = \frac{d\sigma^{\Lambda_+}_{+0} - d\sigma^{\Lambda_-}_{+0}}{d\sigma^{\Lambda}} = \frac{y(2-y)}{1+(1-y)^2}\,\frac{\sum_q e_q^2\,q(x)\,\Delta D_{\Lambda/q}(z)}{\sum_q e_q^2\,q(x)\,D_{\Lambda/q}(z)}\,, \tag{11}$$

and the spin transfer from N to Λ (with an unpolarized lepton)

$$P_{0+} = \frac{d\sigma^{\Lambda_+}_{0+} - d\sigma^{\Lambda_-}_{0+}}{d\sigma^{\Lambda}} = \frac{\sum_q e_q^2\,\Delta q(x)\,\Delta D_{\Lambda/q}(z)}{\sum_q e_q^2\,q(x)\,D_{\Lambda/q}(z)}\,. \tag{12}$$

The above quantities are all measurable; P_{+0} means the polarization of the hyperon Λ semi-inclusively produced in the DIS scattering of a longitudinally polarized lepton (+ helicity) off an unpolarized proton (helicity 0), and so on. These combined measurements allow one to obtain new information and/or to test available information on longitudinally polarized and unpolarized fragmentation and distribution functions, q, Δq, D and ΔD. A detailed discussion with numerical estimates, as well as a complete list of references, can be found in Refs. [20–22].

In particular, the above measurements should give some new information on the Λ fragmentation functions; in fact, from e^+e^- data one can only extract information on [23]

$$\sum_q [D_q^\Lambda + D_{\bar{q}}^\Lambda] \qquad \text{and} \qquad \sum_q [\Delta D_q^\Lambda - \Delta D_{\bar{q}}^\Lambda] \,. \tag{13}$$

3.1 Transverse polarization, polarized protons

We consider the process $\ell\, p^\uparrow \to \ell\, \Lambda^\uparrow\, X$ with an unpolarized lepton, a transversely polarized proton (S_N) and the measurement of the Λ transverse polarization P_N; transverse means orthogonal to the $\gamma^* - \Lambda$ plane, see Fig. 4. One has:

$$P_N^{[0S_N]} = \frac{2(1-y)}{1+(1-y)^2} \, \frac{\sum_q e_q^2\, h_{1q}(x)\, \Delta_T D_{\Lambda/q}(z)}{\sum_q e_q^2\, q(x)\, D_{\Lambda/q}(z)} \,, \tag{14}$$

where the transversity distribution h_1 appears coupled to $\Delta_T D = D_\uparrow^\uparrow - D_\uparrow^\downarrow$, the chiral-odd transversity fragmentation function (so far unknown).

Equation (14) offers a direct access to the product of h_1 and $\Delta_T D$ and one might hope to obtain separate information by studying the x and z dependences of P_N. Notice that there is no dependence on any $k_\perp$ in this case. Notice also that neglecting contributions from sea quarks (which should be safe in the large x and z regions) Eq. (14) simplifies to:

$$P_N^{[0S_N]} \simeq \frac{2(1-y)}{1+(1-y)^2} \, \frac{4h_{1u} + h_{1d}}{4u+d} \, \frac{\Delta_T D_{\Lambda/u}}{D_{\Lambda/u}} \,. \tag{15}$$

Convolutions of the same unknown functions appear in the transverse polarization of Λ's produced in pp interactions with one transversely polarized proton, $p\, p^\uparrow \to \Lambda^\uparrow\, X$, for example at RHIC [24]:

$$P_N(\Lambda) \sim \sum_{abc} f_{a/p} \otimes h_{1b} \otimes \Delta d\hat{\sigma}^{ab\to c\cdots} \otimes \Delta_T D_{\Lambda/c} \,, \tag{16}$$

where $f_{a/p}$ is a parton (quark or gluon) distribution function and the $\Delta d\hat{\sigma}$ are differences of polarized elementary QCD interactions. A combined measurement of P_N in both processes might help to extract more information.

3.2 Transverse polarization, unpolarized protons

This case is particularly interesting, as it relates to the longstanding problem of understanding the transverse polarization of Λ's and other hyperons produced in the unpolarized collisions of nucleons. This polarization might originate from spin effects in the fragmentation of unpolarized quarks into polarized baryons, the so-called polarizing fragmentation functions [25, 26]. These functions $\Delta^N D_{\Lambda^\uparrow/q}$ can, again, be described by Fig. 3 if one takes an initial *unpolarized* quark and replaces the final pion with a transversely (up or down) polarized Λ baryon [11].

Indeed the polarizing fragmentation functions can contribute to the transverse Λ polarization in SIDIS [27];

$$\begin{aligned} P_N(\Lambda, x, y, z, p_T) &= \frac{\sum_q\, e_q^2\, q(x)\, \Delta^N D_{\Lambda^\uparrow/q}(z, p_T)}{\sum_q\, e_q^2\, q(x)\, \hat{D}_{\Lambda/q}(z, p_T)} \\ &\simeq \frac{(4u+d)\, \Delta^N D_{\Lambda^\uparrow/u} + s\, \Delta^N D_{\Lambda^\uparrow/s}}{(4u+d)\, \hat{D}_{\Lambda/u} + s\, \hat{D}_{\Lambda/s}} \,, \end{aligned} \tag{17}$$

where p_T is the Λ transverse momentum in the $\gamma^* - p$ c.m. frame.

Equation (17) holds for neutral current, parity conserving, SIDIS processes. Even more interesting is the same quantity for the charged current weak process $\nu\, p \to \ell\, \Lambda^\uparrow\, X$, investigated by the NOMAD Collaboration [28]; in such a case one has an almost direct measurement of the polarizing fragmentation function:

$$P_N^{[\nu\ell]} \simeq \frac{\Delta^N D_{\Lambda^\uparrow/u}}{\hat{D}_{\Lambda/u}} \,. \tag{18}$$

Details and estimates can be found in Ref. [27].

4. CONCLUSIONS

The transversity distribution, the last fundamental missing piece of the polarized nucleon structure, can be accessed in semi-inclusive DIS. At the moment this looks like the most promising approach to the elusive transversity and should be strongly pursued. Ongoing and future COMPASS experiments offer an almost unique opportunity.

The main difficulty with measuring transversity is the necessity of coupling it to another unknown chiral-odd function, which is often very interesting by itself; the actual data are always products or convolutions of these new functions. However, luckily, the unknown functions depend essentially on different kinematical variables and one can devise a strategy to obtain separate information, provided enough data are available.

Typically, transversity contributes to spin asymmetries; another problem is that of controlling other possible contributions—independent of transversity—to these asymmetries. This might arise in case of Sivers and Collins contributions to A_N; whereas the latter is coupled to h_1, the former is not and such a contribution must be understood before drawing conclusions on h_1 from data on A_N. Also in this case some strategies are possible.

The measurement of transverse Λ polarization in SIDIS processes initiated by transversely polarized protons is a little explored, so far, channel to access h_1; the chiral-odd partner in this case is the transversity fragmentation function, which, again, is unknown: however, contrary to the Collins function, it does not require any intrinsic quark motion and does not vanish when $k_\perp = 0$. Moreover, one can expect it to be similar to the analogous longitudinal fragmentation function, and easy to model. Also, information on $\Delta_T D$ can be obtained from other processes.

We will learn more about transversity only by combining information from as many processes as possible, in different reactions and different kinematical ranges; the QCD Q^2 evolution of h_1 is known and should also be tested. Once a first knowledge about transversity is available, its many phenomenological applications to the explanation of observed spin asymmetries will test and improve our knowledge.

References

[1] Excellent recent reviews on the nucleon spin structure in general and on quark transverse spin in hadrons can be found in: B.W. Filippone and X. Ji, Adv. Nucl. Phys. **26** (2001) 1; V. Barone, A. Drago and P.G. Ratcliffe, Phys. Rept. **359** (2002) 1.

[2] J. Soffer, Phys. Rev. Lett. **74** (1995) 1292.

[3] J. Soffer, M. Stratmann and W. Vogelsang, Phys. Rev. D **65** (2002) 114024.

[4] For a recent review on ways of mapping the proton transversity see D. Boer, Nucl. Phys. A **711** (2002) 21.

[5] J.C. Collins, Nucl. Phys. B **396**, (1993) 161.

[6] HERMES Collaboration, A. Airapetian *et al.*, Phys. Rev. Lett. **84** (2000) 4047; Phys. Rev. D **64** (2001) 097101.

[7] M. Anselmino and F. Murgia, Phys. Lett. B **483** (2000) 74.

[8] D. Sivers, Phys. Rev. D **41** (1990) 83; Phys. Rev. D **43** (1991) 261.

[9] M. Anselmino, M. Boglione and F. Murgia, Phys. Lett. B **362** (1995) 164; M. Anselmino and F. Murgia, Phys. Lett. B **442** (1998) 470.

[10] D. Boer and P. Mulders, Phys. Rev. D **57** (1998) 5780.

[11] For a phenomenological definition of these new functions see, *e.g.*, M. Anselmino, e-Print Archive: hep-ph/0201150.

[12] See the talk by G. Rakness at SPIN 2002, Brookhaven National Laboratory, September 9-14, 2002, to appear in the proceedings.

[13] S.J. Brodsky, D.S. Hwang and I. Schmidt, Phys. Lett. B **530** (2002) 99; Nucl. Phys. B **642** (2002) 344.

[14] J.C. Collins, Phys. Lett. B **536** (2002) 43.

[15] X. Ji and F. Yuan, Phys. Lett. B **543** (2002) 66.

[16] R.L. Jaffe, X. Jin and J. Tang, Phys. Rev. Lett. **80** (1998) 1166.

[17] A. Bacchetta and P.J. Mulders, Phys. Rev. D **62** (2000) 114004.

[18] M. Anselmino, M. Boglione, J. Hansson and F. Murgia, Phys. Rev. D **54** (1996) 828.

[19] For a review of data see, *e.g.*, K. Heller, in Proceedings of Spin 96, C.W. de Jager, T.J. Ketel and P. Mulders, Eds., World Scientific (1997); or A.D. Panagiotou, Int. J. Mod. Phys. **A5** (1990) 1197.

[20] M. Anselmino, M. Boglione and F. Murgia, Phys. Lett. B **481** (2000) 253.

[21] M. Anselmino, M. Boglione, U. D'Alesio and F. Murgia, Eur. hys. J. **C21** (2001) 501.

[22] M. Anselmino, M. Boglione, U. D'Alesio, E. Leader and F. Murgia, Phys. Lett. B **509** (2001) 246.

[23] D. de Florian, J. Soffer, M. Stratmann and W. Vogelsang, Phys. Rev. D **57** (1998) 5811.

[24] D. de Florian, J. Soffer, M. Stratmann and W. Vogelsang, Phys. Lett. B **439** (1998) 176.

[25] M. Anselmino, D. Boer, U. D'Alesio and F. Murgia, Phys. Rev. D **63** (2001) 054029.

[26] P.J. Mulders and R.D. Tangerman, Nucl. Phys. B **461** (1996) 197; Nucl. Phys. B **484** (1997) 538 (E).

[27] M. Anselmino, D. Boer, U. D'Alesio and F. Murgia, Phys. Rev. D **65** (2002) 114014.

[28] NOMAD Collaboration, P. Astier *et al.*, Nucl. Phys. B **588** (2000) 3; Nucl. Phys. B **605** (2001) 3.