Transverse Spin Phenomena in Lepton Scattering

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Abstract. The transverse spin phenomena are one of the most important topics being presently investigated in semi-inclusive Deep Inelastic Scattering. In the last two years, since SPIN2004, many new data have become available. In parallel a remarkable progress in understanding the spin and the transverse momentum structure of the nucleon has occured.

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Semi-inclusive deep inelastic scattering (SIDIS) has a key role in the investigation of the partonic structure of the nucleons. It allowed to measure the parton momentum distribution functions (DF's) $q(x)$, also indicated with f_1^q, and, using a longitudinal polarised target, the helicity DF's $\Delta q(x)$, or g_1^q [1]. Today it is a well accepted fact that to describe the quark structure of the nucleon at the twist-two level also the still unknown "transversity" DF's $\Delta_T q(x)$ (or h_1^q, or δq) are needed. The transversity DF's give, in a transversely polarised nucleon, the differences of the densities of quarks with polarisation parallel and antiparallel to that of nucleon, and have many interesting properties [2, 3], like the chiral-odd nature and a simple Q^2 evolution. Also, they probe the relativistic nature of quark dynamics, their first moments are related to the tensor charges, they must satisfy a positivity bound, and recently an angular momentum sum rule has been proven in the framework of the parton model.

The chiral-odd transversity DF's cannot be measured in inclusive polarised DIS. They can be accessed, however, in polarised (anti)proton-proton collisions and SIDIS. Their measurement is an important part of the experimental programme of the RHIC-Spin Experiments at the BNL RHIC collider [4], and of the HERMES experiment at DESY and of the COMPASS experiment at CERN, in which SIDIS processes are studies. The HERMES experiment [5] uses a 27.5 GeV electron beam and an internal hydrogen target. Data with target polarisation oriented transversely to the beam momentum were taken from 2002 to 2005. At higher energy, data are being taken by the COMPASS experiment [6]; using a longitudinally polarised μ^+ beam of 160 GeV/c and a transversely polarised solid state ^{6}LiD target data were collected in the years 2002, 2003 and 2004. SIDIS measurements with a transversely polarised target are also foreseen by the JLAB experiments [7] which use a 6 GeV (to be upgraded to 12 GeV) electron beam. The different beam energies, which result in different $x - Q^2$ ranges, make the experiments complementary, and the comparison of their results extremely valuable.

In SIDIS observable effects are given by the product of the chiral-odd $\Delta_T q$ and another chiral-odd function, and, to measure the transversity DF's, the so-called "quark

polarimetry" has to be exploited. Amongst the different methods which have been proposed [8], the present experiments are measuring the "single hadron asymmetry" ("Collins asymmetry"), the "two hadron asymmetry", and the Λ hyperon transverse polarisation. These methods are complementary, since the chiral-odd partners of the transversity DF's are the spin dependent parts of different fragmentation functions (FF's). Due to lack of space, in this report I will mention only the first two methods, and refer to Ref. [9] for the Λ polarimetry.

The Collins asymmetry is related to a modulation in the "Collins angle" of the distribution of inclusively produced hadrons. A quark moving horizontally and polarised upward would emit the leading meson preferentially on the left side of the jet. Thus, the FF has a spin dependent part (the "Collins FF") responsible for the left-right asymmetry in the azimuthal distribution of the hadrons produced in the fragmentation. Comparing the cross-sections on oppositely polarised target nucleons, one can measure the transverse spin asymmetry

$$A_T^h = \frac{d\sigma(\vec{S}) - d\sigma(-\vec{S})}{d\sigma(\vec{S}) + d\sigma(-\vec{S})} = |\vec{S}| \cdot D_{NN} \cdot A_{Coll} \cdot \sin\Phi_{Coll} \tag{1}$$

where $D_{NN} = (1-y)/(1-y+y^2/2)$ is the transverse spin transfer coefficient from the initial to the struck quark, and $\vec{S}$ is the component of the target spin orthogonal to the virtual photon direction. The Collins angle, originally defined as the angle between the transverse momentum of the outgoing hadron and the transverse spin vector of the fragmenting quark, is measured from $\Phi_{Coll} = \phi_h - \phi_{s'} = \phi_h + \phi_S - \pi$ (this is the convention adopted by COMPASS; the HERMES Collaboration defines $\Phi_{Coll} = \phi_h + \phi_S$, which leads to measured asymmetries with opposite sign). The angles ϕ_h and ϕ_S are respectively the azimuthal angle of the hadron and of the target spin in a coordinate system in which the z-axis is the virtual photon direction, and the x-z plane is the lepton scattering plane with positive x-direction along the scattered lepton transverse momentum. In the parton model the Collins asymmetry is given by

$$A_{Coll} = \sum_q e_q^2 \cdot \Delta_T q \otimes \Delta_T^0 D_q^h / \sum_q e_q^2 \cdot q \otimes D_q^h, \tag{2}$$

where $\Delta_T^0 D_q^h$ indicates the Collins FF, and the symbol $\otimes$ the integration over transverse momenta. From (2) it is clear how, using different targets and identifying the final hadrons, one can perform flavour separation, which is a unique feature of SIDIS.

At SPIN2004 the first transversity signals were shown. On the proton target, using the data collected in 2002 and 2003, HERMES measured Collins asymmetries different from zero and with opposite sign for π^+ and for π^-, giving a first important hint for transversity DF's and Collins FF's different from zero. COMPASS measured Collins asymmetries on the deuteron target from the 2002 data for positive (h^+) and negative (h^-) hadrons, obtaining in both cases values compatible with zero, indicating a possible cancellation between the proton and the neutron.

Since that time, remarkable progress has been done. Very good news came from the Belle collaboration which measured in $e^+e^- \to hadrons$ a Collins function different

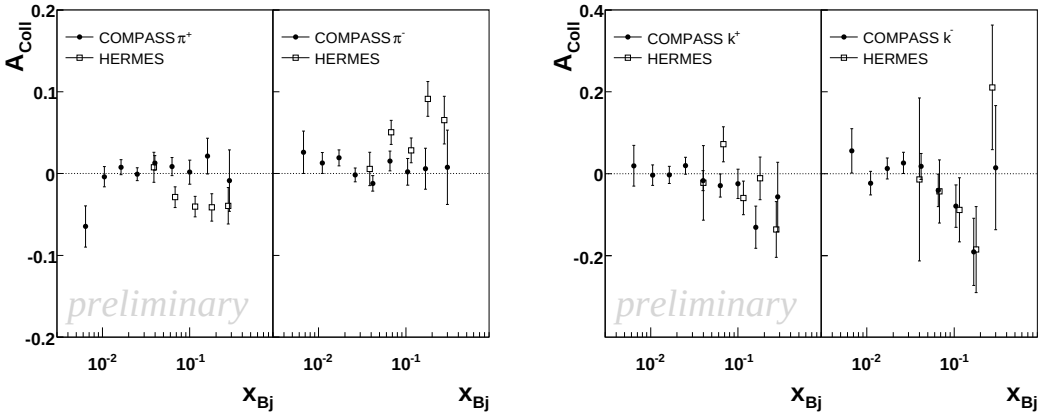

FIGURE 1. Collins asymmetries for π^+ and π^- (left), and for K^+ and K^- (right) as a function of Bjorken x. The open points are the HERMES 2002-2004 preliminary results, while the full circles are the COMPASS 2003-2004 measurements ("all hadron" sample). Note that $\Phi_{Coll} = \phi_h + \phi_S - \pi$ has been used, i.e. the sign of the HERMES data has been changed respect to Ref. [11].

from zero [4, 10], thus providing independent confirmation of the measurability of the transversity DF's in SIDIS. Preliminary results for the Collins asymmetries for π^+ and π^- have been produced by HERMES from the 2002-2004 data [11], confirming with higher statistics the previous results; they are shown as open points in the two left plots of Fig 1. COMPASS has produced by now final results for the Collins asymmetries for h^+ and h^- from the whole 2002-2004 data [12, 13], and confirms with high accuracy that the Collins asymmetry on deuteron is compatible with zero. The new COMPASS and HERMES results in the valence region can be interpreted naively in the framework of the parton model [12, 13]. Phenomenological calculations have already been performed [14, 15, 16] mainly fitting the HERMES data; the comparison with the COMPASS 2002 data and with the Belle measurements is satisfactory. The main result of the calculations is an indication for u-quark dominance and for favoured and unfavoured Collins functions of almost equal strength and opposite sign. A very interesting result. The work will be repeated soon using the HERMES and the new Belle and COMPASS data, and more quantitative information on both the u and d quarks DF's is expected. To further progress, more data are needed; in particular from COMPASS, with a proton target, to investigate the energy dependence of these effects.

New results are also available for $K^\pm$ from HERMES 2002-2004 data [11] and for $\pi^\pm$ and $K^\pm$ from COMPASS 2003-2004 data [12]. All the measured Collins asymmetries are shown in Fig. 1. As expected from the $h^\pm$ measurements, the $\pi^\pm$ asymmetries from COMPASS are compatible with zero inside the slightly larger statistical errors. The $K^\pm$ asymmetries do not exhibit any signal, both on proton and deuteron. These preliminary results are quite recent, and no theoretical interpretation is yet available.

The two hadron asymmetries constitute an alternative way to access the transversity DF's $\Delta_T q$, and, in some models [8], they are expected to carry a stronger signature to the quark spin than the Collins asymmetry itself. The experimental asymmetry is built looking for pairs of inclusively produced hadrons, which must be distinguishable, f.i.

of opposite charge. The expression of the asymmetry is similar to that of the Collins case given in (1), where the angle Φ_{Coll} is now replaced by the azimuthal angle of the hadron pair plane with respect to the lepton scattering plane. Also, the A_{Coll} asymmetry is replaced by

$$A_{2h} = \sum_q e_q^2 \cdot \Delta_T q \otimes H_1^{\sphericalangle} / \sum_q e_q^2 \cdot q \otimes D_q^{2h}, \tag{3}$$

The quark FF into the specific hadron pair is indicated with D_q^{2h}, and $H_1^{\sphericalangle}$ is its spin dependent part. Both of them are presently unknown: their measurement in e^+e^- annihilation is ongoing.

At the time of SPIN2004, only the measurements from HERMES on a longitudinally polarised target data were available. Today preliminary results on transversely polarised proton and deuteron targets, from HERMES [17] and COMPASS [18] respectively, are available. Again, an asymmetry different from zero has been measured by HERMES, while the data on deuteron are compatible with zero. Theoretical interpretations in terms of the interference FF's are being worked out and the present status has been presented at this Symposium [19].

The SIDIS processes on transversely polarised targets give the possibility of investigating several interesting phenomena. In particular, in the last years, new results were obtained for the "Sivers DF's" which are, together with the transversity, the most studied in SIDIS. They are the transverse momentum dependent (TMD) parton distributions describing the correlation of the intrinsic parton transverse momentum with the transverse polarisation of the nucleon. Their properties and the relation with the parton orbital angular momentum in a transversely polarised nucleon can be found f.i. in [20].

Very much like the transversity DF's, the Sivers functions can be measured in SIDIS looking at the azimuthal angle of the inclusively produced hadrons. Now the modulation appears in the "Sivers angle" $\Phi_{Siv} = \phi_h - \phi_S$, and the measurable "Sivers asymmetry" can be written as

$$A_{Siv} = \sum_q e_q^2 \cdot \Delta_0^T q \otimes D_q^h / \sum_q e_q^2 \cdot q \otimes D_q^h, \tag{4}$$

where the only unknown terms are the Sivers functions indicated with $\Delta_0^T q$. It is important to note that, in SIDIS, the asymmetries due to the Collins and to the Sivers mechanisms depend on $\sin\Phi_{Coll}$ and $\sin\Phi_{Siv}$, which are orthogonal functions, and thus can be estimated independently using the same hadrons samples.

First results for $\pi^{\pm}$ from the HERMES 2002-2003 data, and for $h^{\pm}$ from the COMPASS 2002 data were shown at SPIN2004. Values compatible with zero for π^- and significantly positive asymmetries for π^+ were obtained with the proton target, showing that the Sivers effect is a real effect. On deuteron, the asymmetries were measured to be compatible with zero both for h^+ and h^- . All these data could be explained assuming cancellation between the u and d quarks.

Later on, HERMES has completed the analysis of the 2002-2004 data [11]; the measured asymmetries are shown as open points in the left plots of Fig 2. COMPASS has produced results for the whole sample of data collected from 2002 to 2004 [12, 13]. These new results have substantially smaller statistical error and confirm the first findings. Particularly interesting is the null result for the deuteron data, which implies

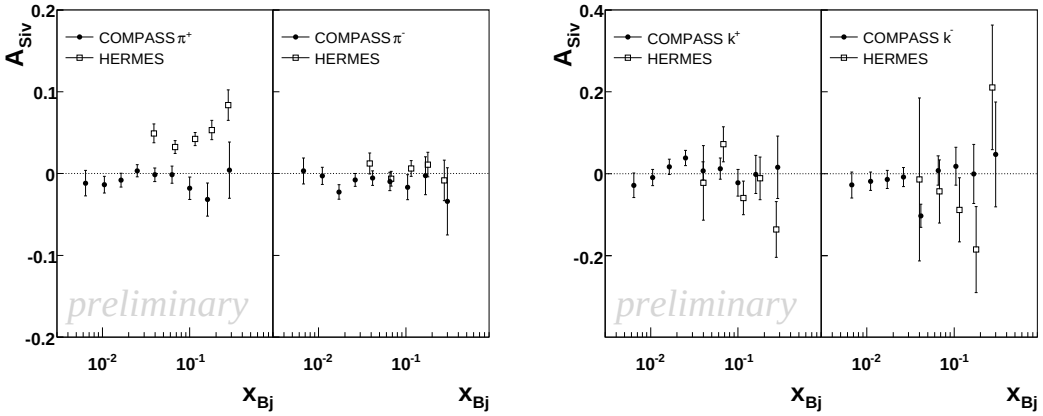

FIGURE 2. Sivers asymmetries for π^+ and π^- (left), and for K^+ and K^- (right) as a function of x. The open points are the HERMES 2002-2004 preliminary results, while the full points are the COMPASS 2003-2004 measurements ("all hadron" sample).

$\Delta_0^T u \sim -\Delta_0^T d$, and has been recently interpreted in terms of absence of gluon orbital angular momentum in the nucleon, as reported in [12]. Very good quality fits of the HERMES data were done, and the comparison with the 2002 COMPASS results was satisfactory [21]. However, when comparing the fits with the new data on deuteron, the agreement looks sometimes marginal [13] and for sure these data will allow to put further constrains on the Sivers DF's. Proton data from COMPASS and neutron data from JLAB are needed to confirm the present picture and to better constrain the d-quark distribution respectively.

Recently HERMES and COMPASS have also measured the Sivers asymmetries for $K^\pm$ and $\pi^\pm$ and $K^\pm$ respectively, which are shown in Fig. 2. As can be seen, the only asymmetries non compatible with zero are those for K^+ on proton. Here the signal is large, and it will be interesting to see which are the implications on the phenomenological descriptions of the data.

When the transverse intrinsic momentum is taken into account, new terms appear in the SIDIS cross-section at leading order [22]. In addition to the Collins and Sivers terms, there is one extra term in the cross section of unpolarised beam and target (related to the so-called Boer-Mulders DF), of unpolarised beam and longitudinally polarised target, of unpolarised beam and transversely polarised target, and of longitudinally polarised beam and transversely polarised target. They are all related to orthogonal functions of the azimuthal angles and the corresponding asymmetries can all be disentangled and measured in SIDIS. These measurements are regarded with increasing interest, because of their dependence on the transverse momentum, and both HERMES and COMPASS will be able to extract them using the already collected data. Presently the only preliminary results are those of CLASS, in which there is evidence for a Boer-Mulders effect.

To summarise, the study of transverse spin effects in SIDIS has progressed remarkably in the last years. Since SPIN2004 new important results have been obtained both on the experimental and the theoretical sides. The Collins mechanism has been firmly

established, the Collins FF's can be measured in e^+e^-, and the transversity DF's in SIDIS. The Sivers mechanism has been confirmed to be a real mechanism and important progress was done in understanding the relevance of the Sivers function and its connection with the orbital angular momentum. The overall picture is becoming clear and first attempts to extract the transversity and the Sivers DF's have already given quantitative results. Further phenomenological calculations, including the Belle results for the Collins FF and the present HERMES and COMPASS data will give soon more insights on the spin dependent DF's. In the near future, more results will come from HERMES with the 2005 data analysis and from COMPASS which will take data with a transversely polarised target in 2007. Also, the JLAB upgrade to 12 GeV and measurements with transversely polarised targets would give new important inputs in the large x regions.

All these measurements constitute a remarkable contribution towards the understanding of the transverse spin phenomena, and a solid starting point for the new projects which are being planned to precisely map all the transverse spin effects, like the high energy ep collider in the U.S., the polarised $\bar{p}p$ experiments at GSI, and the continuation of the SIDIS measurements at CERN.

REFERENCES

1. E. C. Aschenauer, "The Helicity Structure of the Nucleon from Lepton Scattering", these Proceedings.
2. V. Barone, A. Drago, Ph. Ratcliffe, *Phys. Rept.* **359**, 1 (2002).
3. V. Barone, "Understanding transversity: past and future", proceedings of the 16^th International Spin Symposium (SPIN2004), World Scientific, 2005.
4. A. Ogawa, "Transverse Spin Phenomena in pp and Polarized Fragmentation" these Proceedings.
5. D. Hasch, HERMES Collaboration, "Overview of HERMES", these Proceedings.
6. A. Magnon, COMPASS Collaboration, "Overview of COMPASS", these Proceedings.
7. Z.-E. Meziani, "Overview of J-Lab Experiments on Nucleon Spin Structure", these Proceedings.
8. X. Artru, "The Transverse Spin", Proceedings of 10th Rhodanien Seminar, hep-ph/0207309.
9. A. Ferrero, COMPASS Collaboration, "Measurement of Transverse Λ and Λ Polarization at COMPASS", these Proceedings.
10. R. Seidl, "Spin dependent fragmentation function analysis at Belle", these Proceedings.
11. M. Diefenthaler, HERMES Collaboration, "Azimuthal single-spin asymmetries in semi-inclusive deep-inelastic scattering on a transversely polarised hydrogen target", these Proceedings.
12. F. Bradamante, COMPASS Collaboration, "Single Hadron Transverse Spin Asymmetries from COMPASS", these Proceedings.
13. E.S. Ageev et al., COMPASS Collaboration, *Nucl. Phys. B*, in press, CERN-PH-EP-2006-031, hep-ex/0610068.
14. W. Vogelsang and F.Yuan, *Phys. Rev. D* **72**, 054028 (2005).
15. A. Efremov, "Collins Effect in SIDIS and in Electron-Positron-Annihilation", these Proceedings.
16. A. Prokudin, "Collins Effect in polarized SIDIS and e^+e^- Data", these Proceedings.
17. M. Contalbrigo, HERMES Collaboration, "Measurement of Transverse Asymmetries from Interference Fragmentation at HERMES", these Proceedings.
18. R. Joosten, COMPASS Collaboration, "Transversity Signals In Two Hadron Correlation at COMPASS", these Proceedings.
19. M. Radici, "Transversity and Inclusive Two-Pion Production", these Proceedings.
20. M. Budkart, "Hadron Tomography", these Proceedings; W. Vogelsan, "Single-Spin Asymmetries", these Proceedings.
21. M. Anselmino et al., "Comparing extractions of Sivers functions", Proceedings of the Int. Workshop on Transverse Polarization Phenomena in Hard Processes (Transversity 2005), World Scientific, 2006.
22. A. Kotzinian, *Nucl. Phys. B* **441**, 234 (1995). P.J. Mulders and R.D. Tangerman, *Nucl. Phys. B* **461**, 197 (1996). D. Boer and P.J. Mulders, *Phys. Rev. D* **57**, 5780 (1998).