COMPASS Results on Transverse Single-Spin Asymmetries

Anna Martin

University of Trieste and INFN Trieste

on behalf of the COMPASS Collaboration

New results on single spin asymmetries of charged hadrons produced in deep-inelastic scattering of muons on a transversely polarised ^{6}LiD target are presented. The data were taken in the years 2002, 2003 and 2004 with the COMPASS spectrometer using the muon beam of the CERN SPS at 160 GeV/c. Preliminary results are given for the Sivers asymmetry and for all the three "quark polarimeters" presently used in COMPASS to measure the transversity distributions. The Collins and the Sivers asymmetries for charged hadrons turn out to be compatible with zero, within the small ($\sim 1\%$) statistical errors, at variance with the results from HERMES on a transversely polarised proton target. Similar results have been obtained for the two hadron asymmetries and for the Λ polarisation. First attempts to describe the Collins and the Sivers asymmetries measured by COMPASS and HERMES allow to give a consistent picture of these transverse spin effects.

PACS: 13.60.-r, 13.88.+e, 14.20.Dh, 14.65.-q
Key words: transverse single-spin asymmetry, Collins asymmetry, Sivers asymmetry, COMPASS

1 Introduction

The importance of transverse spin effects at high energy is well known since 30 years, when the first measurements took place. It is only in the nineties, however, that the experimental and the theoretical progress allowed to point out their relevance in the understanding of the nucleon structure [1]). In that period, several new experiments (HERMES at DESY, COMPASS at CERN, the RHIC experiments at BNL, ...) were proposed to investigate the spin structure of the nucleon and the transverse spin effects, and important progress was done on the theoretical side. Since that, the activity in the field is continuously growing, giving a more and more complete picture.

Today, it is well established that to fully specify the quark structure of the nucleon at the twist-two level, the transverse spin distribution functions $\Delta_T q$ have to be added to the unpolarised distributions q and the helicity distributions Δq. The "new" parton distribution functions (PDF's), also called "transversity", are related to the probability that the quark spins are aligned parallel or antiparallel to the spin of a transversely polarised nucleon, and are still unknown. The distributions $\Delta_T q$ are in fact difficult to measure, since they are chirally odd and need to be coupled to a chirally odd partner. In particular, they cannot be measured in inclusive deep-inelastic scattering (DIS). They can be measured in

- hard scattering of transversely polarised protons on transversely polarised protons

[1]) For a more detailed description see, f.i., [1] and references therein.

looking at Drell-Yan processes as proposed by the RHIC experiments [3]. Here, however, the measured quantity is related to $\Delta_T q \cdot \Delta_T \bar{q}$ which is expected to be very small;
- hard polarised proton antiproton scattering looking again at Drell-Yan processes. This method has been proposed at the new FAIR facility at GSI [4] and will allow to measure directly $\Delta_T u \cdot \Delta_T u$. It should be a very clean measurement, but will not allow to extract informations on the transversity distribution of the other quarks;
- semi-inclusive DIS (SIDIS) of leptons on transversely polarised nucleons in which final state hadrons are also detected. This method is the subject of the present talk.

To access the transversity PDF in SIDIS, one has to measure the quark polarisation, i.e. to use the so-called "quark polarimetry". Different techniques have been proposed in so far. Three of them are presently used in COMPASS, namely:
- measurement of the single-spin asymmetries (SSA) in the azimuthal distribution of the final state hadrons (the so-called "Collins asymmetry");
- measurement of the SSA in the azimuthal distribution of the plane containing the final state hadron pairs (the so-called "two-hadron asymmetry");
- measurement of the polarisation of final state Λ hyperons (the so-called "Λ polarimetry"),
which are described in the following sections.

In the last ten years, the interest for the intrinsic transverse momentum of quarks inside a nucleon or a hadron grew-up considerably, and the transverse momentum dependent (TMD) distribution functions and fragmentation functions (FF) are today considered an important ingredient in the structure of the nucleon. Some of these TMD distributions can be extracted in SIDIS looking at the azimuthal distributions of the final state hadrons. As explained in the next section, this is true in particular for the so-called "Sivers asymmetry", which is, together with the Collins asymmetry, presently the most studied. Through the Sivers asymmetry it is possible to access the Sivers PDF, which takes into account a possible deformation in the distribution of the quark intrinsic transverse momentum in a transversely polarised nucleon.

1.1 Single hadron asymmetries

1.1.1 The Collins asymmetry

The distributions $\Delta_T q$ may be extracted from measurements of the SSA's in the cross-section of SIDIS of leptons on transversely polarised nucleons.

This method is based on the so-called "Collins effect", which could be responsible for a left-right asymmetry in the fragmentation of transversely polarised quarks [2]. For spinless hadrons, the fragmentation function of a polarised quark is expected to be of the form

$$D_T{}_q^h(z, \vec{p}_T^{\,h}) = D_q^h(z, p_T^h) + \Delta_T^0 D_q^h(z, p_T^h) \cdot \sin \Phi_C,$$

where $\vec{p}_T^{\,h}$ is the hadron transverse momentum with respect to the quark direction, z is the fraction of available energy carried by the hadron, $D_q^h(z, p_T^h)$ is the usual

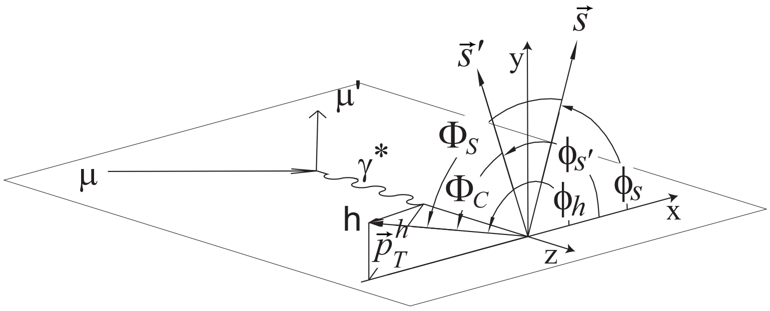

Fig. 1. Definition of the Collins and Sivers angles. The vectors $\vec{p}_T^{\,h}$, $\vec{s}$ and $\vec{s}\,'$ are the hadron transverse momentum and the spins of the initial and struck quarks respectively.

FF, and the Collins function $\Delta_T^0 D_q^h$ is the spin dependent T-odd part of the FF of a transversely polarised quark q into a hadron h. The "Collins angle" $\Phi_C = \phi_h - \phi_{s'}$ is the difference between the azimuthal angle of the hadron and the azimuthal angle of the spin of the fragmenting quark evaluated from the quark momentum. The Collins function $\Delta_T^0 D_q^h$ has to be measured independently, and, after some attempts to extract it from the e^+e^- annihilation data from the DELPHI experiment at LEP, it is now being measured at BELLE. First results [5, 6] indicate very clearly that the Collins effect is real and that the spin dependent FF is different from zero. The Collins effect is also expected to be largest for the leading hadron in the current jet, i.e. the hadron with the highest momentum [7].

In SIDIS on a transversely polarised target, the Collins effect is responsible for a measurable asymmetry in the distribution of final state hadrons, related to a convolution of the transversity distributions and the Collins fragmentation functions. The number of hadrons h in a given bin of the Bjorken variable x, or of z, or of p_T^h is given by

$$N^{h\,\pm}(\Phi_C) = N_0^{h\,\pm} \cdot (1 \pm A_C^m \cdot \sin\Phi_C)$$

where $\pm$ refers to the target spin orientation (spin "up" and "down" in the laboratory system), and $N_0^{h\,\pm}$ is the mean number of hadrons, depending on the incident lepton flux, the acceptance and efficiency of the apparatus and the unpolarised cross-section. The Collins angle Φ_C is evaluated as if the target spin is always oriented "up". In SIDIS, since $\phi_{s'} = \pi - \phi_s$, where ϕ_s is the azimuthal angle of the initial state quark with respect to the lepton scattering plane, it is given by

$$\Phi_C = \phi_h + \phi_S - \pi\,.$$

where ϕ_h and ϕ_S are the azimuthal angles with respect to the lepton scattering plane of the hadron transverse momentum and of the initial nucleon spin respectively, as illustrated in Fig. 1.

From the angular distribution of the hadrons, one can thus measure the asymmetry

$$A_C^m = P_T \cdot f \cdot D_{NN} \cdot A_{Coll}\,,$$

where f is the polarised target dilution factor, P_T is the target polarisation, and $D_{NN} = (1-y)/(1-y+y^2/2)$ is the transverse spin transfer coefficient from the initial to the struck quark. At leading twist in the collinear parton model, the "Collins asymmetry" is given by

$$A_{Coll} = \frac{\sum_q e_q^2 \cdot \Delta_T q \cdot \Delta_T^0 D_q^h}{\sum_q e_q^2 \cdot q \cdot D_q^h} .$$

Using proton and deuteron (or neutron) targets and selecting different final state hadrons and knowing the Collins FF's, it is thus possible separate the contributions of the quarks of different flavour and thus extract the transversity distributions.

In the most general case in which the quark intrinsic momentum is considered and TMD distributions and fragmentation functions are used, convolution integrals appear in the SIDIS cross-section [8, 9]. Still, assuming Gaussian distributions for the parton and the hadron transverse momenta in the PDF's and in the FF's, the previous expression for the Collins asymmetry is valid when multiplied by a factor which depends on mean values of the transverse momenta (see f.i. [10, 11]).

1.1.2 The Sivers asymmetry

When considering the parton and the hadron transverse momenta, at leading order, in addition to the transversity PDF, in the SIDIS cross-section two other PDF's appear in the case of unpolarised lepton beam and transversely polarised target, and one more if the lepton beam is longitudinally polarised.

The corresponding SSA's depend on different and independent functions of the azimuthal angles of the target nucleon spin and of the momentum of the hadron, and can all be extracted from the same data samples.

Till now only the "Sivers asymmetry" has been measured, in addition to the Collins one.

As suggested by Sivers [12] there is a possible correlation between the transverse momentum $\vec{k}_T$ of an unpolarised quark in a transversely polarised nucleon and the nucleon polarisation vector, i.e. the spin-averaged quark distribution $q(x)$ can be written as

$$q_T(x, \vec{k}_T) = q(x, k_T) + |\vec{S}_\perp| \cdot \Delta_0^T q(x, k_T) \cdot \sin \Phi_S$$

where the "Sivers angle" $\Phi_S = \phi_q - \phi_S$ is the relative azimuthal angle between the quark transverse momentum $\vec{k}_T$ and the target spin $\vec{S}_\perp$, and the PDF $\Delta_0^T q(x, k_T)$ is the so-called "Sivers function". If the hadron produced in the fragmentation and the fragmenting quark are collinear, i.e. if all the hadron transverse momentum originates from the intrinsic transverse momentum of the quark in the nucleon, the Sivers angle, shown in Fig. 1, becomes $\Phi_S = \phi_h - \phi_S$. The distribution of the number of events in the Sivers angle for the two target orientations is then given by

$$N^{h\,\pm}(\Phi_S) = N_0^{h\,\pm} \cdot (1 \pm A_S^m \cdot \sin \Phi_S) .$$

In this case the measurable asymmetry is

$$A_S^m = P_T \cdot f \cdot A_{Siv} .$$

At leading twist and assuming the final hadron to be collinear with the fragmenting quark, the "Sivers asymmetry" is given by

$$A_{Siv} = \frac{\sum_q e_q^2 \cdot \Delta_0^T q \cdot D_q^h}{\sum_q e_q^2 \cdot q \cdot D_q^h} .$$

In this case the FF's are known; combining data collected with proton and deuteron (or neutron) targets and selecting different final state hadrons it is thus possible to separate the contributions of the quarks of different flavour from SIDIS data only.

As for the Collins asymmetry, assuming Gaussian distributions for the parton and the hadron transverse momenta in the PDF and in the FF, the previous expression for the asymmetry is still valid when multiplied by a factor which depends on the mean values of the transverse momenta.

1.2 Two-hadron asymmetry

In accessing transversity via single hadron Collins asymmetry, one may be sensible to different effects which might damp the effect or even spoil the measurement. As an alternative method it has been proposed (see [7] and references therein) to measure the "relative Collins effect" between two fast particles of the jet, which allows to measure an asymmetry which is practically not affected by fluctuations in the fragmenting quark momentum. Assuming that the $q\bar{q}$ pairs are created in the $^3P_0$ state, an asymmetry is expected in a semi-classically model of string fragmentation. In the S-matrix theory, the asymmetry is due to the interference between the helicity-flip amplitude and the helicity-conserving one (the "interference fragmentation") [13].

Experimentally, this asymmetry is measured very much like the Collins one, essentially replacing the azimuthal angle of the hadron ϕ_h with the azimuthal angle of the plane of the two hadrons ϕ_R. In COMPASS ϕ_R is defined as the azimuthal angle with respect to the lepton scattering plane of $\vec{R}_T$, the component transverse to the virtual photon of the vector

$$\vec{R} = \frac{z_2 \cdot \vec{p}^{h_1} - z_1 \cdot \vec{p}^{h_2}}{z_1 + z_2} ,$$

where the indexes 1 and 2 refer to the two final state hadrons.

Form the angular distribution in $\phi_{RS} = \phi_R - \phi_h$ it is possible to measure the asymmetry

$$A_{2h}^m = P_T \cdot f \cdot D_{NN} \cdot A_{RS} ,$$

where

$$A_{RS} = \frac{\sum_q e_q^2 \cdot \Delta_T q \cdot H_q^{2h}}{\sum_q e_q^2 \cdot q \cdot D_q^{2h}} .$$

Both the spin dependent fragmentation function H_q^{2h}, and the corresponding spin-averaged FF D_q^{2h}, are unknown, and need to be measured in e^+e^- annihilation or to be evaluated using models. They are expected to depend on $z = z_1 + z_2$ and on the invariant mass of the two hadrons.

1.3 Λ polarimetry

This is one of the first methods proposed to access transversity, and the favoured one by some authors (see f.i. [7] and [14]). In this case, the information on the transversity PDF is obtained by measuring the polarisation of the current jet Λ ($\bar{\Lambda}$) produced in SIDIS.

The transverse polarisation of the Λ measured with respect to the nucleon spin axis $\vec{S}_\perp$ is related to the transversity PDF by

$$P_\Lambda^S = f \cdot P_T \cdot D_{NN} \cdot \frac{\sum_q e_q^2 \cdot \Delta_T q \cdot \Delta_T D_q^\Lambda}{\sum_q e_q^2 \cdot q \cdot D_q^\Lambda}\,, \qquad (1)$$

where $\Delta_T D_q^\Lambda$ is the transversely polarised fragmentation function of the quark q into a Λ. It needs to be measured independently, and is interesting by itself.

Introducing in the Λ rest frame the angle θ_S^* between $\vec{S}_\perp$ and the momentum of the proton emitted in the Λ decay, P_Λ^S can be measured by the distribution of the number of events, since

$$N^\pm(\theta_S^*) \simeq 1 \pm \alpha \cdot P_\Lambda^S \cdot \cos\theta_S^*\,,$$

where $\alpha = 0.642 \pm 0.013$ is the decay asymmetry parameter. The sign $\pm$ refer to the two possible orientations of the target spin ($\vec{S}_\perp$ is defined pointing upward in the laboratory system for both target spin orientations).

The only disadvantage of this measurement, which makes it less popular than the previous ones, is that, as expected, its statistical efficiency as a quark polarimeter is poor, due to the relatively small abundance of weak-decaying hyperons in quark jets.

2 The COMPASS experiment

COMPASS is a fixed target experiment which was proposed to CERN in 1996 to investigate hadron structure and hadron spectroscopy using both hadron and muon high-energy beams from the SPS. Apart from a short pilot run in 2004 with a pion beam, in so far the experiment has focussed on the study of the spin structure of the nucleon, taking data from 2002 to 2004 with a μ^+ beam and a polarised deuteron target.

The experiment has been run at a muon energy of 160 GeV. The μ^+ beam, originated from the decay of π and K mesons, has a longitudinal polarisation of about -76%. The target polarisation can be oriented both longitudinally and transversely with respect to the beam direction. Most of the time, data have been taken in the longitudinal target spin mode, to measure $\Delta G/G$ [15, 16], the polarisation of the gluons in a longitudinally polarised nucleon; in parallel very precise A_1^d data are also collected [17, 18, 19]. In about 20% of the running time, data were taken with the transverse target polarisation to measure transverse spin effects. The initial choice of the deuteron (^{6}LiD) as target material was due to the favourable value of the dilution factor ($f \simeq 0.4$), particularly important for the measurement of $\Delta G/G$.

Measurements with a NH_3 polarised proton target are also part of the experimental programme.

The uniqueness of the COMPASS experiment consists in its capability to measure lepton-nucleon scattering with a high energy and high intensity beam over a broad kinematical range, and with a large angular acceptance for the final state particles. To match these goals, the spectrometer [20] comprises two magnetic stages, which include state-of-the-art small and large area tracking detectors, a RICH detector [21], hadronic calorimeters, and systems for muon identification.

The first magnetic stage (the "large angle spectrometer") has a design acceptance of about ±200 mrad in both planes, to fully contain the hadrons of the current jet. The second stage (the "small angle spectrometer") measures the higher energy forward particles.

The polarised target system [20, 22] consists of two oppositely polarised target cells, 60 cm long each and 3 cm diameter sitting in a superconducting polarised target magnet (PTM), so that data are collected simultaneously for the two target spin orientations. In the first three years of data taking, the large acceptance COMPASS PTM was not available, and the PTM from the previous experiment SMC was used, with a reduction in the acceptance of the apparatus. The PTM provides both a solenoidal field and a dipole field used for adiabatic spin rotation and for the transversity measurements. To run in the transverse polarisation mode, the target is first polarised in the solenoidal field (typical values of the polarisation are $P_T \simeq 0.50$), then the spins are frozen and rotated adiabatically to the transverse direction.

Since the spectrometer acceptance is somewhat different for the two target halves, the asymmetries cannot be obtained from a direct comparison of the number of events collected in the two cells. Usually, in a data taking period in the transverse mode, the spins of both the target cells are reversed by exchanging the microwave frequencies of the cells after about 5-6 days of data taking. To reduce possible systematic effects the asymmetries have been evaluated using combinations of the number of events collected in the two cells with opposite polarisation, before and after the spin reversal. In order to minimise possible efficiency variations before and after the spin reversal, during the data taking in the transverse spin mode, particular care was put in keeping the spectrometer functioning smoothly.

In the first three years of data taking from 2002 to 2004, COMPASS collected about 200 TByte of raw data in the transverse configuration. Thanks to the continuous improvement of the hardware and of the reconstruction software, the number of reconstructed events increased by about a factor of 2 each year.

3 COMPASS results

The results for the Collins and Sivers asymmetries from the 2002 data have been published at the beginning of 2005 [23]. In the mean time the 2003 and 2004 data have been fully analysed, and the paper has been sent for publication [1] soon after this Conference.

Preliminary results for the Collins and Sivers asymmetries for identified particles from the 2003 and 2004 data, for the two-hadron asymmetry from the whole data set, and for the Λ polarisation from the 2002 and 2003 data have been produced, and are also described in the following.

3.1 The Collins and Sivers asymmetries for charged hadrons

3.1.1 Data analysis

The 2003 and 2004 data have been analysed essentially in the same way as the 2002 data. Only DIS events (defined by a photon virtuality $Q^2 > 1$ (GeV/c)^2, and a fractional energy of the virtual photon $0.1 < y < 0.9$) with at least one reconstructed charged hadron produced in the muon interaction point have been used. The asymmetries have been evaluated for two (correlated) data samples:
- the "leading hadron" sample, in which only the leading (i.e. the most energetic) reconstructed hadron in the DIS event is used. In our selection the leading hadron must have $z > 0.25$. The total statistics from the data collected in the years 2002, 2003, and 2004 is 1.4, 3.0, and 5.8 million events.
- the "all hadron" sample, in which all the reconstructed hadrons with $z > 0.2$ are used.

The reason for this "double" evaluation is that, in the string model [7], it is expected that in the fragmentation the sub-leading meson prefers the opposite side with respect to the leading one, thus diluting the signal.

As already mentioned, the Collins and Sivers asymmetries have been extracted from the same data sample looking separately at the modulation of the distribution in the Collins and Sivers angles Φ_C and Φ_S. Taking advantage of the two-cell configuration of the polarised target system, we used as estimators the quantities

$$A_j(\Phi_j) = \frac{N^+_{j,u}(\Phi_j)}{N^-_{j,u}(\Phi_j)} \cdot \frac{N^+_{j,d}(\Phi_j)}{N^-_{j,d}(\Phi_j)} \simeq 1 + 4 \cdot A^m_j, \quad j = C, S\,.$$

These estimators, used as cross-check in the 2002 analysis, have several advantages. In particular they minimise the possible acceptance effects, and spin independent term in the cross-section cancel out at first order.

Because of the large statistics used to extract the final asymmetries (about a factor of 8 with respect to that of the 2002 data), a large amount of work has been done to evaluate the systematic errors. The data have been scrutinised, and the stability of the spectrometer during the different periods of data taking has been checked. Thanks to the fact that the transverse spin measurements usually were carried out at the end of the data taking, when the spectrometer was fully operational and functioning smoothly, only a small fraction of the data had to be rejected. Many tests have been performed on the stability of the results vs time and acceptances, and on the consistency of the results from the different data taking periods. In all the tests no indication for systematic effects has been observed, with the conclusion that the systematic errors are considerably smaller than the statistical ones.

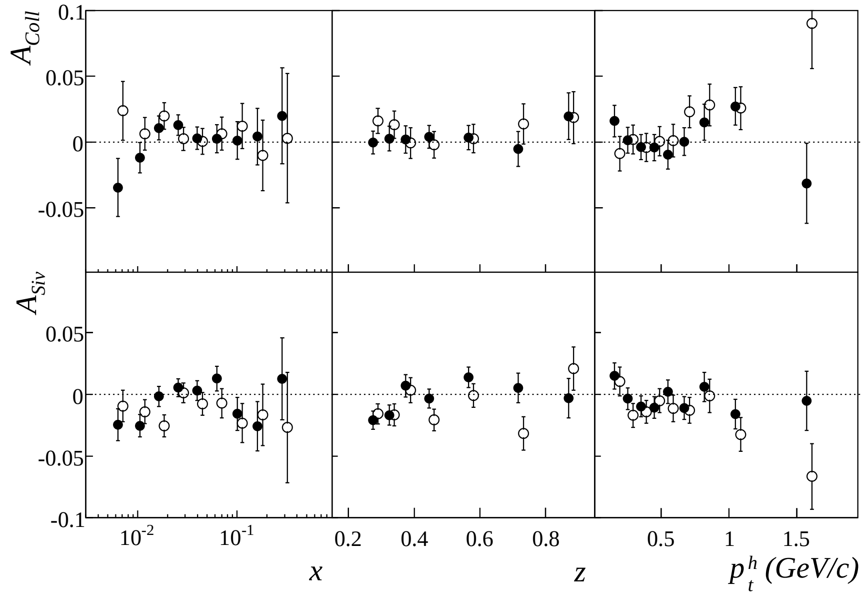

Fig. 2. Collins asymmetry (top) and Sivers asymmetry (bottom) against the Bjorken variable x (or x_{Bj}), z and p_T^h for positive (full circles) and negative leading hadrons (open circles) from the 2002, 2003, and 2004 data.

3.1.2 Results

The results from the 2002-2004 data [1] for the leading hadron sample and for the all hadron sample are given in Fig. 2 and 3 respectively. They confirm with much better precision the results from the 2002 data: all the asymmetries are compatible with zero, within the statistical errors, now of the order of percent.

The results for the Collins asymmetry are at variance with the HERMES [24] measurement on the transversely polarised proton target. This is true not only at small values of the Bjorken variable x, where anyhow the transversity distributions are expected to be small, but also in the range $0.05 < x < 0.3$, where HERMES observed asymmetries different from zero, both for positive and negative pions. Moreover, the fact that our results are obtained for unidentified hadrons cannot justify the difference since most of charged hadrons are in fact pions (see also next section). Thus, the obvious conclusions is that the asymmetries compatible with zero measured by COMPASS are due to the use of a deuteron target. i.e. to the different combination of the transversity PDF's we are probing. In a simplified parton model framework, assuming that only pions are involved and neglecting the contribution of the sea quarks, in the case of a deuteron target it is

$$A_{Coll}^{d,\pi^+} \simeq \frac{\Delta_T u_v + \Delta_T d_v}{u_v + d_v} \frac{4\Delta_T^0 D_1 + \Delta_T^0 D_2}{4D_1 + D_2}\,,\; A_{Coll}^{d,\pi^-} \simeq \frac{\Delta_T u_v + \Delta_T d_v}{u_v + d_v} \frac{\Delta_T^0 D_1 + 4\Delta_T^0 D_2}{D_1 + 4D_2}$$

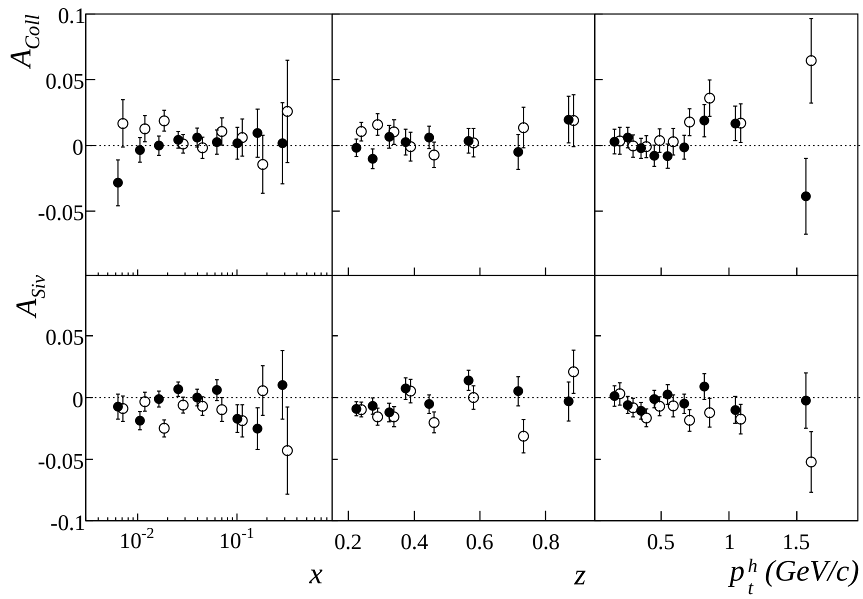

Fig. 3. Collins asymmetry (top) and Sivers asymmetry (bottom) against x, z and p_T^h for all positive (full circles) and all negative hadrons (open circles) from 2002 - 2004 data.

where $D_1 = D_u^{\pi^+} = D_d^{\pi^-}$ and $D_2 = D_d^{\pi^+} = D_u^{\pi^-}$ are the favoured and unfavoured FF's. For a proton target, the asymmetries are given by

$$A_{Coll}^{p,\pi^+} \simeq \frac{4\Delta_T u_v \Delta_T^0 D_1 + \Delta_T d_v \Delta_T^0 D_2}{4u_v D_1 + d_v D_2}\,,\; A_{Coll}^{p,\pi^-} \simeq \frac{4\Delta_T u_v \Delta_T^0 D_2 + \Delta_T d_v \Delta_T^0 D_1}{4u_v D_2 + d_v D_1}\,.$$

Neglecting the d quark contribution to the asymmetries, the HERMES data suggest $\Delta_T^0 D_2 \simeq -\Delta_T^0 D_1$, a somehow unexpected result which is not excluded from the BELLE measurements [5, 6]. Even in this case, however, it is not straightforward to understand why the deuteron asymmetries are so small.

Phenomenological calculations have been performed by three different groups [25, 11, 26] to extract information on the transversity PDF's and the Collins FF's. The common approach has been to first fit the HERMES data [27, 24] and then compare the model calculations with the BELLE and COMPASS 2002 measurements [23]. All the considered data are in agreement with the result that the favoured and unfavoured Collins FF's are of the same magnitude and of opposite sign, and that the u quark contribution is dominant. The comparison between our new data and the calculations of Ref. [25] (upper plots) and Ref. [11] (lower plots) is shown in Fig. 4. The agreement is still satisfactory, but clearly a global analysis including the present deuteron data will allow to put tighter constrains on the transversity distributions. It is also clear, however, that more data from BELLE, HERMES, and COMPASS (in particular with a proton target), are needed to extract precise information.

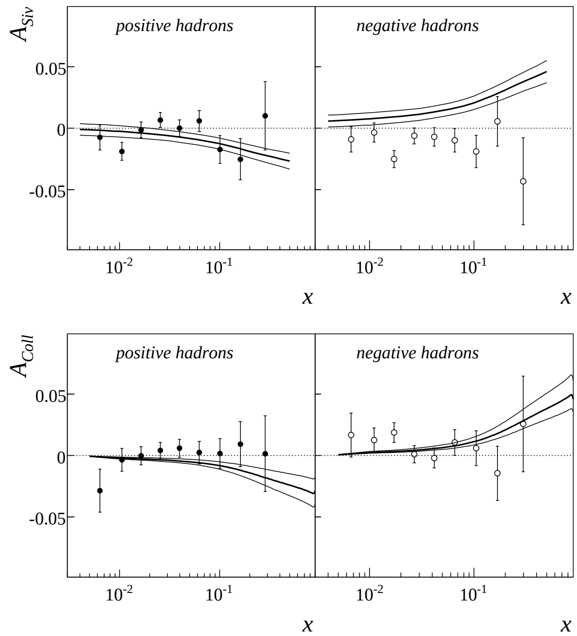

Fig. 4. Collins asymmetry: comparison between the 2002-2004 COMPASS results for positive (left) and negative (right) hadrons with the calculations of Ref. [25] (upper plots) and Ref. [11] (lower plots). The upper and lower curves represent the theoretical uncertainty.

The new precise results for the Sivers asymmetry confirm that also this effect on a deuteron target at COMPASS energies is very small, while the measurements on a proton target from HERMES [27, 24] give a clear indication for a positive asymmetry for π^+ and values compatible with zero for π^-. In the simplified parton model described before, the Sivers asymmetries are given by

$$A_{Siv}^{p,\pi^+} \simeq \frac{4\Delta_0^T u_v D_1 + \Delta_0^T d_v D_2}{4u_v D_1 + d_v D_2}\,, \; A_{Siv}^{p,\pi^-} \simeq \frac{4\Delta_0^T u_v D_2 + \Delta_0^T d_v D_1}{4u_v D_2 + d_v D_1}\,.$$

and

$$A_{Siv}^{d,\pi^+} \simeq A_{Siv}^{d,\pi^-} \simeq \frac{\Delta_0^T u_v + \Delta_0^T d_v}{u_v + d_v}\,.$$

The COMPASS result thus indicates a cancellation between the u and d quark Sivers functions while the HERMES results suggest $\Delta_0^T d_v \simeq -2\Delta_0^T u_v$.

Much more complete theoretical calculations have been done [25, 28, 10, 29] to constrain the Sivers functions, using mainly the HERMES data. In all cases, the result is that the u and d quark PDF are of the same size and have opposite sign, and their parametrisations give asymmetries for the deuteron which are in agreement COMPASS 2002 results. The agreement with the new COMPASS data is not always as good as for the 2002 results, as can be seen in Fig. 5, in which the

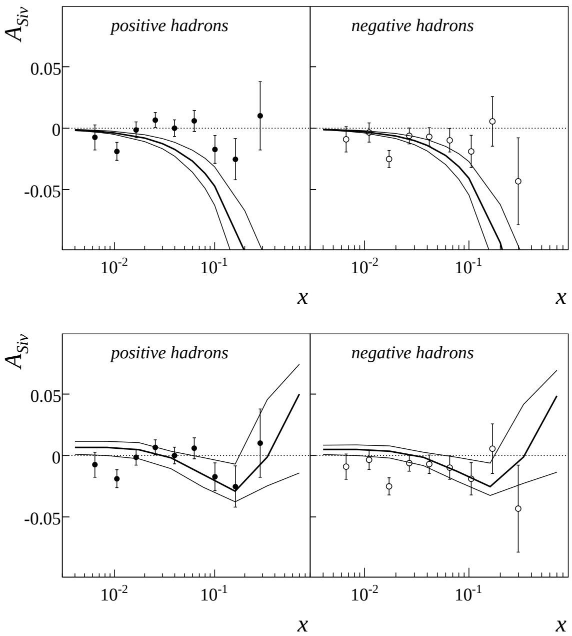

Fig. 5. Sivers asymmetry: comparison between the 2002-2004 COMPASS results for positive (left) and negative (right) hadrons with the calculations of Ref. [25] (upper plots) and Ref. [28] (lower plots).

curves are the calculations from Ref. [25] (upper plots) and Ref. [28] (lower plots). It is clear that our results will allow to better define the overall picture.

3.2 The Collins and Sivers asymmetries for identified hadrons

The RICH detector was fully operational during transverse spin data taking in the years 2003 and 2004. For these data, the full analysis including particle identification has been performed to measure π and K asymmetries. Momentum cuts have been applied to be above the Cherenkov threshold ($p_\pi \simeq 2$ GeV/c and $p_K \simeq 9$ GeV/c) and to guarantee at least a 1.5 σ mass separation between the two hypothesis ($p_{\pi,K} < 50$ GeV/c). The statistics of the final all hadron samples is 5.2 and 4.5 millions of π^+ and π^-, and 0.9 and 0.45 millions of K^+ and K^-.

The Collins and Sivers asymmetries have been evaluated both for the all hadron and the leading hadron samples, getting in the two cases very similar results. The Collins asymmetries for all pions and all kaons are shown in Fig. 6 against x, z and p_T^h. The corresponding Sivers asymmetries are given in Fig. 7. The errors shown in the figures are statistical only (all the tests performed following the charged hadron analysis have shown no evidence for systematic effects) and they are comparable with the HERMES statistical errors in the overlapping x range, i.e. in the last five bins.

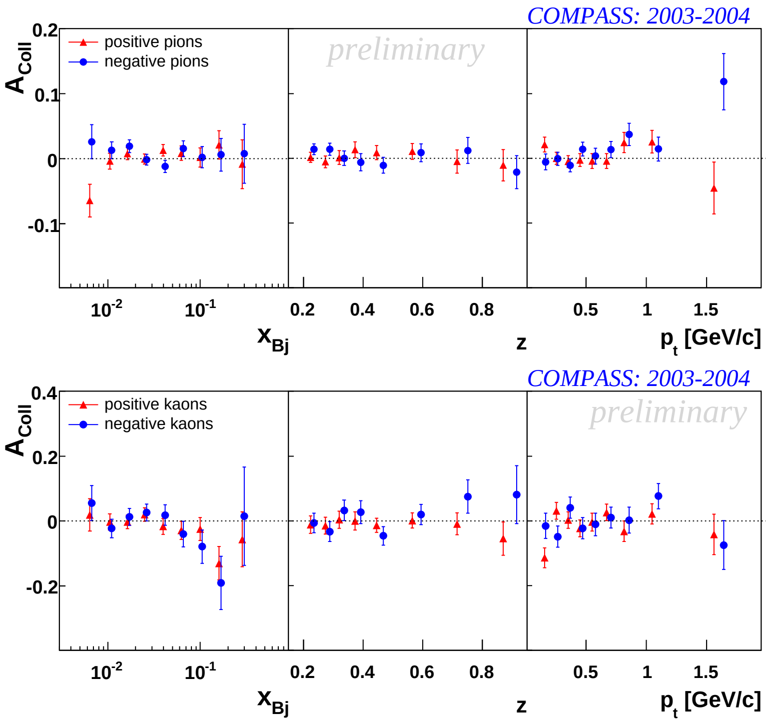

Fig. 6. Collins asymmetry against x, z and p_T^h for positive (full triangles) and negative (full circles) π in the upper plots, and K in the lower plots, from 2003 and 2004 data.

As expected, the measured pion asymmetries are very similar to the unidentified hadron asymmetries, thus confirming the picture described in the previous section.

The kaon asymmetries have somewhat larger errors, and again no significant signal is visible both in the Collins and the Sivers asymmetries. The recent results on proton from HERMES [30] show a clear positive asymmetry only in the Sivers case, for positive K, and the COMPASS result could again indicate a cancellation due to the deuteron target. Both the HERMES and COMPASS data are new, and the interpretation work is ongoing.

3.3 Two-hadron asymmetry

Preliminary results from the 2002 and 2003 data have been produced last year. Now the analysis is almost over and the results from the 2004 data, which double the available statistics, are presented.

The analysis has been performed much as the for the single hadron asymmetries measurements, the main difference being that now a hadron pair in the final state has to be identified.

The “standard” recepi is to consider all combinations of positive - negative

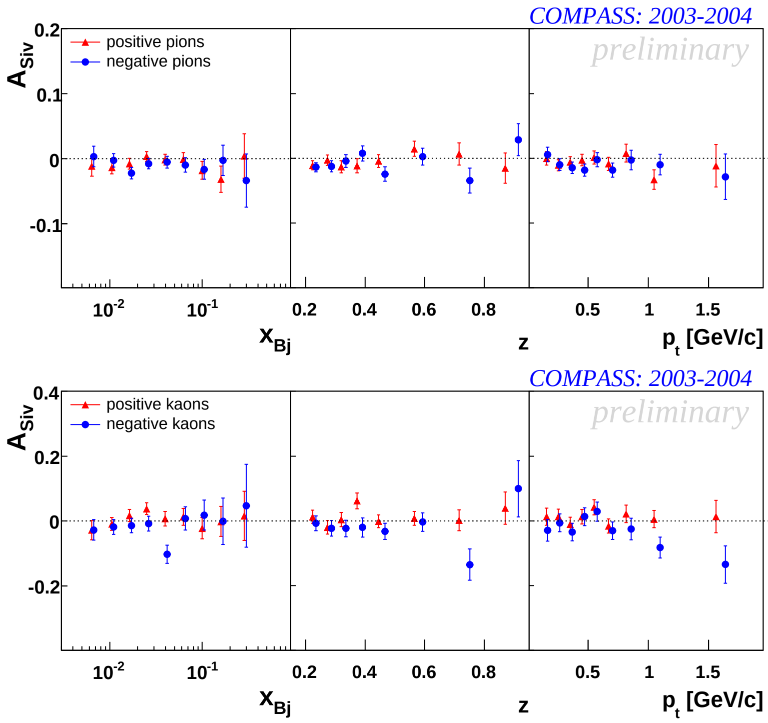

Fig. 7. Sivers asymmetry against x, z and p_T^h for positive (full triangles) and negative (full circles) π in the upper plots, and K in the lower plots, from 2003 and 2004 data.

hadrons, labelling as "hadron 1" the positive one in the angle ϕ_{RS} calculation. Only pairs with $z_1 > 0.1$, $z_2 > 0.1$ and $z = z_1 + z_2 < 0.9$ have been used. The total number of pairs for the whole data sample consists of about 6 million pairs. The preliminary results for A_{RS} against x, against the invariant mass of the pair M_{inv}, and against z are shown in Fig. 8. The error bars show the statistical error. Once more, the asymmetries are compatible with zero, within the small statistical error. This is at variance with the HERMES measurement for a proton target [31] of a significantly different from zero two-hadron asymmetry. The COMPASS result may be a further evidence of the cancellation which takes place in the case of the deuteron target. Theoretical work on the interpretation and the modelling of the two hadron asymmetry is ongoing [13], and, in spite of the still unknown FF's which appear in its expression, it looks to be a very promising tool to better understand transversity.

Several attempts to isolate a signal in the COMPASS data have been done looking at different definitions of the hadron pair. In particular in each event we considered only the two hadrons with the largest p_T, to look at hard DIS processes, measuring again asymmetries compatible with zero [32]. An other approach consists in selecting only the leading and subleading produced particles ("z-ordered" pairs)

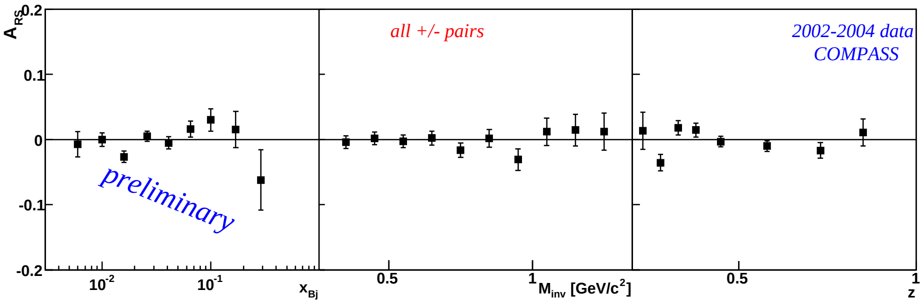

Fig. 8. Two hadron asymmetry against x, the invariant mass of the hadron pair M_{inv}, and z for all oppositely charged hadron pairs from 2002, 2003 and 2004 data.

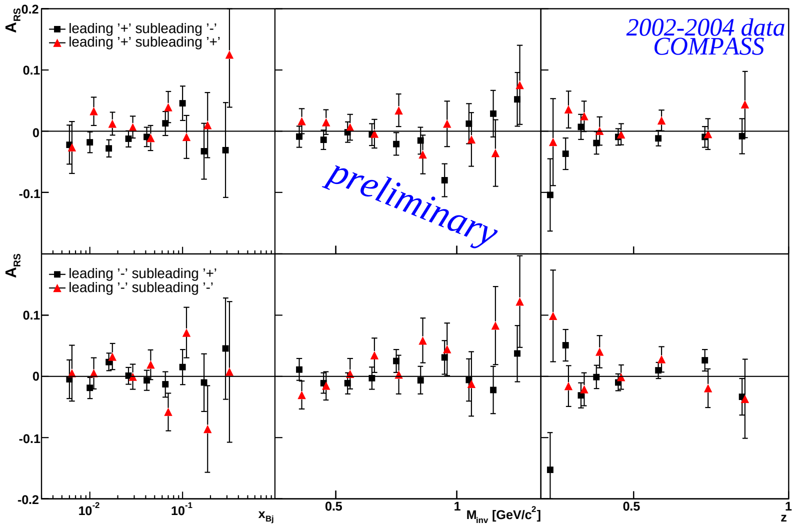

Fig. 9. Two hadron asymmetry against x, the invariant mass of the hadron pair M_{inv} and z for "z-ordered" hadron pairs from 2002, 2003 and 2004 data.

in the event, which should be the most favourable combination following the string model. The preliminary results are shown in Fig. 9; also in this case it is hard to see a signal. Work to measure the asymmetries using the RICH information is in progress, and preliminary results should be available soon.

3.4 Λ polarimetry

The analysis of the 2004 data is still ongoing, and the preliminary results on Λ polarisation discussed here are from the 2002 and 2003 data.

Presently, the RICH information is not used in the Λ identification, which relies

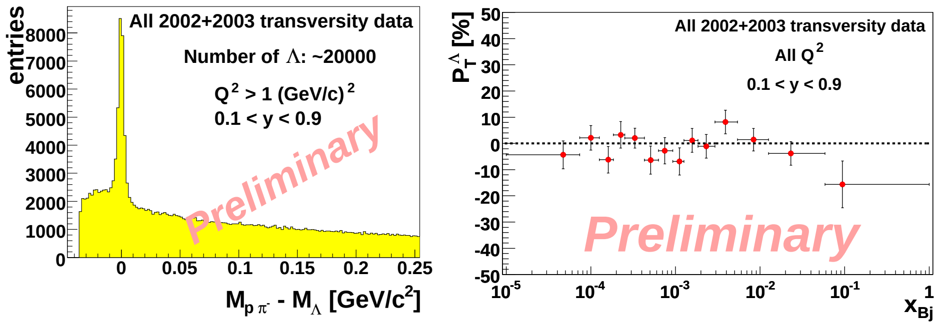

Fig. 10. Left: invariant mass spectrum for all DIS events with $Q^2 > 1$ (GeV/c)^2. Right: transverse Λ polarisation for all Q^2 events.

on kinematical cuts [33]. The background is mainly due to K^0 decays, photon conversion, and wrongly reconstructed decay vertices. To reduce these last two contributions the decay vertex is required to fall in between the downstream-end of the target and the first tracking detector (about 1.1 m downstream of the target). Also, cuts on the transverse momentum of the positively charged secondary particle with respect to the Λ candidate direction are applied. As can be seen in Fig. 10 (left plot) the invariant mass spectrum shows a very clean signal over a smooth background. The number of Λ's inclusively produced is about 20k for $Q^2 > 1$ (GeV/c)^2 and 10 times more for all Q^2. Similar numbers are expected from the 2004 data alone. The number of $\bar{\Lambda}$'s is about a factor of 2 smaller.

The preliminary result for the transverse Λ polarisation from the 2002 and 2003 data is shown in Fig. 10 (right) for all Q^2 events. Given the correlation between x and Q^2, the contribution of the events with $Q^2 > 1$ (GeV/c)^2 is dominant in the last two x bins. The errors on the data points are the statistical ones (systematic errors have been evaluated to be not larger than the statistical errors); as expected, they are much larger than for the hadron asymmetries. More input on this interesting channel will come from the 2004 data and from the $\bar{\Lambda}$ polarisation [34].

4 Conclusions

The data collected by the COMPASS experiment with the transversely polarised deuteron target in the years 2002-2004 have been almost completely analysed.

All the transverse spin effects investigated in so far (Collins and Sivers asymmetries, two-hadron asymmetries, Λ polarisation) are compatible with zero and can be interpreted as an indication of a cancellation between the u and the d contributions in the deuteron.

Important theoretical work is ongoing to extract informations on the transversity PDF's from the new measurements of the Collins asymmetries by COMPASS and HERMES, and of the Collins FF's by BELLE.

A first interpretation of the measured Sivers asymmetries in terms of PDF's has also been put forward and the new data will help in better specifying the global picture.

The general feeling is that much more data and a global analysis of all available measurements are needed to formulate a more quantitative picture. In addition to the finalisation of the analysis of the 2002-2004 data the COMPASS contribution in the near future will be the measurement, with comparable statistics, of the transverse spin effects with the proton target, now scheduled at the beginning of the 2007 run.

On a longer time scale, plans are being defined to continue this promising and exciting field of research in SIDIS at CERN [35].

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