First measurements of Collins and Sivers deuteron asymmetries

The COMPASS Collaboration

V.Yu. Alexakhin [7], Yu. Alexandrov [14], G.D. Alexeev [7], B. Badełek [24], F. Balestra [23], J. Ball [19], G. Baum [1], Y. Bedfer [19], P. Berglund [12], C. Bernet [19], R. Bertini [23], R. Birsa [22], J. Bisplinghoff [3], F. Bradamante [22], A. Bravar [13], A. Bressan [22], E. Burtin [19], M.P. Bussa [23], L. Cerini [22], A. Chapiro [21], A. Cicuttin [21], M. Colantoni [23†], A.A. Colavita [21], S. Costa [23], M.L. Crespo [21], N. d'Hose [19], S. Dalla Torre [22], S. Dasgupta [5], R. De Masi [15], N. Dedek [16], O.Yu. Denisov [23‡], L. Dhara [6], V. Diaz Kavka [21], A.V. Dolgopolov [18], S.V. Donskov [18], V.A. Dorofeev [18], N. Doshita [17], V. Duic [22], W. Dünnweber [16], A. Efremov [7], J. Ehlers [11], P.D. Eversheim [3], W. Eyrich [8], M. Fabro [22], M. Faessler [16], P. Fauland [1], A. Ferrero [23], L. Ferrero [23], M. Finger [7], M. Finger jr. [7], H. Fischer [9], J. Franz [9], J.M. Friedrich [15], V. Frolov [23‡], U. Fuchs [10], R. Garfagnini [23], F. Gautheron [1], O.P. Gavrichtchouk [7], S. Gerassimov [14,15], R. Geyer [16], M. Giorgi [22], B. Gobbo [22], S. Goertz [2], O. Grajek [24], A. Grasso [23], B. Grube [15], A. Grünemaier [9], J. Hannappel [4], D. von Harrach [13], T. Hasegawa [17], S. Hedicke [9], F.H. Heinsius [9], F. Hinterberger [3], M. von Hodenberg [9], N. Horikawa [17], S. Horikawa [17], R.B. Ijaduola [21], C. Ilgner [16], S. Ishimoto [17], T. Iwata [17], R. Jahn [3], A. Janata [7], R. Joosten [3], N.I. Jouravlev [7], E. Kabuß[13], V. Kalinnikov [22], D. Kang [9], F. Karstens [9], W. Kastaun [9], B. Ketzer [15], G.V. Khaustov [18], Yu.A. Khokhlov [18], Y. Kisselev [1], F. Klein [4], J.H. Koivuniemi [12], V.N. Kolosov [18], E.V. Komissarov [7], K. Kondo [17], K. Königsmann [9], A.K. Konoplyannikov [18], I. Konorov [15], A.S. Korentchenko [7], A. Korzenev [12‡], A.M. Kotzinian [6,23], N.A. Koutchinski [7], K. Kowalik [24], N.P. Kravchuk [7], G.V. Krivokhizhin [7], Z.V. Kroumchtein [7], R. Kuhn [15], F. Kunne [19], K. Kurek [24], M. Lamanna [10,22], J.M. Le Goff [19], M. Leberig [13], J. Lichtenstadt [20], A. Maggiora [23], M. Maggiora [23], A. Magnon [19], G.K. Mallot [10], I.V. Manuilov [18], C. Marchand [19], J. Marroncle [19], A. Martin [22], J. Marzec [25], T. Matsuda [17], A.N. Maximov [7], K.S. Medved [7], W. Meyer [2], A. Mielech [24], Yu.V. Mikhailov [18], M.A. Moinester [20], O. Nähle [3], J. Nassalski [24], D.P. Neyret [19], V.I. Nikolaenko [18], A.A. Nozdrin [7], V.F. Obraztsov [18], A.G. Olshevsky [7], M. Ostrick [4], A. Padee [25], P. Pagano [22], S. Panebianco [19], D. Panzieri [23†], S. Paul [15], H.D. Pereira [9,19], D.V. Peshekhonov [7], V.D. Peshekhonov [7], G. Piragino [23], S. Platchkov [19], K. Platzer [16], J. Pochodzalla [13], V.A. Polyakov [18], A.A. Popov [7], J. Pretz [4], P.C. Rebourgeard [19], G. Reicherz [2], J. Reymann [9], A.M. Rozhdestvensky [7], E. Rondio [24], A.B. Sadovski [7], E. Saller [7], V.D. Samoylenko [18], A. Sandacz [24], M.G. Sapozhnikov [7], I.A. Savin [7], P. Schiavon [22], T. Schmidt [9], H. Schmitt [9], L. Schmitt [15], A.A. Shishkin [7], H. Siebert [11], L. Sinha [6], A.N. Sissakian [7], A. Skachkova [23], M. Slunecka [7], G.I. Smirnov [7], V.P. Sugonyaev [18], F. Stinzing [8], R. Sulej [25], N. Takabayashi [17], V.V. Tchalishev [7], F. Tessarotto [22], A. Teufel [8], D. Thers [19], L.G. Tkatchev [7], T. Toeda [17], V.I. Tretyak [7], S. Trousov [7], N.V. Vlassov [7], T. Walcher [13], R. Webb [8], E. Weise [3], M. Wiesmann [15], R. Windmolders [4], S. Wirth [8], W. Wiślicki [24], A.M. Zanetti [22], K. Zaremba [25], J. Zhao [13], R. Ziegler [3] and A. Zvyagin [16]

[1] *Universität Bielefeld, Fakultät für Physik, 33501 Bielefeld, Germany*
[2] *Universität Bochum, Institut für Experimentalphysik, 44780 Bochum, Germany*
[3] *Universität Bonn, Helmholtz-Institut für Strahlen- und Kernphysik, 53115 Bonn, Germany*
[4] *Universität Bonn, Physikalisches Institut, 53115 Bonn, Germany*
[5] *Burdwan University, Burdwan 713104, India*
[6] *Matrivani Institute of Experimental Research & Education, Calcutta-700 030, India*
[7] *Joint Institute for Nuclear Research, 141980 Dubna, Moscow region, Russia*
[8] *Universität Erlangen–Nürnberg, Physikalisches Institut, 91058 Erlangen, Germany*
[9] *Universität Freiburg, Physikalisches Institut, 79104 Freiburg, Germany*
[10] *CERN, 1211 Geneva 23, Switzerland*
[11] *Universität Heidelberg, Physikalisches Institut, 69120 Heidelberg, Germany*
[12] *Helsinki University of Technology, Low Temperature Laboratory, 02015 HUT, Finland and University of Helsinki, Helsinki Institute of Physics, 00014 Helsinki, Finland*
[13] *Universität Mainz, Institut für Kernphysik, 55099 Mainz, Germany*
[14] *Lebedev Physical Institute, 119991 Moscow, Russia*
[15] *Technische Universität München, Physik Department, 85748 Garching, Germany*

[16] Ludwig-Maximilian-Universität München, Physik Department, 80799 Munich, Germany
[17] Nagoya University, 464 Nagoya, Japan
[18] State Research Center of the Russian Federation, Institute for High Energy Physics, 142281 Protvino, Russia
[19] CEA DAPNIA/SPhN Saclay, 91191 Gif-sur-Yvette, France
[20] Tel Aviv University, School of Physics and Astronomy, 69978 Tel Aviv, Israel
[21] ICTP–INFN MLab Laboratory, 34014 Trieste, Italy
[22] INFN Trieste and University of Trieste, Department of Physics, 34127 Trieste, Italy
[23] INFN Turin and University of Turin, Physics Department, 10125 Turin, Italy
[24] Sołtan Institute for Nuclear Studies and Warsaw University, 00-681 Warsaw, Poland
[25] Warsaw University of Technology, Institute of Radioelectronics, 00-665 Warsaw, Poland
[†] Also at University of East Piedmont, 15100 Alessandria, Italy
[‡] On leave of absence from JINR Dubna

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First measurements of the Collins and Sivers asymmetries of charged hadrons produced in deep-inelastic scattering of muons on a transversely polarized ^{6}LiD target are presented. The data were taken in 2002 with the COMPASS spectrometer using the muon beam of the CERN SPS at 160 GeV/c. The Collins asymmetry turns out to be compatible with zero, as does the measured Sivers asymmetry within the present statistical errors.

The importance of transverse spin effects at high energy in hadronic physics was first suggested by the discovery in 1976 that Λ hyperons produced in pN interactions exhibited an anomalously large transverse polarization [1]. This effect could not be easily explained. For a long time it was believed to be forbidden at leading twist in quantum chromodynamics (QCD) [2], and very little theoretical work was devoted to this field for more than a decade.

This situation changed in the nineties. After the first hints of large single transverse spin asymmetries in inclusive π^0 production in polarized pp scattering at CERN [3], remarkably large asymmetries were found at Fermilab both for neutral and charged pions [4]. In parallel, intense theoretical activity was taking place: the significance of the quark transversity distribution, already introduced in 1979 [5] to describe a quark in a transversely polarized nucleon, was reappraised [6] in 1990, and its measurability via the Drell–Yan process established. In 1991 a general scheme of all leading twist and higher-twist parton distribution functions was worked out [7], and in 1993 a way to measure transversity in lepton nucleon polarized deep-inelastic scattering (DIS) was suggested [8]. On the experimental side, the RHIC-Spin Collaboration [9] and the HELP Collaboration [10] put forward the first proposals to measure transversity. Today transversity is an important part of the scientific programme of the HERMES experiment at DESY and of the COMPASS experiment at CERN, both presently taking data. First results on a transversely polarized proton target have been published recently by the HERMES Collaboration [11].

To specify completely the quark structure of the nucleon at the twist-two level, the transverse spin distributions $\Delta_T q(x)$ must be added to the momentum distributions $q(x)$ and the helicity distributions $\Delta q(x)$ [7]. For a discussion on notation, see Ref. [12]. If the quarks are collinear with the parent nucleon (no intrinsic quark transverse momentum k_T), or after integration over k_T, these three distributions exhaust the information on the internal dynamics of the nucleon. More distributions are allowed if one admits a finite k_T, or at higher-twist [12–15].

The distributions $\Delta_T q$ are difficult to measure, since they are chirally odd and therefore absent in inclusive DIS. They may instead be extracted from measurements of the single-spin asymmetries in cross-sections for semi-inclusive DIS (SIDIS) of leptons on transversely polarized nucleons, in which a hadron is also detected in the final state. In these processes the measurable asymmetry, the "Collins asymmetry" A_{Coll}, is due to the combined effect of $\Delta_T q$ and another chirally-odd function, $\Delta_T^0 D_q^h$, which describes the spin-dependent part of the hadronization of a transversely polarized quark q into a hadron h. At leading order in the collinear case A_{Coll} can be written as

$$A_{Coll} = \frac{\sum_q e_q^2 \cdot \Delta_T q \cdot \Delta_T^0 D_q^h}{\sum_q e_q^2 \cdot q \cdot D_q^h} \tag{1}$$

where e_q is the quark charge. According to Collins [8], the quantity $\Delta_T^0 D_q^h$ can be obtained by investigating the fragmentation of a polarized quark q into a hadron h, and is related to the $\vec{p}_T^{\,h}$ dependent fragmentation function

$$D_{T\,q}^{\;h}(z, \vec{p}_T^{\,h}) = D_q^h(z, |\vec{p}_T^{\,h}|^2) + \Delta_T^0 D_q^h(z, |\vec{p}_T^{\,h}|^2) \cdot \sin \Phi_C . \tag{2}$$

Here $\vec{p}_T^{\,h}$ is the hadron transverse momentum with respect to the struck quark direction, i. e. the virtual photon direction, and $z = E_h/(E_l - E_{l'})$ is the fraction of available energy carried by the hadron. E_h, E_l, and $E_{l'}$ are the energies of the hadron, the incoming lepton, and the

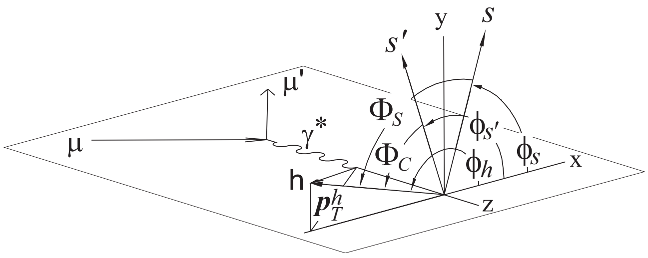

FIG. 1: Definition of the Collins and Sivers angles.

scattered lepton respectively. The "Collins angle" Φ_C is conveniently defined in a coordinate system in which the z-axis is the virtual photon direction and the x-z plane is the lepton scattering plane, as illustrated in Fig. 1. In this reference system $\Phi_C = \phi_h - \phi_{s'}$, where ϕ_h is the azimuthal angle of the hadron, and $\phi_{s'}$ is the azimuthal angle of the transverse spin of the struck quark. Since $\phi_{s'} = \pi - \phi_s$, with ϕ_s the azimuthal angle of the transverse spin of the initial quark (nucleon), one obtains $\sin\Phi_C = -\sin(\phi_h + \phi_s)$.

An entirely different mechanism was suggested by Sivers [16] as a possible cause of the transverse spin effects observed in pp scattering. This mechanism could also be responsible for a spin asymmetry in the cross-section of SIDIS of leptons on transversely polarized nucleons. Allowing for an intrinsic $\vec{k}_T$ dependence of the quark distribution in a nucleon, a left-right asymmetry could be induced in such a distribution by a transverse nucleon polarization, $q_T(x, \vec{k}_T) = q(x, |\vec{k}_T|^2) + \Delta_0^T q(x, |\vec{k}_T|^2) \cdot \sin\,\Phi_S$, where $\Phi_S = \phi_h - \phi_s \neq \Phi_C$ is the "Sivers angle". Neglecting the hadron transverse momentum with respect to the fragmenting quark, this $\vec{k}_T$ dependence could cause the "Sivers asymmetry"

$$A_{Siv} = \frac{\sum_q e_q^2 \cdot \Delta_0^T q \cdot D_q^h}{\sum_q e_q^2 \cdot q \cdot D_q^h} \qquad (3)$$

in the distribution of the hadrons resulting from the quark fragmentation with respect to the nucleon polarization which could be revealed as a $\sin\Phi_S$ modulation in the number of produced hadrons. Measuring SIDIS on a transversely polarized target allows the Collins and the Sivers effects to be disentangled [17].

In this paper first results are given of the charged hadron single-spin asymmetries in SIDIS of high energy muons on a transversely polarized ^{6}LiD target measured in 2002 by the COMPASS Collaboration.

The COMPASS spectrometer has been set up at the CERN SPS muon beam. The experiment has taken data from 2002 to 2004 at a muon momentum of 160 GeV/c with beam rates of $4{\cdot}10^7$ muons/s. The beam is naturally polarized by the π-decay mechanism, with a polarization of about –76%. The polarized target system [18] consists of two cells (upstream u, downstream d), each 60 cm long, located along the beam one after the other in two separate RF cavities, and oppositely polarized. The target magnet can provide both a solenoid field (2.5 T), and a dipole field (0.4 T) used for adiabatic spin rotation and for the transversity measurements. Correspondingly, the target polarization can be oriented either longitudinally or transversely to the beam direction. Polarizations of 50% have been reached routinely with the ^{6}LiD target, which has a favorable dilution factor $f \simeq 0.4$, since ^{6}Li basically consists of a deuteron plus an ^{4}He core. The target polarization is measured with a relative precision of 5%. Particle tracking is performed using several stations of scintillating fibres, micromesh gaseous chambers, and gas electron multiplier chambers. Large-area tracking devices comprise gaseous detectors (drift chambers, straw tubes, and MWPCs) placed around the two spectrometer magnets. Muons are identified in large-area Iarocci tubes and drift tubes downstream of hadron absorbers. The trigger [19] is formed by several hodoscope systems supplemented by two hadron calorimeters. Veto counters are installed in front of the target to reject the beam halo. More information on the COMPASS spectrometer can be found in Ref. [20].

In 2002 about $6 \cdot 10^9$ events, corresponding to 260 TBytes of data, were collected. About 20% of the sample was taken in the transverse spin mode, in two separate periods. Each period started with the u-cell of the target downwardly polarized and the d-cell upwardly polarized. After 4–5 days a polarization reversal was performed by changing the RF frequencies in the two cells.

Because the asymmetries are obtained by comparing data taken several days apart, the stability of the apparatus is crucial. To check the stability of reconstruction, the data were sampled in time. The hit distributions on all trackers were scrutinized, as well as the number of reconstructed events, the number of vertices per event, and the number of tracks per event in the whole spectrometer and in its various subregions. In addition, the distributions of a few relevant quantities were monitored for their stability throughout the data, like the Bjorken variable x, the relative energy transfer in the muon scattering process $y = (E_l - E_{l'})/E_l$, the photon virtuality Q^2. These investigations led to the exclusion of about 4% of the data from the final sample.

In the analysis, events were selected in which a vertex with incident and scattered muon and at least one outgoing charged hadron was found in one of the two target cells. A clean identification of muons and hadrons was achieved on the basis of the amount of material traversed in the spectrometer. In addition, DIS cuts $Q^2 > 1$ (GeV/c)^2, $W > 5$ GeV/c^2, and $0.1 < y < 0.9$ were applied to the data as well as a cut on the transverse momentum of the hadrons ($p_T^h > 0.1$ GeV/c).

To enhance the asymmetry signal, we first evaluated the Collins and Sivers asymmetries for the leading hadron of each event, the underlying idea being that in the string fragmentation it is the most sensitive to the properties of the parent quark spin [21]. The leading hadron was defined as the most energetic hadron with $z > 0.25$, and originating from the reaction vertex. The total number of events which finally entered the analysis was $1.6 \cdot 10^6$ comprising $8.7 \cdot 10^5$ events with positive leading hadrons and $7.0 \cdot 10^5$ events with negative leading hadrons.

We searched separately for Collins and Sivers asymmetries in the data. The Φ distribution of the number of events for each cell and for each polarization state can be written as

$$N_j(\Phi_j) \;=\; F\, n\, \sigma \cdot a_j(\Phi_j) \cdot (1 + \epsilon_j \sin \Phi_j), \tag{4}$$

where $j = C, S$, and F is the muon flux, n the number of target particles, σ the spin averaged cross-section, and a_j the product of angular acceptance and efficiency of the spectrometer. The asymmetries ϵ_j are $\epsilon_C = f \cdot |P_T| \cdot D_{NN} \cdot A_{Coll}$ and $\epsilon_S = f \cdot |P_T| \cdot A_{Siv}$. The factor f is the polarized target dilution factor, P_T the deuteron polarization, and $D_{NN} = (1-y)/(1-y+y^2/2)$ the transverse spin transfer coefficient from the initial to the struck quark [12]. To highlight the physics process we are after, in Eq. 4 we have omitted terms which either average out in the evaluation of the asymmetry or only lead to negligible corrections due to a non-uniform angular acceptance. The beam polarization contributes to the asymmetry only by higher-twist effects, which are not considered in this leading-order analysis.

The asymmetries ϵ_C and ϵ_S were evaluated from the number of events with the two target spin orientations ($\uparrow$ spin up, and $\downarrow$ spin down) by fitting the quantities

$$A^m_j(\Phi_j) = \frac{N^\uparrow_j(\Phi_j) - r \cdot N^\downarrow_j(\Phi_j + \pi)}{N^\uparrow_j(\Phi_j) + r \cdot N^\downarrow_j(\Phi_j + \pi)} \tag{5}$$

with the functions $\epsilon_C \cdot \sin \Phi_C$ and $\epsilon_S \cdot \sin \Phi_S$. The normalization factor r has been taken equal to the ratio of the total number of detected events in the two orientations of the target polarization. Note that two events having the same topology in the laboratory before and after the target spin rotation have angles Φ_j and $\Phi_j + \pi$ respectively, thus the acceptance cancels in Eq. 5 as long as the ratio $a^\uparrow_j(\Phi_j)/a^\downarrow_j(\Phi_j + \pi)$ is constant in Φ_j.

The evaluation of the asymmetries was performed separately for the two data-taking periods and for the two target cells. These four sets of measured asymmetries turned out to be statistically compatible, and were then combined by taking weighted averages. Plots of the measured values of A_{Coll} and A_{Siv} against the three kinematic variables x, z and p^h_T are given in Fig. 2. The errors shown in the figure are only statistical. The mean values of z and p^h_T are roughly constant (~ 0.44 and 0.51 GeV/c respectively) over the whole x range while $\langle Q^2 \rangle$ increases from ~ 1.1 (GeV/c)^2 in the first x bin to ~ 20 (GeV/c)^2 in the last one.

Systematic errors due to the uncertainties in P_T, D_{NN}, and f are negligibly small. Several tests were made to check that there are no effects distorting the measured asymmetries, splitting the data sample *i*) in time, *ii*) in two halves of the target cells, and *iii*) according to the hadron momentum. The asymmetries measured for the different samples were found to be compatible. Also, the results were stable with respect to different choices of the normalization factor r.

The method of extracting the asymmetries is expected to minimize systematic effects due to acceptance, and this is confirmed by the compatibility of the asymmetries measured in the two cells u and d. Under the reasonable assumption that the ratio $a^\downarrow_{j,u}(\Phi_j + \pi)/a^\uparrow_{j,d}(\Phi_j)$ before the polarization reversal be equal to the corresponding ratio $a^\uparrow_{j,u}(\Phi_j)/a^\downarrow_{j,d}(\Phi_j + \pi)$ after the reversal, the requirement that the ratios $a^\downarrow_{j,u}(\Phi_j+\pi)/a^\uparrow_{j,u}(\Phi_j)$ and $a^\uparrow_{j,d}(\Phi_j)/a^\downarrow_{j,d}(\Phi_j+\pi)$, be constant in Φ_j within each data-taking period has been verified by constructing the ratio

$$R_j(\Phi) = \frac{N^\uparrow_{j,u}(\Phi_j) \cdot N^\downarrow_{j,d}(\Phi_j + \pi)}{N^\downarrow_{j,u}(\Phi_j + \pi) \cdot N^\uparrow_{j,d}(\Phi_j)} \simeq \frac{[a^\downarrow_{j,u}(\Phi_j)]^2}{[a^\uparrow_{j,u}(\Phi_j + \pi)]^2} \tag{6}$$

and verifying its constancy in Φ_j. This constancy holds even using the entire data sample after releasing the z-cut. It has to be stressed also that, under the same assumption, possible false asymmetries due to variations in Φ_j of the acceptance ratios to first order have opposite sign in the two cells and should cancel in the average.

To estimate the size of possible systematic effects, the asymmetries have also been evaluated using two other estimators which are independent of relative luminosities and rely on different assumptions of the acceptance variations, e.g. the ratio product

$$\frac{N^\uparrow_{j,u}(\Phi_j)}{N^\downarrow_{j,u}(\Phi_j + \pi)} \cdot \frac{N^\uparrow_{j,d}(\Phi_j)}{N^\downarrow_{j,d}(\Phi_j + \pi)}, \tag{7}$$

and the geometric mean

$$\frac{\sqrt{N^\uparrow_j(\Phi_j) \cdot N^\downarrow_j(\Phi_j + \pi)} - \sqrt{N^\downarrow_j(\Phi_j) \cdot N^\uparrow_j(\Phi_j + \pi)}}{\sqrt{N^\uparrow_j(\Phi_j) \cdot N^\downarrow_j(\Phi_j + \pi)} + \sqrt{N^\downarrow_j(\Phi_j) \cdot N^\uparrow_j(\Phi_j + \pi)}}\,. \tag{8}$$

Differences from the results displayed in Fig. 2 were only observed within the statistical errors of the measured asymmetries.

The conclusion from all these studies is that systematic errors are smaller than the quoted statistical errors.

Within the statistical accuracy of the data, both A_{Coll} and A_{Siv} turn out to be small and compatible with zero, with a marginal indication of a Collins effect at large z in both the positive and the negative hadron data. By means of Monte Carlo simulations, we estimated that the following factors could together dilute a possible leading

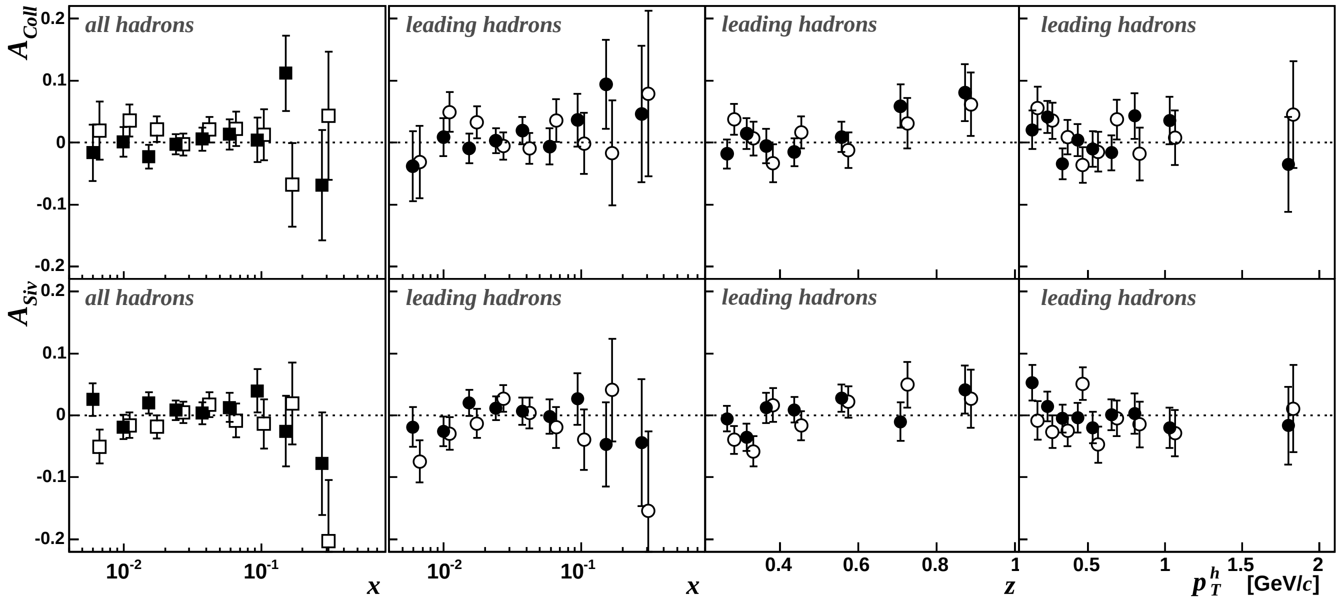

FIG. 2: Collins asymmetry (top) and Sivers asymmetry (bottom) against x, z and p_T^h for positive (full points) and negative hadrons (open points). Error bars are statistical only. The first column gives the asymmetries for all hadrons, the other three columns for the leading hadrons. In all the plots the points are slightly shifted horizontally with respect to the measured value.

pion asymmetry by a factor of 0.6 at most: *i)* the acceptance of the spectrometer for leading hadrons (by cutting at $z > 0.25$ the reconstructed charged leading particle is the generated most energetic hadron in about 80% of the cases); *ii)* non identification of the charged hadron (about 80% of the charged leading hadrons are pions); *iii)* smearing of the kinematical quantities due to the experimental resolution of the spectrometer (negligible effect). For the simulation, which reproduces well the experimental distributions, we used LEPTO 6.5.1 and GEANT 3. Simulations were also performed to check the possible correlation between the measured values of ϵ_C and ϵ_S; asymmetries up to 20% were generated and no appreciable mixing was observed.

This analysis has been repeated for all hadrons, i. e. both the Collins and the Sivers asymmetries have been evaluated for all the reconstructed hadrons with $z > 0.2$. The total number of hadrons entering the analysis is increased by a factor of 1.5 with respect to the leading hadron analysis, but the results are very similar, i. e. small values for the asymmetries. For reasons of space, the asymmetries are displayed in Fig. 2 as function of x only. All the measured asymmetries are available on HEPDATA [22].

The COMPASS measurements on the transversely polarized deuteron target have a statistical accuracy of the same order as the recent measurement on protons performed by the HERMES Collaboration [11]. The small measured values of the deuteron asymmetries can be understood because $\Delta_T u$ and $\Delta_T d$ are likely to have the opposite sign as for the helicity distributions, and some cancellation is expected between the proton and the neutron asymmetries. Still, at large x, the measured values of A_{Coll} for positive leading hadrons seem to hint at positive values, at variance with the naive expectation $A^{\pi^+}_{Coll} \propto -\Delta_T u/u$. Also, A_{Coll} for all positive hadrons does not show the negative trend foreseen by the model prediction of Ref. [23]. Attention is drawn to the fact that the conventions used in Ref. [11] and [23] give an opposite sign for the Collins asymmetry as compared to this paper. Alternatively, it could be that the Collins effect is too small to allow for quark polarimetry with this set of data. Different quark polarimeters are also being tried, e. g. hadron pairs and Λ production. The analysis of the full sample of deuteron data, including the 2003 and 2004 runs, will reduce the errors by at least a factor of two, and the Collaboration also intends to take data with a polarized proton target. Precise transversely polarized proton and deuteron data will allow a flavor separation of transversity in the near future.

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