Physics Letters B 692 (2010) 240–246

Contents lists available at ScienceDirect

Physics Letters B

www.elsevier.com/locate/physletb

Measurement of the Collins and Sivers asymmetries on transversely polarised protons

COMPASS Collaboration

M.G. Alekseev[ab], V.Yu. Alexakhin[g], Yu. Alexandrov[o], G.D. Alexeev[g], A. Amoroso[aa], A. Austregesilo[j,q], B. Badełek[ad], F. Balestra[aa], J. Ball[v], J. Barth[d], G. Baum[a], Y. Bedfer[v], J. Bernhard[m], R. Bertini[aa], M. Bettinelli[p], R. Birsa[x], J. Bisplinghoff[c], P. Bordalo[l,2], F. Bradamante[y], A. Bravar[x], A. Bressan[y], G. Brona[j,ad], E. Burtin[v], M.P. Bussa[aa], D. Chaberny[m], M. Chiosso[aa], S.U. Chung[q], A. Cicuttin[z], M. Colantoni[ab], M.L. Crespo[z], S.Dalla Torre[x], S. Das[f], S.S. Dasgupta[f], O.Yu. Denisov[j,ab], L. Dhara[f], V. Diaz[z], S.V. Donskov[u], N. Doshita[b,af], V. Duic[y], W. Dünnweber[p], A. Efremov[g], A. El Alaoui[v], C. Elia[y], P.D. Eversheim[c], W. Eyrich[h], M. Faessler[p], A. Ferrero[v], A. Filin[u], M. Finger[s], M. Finger jr.[g], H. Fischer[i], C. Franco[l], J.M. Friedrich[q], R. Garfagnini[aa], F. Gautheron[b], O.P. Gavrichtchouk[g], R. Gazda[ad], S. Gerassimov[o,q], R. Geyer[p], M. Giorgi[y], I. Gnesi[aa], B. Gobbo[x], S. Goertz[b,d], S. Grabmüller[q], A. Grasso[aa], B. Grube[q], R. Gushterski[g], A. Guskov[g], F. Haas[q], D. von Harrach[m], T. Hasegawa[n], F.H. Heinsius[i], R. Hermann[m], F. Herrmann[i], C. Heß[b], F. Hinterberger[c], N. Horikawa[r,3], Ch. Höppner[q], N. d'Hose[v], C. Ilgner[j,p], S. Ishimoto[r,4], O. Ivanov[g], Yu. Ivanshin[g], T. Iwata[af], R. Jahn[c], P. Jasinski[m], G. Jegou[v], R. Joosten[c], E. Kabuß[m], W. Käfer[i], D. Kang[i], B. Ketzer[q], G.V. Khaustov[u], Yu.A. Khokhlov[u], Yu. Kisselev[b], F. Klein[d], K. Klimaszewski[ad], S. Koblitz[m], J.H. Koivuniemi[b], V.N. Kolosov[u], K. Kondo[b,af], K. Königsmann[i], R. Konopka[q], I. Konorov[o,q], V.F. Konstantinov[u], A. Korzenev[m,5], A.M. Kotzinian[aa], O. Kouznetsov[g,v], K. Kowalik[ad,v], M. Krämer[q], A. Kral[t], Z.V. Kroumchtein[g], R. Kuhn[q], F. Kunne[v], K. Kurek[ad], L. Lauser[i], J.M. Le Goff[v], A.A. Lednev[u], A. Lehmann[h], S. Levorato[y], J. Lichtenstadt[w], T. Liska[t], A. Maggiora[ab], M. Maggiora[aa], A. Magnon[v], G.K. Mallot[j,*], A. Mann[q], C. Marchand[v], A. Martin[y], J. Marzec[ae], F. Massmann[c], T. Matsuda[n], W. Meyer[b], T. Michigami[af], Yu.V. Mikhailov[u], M.A. Moinester[w], A. Mutter[i,m], A. Nagaytsev[g], T. Nagel[q], J. Nassalski[ad,1], T. Negrini[c], F. Nerling[i], S. Neubert[q], D. Neyret[v], V.I. Nikolaenko[u], A.S. Nunes[l], A.G. Olshevsky[g], M. Ostrick[m], A. Padee[ae], R. Panknin[d], D. Panzieri[ac], B. Parsamyan[aa], S. Paul[q], B. Pawlukiewicz-Kaminska[ad], E. Perevalova[g], G. Pesaro[y], D.V. Peshekhonov[g], G. Piragino[aa], S. Platchkov[v], J. Pochodzalla[m], J. Polak[k,y], V.A. Polyakov[u], G. Pontecorvo[g], J. Pretz[d], C. Quintans[l], J.-F. Rajotte[p], S. Ramos[l,2], V. Rapatsky[g], G. Reicherz[b], A. Richter[h], F. Robinet[v], E. Rocco[aa], E. Rondio[ad], D.I. Ryabchikov[u], V.D. Samoylenko[u], A. Sandacz[ad], H. Santos[l], M.G. Sapozhnikov[g], S. Sarkar[f], I.A. Savin[g], G. Sbrizzai[y], P. Schiavon[y], C. Schill[i], T. Schlüter[p], L. Schmitt[q,6], S. Schopferer[i], W. Schröder[h], O.Yu. Shevchenko[g], H.-W. Siebert[m], L. Silva[l], L. Sinha[f], A.N. Sissakian[g,1], M. Slunecka[g], G.I. Smirnov[g], S. Sosio[aa], F. Sozzi[y], A. Srnka[e], M. Stolarski[j], M. Sulc[k], R. Sulej[ae], S. Takekawa[y], S. Tessaro[x], F. Tessarotto[x], A. Teufel[h], L.G. Tkatchev[g], S. Uhl[q], I. Uman[p], M. Virius[t], N.V. Vlassov[g], A. Vossen[i], Q. Weitzel[q], R. Windmolders[d], W. Wiślicki[ad], H. Wollny[i], K. Zaremba[ae], M. Zavertyaev[o], E. Zemlyanichkina[g], M. Ziembicki[ae], J. Zhao[m,x], N. Zhuravlev[g], A. Zvyagin[p]

[a] *Universität Bielefeld, Fakultät für Physik, 33501 Bielefeld, Germany*[7]
[b] *Universität Bochum, Institut für Experimentalphysik, 44780 Bochum, Germany*[7]
[c] *Universität Bonn, Helmholtz-Institut für Strahlen- und Kernphysik, 53115 Bonn, Germany*[7]
[d] *Universität Bonn, Physikalisches Institut, 53115 Bonn, Germany*[7]
[e] *Institute of Scientific Instruments, AS CR, 61264 Brno, Czech Republic*[8]
[f] *Matrivani Institute of Experimental Research & Education, Calcutta-700 030, India*[9]
[g] *Joint Institute for Nuclear Research, 141980 Dubna, Moscow region, Russia*[10]
[h] *Universität Erlangen–Nürnberg, Physikalisches Institut, 91054 Erlangen, Germany*[7]

doi:10.1016/j.physletb.2010.08.001

[i] Universität Freiburg, Physikalisches Institut, 79104 Freiburg, Germany [7]
[j] CERN, 1211 Geneva 23, Switzerland
[k] Technical University in Liberec, 46117 Liberec, Czech Republic [8]
[l] LIP, 1000-149 Lisbon, Portugal [11]
[m] Universität Mainz, Institut für Kernphysik, 55099 Mainz, Germany [7]
[n] University of Miyazaki, Miyazaki 889-2192, Japan [12]
[o] Lebedev Physical Institute, 119991 Moscow, Russia
[p] Ludwig-Maximilians-Universität München, Department für Physik, 80799 Munich, Germany [7,13]
[q] Technische Universität München, Physik Department, 85748 Garching, Germany [7,13]
[r] Nagoya University, 464 Nagoya, Japan [12]
[s] Charles University in Prague, Faculty of Mathematics and Physics, 18000 Prague, Czech Republic [8]
[t] Czech Technical University in Prague, 16636 Prague, Czech Republic [8]
[u] State Research Center of the Russian Federation, Institute for High Energy Physics, 142281 Protvino, Russia
[v] CEA IRFU/SPhN Saclay, 91191 Gif-sur-Yvette, France
[w] Tel Aviv University, School of Physics and Astronomy, 69978 Tel Aviv, Israel [14]
[x] Trieste Section of INFN, 34127 Trieste, Italy
[y] University of Trieste, Department of Physics and Trieste Section of INFN, 34127 Trieste, Italy
[z] Abdus Salam ICTP and Trieste Section of INFN, 34127 Trieste, Italy
[aa] University of Turin, Department of Physics and Torino Section of INFN, 10125 Turin, Italy
[ab] Torino Section of INFN, 10125 Turin, Italy
[ac] University of Eastern Piedmont, 1500 Alessandria, and Torino Section of INFN, 10125 Turin, Italy
[ad] Sołtan Institute for Nuclear Studies and University of Warsaw, 00-681 Warsaw, Poland [15]
[ae] Warsaw University of Technology, Institute of Radioelectronics, 00-665 Warsaw, Poland [15]
[af] Yamagata University, Yamagata 992-8510, Japan [12]

ARTICLE INFO

Article history:
Received 1 June 2010
Received in revised form 5 July 2010
Accepted 2 August 2010
Available online 4 August 2010
Editor: M. Doser

Keywords:
Transverse spin effects
Proton
Collins asymmetry
Sivers asymmetry
COMPASS

ABSTRACT

The Collins and Sivers asymmetries for charged hadrons produced in deeply inelastic scattering on transversely polarised protons have been extracted from the data collected in 2007 with the CERN SPS muon beam tuned at 160 GeV/c. At large values of the Bjorken x variable non-zero Collins asymmetries are observed both for positive and negative hadrons while the Sivers asymmetry for positive hadrons is slightly positive over almost all the measured x range. These results strongly support the present theoretical interpretation of these asymmetries, in terms of leading-twist quark distribution and fragmentation functions.

After first indications of transverse spin effects in hadron physics in the 1970s [1,2] their importance was unambiguously established by the remarkably large single spin asymmetries (SSAs) found in pp collisions at Fermilab both for neutral and charged pions [3]. Following the discovery by the EMC at CERN in 1988 that the quark spins contribute only little to the proton spin [4], the interest in the nucleon spin structure was revived and a more complete description including quark transverse spin and transverse momentum has been worked out.

The quark structure of the nucleon in the collinear approximation or after integration over the intrinsic quark transverse momentum $\vec{k}_T$ is fully specified at the twist-two level by three parton distribution functions (PDFs) for each quark flavour [5]: the momentum distributions $q(x)$, the helicity distributions $\Delta q(x)$ and the transverse spin distributions $\Delta_T q(x)$, where x is the Bjorken variable. The latter distribution—often referred to as transversity—is chiral-odd and thus not directly observable in deep inelastic scattering (DIS). In 1993 it was suggested [6] that transversity could be measured in semi-inclusive lepton–nucleon scattering (SIDIS) due to a mechanism involving another chiral-odd function in the hadronisation, known today as the Collins fragmentation function (FF). The mechanism leads to a left–right asymmetry in the distribution of the hadrons produced in the fragmentation of transversely polarised quarks. Thus a transverse spin dependence in the azimuthal distributions of the final state hadrons can be generated both in transversely polarised pp scattering and in SIDIS off transversely polarised nucleons. In the latter case the measurable Collins asymmetry, A_{Coll}, is proportional to the convolution of the transversity PDF and the Collins FF.

Admitting a finite $\vec{k}_T$, in total eight PDFs are needed for a full description at leading twist and leading order in α_S [7–9]. All these functions lead to azimuthal asymmetries in the distribution of hadrons produced in SIDIS processes and can be disentangled measuring the different angular modulations. Amongst the transverse momentum dependent PDFs, the T-odd Sivers function [10]

* Corresponding author.
E-mail address: gerhard.mallot@cern.ch (G.K. Mallot).
[1] Deceased.
[2] Also at IST, Universidade Técnica de Lisboa, Lisbon, Portugal.
[3] Also at Chubu University, Kasugai, Aichi 487-8501, Japan (see footnote 12).
[4] Also at KEK, 1-1 Oho, Tsukuba, Ibaraki 305-0801, Japan.
[5] On leave of absence from JINR Dubna.
[6] Also at GSI mbH, Planckstr. 1, D-64291 Darmstadt, Germany.
[7] Supported by the German Bundesministerium für Bildung und Forschung.
[8] Suppported by Czech Republic MEYS grants ME492 and LA242.
[9] Supported by SAIL (CSR), Govt. of India.
[10] Supported by CERN-RFBR grant 08-02-91009.
[11] Supported by the Portuguese FCT – Fundação para a Ciência e Tecnologia grants POCTI/FNU/49501/2002 and POCTI/FNU/50192/2003.
[12] Supported by the MEXT and the JSPS under the Grants No. 18002006, No. 20540299 and No. 18540281; Daiko Foundation and Yamada Foundation.
[13] Supported by the DFG cluster of excellence 'Origin and Structure of the Universe' (http://www.universe-cluster.de).
[14] Supported by the Israel Science Foundation, founded by the Israel Academy of Sciences and Humanities.
[15] Supported by Ministry of Science and Higher Education grant 41/N-CERN/2007/0.

is of particular interest. This function arises from a correlation between the transverse momentum of an unpolarised quark in a transversely polarised nucleon and the nucleon spin. It can be different from zero because of final state interactions mediated by soft gluon exchange between the interacting quark and the target remnants [11]. It is responsible for the Sivers asymmetry, A_{Siv}, which is proportional to the convolution of the Sivers function and the unpolarised FF. The Sivers mechanism might also be the reason for the large asymmetries observed in pp collisions.

Transverse spin effects in SIDIS are investigated, at different beam energies, by the HERMES experiment at DESY and the COMPASS experiment at CERN. An experiment to measure transversity using a transversely polarised ^{3}He target has recently been performed at JLab [12]. Transverse spin effects are also an important part of the scientific programme of the RHIC spin experiments at BNL.

Up to now, sizable Collins asymmetries for the proton were observed recently by HERMES using a proton target [13]. This implies non-vanishing Collins fragmentation and transversity functions. Direct measurements at the KEK e^+e^- collider by the BELLE experiment established that this Collins FF is sizable [14,15]. COMPASS measured vanishing asymmetries by scattering high energy muons off a deuteron target [16–18]. All these data were well described by a global fit [19,20] which allowed for a first extraction of the u and d-quark transversity PDFs.

The Sivers asymmetry for the proton was measured by HERMES [13,21] to be different from zero for positive hadrons, while it was found to be compatible with zero for deuteron by COMPASS [16–18]. These HERMES and COMPASS data could also be well described by theoretical calculations and fits, and allowed for extractions of the Sivers function [22], which turned out to be different from zero and opposite in sign for u and d-quarks.

In this Letter, we present the COMPASS results on the Collins and Sivers asymmetries for charged hadrons produced in SIDIS of high energy muons on transversely polarised protons. The data were collected in 2007 using NH_3 as target material and a 160 GeV/c beam with a momentum spread $\Delta p/p = \pm 5\%$. The beam was naturally polarised by the π–decay mechanism, with a longitudinal polarisation of about -80%. This measurement followed the measurements performed in 2002, 2003 and 2004 at the same energy with the transversely polarised ^{6}LiD target.

The COMPASS spectrometer [23] is in operation on the M2 beam line of CERN since 2002. Two magnetic stages are used to ensure large angular and momentum acceptance. A variety of tracking detectors is used to cope with the different requirements of position accuracy and rate capability at different angles. Particle identification is provided by a large acceptance RICH detector, calorimeters, and muon filters. The trigger system uses scintillator hodoscopes to trigger on the scattered muon and the calorimeters to trigger on the produced hadrons. Major upgrades in 2005 mainly concerned the polarised target, the tracking system, the RICH detector, and the electromagnetic calorimeters. The new target solenoid magnet provides a field of 2.5 T and has a polar angle acceptance of 180 mrad as seen from the upstream end of the target. In the earlier measurements with the ^{6}LiD target the polar angle acceptance was 70 mrad. The target material is cooled in a ^{3}He–^{4}He dilution refrigerator, and the protons in the H atoms are polarised to 0.80–0.90 by dynamical nuclear polarisation. About 48 hours are necessary to reach 95% of the maximal polarisation. A pair of saddle-shaped coils can provide a 0.6 T vertical field which is used to rotate the target nucleon spin and to hold the polarisation vertical for the transversity measurements. In the frozen spin mode, and with the holding field at its operational value, the relaxation time of the polarisation exceeds 3000 hours.

The target consisted of three cylindrical cells with 4 cm diameter, one central cell of 60 cm length and two outer ones of 30 cm length, all separated by 5 cm. Neighbouring cells were polarised in opposite directions, so that data with both spin directions were recorded at the same time. In order to minimise the effects due to different spectrometer acceptance for different target cells, in each period of data taking a polarisation reversal was performed after 4–5 days by changing the microwave frequencies in the three cells.

The geometry of the polarised target and the data taking procedure were chosen such as to optimise the extraction of spin asymmetries. The principle of the measurement can be understood by considering the “ratio product” [17]

$$R = \frac{N^{\uparrow}_{inner}}{N^{\downarrow}_{inner}} \cdot \frac{N^{\uparrow}_{outer}}{N^{\downarrow}_{outer}}, \qquad (1)$$

where $N^{\uparrow}_{inner}$ and $N^{\downarrow}_{outer}$ are the number of hadrons produced in the first sub-period on oppositely polarised cells, and $N^{\downarrow}_{inner}$ and $N^{\uparrow}_{outer}$ are the corresponding numbers in the second sub-period, i.e. after polarisation reversal. The ratio product is constructed such that beam flux, spin-averaged cross section, and the number of scattering centres cancel. As long as the ratios between the spectrometer acceptances of each cell are the same in the two sub-periods and the number of produced hadrons follows the generic azimuthal modulation $N^{\uparrow\downarrow} \sim 1 \pm \epsilon \sin\Phi$, one simply gets $R = 1 + 4\epsilon \sin\Phi$, and the extraction of the amplitude ϵ of the azimuthal modulation is straightforward.

In 2007 data were taken at a mean beam intensity of about 5×10^7 μ^+/s (typically 2.4×10^8 μ^+/spill, for a spill length of 4.8 s every 16.8 s). Using up 4×10^{13} muons, about 12×10^9 events were collected in six separate periods, corresponding to 440 TB of data.

In the data analysis, events were selected if they had at least one “primary vertex”, defined as the intersection point of a beam track, the scattered muon track, and other possible outgoing tracks. The momenta of both incoming and outgoing charged particles were measured. The primary vertex was required to be inside a target cell. In order to guarantee the same muon flux along the target material, the extrapolated beam track had to traverse all the three target cells. For incoming and scattered muon tracks, as well as for the other reconstructed tracks, χ^2 cuts were applied to assure the quality of track reconstruction. Tracks from the primary vertex which traversed more than 30 radiation lengths were identified as scattered muons. The event was rejected if more than one of such tracks were found.

In order to be in the DIS regime, only events with a photon virtuality $Q^2 > 1$ (GeV/c)^2, a fractional energy of the virtual photon $0.1 < y < 0.9$, and a mass of the hadronic final state $W > 5$ GeV/c^2 were considered. The variable x covers the range from 0.004 to 0.7.

All particles emerging from the primary vertex were assumed to be hadrons if they traversed less than 10 radiation lengths of material. For tracks with an associated cluster in one of the hadronic calorimeters, a minimal amount of deposited energy was required to further reduce the electron and muon contamination. Finally, tracks reconstructed only in the fringe field of the first analysing magnet of the spectrometer were rejected. This roughly corresponds to a cut at 1.5 GeV/c in the hadron momenta. In order to reconstruct the hadron azimuthal angle with good precision, the hadron transverse momentum with respect to the virtual photon direction, p^h_T, was required to be above 0.1 GeV/c. A minimum value of 0.2 for z, the relative energy of the hadron with respect to the virtual photon energy, was chosen to avoid hadrons from the target fragmentation region.

As explained in detail in Ref. [17], the Collins effect shows up as a modulation $[1+\epsilon_C \sin(\phi_h+\phi_S-\pi)]$ in the number of events, where ϕ_h and ϕ_S are the azimuthal angles of the hadron and of the target nucleon spin vector in a reference system in which the z-axis is the virtual photon direction and the x–z plane is the lepton plane according to Ref. [24]. The amplitude of the modulation is $\epsilon_C = D_{NN} f P_T A_{Coll}$, where $D_{NN} = (1-y)/(1-y+y^2/2)$ is the transverse spin transfer coefficient from target quark to struck quark, f the dilution factor of the NH_3 material, and P_T is the proton polarisation. Similarly, the Sivers effect results in a modulation $[1+\epsilon_S \sin(\phi_h-\phi_S)]$, where $\epsilon_S = f P_T A_{Siv}$.

The transverse spin asymmetries were obtained by comparing the azimuthal distributions of the detected hadrons as measured in the first sub-period of data taking with the corresponding distributions of the second half measured with opposite target polarisation. Since the two sets of data were taken typically one week apart, the stability of the apparatus is a central point in the measurement. As a first step in the data selection, the hit distributions of all trackers were scrutinised, as well as the number of reconstructed events, the number of vertices per events, and the number of tracks per event. Instabilities of components of the tracking detectors and/or of the trigger system could thus be identified. About 20% of the events were rejected at this stage. In a second step, the stability of the average $\pi^+\pi^-$ invariant mass in the K^0 region as well as the distribution of twelve kinematic quantities $(x, y, W, z, \ldots)$ were investigated dividing the data in small time-ordered sub-samples. Each distribution of each sub-sample was compared with the corresponding ones of each other sub-sample within the same data taking period, and sub-samples were rejected when deviating from the mean values more than expected statistically. A cut at 3.5 σ_{stat} (corresponding to a probability of 0.001) rejected on average 14% of the data.

As a final selection criterion, the data were tested for a possible dependence on either $\sin(\phi_h+\phi_S)$ or $\sin(\phi_h-\phi_S)$ of the acceptance ratio between two consecutive sub-periods with opposite target polarisation. In spite of the very large number of trackers in the spectrometer, acceptance variations could be caused by instabilities of the thresholds of the trigger counters, in particular of the calorimeters. Combining the number of events reconstructed in the different target cells in two consecutive data taking sub-periods, one can construct two different estimators on the stability of the acceptance. The first estimator measures the mean modulation in the relevant azimuthal angle of the acceptance ratio between two sub-periods. The second one probes possible large differences in the acceptance ratios for the different target cells which could affect the physics asymmetry. These two pieces of information have been used to construct a χ^2 and the final selection of the data taking periods was done on the basis of its value.

As a result of the quality control, all data collected in the six periods were used for the extraction of the Collins asymmetry, while only four periods were used for the Sivers asymmetry. This can be understood because the Sivers asymmetry is very sensitive to instabilities in the acceptance of the spectrometer since it is the amplitude of a modulation of the azimuthal angle of the hadron transverse momentum with respect to the target spin vector, i.e. a fixed direction in the spectrometer. On the contrary, the Collins asymmetry is an asymmetry in the azimuthal angle between the hadron transverse momentum and a direction which depends on the target spin direction and the lepton scattering plane, which is different for each event. The final sample contains 23.1×10^6 SIDIS events for the Collins asymmetry and 15.6×10^6 for the Sivers asymmetry.

The asymmetries were evaluated for positive and negative hadrons in bins of the three kinematic variables x, z and p_T^h. The binning is the same as used for the previous analyses of deuteron data and consists of 9 bins in x, 8 bins in z and 9 bins in p_T^h, integrating over the other two variables. For each period, the physics asymmetries were obtained by dividing the raw asymmetries by the target polarisation, the dilution factor, and, in the case of Collins analysis, by the D_{NN} factor. The target polarisation was measured individually for each cell and each period. The dilution factor of the ammonia target was evaluated for each bin. It is 0.15 in average, and increases with x from 0.14 to 0.17.

The estimator used for the evaluation of the raw asymmetries is based on an extended unbinned maximum likelihood method [25]. The likelihood function is built as the product of the probability densities p corresponding to each hadron i from each target cell. The likelihood for hadrons from a given target cell in one period is written as

$$\mathcal{L} = \left(e^{-I^+} \prod_{i=0}^{N^+} p^+(\phi_{h,i}, \phi_{S,i}) \right)^{\frac{1}{N^+}} \cdot \left(e^{-I^-} \prod_{i=0}^{N^-} p^-(\phi_{h,i}, \phi_{S,i}) \right)^{\frac{1}{N^-}}. \tag{2}$$

The $+$ and $-$ signs refer to the orientation of the target polarisation in the two sub-periods and $N^\pm$ is the corresponding total number of hadrons. The quantities $I^\pm$ are the integrals of the probability densities over ϕ_S and ϕ_h. The probability densities $p^\pm$ are the product of two parts, one corresponding to the acceptance description and the other to the SIDIS cross section of longitudinally polarised leptons on transversely polarised nucleons. Various parametrisations of the acceptance part were tested, resulting in a negligible dependence of the extracted asymmetries on the acceptance description. The cross section was parametrised taking into account both the unpolarised and polarised parts. The polarised part consists of all the expected eight modulations, namely $\sin(\phi_h+\phi_S-\pi)$, $\sin(\phi_h-\phi_S)$, $\cos(\phi_h-\phi_S)$, $\sin(2\phi_h-\phi_S)$, $\cos(2\phi_h-\phi_S)$, $\sin(\phi_S)$, $\cos(\phi_S)$, and $\sin(3\phi_h-\phi_S)$, and all their amplitudes were extracted at the same time. The Collins and Sivers asymmetries are proportional to the amplitudes of the first two terms. The other six amplitudes are not further discussed in the context of this Letter.

The fit results obtained with the likelihood method were compared with the asymmetries extracted using several other estimators, including the ones used in the previous publications which were based on the "ratio product" R (Eq. (1)). An excellent agreement has been found between all the results. The correlation coefficient between the Collins and the Sivers asymmetries turned out to be small, less than 0.2 in absolute value over the whole x range.

Extensive studies were performed in order to assess the systematic uncertainty of the measured asymmetries. All the studies were done separately for positive and negative hadrons and for the Collins and the Sivers asymmetries.

The largest systematic error is due to residual acceptance variations within pairs of data taking sub-periods. To quantify these effects, two different types of false asymmetries were calculated, using the external cells and the internal cell divided in two parts, and assuming wrong sign polarisation for one of the two. Moreover, the physical asymmetries were also extracted using only the first and only the second half of the target. The difference between these two physical asymmetries, the false asymmetries, and the degree of compatibility of the results from different periods were all used to quantify the systematic uncertainty.

In the case of the Collins asymmetry, the systematic uncertainty is estimated to be 0.5 σ_{stat} for positive and 0.6 σ_{stat} for negative hadrons. In the case of the Sivers asymmetry, the systematic error is 0.8 σ_{stat} for positive and 0.4 σ_{stat} for negative hadrons. A further systematic uncertainty of ± 0.01 is present in the absolute scale of the Sivers asymmetry for positive hadrons. It reflects a 0.02 differ-

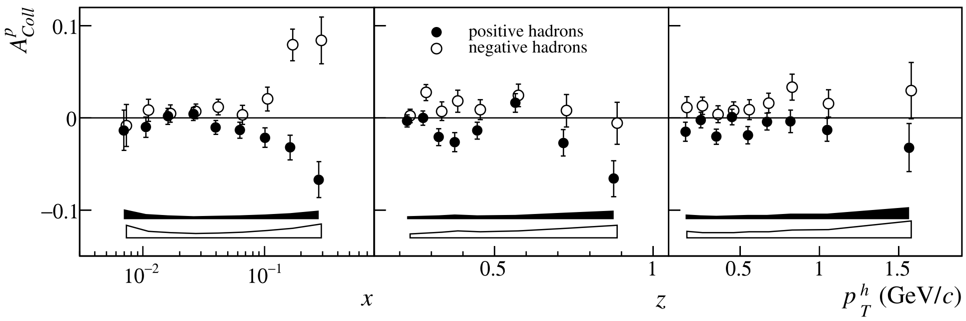

Fig. 1. Collins asymmetry as a function of x, z, and p_T^h, for positive (closed circles) and negative (open circles) hadrons. The bars show the statistical errors. The point to point systematic uncertainties have been estimated to be 0.5 σ_{stat} for positive and 0.6 σ_{stat} for negative hadrons and are given by the bands.

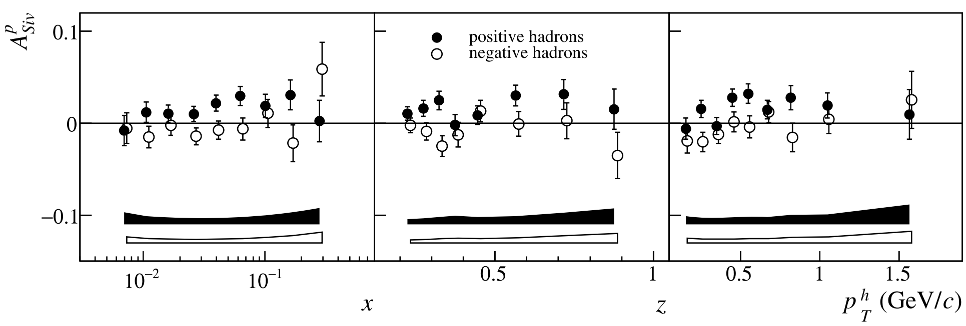

Fig. 2. Sivers asymmetry as a function of x, z, and p_T^h, for positive (closed circles) and negative (open circles) hadrons. The bars show the statistical errors. The point to point systematic uncertainties have been estimated to be 0.8 σ_{stat} for positive and 0.4 σ_{stat} for negative hadrons and are given by the bands. For positive hadrons only, an absolute scale uncertainty of ±0.01 has also to be taken into account.

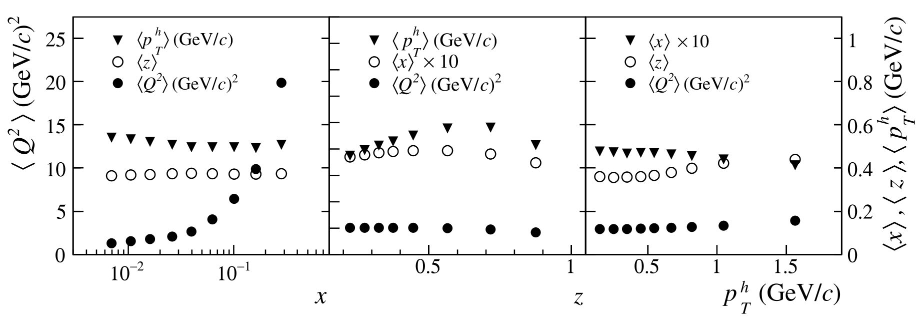

Fig. 3. Mean values of some kinematic variables in the final data sample. From left to right: mean values of p_T^h, z and Q^2 as functions of x; mean values of p_T^h, x and Q^2 as functions of z; mean values of x, z and Q^2 as functions of p_T^h.

ence in the mean value of the asymmetries extracted in the first two and in the second two periods of data taking used for this analysis. In spite of throughout studies, the origin of this difference, which affects only the Sivers asymmetry for positive hadrons, could not be identified and had therefore to be included in the systematic uncertainty.

The results of this measurement of the Collins and Sivers asymmetries are shown in Fig. 1 and 2 as a function of x, z, and p_T^h, for positive and negative hadrons. Fig. 3 displays the mean values of kinematic variables for positive hadrons in the x, z, and p_T^h bins. The corresponding quantities for negative hadrons are very similar.[16]

As it is clear from Fig. 1, the Collins asymmetry has a strong x dependence. It is compatible with zero at small x within the small statistical errors and increases in absolute value up to about 0.1 for $x > 0.1$. There, the values agree both in magnitude and in sign with the previous measurements of HERMES [13], which were performed at the considerably lower electron beam energy of 27.5 GeV. Also, the present results agree with the predictions of the global analysis of Refs. [19,20] and thus strongly support the underlying interpretation of the Collins asymmetry in terms of a convolution of the twist-two transversity PDF and the FF of a transversely polarised quark. An important issue to establish the leading-twist nature of the Collins asymmetry is its Q^2 dependence. As shown in Fig. 3 in the three large x bins the mean Q^2 values are already large enough to be insensitive to twist-3 effects which decrease as $1/Q$. Moreover, our results at large x are compatible with the HERMES data in spite of the higher Q^2 values which exceed those of HERMES by a factor two to three increasing with x. This indicates that the possible Q^2 dependence, if any, should be very mild, a strong argument in support of a leading-twist nature of the Collins asymmetry.

The results for the Sivers asymmetry for negative hadrons exhibit values compatible with zero within the statistical accuracy of the measurement. For positive hadrons, the data indicate small positive values, up to about 3% in the valence quark region. These values are somewhat smaller than but still compatible with the

[16] All numerical values have been put to HEPDATA.

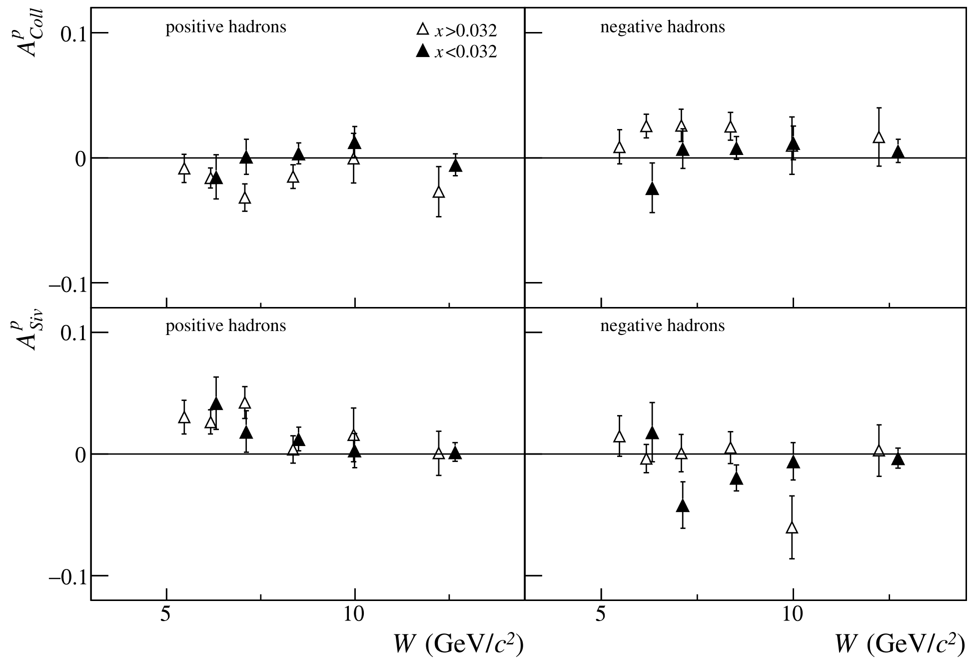

Fig. 4. Collins (upper row) and Sivers (lower row) asymmetry as a function of W, for positive (left) and negative (right) hadrons. The open and closed triangles give the values for the $x > 0.032$ and $x < 0.032$ ranges respectively. The errors are statistical only.

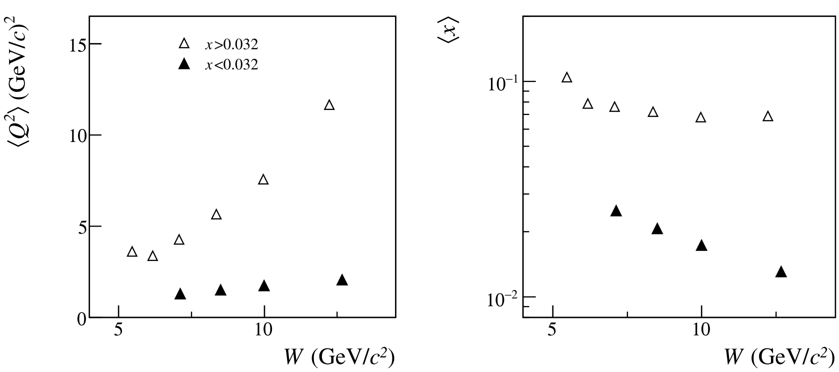

Fig. 5. Mean values of Q^2 (left) and x (right) as functions of W. The open and closed triangles give the values for the $x > 0.032$ and $x < 0.032$ ranges respectively.

ones measured by HERMES at smaller Q^2. Given the importance of the Sivers function in the present description of the transverse momentum structure of the nucleon, we looked at a possible kinematic dependence of our measurements. In particular, we evaluated the asymmetries as a function of W, separately for the "large-x" ($x > 0.032$) and "small-x" ($x < 0.032$) samples. The results are shown in Fig. 4. The mean values of Q^2 and x in all W bins are given in Fig. 5. As it is apparent from Fig. 4, no conclusion can be drawn about a possible W dependence of the Collins asymmetry. On the other hand, the signal of the Sivers asymmetry for positive hadrons seems to be concentrated at small W, in the region where HERMES measures, and goes to zero at large W, which for large x means large Q^2. Thus our data give an indication for a possible W dependence of the Sivers asymmetry for positive hadrons.

In summary, for the first time the Collins and Sivers asymmetries for positive and negative hadron production in DIS off the proton have been measured at high energy. Our data extend the kinematic range to large Q^2 and large W values. The x range has been extended to considerably smaller values which are needed to evaluate the first moments of the transversity distributions. For the Sivers asymmetry, a signal is seen for positive hadrons, which persists to rather small x values. The data give an indication for a possible W dependence of this asymmetry, but the present statistical and systematic uncertainties do not allow definite conclusions. The measured Collins asymmetry is sizable for both positive and negative hadrons also at high energies and large Q^2, as expected for leading twist effects. Thus Collins asymmetries measured in SIDIS are an appropriate tool to investigate the transversity PDF.

Acknowledgements

We gratefully acknowledge the support of the CERN management and staff and the skill and effort of the technicians of our collaborating institutes. Special thanks go to V. Anosov and V. Pesaro for their technical support during the installation and running of this experiment.

References

[1] G. Bunce, et al., Phys. Rev. Lett. 36 (1976) 1113.
[2] J. Antille, et al., Phys. Lett. B 94 (1980) 523.
[3] A. Bravar, et al., Fermilab E704 Collaboration, Phys. Rev. Lett. 77 (1996) 2626.
[4] J. Ashman, et al., European Muon Collaboration, Phys. Lett. B 206 (1988) 364; J. Ashman, et al., European Muon Collaboration, Nucl. Phys. B 328 (1989) 1.
[5] R.L. Jaffe, X.D. Ji, Phys. Rev. Lett. 67 (1991) 552.

[6] J. Collins, Nucl. Phys. B 396 (1993) 161.
[7] A. Kotzinian, Nucl. Phys. B 441 (1995) 234.
[8] P.J. Mulders, R.D. Tangerman, Nucl. Phys. B 461 (1996) 197;
P.J. Mulders, R.D. Tangerman, Nucl. Phys. B 484 (1997) 538, Erratum.
[9] A. Bacchetta, M. Diehl, K. Goeke, A. Metz, P.J. Mulders, M. Schlegel, JHEP 0702 (2007) 093.
[10] D.W. Sivers, Phys. Rev. D 41 (1990) 83.
[11] S.J. Brodsky, F. Yuan, Phys. Rev. D 74 (2006) 094018.
[12] Experiment E-06-10/E-06-11 in HALL A at Jefferson Laboratory, http://www.jlab.org/exp_prog/CEBAF_EXP/E06010.html.
[13] A. Airapetian, et al., HERMES Collaboration, Phys. Rev. Lett. 94 (2005) 012002.
[14] K. Abe, et al., Belle Collaboration, Phys. Rev. Lett. 96 (2006) 232002.
[15] R. Seidl, et al., Belle Collaboration, Phys. Rev. D 78 (2008) 032011.
[16] V.Y. Alexakhin, et al., COMPASS Collaboration, Phys. Rev. Lett. 94 (2005) 202002.
[17] E.S. Ageev, et al., COMPASS Collaboration, Nucl. Phys. B 765 (2007) 31.
[18] M. Alekseev, et al., COMPASS Collaboration, Phys. Lett. B 673 (2009) 127.
[19] M. Anselmino, et al., Phys. Rev. D 75 (2007) 054032.
[20] M. Anselmino, et al., Nucl. Phys. Proc. Suppl. 191 (2009) 98.
[21] A. Airapetian, et al., HERMES Collaboration, Phys. Rev. Lett. 103 (2009) 152002.
[22] M. Anselmino, et al., Proceedings of Transversity 2005, World Scientific, 2006, arXiv:hep-ph/0511017, p. 236.
[23] P. Abbon, et al., COMPASS Collaboration, Nucl. Instrum. Meth. A 577 (2007) 455.
[24] A. Bacchetta, U. D'Alesio, M. Diehl, C.A. Miller, Phys. Rev. D 70 (2004) 117504.
[25] R.J. Barlow, Nucl. Instrum. Meth. A 297 (1990) 496.