TRANSVERSITY AND SPIN STRUCTURE FUNCTIONS

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ABSTRACT

Measurements of single-spin asymmetries for semi-inclusive electro-production of pions and kaons in deep-inelastic scattering with transverse target polarization open a new window on the transverse quark and gluon structure of the nucleon. The first experimental results from such measurements as well as experiments in progress are discussed. Properties of the the spin-dependent Collins fragmentation function and prospects for extracting the transversity are reviewed and evidence for nonzero Sivers asymmetries as manifestations of quark orbital angular momentum is evaluated.
1 Introduction

A complete description of the quark structure of the proton at leading order in deep-inelastic scattering (DIS) requires three flavor-dependent parton distribution functions (PDF’s). The most familiar of these is the unpolarized distribution function \( q(x, Q^2) \). It describes the quark momentum distribution at infinite momentum. Here \( x \) is the dimensionless Bjorken scaling variable which is the momentum fraction carried by a parton and \(-Q^2\) is the four momentum transfer. The first moment of \( q(x, Q^2) \) provides a measure of the quark vector charge, i.e. \( \langle PS|\bar{\psi}\gamma^\mu\psi|PS \rangle = \int_0^1 dx (q(x) - \bar{q}(x)) \). It has been thoroughly studied \cite{1, 2} and is well known for all flavors. In the quark parton model, the \( F_2 \) structure function is given by \( F_2(x) = \sum_q e_q^2 q(x) \). The second PDF is the longitudinal polarized distribution function \( \Delta q(x, Q^2) \) which describes the longitudinal helicity distribution of the quarks in a proton polarized parallel to its momentum. Its first moment determines the axial charge of the quarks, i.e. \( \langle PS|\bar{\psi}\gamma^\mu\gamma_5\psi|PS \rangle = \int_0^1 dx (\Delta q(x) + \Delta \bar{q}(x)) \). In terms of the polarized PDF’s, the polarized proton structure function is given by \( g_1(x) = 0.5 \sum_q e_q^2 \Delta(x, Q^2) \). In recent years much has much has been learned about \( g_1 \) from studies of polarized DIS \cite{3}. The third PDF is the transversity distribution function \( \delta q(x, Q^2) \) which measures the quark helicity distribution in a proton polarized perpendicular to the proton momentum at infinite momentum. It is related to the quark tensor charge through its first moment, i.e. \( \langle PS|\bar{\psi}\sigma^{\mu\nu}\gamma_5\psi|PS \rangle = \int_0^1 dx (\delta q_1(x) + \delta \bar{q}_1(x)) \). Until now its properties have been unobserved.

For non-relativistic quarks, \( \Delta q \) and \( \delta q \) would be identical since by means of commuting rotations and Euclidean boosts one can convert a longitudinally polarized proton into a transversely polarized proton at infinite momentum. However, because the internal motion of the quarks is relativistic, this is not true and a comparison of the two PDFs will reflect the relativistic character of quark motion in the proton. In contrast to its chiral-even partners, \( q \) and \( \Delta q \), the transversity distribution is chiral-odd. This property of transversity makes its measurement difficult since hard QCD and electroweak processes preserve chirality. It decouples from inclusive DIS and other deep inelastic processes. However, it is of considerable interest because of its unique properties. The \( Q^2 \) evolution of \( \delta q(x, Q^2) \) is much simpler than that of its leading order partners, because it does not couple to gluons. It is a valence quantity. Lattice gauge calculations can provide reliable estimates of its first moment, the quark tensor charge.

Chirality can be conserved in DIS processes involving transversity by coupling it to a second chiral-odd function, in the case of Drell-Yan to the transversity
of the beam particle, or in the case of semi-inclusive hadron production to a fragmentation function which also has a chiral-odd structure. Consequently, reactions involving at least two hadrons are required to explore the properties of transversity. Indeed, transversity was first introduced by Ralston and Soper \cite{4} in their treatment of the production of muon pairs in polarized Drell-Yan production. Perhaps the most striking example of such reactions came almost 10 years ago from the Fermilab experiment E704 which reported measuring a large analyzing power $A_N$ in the inclusive production of pions from a transversely polarized proton beam of 200 GeV incident on an unpolarized target \cite{5}. Very strong azimuthal asymmetries were reported for positive and neutral pions which were of opposite sign when measured for negative pions.

Two explanations were developed for these results. The observable $A_N$ is odd under the application of naive time reversal and was assumed therefore to arise from the non-perturbative part of the reaction amplitude. Assuming factorization of the amplitude as shown in Figure 1 either a $T$-odd fragmentation function or a $T$-odd distribution function must be involved. In one case the measured analyzing power was postulated to be proportional to the product of transversity $\delta q$ times a Collins fragmentation function $H^+_{T}$ which is $T$- and chiral-odd. In the second case the $T$-odd chiral-even distribution function $f^{T}_{1}(x, k_T)$ first postulated by Sivers \cite{6} is coupled to the usual unpolarized fragmentation function $D^h$. Either a pure Collins amplitude \cite{7} or a pure Sivers amplitude \cite{8} provides a complete fit to the data.

2 Azimuthal spin asymmetries

The Collins mechanism \cite{9} is of special interest because it provides a direct probe of $\delta q$. It produces a correlation in the fragmentation process between the axis of

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{figure1.png}
\caption{Deep-inelastic scattering processes involving a chiral-odd process that couples to transversity to conserve chirality.}
\end{figure}
Figure 2: The definitions of the azimuthal angles of the hadron production plane and the axis of the relevant component $\vec{S}_\perp$ of the target spin, relative to the plane containing the momentum $\vec{k}$ ($\vec{k}'$) of the incident (scattered) lepton. Explicitly, $\phi = \frac{\vec{q} \times \vec{k} \cdot \vec{P}_h}{|\vec{q} \times \vec{k}| |\vec{q} \times \vec{P}_h|} \cos^{-1} \frac{\vec{q} \times \vec{k} \cdot \vec{q} \times \vec{S}_\perp}{|\vec{q} \times \vec{k}| |\vec{q} \times \vec{S}_\perp|}$ and $\phi_s = \frac{\vec{q} \times \vec{k} \cdot \vec{S}_\perp}{|\vec{q} \times \vec{k}| |\vec{q} \times \vec{S}_\perp|} \cos^{-1} \frac{\vec{q} \times \vec{k} \cdot \vec{q} \times \vec{P}_h}{|\vec{q} \times \vec{k}| |\vec{q} \times \vec{P}_h|}$, where $0 < \cos^{-1} < \pi$.

transverse target spin and the vector $\vec{P}_T \times \vec{q}$ where $\vec{P}_T$ is the momentum of final state hadron and $\vec{q}$ is the virtual photon momentum. (See Figure 2.) Because it is a chiral-odd correlation it combines with $\delta q$ to provide an observable which is accessible in semi-inclusive DIS. The Collins fragmentation function $H^{1+}_1$ which describes this spin-momentum correlation is chiral-odd and odd under naive time reversal (T-odd), i.e. time reversal without interchange of the initial and final states. This “Collins function” arises from the interference of amplitudes with different imaginary parts and gives rise to hadron single-spin asymmetries. It describes the influence of the transverse polarization on the momentum component $\vec{P}_{h \perp}$ of the hadron transverse to the virtual photon direction which will effect its distribution in the azimuthal angle $\phi$ shown in Figure 2. The characteristic signature for the Collins effect in semi-inclusive scattering of an unpolarized lepton beam by a transversely polarized target producing a pseudoscalar meson is a $\sin(\phi + \phi_S)$ variation in the azimuthal distribution.

Azimuthal spin asymmetries can also be generated by the T-odd Sivers distribution function $f_{T}^{1T}(x, k_T)$ discussed in the previous section, which describes a correlation between the transverse polarization of the target nucleon and the $\vec{p}_T$ of the struck quark. This $\vec{p}_T$ survives fragmentation to be inherited by the hadron $\vec{P}_{h \perp}$. The familiar unpolarized fragmentation function $D_1$ describes the fragmentation process. Because this mechanism is related to a forward scattering amplitude in which the helicity of the target nucleon is flipped ($N^=q \rightarrow N^=\bar{q}$), the angular momentum of the unpolarized quark plays a role. The polarization state of the virtual photon and the orientation of the lepton scattering plane are irrelevant to the Sivers effect. The characteristic signature for this mechanism is a target spin
asymmetry with a $\sin(\phi - \phi_S)$ variation.

Measurements of spin asymmetries with transverse target polarization, permit one to use the variation in the two azimuthal angles $\phi$ and $\phi_S$ to distinguish the Collins and Sivers effects. The quantity measured is the two dimensional asymmetry

$$A_{UT}^h(\phi, \phi_S) = \frac{1}{|S_T|} \left( \frac{N^\uparrow_h(\phi, \phi_S) - N^\downarrow_h(\phi, \phi_S)}{N^\uparrow_h(\phi, \phi_S) + N^\downarrow_h(\phi, \phi_S)} \right)$$

where $N_h^{\uparrow(\downarrow)}(\phi, \phi_S)$ is the semi-inclusive luminosity-normalized yield in that target spin state, and $\phi_S$ always indicates the spin direction of the $\uparrow$ state. Measurement with an unpolarized beam and transversely polarized target is indicated by the UT subscripts. This asymmetry is then fit with a sum of contributions from two sinusoidal dependences as shown above. Monte Carlo simulations confirm that extraction of both contributions is made from this fit without measurable cross-contamination even in the case that their magnitudes in the acceptance are very different.

3 Experimental measurements

3.1 HERMES

The studies of $\delta q$ and $f_T^1$ in the HERMES experiment employ a transversely nuclear-polarized hydrogen gas target $^{11}$ which intercepts the $E = 27.6 \text{ GeV}$ beam of the HERA positron storage ring. The beam was unpolarized for these measurements.
An open-ended cell is fed by an atomic-beam source based on Stern-Gerlach separation with hyperfine transitions. The nuclear polarization of the atoms is flipped at 60 s time intervals, and the average proton polarization $S_T$ was $0.78 \pm 0.04$. Scattered beam leptons and coincident hadrons are detected by the HERMES spectrometer [12]. Its geometrical acceptance covers the range $40 < |\theta_y| < 140$ mrad and $|\theta_x| < 170$ mrad where $\theta_x$ and $\theta_y$ are projections of the polar scattering angle. The scattered leptons are identified with 98% efficiency and less than 1% hadron contamination by means of an electromagnetic calorimeter, a transition-radiation detector, a preshower scintillator counter, and a Čerenkov detector. Charged pions are identified by means of a dual-radiator ring-imaging Čerenkov detector [13].

Events are accepted within the kinematic limits $W^2 > 10 \text{ GeV}^2$, $0.1 < y < 0.85$ and $Q^2 > 1 \text{ GeV}^2$, where $W$ is the invariant mass of the photon-nucleon system and $y = (P \cdot q)/(P \cdot k)$. Coincident hadrons were required to be in the range $0.2 < z < 0.7$ and $\theta_{\gamma^*} > 0.02$ rad, where $z = (P \cdot P_h)/(P \cdot q)$ and $\theta_{\gamma^*}$ is the angle between the direction of the virtual photon and that of the hadron. All hadrons detected for each event were included. Effects of acceptance, instrumental smearing, and QED radiation were all found to be negligible in Monte Carlo simulations. Data for the single spin asymmetry $A_{UT}^{\pi^+}(\phi, \phi_S)$ presented in Figure 4 show the expected sinusoidal two-dimensional behaviour.

Figure 4: Measured $\pi^+$ cross section asymmetries in transverse polarization averaged over the experimental acceptance as a function of azimuthal angles shown in Figure 2. Projections of the upper panel are shown in the lower panels, selected from the indicated ranges in the other angle.
The HERMES analysis \[14\] is based on the extraction of a Collins azimuthal moment \( \langle \sin(\phi + \phi_S) \rangle_{UT}^h \) and Sivers moment \( \langle \sin(\phi - \phi_S) \rangle_{UT}^h \) of the virtual-photon asymmetry from the fit to a modified version of equation \[1\]

\[
\frac{A_{UT}^h(\phi, \phi_S)}{2} = \langle \sin(\phi + \phi_S) \rangle_{UT}^h \frac{B(\langle y \rangle)}{A(\langle x \rangle, \langle y \rangle)} \sin(\phi + \phi_S) \\
+ \langle \sin(\phi - \phi_S) \rangle_{UT}^h \sin(\phi - \phi_S). \tag{2}
\]

where \( B(y) \equiv (1 - y) \), \( A(x, y) \equiv \frac{y^2}{2} + (1 - y)(1 + R(x, y))/(1 + \gamma(x, y)^2) \), \( R(x, y) \) is the ratio of longitudinal to transverse DIS cross sections, \( \gamma(x, y)^2 \equiv 2M_p x/(Ey) \), and \( E \) is the lepton energy. The extracted asymmetries in the form of azimuthal moments averaged over the experimental acceptance and selected ranges of \( x \) and \( z \) of \( 0.023 < x < 0.4 \) and \( 0.2 < z < 0.7 \) are shown in Figure 5. The corresponding mean values of

![Figure 5: Virtual-photon Collins (Sivers) moments for charged pions as labelled in the upper (middle) panel, as a function of \( x \) and \( z \). The error bars represent the statistical uncertainties. In addition, there is a common 8% scale uncertainty in the moments. The lower panel shows the relative contributions to the data from simulated exclusive vector meson production.](image)

the kinematic parameters are \( \langle x \rangle = 0.09, \langle y \rangle = 0.54, \langle Q^2 \rangle = 2.41 \text{GeV}^2, \langle z \rangle = 0.36 \)
and \( P_{\pi \perp} = 0.41 \text{ GeV} \). The bottom section of Figure 5 presents simulations based on pythia6 [15], tuned for HERMES kinematics, of the fractions of the semi-inclusive pion yield from exclusive production of vector mesons, the asymmetries of which are poorly determined.

The results for the Collins moments show an unexpected behaviour. The averaged Collins moment for \( \pi^+ \) is positive at \( 0.021 \pm 0.007 \text{(stat)} \), while it is negative at \( -0.038 \pm 0.008 \text{(stat)} \) for \( \pi^- \). The suggestion that transversity distributions should resemble helicities distributions, at least in their general trends is not born out by the data. To the extend that \( \delta u \) is positive and \( \delta d \) is negative the data is similar to model predictions [16]. However, the magnitude of the negative \( \pi^- \) moment appears to be at least as large as that for \( \pi^+ \). This trend becomes more pronounced as the magnitude of the transverse moments increase at large \( x \) where valence quark effects dominate, as they do in previously measured longitudinal spin asymmetries. Unlike the case of \( \pi^+ \) where u-quark dominance is expected, large negative \( \pi^- \) moments are a surprise, because neither quark flavor dominates \( \pi^- \) production, and one expects \( |\delta d| < |\delta u| \) in analogy with \( |\Delta d| < |\Delta u| \). In addition, the Collins moments shown in the right portion of Figure 5 do not show the increase with increasing \( z \) which has been predicted [17] on the basis of a corresponding \( z \) dependence found for the Collins fragmentation function.

The HERMES results for the Sivers moment are very suggestive. The value found is positive and nonzero at \( 0.017 \pm 0.004 \text{(stat)} \) for \( \pi^+ \), while the \( \pi^- \) moment is consistent with zero: \( 0.002 \pm 0.005 \text{(stat)} \). The large moment for \( \pi^+ \) appears to provide the first evidence in leptoproduction for the T-odd Sivers parton distribution. Because the \( \pi^+ \) moment is dominated by up quarks, with the sign convention which has been adopted in relating the azimuthal asymmetries to the the parton distributions [18] a positive asymmetry implies a negative value for the Sivers function of this flavor. However, a substantial contamination of pions from \( \rho^0 \) decay are present. Studies to date of a small sample of exclusive \( \rho^0 \) events in which both pions are detected suggest that this asymmetry extracted for the \( \pi^+ \) in the same manner as in the HERMES semi-inclusive analysis also has a significant positive \( \langle \sin(\phi - \phi_S) \rangle^h_{UT} \) asymmetry which could complicate the interpretation of the data for the Sivers effect.

3.2 COMPASS

The measurement of transversity is a major component of the physics program of the COMPASS experiment which uses the CERN SPS muon beam. The experiment has
been run at a muon energy of 160 GeV. The beam intensity is $2 \cdot 10^8$ muons per spill which is 4.5 seconds long. A polarized $\vec{L}i\vec{D}$ target containing two simultaneously oppositely transversely polarized sections is viewed by a two stage fixed target magnetic spectrometer shown in Figure 6. To date, data reported results from events in which leading hadrons are accepted without further particle identification.

Preliminary results for the Collins asymmetry as measured by COMPASS [19] is presented in Figure 7. The kinematic restrictions on the scattered muon give $Q^2 > 1 \text{GeV}^2$, $0.1 < y < 0.9$, and $w > 5 \text{GeV}$. Leading hadrons are accepted if $p_T > 0.1 \text{GeV/c}$ and $z > 0.25$. While the statistical precision is still less than required for clear extraction of asymmetries of the size indicated by the HERMES results, the trends in the COMPASS data are clearly consistent with the HERMES data discussed above. With continued running very much improved precision is expected for the COMPASS measurements.

Figure 6: Top view of the COMPASS spectrometer.
3.3 Related measurements

Because the single spin asymmetries measured in SIDIS are determined by the product $\delta q \cdot H^\perp_1$, an independent determination of $H^\perp_1$ will greatly facilitate the extraction of $\delta q$. Measurements of spin-dependent fragmentation functions are planned by the BELLE experiment at the KEKB asymmetric collider by studying azimuthal angle correlations in $e^+e^- \to \pi^+\pi^-X$ reactions. The analysis in progress is focused on the separation of Collins asymmetries from physics background.

At RHIC measurements of the Sivers and Collins effects are planned in $p \uparrow p$ reactions. Significant single spin asymmetries already have been reported by the STAR collaboration for forward-produced $\pi^0$’s at $\sqrt{s}=200$ GeV and $x_q \geq 0.6$. Star will measure $A_N^{\pi^0}$ in a different kinematic region, midrapidity where $x_q \approx 0.1$.

4 Discussion of Results

Perhaps the most interesting feature of the HERMES data is the unexpectedly large negative $\pi^-$ Collins azimuthal moment. As a result of the proof of factorization[20] for spin-dependent DIS cross sections that involve in leading twist the effects of

Figure 7: The Collins asymmetry as measured by COMPASS. HERMES data are also shown for comparison.
intrinsic $p_T$ or fragmentation $K_T$, the single-spin asymmetries can be expressed in terms of the usual product of distribution (e.g. transversity) and fragmentation (e.g. Collins) functions. Thus, a reasonable leading order ansatz for the Collins asymmetry is

$$A_{UT}^h \propto \frac{S_\perp \sum_q e_q^2 \delta q(x) H_1^{i_q}(z)}{\sum_{{q'} \neq q} e_{{q'} q}' \delta q'(x) D_1^{i_q}(z)}$$

where $e_q$ is the electric charge of the quark of flavor $q$. The negative $\pi^-$ moment would be explained by a substantial disfavored Collins function that describes the fragmentation of $u$ quarks to $\pi^-$ mesons with the opposite sign to that of the favored function. Because the Collins function acts as an analyzing power for transverse quark polarization, either sign for its amplitude is possible.

A simple model the Collins fragmentation process\textsuperscript{21} based on the Lund semiclassical colored string mechanism provides a plausible explanation for the opposite signs of the favored and unfavored fragmentation functions. The implications of this model for pion electroproduction are illustrated in Figure 8. With the absorption of the virtual photon, the spin of the struck quark is flipped and the string

Figure 8: String model of spin dependent fragmentation of X. Artu et al.\textsuperscript{21}. The sections at the right present the results of a Lund Monte Carlo simulation which shows the back to back emission of fragmentation pions at high $z$.
connecting the quark to the remanent diquark is stretched until the first string break as illustrated in the Figure. It is assumed in the model that the $q\bar{q}$ pair formed at the break is produced in a triplet P state, e.g. $J^P = 0^+$. As indicated in this configuration the leading pion is preferentially produced with momentum into the plane. The quark spins at the break will have spin orientations opposite to those of the emerging struck quark. Applying the same model at the second string break where a disfavored pion is formed, the disfavored pion will be produced with transverse momentum opposite in direction to that of the leading pion. This anticorrelation in $P_{\pi \perp}$ between the favored and unfavored pions is demonstrated by the Jetset simulation shown at the right of Figure [3]. The results of this model which is based on Lund string fragmentation show, particularly for $z_{\text{favored}} > 0.2$, a strong back to back azimuthial correlation between favored and unfavored pions.

In theoretical representation of the single spin azimuthal asymmetry as measured, a $p_T$-dependent density function (e.g. Sivers) or a $k_T$-dependent fragmentation function (e.g. Collins) appears inside a convolution integral over $p_T$ and $k_T$. When asymmetry data is averaged over $|P_{h \perp}|$, the deconvolution of distribution and fragmentation functions can only be made with some assumption about their dependence on $p_T$ and $k_T$, respectively. However it has been demonstrated [22] that a model independent extraction can be made by weighting the experimental cross sections by $|P_{h \perp}|/z$ in the integral over this quantity, prior to any moment analysis. With this weighting the Collins asymmetry takes the form

$$\langle \frac{|P_{h \perp}|}{(zM_h)} \sin (\phi + \phi_S) \rangle_{UT} (x, y, z) = \frac{\int d\phi_S d^2P_{h \perp} |P_{h \perp}|/(zM_h) \sin (\phi + \phi_S) d^6\sigma_{UT}}{\int d\phi_S d^2P_{h \perp} d^6\sigma_{UU}}$$

$$= |S_T| \frac{B(y) \sum q e_q^2 \delta_q(x) H_1^{(1)}(z)}{A(y) \sum' q' e_{q'}^2 f_1^{q'}(x) D_{q'}^h(z)}, \quad (4)$$

where including the $1/z$ in the weight relates the asymmetry to the first $z$-moment of the Collins function. For the Sivers asymmetry the form is

$$\langle \frac{|P_{h \perp}|}{(zM_p)} \sin (\phi - \phi_S) \rangle_{UT} (x, y, z) = |S_T| \frac{\sum q e_q^2 f_{1T}^{q}(x) D_{q}^h(z)}{\sum' q' e_{q'}^2 f_1^{q'}(x) D_{q'}^h(z)}, \quad (5)$$

where including the $1/z$ in the weight relates the asymmetry to the first $x$-moment of the Sivers function. $M_h$ is the hadron mass, $M_p$ is the proton mass, and the superscript(1) indicates the $p_T$- or $k_T$-moment of the distribution or fragmentation function, respectively. These equations form the basis for subsequent analysis to extract $\delta_q(x)$ from the Collins moment and $f_{1T}^{q}(x)$ from the the Sivers moment.

Extraction of the flavor-dependent Sivers function is more accessible than that of transversity, because the required unpolarized fragmentation functions $D_{q'}^h(z)$
are known independently. A purity technique, previously used to extract longitudinal helicity distributions [23] can be applied. From equation 5 the Sivers asymmetry takes the form

$$A^h_S(x) = -|S_T| \int_{z_{min}}^{1} dz \sum_q e_q^2 q(x) \cdot z D^h_q(z) \cdot \frac{\delta q(x)}{q(x)} = \sum_q P^h_q(x) \frac{\delta q(x)}{q(x)}$$  (6)

where the hadron quark purity $P^h_q(x)$ is the probability that a quark $q$ was struck in an event $e^+ + N \rightarrow e^{+'} + h + X$. It is a spin-independent quantity which can be calculated from a Monte Carlo simulation of the fragmentation process. One can rewrite equation 6 in a matrix form as

$$\vec{A} = \begin{pmatrix} A^h_1(x) \\ \vdots \\ A^h_n(x) \end{pmatrix}, \vec{Q} = \begin{pmatrix} \delta q_1(x)/q_1(x) \\ \vdots \\ \delta q_n(x)/q_n(x) \end{pmatrix}, \vec{P} = [P^h_q(x)] \Rightarrow \vec{A} = \vec{P} \vec{Q}(x)$$  (7)

where $A(x)$ becomes a vector whose elements are all the integrated measured asymmetries which are to be included in the analysis. The $\vec{Q}(x)$ vector contains the quark transversities. These quantities are now connected by the purity matrix which contains effective integrated purities. The determination of the quark transversities from the experimentally determined measured azimuthal asymmetries is reduced to the task of inversion of equation 6 to obtain $\vec{Q}(x)$. Such an analysis of the HERMES data is in progress. In principle, a similar procedure can be used to extract transversity from the Collins asymmetries, however, in this case the calculation of the purities is prevented at present by the lack of reliable estimates of the Collins fragmentation functions.

An interesting conjecture based on the use of generalized parton distributions to determine the spacial distribution of partons in the transverse plane [24] indicates that Sivers asymmetries for $u$ and $d$ quarks should have opposite signs. In this model the scattering process is treated in terms of an impact parameter ($b_X, b_y$) formalism. The left-right asymmetry in the hadron emission is attributed to final state interactions of the struck quark as it leaves the target. These interactions with a parton distribution which has been distorted by quark orbital motion leads to the asymmetry. Examples of the distortion as represented in the distribution of parton density in impact parameter space is shown in Figure 9.

5 Summary and outlook

The first measurements of asymmetries directly related to transversity and the Sivers function have been made. From the data on the Collins asymmetry the flavor-disfavored Collins fragmentation function appears to be opposite in sign to the
Figure 9: Parton distributions in impact parameter space from ref. [24]. For each plot the grayscales are normalized to the central value. For each quark flavor the left column is for a longitudinally polarized nucleon and the right column for a nucleon polarized in the $x$ direction.

favored one and large. The nonzero Sivers asymmetries can be interpreted as a manifestation of quark orbital angular momentum. The results to date provide a demonstration of a new tool for studying the transverse structure of the nucleon. Such measurements will provide estimates of the nucleon’s transversity distribution and promise to shed light on the relativistic properties of the confined states of quarks and gluons.

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References

1. J. Pumplin et al, JHEP 07, 012 (2002)

2. A.D. Martin et al, Eur. Phys. J. C23, 73 (2002)
3. B. Filippone and X. Ji, Ad. Nucl. Phys. **26**, 1 (2001).
4. J. Ralston and D.E. Soper, Nucl. Phys. **B152**, 109 (1979).
5. FNAL-E704 Collab., A. Bravar et al, Phys. Rev. Lett. **77**, 2626 (1996).
6. D. Sivers, Phys. Rev. **D41**, 83 (1990).
7. M. Anselmino, M. Boglione, and F. Murgia, Phys. Rev. **D60**, 054027 (1999).
8. M. Anselmino and F. Murgia, Phys. Lett. **B442**, 470 (1998).
9. J.C. Collins, Nucl. Phys. **B396**, 161 (1993).
10. D. Boer and P.J. Mulders, Phys. Rev. **D57**, 5780 (1998).
11. F. Stock et al, Nucl. Inst. & Meth. **A343**, 334 (1994).
12. HERMES Collab., K. Ackerstaff et al, Nucl. Inst. & Meth. **A417**, 230 (1998).
13. N. Akopov et al, Nucl. Inst. & Meth. **A479**, 511 (2002).
14. HERMES Collab., A Airapetian et al, hep-ex/0408013, submitted to Phy. Rev. Lett.
15. T. Sjöstrand et al, Comp. Phys. Commun. **135**, 238 (2001).
16. V. Barone, A. Drago, and P.G. Ratcliffe, Phys. Rept. **359**, 1 (2002).
17. A. Bacchetta, R. Kunda, A. Metz, and P.J. Mulders, Phys. Rev. **D65**, 094021 (2002).
18. P.J. Mulders and R.D. Tangerman, Nucl. Phys. **B461**, 373 (1996).
19. COMPASS Collab., H. Fischer, Transverse Collins Asymmetry for Charged Hadrons, in: Proc. International Workshop in Deep Inelastic Scattering, April (2004), to be published.
20. X. Ji, P. Ma, and F. Yuan, hep-ph/0405085.
21. X. Artu, J. Czyżewski, and H Yabuki, Z. Phys. **C73**, 527 (1997).
22. A.M. Kotzinian and P.J. Mulders, Phys. Lett. **B406**, 373 (1997).
23. A. Airapetian et al, Phys. Rev. Lett. **92**, 012005 (2004).
24. M. Burkhardt, hep-ph/0309269.