Measurement of Collins and Sivers asymmetries at HERMES

L. L. Pappalardo
(On behalf of the HERMES Collaboration)

Università degli studi di Ferrara
Dipartimento di Fisica
Via Saragat, 1 44100 Ferrara
E-mail: pappalardo@fe.infn.it
http://df.unife.it/

Preliminary results on azimuthal single-spin asymmetries in semi-inclusive electro-production of pions and charged kaons at the HERMES experiment are presented. Significant amplitudes for both the Collins and the Sivers mechanisms are extracted from the full data set collected with a transversely polarized target. A new method for the evaluation of the acceptance effects, developed in view of a future extraction of the $P_{h,\perp}$-weighted moments, is also discussed.

Keywords: Transversity, Sivers function, Collins mechanism, Sivers mechanism.

1. The Collins and Sivers mechanisms

After integrating over the quark transverse momentum $p_T$, three parton distribution functions are needed at leading twist for a complete description of the momentum and spin distributions of the quarks within the nucleon. Two of these have been experimentally explored in some detail: the momentum distribution $q(x, Q^2)$, and the helicity distribution $\Delta q(x, Q^2)$. In contrast, the third one, known as transversity [1,2], remained unmeasured until very recently [3]. In a basis of transverse spin eigenstates, it reflects the difference in probabilities to find, in a transversely polarized nucleon, quarks with their spin aligned and anti-aligned to the spin of the nucleon. This quantity, however, has no probabilistic interpretation in the helicity basis, in which the other two distribution functions are naturally defined. In this basis, indeed, it is related to a forward scattering amplitude involving helicity flip of both quark and target nucleon ($N \rightarrow q^- \rightarrow N^{-2q}$), which is suppressed by chirality conservation. Being a chiral-odd object, transversity is not measurable in inclusive Deep Inelastic Scattering (DIS).

At HERMES azimuthal Single Target-Spin Asymmetries (SSA) in Semi-
Inclusive Deeply Inelastic Scattering (SIDIS) on a transversely polarized proton target are investigated. In such events the scattered lepton is detected in coincidence with at least one of the hadrons produced in the fragmentation of the struck quark. This allows, in particular, to access the so-called Collins moments, in which transversity is convoluted with the chiral-odd Collins fragmentation function, describing the correlation between the transverse spin of the struck quark and the transverse momentum $P_{h\perp}$ of the produced hadron \[4\]. The transverse polarization of the struck quark can indeed influence the transverse (with respect to the virtual photon direction) component of the hadron momentum, leading to an azimuthal asymmetry in the momentum distribution of the produced hadrons (Collins mechanism). Similar asymmetries might also arise from a completely different mechanism involving a correlation between the transverse polarization of the target nucleon and the transverse momentum $p_T$ of quarks (Sivers mechanism) \[5\]. This correlation is accounted for by the naïve T-odd Sivers function $f_{1T}^\perp$, which, being related to a forward scattering amplitude involving helicity flip of only the target nucleon ($N^\sigma q^- \rightarrow N^\sigma q^-$), must involve orbital angular momentum of the quarks \[6,7\]. The so-called Sivers moments, which are proportional to a convolution of the Sivers function with the spin-independent fragmentation function, are also accessible at HERMES in SIDIS.

2. The HERMES experiment

The data analyzed was recorded during the 2002–2005 running period of the HERMES experiment using a transversely nuclear-polarized hydrogen gas target internal to the $E = 27.6$ GeV HERA positron/electron storage ring at DESY. Being interested in the extraction of azimuthal moments which are independent on the beam polarization, the two beam helicity states were combined resulting in a vanishing net beam polarization. The open-ended target cell was fed by an atomic-beam source \[8\] based on Stern-Gerlach separation and RF transitions of hyperfine states. The nuclear polarization of the atoms was flipped at 1 – 3 min time intervals. The average value of the proton polarization was $\langle P_z \rangle = 0.73 \pm 0.05$.

Scattered leptons and any coincident hadrons were detected by the HERMES spectrometer \[9\], whose acceptance spans the vertical and horizontal scattering-angle ranges $40 < |\theta_y| < 140$ mrad and $|\theta_x| < 170$ mrad. Leptons are identified with an efficiency exceeding 98% and a hadron contamination of less than 1%. A dual radiator RICH allows to identify the charged hadrons ($\pi^\pm, K^\pm, p$) in the momentum range $2$ GeV $< P_h < 15$ GeV.
3. Extraction of Collins and Sivers moments

Events were selected subject to the kinematic requirements $W^2 > 10 \text{ GeV}^2$, $0.1 < y < 0.95$ and $Q^2 > 1 \text{ GeV}^2$, where $W$ is the invariant mass of the photon-nucleon system and $y$ is the fractional beam energy transfer to the target. Coincident hadrons were only accepted in the semi-inclusive range $0.2 < z < 0.7$, where $z$ is the hadron energy fraction. The cross section asymmetry with respect to the target polarization was evaluated as:

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

(1)

were $N^\uparrow_h(\phi)$ represents the yield in the target spin state “$\uparrow$” for a hadron type $h$, and $\phi$ and $\phi_S$ are two azimuthal angles, defined with respect to the lepton scattering plane, as shown in Fig. 1.

![Fig. 1. Kinematics of semi-inclusive DIS on a transversely polarized target.](image)

The asymmetry (1) can be expanded in terms of azimuthal moments. Each of these moments is characterized by a peculiar modulation in the azimuthal angles $\phi$ and $\phi_S$. In particular, the Collins and Sivers moments are modulated by $\sin(\phi + \phi_S)$ and $\sin(\phi - \phi_S)$, respectively. Their different azimuthal modulation allows to extract them separately.

In 2005 the HERMES Collaboration published a first evidence of non-zero Collins and Sivers moments for charged pions [10]. The results, based on a limited data sample, were extracted in a least-squares fit of the asymmetry (1). The Collins and Sivers moments have now been extracted using the full HERMES transverse data set, resulting in a substantial increase of the statistical precision. Furthermore, these moments have also been extracted for neutral pions and charged kaons. Due to the relatively poor statistics for kaons, which would have produced non reliable fit results in some azimuthal $(\phi, \phi_S)$ bins, an unbinned Maximum Likelihood fit was adopted, based on the following probability density function (p.d.f.):
\[ F(P_z, \phi, \phi_S) = 1 + P_z \cdot \left[ 2\langle \sin(\phi + \phi_S) \rangle_{UT} \sin(\phi + \phi_S) + \right. \]
\[ 2\langle \sin(\phi - \phi_S) \rangle_{UT} \sin(\phi - \phi_S) + 2\langle \sin(3\phi - \phi_S) \rangle_{UT} \sin(3\phi - \phi_S) + \]
\[ 2\langle \sin(2\phi - \phi_S) \rangle_{UT} \sin(2\phi - \phi_S) + 2\langle \sin(\phi_S) \rangle_{UT} \sin(\phi_S) \right]. \]  

(2)

Here \( P_z \) denotes the value of the target polarization and the indices \( U \) and \( T \) stand for Unpolarized beam and Transversely polarized target, respectively. For completeness, three additional terms are included in the fit besides the Collins and Sivers ones: the leading twist \( \langle \sin(3\phi - \phi_S) \rangle_{UT} \) moment and two twist-3 \( \langle \sin(2\phi - \phi_S) \rangle_{UT} \) and \( \langle \sin(\phi_S) \rangle_{UT} \) moments.

The preliminary results for the Collins moments for charged pions are reported in Fig. 2 as a function of \( x, z \) and \( P_{h\perp} \). The shaded bands represent the systematic uncertainty, which include contributions from acceptance effects, instrumental smearing, QED radiation and hadron misidentification. A common 8.1% scale uncertainty arises from the uncertainty on the target polarization.

![Collins moments for \( \pi^+ \) (upper panels) and \( \pi^- \) (lower panels)](image)

Significantly positive (negative) Collins amplitudes are observed for \( \pi^+ \) (\( \pi^- \)). These results confirm the previously published ones [10] and demonstrate that both transversity and Collins function are non-zero.
The fragmentation of an u-quark is said to be *favored* if the produced hadron contains an u-quark as a valence quark (e.g. \( \pi^+ \)) and *unfavored* in the opposite case (e.g. \( \pi^- \)). Assuming that the scattering off u-quarks is the dominating subprocess (u-quark dominance), the unexpectedly high negative Collins amplitude for \( \pi^- \) suggests a unfavored Collins function with a magnitude similar to that of the favored one but with opposite sign.

The Sivers moments, reported in Fig. 3, show a significantly positive amplitude for \( \pi^+ \). This result demonstrates that the Sivers function is non-zero and implies the existence of non-zero orbital angular momentum of the quarks, which is one of the still unmeasured contributions to the nucleon spin [7]. An amplitude consistent with zero is measured for \( \pi^- \).

The Collins and Sivers moments were also extracted for \( \pi^0 \), as shown in Fig. 4. The results show a Collins amplitude consistent with zero and a Sivers amplitude slightly positive.

The measured Collins and Sivers moments are in agreement with the following relation based on the isospin symmetry for the \( \pi^- \)-meson triplet:

\[
\langle \sin(\phi \pm \phi_S) \rangle^\pi_\pm UT + C \cdot \langle \sin(\phi \pm \phi_S) \rangle^{\pi^-} UT - (1 + C) \cdot \langle \sin(\phi \pm \phi_S) \rangle^{\pi^0} UT = 0, \quad (3)
\]

The coefficient \( C \) represents the unpolarized cross-section ratio for semi-inclusive negative and positive pion production \( (C = \sigma^-_{UT}/\sigma^+_{UT}) \).
which predicts, for the $\pi^0$, amplitudes intermediate between those of $\pi^+$ and $\pi^-$. To probe the contribution from the sea quarks, the Collins and Sivers moments were also extracted for the charged kaons. The corresponding results are compared in Figs. 3 and 5 with those obtained for the charged pions. The Collins moments for $\pi^+$ and $K^+$ are compatible within the statistical uncertainty, while those for $K^-$ and $\pi^-$ are of opposite sign. However, there is in principle no reason to expect a similar amplitude for $K^-$ and $\pi^-$ since, differently from the $\pi^-$, the $K^-$ has no valence quarks in common with the target proton. Unexpectedly, the Sivers amplitude for $K^+$ is found to be roughly twice as big as that for $\pi^+$. Since the valence content of these two mesons differs only in the anti-quark involved, this observation suggests a significant Sivers function for the proton sea quarks.

4. A method for the estimation of the acceptance effects

The extraction of the transversity and the Sivers function from the measured Collins and Sivers moments reported above is not straightforward since these distribution functions are embedded within convolution integrals over the intrinsic transverse momenta. In order to solve these integrals one
Fig. 5. Collins (upper plot) and Sivers (lower plot) moments for $K^+$ (upper panels) and $K^-$ (lower panels). The pion results (open dots) are also shown for comparison.

needs to make an assumption (model) for the distribution of the transverse momenta. The most popular one is the so-called Gaussian ansatz [11].

A model-independent extraction of the transversity and the Sivers function is possible from the so-called $P_{h\perp}$-weighted Collins and Sivers moments. Differently from the 'unweighted' moments presented above, these moments
have an extra weight, given by the ratio $P_{h\perp}/z$, which allows to solve the convolution integral without the need of any assumption on the intrinsic transverse momenta distribution. However, $P_{h\perp}$-weighted moments can be affected by severe acceptance effects due to the acceptance in $P_{h\perp}$ of the spectrometer.

An innovative method for the estimation of the acceptance effects has been developed. This method consists of two main steps. As a first step the full kinematic dependence of the Collins and Sivers moments is extracted from the data in a Maximum Likelihood fit based on a fully differential p.d.f.:

$$F = 1 + P_z \cdot \left[ A_{\text{Col}}(x, Q^2, z, P_{h\perp}; a_C) \sin(\phi + \phi_S) + A_{\text{Siv}}(x, Q^2, z, P_{h\perp}; a_S) \sin(\phi - \phi_S) \right].$$

(4)

Here the Collins and Sivers amplitudes $A_{\text{Col}}$ and $A_{\text{Siv}}$ are parameterized in terms of a Taylor expansion on the four relevant kinematic variables $x$, $Q^2$, $z$, $P_{h\perp}$ through the sets of coefficients $a_C$ and $a_S$, extracted as fit parameters. In the second step, these parameterizations are folded with the unpolarized cross section $\sigma_{UU}$, evaluated either in $4\pi$ and within the HERMES acceptance. The difference between the amplitudes folded in $4\pi$ and those folded within the acceptance then provides an estimate, based on the data signal itself, of the acceptance effects affecting the measured Collins and Sivers moments. This method has been successfully tested using a Monte Carlo simulation based on the GMC\_TRANS generator, which allows to generate events based on phenomenological models for the Collins and Sivers mechanisms. In the future this method will be applied to the real data for the extraction of the $P_{h\perp}$-weighted moments.

References

8. A. Airapetian et al. (HERMES), Nucl. Instr. and Meth. A540, 68 (2005).