Single-Spin Asymmetries in SIDIS off Transversely Polarised Protons at HERMES

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

INFN – Università degli Studi di Ferrara - Dipartimento di Fisica
Polo Scientifico e Tecnologico, Edificio C, Via Saragat 1, 44100 Ferrara - Italy

Azimuthal single-spin asymmetries in semi-inclusive electro-production of pions and charged kaons are investigated at the HERMES experiment. Non-zero amplitudes for both the Collins and the Sivers mechanisms were extracted from the full data set collected with a transversely polarised target. For the first time a 2-dim extraction on x, z and $P_{h\perp}$ of the Collins and Sivers amplitudes for charged pions is reported.

1 The Collins and Sivers mechanisms

At HERMES azimuthal Single Spin Asymmetries (SSA) in Semi-Inclusive Deep Inelastic Scattering (SIDIS) on a transversely polarised proton target are investigated. In the selected events the scattered lepton is detected in coincidence with one of the hadrons produced in the fragmentation of the struck quark. The analysis of these events allowed to extract azimuthal moments, such as the *Collins moments* and the *Sivers moments*, that in turn allow to access fundamental parton distribution and fragmentation functions.
The Collins moments are proportional to the convolution of the *transversity* and the *Collins function*. In a basis of transverse spin eigenstates, the transversity reflects the probability to find, in a transversely polarised nucleon, quarks with their spin aligned or anti-aligned to the spin of the nucleon [1, 2]. Being a chiral-odd object it has no probabilistic interpretation in the helicity basis, in which the other two leading-twist parton distribution functions — the *unpolarised* and the *helicity* distribution functions — are naturally defined. Furthermore, transversity is not measurable in inclusive Deep Inelastic Scattering (DIS) and therefore it remained unmeasured until very recently [3]. The Collins function describes the correlation between the transverse spin of the struck quark and the transverse momentum $P_{h\perp}$ of the produced hadron [4]. The transverse polarisation 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 polarisation 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*, which, being related to a forward scattering amplitude involving helicity flip of only the target nucleon ($N^{\Rightarrow}q^{\leftarrow}\rightarrow N^{\Leftarrow}q^{\leftarrow}$), must involve orbital angular momentum of the quarks [6, 7]. The so-called *Sivers moments*, which are proportional to the convolution of the Sivers function with the spin-independent fragmentation function, are also accessible at HERMES in SIDIS.

2 Extraction of Collins and Sivers moments

The data analysed was recorded during the 2002–2005 running period of the HERMES experiment using a transversely nuclear-polarised hydrogen gas target internal to the $E = 27.6$

GeV HERA positron/electron storage ring at DESY. The open-ended target cell was fed by a polarised atomic-beam source [8] based on Stern-Gerlach separation and RF transitions of hyperfine states. The nuclear polarisation of the atoms was flipped at $1-3$ minutes time intervals. The average value of the proton polarisation was $\langle P_z \rangle = 0.73 \pm 0.05$. Scattered leptons and any coincident hadrons were detected by the HERMES spectrometer [9]. 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. Events were selected subject to the kinematic requirements $W^2 > 10$ GeV^2, $0.1 < y < 0.95$ and $Q^2 > 1$ 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 asymmetry with respect to the target polarisation was evaluated as:

$$A_{UT}^{h}\left(\phi,\phi_S\right) = \frac{1}{\langle P_z \rangle} \frac{N_h^{\Uparrow}\left(\phi,\phi_S\right) + N_h^{\Downarrow}\left(\phi,\phi_S\right)}{N_h^{\Uparrow}\left(\phi,\phi_S\right) - N_h^{\Downarrow}\left(\phi,\phi_S\right)} \,, \tag{1}$$

were $N_h^{\Uparrow(\Downarrow)}$ represents the yield in the target spin state "$\Uparrow$ ($\Downarrow$)" for a hadron type h, and ϕ and ϕ_S are two azimuthal angles, defined with respect to the lepton scattering plane. The asymmetry (1) can be expanded in terms of azimuthal moments. Each of these moments is characterised by a peculiar modulation in the azimuthal angles ϕ and ϕ_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). More recently, the Collins and Sivers moments were extracted also for neutral pions and charged kaons using the full HERMES transverse data set. This extraction was performed through a Maximum Likelihood fit (unbinned in the azimuthal angles ϕ and ϕ_S) of the SIDIS events based on the probability density function:

$$F(\phi,\phi_S) = 1 + P_z \cdot \Big[2\langle \sin(\phi+\phi_S) \rangle_{UT}^{h} \, \sin(\phi+\phi_S) \, + 2\langle \sin(\phi-\phi_S) \rangle_{UT}^{h} \, \sin(\phi-\phi_S) \, + ... \Big] \,. \tag{2}$$

Here P_z denotes the value of the target polarisation and the indices U and T stand for Unpolarised beam and Transversely polarised target, respectively. For convenience only the Collins and Sivers terms are written out explicitly, although three additional terms were included in the fit: the leading twist $\langle \sin(3\phi - \phi_S) \rangle_{UT}^{h}$ moment and two twist-3 $\langle \sin(2\phi - \phi_S) \rangle_{UT}^{h}$ and $\langle \sin(\phi_S) \rangle_{UT}^{h}$ moments.
The preliminary results for the Collins (Sivers) moments for pions and charged kaons are reported in [11, 12]. Significantly positive (negative) Collins amplitudes are observed for π^+ (π^-). 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 *favoured* if the produced hadron contains an u-quark as a valence quark (e.g. π^+) and *unfavoured* in the opposite case (e.g. π^-). Assuming that the scattering off u-quarks is the dominating subprocess (u-quark dominance), the unexpectedly large negative Collins amplitude for π^- suggests an unfavoured Collins function with a magnitude similar to that of the favoured one but with opposite sign. The Collins moments for π^+ and K^+ are compatible within the statistical uncertainty, as expected due to the common dominance of

the u-quark fragmentation, while those for π^- and K^- are of opposite sign. However, there is in principle no reason to expect a similar amplitude for π^- and K^- since, differently from the π^-, the K^- has no valence quarks in common with the target proton.
The Sivers moments show a significantly positive amplitude for π^+ and K^+. 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]. Unexpectedly, the Sivers amplitude for K^+ is found to be larger than that for π^+. Since the valence content of these two mesons differs only in the anti-quarks involved, this observation suggests a significant Sivers function for the sea quarks in the proton. An amplitude consistent with zero is measured for π^- and K^-.
Here, for the first time, a 2-dimensional extraction of the Collins and Sivers amplitudes in the variables x, z and $P_{h\perp}$ is reported for charged pions[a]. The preliminary results for the Collins amplitudes are shown in Fig. 1 (Fig. 2) for bins in x as a function of z ($P_{h\perp}$) and vice-versa. Similarly, the preliminary results for the Sivers amplitudes are shown in Fig. 3 (Fig. 4) for bins in x as a function of z ($P_{h\perp}$) and vice-versa. 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 polarisation.

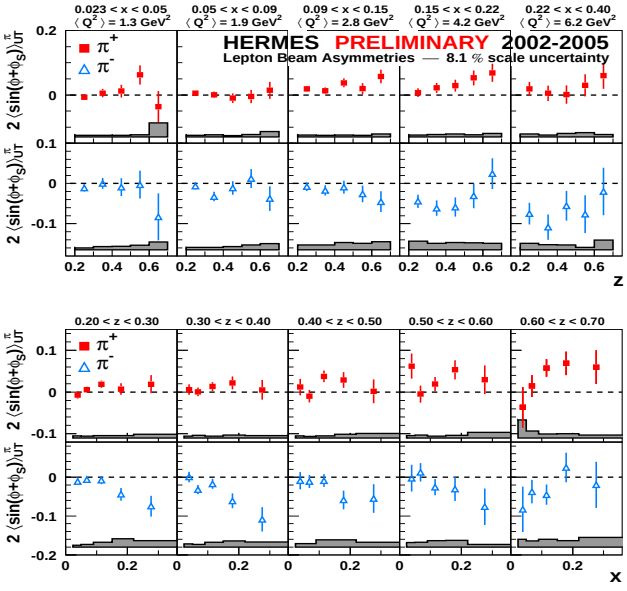

Figure 1: Collins amplitudes for π^+ (full squares) and π^- (open triangles). Upper panels: bins in x as a function of z. Lower panels: bins in z as a function of x

[a] A similar 2-dimensional extraction for charged kaons and neutral pions would be prohibitive due to their much lower statistical power.

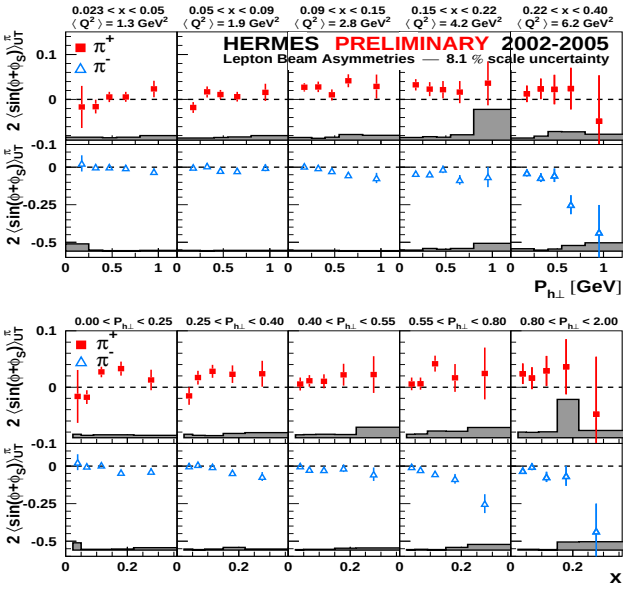

Figure 2: Collins amplitudes for π^+ (full squares) and π^- (open triangles). Upper panels: bins in x as a function of $P_{h\perp}$. Lower panels: bins in $P_{h\perp}$ as a function of x

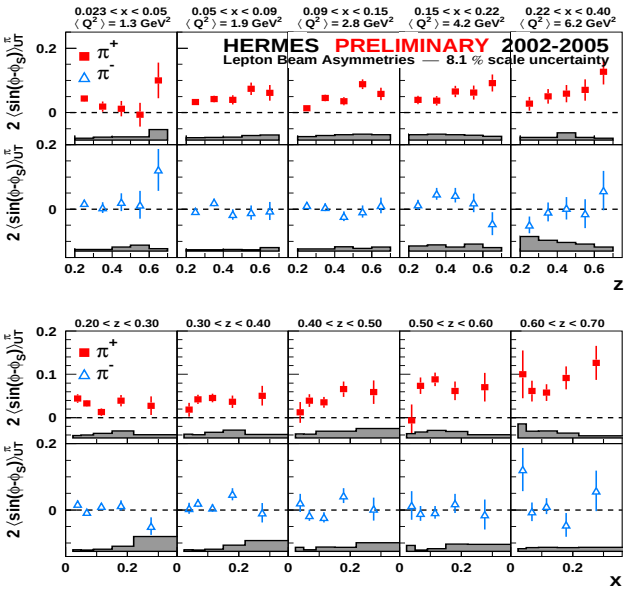

Figure 3: Sivers amplitudes for π^+ (full squares) and π^- (open triangles). Upper panels: bins in x as a function of z. Lower panels: bins in z as a function of x

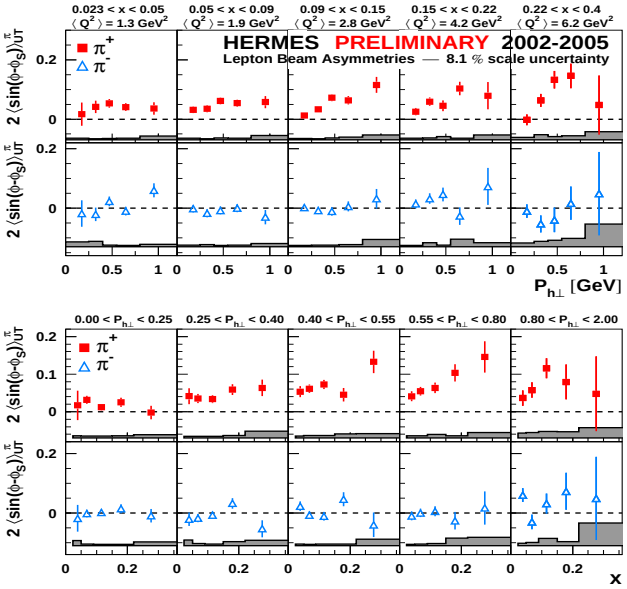

Figure 4: Sivers amplitudes for π^+ (full squares) and π^- (open triangles). Upper panels: bins in x as a function of $P_{h\perp}$. Lower panels: bins in $P_{h\perp}$ as a function of x

3 Conclusions

Azimuthal Single Spin Asymmetries in semi-inclusive electro-production of pions and kaons were measured at HERMES in semi-inclusive deep inelastic scattering of positrons and electrons on a transversely polarised hydrogen target. Significant amplitudes for both the Collins and the Sivers mechanisms were observed indicating the existence of non-zero distribution functions — the transversity and the Sivers function — of utmost importance for the understanding of the transverse structure of the nucleon.

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