

Collins effect and single spin azimuthal asymmetries in the HERMES and COMPASS experiments

A.V. Efremov¹, K. Goeke², P. Schweitzer²

¹ Joint Institute for Nuclear Research, Dubna, 141980 Russia

² Institut für Theoretische Physik II, Ruhr-Universität Bochum, 44780 Bochum, Germany

Received: 18 September 2003 /

Published online: 26 November 2003 – © Springer-Verlag / Società Italiana di Fisica 2003

Abstract. Predictions are made for single spin azimuthal asymmetries due to the Collins effect in pion production from semi-inclusive deeply inelastic scattering off transversely and longitudinally polarized targets for the HERMES and COMPASS experiments. The x -dependence of the asymmetries is evaluated using the parton distribution functions from the chiral quark–soliton model. The overall normalization of the predicted asymmetries is determined by the information on the Collins fragmentation function extracted from previous HERMES data on azimuthal asymmetries $A_{UL}^{\sin\phi}$ from a *longitudinally* polarized target. The single spin asymmetries A_{UT} from the *transversely* polarized proton target are found to be about 20% for positive and neutral pions both at HERMES and COMPASS. For a *longitudinally* polarized target we obtain for COMPASS $A_{UL}^{\sin\phi} \sim 1\%$ and $A_{UL}^{\sin 2\phi} \sim 3\%$.

1 Introduction

Noticeable single spin azimuthal asymmetries¹ $A_{UL}^{\sin\phi}$ have been observed by the HERMES collaboration in pion and kaon electro-production in semi-inclusive deep-inelastic scattering (SIDIS) of an unpolarized lepton beam off a longitudinally polarized proton or deuteron target [1–4]. Recently the CLAS collaboration reported the measurement of the azimuthal asymmetry $A_{LU}^{\sin\phi}$ from SIDIS of a polarized beam off an unpolarized target [5]. Previously indications for the azimuthal asymmetry A_{UT} from SIDIS of an unpolarized beam off a transversely polarized target were reported by the SMC collaboration [6].

Assuming factorization these single spin asymmetries can be explained by the Collins [7] and Sivers effect [8] in terms of so far unexplored distribution and fragmentation functions, namely the nucleon chirally odd twist-2 transversity distribution h_1^a and twist-3 distribution functions h_L^a and e^a [9], the Collins fragmentation function $H_1^{\perp a}$ [7, 10], the chirally even Sivers distribution function $f_{1T}^{\perp a}$ [8, 11–14] (and/or transverse momentum weighted moments thereof [15, 16]). The $H_1^{\perp a}$ and $f_{1T}^{\perp a}$ quantify the Collins and Sivers effect. The former describes the left–right asymmetry in the fragmentation of a transversely

polarized quark into an unpolarized hadron; the latter describes the distribution of unpolarized quarks in a transversely polarized nucleon. Both are referred to as T -odd since, if there were no interactions, these functions would be forbidden by time reversal.

The HERMES data on single spin azimuthal asymmetries from SIDIS off a longitudinally polarized target [1–4] provide important indications that the mechanisms suggested by Collins and Sivers [7, 8] work, which makes them most exciting but also difficult to interpret. It is not clear which portion of the observed effect should be assigned to the Collins, and which to the Sivers mechanism. Moreover, numerous novel distribution and fragmentation functions complicate the analysis. Reasonable descriptions of the HERMES data [1–4] using different assumptions and models were given in [17–23] in terms of the Collins effect only. Noteworthy is that information on the Sivers function gained from a phenomenological description of single spin asymmetries in $pp^\uparrow \rightarrow \pi X$ [14] indicates that neglecting the Sivers effect in the analysis of the HERMES experiment could be justified [24].

The understanding of the underlying phenomena is difficult also because so far there is only one clear observable for target single spin asymmetries in SIDIS with polarized targets, the $A_{UL}^{\sin\phi}$ asymmetry measured by HERMES [1–4]. Although at HERMES $A_{UL}^{\sin\phi}$ was measured in electro-production of different hadrons from different targets – providing valuable insights into the flavor dependence of the process – the observation of other independent observables which allow one to distinguish the Collins and Sivers effect is needed to clarify the situation.

¹ U denotes the unpolarized beam. L (below also T) denotes the longitudinal (and transverse) target polarization with respect to the beam. The superscript $\sin\phi$ characterizes the azimuthal distribution of the produced hadrons with respect to the direction of the exchanged virtual photon. The precise definitions are given in the appendix

The azimuthal asymmetry $A_{UL}^{\sin 2\phi}$ is such an observable, for it is generated by the Collins effect only [15, 16]. Unfortunately, in the kinematics of the HERMES experiment $A_{UL}^{\sin 2\phi}$ was found to be rather small and consistent with zero within (relatively large) error bars [1–4]. This asymmetry could be accessed in the CLAS experiment, which operates at somehow lower energies and higher luminosity than HERMES. In the different kinematics of the CLAS experiment $A_{UL}^{\sin 2\phi}$ is expected to be larger than at HERMES and measurable [25],² and, indeed, encouraging preliminary results have already been reported in [26]. Also in the COMPASS experiment $A_{UL}^{\sin 2\phi}$ will probably be observable – as we will estimate below.

More conclusive insights, however, are expected from SIDIS experiments with *transversely* polarized targets³, where the Collins and Sivers effects [7, 8], can cleanly be distinguished [16]. Those experiments are presently in progress at HERMES [27] and COMPASS [28]. Estimates of these asymmetries for HERMES were presented in [21, 29].

In this paper we will predict the azimuthal single spin asymmetry due to the Collins effect from a transversely polarized target for the kinematics of the HERMES and COMPASS experiments. For that we shall use predictions for the transversity distribution function $h_1^q(x)$ from the chiral quark–soliton model [30] and information on the analyzing power $\langle H_1^\perp \rangle / \langle D_1 \rangle$ from a previous analysis [22] of the HERMES data.⁴ Indeed, the present approach, based on the chiral quark–soliton model and the instanton vacuum picture, describes in a theoretically consistent and phenomenologically satisfying way [22, 23] the x -dependence of the HERMES data [1–4]. In a certain sense the analyzing power $\langle H_1^\perp \rangle / \langle D_1 \rangle$ from [22] quantifies the amount of Collins effect needed to understand the HERMES data [1–4] within this approach. Therefore the comparison of our prediction to the outcome of the HERMES and COMPASS transverse target polarization experiments will yield more than an important test of the approach and its consistency. An agreement would support also the conclusion of [24] that the Sivers effect can be neglected in the $A_{UL}^{\sin \phi}$ asymmetries and it would justify, a posteriori, the attempts [17–23] to understand the HERMES data on A_{UL} in terms of the Collins effect only.

This paper is organized as follows. In Sect. 2 the SIDIS process and its description is discussed under the assumption

² The different kinematics and high luminosity at CLAS have already been explored to measure another azimuthal asymmetry previously found consistent with zero at HERMES, namely the azimuthal asymmetry in SIDIS of a polarized beam off an unpolarized target, $A_{LU}^{\sin \phi}$. This asymmetry could be due to the Collins effect [15, 16] and provide first indications to the twist-3 distribution function $e^a(x)$ [25]

³ A first observation of single spin azimuthal asymmetries in SIDIS from a transversely polarized target – which unfortunately retained its preliminary status – was reported from the SMC experiment [6]

⁴ Actually, in that analysis [22] the Sivers function was neglected, which has later been shown to be theoretically consistent and phenomenologically justified [24]

tion of factorization. In Sect. 3 our assumptions on the novel distribution and fragmentation functions are described. In Sects. 4 and 5 the predictions are presented for the HERMES and COMPASS transverse target polarization experiments, as well as for the longitudinal target polarization experiment at COMPASS. In Sect. 6 we present general comments on the Sivers effect in SIDIS asymmetries. Section 7 contains the summary and conclusions.

2 The contribution of the Collins effect to the azimuthal asymmetry from a transversely polarized target

In the HERMES and COMPASS experiments the cross sections $\sigma_N^{\uparrow\downarrow}$ for the process $lN^{\uparrow\downarrow} \rightarrow l'hX$ will be measured, where $N^{\uparrow\downarrow}$ means: transversely with respect to the beam polarized target; see Fig. 1.

With P , l and l' denoting the momenta of the target and of the incoming and outgoing lepton the kinematic variables are defined as $s := (P + l)^2$, $q := l - l'$ with $Q^2 := -q^2$, and $W^2 := (P + q)^2$, and

$$x := \frac{Q^2}{2Pq}, \quad y := \frac{Pq}{Pl}, \quad z := \frac{PP_h}{Pq}. \quad (1)$$

Let $S^{\uparrow\downarrow}$ denote the modulus of the polarization vector. The component of the target polarization vector which is *transverse with respect to the hard photon* is characterized by the angle Θ_S , see Fig. 1, given by

$$\sin \Theta_S = \frac{S_T^{\uparrow\downarrow}}{S^{\uparrow\downarrow}} = \cos \theta_\gamma \sqrt{1 + \tan^2 \theta_\gamma \sin^2 \phi_S} \approx \cos \theta_\gamma, \quad (2)$$

where ϕ_S is the azimuthal angle of the target spin direction around the lepton beam direction counted from the scattering plane, and $\cos \theta_\gamma$ is given by

$$\cos \theta_\gamma = \sqrt{1 - \frac{(4M_N^2 x^2)(1 - y - M_N^2 x^2 y^2 / Q^2)}{(Q^2 + 4M_N^2 x^2)}}. \quad (3)$$

Since $\tan^2 \theta_\gamma = \mathcal{O}(M^2/Q^2)$ the approximation in the last step of (3) works well.

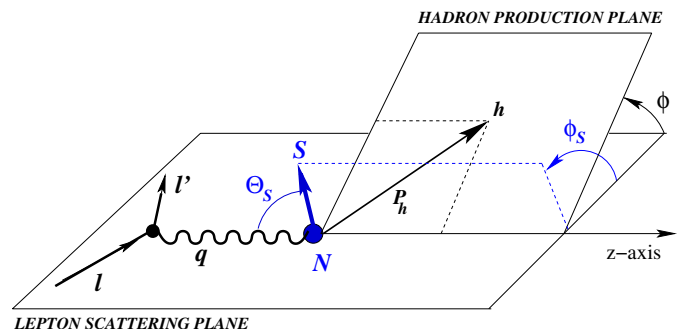


Fig. 1. Kinematics of the process $lN^{\uparrow} \rightarrow l'hX$ in the lab frame

With ϕ (ϕ_s) denoting the azimuthal angles between the hadron production plane (the nucleon spin) and the lepton scattering plane, see Fig. 1, the observables of interest are defined as

$$A_{\text{UT}}^{\sin(\phi+\phi_s)}(x) = \left(\int dz dy d^2\mathbf{P}_{h\perp} \sin(\phi + \phi_s) \times \left(\frac{1}{S^\uparrow} \frac{d^5\sigma^\uparrow}{dx dy dz d^2\mathbf{P}_{h\perp}} - \frac{1}{S^\downarrow} \frac{d^5\sigma^\downarrow}{dx dy dz d^2\mathbf{P}_{h\perp}} \right) \right) / \left(\frac{1}{2} \int dz dy d^2\mathbf{P}_{h\perp} \times \left(\frac{d^5\sigma^\uparrow}{dx dy dz d^2\mathbf{P}_{h\perp}} + \frac{d^5\sigma^\downarrow}{dx dy dz d^2\mathbf{P}_{h\perp}} \right) \right), \quad (4)$$

$$A_{\text{UT}}^{\sin(\phi+\phi_s)k_\perp/\langle P_{h\perp} \rangle}(x) = \left(\int dz dy d^2\mathbf{P}_{h\perp} \sin(\phi + \phi_s) \frac{k_\perp}{\langle P_{h\perp} \rangle} \times \left(\frac{1}{S^\uparrow} \frac{d^5\sigma^\uparrow}{dx dy dz d^2\mathbf{P}_{h\perp}} - \frac{1}{S^\downarrow} \frac{d^5\sigma^\downarrow}{dx dy dz d^2\mathbf{P}_{h\perp}} \right) \right) / \left(\frac{1}{2} \int dz dy d^2\mathbf{P}_{h\perp} \times \left(\frac{d^5\sigma^\uparrow}{dx dy dz d^2\mathbf{P}_{h\perp}} + \frac{d^5\sigma^\downarrow}{dx dy dz d^2\mathbf{P}_{h\perp}} \right) \right). \quad (5)$$

The weight $\sin(\phi + \phi_s)$ in (4) has the drawback that it leaves convoluted the transverse momenta in the unintegrated distribution and fragmentation functions – in this case $h_1(x, P_{N\perp}^2)$ and $H_1^\perp(z, k_T^2)$ [15]. (For the meaning and definition of unintegrated distribution functions in QCD see [31] and references therein.) The additional power of the transverse momentum⁵ $k_\perp = |\mathbf{P}_{h\perp}|/z$ in the weight in (5) yields expressions where the transverse momenta are disentangled in a model independent way [16].

Though the asymmetry weighted with k_\perp in (5) is preferable from a theoretical point of view [16], we shall consider both asymmetries, (4) and (5). Considering also the asymmetry (4) will allow us to directly compare the predicted effect to the $A_{\text{UL}}^{\sin\phi}$ asymmetries measured at HERMES [1–4] which were analyzed in a way analogous to (4).

The expressions for the differential cross sections entering the asymmetries in (4) and (5) were derived in [15] assuming factorization. In order to deconvolve the transverse momenta in $A_{\text{UT}}^{\sin(\phi+\phi_s)}$ in (4) we assume the distributions of transverse momenta in the unintegrated distribution and fragmentation functions to be Gaussian. This ansatz is in fair agreement with the HERMES data in the case of $A_{\text{UL}}^{\sin\phi}$

⁵ We use the notation of [15, 16] with H_1^\perp normalized to $\langle P_{h\perp} \rangle$ instead of m_h . Correspondingly we choose $\langle P_{h\perp} \rangle$ to compensate the dimension of k_\perp in (5)

asymmetries [1–4]. Under this assumption one obtains [15] (cf. also [22])

$$A_{\text{UT}}^{\sin(\phi+\phi_s)}(x) = a_{\text{Gauss}} B_T(x) \frac{\sum_a e_a^2 x h_1^a(x) \langle H_1^{\perp a} \rangle}{\sum_b e_b^2 x f_1^b(x) \langle D_1^b \rangle}, \quad (6)$$

while the result for the k_\perp -weighted asymmetry is given by [16]

$$A_{\text{UT}}^{\sin(\phi+\phi_s)k_\perp/\langle P_{h\perp} \rangle}(x) = B_T(x) \frac{\sum_a e_a^2 x h_1^a(x) \langle H_1^{\perp(1)a} \rangle}{\sum_b e_b^2 x f_1^b(x) \langle D_1^b \rangle}, \quad (7)$$

where $B_T(x)$ and a_{Gauss} are defined as (experimental cuts have to be considered in the integration over y)

$$B_T(x) = \frac{2 \int dy (1-y) \sin \Theta_S / Q^4}{\int dy (1-y + y^2/2) / Q^4}, \quad (8)$$

$$a_{\text{Gauss}} = \frac{1}{2 \langle z \rangle \sqrt{1 + \langle z^2 \rangle \langle P_{N\perp}^2 \rangle / \langle P_{h\perp}^2 \rangle}}, \quad (9)$$

where $\langle P_{N\perp}^2 \rangle$ and $\langle P_{h\perp}^2 \rangle / \langle z^2 \rangle$ are the mean transverse momentum squares characterizing the Gaussian distributions of transverse momenta in the unintegrated distribution and fragmentation function. The prefactor a_{Gauss} contains the model dependence; it would be different if we assumed the distributions of transverse momenta to be different from Gaussian. $H_1^{\perp(1)a}(z)$ in (7) is defined by [16] (cf. footnote 5)

$$H_1^{\perp(1)a}(z) = \int d^2\mathbf{k}_T \frac{z^2 \mathbf{k}_T^2}{2 \langle P_{h\perp} \rangle^2} H_1^{\perp a}(z, z^2 \mathbf{k}_T^2). \quad (10)$$

3 Transversity distribution and Collins fragmentation function

In order to estimate the azimuthal asymmetries, (4) and (5) and (6) and (7), one has to know h_1^a and $H_1^{\perp a}$. For the former we shall use the predictions of the chiral quark–soliton model (χ QSM) [30], and for the latter our analysis of the HERMES data from [22].

Chirally and T -odd distribution functions

The χ QSM is an effective relativistic quantum field-theoretical model with explicit quark degrees of freedom, in which twist-2 nucleon distribution functions can unambiguously be defined and evaluated at a low renormalization point of about (600–700) MeV. The χ QSM has been derived from the instanton model of the QCD vacuum [32] and has been shown to describe well numerous static nucleonic observables without adjustable parameters [33]. The field-theoretical nature of the model is crucial to ensure the theoretical consistency of the approach: the quark and antiquark distribution functions computed in the model satisfy all general QCD requirements [34]. The results of the model agree for the distribution functions $f_1^a(x)$, $g_1^a(x)$ and $g_T^a(x)$ [34–36] within (10–30)% with phenomenological

information. This encourages confidence that the model describes the nucleon transversity distribution function $h_1^a(x)$ [30] with a similar accuracy.

In the following we will need also the deuteron transversity distribution. Corrections due to the D-state admixture were estimated to be very similar to the corresponding corrections in the case of the helicity distribution function [37]. Since these corrections are smaller than other theoretical uncertainties in our approach we shall disregard them here and estimate e.g. for the u -quark

$$h_1^{u/D}(x) \approx h_1^{u/p}(x) + h_1^{u/n}(x) = h_1^u(x) + h_1^d(x), \quad (11)$$

where isospin symmetry was used in the last step, and $h_1^u(x)$ and $h_1^d(x)$ refer (as always) to the proton.

In the χ QSM $h_1^a(x) \neq g_1^a(x)$ already at a low normalization point. However, due to the large error bars the present data do not discriminate between different models. Therefore reasonable descriptions of the $A_{\text{UL}}^{\sin\phi}$ asymmetries have also been obtained assuming $h_1^a(x) = g_1^a(x)$ being motivated by the non-relativistic quark model or using other models [20]. An advantage of relying on predictions from the χ QSM (based on the instanton vacuum) lies in the fact that all novel distribution functions are taken from an approach which is internally consistent and which has been shown in many different observables to be reasonable. For example, in the instanton vacuum model the pure twist-3 contribution $\tilde{h}_L^a(x)$ to $h_L^a(x)$ is strongly suppressed [38]. Thus in this approach one can justifiably approximate $h_L^a(x)$ by its twist-2 (“Wandzura–Wilczek” like) term $h_L^a(x) = 2x \int_x^1 dx' h_1^a(x')/x'^2$. Moreover, T -odd distribution functions vanish in the χ QSM (as they do in a large class of other chiral soliton models) [39]. Therefore in this approach it is consistent to neglect the Siverson effect in $A_{\text{UL}}^{\sin\phi}$ asymmetries [24]; see also Sect. 6 for further comments.

In [22, 23] the present approach has been shown to describe well the x -dependence of A_{UL} from the HERMES longitudinal target polarization experiments [1–4].

The Collins fragmentation function

Let us define the favored Collins fragmentation function as

$$\begin{aligned} H_1^\perp &\equiv H_1^{\perp u/\pi^+} = H_1^{\perp \bar{d}/\pi^+} = H_1^{\perp d/\pi^-} = 2H_1^{\perp u/\pi^0} = \dots \text{ etc.} \\ &\gg H_1^{\perp d/\pi^+} = H_1^{\perp \bar{u}/\pi^+} = \dots \text{ etc.} \end{aligned} \quad (12)$$

The equalities in (12) follow from charge conjugation and isospin symmetry. The strong suppression of the unfavored with respect to the favored Collins fragmentation function has been concluded to on the basis of the Schäfer–Teryaev sum rule [40].

In [22] information on H_1^\perp was gained from the HERMES data on the $A_{\text{UL}}^{\sin\phi}$ asymmetry in π^+ and π^0 production [2, 3]. With this aim the transverse momentum distributions were assumed to be Gaussian and the parton distribution functions h_1^a and h_L^a were taken from the

chiral quark–soliton model. For the analyzing power the value was found (D_1 denotes the favored unpolarized fragmentation function)

$$\langle H_1^\perp \rangle / \langle D_1 \rangle = (13.8 \pm 2.8)\% \quad (13)$$

at $\langle z \rangle = 0.4$ and $\langle Q^2 \rangle = 2.5 \text{ GeV}^2$ [22]. The result in (13) contains – apart from the shown statistical error from the HERMES experiment – further uncertainties due to the systematic error of the HERMES experiment and model dependence. These errors need not be considered in the following, when the above result is used to make predictions for $A_{\text{UT}}^{\sin(\phi+\phi_S)}$ in the HERMES experiment in combination with results from the chiral quark–soliton model and the instanton vacuum model. In a certain sense the result in (13) can be considered as a fit to the $A_{\text{UL}}^{\sin\phi}$ data [2, 3]. Remarkably, a result numerically close to (13) was obtained in the model calculation of [29].

In e^+e^- annihilation the Collins effect can give rise to a specific azimuthal asymmetry of a hadron in a jet around the axis in the direction of the second hadron in the opposite jet. This asymmetry was measured using the DELPHI data collection and a value $|\langle H_1^\perp \rangle / \langle D_1 \rangle| = (12.5 \pm 1.4)\%$ for $\langle z \rangle \simeq 0.4$ at a scale of M_Z^2 was reported [41, 42].⁶ In previous works [22, 23] this value (assuming a positive sign) was used to analyze the HERMES data [1–4]. In order to do this the scale dependence of the ratio $\langle H_1^\perp \rangle / \langle D_1 \rangle$ was assumed to be weak and possible Sudakov suppression effects [43] were neglected. However, as shown in [44] the Collins fragmentation function could be process dependent, i.e. different in e^+e^- annihilation and SIDIS.

Therefore, in this note we shall use the result in (13) extracted from SIDIS HERMES data. Numerically the difference is not relevant – from a theoretical point of view, however, the use of the result in (13) is preferable for our purpose of describing SIDIS processes.

4 Collins A_{UT} asymmetries in the HERMES experiment

The asymmetry $A_{\text{UT}}^{\sin(\phi+\phi_S)}$

In order to estimate $A_{\text{UT}}^{\sin(\phi+\phi_S)}$ in the HERMES experiment we rely on the same assumptions and approximations as were used in [22, 23] to analyze the HERMES data on the $A_{\text{UL}}^{\sin\phi}$ asymmetries. In particular we assume a Gaussian distribution of transverse momenta (cf. Sect. 2), take $h_1^a(x)$ from the χ QSM and H_1^\perp from our previous analysis of HERMES data [24] and assume favored fragmentation – as described in Sect. 3. For the unpolarized distribution functions $f_1^a(x)$ we use the parameterization of [45]. For

⁶ This result is referred to as “more optimistic” since it is subject to presumably larger systematic uncertainties than the “more reliable” value $|\langle H_1^\perp \rangle / \langle D_1 \rangle| = (6.3 \pm 2.0)\%$ reported in [41, 42] which has presumably smaller systematic errors. For both values no estimate of systematic errors could be given in [41, 42]

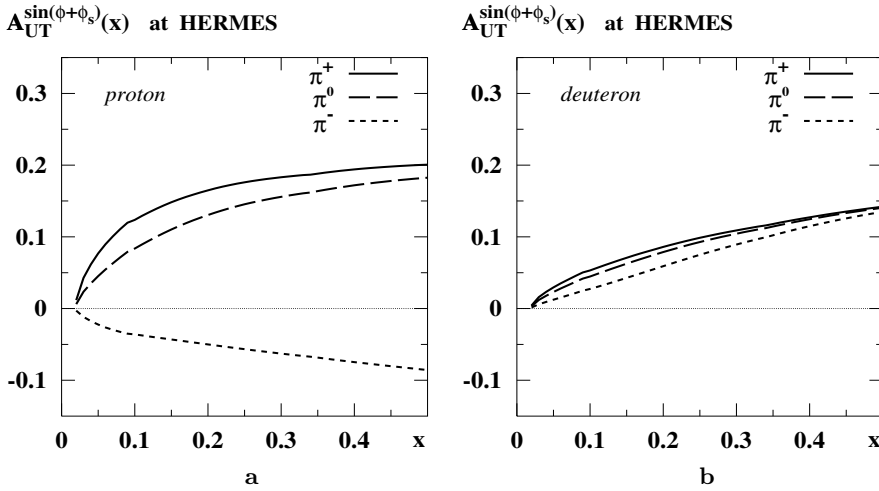


Fig. 2. Predictions for azimuthal asymmetries $A_{\text{UT}}^{\sin(\phi+\phi_s)}(x)$ in SIDIS pion productions from transversely polarized proton **a** and deuteron **b** targets for kinematics of the HERMES experiment

the parameter characterizing the (Gaussian) distribution of transverse momenta in the nucleon we shall use the estimate $\langle P_{N\perp} \rangle = 0.4$ GeV from [46,47]. The result, however, is only weakly sensitive to the actual choice for this parameter.

The beam in the HERMES experiment has an energy of $E_{\text{beam}} = 26.7$ GeV. We assume the cuts implicit in the integrations in (8) to be the same as in the longitudinal target polarization experiments [1–4]

$$1 \text{ GeV}^2 < Q^2 < 15 \text{ GeV}^2, \quad 2 \text{ GeV} < W, \\ 0.2 < y < 0.85, \quad 0.023 < x < 0.4, \quad (14)$$

and $0.2 < z < 0.7$ with $\langle z \rangle = 0.4$, and $\langle P_{h\perp} \rangle = 0.4$ GeV. Note that strictly speaking we neglect the implicit dependence of distribution and fragmentation functions on y through the scale $Q^2 = xy(s - M_N^2)$, and evaluate them instead at the average scale in the HERMES experiment $\langle Q^2 \rangle = 2.5 \text{ GeV}^2$. The predictions for $A_{\text{UT}}^{\sin(\phi+\phi_s)}$ for the transversely polarized proton and deuterium target are shown in Figs. 2a,b, respectively.

Figures 2a,b demonstrate that $A_{\text{UT}}^{\sin(\phi+\phi_s)}$ is sizable, roughly 20% for positive and neutral pions for the proton target and about 10% for all pions for the deuteron target. Comparing this result with the $A_{\text{UL}}^{\sin\phi}$ asymmetries $\sim (2-4)\%$ [1–4] we see that $A_{\text{UT}}^{\sin(\phi+\phi_s)}$ asymmetry can clearly be observed, cf. [21]. A comparably large value for this asymmetry was estimated in [29] on the basis of a model calculation for the Collins function and assuming $h_1^a(x)$ to saturate the Soffer bound [48].

The accuracy of the predictions – for π^+ and π^0 asymmetries from a proton target – is mainly determined by the theoretical uncertainty of the χ QSM prediction for $h_1^a(x)$ of about 20% and the statistical error of the analyzing power (13) from the HERMES experiment. For negative pions from a proton, however, there might be additional sizable corrections due to unfavored flavor fragmentation [20]. In this case the small unfavored Collins fragmentation function is multiplied by the large $\frac{4}{9}h_1^u(x)$ while the large favored fragmentation function is multi-

plied by the small $\frac{1}{9}h_1^d(x)$.⁷ Therefore π^- is more sensitive to corrections due to unfavored fragmentation than π^+ and π^0 where u -quark dominance ($h_1^u(x) \gg |h_1^d(x)|$) tends to enhance the favored fragmentation effect. Similar reservations apply to the deuteron target where there is no u -quark dominance – apart from that introduced by the quark electric charges.

In [23] $A_{\text{UL}}^{\sin\phi}$ asymmetries for kaons have been estimated assuming that the analyzing power for kaons is approximately equal to that of pions, i.e. $\langle H_1^\perp \rangle / \langle D_1 \rangle|_{\text{kaon}} \approx \langle H_1^\perp \rangle / \langle D_1 \rangle|_{\text{pion}}$. This relation would hold exactly in the chiral limit (where pions and kaons would be massless Goldstone bosons). The kaon $A_{\text{UL}}^{\sin\phi}$ asymmetries predicted in [23] on the basis of this assumption compare well with the HERMES data within the (admittedly rather large) statistical error [4]. Under this assumption one could expect for the transverse target polarization experiment (cf. [23] for further details)

$$A_{\text{UT}}^{\sin(\phi+\phi_s)}(K^+) \approx A_{\text{UT}}^{\sin(\phi+\phi_s)}(K^0) \approx A_{\text{UT}}^{\sin(\phi+\phi_s)}(\pi^+), \\ A_{\text{UT}}^{\sin(\phi+\phi_s)}(\bar{K}^0) \approx A_{\text{UT}}^{\sin(\phi+\phi_s)}(K^-) \approx 0. \quad (15)$$

The asymmetry $A_{\text{UT}}^{\sin(\phi+\phi_s)k_\perp} / \langle P_{h\perp} \rangle$

In this case we need the transverse momentum weighted moment of the favored Collins fragmentation function $H_1^{\perp(1)}$; see (7). Under the assumption of a Gaussian distribution of transverse momenta in (10) one obtains for $H_1^{\perp(1)}$ averaged over z

$$\langle H_1^{\perp(1)} \rangle = \frac{\langle P_{h\perp}^2 \rangle}{2\langle P_{h\perp} \rangle^2} \langle H_1^\perp \rangle = \frac{2}{\pi} \langle H_1^\perp \rangle, \quad (16)$$

⁷ The antiquark distributions can be disregarded for this qualitative consideration. The same applies to unpolarized fragmentation. Since $f_1^a(x)$ and $D_1^a(z)$ are positive, the effect of unpolarized unfavored fragmentation may decrease the asymmetry but cannot change its sign as the polarized unfavored fragmentation in the case of π^- from a proton target [20] could

where we used the relation $\langle P_{h\perp}^2 \rangle / \langle P_{h\perp} \rangle^2 = 4/\pi$ valid for a Gaussian distribution. The $\langle H_1^\perp \rangle$ in (16) can be taken from (13) (recall that the analyzing power (13) was extracted under the assumption of a Gaussian transverse momentum distribution [23]).

Therefore we obtain the relation

$$A_{\text{UT}}^{\sin(\phi+\phi_S)k_\perp/\langle P_{h\perp} \rangle} = \beta_{\text{Gauss}} A_{\text{UT}}^{\sin(\phi+\phi_S)}. \quad (17)$$

The constant β_{Gauss} “converts” between the differently weighted asymmetries and is given by

$$\beta_{\text{Gauss}} = \frac{2}{\pi a_{\text{Gauss}}} = \frac{4\langle z \rangle}{\pi} \sqrt{1 + \langle z^2 \rangle \langle P_{N\perp}^2 \rangle / \langle P_{h\perp}^2 \rangle} \approx 0.55 \quad (18)$$

for the numbers in the HERMES experiment. Thus, in order to obtain our prediction for $A_{\text{UT}}^{\sin(\phi+\phi_S)k_\perp/\langle P_{h\perp} \rangle}$ it is sufficient to multiply the results in Figs. 2a,b by the factor 0.55. We stress that the “conversion factor” β_{Gauss} is model dependent. For a different model of transverse momenta $\beta_{\text{model}} \neq \beta_{\text{Gauss}}$. In particular, β_{model} could numerically be different from the result in (18).

Our prediction for $A_{\text{UT}}^{\sin(\phi+\phi_S)}$ is more robust than that for $A_{\text{UT}}^{\sin(\phi+\phi_S)k_\perp/\langle P_{h\perp} \rangle}(x)$ since the latter – in addition to other assumptions in our approach – also tests the assumption of a Gaussian transverse momentum distribution. In fact, the only assumption entering our prediction for $A_{\text{UT}}^{\sin(\phi+\phi_S)}$ – and the analysis of $A_{\text{UL}}^{\sin\phi}$ in [23] – is that a generic unintegrated fragmentation function $F(z, \mathbf{k}_T^2)$ can be approximated by

$$F(z, \mathbf{k}_T^2) \approx F(z) G(\mathbf{k}_T^2), \quad (19)$$

where $G(\mathbf{k}_T^2)$ satisfies $\int d^2\mathbf{k}_T G(\mathbf{k}_T^2) = 1$, and analogous for unintegrated distribution functions. For a Gaussian distribution one sets $G(\mathbf{k}_T^2) = \exp(-\mathbf{k}_T^2/\langle \mathbf{k}_T^2 \rangle)/(\pi\langle \mathbf{k}_T^2 \rangle)$. Assuming (19) but taking a different model for $G(\mathbf{k}_T^2)$ we would obtain a *different* constant $a_{\text{model}} \neq a_{\text{Gauss}}$ in (9). With a different model for transverse momenta, however, we also would have obtained a different result in (13) for $\langle H_1^\perp \rangle_{\text{model}}$. (In this context the $\langle H_1^\perp \rangle$ in (13) should be labelled $\langle H_1^\perp \rangle_{\text{Gauss}}$ for clarity.) Thus under the assumption (19) the relation $A_{\text{UT}}^{\sin(\phi+\phi_S)} \propto a_{\text{model}} \langle H_1^\perp \rangle_{\text{model}}$ is model independent. Therefore our predictions for $A_{\text{UT}}^{\sin(\phi+\phi_S)}$ shown in Figs. 2a and 2b do not depend on the Gaussian model but rely solely on the assumption (19). If the assumption (19) held one could discriminate between different models for the transverse momentum distributions by considering different powers of transverse momentum in the weight $\sin(\phi + \phi_S) |\mathbf{k}_\perp|^n$ ($n = 0, 1$). Considering different weights could provide interesting phenomenological insights. However, from a strict theoretical point of view the weighting with an adequate power of $|\mathbf{k}_\perp|$ is preferable [16].

Preliminary SMC results

Though devoted to the HERMES experiment let us conclude this section with a comment on the preliminary SMC

data reported in [6]. In the SMC experiment indications were found that the transverse target spin asymmetry $\propto \sin\phi_c A_N$ with $A_N = 0.11 \pm 0.06$, where the Collins angle $\phi_c \equiv \phi + \phi_S - \pi$ (cf. [6] for the precise definition of A_N). Our approach yields $A_N = -0.12$, i.e. an asymmetry of opposite sign [22, 23] (due to $\sin\phi_c = -\sin(\phi + \phi_S)$). Considering the preliminary status of the data of [6] it is not possible to draw any conclusions at this stage.

5 COMPASS experiment

Transverse target spin asymmetry

The beam energy available at COMPASS is $E_{\text{beam}} = 160$ GeV [28]. For the kinematic cuts we shall take

$$2 \text{ GeV}^2 < Q^2 < 50 \text{ GeV}^2, \quad 15 \text{ GeV}^2 < W^2 < 300 \text{ GeV}^2, \\ 0.05 < y < 0.9, \quad x < 0.4, \quad (20)$$

and evaluate the distribution functions at $Q^2 = 10 \text{ GeV}^2$. We take $\langle P_{h\perp} \rangle \approx 0.4 \text{ GeV}$ and $\langle z \rangle \approx 0.4$. The latter means that we can use for $\langle H_1^\perp \rangle / \langle D_1 \rangle$ the result in (13) – if we assume that the ratio $\langle H_1^\perp \rangle / \langle D_1 \rangle$ is only weakly scale dependent in the range of scales relevant in the HERMES and COMPASS experiments. The estimate of $A_{\text{UT}}^{\sin(\phi+\phi_S)}$ obtained in this way is shown in Fig. 3a.

In the HERMES experiment the analyzing power (assuming our approach) is $H_1^\perp(z)/D_1(z) \approx az$ where the constant $a \approx \frac{1}{3}$ [22]. This means that $\langle H_1^\perp \rangle / \langle D_1 \rangle \approx a\langle z \rangle$. If such a pattern held also at COMPASS energies, it would be preferable to choose a larger low- z cut in order to increase $\langle z \rangle$ and thus the analyzing power $\langle H_1^\perp \rangle / \langle D_1 \rangle$ (at the price of a lower statistics) [28]. For a different $\langle z \rangle$ the results shown in Fig. 3a have to be rescaled appropriately.

Figure 3a shows that $A_{\text{UT}}^{\sin(\phi+\phi_S)}$ can be of $\mathcal{O}(20\%)$ at COMPASS energies, i.e. as large as at HERMES. This is not unexpected since this asymmetry is twist-2 (in the sense that it is not power suppressed). Thus, the COMPASS experiment can equally well shed some light on the dynamics of the Collins effect. Actually, the theoretical accuracy of the predictions in Fig. 3a is less than in the case of the predictions for HERMES presented in the previous section because one has to consider the uncertainty introduced by assuming that the HERMES value for the analyzing power (13) can be used at COMPASS energies.

Longitudinal target spin asymmetries

About 80% of the beam time the target polarization in the COMPASS experiment will be longitudinal [28]. This will allow one to measure the longitudinal target spin asymmetries $A_{\text{UL}}^{\sin\phi}$ and $A_{\text{UL}}^{\sin 2\phi}$. (In the case of longitudinal target polarization the azimuthal angle of the target polarization vector $\phi_S = 0$ or π ; cf. Fig. 1.) The estimates for these asymmetries in our approach are shown in Figs. 3b,c. Clearly, the longitudinal target spin asymmetries are much smaller than the transverse target spin

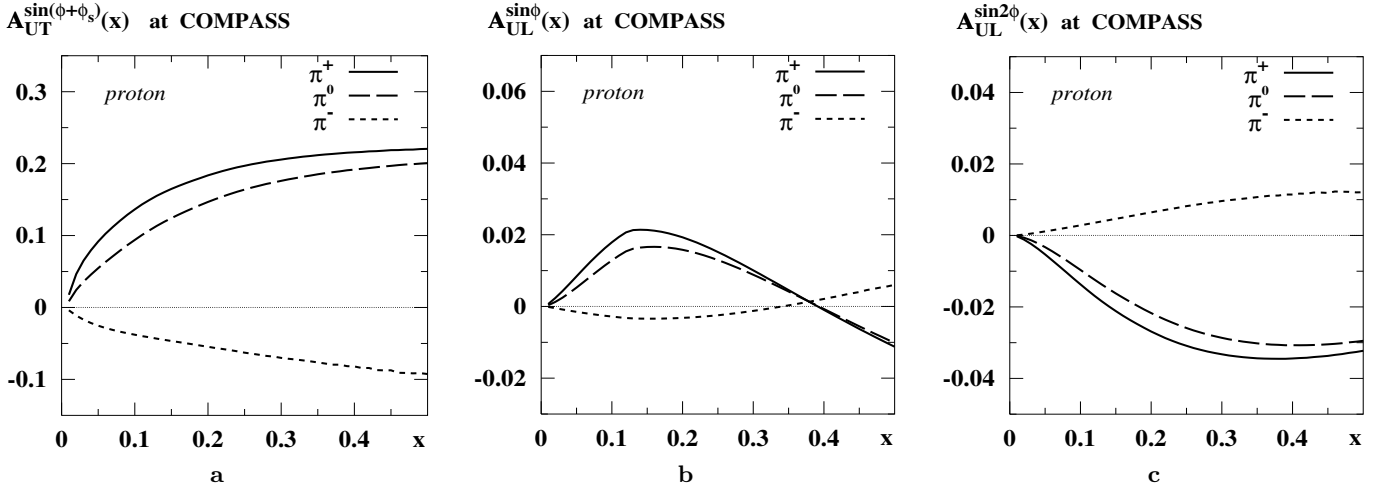


Fig. 3. **a** Prediction of the azimuthal asymmetry $A_{\text{UT}}^{\sin(\phi+\phi_s)}(x)$ in SIDIS pion production from a transversely polarized proton target for the kinematics of the COMPASS experiment. Predictions of the azimuthal asymmetries $A_{\text{UL}}^{\sin\phi}(x)$ **b** and $A_{\text{UL}}^{\sin 2\phi}(x)$ **c** from a longitudinally polarized proton target for the kinematics of the COMPASS experiment

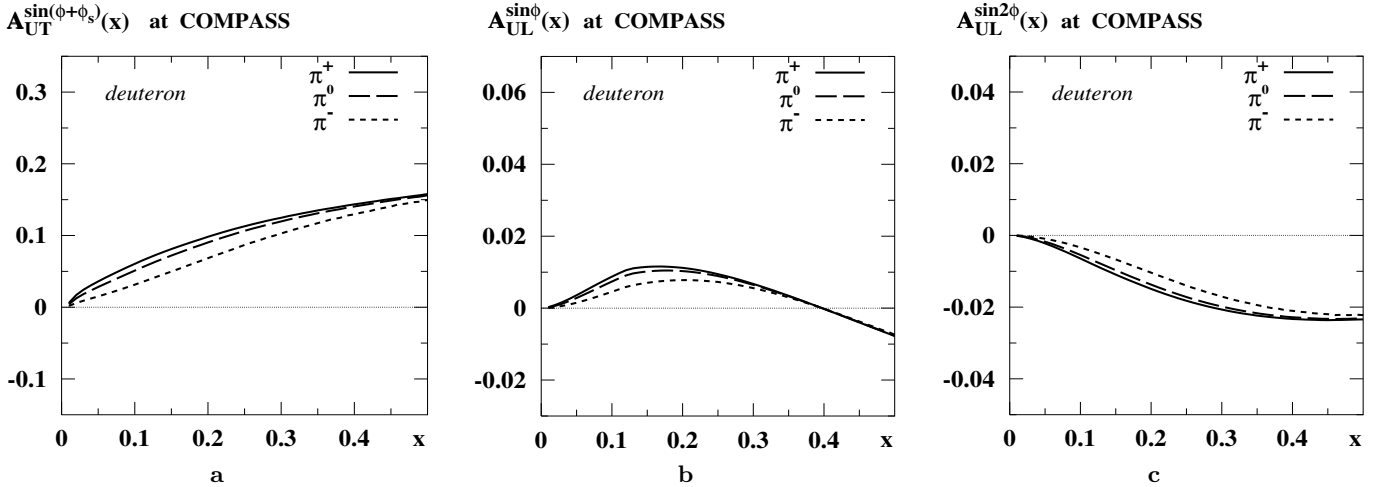


Fig. 4a–c. The same as Fig. 3 but for the deuteron target

asymmetry $A_{\text{UT}}^{\sin(\phi+\phi_s)}$, however, the larger statistics could help to resolve them.

The $A_{\text{UL}}^{\sin 2\phi}(x)$ asymmetry is of particular interest – since it is one of the “independent observables” which could provide further insights; cf. Sect. 1. This asymmetry was found to be consistent with zero within error bars at HERMES [1–4]. In our approach at HERMES energies $A_{\text{UL}}^{\sin 2\phi} = \mathcal{O}(1\%)$ [22, 23] – in agreement with the experiment. In the kinematics of the COMPASS experiment we find $A_{\text{UL}}^{\sin 2\phi}(x) = \mathcal{O}(3\%)$, i.e. of the order of magnitude of the $A_{\text{UL}}^{\sin\phi}(x)$ asymmetry observed at HERMES.

Deuteron target

The single target spin asymmetries $A_{\text{UL}}^{\sin(\phi+\phi_s)}$, $A_{\text{UL}}^{\sin 2\phi}$ and $A_{\text{UL}}^{\sin\phi}$ for the deuteron target at COMPASS energies are

shown respectively in Figs. 4a,b,c. The deuteron asymmetries for π^+ , π^0 and π^- are all of comparable order of magnitude and about half the magnitude of the π^+ proton asymmetries.

6 Siverts effect azimuthal asymmetries

Actually, our approach would imply the vanishing of the $A_{\text{UT}}^{\sin(\phi-\phi_s)}(x)$ asymmetry, which is due to the Siverts effect [16] and will be measured at HERMES and COMPASS simultaneously with $A_{\text{UT}}^{\sin(\phi+\phi_s)}(x)$. However, this cannot be taken literally as a prediction for the following reason. The chiral quark–soliton model was derived from the instanton vacuum model and can be considered as the leading order in terms of the so-called instanton packing fraction $\frac{\rho}{R} \sim \frac{1}{3}$ (ρ and R are respectively the average size and

separation of instantons in Euclidean space time). In this order the T -odd distribution functions vanish. In higher orders the Siverson function may well be non-zero and all one can conclude at this stage is that the Siverson function is suppressed with respect to the T -even⁸ twist-2 distribution functions $f_1^a(x)$, $g_1^a(x)$ and $h_1^a(x)$.⁹ However, considering that $H_1^\perp(z)$ is much smaller than $D_1(z)$, cf. (13), it is questionable whether such a suppression could be sufficient such that in physical cross sections the Collins effect $\propto h_1^a(x)H_1^\perp(z)$ is dominant over the Siverson effect $\propto f_{1T}^\perp(x)D_1(z)$. In [24] it was estimated that for the particular case of $A_{\text{UT}}^{\sin\phi}$ asymmetries in the HERMES kinematics this still could be true: Using the Siverson function of [14] fitted to explain the E704 data [51] on single spin asymmetries in $pp^\uparrow \rightarrow \pi X$ solely in terms of the Siverson effect, it was shown that the Siverson effect could give rise to $A_{\text{UT}}^{\sin(\phi-\phi_S)} = \mathcal{O}(10\%)$ while its contribution to $A_{\text{UL}}^{\sin\phi}$ is negligible with respect to the Collins effect. Of course, the E704 data need not to be due to the Siverson effect alone, and the Siverson effect in $pp^\uparrow \rightarrow \pi X$ need not to be simply related to the Siverson effect in SIDIS.¹⁰ Therefore the observation of [24] has to be considered with care. Interestingly, in the quark–diquark model one finds a comparably large $A_{\text{UT}}^{\sin(\phi-\phi_S)} = \mathcal{O}(10\%)$ [50].

To summarize, though in our approach the Siverson function vanishes, there need not be a contradiction if the Siverson effect asymmetry $A_{\text{UT}}^{\sin(\phi-\phi_S)}$ would be observed to be sizable. The measurements of $A_{\text{UT}}^{\sin(\phi\pm\phi_S)}$ at HERMES and COMPASS (and $A_{\text{UL}}^{\sin 2\phi}$ at COMPASS) will clarify the situation.

7 Conclusions

Recently HERMES observed noticeable azimuthal single spin asymmetries $A_{\text{UL}}^{\sin\phi}$ in SIDIS off a longitudinally polarized target [1–4]. These asymmetries could arise from both the Collins and the Siverson effect and are therefore difficult to interpret. Important further insights can be gained from the study of azimuthal asymmetries in SIDIS off a transversely polarized target because the angular distribution of the produced pions allows one to cleanly distinguish between the Collins and Siverson effect [15, 16].

⁸ The suppression of T -odd with respect to T -even distributions is natural. E.g. in the quark–diquark models with gluon exchange [12, 49, 50] – where the Siverson function was “rediscovered”, cf. [11] – T -even distributions appear at the tree level while T -odd ones appear only at one-loop level. Thus, whatever (small) parameter justifies the perturbative calculation of distribution functions in the quark–diquark model, it generically suppresses T -odd distributions with respect to T -even ones

⁹ In the case of the pure twist-3 $\tilde{h}_L^a(x)$ [38] (or $\tilde{g}_T^a(x)$ [36]) it was shown on the basis of [52] that the suppression in the instanton medium with respect to twist-2 distributions is very strong

¹⁰ Cf. the corresponding discussions of the Siverson effect in SIDIS and the Drell–Yan process, where the Siverson functions differ by an overall sign [11, 13]

In this note we have presented estimates of the azimuthal single spin asymmetries due to the Collins effect, $A_{\text{UT}}^{\sin(\phi+\phi_S)}$, both for the HERMES and COMPASS experiments. These calculations are based on two ingredients. One ingredient, which is responsible for the x -shape of the predicted asymmetries, is the chirally odd transversity distribution function $h_1^a(x)$ provided by the chiral quark–soliton model (χ QSM) [30]. The sign and the overall normalization of the predicted A_{UT} asymmetries are fixed by the second ingredient, namely by the properties of the Collins fragmentation function H_1^\perp resulting from our analysis [22] of the $A_{\text{UL}}^{\sin\phi}$ asymmetries observed in the HERMES experiment. On the basis of this approach we estimate the $A_{\text{UT}}^{\sin(\phi+\phi_S)}$ to be about 20% for π^+ and π^0 from a proton target and roughly 10% for all pions from a deuterium target.

Choosing another weight, namely $\sin(\phi-\phi_S)$, it is possible to project out another azimuthal asymmetry which is due to the Siverson effect only [16]. If taken *literally*, our approach would predict a vanishing Siverson effect asymmetry $A_{\text{UT}}^{\sin(\phi-\phi_S)}$ because in the χ QSM the Siverson distribution function vanishes. This shortcoming is met basically in all chiral effective models [39] and reflects the limitations of such models to describe T -odd distribution functions. In the χ QSM, which is based on an expansion in terms of the packing fraction of the instantons in the vacuum, T -odd distribution functions are subleading quantities in contrast T -even distribution functions. However, a Siverson function as large as obtained in the quark–diquark models with gluon exchange [12, 49, 50] yielding $A_{\text{UT}}^{\sin(\phi-\phi_S)} = \mathcal{O}(10\%)$ [50] would not be in contradiction with our approach [24].

Noteworthy is that the longitudinal target polarization program of the COMPASS experiment may also well contribute to the understanding of single spin asymmetries in SIDIS. Our approach predicts the $A_{\text{UL}}^{\sin 2\phi}$ asymmetry, which was found consistent with zero within (relatively large) error bars at HERMES, is of $\mathcal{O}(3\%)$ in the COMPASS kinematics and can probably be resolved. This asymmetry is due to the Collins effect only and its measurement would provide valuable independent information. The $A_{\text{UL}}^{\sin\phi}$ asymmetry is about (1–2)% and more difficult to measure for COMPASS.

A measurement of the $A_{\text{UT}}^{\sin(\phi+\phi_S)}$ asymmetry at HERMES and COMPASS and the $A_{\text{UL}}^{\sin 2\phi}$ at COMPASS of comparable magnitude as we estimated here would support the observation [24] that the Siverson effect could play a subdominant role in the $A_{\text{UL}}^{\sin\phi}$ asymmetries measured by HERMES [1–4] and a posteriori justify the attempts [17–23] to interpret these data in terms of the Collins effect only. In contrast, deviations from our predictions could provide valuable hints how those attempts should be modified. We will – in any case – soon learn a lot from the HERMES and COMPASS experiments.

Acknowledgements. We are grateful to H. Avakian, M. Beckmann, I. Ludwig, R. Seidl for fruitful discussions. A.E. is partially supported by INTAS grant 00/587 and RFBR grant 03-02-16816 and DFG-RFBR 03-02-04022. This work has partly

been performed under the contract HPRN-CT-2000-00130 of the European Commission. The work is partially supported by BMBF and DFG of Germany and by the COSY-Juelich project.

A Expressions for longitudinal target polarization asymmetries

For the convenience of the reader we summarize the expressions for $A_{UL}^{\sin 2\phi}$ and $A_{UL}^{\sin \phi}$ which were derived in [19,22,23] on the basis of the results from [15]:

$$A_{UL}^{\sin \phi}(x) = a_{\text{Gauss}} \left(P_L(x) \frac{\sum_a e_a^2 x^2 h_L^a(x) \langle H_1^{\perp a} \rangle}{\sum_b e_b^2 x f_1^b(x) \langle D_1^b \rangle} + P_1(x) \frac{\sum_a e_a^2 x h_1^a(x) \langle H_1^{\perp a} \rangle}{\sum_b e_b^2 x f_1^b(x) \langle D_1^b \rangle} \right), \quad (\text{A.1})$$

$$A_{UL}^{\sin 2\phi}(x) = 4\langle z \rangle^2 a_{\text{Gauss}}^2 \frac{2M_N}{\langle P_{\perp h} \rangle} P_2(x) \times \frac{\sum_a e_a^2 2x^3 \int_x^1 dy h_1^a(y)/y^2 \langle H_1^{\perp a} \rangle}{\sum_b e_b^2 x f_1^b(x) \langle D_1^b \rangle}, \quad (\text{A.2})$$

where a_{Gauss} is defined as in (9) and the P_i ($i = L, 1, 2$) are given by

$$P_L(x) = \frac{2 \int dy 2(2-y) \sqrt{1-y} \cos \theta_\gamma M_N / Q^5}{\int dy (1-y+y^2/2) / Q^4}, \quad P_1(x) = -\frac{2 \int dy (1-y) \sin \theta_\gamma / Q^4}{\int dy (1-y+y^2/2) / Q^4}, \quad P_2(x) = \frac{2 \int dy (1-y) \cos \theta_\gamma / Q^4}{\int dy (1-y+y^2/2) / Q^4}. \quad (\text{A.3})$$

References

1. H. Avakian et al. [HERMES Collaboration], Nucl. Phys. Proc. Suppl. **79**, 523 (1999)
2. A. Airapetian et al. [HERMES Collaboration], Phys. Rev. Lett. **84**, 4047 (2000)
3. A. Airapetian et al. [HERMES Collaboration], Phys. Rev. D **64**, 097101 (2001)
4. A. Airapetian et al. [HERMES Collaboration], Phys. Lett. B **562**, 182 (2003)
5. H. Avakian et al. [CLAS Collaboration], hep-ex/0301005
6. A. Bravar [Spin Muon Collaboration], Nucl. Phys. Proc. Suppl. **79**, 520 (1999)
7. J.C. Collins, Nucl. Phys. B **396**, 161 (1993); X. Artru, J.C. Collins, Z. Phys. C **69**, 277 (1996)
8. D.W. Sivers, Phys. Rev. D **41**, 83 (1990); **43**, 261 (1991)
9. J. Ralston, D.E. Soper, Nucl. Phys. B **152**, 109 (1979); J.L. Cortes, B. Pire, J.P. Ralston, Z. Phys. C **55**, 409 (1992); R.L. Jaffe, X. Ji, Phys. Rev. Lett. **67**, 552 (1991); Nucl. Phys B **375**, 527 (1992)

10. A.V. Efremov, L. Mankiewicz, N. Törnqvist, Phys. Lett. B **284**, 394 (1992)
11. J.C. Collins, Phys. Lett. B **536**, 43 (2002)
12. S.J. Brodsky, D.S. Hwang, I. Schmidt, Phys. Lett. B **530**, 99 (2002)
13. A.V. Belitsky, X. Ji, F. Yuan, Nucl. Phys. B **656**, 165 (2003); X.D. Ji, F. Yuan, Phys. Lett. B **543**, 66 (2002)
14. M. Anselmino, M. Boglione, F. Murgia, Phys. Lett. B **362**, 164 (1995); M. Anselmino, F. Murgia, Phys. Lett. B **442**, 470 (1998)
15. P.J. Mulders, R.D. Tangerman, Nucl. Phys. B **461**, 197 (1996) [Erratum B **484**, 538 (1997)]
16. D. Boer, P.J. Mulders, Phys. Rev. D **57**, 5780 (1998)
17. E. De Sanctis, W.D. Nowak, K.A. Oganessian, Phys. Lett. B **483**, 69 (2000); K.A. Oganessian, N. Bianchi, E. De Sanctis, W.D. Nowak, Nucl. Phys. A **689**, 784 (2001)
18. M. Anselmino, F. Murgia, Phys. Lett. B **483**, 74 (2000)
19. A.V. Efremov, K. Goeke, M.V. Polyakov, D. Urbano, Phys. Lett. B **478**, 94 (2000)
20. B.Q. Ma, I. Schmidt, J.J. Yang, Phys. Rev. D **66**, 094001 (2002); **65**, 034010 (2002); **63**, 037501 (2001)
21. V.A. Korotkov, W.D. Nowak, K.A. Oganessian, Eur. Phys. J. C **18**, 639 (2001)
22. A.V. Efremov, K. Goeke, P. Schweitzer, Phys. Lett. B **522**, 37 (2001) [Erratum B **544**, 389 (2002)]
23. A.V. Efremov, K. Goeke, P. Schweitzer, Eur. Phys. J. C **24**, 407 (2002); Nucl. Phys. A **711**, 84 (2002); Acta Phys. Polon. B **33**, 3755 (2002)
24. A.V. Efremov, K. Goeke, P. Schweitzer, Phys. Lett. B **568**, 63 (2003)
25. A.V. Efremov, K. Goeke, P. Schweitzer, Phys. Rev. D **67**, 114014 (2003); for a recent overview on $e^a(x)$ see A.V. Efremov, P. Schweitzer, JHEP **0308**, 006 (2003)
26. H. Avakian, talk at 8th Conference On The Intersections Of Particle And Nuclear Physics (CIPANP 2003), 19–24 May 2003, New York
27. N.C. Makins, M. Düren [HERMES Collaboration], Acta Phys. Polon. B **33**, 3737 (2002); N.C. Makins [HERMES Collaboration], Nucl. Phys. A **711**, 41 (2002)
28. J.M. Le Goff [COMPASS Collaboration], Nucl. Phys. A **711**, 56 (2002); M. Lamanna [COMPASS Collaboration], Nucl. Phys. A **711**, 50 (2002)
29. A. Bacchetta, R. Kundu, A. Metz, P.J. Mulders, Phys. Rev. D **65**, 094021 (2002)
30. P.V. Pobylitsa, M.V. Polyakov, Phys. Lett. B **389**, 350 (1996); P. Schweitzer et al., Phys. Rev. D **64**, 034013 (2001)
31. J.C. Collins, Acta Phys. Polon. B **34**, 3103 (2003)
32. For reviews see D.I. Diakonov, Prog. Part. Nucl. Phys. **51**, 173 (2003); D.I. Diakonov, V.Y. Petrov, Contribution to the Festschrift in honor of B.L. Ioffe, edited by M. Shifman [hep-ph/0009006]
33. C.V. Christov et al., Prog. Part. Nucl. Phys. **37**, 91 (1996)
34. D.I. Diakonov, V. Yu. Petrov, P.V. Pobylitsa, M.V. Polyakov, C. Weiss, Nucl. Phys. B **480**, 341 (1996)
35. D.I. Diakonov et al., Phys. Rev. D **56**, 4069 (1997); P.V. Pobylitsa et al., Phys. Rev. D **59**, 034024 (1999); C. Weiss, K. Goeke, preprint RUB-TPII-12-97 [hep-ph/9712447]; K. Goeke et al., Acta Phys. Polon. B **32**, 1201 (2001)
36. J. Balla, M.V. Polyakov, C. Weiss, Nucl. Phys. B **510**, 327 (1998)
37. A.Y. Umnikov, H.X. He, F.C. Khanna, Phys. Lett. B **398**, 6 (1997)

38. B. Dressler, M.V. Polyakov, Phys. Rev. D **61**, 097501 (2000)
39. P.V. Pobylitsa, hep-ph/0212027
40. A. Schäfer, O.V. Teryaev, Phys. Rev. D **61**, 077903 (2000)
41. A.V. Efremov, O.G. Smirnova, L.G. Tkachev, Nucl. Phys. Proc. Suppl. **74**, 49 (1999); **79**, 554 (1999)
42. A.V. Efremov, Y.I. Ivanshin, O.G. Smirnova, L.G. Tkachev, R.Y. Zulkarneev, Czech. J. Phys. **49**, S75 (1999) [hep-ph/9901216]
43. D. Boer, Nucl. Phys. B **603**, 195 (2001)
44. D. Boer, P.J. Mulders, F. Pijlman, Nucl. Phys. B **667**, 201 (2003)
45. M. Glück, E. Reya, A. Vogt, Z. Phys. C **67**, 433 (1995)
46. A.D. Martin, R.G. Roberts, W.J. Stirling, R.S. Thorne, Eur. Phys. J. C **4**, 463 (1998)
47. P. Abreu et al. [DELPHI Collaboration], Z. Phys. C **73**, 11 (1996)
48. J. Soffer, Phys. Rev. Lett. **74**, 1292 (1995); G.R. Goldstein, R.L. Jaffe, X.D. Ji, Phys. Rev. D **52**, 5006 (1995)
49. S.J. Brodsky, D.S. Hwang, I. Schmidt, Phys. Lett. B **553**, 223 (2003); Nucl. Phys. B **642**, 344 (2002); D. Boer, S.J. Brodsky, D.S. Hwang, Phys. Rev. D **67**, 054003 (2003)
50. L.P. Gamberg, G.R. Goldstein, K.A. Oganessyan, Phys. Rev. D **67**, 071504 (2003)
51. D.L. Adams et al. [FNAL-E704 Collaboration], Phys. Lett. B **264**, 462 (1991); **276**, 531 (1992); Z. Phys. C **56**, 181 (1992)
52. D. Diakonov, M.V. Polyakov, C. Weiss, Nucl. Phys. B **461**, 539 (1996)