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# Subleading-twist effects in single-spin asymmetries in semi-inclusive deep-inelastic scattering on a longitudinally polarized hydrogen target

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## Abstract

Single-spin asymmetries in the semi-inclusive production of charged pions in deep-inelastic scattering from transversely and longitudinally polarized proton targets are combined to evaluate the subleading-twist contribution to the longitudinal case. This contribution is significantly positive for  $\pi^+$  mesons and dominates the asymmetries on a longitudinally polarized target previously measured by HERMES. The subleading-twist contribution for  $\pi^-$  mesons is found to be small.

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Single-spin asymmetries in the distribution of lepto-produced hadrons in the azimuthal angle around the virtual photon direction are a valuable tool for the exploration of transverse spin and momentum degrees of freedom in nucleon structure. Whereas two out of the three fundamental quark distributions, the unpolarized quark density and the helicity density, can be accessed in inclusive measurements, this is not true for the remaining and so far unmeasured transversity distribution [1–3]. Since transversity is chiral-odd and since hard interactions conserve chirality, it can only be probed by a process involving some additional chiral-odd object. Single-spin asymmetries in semi-inclusive deep-inelastic scattering (SIDIS), e.g., involving the chiral-odd Collins fragmentation function [4], could be the required quark “polarimeter” to access transversity. This has been a main motivation to look for azimuthal single-spin asymmetries. Such asymmetries have been observed in SIDIS with unpolarized beams and with targets polarized both longitudinally and transversely with respect to the beam direction [5–9]. Asymmetries have also been observed with polarized beams and unpolarized nucleons [10,11]. The asymmetry for a transversely polarized target can be interpreted in terms of the transversity distribution function, convoluted with the Collins fragmentation function, as well as in terms of the Sivers [12] function, which appears with the ordinary unpolarized fragmentation function. In the case of targets that are polarized longitudinally with respect to the incoming beam direction, the interpretation is more complex. In fact, the asymmetry for a target polarized along the virtual photon direction contains various contributions from subleading-twist quark distribution and fragmentation functions. These contributions have—for dynamics reasons—an additional  $1/Q$  suppression compared to the ordinary  $1/Q^4$  suppression of the Mott cross section. When the polarization is along the beam direction, the small but non-vanishing component of the nuclear spin transverse to the photon direction, although  $1/Q$  suppressed for kinematical reasons, also contributes to the measured asymmetry. This feature has been exploited in several estimates [13–19] for the hitherto unknown transversity distribution and Collins fragmentation functions. However, some or all of the above-mentioned subleading-twist terms have been neglected in all these estimates.

In this Letter the recently measured asymmetries on a transversely polarized hydrogen target [8] are used to eliminate the contribution due to the transverse spin component from the measured asymmetries on a longitudinally polarized hydrogen target [5], thereby allowing, for the first time, the extraction of the purely subleading-twist contribution. Knowledge of this subleading contribution is essential to any extraction of information on the transversity distribution or Collins fragmentation function from data with longitudinal target polarization.

Whenever the target is polarized with respect to the incoming beam direction the measured asymmetries contain contributions from both the transverse and longitudinal polarization components with respect to the virtual photon direction. Throughout this Letter asymmetries and their azimuthal moments will carry one of the following superscripts for distinction: “q” when the reference axis is the photon direction and “l” when it is the lepton beam. They will be called photon-axis or lepton-axis asymmetries/moments, respectively. Asymmetries and moments will also carry two-letter subscripts denoting the polarization of beam and target. For the definition of azimuthal angles, asymmetries, and azimuthal moments thereof the *Trento Conventions* [20] will be used.

The size of the component of the nucleon spin vector that is transverse to the virtual photon direction depends on  $\theta_{\gamma^*}$ , the polar angle between the incoming beam direction and the virtual photon direction (see Fig. 1). Hence it strongly depends on the event kinematics. At HERMES kinematics  $\sin \theta_{\gamma^*}$  can be as large as 15%. In the configuration shown in Fig. 1, where in the lab frame the target spin vector is opposite to the incoming beam direction, the transverse spin component lies in the lepton scattering plane. Therefore  $\phi_S$ , the azimuthal angle of the target spin relative to the scattering plane, is equal to  $\pi$ .

The azimuthal moments of the distribution of hadrons around the virtual-photon direction can be separated into contributions from the longitudinal and transverse components of the target polarization with respect to the virtual photon direction. For the case of the longitudinal lepton-axis moment  $\langle \sin \phi \rangle_{UL}^l$ , the contributions from the

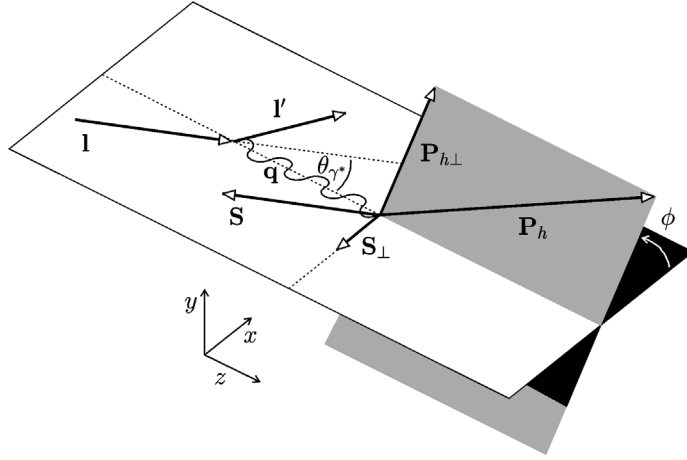


Fig. 1. The definitions of the azimuthal angle  $\phi$  of the hadron production plane, relative to the plane containing the momentum  $l$  ( $l'$ ) of the incident (scattered) lepton, the polar angle  $\theta_{\gamma^*}$  between the virtual photon and the incoming lepton directions, and of the transverse component  $S_{\perp}$  of the target spin  $S$  with respect to the photon direction  $q \equiv l - l'$ .

transverse component are the Sivers and Collins moments  $\langle \sin(\phi - \phi_S) \rangle_{UT}^q$  and  $\langle \sin(\phi + \phi_S) \rangle_{UT}^q$ . Since in this case  $\phi_S = \pi$ , both moments contribute to the  $\sin \phi$  Fourier component of the longitudinal lepton-axis asymmetry with a minus sign. In case of a transversely polarized target contributions arise from the dominating transverse and from the small but non-vanishing longitudinal component. Both the measured lepton-axis moments  $\langle \sin(\phi + \phi_S) \rangle_{UT}^l$  and  $\langle \sin(\phi - \phi_S) \rangle_{UT}^l$  contain contributions from  $\langle \sin \phi \rangle_{UL}^q$ . The lepton-axis moments are related to the photon-axis moments via the equation

$$\begin{pmatrix} \langle \sin \phi \rangle_{UL}^l \\ \langle \sin(\phi - \phi_S) \rangle_{UT}^l \\ \langle \sin(\phi + \phi_S) \rangle_{UT}^l \end{pmatrix} = \begin{pmatrix} \cos \theta_{\gamma^*} & -\sin \theta_{\gamma^*} & -\sin \theta_{\gamma^*} \\ \frac{1}{2} \sin \theta_{\gamma^*} & \cos \theta_{\gamma^*} & 0 \\ \frac{1}{2} \sin \theta_{\gamma^*} & 0 & \cos \theta_{\gamma^*} \end{pmatrix} \begin{pmatrix} \langle \sin \phi \rangle_{UL}^q \\ \langle \sin(\phi - \phi_S) \rangle_{UT}^q \\ \langle \sin(\phi + \phi_S) \rangle_{UT}^q \end{pmatrix}, \quad (1)$$

which is valid up to corrections of order  $\sin^2 \theta_{\gamma^*}$  [21].

The complete analysis up to subleading-twist and leading order in  $\alpha_s$  of longitudinal single-spin asymmetries in semi-inclusive DIS was presented in Ref. [22], completing previous work of Refs. [23,24]. Neglecting quark mass effects, the first term of the photon-axis moments on the right-hand side of Eq. (1) is

$$\langle \sin \phi \rangle_{UL}^q = -\frac{(2-y)\sqrt{1-y}}{1-y+\frac{y^2}{2}} \frac{M}{Q} \frac{\mathcal{I}[\frac{\hat{p}_{h\perp} \cdot k_T}{M_h} (\frac{M_h}{zM} g_{1L} G^\perp + x h_L H_1^\perp) + \frac{\hat{p}_{h\perp} \cdot p_T}{M} (\frac{M_h}{zM} h_{1L}^\perp \tilde{H} - x f_L^\perp D_1)]}{f_1 D_1}. \quad (2)$$

The shorthand notation  $\mathcal{I}[\mathcal{W}fD]$  is used here for the convolution integral appearing in the SIDIS cross section when quark transverse momenta are included, i.e.,

$$\mathcal{I}[\mathcal{W}fD] \equiv \int d^2 \mathbf{P}_{h\perp} d^2 \mathbf{p}_T d^2 \mathbf{k}_T \delta^{(2)}\left(\mathbf{p}_T - \frac{\mathbf{P}_{h\perp}}{z} - \mathbf{k}_T\right) [\mathcal{W}f(x, p_T^2) D(z, z^2 k_T^2)], \quad (3)$$

where  $\mathbf{P}_{h\perp}$  is the transverse momentum of the detected hadron,  $\mathbf{p}_T$  ( $\mathbf{k}_T$ ) is the intrinsic quark transverse momentum in the generic distribution function  $f$  (fragmentation function  $D$ ), and  $\mathcal{W}$  is a weight that depends on the involved distribution and fragmentation functions. The masses  $m_q$ ,  $M$ , and  $M_h$  are the quark, nucleon and hadron masses and  $x$ ,  $y$ , and  $z$  are the usual semi-inclusive DIS Lorentz invariants. The quark charge squared weighted sum over the various (anti)quark flavors and the dependence on  $x$  ( $z$ ),  $p_T^2$  ( $k_T^2$ ), and  $Q^2$  of the distribution (fragmentation) functions have been omitted in Eq. (2).

Since the extraction of the subleading-twist term  $\langle \sin \phi \rangle_{UL}^q$  is the main result of this work, its components are described briefly. The asymmetry arises from the interference of the scattering amplitudes of a longitudinal and transverse photon. This leads to the specific dependence of the numerator on the variable  $y$ . All terms in the numerator of Eq. (2) involve either combinations of subleading-twist distribution functions ( $h_L$ ,  $f_L^\perp$ ) with leading-twist fragmentation functions or of leading-twist distribution functions in conjunction with subleading-twist fragmentation functions ( $G^\perp$ ,  $\tilde{H}$ ). One should note that it is not possible to give a simple probabilistic interpretation to the subleading-twist functions. The terms containing  $h_L$  and  $h_{1L}^\perp$  have been studied in some detail in Refs. [14,15], making use of Wandzura–Wilczek approximations, and of Lorentz covariance relations. (The latter have been proven to be not rigorous in Ref. [25].) Note that the function  $h_{1L}^\perp$  appears also in the  $\sin 2\phi$  Fourier component of the longitudinal single-spin asymmetry [23]. Recent preliminary results of CLAS support a non-vanishing  $\sin 2\phi$  moment [26]. However, in measurements at HERMES which were in a different kinematic region than the ones at CLAS, it was found to be consistent with zero [5]. The term with the helicity distribution  $g_{1L}$  contains the fragmentation function  $G^\perp$ , which is at present unknown. A similar term appears also in the longitudinal beam-helicity asymmetry,  $A_{LU}$  [22]. The latter has been found to be non-zero both at HERMES [11] and at CLAS [10]. Finally, the last term of the numerator contains the function  $f_L^\perp$ . Similar to the Siverson function  $f_{1T}^\perp$  it is odd under time reversal (T-odd) and for this reason has been neglected in virtually all theoretical treatments of the measured lepton-axis asymmetries on a longitudinally polarized target. Recently, it has been recognized that such T-odd distribution functions can arise through initial or final state interactions [27–30]. A calculation of the function  $f_L^\perp$  has been performed in Ref. [31] in the context of a simple diquark spectator model. It should be noted that so far factorization has been proven only for leading-twist observables in semi-inclusive deep-inelastic scattering with hadrons in the current fragmentation region detected at low transverse momentum [32,33]. A factorization proof for subleading-twist observables is still open. At the moment no firm experimental information about any of the subleading-twist terms in Eq. (2) exist.

The extraction of  $\langle \sin \phi \rangle_{UL}^q$  reported here gives a first indication about the size of such subleading-twist effects in azimuthal target-spin asymmetries. This is especially important when measuring leading-twist asymmetries of the same order of magnitude where the question arises whether or not subleading-twist contributions can be neglected.

The other two terms on the right-hand side of Eq. (1) read

$$\langle \sin(\phi - \phi_S) \rangle_{UT}^q = - \frac{\mathcal{I} \left[ \frac{\hat{P}_{h^\perp \cdot p_T}}{2M} f_{1T}^\perp D_1 \right]}{f_1 D_1}, \quad (4)$$

$$\langle \sin(\phi + \phi_S) \rangle_{UT}^q = - \frac{1-y}{1-y+\frac{y^2}{2}} \frac{\mathcal{I} \left[ \frac{\hat{P}_{h^\perp \cdot k_T}}{2M_h} h_1 H_1^\perp \right]}{f_1 D_1}, \quad (5)$$

which are the leading-twist Siverson and Collins moments, involving either the Siverson distribution function, or the transversity distribution  $h_1$  in conjunction with the Collins fragmentation function  $H_1^\perp$ .

Measurements of azimuthal single-spin asymmetries on a transversely polarized target can be used to eliminate the contribution of these leading-twist moments (4) and (5) to the longitudinal lepton-axis moment  $\langle \sin \phi \rangle_{UL}^1$ . Hence the subleading-twist terms (Eq. (2)) can be isolated. At HERMES kinematics the deviation from unity of  $\cos \theta_{\gamma^*}$  can be neglected. The subleading-twist contribution  $\langle \sin \phi \rangle_{UL}^q$  then reads

$$\langle \sin \phi \rangle_{UL}^q = \langle \sin \phi \rangle_{UL}^1 + \sin \theta_{\gamma^*} \langle \sin(\phi + \phi_S) \rangle_{UT}^1 + \sin \theta_{\gamma^*} \langle \sin(\phi - \phi_S) \rangle_{UT}^1. \quad (6)$$

Here  $\sin \theta_{\gamma^*}$  is evaluated from the lepton kinematics as  $2xMQ^{-1} \sqrt{1-y-y^2x^2M^2/Q^2} / \sqrt{1+4x^2M^2/Q^2}$ .

For the extraction of the subleading-twist contribution  $\langle \sin \phi \rangle_{UL}^q$  according to Eq. (6) the lepton-axis asymmetries on a longitudinally polarized hydrogen target [5] were reanalyzed to have the same binning in  $x$  and  $z$  as in the measurement on a transversely polarized hydrogen target [8]. Furthermore, the  $\sin \phi$  modulation of the

semi-inclusive cross section has been extracted in a fit of the normalized-yield asymmetry<sup>1</sup>

$$A_{UL}^1(\phi) = \frac{1}{|P_L|} \frac{N^{\rightarrow}(\phi) - N^{\leftarrow}(\phi)}{N^{\rightarrow}(\phi) + N^{\leftarrow}(\phi)}, \quad (7)$$

where  $P_L$  is the longitudinal target polarization and  $\rightarrow/\leftarrow$  denotes a target polarized antiparallel/parallel to the incoming beam direction. The same requirements on the lepton kinematics were used as in the analysis of the transverse target data, i.e.,  $W^2 > 10 \text{ GeV}^2$ ,  $0.023 < x < 0.4$ ,  $0.1 < y < 0.85$  and  $Q^2 > 1 \text{ GeV}^2$ , where  $W$  is the invariant mass of the initial photon–nucleon system. Coincident hadrons were accepted only if  $0.2 < z < 0.7$  and  $\theta_{\gamma^*h} > 0.02 \text{ rad}$ , where  $\theta_{\gamma^*h}$  is the angle between the directions of the virtual photon and the hadron. The latter requirement was imposed to avoid a region where the azimuthal angle  $\phi$  is poorly reconstructed due to detector smearing. Pions were identified in the momentum range  $4 \text{ GeV} < P_\pi < 13.8 \text{ GeV}$  using either a threshold Cherenkov counter for the longitudinally polarized data set or a ring imaging Cherenkov counter for the transversely polarized target data. The lepton-axis moments from the transversely polarized target data set were extracted in the fit

$$A_{UT}^1(\phi, \phi_S) = 2\langle \sin(\phi + \phi_S) \rangle_{UT}^1 \sin(\phi + \phi_S) + 2\langle \sin(\phi - \phi_S) \rangle_{UT}^1 \sin(\phi - \phi_S) \quad (8)$$

of the transverse asymmetry in Eq. (1) of Ref. [8].<sup>2</sup>

A possible uncertainty in the interpretation of the extracted asymmetries in terms of Eq. (2) is the contribution to the analyzed pion samples from the decay of exclusively produced vector mesons (VM). Due to the limited acceptance of the HERMES spectrometer, a large fraction of these vector mesons cannot be identified. Although the contribution of their decay pions to the observed pion yield is small—less than 15% for the highest  $z$  bin [8], based on a PYTHIA6 Monte Carlo simulation tuned for HERMES kinematics reproducing the exclusive VM cross section on a 10% level [34]—their contribution to  $\langle \sin(\phi - \phi_S) \rangle_{UT}^q$  for a transversely polarized target could be significant [35]. For  $\langle \sin \phi \rangle_{UL}^q$  this contributes only through the transverse component and is thus subtracted through Eq. (6). The VM contribution to the  $\langle \sin \phi \rangle_{UL}^q$  moments from the longitudinal spin component of the target can be treated as a dilution as no  $\sin \phi$  dependence on the longitudinal target polarization of either the VM production or its decay distribution is expected [36]. For an estimate of such effects moments were extracted that have the diluting contribution from this exclusive channel subtracted. This was done by dividing the  $\langle \sin \phi \rangle_{UL}^q$  moments of Eq. (6) by  $(1 - N_{VM}/N_{\text{tot}})$  where  $N_{VM}$  and  $N_{\text{tot}}$  are the numbers of pions from VM decays and all detected pions, respectively.

The main contribution to the systematic uncertainty in the extracted moments arises from the measurement of the target polarization. Other contributions include smearing due to detector resolution and radiative effects. The combined systematic uncertainty is found to be less than 0.003.

The moments for charged pions are shown as functions of  $x$  and  $z$  in Fig. 2 and summarized in Table 1. In addition to the extracted longitudinal photon-axis moments  $\langle \sin \phi \rangle_{UL}^q$  the lepton-axis moments for longitudinally and transversely polarized targets are plotted in Fig. 2. The latter include the prefactor  $-\sin \theta_{\gamma^*}$  with which they appear in the  $\langle \sin \phi \rangle_{UL}^1$  measurement. The resulting longitudinal photon-axis moments are significantly positive for the  $\pi^+$  and consistent with zero for the  $\pi^-$ . Hence in the case of the  $\pi^+$  this subleading-twist contribution dominates the measured lepton-axis asymmetries on a target that is polarized longitudinally with respect to the beam direction. Therefore it becomes clear that those asymmetries cannot be interpreted in terms of only the Collins fragmentation function or the Sivers function. In particular, the contribution from the Sivers function to the measured longitudinal lepton-axis asymmetries is small compared to the subleading-twist contribution as it appears only for

<sup>1</sup> This is in contrast to the previous publication on longitudinal single-spin asymmetries [5] where a weighting method has been used to extract the  $\sin \phi$  Fourier component of the asymmetry.

<sup>2</sup> Note that in Ref. [8] a superscript on the asymmetry is used that is different and not related to the one here. Also the fit in Ref. [8] includes kinematic prefactors that are not needed here.

Table 1

The  $2\langle\sin\phi\rangle_{UL}^q$  moments of the  $\pi^+$  and  $\pi^-$  production cross section for different  $x$  (top) and  $z$  (bottom) bins. Only statistical uncertainties are included. In addition there is a common systematic uncertainty of 0.003. Results are shown for all detected pions and for the case where the contribution from the decay of exclusive VM has been subtracted

$\langle x \rangle$	$\langle z \rangle$	$\langle P_{h\perp} \rangle$ [GeV]	$\langle y \rangle$	$\langle Q^2 \rangle$ [GeV <sup>2</sup> ]	All $\pi$ 's		$\pi$ 's from exclusive VM subtracted	
					$2\langle\sin\phi\rangle_{UL}^{q,\pi^+}$	$2\langle\sin\phi\rangle_{UL}^{q,\pi^-}$	$2\langle\sin\phi\rangle_{UL}^{q,\pi^+}$	$2\langle\sin\phi\rangle_{UL}^{q,\pi^-}$
0.038	0.36	0.50	0.68	1.3	$0.023 \pm 0.008$	$-0.012 \pm 0.010$	$0.025 \pm 0.009$	$-0.013 \pm 0.011$
0.067	0.41	0.45	0.59	2.0	$0.022 \pm 0.007$	$-0.012 \pm 0.010$	$0.023 \pm 0.008$	$-0.012 \pm 0.010$
0.114	0.43	0.42	0.55	3.2	$0.039 \pm 0.010$	$-0.016 \pm 0.013$	$0.041 \pm 0.010$	$-0.017 \pm 0.014$
0.178	0.44	0.41	0.52	4.8	$0.057 \pm 0.016$	$0.028 \pm 0.022$	$0.059 \pm 0.016$	$0.029 \pm 0.023$
0.274	0.46	0.40	0.48	6.8	$0.053 \pm 0.025$	$-0.023 \pm 0.035$	$0.054 \pm 0.025$	$-0.024 \pm 0.036$
0.065	0.26	0.42	0.71	2.3	$0.027 \pm 0.009$	$0.000 \pm 0.012$	$0.028 \pm 0.009$	$0.000 \pm 0.012$
0.080	0.35	0.45	0.62	2.5	$0.029 \pm 0.008$	$-0.018 \pm 0.011$	$0.030 \pm 0.009$	$-0.019 \pm 0.012$
0.091	0.47	0.48	0.55	2.4	$0.033 \pm 0.008$	$-0.002 \pm 0.011$	$0.035 \pm 0.009$	$-0.002 \pm 0.012$
0.098	0.62	0.49	0.49	2.3	$0.033 \pm 0.011$	$-0.021 \pm 0.015$	$0.037 \pm 0.012$	$-0.024 \pm 0.018$

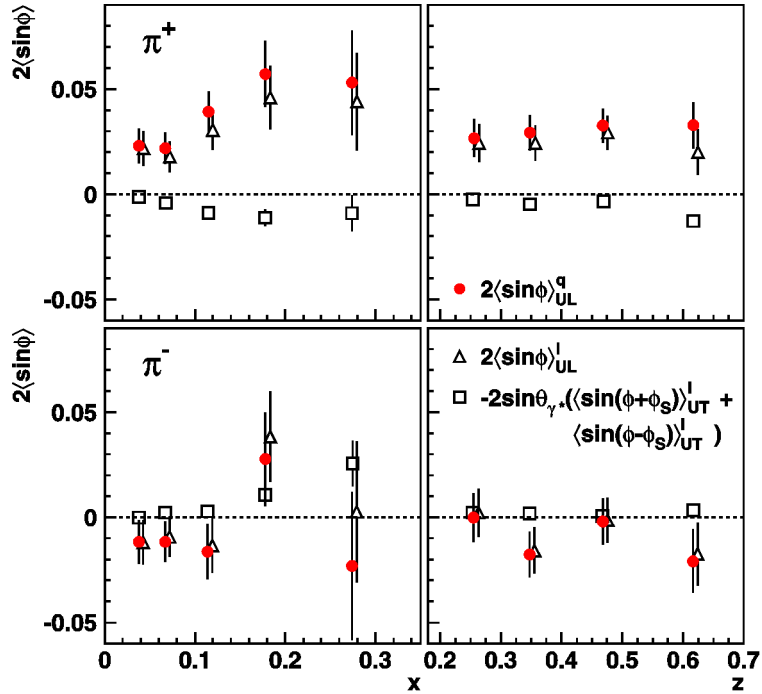


Fig. 2. The various azimuthal moments appearing in the measurement of the  $\sin\phi$  modulations of single-spin asymmetries on a longitudinally polarized hydrogen target for charged pions as functions of  $x$  and  $z$ . The open symbols are the measured lepton-axis moments. The ones from a transversely polarized target are multiplied by  $-\sin\theta_{\gamma^*}$  according to their appearance in the longitudinal lepton-axis moments. The closed symbol is the subleading-twist contribution to the measured lepton-axis asymmetries on a longitudinally polarized target. The triangles are slightly shifted horizontally for distinction. An overall systematic error of 0.003 is not included in the figure.

the transverse component of the target spin. Unfortunately, due to the presence of several contributions (Eq. (2)), it is not possible to make any statements about the size of any subleading-twist function separately. Nevertheless, it is clear that subleading-twist effects cannot be neglected a priori. This will be important when interpreting the measured lepton-axis asymmetries on a transversely polarized target which for experimental reasons receive not



only contributions from the transverse target spin component (e.g., the Collins and Sivers effects) but also from the longitudinal component (subleading-twist) as in Eq. (1).<sup>3</sup>

In summary, single-spin asymmetries on hydrogen polarized longitudinally along the photon direction have been extracted for the first time. The contribution to the lepton-axis asymmetries from the transverse spin component in the measurement on a target polarized longitudinally with respect to the beam has been subtracted using the data from a transversely polarized hydrogen target. The averaged asymmetries in the range  $0.023 < x < 0.4$  ( $\langle x \rangle = 0.082$ ) and  $0.2 < z < 0.7$  ( $\langle z \rangle = 0.40$ ) are  $0.030 \pm 0.004_{\text{stat}} \pm 0.002_{\text{sys}}$  for  $\pi^+$  and  $-0.009 \pm 0.006_{\text{stat}} \pm 0.001_{\text{sys}}$  for  $\pi^-$ . For  $\pi^+$  the  $\langle \sin \phi \rangle_{UL}^q$  result is the dominating component in this range. This shows that subleading-twist effects are large and can, at HERMES kinematics, be comparable to leading-twist effects. This must be taken into account when interpreting asymmetries on transversely or longitudinally polarized targets solely in terms of leading-twist functions. At lower energies the isolation of leading-twist effects may be even more difficult.

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<sup>3</sup> It should be noted that a similar analysis for the azimuthal moments on a transversely polarized target yields corrections to the measured lepton-axis moments [8] that are negligible compared to their statistical uncertainty.

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