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Transverse target single-spin asymmetry in inclusive electroproduction of charged pions and kaons ☆

HERMES Collaboration

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ABSTRACT

Single-spin asymmetries were investigated in inclusive electroproduction of charged pions and kaons from transversely polarized protons at the HERMES experiment. The asymmetries were studied as a function of the azimuthal angle ψ about the beam direction between the target-spin direction and the hadron production plane, the transverse hadron momentum P_T relative to the direction of the incident beam, and the Feynman variable x_F. The $\sin\psi$ amplitudes are positive for π^+ and K^+, slightly negative for π^- and consistent with zero for K^-, with particular P_T but weak x_F dependences. Especially large asymmetries are observed for two small subsamples of events, where also the scattered electron was recorded by the spectrometer.

Transverse single-spin asymmetries (SSAs) observed in the azimuthal distributions of hadrons produced in high-energy electromagnetic and hadronic reactions (where either the projectile or the target nucleon is polarized transversely to the beam direction) are a window for our understanding of the nucleon structure and the process of hadronization in the framework of quantum-chromodynamics (QCD). They originate from correlations of the transverse spin of the nucleon and/or the transverse spins of the quarks with transverse quark momentum and could in models be related to spin-orbit effects and to the elusive orbital motion of partons within the nucleon. Left-right cross-section asymmetries A_N for the inclusive production of various hadrons in hadron-nucleon collisions have been measured over the past three decades by numerous experiments [1–25] for center-of-mass energies in the range 4.9–500 GeV. Large values of A_N were observed for single hadrons in $p^\uparrow p \to hX$ reactions at large transverse hadron momenta, P_T, and large positive values of x_F, exceeding $|A_N| = 0.4$ for charged pions. The Feynman variable x_F is defined as the ratio of the longitudinal hadron momentum P_L along the beam direction to its maximum possible value. Transverse single-spin asymmetries have also been investigated in semi-inclusive deep-inelastic lepton scattering, $lN^\uparrow \to l'hX$, from transversely polarized hydrogen [26–31], deuterium [32–34], and ^{3}He [35] targets. Here, substantial azimuthal SSAs up to about 0.1 have been observed for hydrogen targets. A review of experimental results can be found in Refs. [36] and [37], together with an extended discussion on contemporary theoretical work.

The large size of these single-spin asymmetries indicates the importance of effects beyond the standard leading-twist framework based on collinear factorization. One approach [38] is based on the use of parton distribution and fragmentation functions that are unintegrated in transverse momenta. In this approach, the asymmetries are caused mainly by two mechanisms: the Sivers [39] and Collins [40] effects. The former is related to the transverse-momentum-dependent naive-time-reversal odd Sivers distribution function of unpolarized quarks with non-zero transverse momenta in a transversely polarized nucleon. The latter is related to the chiral-odd transversity distribution of transversely polarized quarks in a transversely polarized nucleon, in conjunction with the transverse-momentum-dependent chiral-odd Collins fragmentation function. The other approach [41–46] links collinear parton dynamics to higher-twist multiparton correlations. Again, two mechanisms dominate where either a twist-three chiral-odd fragmentation function couples to the transversity distribution, or where a twist-three chiral-even distribution function enters with the ordinary leading-twist unpolarized fragmentation function. These approaches have different kinematic domains of validity, but with a region in common. In the past it was believed that they succeeded in reproducing the existing measurements of A_N in hadron–hadron reactions to a very large extent, and have been shown to be related to and consistent with each other in the kinematic region where they both apply [47]. Recently, however, a sign error was identified [48] that invalidates the good agreement observed earlier. Presently the situation is unsettled [49].

There exist several theoretical expectations for aspects of the SSAs in hadron electroproduction. Their validity depends on the relative magnitude of the three relevant scales Λ_{QCD}, P_T and Q, where $\Lambda_{\mathrm{QCD}} \cong 0.3$ GeV is the QCD scale parameter and $-Q^2$ is the squared four-momentum of the virtual photon that mediates the lepton-nucleon scattering process:

(i) Theory makes no reliable prediction for the kinematic region where both P_T and Q are small and of order Λ_{QCD};
(ii) The twist-three approach leads to a characteristic power suppression by $1/P_T$ for large P_T, provided P_T is the largest scale in the process. For $P_T < 1$ GeV such power suppressions typically become less efficient;
(iii) The Sivers and Collins effects become significant when $Q^2 > P_T^2$ and $Q^2 \gg \Lambda_{\mathrm{QCD}}^2$ and give a contribution that is not P_T-suppressed. For large Q^2, the dominant contribution to the asymmetry should therefore come from the Sivers and Collins mechanisms. The SSAs measured in semi-inclusive DIS were, in fact, the basis for an extraction of the Sivers and transversity distribution functions and the Collins fragmentation function (see e.g., Refs. [50,51]);
(iv) It was shown that, for the kinematic regime $Q \gg P_T \gg \Lambda_{\mathrm{QCD}}$, the descriptions in terms of the Sivers distribution function and of twist-three quark-gluon correlation functions become

equivalent [52] and that there also exists a kinematic region in which a twist-three fragmentation function and the leading-twist Collins fragmentation function can be mapped onto one another [53]. For $P_T^2 \sim Q^2$ one cannot make any quantitative theoretical statement about their connection.

A substantial number of theoretical predictions (see, e.g., Refs. [44,47,54–60]) have not yet been confronted with experimental data. More data are required in a wider kinematic range that covers transverse momenta as high as possible but also approaches P_T values as small as Λ_{QCD} for both A_N in hadron–hadron reactions and SSAs in electroproduction of hadrons, $lp^\uparrow \to hX$. This Letter reports on the first measurement of azimuthal SSAs in inclusive electroproduction of charged pions and kaons off transversely polarized protons. It addresses a portion of this unexplored kinematic space.

The data reported here were collected during the period 2002–2005 with the HERMES spectrometer [61] using the 27.6 GeV lepton beam (electrons or positrons) incident upon a transversely nuclear-polarized gaseous hydrogen target internal to the HERA lepton storage ring at DESY. The integrated luminosity of the data sample was approximately 146 pb^{-1}. The average magnitude of the proton-polarization component perpendicular to the beam direction, S_T, was 0.713 ± 0.063. The direction of the target-spin vector was reversed between the "upward" and "downward" directions at 1–3 minute intervals to minimize systematic effects, while both the nuclear polarization and the atomic fraction inside the target cell were measured continuously [62]. The beam was longitudinally polarized and its helicity reversed every few months. A helicity-balanced data sample was used to obtain an effectively unpolarized beam.

Selected events had to contain at least one charged-hadron track, identified as either a pion or a kaon, within the angular acceptance of the spectrometer (± 170 mrad horizontally and $\pm$(40–140) mrad vertically) independent of whether there was also a scattered lepton in the acceptance or not. Hadrons were distinguished from leptons by using a transition-radiation detector, a scintillator pre-shower counter, and an electromagnetic calorimeter. This resulted in a tiny lepton contamination in the hadron sample of less than 0.1%. Hadrons within the momentum range 2–15 GeV were further identified using a dual-radiator ring-imaging Cherenkov detector [63]. This identification is based on a direct ray tracing algorithm that deduces the most probable particle types from the event-level hit pattern of Cherenkov photons on the photomultiplier matrix [64].

The trigger of the experiment was formed, for each detector half, by a coincidence of signals from a scintillation counter in front of the spectrometer magnet and from a scintillator hodoscope and the pre-shower counter behind the magnet, spaced by 1 m, with the requirement of an energy deposit greater than 1.4 GeV in the electromagnetic calorimeter. The trigger was almost 100% efficient for leptons with energies above threshold. The energy threshold of the calorimeter was low enough to trigger also on events with only charged hadrons and no leptons in its geometrical acceptance. In this case, the trigger efficiency was substantially smaller and depended on the hadron momentum P_h, as well as on the impact position and angle of the hadron track on the calorimeter surface and the hadron multiplicity in the event. Averaged over the hadron multiplicity, the trigger efficiency was about 40–45% for hadron momenta greater than approximately 7 GeV and decreased smoothly with decreasing P_h to about 15% at $P_h \approx 2$ GeV. In order not to bias the inclusive-hadron sample towards events with a coincident lepton in the detector acceptance, trigger-efficiency corrections dependent on the event topology (e.g., additional lepton or further hadrons in the event) were applied. In total, about

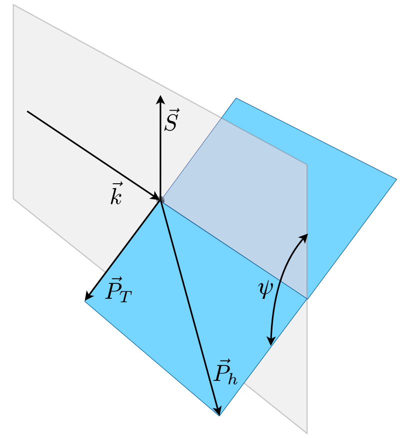

Fig. 1. The definition of the azimuthal angle ψ.

$60 \cdot 10^6$ ($50 \cdot 10^6$) tracks of positively (negatively) charged pions and $5.1 \cdot 10^6$ ($2.8 \cdot 10^6$) tracks of positively (negatively) charged kaons were collected. These correspond to about $172 \cdot 10^6$ ($142 \cdot 10^6$) positively (negatively) charged pions and $14.5 \cdot 10^6$ ($7.3 \cdot 10^6$) positively (negatively) charged kaons after trigger-efficiency correction (cf. Table 1), which are used in all of the subsequent results.

As the scattered lepton was not required for the primary analysis, the following hadron variables were used: P_T, the transverse momentum of the hadron with respect to the lepton beam direction; x_F, here calculated in the lepton-nucleon center-of-momentum frame; and ψ, the azimuthal angle about the beam direction between the "upward" target spin direction and the hadron production plane, in accordance with the *Trento Conventions* [65] (see Fig. 1).

The cross section for inclusive electroproduction of hadrons using an unpolarized lepton beam and a transversely polarized target includes a polarization-averaged and a polarization-dependent part and is given for each hadron species as

$$d\sigma = d\sigma_{UU}\left[1 + S_T A_{UT}^{\sin\psi} \sin\psi\right]. \tag{1}$$

Here, the first subscript U denotes unpolarized beam, the second subscript $U(T)$ an unpolarized (transversely polarized) target. The dependences of the cross section and of the azimuthal amplitude $A_{UT}^{\sin\psi}$ on P_T and x_F have been omitted. The $\sin\psi$ azimuthal dependence follows directly from the term $\vec{S} \cdot (\vec{P}_h \times \vec{k})$ in the spin-dependent part of the cross section (see, e.g., Ref. [60]), with $\vec{S}$ being the target-spin vector, and $\vec{k}$ and $\vec{P}_h$ the three-momenta of the incident lepton and of the final-state hadron, respectively.

The $\sin\psi$ amplitude $A_{UT}^{\sin\psi}$ is related to the left-right asymmetry A_N along the direction of the incident lepton beam and with respect to the nucleon-spin direction,[2] measured with a detector with full 2π-coverage in ψ and constant efficiency, by

$$A_N \equiv \frac{\int_\pi^{2\pi} d\psi\, d\sigma - \int_0^\pi d\psi\, d\sigma}{\int_\pi^{2\pi} d\psi\, d\sigma + \int_0^\pi d\psi\, d\sigma} = -\frac{2}{\pi} A_{UT}^{\sin\psi}. \tag{2}$$

Experimentally, the $A_{UT}^{\sin\psi}$ amplitudes were extracted by performing a maximum-likelihood fit to the cross section of Eq. (1), i.e., the measured yield distribution for the two target-spin states weighted with the inverse of the trigger efficiencies and luminosity, binned in P_T and x_F, but unbinned in ψ. The detection

[2] The sign convention of A_N in hadron collisions commonly differs through defining "left" and "right" with respect to the momentum and transverse-spin directions of the incoming polarized hadron.

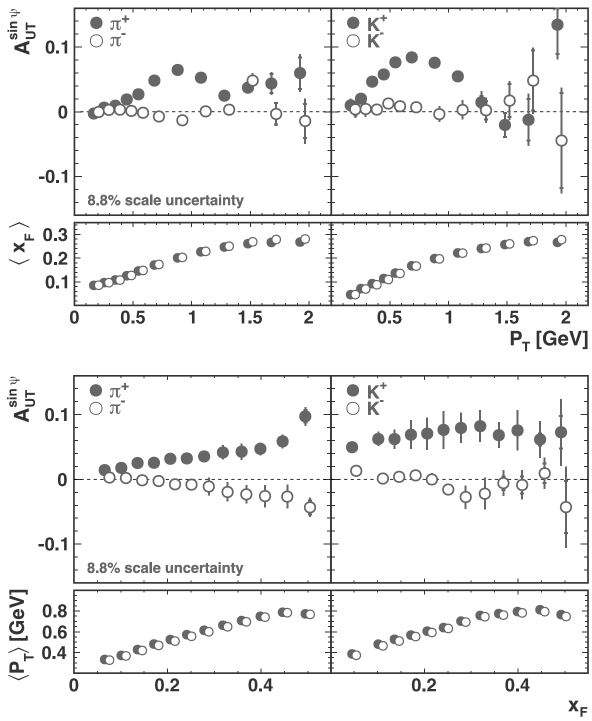

Fig. 2. $A_{UT}^{\sin\psi}$ amplitudes for charged pions and kaons as a function of P_T (top) and x_F (bottom). Positive (negative) particles are denoted by closed (open) symbols. When visible, the inner error bars show the statistical uncertainties, while the total ones represent the quadratic sum of statistical and systematic uncertainties. Not shown is an additional 8.8% scale uncertainty due to the precision of the measurement of the target polarization. The bottom subpanels show the P_T dependence (x_F dependence) of the average x_F (P_T). Data points for negative particles are slightly shifted horizontally for legibility.

efficiency, if independent of the target-spin state, cancels in the fit as long as the polarization-weighted luminosity vanishes, i.e., $\int S_T(t)L(t)\,dt = 0$, as is the case for the present data.

The extracted $A_{UT}^{\sin\psi}$ amplitudes for charged pions and kaons are presented as a function of P_T in the top panels of Fig. 2. The amplitudes are positive for the positive hadrons, being slightly larger for kaons compared to pions. They rise smoothly with P_T up to a maximum value of approximately 0.06 (0.08) for pions (kaons) at $P_T \simeq 0.8$ GeV and then decrease again with increasing P_T. Note that at $P_T = 0$ GeV the amplitude $A_{UT}^{\sin\psi}$ vanishes by definition. For $P_T > 1.3$ GeV, the statistical uncertainties increase substantially with P_T. Here, there is an indication of an increase of the amplitude for pions, while for kaons it is compatible with zero within the uncertainties, apart from the point at the highest P_T, where the amplitude is 2.8 standard deviations above zero. For negative hadrons the amplitudes are much smaller in magnitude, sometimes positive and sometimes negative, apart from the π^- point at $P_T = 1.5$ GeV. Detailed investigations of the data and the analysis leading to this exceptionally large asymmetry amplitude have not revealed any instrumental origin.

In the bottom panels of Fig. 2, the measured $A_{UT}^{\sin\psi}$ amplitudes are presented as a function of x_F. For positive pions, the amplitudes are positive everywhere and increase nearly linearly with x_F up to a value of approximately 0.06, with the exception of the point in the highest x_F bin, where the value is $0.10 \pm 0.01_{\text{stat}} \pm 0.01_{\text{sys}}$. For negative pions, the amplitude is negative over most of the x_F range and decreases linearly down to a value of about -0.04 for the last x_F bin. These x_F dependences of the pion asymmetry amplitudes look similar to the one observed in hadron-hadron collisions. For positive kaons, the amplitude is about constant around 0.07, with some small variation with x_F. For negative kaons, the asymmetry amplitude is compatible with zero over most of the x_F range, with a small positive excursion in the lowest x_F bin, and a negative one in the region around $x_F = 0.3$.

The variables x_F and P_T are strongly correlated in these measurements as can be seen from the bottom subpanels of Fig. 2, where they are shown at the average bin kinematics. Hence, any observed kinematic dependence of $A_{UT}^{\sin\psi}$ cannot be uniquely ascribed to the variable plotted against but may stem from the underlying dependence on the kinematic variable over which the data are integrated. For this reason, a two-dimensional extraction of the asymmetry amplitudes was performed by binning simultaneously in P_T and x_F. The resulting $A_{UT}^{\sin\psi}$ amplitudes are shown as a function of P_T in four slices of x_F in Fig. 3, and in Fig. 4 as a function of x_F in four slices of P_T. Only data points with a statistical uncertainty of the asymmetry amplitude smaller than 0.1 are shown. The P_T dependence in the four x_F slices is very similar in shape and magnitude, apart from increased statistical fluctuations. For positive pions the amplitude is seen to be essentially independent of x_F in all four slices in P_T. Therefore, it can be concluded that the apparent increase of the magnitude of the asymmetry amplitude with x_F seen for positive pions in Fig. 2 is just a reflection of the underlying dependence on P_T. In contrast, for negative pions the decrease with x_F follows the one observed in the one-dimensional extraction. The dependence on x_F of the kaon asymmetry amplitudes is less pronounced in the two-dimensional extraction, with a slight tendency towards an increase (decrease) with x_F for positive (negative) kaons. Note that in measurements of inclusive SSAs in proton–proton collisions, A_N is seen to rise strongly for values of x_F larger than about 0.3–0.4. For charged pions [22] and neutral pions [23] such an increase of A_N with x_F was seen even after binning the data in slices of P_T.

In Figs. 2–5, the systematic uncertainties are added in quadrature to the statistical ones. One contribution arises from different methods employed for the trigger-efficiency correction. An additional contribution, added in quadrature to the previous one, arises from typical effects due to non-perfect experimental resolution and acceptance, and is determined in a manner to include the effects of the necessary binning of finite statistics. This second contribution was determined from a high-statistics Monte Carlo data sample obtained from a simulation using the program PYTHIA 6.2 [66,67]. This simulation [68] contained a full description of the detector, including effects such as acceptance, correction for particle deflection in the vertical target holding field, losses due to decay in flight and secondary strong interactions, and particle identification. In addition, a spin-dependent azimuthal asymmetry was imposed on the simulated event sample according to Eq. (1). The functional form $\mathcal{A}_{UT,MC}^{\sin\psi}$ is a Taylor expansion in P_T (up to fifth order) and x_F (up to first order) around the average kinematics of the entire experimental data sample. The set of (up to) twelve parameters for each hadron species was obtained in a maximum-likelihood fit to the experimental data where the number of terms in the expansion was tuned to describe all measured asymmetry amplitudes. The $\sin\psi$ amplitudes $A_{UT,MC}^{\sin\psi}$ were then extracted from the now spin-dependent Monte Carlo sample in the same way as described above for data. The total systematic uncertainty in each bin corresponds to the maximum value of either the (in most bins negligibly small) statistical uncertainty in the Monte Carlo sample or the deviation between the model function $\mathcal{A}_{UT,MC}^{\sin\psi}$ evaluated at the average kinematics of the bin and the reconstructed $A_{UT,MC}^{\sin\psi}$ amplitude. This calculational approach is designed to address, among others, the differences between the asymmetry amplitudes evaluated at the average values of their kinematical dependences and the asymmetry amplitudes averaged

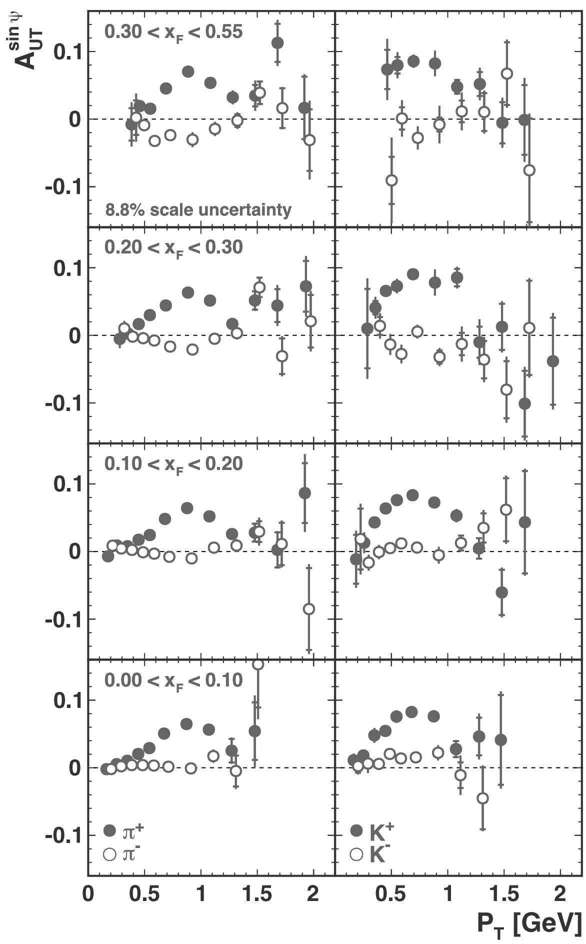

Fig. 3. $A_{UT}^{\sin\psi}$ amplitudes for charged pions and kaons as a function of P_T for various slices in x_F. Symbol definitions and additional 8.8% scale uncertainty as in Fig. 2.

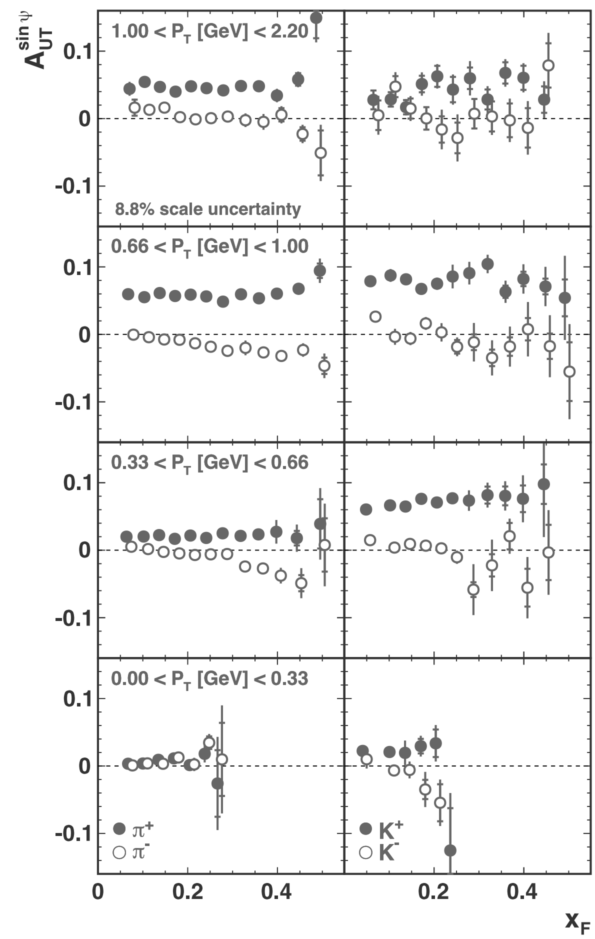

Fig. 4. $A_{UT}^{\sin\psi}$ amplitudes for charged pions and kaons as a function of x_F for various slices in P_T. Symbol definitions and additional 8.8% scale uncertainty as in Fig. 2.

over the bin range(s) of the kinematical dependences. These differences can become large whenever an amplitude's dependence deviates significantly from linear behavior over the width of the bin in that dependence. This makes the one-dimensional representation of Fig. 2, where one integrates over the whole range in the variable not shown, more susceptible to systematic deviations. These can be observed, e.g., in the x_F dependence of the K^+ asymmetry amplitudes, where the integration is over a strongly varying P_T dependence. Additionally, the uncertainty on the measurement of the target polarization produces a 8.8% scale uncertainty on the value of $A_{UT}^{\sin\psi}$ that is not included in the error bars. Other possible sources of systematic uncertainty not included in the Monte Carlo simulation such as time-dependence of the measured amplitudes and the effect of different beam charges were found to be negligible.

The inclusive data set presumably is a mixture of various contributions with different kinematic dependences. Therefore, it is difficult to draw conclusions about the underlying physics from the observed kinematic dependences of the inclusive asymmetry amplitudes. More insight may be gained by studying separately the asymmetries for the events without a scattered lepton in the acceptance ('anti-tagged' category) and the events with a scattered lepton in the acceptance ('tagged' or semi-inclusive category). These categories cover different kinematic regimes and are defined as follows:

1) *'Anti-tagged' category*: The undetected lepton in most cases had a small scattering angle and remained within the beam pipe. Hence Q^2 is small and P_T is the only hard scale. For these events, the difference between the transverse hadron momentum with respect to the beam direction, P_T, and with respect to the virtual-photon direction, $P_{h\perp}$, is small. The latter was used in the previous analyses of SSAs in semi-inclusive deep-inelastic scattering [26–28]. The present data sample is dominated by the kinematic regime $Q^2 \approx 0$ GeV^2 of quasireal photoproduction where the cross section is largest and where the hadronic component of the photon plays an important role. Generally speaking, in this kinematic range $l + p^\uparrow$ reactions are expected to be quite similar in nature to $h + p^\uparrow$ reactions. The 'anti-tagged' category contains a small contamination of events at higher Q^2 where the electron is scattered into the horizontal gap of the spectrometer. These events amount to about one third in statistics of the semi-inclusive category, discussed below. Another tiny high-Q^2 contamination arises from lepton scattering angles beyond the maximum polar angular acceptance of the spectrometer. These events occur dominantly at high P_T. Here, the large angle of the virtual photon with respect to the beam axis often results in a significantly larger P_T than $P_{h\perp}$ of the hadrons. After correction for trigger efficiency, about 98% of all hadrons belong to the 'anti-tagged' category. The fraction of these hadrons with respect to the total inclusive sample is nearly 100% at low P_T. It decreases monotonically to about 85–90% for positive hadrons and to more than 90% for negative hadrons at the highest P_T values.

2) *'Tagged' or semi-inclusive category:* The scattered positron was recorded in the spectrometer acceptance and kinematic quantities like y, z, Q^2, x, and W^2 could be determined, where in the

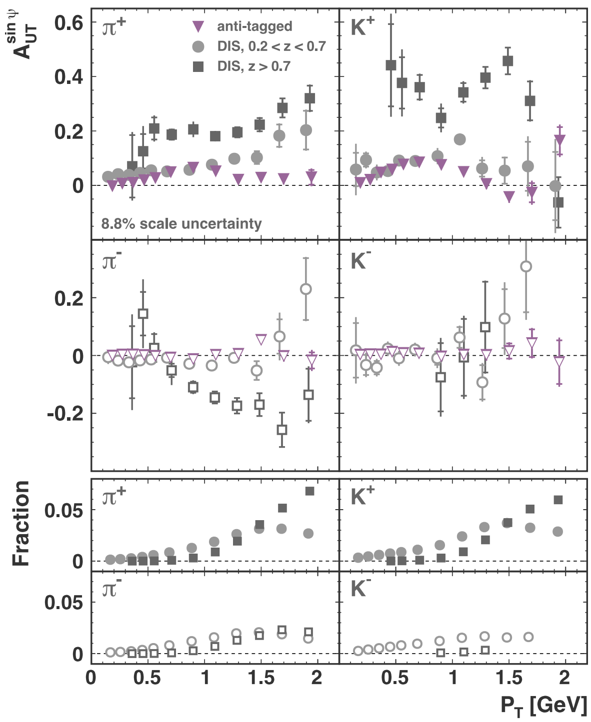

Fig. 5. $A_{UT}^{\sin\psi}$ amplitudes for charged pions and kaons for the 'anti-tagged' category and the two DIS subsamples with $0.2 < z < 0.7$ and $z > 0.7$, respectively. Also shown are the relative fractions of the two DIS subsamples with respect to the total inclusive sample of the corresponding hadron species after correction for trigger efficiency. Positive (negative) particles are denoted by filled (open) symbols. Inner error bars show the statistical uncertainties and the total error bars represent statistical and systematic uncertainties added in quadrature. Not shown is an additional 8.8% scale uncertainty due to the precision of the measurement of the target polarization.

laboratory system $y \equiv P \cdot q/(P \cdot k)$ is the fractional beam energy carried by the virtual photon and $z \equiv P \cdot P_h/(P \cdot q)$ is the fractional virtual-photon energy carried by the hadron. The quantity $x \equiv Q^2/(2P \cdot q)$ is the Bjorken scaling variable with $-Q^2 = q^2 \equiv (k-k')^2$, and $W^2 \equiv (P+q)^2$ is the squared invariant mass of the virtual-photon nucleon system. Here, P, k, k', and P_h are the four-momenta of the target nucleon, the incident and scattered lepton, and the produced hadron, respectively. This category can be further divided into several subsamples covering different kinematic regions.

For the present analysis, two of these subsamples have been selected that affect substantially the observed asymmetries at large P_T:

DIS events with $0.2 < z < 0.7$: This subsample is identical to the one used previously [26–28] for the determination of azimuthal transverse single-spin asymmetries in semi-inclusive deep-inelastic scattering related to the Sivers and transversity distributions and the Collins fragmentation function. Here, events were selected according to the kinematic requirements $Q^2 > 1$ GeV^2, $W^2 > 10$ GeV^2, $0.023 < x < 0.4$, and $0.1 < y < 0.95$. The fractional hadron energy was required to be in the range $0.2 < z < 0.7$. For this sample, $\langle Q^2 \rangle$ rises from ~ 2.2 GeV^2 at low P_T to ~ 4.3 GeV^2 at high P_T, and $\langle Q^2 \rangle$ is always larger than $\langle P_T^2 \rangle$ apart from the two highest P_T bins;

DIS events with $z > 0.7$*:* The kinematic requirements are identical to those of the above subsample, apart from the requirement for the fractional hadron energy. Only hadrons with $z > 0.7$ are selected. The average value of Q^2 rises from ~ 1.5 GeV^2 to ~ 5.5 GeV^2 and $\langle Q^2 \rangle > \langle P_T^2 \rangle$ over the whole P_T range.

Table 1
Accumulated yields of hadrons (in million) for the various event samples without and with an electron in the spectrometer acceptance, after correction for trigger efficiency. The DIS subsamples are part of the 'tagged' category, as explained in the text.

subsample	π^+	π^-	K^+	K^-
'anti-tagged'	170.5	140.7	14.3	7.2
'tagged'	1.93	1.49	0.26	0.13
DIS, $0.2 < z < 0.7$	0.69	0.49	0.12	0.05
DIS, $z > 0.7$	0.061	0.037	0.013	0.001

The total number of hadron tracks in the 'anti-tagged' and the 'tagged' categories and in the two DIS subsamples is listed in Table 1. The remaining events of the 'tagged' category contribute only at $x_F < 0.2$ and $P_T < 0.9$ GeV and will not be discussed further.

In Fig. 5, the $A_{UT}^{\sin\psi}$ amplitudes are presented as a function of P_T for the 'anti-tagged' category and the two DIS subsamples with $0.2 < z < 0.7$ and $z > 0.7$, respectively. Also shown are the relative fractions of these two subsamples with respect to the total inclusive sample of the corresponding hadron species after correction for trigger efficiency. The relative fractions are generally larger for positive hadrons than for negative hadrons. For $P_T < 1$ GeV, the fractions are below 1%. In the highest two P_T bins, the fraction of DIS events with $z > 0.7$ dominates for positive hadrons and reaches values of about 6%, while the DIS contribution with $0.2 < z < 0.7$ stays below 4%. As can be seen from Fig. 5, the asymmetry amplitudes for the 'anti-tagged' category and for the two subsamples of the 'tagged' category show several remarkable peculiarities:

'Anti-tagged' category: The asymmetry amplitudes are, over most of the P_T range, essentially identical to the inclusive amplitudes as expected from the fact that this sample comprises about 98% of the whole statistics. One can therefore safely conclude that essentially all of the kinematic dependences of the inclusive data set observed for P_T below approximately 1.5 GeV originate from quasi-real photoproduction. Since P_T is the only hard scale, the origin of the asymmetries can most likely be explained by higher-twist contributions. At low values of P_T, where one observes a rise of the asymmetry amplitudes for positive hadrons, P_T is comparable to Λ_{QCD} and theory cannot presently make reliable predictions about the magnitude and P_T dependence of the amplitudes. At high P_T, the 'anti-tagged' asymmetry amplitude is consistently smaller than the inclusive amplitude for positive pions and its P_T dependence is, within uncertainties, compatible with a constant or a decrease with P_T as one would expect for this class of events [59,60]. At $P_T > 1.3$ GeV the contributions from the other subsamples become sizable causing the increase with P_T observed for the inclusive asymmetry amplitude.

DIS events with $0.2 < z < 0.7$: For positive pions, $A_{UT}^{\sin\psi}$ is positive and larger than the 'anti-tagged' amplitude. It rises rather linearly with P_T from a value of approximately 0.04 at low P_T to approximately 0.2 at the highest P_T values, where the statistical uncertainties are rather large. For negative pions, the amplitude is (apart from the two highest P_T points) consistently negative and larger in magnitude than the asymmetry amplitude for the 'anti-tagged' sample over the whole range of P_T. As stated above, Q^2 is the largest scale over essentially the whole P_T range and transverse-momentum-dependent distribution and fragmentation functions can contribute without P_T-suppression. Since the angle ψ and the Sivers angle $\phi - \phi_s$ are closely related, one can expect that the observed P_T dependence is predominantly caused by the Sivers effect. In fact, the asymmetries are very similar to those in Ref. [27], where it was concluded that the small amplitudes for π^-

require cancellation effects, e.g., from a down-quark Sivers function opposite in sign to the dominant up-quark Sivers function.

DIS events with $z > 0.7$: Large asymmetries are observed for this subsample for both pion charges and especially for positive kaons, where the amplitudes reach values of more than 0.4. For positive pions the amplitude is rather constant with a value of around 0.2 in the P_T range 0.5–1.5 GeV, and rises up to a value above 0.3 at the highest P_T bin. For negative pions, the amplitude is negative and decreases from approximately zero at $P_T \sim 0.5$ GeV down to a value of about -0.2 at high P_T. This subsample receives contributions from processes that can become significant only in this kinematic region. Pions receive contributions from decays of exclusive mesons like, e.g., the ρ meson [69] that can contribute up to about 50% (30%) to the yield of π^- (π^+) at large z [70]. For kaons, the corresponding contributions from ϕ decays are less than 10%. For positive pions there is in addition a contribution from exclusive production, $lp \to l'\pi^+ n$, which has, however, been measured [71] to constitute only approximately 3% of this sample. The corresponding contributions for the quasi-exclusive production of negative pions from $lp \to l'\pi^-\Delta^{++}$ or positive kaons from $lp \to l'K^+\Lambda$ are expected to be even smaller [72] and no such quasi-exclusive channel exists for negative kaons. The large asymmetry amplitude seen for negative pions may indicate that a large fraction of events in this subsample stems from the favoured fragmentation of the struck quark (here the down quark) and that the asymmetry possibly preserves information from the down-quark Sivers function without dilution from disfavoured fragmentation of the otherwise dominating up quark. Indeed, the signs and relative magnitudes of the pion and kaon asymmetry amplitudes observed are not inconsistent with the values of the up and down quark Sivers functions extracted in phenomenological fits [50].

In summary, transverse azimuthal single-spin asymmetries are measured in inclusive and semi-inclusive electroproduction of charged pions and kaons. A two-dimensional extraction of the asymmetry amplitudes is performed by binning simultaneously in the component of the hadron-momentum transverse to the incoming lepton beam, P_T, and the Feynman-x variable, x_F. For positive pions, the resulting amplitudes are found to be essentially independent of x_F. The apparent increase with x_F after integration over P_T is mostly a reflection of the underlying dependence on P_T. For negative pions, and less significantly for negative (positive) kaons, the asymmetry amplitudes decrease (increase) with x_F, also in the case of a two-dimensional extraction. The amplitudes as a function of P_T are positive for the positive hadrons and slightly larger for K^+ compared to π^+. They rise smoothly with P_T from zero at low P_T up to a maximum value of approximately 0.06 (0.08) for pions (kaons) at $P_T \simeq 0.8$ GeV and then decrease with increasing P_T. The data sample is dominated by the kinematic regime $Q^2 \approx 0$ GeV^2 of quasi-real photoproduction, where P_T is the only hard scale. The origin of the observed asymmetries can, therefore, most likely be explained by higher-twist contributions. At P_T values above 1.5 GeV there are sizable contributions from events with an electron in the acceptance and large values of Q^2. The asymmetries for the subsample within DIS kinematics and fractional energies of the hadron in the range $0.2 < z < 0.7$ can likely be related to the transverse-momentum dependent Sivers distribution function. Very large asymmetry amplitudes are observed for positive pions and kaons and negative pions for the DIS subsample with high values of the fractional hadron energy z. In this kinematic regime exclusive processes can contribute substantially to the asymmetry and effects from the favoured fragmentation of the struck quark dominate. The data may be very helpful in formulating a better understanding of spin-orbit effects of partons within the nucleon.

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