Transverse single-spin asymmetries in inclusive hadron electroproduction at HERMES

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Abstract. Single-spin asymmetries were investigated in inclusive electroproduction of charged pions and kaons from a transversely polarized hydrogen target at the HERMES experiment. In the kinematic range \( p_T < 3.0 \) GeV and \(-0.01 < x_F < 1\), positive asymmetries were measured for positive hadrons, while for negative hadrons they were found to be of smaller magnitude and with significantly different \( p_T \) dependence for different bins in \( x_F \).

1. Introduction
Transverse single-spin asymmetries \( A_N \) for inclusive hadron production with transversely polarized proton beams or targets, \( p^\uparrow(p^\downarrow) + p \rightarrow h + X \), have been studied since more than 30 years. Up to date, such left-right asymmetries \( A_N \) have been observed over a large kinematic range with center-of-mass energies from \( \sqrt{s} = 4.9 \) GeV up to 200 GeV. They were found to be positive for \( \pi^+, \pi^0, \eta, K^+, K^- \), and anti-protons, negative for \( \pi^- \) and neutrons, and compatible with zero for protons. In all non-zero cases, \( A_N \) increases in magnitude with increasing \( p_T \) and \( x_F = 2p_L/\sqrt{s} \), where \( p_T (p_L) \) is the transverse (longitudinal) momentum of the produced hadron with respect to the direction of the incident proton. A review of experimental results can be found, e.g., in Refs. [1, 2] together with a discussion on the current theoretical work. Originally it was expected from QCD that at high center-of-mass energies and transverse momenta the cross sections should have very little spin dependence and that transverse asymmetries should be suppressed by \( \alpha_s m_q/M \), where \( \alpha_s \) is the strong coupling constant and \( m_q (M) \) is the quark (nucleon) mass. Recent theoretical attempts to explain the experimental results include two approaches. One is based on unintegrated, transverse-momentum dependent distribution and fragmentation functions, in particular the quark transversity distribution and the Collins fragmentation function [3, 4], or the Sivers effect [5] which originally has been invented to explain the observed large single-spin asymmetries. The other approach links collinear parton dynamics to higher-twist quark-gluon correlations [6, 7, 8]. Both approaches succeed to reproduce the existing measurements of \( A_N \) to a very good extent, and have been shown to be related to and consistent with each other [9].

As discussed in Refs. [7, 10], the measurement of transverse target single-spin asymmetries in inclusive hadron electroproduction, \( e p^\uparrow \rightarrow h X \), at high transverse hadron momenta might be more easy to interpret. The HERMES experiment has performed first measurements of this kind. Preliminary results for charged pions and kaons are presented in this contribution.
2. Experiment
The data were collected with the HERMES spectrometer [11] at the HERA e-p accelerator facility. The 27.6 GeV lepton (electron or positron) beam was scattered off a nuclear-polarized gaseous hydrogen target internal to the lepton ring. The direction of the target-spin vector was transverse to the beam direction. It was reversed in both “upward” (↑) and “downward” (↓) directions at 1-3 minute time intervals to minimize systematic effects. Both the nuclear polarization $P$ and the atomic fraction inside the target cell were continuously measured [12]. The beam was longitudinally polarized, but a helicity-balanced data sample was used to obtain an effectively unpolarized beam. Events were selected with at least one charged-hadron track. The scattered lepton was not requested for this analysis and therefore the data sample is dominated by events from quasi-real photoproduction ($Q^2 \approx 0$ GeV$^2$, where $-Q^2$ is the four-momentum squared of the virtual photon). Hadrons were identified using a dual-radiator ring-imaging Cherenkov (RICH) detector, and distinguished from leptons by using a transition-radiation detector, a scintillator pre-shower counter, the RICH detector, and an electromagnetic calorimeter, resulting in a hadron-lepton misidentification of less than 2% in the hadron momentum range 2 GeV < $p$ < 15 GeV. The total statistics collected amount to about 120 million (8 million) pion (kaon) tracks.

The differential yield for a given target spin direction can be expressed as

$$\frac{d^3N^{↑(↓)}}{dx_F dp_T d\phi} = d^3\sigma_{UU} \left[ L^{↑(↓)} + (-) L_P^{↑(↓)} A_{UT}^{\sin\phi}(x_F, p_T) \sin\phi \right] \Omega(x_F, p_T, \phi).$$

Here, $\phi$ is the azimuthal angle about the beam direction between the hadron production plane and the “upwards” target spin direction, and $\sigma_{UU}$ denotes the unpolarized cross section, $x_F \simeq 2p_L/\sqrt{s}$ is the Feynman variable with $\sqrt{s}$ being the lepton-nucleon center-of-mass energy and $p_L (p_T)$ is the longitudinal (transverse) momentum of the hadron with respect to the lepton beam direction. Also, $L^{↑(↓)}$ is the total luminosity in the ↑ (↓) polarization state, $L_P^{↑(↓)}$ is the luminosity weighted by the magnitude $P$ of the target polarization, and $\Omega$ is the detector acceptance efficiency. The average beam polarization was about 0.76 (0.71) for the data taking periods with a positron (electron) beam. The $\sin\phi$ azimuthal dependence follows directly from the form $\vec{S} \cdot (\vec{k} \times \vec{p})$ of the spin-dependent part of the cross section (see, e.g., Ref. [10]), and $A_{UT}^{\sin\phi}$ refers to its amplitude, with $\vec{S}$ being the target spin, and $\vec{k}, \vec{p}$ the momenta of the incident lepton and the produced hadron, respectively.

The asymmetry was calculated as

$$A_{UT}(x_F, p_T, \phi) = \frac{N^{↑}/L_P^{↑} - N^{↓}/L_P^{↓}}{N^{↑}/L^{↑} + N^{↓}/L^{↓}} \simeq A_{UT}^{\sin\phi} \sin\phi,$$

where $N^{↑(↓)}$ are the number of events measured in bins of $x_F$, $p_T$, and $\phi$. Due to the rapid reversal of the target-spin direction, the acceptance function $\Omega$ cancels in each $(x_F, p_T, \phi)$ kinematic bin, if the bin size or the asymmetry is small. Experimentally, the $A_{UT}^{\sin\phi}$ amplitudes were extracted performing a maximum-likelihood fit to the asymmetry alternately binned in $p_T$ and $x_F$, and unbinned in $\phi$. For a detector with full 2$\pi$-coverage in $\phi$, the $\sin\phi$ amplitude and the left-right asymmetry $A_N$ are related by $A_N = -2A_{UT}^{\sin\phi}/\pi$.

3. Results
Preliminary results for the $A_{UT}^{\sin\phi}$ amplitudes for charged pions and kaons are shown as a function of $p_T$ in the left panel of Fig. 1 and as a function of $x_F$ in the right panel of the figure. The error bars indicate the statistical uncertainties of the measurement. The amplitudes vanish, as expected, for small $p_T$. For positive pions and kaons they increase with $p_T$ up to $p_T \simeq 0.8$ GeV and seem to decrease again for larger $p_T$. This $p_T$ dependence resembles very much the
The asymmetries for $K$ is assumed that the inclusive asymmetry is mainly caused by the Sivers effect. For that of the Collins asymmetry [14], in agreement with the prediction in Ref. [10], where it one observed for the Sivers asymmetry in semi-inclusive deep-inelastic scattering [13] but not that of the Collins asymmetry [14], in agreement with the prediction in Ref. [10], where it is assumed that the inclusive asymmetry is mainly caused by the Sivers effect. For $\pi^-$ and $K^-$, the asymmetry amplitudes oscillate around zero, with slightly positive values at high $p_T$. Similar to the Sivers asymmetry, the $K^+$ asymmetry is slightly larger than the $\pi^+$ asymmetry. The asymmetries for $K^+$ and $K^-$ are very different in contrast to the results in pp scattering, where they are rather similar [2]. For $\pi^+$ and $K^+$, the amplitudes increase smoothly with $x_F$ up to values of about 0.1. For $\pi^-$, the (negative) asymmetry increases in magnitude up to values of about 0.04. It is essentially zero for $K^-$. Systematic uncertainties are shown in Fig. 1 as bands. They include contributions due to corrections for misalignment of the detector, beam position and slope at the interaction point and bending of the beam and the produced hadron in the transverse holding field of the target magnet. They were determined from a high-statistics Monte Carlo sample obtained from a simulation containing a full description of the detector, where an artificial spin-dependent azimuthal asymmetry was implemented with a functional form that described all measured asymmetries. For each measured point the systematic uncertainty was obtained as the maximum value of either the statistical uncertainty of the Monte Carlo sample or the difference between the input asymmetry and the extracted one. An overall 8.8% scale uncertainty stems from the uncertainty of the target polarization.

The variables $x_F$ and $p_T$ are strongly correlated through the HERMES acceptance as can be seen in the bottom panels of Fig. 1. To separate the kinematical dependences a two-dimensional extraction of the asymmetries was performed binning simultaneously in $x_F$ and $p_T$. Preliminary results for the extracted asymmetry amplitudes are shown in Fig. 2 as a function of $p_T$ for three different bins in $x_F$. Total uncertainties are shown, obtained by combining statistical and systematic uncertainties in quadrature, with the inner error bars representing statistical uncertainties only. For $\pi^+$ and $K^+$, the $p_T$ dependence is very similar in all three $x_F$ bins. For negative pions, however, the asymmetry is negative in the highest $x_F$ bin ($0.20 < x_F < 1.00$), oscillates around zero in the middle $x_F$ bin and is slightly positive in the lowest $x_F$ bin. For $K^-$, the amplitudes are consistent with zero for high $x_F$ and slightly positive at low $x_F$.

A thorough interpretation of these interesting results is rather challenging due to the relatively small range in $p_T$ covered by the data. The predictions in Ref. [10] are made for pions only and for $p_T$ values of 1.5 GeV and 2.5 GeV, i.e., above the range covered by these preliminary data. So far, no theoretical calculations for kaons are available. The final results of these measurements will be presented with an extended $p_T$ range up to 2 GeV and for four bins in $x_F$.}

Figure 1. Preliminary HERMES results for $A_{UT}^{bin \phi}$ amplitudes for charged pions and kaons as a function of $p_T$ (left) and $x_F$ (right).
Figure 2. Preliminary HERMES results for $A_{UT}^{\sin \phi}$ amplitudes for charged pions and kaons as a function of $p_T$ for three different bins of $x_F$.

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