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HERMES results on transverse target single-spin asymmetries in inclusive electroproduction of charged pions and kaons

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Single-spin asymmetries were investigated in inclusive electroproduction of charged pions and kaons from transversely polarised protons at the HERMES experiment. The asymmetries were studied as a function of the azimuthal angle Ψ around 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. Large asymmetries are observed for two small subsamples of events, where also the scattered electron was recorded by the spectrometer.

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1. Introduction

Left-right cross-section asymmetries A_N for the inclusive production of various hadrons in hadron-nucleon collisions with transversely polarised beams or targets have been studied over the past three decades by numerous experiments for centre-of-mass energies in the range 4.9 - 500 GeV. They were found to be positive for π^+, π^0, η, K^+, K^-, and anti-protons, negative for π^- 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, exceeding $|A_N| = 0.4$ for charged pions. Here, P_T is the transverse momentum of the produced hadron with respect to the direction of the incident hadron and 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. A review of experimental results can be found, e.g., in Refs. [1] and [2], together with a discussion on current theoretical work. The 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 chiral-odd *transversity* distribution of transversely polarised quarks in a transversely polarised nucleon, in conjunction with the chiral-odd *Collins* fragmentation function [3], or the transverse-momentum-dependent time-reversal odd *Sivers* distribution function [4] of unpolarised quarks with non-zero transverse momenta in a transversely polarised nucleon. The latter has originally been invented to explain A_N in hadron-nucleon reactions. The other approach links collinear parton dynamics to higher-twist multiparton correlations [5, 6, 7]. Both approaches succeeded in reproducing the existing measurements of A_N to a large extent, and have been shown to be related to and consistent with each other in the kinematic region where they both apply [8]. Recently, however, a sign error was identified [9] that invalidates the good agreement observed earlier.

While A_N was studied in detail in hadron-nucleon reactions, no experimental information about this quantitity was available until recently from inclusive electroproduction of hadrons, $lp^\uparrow \rightarrow hX$. For electroproduction, the theoretical expectations depend on the relative magnitude of the three relevant scales Q, P_T and Λ_{QCD}, where -Q^2 is the squared four-momentum of the virtual photon that mediates the lepton-nucleon scattering process and $\Lambda_{QCD} \cong 0.3$ GeV is the QCD scale parameter. The Sivers and Collins effects become significant when $Q^2 > P_T^2$ and $Q^2 \gg \Lambda_{QCD}^2$ 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 single-spin asymmetries measured in semi-inclusive deep-inelastic scattering were, in fact, the basis for an extraction of the Sivers and transversity distribution functions and the Collins fragmentation function (see e.g., Refs. [10, 11]). 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.

2. Experiment

In this contribution, the results from the first measurements of A_N in inclusive electroproduction of charged pions and kaons [12] performed by the HERMES experiment are reported. The data were collected with the HERMES spectrometer [13] at the HERA e-p accelerator facility. The 27.6 GeV lepton (electron or positron) beam of HERA was scattered off a transversely polarised gaseous hydrogen target internal to the lepton ring. The average magnitude of the protonpolarisation was $S_T \approx 0.71$. The direction of the target-spin vector was reversed between the 'upward' and 'downward' directions at 1-3 minute time intervals to minimize systematic effects. The beam was longitudinally polarised, but a helicity-balanced data sample was used to obtain an effectively unpolarised 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. 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 a scintillator pre-shower counter behind the magnet with the requirement of an energy deposit greater than 1.4 GeV in an 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. 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 to about 15% at $P \approx 2$ GeV. Hadrons were distinguished from leptons by using a transition-radiation detector, the scintillator pre-shower counter, and the 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. In total, about $60 \cdot 10^6$ ($50 \cdot 10^6$) 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.

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

$$\mathrm{d}\sigma(P_T, x_F, \psi) = \mathrm{d}\sigma_{UU}(P_T, x_F)\left[1 + S_T A_{UT}^{\sin\psi}(P_T, x_F)\sin\psi\right]. \tag{2.1}$$

Here, the first subscript U denotes unpolarised beam, the second subscript U (T) an unpolarised (transversely polarised) target. The cross section depends on the hadron variables x_F, P_T and ψ, where ψ is the azimuthal angle around the beam direction between the 'upward' target spin direction and the hadron production plane. Note, that in cases where the scattered electron is recorded and the angle between the virtual photon and the lepton beam is small, this angle ψ is approximately equal to the Sivers-angle $\phi - \phi_s$, where ϕ (ϕ_s) is the azimuthal angle about the virtual-photon direction between the lepton scattering plane and the hadron production plane (the 'upward' target spin direction). For a detector with full 2π-coverage in ψ and constant efficiency, the amplitude $A_{UT}^{\sin\psi}$ and the left-right asymmetry A_N along the direction of the incident beam and with respect to the spin direction are related by $A_N = -(2/\pi)A_{UT}^{\sin\psi}$. The $A_{UT}^{\sin\psi}$ amplitudes were extracted by performing a maximum-likelihood fit to the cross section of Eq. 2.1, 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.

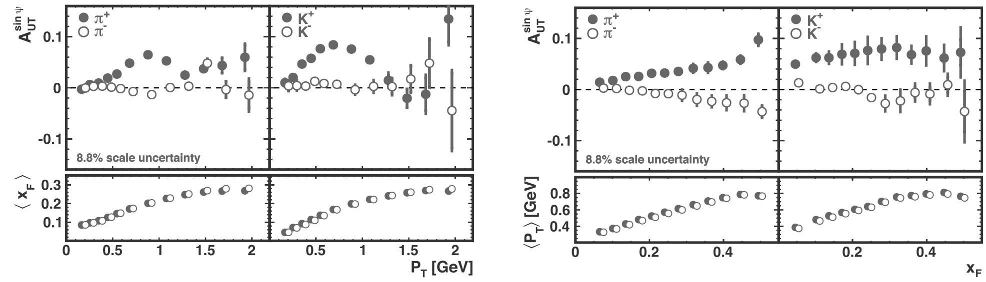

Figure 1: $A_{UT}^{sin\psi}$ amplitudes for charged pions and kaons as a function of P_T (left) and of x_F (right). Positive (negative) particles are denoted by closed (open) symbols. The bottom subpanels show the P_T (x_F) dependence of the average x_F (P_T). Data points for negative particles are slightly shifted horizontally for legibility.

3. Results

The extracted $A_{UT}^{\sin\psi}$ amplitudes for charged pions and kaons, integrated over the variable not shown, are presented as a function of P_T (x_F) in the left (right) panels of Fig. 1. When visible, the inner error bars show the statistical uncertainties, while the total ones represent the quadratic sum of statistical and systematic uncertainties. The latter 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. Not shown is an additional 8.8% scale uncertainty due to the precision of the measurement of the target polarisation. The amplitudes are positive for the positive hadrons being slightly larger for kaons compared to pions, while for negative hadrons they are much smaller in magnitude, sometimes positive, sometimes negative. The P_T dependences of the amplitudes have a rather peculiar behaviour. The amplitudes vanish for $P_T \to 0$, as they have to by definition. For positive hadrons they increase smoothly with P_T up to a maximum value of 0.06 (0.08) for pions (kaons) at $P_T \simeq 0.8$ GeV and then decrease again for larger P_T. For π^+ there is an indication of another increase at $P_T > 1.3$ GeV. The asymmetries for K^+ and K^- are very different from each other in contrast to the results in pp scattering, where they are rather similar [15]. In the right panels of Fig. 1 the amplitudes are shown as a function of x_F. For π^+ (π^-) they increase (decrease) smoothly with x_F up to values of about 0.1 (-0.04). For K^+, the amplitude is nearly constant around 0.07 while for K^- it is compatible with zero over most of the x_F range.

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. The results for the extracted asymmetry amplitudes are shown in the left panels of Fig. 2 as a function of P_T for four slices in x_F. For π^+ and K^+, the P_T dependence is very similar in all four x_F bins, as well in shape as in magnitude, apart from increased statistical fluctuations. Therefore, it can be concluded that the apparent increase of the magnitude of the asymmetry amplitude seen for π^+ in the right panel of Fig. 1 is just a reflection of the underlying dependence on P_T. In contrast, for π^- the decrease with x_F follows the one observed in the one-dimensional extraction.

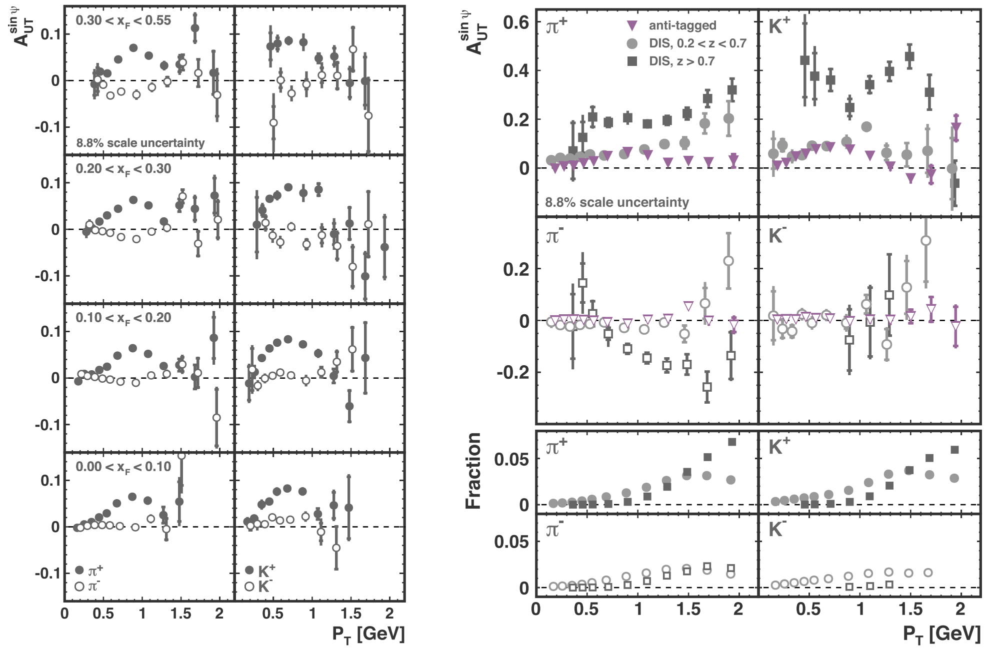

Figure 2: $A_{UT}^{sin\psi}$ amplitudes for charged pions and kaons as a function of P_T for various slices in x_F (left) and for the 'anti-tagged' category and the two DIS subsamples with 0.2 < z < 0.7 and z > 0.7, respectively (right). The bottom panels of the right figure show the relative fractions of the two DIS subsamples with respect to the total inclusive sample of the corresponding hadron species after correction for trigger efficiency.

More insight, especially concerning the peculiar P_T dependence, can be gained by studying separately the asymmetries for events without a scattered lepton in the acceptance ('anti-tagged' category) and events with a scattered lepton in the acceptance, especially those fulfilling the kinematic requirements for deep-inelastic scattering ('DIS'), i.e., $Q^2 > 1\,\text{GeV}^2$, $W^2 > 10\,\text{GeV}^2$, $0.023 < x < 0.4$, and $0.1 < y < 0.95$, where W^2 is the squared invariant mass of the virtual-photon nucleon system, x is the Bjorken scaling variable and y is the fractional beam energy carried by the virtual photon in the laboratory system. 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. For this category, the undetected lepton in most cases had a small scattering angle and remained within the beam pipe. This data sample is dominated by the kinematic regime $Q^2 \approx 0\,\text{GeV}^2$ of quasi-real photoproduction. Hence, P_T is the only hard scale, while for the DIS-events $\langle Q^2\rangle$ is always larger than $\langle P_T^2\rangle$. The 'DIS' sample has further been divided into two subsamples with $0.2 < z < 0.7$ and $z > 0.7$, where z is the fractional virtual-photon energy carried by the hadron in the laboratory system. The former subsample is identical to the one used previously [16, 17] 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.

In the right panel of Figure 2, the $A_{UT}^{\sin\psi}$ amplitudes are presented as a function of P_T for the 'anti-tagged' category and the two DIS subsamples. 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. 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. The origin of the observed asymmetry can most likely be explained by higher-twist contributions. At $P_T > 1.3$ GeV the contributions from the other subsamples become sizeable causing the increase with P_T observed for the inclusive asymmetry amplitude. For the DIS events with $0.2 < z < 0.7$ the observed asymmetries are very similar to those in Ref. [16] and we can conclude that the P_T dependence is dominantly caused by the Sivers effect as predicted in Ref. [18]. The asymmetries for the DIS events with $z > 0.7$ are even larger, reaching values of over 0.4 (0.3) for K^+ (π^+) and -0.25 for π^-. In this kinematic regime of high z, exclusive processes can contribute substantially to the asymmetry. Especially remarkable is the large negative amplitude observed for negative pions. This 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.

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