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Recent results on TMDs from the HERMES experiment

L.L. Pappalardo (For the HERMES Collaboration)

Dipartimento di Fisica e Scienze della Terra, Università di Ferrara, 44122 Ferrara, Italy

Abstract. Single-spin azimuthal asymmetries were extracted at HERMES in inclusive electroproduction of charged hadrons from transversely polarized protons. The asymmetries were studied as a function of the transverse hadron momentum P_T relative to the beam direction, and the Feynman variable x_F. The asymmetry amplitudes are positive for π^+ and K^+, slightly negative for π^- and consistent with zero for K^-. Especially large asymmetries are observed for two small subsamples of events, where also the scattered electron was recorded, revealing important contributions from TMDs.

1. Introduction

Unexpectedly large left-right cross-section asymmetries A_N for the inclusive production of various hadrons in hadron-nucleon collisions have been measured over the past four decades by numerous experiments for center-of-mass energies ranging in the broad interval 4.9–500 GeV (see e.g. [1] for a review of the experimental results and theoretical models). The size of these asymmetries is a clear indication of novel effects arising from the complex dynamics of quarks and gluons in the nucleon, that cannot be interpreted within the framework of the standard leading-twist collinear factorization. Two different approaches were proposed to explain these results: contributions from transverse momentum dependent (TMDs) parton distribution and fragmentation functions through, e.g., the Collins and the Sivers mechanism [2], and contributions from higher-twist multi-parton correlations [3, 4]. These two approaches are however not completely consistent with each other and a full understanding of these asymmetries is still missing. Indirect information on the A_N asymmetries, that can help to shed light on the underlying mechanisms, can be drawn from different processes, e.g. through the study of single-spin asymmetries (SSAs) in inclusive electroproduction of hadrons off transversely polarized protons ($lp^\uparrow \to hX$). The cross section of this process can be written in the compact form:

$$d\sigma = d\sigma_{UU}\left[1 + S_T A_{UT}^{\sin\psi} \sin\psi\right], \quad (1)$$

where UU (UT) stands for unpolarized beam and unpolarized (transversely polarized) target, S_T is the target transverse polarization, and ψ is the azimuthal angle about the lepton-beam direction between the target-spin direction and the hadron production plane. The Fourier amplitudes $A_{UT}^{\sin\psi}$ are closely related to the left-right asymmetries[1]. Recently, first measurements of $A_{UT}^{\sin\psi}$ were reported by the HERMES

[1] For an ideal detector with a 2π coverage in ψ one has for the left-right asymmetries: $A_N = -\frac{2}{\pi} A_{UT}^{\sin\psi}$.

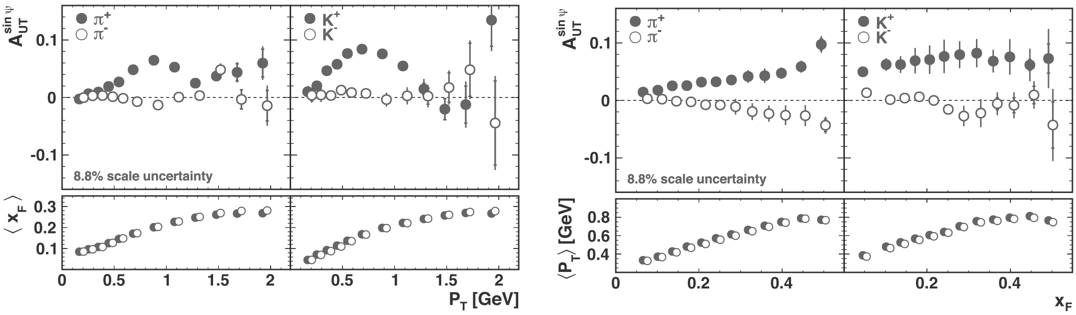

Figure 1. $A_{UT}^{\sin\psi}$ amplitudes for charged pions and kaons as a function of P_T (left) and x_F (right). The bottom panels show the P_T (x_F) dependence of the average x_F (P_T).

Collaboration for charged pions and kaons, based on an integrated luminosity of about 146 pb^{-1} [5]. The main results are here summarized.

2. Data analysis and results

The data were collected by the HERMES spectrometer during the period 2002–2005 using the 26.7 GeV HERA lepton beam (electrons and positrons) and a transversely nuclear-polarized gaseous hydrogen target, with an average polarization $S_T = 0.713 \pm 0.063$. The selected events had to contain at least one charged-hadron track, identified as either a charged pion or kaon, independent of whether there was also a scattered lepton in acceptance or not. In the absence of the scattered lepton, and thus of any knowledge on Q^2, the squared four-momentum of the exchanged virtual photon, the following variables were used: P_T, the transverse momentum of the hadron with respect to the lepton beam direction, and the Feynman variable x_F, calculated in the lepton-nucleon center-of-mass frame. Experimentally, the $A_{UT}^{\sin\psi}$ amplitudes were extracted by performing a maximum-likelihood fit to the measured hadron yields, distributed according to the cross section of Eq. (1) for two opposite target-spin states. The extracted $A_{UT}^{\sin\psi}$ amplitudes for charged pions and kaons are presented as a function of P_T and x_F in Fig. 1.

The extracted amplitudes are positive for the positive hadrons, being slightly larger for kaons compared to pions. Concerning the P_T projections (left figure): 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. For $P_T > 1.3$ GeV there is an indication of a further increase of the amplitude for positive pions, whereas for positive kaons it is comparable with zero within the uncertainties (with the exception of the highest P_T bin, where the amplitude is 2.8 standard deviations above zero). The amplitudes for negative hadrons are much smaller in magnitude, with a hint of sign changes. Noteworthy, the x_F projections (right figure) for charged pions look similar to those measured in hadron-hadron collisions (A_N): the amplitudes, positive for π^+ and negative for π^-, rise in magnitude nearly linearly with x_F. However, differently from the A_N results, the π^+ and π^- amplitudes are not mirror-symmetric and reach, at high x_F, a significantly smaller magnitude (about 10% for π^+ and 4% for π^- against about 40%). For positive kaons, the amplitude is about constant around 7%, whereas for negative kaons the amplitude is comparable with zero over most of the x_F range.

As it is clearly visible from the bottom panels, which show the P_T dependence (x_F dependence) of the average x_F (P_T), the two variables are strongly correlated. Hence, the kinematic dependencies shown in Fig. 1 are partially affected by this correlation. For this reason, the $A_{UT}^{\sin\psi}$ was also extracted in a two-dimensional binning in P_T and x_F. The two-dimensional projections in Fig. 2 reveal that the

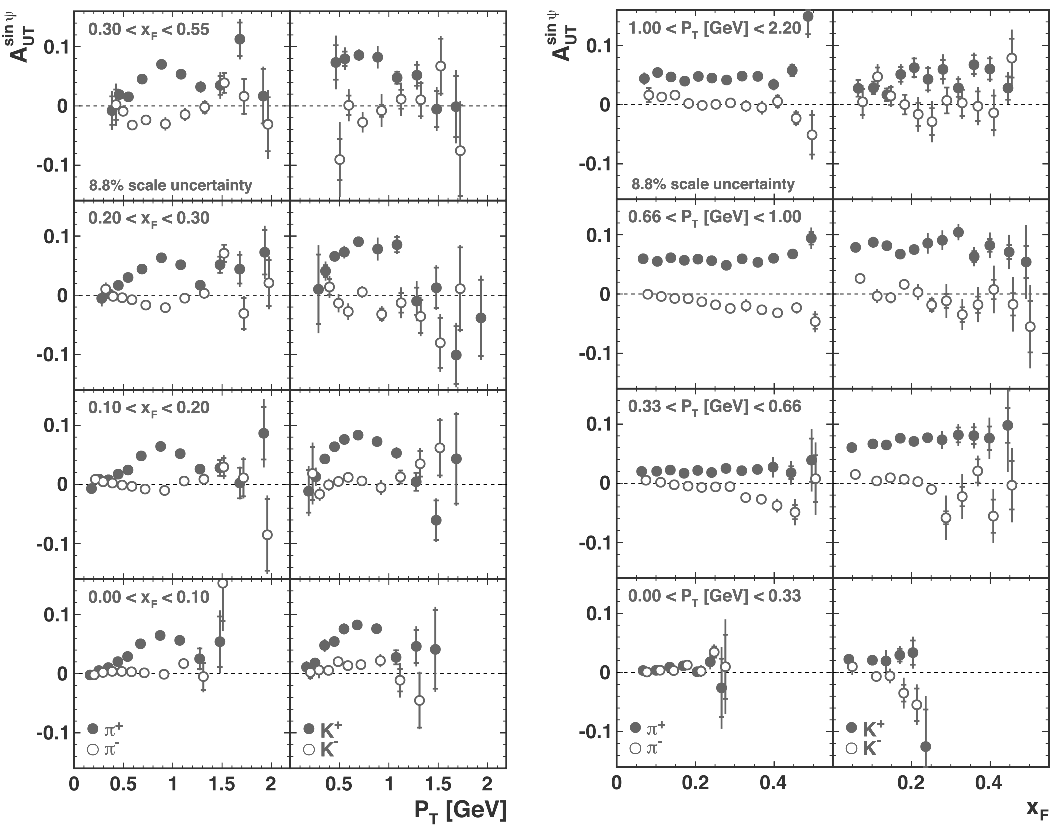

Figure 2. $A_{UT}^{\sin\psi}$ amplitudes for charged pions and kaons as a function of P_T in slices in x_F (left) and as a function of x_F in slices of P_T (right). Positive (negative) hadrons are denoted by closed (open) symbols.

π^+ amplitude is basically independent of x_F in all four slices in P_T. Therefore the apparent linear increase of its magnitude seen in the one-dimensional projections as a function of x_F (Fig. 1 right) is just a reflection of the underlying dependence on P_T. In contrast, for negative pions the decrease in x_F survives in the two-dimensional projections, and is thus real. The x_F dependence of the kaon asymmetries is less pronounced in the two-dimensional extraction, with a slight increase (decrease) with x_F for K^+ (K^-).

3. Interpretation

The data sample is largely dominated by the quasi-real photoproduction regime ($Q^2 \approx 0$). In this regime, the undetected lepton has generally a very small scattering angle and remains confined within the beam pipe. At large P_T (above 1.5 GeV), however, there are sizeable contributions from events with large Q^2 and with the scattered lepton in the spectrometer acceptance. The full data set was then divided into two main categories: the *Anti-tagged category* and the *Tagged category*, including, respectively, events with the scattered lepton outside and within the acceptance. The events in the *Anti-Tagged category* account for about 98% of the full statistics and are thus dominated by the quasi-real photoproduction regime ($Q^2 \approx 0$). For the events in the *Tagged category*, for which the Q^2 is accessible, the standard DIS variables could be determined. This category has been further divided into two subsamples:

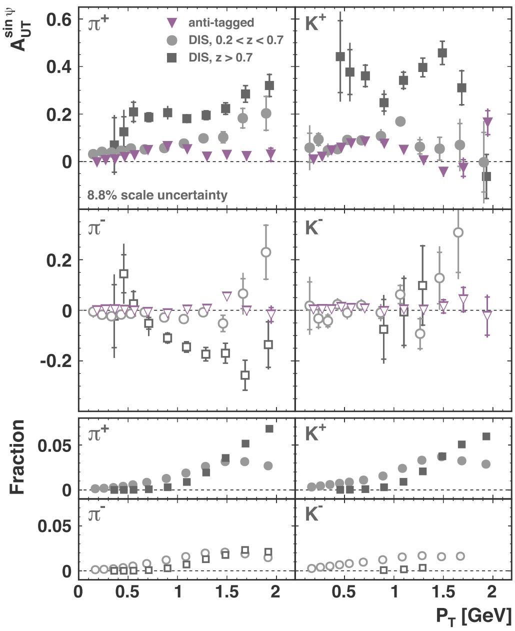

Figure 3. $A_{UT}^{\sin\psi}$ amplitudes for charged pions and kaons as a function of P_T for the *Anti-tagged category* (triangles) and for the two *Tagged* DIS subsamples: with $0.2 < z < 0.7$ (circles) and with $z > 0.7$ (squares). Also shown are the relative fractions of the two DIS subsamples with respect to the total inclusive sample of the corresponding hadron species.

"*DIS events with* $0.2 < z < 0.7$" and "*DIS events with* $z > 0.7$", where z denotes the fractional hadron energy. The separated results are shown in Fig. 3 as a function of P_T.

As expected, the asymmetry amplitudes for the *Anti-Tagged category* are essentially identical to the inclusive amplitudes over most of the P_T range. Since P_T is the only hard scale, the origin of the observed asymmetries can most likely be explained in terms of higher-twist contributions. At high P_T (above 1.3 GeV) the contributions from the other subsamples to the full inclusive sample become sizeable. The amplitudes for the two *Tagged* subsamples are much larger in magnitude than those of the *Anti-Tagged* sample. In particular, those for "*DIS events with* $z > 0.7$" are above 20% for positive and negative pions, and up to 40% for K^+. More in detail, concerning the "*DIS events with* $0.2 < z < 0.7$", the π^+ amplitude rises linearly with P_T from about 4% at low P_T to about 20% at high P_T, whereas the π^- amplitude is slightly negative (apart for the two highest P_T points). In this regime, 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. In particular, since the ψ angle and the *Sivers angle* $(\phi - \phi_S)$ are closely related, it is reasonable to assume that the observed P_T dependence is predominantly caused by the Sivers effect. Concerning the interpretation of the amplitudes for the "*DIS events with* $z > 0.7$", one should consider that in this particular regime favored fragmentation prevails, e.g., reducing cancellation effects from the opposite signs of the up and down Sivers functions, though it also receives a large contribution from decays of exclusively produced vector mesons. The latter contribute up to about 50% (30%) to the π^+ (π^-) yield. For kaons the corresponding contributions from decays of ϕ mesons are less than 10%. The large π^- asymmetry may indicate a substantial contribution from the down-quark Sivers function in conjunction with the favored unpolarized fragmentation ($D_1^{d\to\pi^-}$).

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