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The HERMES view on the nucleon's transverse-momentum-dependent partonic structure

Gunar Schnell [For the HERMES Collaboration]
DESY, 15738 Zeuthen, Germany
E-mail: gunar.schnell@desy.de

Azimuthal single-spin asymmetries in inclusive and semi-inclusive electro-production of pions and charged kaons were measured on a transversely polarized hydrogen target. Evidence for a naive-T-odd, transverse-momentum-dependent parton distribution function is deduced from non-vanishing Sivers effects for π^+, π^0, and $K^\pm$, as well as in the difference of the π^+ and π^- cross sections. Further azimuthal modulations of the semi-inclusive single-spin asymmetry were found to be consistent with zero except the one related to the Collins effect and one that is sub-leading in an expansion of the cross section in $1/Q$. The single-spin asymmetries in inclusive electro-production of charged pions and kaons were found to be non-zero except for K^-, and to qualitatively resemble the pattern of the Sivers amplitudes.

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1. Single-spin azimuthal asymmetries in semi-inclusive deep-inelastic scattering

Ten years have passed since the HERMES Collaboration measured non-vanishing target-spin-dependent azimuthal distributions of pions produced in deep-inelastic scattering (DIS) [1]. While first interpretations of those data focussed on the *Collins* effect [2]—a left-right asymmetry, with respect to the transverse spin of a fragmenting quark, in the momentum distribution of the produced hadrons—the seminal paper [3] demonstrated that also an asymmetric momentum distribution of unpolarized quarks in transversely polarized nucleons can lead to such azimuthal distributions not suppressed by $1/Q$. When scattering off longitudinally polarized nucleons, this *Sivers* effect [4] is indistinguishable from the Collins effect and only data using transversely polarized nucleons could give the final verdict on the origin of the azimuthal dependences observed.

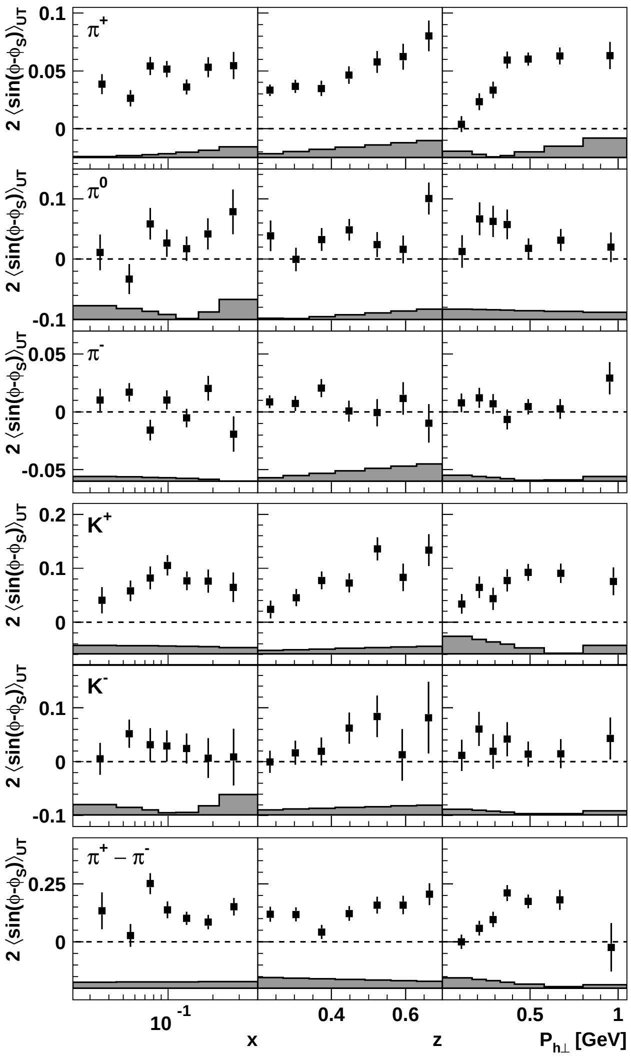

Figure 1: Sivers amplitudes for pions, charged kaons, and the pion-difference asymmetry (as denoted in the panels) as functions of x, z, or $P_{h\perp}$. The systematic uncertainty is given as a band at the bottom of each panel. In addition there is a 7.3% scale uncertainty from the target-polarization measurement.

The Sivers parton distribution function (PDF) is just one example of several PDFs that parametrize correlations between the parton's transverse momentum and the parton's and/or nucleon's spin. Among those the Sivers function relates to the distribution of unpolarized quarks in a transversely polarized nucleon and is rather particular as it is naive-T-odd, thus requiring in DIS final-state interactions. It breaks the conventional understanding and interpretation of factorization and universality. If measured in Drell–Yan, QCD quite firmly predicts the Sivers function to be of opposite sign as in DIS [5]. In $pp \to hX$ no firm prediction can even be made at all at present [6].

Nevertheless, the situation is rather straight-forward in a DIS experiment: one needs to measure the azimuthal distribution of hadrons produced in the scattering of unpolarized leptons by transversely polarized nucleons. When polarized transverse to the virtual-photon momentum direction five distinct Fourier modulations of the cross section can be identified (cf., e.g., Ref. [7]). The $\sin(\phi - \phi_S)$ modulation[1] is the signature of the Sivers effect while, e.g., the $\sin(\phi + \phi_S)$ modulation arises through the interplay of *transversity* [9] and the Collins fragmentation function [2]. Other modulations involve the *Mulders–Tangerman* distribution[2] [10] and genuine twist-3 contributions. When the target is polarized perpendicular to the beam direction a sixth modulation arises from the small but non-vanishing longitudinal component of the target spin w.r.t. the momentum direction of the virtual photon [11]. This $\sin(2\phi + \phi_S)$ modulation is sensitive to one of the *worm-gear* distributions.

The HERMES experiment [12] took data with transversely polarized protons and the 27.5 GeV e^+/e^- beam at HERA during the years 2002-2005. The excellent particle identification allowed for measurements of the azimuthal modulations in inclusive DIS and in the cross sections for lepto-produced pions as well as charged kaons. In Fig. 1 the Sivers, i.e., the $\sin(\phi - \phi_S)$, amplitudes of the semi-inclusive cross section are presented for pions, charged kaons, and for the charged-pion cross-section difference [13]. Clear evidence for a non-vanishing Sivers function can be deduced from the significantly positive amplitudes for all but the π^-. These results lead to Sivers distributions that are opposite in sign for u- and d-quarks: π^+ production is dominated by scattering off u-quarks, which determines the sign of the u-quark Sivers function. As π^- production receives a large contribution from scattering off d-quarks, the vanishing Sivers amplitude for π^- thus requires cancelation, i.e., the opposite sign of the Sivers function for d-quarks as compared to u-quarks.

A puzzling facet of the data is the difference in magnitude of the amplitudes for π^+ and K^+. On the basis of u-quark dominance, e.g., the dominant contribution of u-quark scattering to the production of π^+ and K^+, one would naively expect amplitudes of similar size, while in reality the K^+ amplitudes are partially double in size of the π^+ amplitudes. One apparent difference between the two mesons are their different valence structures: besides the u-quark, which is a valence quark in the target nucleon as well, the π^+ is made of an anti-d quark in contrast to the anti-s quark for

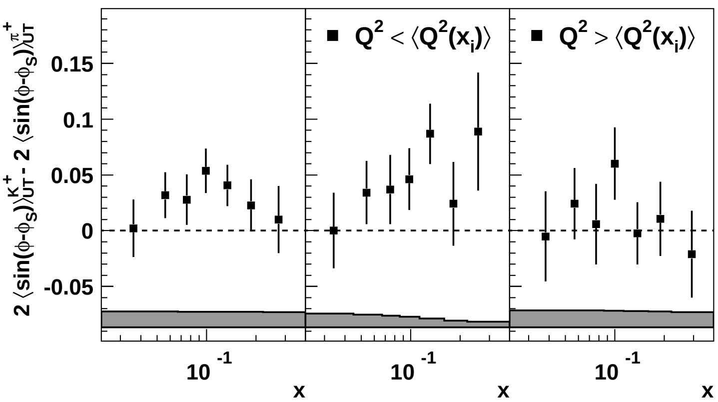

Figure 2: Difference of Sivers amplitudes for K^+ and π^+ as functions of x for all Q^2 (left), and separated into "low-" and "high-Q^2" regions above and below the average Q^2, $\langle Q^2(x_i)\rangle$, of that x-bin.

[1] All angles and asymmetries are defined in line with the *Trento Conventions* [8]. In particular, ϕ (ϕ_S) is the azimuthal angle of the hadron momentum (the target-spin vector) about the virtual photon direction w.r.t. the lepton scattering plane.

[2] It is also known as *pretzelosity*.

the K^+, both being sea quarks in the target nucleon. The question to ask therefore is whether there can be a significantly different role of the various sea quarks in the Sivers effect? One hint might come from an earlier result [14] by HERMES, the distribution of strange quarks in nucleons. It was found to be much softer than the one for the light sea, with the difference being largest where also the difference between the π^+ and K^+ Sivers amplitudes is the biggest (c.f. Figs. 2 (left) and 3).[3]

There are other aspects that need to be taken into account in the π^+/K^+ comparison. Even in the case of scattering solely off u-quarks the role of the fragmentation function cannot be neglected as the fragmentation function appears in different convolutions over intrinsic and fragmentation quark transverse momenta in the numerator and denominator of the asymmetry [7]. For example, varying dependences of the fragmentation functions on transverse momentum can lead to varying magnitudes of the asymmetry amplitudes. Another crucial aspect may also lead to the differences observed: unrelated $1/Q^2$-suppressed contributions to the amplitudes. Indeed, looking at the Q^2 dependence of the $K^+ - \pi^+$ difference, the latter seems to be significantly non-zero at lower values of Q^2 only (Fig. 2). In addition, while there is no evidence for any Q^2 dependence of the π^+ amplitudes there is a hint of systematically smaller K^+ Sivers amplitudes at larger values of Q^2 (Fig. 4).

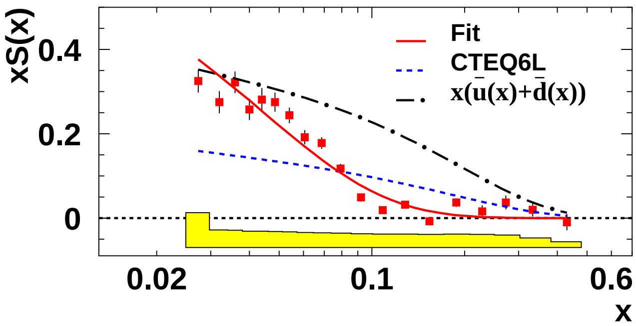

Figure 3: The strange-quark distribution $S(x) \equiv s(x) + \bar{s}(x)$ as a function of x and compared to its CTEQ6L parameterization as well as to the light sea.

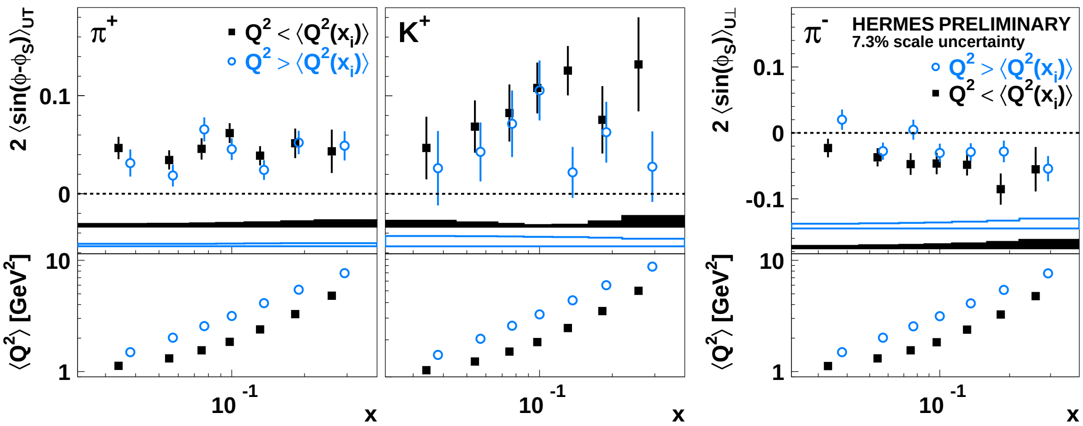

Figure 4: Sivers amplitudes for π^+ (left) and K^+ (middle) and the subleading-twist $\sin\phi_S$ amplitude (right) as functions of x. The Q^2 range for each bin was divided into the two regions above and below $\langle Q^2(x_i)\rangle$ of that bin. In the bottom the average Q^2 values are given for the two Q^2 ranges.

[3] It is interesting to note that it is sufficient to have Sivers functions for sea quarks that are opposite in sign of the one for u-quarks to explain the π^+ / K^+ difference: the respective sea-quark contribution to K^+ production will *reduce* the contribution from u-quarks *less* than to π^+ production as there are fewer anti-s than anti-d quarks in the proton.

An entirely different azimuthal modulation is the $\sin\phi_S$ modulation. It receives subleading-twist contributions only, but nevertheless was found to be non-zero—though decreasing with Q^2—for the π^- (Fig. 4 right). It can be related to several interesting distribution and fragmentation functions, e.g., transversity in conjunction with the novel interaction-dependent fragmentation function $\tilde{H}$, but also to the Sivers function or to the worm-gear distribution correlating the longitudinal quark and transverse nucleon polarizations. While disentangling these contribution will require further detailed studies, a rather interesting aspect can already be highlighted. The inclusive analogue, i.e., summing over all final-state hadrons and integrating over their four-momenta, must vanish—at least in the one-photon approximation. (This was tested at HERMES and no asymmetry at the 10^{-3} level was found [15] as shown in Fig. 5.) As a sizable asymmetry amplitude is seen for the π^- only, which is negative and does not change sign in the kinematic range examined, the question arises where the missing strength is hidden that is needed to balance out the π^- amplitude to zero. Indeed, a rather large and positive asymmetry was reported for exclusive π^+ production at HERMES [16].

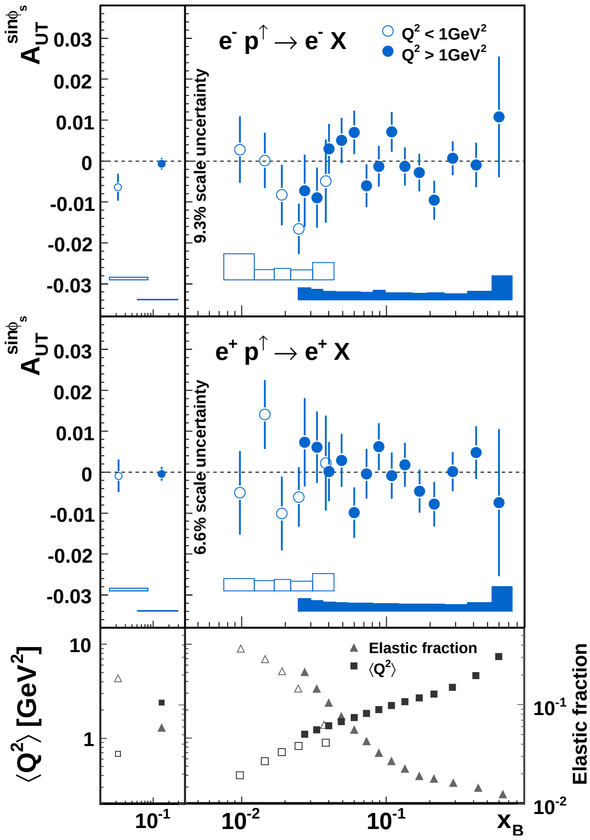

Figure 5: Azimuthal SSA in inclusive DIS off transversely polarized protons.

Of the remaining amplitudes on a transversely polarized target, only the Collins asymmetry is significantly non-zero [17] as shown in Fig. 6. From these non-vanishing asymmetries it becomes clear that both transversity is non-zero and transversely polarized quarks do fragment into hadrons that have a preferred momentum direction transverse to the quark spin as quantified by the Collins fragmentation function [2]. Moreover, the opposite sign observed for the Collins amplitudes for π^+ and π^- indicates that favored and disfavored pion production from a transversely polarized quark exhibit an opposite preference in the momentum direction. However, this picture at the moment applies only to production of pions, the kaons follow a rather different pattern with K^+ having a large Collins asymmetry but the K^- a with zero consistent result.

The Collins function also appears in the $\sin(3\phi - \phi_S)$ modulation, there in conjunction with the Mulders–Tangerman distribution. In the multipole patterns associated with the various TMDs, the Mulders–Tangerman distribution is the only one related to a quadrupole deformation. Particular interest in the Mulders–Tangerman distribution arises also through its model-dependent relation to orbital angular momentum and to the difference between transversity and the helicity distributions. However, the signal observed at HERMES is consistent with zero, either because of cancellations of the various quark flavors, the Mulders–Tangerman distribution being too small, or because of the additional $P_{h\perp}^2$ suppression of the $\sin(3\phi - \phi_S)$ modulation of the cross section.

2. Single-spin azimuthal asymmetries in inclusive electro-production of charged pions and kaons

While the interpretation of single-spin asymmetries in semi-inclusive DIS is based by now on a firm foundation in terms of transverse-mometum dependent (or *unintegrated*) parton distribution and fragmentation functions, the situation is different for inclusive hadron production, e.g., in hadron collisions (originally leading to the idea of the Sivers effect [4]). However, substantial asymmetries have been observed in a wide range of center-of-mass energies—unexpected from a pQCD point of view—and still today they are subject to intense investigations (for a review on this subject see, e.g., Ref. [18]). This stimulated interest in looking at inclusive electro-production of hadrons, i.e., $ep \rightarrow hX$ where only one hadron of the final state is tagged.

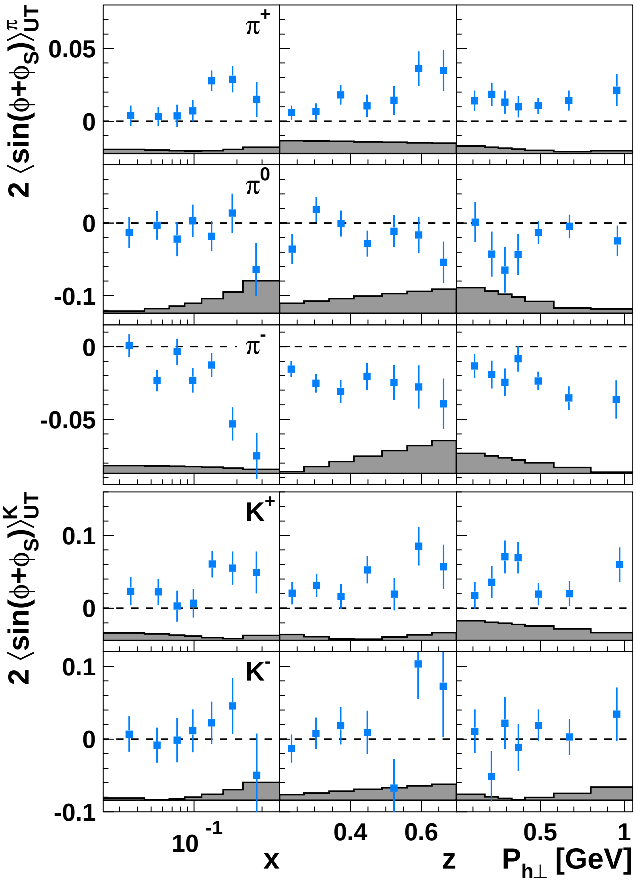

Figure 6: Collins amplitudes for pions and charged kaons (as denoted in the panels) as functions of x, z, or $P_{h\perp}$. The systematic uncertainty is given as a band at the bottom of each panel. In addition there is a 7.3% scale uncertainty from the target-polarization measurement.

HERMES has collected a wealth of data on inclusive charged pion and kaon production, allowing for a rather precise measurement of single-spin asymmetries in the scattering from transversely polarized protons. As the scattered lepton is not considered in the analysis, the event sample is dominated by low-Q^2 quasi-real photo-production. (One should keep in mind that also for this process any attempt of factorization (see, e.g., Ref. [19]) requires a hard scale, e.g., the transverse momentum p_T of the hadron with respect to the lepton-beam direction.) As the scattered lepton escapes detection, the usual DIS kinematics, in particular the four-momentum of the virtual photon, are not known. Therefore, p_T, $x_F \simeq 2p_L/\sqrt{s}$ with p_L being the longitudinal component of the hadron momentum, and the azimuthal angle ϕ of the hadron's transverse momentum with respect to the polarization direction of the target proton are measured using the incoming lepton beam as the reference.

In Fig. 7 the $\sin\phi$ amplitude of the transverse single-spin asymmetry in inclusive electro-production of charged pions and kaons is shown as a function of p_T in three bins of x_F. All except the K^- exhibit significantly non-zero asymmetries, substantially larger for π^+ and K^+ than for π^-. More strikingly, the π^- amplitude changes sign going from low values of x_F to large values of x_F. In general, the amplitudes rise with increasing p_T with a turnover at a value in p_T of about 1 GeV.

As the origin of such asymmetries is completely nebulous, one may be tempted to compare these results with similar single-spin asymmetries. The DIS analogue reported on in Sec. 1 requires the presence of the lepton-scattering plane, except for the Sivers effect. The latter is also a $\sin(\psi)$ amplitude of the single-spin asymmetry with ψ being the angle between the hadron's transverse momentum with respect to the polarization direction of the target proton—this time measured about the virtual-photon direction. Indeed, $\psi \simeq \phi$ in the case of small angles between the incoming-beam and the virtual-photon directions, and the qualitative behavior as well as the magnitudes of the asymmetries vs. $P_{h\perp}$ (DIS) and p_T (inclusive hadrons) resemble each other. This is not the case for the other amplitudes in semi-inclusive DIS, e.g., for the Collins effect. Whether the similarity of the Sivers effect in DIS and the asymmetry in inclusive hadron electro-production is purely accidental or some aspect of duality is at the moment highly premature to conclude.

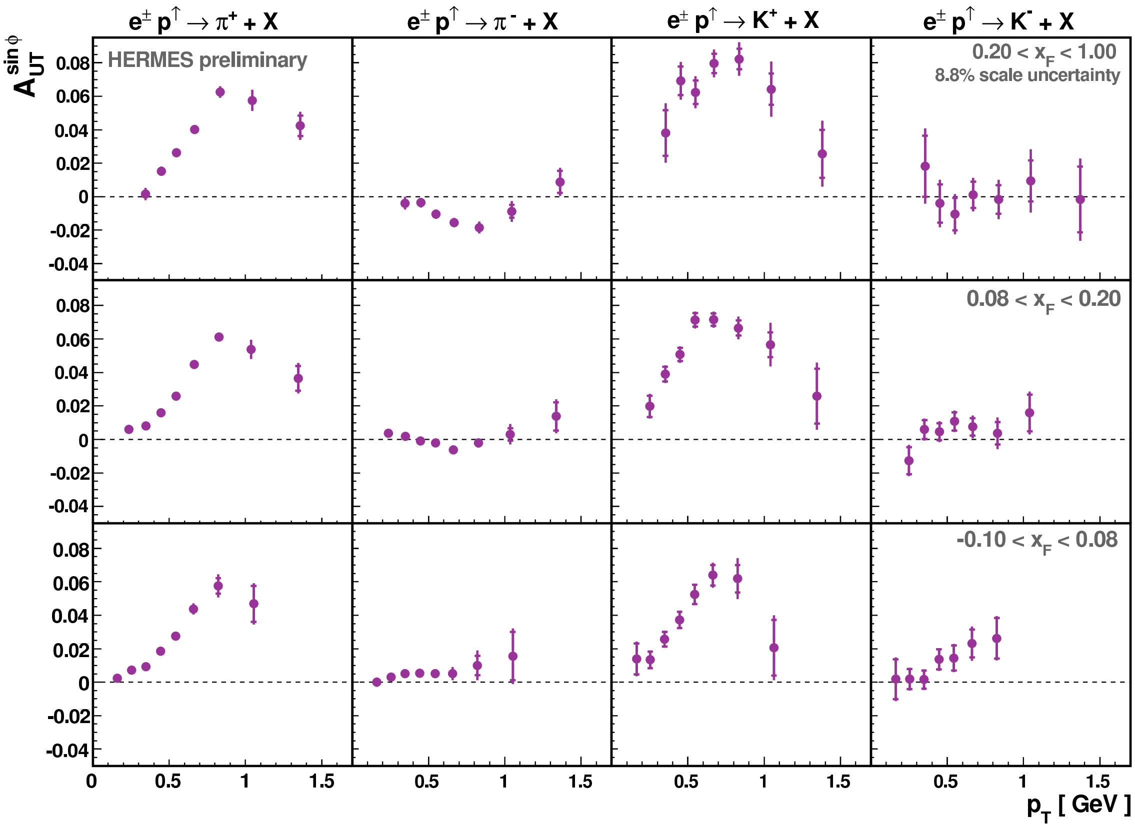

Figure 7: Azimuthal SSA in inclusive hadron production off transversely polarized protons as a function of p_T and x_F for charged pions and kaons as labelled.

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