Semi-Inclusive Deep-Inelastic Scattering

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TRIUMF

Abstract. Some prominent new semi-inclusive DIS results from JLAB and HERMES that have appeared since SPIN 2000 are presented. Polarized quark distributions have been extracted from the complete HERMES data set on H and D from 1996-2000, based on Monte Carlo "purities". The data quality permits for the first time the separation of the $\bar{u}$, $\bar{d}$ and $s+\bar{s}$ sea quark polarizations. Also, both laboratories have produced new single-spin asymmetries in the azimuthal distributions of semi-inclusive hadrons. New SSAs from longitudinally polarized proton and deuteron targets are presented, as well as beam-helicity SSAs from unpolarized protons.

POLARIZED QUARK DISTRIBUTIONS

The last decade has seen remarkable progress in defining the polarized quark distributions $\Delta q_f(x) \equiv q_f^{\uparrow\uparrow}(x) - q_f^{\uparrow\downarrow}(x)$, where e.g. $q_f^{\uparrow\uparrow}(x)$ represents the probability of finding a quark of any particular flavor f with momentum fraction x of the target nucleon, and with its spin parallel to that of the nucleon. The most precise and clearly interpreted experimental tool has been inclusive deeply inelastic lepton scattering (DIS), applied at the CERN, SLAC and DESY laboratories. In this process, the beam lepton emits a virtual photon with energy ν and invariant mass $-Q^2$, which can be considered to be absorbed by a single quark provided that $Q^2 > 1\,\mathrm{GeV}^2$. However, the information available from this process has inherent limitations, as the cross sections are sensitive to only the *square* of the charge of the quark absorbing the exchanged virtual photon. Hence sea quarks can not be distinguished from valence quarks, and only one particular flavor non-singlet combination of distributions can be directly inferred from a combination of inclusive DIS data on both proton and "neutron" targets: $\Delta q_3(x,Q^2) = \Delta u + \Delta\bar{u} - \Delta d - \Delta\bar{d} = 6(g_1^p - g_1^n)$. Here the $g_1(x)$'s are the spin structure functions extracted from the measured cross section polarization asymmetries that correlate beam and target spins. Further inference from inclusive data requires an additional assumption of SU(3) flavor symmetry relating the spin structure of various hadrons. This allows the use of hyperon beta decay to constrain the first moment of another non-singlet flavor combination involving the strange sea. The celebrated result of this approach is that quark helicities seem to make a small net contribution to the nucleon spin, and the strange sea appears to be somewhat negatively polarized [1, 2, 3].

The questionable assumption of SU(3) flavor symmetry can be avoided at the cost of some complexity in the extraction of more information from the DIS measurements. Leading hadrons produced by fragmentation of the struck quark carry information about that quark's flavor. Hence identification of the type of hadrons detected together with the scattered lepton in these *semi-inclusive* measurements effectively "tags" the quark flavor.

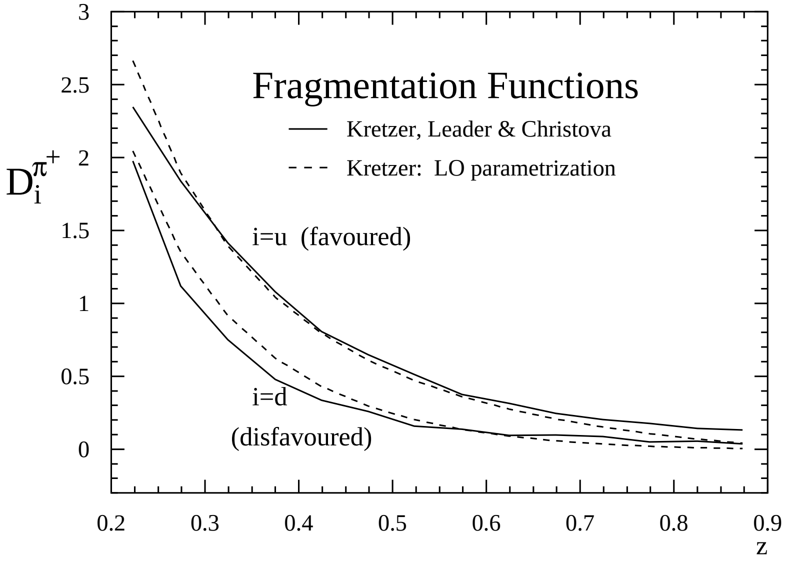

FIGURE 1. A comparison at $\langle Q^2 \rangle = 2.5\,\mathrm{GeV}^2$ of the π^+ fragmentation functions from the leading-order parameterization of ref. [4] fitted to e^+e^- data (dashed curves) with those extracted from a combination of HERMES semi-inclusive DIS multiplicity data and the singlet fragmentation function $D_\Sigma^{\pi^+}$ from e^+e^- data [5] (solid curves).

This method obviously depends on knowledge of the set of probabilities that each quark flavor f will fragment into each type of hadron h carrying energy fraction $z = E_h/\nu$ of the virtual photon energy, information which is encoded in *fragmentation functions* $D_f^h(z)$. These functions can now be extracted from hadron multiplicity distributions either in flavor-enriched jets at the $e^+e^- \rightarrow Z^0$ pole, or in DIS measurements on both proton and “neutron" targets. Fig. 1 shows a comparison of a parameterization [4] based on e^+e^- data with the results of a hybrid analysis of pion multiplicities from DIS on a hydrogen target in combination with the singlet fragmentation function $D_\Sigma^{\pi^+}$ from e^+e^- data [5]. The consistency of the results lends support to the universality of the extracted fragmentation functions, particularly in the kinematic conditions of this DIS experiment.

Semi-inclusive DIS measurements require a combination of a polarized lepton beam with good duty factor, polarized targets of both hydrogen and e.g. deuterium, and a spectrometer with substantial acceptance for the produced hadrons. The first attempt to extract polarized quark distributions from semi-inclusive asymmetries was made several years ago by the SMC experiment [6]. As the detected hadrons were unidentified except for charge, and the statistical precision was limited, different flavors of sea quarks could not be distinguished in the analysis. Now the HERMES collaboration has released a new preliminary five-flavor $(u, d, \bar{u}, \bar{d}, s = \bar{s})$ extraction from their entire 1996-2000 data set comprising identified semi-inclusive pions from a hydrogen target and identified pions and kaons from a deuterium target. Important features of this experiment include pure nuclear-polarized atomic gas targets in a polarized electron storage ring, and the capability in the spectrometer for hadron identification. The quality of the resulting deuterium asymmetry data is shown in Fig. 2. They have been integrated over the range

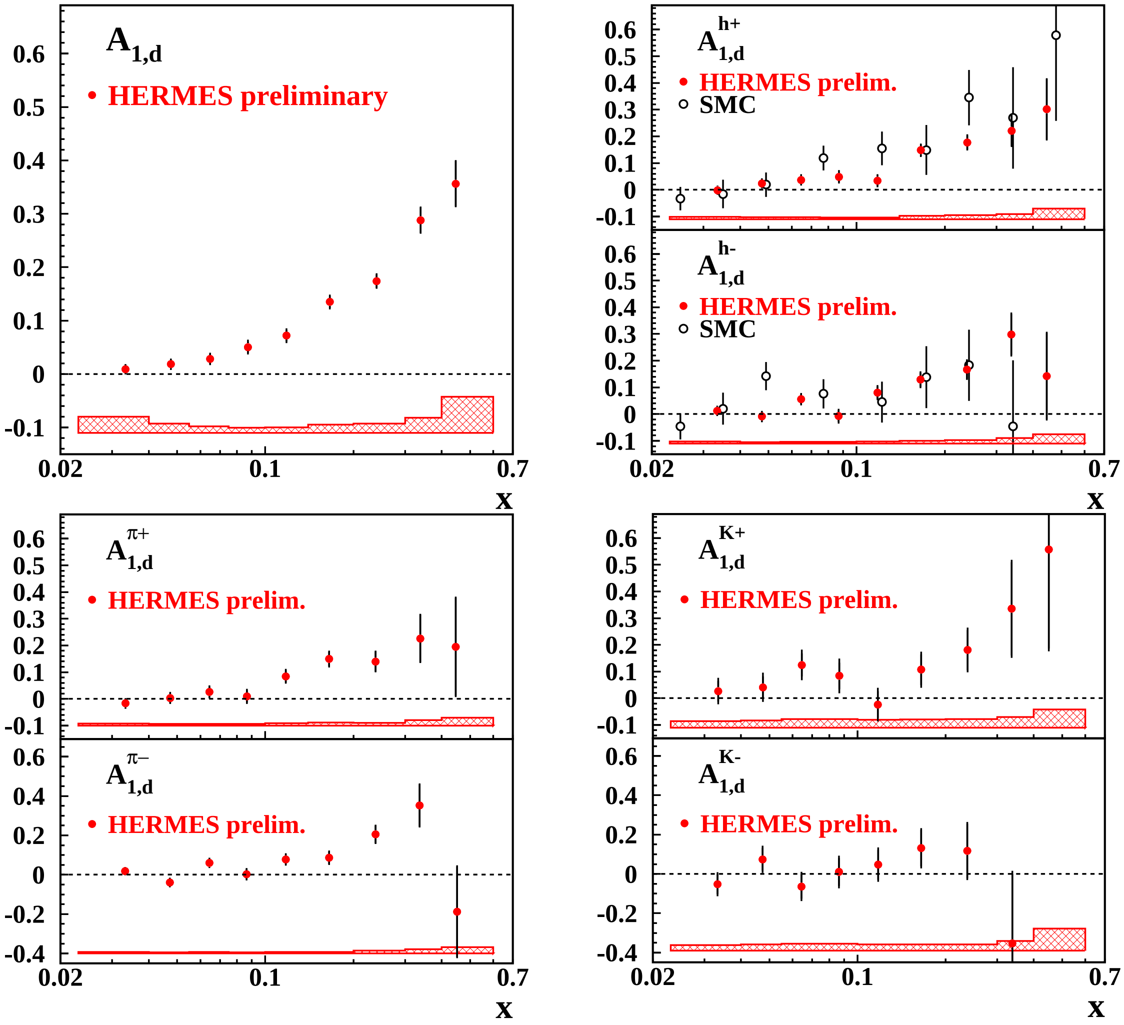

FIGURE 2. Preliminary photo-absorption asymmetries A_1 on the deuterium target from the HERMES collaboration. The upper left panel shows the inclusive asymmetries, the upper right the semi-inclusive asymmetries for all unidentified hadrons for comparison with SMC [6], and the lower panels are for identified pions and kaons as indicated. No corrections have been applied at this stage for the effects of experimental acceptance, which LEPTO simulations suggest are small.

$0.2 < z < 0.8$. The lower limit is chosen to suppress hadrons from target fragmentation. The absence of any z-dependence of the asymmetries in this accepted range is taken as evidence for the dominance of current fragmentation. Kinematic migration due to instrumental and radiative effects has been fully unfolded using information internal to a DIS Monte Carlo event simulation incorporating the significant radiative diagrams and vertex corrections, as well as a detailed simulation of the spectrometer.

The experimental data set thus consists in each x bin of a vector of asymmetries on both hydrogen and deuterium targets, both inclusive and semi-inclusive for various hadrons:

$$\vec{A} = (A_{1,\mathrm{p}}, A_{1,\mathrm{d}}, A_{1,\mathrm{p}}^{\pi^\pm}, A_{1,\mathrm{d}}^{\pi^\pm}, A_{1,\mathrm{d}}^{\mathrm{K}^\pm}). \qquad (1)$$

To these data are fit independently in each x bin a vector of five quark polarizations:

$$\vec{Q} = \left(\frac{\Delta u}{u}, \frac{\Delta d}{d}, \frac{\Delta \bar{u}}{\bar{u}}, \frac{\Delta \bar{d}}{\bar{d}}, \frac{\Delta s + \Delta \bar{s}}{s + \bar{s}} \right). \tag{2}$$

The leading-order relationship that is fit is

$$A_1^h(x) \overset{g_2=0}{\simeq} \frac{\sum_f e_f^2 \, \Delta q_f(x) \, \int \mathrm{d}z \, D_f^h(z)}{\sum_{f'} e_{f'}^2 \, q_{f'}(x) \, \int \mathrm{d}z \, D_{f'}^h(z)} \frac{(1+R(x))}{(1+\gamma^2)} \tag{3}$$

$$= \sum_f \underbrace{\frac{(1+R(x))}{(1+\gamma^2)} \frac{e_f^2 \, q_f(x) \int \mathrm{d}z \, D_f^h(z)}{\sum_{f'} e_{f'}^2 \, q_{f'}(x) \, \int \mathrm{d}z \, D_{q_{f'}}^h(z)}}_{\mathscr{P}_f^h(x) \, \equiv \, \text{Purity}} \frac{\Delta q_f(x)}{q_f(x)}. \tag{4}$$

For simplicity, the weak logarithmic dependences of all functions on Q^2 are suppressed here. The factor involving the kinematic value $\gamma^2 = Q^2/\nu^2$ and R, the ratio of longitudinal to transverse cross sections, accounts for the longitudinal component included in parametrizations of the unpolarized parton distribution functions $q_f(x)$. This set of equations may be represented in matrix form

$$\vec{A}(x) = \mathscr{P}_f^h(x) \cdot \vec{Q}(x), \tag{5}$$

where all of the information that comes from previous unpolarized measurements — both distribution and fragmentation functions — is combined in the *purity* functions $\mathscr{P}_f^h(x)$, each of which represents the conditional probability that an observed hadron of type h was produced by a struck quark of flavor f with momentum fraction x. The purities used in the new HERMES analysis were extracted from the above-mentioned Monte Carlo simulation (but now excluding QED radiative and detector resolution effects) as $\mathscr{P}_f^h(x) = N_f^h(x) / \sum_{f'} N_{f'}^h(x)$, where N_f^h is the number of hadrons of type h, in the geometric experimental acceptance and in the interval $0.2 < z < 0.8$, that were produced from quarks of flavor f. The simulation employs the CTEQ5 Low–Q^2 parametrization [2] for the unpolarized PDF's, and JETSET fragmentation parameters that were tuned to fit hadron multiplicities measured at HERMES [7]. The simulated purities were then augmented by the $1 + R$ factor evaluated as per ref. [8], as well as nuclear corrections for the deuteron target based on a d-state probability $\omega_D = 0.05 \pm 0.01$.

The over-constrained linear system Eq. 5 is solved for the unknown $\vec{Q}$ vector by the usual χ^2 minimization. The precision with which this system can be solved clearly depends on the degree of orthogonality of the purities — i.e. how well flavor-tagging works. Positive hadrons alone can distinguish valence u and d quarks. In this case, u-quark dominance of h^+ production from both proton and neutron targets is helpful. Negative hadrons can perform a similar separation for sea quark flavors, as production of h^- from sea quarks is relatively larger than h^+, and again dominated by $\bar{u}$ quarks. The general separation of valence and sea quarks is mainly done by hadron charge. Identified kaons available in the data set from the HERMES deuterium target have a

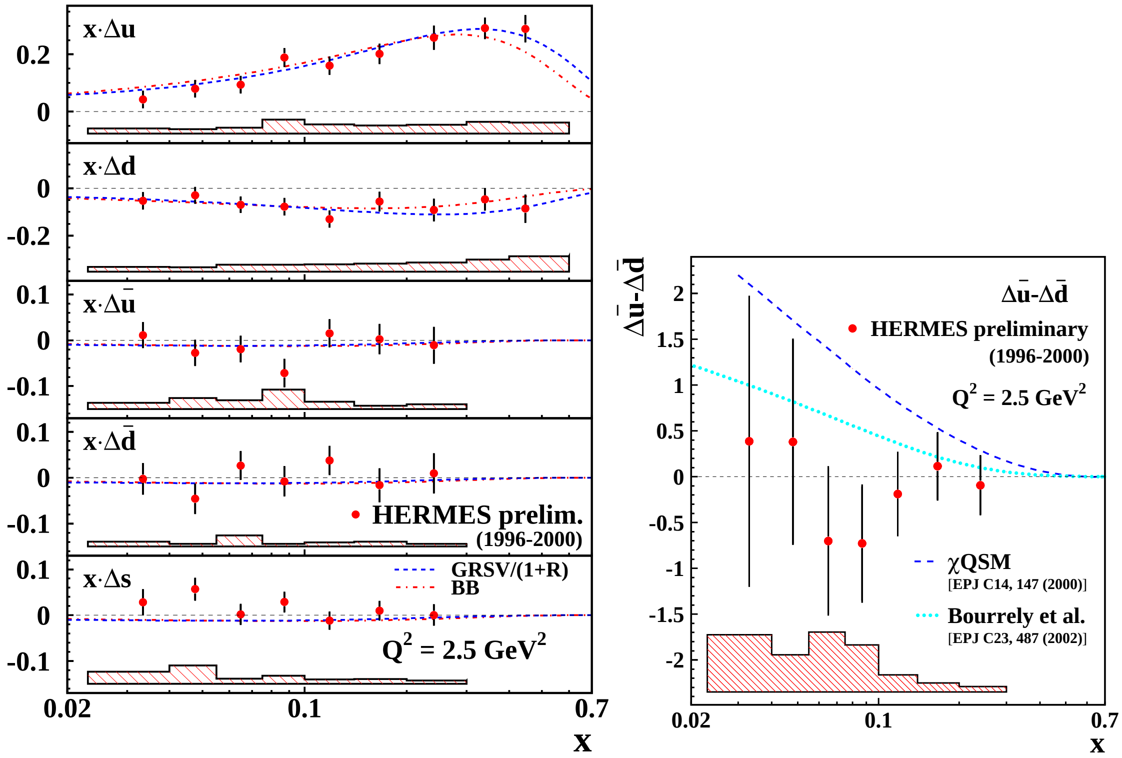

FIGURE 3. Left panel *(a)*: Extracted polarized quark distributions as a function of Bjørken x, compared to two NLO QCD fits to world inclusive data [3, 9]. Right panel *(b)*: The light quark sea flavor asymmetry $\Delta\bar{u} - \Delta\bar{d}$ in the polarized distributions, compared to theoretical predictions based on the chiral quark soliton model [10] and on a statistical model [11]

larger sensitivity to the strange sea, but still at only the 10% level due to u or $\bar{u}$ quark dominance. The systematic uncertainties in kaon purities are presently large due to the uncertainties in both the fragmentation functions and unpolarized parton densities. However, examination of Eq. 4 reveals that the effects of individual unpolarized densities $q_f(x)$ tend to cancel when the polarized densities $\Delta q_f(x)$ are finally derived from the quark polarizations (the solutions of that equation) by multiplying by the unpolarized densities.

The polarized densities $\Delta q_f(x)$ resulting from the analysis are shown in Fig. 3*a)*, compared to two NLO QCD fits to world inclusive data that assume SU(3) flavor symmetry. The systematic uncertainties include contributions from the $A_1^{(h)}$ and from the unpolarized PDF's and purities. Further support for the assumption of pure current fragmentation in the employed z-range is given by the finding that the extracted densities are little affected by omission of the inclusive asymmetries from the extraction, even though the inclusive data tends to have better statistical precision.

The extracted Δu and Δd are consistent with previous semi-inclusive results [6, 12]. The sea distributions, extracted separately here for the first time, are consistent with zero. There is no indication that the strange polarization is negative, in contrast to the findings from the inclusive data that are based on SU(3) flavor symmetry. Another surprise shown

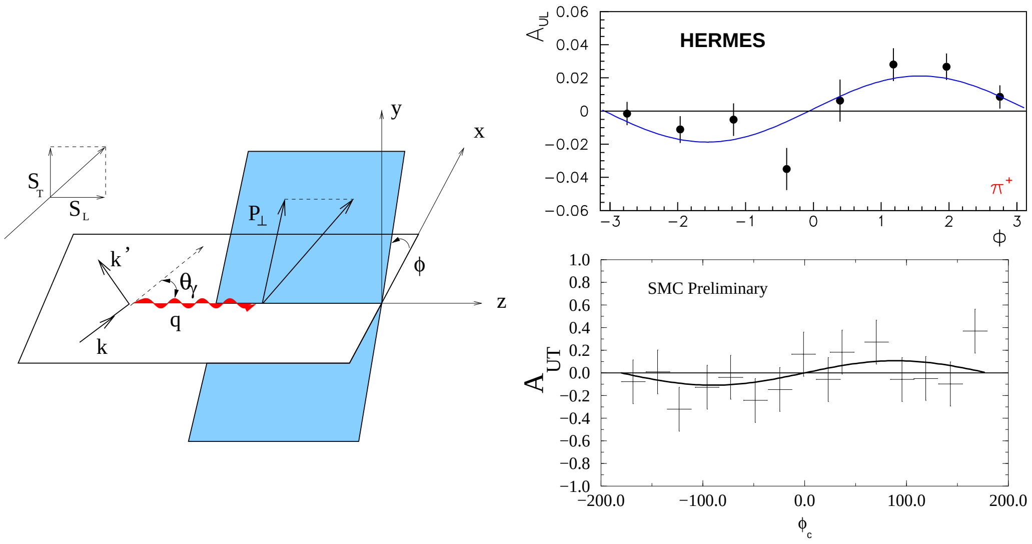

FIGURE 4. *a)* Kinematic geometry for semi-inclusive DIS. *b)* Single-spin asymmetries for longitudinal (HERMES) and transverse (SMC) target polarization.

in Fig. 3*b)* is that there is no evidence of the positive flavor asymmetry $\Delta\bar{u}-\Delta\bar{d}$ in the light quark sea that is predicted by some theoretical models [10].

SINGLE-SPIN AZIMUTHAL ASYMMETRIES

In 1999, HERMES [13] and SMC [14] released observations of semi-inclusive single-spin asymmetries that depend on the orientation of the hadron's $P_\perp$ azimuthally about the direction of the virtual photon (see Fig. 4*a)*). Relative to the lepton beam axis, the target polarization was transverse for SMC, and longitudinal for HERMES. In either case, the linear polarization of the virtual photon in the lepton plane selects transverse polarization of the struck quark. In leading twist, $P_\perp$ can arise from two sources: primordial p_T of the quark in the target, or k_T produced in the fragmentation process. A single-spin asymmetry requires the participation of some time-odd object correlating that p_T or k_T with some spin. Theoretical explanations of these asymmetries have focussed on a T-odd fragmentation process sensitive to the transverse polarization of the fragmenting quark [15]. The associated “Collins fragmentation function", designated $H_1^{\perp(1)}(z)$, is T-odd not in the fundamental sense, but only through the soft interactions in the final state. The wonderful implication of such an interpretation is that this “quark polarimeter” could provide access to the chiral-odd, and hence otherwise-inscrutable, *transversity* distribution. Transversity is the last remaining unmeasured one of the three leading-twist quark distributions that survive integration over intrinsic p_T. It is related to the probability of finding a transversely polarized quark in a nucleon polarized transversely with respect to its infinite momentum.

Unfortunately, almost all of the existing data revealing target-related single-spin asymmetries have been measured with a *longitudinally* polarized target. However, even

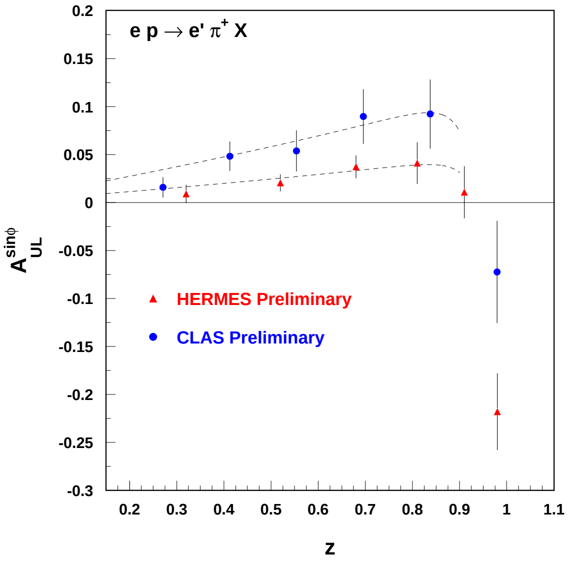

FIGURE 5. Analyzing powers in the $\sin\phi$ moment of single-spin azimuthal asymmetries with a longitudinally polarized hydrogen target, from both HERMES and CLAS. The arbitrarily normalized curves are from ref. [18].

these data can be interpreted [16] in terms of the same Collins fragmentation function, operating together with transversity-related distribution functions — one twist-2 ($h_{1L}^{\perp}$, representing the probability of finding a transversely polarized quark in a longitudinally polarized nucleon) and one twist-3 (h_L). Hence such data from the HERMES collaboration, and now emerging from the CLAS collaboration at JLAB as well, offer important evidence that the Collins function has a substantial magnitude. However, there are presently too may unknowns for an unambiguous interpretation. Some assumptions must be made — e.g. neglecting either the interaction-dependant part of h_L, or neglecting $h_{1L}^{\perp}$ altogether. It has then been found possible to explain most of the existing data [17]. For example, the z-dependence of the asymmetries appear to be explained by new theoretical calculations done at the one-loop level in a chiral- invariant model [18], as shown in Fig. 5. Their model also predicts azimuthal asymmetries for $e^+e^- \rightarrow 2$ jets up to of order 5%, consistent with preliminary DELPHI data within their rather large systematic uncertainty [19].

HERMES has now also released results on the same observable for both pions and kaons from a deuterium target. These are shown in Fig. 6, where selected examples are compared in the lower panels to theoretical predictions where the transversity distributions are calculated in the chiral quark soliton model [20]. In these calculations, the interaction-dependent part of h_L was neglected. The Collins function was parameterized to fit the HERMES proton data, now resulting in a magnitude which corresponds to the "optimistic" (large) extreme from DELPHI: $\frac{\langle H_1^{\perp(1)}\rangle}{\langle D_1\rangle} = (12.5 \pm 1.4)\%$. Previous estimates of the Collins function were only half this size, due to an error in the sign of the contribution of that component of the target polarization that is orthogonal to the virtual photon direction. (This component appears even in the HERMES experiment with target polar-

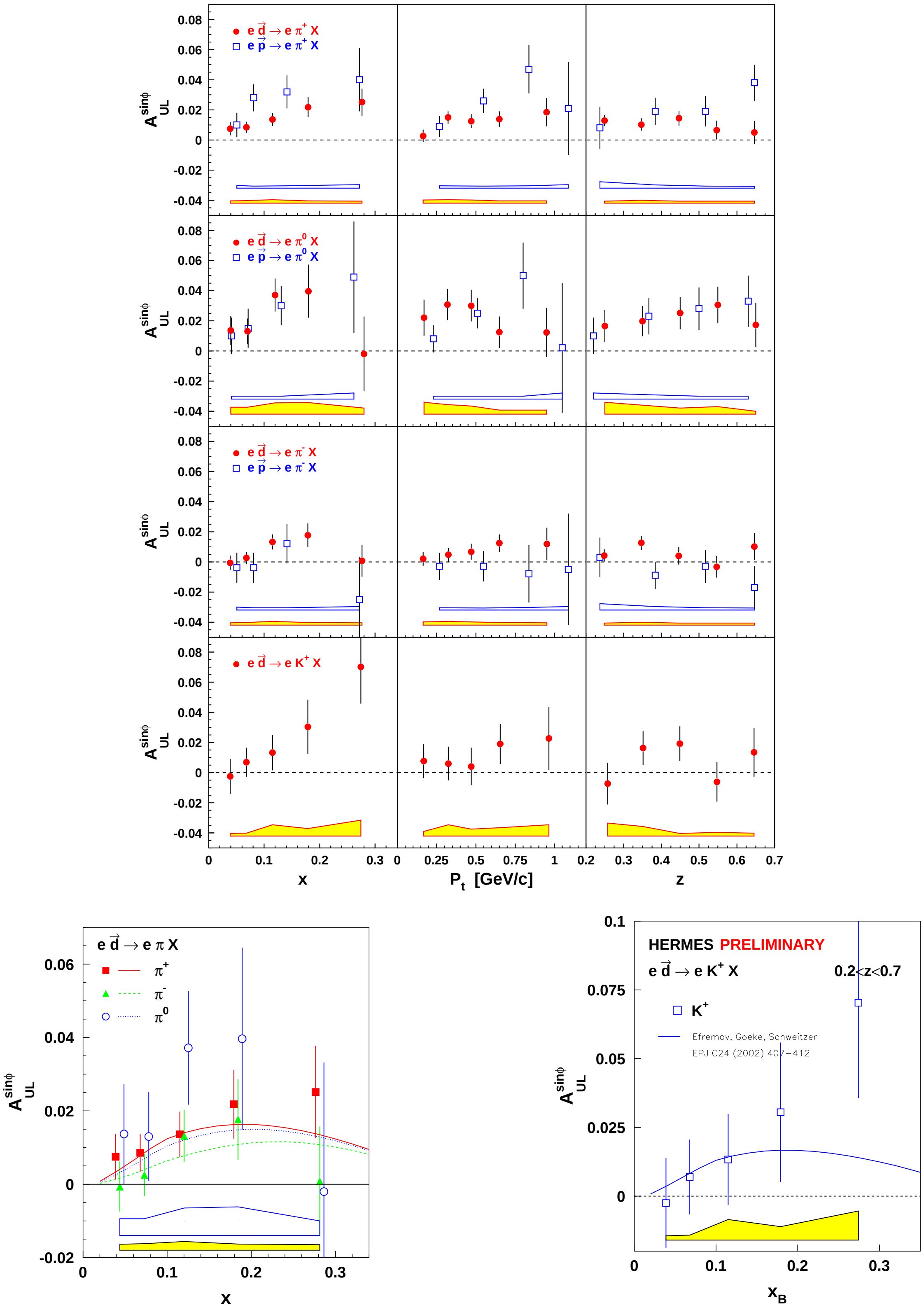

FIGURE 6. Preliminary HERMES analyzing powers in the $\sin\phi$ moment of single-spin asymmetries with a longitudinally polarized deuterium target. The curves are theoretical calculations from ref. [20]

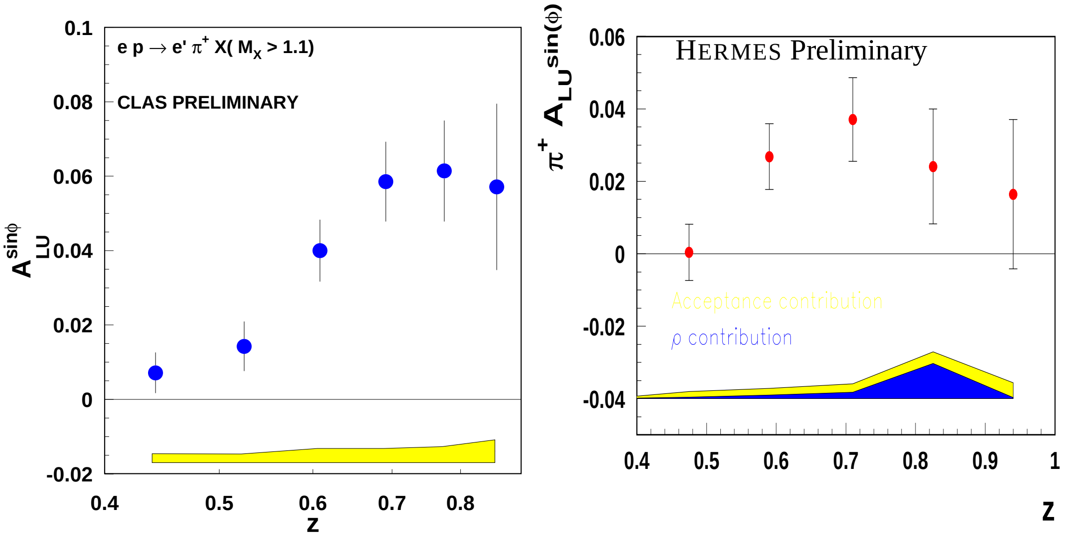

FIGURE 7. Analyzing powers in the $\sin\phi$ moment for single-spin azimuthal asymmetries with a longitudinally polarized positron beam.

ization parallel to the *lepton* beam.) Another result of the corrected sign is that the sign of the SMC preliminary asymmetry with a transversely polarized target no longer appears to be theoretically consistent with that of the HERMES results with a longitudinally polarized target, although those SMC data are not statistically definitive.

Beam-helicity related single-spin azimuthal asymmetries are also understood to be generated by the same Collins fragmentation function, but in conjunction with an unknown twist-3 chiral-odd distribution function designated $e(x)$, whose first moment is related to the pion-nucleon σ term [21]:

$$\int_{-1}^{1} \mathrm{d}x [e^u + e^d](x) = \frac{\sigma}{m_{av}} \tag{6}$$

$$m_{av} \equiv \frac{1}{2}(m_u + m_d) \simeq 5\,\mathrm{MeV} \tag{7}$$

Some newly released results for the beam-related single-spin asymmetry from both HERMES and CLAS are shown in Fig. 7. The increased magnitude at larger z is again what is expected of the Collins fragmentation function, while no x-dependence of the asymmetry is observed.

Recently, this arena of single-spin asymmetries has seen some theoretical turmoil, not only because of the detected sign error mentioned above. Even more excitement was precipitated by Brodsky, Hwang and Schmidt [22], who presented a model calculation including a short-distance (hard) “final state interaction” (FSI) between struck quark and spectator. They showed that this mechanism can also generate a single-(transverse)spin azimuthal asymmetry, although no quantitative predictions are yet available based on this model. Contrary to naive appearances, it’s a leading twist mechanism. This model inspired John Collins to realize [23] that such a mechanism is the old Sivers Effect [24, 25] in disguise. The model calculation reveals that the T-odd *distribution* function representing the Sivers Effect as the correlation between intrinsic quark p_T and transverse quark polarization in an unpolarized nucleon does not violate fundamental time reversal invariance after all (contrary to Collins' own apparent proof of a few years ago). Furthermore, Ji and Huang [26] explained how parton distributions in the light cone guage can still be interpreted as parton densities, in spite of the claim by Brodsky *et al.* that the nucleon wave function does not contain any information about the FSI.

Thus we are now left with two competing explanations for target-related single-spin asymmetries: the T-odd Collins fragmentation function, and the T-odd distribution function introduced by Sivers. Fortunately they can be distinguished [27] by new data now being recorded by both HERMES and COMPASS with transversely polarized targets, through the different azimuthal dependences of the asymmetry — the Sivers effect depends on the azimuthal angle *difference* between the target spin axis and hadron plane, through $\sin(\theta_h^l - \theta_S^l)$, while the Collins effect depends on the *sum* of these angles relative to the lepton scattering plane via $\sin(\theta_h^l + \theta_S^l)$. If the Collins effect is confirmed to be substantial, the first measurements of transversity can be extracted.

For more details on this rich and rapidly evolving subject of single-spin asymmetries, please find in this volume the theoretical talk by Phillip Ratcliffe, and the experimental talks by Harut Avakian and Delia Hasch.

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