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Spin physics and more with HERMES

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Abstract. A review of recent results obtained by the HERMES experiment is given. Inclusive measurements on polarized and unpolarized targets provide precise information on the polarized structure functions g_1^d and g_1^p and the isoscalar unpolarized structure function ratio F_2^A/F_2^d. The geometrical acceptance of the HERMES detector and the good particle identification capabilities allow the study of semi-inclusive reactions as well. Using polarized targets, the polarized quark distribution functions Δq can be extracted as well as a first indication of the transversity distributions δq. On unpolarized heavy targets, hadron formation in a nuclear environment is studied. Finally, data on Deeply Virtual Compton Scattering, the hard exclusive electroproduction of real photons, are presented, which are closely linked to the novel framework of Generalised Parton Distributions. For this reaction HERMES has measured the asymmetry main beam charge as well as in-beam spin.

PACS. 13.60.Hb Total and inclusive cross-sections (including deep-inelastic processes) – 13.60.Le Meson production – 24.85.+p Quarks, gluons, and QCD in nuclei and nuclear processes – 25.30.Mr Muon scattering (including the EMC effect)

1 Introduction

The nature of the structure of polarized nucleons is one of the central questions of present hadron physics. The nucleon is a composite fermion and its spin should be obtained as a superposition of the spins and angular momenta of its constituents, the quarks and gluons.

The HERMES experiment at DESY was designed to study the spin structure of the nucleon using the Deep Inelastic Scattering (DIS) process. It is built around a fixed-target spectrometer with good acceptance [1]. Over the years it was recognized that HERMES provides an appropriate kinematical range interesting to perform various studies both in polarized and unpolarized DIS on both nucleonic and nuclear targets. The combination of pure polarized and unpolarized internal gas targets with the polarized 27.5 GeV HERA lepton beam allows precise measurements of cross-section asymmetries and ratios in inclusive and semi-inclusive scattering. Data were taken using longitudinally polarized ^{3}He, hydrogen and deuterium with average polarizations of $0.45 \pm 0.05, 0.88 \pm 0.04$ and 0.84 ± 0.03, respectively. The average polarization of the HERA beam was 0.55. A wide range of unpolarized targets is available at HERMES, usually used in high-density running towards the end of a HERA fill providing comparatively high luminosities. The analyses presented include data taken on H_2, D_2, ^{4}He, ^{14}N and ^{84}Kr.

The momentum resolution of the spectrometer is $\delta p/p = 0.7$–1.3%. Information from a transition radiation detector, a pre-shower detector and a lead glass calorimeter give a lepton identification efficiency of 98% with a hadron contamination of $< 1\%$. For the data taken since 1998, identification of pions, kaons and protons is made possible by using a RICH detector [2]. The design of the experiment allows the following three different analysis approaches; namely inclusive scattering, where only the information of the scattered lepton is used, semi-inclusive scattering, where in addition to the scattered lepton also the information of coincident hadrons is used, and last but not least exclusive scattering, where the complete final state can be reconstructed.

2 Inclusive scattering

The understanding of the strong interaction including spin as an additional degree of freedom has been intensively discussed since QCD became the established gauge field theory of strong interactions, leaving the intuitive quark model as the valid concept for nucleon substructure. The Quark-Parton Model (QPM) could successfully explain the positive cross-sections asymmetries observed in polarized DIS on the protons preformed early at SLAC [3]. It

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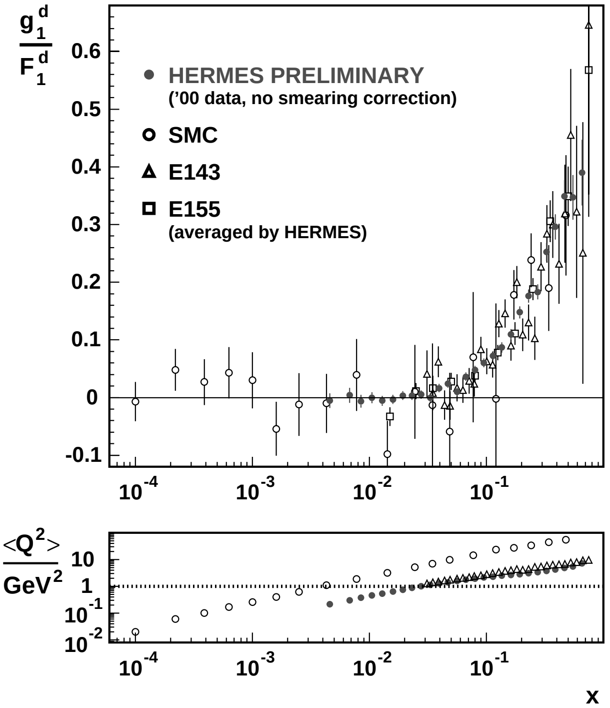

Fig. 1. HERMES preliminary data on the structure function ratio g_1^d/F_1^d as a function of the Bjorken scaling variable x compared to previous measurements at SLAC (E143, E155) and CERN (SMC). The data are given at the measured Q^2 values indicated in the lower panel.

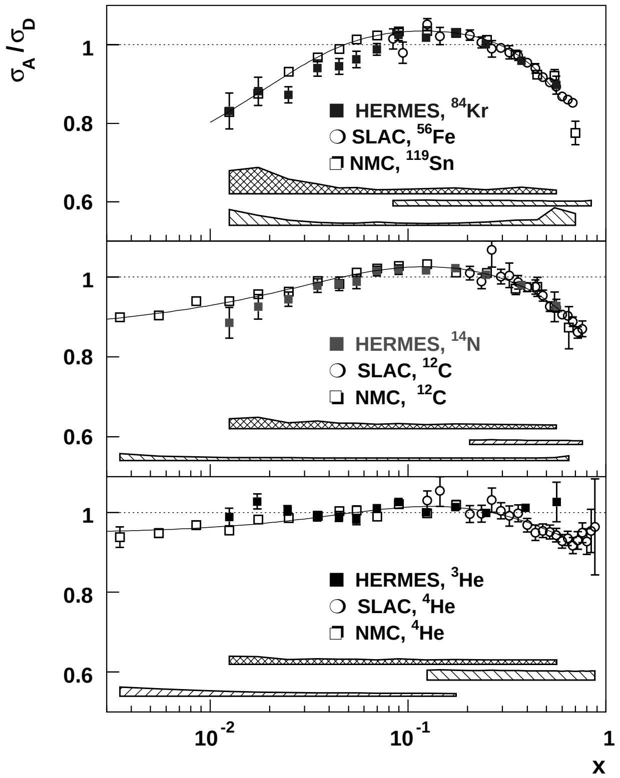

Fig. 2. Ratio of Born cross-sections of inclusive DIS from nuclei A and D *versus* x. The error bars represent the statistical uncertainties, the systematic uncertainties are given by the error bands.

came as a surprise when the EMC experiment at CERN [4] covering a larger kinematic range discovered that only a small fraction of the nucleon spin is actually carried by quarks, contrary to the naive QPM and its relativistic extensions. Since then, a wealth of experimental data using DIS of polarized lepton beams on polarized targets has been collected by experiments at SLAC [5], CERN [6] and DESY [7,8] confirming the initial results.

Figure 1 shows the preliminary HERMES data on the ratio g_1^d/F_1^d of the polarized to unpolarized structure function as a function of the Bjorken scaling variable x at measured Q^2. These very precise results are based on more than 10 million events taken on a polarized deuterium target in the kinematic range $Q^2 > 0.1$ GeV^2 and $W^2 > 3.24$ GeV^2. Despite the differences in the average values of $\langle Q^2 \rangle$ per bin, there is observed a good consistency of the HERMES data with earlier measurements of SMC at larger values of $\langle Q^2 \rangle$ and measurements at SLAC taken at similar values of $\langle Q^2 \rangle$. The close agreement is a clear indication for very similar Q^2-evolutions for both the polarized and unpolarized structure functions over the range in Q^2 covered by these experiments.

The dependence of the nucleon structure function $F_2(x)$ on the mass A of the target nucleus came as a big surprise [9]. At large x, this effect became known as the EMC effect, while it is attributed to shadowing at low x. With $F_2(x)$ being found A-dependent, further light can be shed onto this problem by investigating whether this dependence is the same for the longitudinal and transverse constituents. A possible difference can be investigated by measuring the ratio of the longitudinal-to-transverse DIS cross-sections $R = \sigma_L/\sigma_T$. Extending previous studies, HERMES has provided values of ratios of R taken on ^{3}He, ^{14}N and ^{84}Kr to R determined on deuterium in the kinematic regime $x < 0.06$ and $Q^2 < 1$ GeV^2 [10]. Note that all cross-sections were defined as cross-sections per nucleon and converted to cross-sections for isoscalar nuclei, *i.e.* the measured cross-sections are divided by the atomic number A and corrected for any difference in the number of protons and neutrons.

The results extracted for the ratios of DIS cross-sections on nuclei to those on the corresponding sets of free nucleons are shown in fig. 2. They are in reasonable agreement with the results from previous measurements. No significant Q^2-dependence is observed over the wide range in Q^2 covered by the combined data sets of HERMES and NMC. Values for the ratio R_A/R_D with R being the ratio of longitudinal-to-transverse DIS cross-sections are found to be consistent with unity even over the extended kinematical range down to $x = 0.01$ and $Q^2 = 0.5$ GeV^2.

3 Semi-inclusive scattering

Inclusive and semi-inclusive polarized DIS of polarized leptons on polarized targets is the main experimental basis for the present understanding of the spin structure of

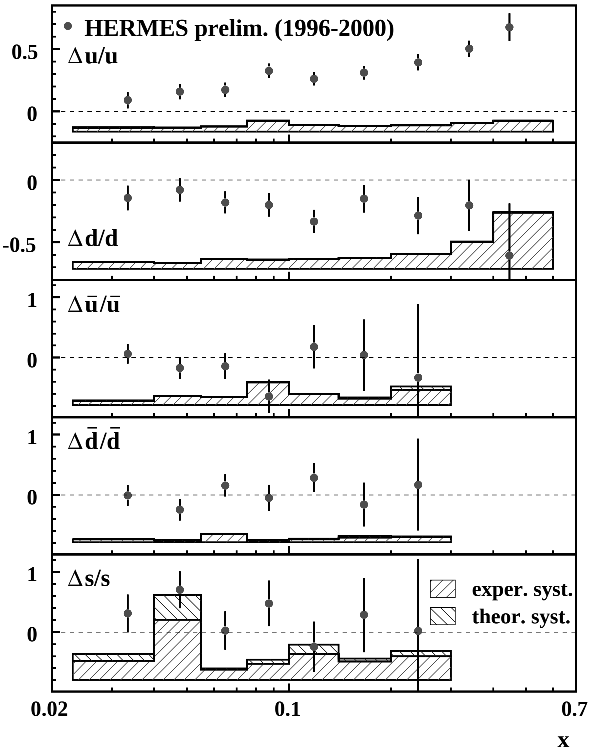

Fig. 3. HERMES preliminary results on the polarization of $u, \bar{u}, d, \bar{d}$ and $(s+\bar{s})$ quark flavors *versus* x. The error bars are statistical, while the shaded bands indicate the systematic uncertainty of the results. The contribution labeled "theor. syst." gives the uncertainty due to the use of two different unpolarized parton densities [11].

the nucleon. Precise measurements on polarized structure functions using inclusive data were presented in the previous section. The quark helicity distributions Δq are accessed by semi-inclusive scattering of polarized leptons on polarized nucleons using the leading hadron to provide a flavor tag for the struck quark. The HERMES spectrometer has a large enough acceptance to detect and identify hadrons coincident with the scattered lepton. The installation of a Ring Imaging Čerenkov detector in 1998 allows the identification and separation of pion, kaons and protons essentially over the whole momentum range. Thus, HERMES is well suited to perform these measurements. By selecting a leading hadron, a tag on the flavor of the struck quark inside the target nucleon is possible allowing for a flavor decomposition of the quark contributions to the nucleon spin. According to the favored fragmentation process, the charge of the leading hadron and its valence quark composition provide sensitivity to the flavor of the struck quark, as is transparent within the QPM. This flavor tagging probability is determined by simulation using the Lund string fragmentation model. Together with the measured asymmetries, this allows the extraction of Δq_f in LO QCD.

HERMES has measured double-spin asymmetries of inclusive and semi-inclusive cross-sections for the production of charged hadrons in deep inelastic scattering of polarized positrons on polarized hydrogen and deuterium targets, in the kinematic range $0.023 < x < 0.7$ and $1\ \mathrm{GeV}^2 < Q^2 < 15\ \mathrm{GeV}^2$. For the data taken on the deuterium target, a RICH detector provides the complete identification of pions and kaons. Taking the precise measurement of the polarized cross-sections asymmetries A_1^d on deuterium presented above and A_1^p on hydrogen together with the semi-inclusive measurements, quark polarizations are extracted separately for the $u, \bar{u}, d, \bar{d}$ and $(s+\bar{s})$ flavors in a LO QCD analysis. The detailed description of the basis of this procedure can be found in ref. [12]; its extension is given in ref. [13].

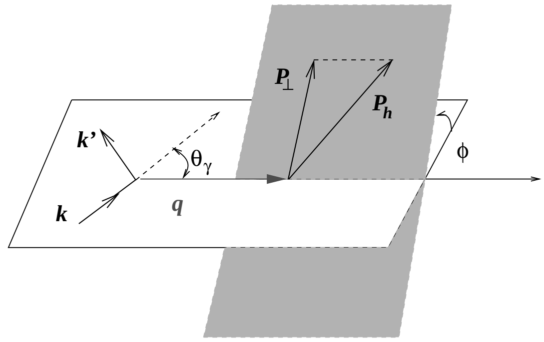

Fig. 4. The kinematics planes (scattering and hadronic plane) and definition of the azimuthal angle ϕ for hadron production in semi-inclusive DIS.

Preliminary results on the polarization of $u, \bar{u}, d, \bar{d}$ and $(s+\bar{s})$ quark flavors *versus* x are shown in fig. 3. The polarization of the up quarks is found to be positive over the whole measured range. The down-quark polarization ranges between -0.1 and -0.4 almost independently of x. For the light sea quarks the polarization is compatible with zero, while for the strange quarks a slightly positive polarization is favored within the measured range. Within the total uncertainty however, the polarization of the strange quarks is also zero.

In an infinite momentum frame these quark helicity distributions Δq describe the probability to find a quark with its longitudinal spin aligned to the nucleon spin. In order to obtain a complete leading-twist description of the spin structure of the nucleon, a second spin-dependent quark distribution is needed. This so-called transversity δq describes the probability to find a transversely polarized quark in a nucleon polarized transverse to its momentum [14].

While the momentum and helicity distributions are well measured, transversity is still unknown. Since transversity is a chiral odd object, it can only be measured in combination with another chiral odd object. One suggestion to access transversity experimentally is via semi-inclusive measurements which involve a chiral odd fragmentation function, the so-called Collins function [15]. The chiral odd quark distribution function h_1 together with the chiral odd Collins fragmentation function $H_1^{\perp}$ can produce a target-spin dependence in the azimuthal distribution of the produced mesons around the scattering plane. One experimentally accessible quantity

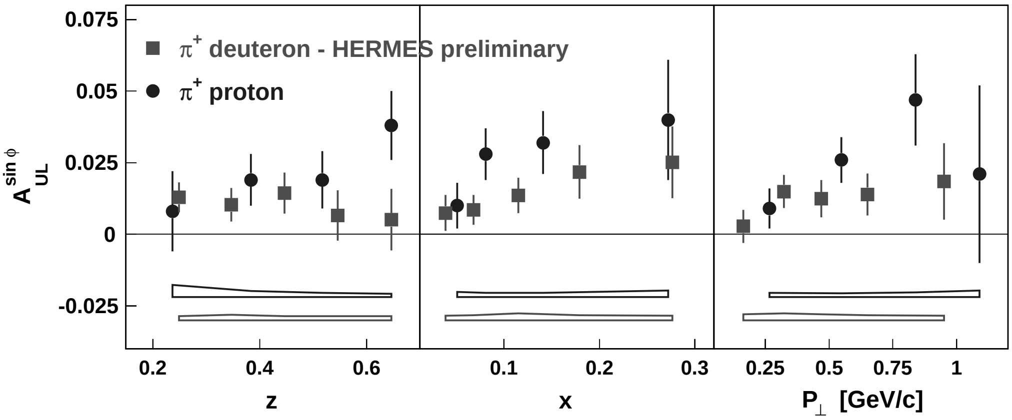

Fig. 5. $A_{UL}^{\sin\phi}$ as a function of $z, x, P_\perp$ for π^+ produced on the proton and the deuteron. The upper and lower bands represent the systematic uncertainties for both targets, respectively.

is the single-spin asymmetry $A_{UL}^{\sin\phi}$ for unpolarized beam and longitudinal polarized target as a function of the azimuthal angle ϕ between the scattering plane and the hadronic plane. The corresponding kinematics and the definition of planes and angles is depicted in fig. 4.

The magnitude of $A_{UL}^{\sin\phi}$ depends on the unknown functions h_1 and $H_1^\perp$. Little experimental data are yet available for hadron leptoproduction in DIS from a transversely polarized target. However, two complementary measurements strongly suggest that $H_1^\perp$ might be non-zero: i) azimuthal correlations measured between particles produced from opposite jets in Z decay [16] and ii) the observation of a single–target-spin asymmetry in semi-inclusive pion production on a longitudinally polarized proton target [17]. $A_{UL}^{\sin\phi}$ has been studied at HERMES for both the proton and the deuteron targets and for various types of hadrons. Here only the results for the production of π^+ are discussed. The results for $A_{UL}^{\sin\phi}$ are shown in fig. 5 as a function of the pion fractional energy z, the Bjorken scaling variable x and the pion transverse momentum $P_\perp$.

The observed kinematic dependences support the theoretical expectations. The increase of $A_{UL}^{\sin\phi}$ with x suggests that the single-spin asymmetries are associated with valence quark contributions. This is expected for h_1 as well. The dependence on $P_\perp$ can be related to the dominant kinematic role of the quarks intrinsic transverse momentum, as expected by the Collins model for $H_1^\perp$. The non-vanishing asymmetries on both targets suggest that both h_1 and $H_1^\perp$ are non-zero and that $H_1^\perp$ is sizeable, giving a strong motivation for the upcoming running of HERMES with a transversely polarized hydrogen target. Studies have shown that HERMES and COMPASS could make the first measurement of the transverse u quark distribution δu [18].

By carrying out semi-inclusive DIS experiments on nuclear targets, it is possible to study the hadronisation process during the time period after the quark has been struck by the virtual photon [19]. In the simplest scenario the nucleus acts as an ensemble of targets with which the struck quark or the produced hadrons may interact. If an interaction occurs, the number of leading hadrons produced per

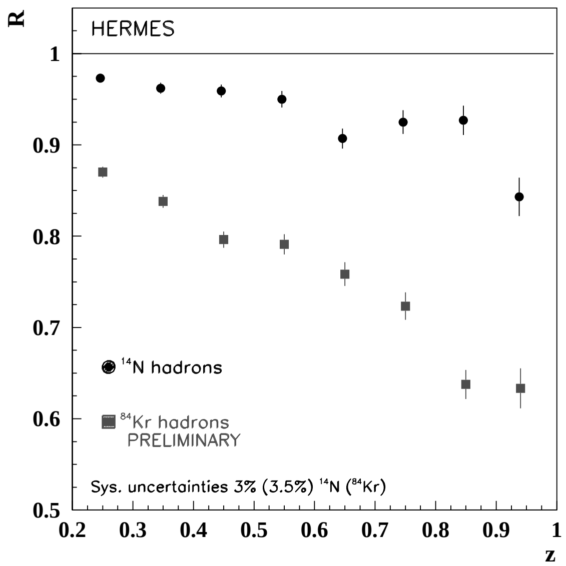

Fig. 6. Hadron multiplicity ratio as a function of z measured on ^{14}N and ^{84}Kr.

DIS event and per nucleon is reduced compared to that for a free nucleon. The reduction of hadron multiplicity depends on the distance traversed by the struck quark before the hadron is formed, the (unknown) quark-nucleon cross-section and the (known) hadron-nucleon cross-section. Hence, measurements of the multiplicity of hadrons produced on nuclei can provide information on the space-time structure of the hadronisation process. Data taken on ^{14}N studying these multiplicities as a function of diverse kinematical variables were presented by HERMES in ref. [20]. Recently, data taken on ^{84}Kr and shown together with previous data as a function of the hadron energy fraction z in fig. 6 became available.

The attenuation observed on ^{84}Kr is much stronger than on ^{14}N. The observed ratio $R_{\mathrm{Kr}}/R_{\mathrm{N}} = 3.7$ is within the experimental uncertainties in agreement with the theoretical estimate of $R_{\mathrm{Kr}}/R_{\mathrm{N}} = 3.3$ based on an $A^{2/3}$ scaling predicted in ref. [21]. This model is based on medium modifications of parton fragmentation functions induced by multiple scattering and gluon bremsstrahlung calculated within a systematic expansion of higher-twist contributions. These calculations describe also the shape of the data well.

4 Exclusive reactions

Inclusive and semi-inclusive measurements cannot access the orbital angular momentum of the quarks and gluons. The only viable although indirect access to this quantity known presently is through Generalized Parton Distributions [22,23]. The cleanest process to measure these is the Deeply Virtual Compton Scattering, the electroproductions of a real photon [24]. This process, however, leads to the same final state as the Bethe-Heitler process. Hence, these two processes interfere quantum-mechanically. At HERMES energies, the comparatively large BH amplitude serves as a lever arm to access the small DVCS amplitude. Furthermore, this interference allows direct access to both the real and imaginary parts of the scattering amplitude which are linked directly to linear combinations of the Generalized Parton Distributions. Two observables making use of this interference were studied at HERMES so far: the beam helicity asymmetry and the beam charge asymmetry on an unpolarized target as a function of the azimuthal angle ϕ (see fig. 4 for a definition of ϕ).

In these asymmetries, a direct access to linear combinations of GPDs is provided via the interference term on the amplitude level. The beam charge asymmetry A_C, directly linked to the real part of the DVCS-BH interference amplitude, is expected to show a $\cos\phi$ behavior. The preliminary HERMES result is shown in fig. 7. A clear $\cos\phi$ behavior is observed. A value of $A_C^{\cos\phi} = 0.11 \pm 0.04 \pm 0.03$ is found. The total uncertainty is dominated by the low-statistics electron data sample. Details on this analysis can be found in ref. [25]. An improved measurement is expected from HERMES Run II, where extended periods with either beam charge are foreseen.

Data on the beam helicity asymmetry were recently published by HERMES [26]. These data are directly linked to the imaginary part of the DVCS-BH interference amplitude and compare favorably with calculations within the GPD framework. Since then, new data have been analyzed. The preliminary results are shown together with the published data in fig. 8. The two data sets are in agreement.

HERMES will continue its efforts on studying hard exclusive reactions. First interesting data are expected from hard exclusive meson production on the transversely polarized target. In the year 2004 HERMES will install a recoil detector around the target cell with special emphasis to improve kinematical resolution as well as the exclusivity and thus the systematical accuracy of the present DVCS measurement. The planned running period using this detector will also enhance the statistical precision significantly. Measurements with these detector will allow a fine binning in all relevant kinematical variables and a large sensitivity to model calculations [27].

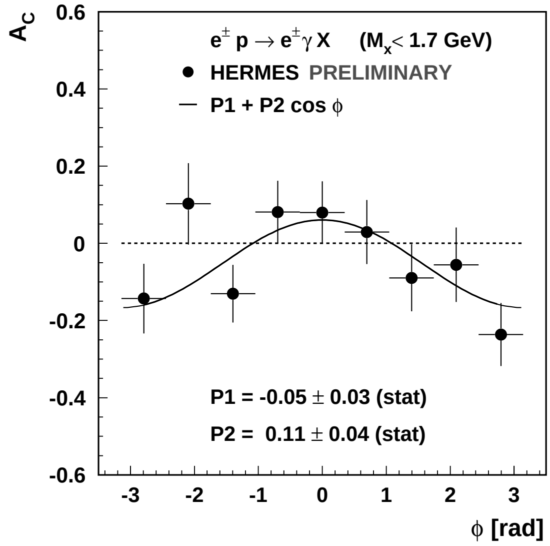

Fig. 7. Preliminary HERMES data for the beam charge asymmetry A_C. The curve represents a fit to the data.

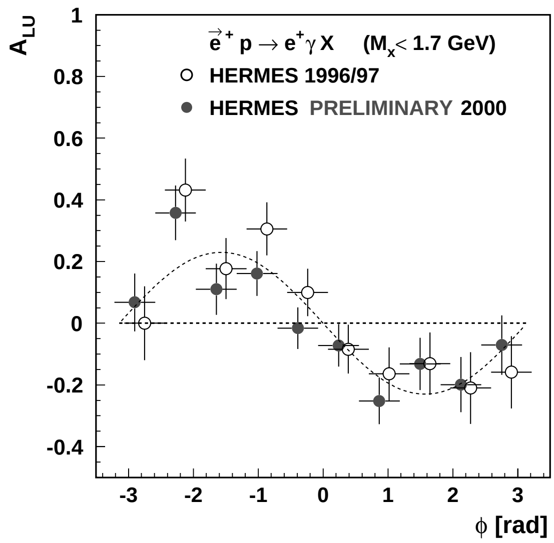

Fig. 8. Preliminary HERMES data for the azimuthal dependence of the single-spin asymmetry A_{LU} together with the data published in ref. [26]. The dashed line represents a fit to the new data.

5 Summary

HERMES has collected a large data sample of inclusive and semi-inclusive DIS data on pure targets of polarized hydrogen and deuterium and on various unpolarized nuclei. From the polarized inclusive data precise results on the polarized structure function g_1^d were extracted. Inclusive data on unpolarized targets extend the kinematic range of measurements of the isoscalar cross-section ratio F_2^A/F_2^d to previously unexplored regions. Combining polarized semi-inclusive data taken on polarized hydrogen and deuterium, the polarized parton densities for $u, \bar{u}, d, \bar{d}$ and $(s + \bar{s})$ flavors have been extracted in the range $0.023 < x < 0.6$ within a LO QCD analysis. These data were also used to extract the single-spin asymmetry $A_{UL}^{\sin\phi}$ which is linked to transversity h_1 and the Collins fragmentation function $H_1^{\perp}$. The current data suggest that $H_1^{\perp}$ is sizeable providing a strong motivation for HERMES Run II on a transversely polarized hydrogen target. Semi-inclusive data from unpolarized nuclei with full hadron identification have been analyzed. They show an attenuation of hadron production as a function of the hadrons' energy fraction z and can be described by a model based on medium modifications of parton fragmentation functions induced by multiple scattering and gluon bremsstrahlung. First data are provided for the beam charge and beam spin asymmetries in DVCS. This reaction is closely related to the novel framework of GPDs and show satisfactory agreement with present calculations. HERMES plans the installation of a recoil detector to improve both the systematical precision and kinematical resolution to study this new class of reactions.

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