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POLARIZED SEMI-INCLUSIVE DEEP-INELASTIC SCATTERING ON TRANSVERSELY AND LONGITUDINALLY POLARIZED NUCLEONS AT HERMES

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The HERMES experiment has measured double spin asymmetries in the cross section for deep-inelastic scattering of longitudinal polarized positrons off longitudinal polarized hydrogen and deuterium targets. From these asymmetries, based on inclusive and semi-inclusive measurements, polarized quark distribtions were extracted as a function of x. Single-spin azimuthal asymmetries in semi-inclusive pion production were measured by the HERMES experiment for the first time, with a transversely polarized hydrogen target. Two different sine-dependencies were extracted which can be related to the quark transversity distribution $h_1^q(x)$ and the Sivers function $f_{1T}^{\perp}(x)$.

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1 Introduction

The quark substructure of hadrons is often probed in the Deep-Inelastic Scattering (DIS) of leptons *i.e.* the absorption by a quark of a spacelike virtual photon with large squared four-momentum $q^2 = -Q^2$. The physics of DIS is most transparent in the frame in which the nucleon target moves contrary to the photon with "infinite" momentum. In this frame the transverse motion of the partons is "frozen" during the interaction time. After averaging over this intrinsic transverse momentum p_T, three fundamental distributions in longitudinal quark momentum can be interpreted as number densities. Two of these have been experimentally explored in some detail: the unpolarized density $q(x)$ and the helicity density $\Delta q(x) \equiv q^{\overset{\rightarrow}{\Rightarrow}}(x) - q^{\overset{\rightarrow}{\Leftarrow}}(x)$ reflecting the probability of finding the helicity of the quark to be the same as that of the target nucleon. Here $x = Q^2/(2P\cdot q)$ is the dimensionless Bjorken scaling variable representing the momentum fraction of the target nucleon carried by the parton, where P is the four-momentum of the target proton. Viewed in the same helicity basis, the third distribution known as transversity δq or alternatively h_1^q has no probabilistic interpretation. However, it is a number density in a basis of transverse spin eigenstates: $\delta q = q^{\uparrow\Uparrow} - q^{\uparrow\Downarrow}$. The transversity and helicity densities may

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differ because dynamically bound light quarks move relativistically, in which regime boosts and rotations don't commute.

Inclusive and semi-inclusive longitudinally polarized measurements at HERMES allowed for the first time a precise flavor decomposition of the quark helicity densities $\Delta q(x)$. In addition the very first measurement of the transversity δq could be accomplished at HERMES, using a transversely polarized target.

2 The HERMES spectrometer

The HERMES experiment makes use of the 27.5 GeV positron beam of the HERA storage ring at DESY. For the $\Delta q(x)$ measurements the HERMES gaseous target contained longitudinally polarized hydrogen or deuterium, while transversely polarized hydrogen was used for the measurement of δq. The HERMES spectrometer [1] consists of two identical halves located above and below the positron beam pipe. The lead glass calorimeter, hodoscope scintillators and transition radiation detector can be used for lepton-hadron separation, with an average efficiency of 98% at a hadron contamination of less than 1%. The Ring-Imaging Čerenkov detector [2] provides separation of (charged) pions, kaons and protons over most of the kinematic acceptance of the spectrometer. Neutral pions are selected by their decay in two photons, which are identified in the calorimeter. The spectrometer magnet is a dipole magnet with a field integral of 1.3 Tm.

3 Measurement of the quark helicity distributions

Until recently, all of the information on the flavor decomposition of quark helicity distributions resulted from analyses of inclusive data under the assumption of SU(3) symmetry. In order to improve the sensitivity to flavor dependencies, the HERMES experiment uses semi-inclusive deep-inelastic scattering to determine the separate contributions $\Delta q_f(x)$ of the quarks and antiquarks of flavor f to the total spin of the nucleon. By means of the technique of flavor tagging, individual spin contributions can be determined from spin asymmetries of hadrons with the appropriate flavor content. The measured semi-inclusive spin asymmetry, $A_\parallel^h$, and the corresponding photon-nucleon asymmetry, A_1^h, for the hadron of type h are given by

$$A_\parallel^h = \frac{1}{\langle P_B P_T \rangle} \cdot \frac{(N^h/L)^{\overleftarrow{\rightarrow}} - (N^h/L)^{\overrightarrow{\rightarrow}}}{(N^h/L)^{\overleftarrow{\rightarrow}} + (N^h/L)^{\overrightarrow{\rightarrow}}}, A_1^h = \frac{A_\parallel^h}{D(1+\eta\gamma)}. \tag{1}$$

Here $(N^h/L)^{\overleftarrow{\rightarrow}}$ and $(N^h/L)^{\overrightarrow{\rightarrow}}$ are the number of DIS events with coincident hadrons for target polarization parallel (anti-parallel) to the beam polarization. The beam and target polarizations are denoted by P_B and P_T and L is the luminosity. D is the depolarization factor for the virtual photon and η and γ are kinematic factors. In leading order QCD, assuming the validity of factorization, one can derive a relationship between the photon-nucleon asymmetry A_1^h and the quark helicity distributions

$$A_1^h(x) = \frac{1+R(x)}{1+\gamma^2} \sum_q P_q^h(x) \frac{\Delta q(x)}{q(x)}, \tag{2}$$

where all quantities were integrated at each x over the corresponding range of Q^2. The factor $R = \sigma_L/\sigma_T$ is the ratio of the longitudinal to transverse photoabsorption cross sections. The purities P_q^h describe the probability that a hadron h originates from an event where a quark of flavor q was struck. They depend on the fragmentation functions, the unpolarized parton densities and in case of the deuterium target on the relative fluxes of hadrons originating from the two nucleons. To account for the limited acceptance of the spectrometer, the purities were extracted from Monte Carlo simulations. Equation (2) can be generalized for a set of measured asymmetries combined into a vector $\vec{\mathcal{A}}$: $\vec{\mathcal{A}} = \mathcal{P}\vec{Q}$, where $\mathcal{P}$ is now a matrix of purities and $\vec{Q}$ is the vector of quark polarizations to be determined. For the recent analysis [3], $\vec{Q} = (\Delta u/u, \Delta d/d, \Delta\bar{u}/\bar{u}, \Delta\bar{d}/\bar{d}, \Delta s/s = \Delta\bar{s}/\bar{s})$. The vector $\vec{\mathcal{A}}$ contains the semi-inclusive asymmetries of both proton and deuteron targets as well as the inclusive asymmetries within the same kinematic range. From the solution vector $\vec{Q}$ obtained by minimization methods, the quark helicity distributions $\Delta q(x)$ can be derived by multiplying each of the quark polarizations with the corresponding unpolarized parton distribution function at fixed Q^2 = 2.5 GeV^2. The polarizations are assumed to be Q^2 independent. Fig. 1 shows the results of this procedure for the x-weighted distributions $x\Delta q(x)$. Note that in contrast to earlier experimental analyses [4] and the LO QCD fits to inclusive data [5, 6] overlaid in Fig. 1, in the HERMES analysis no assumptions were made on the symmetry of the sea flavors, except the symmetry assumption of the strange quark sea. The helicity density of the u quark is found to be positive and large at $x > 0.1$, while that of the d quark is negative and rather flat in x. The helicity densities of the light sea quarks are compatible with zero. Contrary to the small negative strange sea polarization resulting from QCD fits to inclusive data, the strange quark helicity appears slightly positive. However, within the uncertainties there is no disagreement with the QCD fits.

4 Single spin azimuthal asymmetries and transversity

In DIS chirality is conserved, thus transversity (which is chiral-odd) can be measured only in a process in which it is combined with another chiral-odd object. Using a transversely polarized nucleon target, the transversity enters the semi-inclusive cross section combined with the chiral-odd fragmentation function (FF) $H_1^\perp$ known as the Collins function [7] which correlates the transverse polarization of the struck quark with the transverse momentum of the produced hadron. In addition, a second distribution function (DF) $f_{1T}^\perp$ - the so-called Sivers function - appears in the cross section together with the unpolarized FF. This DF describes the probability to find an unpolarized quark in a transversely polarized nucleon.

Since the Sivers and the Collins functions do not survive integration over the intrinsic transverse momentum p_T of the quark and its transverse momentum k_T acquired in the fragmentation process, respectively, the tools to measure the objects of interest are azimuthal asymmetries which depend on two azimuthal angles ϕ and ϕ_S. The angle ϕ is defined between the lepton scattering plane containing the incoming and outgoing lepton and the hadron production plane spanned by the produced hadron and the virtual photon. ϕ_S is the angle between the scattering plane and the transverse spin component of the target nucleon. The luminosity normalised count rate asymmetry between opposite target spin states (↑,↓), weighting each event with the

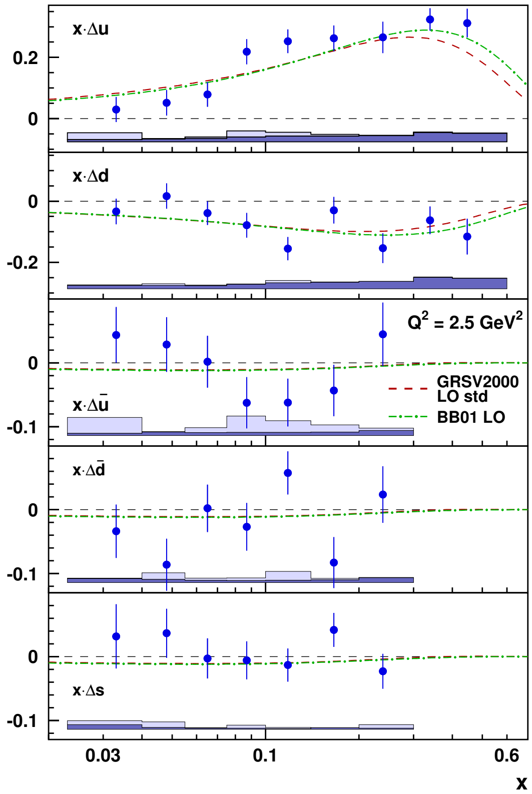

Fig. 1. The x-weighted polarized parton distributions $x\Delta q$ extracted from HERMES semi-inclusive asymmetries on polarized hydrogen and deuterium targets. The data are shown at fixed $Q^2 = 2.5$ GeV^2. The curves show results from LO QCD fits to previously published inclusive data from [5] (GRSV 2000, dashed) and [6] (Blümlein-Böttcher, dot-dashed). The light shaded error band shows the systematic uncertainties arising from uncertainties of the fragmentation model, the dark shaded area shows the ones due to the uncertainties of the experimental asymmetries.

transverse momentum of the detected hadron $P_{h\perp}$, can be written as

$$A(\phi,\phi_S) = \frac{1}{S_\perp}\frac{\sum_{i=1}^{N^\uparrow(\phi,\phi_S)} P_{h\perp\, i} - \sum_{i=1}^{N^\downarrow(\phi,\phi_S)} P_{h\perp\, i}}{N^\uparrow(\phi,\phi_S) + N^\downarrow(\phi,\phi_S)}$$

$$\sim \sin(\phi+\phi_S)\sum_q e_q^2 \cdot h_1^q(x)\cdot H_1^{\perp(1)q}(z) + \sin(\phi-\phi_S)\sum_q e_q^2\cdot f_{1T}^{\perp(1)q}(x)\cdot D_1^q(z).$$

Here $S_\perp$ is the transverse polarization of the target and the superscript (1) denotes the p_T^2- or k_T^2-moment of the DF or FF, respectively. The kinematical variable z is the fraction of the photon energy transferred to the final state hadron. The $P_{h\perp}$ weighting is performed in order to avoid assumptions [8] about the quark transverse momentum dependencies. The amplitudes of each

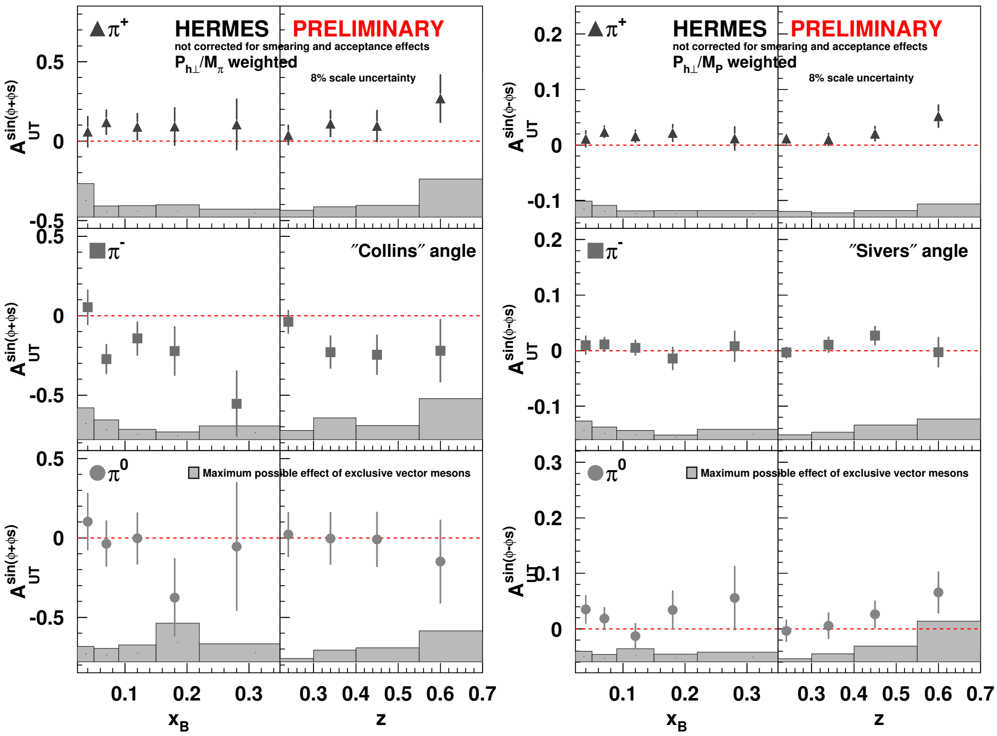

Fig. 2. Asymmetry moments $A_{UT}^{sin(\phi\pm\phi_S)}$ for π^+, π^- and π^0 mesons depending on x and z.

sine term are proportional in leading order to the product of a DF and a FF. These sine-moments $A_{UT}^{sin(\phi\pm\phi_S)}$ (the subscript UT indicates the unpolarized beam and the transversely polarized target) of the asymmetry were extracted performing a two-dimensional fit of the experimentally measured $A(\phi,\phi_S)$. In Fig. 2 these moments are plotted for the production of π^+, π^-, and π^0 mesons. The moments $A_{UT}^{\sin(\phi+\phi_S)}$ containing the product of transversity and Collins function are positive for π^+, negative for π^- and consistent with zero for π^0. Positive asymmetries $A_{UT}^{\sin(\phi-\phi_S)}$ are measured for π^+ and π^0 whereas the moment is consistent with zero for π^-. The grey error bands represent the maximum possible effect of pions coming from the decay of diffractive vector mesons.

5 Conclusions

The HERMES collaboration has measured inclusive and semi-inclusive asymmetries on longitudinally polarized proton and the deuterium targets. Polarized parton densities were extracted from these asymmetries. The densities of the u and d quark were determined with good precision to be positive and negative respectively. The polarized quark sea was decomposed for the first time. Within the experimental uncertainty these densities $\Delta\bar{u}$, $\Delta\bar{d}$ and $\Delta\bar{s} = \Delta s$ are compatible with zero.

A measurement with transverse target polarization of single spin asymmetries for semi-inclusive electroproduction of pions has for the first time disentangled two different phenomena, the Collins FF and Sivers DF. A significant positive π^+ asymmetry has been observed, corresponding to a negative value of the Sivers DF.

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