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THE SPIN PUZZLE:
RECENT RESULTS FROM THE HERMES EXPERIMENT

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The HERMES experiment at DESY has been designed to study the spin structure of the nucleon. Impressive results have been obtained not only in inclusive processes but also for semi-inclusive and exclusive processes in deep-inelastic lepton scattering, helping to clarify the spin puzzle of the nucleon.

Keywords: nucleon spin; semi-inclusive; transversity.

1. The Spin Puzzle

Polarised deep-inelastic lepton scattering (DIS) has been the primary experimental basis for our present understanding of the spin structure of the nucleon. In a formal way, the nucleon's total spin of 1/2 can be decomposed into its constituents:

$$< s_N > = \frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + \Delta L = \frac{1}{2}(\Delta u_v + \Delta d_v + \Delta q_s) + \Delta G + \Delta L_q + \Delta L_G$$

where the three terms are the contributions from the quark and gluon spins and from their orbital angular momentum. The total quark helicity $\Delta\Sigma$ is defined as the sum of the helicity distributions of up, down and strange quarks and antiquarks. The HERMES experiment can probe all the single pieces of this relation. In fact from inclusive DIS measurements it is possible to obtain the polarised structure function g_1, related to $\Delta\Sigma$; by semi-inclusive DIS (SIDIS) measurements with observation of the produced hadron, the helicity distributions of individual quark flavours in the nucleon can be extracted; by measuring the asymmetry for DIS of a transversely polarised target it is possible to access the transversity distribution, which probes the spin of the nucleon while switching off the gluon contribution; moreover, the possible role of quark orbital angular momentum is addressed by studying (almost) exclusive reactions, which can be interpreted in terms of the Generalized Parton Distributions (GPDs).

HERMES is located in the East Hall of the HERA *ep* collider at DESY in Hamburg, Germany and it is taking data since 1995, immediately after its installation. HERMES scatters longitudinally polarised electron and positron beams of 27.5

GeV from longitudinally or transversely polarised targets internal to the HERA storage ring. The HERMES spectrometer is described in detail in[1]. It is a forward spectrometer in which both scattered positron and produced hadrons are detected within an angular acceptance of $\pm$ 170 mrad horizontally and $\pm$ (40-140) mrad vertically. The beam line separates the spectrometer in an upper and lower part with independent detector systems and trigger for the top and bottom sections. Drift chambers before and after the spectrometer magnet are used for the track reconstruction and momentum analysis. The Particle Identification (PID) is obtained by a transition radiation detector, an electromagnetic calorimeter with a preshower detector preceding it and a threshold Cherenkov counter, upgraded to a dual Ring Imaging System (RICH) in 1998: the use of these detectors in combination allows the identification of leptons with an efficiency of 98% or better with a hadron contamination of less than 1%. The RICH provides full separation between charged pions, kaons and protons over essentially the entire momentum range of the experiment: this is a mandatory prerequisite in *flavour tagging*, which is the technique used to relate a produced hadron of a given type to a struck quark of a given flavour.

2. Inclusive DIS: The Spin Structure Function g_1

The structure function $g_1(x)$ contains information on the helicity-dependent parton contribution to the deep-inelastic lepton scattering cross section. Final results on $g_1(x, Q^2)$ are obtained from a refined analysis of data taken with longitudinally polarised hydrogen and deuterium targets in the kinematic range $Q^2 >0.1$ GeV^2 and $W >1.8$ GeV. For both targets, g_1 is determined from the ratio g_1/F_1, which is approximately equal to the virtual photon asymmetry A_1 measured via the longitudinal cross section asymmetry $A_{\parallel}$. The neutron spin structure function is obtained from a ^{3}He target. Statistical better results are obtained when g_1^n is obtained from the difference of g_1^d and g_1^p. The measured asymmetries have been corrected for detector smearing and QED radiative effects in a rigorous model-independent unfolding procedure in which Monte Carlo is used to compute the migration of events between kinematical bins. A compilation of the world data on the x-weighted structure function g_1 is presented in Fig. 1 (left panel) at their measured Q^2: all the data are in excellent agreement with each other, even though the Q^2 values of the measurements are different, indicating that the scaling violations are small over the accessible Q^2 range. The HERMES data set is the most precise and complete. From the polarised structure function it can be deduced that only about 30% of the nucleon spin is carried by the quarks.

3. Semi-Inclusive DIS: The Flavour Decomposition

Semi-inclusive DIS (SIDIS) is a powerful tool to determine the separate contributions $\Delta q_f(x)$ of the quarks and antiquarks of flavour f to the total spin of the nucleon. The hadron asymmetries $A_1^h(x)$ are related to the quark distributions
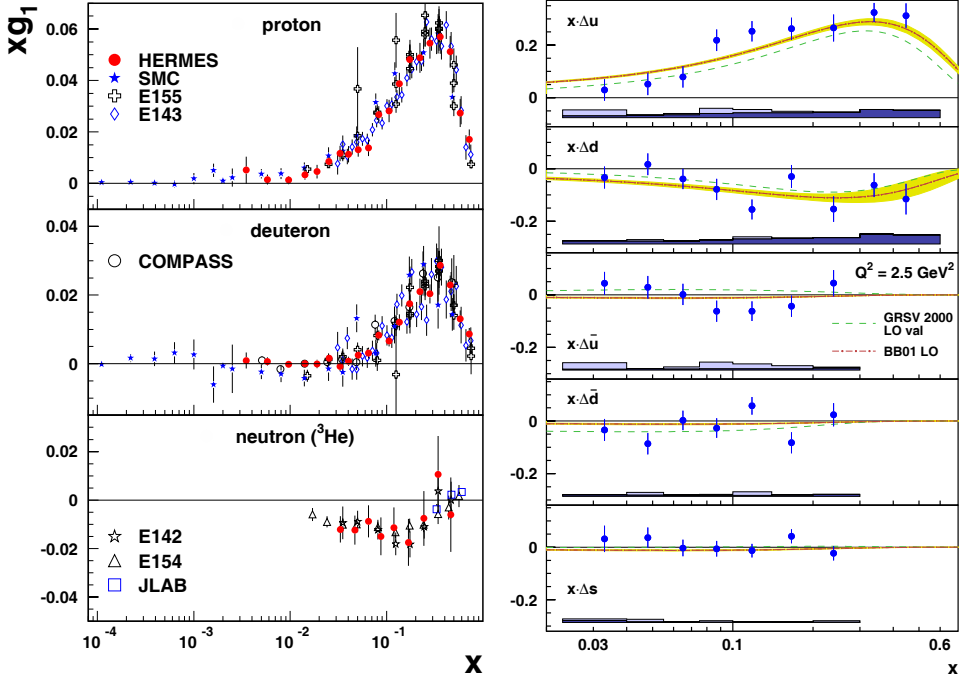
Fig. 1. *Left*: World data on the x weighted spin structure function g_1 for the proton (*top*), deuteron (*middle*) and neutron (*bottom*). *Right*: The quark helicity distributions $x\Delta q(x, Q_0^2)$ evaluated at a common value of Q_0^2=2.5 GeV^2 as a function of x. The curves show LO QCD analyses of polarised data.

$\Delta q_f(x)$ through the so-called purity matrix P_f^h, which describes the probability that a hadron h originates from a quark of flavour f. They have been extracted using Monte Carlo simulations with the limited acceptance of the spectrometer taken into account. For the unpolarised quark distributions the CTEQ5L parameterization was used, for the fragmentation functions the parameters of the LUND string fragmentation model implemented in JETSET have been tuned to fit the hadron multiplicities measured. The quark helicity distributions $\Delta q(x)_f(x)$ can be derived by multiplying each of the quark polarizations with the corresponding unpolarised parton distribution function at fixed Q^2=2.5 GeV^2. For the first time, a global analysis of the smearing unfolded inclusive and semi-inclusive spin asymmetries for π^+, π^-, K^+ and K^- has been carried out for longitudinally polarised targets of hydrogen and deuterium[2]. The results of the decomposition are presented in Fig. 1 (right panel) and compared to LO QCD analyses. No assumptions have been made on the symmetry of the sea flavours, except that $\Delta\bar{s}/\bar{s}$ is assumed to be zero. For $x >$0.3, the polarization of the sea flavours was fixed to zero and the small variations from this value have been included in the systematic errors. As expected, the helicity density of the u quark is found to be positive and large at $x >$0.1, and that of the d quark is negative, while the helicity densities of the light sea quarks are

found to be compatible with zero. For sea quarks there is no disagreement with the QCD fits within the experimental uncertainties.

4. Transverse Spin Asymmetries

Apart from the structure functions $F_1(x)$ and $g_1(x)$, there is a third leading order structure function $h_1(x)$, known as transversity distribution, which is required to provide a complete description of the quark structure of the nucleon. It is related to a forward scattering amplitude involving helicity flip of both quark and target nucleon. However, in a basis of transverse eigenstates it becomes a number density reflecting the difference in probabilities to find quarks in a transversely polarised nucleon with their spin aligned to the spin of the nucleon and quarks with their spin anti-aligned. Since hard interactions conserve chirality, transversity has so far remained unmeasured in inclusive processes due to its chiral-odd nature. Contrary to the longitudinal case, this distribution can only be accessed in SIDIS processes as both the quark and nucleon need to flip their spin. Hence, additional angular momentum needs to be absorbed by a hadron produced in the reaction. The transverse polarization of the struck quark can influence the transverse momentum component of the produced hadron orthogonal to the virtual photon, thereby leading to an azimuthal angle ϕ dependence of the cross section about the virtual photon direction in the lepton scattering plane. A fragmentation function (FF) describing this spin-momentum correlation is known as the Collins FF $H_1^\perp(z)$: it represents the interference of two scattering amplitudes with different imaginary parts giving rise to single-spin asymmetries. Azimuthal spin asymmetries can also be generated by the T-odd Sivers distribution function (DF) $f_{1T}^\perp(x, k_T)$ that appears in the cross section together with the unpolarised FF $D(z)$. The $f_{1T}^\perp(x, k_T)$ describes a correlation between the transverse polarisation of the target nucleon and the intrinsic transverse momentum of the struck quark. The Collins and Sivers mechanisms can be separated in a transversely polarised target since they have a different azimuthal dependence with respect to the axis of transverse polarisation. While the Sivers mechanism give rise to a $\sin(\phi - \phi_S)$ behavior, the Collins mechanism exhibits a $\sin(\phi + \phi_S)$ behaviour in the azimuthal angle, with ϕ being the azimuthal angle between the hadron production plane and the lepton scattering plane and ϕ_S the angle between the lepton scattering plane and the transverse spin component of the target nucleon. The extracted Collins and Sivers moments[3] for charged pions are shown in Fig. 2 as a function of x, z and transverse hadron momentum $P_{h\perp}$. The Collins amplitude, shown in the left panel, is positive for π^+ and negative for π^-. These opposite signs can be expected if the transversity densities resemble the helicity densities, although the absolute magnitude of the π^- asymmetry is surprising, suggesting a substantial disfavoured Collins function with opposite sign to that of the favoured function. The Sivers amplitude, shown in the right panel, is significantly positive for π^+, providing an indication for nonzero orbital angular momentum of quarks in the nucleon and the first evidence of a T-
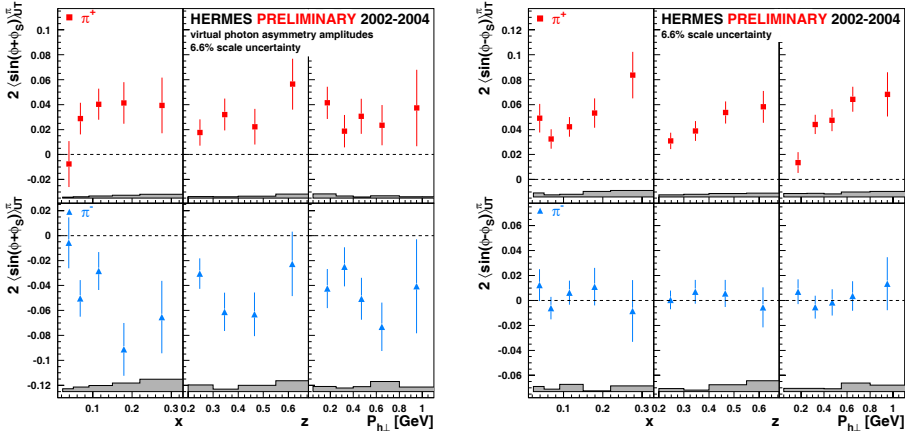
Fig. 2. Virtual photon Collins (*left*) and Sivers (*right*) moments for charged pions as a function of x, z and transverse hadron momentum $P_{h\perp}$. Error bars represent the statistical uncertainties, while the lower band represents the maximal systematic uncertainty due to acceptance and detector smearing as well as possible contributions from $\cos\phi$ moments of the unpolarised cross section. The 6.6% scale uncertainty is due to the target polarization.

odd DF, while it is consistent with zero for π^-. The apparently negative value of the naively T-odd Sivers DF describing this correlation can in future be compared to its appearance in polarised Drell Yan processes, where it is predicted to have opposite signs due to its fundamental time reversal invariance in QCD.

5. Exclusive Processes

The measurement of hard exclusive reactions provides a new tool in understanding the structure of the nucleons in terms of the so-called Generalised Parton Distributions (GPDs). They represent a new theoretical development, which encompasses both the well known parton distribution functions and the nucleon form factors as limiting cases and they are sensitive to partonic correlations. By making use of different polarization states, targets and final states hadrons the experiments are sensitive to different combinations of GPDs. Since in the present data set the recoiling target nucleon is not detected, the exclusivity of the processes has been ensured by the missing mass technique or missing energy technique, and the non-exclusive background has been subtracted.

5.1. *Deeply Virtual Photon Scattering*

The cleanest process to measure GPDs is Deeply Virtual Compton Scattering (DVCS), the hard electroproduction of a real photon. DVCS amplitudes can be determined through a measurement of the interference between the DVCS and the Bethe Heitler (BH) processes, in which the photon is radiated from a parton and from a lepton, respectively. As the interference term in the cross section depends
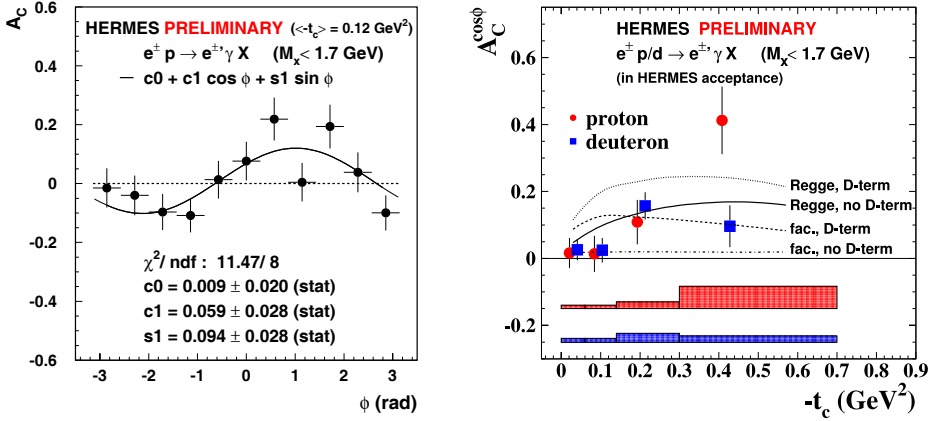
Fig. 3.   *Left*: Beam charge asymmetry (BCA) for hard electroproduction of photon off the proton as function of the azimuthal angle ϕ. the solid curve shows the result of the indicated fit. *Right*: The $\cos\phi$ amplitude of the BCA for proton and deuterium as a function of $-t$. The curves represent the model calculations based on different GPD parameterizations.

on the polarization and charge of the beam, and the azimuthal angle ϕ of the emitted photon, measurements of the ϕ dependence of the beam spin and beam charge asymmetry make it possible to obtain data that are proportional to the real and imaginary parts, respectively, of the DVCS amplitudes. A measurement of the beam charge asymmetry requires the availability of both electron and positron beams at the same experimental setup: both beams are available at HERA.

5.1.1. *Beam Charge Asymmetry*

Results on azimuthal asymmetries with respect to the beam helicity have been already published by HERMES[4]. In Fig. 3 the first measurement of the beam charge asymmetry A_C from a hydrogen and deuterium target is reported. On the left panel the A_C for the proton as a function of the azimuthal angle ϕ is shown: the asymmetry is fitted with the function $P_1 \cos\phi + P_2 \sin\phi$ because the two beams have different average polarizations and also the $\sin\phi$ dependent part of the interference term contributes. On the right panel the $\cos\phi$ amplitude derived from the two parameter fits and corrected for background is shown as a function of the four momentum transfer to the target $-t$ for the proton and deuteron. The comparison with a GPD based model calculations assuming a factorised or Regge inspired t dependence with and without the D-term contribution is done, showing that the beam charge asymmetry has high sensitivity to different GPD parameterizations[5].

5.1.2. *Target Spin Asymmetry*

Access to the GPD E can be gained through measuring the transverse target spin asymmetry in hard exclusive electroproduction of vector mesons where the asym-
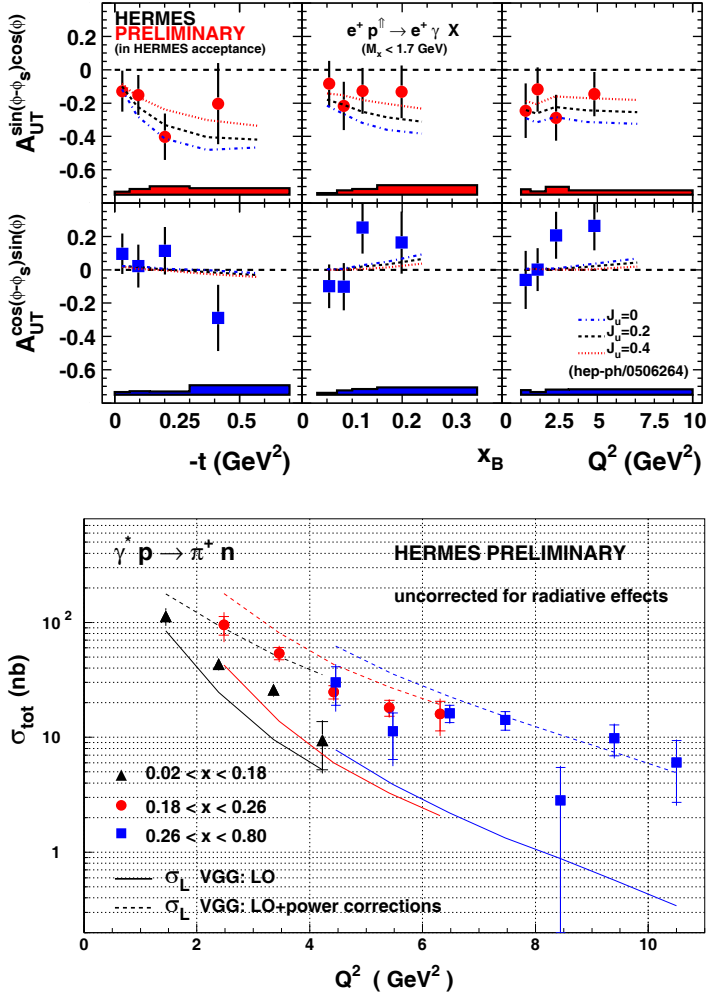
Fig. 4. *Up*: The $A_{UT}^{\sin(\phi-\phi_S)\cos\phi}$ moments as a function of $-t$, x and Q^2 compared to the predictions based on the VGG model. The symbol UT is related to the unpolarised beam and to the transversely target polarisation. *Down*: Total cross section for exclusive π^+ production as a function of Q^2 for three different ranges, integrated over t. The curves represent calculations based on a GPD model.

metry depends linearly on E. This observable also provides sensitivity to the total angular momentum carried by the u-quarks. A parameterization for GPDs has been proposed[6], where the GPD E is modelled using the quark total angular momentum J_u and J_d as free parameters. In Fig. 4 (upper panel) the first results obtained at HERMES[7] on the transverse target spin asymmetry associated with DVCS on the proton are shown and a model dependent constraint on J_u obtained by comparing the HERMES results and theoretical predictions based on the above mentioned GPD model. The data analysed represent only 50% of the full data set.

5.2. *Exclusive Pion Production*

GPDs can also be accessed in the hard electroproduction of mesons. While exclusive vector meson production is only sensitive to unpolarised GPDs, pseudoscalar meson production is sensitive to polarised GPDs without the need for a polarised target or beam. The factorisation theorem for hard exclusive production of meson has been proven for longitudinal photons only. However, the transverse contribution to the cross section is predicted to be suppressed by a power of $1/Q^2$ with respect to the longitudinal one which is expected to fall like $1/Q^6$. The total cross section for exclusive π^+ production is shown on the bottom panel of Fig. 4 as a function of Q^2 for three different x ranges. Data are not corrected for radiative effects and they are compared to a calculation of the longitudinal part of the cross section computed in a GPD model. At HERMES the separation of the transverse and longitudinal component of the cross section is not feasible. As said before, the data at large Q^2 are expected to be dominated by the longitudinal part. The full lines show the leading order calculations, the dashed lines include power corrections due to the intrinsic transverse momenta of the partons and due to soft overlap type contributions. All calculations have been performed at average x and Q^2 and integrated over t. The Q^2 dependence is in general agreement with the data. While the leading order calculations underestimate the data, the evaluation of power corrections appears to be overestimated. As the data contain some x dependence, a reduced cross section has been evaluated in order to remove kinematical factors which depend strongly on x. Within the uncertainties, the Q^2 dependence of the reduced cross section is in good agreement with the $1/Q^2$ theoretical expectation.

6. Outlook

The preliminary results shown will be improved with the inclusion of 2005 data.New precision data on hard exclusive reactions, extending the studies presented here, will be available with the help of the upgrade recoil detector, installed at the end of last year.

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