Eur Phys J A (2005) **24**, s1, 23–28
DOI: 10.1140/epjad/s2005-05-004-0

EPJ A direct
electronic only

Spin structure of the nucleon

Pasquale Di Nezza

Istituto Nazionale di Fisica Nucleare – Laboratori Nazionali di Frascati, via E. Fermi 40, I-00044 Frascati, Rome, Italy
e-mail: Pasquale.DiNezza@lnf.infn.it

Received: 24 September 2004 / Published Online: 8 February 2005

Abstract. HERMES is a second generation experiment to study the spin structure of the nucleon, in which measurements of the spin dependent properties of semi-inclusive deep-inelastic lepton scattering are emphasized. The first experimental results from measurements of single-spin asymmetries for pions and kaons in deep-inelastic scattering with transverse target polarization are discussed. Longitudinally polarized beam and target data provide information on the flavor decomposition of the polarized quark distributions in the nucleon and a first glimpse of the gluon polarization. Moreover, first preliminary results for the unpolarized $ep \to en\pi^+$ total cross section are presented and compared to Generalized Parton Distribution calculations.

PACS. 13.87.Fh – 13.60.-r – 13.88.+e

1 Introduction

In the last decades, one particular issue which has received much attention is how to perform measurements that dissect the spin structure of the nucleon, elucidating the role of the various quark flavors as well as that of the gluon field. These basic constituents are capable of contributing to the nucleon's spin both via their intrinsic spin as well as via their orbital motion:

$$\langle s^N{}_z \rangle = \frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + \Delta L_z, \qquad (1)$$

where the three terms are the quark and gluon spins, and the total orbital angular momenta of the quarks and gluons, respectively. From early measurements it was realized that a simple leading order considerations without the inclusion of contributions from gluons was too naive. More recent next-to-leading order treatments provide a picture more consonant with our present understanding of QCD. The key to further progress is more specific probes of the individual contributions of (1) to the proton spin. Determination of the polarization of the gluons is clearly of very high priority, and in addition, a more precise measurement will eliminate a major current ambiguity in the implications of existing inclusive data. A more direct determination of the strange quark polarization, Δs, will avoid the need for the use of data from hyperon decay and the assumption of SU(3) symmetry. Measurements which are sensitive to quark charges will allow the separation of quark and antiquark polarizations. The HERMES experiment attempts to achieve these objectives, by emphasizing semi-inclusive deep-inelastic scattering in which a π or K is observed in coincidence with the scattered lepton. The added dimension of flavor in the final hadron provides a valuable probe of the flavor dependence and other features of polarized parton distributions. In the sections which follow, we present a brief description of the HERMES experiment followed by reports on recent results transverse spin physics, on the flavor decomposition of polarized parton distributions, gluon polarization, and exclusive pion production. Indeed, such studies appear to mark a major advance in unraveling the spin structure of the nucleon.

2 The HERMES experiment

The HERMES experiment employ a transversely or longitudinally polarized gas target which intercepts the $E =$ 27.6 GeV longitudinally polarized beam of the HERA positron storage ring. The beam can become longitudinally polarized by emission of spin-flip synchrotron radiation and by spin rotators. The typical asymptotic beam polarization is $P_b = 0.55$ with a rise time of about 20 min. An open-ended cell is fed by an atomic-beam source based on Stern-Gerlach separation with hyperfine transitions. The nuclear polarization of the atoms is flipped at 60 s time intervals, and the average target polarization was $S_T = 0.78$ in the transverse case and S_L ranging between 0.75 and 0.85 for the longitudinally polarized one. Scattered positron beam and coincident hadrons are detected by the HERMES spectrometer [1]. Its geometrical acceptance covers the range $40 < |\theta_y| < 140$ mrad and $|\theta_x| < 170$ mrad where θ_x and θ_y are projections of the polar scattering angle. The scattered positrons are identified with 98% efficiency and less than 1% hadron contamination by means of an electromagnetic calorimeter [2], a transition-radiation detector, a preshower scintillator counter, and a dual-radiator ring-imaging Čerenkov detector [3].

3 Transverse spin physics

A complete description of the quark structure of the proton at leading order in deep-inelastic scattering (DIS) requires three flavor-dependent parton distribution functions (PDF's). The most familiar of these is the unpolarized distribution function $q(x, Q^2)$. It describes the quark momentum distribution in the infinite momentum frame. In the quark parton model, the F_2 structure function is given by $F_2(x) = x\sum_q e_q^2 q(x)$. The second PDF is the longitudinal polarized distribution function $\Delta q(x, Q^2)$ which describes the longitudinal helicity distribution of the quarks in a proton polarized parallel to its momentum. In terms of the polarized PDF's, the polarized proton structure function is given by $g_1(x) = 0.5\sum_q e_q^2 \Delta(x, Q^2)$. In recent years much has much has been learned about g_1 from studies of polarized DIS [4]. The third PDF is the transversity distribution function $\delta q(x, Q^2)$ which measures the quark helicity distribution in a proton polarized perpendicular to the proton momentum at infinite momentum. Until now its properties have been unobserved.

For non-relativistic quarks, Δq and δq would be identical since by means of commuting rotations and Euclidean boosts one can convert a longitudinally polarized proton into a transversely polarized proton at infinite momentum. However, because the internal motion of the quarks is relativistic, this is not true and a comparison of the two PDFs will reflect the relativistic character of quark motion in the proton. In contrast to its chiral-even partners, q and Δq, the transversity distribution is chiral-odd. This property of transversity makes its measurement difficult since hard QCD and electroweak processes preserve chirality. It decouples from inclusive DIS and other deep inelastic processes. However, it is of considerable interest because of its unique properties. The Q^2 evolution of $\delta q(x, Q^2)$ is much simpler than that of its leading order partners, because it does not couple to gluons. Lattice gauge calculations can provide reliable estimates of its first moment, the quark tensor charge.

Due to its chiral-odd nature, transversity can be measured in a process in which is combined with another chiral-odd object. Using a transversely polarized nucleon target, the transversity enters the cross section combined with the chiral-odd FF $H_1^\perp$ known as Collins function [6,8].

The Collins mechanism is of special interest because it provides a direct probe of δq. It produces a correlation in the fragmentation process between the axis of transverse target spin and the vector $\mathbf{P}_\pi \times \mathbf{q}$ where $\mathbf{P}_\pi$ is the momentum of final state hadron and $\mathbf{q}$ is the virtual photon momentum, Fig. 1. Because it is a chiral-odd correlation it combines with δq to provide an observable which is accessible in semi-inclusive DIS. The characteristic signature for the Collins effect in semi-inclusive scattering of an unpolarized lepton beam by a transversely polarized target producing a pseudoscalar meson is a $sin(\phi+\phi_S)$ variation in the azimuthal distribution [9].

Azimuthal spin asymmetries can also be generated by the T-odd Sivers distribution function $f_{1T}^\perp(x, k_T)$ [5] that appears in the cross section together with the unpolarized FF, D_q^h. The DF $f_{1T}^\perp(x, k_T)$ describes a correlation between the transverse polarization of the target nucleon and the $\mathbf{p}_T$ of the struck quark. This $\mathbf{p}_T$ survives fragmentation to be inherited by the hadron $\mathbf{P}_{h\perp}$. The characteristic signature for this mechanism is a target spin asymmetry with a $sin(\phi - \phi_S)$ variation [7].

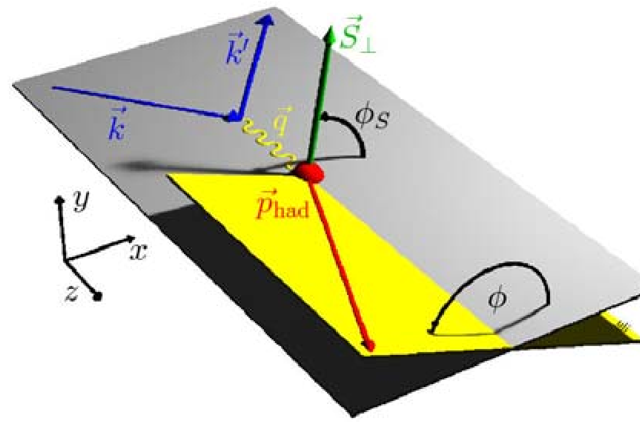

Fig. 1. The definitions of the azimuthal angles of the hadron production plane and the axis of the relevant component $\mathbf{S}_\perp$ of the target spin, relative to the plane containing the momentum $\mathbf{k}$ ($\mathbf{k}'$) of the incident (scattered) lepton

Measurements of spin asymmetries with transverse target polarization, permit one to use the variation in the two azimuthal angles $\phi+\phi_S$ and $\phi-\phi_S$ to distinguish the Collins and Sivers effects. The quantity measured is the two dimensional asymmetry

$$A_{UT}^h(\phi, \phi_S) = \frac{1}{|S_T|}\frac{\left(N_h^\uparrow(\phi, \phi_S) - N_h^\downarrow(\phi, \phi_S)\right)}{\left(N_h^\uparrow(\phi, \phi_S) + N_h^\downarrow(\phi, \phi_S)\right)} \qquad (2)$$
$$= A_C^h sin(\phi+\phi_S) + A_S^h sin(\phi-\phi_S)$$

where $N_h^{\uparrow(\downarrow)}(\phi, \phi_S)$ is the semi-inclusive luminosity-normalized yield in each target spin state, and ϕ_S always indicates the spin direction of the $\uparrow$ state. Measurement with an unpolarized beam and transversely polarized target is indicated by the UT subscripts. This asymmetry is then fit with a sum of contributions from two sinusoidal dependences as show above. Monte Carlo simulations confirm that extraction of both contributions is made from this fit without measurable cross-contamination even in the case that their magnitudes in the acceptance are very different.

The extracted asymmetries [10] in the form of azimuthal moments averaged over the experimental acceptance and selected ranges of x and $z = E_h/\nu$, with ν the energy of the virtual photon, of $0.023 < x < 0.4$ and $0.2 < z < 0.7$ are shown in Fig. 2. The bottom section of Fig. 2 presents simulations based on PYTHIA6 [11], tuned for HERMES kinematics, of the fractions of the semi-inclusive pion yield from exclusive production of vector mesons, the asymmetries of which are poorly determined. The averaged Collins moment for π^+ is positive at 0.021 ± 0.007(stat), while it is negative at -0.038 ± 0.008(stat) for

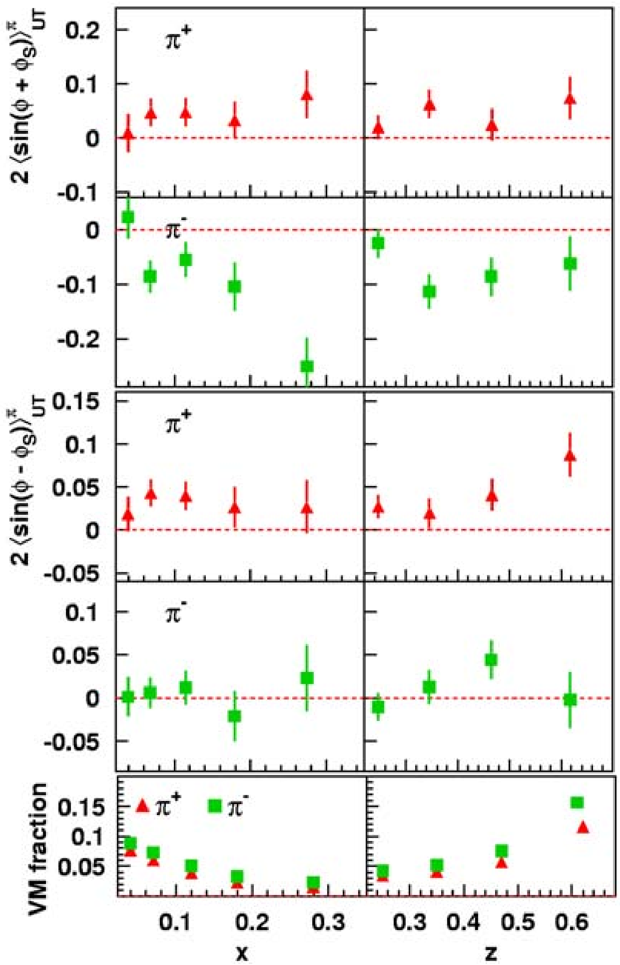

Fig. 2. Virtual-photon Collins (Sivers) moments for charged pions as labeled in the *upper* (*middle*) *panel*, as a function of x and z. The *error bars* represent the statistical uncertainties. In addition, there is a common 8% scale uncertainty in the moments. The *lower panel* shows the relative contributions to the data from simulated exclusive vector meson production

π^-. The suggestion that transversity distributions should resemble helicities distributions, at least in their general trends is not born out by the data. To the extend that δu is positive and δd is negative the data is similar to model predictions [12]. However, the magnitude of the negative π^- moment appears to be at least as large as that for π^+. This trend becomes more pronounced as the magnitude of the transverse moments increase at large x where valence quark effects dominate, as they do in previously measured longitudinal spin asymmetries [13]. Unlike the case of π^+ where u-quark dominance is expected, large negative π^- moments are a surprise, because neither quark flavor dominates π^- production, and one expects $|\delta d| < |\delta u|$ in analogy with $|\Delta d| < |\Delta u|$. In addition, the Collins moments shown in the right portion of Fig. 2 do not show large increase with increasing z which has been predicted [14] on the basis of a corresponding z dependence found for the Collins fragmentation function.

The HERMES results for the Sivers moment are very suggestive. The value found is positive and nonzero at 0.017 ± 0.004(stat) for π^+, while the π^- moment is consistent with zero: 0.002 ± 0.005(stat). The large moment for π^+ appears to provide the first evidence in leptoproduction for the T-odd Sivers parton distribution. Because the π^+ moment is dominated by *up* quarks, with the sign convention which has been adopted in relating the azimuthal asymmetries to the the parton distributions [15] a positive asymmetry implies a negative value for the Sivers function of this flavor. However, a substantial contamination of pions from ρ^0 decay are present. Studies to date of a small sample of exclusive ρ^0 events in which both pions are detected suggest that this asymmetry extracted for the π^+ in the same manner as in the HERMES semi-inclusive analysis also has a significant positive $\langle\sin(\phi - \phi_S)\rangle^h_{UT}$ asymmetry which could complicate the interpretation of the data for the Sivers effect.

4 Flavor decomposition

Semi-inclusive deep-inelastic scattering is a powerful tool 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 directly from spin asymmetries of hadrons with the appropriate flavor content. The measured semi-inclusive photon-nucleon asymmetry, A_1^h, for the hadron of type h can be written as a function of the quark and antiquark polarization $\Delta q_f(x)$ by

$$A_1^h(x,Q^2,z) = \frac{\sum_f e_f^2 \Delta q_f(x,Q^2) \cdot D_f^h(z,Q^2)}{\sum_{f'} e_{f'}^2 q_{f'}(x,Q^2) \cdot D_{f'}^h(z,Q^2)} \qquad (3)$$

$$= \sum_f P_f^h(x,Q^2,z) \frac{\Delta q_f(x,Q^2)}{q_f(x,Q^2)}. \qquad (4)$$

The quantities, $P_f^h(x,Q^2,z)$, are the integrated purities, representing the probability that the quark, q_f was struck in the DIS event.

This formalism has been used in the HERMES analysis to make a flavor decomposition into polarized quark distributions for $u, \overline{u}, d, \overline{d}$, and $s + \overline{s}$. The purities were obtained with a Monte Carlo calculation which used CTEQ5 leading order parton distributions [16] and a LUND fragmentation model [17] tuned to HERMES kinematics.

For the first time, a global analysis of inclusive spin asymmetries and semi-inclusive spin asymmetries for π^+, π^-, K^+, and K^- has been carried out for longitudinally polarized targets of hydrogen, and deuterium [22]. The results of the decomposition obtained by solving (4) are presented in Fig. 3. A symmetric strange sea polarization was assumed, i.e. $\Delta s/s = \Delta\overline{s}/\overline{s}$. The polarization $\Delta u/u(x)$ was found to be positive and rising over the entire range in x, while $\Delta d/d(x)$ is negative. These first results on the individual sea quark polarizations $\Delta\bar{u}/\bar{u}(x)$, $\Delta\bar{d}/\bar{d}(x)$, and $\Delta s/s(x)$ are consistent with zero. The triplet strength

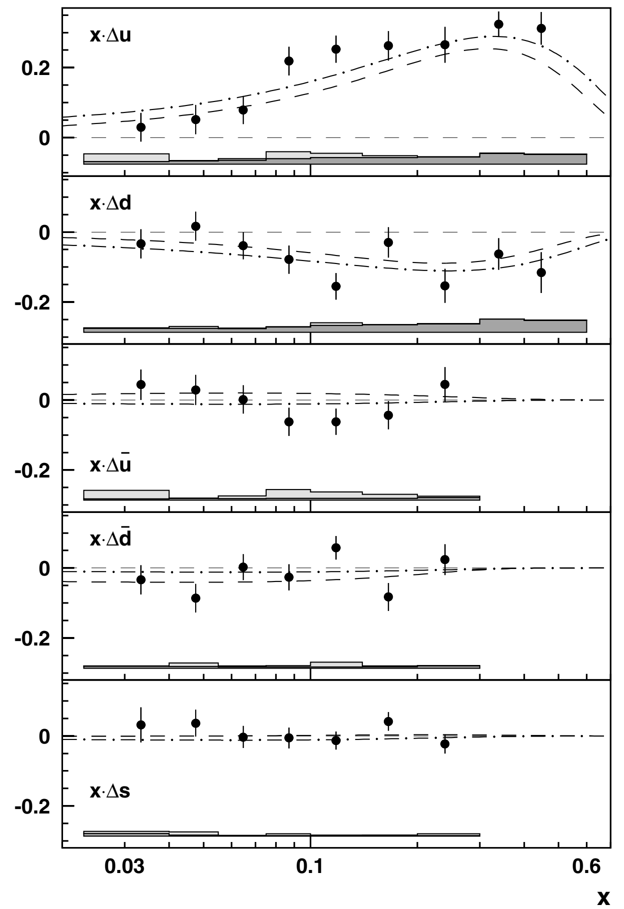

Fig. 3. The x-weighted polarized quark densities. The plots show a five parameter fit to the data assuming a symmetric strange sea polarization. The data have been evolved to a common $Q^2 = 2.5$ GeV^2. The *dashed line* shows a GRSV2000 [18] parameterization, and the *dashed-dotted curve* an alternate parameterization of Bluemlein and Boettcher [19]

$\Delta q_3 = \Delta u - \Delta d$ extracted from the HERMES data is in agreement with the Bjorken sum rule.

The first direct experimental extraction of the helicity density asymmetry $\Delta\bar{u}(x) - \Delta\bar{d}(x)$ in the light quark sea, which is predicted to be non zero by many models in analogy to the unpolarized sector ($\bar{u}(x) \neq \bar{d}(x)$), does not establish broken $SU(2)$ flavor symmetry, as shown in Fig. 4. The data disfavor the substantial positive asymmetry predicted by the χQSM model [20] and are consistent with the small negative asymmetry characteristic of the meson cloud model [21].

5 Gluon polarization

The analysis of the Q^2 evolution of inclusive spin asymmetries[23,24] suggest that the first moment of the gluon polarization, ΔG is positive and large, although the precise value is poorly constrained. A direct measurement of ΔG is of high priority in understanding the nucleon spin, and much effort is focused on its measurement. HERMES has exploited this sensitivity by measuring the spin

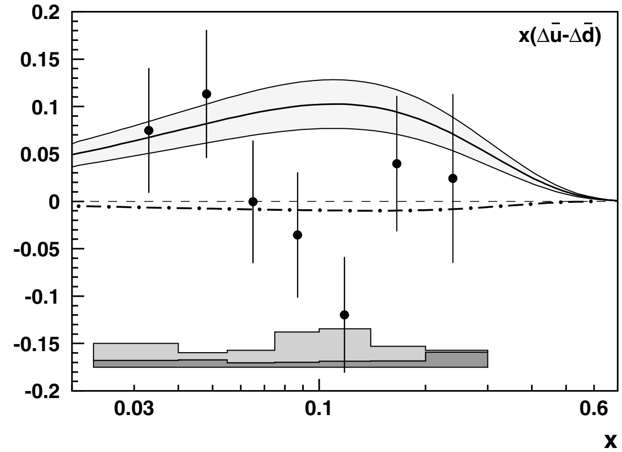

Fig. 4. The flavor asymmetry in the helicity densities of the light sea evaluated at Q_0^2=2.5 GeV^2. The data are compared with predictions in the χQSM [20] and a meson cloud model [21]. The *solid line* with the surrounding *shaded band* show the χQSM prediction together with its $\pm 1\,\sigma$ uncertainties while the *dash–dotted* line shows the prediction in the meson cloud model

asymmetry in photoproduction of pairs of high-p_T hadrons produced on a polarized hydrogen target. Events are selected by requiring at least two hadrons of opposite charge with an invariant mass assuming both hadrons to be pions of $M_{\pi\pi} > 1.0$ GeV to suppress contributions from vector mesons. While a number of processes can, in principle, contribute the asymmetry for high-p_T hadron pairs, Monte-Carlo simulations using LEPTO and PYTHIA event generators [25] show that only photon-gluon fusion (PGF) and the QCD Compton effect (QCDC) generate significant asymmetries. The measured asymmetry can then be expressed in terms of the total quark polarization $\Delta q/q$ and the gluon polarization $\Delta G/G$.

In Fig. 5, $\Delta G/G$ as a function of x_G and for $p_T^{h^2} > 0.8$ GeV is shown. The resulting values [25] were then averaged to obtain the value $\Delta G/G = 0.41 \pm 0.18(stat) \pm 0.03(syst)$ for $\langle x_G \rangle = 0.17$ and $\langle \hat{p}_T^2 \rangle = 2.1$ GeV^2. Data suggest a substantial positive gluon polarization.

6 Exclusive π^+ total cross section

A new class of parton distribution has an extreme importance in the panorama of the spin physics. While the usual forward parton distribution functions (PDF's) give the probability of finding a quark with a momentum fraction $x = k/p$ in the nucleon, generalized parton distributions (GPD's) describe the removal of a quark $q(k - \frac{\Delta}{2})$ and implantation of $q'(k + \frac{\Delta}{2})$. At the amplitude level, the strong interest in GPD's comes, in part, from the consideration [28] that their second moments can be connected to the total angular momentum carried by the partons through the relation

$$J^q = \frac{1}{2}\Delta\Sigma + L^q \tag{5}$$

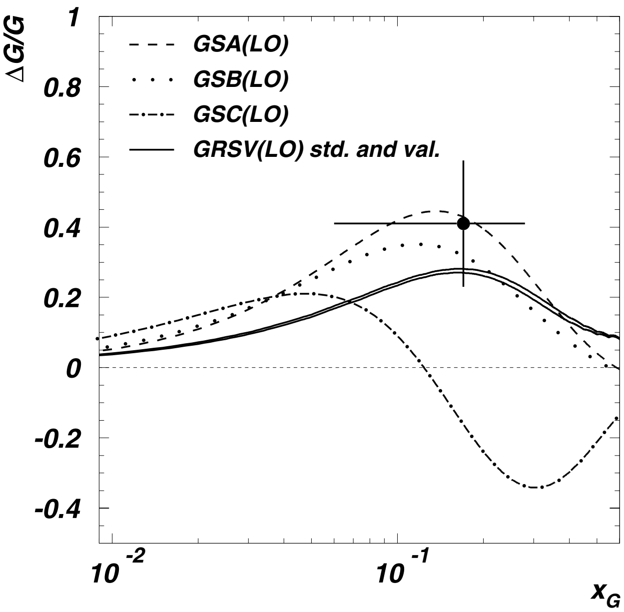

Fig. 5. The extracted value of $\Delta G/G$ compared with phenomenological QCD fits to a subset of the world's data on $g_1^{p,n}(x,Q^2)$. The *curves* are from [26,27] evaluated at a scale of 2 GeV^2. The error indicated on $\Delta G/G$ represents statistical and experimental systematic uncertainties only; no theoretical uncertainty is included

$$= \frac{1}{2}\int_{-1}^{1} x dx [H^q(x,\xi,t=0) + E^q(x,\xi,t=0)].$$

Thus, GPD's may provide a measure of the J^q and therefore with prior knowledge of $\Delta\Sigma$ (1), of the orbital angular momentum of the partons, L^q.

HERMES has already published results about reactions involving GPDs, like single-spin azimuthal asymmetries of pion [29], exclusive two-pion production [30] or Deep Virtual Compton Scattering [31]. One of the latest result is the first determination of the $ep \to en\pi^+$ total cross section [32]. While exclusive vector meson production is only sensitive to unpolarized GPDs (H and E), pseudoscalar meson production is sensitive to polarized GPDs ($\tilde{H}$ and $\tilde{E}$) without the need for a polarized target or beam. Moreover, in the case of π^+ production, the pseudoscalar contribution $\tilde{E}$ is dominated at low t by the pion-pole exchange, and therefore $\tilde{E}$ is related to the pion form factor. The recoiling neutron was not detected, and exclusive production of mesons was selected by requiring that the missing mass square (M_X^2) of the reaction $ep \to e\pi^+ X$ corresponds to the nucleon mass square. Due to the limited experimental resolution, the exclusive π^+ reaction cannot be separated from the neighboring channels (defined as non-exclusive) which can be smeared into the exclusive region. Therefore the process $ep \to e\pi^- X$ was used to subtract non-exclusive channels [29]. For the total cross section measurement, data from 1996 to 2000 on unpolarized and polarized hydrogen targets were used. Approximately 3.5 k exclusive π^+ were selected. The Q^2 dependence of the cross section has been determined for three different bins in x following:

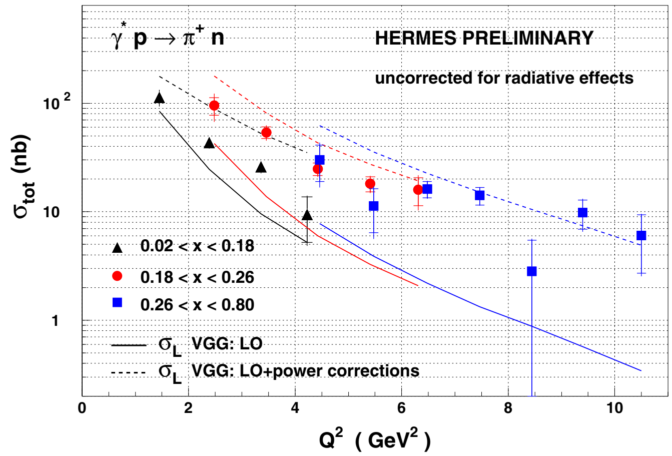

Fig. 6. Total cross section for exclusive π^+ production as function of Q^2 for three different x ranges and integrated over t. The *inner error bars* represent the statistical uncertainty and the outer error bars the quadratic sum of statistical and systematic uncertainty. The *curves* represent calculations based on a GPD-model [34]

$$\sigma^{\gamma^* p \to n\pi^+}(x,Q^2) = \frac{N_{\pi^+}^{excl}(x,Q^2)}{L\Delta x \Delta Q^2 \Gamma_V(\langle x\rangle, \langle Q^2\rangle)\kappa(x,Q^2)} \quad (6)$$

where $N_{\pi^+}^{excl}$ is the number of π^+ corrected for background, Γ_V is the virtual photon flux factor and κ is the probability to detect the scattered positron and the produced π^+. The detection probability has been determined using two exclusive Monte Carlos based on two different GPD parameterizations [33,34]. Figure 6 shows the Q^2 dependence of the total cross section for three different x ranges. These preliminary data have not yet been corrected for radiative effects. This correction has been roughly estimated to be as large as 20% showing almost no dependence on x or Q^2. The data have been compared to calculations for the longitudinal part of the cross section computed by GPD-model [34]. The total cross section can be written as $\sigma = \sigma_T + \epsilon\sigma_L$ where σ_T (σ_L) is the transverse (longitudinal) virtual photons contribution and ϵ is the virtual photon polarization parameter. Since the transverse contribution is predicted to be suppressed by a power of $1/Q^2$ with respect to the longitudinal one [35] and since ϵ ranges from 0.8 to 0.95, the data at larger Q^2 are expected to be dominated by the longitudinal part. The full lines in Fig. 6 show the leading-order calculation computed for the mean x and Q^2 corresponding to the data and integrated over t. The dashed lines include power corrections due to intrinsic transverse momenta of the partons in the nucleon and due to soft overlap type contributions. The Q^2 dependence is in general agreement with the theoretical expectation. But while the leading-order calculations underestimate the data, the evaluation of the power corrections appears too large.

7 Summary

In spite of many dedicated experiments, nucleon spin structure remains a complex and subtle problem. A detailed decomposition of the spin of the nucleon is still elusive. However, as the data from the HERMES experiment indicate, we are obtaining information on some of the central questions. The first measurements of asymmetries directly related to transversity and the Sivers function have been made. From the data on the Collins asymmetry the flavor-disfavored Collins fragmentation function appears to be opposite in sign to the favored one and large. The non zero Sivers asymmetries can be interpreted as a manifestation of quark orbital angular momentum. The results to date provide a demonstration of a new tool for studying the transverse structure of the nucleon.

Data collected on longitudinally polarized atomic hydrogen and deuterium gas targets were used to have, for the first time, the independent determination of five out of six quark polarizations in the nucleon. Quark polarizations $\Delta q/q(x)$ were obtained using purities that were calculated in a Monte Carlo based on parameterizations of unpolarized parton densities and a modeling of hadron multiplicities measured at HERMES. The polarization $\Delta u/u(x)$ was found to be positive and rising over the entire range in x, while $\Delta d/d(x)$ is negative. These first results on the individual sea quark polarizations $\Delta\bar{u}/\bar{u}(x)$, $\Delta\bar{d}/\bar{d}(x)$, and $\Delta s/s(x)$ are consistent with zero. The first direct experimental extraction of the helicity density asymmetry $\Delta\bar{u}(x) - \Delta\bar{d}(x)$ in the light quark sea, which is predicted to be non zero by many models in analogy to the unpolarized sector ($\bar{u}(x) \neq \bar{d}(x)$), does not establish broken $SU(2)$ flavor symmetry. The data disfavor the substantial positive asymmetry predicted by the χQSM model and are consistent with the small negative asymmetry characteristic of the meson cloud model.

A positive value for the gluon polarization has been extracted from a measurement of the spin asymmetry in the photoproduction of pair of hadrons at high p_T giving the first glimpse for the $\Delta G/G$.

Measurements of exclusive processes may provide sufficient access to GPD's to enable mapping out their variation with kinematic variables, posing a major challenge to experimenters. The preliminary total cross section for hard exclusive π^+ production has been measured as a function of Q^2 for different x values and has been compared to calculations based on a GPD-model showing a general agreement with the theoretical expectations.

References

1. HERMES Collab., K. Ackerstaff et al.: Nucl. Inst. & Meth. A **417**, 230 (1998)
2. H. Avakian et al.: Nucl. Inst. & Meth. A **417**, 69 (1998)
3. N. Akopov et al.: Nucl. Inst. & Meth. A **479**, 511 (2002)
4. B. Filippone, X. Ji: Ad. Nucl. Phys. **26**, 1 (2001)
5. D. Sivers: Phys. Rev. D **41**, 83 (1990)
6. M. Anselmino, M. Boglione, F. Murgia: Phys. Rev. D **60**, 054027 (1999)
7. M. Anselmino, F. Murgia: Phys. Lett. B **442**, 470 (1998)
8. J.C. Collins: Nucl. Phys. B **396**, 161 (1993)
9. D. Boer, P.J. Mulders: Phys. Rev. D **57**, 5780 (1998)
10. HERMES Collab., A. Airapetian et al.: submitted to Phys. Rev. Lett., hep-ex/0408013
11. T. Sjöstrand et al.: Comp. Phys. Commun. **135**, 238 (2001)
12. V. Barone, A. Drago, P.G. Ratcliffe: Phys. Rept. **359**, 1 (2002)
13. HERMES Collab., A. Airapetian et al.: Phys. Lett. B **562**, 182 (2003); Phys. Rev. D **64**, 097101 (2001); Phys. Rev. Lett. **84**, 4047 (2000)
14. A. Bacchetta, R. Kunda, A. Metz, P.J. Mulders: Phys. Rev. D **65**, 094021 (2002)
15. P.J. Mulders, R.D. Tangerman: Nucl. Phys. B **461**, 373 (1996)
16. H.L. Lai et al.: Eur. Phys. J C **12**, 375 (2000)
17. G. Ingelman, A. Edin, J. Rathsman: DESY Report **96-057**, (1996)
18. M. Glück, E. Reya, M. Stratmann, W. Vogelsang: Phys. Rev. D **63**, 094005 (2001)
19. J. Blümlein, H. Böttcher: Nucl. Phys. B **636**, 225 (2002)
20. B. Dressler, K. Goeke, M. Polyakov, C. Weiss: Eur. Phys. J C **14**, 147 (2000)
21. F.-G. Cao, A.I. Signal: Phys. Rev. D **68**, 074002 (2003)
22. HERMES Collab., A. Airapetian et al.: submitted to Phys. Rev. D, hep-ex/0407032; HERMES Collab., A. Airapetian et al.: Phys. Rev. Lett. **92** 012005 (2004)
23. G. Altarelli, R.D. Ball, S. Forte, G. Ridolfi: Nucl. Phys. B **496**, 337 (1997)
24. B. Adeva et al.: Phys. Rev. D **58**, 112002 (1998)
25. HERMES Collab., A. Airapetian et al.: Phys. Rev. Lett. **84**, 2584 (2000)
26. T. Gehrmann, W.J. Stirling: Phys. Rev. D **53**, 6100 (1996)
27. M. Glück, E. Reya, M. Stratmann, W. Vogelsang: Phys. Rev. D **53**, 4775 (1996)
28. X. Ji: Phys. Rev. Lett. **78**, 610 (1997); Phys. Rev. D **55**, 7114 (1997)
29. HERMES Collab., A. Airapetian et al.: Phys. Lett. B **535** 85 (2002)
30. HERMES Collab., A. Airapetian et al.: Phys. Lett. B **599** 212 (2004)
31. HERMES Collab., A. Airapetian et al.: Phys. Rev. Lett. **87**, 182001 (2001)
32. HERMES Collab., C. Hadjidakis, D. Hasch, E. Thomas: hep-ex/0405078
33. L. Mankiewicz, G. Piller, A. Radyushkin: Eur. Phys. J C **10**, 307 (1999)
34. M. Vanderhaegen, P.A.M. Guichon, M. Guidal: Phys. Rev. D **60**, 094017 (1999)
35. J.C. Collins, L. Frankfurt, M. Strikman: Phys. Rev. D **56,** 2982 (1997)