# Lepton-Nucleon Spin Physics

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**Abstract.** An overview of recent experimental results in the field of nucleon spin physics is given. The emphasis is on experiments using polarized deep inelastic scattering, but some important new results from $e^+e^-$-annihilation and $pp$-scattering are included as well.

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## INTRODUCTION

Traditionally the topic of spin structure of the nucleon has been studied almost exclusively using polarized deep inelastic scattering (DIS). In the past, most of the experimental work dealt with the determination of the helicity structure of the nucleon, trying to determine the various contributions to its spin. Consequently, most of the data were on the helicity structure function $g_1(x)$ and its associated distribution function $\Delta q(x)$[1] and only very few other subjects received any attention. Two exceptions were measurements of the second polarized structure function $g_2(x)$ and the polarization distribution of the gluon $\Delta G(x)$.

It is only recently that other topics dealing with the nucleon spin structure received experimental attention as it was realized that a complete understanding of the quark-gluon structure of the proton required measurements of other observables as well. Topics like the Collins- and Sivers-effect, orbital motion of the quarks, higher twist, and other parton-correlation effects have been addressed both theoretically and experimentally and the new results have added considerably to our understanding of the structure of the polarized nucleon. At the same time new facilities have become available to probe this structure. Polarized fragmentation functions are now being probed at $e^+e^-$ collider experiments and polarization phenomena in $pp$ scattering are accessible with high accuracy from the RHIC-collider.

## EXPERIMENTS

The main fixed-target experiments studying nucleon spin physics are listed in Tables 1 and 2. HERMES has been running the longest and to a large extent compensates its relatively low luminosity by the extended periods of data taking (for almost a decade

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[1] Further on we will also use $g_1^q(x)$ to denote this distribution function.

**TABLE 1.** Main beam properties and (typical) kinematic coverage of the major lepton-nucleon spin physics experiments.

| exp. | $E_b$ (GeV) | $x$ | $Q^2$ (GeV$^2$) | $P_b$ |
|---|---|---|---|---|
| HERMES | 27.6 $e^\pm$ | 0.02 - 0.6 | 0.1 - 15 | $\pm$0.55 |
| COMPASS | 160 $\mu$ | 0.003 - 0.6 | 1 - 100 | -0.76 |
| JLAB | <6 $e^-$ | 0.1 - 0.85 | 1 - 4.5 | $\pm$0.7 |

**TABLE 2.** Main target properties of the major lepton-nucleon spin physics experiments.

| exp. | $P_t$ | target | $\mathscr{L}$ (cm$^{-2}$s$^{-1}$) |
|---|---|---|---|
| HERMES | 0.85 | $\vec{\mathrm{H}},\vec{\mathrm{D}}$ | $10^{31}$ |
| COMPASS | 0.50 | $\vec{\mathrm{Li}}\vec{\mathrm{D}}$ | $5 \cdot 10^{32}$ |
| Hall A | 0.35 | $^3\vec{\mathrm{He}}$ | $10^{36}$ |
| CLAS | 0.8 (0.3) | $NH_3$ ($ND_3$) | $10^{34}$ |

now) as compared to the other experiments. Moreover, the gaseous targets used by HERMES have no dilution from unpolarized nucleons, which can be a disadvantage in other experiments. At the present time both HERMES and COMPASS have yielded results on transverse degrees of freedom with comparable statistical accuracy. The JLAB experiments run at much higher luminosity but due to the low energy of the electron beam they are usually limited to a rather narrow range in kinematics. With the planned upgrade of the JLAB accelerator to 12 GeV this range will be substantially expanded in the future. Common to most experiments today is their large acceptance enabling the efficient detection of hadrons emitted in the DIS reaction. Only Hall A at JLAB works with (relatively) small acceptance magnetic spectrometers and is limited to inclusive DIS studies, albeit at high luminosity.

## HELICITY DISTRIBUTIONS

Inclusive DIS experiments where only the scattered lepton is detected are mainly used to determine the polarized structure function $g_1(x)$ which -in the quark parton model- is related to the helicity distribution of quarks by:

$$g_1(x) = \frac{1}{2}\sum_q e_q^2[q^+(x) - q^-(x)] = \frac{1}{2}\sum_q e_q^2 \Delta q(x) \tag{1}$$

where $q^{+(-)}(x)$ denotes the probability to find a quark of flavour $q$ with momentum fraction $x$ and the same (opposite) helicity to that of the nucleon.

A summary of world data on the helicity structure function for the proton and the deuteron is shown in Figure 1. (See the contribution by D. Reggiani to these proceedings for more details on the HERMES data presented in this figure.) These data from several different experiments show a remarkable degree of agreement. In fact, since the data were taken at quite different values of the scale $Q^2$ this is important input to pQCD

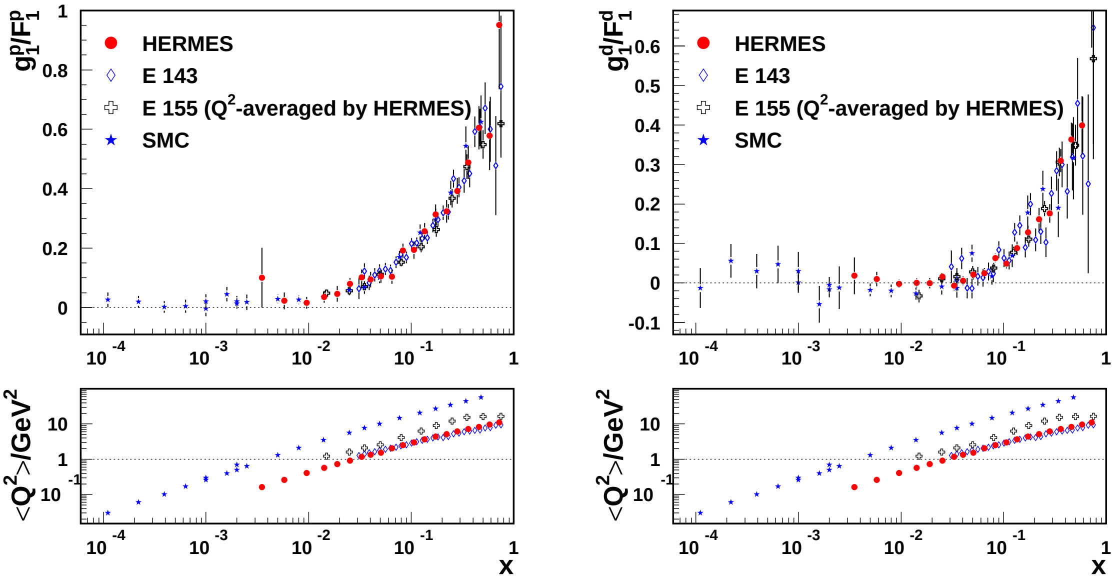

**FIGURE 1.** Summary of world data on $g_1(x)$

analyses of the helicity structure. Although the statistical accuracy is definitely good enough to allow a detailed analysis of the overall features of the structure function there still remain domains where our present knowledge is insufficient. This is mainly at the highest and lowest ends of the $x$-range.

At the highest values of $x$ there are clear -and sometimes strikingly different- predictions from various models for $g_1$ on the proton and the neutron. The data plotted in Figure 1 are not accurate enough to decide which of the models can be ruled out. However, new data from JLAB (see the contributions by e.g. J-P. Chen to these proceedings) have considerably better statistical accuracy and indeed show the capability to distinguish between model predictions.

The lowest values in $x$ are important to determine the sum rule over $g_1(x)$ which is directly proportional to the total quark spin contribution $\Delta\Sigma$ to the nucleon spin. Since the sum rule involves an integration over the unmeasured region at low $x$ its value is highly dependent on the extrapolation to that region. Hence a better knowledge of $g_1$ at the lowest possible values of $x$ is essential. The COMPASS experiment (see the contribution by J. Hannappel to these proceedings) has recently released results for a deuteron target which show an improvement in statistical accuracy in this $x$-domain of more than a factor of two over the older SMC data shown in the figure.

## GLUON POLARIZATION

From pQCD analyses of the $Q^2$ dependence of the world data on $g_1$, and further data on among others the flavour decomposition of the helicity distribution $\Delta q(x)$ obtained by

HERMES [1], it is now clear that the quark spin only contributes a minor part to the total nucleon spin. The issue which most experiments have therefore been addressing lately is which other contributions make up the remainder of the nucleon spin. A prime suspect is the polarization of the gluons $\Delta G$. The pQCD analyses performed so far all indicate a relatively large and positive polarization for the gluons, but the uncertainties on these results are large. This is mainly caused by the limited lever arm in $Q^2$ that is available in the data. More direct methods are needed. The gluons being electrically neutral $\Delta G$ cannot be probed directly in DIS and other ways have been identified to gain access to this quantity. In particular the production of (open) charm and the production of pairs of jets or hadrons at high transverse momentum are seen as promising avenues towards a determination of $\Delta G$. In fact, all existing data up to now come from analyses of high-$p_T$ pairs. Some years ago HERMES has published [2] a significantly positive value for $\Delta G$, albeit with large systematic errors due to the uncertainties in determining the relative contributions of competing production mechanisms. Recently, SMC [3] has released a negative value which is, however, consistent with zero. The COMPASS experiment is ideally placed to remedy this unsatisfactory experimental situation due to its higher center-of-mass energy than e.g. HERMES. In the contribution by C. Bernet to these proceedings the COMPASS experiment shows the most accurate determination to day of $\Delta G$, which is within error bars equal to zero. Further data from COMPASS also from open charm production should help to elucidate this situation in the near future.

## THE STRUCTURE FUNCTION $G_2(X)$

In inclusive scattering of longitudinally polarized leptons off longitudinally polarized nucleons a second structure function $g_2$ arises. This is related to the transverse polarization of the target nucleon with respect to the virtual photon direction, and was long wrongly assumed to represent the transverse spin structure of the nucleon. In fact, it is the best known example of a twist-3 function. As seen in Eq. (2) this structure function contains a twist-2 part, directly related to the standard polarized structure function $g_1$ and a part stemming from actual twist-3 operators $\tilde{g}_2$.

$$g_2(x) = -g_1(x) + \int_x^1 g_1(x')dx'/x' + \tilde{g}_2(x) = g_2^{WW}(x) + \tilde{g}_2(x) \qquad (2)$$

Several experiments have been performed to determine $g_2$, and in particular to measure the deviation from the (dominant) twist-2 part. Moments of this deviation can be compared directly to results of lattice QCD calculations. The most precise determination of these moments were given by the E155x experiment [4] at SLAC some years ago. However, in several limited kinematic domains two JLAB experiments have now shown results for $g_2$ with considerably improved statistical accuracy. In contributions to this workshop the latest results are discussed in detail.

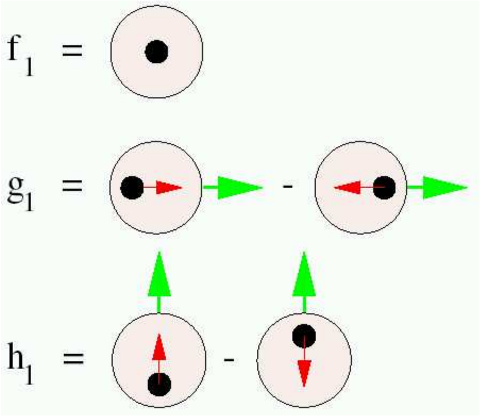

**FIGURE 2.** Schematic representation of the three twist-2 distribution functions that survive integration over intrinsic transverse momentum: the momentum density $f_1$, the helicity distribution $g_1$ and the transversity $h_1$.

# TRANSVERSITY

A full tree-level description of all distribution and fragmentation functions appearing at twist-2 and twist-3 in polarized DIS has been available for some time [5]. Most of these functions are explicitely dependent on intrinsic transverse momentum of the quarks in the nucleon or hadron. Only 3 functions do not disappear when integrated over this intrinsic $k_T$ or $p_T$. For the distribution functions these are the unpolarized distribution $f_1^q(x)$, the helicity distribution $g_1^q(x)$ and the transversity distribution $h_1^q(x)$. When integrated over $x$ these distributions contain information on the vector charge, the axial charge and the tensor charge, respectively, of the nucleon. While the former two are well known from inclusive DIS measurements, there is no experimental information on the latter one. This is a consequence of the chiral-odd nature of this distribution function, which means that it cannot appear in an inclusive cross section. The transversity distribution is chiral-odd since it involves, in a helicity basis, a simultaneous helicity flip of the target and the quark. For massless quarks this is impossible in a pure inclusive reaction.

The transversity distribution has several features which make it an attractive object of study. As indicated before it is the last forward distribution function to be measured after $f_1(x)$ and $g_1(x)$. It differs from the helicity distribution in a subtle way. Firstly, for relativistic particles the Lorentz boost and rotations do not commute, which means that in this case helicity and transversity are different. Differences between $g_1^q(x)$ and $h_1^q(x)$ thus give information on the relativistic nature of the quark motion. Secondly, and probably more importantly, is the fact that since the transversity distribution involves a spin-flip amplitude which is impossible for (spin 1) gluons in a spin 1/2 target, the transversity distribution decouples from the gluons. This leads to a very different QCD-evolution for $h_1^q(x)$ as compared to $g_1^q(x)$.

As mentioned before it is impossible to observe transversity in inclusive DIS. However, in a semi-inclusive DIS reaction, where at least one of the produced hadrons is

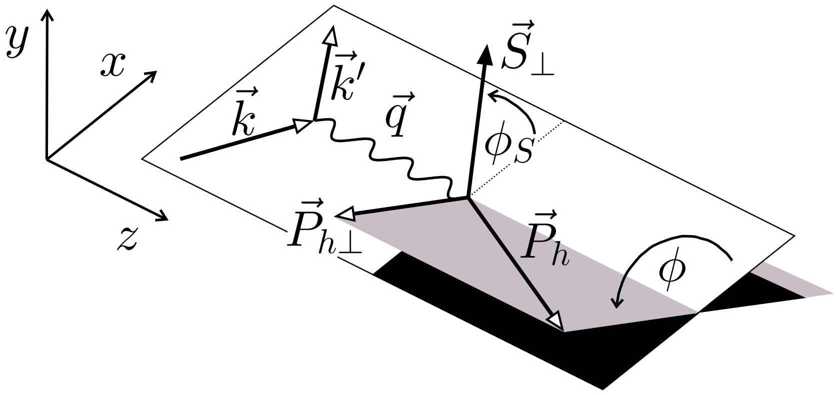

**FIGURE 3.** Definition of the various azimuthal angles relevant in semi-inclusive DIS on a transversely polarized target. $\vec{S}_\perp$ indicates the direction of the nucleon target spin, while $\vec{k}$, $\vec{k}'$ and $\vec{P}_h$ represent the momentum of the incoming lepton, the scattered lepton and the produced hadron, respectively

detected, the cross section also depends on the fragmentation function:

$$\sigma^{ep\rightarrow ehX} = \sum_q f^{p\rightarrow q} \otimes \sigma^{eq\rightarrow eq} \otimes D^{q\rightarrow h}. \tag{3}$$

In this equation $f^{p\rightarrow q}$ is the distribution function representing the probability to find a quark $q$ in the proton $p$ (possibly carrying a certain spin polarization), $\sigma^{eq\rightarrow eq}$ is the elementary $e-q$ cross section as given by QED, and $D^{q\rightarrow h}$ is the fragmentation function describing the probability to find a certain hadron $h$ in a quark $q$.

This factorized approach to semi-inclusive DIS has been used with great success by the HERMES collaboration [1] to determine the flavour decomposition of the helicity distribution $g_1^q(x)$ (or in a different notation $\Delta q(x)$). In that case the unpolarized fragmentation function $D_1(z)$ was used as a flavour filter to disentangle the contribution of different quark flavours.

## Collins effect

In the case of transversity the presence of a second soft object in the form of a fragmentation function allows the actual observation of the distribution function provided that the fragmentation function is also chiral-odd. Such a mechanism is the basis of the Collins effect [6] where the chiral-odd Collins fragmentation function $H_1^\perp(z)$ appears. This fragmentation function describes a correlation between the direction of the outgoing hadron and the transverse spin direction of the initial quark. An important feature of the Collins fragmentation function is that it is also (naive) time-reversal odd (see e.g. the contribution of D. Sivers to these proceedings). As such it causes the appearance of a single spin asymmetry (SSA) in the azimuthal distribution of the outgoing hadrons. Such SSA's have already been observed by HERMES [7] using a longitudinally polarized target, indicating that the Collins fragmentation function is non-zero.

The relevant azimuthal angles are defined in fig. 3. Transversity manifests itself in the Collins effect through a sine modulation in the angle $\Phi = \phi + \phi_S$.

## Sivers effect

A completely different mechanism has been suggested that also leads to SSA's in semi-inclusive DIS. A correlation between the intrinsic transverse momentum of an unpolarized quark and the direction of the transverse spin of its parent nucleon can exist and is described by the Sivers distribution function $f_{1T}^{\perp}(x)$ [8]. Part of this correlation may survive the fragmentation process and result again in a correlation between the target spin direction and the direction of the outgoing hadron. This effect was proposed more than a decade ago as a possible explanation for the observed asymmetries in hadron-hadron scattering experiments, but was largely ignored in the context of semi-inclusive DIS. This is because the corresponding distribution function $f_{1T}^{\perp}(x)$ is, like the Collins fragmentation function, a (naive) time-reversal odd object. Hence, the observation of effects related to $f_{1T}^{\perp}(x)$ requires the interference of at least two amplitudes, but this was assumed to be impossible for a distribution function. However, recent insights [9] have shown that restoration of gauge invariance entails the existence of gauge links which appear as a kind of final state interaction involving the exchange of a soft gluon. This extra diagram then enables the existence of the naive time-reversal odd distribution functions.

The importance of such final state interactions could call the universality of distribution and fragmentation functions in doubt. It was, however, shown that up to a non-trivial sign change the distribution functions and fragmentation function are indeed universal between semi-inclusive DIS, Drell-Yan production and $e^+e^-$ annihilation [10].

An interesting feature of the Sivers distribution function is, apart from its T-odd character, the fact that it requires a non-zero orbital angular momentum of the unpolarized quark. It may therefore eventually give access to this elusive component of the nucleon spin structure.

In semi-inclusive DIS the Sivers effect appears as a SSA sine modulation in the angle $\phi - \phi_S$. It can be seen from fig. 3 that this angle does not depend on the orientation of the lepton scattering plane, but only on the angle between the target spin vector and the hadron production plane, as should be the case for the mechanism outlined above.

## Single Spin Asymmetries

Both the COMPASS and HERMES collaborations have now released first SSA measurements based on semi-inclusive DIS experiments on transversely polarized targets. While COMPASS used polarized LiD as a deuterium target, HERMES has used a pure hydrogen target (see the contributions by P. Pagano and M. Diefenthaler to these proceedings). The results of HERMES are displayed in figs. 4 and 5. The Collins asymmetries are somewhat surprising. Firstly, their magnitude is smaller than what could be expected on the basis of the published longitudinally polarized target data [11]. Secondly, the absolute magnitude for the $\pi^-$ asymmetry is actually larger than the one for the $\pi^+$ mesons. Keeping in mind that the contribution of $u$-quarks is usually dominant due to their larger electric charge, one possible explanation is that the disfavoured Collins fragmentation function of a $u$-quark hadronizing into a $\pi^-$ has a sizeable magnitude and is of the opposite sign as compared to the favoured fragmentation function. Since the Collins

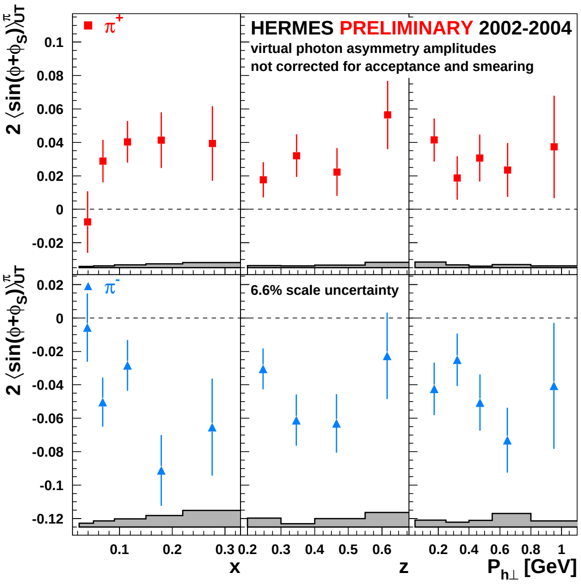

**FIGURE 4.** HERMES preliminary results for the amplitude of the Collins asymmetries on a transversely polarized hydrogen target, as a function of the kinematic variables $x, z$ and $P_{h\perp}$. The top panels correspond to $\pi^+$ production, while the bottom panels represent $\pi^-$ production.

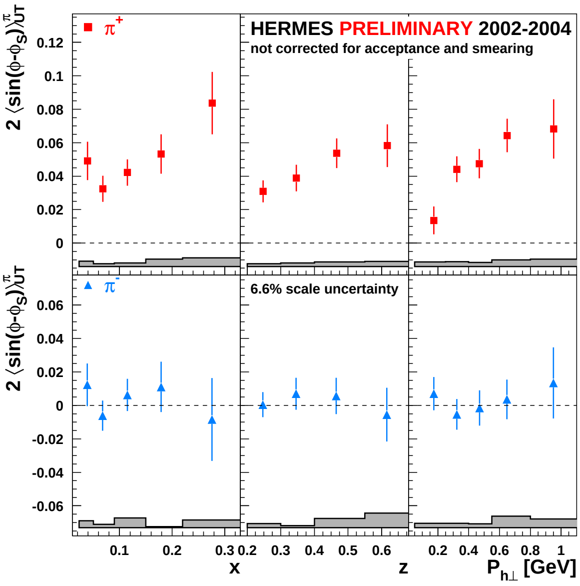

**FIGURE 5.** HERMES preliminary results for the amplitude of the Sivers asymmetries on a transversely polarized hydrogen target, as a function of the kinematic variables $x, z$ and $P_{h\perp}$. The top panels correspond to $\pi^+$ production, while the bottom panels represent $\pi^-$ production.

fragmentation function actually describes a correlation between two directions there is nothing inherently strange about a negative sign. Such a possibility could also explain the COMPASS result which is consistent with zero on a deuterium target because the proton and neutron fragmentation functions may entail strong cancellations.

In any case the significantly non-zero results from HERMES prove the existence of the Collins fragmentation function and the transversity distribution function. Fortunately the Collins mechanism is not the only way to access transversity. There are other chiral-odd fragmentation functions which can act in conjunction with $h_1(x)$ to produce observable asymmetries. In particular there has been the suggestion to look at asymmetries in 2-hadron production where an interference fragmentation function would be active. This would provide an interesting independent measurement of transversity (see contribution by P. van der Nat to these proceedings).

The Sivers asymmetries from HERMES are also significantly different from zero, whereas the COMPASS results are again consistent with zero. In this case there is only one unknown distribution at work: the Sivers distribution function $f_{1T}^{\perp}(x)$, which in conjunction with the normal unpolarized fragmentation function $D_1(z)$ determines the semi-inclusive DIS cross section. The observation of a non-zero asymmetry is immediate evidence for a non-zero orbital angular momentum for the quarks. This would in particular hold for the $u$-quark which determines the $\pi^+$-asymmetry. Further analysis of both HERMES and COMPASS results should make it possible to have at least a rough idea of the flavour decomposition of the Sivers distribution function.

## Collins Fragmentation Function

As mentioned before, the Collins asymmetries observed in semi-inclusive DIS depend on two completely unknown functions: the Collins fragmentation function and the transversity distribution. In order to determine the transversity distribution separately one needs independent information on the fragmentation function. This can come from analysis of high-energy $e^+e^-$ collisions. In the past there have been preliminary analyses of LEP data which gave tentative evidence for a non-vanishing Collins fragmentation mechanism, but they were certainly not conclusive about the magnitude of the function.

Recently there has been an effort going on to analyse the massive amount of fragmentation data available from the high-luminosity asymmetric $e^+e^-$ colliders built for studies of CP violation in B-physics. In particular a group at the BELLE experiment has looked for evidence for polarized fragmentation in their data. In his contribution to these proceedings R. Seidl shows for the first time conclusive evidence for a significant non-zero Collins fragmentation function. Further refined analysis of these data, together with the semi-inclusive data, will eventually enable the full determination of the transversity distribution.

## Hadron-hadron scattering

Historically the first non-zero SSA's were observed in pion production in $\vec{p}p$-scattering [12]. There have been many theoretical calculations aiming at a reproduction of these data, basically invoking either the Collins mechanism, the Sivers mechanism or both. A point of uncertainty has, however, always been the rather low scale of the measurements. With the advent of RHIC, and in particular the availability of intense

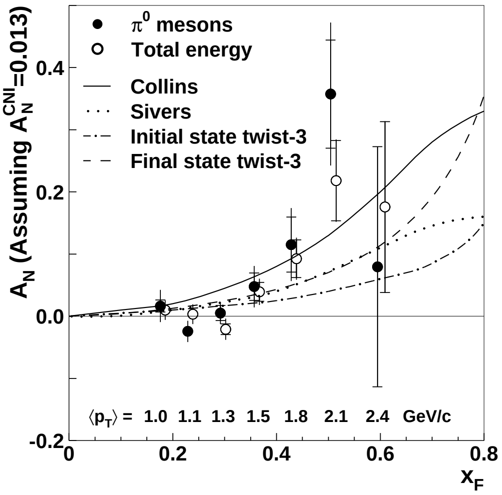

**FIGURE 6.** Analyzing powers for $\pi^0$ production in STAR [13].

proton beams with high polarization, this situation is being remedied. Recent data from both the PHENIX and STAR experiments have shown very good agreement between measured cross sections and NLO pQCD calculations, thus establishing the validity of this framework in the kinematic region covered. The RHIC experiments have now published the first results on single spin asymmetries which confirm and extend the older data. In fig. 6 the analyzing power for $\pi^0$ production from STAR [13] is plotted as an example. It is clear from the figure that models based on either Collins or Sivers mechanisms are able to reproduce the data with the present accuracy. However, with the much improved statistics which will become available with continued running of the RHIC-spin programme, a differentiation between the models may be possible. (See the contributions by S. Heppelmann, M. Chiu and F. Videbaek to these proceedings.) This would again give an independent means of determining the transversity distribution, provided that the Collins mechanism proves to be dominant.

In the last runs RHIC actually had both proton beams polarized. This makes the study of double-polarized processes possible. Of particular interest will be the determination of the gluon polarization $\Delta G$. First preliminary results have shown the power of this method (see the contributions by A. Desphande and R. Cadman to these proceedings), which is again completely independent of the measurements in lepton scattering. The statistical accuracy at present is, however, not yet sufficient to edtract a value of $\Delta G$, with a meaningfull significance.

## Subleading twist

In a previous section we already discussed the possibility to make quantitative studies of higher twist contributions. Also in the context of SSA measurements this is possible. HERMES has collected a large amount of semi-inclusive DIS data on a longitudinally polarized target. The SSA for such a target contain contributions from both the Collins

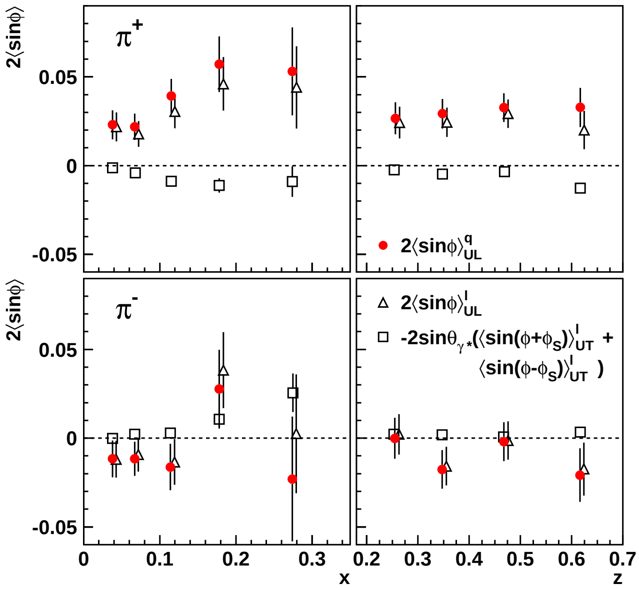

**FIGURE 7.** The various azimuthal moments appearing in the measurement of the $\sin\phi$ modulations of SSA on a longitudinally polarized proton target. Open triangles: total SSA; open squares: contribution from Collins and Sivers mechanisms; closed circles: subleading twist contributions.

and the Sivers effects, but also contributions from unmeasured twist-3 functions. (In fact, one usually sees a twist-3 distribution function coupled with a twist-2 fragmentation function and vice-versa [5].) Using the asymmetries for Collins and Sivers measured separately on a transverse target (and corrected for different kinematic factors) one can subtract the leading twist contribution to the longitudinal SSA and derive an estimate for the subleading twist part. This was recently done by HERMES [14] and the result is shown in fig. 7. It is observed that at the moderate $Q^2$ of the experiment the subleading twist terms can be large, certainly in conditions where the leading twist contributions are suppressed (like here).

## CONCLUSIONS

The field of nucleon spin physics has seen a proliferation of new topics over the last decade. This reflects our deeper understanding of the complexities involved in the spin degrees of freedom in the nucleon. New sectors of the spin structure are being explored at several, often new, experiments. It is particularly gratifying to see that also facilities outside the traditional field of polarized DIS are now actively contributing to the growing body of experimental data.

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