Nucleon structure at low energies

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Understanding the structure of the nucleon in terms of quark and gluon degrees of freedom is one of the key objectives of nuclear physics. Over the last decade, theoretical breakthroughs lead to the new concepts of Generalized Parton Distributions (GPDs) and Transverse Momentum Dependent parton distributions (TMDs), which offer a means to unravel the true 3-dimensional nucleon structure and to shead new light on the yet unsolved 'nucleon spin crises'. After reviewing our current understanding of the spin structure of the nucleon, novel and pioneering measurements of hard exclusive processes and transverse spin phenomena are presented, which may provide access to the GPDs and TMDs, respectively. The measurements have been performed at second generation polarised lepton-nucleon and proton-proton scattering experiments at CERN, DESY, JLAB and RHIC.

1 Introduction

Over the past 40 years, an understanding of the nucleon in terms of elementary constituents (partons, i.e., quarks and gluons) has gradually and successfully emerged from experiments that scatter high energetic leptons (l) off protons or nuclear targets (N) with large four-momentum transfer from the initial to the final lepton, Q. Such deep-inelastic scattering (DIS) experiments have been successfully interpreted within the QCD parton model introducing parton distribution functions (PDFs). The universality property of these functions allows their measurement in various different hard processes such as lepton-nucleon and proton-proton scattering.

The parton distributions $f_{q/g}(x_{\rm B}, Q^2)$, describing the distribution of quarks and gluons in terms of their longitudinal momentum fraction $x_{\rm B}$, known as the Bjorken variable, are well mapped in a kinematic range that spans five orders of magnitude in both $x_{\rm B}$ and Q^2 [1]. In contrast, a detailed decomposition of the spin of the nucleon in terms of parton *helicity* distributions, $\Delta f_{q/g}(x_{\rm B}, Q^2)$, including a measure of the contribution from orbital angular momenta (OAM) of quarks and gluons, remains elusive. Here, $\Delta f_{q/g}(x_{\rm B}, Q^2) = f^+_{q/g}(x_{\rm B}, Q^2) - f^-_{q/g}(x_{\rm B}, Q^2)$ is the difference of partons with their spin aligned (+) or anti-aligned (−) to the spin of the nucleon. The striking result that only an unexpectedly small fraction, about a quarter, of the nucleon's spin can be attributed to the spins of quarks and anti-quarks is famously dubbed the 'nucleon spin crises'. Moreover, unravelling the true 3-dimensional nucleon structure requires to answer long-standing questions concerning the spatial distribution of quarks and gluons inside the nucleon, their orbital motion and a possible connection between their orbital motion, their spin and the spin of the nucleon.

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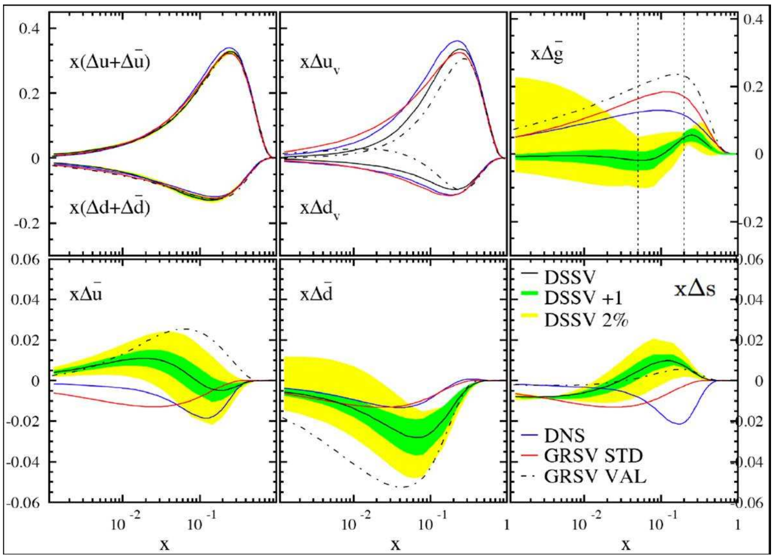

Figure 1: Parton helicity distributions of the nucleon obtained in NLO analyses of data from inclusive and semi-inclusive DIS (DNS [5]) as well as from proton-proton scattering (DSSV [3]). The figure is taken from [3] where also complete reference to all data is given.

which offer a multi-dimensional space and momentum resolution of the nucleon structure. These new functions allow studying a completely new aspect of nucleon structure: the localisation of partons in the plane transverse to the motion of the nucleon. As such GPDs and TMDs are excellent tools for nucleon tomography.

Modern experiments aim to obtain information about all contributions to the spin of the nucleon and to explore its multi-dimensional structure by measuring polarized inclusive, semi-inclusive and exclusive deep-inelastic scattering processes (Compass at CERN, HallA-C at JLab, Hermes at DESY) as well as by exploring polarized high energy proton-proton scattering (Brahms, Phenix and Star at RHIC, BNL).

2 The spin budget of the nucleon

The spin contribution of a quark or gluon to the nucleon spin is given by the intregral $\Delta f^1_{q/g}(Q^2) = \int_0^1 f_{q/g}(x_{\rm B}, Q^2)dx$. The helicity distributions $\Delta f_{q/g}(x_{\rm B}, Q^2)$ can be extracted from double-spin asymmetries

$$A_{\rm LL} \equiv \frac{d\Delta\sigma}{d\sigma} \equiv \frac{d\sigma^{++} - d\sigma^{+-}}{d\sigma^{++} + d\sigma^{+-}} \tag{1}$$

measured over a wide kinematic range in $x_{\rm B}$ and Q^2. Here, both beam and target have to be longitudinally polarized with helicity settings $\pm$. Analyses of such asymmetries measured over the past three decades in inclusive DIS, where only the scattered lepton is observed, revealed that surprisingly little of the nucleon spin is carried by the quark spins [2]. This finding has triggered much theoretical progress and new experiments dedicated to unraveling the nucleon spin structure.

From experimental side, the measurement of less inclusive observables in DIS (by Hermes and Compass) and of hadron production in polarized proton-proton collisions (by Phenix and Star) have opened a new stage in the quest for the spin of the nucleon. Semi-inclusive DIS (SIDIS), where a hadron is observed in the final state along with the scattered lepton, is a powerful tool to determine the individual spin contributions of quarks and antiquarks to the total spin of the nucleon. The production of hadrons with large transverse momentum in polarized proton-proton scattering provides unprecedented constraints on the gluon helicity distribution.

Figure 1 shows the helicity distributions obtained in a recent *global* next-to-leading order (NLO) analysis (labeled as DSSV) of available data from polarized inclusive and semi-inclusive DIS as well as from polarized proton-proton scattering [3]. They are compared with earlier fits of inclusive [4] (labeled as GRSV) and semi-inclusive DIS data only [5] (labeled as DNS). The DSSV analysis consequently utilizes new fragmentation functions (DSS) [6], which, for the first time, provide a good description of identified hadron yields over the entire kinematic range relevant for the analysis of polarized SIDIS and *pp* scattering data.

The total up and down quark helicity distributions, which are primarily probed in inclusive DIS, are by far the best determined distributions. Their uncertainty bands are very narrow and results from verious different analyses agree very well and are also in good agreement with recent lattice calculations for the first moments [7]. The light sea quark and antiquark helicity distributions are mainly constraint by the semi-inclusive DIS data. As shown in Ref. [3], differences in the light sea quark distributions between the DSSV and DNS extractions, which both use inclusive and semi-inclusive DIS data, can be fully attributed to the use of different sets of fragmentation functions. Of particular interest is a possible flavour symmetry breaking in the light sea, i.e., $\Delta\bar{u} \neq \Delta\bar{d}$, given the well-established flavour asymmetry in the spin-averaged case. In fact, Fig. 1 demonstrates a slightly positive $\Delta\bar{u}$ and a negative (with larger magnitude) $\Delta\bar{d}$ yielding a non-zero difference in agreement with various model calculations.

The polarization of strange quarks has been a focus since the very beginning of the nucleon spin crises. Assuming SU(3) symmetry, the small value found for the total quark spin contribution to the nucelon spin implies - within the parton model - a significant negative polarization of strange quarks. Indeed, most fits to only inclusive DIS data prefer a sizeable negative strange quark polarization, even if the commonly assumed SU(3) symmetry is not enforced. In contrast to these results, Fig. 1 shows a strange quark polarization for DSSV that is positive at larger $x_{\rm B}$ and turns negative around $x_{\rm B} = 0.02$. This result is fully driven by the kaon data from semi-inclusive DIS used for both the PDF fits (DSSV) and the fragmentation function fits (DSS). It is also in agreement with LO extractions of the strange helicity distribution by Hermes [8] and Compass [9] from their kaon data.

In view of the small contribution of quarks to the nucleon spin, an understanding of the role of gluons and the determination of their polarization has become a major focus of the field. A large polarization of gluons was expected from investigations of the QCD axial anomaly that tried to attribute the lacking spin contribution by quarks to Q^2 dependent contributions by gluons. Experimentally, the gluon helicity distribution remains the most elusive one. The available inclusive DIS data cover a kinematic range in $x_{\rm B}$ and Q^2 that is yet unsufficient to constrain the gluon helicity distribution from scaling violation of the polarized structure function. More direct probes are indispensable for gaining more knowledge about the gluon polarization. As shown in Fig. 1, the gluon polarization obtained by DSSV is small with a possible node in the distribution. This is driven largely by the RHIC data, which strongly constrain Δg in the range $0.05 \leq x_B \leq 0.2$ but cannot determine its sign as they mainly probe Δg squared. A small gluon polarization at x_B around 0.1-0.2 is also found in LO analyses of lepton-nucleon scattering data that dominantly select the photon-gluon fusion process in reactions like $lN \to hX$ or $lN \to h^+h^-X$ and in heavy flavour production [10].

Due to the lack of data in the small x_B region, it is yet not possible to reliably evaluate the full integral of $\Delta g(x_B, Q^2)$. However, a very large gluon polarization as proposed in the context of the QCD axial anomaly is clearly ruled out by the data. Current and future measurements at RHIC focus on the golden channels of two-particle, jet-jet and γ-jet correlations which provide direct access to the hard-scattering subprocess kinematics. The spin asymmetry for prompt photon production is linear in Δg and therefore determines the sign of the distribution. However, the investigation of the region $x_B < 10^{-3}$ will only be possible at a high-energy polarized electron-proton collider [11].

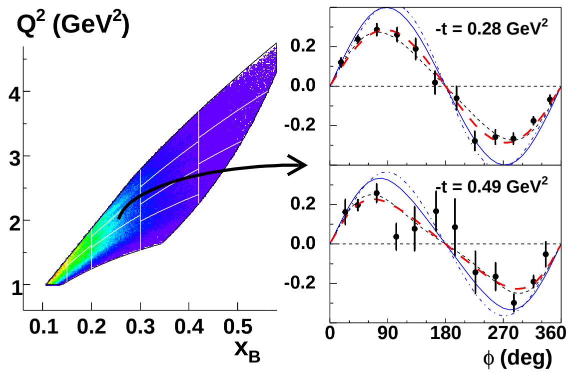

Figure 2: [colour online] Clas measurements of the DVCS beam-helicity asymmetry [14]. Left: kinematic coverage and binning in (x_B, Q^2) space, which is further subdivided into t bins. Right: For each bin in x_B, Q^2 and t the ϕ dependence of the cross section asymmetry w.r.t. the beam helicity is determined (red long-dashed curve). The data is compared to model calculations: the black dashed curves correspond to a Regge calculation [16]; the blue curves correspond to a GPD calculation [17], at twist-2 (solid) and twist-3 (dot-dashed) levels, with H contribution only.

Then, the remaining big piece in the puzzle is the contribution from quark and gluon orbital angular momenta (OAM) to the nucleon spin. For the first time, the newly developed formalism of GPDs offers a means to address this outstanding question.

3 Nucleon tomography and the quest for the OAM

Information towards a genuine multi-dimensional representation of the nucleon structure is offered by the so-called Generalized Parton Distributions (GPDs). GPDs unify the momentum-space parton distributions measured in inclusive DIS with the spatial distributions (form factors) measured in elastic lepton-nucleon scattering, which appear as kinematic limits and moments of GPDs, respectively. This new formalism provides a coherent and homogenous description of the nucleon structure as it reveals simultaneously (transverse) position and (longitudinal) momentum distributions of partons and describes their *correlations*. As such, GPDs are the basis for novel representations of the nucleon as an extended object in space (nucleon tomography) and provide access to fundamental static properties like the orbital angular momentum of partons in the nucleon - a question of fundamental importance for the understanding of nucleon structure. Generalized parton distributions depend on the squared four-momentum transfer t to the nucleon and on x and ξ, which represent respectively the average and half the difference

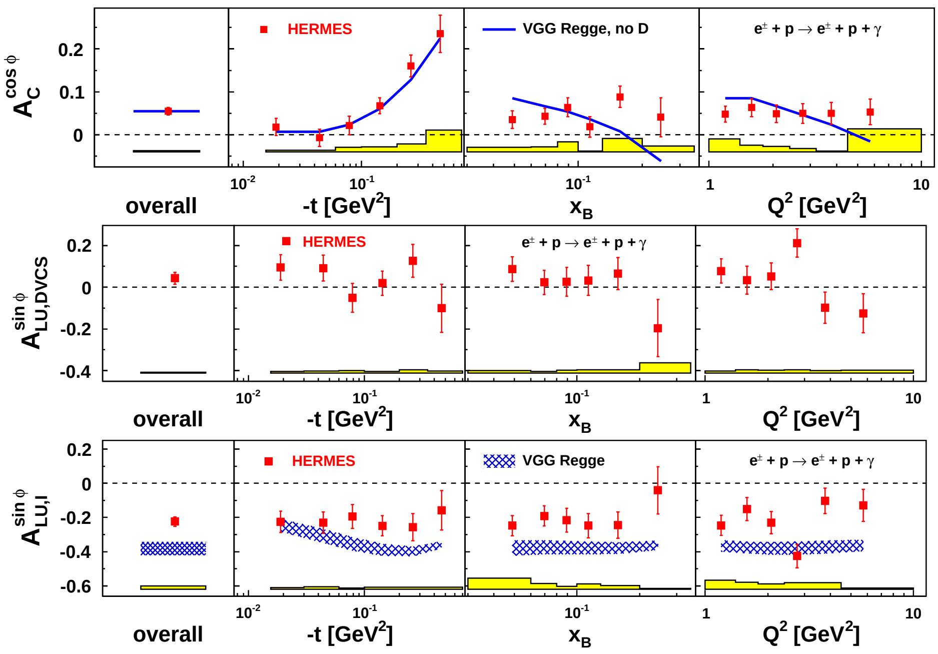

Figure 3: [colour online] Hermes measurement of the DVCS beam-charge (upper panel) and beam-helicity asymmetries [18]. The analysis of yield asymmetries w.r.t. the combined dependence of the cross section on beam helicity and charge allows for an experimental separation of the contribution from DVCS (middle panel) and its interference with the Bethe-Heitler process (lower panel). The data is compared to a GPD model (labeled VGG) [17] using a Regge-motivated t-dependence.

of the longitudinal momentum fractions carried by the probed parton in initial and final states. The skewness parameter ξ is related to the Bjorken variable x_B in the Bjorken limit. Most often discussed are the four twist-2 quark-helicity-conserving GPDs for each quark species in the nucleon: the quark-polarization averaged distributions H and E and the quark-polarization related distributions $\widetilde{H}$ and $\widetilde{E}$.

The crucial new information about the correlation of the spatial and momentum distributions is provided from measurements of exclusive processes at large momentum transfer, namely deeply-virtual Compton scattering (DVCS, $lN \rightarrow lN\gamma$) and meson production ($lN \rightarrow lN\pi(\rho, \phi, \mathrm{etc.})$). The theoretically cleanest way to access GPDs appears to be the DVCS process. Since GPDs carry information about longitudinal and transverse degrees of freedom, the DVCS amplitudes need to be known completely, i.e., by magnitude and phase. This is possible through a measurement of the interference between the DVCS and the Bethe-Heitler processes, where the photon is radiated from a parton in the former and from the lepton in the latter process. Their interference has the potential to reveal the 3-dimensional structure of the nucleon at parton level. In order to isolate the real part of the interference term in a measurement, lepton beams of both charges are needed. The imaginary part can be accessed by measuring the angular dependence of the produced photon if polarized lepton beams or polarized targets are available. A determination of all relevant moments of the angular dependence in beam-charge, beam-spin and target-spin asymmetry measurements allows one to perform a global analysis of all observables to obtain detailed information on GPDs.

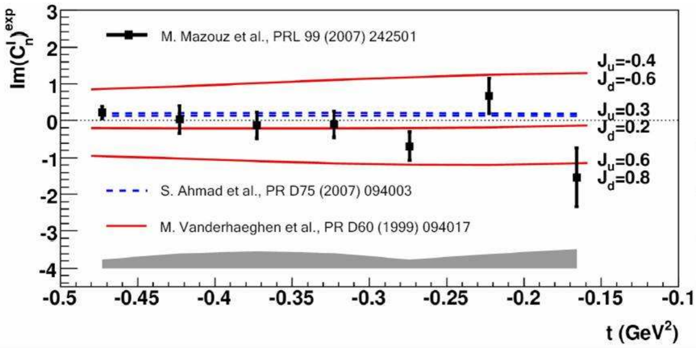

Figure 4: Hall-A extraction of the interference term from the DVCS beam-spin cross section difference for the neutron [19]. The curves are calculations of GPD models with different values for the up and down quark total angular momenta J_u and $J_d = 0$.

Hard exclusive processes are very challenging to measure as they require high beam energies (to ensure the hard regime), very high luminosities (due to the small cross sections) and an excellent resolution of the spectrometer (to ensure the exclusivity of the process). Pioneering measurements have been performed at DESY (Hermes, H1, Zeus) and JLAB (Clas, HallA). After the first signals for GPDs from Hermes [12] and Clas [13], dedicated measurements have been and are going to be performed and a new quality of data analysis is reached. While measurements at Jlab focus on high statistics allowing for a multidimensional analysis of data (see Fig. 2), Hermes concentrates on new analysis methods making simultaneous use of polarization observables and data taken with different beam charges thereby providing full experimental separation of the different contributions to the measured cross section asymmetries (see Fig. 3).

The ability to describe longitudinal momentum distributions at a fixed transverse localization is a prerequisite for studying the so-called Ji relation [15], which links a certain combination of GPDs (H and E) to the total angular momentum ($J_{q,g}$) of a parton in the nucleon. Only few observables show a substantial sensitivity to the total angular momentum of quarks, mainly to J_u and J_d. Among them are the DVCS beam-helicity cross section difference for a neutron target (see Fig. 4) and the DVCS asymmetries w.r.t. transverse target polarization (see Fig. 5). Both measurements are compared to GPD model calculations [17] that embody explicitly the quark total angular momenta J_u and J_d in the parameterization of the spin-flip GPD E. Hence *model dependent* constraints on J_u and J_d can be derived by fitting them to the observables in Figs. 4 and 5.

These first attempts of extracting information about the total angular momentum of quarks reveal the potential of the data to provide quantitative information. Obviously, much more data and theoretical developments are needed to obtain GPD parameterization that allow for a description of all available DVCS data. By then, the model dependence of the above extractions might get under control.

4 Transverse spin phenomena and spin-orbit correlations

In addition to the quark momentum $f(x)$ and helicity $\Delta f(x)$ distributions discussed before a third independent quark distribution, the so-called transversity distribution $\Delta_T f(x)$, exists because of the relativistic nature of bound quarks. Transversity describes the distribution of transversely polarized quarks in a transversely polarized nucleon. In the non-relativistic limit

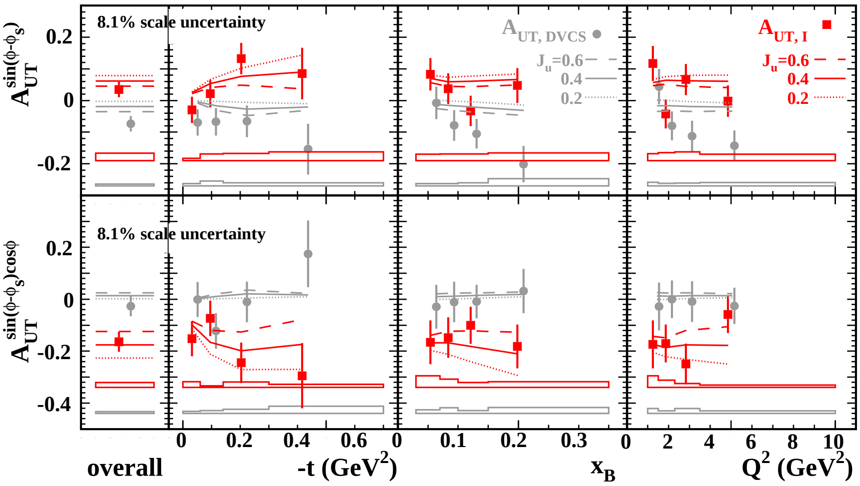

Figure 5: Hermes asymmetries describing the dependence of the squared DVCS amplitude (circles, $A_{UT,DVCS}$) and the interference term (squares, $A_{UT,I}$) on the transverse target polarization [20]. The curves are calculations of a GPD model [17] with three different values for the up quark total angular momentum J_u with fixed value for the down quark, $J_d = 0$.

$\Delta_T f(x)$ and $\Delta f(x)$ are identical as both functions describe the orientation of the quark spins relative to the nucleon spin, $\Delta f(x)$ in the helicity basis and $\Delta_T f(x)$ in a basis of transverse spin eigenstates. However, transversity and helicity distributions differ because quarks inside the nucleon move relativistically, hence boosts and rotations do not commute. They are therefore independent quantities which probe different QCD properties. Any experimental evidence for a deviation of $\Delta_T f(x)$ from $\Delta f(x)$ would be a measure of relativistic effects.

Viewed in the helicity basis, transversity is related to a forward scattering amplitude involving a *helicity flip* of both quark and target nucleon. Due to this chiral-odd nature, transversity - unlike the other two basic quark distributions - cannot be measured in inclusive DIS but only in a process in which it combines with another chiral-odd quantity. The most direct approach is to measure double transverse-spin asymmetries in polarized Drell-Yan processes which couple two transversity distributions. This approach is however experimentally not yet feasible. Another possibility is the semi-inclusive DIS process where fragmentation functions enter the cross section in conjunction with the distribution functions. Such a mechanism has been proposed by Collins [21] where the chiral-odd *Collins* fragmentation function relates the transverse polarization of the struck quark with the transverse momentum $P_{h\perp}$ of the produced hadron. This mechanism manifests itself in a single-spin asymmetry, i.e., a left-right asymmetry in the production of hadrons in the plane transverse to the direction of the virtual photon.
Single-spin asymmetries in semi-inclusive DIS on a transversely polarized target can also originate from the *Sivers mechanism* [22]: it emerges from the combination of the ordinary spin-averaged fragmentation function with the Sivers distribution. This naive time-reversal odd function, i.e., time-reversal without interchange of initial and final state, can be related to the interference of wave functions for different orbital momentum states. As such it parameterizes

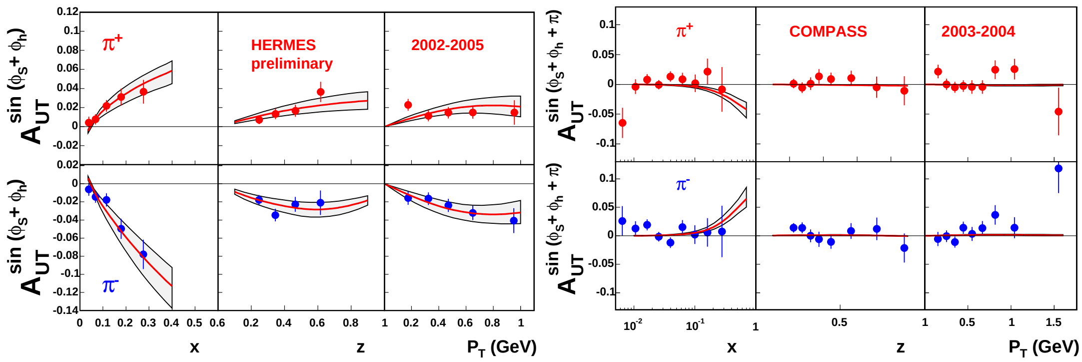

Figure 6: Left: most recent Hermes results for the Collins asymmetry for π-mesons. The strikingly non-zero amplitudes for charged pions demonstrated for the first time that both transversity and the Collins fragmentation function exist and are sizeable. Right: Compass results for the Collins asymmetry for π-mesons measured with a deuterium target. Both figures are taken from [28].

the correlations between the transverse momentum of quarks and the spin of the transversely polarized nucleon. The information on these spin-orbit correlations will be a key to construct a complete picture of the internal structure of hadrons beyond the collinear approximation.

Single-transverse spin asymmetries have a long history, starting from the 70s and 80s when surprisingly large asymmetries were observed in hadron reactions such as $p^{\uparrow}p \rightarrow \pi X$ at forward angles of the produced pion [23]. Experiments at RHIC found that large single-spin effects at forward rapidity persist even at very high energies up to $\sqrt{s} = 200$ GeV [23]. Such asymmetries could arise from both Collins or Sivers effect or from twist-3 contributions (Qui-Sterman effect). Experimentally, these mechanisms cannot be distinguished with the observables measured so far at RHIC but will become feasible in studies of Drell-Yan processes, di-jet or jet-jet correlations which, however, require high luminosities.

In contrast, semi-inclusive DIS on a *transversely* polarized target provide an additional degree of freedom due to the two azimuthal angles ϕ and ϕ_S involved, which are the azimuthal angle of the produced hadron and of the transverse target polarization vector, respectively, with respect to the virtual photon direction. These provide a distinct angular signature for the Collins and Sivers effects, which appear as $\sin(\phi + \phi_S)$ and $\sin(\phi - \phi_S)$ modulation of the SIDIS cross section, respectively. Both mechanisms were studied at Hermes with a proton target [24] and at Compass with deuterium and proton targets [25]. Figure 6 (left) shows the Collins amplitudes for pions measured by Hermes. These results are milestones in the field as the significant non-zero asymmetries for charged pions demonstrated for the first time unambiguously that both the transversity distribution and the Collins fragmentation function exist and are non-zero! Recent Compass asymmetries are in very good agreement with the Hermes data in the kinematic region of overlap and go to zero for smaller values of x_{B}. The asymmetries measured with a deuterium target are all compatible with zero, which can be understood as a cancellation of the contribution from up and down quarks when measuring on a isoscalar target. These data in combination with further information from jet asymmetries in e^+e^- scattering studied at Belle (KEK) [26], shown in Fig. 7 (left), which are sensitive to the Collins fragmentation function, allowed for the first extraction of the up and down quark

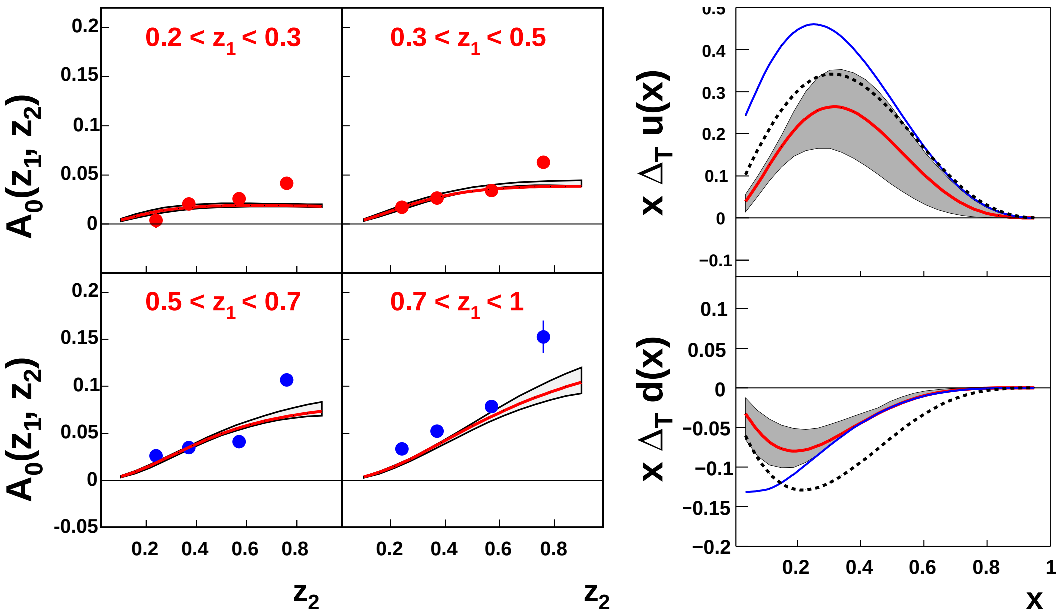

Figure 7: [colour online] Left: most recent BELLE results for jet asymmetries sensitive to the Collins fragmentation function [26]. The curves are results of a global fit [28] to these data as well as to Hermes and Compass data [25]. Right: As a result of the global fit the up and down quark transversity distributions are obtained and compared to the helicity distributions (dashed line). The blue line represents an upper bound for the transversity distribution. Both figures are taken from [28].

transversity distributions (see Fig. 7, right) [28] [1].

A measurement of the Siver asymmetries from Hermes [27] is presented in Fig. 8 (left). Also these results constitute milestones in the field as the significant non-zero asymmetries for π^+ and K^+ demonstrated for the first time that T-odd distribution functions indeed exist in DIS. Compass asymmetries measured with a deuterium target are compatible with zero [25]. The middle panel of Fig. 8 shows, as examples, two different extractions of the up and down quark Sivers distributions [29, 30] using parameterizations of the usual unpolarized fragmentation functions. These extractions are in agreement with recent lattice calculations of the Sivers distribution [7] shown in the right panel (note that the is a factor -1 in the definitions of the Sivers distribution). The oposite sign found for the Sivers up and down quark distributions indicates orbital angular momenta for up and down quarks of opposite sign.

The existence of such functions depending on the transverse momentum of quarks inside the nucleon implies that quarks also carry non-vanishing orbital angular momentum which is one of the still missing pieces in the *spin puzzle*. A direct relation, however, between the Sivers function or other similar functions that describe spin-orbit correlations and the angular momentum contribution of the quarks to the nucleon spin could not yet be established.

The most crucial test of our current understanding of azimuthal single-spin asymmetries in

[1] The updated analysis of [28] makes use of the new, high statistics data from Belle and Hermes but does not yet incorporate the Compass proton asymmetries.

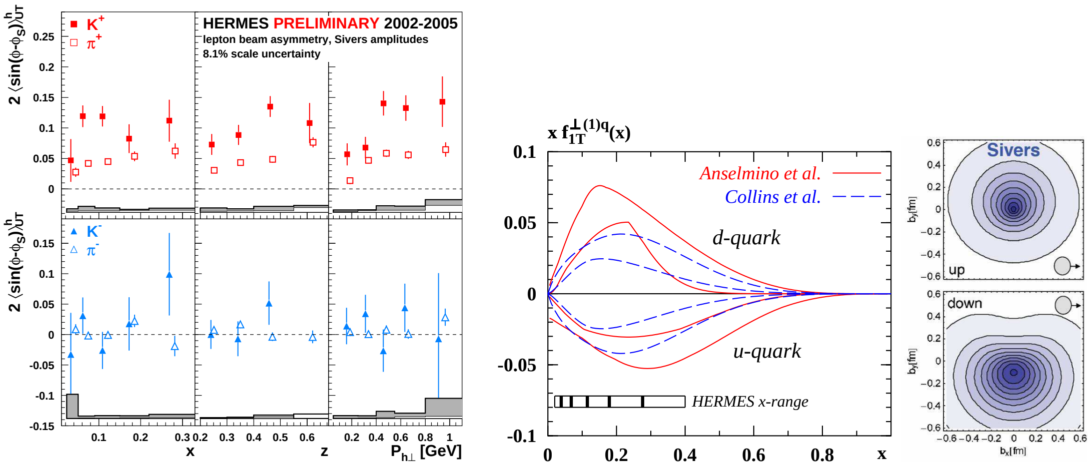

Figure 8: Left: Hermes results for the Sivers amplitudes for charged pions and kaons [27]. The striking non-zero asymmetries for π^+ and K^+ demonstrated for the first time that T-odd distribution functions indeed exist in DIS. Middle: Sivers up and down quark distributions extracted from the Hermes data (and for the full line also from Compass deuteron data) using two different parameterizations [29, 30]. The curves indicate the 1-sigma regions of the various parameterizations. The oposite sign found for the Sivers up and down quark distributions agrees with recent lattice calculation (right panel) [7] and indicates orbital angular momenta for up and down quarks of opposite sign.

terms of pertubative QCD will be the experimental verification of the predicted sign change of T-odd distribution functions, like the Sivers function, when being measured in DIS or in Drell-Yan processes. Such measurements of T-odd distribution functions in Drell-Yan processes are planned by Compass when running in the hadron-beam mode and by the proposed PAX experiment at the future FAIR facility at GSI [31].

5 Prospects of spin physics

Exciting new information has been obtained on the nucleon spin structure from polarized lepton-nucleon and proton-proton scattering. However, a detailed measurement of the gluon polarization remains one of the most important issues in spin physics. Running RHIC at higher energy ($\sqrt{s} = 500$ GeV) will shed more light on this issue.

The new concepts of Generalized Parton Distributions (GPDs) and Transverse Momentum Dependent parton distributions (TMDs) offer for the first time a multi-dimesional space and momentum resolution of the nucleon structure. Polarization observables serve as a very powerful tool to access the different GPDs and TMDs. The interplay between spin degrees of freedom and parton orbital angular momentum will be a key to understand the spin structure of the nucleon. The first extractions of transversity and of transverse momentum dependent distribution and fragmentation functions like the Sivers distribution and the Collins fragmentation function are milestones in the field. They constitute the first step towards a complete description of the partonic structure of hadrons beyond the collinear parton model.

The mapping of the nucleon GPDs and TMDs has been widely recognized as one of the key objectives of nuclear physics in the next decades. This requires a comprehensive programme, combining dedicated experiments at new facilities that provide high energy, high luminosity and polarization [11] with intense theoretical studies and lattice QCD simulations.

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Discussion

Tom LeCompte (Argonne National Laboratory): The questioner found the quark orbital motion and nucleon tomography discussion interesting. Could such a correlation between quarks in a nucleon show up in the unpolarized double parton scattering measurements described in Markus' talk? What constraints can double parton scattering put on orbital angular momentum of quarks?
Answer: This is an very interesting question. In principle, a measurement of the correlation of quarks in a proton should carry information about their relative orbital motion. One would have do find an observable that is sensitive to this relative orientation. The fractions of double parton production measured so far by CDF and D0 do not carry such information. Possibly, azimuthal dependences of the produced jets could be investigated. Thank you for this interesting point.
V. Braun (University of Regensburg): What is the relation between unintegrated parton distributions and Fourier transforms of GPDs? Does this relative exist in QCD?
Answer: Till now, only model dependent relations between TMDs and GPDs could be established. There is for example the pioneering work of Matthias Burkhardt who showed a relation between the Sivers fct. and the GPD E within a quark-diquark model. More recently, Andreas Metz and collaborators are investigating such relations in a systematic way. However, it's not clear if model independent relations might exist in principle.