THE PROTON IN 3D

ALESSANDRO BACCHETTA[1]*, **MARCO CONTALBRIGO**[2]**
[1] *Università di Pavia and INFN Pavia, Italy*
[2] *INFN Ferrara, Italy*

Protons and neutrons constitute the building blocks of normal matter, accounting for almost all the mass of our world. We are still far from understanding the intricacies and mysteries of their inner structure. In the course of several decades of successful studies, we dedicated our efforts to delving deeper and deeper into them. A few years ago, thanks to a fruitful synergy of theoretical and experimental progress, we started to collect unprecedented multi-dimensional images of the distribution of quarks and gluons inside protons and neutrons. These pictures of the universe within the nucleon challenge our comprehension of the underlying theory of quark and gluon dynamics (quantum chromodynamics – QCD) and at the same time put us face to face with fundamental questions, such as: What is the shape of the nucleon? Where is the spin of the nucleon coming from?

1 Introduction

Atoms are made of protons, neutrons, and electrons, approximately in equal numbers. Electrons weigh about 0.5 MeV, protons and neutrons about 1000 MeV. It follows that nucleons (*i.e.*, protons and neutrons) are responsible for about 99.97% of the mass of matter around us.

When we study nucleons, we are embarked on the quest to understand the ultimate constituents of matter, one of the most fascinating adventures of the history of human thought.

Nucleons are not elementary particles. They have an extension of the order of 1 femtometer (10^{-15} m). The nucleon is thus a "femtostructure", *i.e.*, one million times smaller than nanostructures. The smallness of this scale is astonishing. Resolving the internal structure of the protons (10^{-15} m) in the magazine you are reading (10^{-1} m) is similar to reading the magazine from outside the Solar System (10^{13} m).

Inside nucleons, we know that there are quarks and gluons, collectively called partons (see fig. 1 for an artistic impression). Their life and interaction is governed by the strong force, the strongest one among the fundamental forces known to exist in the Universe, which is described by Quantum Chromodynamics (QCD) as part of the Standard Model of Particle Physics.

When we look into the nucleons at extremely high resolution, we are in the regime of perturbative QCD. Quarks and gluons appear almost free. We can explain this feature (asymptotic freedom) starting from the QCD Lagrangian. With the due caveats, we can compare the situation to observing a thick cloud at extreme magnifications, and seeing quasi-free water molecules. As we reduce the magnification, we realize that the molecules clump together in heavier, composite water droplets. Eventually, at low magnification they form a single, thick cloud: the nucleon. The details of this transition are largely unknown. We are unable to describe the cloud starting from the dynamics of water molecules, in other

---

* e-mail: `alessandro.bacchetta@unipv.it`
** e-mail: `mcontalb@fe.infn.it`

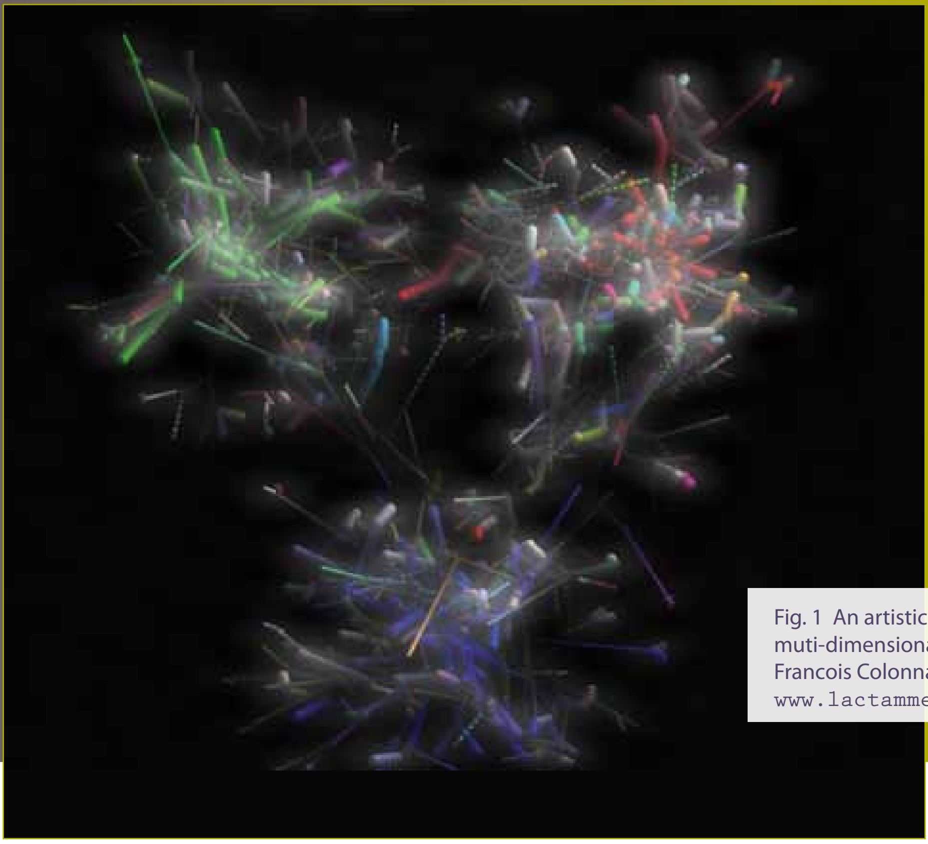

Fig. 1 An artistic view of the proton inner muti-dimensional structure. Courtesy of Jean-Francois Colonna (CMAP/Ecole Polytechnique, `www.lactamme.polytechnique.fr`).

words we do not understand QCD in the nonperturbative regime. In fact, we are unable to describe its most crucial characteristic: confinement, *i.e.*, the fact that quarks and gluons are inescapably bound into nucleons. Confinement represents one of the hardest physics problems of today. Giving a mathematical proof that QCD displays confinement is a formidable and groundbreaking task, to the point that it has been included among the seven Millenium Prize Problems in Mathematics issued in the year 2000 by the Clay Mathematics Institute [1].

At present, the most powerful attempts to understand QCD in the nonperturbative regime are performed by means of lattice QCD, where QCD computations are carried out on a discrete lattice instead of a space continuum. It is beyond the scope of this article to describe the many successes of lattice QCD. Nevertheless, the topic is of enormous relevance for nucleon studies. In fact, using lattice QCD it is possible to calculate that 95% of the proton's mass directly comes from the binding energy of color interactions. The Nobel laureate Frank Wilczek expressed his awe for lattice QCD results with these words: "Through difficult calculations of merciless precision that call upon the full power of modern computer technology, […] they have demonstrated the origin of the proton's mass, and thereby the lioness's share of our mass. I believe this is one of the greatest scientific achievements of all time" [2].

In spite of these achievements, we are still profoundly far from fully understanding QCD and nucleons. If we take a look at the list of nucleon's properties in the Particle Data Group tables, apart from the mass we can read what is the nucleon's spin, its quark content, its charge, its magnetic moment, its charge radius… But it is fair to say that we cannot explain any single one of these quantities from first principles.

Nevertheless, we are not groping in total darkness. We are in a situation that a scientist should love: we face hard and fundamental questions, we can build upon successful ideas, we have many things to do to pave the way towards the required leap of knowledge. At some point, we expect some exceptional breakthrough.

One of the ways we can follow to better understand QCD and confinement is to study the inner structure of the nucleon in higher and higher details. In these years, we are reaching the opportunity to reconstruct multi-dimensional "pictures" of the nucleon. The knowledge of the multi-dimensional structure allows the analysis of properties otherwise inaccessible: quark-gluon correlations, effects of final-state interactions, spin-orbit and spin-spin correlations, and much more. The situation may be compared to protein studies: our present knowledge of the proton structure is limited to one dimension and can be compared to knowing the sequence of amino acids of proteins. It is an extremely important piece of information, but insufficient to understand them. Starting from the 1960s, it has become possible to reconstruct their 3D structure. These advances literally revolutionized our understanding of protein chemistry.

In a certain sense, as astronomers of the Renaissance explored the Universe, we observe the constituents of the proton with higher and higher accuracy and from all possible sides (fig. 2). We strive to maintain a fresh and unbiased view, and we look for unexpected details, like solar spots and Jovian satellites. We hope at some point to spark the genius of some novel Newton.

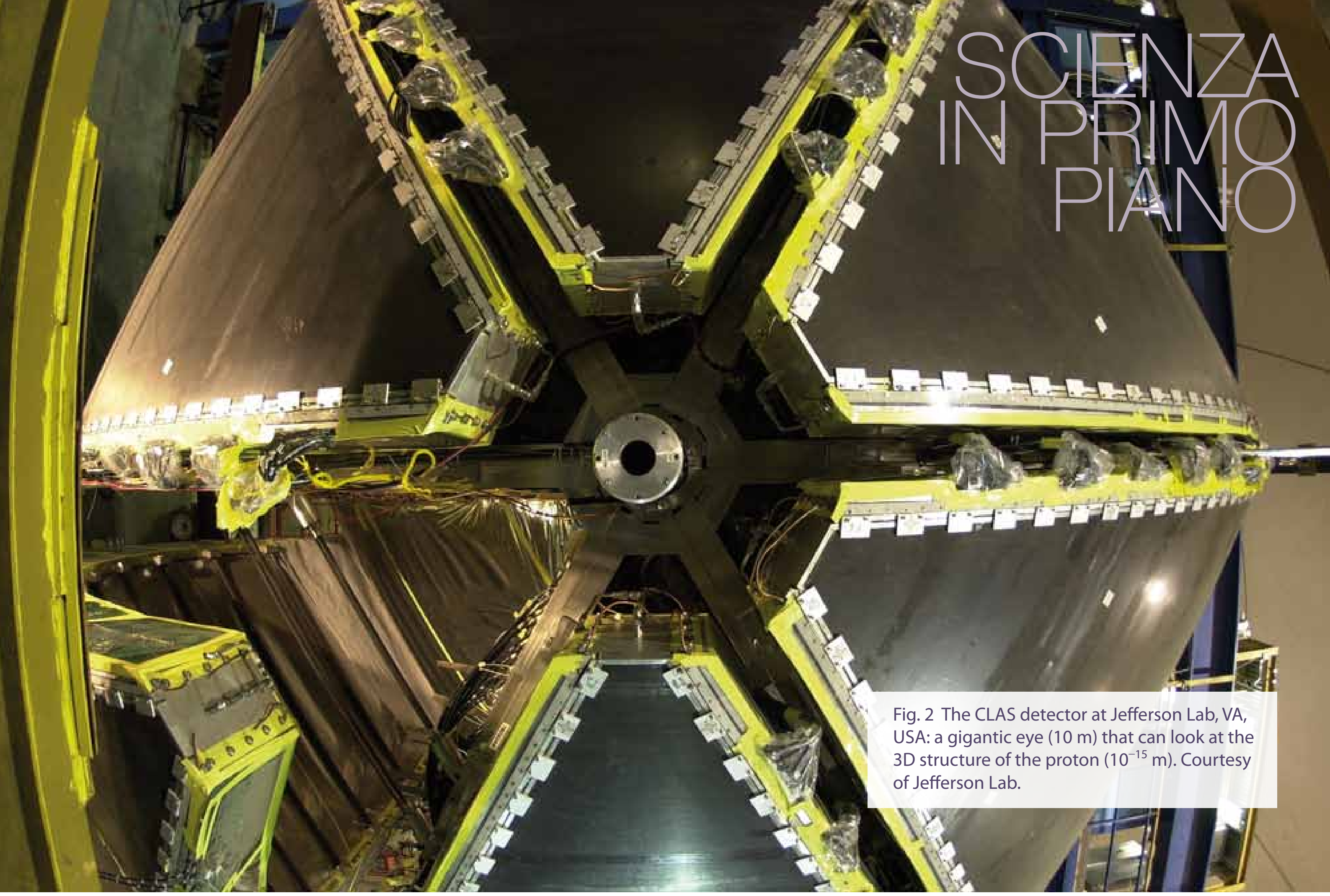

Fig. 2 The CLAS detector at Jefferson Lab, VA, USA: a gigantic eye (10 m) that can look at the 3D structure of the proton (10^{-15} m). Courtesy of Jefferson Lab.

2 Multi-dimensional images of the proton

> *"With 3D projection, we will be entering a new age. Something which was never technically possible before: a stunning visual experience which 'turbocharges' the viewing."*
>
> James Cameron

Partons inside the proton can have a specific momentum and a specific position (with respect to some definition of the "center" of the proton). Their state can be described by Wigner distributions in six-dimensions (three position and three momentum coordinates) [3]. Wigner distributions are the quantum-mechanical constructions that are closest to a classical probability density in phase space. Strictly speaking, due to the Heisenberg uncertainty principle, they cannot be considered as probability densities and are not positive definite. For this reason, they are often defined as "quasi-probability" distributions. However, they can be used to compute the expectation value of any physical observable. In this sense, they represent the maximal knowledge of the partonic structure. They are equivalent to knowing the complete wave function of partons inside the nucleon.

Projections of Wigner distributions on some of the available dimensions do have a probabilistic interpretation (see, *e.g.*, [4, 5]). Of these, we will take into consideration only some interesting examples. In order to be more specific, we need to distinguish a longitudinal direction from two transverse directions. To observe the internal structure of the proton we need a "hard" probe (*i.e.*, with high four-momentum). This requirement allows us to define a longitudinal direction: it could be defined as the direction of the probe in the rest frame of the nucleon, or the direction of the nucleon in the center-of-mass frame of nucleon and probe (or in any other frame where proton and probe are collinear). The "transverse" plane is the one orthogonal to the longitudinal direction.

If we integrate over all coordinates and the two transverse components of momentum we obtain a projection of the Wigner distributions on the longitudinal momentum only. These projections are well studied and have a name: they correspond to the standard "parton distribution functions" (PDFs). They represent the probability of finding a parton inside a nucleon with a given fraction of the nucleon's longitudinal momentum, usually denoted with the variable x. In this sense, they are pictures of the partonic structure of the nucleon in only one dimension in momentum space. At this point, it is worthwhile remarking that this interpretation is valid at the parton model level, *i.e.*, when the nucleon constituents can be treated approximately as free for the purpose of calculating the interaction with the probe. In the formal QCD treatment, this interpretation is modified and corresponds to the parton model concept only in the lowest

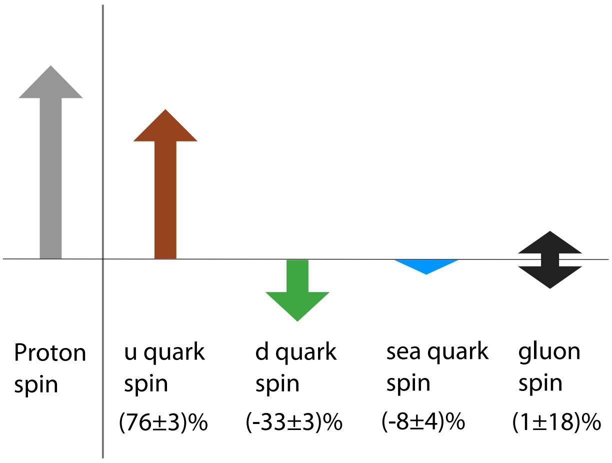

Fig. 3 The origin of the spin of the proton is still a conundrum. At present, we know that only about 1/3 of it comes from the spin of the partons. Will we be able to show that the rest comes from the orbital angular momentum of partons? (The numbers above refers to a scale $Q^2 = 10\ \mathrm{GeV}^2$ and are taken from Tab. II of ref. [7]. See there for the precise meaning of the quoted quantities.)

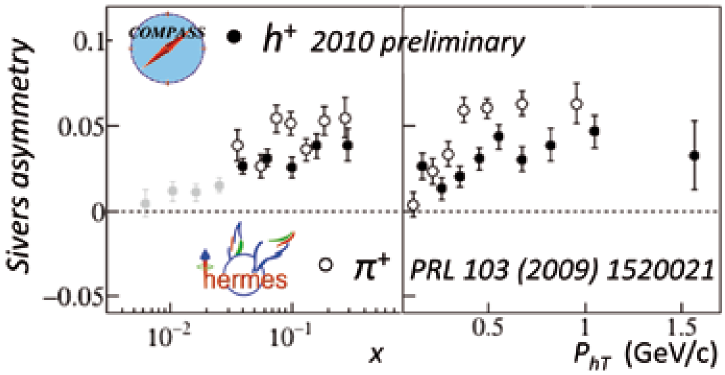

Fig. 4 To obtain information about the missing contributions to the proton spin budget, we need to go beyond the study of standard parton distributions and explore the multi-dimensional structure of the proton. For this purpose, we can use recent data as the ones shown in the plot.

order of perturbation theory [6]. With this in mind, we can say that parton distributions are approximate images of the partonic structure.

At the highest possible resolutions currently available, we see approximately the same density of light quarks (up, down, strange) and their antiquarks, together with a much larger number of gluons. We could say that nucleons are essentially lumps of glue with some grains of powder inside. Quarks and antiquarks carry about half of the momentum of the nucleon, and gluons the other half. The charge, the baryon number and the isospin of the nucleon are due to the small imbalance between quarks and antiquarks (*i.e.*, by the so-called valence quarks), yielding, *e.g.*, a net number of two up-quarks and one down-quark for the proton. However, the details of the quark and antiquark distributions are somewhat surprising. For instance, we may naively think that everything other than the valence quark distributions is generated by purely perturbative QCD processes (*e.g.*, quark radiating gluons, gluons splitting into quark-antiquark pairs). From the point of view of perturbative QCD there is no difference between, *e.g.*, anti-up and anti-down quarks. Therefore, we would naively expect the distributions of anti-up and anti-down to be the same. However, data indicate that there is a significant deviation from this expectation: in a proton, there are more anti-down than anti-up quarks. There must be a nonperturbative mechanism that favors the presence of down/anti-down pairs compared to up/anti-up pairs.

Equally intriguing observations can be made when the spins of partons and nucleons are taken into consideration. For instance, we can ask ourselves if there is an imbalance between partons with their spin aligned or antialigned to the nucleon's spin, when it is oriented in the longitudinal direction. The naive quark model would suggest that about two-thirds of the quarks are aligned to the nucleon and one-third antialigned, so that the spin of the nucleon is entirely due to the spin of the quarks. But Nature is less trivial than that: it turns out that quarks' spin contributes to only about 1/3 of the total spin of the nucleon. Ongoing investigations reveal that the contribution from the spin of the gluons is very small in the kinematical range explored so far. Therefore, we are at present unable to account for more than half of the spin of the nucleon [8, 9] (see fig. 3). The missing contribution should come from the orbital angular momentum of quarks and gluons. An answer to this critical question is still missing and cannot come from the study of standard parton distribution functions, but requires to investigate the multi-dimensional structure of the proton (see fig. 4).

Naively, we may also expect that the number of quarks spinning in the same direction as the nucleon is the same whether we orient the nucleon's spin in the longitudinal direction or in a transverse direction. This would be true in a nonrelativistic system, but the infinitesimal distances we are probing require the use of high-momentum probes and puts us immediately in a relativistic context. Then, the distributions of quark spin in the longitudinal and transverse directions are in general different, and they are described by two independent parton distributions: the helicity and transversity distributions. The difference between the two depends on the dynamics inside the nucleon. Different models of the nucleon structure may predict the same helicity distribution, but different transversity distributions. In summary, measuring the helicity and transversity distributions gives two orthogonal views of the quark spin distribution, head-on and sideways. These two independent perspectives can be used to better discriminate between alternative descriptions of the inner structure of the nucleon. Amazingly, the first experimental "sideways look" to the quark spin was taken only a few years ago, in 2004, by the HERMES collaboration (DESY), soon followed by the COMPASS collaboration (CERN). These measurements were reported in pioneering papers that are cited on average more than 50 times a year, rivaling papers on, *e.g.*, neutrino oscillations published in the same year [10, 11].

Although parton distribution functions are extremely useful for studying any process involving hadrons (including the hardest ever human-made proton-proton collisions taking place at the LHC), from the point of view of nucleon imaging they are rather limited, because they describe the distribution of partons in a single dimension. Their information content could be compared to electroencephalograms, which give a mono-dimensional monitoring of brain's activity. In contrast, Wigner distributions could be compared to functional magnetic resonance imaging, which monitors brain's structure and activity in three dimensions, opening entirely new ways to study brain physiology and brain dysfunctions.

Let us then turn our attention to two classes of distribution, representing two "projections" of the six-dimensional Wigner distributions onto two smaller subspaces.

Challenging measurements

The steps forward in our knowledge of the world are usually driven by those measurements that do not fit in the framework of a well-established theory. In hadronic physics, there are several observations that are hard to explain with QCD and have awaited explanation for almost 20 years.

What was initially known as the "spin crisis" emerged in the late 1980s when the EMC experiment reported an unexpectedly small, or even vanishing, contribution of the quark spins to the nucleon spin. After 20 years of exploration, we obtained a rather precise determination of the global quark contribution, to be at the level of 1/3, although the role of the sea partons is not well constrained yet.

Also in the late 1980s, two unpolarized Drell-Yan experiments, NA10 at CERN and E615 at Fermilab, demonstrated that the Lam-Tung relation derived 10 years before, although theoretically robust since analogous to the Callan-Gross relation for spin –½ quark and hardly sensitive to higher-order corrections, is badly violated when using pion beams (containing a valence anti-quark).

In 1991, a striking azimuthal dependence was found at Fermilab for inclusive pion production with a 200 GeV polarized proton beam. Positive- and negative-charged pions move in opposite directions with respect to the beam spin transverse orientation, with asymmetries as large as 40% in the forward limit. This surprising behavior was later found to persist even at very high center-of-mass energies, in contrast to expectations based on perturbative QCD.

Since the late 1970s, it has been known that hyperon production in unpolarized hadronic reactions comes with a spontaneous polarization, which increases with transverse momentum up to 30%. A spontaneous polarization is observed also in J/ψ meson production, which is challenging for the theory.

All of these observations naturally relate to the correlations between transverse momentum and spin, *i.e.* spin-orbit correlations at the partonic level. In order to study those, one has to overcome the historical collinear approximation and start to work in the real 3D world.

(For more details see, *e.g.*, refs. [12, 13].)

3 Transverse-momentum distributions

If we integrate Wigner distributions over all coordinates, we obtain the so-called "transverse-momentum distributions" (TMDs). They represent pictures of three-dimensional densities in momentum space. Contrary to a naive expectation, these pictures are not spherically symmetric. Since they are taken using a hard probe, there is a clear distinction between the longitudinal dimension and the two transverse directions. In fact, the nucleon seen from the point of view of the probe does not look spherical at all, but rather like a flat dish, due to Lorentz contraction. There are many nontrivial questions concerning TMDs that do not have an answer yet. For instance, we still do not have sufficient information to discern if the parton density (in momentum space) is higher in the center of the "dish" and decreasing monotonically as we move to the borders (similar to a pie), or decreases in the center (similar to a doughnut, see fig. 5). The distribution changes depending on the energy scale at which it is probed (in a way that is calculable using perturbative QCD) and on the value of the longitudinal fractional momentum. At present, we know that experimental data are consistent with a Gaussian distribution with a width (*i.e.*, an average transverse momentum) of about 0.6 GeV at an energy scale of 2 GeV. Roughly speaking, half of it is coming from the primordial transverse momentum of the quark and half is acquired through perturbative gluon radiation. There are indications that the transverse-momentum distribution becomes larger when longitudinal momentum is lower.

We also do not know if there is a difference in the distribution of partons with different flavors: is one flavor more concentrated in the center and the other on the sides (like yolk and albumen in a fried egg)? Or are the flavors uniformly mixed (like a scrambled egg)? There are first feeble indications from experimental measurements and from lattice QCD computations that the down-quark distribution is larger than the up-quark one [14, 15] (see fig. 6).

The above considerations apply when we average over the nucleon's spin direction. There is even more fun when spin is taken into account. For instance, suppose the spin of the nucleon is moving toward us and its spin is pointing upwards: it turns out that we see up-quarks moving preferentially to the right and down-quarks to the left. In terms of images in momentum space, the distributions are not cylindrically symmetric anymore, but distorted in opposite ways for up- and down-quarks. Sticking to our gastronomic analogies, the proton looks like a round dish with some ingredients on one

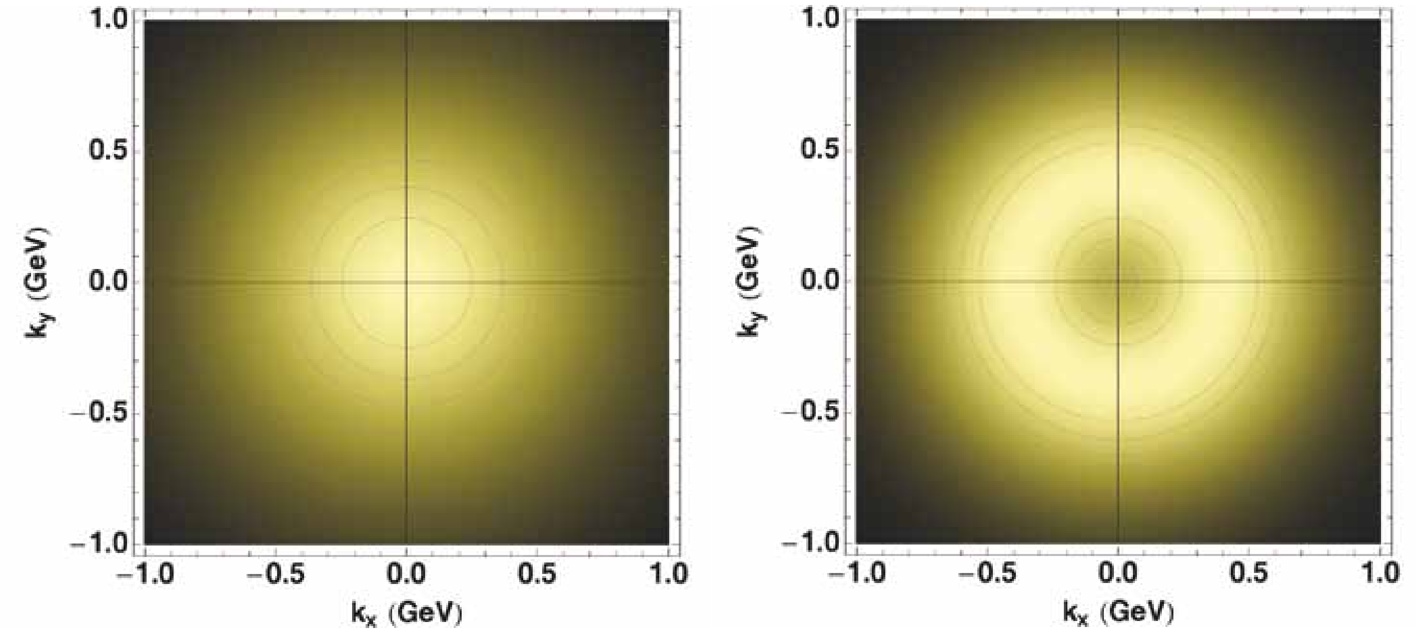

Fig. 5 We do not know enough yet about the distribution of quarks in momentum space, qualitatively depicted in the figure: does it look like a pie (left) or like a doughnut (right)?

side and some others on the opposite side (see fig. 7). It is worthwhile describing the progress made in understanding this kind of effect. It was first proposed by D. Sivers in 1990 as a way to explain large left-right asymmetries observed in pion-nucleus collisions [16]. For this reason we nowadays normally speak about the "Sivers effect," and the "Sivers function" describes the left-right distortion in the distribution of partons. For more than a decade, this effect was thought to vanish due to time-reversal symmetry. Starting from a model calculation in 2002, theory studies made clear that the Sivers function could be nonzero [17]. In 2004, the first experimental evidence of a nonzero Sivers effect was reported by the HERMES collaboration [10], later confirmed by the COMPASS collaboration later confirmed by the COMPASS collaboration. Figure 4 shows the state-of-the-art data from the two collaborations. These breakthroughs forced a profound revision of the QCD treatment of transverse momentum distributions, still partially underway [6]. For instance, one of the consequences is that the Sivers function in deep inelastic scattering (where an electron strikes a quark inside the nucleon) has an opposite sign compared to the Sivers function in Drell-Yan processes (where an antiquark annihilates a quark inside the nucleon). In other words, an antiquark probe should see a distortion exactly opposite to fig. 7. This striking prediction should be confirmed (or falsified!) in the next few years by planned experiments (COMPASS at CERN, AnDY at Brookhaven National Lab).

The technological journey

Spin, a fundamental property of the particles, is a crucial ingredient in the mapping of nucleon structure. Controlling the polarization in the initial (or final) state of an experiment is a tough problem, which has been a source of continuous technological challenges.

Solid-state polarized targets, such as NH_3(for protons) or ^{6}LiD (for deuterons) used by the COMPASS experiment at CERN (Geneve, Switzerland), have been the workhorses in this field. These massive cryogenic targets have been used with extracted beams since the 1970s, with a long history of successes mainly related to the collinear nucleon structure investigation. However, it is not clear how much the fraction of not-polarizable heavier nuclei, which dilute the polarization and introduce nuclear effects, might affect cutting-edge measurements such as the ones sensitive to the partonic transverse momentum.

The alternative solution proposed by the HERMES experiment at DESY (Hamburg, Germany) is the use of a gaseous target inside a storage ring. The pure target material is provided by an atomic beam source, which selects the hydrogen or deuterium hyperfine states to be injected in the target cell. The HERMES collaboration has published several pioneering results on partonic spin-orbit effects, but the trade-off for such a target is the limited luminosity and statistical precision.

Jefferson Lab (Newport News, USA) is committed to go beyond such limitations by developing a novel target concept. The HD-ice target works in a frozen spin mode at very low temperature and moderate magnetic fields. It has a small dilution and allows the independent control of the proton and deuterium polarizations. It will be exposed to charged beams in spring 2012 for the first time.

Some experiments rely on natural polarization effects to get a polarized beam. The COMPASS experiment uses a muon beam that comes naturally polarized by meson decays. The HERMES experiment exploited the natural build-up of transverse polarization in a stored electron beam due to the tiny spin-flip asymmetry in synchrotron radiation (Sokolov-Ternov effect).

Other experiments tackle the hard task of accelerating particles while maintaining their initial polarization. The fight against all the energy-dependent depolarization resonances was desperate before the invention of the Syberian Snakes, which control the phase of spin precession. This allowed the construction of the world largest polarized hadron collider at BNL (Upton, USA), which is able to reach beam energies up to 500 GeV. At the intensity frontier, Jefferson Lab reached the luminosity record of 10^{36} cm^{-2} s^{-1} with a 10 atm ^{3}He polarized target and a 12 μA beam of polarized electrons extracted from a GaAs photocatode by a circularly polarized laser and then accelerated to 6 GeV/*c*.

Polarized antiproton beams would be a unique source of polarized valence anti-quarks. Several methods have been attempted in the past, although none has been proven to achieve the desired factor of merit (intensity times polarization) so far. The spin-filtering technique, for which a proof of principle exists, is currently under study at COSY (Jülich, Germany).

In the next future, the envisaged facility for the complete mapping of the 3D structure of the nucleon is a high-energy polarized electron-ion collider, which should merge together the strengths of a polarized hadron collider (as at BNL) and a high-luminosity electron beam (as at Jefferson Lab).

(For more information see, *e.g.*, ref. [18].)

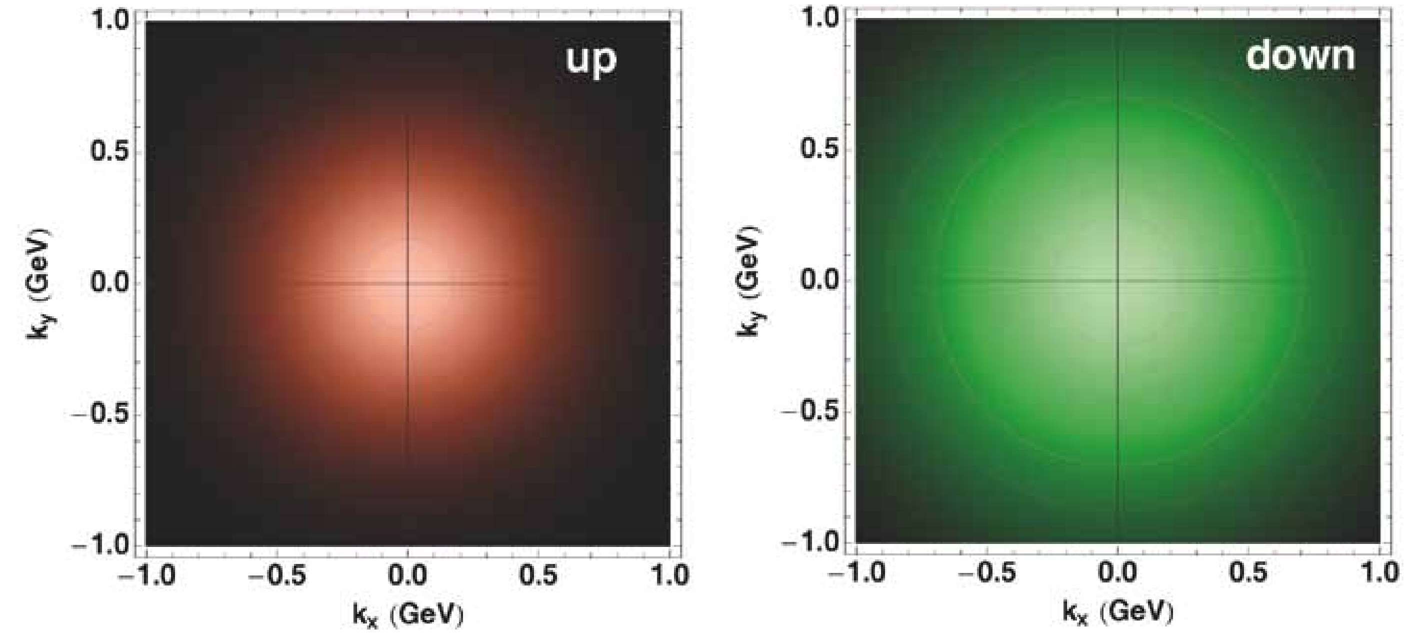

Fig. 6 The transverse-momentum distribution may be different for quarks of different flavors. There are some indications that the up-quarks are closer to the center than the down-quarks. The above pictures are compatible with existing data.

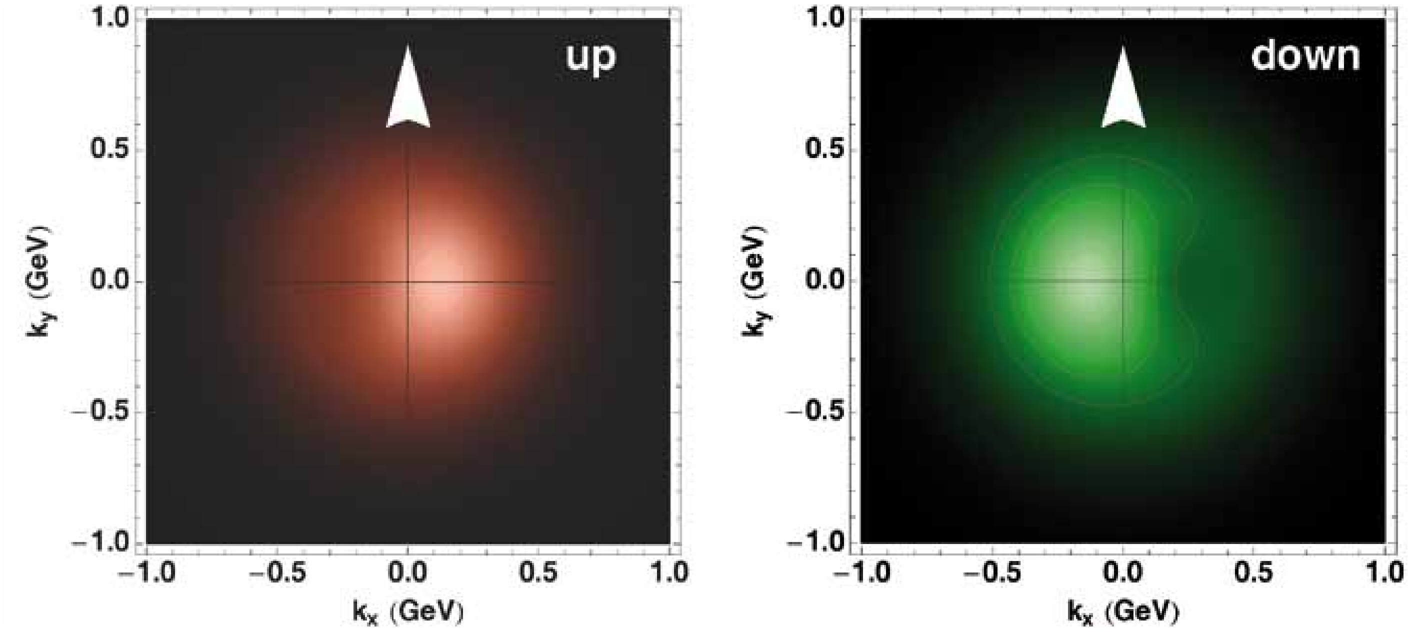

Fig. 7 Polarization-averaged distributions, as in figs. 4 and 5, are cylindrically symmetric. But when the spin of the nucleon is taken into account (indicated by the white arrow in the plots), the distribution can be distorted. These images are elaborated starting from real data and show that the distortion for up- and down-quarks is opposite (see, *e.g.*, [19, 20]). Large uncertainties are still affecting these pictures.

4 Impact parameter distributions

If we integrate the Wigner distributions over transverse momenta and the longitudinal coordinate, we obtain the so-called "impact parameter distributions" [21]. They reveal the distribution of partons as a function of their longitudinal momentum and their transverse position with respect to the center of momentum of the nucleon (*i.e.*, the relevant transverse coordinates). If we integrate even over the longitudinal momentum, we obtain pictures of the partonic structure in transverse coordinate space, as seen from the point of view of a hard probe hitting the nucleon. As far as we know today, this is probably as close as we can get to the everyday concept of a photo of the nucleon.

These distributions can be computed using models or lattice QCD techniques. But the good news is that they can also be reconstructed from experimental data. In fact, they are directly related to two-dimensional Fourier transforms of the nucleon form factors. Historically, nucleon form factors provided the first indications that protons and neutrons are not elementary particles. For instance, when in 1933 the first Stern-Gerlach experiment on the proton was performed, most physicists expected the magnetic moment of the proton (*i.e.*, the value of the magnetic form factor $G_M(t)$ at $t = 0$) to be one nuclear magneton. Shockingly, it turned out to be 2.5 magnetons. Form factor measurements started in the 1950s led to the first estimates of the proton radius (to be precise, one if its possible definitions), fixing it at around 0.8 femtometers. After fifty years of studies, we have made some steps forward, but we have also unearthed many mysteries. For instance, the proton seems to "shrink" in a muonium atom (made by a proton and a muon): the radius of the proton in a muonium atom is 0.84184 ± 67 fm, which differs by five standard deviations from the hydrogen value of 0.8768 ± 69 fm [22]. These estimates are inferred from Lamb-shift measurements, not from the direct measurement of form factors. From the point of view of nucleon imaging, we can measure the transverse densities of partons, as seen from a hard probe, and their associated radius. We cannot reach the precision quoted above, but the information we obtain is much richer.

For instance, measuring the Dirac and Pauli form factors of protons and neutrons and performing a two-dimensional Fourier transform [23], we can obtain the images of the quark density in impact parameter space shown in figs. 8 and 9. As for momentum distributions, we can first take a look at the average over nucleon polarization. From the information we have on the proton and neutron form factors and using some assumptions, we can conclude that the up-quark distribution is narrower than the down-quark one.

When the orientation of the nucleon spin is fixed, we discover that the up- and down-quark distributions are distorted in opposite ways. The distortion of the down-quarks seems to be much larger than that of the up-quarks.

When looking at the distributions in the impact parameter space, we are tempted to compare them with the momentum distributions. First of all, it must be stressed that the two distributions are not connected by a Fourier transform. Secondly, it must be kept in mind that the impact parameter distributions obtained from the form factors refer to the valence quark combinations (*i.e.*, quark minus antiquarks). Finally, the impact parameter distributions obtained from form factors are integrated over the longitudinal momentum fraction *x*.

In order to overcome these limitations, we have to turn our attention to a generalization of the form factors that embodies also the dependence on *x*. Such quantities are called "generalized parton distributions" (GPDs) [24]. They are hybrids between a parton distribution function and a form factor and correspond to integrations of the Wigner distributions over transverse momentum and longitudinal position. They effectively are like tomographic slices of the form factors at a fixed value of the momentum fraction *x*. The *x*-dependence of GPDs is extremely important, in particular it is essential to quantify partonic angular momentum, which can be related to an *x*-weighted integral of the GPDs corresponding to the Pauli and Dirac form factors.

The first GPD measurements sensitive to partonic angular momentum were published between the end of 2007 by E03-106 experiment at Jefferson Lab [25] and the beginning of 2008 by HERMES Collaboration [26]. Based on two different reaction channels, two experimental constraints on the u- and d-quark total angular momentum were derived in a model-dependent way. These first exploratory results are consistent with predictions from lattice QCD. Although far from being completely reliable, the conclusions are perplexing: up and down orbital angular momenta are approximately equal and opposite, thus giving a small net contribution to the proton spin… This brings us back to the question of the origin of the proton's spin, possibly more puzzled than before.

Form factors, GPDs, and TMDs are projections of the nulceon's Wigner distributions that can be accessed experimentally and in fact are subjects of intense studies at present deep-inelastic-scattering experiments (HERMES at DESY, COMPASS at CERN, and experiments at Jefferson Lab) and represent flagship topics for their future upgrades (see fig. 10). Complementary perspectives are offered by final-state correlations in electron-positron collisions at the B-factories (BaBar, Belle and their upgrades) and by polarized proton-proton collisions at present machines (RICH at Brookhaven National Lab, the Main Injector at Fermilab and the IHEP U70 accelerator) and future facilities (FAIR in Europe, J_PARC in Japan, and NICA in Russia). Apart from valence quarks, more investigations are needed to pin down

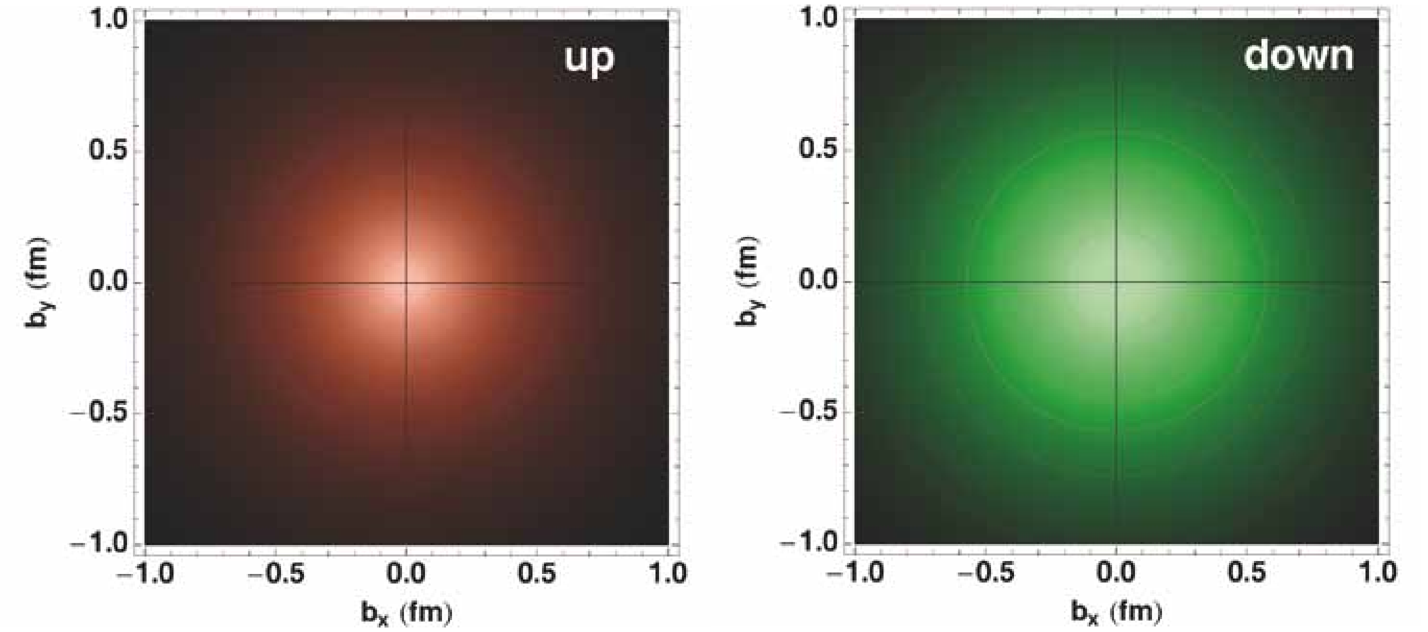

Fig. 8 distribution of quarks in impact parameter space, as obtained by a two-dimensional Fourier transform of the nucleon Dirac form factors. The distribution of the up-quarks turns out to be narrower than that of the down-quarks. Among other things, this means that a high-energy probe sees a core of positive charge in the center of the proton and a cloud of negative charge around it.

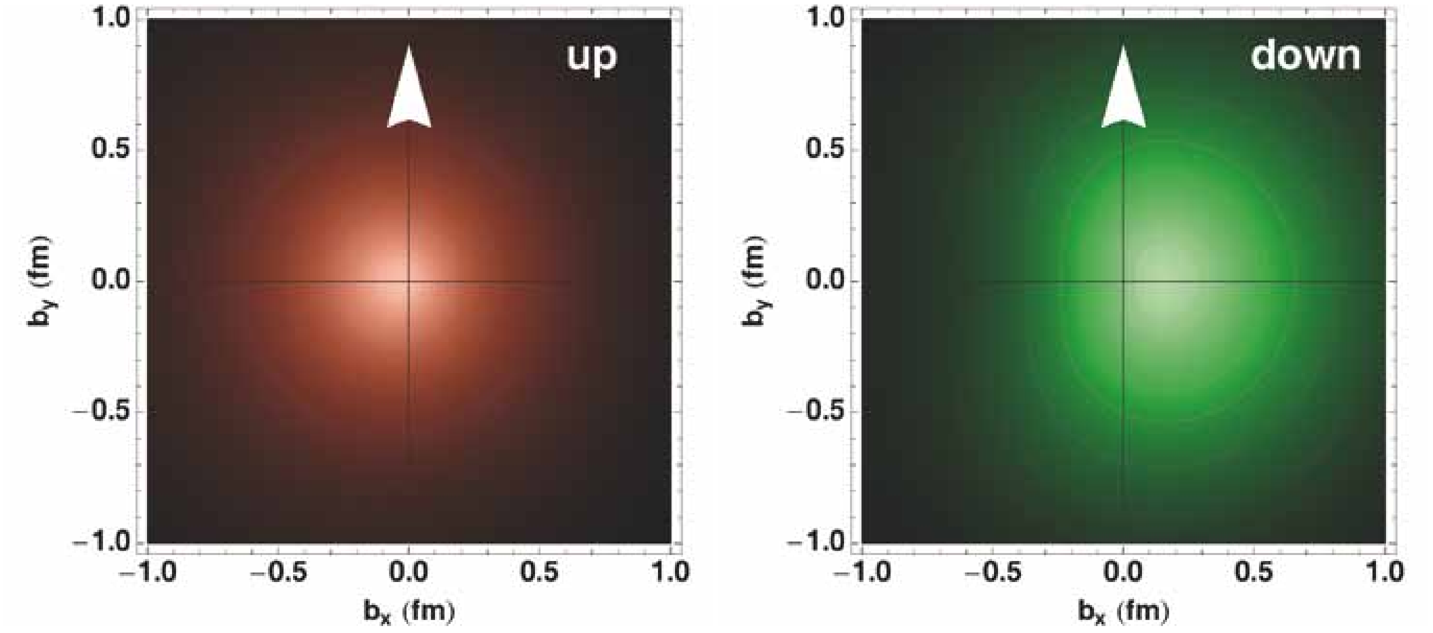

Fig. 9 When the spin of the nucleon is taken into consideration, the quark distribution is distorted in opposite ways for up- and down-quarks. This distortion indirectly suggests that the up-quarks have a large orbital angular momentum opposite to the proton spin. Vice-versa for the down-quark.

the structure of sea-quarks and gluons. The best possible tool to perform this study is a polarized electron-proton collider, which is a project currently under intense study [27]. Italy is well represented in the nucleon-3D quest, contributing to many of these projects with recognized experimental competence and a strong support from an active national theoretical community.

5 Conclusions

We have just started looking at intriguing features in the 3D distribution of quarks in momentum space or impact parameter space and most of the landscape lies unexplored in front of us. We anticipate several years of exciting investigation and breakthrough results, which eventually will increase our comprehension of one of the most fascinating mysteries of our world: the ultimate nature of the matter we are made of.

> *"We shall not cease from exploration*
> *and the end of all our exploring*
> *will be to arrive where we started...*
> *and know the place for the first time."*
> *T. S. Elliot, Four Quartets*

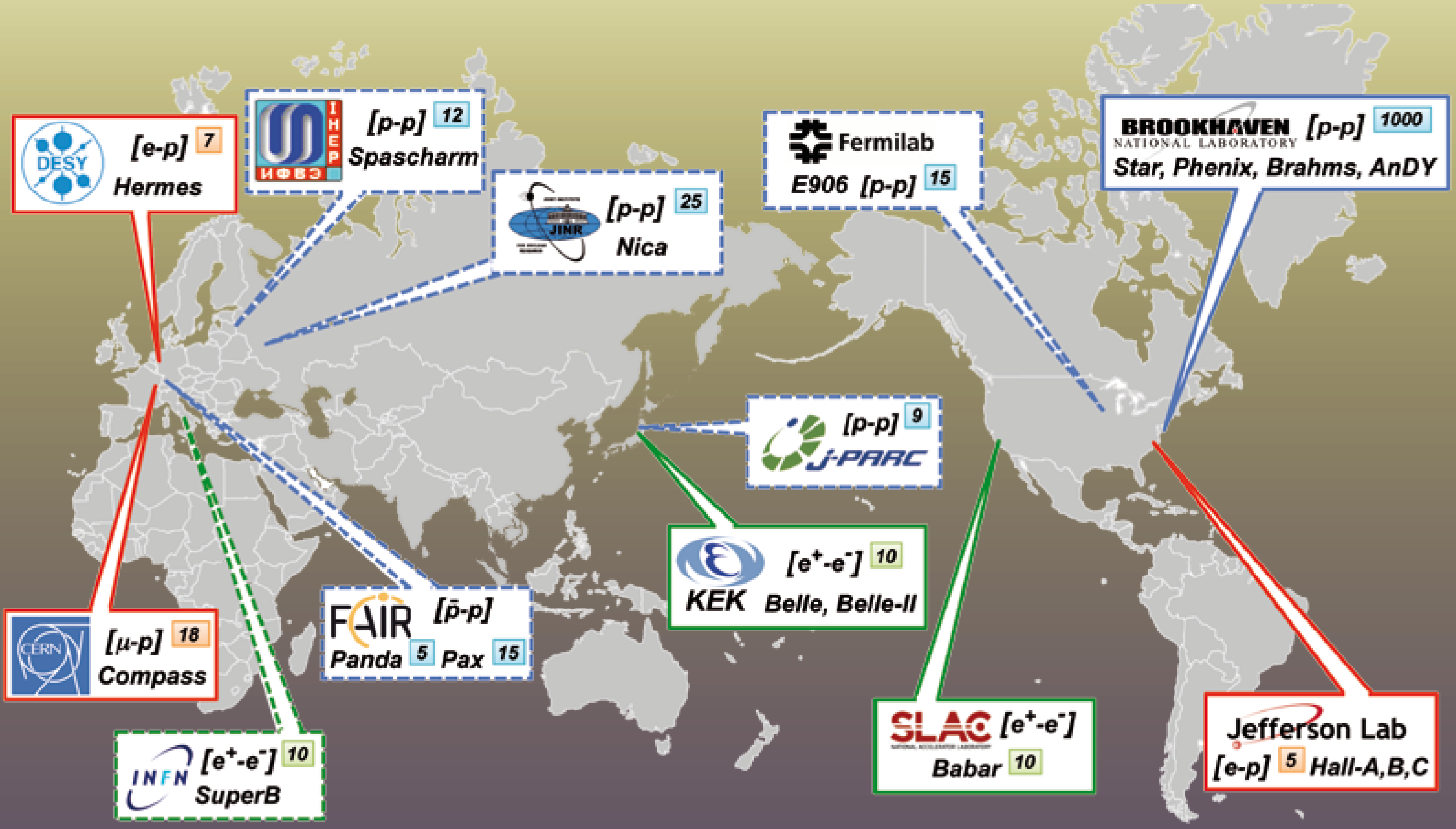

Fig. 10 A map of present (solid line) and future (dotted line) experimental venues involved in the exploration of the 3D structure of the nucleons. For each laboratory (indicated by the logo), the interacting particles (within parenthesis) and the center-of-mass energy in GeV (within colored circles) are indicated together with the experiment names. Deep-inelastic-scattering experiments with leptonic probes (red) and Drell-Yan experiments with hadronic probes (blue) provide direct information about the partonic structure of the nucleon. Electron-positron colliders (green) provide complementary information on the quark fragmentation into final-state hadron.

Acknowledgements

In this note we made an effort to be concise and give a fresh perspective on our field of research without describing too many details. We hope we managed to convey part of the emotions we share working in this complex but fascinating field: the love, the enthusiasm, the marvel for exploring the frontiers of the infinitesimally small, and the sense of privilege for advancing on one of the edges of fundamental knowledge. We would like to thank the community of Italian physics working in hadronic physics, with whom we share this adventure: a dynamic and friendly group, with a top international reputation.

Bibliography

[1] D. Sivers, "*The Adventure and the Prize*" (2011). `http://arxiv.org/abs/arXiv:1109.2521`

[2] F. Wilczek, "*The Lightness of Being: Big Questions, Real Answers*" (Penguin Books, London, UK) 2010.

[3] X. Ji, "*Viewing the proton through 'color'-filters*", *Phys. Rev. Lett.*, 91 (2003) 062001.

[4] A. V. Belitsky, X. Ji, and F. Yuan, "*Quark imaging in the proton via quantum phase-space distributions*", *Phys. Rev. D*, 69 (2004) 074014.

[5] C. Lorcé, B. Pasquini, and M. Vanderhaeghen, "*Unified framework for generalized and transverse-momentum dependent parton distributions within a 3Q light-cone picture of the nucleon*", *JHEP*, 1105 (2011) 041.

[6] J. Collins, *Foundations of perturbative QCD* (Cambridge University Press, Cambridge) 2011.

[7] D. de Florian, R. Sassot, M. Stratmann, and W. Vogelsang, "*Global Analysis of Helicity Parton Densities and Their Uncertainties*", *Phys. Rev. Lett.*, 101 (2008) 072001, 10.1103/PhysRevLett.101.072001.

[8] R. Jaffe, "*Where does the proton really get its spin?*", *Physics Today*, 48N9 (1995) 24.

[9] K. Rith and A. Schaefer, "*The mistery of nucleon spin*", *Scientific American*, 1999N1 (1999) 42.

[10] HERMES Collaboration, A. Airapetian *et al.*, "*Single-spin asymmetries in semi-inclusive deep-inelastic scattering on a transversely polarized hydrogen target*", *Phys. Rev. Lett.*, 94 (2005) 012002.

[11] COMPASS Collaboration, V. Alexakhin *et al.*, "*First measurement of the transverse spin asymmetries of the deuteron in semi-inclusive deep inelastic scattering*", *Phys. Rev. Lett.*, 94 (2005) 202002.

[12] U. D'Alesio and F. Murgia, "*Azimuthal and Single Spin Asymmetries in Hard Scattering Processes*", *Prog. Part. Nucl. Phys.*, 61 (2008) 394.

[13] V. Barone, F. Bradamante, and A. Martin, "*Transverse-spin and transverse-momentum effects in high- energy processes*", *Prog. Part. Nucl. Phys.*, 65 (2010) 267.

[14] JLab Hall C, H. Mkrtchyan *et al.*, "*Transverse momentum dependence of semi-inclusive pion production*", *Phys. Lett. B*, 665 (2008) 20.

[15] B. U. Musch, P. Hagler, J. W. Negele, and A. Schafer, "*Exploring quark transverse momentum distributions with lattice QCD*", *Phys. Rev. D*, 83 (2011) 094507.

[16] D. W. Sivers, "*Single spin production asymmetries from the hard scattering of pointlike constituents*", *Phys. Rev. D*, 41 (1990) p. 83.

[17] S. J. Brodsky, D. Sung Hwang, and I. Schmidt, "*Final-state interactions and single-spin asymmetries in semi-inclusive deep inelastic scattering*", *Phys. Lett. B*, 530 (2002) 99.

[18] G. Ciullo, M. Contalbrigo, and P. Lenisa (Editors), "*Polarized Sources, Targets and Polarimetry*" (World Scientific, Singapore) 2011.

[19] M. Anselmino *et al.*, "*Sivers Effect for Pion and Kaon Production in Semi- Inclusive Deep Inelastic Scattering*", *Eur. Phys. J. A*, 39 (2009) 89.

[20] A Bacchetta and M. Radici, "*Constraining quark angular momentum through semi-inclusive measurements*", *Phys. Rev. Lett.*, 107 (2011) 212001.

[21] M. Burkardt, "*Impact parameter dependent parton distributions and off- forward parton distributions for zeta --> 0*", *Phys. Rev. D*, 62 (2000) 071503.

[22] R. Pohl and others, "*The size of the proton*", *Nature*, 446 (2010) 213.

[23] G. A. Miller, "*Charge Density of the Neutron and Proton*", *Phys. Rev. Lett.*, 99 (2007) 112001.

[24] X. Ji, "*Genelarized parton distributions*", *Ann. Rev. Nucl. Part. Sci.*, 54 (2004) 413.

[25] JLab Hall A, M. Mazouz *et al.*, "*Deeply virtual compton scattering off the neutron*," *Phys. Rev. Lett.*, 99 (2007) 242501.

[26] HERMES Collaboration, Airapetian *et al.*, "*Measurement of Azimuthal Asymmetries With Respect To Both Beam Charge and Transverse Target Polarization in Exclusive Electroproduction of Real Photons*".

[27] D. Boer *et al.*, "*Gluons and the quark sea at high energies: Distributions, polarization, tomography*", 2011. `http://arxiv.org/abs/arXiv:1108.1713`

Alessandro Bacchetta

Alessandro Bacchetta is Ricercatore at the Department of Physics of the University of Pavia and affiliated to INFN, Pavia. He works on theoretical hadronic physics within the local group of Hadronic Structure and QCD. He spent several years abroad. He did his PhD in the Netherlands, at the Vrije Universiteit of Amsterdam. He moved to Germany, first as an Alexander von Humboldt fellow at the University of Regensburg, then as a research fellow at DESY, Hamburg. He moved to Jefferson Lab, USA, as a Nathan Isgur distinguished fellow. He finally moved back to Italy in 2009.

Marco Contalbrigo

Marco Contalbrigo is Ricercatore at INFN, Ferrara. In the past he collaborated with the University of Padova, Perugia and Ferrara on neutrino oscillation and kaon *CP*-violation topics. For about ten years he has been working on experimental hadronic physics within several international collaborations, concentrating on the quest of nucleon spin structure. He is Analysis Coordinator and Transverse Physics Convener of the HERMES experiment, a pioneering experiment in this field. He is co-spokesperson of two deep-inelastic-scattering experiments at Jefferson Lab and one of the initial promoters of the PAX project for antiproton polarized beams.