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Spin and 3D structure of the nucleon

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We provide a concise presentation of the state of the art in the study of the polarized and three-dimensional structure of the nucleon, with particular emphasis on Transverse Momentum Distributions

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1. Introduction

In the last few years, two documents of strategic importance have been released in the United States: in 2015, the Nuclear Science Advisory Committee (NSAC) published the Long Range Plan for Nuclear Science [1] at the request of the Department of Energy (DOE) Office of Science and the National Science Foundation (NSF); in 2018, the U.S.A. National Academies of Sciences, Engineering, and Medicine published a consensus study report on the science of a U.S.-based Electron-Ion Collider (EIC) [2]. In these documents, the study of the spin and three-dimensional (3D) structure of the nucleon featured prominently.

The NSAC report [1] recommended to realize the forefront programs to study the quark and gluon structure of the proton and its spin, using the upgraded facilities of Jefferson Lab [3] and Brookhaven National Lab [4]. Moreover, the NSAC recommended the building of an Electron-Ion Collider as the highest priority for the next big construction of a Nuclear Physics facility in the U.S. The EIC with its high energy collision mode will precisely image gluons in nucleons and nuclei and reveal the origin of the nucleon spin.

The National Academies report [2] stated that an EIC can uniquely address three profound outstanding questions about nucleons: 1). How does the mass of the nucleon arise? 2). How does the spin of the nucleon arise? 3). What are the emergent properties of dense systems of gluons? *These three high-priority science questions can be answered by an EIC with highly polarized beams of electrons and ions, with suf ciently high luminosity and suf cient, and variable, center-of-mass energy.*

These few statements by themselves already make it clear that the study of the spin and 3D structure of the nucleon is strongly present in the strategic plans of the U.S. Nuclear Physics community. Recently, also in the European Union much work is going into the preparation of the European strategic plan for particle physics: we hope and we expect that it will emphasize the importance the study of the structure of the nucleon.

In this article we will briefly review the study of the partonic structure the nucleon, taking into account its dependence on polarization and on multiple dimensions, mainly in momentum space. For many decades the so-called one-dimensional structure of the nucleon was investigated, mainly by analysing the data obtained in Deep Inelastic Scattering (DIS), Drell-Yan (DY), and electron-positron annihilation (e^+e^-) experiments. The one-dimensional nucleon structure is encoded in nonperturbative objects called parton distribution and fragmentation functions (PDFs and FFs). These functions depend on the longitudinal momentum fraction carried by partons, (x for PDFs, z for FFs) and on the resolution scale Q provided, for example, by the virtuality of the photon in DIS. In order to separate short and long distance dynamics and to apply QCD factorization theorems, Q must be much larger than typical hadronic scales, such as the mass of the nucleon M or intrinsic QCD scale Λ. Thus these functions lack direct information on large distance scales (~ 1 fm) relevant to the mechanism of confinement. An additional parameter related to confinement can be provided by the transverse momentum of quarks and gluons bound inside of the nucleon. Transverse momentum of quarks and gluons is not measured directly experimentally, however it can be related to the measured transverse momentum of the produced hadron in Semi-Inclusive Deep Inelastic Scattering (SIDIS), lepton pair in Drell-Yan, or transverse momentum imbalance of two almost back-to-back hadrons produced in e^+e^- annihilation. To describe these processes, a new

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type of functions has to be introduced: they are called Transverse Momentum Distributions (TMDs) or Transverse Momentum Dependent parton distribution and fragmentation functions (TMD PDFs and TMD FFs respectively).

The phenomenology of TMDs flourished in the recent decade thanks to experimental measurements in SIDIS by the HERMES and COMPASS Collaborations and by experiments at Jefferson Lab, in e^+e^- by BaBar, BELLE and BESIII, and in proton proton collisions by RHIC experiments. New polarized Drell-Yan measurements have taken place at COMPASS and RHIC [4] and are planned at Fermilab. Jefferson Lab has just started the data-taking phase after the 12 GeV upgrade [3]. The Large Hadron Collider has become an important source of information on TMDs via Drell-Yan, $Z, W^{\pm}$ production data and jet measurements.

2. Spin

As clearly emphasized in the NAS report mentioned in the introcution, one of the key questions of understanding the structure of hadrons is: where does the spin of the nucleons come from? In the naive quark model, the spin of quarks add up to yield the total spin of the proton. However, hard scattering experiments show the importance of other contributions. Generally speaking, it is always possible to express the total angular momentum of the proton in terms of the spin and orbital angular momenta of quarks and gluons (see Ref. [5] for a discussion of the formulation of the spin sum rule)

$$J = \sum_q (S^q + L^q) + S^g + L^g. \tag{2.1}$$

The definition of each single term is not unique and must be specified clearly and consistently (see, e.g., [6, 7, 8, 9]). In principle, it is possible to determine each separate contribution through the study of helicity PDFs, together with Generalized Parton Distributions (GPDs) [10] and Wigner distributions [11]. Each contribution can be also computed in lattice QCD [12, 13]. Helicity PDFs give access to the S^q and S^g components of Eq. (2.1) and are extracted from polarized DIS and pp scattering data. Recent determinations are available in Refs. [14, 15, 16]. Their integrals are in remarkable agreement with lattice QCD [17]. The gluon helicity PDF is however still poorly constrained. In the future, more data from RHIC, and eventually from the EIC [18], will dramatically decrease the uncertainty in the determination of the gluon spin.

The situation is different for what concerns the so-called transversity PDF. Together with the unpolarized and helicity PDFs, it describes the collinear structure of a spin-1/2 hadron at leading twist. Being chiral-odd, $h_1(x)$ cannot be directly accessed in DIS, as another chiral-odd function is needed to form a chiral even observable. At present, it has been observed in SIDIS in combination with the Collins fragmentation function [19] or in two-hadron production in combination with a polarized dihadron fragmentation function. Recent determinations of the transversity PDF in the former approach can be found in Refs. [20, 21, 22], and in the latter approach in Ref. [23]. The two approaches rely on two different formalisms, but yield results in good agreement with each other.

The integral of the transversity PDF is related to the tensor charge of the nucleon and can be computed in lattice QCD (see for instance Ref. [17]). Surprisingly, the integrals of the up and down quark transversities are not in good agreement with phenomenological extractions [24]. A

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description of the data can be achieved [22] with a value of the isovector combination u-d compatible with lattice computations, but without reproducing the individual values of u and d. The error bars associated to the phenomenological extractions are however still large [24], due to the limited number of available data points and the need for extrapolations beyond the region explored by the measurements. The determination of the transversity PDF and of the tensor charge of the nucleon may have an impact also beyond hadronic physics, in the search for physics beyond the Standard Model [25]. Significant improvements are expected to come in the large-x region from experiments at Jefferson Lab [26] and in the low-x region from the future EIC.

The observables used in the extraction of transversity belong to the wider class of transverse single-spin asymmetries (SSA), where a collision with an unpolarized particle and a polarized one gives rise to a specific angular distribution of the scattered products. The naive expectation based on perturbative QCD arguments is that SSA should be suppressed as $\alpha_S m_q/Q$, where m_q is the quark mass and Q is the hard scale of the process. However, large SSA have been observed in hadron-hadron collisions since the 70s. They survive with growing collision energies and have been reported in measurements at $\sqrt{s}$ of 200 and 500 GeV at RHIC [27]. Nowadays it has been clarified that many of these asymmetries can be formally interpreted in terms of collinear twist-3 multi-parton correlations. Such description also successfully reproduces the size of the measured effects, as demonstrated for instance by the recent phenomenological studies in Refs. [28, 29].

Many of other SSAs, in particular in SIDIS, require going beyond the collinear description of the internal structure of the hadrons and use 3D parton distributions.

3. Three dimensional nucleon structure

TMDs allow to study various spin and/or Orbital Angular Momentum correlations with the transverse motion of partons and thus become richer than the usual collinear PDFs and FFs. The definition of TMDs follows from QCD factorization theorems, see for instance Ref. [30]. A generic unpolarized TMD PDF f in momentum space, k_T, is related to TMD $\tilde{f}$ in conjugate space, b_T, via the inverse two-dimensional Fourier transform:

$$f_1(x,k_T) = \int \frac{d^2b_T}{(2\pi)^2}\, e^{ik_T\cdot b_T}\, \tilde{f}_1(x,b_T) = \int \frac{db^- d^2b_T}{(2\pi)^3}\, e^{ik\cdot b}\, \langle P|\bar{\psi}(0)\,\mathscr{L}^{n_-}_{(0,\infty)}\,\frac{\gamma^+}{2}\,\mathscr{L}^{n_-}_{(\infty,b)}\,\psi(b)|P\rangle\Big|_{b^+=0}, \tag{3.1}$$

where ψ are quark field operators and $\mathscr{L}$ denote Wilson lines. The above definition does not include QCD corrections and the dependence on the scale. Experimentally measured observables, such as cross-sections and structure functions, can be expressed in terms of convolutions of two TMDs. The convolution in momentum space implies an integration over the unobserved parton momenta, while in configuration space the convolution becomes a simple product [31] of TMDs in b_T space. Thus experimentally measured cross-sections are not a direct measure of TMDs and the global QCD fits have to deal with model dependence and shape bias of TMD parametrizations.

TMDs are related to the 3D momentum hadron structure. In momentum space TMDs describing a spin-1/2 nucleon [32] can be axially symmetric, or can have a dipole, or a quadrupole modulation in the parton transverse momentum. These modulations depend on the polarization state of the nucleon, polarization of the parton, etc., and allow one to study the correlations between parton momenta and spin. Eq. (3.1) shows that if one wants to reconstruct a TMD in k_T

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space, one needs to know $\tilde{f}(x, b_T)$ for all values of b_T. Moreover the Fourier transform in (3.1) is dominated by the values $b_T \sim 1/k_T$ and thus there are two regions: a *perturbative* region of small $b_T \sim 1/Q$ and *nonperturbative* region of $b_T \sim 1/M$. Different experiments can be dominated kinematically by either the perturbative region (high energy experiments such as Drell-Yan and $W^{\pm}, Z$ boson production at the Fermilab or LHC) or by the nonperturbative region (SIDIS experiments COMPASS, HERMES, Jefferson Lab). The TMD formalism, valid in the region $\Lambda \sim q_T \ll Q$, where q_T is the measured transverse momentum, should in principle smoothly transition in the region $\Lambda \ll q_T \ll Q$ to a description based on collinear QCD, valid at $\Lambda \ll q_T \sim Q$. Thus a careful matching of TMD and collinear descriptions is also needed [33].

The details of TMD factorization, related to the original Collins-Soper-Sterman (CSS) resummation formalism [34], were studied in several works (see, e.g., Refs. [30, 35, 36]) and TMD evolution equations successfully implemented in several phenomenological studies (see, e.g., Refs. [37, 38, 39, 40, 21, 41].

At present, the most sophisticated analyses of TMDs are applied to unpolarized quark TMDs. Ref. [42] for the first time put together data from SIDIS, Drell-Yan and Z-boson production to achieve an extraction of TMDs at next-to-leading logarithmic (NLL) accuracy. Ref. [43] took into consideration only Drell-Yan and Z-boson production data, but reached a remarkable NNLL accuracy. Recently, also an extraction of pion TMDs has been attempted for the first time [44].

However, the situation is not free of puzzles. For instance, problems have been found in the description of SIDIS and Drell-Yan data at high transverse momentum [45, 46] at $q_T \sim Q$, where the collinear QCD approach should be applicable. This hints at a still incomplete understanding of the corrections to the formalism and its regions of applicability [47], especially at relatively low values of Q, where the boundaries of regions of applicability of different factorization theorems become less clear. Problems have been also reported in describing the normalization of SIDIS data at low transverse momentum [48].

Another open question is the dependence of unpolarized TMDs on the flavor. In Ref. [49] it was shown that there is room for a significant flavor dependence, i.e., different flavors may have different distributions in transverse momentum space. This question is relevant not only for a better understanding of nonperturbative QCD effects, but also because it may have an impact on the determination of the W boson mass [50]. This is only an example of a general truth: nonperturbative QCD effects introduce uncertainties in high-precision predictions involving hadrons, which are particularly relevant when very high precision is required. One of the goals of hadronic physics is to reduce these uncertainties.

The determination of TMD parton distributions requires also the knowledge of unpolarized TMD fragmentation functions. Only recently, data from e^+e^- colliders is being used to study 3D fragmentation functions [51]. A pioneering measurement has been presented in Ref. [52], where the transverse momentum of a final-state hadron is measured with respect to the thrust axis. It may be possible to interpret this measurement in a way similar to hadron-in-jet fragmentation functions, which may in their turn be related to standard fragmentation functions (see, e.g., Ref. [53]).

When spin is taken into account, the 3D structure of the proton becomes more intricate and fascinating. The simplest effect is the appearance of a distortion of parton densities related to the Sivers function [54]. This function describes the distribution of unpolarized quarks inside a transversely polarized proton, it encodes the correlation between the partonic intrinsic motion and the transverse spin of the nucleon, and generates a dipole deformation in momentum space. The Sivers function requires the presence of nonzero partonic orbital angular momentum and final-state interactions between the struck quark and the rest of the nucleon. It has so far received the widest attention, from both phenomenological [55, 56, 57, 58, 59] and experimental points of view [60, 61, 62, 63] , also because of a property that should test the validity of TMD factorization: it is predicted to change sign in Drell-Yan compared to SIDIS, due to the different effect of the initial-state interactions compared to the final-state ones [64].

First measurements of the Sivers effect in Drell-Yan processes have been reported by the STAR [63] and COMPASS [62] experiments. They are compatible with the predicted sign change, but within large uncertainties [65]. Surprisingly, however, they seem to be in better agreement with predictions that do not take into account TMD evolution.

Apart from testing perturbative QCD predictions such as the sign change and TMD evolution, it is possible also to obtain encouraging comparisons between the extracted Sivers distortion and exploratory lattice QCD computations [66].

We end this section by mentioning that the field of 3D structure includes also the study of GPDs and Wigner distributions, already mentioned in the context of the spin sum rule. While TMDs describe the distribution of partons in momentum space, GPDs are related (via Fourier transform) to the distribution of partons in combined longitudinal-momentum and impact-parameter space, and Wigner distributions combine the two concepts into a complete, five-dimensional phase-space distribution (see, e.g., [67]). Ref. [68] presented the first attempt based on data to reconstruct the parton density associated to GPDs. GPD-related observables can also be used to indirectly reconstruct the proton energy-momentum tensor. A pioneering investigation of the radial pressure distribution in the proton was presented in Ref. [69], although it was pointed out that very different conclusions are also consistent with the same experimental data [70].

4. Future perspectives

The steady progress in the field of 3D structure and spin is due to the combination of theoretical advances and new experimental measurements, from different processes and different laboratories. HERMES has been a pioneering experiment in this field, and in spite of the fact that it stopped operating more than ten years ago, it is still analyzing data and producing valuable output [71]. COMPASS is presently producing an abundance of results that will have a strong impact on the determination of TMDs and GPDs. For instance, the recent measurement of multidimensionally binned SIDIS multiplicites off deuterons [72] will be crucial for the extraction of unpolarized TMDs. A similar set of measurements off the proton is also expected in the near future. JLab experiments started collecting data after the 12 GeV upgrade. Preliminary results have been presented in the last months and look impressive, because the analysis of only 2% of approved data-taking time already reached a statistics comparable to that of several year of HERMES data taking. RHIC spin program [27] has been and will continue being important for studies dedicated to the nucleon structure.

As already mentioned at the beginning, the EIC will bring an enormous contribution to this field of research (see for instance Ref. [73]). However, in order to pin down TMDs it is important to measure various processes, such as Drell-Yan, e^+e^-, hadron-hadron, etc. Proposals to introduce

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fixed targets into the LHC, possibly polarized, have been put forward and would require relatively moderate efforts [74, 75]. These future experimental facilities will make it possible to investigate non only quark 3D distributions, but also gluon ones (see, e.g., [76] and references therein).

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