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Small- and large-x nucleon spin structure from a global QCD analysis of polarized parton distribution functions

E.R. Nocera

Dipartimento di Fisica, Università di Genova and INFN, Sezione di Genova, Via Dodecaneso, 33, I-20146 Genova, Italy

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ABSTRACT

I investigate the behavior of spin-dependent parton distribution functions in the regions of small and large momentum fractions x. I present a systematic comparison between predictions for relevant observables obtained with various models of nucleon spin structure and a recent global analysis of spin-dependent distributions, `NNPDFpol1.1`. Together with its unpolarized counterpart, `NNPDF2.3`, they form a mutually consistent set of parton distributions. Because they include most of the available experimental information, and are determined with a minimally biased methodology, these are especially suited for such a study. I show how `NNPDFpol1.1` can discriminate between different theoretical models, even though `NNPDF` uncertainties remain large near the endpoints $x \to 0$ and $x \to 1$, due to the lack of experimental information. I discuss how our knowledge of nucleon spin structure may be improved at small x by future measurements at an Electron–Ion Collider, and at large x by recent measurements at Jefferson Lab, also in view of its 12 GeV upgrade.

1. Introduction

The behavior of spin-dependent, or polarized, Parton Distribution Functions (PDFs) at small and large momentum fractions x has been recognized for a long time to be of particular physical interest [1,2]. On the one hand, the small-x region is pivotal for revealing new aspects of the nucleon picture depicted by Quantum Chromodynamics (QCD), related, for instance, to PDF evolution. On the other hand, the large-x region is definitive of hadrons: indeed, all Poincaré-invariant properties of a hadron, like flavor content and total spin, are determined by valence quark PDFs in the region $x \gtrsim 0.2$, where they are expected to dominate. Above all, an accurate knowledge of polarized PDFs over a broad range of x values is required to reduce the uncertainty with which the first moments of polarized distributions and structure functions can be determined. This is relevant for testing various sum rules [3–6] and potential SU(3) flavor-symmetry breaking [7], and finally for assessing quark and gluon contributions to the nucleon spin.

Several recent studies [8–16] have presented a determination of polarized PDFs, along with an estimate of their uncertainties. These parton sets differ in the choice of data sets, details of the QCD analysis (such as the treatment of heavy quarks or higher-twist corrections) and the methodology used to determine PDFs, including the form of PDF parameterization and error propagation (for details, see *e.g.* Chap. 3 in Ref. [17]).

Despite remarkable experimental efforts, the kinematic coverage of the available data sets to be included in global analyses is still rather limited. Specifically, the accessed range of parton momentum fractions is roughly $10^{-3} \lesssim x \lesssim 0.5$: thus, a determination of polarized PDFs outside this region would be very much prone to the functional form used for extrapolation.

Various models have been developed for predicting the polarized PDF behavior at small and large x. Computations based on different models often lead to rather different expectations for some polarized observables. A way to discriminate among models, and eventually test their validity, is to compare predictions for such observables, obtained within either a given model or a reference parton set. The latter should be determined from a global QCD analysis of experimental data.

The goal of this paper is to present such a comparison in a systematic way, separately for small- and large-x regions. I will also discuss how our knowledge of nucleon spin structure may be improved, respectively at small and large x, by future measurements at a high-energy polarized Electron–Ion Collider (EIC) [18], and by recent measurements at Jefferson Lab (JLAB), also in view of its 12 GeV upgrade [19].

In order for this study to be effective, the choice of the reference PDF set is crucial. On the one hand, it is highly desirable that most of the available experimental information is included in it, so

E-mail address: emanuele.nocera@edu.unige.it.

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that the unknown extrapolation region is reduced as much as possible. On the other hand, it is fundamental that a minimal set of theoretical assumptions and a procedure which allows for a faithful estimate of PDF uncertainties are used.

Among all PDF sets available in the literature, the NNPDF parton sets are those which best fulfill the aforementioned requirements (and possibly the only). Hence, these will be used in this study: specifically, NNPDFpol1.1 [16] for polarized PDFs and NNPDF2.3 [20] for the unpolarized, whenever also these will be needed.

Concerning the experimental information included in these parton sets, a large amount of high-precision Hadron Electron Ring Accelerator (HERA) and Large Hadron Collider (LHC) data are taken into account in NNPDF2.3, while polarized hadron collider data sets, specifically jet and W-boson production provided by the Relativistic Heavy Ion Collider (RHIC), are used in NNPDFpol1.1. Some of these data are missing in other global unpolarized/polarized analyses so far. In the unpolarized case, only a subset of LHC data are included in recent PDF determinations [21]. In the polarized case, W-boson production data are included only in NNPDFpol1.1, and jet production data are included only in NNPDFpol1.1 and in the determination of Ref. [15]. Other recent analyses are based on inclusive Deep-Inelastic Scattering (DIS) data solely [8,11,12,14], or on inclusive and semi-inclusive DIS (SIDIS) data [9,10,13].[1] SIDIS data sets are not included in NNPDFpol1.1. However, these bring in information mostly on quark–antiquark separation at medium-x values, and they are expected to be of limited importance in the small- and large-x regimes, where, in addition, one expects respectively $\Delta q \sim \Delta\bar{q}$ and $\Delta q \gg \Delta\bar{q}$. Then, NNPDF parton sets include all the experimental information relevant for this study.

Concerning the procedure used for PDF determination, NNPDF parton sets are based on a methodology which uses a Monte Carlo sampling and representation of PDFs, and a parameterization of PDFs based on neural networks with a redundant number of free parameters. Both these features allow for providing a PDF set in which the *procedural* uncertainty (due to the methodology used to determine PDFs from data) is reduced as much as possible. Most importantly, thanks to the neural network parameterization, the PDF behavior at small and large x can deviate from the powerlike functional form usually assumed in other PDF parameterizations. All NNPDF parton sets, both unpolarized and polarized, are determined within this methodology in a mutually consistent way.

2. Small-x behavior

What the behavior of polarized PDFs should be at $x \to 0$ is presently not well understood. Nevertheless, several models attempt to provide an estimate of the polarized, neutral-current, virtual-photon, DIS structure function g_1 at small-x values. Arguments based on the dominance of known Regge poles [22] lead to the expectation

$$g_1(x) \xrightarrow{x\sim 0} x^{-\lambda}, \qquad (1)$$

where λ is the intercept of the $a_1(1260)$ meson Regge trajectory in the isovector channel and the $f_1(1285)$ meson trajectory in the isoscalar channel. Roughly, this leads to [23]

$$-0.4 \le \lambda_{a_1} \approx \lambda_{f_1} \le -0.18. \qquad (2)$$

[1] Note that pion production data from RHIC, not included in NNPDFpol1.1, are also taken into account in the determinations of Refs. [9,15]. It was argued in Ref. [16] that these data may have a limited impact though.

A model of the pomeron based on nonperturbative gluon exchange [24] gives the singular behavior

$$g_1(x) \xrightarrow{x\sim 0} A(-2\ln x - 1), \qquad (3)$$

while it has also been argued [25] that it is possible to induce the extremely singular behavior

$$g_1(x) \xrightarrow{x\sim 0} \frac{B}{x\ln^2 x}, \qquad (4)$$

where A and B are normalization coefficients determined from a fit to experimental data.

Regge theory is expected to be valid only at low Q^2 and a behavior of the form (1) is unstable under DGLAP evolution [26–28]. Indeed, as Q^2 increases, contributions proportional to $\ln(1/x)$ enter the evolution equations via the splitting functions, which, in the polarized case, all contain singularities [29]. Small-x logarithms are included via DGLAP evolution up to NLO accuracy in global QCD analyses of polarized PDFs. However, polarized splitting functions are further enhanced at N^{n}LO by *double* logarithms of the form $\alpha_s^n \ln^{2n-1} x$, which correspond to the ladder diagrams with quark and gluon exchanges along the ladder. Calculations summing up these contributions, either with non-running [30,31] or running [32] values of the strong coupling α_s, found that the singlet flavor combination of proton and neutron structure functions, $g_1^p + g_1^n$, should diverge more rapidly than the nonsinglet combination, $g_1^p - g_1^n$, as x goes to zero, *i.e.*

$$\left|g_1^p + g_1^n\right| - \left|g_1^p - g_1^n\right| \ge 0, \quad x \to 0. \qquad (5)$$

The next-to-next-to-leading order (NNLO) corrections to the polarized splitting functions have been computed very recently [33]: these are found to be small and unproblematic down to at least $x \sim 10^{-4}$.

Finally, coherence arguments [34,35] suggest that, at a typical nucleon scale, the polarized gluon distribution $\Delta g(x)$ should be related to its unpolarized counterpart, $g(x)$, according to

$$\frac{\Delta g(x)}{g(x)} \xrightarrow{x\sim 0} 2x. \qquad (6)$$

In order to test the validity of expectations (1)–(6), corresponding predictions are made using NNPDFpol1.1 [16] and NNPDF2.3 [20] parton sets. No model assumptions were imposed for constraining the small-x behavior of these PDFs, except the requirement that polarized PDFs must be integrable, *i.e.* they have finite first moments.

In order to study the potential impact of future measurements at an EIC, the NNPDFpolEIC-B [36] parton set will be used too. This was determined from a fit to the inclusive DIS data in NNPDFpol1.1, supplemented with simulated inclusive DIS pseudodata at a future EIC down to $x \sim 10^{-5}$. These pseudodata were generated assuming that the *true* underlying set of PDFs is that in Ref. [9], even though the behavior of polarized PDFs at such small-x values is not known. Hence, the NNPDFpolEIC-B parton set does encode information on the potential reduction of PDF uncertainties from future DIS measurements at an EIC, but definitely does not encode additional information on the small-x behavior of polarized PDFs.

The impact of future measurements at an EIC was previously addressed also in Ref. [37], where projected neutral–current DIS and SIDIS artificial data were added to the DSSV polarized PDF set of Ref. [9]. In comparison to the NNPDFpolEIC-B determination, pseudodata were generated assuming the same underlying set of PDFs, but they were then included in a global QCD analysis using a substantially different fitting methodology. For this reason,