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ScienceDirect
Nuclear Physics B 911 (2016) 246–273
NUCLEAR PHYSICS B
www.elsevier.com/locate/nuclphysb

Nucleon helicity and transversity parton distributions from lattice QCD

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Received 11 May 2016; received in revised form 23 July 2016; accepted 31 July 2016

Available online 12 August 2016

Editor: Hong-Jian He

Abstract

We present the first lattice-QCD calculation of the isovector polarized parton distribution functions (both helicity and transversity) using the large-momentum effective field theory (LaMET) approach for direct Bjorken-x dependence. We first review the detailed steps of the procedure in the unpolarized case, then generalize to the helicity and transversity cases. We also derive a new mass-correction formulation for all three cases. We then compare the effects of each finite-momentum correction using lattice data calculated at $M_\pi \approx 310$ MeV. Finally, we discuss the implications of these results for the poorly known antiquark structure and predict the sea-flavor asymmetry in the transversely polarized nucleon.

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http://dx.doi.org/10.1016/j.nuclphysb.2016.07.033

1. Introduction

Parton distribution functions (PDFs) provide a universal description of the proton's constituents (quarks, antiquarks and gluons). They are critical inputs [1–6] for the discovery of the Higgs boson, the last particle of the Standard Model, found at the Large Hadron Collider (LHC) through proton–proton collisions [7,8]. Despite this great victory, the LHC has many tasks remaining, and the focus of the future Runs 2–5 will be to search for physics beyond the Standard Model. In order to discriminate new-physics signatures from the Standard-Model background, we need to improve the precision of the latter. Unfortunately, our knowledge of many Higgs-production cross sections remains dominated by PDF uncertainties. Improvement on current PDF uncertainties is important to assist LHC new-physics searches.

In addition to their applications to the energy frontier, PDFs also reveal nontrivial structure inside the nucleon, such as the momentum and spin distributions of partons. Many ongoing and planned experiments at facilities around the world, such as Brookhaven and Jefferson Laboratory in the United States, GSI in Germany, J-PARC in Japan, or a future electron–ion collider (EIC), are set to explore the less-known nucleon structures and more. In order to distinguish the flavor content of the PDFs, one would need to use nuclear data, such as neutrino scattering off heavy nuclei. However, the current understanding of medium corrections in these cases is limited. Thus, the uncertainty in the strange PDFs remains large. In some cases, the assumption $\overline{s}(x) = s(x)$ made in global analyses can agree with data due to the large uncertainty. At the LHC, strangeness can be extracted through the $W + c$ associated-production channel, but their results are not yet well-determined. For example, ATLAS gets $(s + \overline{s})/(2\overline{d}) = 0.96^{+0.26}_{-0.30}$ at $Q^2 = 1.9\ \text{GeV}^2$ and $x = 0.23$ [9]. CMS performs a global analysis with deep-inelastic scattering (DIS) data and the muon-charge asymmetry in W production at the LHC to extract the ratios of the total integral of strange and anti-strange to the sum of the anti-up and -down, finding it to be $0.52^{+0.18}_{-0.15}$ at $Q^2 = 20\ \text{GeV}^2$ [10]. Future high-luminosity studies may help to improve our knowledge of the strangeness. In the polarized case, SU(3)-flavor symmetry is often assumed due to lack of precision experimental data. We learn from the unpolarized case that this assumption introduces an underestimated uncertainty. In addition, there have been long debates concerning how big the intrinsic charm contribution is or whether other heavy flavors contribute. Again, the data is too inconclusive to narrow down or discriminate between the various proposed QCD models.

Theoretical determination of the parton distributions is complementary to the experimental effort, especially for those not yet accessible kinematically in experiments. On the other hand, in order to be useful for experiments, theoretical calculations need to demonstrate that those already measured parton distributions can be reproduced within the same approach. This turns out to be a challenging task. It is rooted to the nonperturbative nature of parton interactions inside the nucleon. One hint of this nonperturbative nature can be seen in the parton distributions extracted from experimental data. Although the net quark number of the nucleon is 3, the quark and antiquark numbers are both infinite. This implies that there is no hierarchy in quark–antiquark pair production through gluon emission. The production of $N + 1$ quark–antiquark pairs is as important as the production of N pairs, so truncation at a finite N is impossible. This makes the proton effectively an infinite-body system.

Lattice QCD deals with this infinite-body problem by reducing the continuous spacetime to a discrete lattice, rendering the number of integrals in the partition function finite. The lattice is defined in a Euclidean spacetime so that Monte Carlo algorithms can be used to compute these integrals efficiently. The parton distributions are related to nucleon matrix elements of quark cor-