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Recent theoretical progress in nuclear structure

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Experimental evidence shows that the presence of a nuclear environment affects the outcome of observed quantities. These differences can be explained by several, sometimes orthogonal, mechanisms. A less involved phenomenological approach is to assume that the partonic behaviour at the fundamental level is changed non-trivially. Said changes are encoded into sets of nuclear densities, similar to the proton collinear ones, that have to be determined through global fits. In this article we summarise the latest results towards the determination of nuclear parton densities.

The Ninth Annual Conference on Large Hadron Collider Physics - LHCP2021
7-12 June 2021
Online

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1. Introduction

In the context of perturbative QCD (pQCD), the collinear factorisation theorem [1] allows us to write the physical observables in terms of the convolution of perturbative and non-perturbative components. The former are process dependent but can be computed, in principle, for any order of the series expansion. The latter, called parton distribution functions (PDFs), are universal[1] but not feasible of determination from first principles. However, once known at some scale Q^2, one can compute their values at any other scale via the DGLAP evolution equations [2–5]. Assuming that the partons move collinear to the proton and carrying a fraction x of its momentum, the task of finding the PDFs at the (arbitrarily chosen) initial scale Q_0^2 is carried out by writing the distributions as parameter-dependent functions of x, convoluting them with the appropriate perturbative components and comparing with experimental results. In the end one aims to extract the parameters characterising the PDFs that best describe the data. The more diverse the data and the broader their kinematic reach, the easier to distinguish the different partons and the better constrained the distributions will be. As it depends solely on the linear combination of PDFs, the deeply-inelastic-scattering (DIS) process both with fixed targets and in collider mode at HERA [6] has been crucial to extract the proton PDFs. This is complemented with other observables such as flavour-sensitive electroweak boson production and gluon-sensitive jets from Tevatron and LHC. All together, the knowledge of proton PDFs has achieved a spectacular degree of precision, though further improvement is expected from current and future experiments.

The situation is not equally well understood when the hadron (or at least one of them in the case of p+p collisions) is replaced by a nucleus. Though not the first experiment with nuclear targets, the EMC collaboration determined a significant deviation from the proton case when doing DIS off nuclei [7]. This difference can not be explained by assuming that bound nucleons behave in the exact same way as the free ones. It can instead be attributed to the behaviour of the partons being different in a bound nucleon w.r.t. a free proton. This information could in principle be encoded into a different set of parameters to describe the PDFs in nuclei. Despite the lack of a corresponding factorization theorem, the proposed nuclear PDFs (nPDFs) are thought to be universal and to follow the usual DGLAP evolution equations, assumptions compatible with the available data. The nPDFs are interesting in their own right, but also because data from charged current (CC) DIS off heavy nuclei, and DIS and Drell-Yan with deuterium targets are routinely used to improve the flavour separation of the sea sector in proton PDFs. Moreover they are useful to characterise the nuclear effects that serve as baseline for heavy-ion studies. Using as guidance the free proton PDFs, in the last two decades several sets of nPDFs have been determined, improving their precision as newer data and more sophisticated theoretical frameworks are included. Sets have been extracted from leading to next-to and next-to-next-to-leading order (LO, NLO and NNLO, respectively), using different schemes for the treatment of the heavy flavours and different data sets. In the next section we will discuss the latest steps taken towards the upcoming new nPDFs.

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[1] PDFs do depend on the parton and hadron considered, e.g. the u quark density in a proton and in a pion will not be the same, and they will differ from the d quark PDF in a proton.

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2. Improvements in the determination of nPDFs

The determination of (n)PDFs depend both on having adequate experimental results from which to extract information and the strategy followed for this extraction. Ideally the data should span a large fraction of the kinematic space, be sensitive to linearly independent combinations of the distributions and have small experimental uncertainties. Theory and experiment are tightly intertwined in a PDF extraction and in the following the main improvements included in the future releases of nPDF sets will be briefly discussed.

Among the data traditionally included in nPDFs fits we find the Drell-Yan process (fixed target) and the production of electroweak bosons in p+A collisions at the LHC. For the latter, measurements from Run2 [8] have significantly improved their precision and provide constraints over the sea distributions. This is particularly true for the strange quark, whose shape in both the nuclear and proton cases is heavily driven by CC DIS off nuclei. Over the years significant tensions have been found between different experiments, leaving open questions about their origin and the universality of the initial state nuclear effects. The use of these data, incorporated by the EPPS [9], nNNPDF [10] and nCTEQ [11] groups, has produced significant changes in the shape of the sea distributions for some of the fits.

Another type of data being considered now is the DIS high-x and low-Q^2 data, usually left out of the fits due to the need of higher-twist contributions in the calculation of the observable. A pioneering work [12] showed that in order to accommodate these data within current fits, it is necessary to take into account target mass corrections [13]. Following these results the high-x data and, in particular, very precise recent data measured by the CLAS Collaboration [14] are now being included in the fits of the EPPS [9] and nCTEQ [15] groups. The latter study also considers non-perturbative multi-quark interactions and a special modelling of the nuclear effects in deuterium, which they have found to be crucial for the quality of the fit.

The least well known nPDF corresponds to the nuclear gluon density as most of the older data corresponds to fixed target DIS, an observable with poor sensitivity to the gluon. In order to have control over them, data from single inclusive hadron production in d+Au collisions at RHIC [16–20] were incorporated in the fits. However it is clear by comparing the older fits that the treatment given in the process to these data severely impacts the shape of the extracted gluon, a feature that does not appear in the better constrained valence quarks, for which all fits are in agreement within uncertainties. Moreover the computation of this observable requires the precise knowledge of the fragmentation functions (FFs) that describe the the hadronisation of a parton into a final state hadron. The arrival of results from the LHC has significantly changed this situation. On the one hand the new data on single inclusive hadron production in p+Pb at 7 TeV are almost exclusively sensitive to the gluon both in the initial and final state which coupled with modern sets of FFs can be used to determine the gluon nPDF. This opportunity has been explored by the nCTEQ group [21] using several sets of FFs and some assumptions on the normalizations. On the other hand there are now data of di-jets in p+Pb collisions [22], which have been shown to be very sensitive to the nuclear gluon at high-x. Included in the EPPS16 fit [23] as a forward backward ratio, the full CMS data are now included by the nNNPDF and EPPS collaborations. While the data provides a clear constraint over the gluons, both fits find tensions between the extreme rapidity bins and all other data considered. However these can partially be attributed to the inability of the corresponding

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proton PDFs baselines to describe the same observable in p+p collisions.

One last new observable that is being included in the fits is the D0 meson production which has been measured by the LHCb Collaboration [24]. The forward and backward data are very well accommodated in the fits by the EPPS and NNPDF groups and provide constraints for the suppression at low x (shadowing), under the assumption that the nuclear environment does not affect (or affects negligibly) the meson production. The same assumption has to be made for the single-inclusive hadron production.

Improvements on the nuclear distributions are not only restricted to the incorporation of more data and novel observables. Apart form the inclusion of the higher twist effects mentioned above, there has been progress with the consideration of the proton uncertainties in the nPDFs, the use of some data sets in NNLO extractions using K-factors, updates of proton baselines and sophisticated modelling of the nuclear effects in deuterium.

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3. The future

The improvements in the determinations of nPDFs sets presented above are part of the preliminary results of the mentioned groups and shall become publicly available in distributions in the near future. Despite the phenomenal work, tensions remain and more data will be necessary to further separate flavours and constrain the partonic behaviour in previously unexplored regions. Therefore all these changes are but part of the spectacular effort being carried to reach an understanding of how the fundamental blocks of matter come together to give life to the world we see. The current 12 GeV upgrade at JLAB will be able to map the high-x region with unprecedented precision and will be complemented by the results of the future EIC, the first electron-nucleus collider. The physics with nuclear beams constitutes a big portion of the research program at the EIC [25] for which the best suited detectors are to be used. Farther into the future the LHeC and FCC-eh shall find the answer to the phenomena off saturation at low-x. Exciting times for the study of nPDFs are waiting ahead.

4. Acknowledgements

The author was supported by the Deutsche Forschungs-gemeinschaft (DFG, German Research Foundation) - Research Unit FOR 2926, grant number 409651613.

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