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PDFs, nuclear corrections, and the d/u ratio

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Summary. — Constraining the d PDF at large values of x has traditionally relied, in part, on the use of deeply inelastic lepton deuterium scattering data. The use of such data requires the inclusion of nuclear corrections which account for Fermi motion, binding, and off-shell effects. The impact of these corrections in the context of a global fit is examined. The uncertainties due to these nuclear effects are large.

PACS 12.38.Bx – Perturbative calculations.
PACS 13.60.Hb – Total and inclusive cross sections (including deep-inelastic processes).
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1. – Introduction

Parton distribution functions (PDFs) are necessary for QCD-based calculations of observables involving the scattering of hadrons. Separating the various parton flavors when performing global fits for PDFs requires a variety of types of data. In particular, separating the u and d PDFs typically relies on deep inelastic lepton scattering (DIS) data taken with both proton and deuterium targets. However, it is not sufficient to treat deuterium as a sum of a neutron and a proton; nuclear effects can give rise to significant corrections, especially at large values of x.

Conventional global fits typically rely on data in the region $x \lesssim 0.7$ since that is the region covered by most of the high energy experiments included in the fits. This essentially allows one to neglect effects due to target mass corrections and higher twist contributions, thereby allowing the use of only the twist-two PDFs. In this region the nuclear corrections for deuterium targets are thought to be on the order of a few percent and so they are often ignored in global fits.

One unintended result of this procedure is that the PDFs for values of x above about 0.7 are extrapolations of the fitted PDFs and are essentially unconstrained by data. Nevertheless, there are times when PDFs in the large-x region are needed. An example would be the production of a large mass state at high values of rapidity y. In lowest order the relevant values of the PDF momentum fractions are

$$x_{1,2} = \frac{M}{\sqrt{s}} \exp(\pm y).$$

Thus, large values of y result in one large value of x and one small value.

In a previous study [1], the effects of systematically extending the range in x were studied. Target mass effects were included along with a parametrization of higher twist terms. It was found that the twist-two PDFs were stable to variations in the techniques used to calculate the target mass corrections, provided that a sufficiently flexible higher twist parametrization was employed. However, it was observed that the d PDF was particularly sensitive to the assumptions used to calculate the nuclear corrections in deuterium.

In this talk I describe some results from an analysis whose goal is to study the sensitivity of PDFs to various models of nuclear corrections for DIS data taken with deuterium targets. Detailed results, including a description of the issues related to nuclear corrections may be found in ref. [2].

2. – Fit results

The global fits discussed here were performed using the same fitting package and techniques described in ref. [1]. All of the observables are fitted with theoretical expressions calculated to next-to-leading-order in the strong coupling. The new features in this analysis are the inclusion of off-shell corrections as well as the use of a range of deuteron wave functions to calculate the nuclear corrections [2].

Visualizing the results of this analysis is most easily done by displaying the d/u ratio. This is due to the fact that the u PDF is already well constrained by the proton DIS data and by data from lepton pair production and jet production at collider energies. The main constraint on the d PDF is provided by deuterium DIS data, since the roles of the u and d PDFs are interchanged when considering a neutron target. Thus, when different models for nuclear corrections are considered, the d PDF is modified by the greatest amount. Therefore, the effects of the nuclear corrections show up directly in the d/u ratio. This may be made clearer by considering that it is the convolution of the PDFs with the nuclear smearing function that is constrained when fitting the deuterium data. Changes in the nuclear corrections can be compensated by corresponding changes in the d PDF, since the u PDF is already well constrained by other observables.

The left-hand panel of fig. 1 illustrates the variation of the d/u ratio for different models of the off-shell corrections based on the off-shell spectator quark model by Kulagin and Petti [3], as described in ref. [2], when the AV18 [4] deuteron wave function is used. A conventional parametrization of the d and u PDFs is employed, wherein the d PDF vanishes as $x \to 1$ faster than the u PDF, resulting in the vanishing of d/u in this limit. Similar results are shown in the central panel where a modified d PDF has been used: $d \to d + ax^b u$. This choice has the feature that $d/u \to a$ as x approaches 1. The right-hand panel shows the dependence of the results on the choice of the deuteron wave function.

The full range of variations of the d/u ratio due to deuteron wave function and off-shell corrections is shown in fig. 2 along with the PDF fit uncertainties (based on $\Delta\chi^2 = 1$). It is clear that the model-dependent nuclear uncertainties dominate at large values of x.

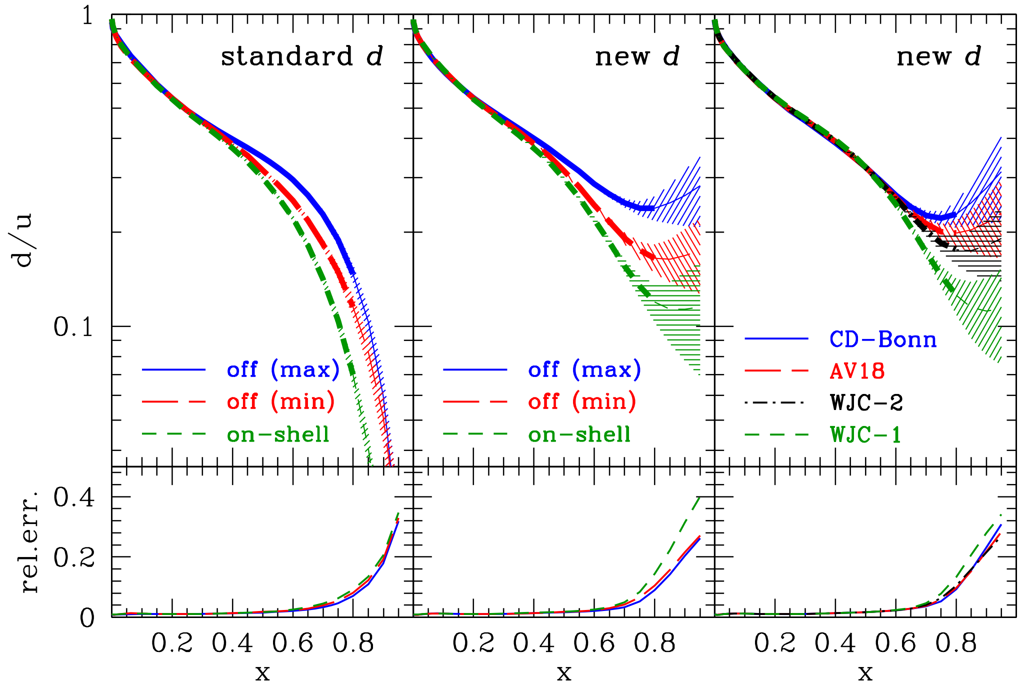

Fig. 1. – The d/u ratio at $Q^2 = 10\,\mathrm{GeV}^2$ obtained with different choices of d-quark parametrization and nuclear corrections. Left panel: standard d-quark parametrization [1] and AV18 deuteron wave function for several off-shell correction models; middle panel: modified d-quark parametrization for the same nuclear corrections; right panel: dependence on the deuteron wave function for a fixed off-shell correction (mKP). The shaded bands and bottom panels show the $\Delta\chi = 1$ PDF errors and the relative PDF errors on the d/u ratio, respectively. The thinner lines above $x \approx 0.8$ denote extrapolations into unmeasured regions.

Moreover, even when one employs cuts on Q^2 and W^2 that limit x to values below 0.7, the deuteron nuclear corrections are potentially substantial.

An interesting feature of the results is summarized in fig. 3. Here the extremes of the fitted u, d, and g PDFs are shown relative to those obtained with a set of choices which lies roughly midway between the extremes of the d PDF. As expected, the u PDF is relatively insensitive to the nuclear models, since it is well constrained by proton data. However, the d and g PDFs appear to be strongly anticorrelated, although the errors on each PDF must be kept in mind when evaluating the significance of this anticorrelation. This effect is due primarily to the influence of the high-p_T collider jet data. As the d PDF is reduced the gluon contribution (and to a very much lesser extent, that of the u PDF) must be increased in order to describe the data. This variation is substantial for values of x even as low as $x = 0.5$, which strongly suggests that nuclear corrections should be included in global fits whenever deuterium data are utilized.

Another interesting feature discussed in ref. [2] is the existence of tension between the deuterium data and data for the W rapidity charge asymmetry [5]. The d/u ratio changed significantly in the low x region when a fit without the deuterium data was performed. This fit showed a marked reduction in the χ^2 for the W asymmetry data. This is particularly interesting since the nuclear corrections in this region are expected

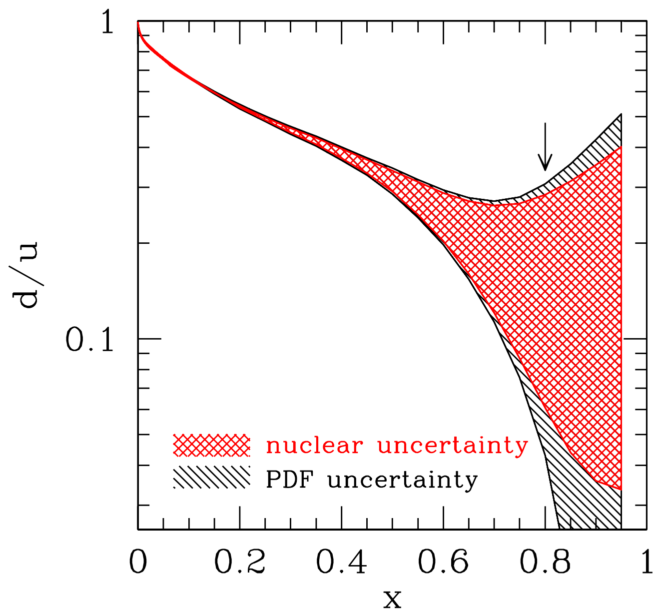

Fig. 2. – Full range of variations of the d/u ratio due to deuteron wave function and off-shell corrections (cross-hashed band) and PDF fit uncertainties (diagonal hashed). The arrow indicates the extrapolation region at large x.

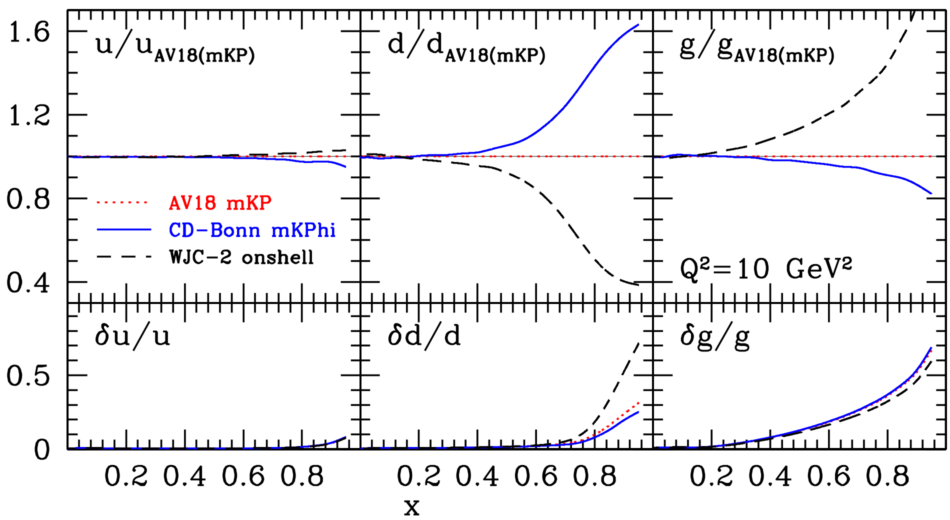

Fig. 3. – The extremes of the variations of the u (left panel), d (middle panel), and gluon (right panel) PDFs, relative to reference PDFs extracted using the smearing function with the AV18 deuteron wave function and mKP (central) off-shell corrections.

to be small. For relatively small values of the W rapidity, the asymmetry is proportional to the slope of the d/u ratio. Without the constraints provided by the deuterium DIS data, the program was able to increase the d PDF at low values of x while keeping it the same at higher values. This resulted in a steepening of the d/u ratio at small values of x which, in turn, resulted in a better description of the W asymmetry data. However, in the context of nuclear corrections, it would require a low-x shadowing correction much larger than expected in order to replicate this effect when the deuterium target data are included in the fit.

In the longer term, the issue of the dependence of the d PDF on the choice of nuclear models may be resolved by data which are sensitive to the d/u ratio but which do not depend sensitively on nuclear corrections. Examples include the BoNuS [6], MARATHON [7], and PVDIS [8] experiments which are scheduled to run after the completion of the 12 GeV upgrade at Jefferson Lab. If the d/u ratio were known independently of the nuclear corrections, then the problem could be turned around —pinning down the d PDF would enable one to determine which nuclear model gave the best results.

This analysis is being extended [9]. The data sets are being updated as new ones become available, including new DIS data, Z rapidity distributions, and high-p_T jet data. The range of nuclear models being considered is under review to insure that representative examples are included without expanding the model dependence to an unwarranted extent. Different choices for the PDF parametrizations are being studied in order to better ascertain the effects of extrapolations beyond the fitted regions. PDF error sets will be generated using the Hessian technique and the software for this is under construction. The goal is to produce NLO PDF sets with errors for each of three choices of nuclear corrections. These sets will allow users to judge whether or not the uncertainties due to nuclear corrections will contribute to the overall PDF uncertainties in regions where their observables are measured.

Although the nuclear corrections needed for deuterium target DIS are largest in the high-x region, their influence on the fitted PDFs can extend to values of x as low as 0.5. Therefore, even calculations for observables measured at collider energies can be affected. These nuclear corrections provide an additional source of uncertainty for the PDFs which should be taken into account when error bands are estimated.

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