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The CJ12 parton distributions

A. Accardi*
Hampton U. and Jefferson Lab
E-mail: `accardi@jlab.org`

J. F. Owens

Florida State University

W. Melnitchouk

Jefferson Lab

Three new sets of next-to-leading order parton distribution functions (PDFs) are presented, determined by global fits to a wide variety of data for hard scattering processes. The analysis includes target mass and higher twist corrections needed for the description of deep-inelastic scattering data at large x and low Q^2, and nuclear corrections for deuterium targets. The PDF sets correspond to three different models for the nuclear effects, and provide a more realistic uncertainty range for the d quark PDF compared with previous fits. Applications to weak boson production at colliders are also discussed.

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*Speaker.

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Introduction. Deep-inelastic lepton-hadron scattering experiments have provided a wealth of data over the past few decades that have yielded considerable information on PDFs over a wide range of x and Q^2. However, typically global fits have focused on the extraction of leading twist PDFs, utilizing cuts on Q^2 and the hadronic final state mass $W^2 = M^2 + Q^2(1-x)/x$, where M is the nucleon mass, of $Q^2 \gtrsim 4\,\text{GeV}^2$ and $W^2 \gtrsim 14\,\text{GeV}^2$. The aim of such cuts is to eliminate regions of kinematics where effects that do not scale with Q^2 may be important, which unfortunately has the effect of excluding a considerable amount of high-precision data that have been collected at intermediate and large values of x.

On the other hand, there are many reasons why accurate information on PDFs at high x is important. For example, it is necessary to have control over uncertainties on QCD backgrounds in searches for new physics in collider experiments at large p_T or large rapidity. Also, the behavior of PDF ratios, such as the d/u ratio, as $x \to 1$ can provide insight into the dynamics of quarks and gluons in the nonperturbative region. In addition, the uncertainty in the extraction of the spin-dependent gluon PDF at small x in forward particle production in polarized pp collisions is limited by the uncertainties on the quark PDFs at large x.

A novel aspect of large-x global fits is their ability to connect elements of high-energy physics with hadronic and nuclear physics at medium energy [1]. For example, data on W and Z boson production at forward rapidity at the Tevatron and LHC, that extend to large values of x, can constrain the extrapolation of PDFs to $x = 1$, where they are sensitive to different mechanisms of quark confinement [2, 3]. Similarly, global PDF fits can be used as a tool to study the structure of nuclei and the differences between bound and free protons, for which current models offer a large range of predictions. This is possible, for example, by exploiting the interplay of deep-inelastic scattering (DIS) data for *deuterium* targets, which allow one to extract a nuclear model dependent d quark distribution at large x [4 – 6], and weak interaction processes on *proton* targets, which also depend on the d quark but are free of nuclear corrections. Global fits can thus relate high-energy experiments at the Tevatron or LHC with nuclear physics experiments at lower energy facilities such as Jefferson Lab.

The CTEQ-Jefferson Lab (CJ) global PDF fits. The CJ global PDF fits utilize the world's data on charged lepton DIS on proton and deuteron targets, lepton pair production with a proton beam on proton and deuteron targets, W asymmetries in $\bar{p}p$ collisions, and jet production data from the Tevatron. The fits include subleading $\mathcal{O}(1/Q^2)$ corrections, such as target mass and higher twist effects, and nuclear corrections for the deuterium data, and incorporate data down to $W \approx 1.7$ GeV. The resulting fits [4 – 6] have culminated in the release of the "CJ12" PDF sets, valid in the range $10^{-5} \lesssim x \lesssim 0.9$ [7]. The fits were performed at next-to-leading order (NLO) in the zero mass variable flavor number scheme, with α_s fixed to the world average value. (Full heavy quark treatments, fits of the strong coupling constant, and inclusion of the available LHC data will be considered in a subsequent analysis.)

The CJ PDFs have been shown to be stable with the weaker cuts on W and Q^2, and the increased DIS data sample (of about 1000 additional points) has led to significantly reduced uncertainties, up to 40–60% on the d quark PDF at large $x \gtrsim 0.6$, where precise data are otherwise scarce [4]. Since d quark flavor separation at large x is currently almost entirely dependent on DIS on deuterium targets, corrections for nuclear Fermi motion and binding effects are included by convo-

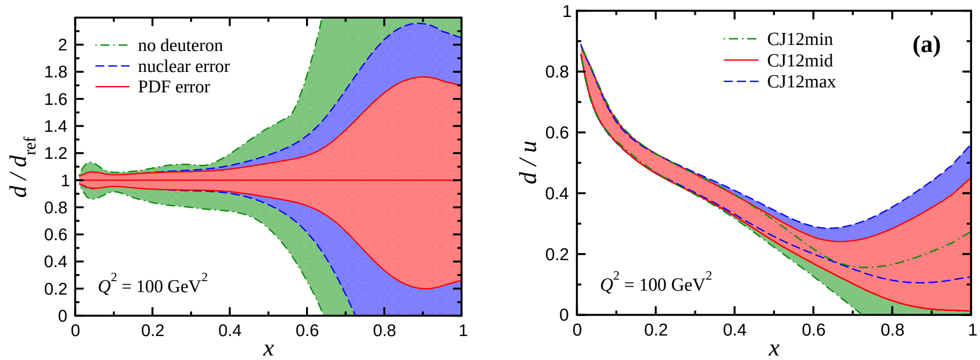

Figure 1: *Left:* PDF uncertainties for the CJ12mid d quark compared with the total uncertainty including nuclear corrections and with a fit excluding all deuterium data relative to the CJ12mid set. *Right:* d/u ratio for the CJ12min, CJ12mid and CJ12max PDFs [6].

luting the nucleon structure functions with a smearing function computed from the deuteron wave function. As the u quark is well constrained by data on proton targets, the d quark becomes directly sensitive to the nuclear corrections. The effect is a large suppression at high x, and a mild but non-negligible increase at intermediate x [4], still inside the "safe" region defined by the larger W cut discussed above. These findings have subsequently been confirmed by Ball *et al.* [8].

The uncertainties on the d quark PDF from theoretical modeling of nuclear corrections (which we refer to as "nuclear uncertainties") have been quantified in Refs. [5, 6]. These range from mild, corresponding to the hardest of the deuteron wave functions (WJC-1) coupled to a 0.3% nucleon off-shell correction, to strong, corresponding to the softest wave function (CD-Bonn) and a large, 2.1% nucleon off-shell correction; the central value corresponds to the AV18 deuteron wave function with a 1.2% off-shell correction [6]. The resulting PDFs are labeled "CJ12min", "CJ12max", and "CJ12mid", respectively. The uncertainties on the CJ12 d quark distribution are illustrated in Fig. 1 (left), with the central (red) band indicating the PDF error calculated with the Hessian method and a tolerance factor $T = 10$. The central (blue) band represents the theoretical nuclear uncertainty, obtained as an envelope of the CJ12min and CJ12max fits, and is of the same order of magnitude as the PDF error. The outer (green) band is the PDF error in a fit that excludes all deuterium data, and exceeds the combuned PDF and nuclear uncertainties. This demonstrates the usefulness of the deuterium data, even in the presence of the nuclear uncertainties that its use introduces.

A further source of theoretical uncertainty was investigated in Refs. [5, 6], where a more flexible parametrization was used for the valence d_v quark at large-x, with a small admixture of the valence u_v PDF,

$$d_v(x) \to d'_v(x) = a_0^d \left[d_v(x)/a_0^d + b\, x^c u_v(x) \right], \tag{1}$$

where a_0^d is the d quark normalization, and b and c are two additional parameters. The result is that the d/u ratio at $x \to 1$ can now span the range $[0, \infty)$ rather than being limited to either 0 or ∞ as in all previous PDF fits. A finite, nonzero value of this ratio is in fact expected from several nonperturbative models of nucleon structure [2, 3, 9]. It is also required from a purely practical point of view because it avoids potentially large biases on the fitted d quark PDF, as we discuss below.

The ratios of the d to u PDFs for the three CJ12 sets are shown in Fig. 1 (right). These are constrained up to $x \approx 0.8$ by the enlarged data set considered in the CJ12 fits, and when extrapolated to $x = 1$ give the limiting value

$$d/u \xrightarrow[x\to 1]{} 0.22 \pm 0.20\,(\text{PDF}) \pm 0.10\,(\text{nucl}), \tag{2}$$

where the first error is from the PDF fits and the second is from the nuclear correction models. These values encompass the full range $\approx 0 - 0.5$ of available theoretical predictions [2, 3]. However, a relatively modest improvement in statistical precision in new data and a reduction of the nuclear uncertainty would restrict the range of allowable nonperturbative models.

The same nuclear uncertainty also affects forward rapidity observables as well as production of large mass particles [10]. For example, the nuclear uncertainty becomes relevant for W production at rapidity greater than 2 at the Tevatron, and greater than 3.5 at the LHC. For particles of heavier mass, such as the putative W' and Z' bosons predicted in models beyond the standard model, the nuclear uncertainty in the production cross section at large x may become larger than 20% above the lower mass limit of ≈ 2.5 TeV set by recent LHC data [11]. This illustrates how nuclear and other large-x theoretical uncertainties may significantly affect the interpretation of signals of new particles and the determination of their properties, which requires a precise determination of QCD backgrounds.

Constraining nuclear uncertainties with proton targets. As discussed in the introduction, global QCD fits allow for the intriguing possibility of combining deuteron and proton data to obtain experimental constraints on nuclear models, and at the same time fully utilize the available statistics of the nuclear target data. For example, the directly reconstructed W asymmetry at the Tevatron is very sensitive to nuclear corrections at rapidities $y \gtrsim 2$ [10]. Comparison with the very precise CDF data, as well as the total χ^2 values in the CJ12 fits, suggests that nuclear effects are somewhere between the minimum and central ones embodied in the CJ12min and CJ12mid fits, respectively. This was also confirmed in a recent analysis by Martin *et al.* [12], where an attempt was made to fit the nuclear corrections to data rather than compute them in a microscopic model. On the phenomenological side, this result disfavors nonperturbative proton models based on SU(6) spin-flavor symmetry, which predict $d/u \to 1/2$ at large x. More importantly, it exemplifies the power of global fits in combining disparate sets of data, and is the first step to establishing the experimental foundation for our ability to theoretically understand and describe high-energy processes in nuclei – using *proton* targets!

At present the W charge asymmetry from CDF appears the only observable that has this potential. The lepton asymmetry has insufficient large-x coverage due to decay vertex smearing, while Z rapidity distributions from CDF and DØ have insufficient precision [6]. At the LHC one would need measurements with better than 10% precision at $y \gtrsim 3.5$, which is at the edge of the LHCb acceptance. The potential for reconstructing W and Z rapidity distributions at large y from pp collisions at RHIC should also be explored. Finally, parity-violating DIS scattering can provide another way to separate u and d quarks. Recent measurements of $F_{2,3}^{\gamma Z}$ at HERA and the planned large-x measurements at the upgraded Jefferson Lab facility will provide additional leverage to constrain the nuclear corrections.

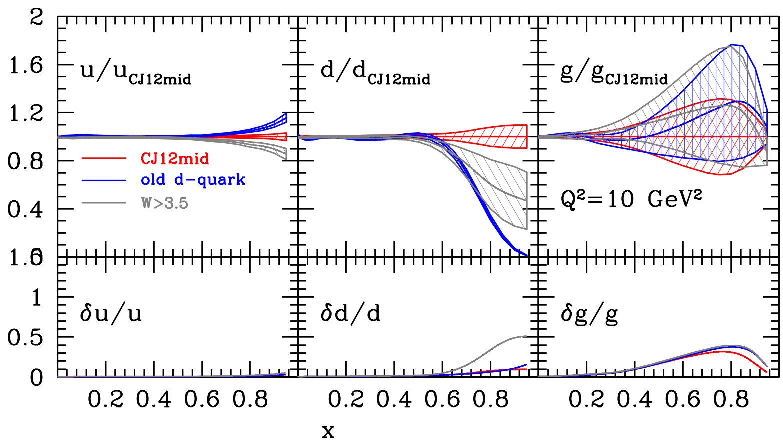

Figure 2: Comparison of PDFs obtained with a conventional $W > 3.5$ GeV cut, and using the old d_v quark parametrization with $W > 1.7$ GeV to the CJ12mid set. A tolerance $T = 1$ is used for clarity.

Theoretical biases at $x \to 1$. The importance of using a more flexible d-quark parametrization than in traditional fits cannot be overemphasized. Figures 2 and 3 show a comparison of the CJ12mid fits to a fit obtained with the standard $W > 3.5$ GeV cut, and a fit obtained with $W > 1.7$ GeV but standard d-quark parametrization (namely, $b = c = 0$ in Eq. (1)).

In Figure 2, the ratios of the u, d and gluon PDFs in the two new fits to the CJ12mid fit are presented with a tolerance $T = 1$ (for clarity). The fit using the standard parametrization starts deviating from the CJ12mid fit at $x \gtrsim 0.5$. This behavior is clearly not data driven (it starts already inside the covered kinematic range), but is forced by the assumed functional form for $d \propto (1-x)^{a_d}$ rather than the more flexible parametrization (1). The dramatic decrease of the standard d quark PDF towards 0 can be compensated in the fit by an increased u quark distribution, due to the correlation induced by the large-x DIS data.

Further insight can be obtained by considering the d/u ratio in Fig. 3. In this case the standard parametrization forces d/u to take either the value of 0 or ∞. In contrast, the extended d' parametrization allows for limiting values in the entire between 0 and ∞. In the CJ12 fit, the data does not seem to warrant the behavior of the standard parametrization, which lies at the edge of the PDF error band of the CJ12mid fit. In summary, not only does the standard d parametrization underestimate the central fitted value at $x \gtrsim 0.5$, it also underestimates the PDF uncertainty, as well as the nuclear uncertainty.

Other potential biases exist at large x, related to theoretical corrections not yet included included in the perturbative QCD calculations utilized in the CJ12 analysis. These include large-x resummation, jet mass corrections, and higher-order terms in the perturbative expansion. However, these typically scale as $1/Q^2$ (or resembloe such a power correction at low Q^2) and will mainly affect the extraction of the HT term, leaving the leading-twist PDFs largely unchanged (as was found for the model dependence of target mass corrections [4]). This makes the choice of parametrization possibly the largest theoretical bias in the determination of the d-quark PDF at large x. A full theoretical unbiasing should be pursued by generalizing the d' quark functional form adopted in the CJ12 fits and investigating the related quantitative extraction of d-quark PDF errors at $x \to 1$.

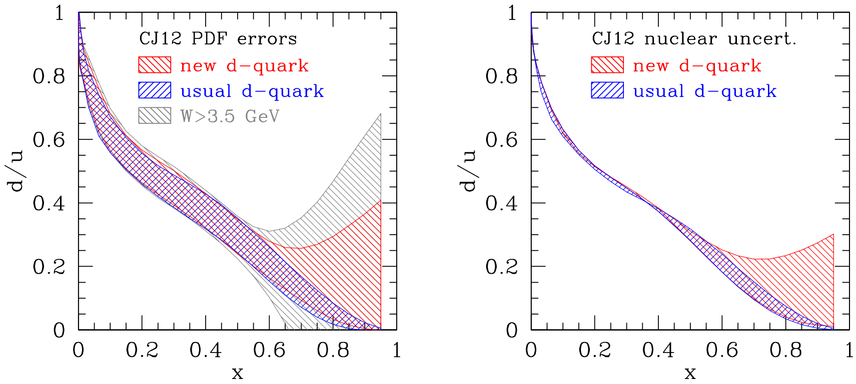

Figure 3: PDF errors with tolerance $T = 10$ and nuclear uncertainties for the fits in Fig. 2.

Conclusions. The recent studies by the CTEQ-Jefferson Lab collaboration, culminating in the release of the CJ12 PDFs [6], have demonstrated the intimate connection of hadronic, nuclear and high-energy physics. Namely, global QCD fits have become capable of constraining theoretical models of nuclear corrections in the deuteron. Not only will this reduce the nuclear uncertainty on the fitted PDFs with important phenomenological consequences on physics, ranging from non-perturbative proton structure to beyond the standard model interactions, it will also provide a new avenue for progress in the theoretical understanding of high-energy processes involving *nuclei*, using weak interactions on *proton* targets from Jefferson Lab to the LHC.

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