

# Constraints on large- $x$ parton distributions from new weak boson production and deep-inelastic scattering data

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## Abstract

We present a new set of leading twist parton distribution functions (PDFs), which take advantage of developments in the theoretical treatment of nuclear corrections as well as new data. The analysis includes for the first time data on the free neutron structure function from the BONuS experiment at Jefferson Lab, and new charged lepton and  $W$ -boson asymmetry data from Fermilab, which significantly reduce the uncertainty on the  $d/u$  ratio at large values of  $x$ .

## I. INTRODUCTION

[XXX to edit]

... general intro ...

... what is new since CJ12 ...

• more complete/consistent/systematic treatment of nuclear corrections esp. nucleon off-shell corrections

• impact of new  $W$ -boson asymmetry data on  $d/u$  ratio

• inclusion of JLab (BONuS) data

• analysis of  $\bar{d} - \bar{u}$  at large  $x$  ... choose either  $\bar{d}/\bar{u} \rightarrow 1$  or  $0$  as  $x \rightarrow 1$  ...

• S-ACOT scheme for heavy quarks

• LO fit

•  $\alpha_s$  treatment

... In Sec. II we ...

## II. THEORETICAL FOUNDATIONS

In this section we present the theoretical framework that is used for the CJ15 analysis.

### A. PDF parametrizations [XXX to edit]

• For the parametrization of the PDFs at the input scale  $Q_0^2$ , a common form has been adopted for all parton species  $f$ ,

$$xf(x, Q_0^2) = a_0 x^{a_1} (1-x)^{a_2} (1 + a_3 \sqrt{x} + a_4 x). \quad (1)$$

This form applies to the valence distributions  $xq_v \equiv x(q - \bar{q})$ , for  $q = u$  and  $d$ , the isoscalar and isovector sea quark distributions  $x(\bar{u} + \bar{d})$  and  $x(\bar{d} - \bar{u})$ , and the gluon distribution  $xg$ . However, to allow for a more flexible parametrization of the valence  $d_v$  PDF in the large- $x$  region, we add in a small admixture of the  $u_v$  PDF,

$$d_v \rightarrow a_0^{d_v} \left( \frac{d_v}{a_0^{d_v}} + b x^c u_v \right), \quad (2)$$

with  $b$  and  $c$  as two additional parameters. The result of this modification is that  $d_v/u_v \rightarrow a_0^{d_v} b$  as  $x \rightarrow 1$ , provided  $a_2^{d_v} > a_2^{u_v}$ , which is usually the case. A finite, nonzero value of this

ratio is indeed expected in several nonperturbative models of hadron structure [6–8]. It is also required from a purely practical point of view, as it avoids potentially large biases on the  $d$ -quark PDF central value [14], as well as on its PDF error estimate, as we discuss in detail in Sec. IV. The  $a_0$  parameters for the  $u_v$  and  $d_v$  distributions are fixed by the appropriate valence quark number sum rules, while  $a_0^g$  is fixed by the momentum sum rule.

- For the input scale  $Q_0$  we choose the charm quark scale,  $Q_0 = m_c$ .
- New parametrization for  $\bar{d} - \bar{u}$  ... avoids negative PDFs? ...

In our analysis we parametrize the  $\bar{d}/\bar{u}$  ratio as

$$\frac{\bar{d}}{\bar{u}} = a_0 x^{a_1} (1-x)^{a_2} + 1 + x^{a_3} (1-x)^{a_4}, \quad (3)$$

which ensures that in the limit  $x \rightarrow 1$  one has  $\bar{d}/\bar{u} \rightarrow 1$ . The existing data are not able to reliably determine the large- $x$  behavior of the ratio, so as an alternative we also perform fits using  $\bar{d}/\bar{u} = a_0 x^{a_1} (1-x)^{a_2} + (1+x^{a_3})(1-x)^{a_4}$ , which vanishes in the  $x \rightarrow 1$  limit. The  $\bar{d}/\bar{u} \rightarrow 1$  limit is what would be expected from perturbative QCD, while the  $\bar{d}/\bar{u} \rightarrow 0$  limit may arise if the trend in  $x \gtrsim 0.3$  points from the E866 experiment [29] were to continue to larger  $x$ .

...[ARE PARAMETERS IN TABLE I FOR  $\bar{d}/\bar{u}$  OR  $\bar{d} - \bar{u}$ ??]...

• The strange quark distribution is not well constrained by existing data ...[SOME DISCUSSION OF ISSUES]... For the strange quark PDF, we follow our previous analyses [14, 15] by assuming flavor independence of the shape of the sea quark PDFs, and consequently take a fixed ratio

$$\kappa = \frac{s + \bar{s}}{\bar{u} + u}, \quad (4)$$

with the further assumption that  $\bar{s} = s$ . In this study we take  $\kappa = 0.4$ .

## B. Heavy quarks [JFO?? to edit]

- Implementation of S-ACOT scheme.
- In our analysis we take the masses of the charm and bottom quarks to be  $m_c = 1.3$  GeV and  $m_b = 4.5$  GeV, respectively.
- The 4-flavor value of the QCD cutoff scale used in this analysis is  $\Lambda_{\text{QCD}}^{(4)} = 226.8$  MeV.

### C. $1/Q^2$ corrections [XXX to edit]

- For target mass corrections, use of OPE (G-P); ... comparisons with EFP, series expansion; ... in practice doesn't matter! (?)
- ... give formula for TMC in  $F_2$  ???
- For other subleading  $1/Q^2$  corrections, such as higher twist and other residual power corrections ...

$$F_2(x, Q^2) = F_2^{(\text{LT}+\text{TMC})}(x, Q^2) \left( 1 + \frac{C_{\text{HT}}(x)}{Q^2} \right), \quad (5)$$

where  $F_2^{(\text{LT}+\text{TMC})}$  denotes the leading twist structure function including TMCs. For simplicity we generically refer to the fitted  $1/Q^2$  term as a “higher twist” correction, and parametrize the higher twist coefficient function by

$$C_{\text{HT}}(x) = h_0 x^{h_1} (1 + h_2 x), \quad (6)$$

assuming it to be isospin independent (see, however, Refs. [62–65]).

### D. Nuclear corrections

As in the previous CJ PDF analyses [11, 14, 15], the use of deuterium DIS and Drell-Yan data necessitates taking into account the differences between PDFs in the deuteron compared to those in the free proton and neutron. The CJ15 analysis follows a similar approach, with a few improvements over the earlier implementations, which we discuss in the following. While the earlier analyses applied nuclear corrections only to deep-inelastic deuteron structure functions, in the present work we formulate the corrections at the parton level, and generalize the smearing corrections to any process involving quark, antiquark or gluon PDFs in the deuteron.

Generally, the nuclear corrections account for Fermi motion, binding and nucleon off-shell effects, which are implemented in the form of convolutions using nuclear smearing functions. These become increasingly important intermediate and large values of  $x$ , and will be the focus of our attention in this section. In addition, rescattering effects mediated by Pomeron and meson exchange mechanisms give rise to shadowing at small values of  $x$  ( $x \lesssim 0.1$ ) and

a small amount of antishadowing at  $x \sim 0.1$  [1] (see also Refs. [2, 3]). However, in practice the shadowing and antishadowing corrections are very small, and have negligible effect on the phenomenology in our analysis.

### 1. Nuclear smearing

From the standard nuclear impulse approximation for the scattering of a projectile (lepton or hadron) from the deuteron  $d$ , the momentum distribution of a parton in the deuteron is given by a convolution of the corresponding PDF in the bound nucleon and a light-cone momentum distribution  $f_{N/d}$  of nucleons in the deuteron (“smearing function”) [66, 67]. Taking for illustration the PDF for a quark of flavor  $q$  (the generalization to antiquarks and gluons is straightforward), the distribution in the deuteron can be computed as

$$q^d(x, Q^2) = \int \frac{dz}{z} dp^2 f_{N/d}(z, p^2) \tilde{q}^N(x/z, p^2, Q^2), \quad (7)$$

where  $z = (M_d/M)(p \cdot q / p_d \cdot q)$  is the nucleon momentum fraction in the deuteron, with  $p$  and  $p_d$  the four-momenta of the nucleon and deuteron, respectively,  $p^2$  is the nucleon virtuality, and  $M_d$  is the deuteron mass. For the isoscalar deuteron, a sum over the nucleons  $N = p, n$  is implied. The function  $\tilde{q}^N$  is the quark PDF in the off-shell nucleon, and in principle includes the  $1/Q^2$  corrections, such as TMCs and higher twist effects, discussed above.

While the off-shell nucleon PDF  $\tilde{q}^N$  is not by itself an observable, its dependence on the virtuality  $p^2$  can be studied within a given framework. Since the bound state effects in the deuteron are the smallest for all atomic nuclei, one can expand the off-shell nucleon distribution about its on-shell limit [68],

$$\tilde{q}^N(x, p^2, Q^2) = q^N(x, Q^2) \left( 1 + \frac{p^2 - M^2}{M^2} \delta f^N(x, Q^2) \right), \quad (8)$$

where the coefficient of the off-shell term is formally given by

$$\delta f^N(x, Q^2) = \left. \frac{\partial \ln \tilde{q}^N(x, p^2, Q^2)}{\partial \ln p^2} \right|_{p^2=M^2}. \quad (9)$$

The on-shell term in Eq. (8) leads to the standard on-shell convolution representation for the nuclear PDF, while the off-shell term can be evaluated as an additive correction. Defining the total quark PDF in the deuteron by  $q^d = q^{d(\text{on})} + q^{d(\text{off})}$ , the on-shell and off-shell

contributions can be written

$$q^{d(\text{on})}(x, Q^2) = \int \frac{dz}{z} f^{(\text{on})}(z) q^N(x/z, Q^2), \quad (10a)$$

$$q^{d(\text{off})}(x, Q^2) = \int \frac{dz}{z} f^{(\text{off})}(z) \delta f^N(x/z, Q^2) q^N(x/z, Q^2). \quad (10b)$$

The on-shell and off-shell smearing functions  $f^{(\text{on})}$  and  $f^{(\text{off})}$  are taken to be the same for the proton and neutron (isospin symmetry breaking effects are not expected to be significant), and are given by [70]

$$f^{(\text{on})}(z) = \int dp^2 f_{N/d}(z, p^2), \quad (11a)$$

$$f^{(\text{off})}(z) = \int dp^2 \frac{p^2 - M^2}{M^2} f_{N/d}(z, p^2). \quad (11b)$$

In practice we compute these within the weak binding approximation (WBA) in terms of the deuteron wave function [68, 69]. At  $Q^2 \rightarrow \infty$  the on-shell smearing function  $f^{(\text{on})}$  has a simple probabilistic interpretation in terms of the light-cone momentum fraction  $z \approx (M_d/M)(p^+/p_d^+) = (p^0 + p^z)/M = 1 + (\varepsilon\dots)$  of the deuteron carried by the struck nucleon, while at finite  $Q^2$  it depends in addition on the parameter  $\rho^2 = 1 + 4x^2 M^2/Q^2$ , which characterizes the deviation from the Bjorken limit.

...[WM EDITING]...

The nuclear corrections at large  $x$  depend partly on the strength of the high-momentum tail of the deuteron wave function, and we use several wave functions based on different nucleon–nucleon potentials to study the deuteron model dependence. We choose the high-precision AV18 [71], CD-Bonn [72] and the relativistic WJC-1 and WJC-2 [73] wave functions, which provide a representative spread of behaviors at high momentum. Note that the effects of the nuclear smearing corrections are not suppressed at large  $Q^2$ , and must be considered at all scales wherever data at  $x \gtrsim 0.3$  are used [11–13].

- Same off-shell functions in DIS and DY.

## 2. Nucleon off-shell corrections [WM]

- The off-shell nucleon correction  $\delta^{(\text{off})} q^d$  is somewhat more model dependent, but several quark model based estimates of this have been made in the literature [68, 74, 75].

- ... give brief history of off-shell corrections

- MST (theoretical)
- KP (model/fitted)
- CJ11 (mKP)
- CJ12 (more consistent mKP)
- CJ15 (calculation at parton level - different treatment of valence quarks, antiquarks and gluons - can apply to any observable, not just  $F_2$  structure function - in CJ11 and CJ12 had used overall multiplicative constant, only for  $F_2$ )

- In Ref. [14] this was computed using the “modified Kulagin-Petti” model. In this model, the corrections were related to the change in the nucleon’s confinement radius in the nuclear medium, as well as the average virtuality of the bound nucleons, and constrained to give no net change in the structure function normalization. In contrast to Ref. [14], however, here we further take into account the correlation between the nucleon “swelling” and the deuteron wave function. The combined effects introduce a theoretical uncertainty in the extracted PDFs, particularly for the  $d$  quark.

- In CJ15 have freed off-shell parameters, allowing them to be determined by the fit. Using either fmKP model (rescaling parameter  $\lambda$ ), or in phenomenological fit.

- In this analysis, we explore the possibility of antishadowing in the deuteron, suggested in the global nuclear analysis of KP [68], in which the  $F_2^d/F_2^N$  ratio is slightly enhanced (above unity) at  $x \approx 0.1 - 0.2$ . To allow for one or more zero crossings in the function  $\delta f^N$ , we use the same parametrization as in Ref. [68],

$$\delta f^N = C_N(x - x_0)(x - x_1)(1 + x_0 - x), \quad (12)$$

but fit the parameters to the deuterium data. The requirement that the off-shell correction does not modify the number of valence quarks in the nucleon provides the constraint

$$\int_0^1 dx \delta f^N(x) (q(x) - \bar{q}(x)) = 0. \quad (13)$$

In practice we fit the zero crossing parameter  $x_0$  and the normalization  $C_N$ , which then allows the second zero crossing  $x_1$  to be determined from Eq. (13) analytically.

## E. PDF Errors [AA/JFO?? to edit]

... as for CJ12 ... Hessian ... tolerance ...

### III. DATA

[XXX to edit]

The CJ15 PDFs are obtained by fitting to a global database of 4035 data points from a variety of high energy scattering processes, listed in Table I. These include deep-inelastic scattering data from BCDMS, NMC, SLAC, HERA and Jefferson Lab (JLab); Drell-Yan  $p$  and  $d$  cross sections from fixed target experiments at Fermilab;  $W$  and  $Z$  asymmetries, as well as jet and  $\gamma$ +jet cross sections from the CDF and DØ collaborations at the Tevatron. The table also lists the corresponding  $\chi^2$  values for each data set. The overall  $\chi^2/\text{dof}$  is 0.979. The fit is slightly better than in our previous CJ12 analysis [15], partly because of the greater flexibility which we have allowed in the current fit for the nucleon off-shell correction.

... do not include HERMES  $F_2^p$  data ... because ...

...[FURTHER DESCRIPTIONS OF DATA]...

...[JUSTIFICATION FOR INCLUDING AND OMITTING SPECIFIC DATA SETS]...

### IV. RESULTS

In this section we present the results of our global QCD analysis. The quality of the fit to data is illustrated in Figs. 1 and 2, where the inclusive  $F_2$  structure functions of the proton and deuteron are compared with the CJ15 calculations over several decades of  $Q^2$  and  $x$ . For the proton  $F_2^p$  structure function in Fig. 1, data from BCDMS [23], NMC [24], SLAC [26] and JLab [27] experiments are shown at approximately constant values of  $x$ , while for the JLab data (see inset in Fig. 1) the structure functions are presented at fixed scattering angles, with  $x$  increasing with  $Q^2$ . The agreement for all the sets is excellent ...[???]..., with the exception of ...[???]...

Similar agreement is seen for the deuteron  $F_2^d$  structure function in Fig. 2, where measurements from BCDMS [23], SLAC [26] and JLab [27] are compared with the CJ15 results (data from NMC are presented as a ratio to the proton structure function,  $F_2^d/F_2^p$ ).

...[SHOW OTHER, e.g. HERA, DATA SEPARATELY??]...



### A. CJ15 PDFs

The CJ15 PDFs themselves are displayed in Fig. 3 at a scale of  $Q^2 = 10 \text{ GeV}^2$  for the  $u$ ,  $d$ ,  $\bar{d} + \bar{u}$  and  $\bar{d} - \bar{u}$  distributions, and the gluon distribution scaled by a factor 1/10. The central CJ15 PDFs are determined using the AV18 deuteron wave function and the nucleon off-shell parametrization in Eq. (12), with the parameter values and their errors for the leading twist distributions given in Table II. at the input scale  $Q_0^2$ . The uncertainty bands on the PDFs correspond to  $\Delta\chi^2 = 1$ . The parameters without errors have been fixed by sum rules or other constraints. (To avoid rounding errors when using these values in numerical calculations, we give the parameter values to 5 significant figures.) PDFs for other flavors, such as strange and charm, are not shown in Fig. 3. The strange quark PDF is assumed to be proportional to the light antiquark sea in the ratio  $\kappa = 0.4$  [see Eq. (4)], while the charm quark distribution is generated perturbatively through  $Q^2$  evolution. While there has been speculation about nonperturbative or intrinsic contributions to PDFs of heavy flavors, there is currently no evidence from global analysis of high energy scattering data to suggest that these are large [89]. Until more conclusive evidence becomes available, in this analysis we follow the conventional approach in setting these to zero. This is in contrast with the light quark sea, for which a nonperturbative component at the input scale is essential to account for the nonzero flavor asymmetry  $\bar{d} - \bar{u}$ .

...[NOTE VERY ASYMMETRIC ERRORS AT SMALL  $x$ ]...

The CJ15 PDFs are compared with PDFs from several recent representative NLO global parametrizations in Fig. 4, in the form of ratios to the central CJ15 distributions. Since different PDF analyses typically utilize different criteria for estimating PDF errors, we display the CJ15 errors for the standard  $\Delta\chi^2 = 1$  (or tolerance  $T = 1$ ), as well as with errors inflated by a tolerance of  $T = 10$  [15]. Generally the MMHT14 [17] and NNPDF3.0 [20] PDF sets have uncertainties that are comparable to the CJ15 PDF errors with  $T = 10$ , while those for the HERAPDF15 [22] distributions are closer to the CJ15  $T = 1$  errors. This may be expected given that the HERAPDF15 analysis only fits HERA data, and therefore uses the  $\Delta\chi^2 = 1$  criterion for generating errors.

As known from most previous analyses, the relative uncertainties on the  $d$ -quark PDFs are significantly larger than those on the  $u$ -quark PDF, especially at large  $x$ . For the  $\bar{u}$  and  $\bar{d}$  distributions the results from the CJ15 fit are similar to those from the MMHT14 and

NNPDF3.0 analyses, while the HERAPDF15 fit gives significantly different results beyond  $x \approx 0.1 - 0.2$ . Note that the  $\bar{d}/\bar{u}$  ratio is most strongly constrained by the E866 Drell-Yan  $pp$  and  $pd$  scattering data. For the strange quark PDF, the uncertainties in CJ15 are somewhat smaller than in MMHT14 and NNPDF3.0. This is mostly due to the fact that the CJ15  $s$ -quark PDF is assumed to scale with the light antiquark sea in the ratio  $\kappa = 0.4$ , while other analyses attempt to constrain  $s$ -quark PDF from neutrino data, which typically have much larger uncertainties. The errors on the gluon distribution in the MMHT14 and NNPDF3.0 fits lie somewhere between the  $T = 1$  and  $T = 10$  CJ15 errors, while the HERAPDF15 uncertainties are comparable to the  $T = 1$  CJ15 results, as was the case for the various quark distributions. Uncertainties in other modern PDF analyses, such as CT14 [18], JR14 [49] or ABM11 [47] are generally between the representative sets illustrated in Fig. 4.

...[ANY OTHER COMMENTS ABOUT THE GENERAL FEATURES/ERRORS?]...

## B. Nuclear corrections at large $x$

As observed in Fig. 4, the uncertainty on the  $d$ -quark distribution at large  $x$  values ( $x \gtrsim 0.3$ ) is generally much larger compared with that on the  $u$ -quark PDF. This reflects the considerable greater quantity of high precision proton  $F_2^p$  structure function data, which, because of the larger charge on the  $u$  quark, is at least an order of magnitude more sensitive to the  $u$ -quark PDF than to the  $d$ . Traditionally, stronger constraints on the  $d$ -quark PDF have been sought from inclusive DIS from the neutron, in which the roles of the  $u$  and  $d$  quark are reversed relative to the proton. However, the absence of free neutron targets has meant that neutron structure information has had to be extracted from measurements on deuterium nuclei. Unfortunately, at high values of  $x$  ( $x \gtrsim 0.5$ ) bound state effects in the deuteron become important, and uncertainties in their computation become increasing large with increasing  $x$ .

The effects of nuclear corrections on the PDFs are illustrated in Fig. 5, where fits using several different deuteron wave function models are compared. The distributions are displayed relative to the central CJ15 PDFs which use the AV18 deuteron wave function. All fits employ the phenomenological nucleon off-shell parametrization in Eq. (12), with the parameters given in Table III for the AV18 deuteron wave function. The results using the CD-Bonn or WJC-2 wave function are very similar to those for the AV18 wave function,

while using the WJC-1 model leads to larger differences. In fact, the AV18 and CD-Bonn models give almost identical total  $\chi^2/\text{dof}$  of 0.979, while the WJC-2 model gives 0.980, making these three fits essentially indistinguishable. This suggests that, for the most part, the nucleon off-shell parametrization in Eq. (12) is sufficiently flexible to compensate for changes induced by these wave functions. For the WJC-1 model, which has the hardest momentum distribution, it is more difficult for the off-shell correction to compensate within the constraints of Eq. (12), and this leads to a slightly worse overall fit, with a  $\chi^2/\text{dof}$  value of 0.983.

As expected, the variations due to the nuclear models have the largest effects in the  $d$ -quark distribution, which is less constrained by proton data and hence more sensitive to uncertainties in the extracted neutron structure function. The spread in the  $d$  PDF at  $x = 0.8$  is  $\approx 20\%$  for all four wave functions. The variations for the AV18, CD-Bonn and WJC-2 wave functions are generally within the  $\Delta\chi^2 = 1$  confidence limit, while the WJC-1 results lie outside the band for the  $u$  and  $d$  PDFs. In particular, the  $d$ -quark PDF for the WJC-1 deuteron model is suppressed at high  $x$  relative to that in the other models, which correlates with the harder smearing function  $f_{N/d}$  at large values of the nucleon light-cone momentum  $y$  and hence a larger  $F_2^d/F_2^N$  ratio at high  $x$ . Interestingly, one also observes an anti-correlation between the behavior of the  $d$ -quark distribution at large  $x$  and the gluon distribution. In fact, using the WJC-1 wave functions leads to slight decreases in all the quark PDFs at high  $x$ , while the gluon PDF has the opposite trend. The spread in the gluon PDF is  $\lesssim 10\%$  for  $x < 0.8$ , although beyond  $x \approx 0.3$  the gluon distribution has a very large uncertainty.

Note that while in Fig. 5 the same functional form from Eq. (12) is used for all fits, the off-shell parameters are refitted for each different deuteron wave function model. The fitted off-shell functions  $\delta f^N$  are shown in Fig. 6 for the four wave function models considered. The off-shell corrections for the AV18, CD-Bonn and WJC-2 models have similar shapes: quite small at low  $x$  but becoming more positive at larger  $x$ . The function  $\delta f^N$  for these models has zero crossings at  $x = x_1 \approx 0.05$  and  $x = x_0 \approx 0.3$ . For the WJC-1 model, on the other hand, the off-shell function is similar in magnitude, but has a shape that is somewhat orthogonal to the others. In this case it becomes more negative for  $x \gtrsim 0.5$ , with the parameter  $x_1 \approx 0.15$ , while the other zero crossing parameter is negative,  $x_0 \approx -0.25$ .

To test the sensitivity of the fit to the off-shell model, we also consider a somewhat

different prescription for the off-shell correction  $\delta f^N$ , along the lines of that adopted in our previous analyses [14, 15] (see also Ref. [68]). Namely, we express the PDF through a spectral representation, in terms of a quark spectral function characterized by an ultraviolet momentum cutoff scale  $\Lambda$  and an invariant mass of the “diquark” system (proton with a quark removed) that is spectator to the deep-inelastic collision. The spectator mass is fixed by comparing with the on-shell proton structure function data, and the variation of the scale  $\Lambda$  with the nucleon virtuality  $p^2$  may be interpreted within a valence approximation as a rescaling of the nucleon confinement radius [68]. To apply the model to observables that are sensitive to both the valence and sea quark sectors, in the present analysis we generalize the single-pole approximation to the spectral function to allow different off-shell behaviors of the valence, sea quark and gluon distributions. The three corresponding spectator state masses (“ $qq$ ” for valence quarks, “ $qq\bar{q}q$ ” for sea quarks, and “ $qqq$ ” for gluons) are then fitted to the isoscalar valence, sea quark and gluon PDFs in the free nucleon. The rescaling parameter  $\partial \log \Lambda^2 / \partial \log p^2$  evaluated at  $p^2 = M^2$  is then included as a parameter in the fit, with errors propagated along with those of the other fit parameters in Tables II and III.

The results of the fit within this model, which we refer to as the off-shell covariant spectator (OCS) model, are displayed in Fig. 7 for various PDFs as ratios to the central CJ15 PDFs (computed using the off-shell parametrization (12) and the AV18 deuteron wave function). For the AV18, CD-Bonn and WJC-2 wave functions, the effects of the more restrictive OCS model (which involves one off-shell parameter instead of three for the parametrization in Eq. (12) and relatively small and generally within the  $\Delta\chi^2 = 1$  bands. The overall  $\chi^2/\text{dof}$  value is 0.982 for both the AV18 and CD-Bonn wave functions, and 0.984 for the WJC-2 wave function. This is marginally higher than the results of the fit with the phenomenological off-shell parametrization in Eq. (12), and comes mostly from a slightly higher  $\chi^2$  values for the SLAC  $F_2^d$  and DØ charged lepton asymmetry data. For the WJC-1 wave function, the results for the  $d$ -quark PDF show significantly greater deviation at large  $x$ , again suggesting that the hard tail of its momentum distribution is difficult to accommodate also within the OCS model, with a total  $\chi^2/\text{dof}$  of 0.989. In addition, for the  $u$ -quark distribution the WJC-1 result lies slightly outside the uncertainty band at  $x \sim 0.05$ .

We should note, however, that the off-shell correction term  $\delta f^N$ , or even the off-shell PDF  $\tilde{q}^N$  in Eq. (8), alone is unphysical. Only the convolution of  $\tilde{q}^N$  with the smearing function  $f_{N/d}$  in Eq. (7) corresponds to the physical deuteron parton distribution (or structure func-

tion), and the two corrections (deuteron wave function and nucleon off-shell) must always be considered together. Since the off-shell correction is fitted, changes in deuteron wave function can in practice be compensated by a corresponding change in the off-shell parameters, to the extent allowed by the specific choice of wave function and off-shell parametrization. This is clearly illustrated in Fig. 8, where the deuteron EMC ratio  $F_2^d/F_2^N$  is shown for the four different wave functions considered, and the 3-parameter off-shell parametrization in Eq. (12). Remarkably the structure function ratio is almost identical for the AV18, CD-Bonn and WJC-2 models, while the WJC-1 result differs slightly from these, reflecting the observations in Figs. 5–7 above.

In addition to the important role played by nuclear corrections in  $F_2^d$  at large values of  $x$ , the effects of finite- $Q^2$  corrections are also significant, especially at low  $Q^2$ . In an earlier study [11], a nontrivial interplay was observed between the kinematical TMCs and the dynamical higher twist corrections parametrized in Eq. (5). The impact of the finite- $Q^2$  corrections on the  $F_2^d/F_2^N$  ratio is illustrated in Fig. 9 for the CJ15 fit, for  $Q^2$  between 2 GeV<sup>2</sup> and 100 GeV<sup>2</sup>. The rise in the ratio at large  $x$  is fastest at the highest  $Q^2$  value, and becomes less steep with decreasing  $Q^2$ . The general shape remains independent of the scale for  $Q^2 \gtrsim 5$  GeV<sup>2</sup>, however, a dramatic change occurs at  $Q^2 \sim 2$  GeV<sup>2</sup>, where  $F_2^d/F_2^N$  rises slowly until  $x \approx 0.75$  before abruptly turning down for larger  $x$ . This behavior arises from the interplay between the TMCs to the free and smeared nucleon structure functions, and the  $Q^2$  dependent corrections to the smearing functions  $f_{N/d}$  at finite values of  $x^2/Q^2$ .

For the standard TMC prescription adopted in this analysis, namely that based on the operator product expansion [52], the fitted higher twist coefficient function  $C_{\text{HT}}$  in Eq. (6) is plotted in Fig. 10, with the parameters given in Table III for the CJ15 fit. The coefficient displays the characteristic rise at large values of  $x$  observed in previous higher twist extractions, and is almost completely independent of the deuteron wave function model for the entire range of  $x$  considered.

### C. $d/u$ ratio

The nuclear and finite- $Q^2$  corrections that manifest themselves in the  $F_2^d/F_2^N$  ratio as observed in Figs. 8 and 9 directly translate into modifying the behavior of the  $d/u$  PDF ratio at large  $x$ . Our previous analyses [11, 14, 15] have made detailed studies of the re-

relationship between the size of the nuclear corrections in the deuteron and the shape and  $x \rightarrow 1$  limit of  $d/u$ . For the CJ12 PDFs [15], three sets of nuclear corrections were considered, corresponding to mild, medium and strong nuclear corrections, and referred to as “CJ12min”, “CJ12mid” and “CJ12max”, respectively. Each of these sets was consistent with the available data constraints, and provided a convenient way to explore the nuclear effects on various observables.

Since our last analysis, new data on charged lepton [32, 33] and  $W$  boson asymmetries [35] over a large range of rapidities have become available from the DØ collaboration, which place significant constraints on the  $d/u$  ratio at high  $x$ . The new DØ electron and muon asymmetry data, together with earlier data from CDF [31], are displayed in Fig. 11 as a function of the lepton pseudorapidity  $\eta_l$  and compared with the CJ15 fit. Compared with the range of nuclear corrections in CJ12, the lepton asymmetry data, and especially the new results from DØ [32, 33], strongly favor a smaller nuclear correction at large  $x$ , closer to the CJ12min set.

The extracted  $W$  boson asymmetries, which are more directly related to the shape of the PDFs, are shown in Fig. 12 as a function of the  $W$  boson rapidity  $y_W$ . The statistical error bars on the DØ  $e$  and  $\mu$  data in particular are extremely small and place severe constraints on the fit. The  $\chi^2/\text{dof}$  for the DØ lepton asymmetries are  $\approx 2$ , although the overall fit to the data in Fig. 11 is good. The earlier CDF electron data have larger errors and give a  $\chi^2/\text{dof} \approx 1$ . The fit to the extracted  $W$  asymmetries gives  $\chi^2/\text{dof} \approx 1$  for both the CDF and DØ data.

The stronger constraints from the charge asymmetry data leads to a significant reduction in the uncertainties on the  $d/u$  ratio, particularly at large values of  $x$ . This is illustrated in Fig. 13, which demonstrates the shrinking of the  $d/u$  uncertainty bands (which are shown here with a tolerance of  $T = 10$ ) with the successive addition of various data sets. Compared with the fit to DIS only data, in which the  $d/u$  ratio has very large uncertainties beyond  $x \approx 0.4$ , the addition of the lepton asymmetries leads to a reduction in  $d/u$  of more than a factor 2 at both small  $x$  and large  $x$ . (Addition of  $Z$  boson rapidity data [36, 37] has only modest impact on  $d/u$ .) Subsequent inclusion of the  $W$  asymmetries leads to a further halving of the uncertainty at  $x \approx 0.6 - 0.8$ , while having minimal effect on the errors at  $x \lesssim 0.4$ .

In fact, independent of the charge asymmetry data, a significant reduction in the  $d/u$

uncertainty at intermediate  $x$  values is already provided by the new Jefferson Lab data on the neutron to deuteron ratio  $F_2^n/F_2^d$  from the BONuS collaboration [85]. While the BONuS data have little or no effect at  $x \lesssim 0.3$ , the reduction in the  $d/u$  error at  $x \sim 0.5 - 0.6$  is almost as large as that from the lepton asymmetries. Curiously, the BONuS data have a slight preference for stronger nuclear corrections, in contrast to the lepton asymmetry data, although the tension is not significant. Using all the available data from DIS and  $W$  boson production, the central value of the extrapolated  $d/u$  ratio at  $x = 1$  is  $\approx 0.1$  at the input scale  $Q_0^2$ . The nuclear model dependence of the central values of the  $x \rightarrow 1$  limit of  $d/u$  is relatively weak, ranging from 0.08 for the WJC-1 wave function to 0.12 for the CD-Bonn model.

While the new charge asymmetry and BONuS  $F_2^n/F_2^d$  data provide significant constraints on the  $d/u$  ratio, the existing inclusive deuteron DIS data still play an important role in global analyses, as does the proper treatment of the nuclear corrections. If one were to fit  $F_2^d$  data without accounting for nuclear effects (assuming  $F_2^d = F_2^p + F_2^n$ ), the resulting  $d/u$  ratio would be strongly overestimated beyond  $x = 0.6$ , where the nuclear EMC ratio begins to deviate significantly from unity (see Fig. 8). This is illustrated in Fig. 14, where the CJ15  $d/u$  ratio is compared with the fit without nuclear corrections. This behavior can be understood from the shape of the  $F_2^d/F_2^N$  ratio Fig. 8 at large  $x$ , where the effect of the nuclear corrections is to increase the ratio above unity for  $x \gtrsim 0.6$ . Since  $F_2^d$  and  $F_2^p$  are fixed inputs, a larger  $F_2^d/F_2^N$  is generated by a smaller neutron  $F_2^n$  and hence a smaller  $d/u$  ratio. For example, the effect of the nuclear corrections is to shift the  $d/u$  ratio at  $x = 0.8$  from the ( $T = 10$ ) range  $\approx 0.1 - 0.3$  to  $\approx 0 - 0.2$  once the smearing and off-shell effects are included. Removing the deuterium data altogether increases the overall uncertainty band for  $x \gtrsim 0.7$ . Surprisingly, the deuteron data also reduce the  $d/u$  uncertainties slightly at smaller  $x$ ,  $0.05 \lesssim x \lesssim 0.15$ .

Effects on large- $x$  PDFs from nuclear corrections have also been investigated by several other groups in recent years [17, 19, 46, 47, 49, 78], and it is instructive to compare the CJ15 results on the  $d/u$  ratio with those analyses. The MMHT14 fit [17] uses a purely phenomenological nuclear correction for the combined effects of nuclear smearing and off-shell corrections, in contrast to our approach in which the (poorly understood) off-shell correction is fitted but the (better known) deuteron wave function correction is computed. Interestingly, the phenomenological MMHT14 nuclear correction has a qualitatively similar

shape to that found in our more microscopic estimate. For  $x \lesssim 0.7$  the MMHT14  $d/u$  uncertainty is comparable to that in CJ15 with  $T = 10$ , although for  $x \gtrsim 0.8$  the uncertainty diverges rapidly due to the different error evaluation methodologies used.

The JR14 analysis [49] uses similar smearing functions to those used in our fit, but does not include nucleon off-shell corrections. Furthermore, it uses the  $\Delta\chi^2 = 1$  criterion for the  $1\text{-}\sigma$  confidence level, based on statistical considerations alone, but introduces additional systematic uncertainties through the dependence of the fit on the input scale. The resulting uncertainty on  $d/u$  is larger than that in CJ15 in the intermediate- $x$  region, which may reflect the absence of the recent  $W$  and lepton asymmetry data in the JR14 fit. The range of  $d/u$  values extrapolated to  $x = 1$  is similar to the CJ15 band within errors (for  $T = 10$ ), although the form of the JR14 parametrization forces  $d/u \rightarrow 0$  at  $x = 1$ .

The CJ15 uncertainty band in Fig. 15 is also similar to that found in the CT14 global analysis [18], which does not apply any nuclear corrections to deuterium data, on the basis of the somewhat higher  $W^2$  cuts utilized. The CT14 analysis uses a parametrization based on Bernstein polynomials multiplying a common factor  $x^{a_1}(1-x)^{a_2}$ , and fixes the exponents  $a_2$  to the same for the  $u$ - and  $d$ -quark PDFs, thereby allowing finite values of the  $d/u$  ratio in the  $x \rightarrow 1$  limit. The results of the two analyses largely overlap over much of the  $x$  range, with the CT14 distributions being slightly above the CJ15 error band at  $x \gtrsim 0.6$ . This is reminiscent of the higher  $d/u$  ratio observed in Fig. 14 when the nuclear corrections are switched off.

...[ANYTHING ELSE TO BE SAID ABOUT  $d/u$  COMPARISONS/ OTHER ANALYSES?]

## V. CONCLUSION

[XXX editing]

In this paper we have ...



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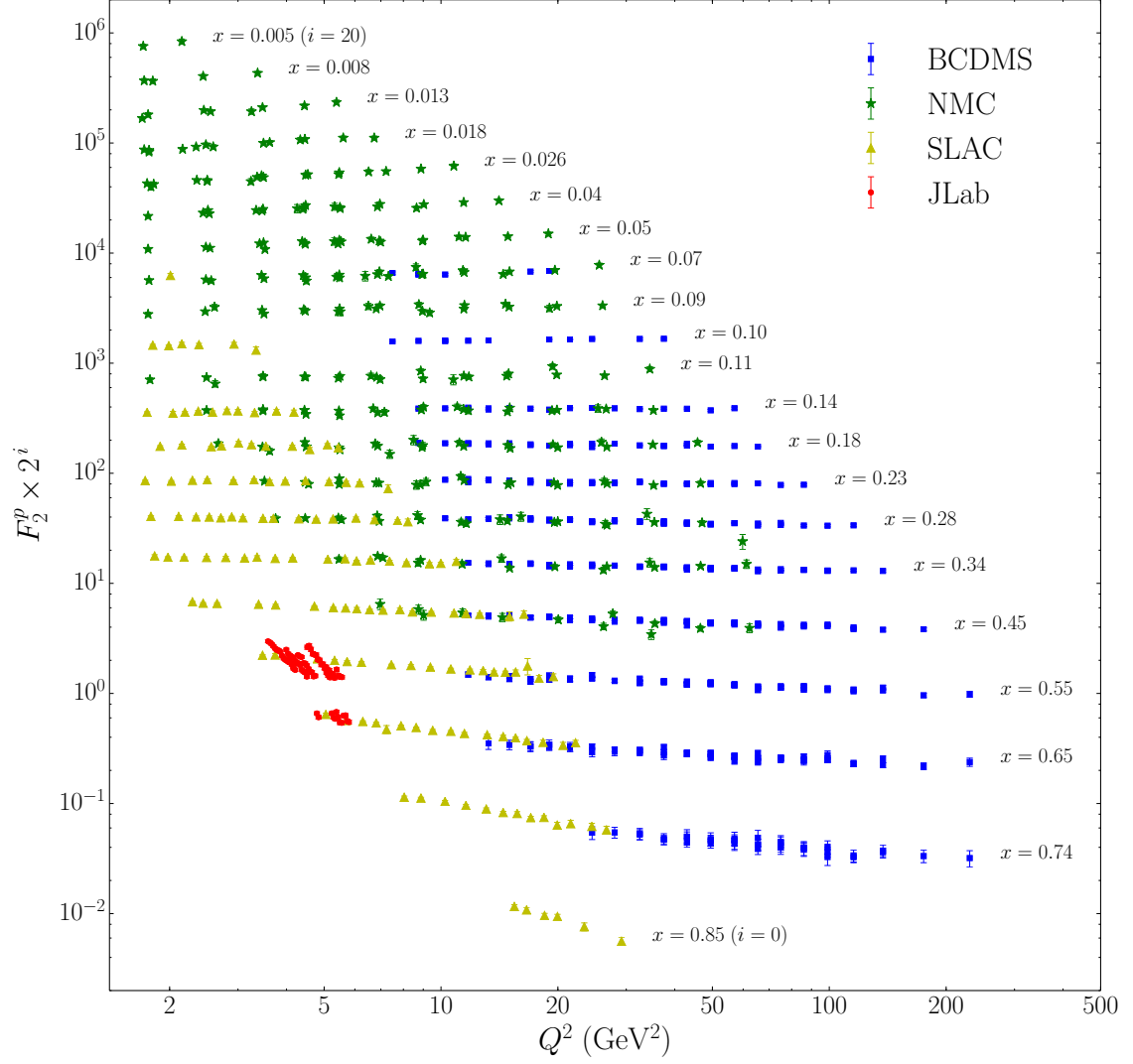


FIG. 1: Comparison of proton  $F_2^p$  structure function data from BCDMS [23], NMC [24], SLAC [26] and JLab [27] with the CJ15 NLO fit, for various  $Q^2$  and  $x$ . The data at fixed  $x$  values have been scaled by a factor  $2^i$ , from  $i = 0$  for  $x = 0.85$  to  $i = 20$  for  $x = 0.005$  in steps of  $i = 1$ .

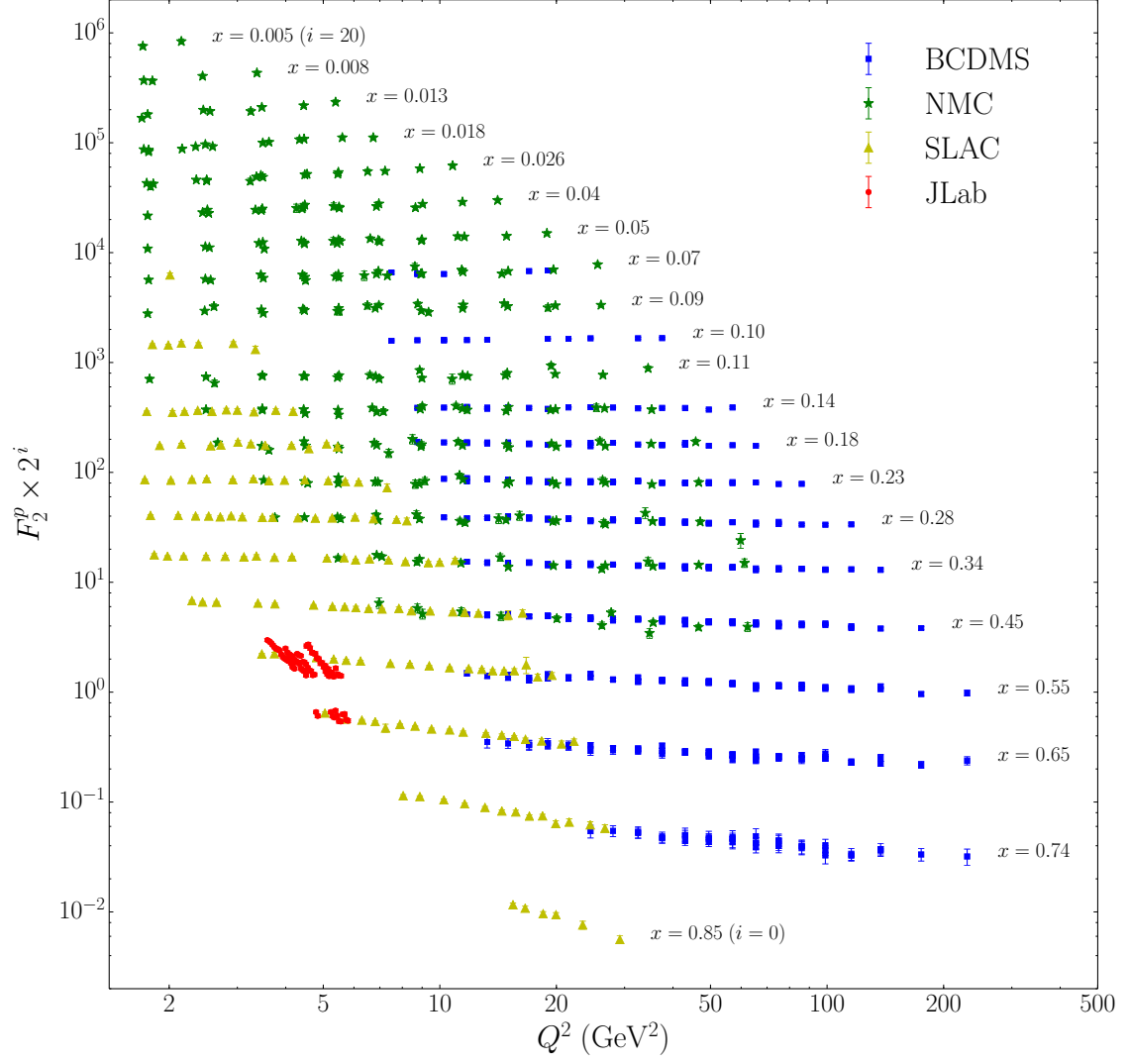


FIG. 2: [PLACEHOLDER FIGURE]... As for Fig. 1, but for the deuteron  $F_2^d$  structure function, illustrating data from BCDMS [23], SLAC [26] and JLab [27]. ...[WHAT TO DO WITH NMC  $F_2^d/F_2^p$  ?]...

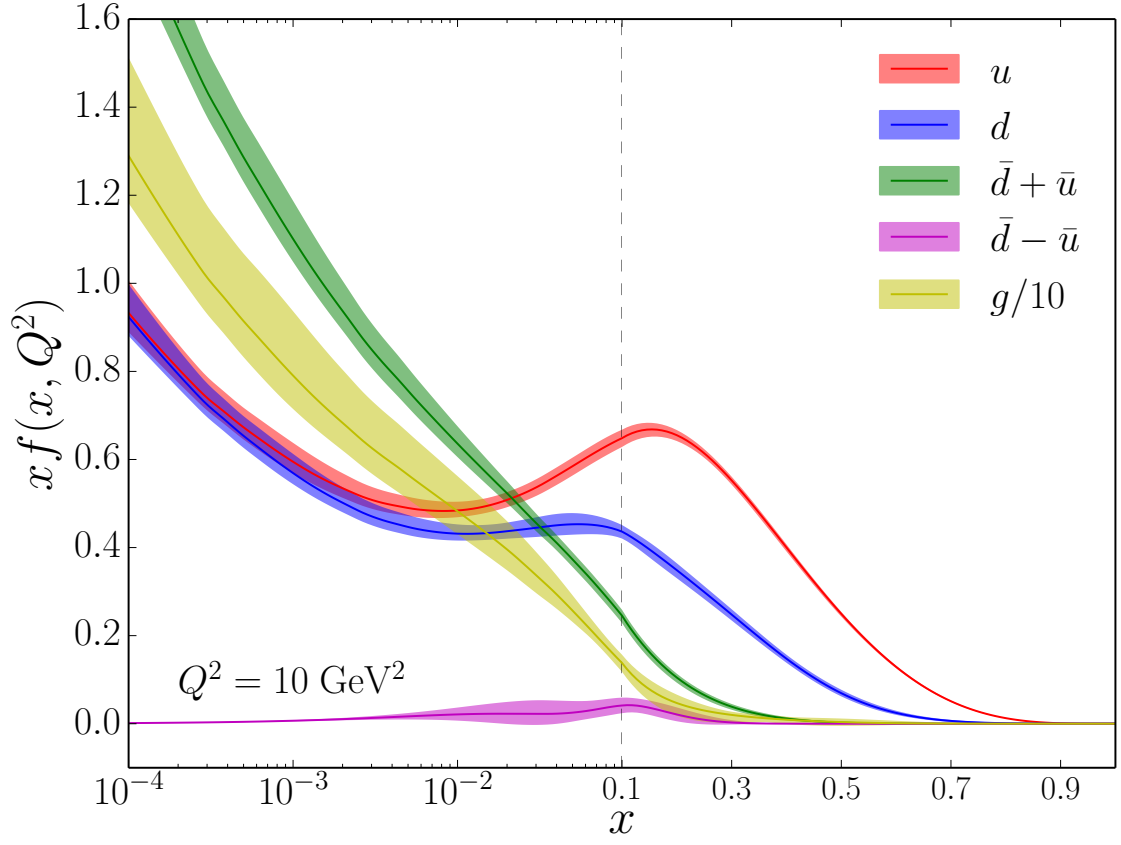


FIG. 3: Comparison of CJ15 PDFs for different flavors ( $u, d, \bar{d} + \bar{u}, \bar{d} - \bar{u}$  and  $g/10$ ) at a scale  $Q^2 = 10 \text{ GeV}^2$ , for  $T = 1$ . Note the combined logarithmic/linear scale along the  $x$ -axis.

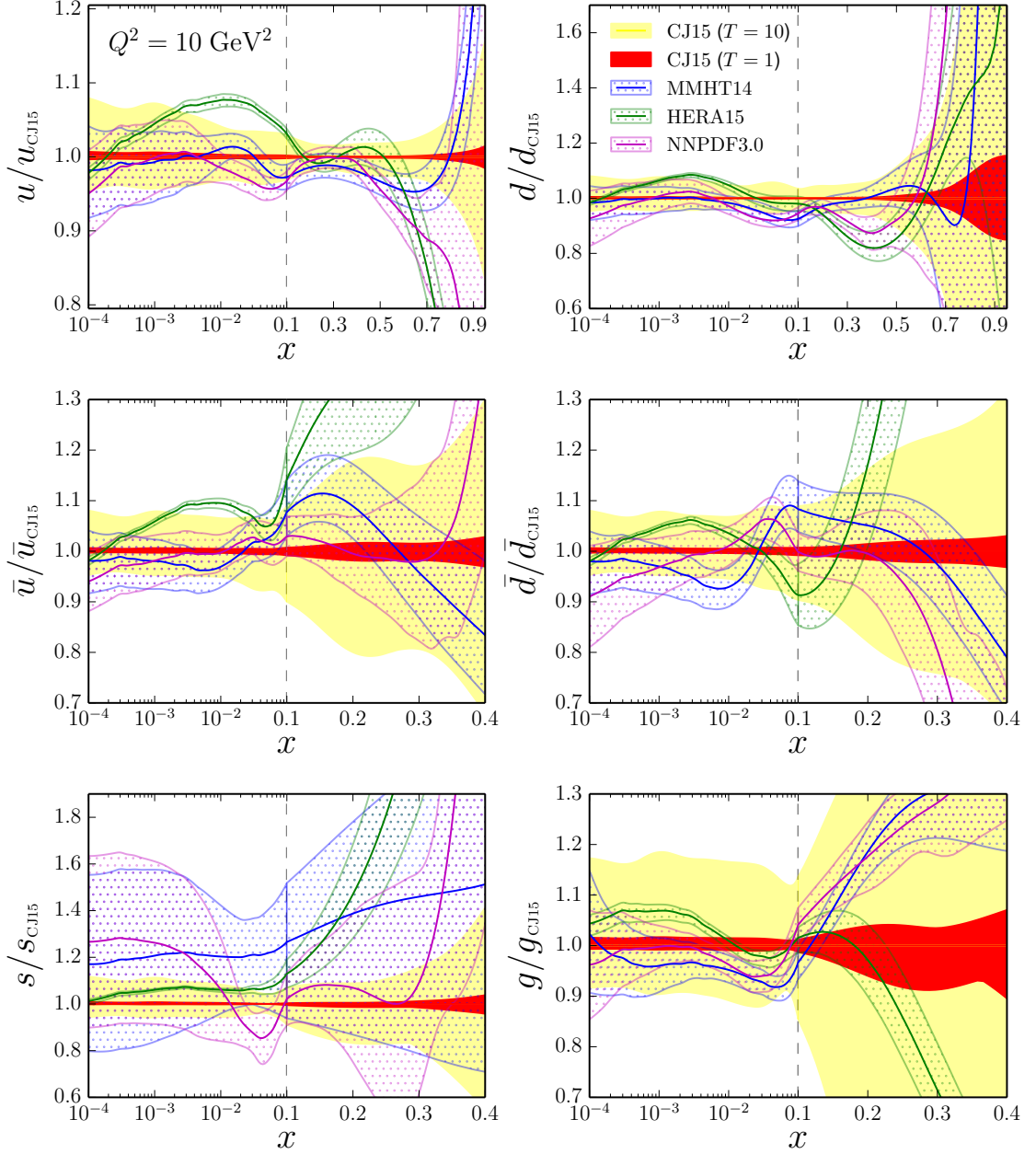


FIG. 4: Ratio of PDFs to the CJ15 central values for various PDF sets: CJ15 for tolerance  $T = 1$  (red) and  $T = 10$  (yellow), MMHT14 [17] (blue), HERAPDF15 [22] (green), and NNPDF3.0 [20] (magenta). Note the different scales on the vertical axes used for different flavors.



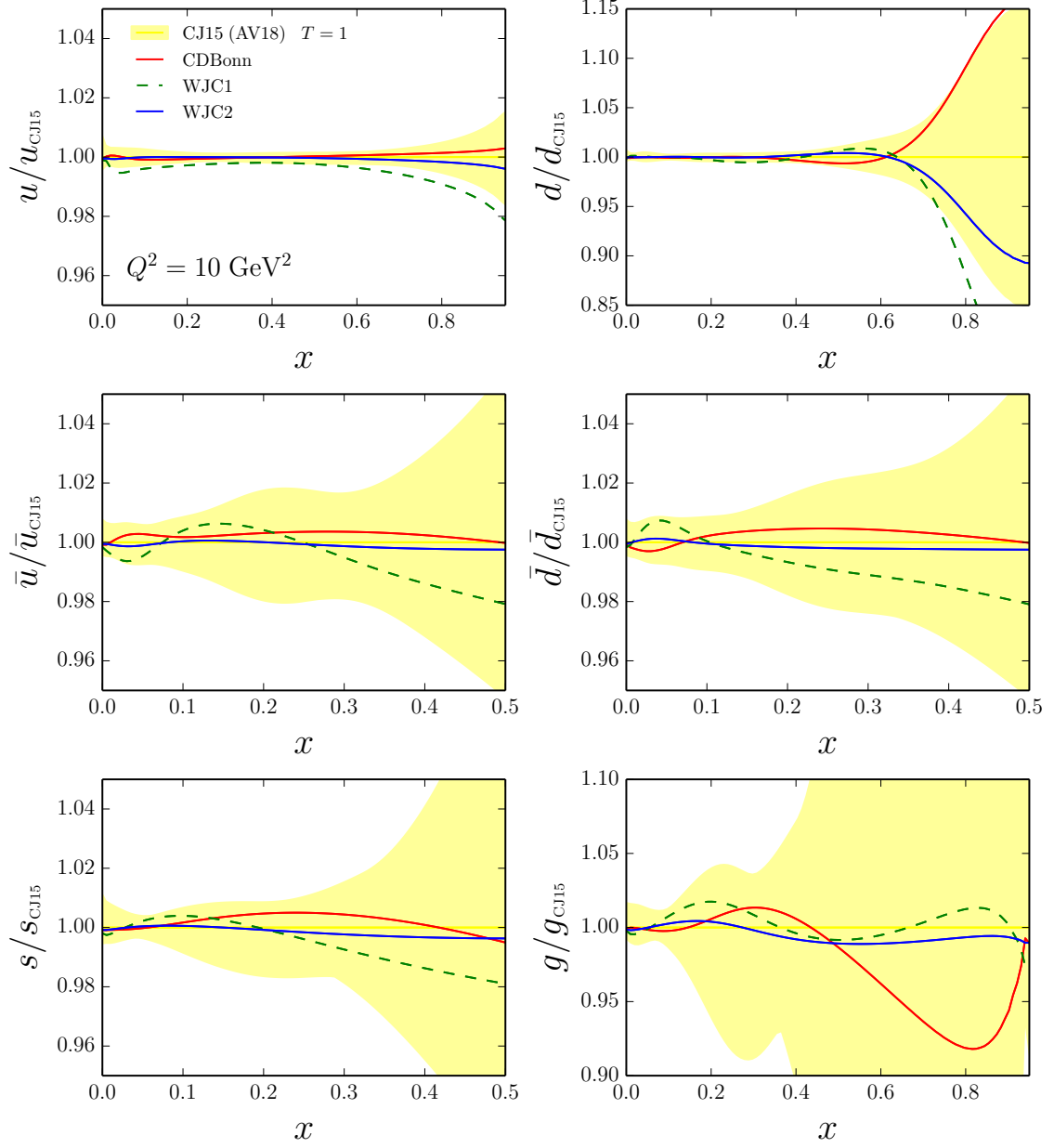


FIG. 5: Ratio of PDFs fitted using various deuteron wave function models to the CJ15 PDFs (which use the AV18 deuteron wave function): CD-Bonn (red solid lines), WJC-1 (green dashed lines), WJC-2 (blue solid lines). The CJ15 PDFs (yellow band) are shown for  $T = 1$ , and the off-shell parametrization (12) is used for all cases. Note the different scale on the vertical axes for the  $d$ -quark and gluon distributions.

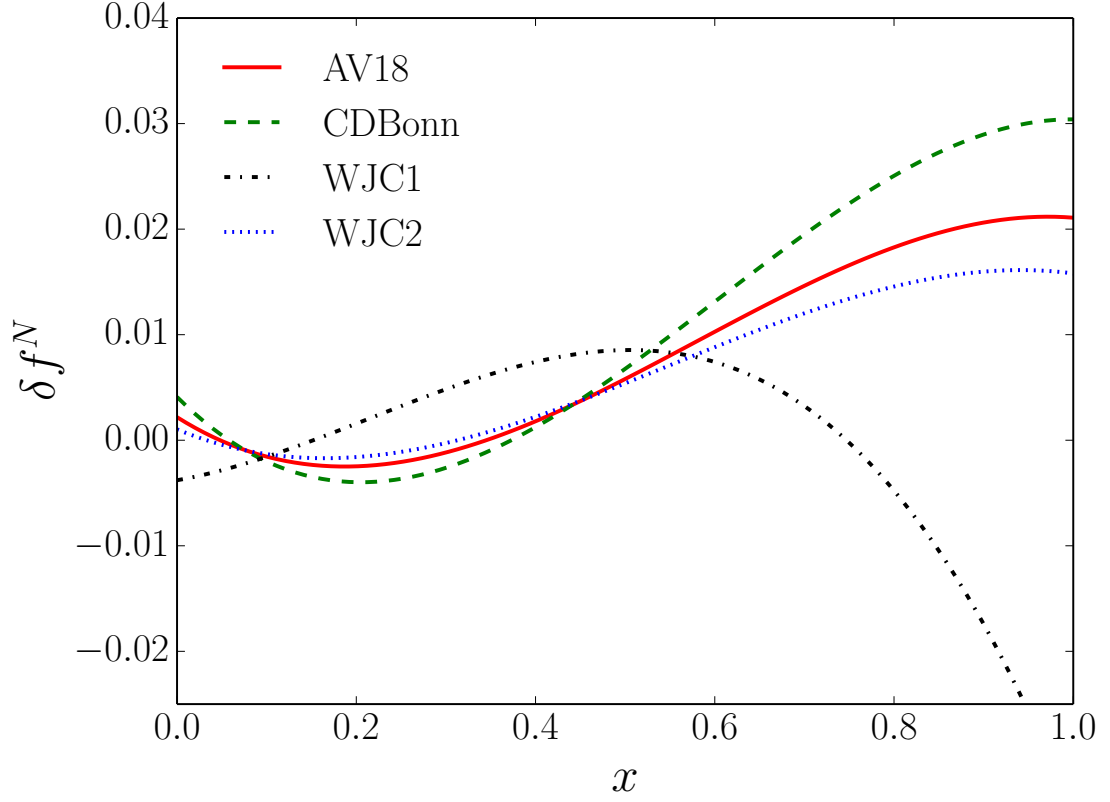


FIG. 6: Fitted nucleon off-shell correction  $\delta f^N$  for the parametrization in Eq. (12), using the AV18 (solid red line), CD-Bonn (dashed green line), WJC-1 (dot-dashed black line) and WJC-2 (dotted blue line) wave functions.

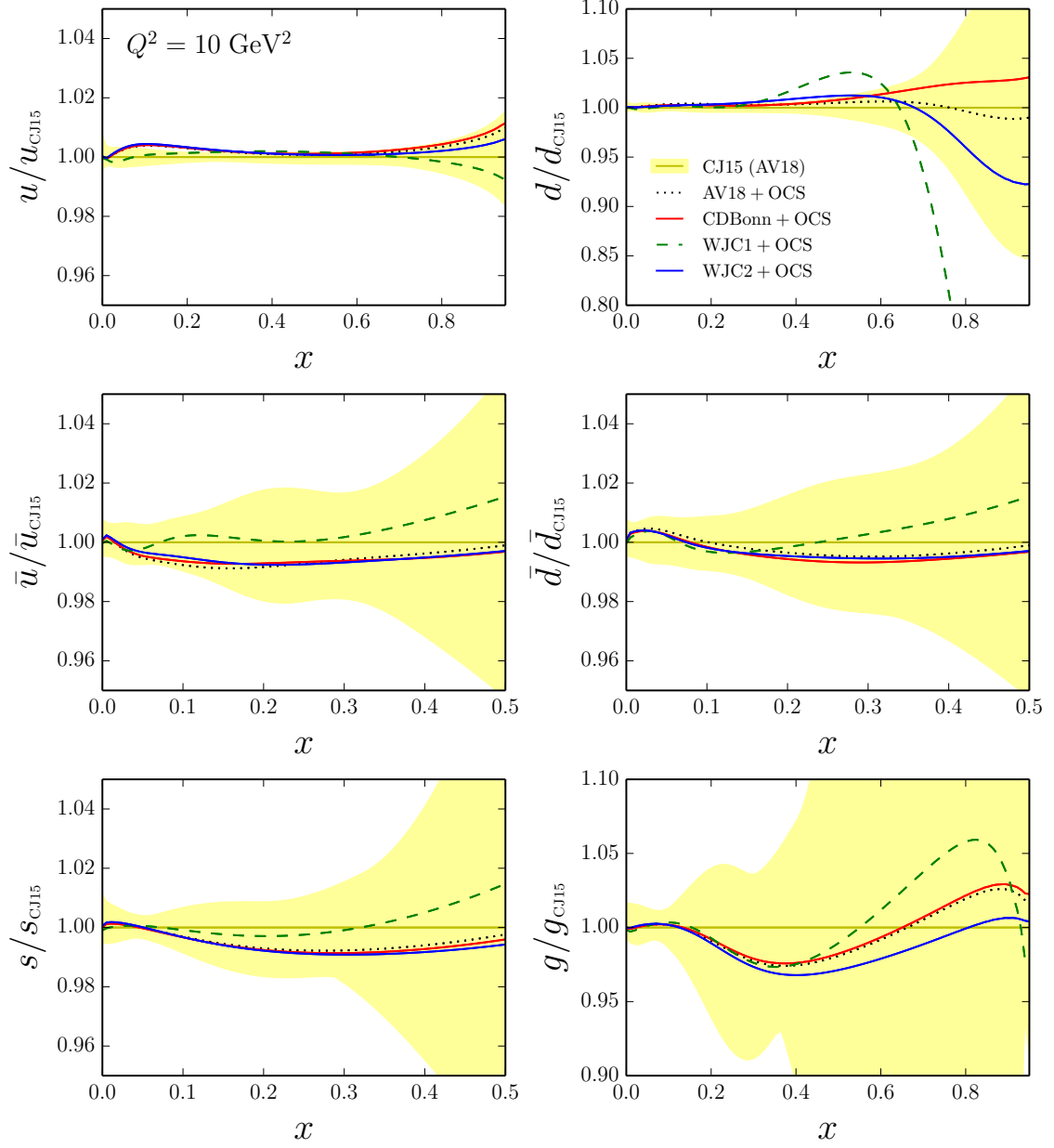


FIG. 7: Ratio of PDFs computed using the off-shell covariant spectator (OCS) model and different deuteron wave functions to the CJ15 PDFs (which use the off-shell parametrization (12) and the AV18 deuteron wave function): OCS model with the AV18 wave function (black dotted lines), CD-Bonn (red solid lines), WJC-1 (green dashed lines), and WJC-2 (blue solid lines). Note the different scale on the vertical axes for the  $d$ -quark and gluon distributions.

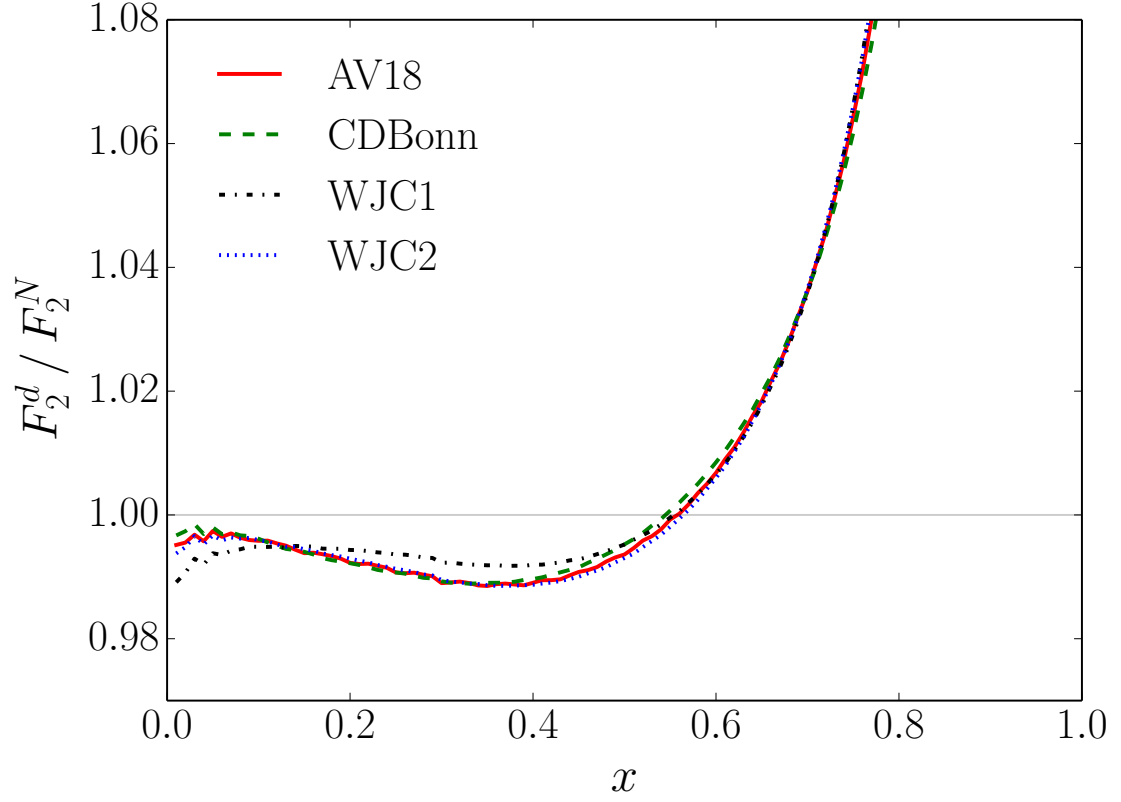


FIG. 8: Ratio of deuteron to isoscalar nucleon structure functions  $F_2^d/F_2^N$  for different deuteron wave function models at  $Q^2 = 10 \text{ GeV}^2$ . ...[SMOOTH CURVES]...

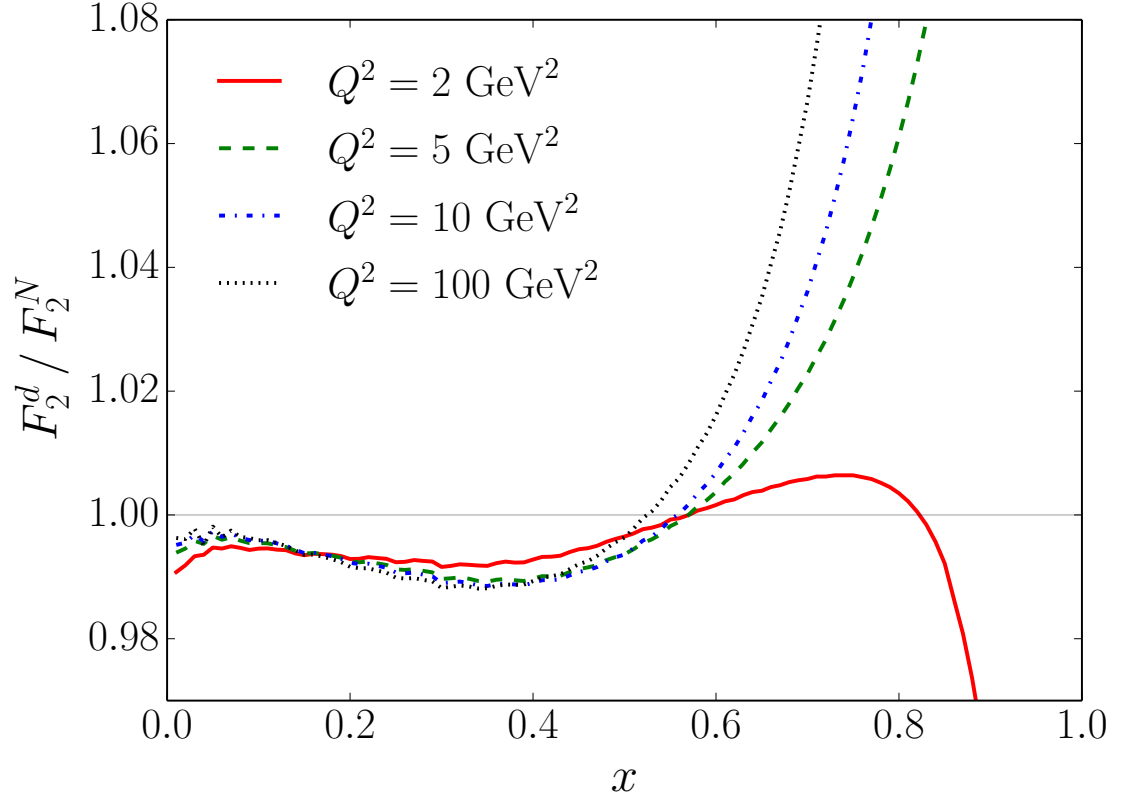


FIG. 9: Ratio of deuteron to isoscalar nucleon structure functions  $F_2^d/F_2^N$  computed from the CJ15 PDFs for different values of  $Q^2$ . ...[SMOOTH CURVES]...

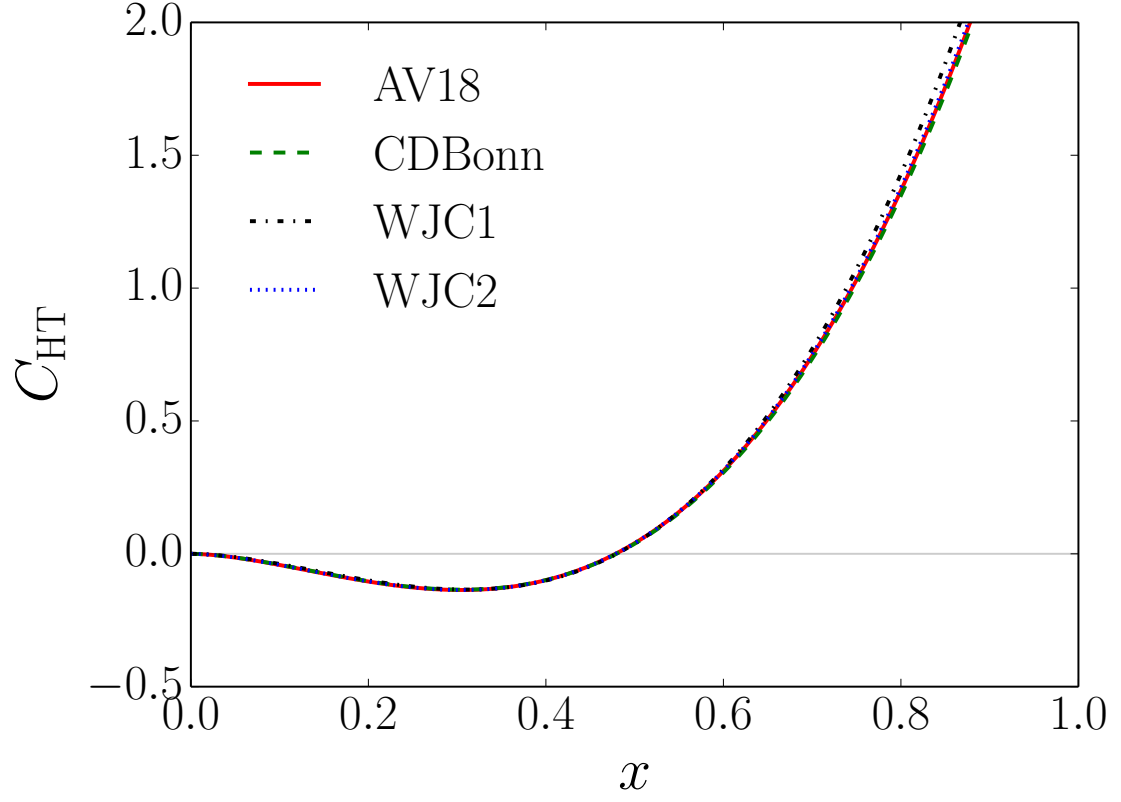


FIG. 10: Fitted higher twist function  $C_{\text{HT}}$  from Eq. (6), in units of  $\text{GeV}^2$ , for different deuteron wave function models.

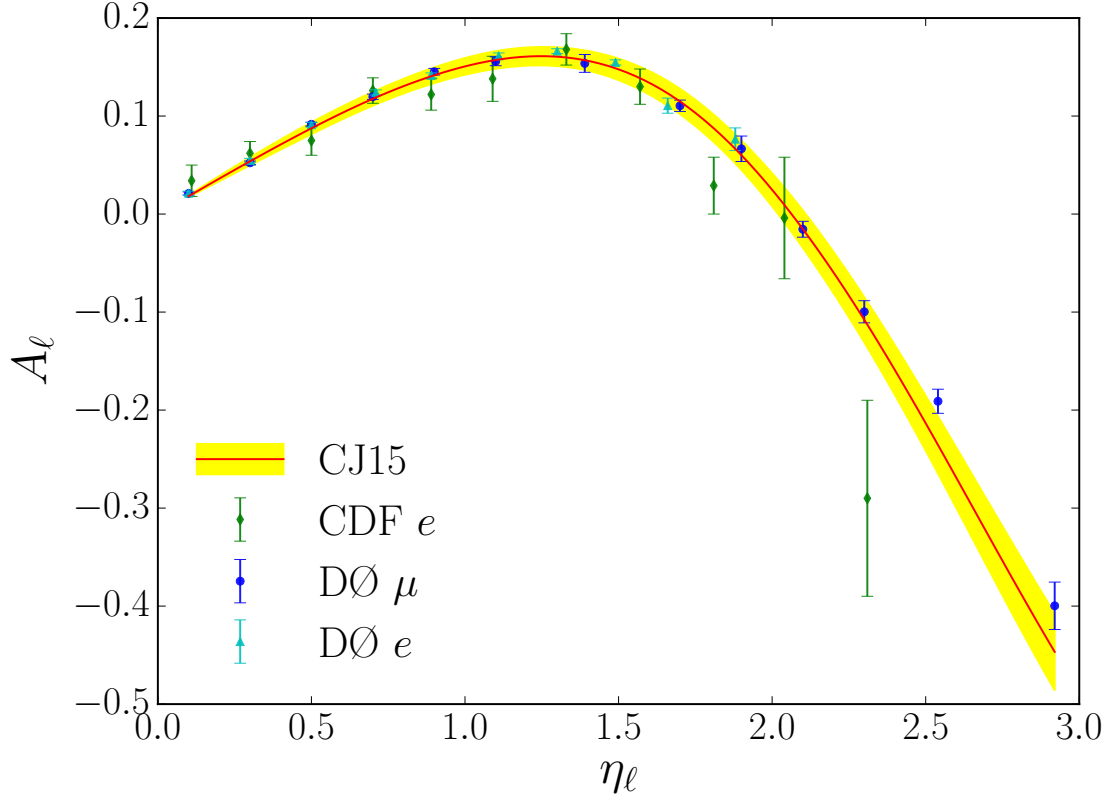


FIG. 11: Lepton charge asymmetry  $A_\ell$  from  $p\bar{p} \rightarrow WX \rightarrow \ell\nu X$  as a function of the lepton pseudorapidity  $\eta_\ell$  from CDF electron (green diamonds) [31], and DØ muon (blue circles) [32] and electron (cyan triangles) [33] data compared with the CJ15 fit.

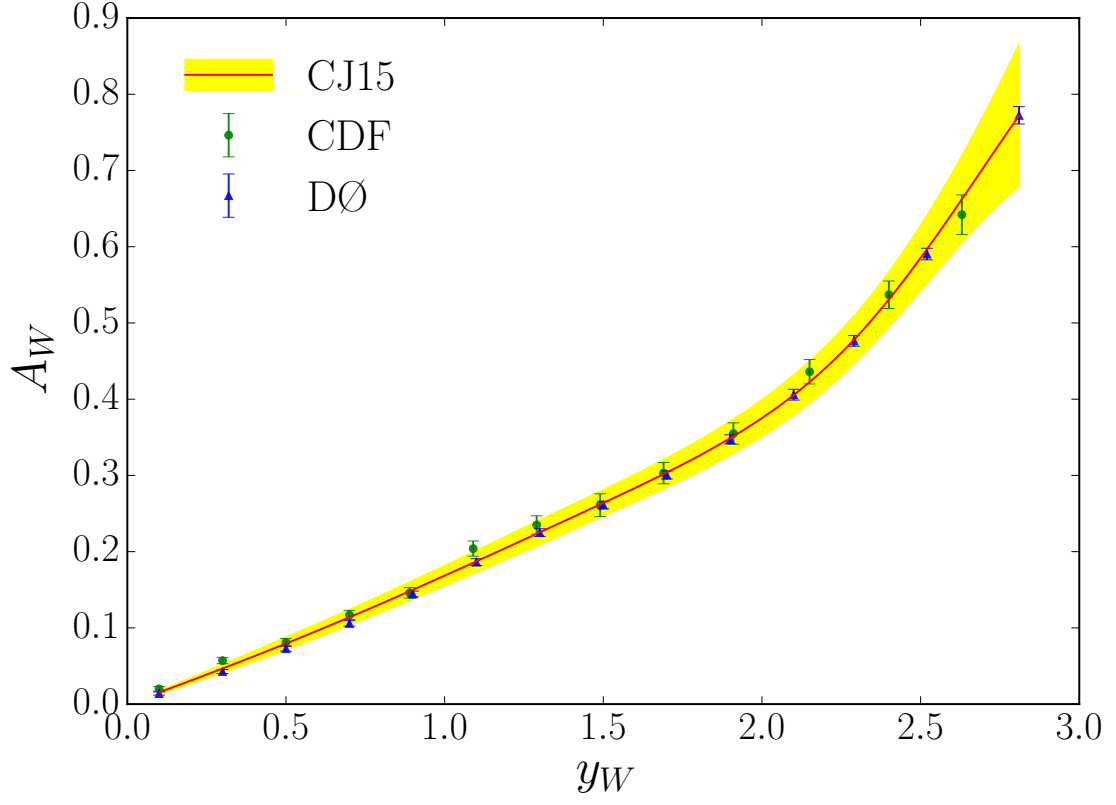


FIG. 12:  $W$  boson charge asymmetry  $A_W$  from  $p\bar{p} \rightarrow WX$  as a function of the  $W$  boson rapidity  $y_W$  for CDF (green circles) [34] and DØ (blue triangles) [35] data compared with the CJ15 fit.



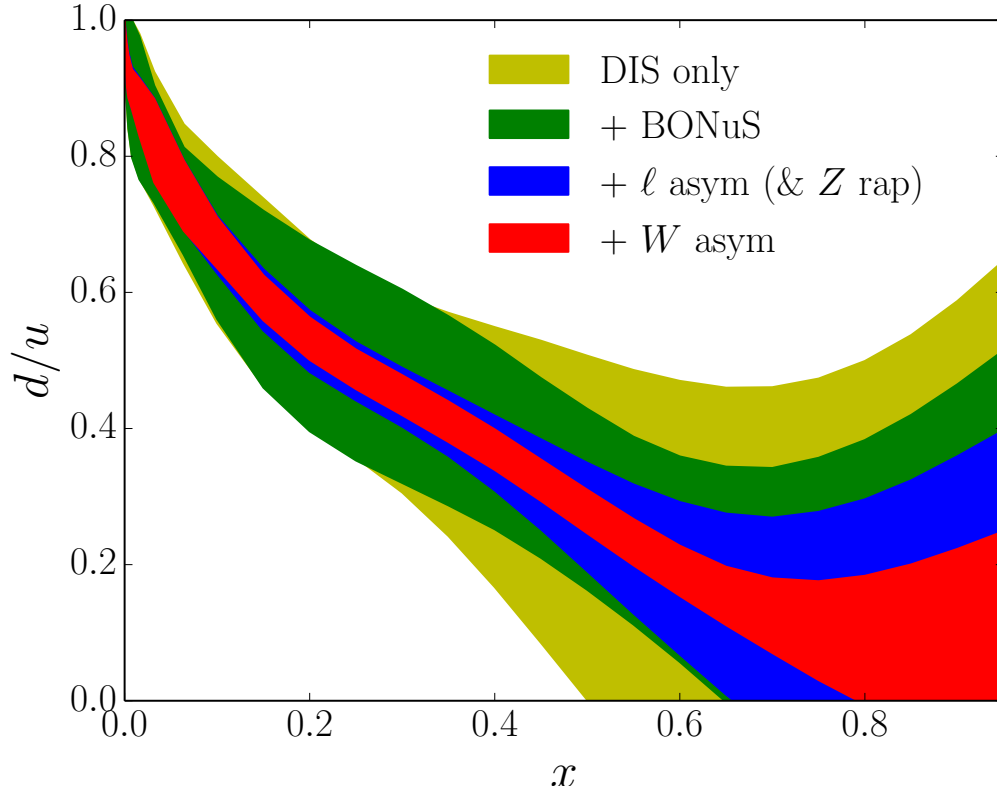


FIG. 13: Impact of various data sets on the  $d/u$  ratio at  $Q^2 = 10 \text{ GeV}^2$ . The uncertainty band is largest for the DIS only data (yellow band), and decreases with the successive addition of JLab  $F_2^n/F_2^d$  [85] data (green band), lepton asymmetry [31–33] (and  $Z$  rapidity [36, 37]) data (blue band), and  $W$  boson asymmetry data [34, 35] (red band). ...[FIGURE NEEDS SMOOTHING]...

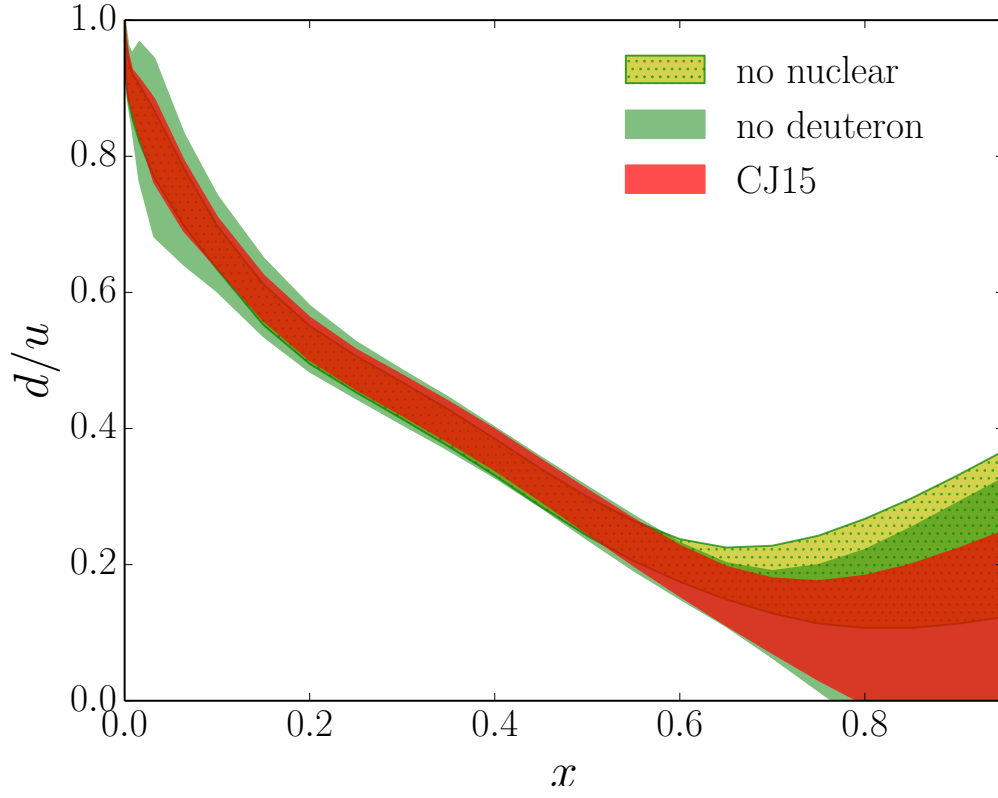


FIG. 14: Impact on the CJ15  $d/u$  ratio (red band) of removing the deuterium nuclear corrections (yellow shaded band), and omitting the deuterium data (green band). ...[FIGURE NEEDS SMOOTHING]...

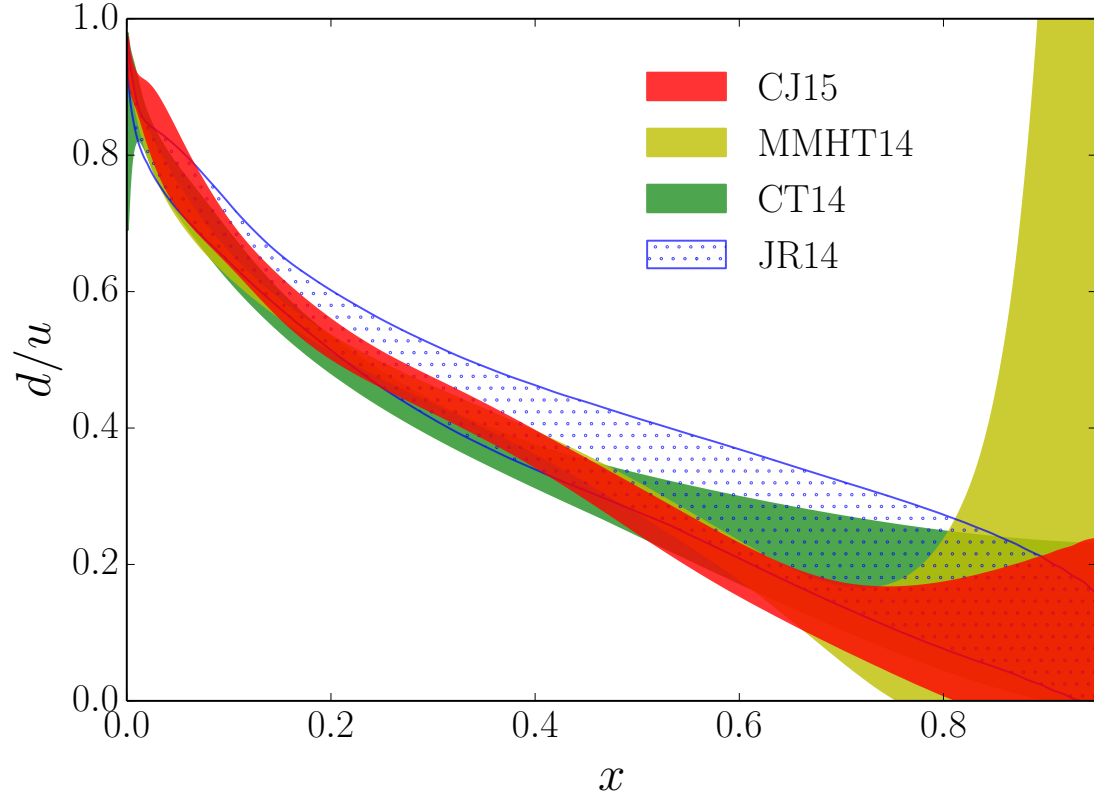


FIG. 15: Comparison of the  $d/u$  ratio at  $Q^2 = 10 \text{ GeV}^2$  for different PDF parametrizations: CJ15 (red band), MMHT14 [17] (yellow band), CT14 [18] (green band), and JR14 [49] (blue dotted band).

TABLE I: Data sets used in the CJ15 NLO global analysis (which uses the AV18 deuteron wave function and off-shell parametrization in Eq. (12), with the corresponding number of data points and the respective  $\chi^2$  values for each set. For comparison the  $\chi^2$  for the LO fit and for an NLO fit with the OCS off-shell model are also given. ...[remove LO & OCS entries?]...

	experiment	# points	$\chi^2$		
			NLO	LO	NLO (OCS)
DIS $F_2$	BCDMS ( $p$ ) [23]	351	437	432	435
	BCDMS ( $d$ ) [23]	254	294	299	289
	NMC ( $p$ ) [24]	275	407	414	406
	NMC ( $d/p$ ) [25]	189	172	180	173
	SLAC ( $p$ ) [26]	564	435	496	436
	SLAC ( $d$ ) [26]	582	372	417	386
	JLab ( $p$ ) [27]	136	166	164	166
	JLab ( $d$ ) [27]	136	124	127	123
	JLab ( $n/d$ ) [85]	191	217	224	215
DIS $\sigma$	HERA (NC $e^-p$ ) [28]	145	112	161	113
	HERA (NC $e^+p$ ) [28]	408	541	872	541
	HERA (CC $e^-p$ ) [28]	34	19	19	19
	HERA (CC $e^+p$ ) [28]	34	31	33	32
Drell-Yan	E605 ( $p\text{Cu}$ ) [45]	119	93	104	93
	E866 ( $pp$ ) [29]	121	139	155	139
	E866 ( $pd$ ) [29]	129	144	191	144
	E866 ( $pd/pp$ ) [30]	12	9	9	8
W/charge asymmetry	CDF ( $e$ ) [31]	11	12	11	12
	DØ ( $\mu$ ) [32]	10	20	21	29
	DØ ( $e$ ) [33]	13	27	56	22
	CDF ( $W$ ) [34]	13	15	12	15
	DØ ( $W$ ) [35]	14	16	47	16
$Z$ rapidity	CDF ( $Z$ ) [36]	28	27	79	28
	DØ ( $Z$ ) [37]	28	16	23	16
jet	CDF (run 2) [39]	72	15	22	15
	DØ (run 2) [41]	110	21	46	22
$\gamma$ +jet	DØ 1 [42]	16	6	20	6
	DØ 2 [42]	16	15	40	15
	DØ 3 [42]	12	25	35	25
	DØ 4 [42]	12	13	77	13
total		4035	<b>3941</b>	4786	3952
total + norm			<b>3950</b>	4918	3961
$\chi^2/\text{dof}$			<b>0.979</b>	1.219	0.982

TABLE II: Leading twist parameter values for the  $u_v$ ,  $d_v$ ,  $\bar{d} + \bar{u}$ ,  $\bar{d} - \bar{u}$  and  $g$  PDFs [Eq. (1)] from the CJ15 NLO analysis at the initial scale  $Q_0$  GeV. Parameters without errors have been fixed. For the strange to non-strange sea quark PDF ratio [Eq. (4)], we take  $\kappa = 0.4$ . (The parameter values are given to 5 significant figures to avoid rounding errors.) ...[make neater/reduce sig. figs?]

parameter	$u_v$	$d_v$	$\bar{d} + \bar{u}$	$\bar{d} - \bar{u}$	$g$
$a_0$	2.3585	23.233	$0.14121 \pm 0.0050459$	35712	46.706
$a_1$	$0.60985 \pm 0.020299$	$1.1387 \pm 0.034586$	$-0.21785 \pm 0.0039454$	$3.9867 \pm 0.049301$	$0.61586 \pm 0.038277$
$a_2$	$3.5377 \pm 0.011405$	$6.6180 \pm 0.15977$	$8.4003 \pm 0.14833$	$20.289 \pm 0.66322$	$6.2335 \pm 1.1222$
$a_3$	0	$-3.5743 \pm 0.090782$	0	17	$-3.2703 \pm 0.16746$
$a_4$	$3.5169 \pm 0.42791$	$4.9133 \pm 0.14586$	$16.055 \pm 1.1403$	$49.881 \pm 7.1398$	$3.0338 \pm 0.31300$
$b$	—	$0.0042424 \pm 0.00070691$	—	—	—
$c$	—	2	—	—	—

TABLE III: Parameter values for the nucleon off-shell [Eq. (12)] and higher twist [Eq. (6)] corrections to  $F_2$  from the CJ15 NLO analysis at the input scale  $Q_0^2$ . The off-shell parameters are fitted using the AV18 deuteron wave function. Parameters without errors have been fixed. (The parameter values are given to 5 significant figures to avoid rounding errors.)

parameter	value
$C_0$	$0.098222 \pm 0.028518$
$x_0$	$0.34487 \pm 0.91982$
$x_1$	0.048
$h_0$	$-3.0094 \pm 0.24080$
$h_1$	$1.7526 \pm 0.10135$
$h_2$	$-2.0895 \pm 0.026853$