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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 W-boson asymmetry data from Fermilab, both of which significantly reduce the uncertainty on the d/u ratio at large values of x. We also review evidence for a sign change in $\bar{d} - \bar{u}$ at large x that has been claimed in recent phenomenological analyses.

I. INTRODUCTION

... 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

• S-ACOT scheme for heavy quarks

• LO fit

• α_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

...[OLD TEXT]...

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

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

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,

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

with b and c as two additional parameters. The result of this modification is that $d_v/u_v \to a_0^{d_v}\, b$ as $x \to 1$, 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.

• New parametrization for $\bar{d} - \bar{u}$ ... avoids negative PDFs? ...

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

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

which ensures that in the limit $x \to 1$ one has $\bar{d}/\bar{u} \to 1$. 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 $x \to 1$ limit. The $\bar{d}/\bar{u} \to 1$ limit is what would be expected from perturbative QCD, while the $\bar{d}/\bar{u} \to 0$ limit may arise if the trend in $x \gtrsim 0.3$ points from the E866 experiment [28] were to continue to larger x.

B. Heavy quarks

• Implementation of S-ACOT scheme.

C. $1/Q^2$ corrections

• For target mass corrections, use of OPE (G-P); ... comparisons with EFP, series expansion; ... in practice doesn't matter!(?)

• For other subleading $1/Q^2$ corrections, such as higher twist and other residual power corrections (

• ... anything different to CJ12??

$$F_2(x, Q^2) = F_2^{\rm LT}(x, Q^2)\left(1 + \frac{C(x)}{Q^2}\right), \tag{4}$$

where $F_2^{\rm LT}$ 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 $C(x) = a_{\rm HT}\, x^{b_{\rm HT}}(1 + c_{\rm HT}x)$, assuming it to be isospin independent (see, however, Refs. [59–62]).

D. Nuclear corrections

• The analysis includes nuclear corrections for deuterium account for nucleon Fermi motion and nuclear binding effects, which are implemented using nuclear smearing functions, as well as rescattering effects mediated by Pomeron and meson exchange mechanisms which give rise to shadowing at small $x \lesssim 0.1$ and a small amount of antishadowing at $x \sim 0.1$. For the shadowing and antishadowing corrections, the model of Ref. [1] is used (see also Refs. [2, 3]), although the effects of these is negligible in our analysis.

The implementation of the nuclear smearing

1. *Nuclear smearing*

Since nucleons bound in a nucleus are not free, the nuclear structure function deviates from a simple sum of free proton and neutron structure functions, especially at large x where the effects of Fermi motion, nuclear binding, and nucleon off-shellness are most prominent. In the nuclear impulse approximation the structure function of the deuteron d can be expressed as a generalized convolution of the bound nucleon structure function and a momentum distribution $f_{N/d}$ of nucleons in the deuteron [63, 64],

$$q^d(x,Q^2) \;=\; \int \frac{dz}{z} dp^2\, f_{N/d}(z,p^2)\, \widetilde{q}^N(x/z,p^2,Q^2), \tag{5}$$

where $f_{N/d}(z,p^2)$ gives the (light-cone) distribution of nucleons in the deuteron for a given nucleon momentum fraction in the deuteron $z = (M_d/M)(p\cdot q/p_d\cdot q)$ and nucleon virtuality p^2, where p and p_d are the four-momenta of the nucleon and deuteron, respectively, and M_d is the deuteron mass. The function $\widetilde{q}^N$ is the off-shell nucleon structure function, and a sum over the nucleons $N = p, n$ is implied. ... The function $\widetilde{q}^N$ includes $1/Q^2$ corrections, such as TMCs and higher twist effects. ... Expanding the off-shell nucleon structure function about the on-shell limit, one finds [65]

$$\widetilde{q}^N(x,p^2,Q^2) \;=\; q^N(x,Q^2)\left(1 + \frac{p^2 - M^2}{M^2}\delta f^N(x,Q^2)\right), \tag{6}$$

where the coefficient of the off-shell term is

$$\delta f^N(x,Q^2) \;=\; \frac{\partial \ln \widetilde{q}^N(x,p^2,Q^2)}{\partial \ln p^2}\bigg|_{p^2=M^2}, \tag{7}$$

and the $\widetilde{q}^N$ includes the parametrized higher twist corrections of Eq. (4). The on-shell term leads to the standard on-shell convolution representation for the nuclear structure function, while the off-shell term can be evaluated as an additive correction, $q^d = q^{d\,(\mathrm{on})} + q^{d\,(\mathrm{off})}$, where

$$q^{d\,(\mathrm{on})}(x,Q^2) \;=\; \int \frac{dz}{z} f^{(\mathrm{on})}(z)\, q^N(x/z,Q^2), \tag{8a}$$

$$q^{d\,(\mathrm{off})}(x,Q^2) \;=\; \int \frac{dz}{z} f^{(\mathrm{off})}(z)\, \delta f^N(x/z,Q^2)\, q^N(x/z,Q^2). \tag{8b}$$

The on-shell and off-shell smearing functions $f^{(\mathrm{on})}$ and $f^{(\mathrm{off})}$ are taken to be the same for the proton and neutron, and are given by [67]

$$f^{(\mathrm{on})}(z) \;=\; \int dp^2\, f_{N/d}(z,p^2), \tag{9a}$$

$$f^{(\mathrm{off})}(z) \;=\; \int dp^2\, \frac{p^2-M^2}{M^2}\, f_{N/d}(z,p^2). \tag{9b}$$

The momentum distributions, or "smearing functions", $f^{(\mathrm{on})}$ and $f^{(\mathrm{off})}$, are computed in the weak binding approximation (WBA) in terms of the deuteron wave function, and include the effects of nuclear binding and Fermi motion [65, 66]. At $Q^2 \to \infty$ the on-shell smearing function $f^{(\mathrm{on})}$ has a simple probabilistic interpretation in terms of the light-cone momentum fraction $z \approx (M_d/M)(p^+/p_d^+)$ of the deuteron carried by the struck nucleon, while at finite Q^2 it depends in addition on the parameter $\rho^2 = 1 + 4x^2M^2/Q^2$, which characterizes the deviation from the Bjorken limit.

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 [68], CD-Bonn [69] and the relativistic WJC-1 and WJC-2 [70] 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.

• The off-shell nucleon correction $\delta^{(\rm off)} q^d$ is somewhat more model dependent, but several quark model based estimates of this have been made in the literature [65, 71, 72].

• ... 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 λ), or in phenomenological fit.

• In this analysis, we explore the possibility of antishadowing in the deuteron, suggested in the global nuclear analysis of KP [65], 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 δf^N, we use the same parametrization as in Ref. [65],

$$\delta f^N \;=\; C_N (x - x_0)(x - x_1)(x - x_2), \tag{10}$$

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

$$\int_0^1 dx\, \delta f^N(x)\, (q(x) - \bar{q}(x)) \;=\; 0. \tag{11}$$

E. PDF Errors

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

III. DATA

• The CJ15 PDFs are obtained by fitting to a global database of 4037 data points from a variety of high energy scattering processes. ...which new data sets have been included (which haven't?)

• In Table I ...

IV. RESULTS

A. CJ15 PDFs

The CJ15 PDFs are displayed in Fig. 1 at a scale of $Q^2 = 10$ 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.

B. d/u ratio

C. $\bar{d} - \bar{u}$ asymmetry

... Connection with Gottfried sum ... Peng et al. paper ...

V. CONCLUSION

Acknowledgments

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TABLE I: Data sets and number of data points used in the CJ15 global fit, and the χ^2 values for each data set.

	Experiment	Ref.	# points	χ^2 CJ12min	χ^2 CJ12mid	χ^2 CJ12max
DIS F_2	BCDMS (p)	[22]	351	434	436	437
	BCDMS (d)	[22]	254	294	297	302
	NMC (p)	[23]	275	434	432	430
	NMC (d/p)	[24]	189	179	177	182
	SLAC (p)	[25]	565	456	455	456
	SLAC (d)	[25]	582	394	388	396
	JLab (p)	[26]	136	170	169	170
	JLab (d)	[26]	136	124	125	126
	JLab $(n) BONuS$	[82]	xxx	xxx	xxx	xxx
DIS σ	HERA (NC e^-)	[27]	145	117	117	118
	HERA (NC e^+)	[27]	384	595	596	596
	HERA (CC e^-)	[27]	34	19	19	19
	HERA (CC e^+)	[27]	34	32	32	32
Drell-Yan	E866 (p)	[28]	184	220	221	221
	E866 (d)	[28]	191	297	307	306
W asymmetry	CDF 1998 (ℓ)	[29]	11	14	16	18
	CDF 2005 (ℓ)	[30]	11	11	11	10
	DØ 2008 (ℓ)	[31]	10	4	4	4
	DØ 2008 (e)	[32]	12	40	36	34
	CDF 2009 (W)	[33]	13	20	25	41
Z rapidity	CDF (Z)	[34]	28	29	27	27
	DØ (Z)	[35]	28	16	16	16
jet	CDF run 1	[36]	33	52	52	52
	CDF run 2	[37]	72	14	14	14
	DØ run 1	[38]	90	21	20	19
	DØ run 2	[39]	90	19	19	20
γ+jet	DØ 1	[40]	16	6	6	6
	DØ 2	[40]	16	13	13	12
	DØ 3	[40]	12	17	17	17
	DØ 4	[40]	12	17	16	17
	TOTAL		3958	4059	4055	4096
	TOTAL + norm			4075	4074	4117

Appendix A: Parameter values

In this appendix we list the initial parameter values and their errors for the three sets of PDFs discussed in the text.....

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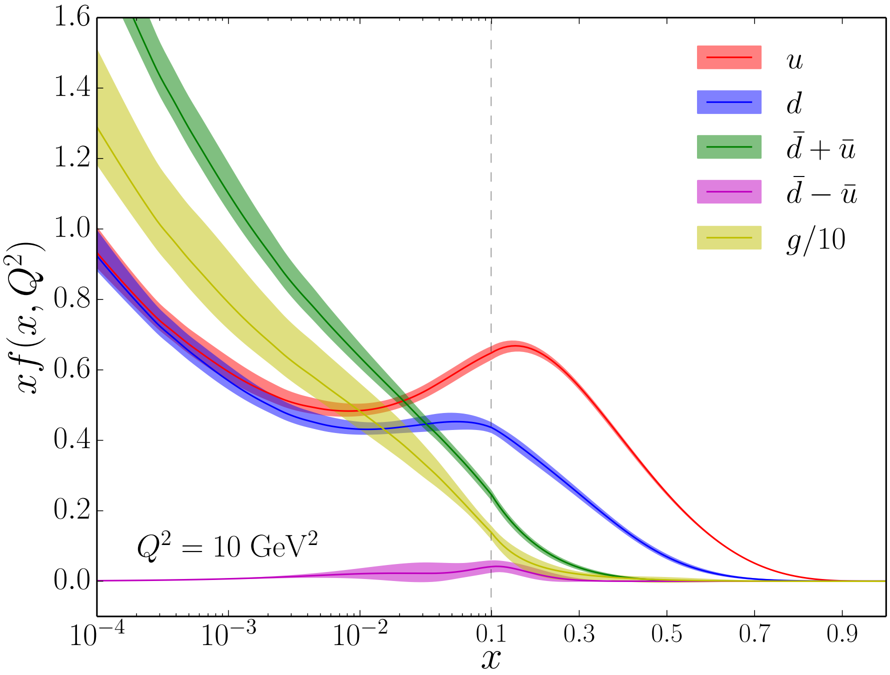

FIG. 1: Comparison of CJ15 PDFs for different flavors ($u, d, \bar{d}+\bar{u}, \bar{d}-\bar{u}$ and $g/10$) at a scale $Q^2 = 10$ GeV^2. Note the combined logarithim/linear scale along the x-axis.

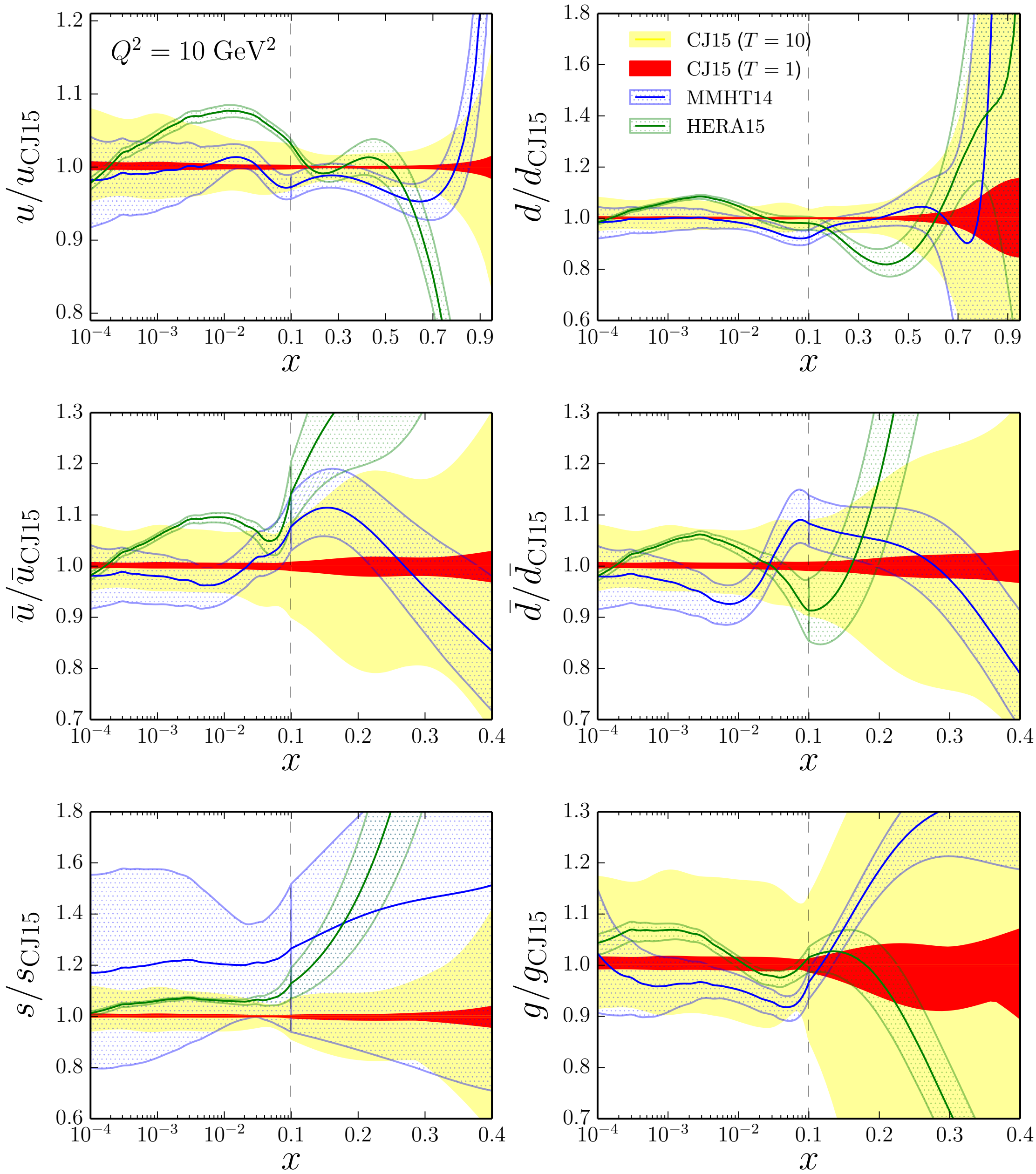

FIG. 2: Ratio of PDFs to the CJ15 central values for various PDF sets: CJ15 for tolerance $T = 1$ (red) and $T = 10$ (yellow), MMHT14 [17] (blue), and HERA15 [21] (green). Note the different scales on the vertical axes used for different flavors.

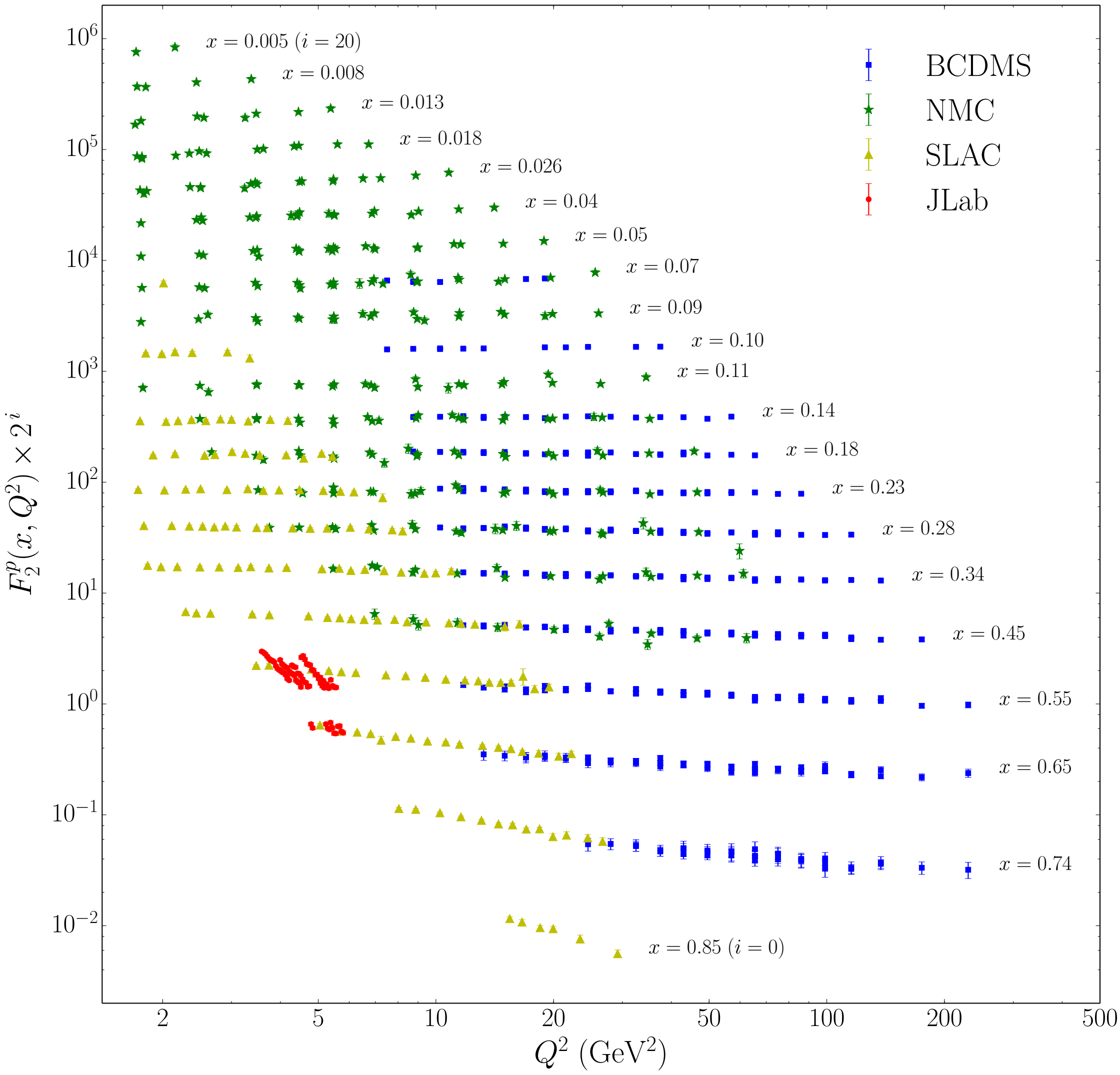

FIG. 3: Comparison of some of the proton F_2^p structure function data used in this analysis with the CJ15 fit.

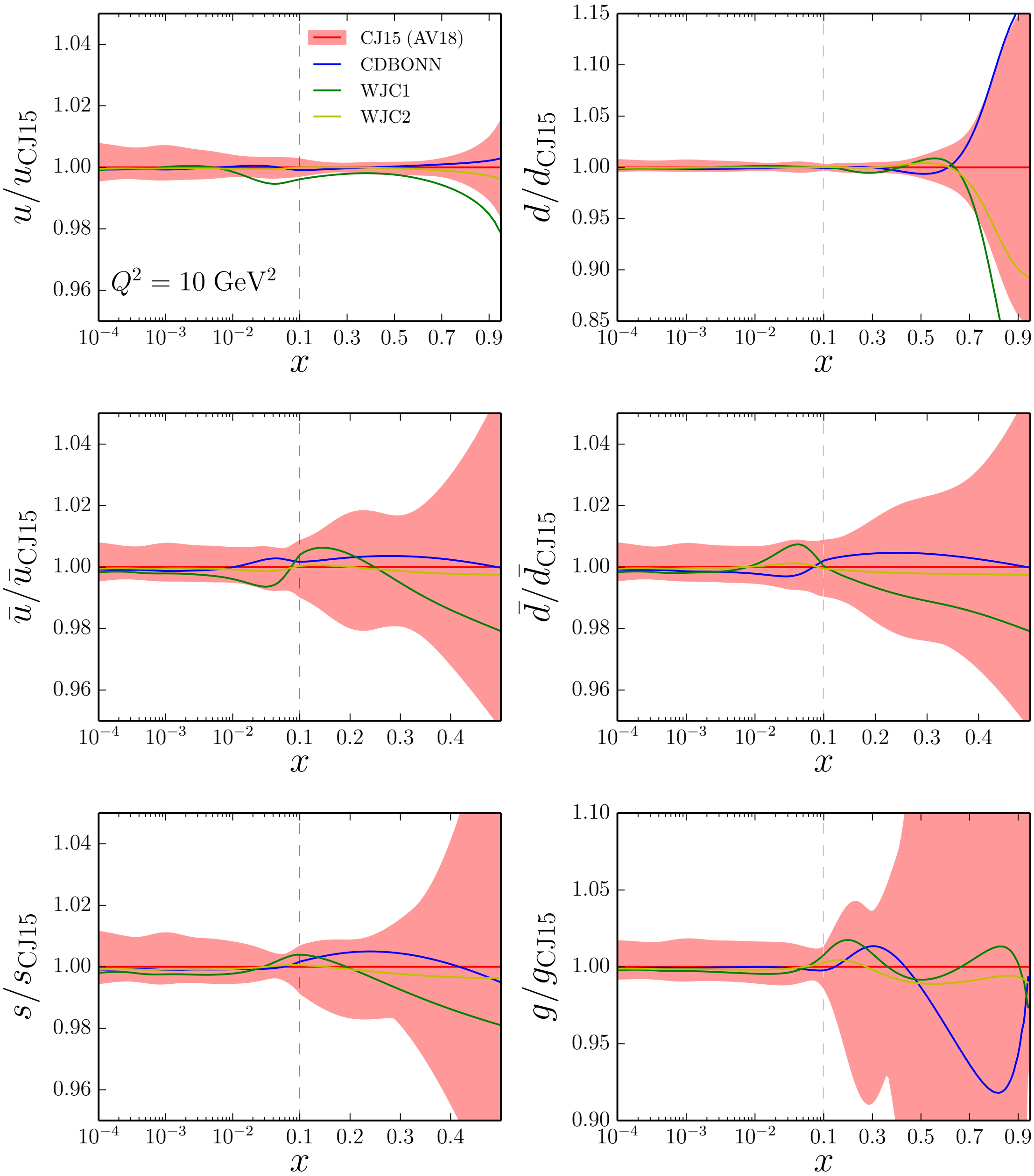

FIG. 4: Ratio of CJ15 PDFs for various deuteron wave function models: AV18 (red band), CD-Bonn (blue solid lines), WJC-1 (green lines), WJC-2 (yellow lines), for the KP off-shell parametrization (10). The PDF ratios are taken with respect to those for the AV18 wave function. Note the different scale on the vertical axes for the d-quark distribution.

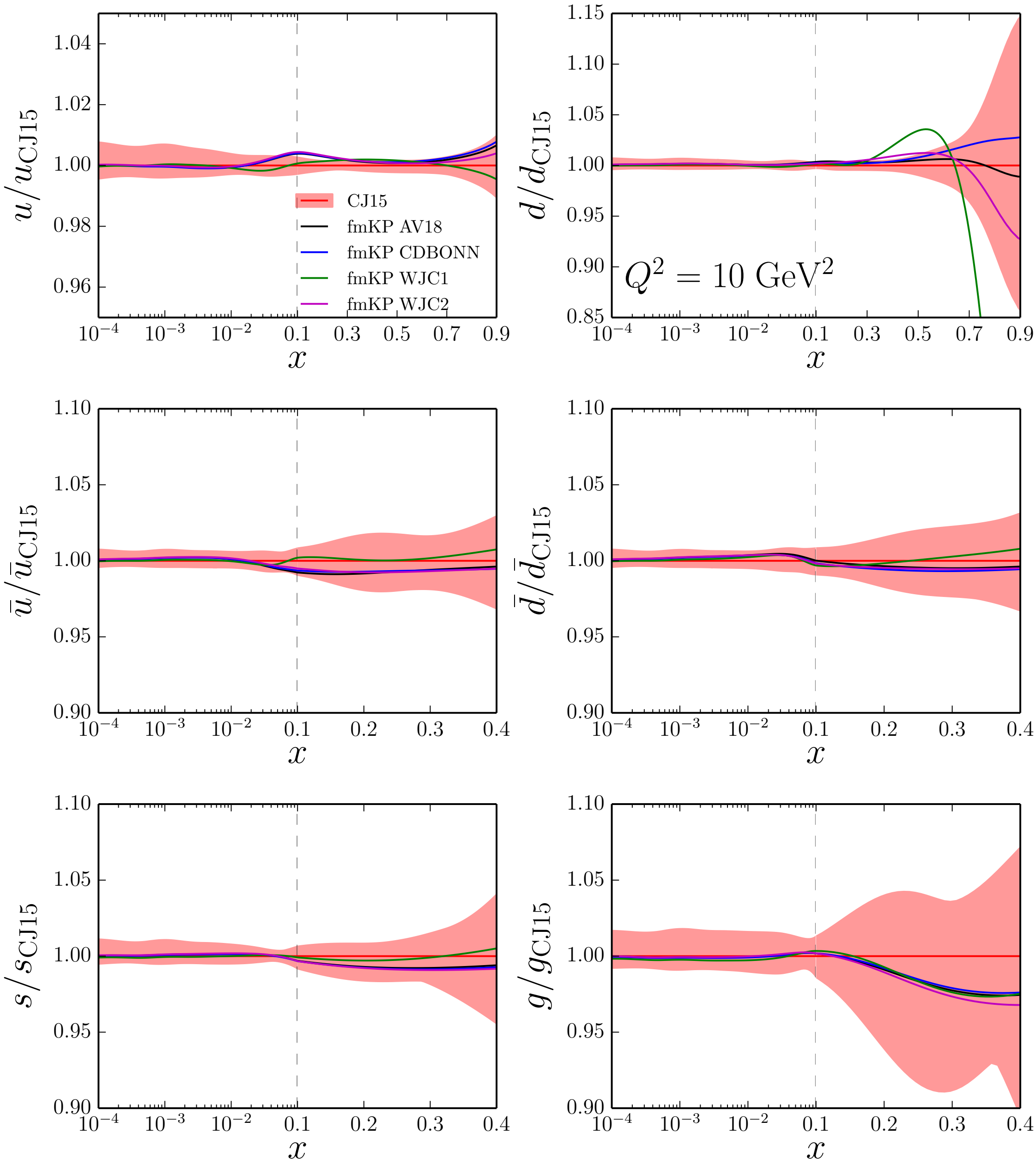

FIG. 5: Ratio of CJ15 PDFs for various nucleon off-shell models and deuteron wave functions: KP fit with AV18 (red band), fmKP model with AV18 (black), fmKP model with CD-Bonn (blue), fmKP model with WJC-1 (green), fmKP model with WJC-2 (magenta). The PDF ratios are taken with respect to those for the KP fit (10) AV18 wave function.

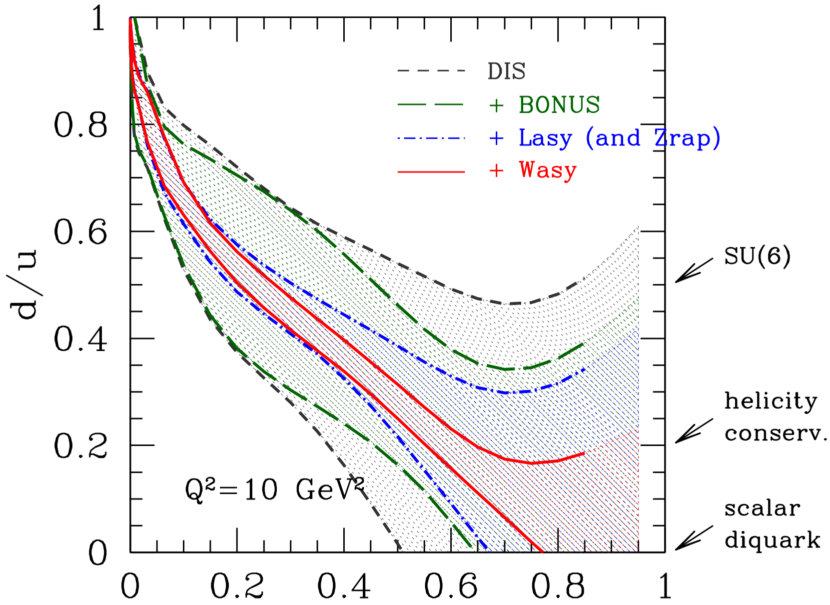

FIG. 6: ...[OLD FIGURE]... Impact of BONuS [82] and W asymmetry data on the d/u ratio.

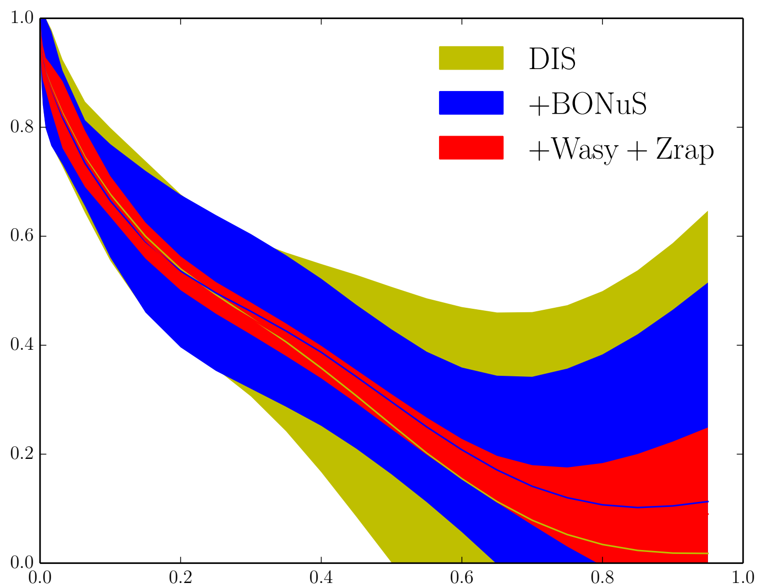

FIG. 7: Impact of BONuS [82] and W asymmetry data on the d/u ratio.

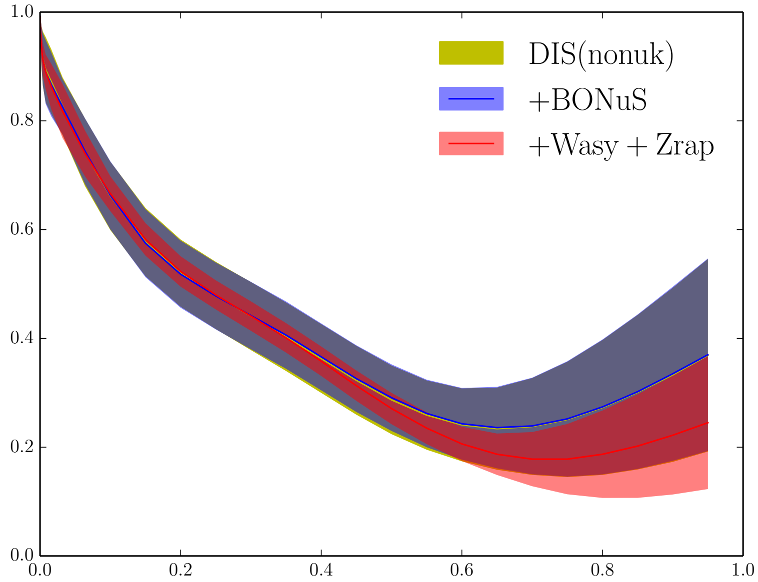

FIG. 8: Impact of BONuS [82] and W asymmetry data on the d/u ratio, for the case of no nuclear corrections applied to the deuterium data.