QCD@LHC, Queen Mary, University of London
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New CTEQ–Jefferson Lab (CJ15) analysis of parton distribution functions

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Jefferson Lab

CTEQ-JLab (CJ) collaboration: http://www.jlab.org/CJ
Alberto Accardi, Jeff Owens, Nobuo Sato (theory)
Eric Christy, Thia Keppel, Simona Malace, Peter Monaghan (experiment)

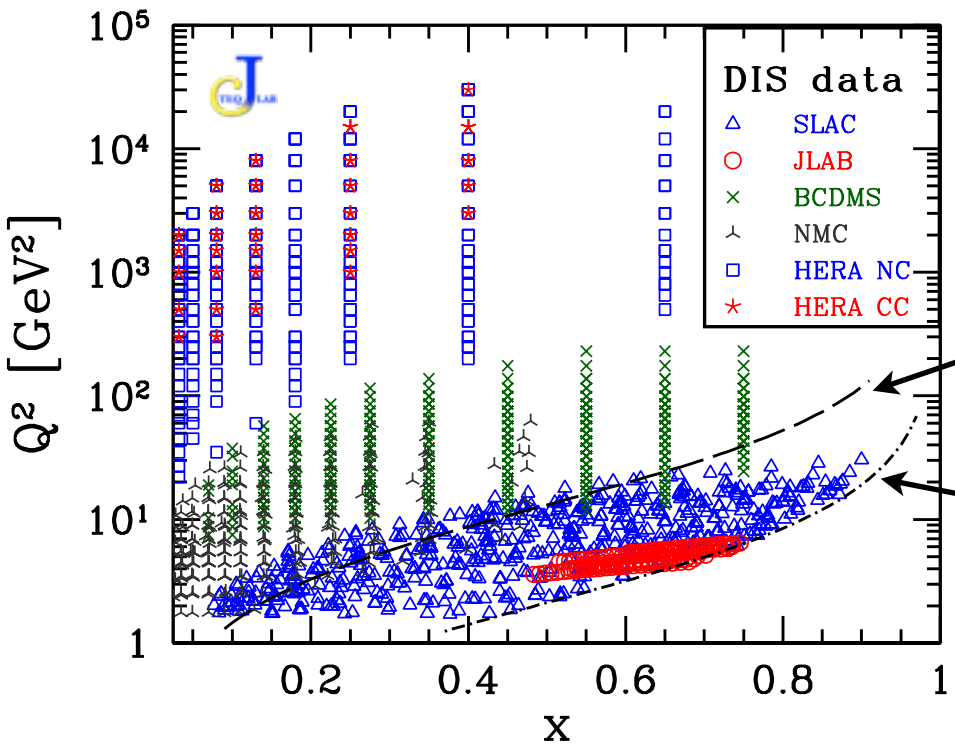
Outline

- CJ PDFs – motivations and goals
- New developments since CJ12
  - → more complete treatment of nuclear corrections
  - → impact of new lepton & W asymmetry data on d/u
  - → inclusion of JLab data
  - → analysis of $\bar{d} - \bar{u}$ at large x
- Future plans
  - → inclusion of new (LHC & JLab) data
  - → Monte Carlo based analysis

- Next-to-leading order (NLO) analysis of expanded set of proton and deuterium data (no heavy nuclei)

  → include high-x region ($x > 0.4$)

- High-x region requires use of data at lower W & Q^2



$$W^2 = M^2 + Q^2 \frac{(1-x)}{x}$$

strong cut:
$Q^2 > 4\ \mathrm{GeV}^2, \quad W^2 > 12.25\ \mathrm{GeV}^2$

weak cut:
$Q^2 > m_c^2\ , \quad W^2 > 3\ \mathrm{GeV}^2$

→ factor 2 increase in # of DIS data points when relax strong cut (excludes most SLAC, all JLab data) → weak cut

- Next-to-leading order (NLO) analysis of expanded set of proton and deuterium data (no heavy nuclei)

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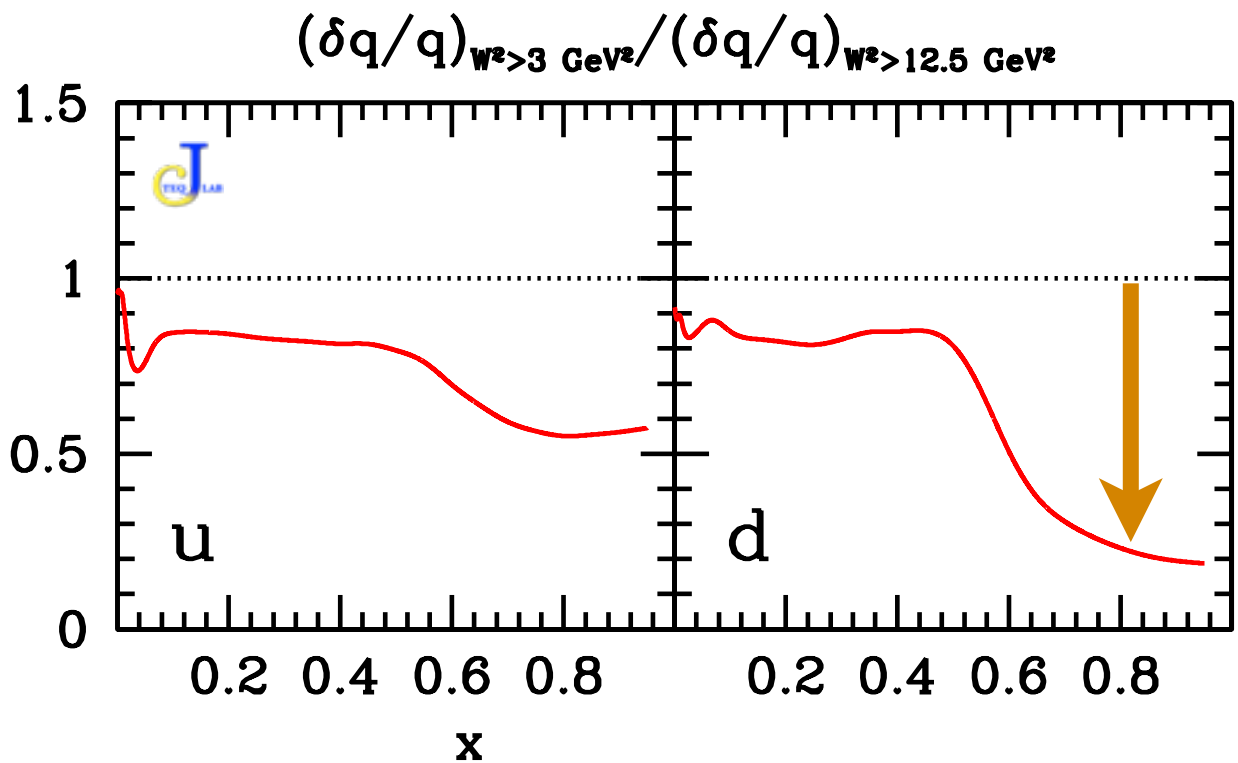


→ significant error reduction at high x

- Next-to-leading order (NLO) analysis of expanded set of proton and deuterium data (no heavy nuclei)

  → include high-x region $(x > 0.4)$

- High-x region requires use of data at lower W & Q^2

- Analysis of high-x data requires careful treatment of subleading $1/Q^2$ corrections

  → target mass corrections, dynamical higher twists

- Correct for nuclear effects in deuteron (binding + off-shell)

  → binding + Fermi motion (well known), nucleon off-shell (less well known)

  → impact on d/u ratio in large-x region

CJ15 data sets and χ^2 values

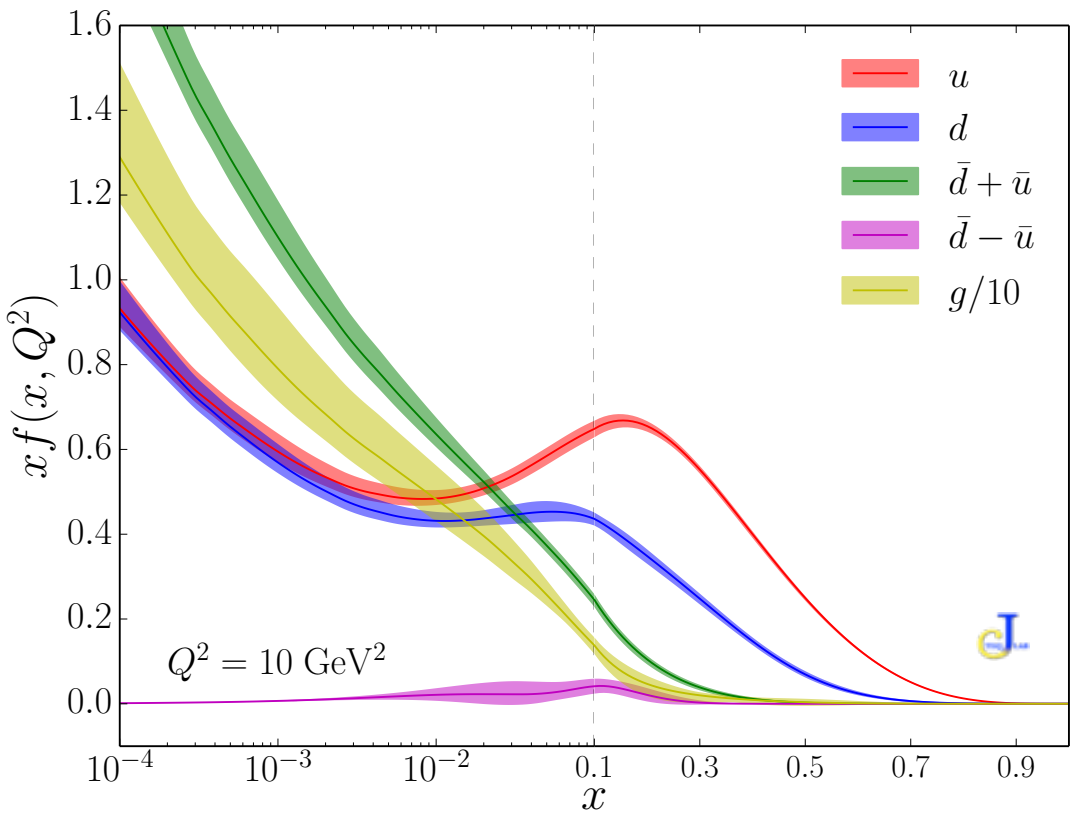
	experiment	# points	χ^2 NLO	χ^2 LO
DIS F_2	BCDMS (p) [23]	351	437	432
	BCDMS (d) [23]	254	294	299
	NMC (p) [24]	275	407	414
	NMC (d/p) [25]	189	172	180
	SLAC (p) [26]	564	435	496
	SLAC (d) [26]	582	372	417
	JLab (p) [27]	136	166	164
	JLab (d) [27]	136	124	127
	JLab (n/d) [85]	191	217	224
DIS σ	HERA (NC e^-p) [28]	145	112	161
	HERA (NC e^+p) [28]	408	541	872
	HERA (CC e^-p) [28]	34	19	19
	HERA (CC e^+p) [28]	34	31	33
Drell-Yan	E605 (pCu) [45]	119	93	104
	E866 (pp) [29]	121	139	155
	E866 (pd) [29]	129	144	191
	E866 (pd/pp) [30]	12	9	9
W/charge asymmetry	CDF (e) [31]	11	12	11
	DØ (μ) [32]	10	20	21
	DØ (e) [33]	13	27	56
	CDF (W) [34]	13	15	12
	DØ (W) [35]	14	16	47
Z rapidity	CDF (Z) [36]	28	27	79
	DØ (Z) [37]	28	16	23
jet	CDF (run 2) [39]	72	15	22
	DØ (run 2) [41]	110	21	46
γ+jet	DØ 1 [42]	16	6	20
	DØ 2 [42]	16	15	40
	DØ 3 [42]	12	25	35
	DØ 4 [42]	12	13	77
total		4035	**3941**	4786
total + norm			**3950**	4918
χ^2/dof			**0.98**	**1.22**

← BONuS F_2^n/F_2^d

← D0 A_l

← D0 A_W

CJ15 PDFs



our "biased" fit form *

$$\boxed{\begin{aligned} x f &= a_0\, x^{a_1} (1-x)^{a_2} \\ &\quad \times (1 + a_3 \sqrt{x} + a_4\, x) \end{aligned}}$$

at $Q^2 = Q_0^2$

* except for d and $\bar{d}\,/\,\bar{u}$

→ for strange assume $s = \bar{s} \propto (\bar{d} + \bar{u})$ (no neutrino data)

→ charm computed perturbatively (S-ACOT scheme);
no compelling reason for intrinsic charm

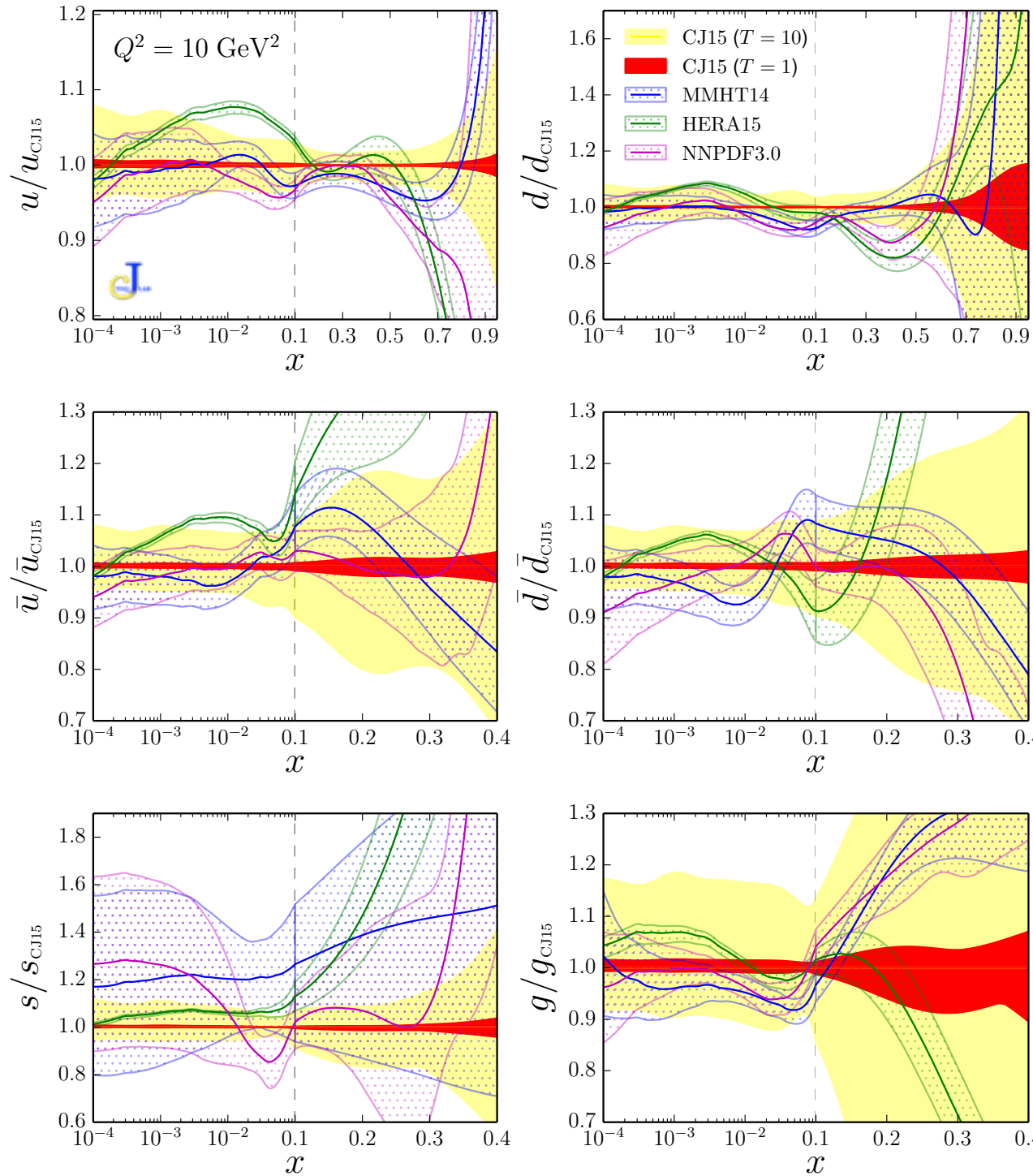
Jimenez-Delgado et al., PRL ***114****, 082002 (2015)*

CJ15 vs. other PDFs

→ currently use $\Delta\chi^2 = 1$ but assume tolerance T=10 for some app's

→ HERAPDF15 errors comparable to T=1, others generally between T=1 & 10

→ larger uncertainty for d PDF at high x than for u



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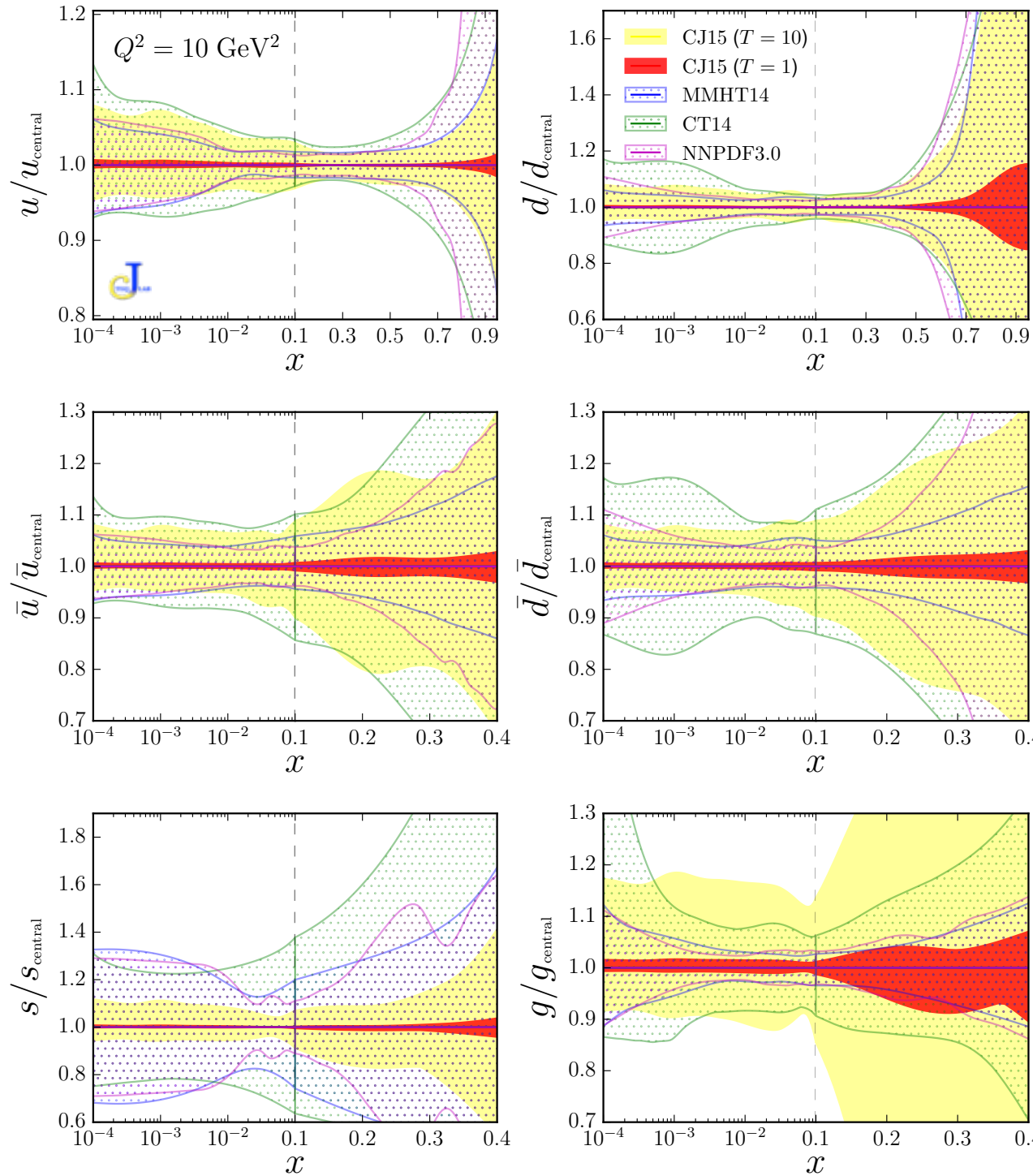


Target mass corrections

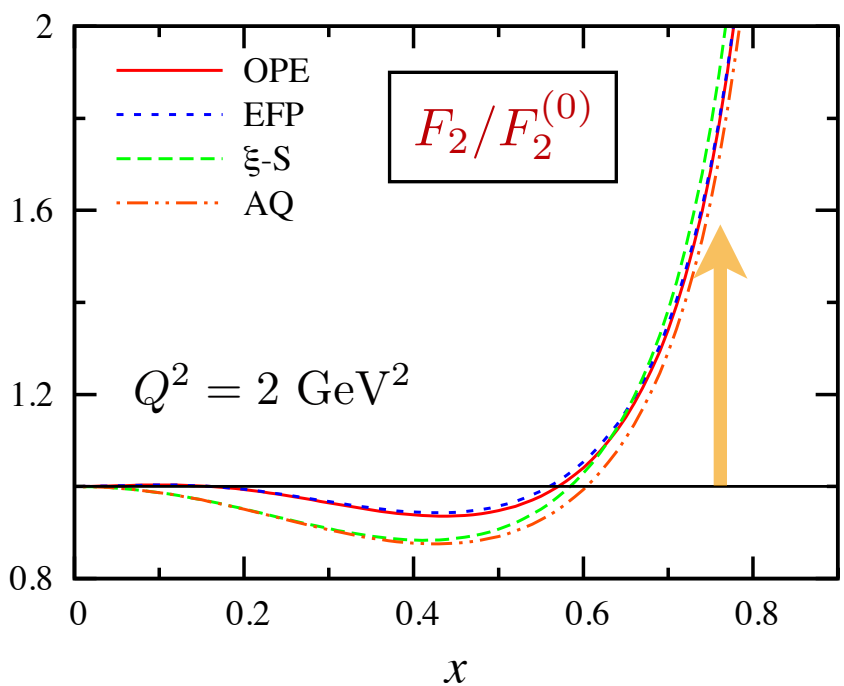
- Operator product expansion

$$F_2(x,Q^2) = \frac{(1+\rho)^2}{4\rho^3} F_2^{(0)}(\xi,Q^2) + \frac{3x(\rho^2-1)}{2\rho^4}\left[h(\xi,Q^2) + \frac{\rho^2-1}{2x\rho} g(\xi,Q^2)\right]$$

with $h(\xi) = \int_\xi^1 dz\, F_2^{(0)}(z)/z^2, \quad g(\xi) = \int_\xi^1 dz\, h(z)$

Nachtmann variable $\xi = \dfrac{2x}{1+\rho}, \quad \rho^2 = 1 + 4M^2x^2/Q^2$

Georgi, Politzer
*PRD **14**, 1829 (1976)*



*Brady et al., PRD **84**, 074008 (2011)*

EFP: collinear factorization

*Elllis, Furmanski, Petronzio, NP **B212**, 29 (1983)*

ξ-S, AQ: various approximations

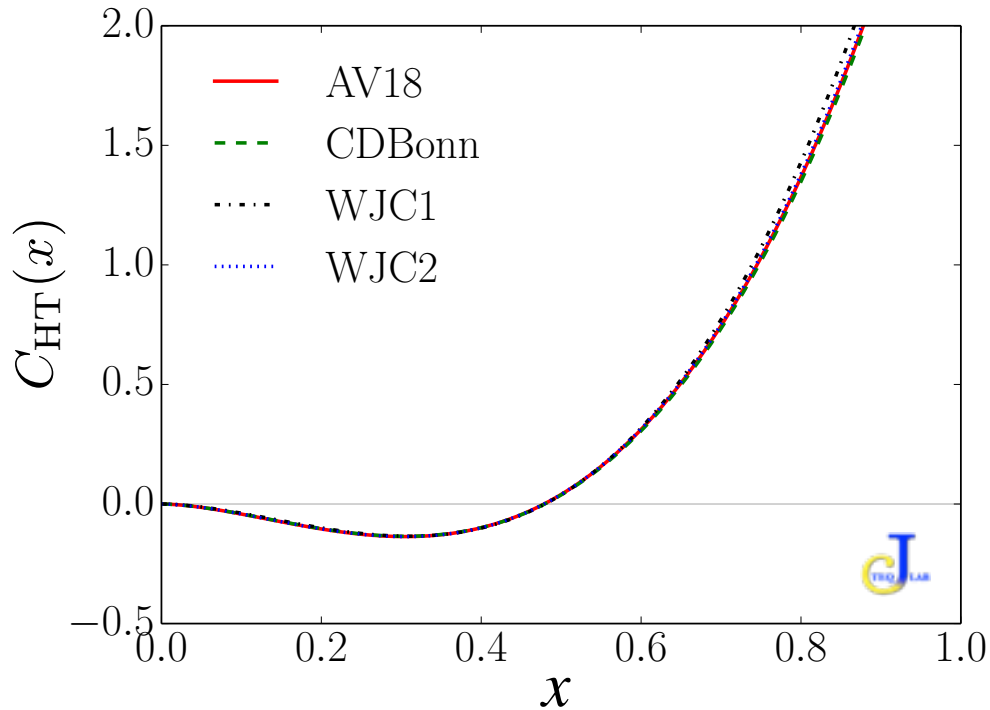
*Accardi, Qiu, JHEP **0807**, 090 (2008)*

Higher twist corrections

- Parametrized phenomenologically

polynomial

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



deuteron wave functions from *NN* scattering

AV18: *Wiringa et al., PRC* ***51****, 38 (1995)*

CD-Bonn: *Machleidt, PRC* ***63****, 024001 (2001)*

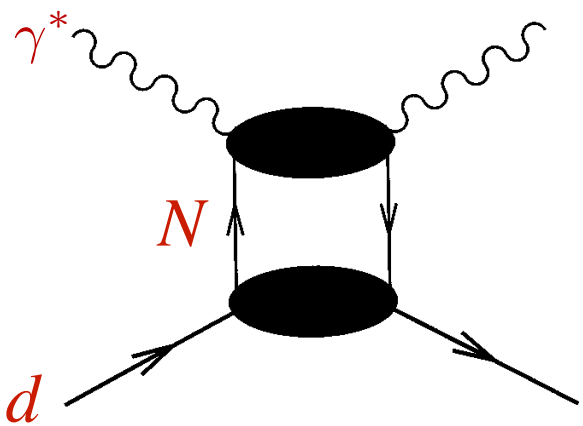
WJC: *Gross, Stadler, PRC* ***82****, 034004 (2010)*

→ stable leading twist when *both* TMCs and HTs included

→ HT essentially independent of deuteron correction

Nuclear corrections

- Nuclear structure function at $x \gg 0$ dominated by incoherent scattering from individual nucleons



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

nucleon momentum distribution in d ("smearing function")

PDF in bound (off-shell) nucleon

$\longrightarrow$ $$z = \frac{p \cdot q}{p_d \cdot q} \approx 1 + \frac{p_0 + \gamma p_z}{M} \qquad \left[p_0 = M + \varepsilon, \quad \varepsilon = \varepsilon_d - \frac{\vec{p}^{\,2}}{2M} \right]$$

momentum fraction of d carried by N

$\longrightarrow$ at finite Q^2, smearing function depends on $\gamma = \sqrt{1 + 4M^2x^2/Q^2}$

Nuclear corrections

- Expand off-shell nucleon PDF about on-shell $(p^2 = M^2)$ limit

$$\widetilde{q}^N(x,p^2) = q^N(x)\left[1 + \frac{(p^2 - M^2)}{M^2}\,\delta q^N(x)\right]$$

$$\delta q^N = \left.\frac{\partial \log \widetilde{q}^N}{\partial \log p^2}\right|_{p^2=M^2}$$

- Deuteron PDF sum of on- and off-shell contributions $q^d = q^{d(\mathrm{on})} + q^{d(\mathrm{off})}$, where

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

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

on-shell & off-shell smearing functions

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

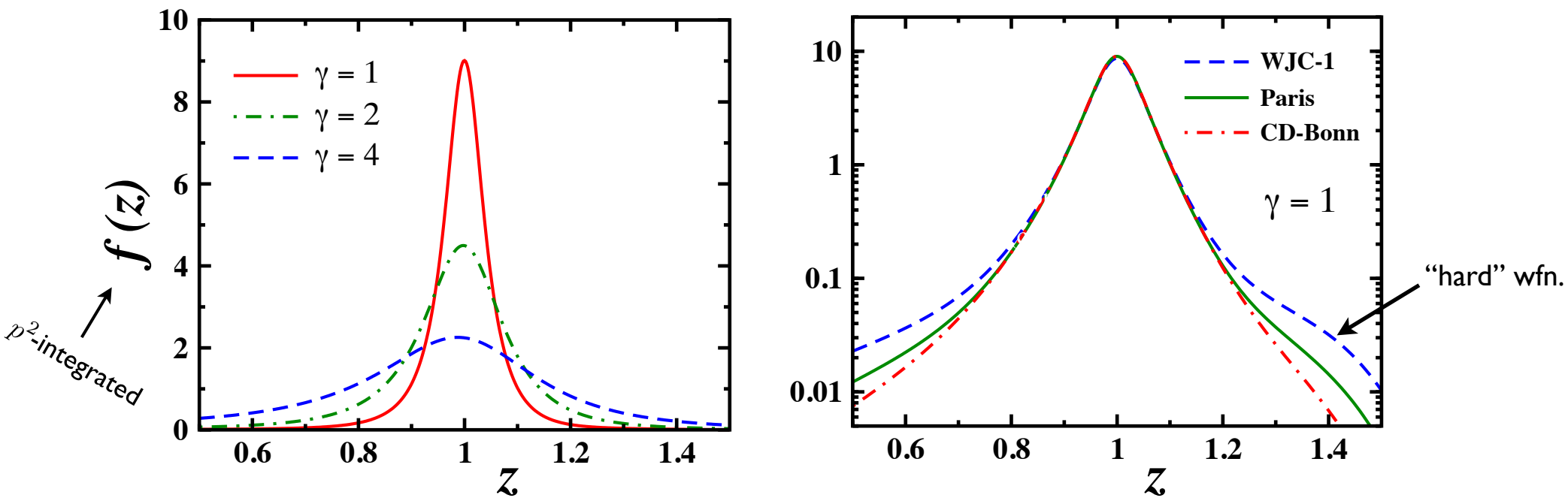
$$f^{(\mathrm{off})}(z) = \int dp^2\, \frac{p^2 - M^2}{M^2} f_{N/d}(z,p^2)$$

Ehlers et al., PRD ***90****, 014010 (2014)*

Nuclear corrections

- Smearing function in the deuteron computed in "weak binding approximation" – expand in powers of $\vec{p}^2/M^2$

$$f_{N/d}(z,p^2) = \frac{1}{(2\pi)^3}\,\frac{1}{\gamma^2}\left[1+\frac{\gamma^2-1}{z^2}\left(1+\frac{2\varepsilon}{M}+\frac{\vec{p}^{\,2}}{2M^2}(1-3\hat{p}_z^2)\right)\right]|\psi_d(p)|^2$$



→ effectively more smearing for larger x and lower Q^2

→ greater wave function dependence at large z (→ large x)

Nuclear corrections

- Nucleon off-shell correction to quark PDF

CJ12

→ off-shell covariant quark "spectator" (OCS) model

$$\widetilde{q}^N(x,p^2) = \int d\hat{p}^2\, \Phi_{q/N}(\hat{p}^2, \Lambda(p^2))$$

momentum distribution of quarks with virtuality $\hat{p}^2$ in bound nucleon

→ scale parameter $\Lambda(p^2)$ suppresses large-p^2 contributions

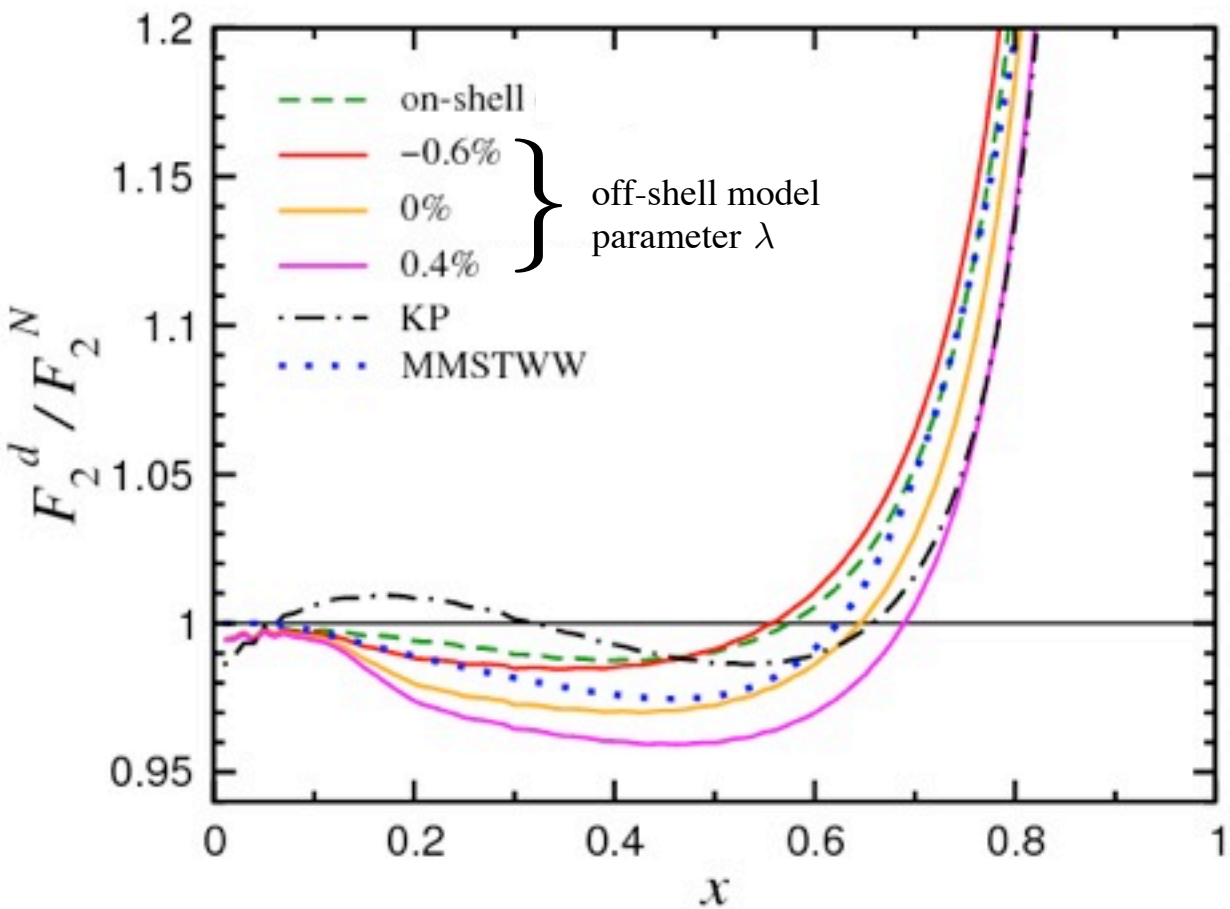
→ off-shell "rescaling" parameter $\lambda = \dfrac{\partial \log \Lambda^2}{\partial p^2}$ fitted

→ applied to valence, antiquark & gluon PDFs

*Owens et al., PRD **87**, 094012 (2013)*
*Ehlers et al., PRD **90**, 014010 (2014)*

Nuclear corrections

- Nucleon off-shell correction to quark PDF



→ larger off-shell effects for larger λ, and for KP model

→ enhancement ("antishadowing") at $x \sim 0.2$ in KP model

Kulagin, Petti
*NPA **765**, 126 (2006)*

Nuclear corrections

- Nucleon off-shell correction to quark PDF

CJ15

→ alternatively, parametrize δq^N phenomenologically

$$\delta q^N = C_N (x - x_0)(x - x_1)(1 + x - x_0)$$

*Kulagin, Petti, NPA **765**, 126 (2006)*

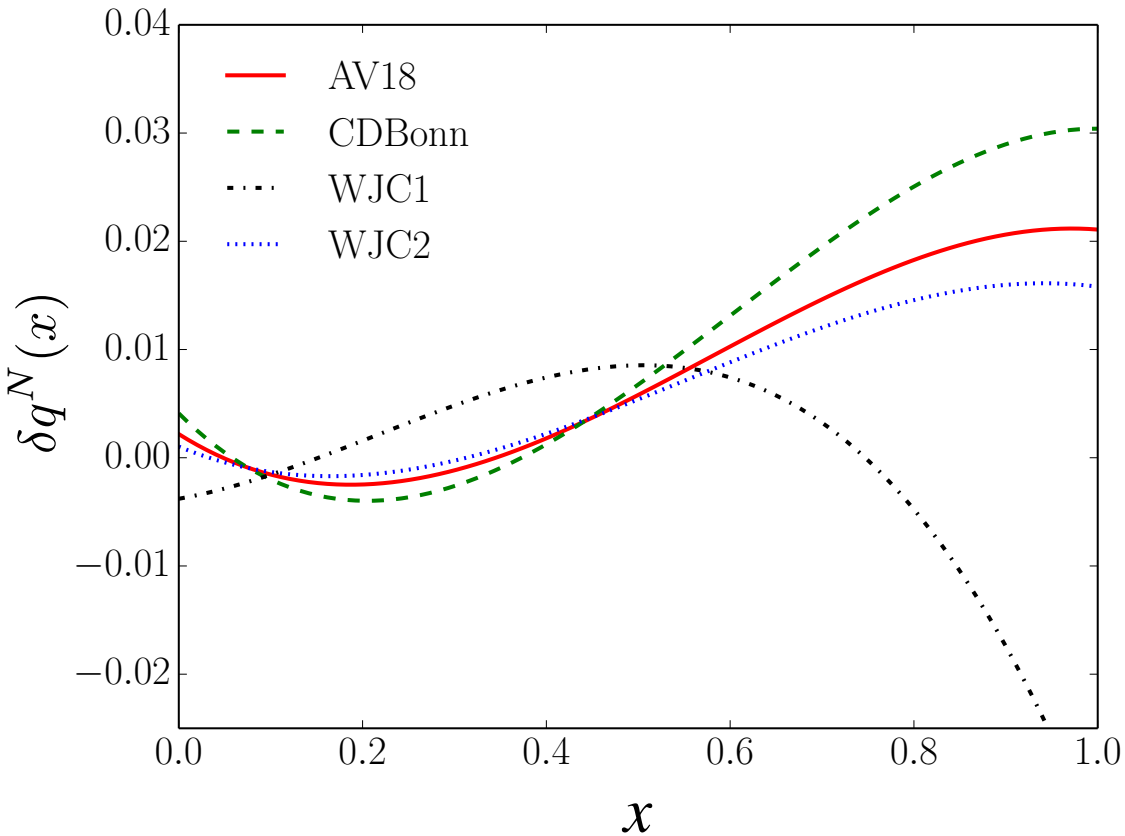
→ fit 2 of $\{C,\, x_0,\, x_1\}$ for given deuteron wave function; fix third parameter from normalization condition

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

→ similar to Kulagin-Petti, but fitted only to *deuteron* data (avoid uncontrolled extrapolations from large-A data)

Nuclear corrections

- Nucleon off-shell correction to quark PDF



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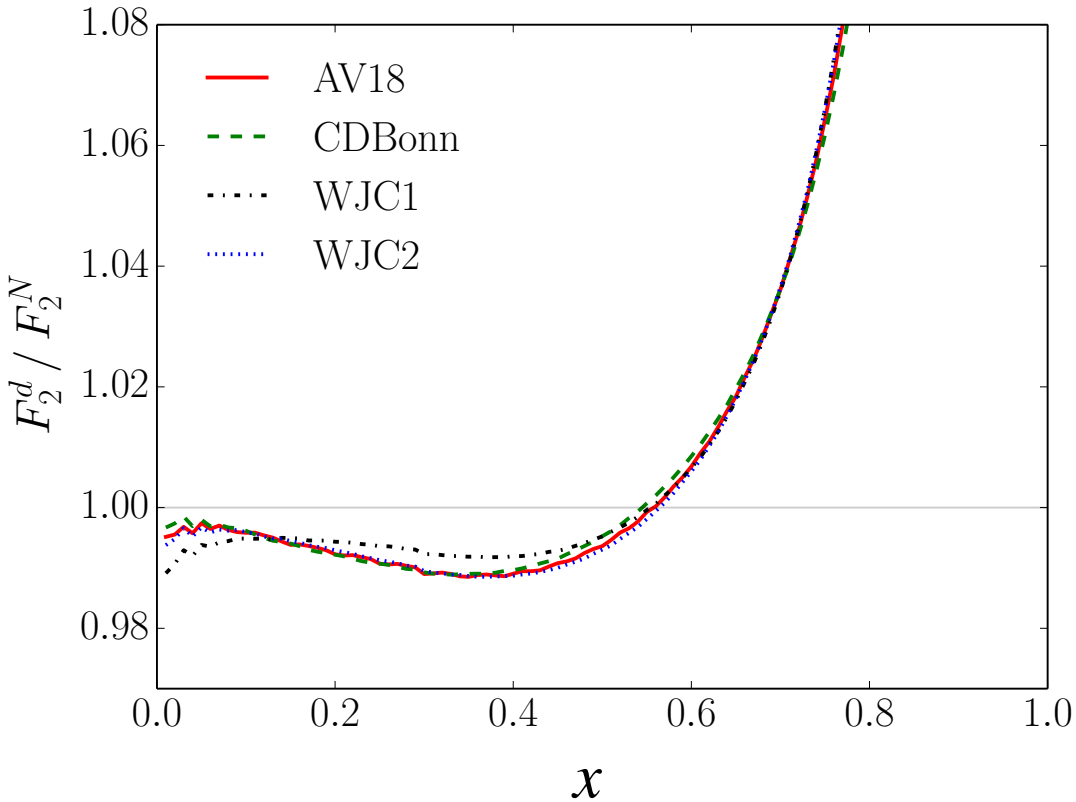
(long-distance part of wfns. is model independent, from chiral symmetry)

→ fitted off-shell corrections weakly dependent on wave function, except for WJC-1
(hardest momentum distribution – largest tail)

Nuclear corrections

- Nuclear EMC ratio in deuteron

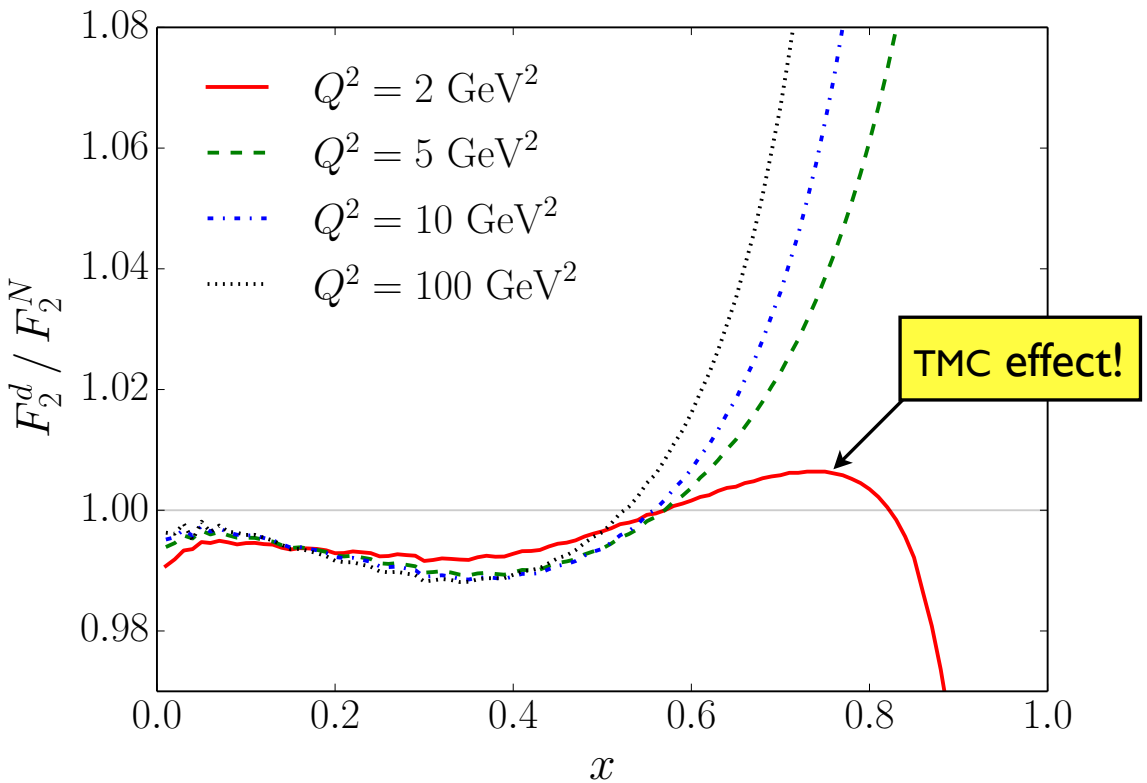


→ observables sensitive only to combined smearing *and* off-shell corrections

→ no evidence for antishadowing at $x \sim 0.1$

Nuclear corrections

- Nuclear EMC ratio in deuteron

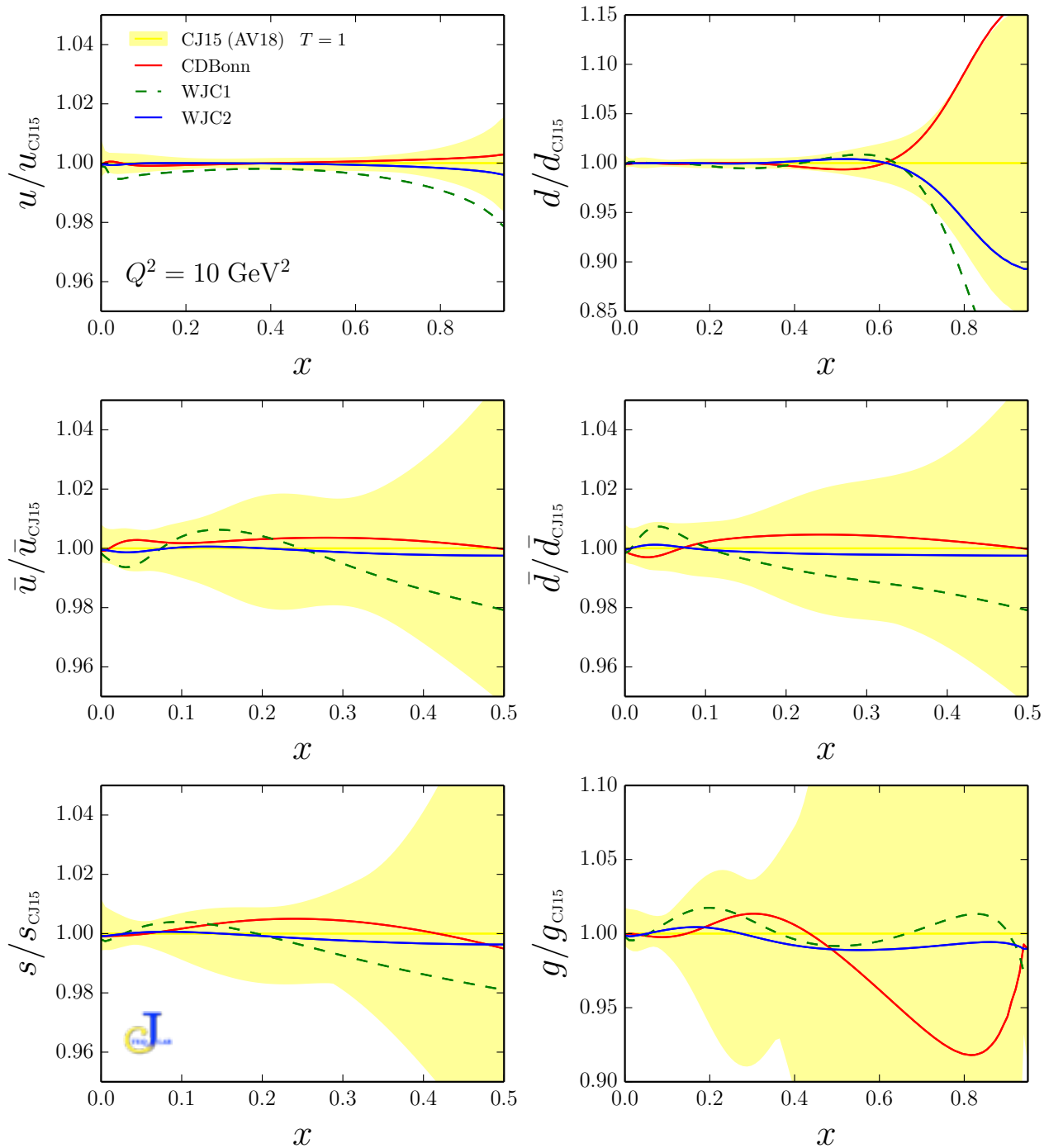


→ ratio has significant Q^2 dependence at low Q^2 from target mass effects

Nuclear corrections & CJ15 PDFs

→ results for PDFs using all wfns. other than WJC-1 are within 1σ

→ WJC-1 outside 1σ error for d at high x & u at low & high x



Nuclear corrections & CJ15 PDFs

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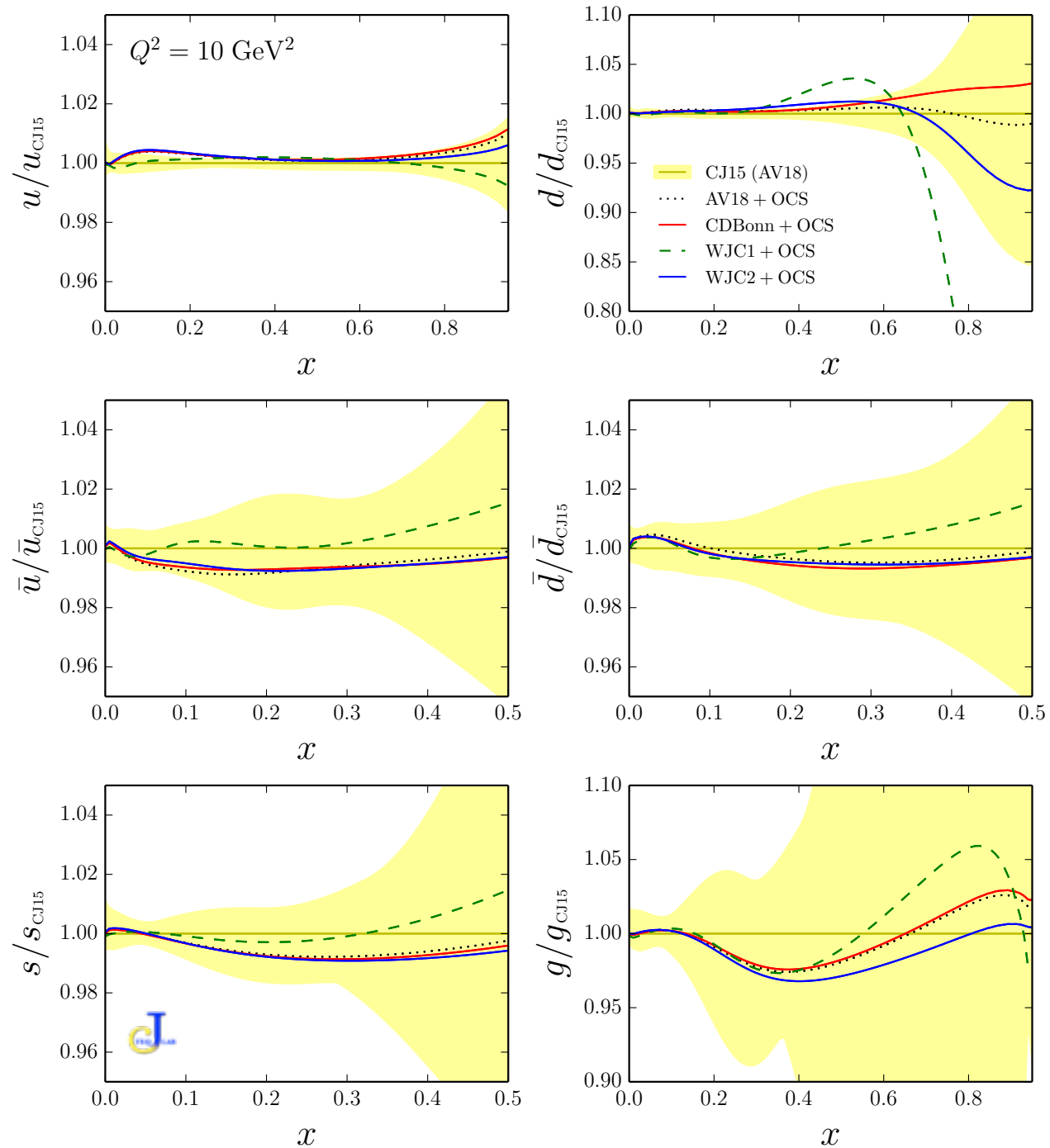
→ off-shell model dep. (*cf.* OCS) generally weak except for d PDF



Nuclear corrections & CJ15 PDFs

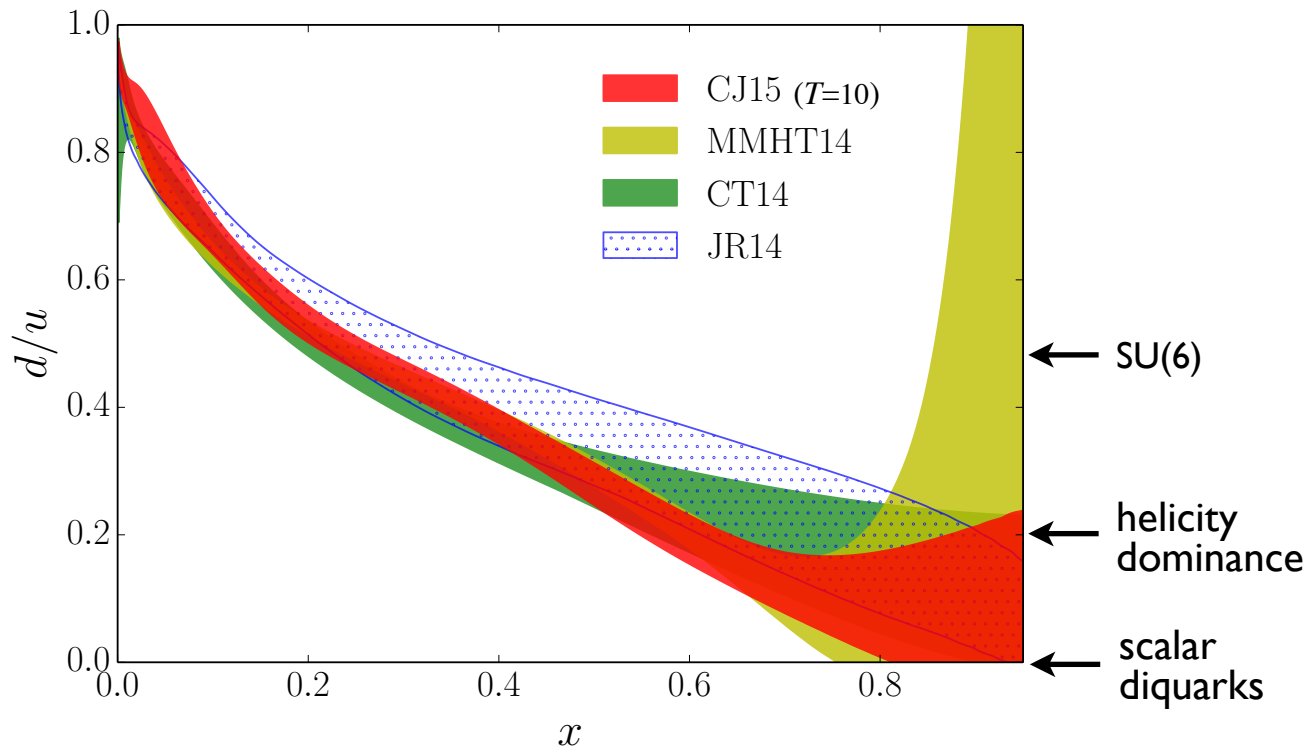
→ d/u ratio at high x of interest for nonperturbative models of nucleon

→ more flexible parametrization

$$d \;\to\; d + b\,x^c\,u$$

allows finite, nonzero $x = 1$ limit

(standard PDF form gives 0 or ∞ unless $a_2^d = a_2^u$)



MMHT14: fitted deuteron correction, "standard" d parametrization

CT14: flexible d parametrization, no nuclear corrections

JR14: similar deuteron correction, no lepton/W asymmetry data

Nuclear corrections & CJ15 PDFs

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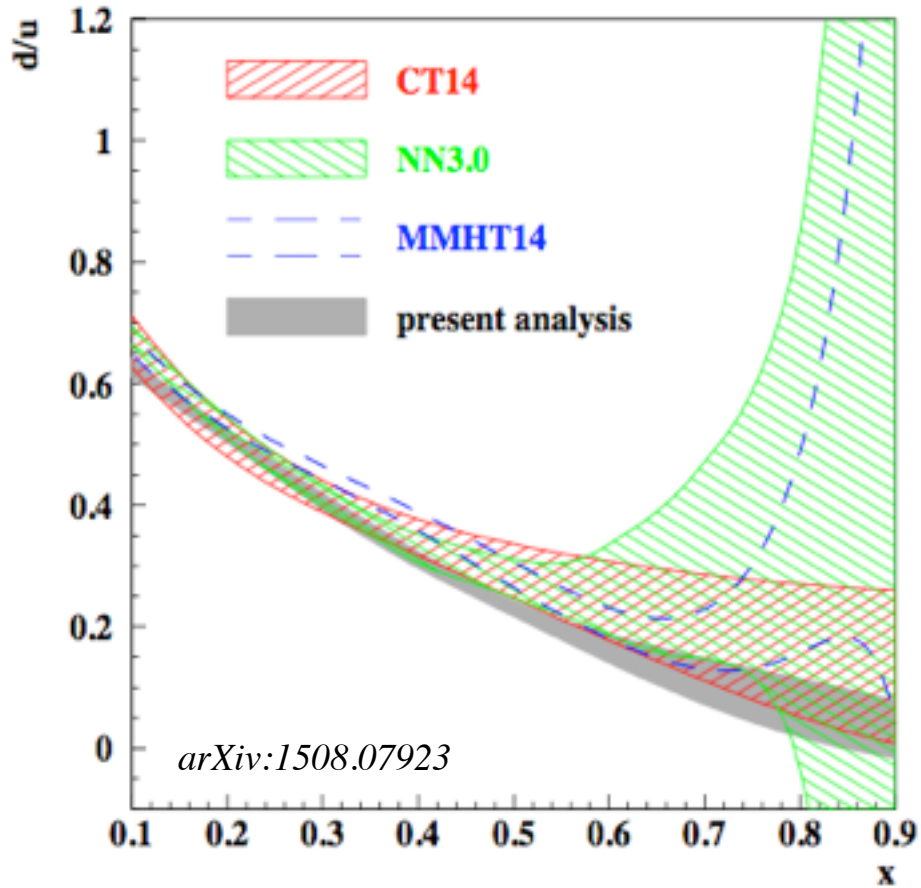
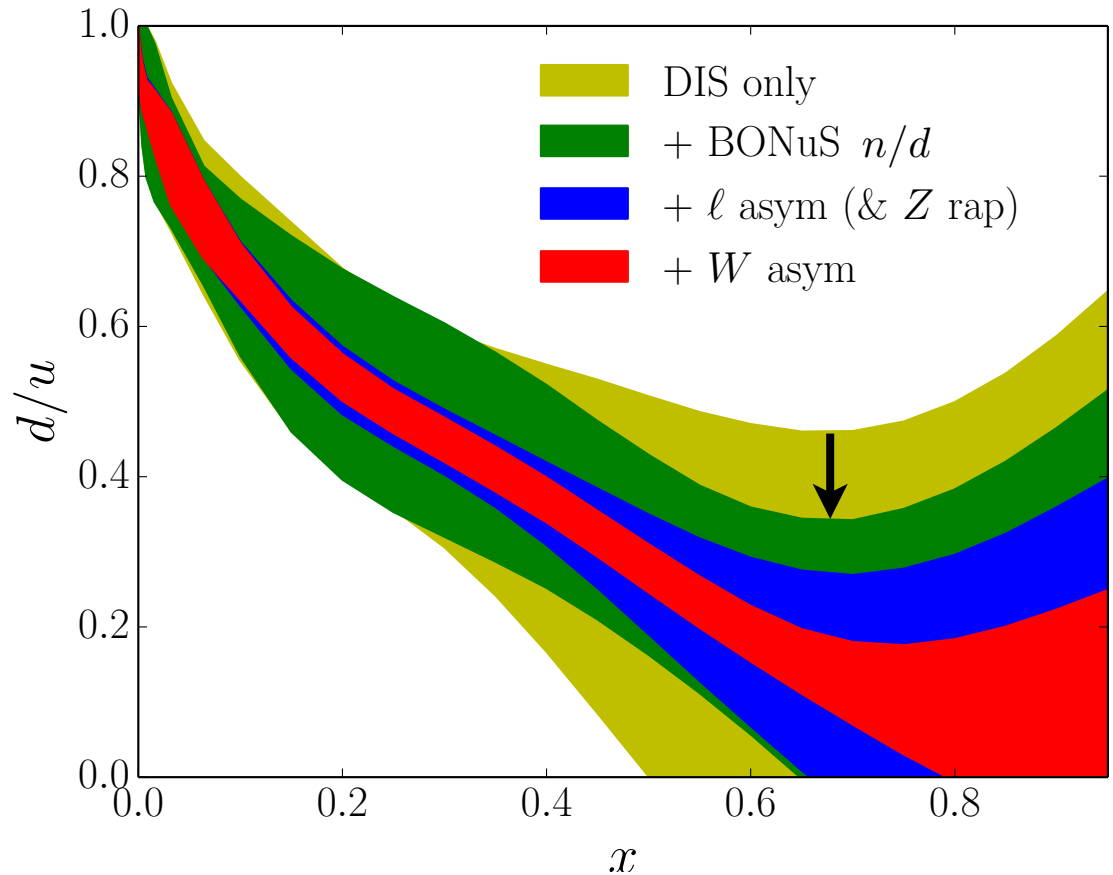


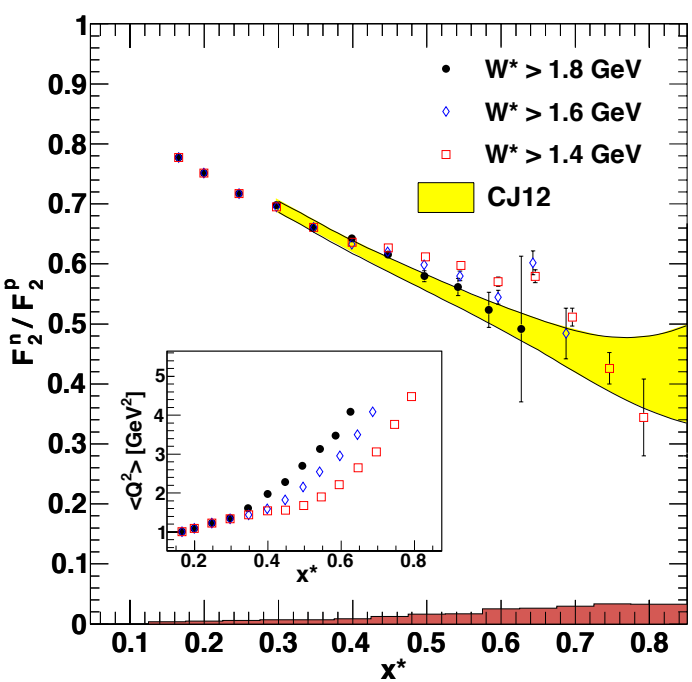
ABMP15: includes new lepton asymmetries, no deuteron data, $\Delta\chi^2 = 1$

Effect of data sets of d/u

→ new JLab (BONuS) data reduces error at $x \sim 0.6$



BONuS: spectator proton tagging in semi-inclusive ed DIS



Baillie et al.
PRL ***108****, 142001 (2012)*

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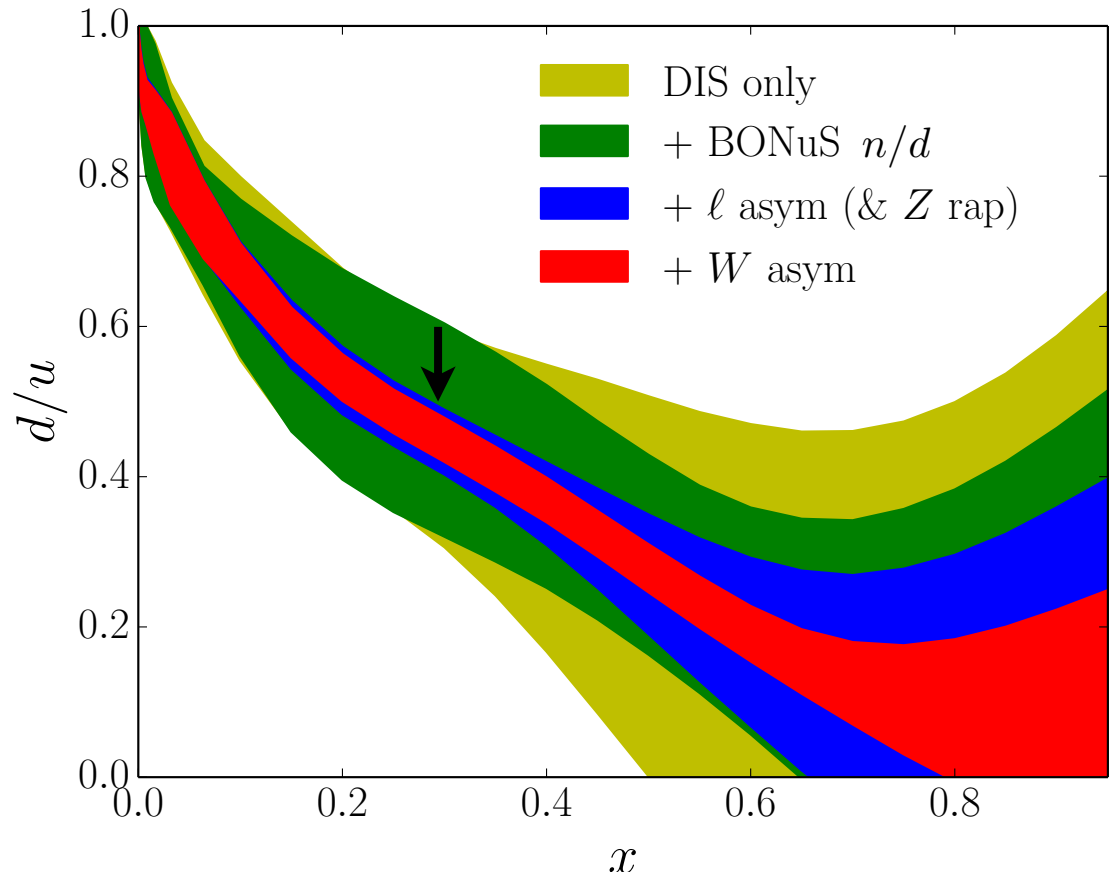
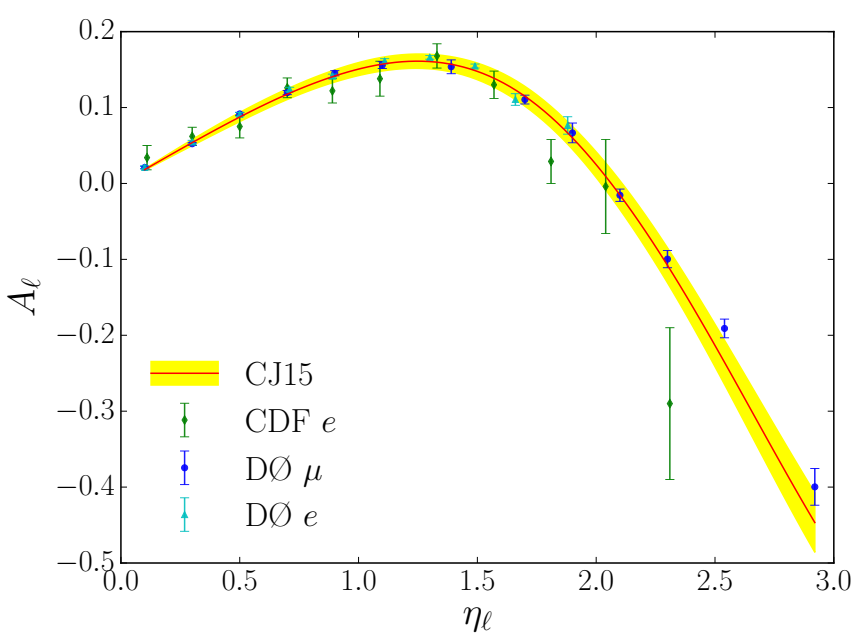
→ significant reduction from new lepton asymmetry data
(little effect from Z rap. data)





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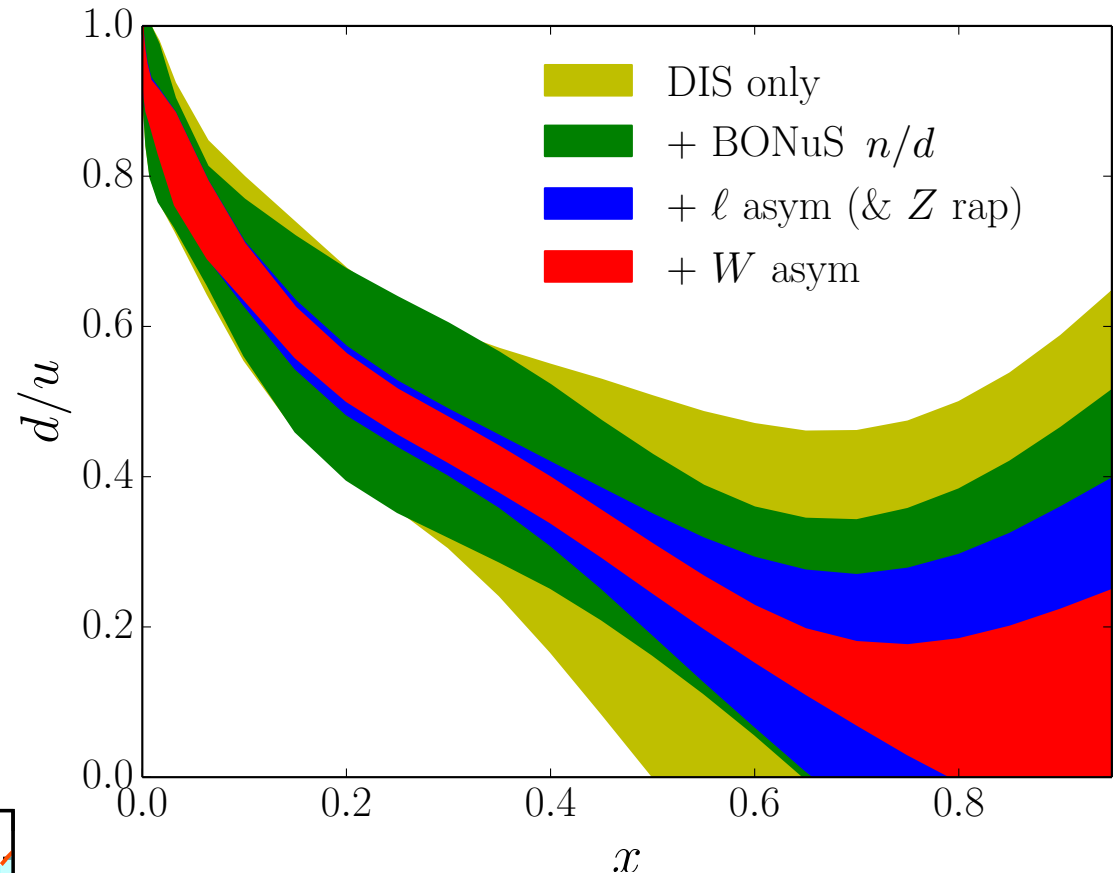

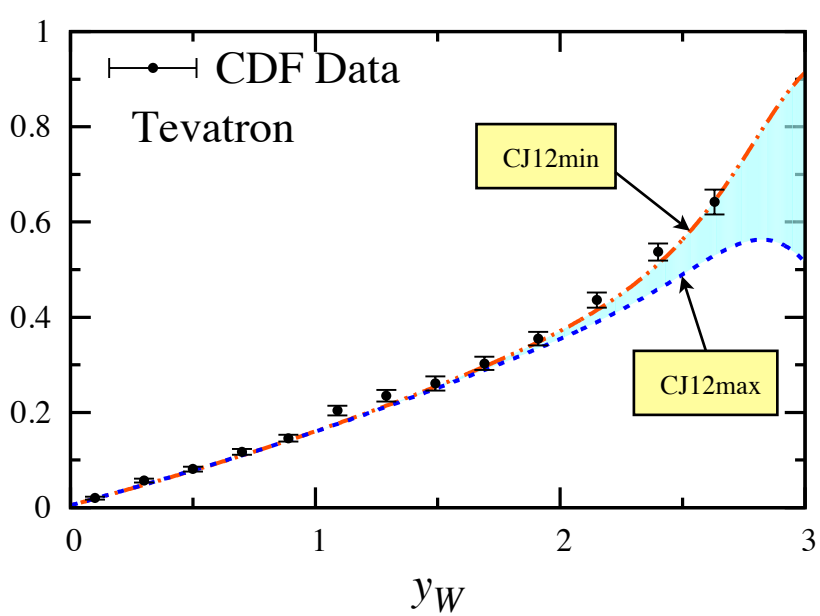

→ W asymmetry at large W rapidity more sensitive to d/u at high x

→ earlier CDF data preferred smaller ("CJ12min") nuclear corrections

Effect of data sets of d/u

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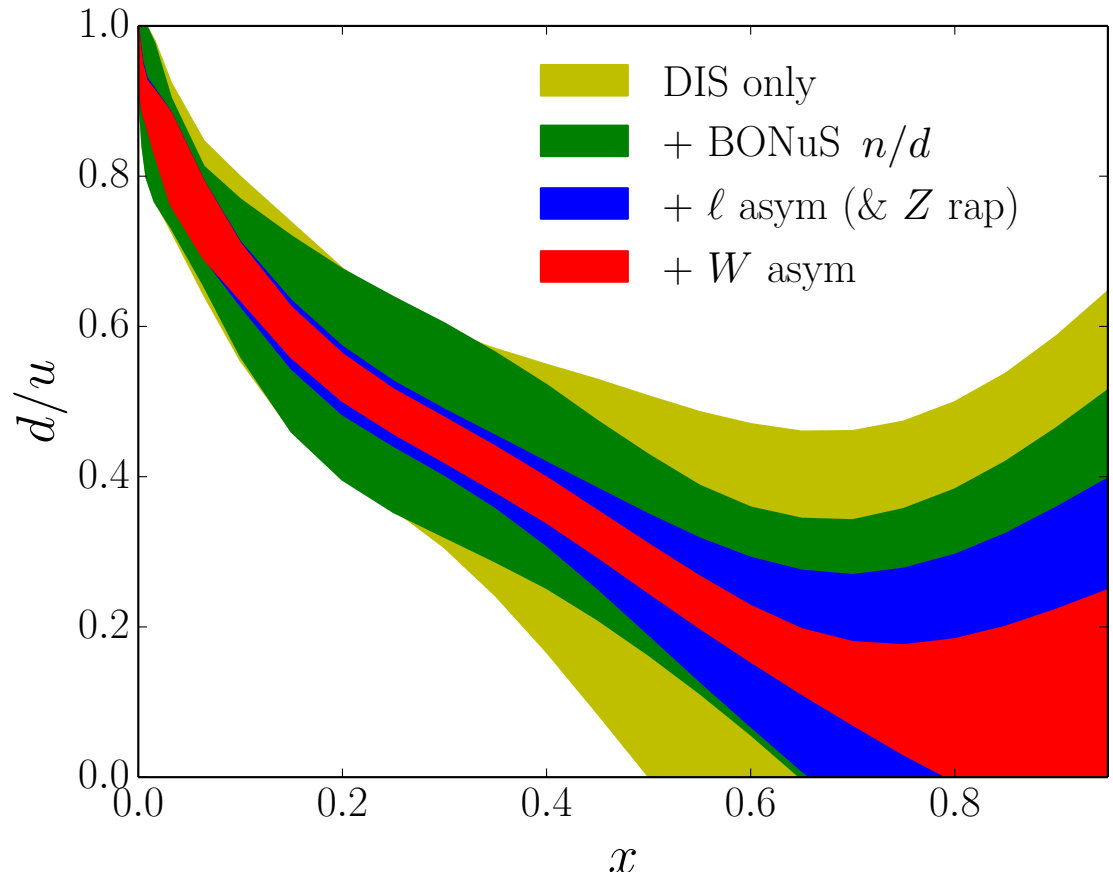

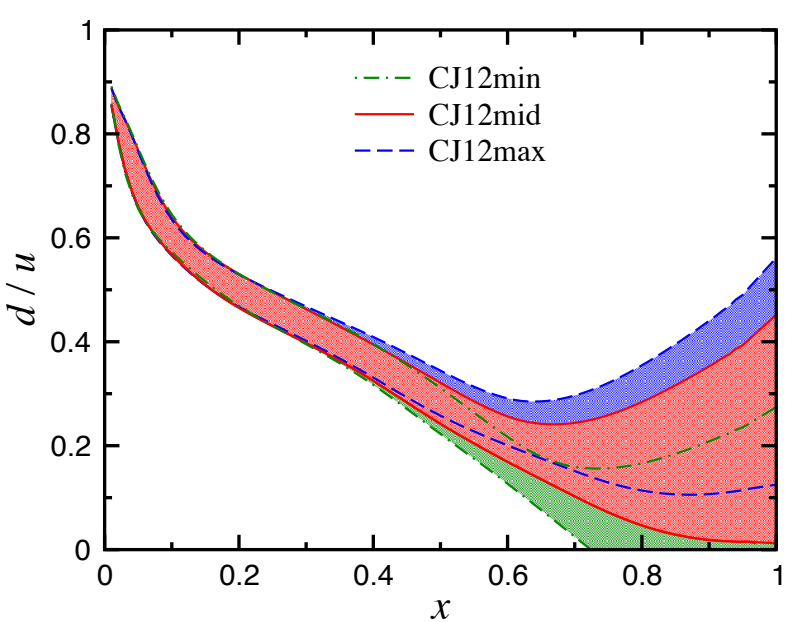

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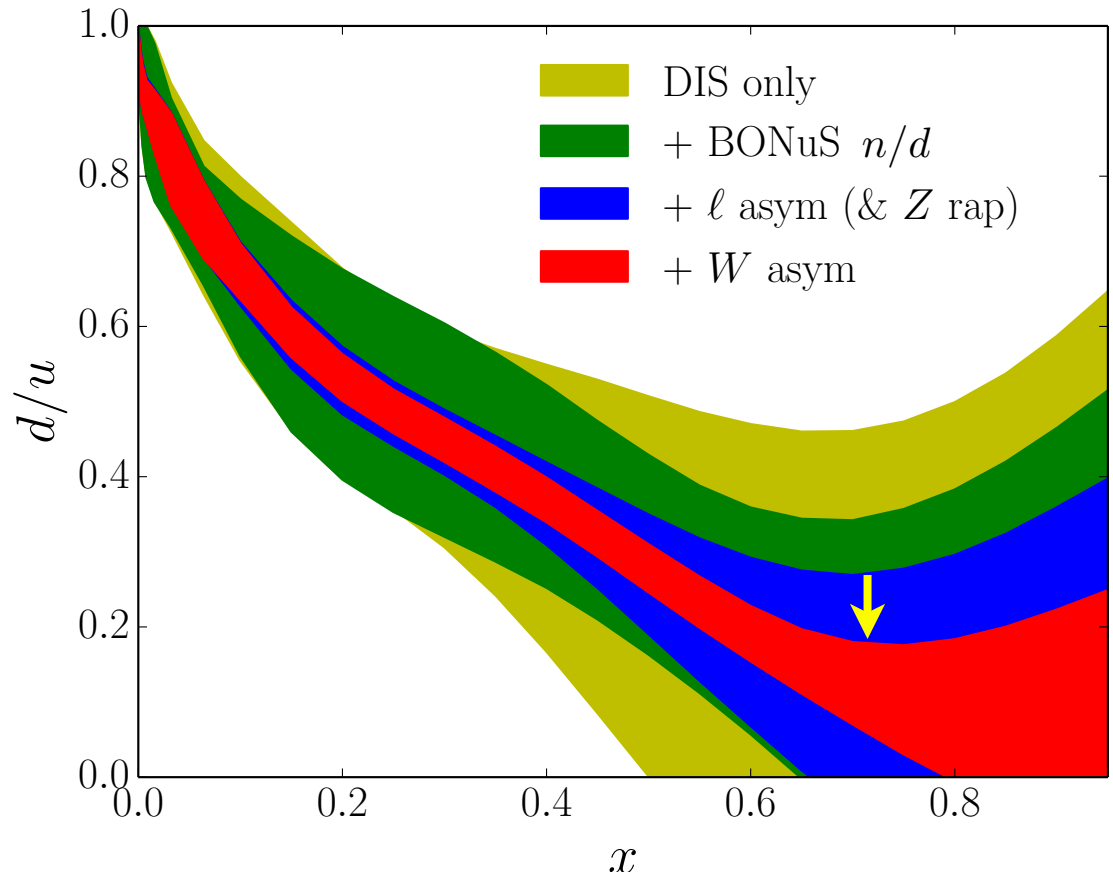
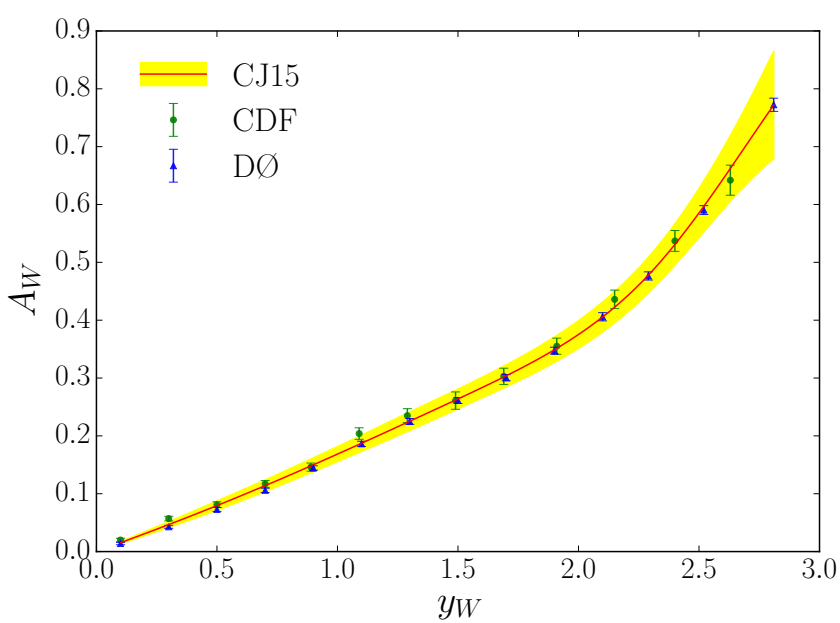


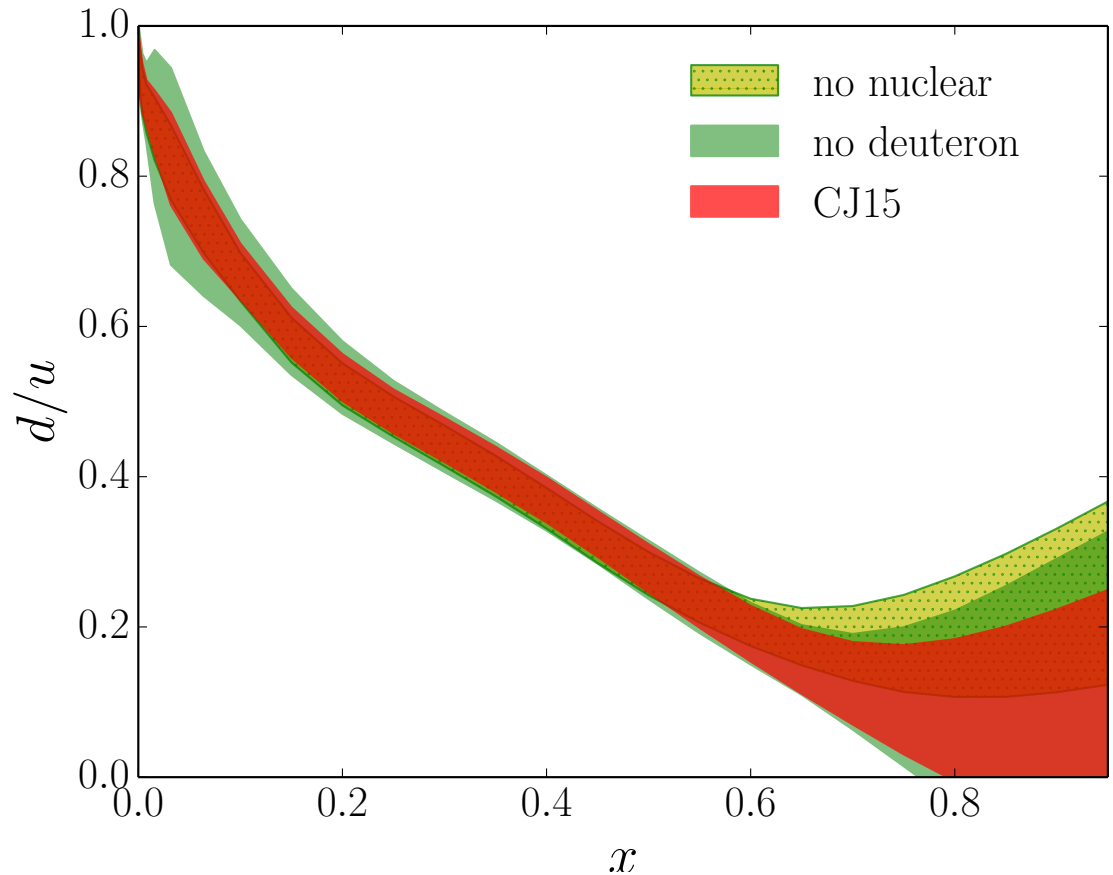


→ W asymmetry at large W rapidity more sensitive to d/u at high x

→ new D0 data reduce uncertainties at $x \sim 0.6 - 0.7$, strongly favor models with small (but nonzero) nuclear corrections

Effect of data sets of d/u

→ deuterium data, and proper treatment of nuclear corrections, are important for *accuracy* and *precision* of d/u determination at $x > 0.6$

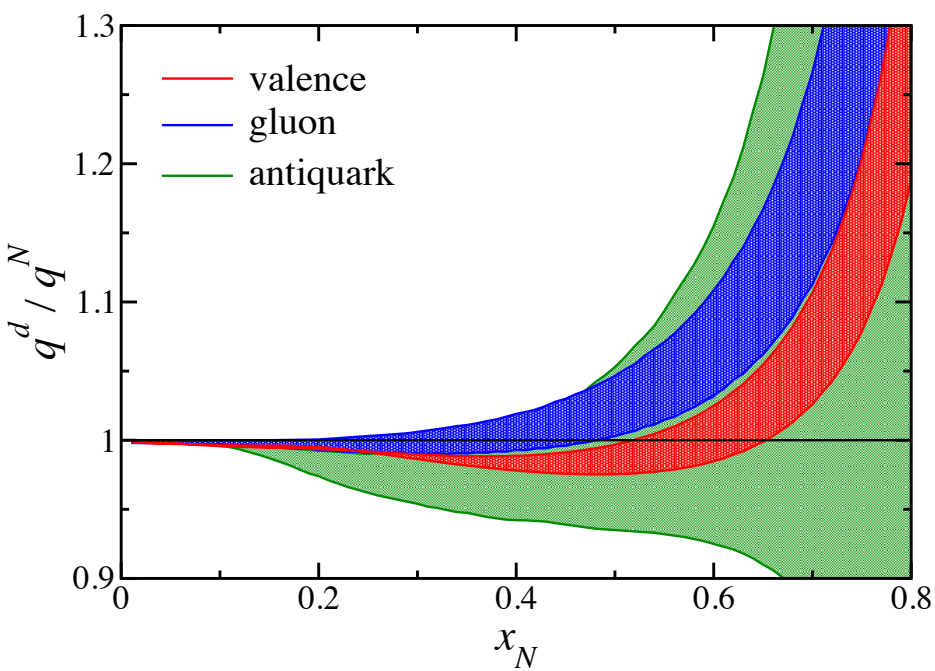


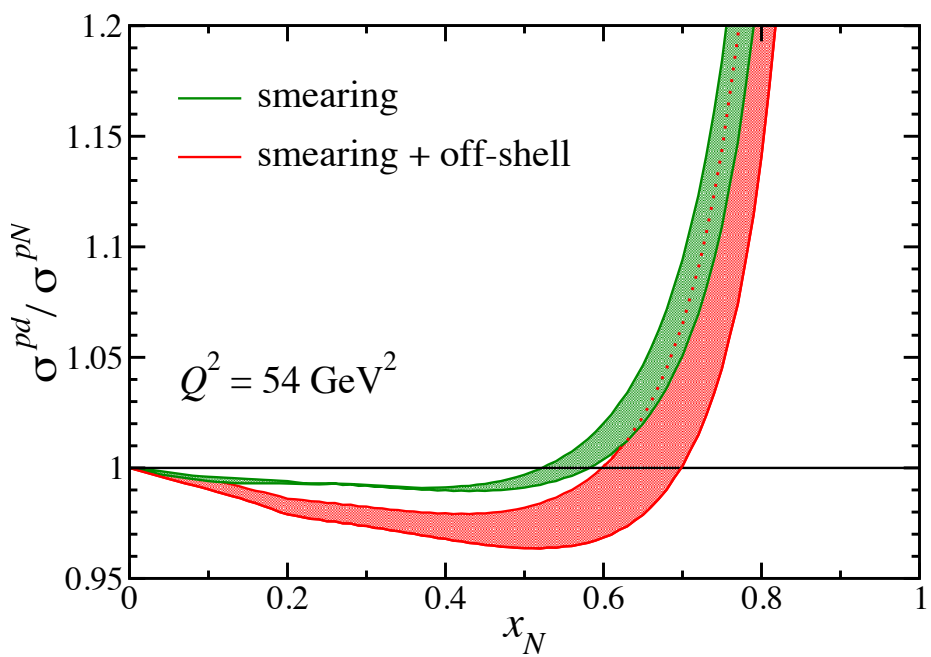
Light antiquark sea

- Flavor asymmetry $\bar{d} - \bar{u}$ in proton sea constrained mostly by FNAL E866 σ^{pd}/σ^{pp} Drell-Yan data

- Recently nuclear corrections to pd data have been computed in same framework (smearing + off-shell) as in DIS

  ⟶ requires nuclear modifications in antiquark and gluon PDFs

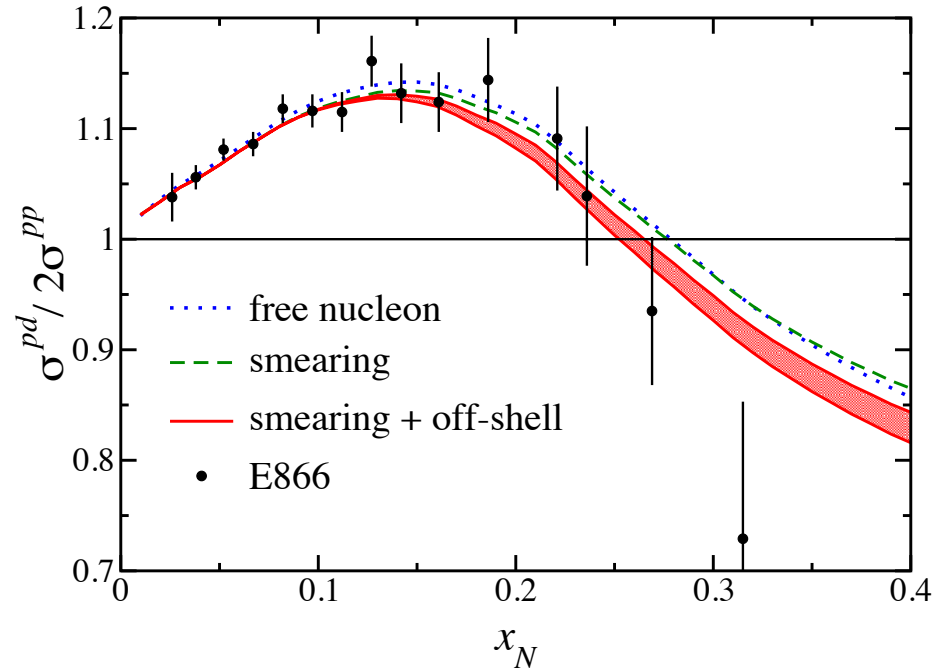




*Ehlers et al., PRD **90**, 014010 (2014)*

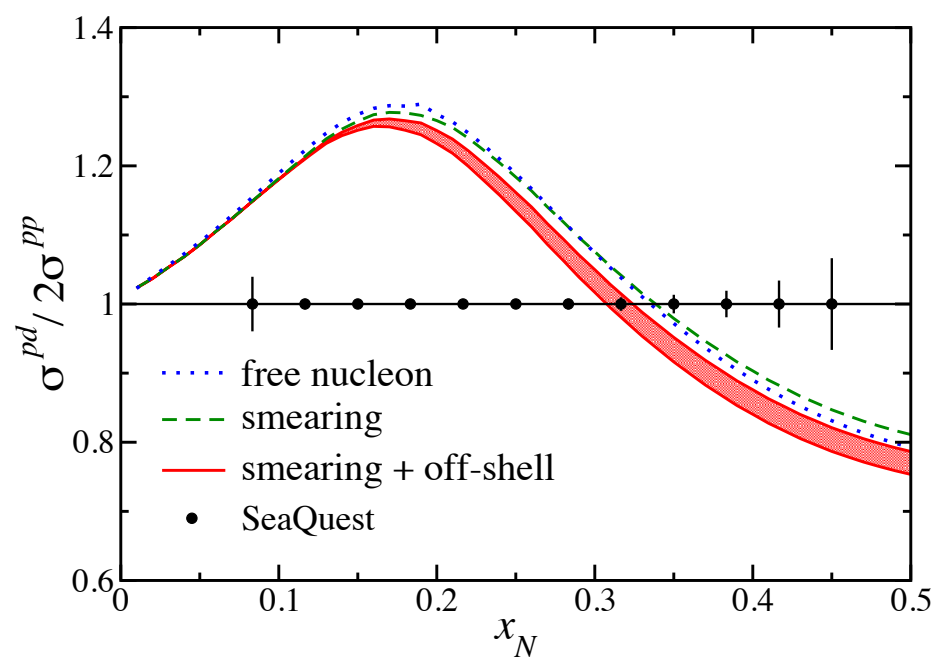
Light antiquark sea

- Modest effect at E866 kinematics, given large errors at high x



- More important effects expected at E906/SeaQuest kinematics at $x > 0.2$

  → relevant for possible sign change of $\bar{d} - \bar{u}$ at high x ?



Summary & outlook

- New CJ15 PDFs will be released soon (~ autumn 2015)

  → constraints on large-x PDFs from new data on lepton & W-asymmetries; first JLab F_2^n data

  → reduced nuclear uncertainties on d quark *cf.* CJ12, with smaller d/u ratio for $x \to 1$ (smaller nuclear corrections)

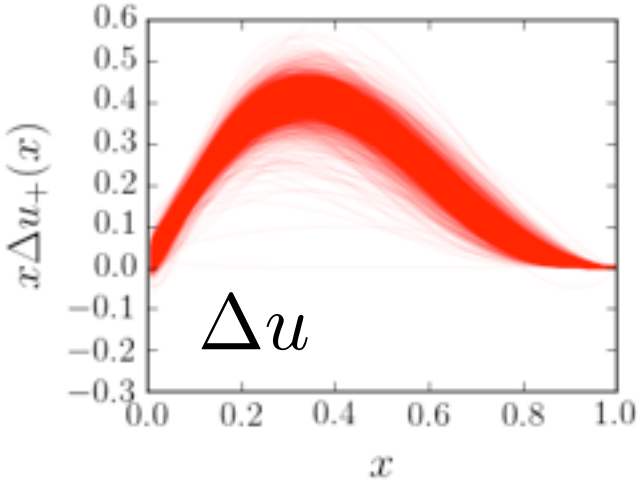
  → treatment of nuclear corrections in deuteron extended to sea quarks and gluons
  (important for pd Drell-Yan cross sections for $\bar{q}$, and for F_L)

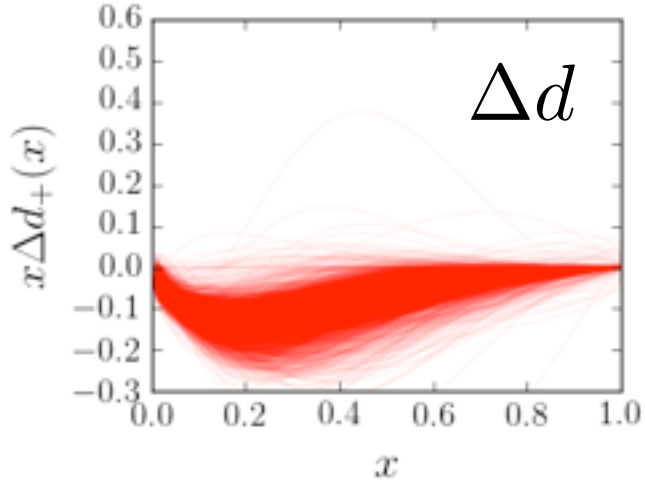
- Future direction: minimize input parameter bias through Monte Carlo analysis

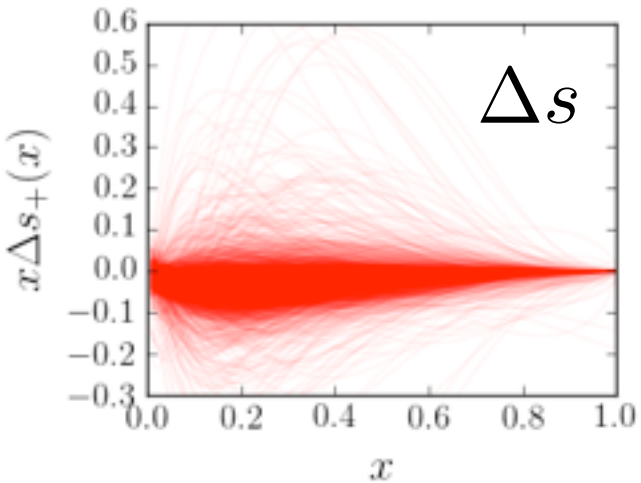
  → explore parameter space through MC sampling

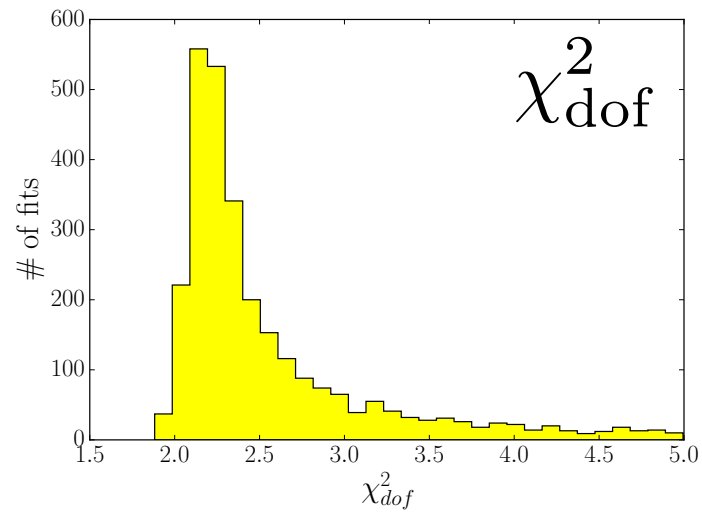
  → no ambiguity in "tolerance criteria" (or assumptions about Gaussian errors)

  → cross validation (random data partition) & bootstrap (data resampling)

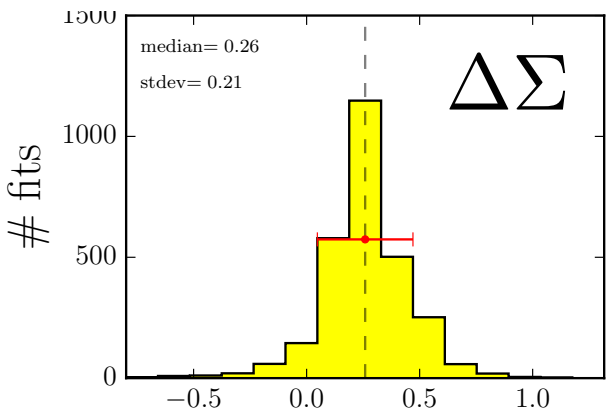








noncentral χ^2 distribution



JAM (JLab Angular Momentum) polarized PDF analysis:
Nobuo Sato et al. (2015)

- ~ 10,000 fits, ~ 3,000 data points (~ 40 parameters)
- fast implementation in Mellin space
- easily extendable to unpolarized sector

Thank you

Key to symbols
Interchange stations
Step-free access from street to train
Step-free access from street to platform
National Rail
Riverboat services
Tramlink
Airport
Emirates Air Line
Explanation of zones
This diagram is an evolution of the original design conceived in 1931 by Harry Beck
Correct at time of going to print: May 2015