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

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Eric Christy, Thia Keppel, Simona Malace, Peter Monaghan (experiment)

Outline

- CJ PDFs – motivations and goals

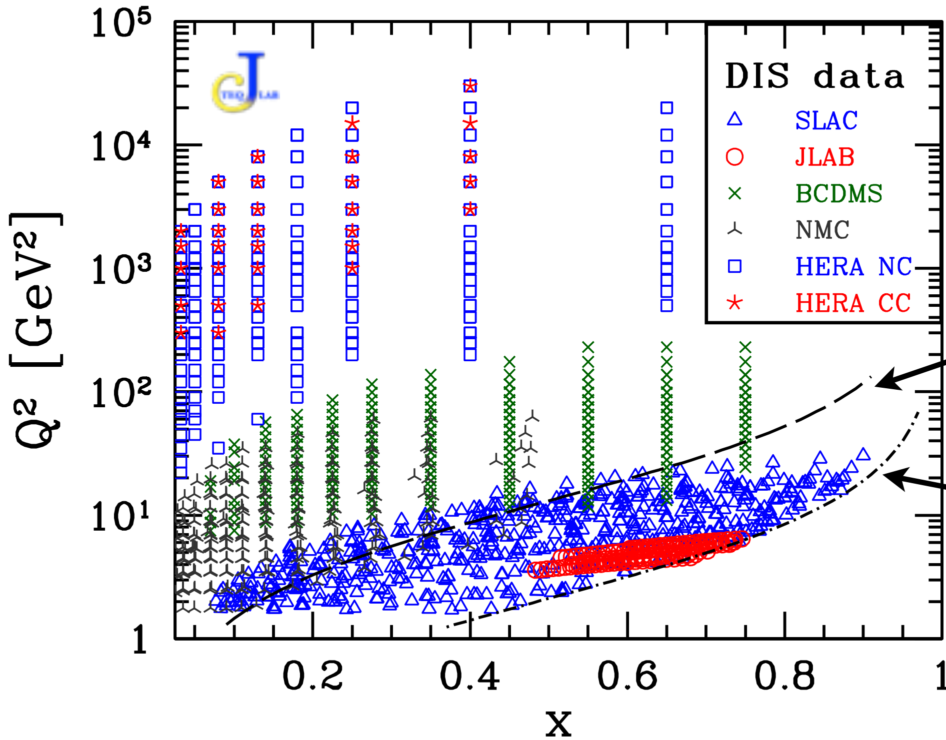
- New developments since CJ12
  - → more complete treatment of nuclear corrections
  - → impact of new lepton & W asymmetry data on d/u
  - → inclusion of JLab data
  - → analysis of $\bar{d} - \bar{u}$ at large x

- 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

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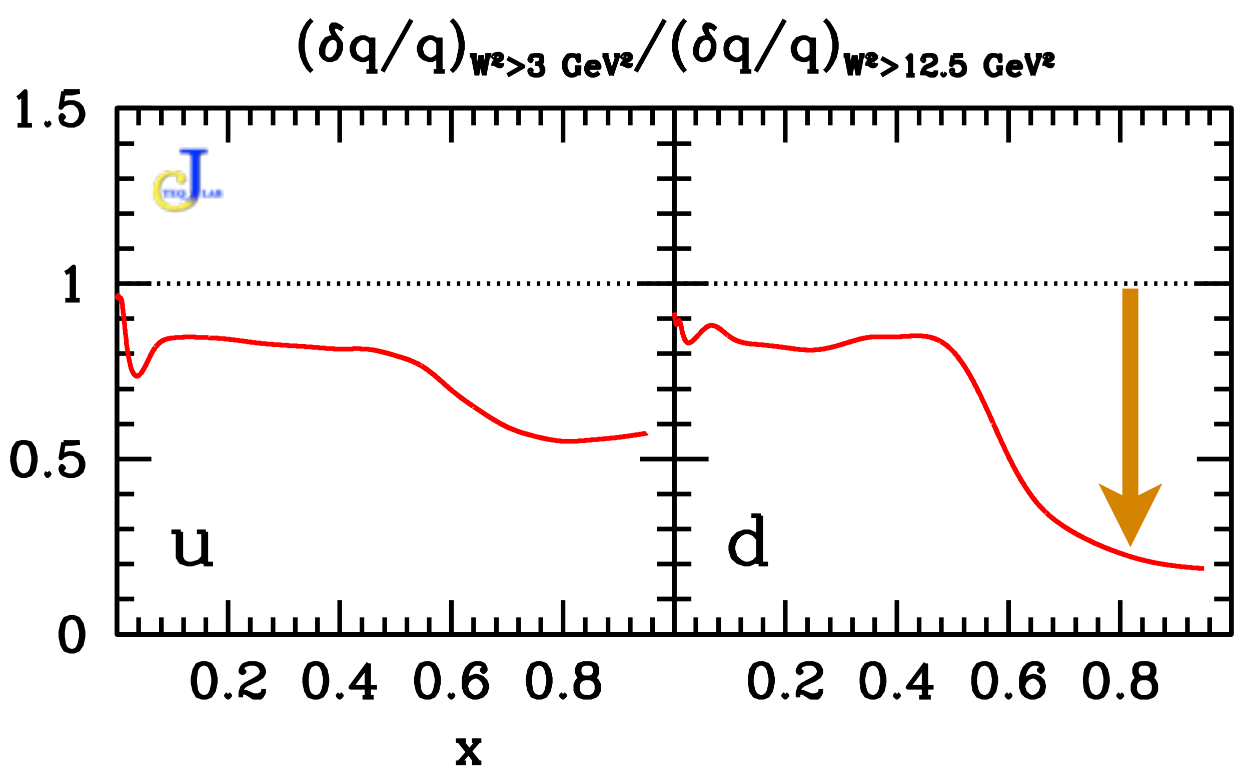


→ significant error reduction at high x

- 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)

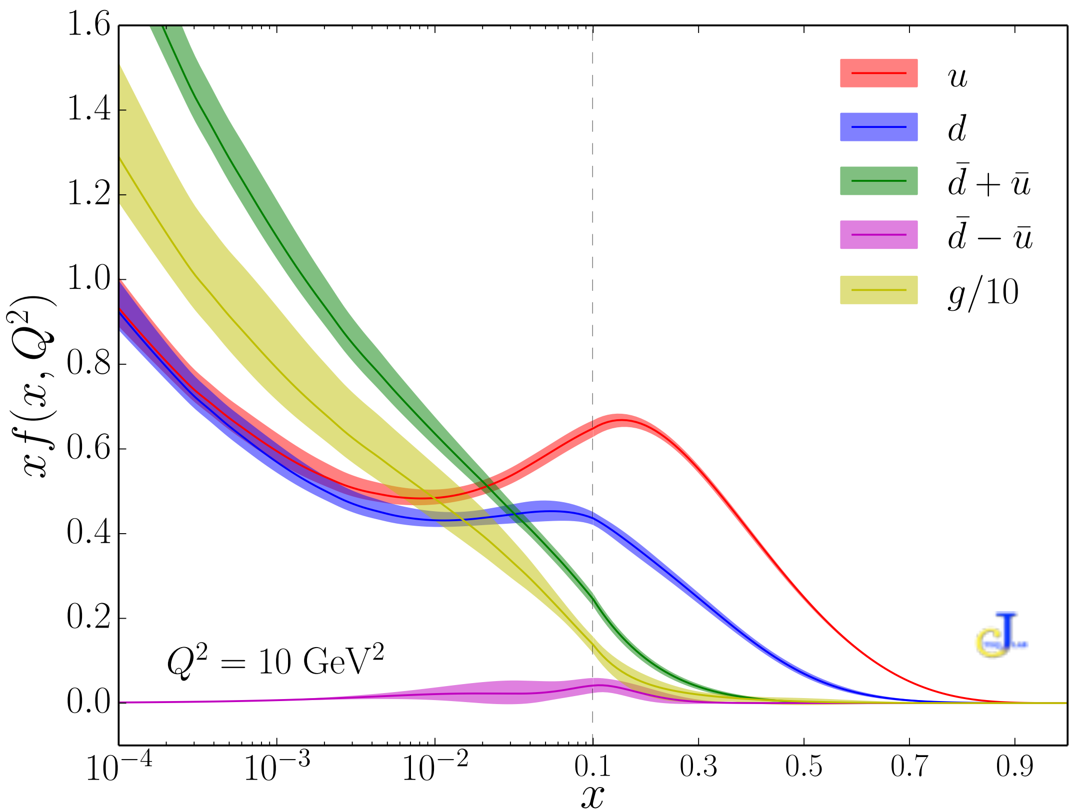
  → binding + Fermi motion (well known), nucleon off-shell (less well known)

  → 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	← BONuS F_2^n/F_2^d
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	← D0 A_l
	DØ (e) [33]	13	27	56	← D0 A_l
	CDF (W) [34]	13	15	12	
	DØ (W) [35]	14	16	47	← D0 A_W
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**	

CJ15 PDFs



our "biased" fit form *

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

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

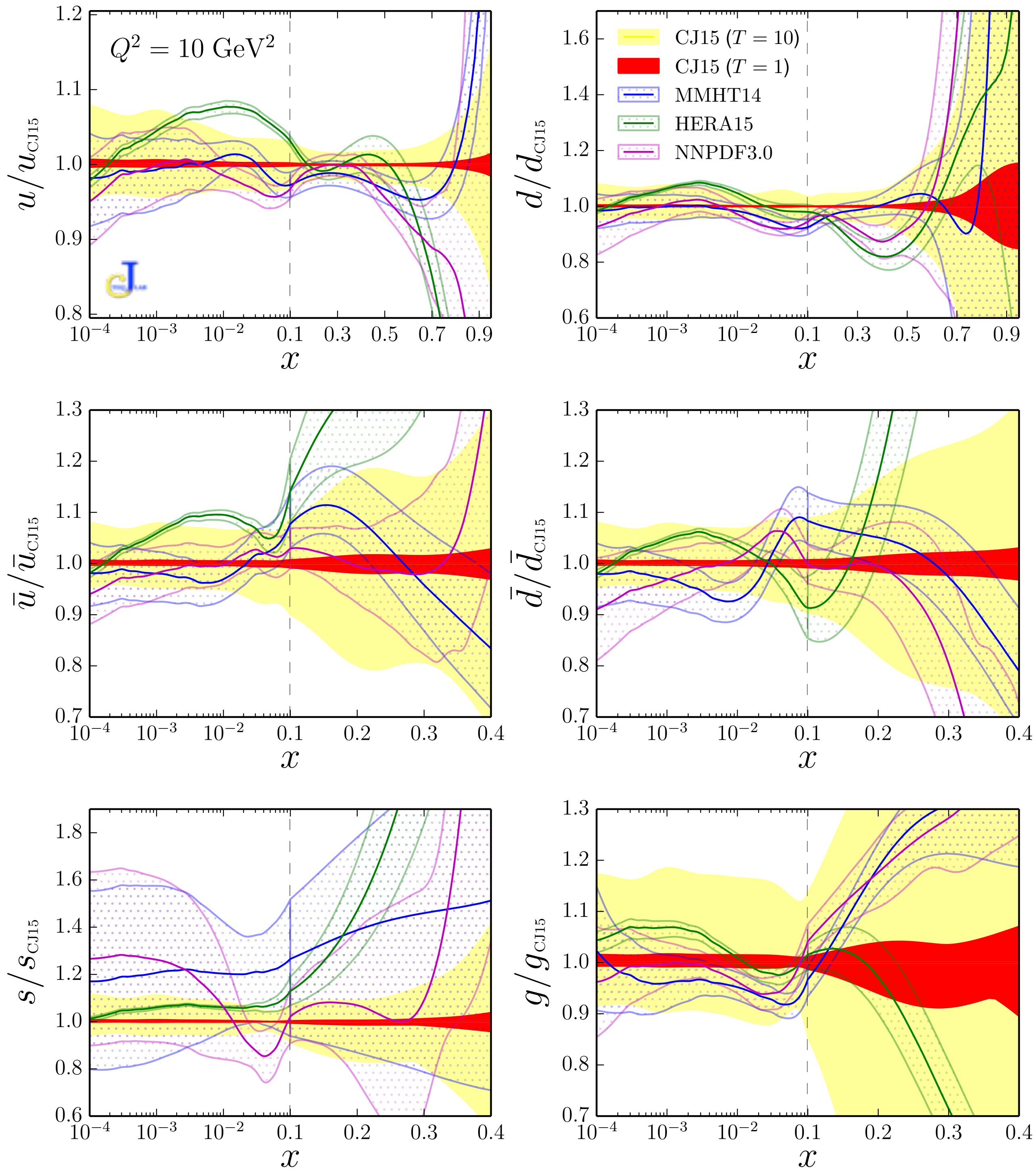
Jimenez-Delgado et al., PRL ***114****, 082002 (2015)*

CJ15 vs. other PDFs

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

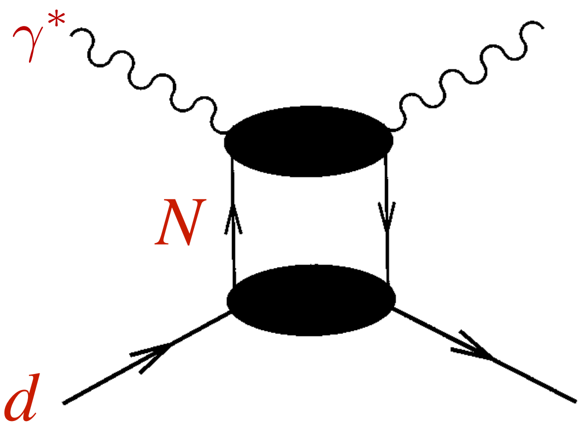
→ HERAPDF15 errors comparable to T=1, others generally between T=1 & 10

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



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

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

momentum fraction of d carried by N

→ 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

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

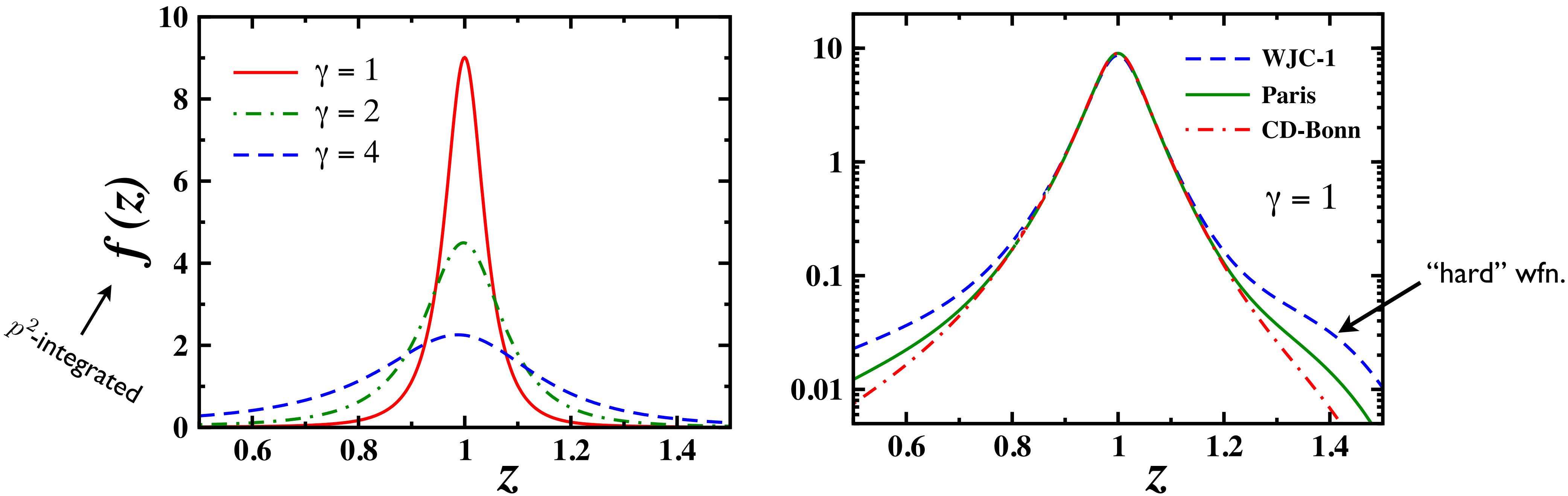
$$f^{(\mathrm{off})}(z) = \int dp^2\, \frac{p^2 - M^2}{M^2} f_{N/d}(z, p^2)$$

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

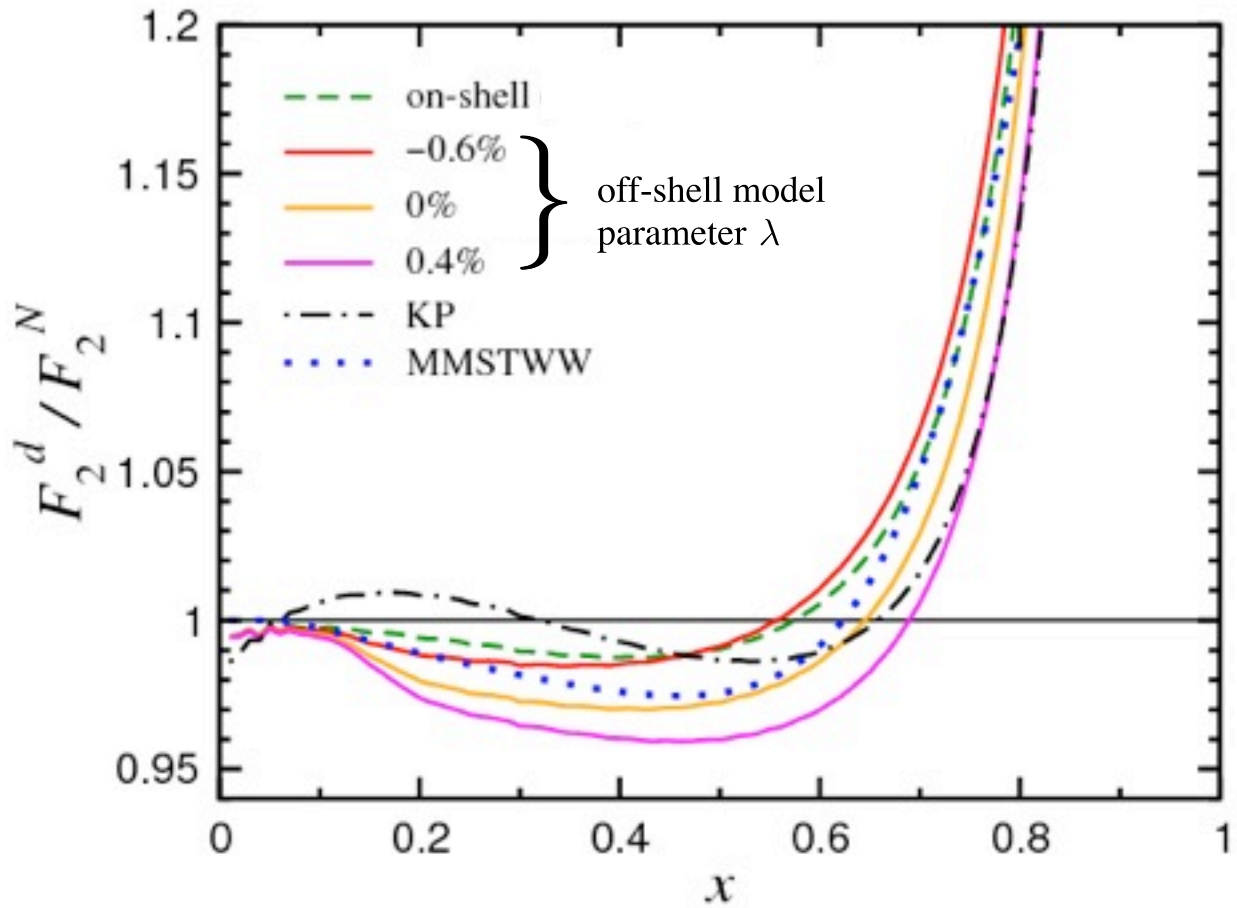
→ off-shell "rescaling" parameter $\lambda = \dfrac{\partial \log \Lambda^2}{\partial p^2}$ fitted

→ 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)*

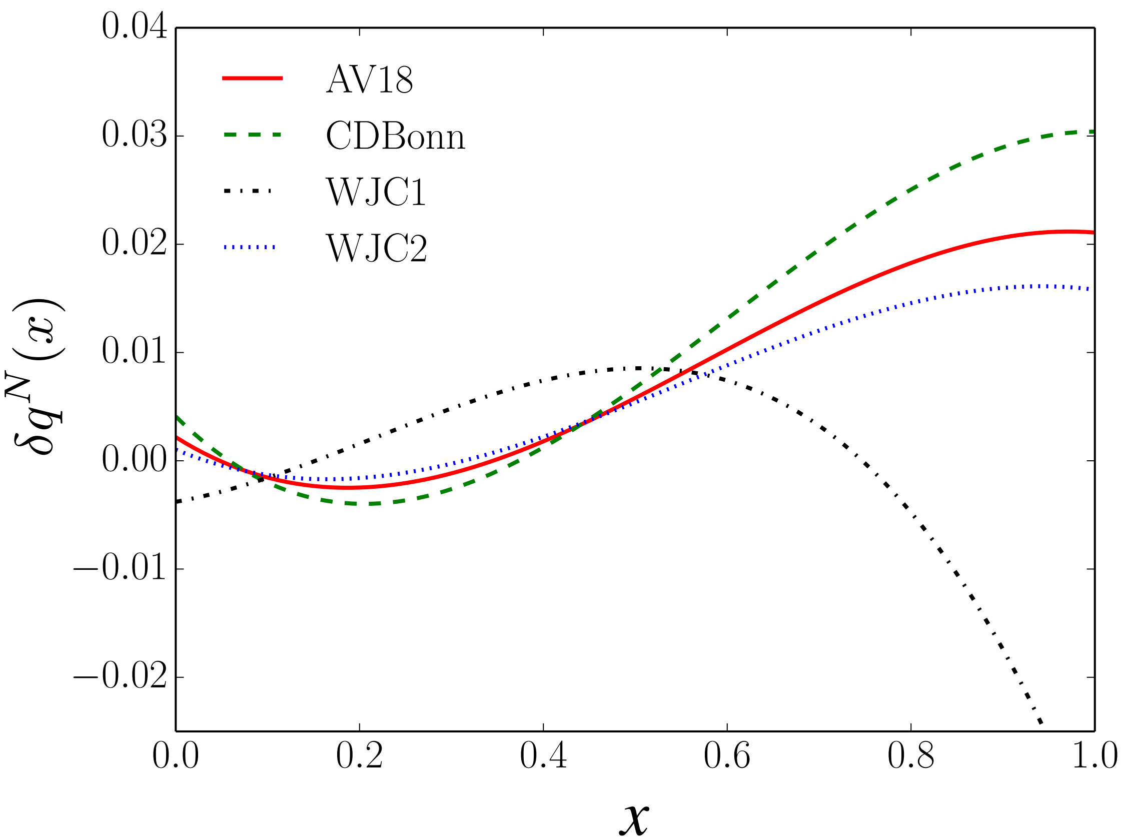
→ fit 2 of $\{C, x_0, x_1\}$ for given deuteron wave function; fix third parameter from normalization condition

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

→ 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



deuteron wave functions from *NN* scattering

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

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

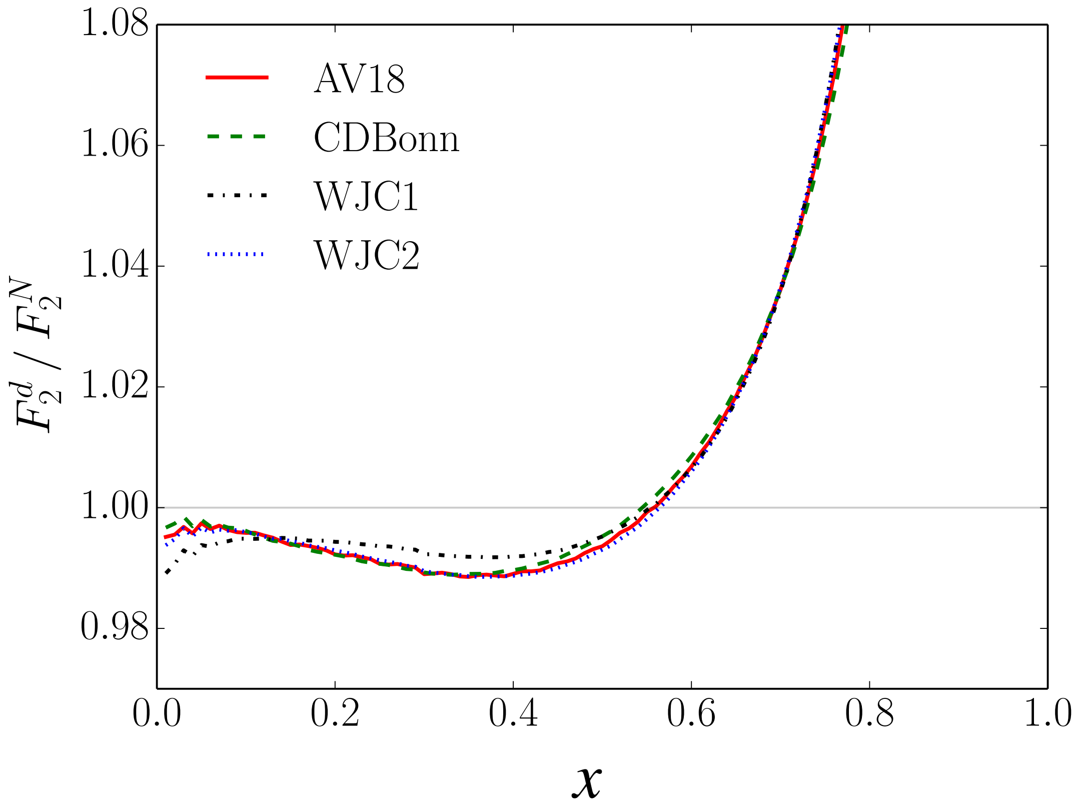
WJC: *Gross, Stadler, PRC* ***82****, 034004 (2010)*

(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

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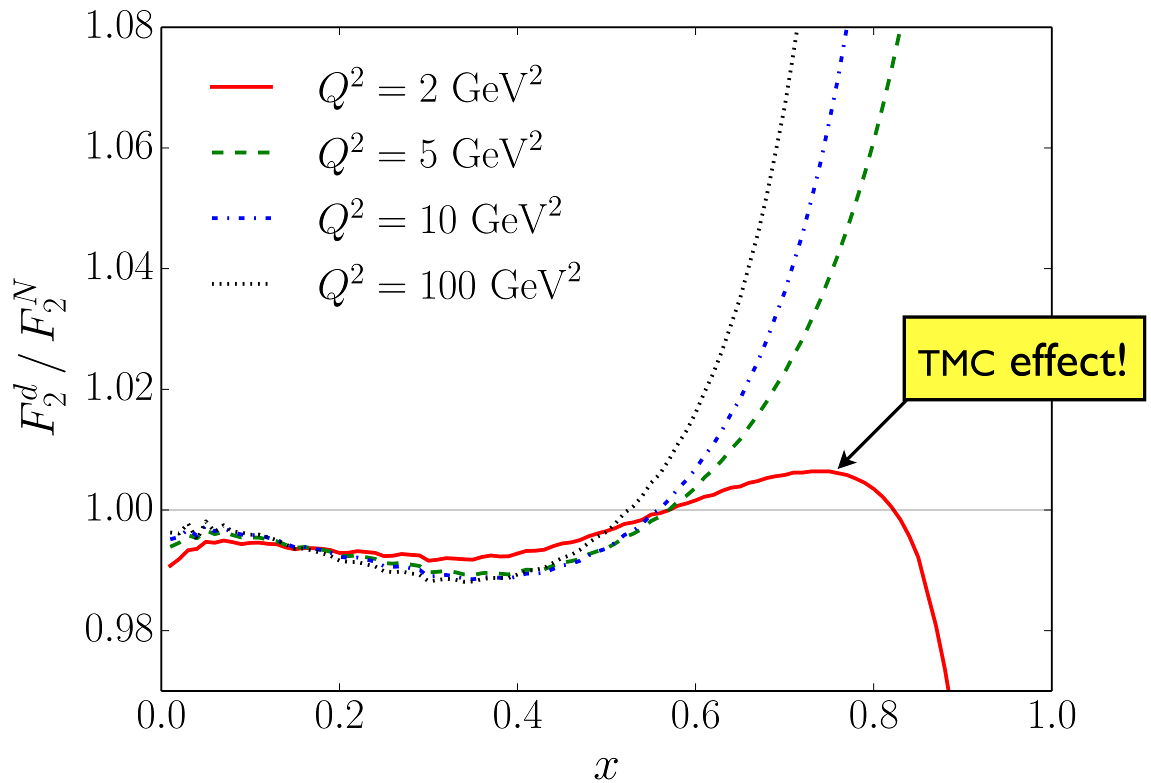
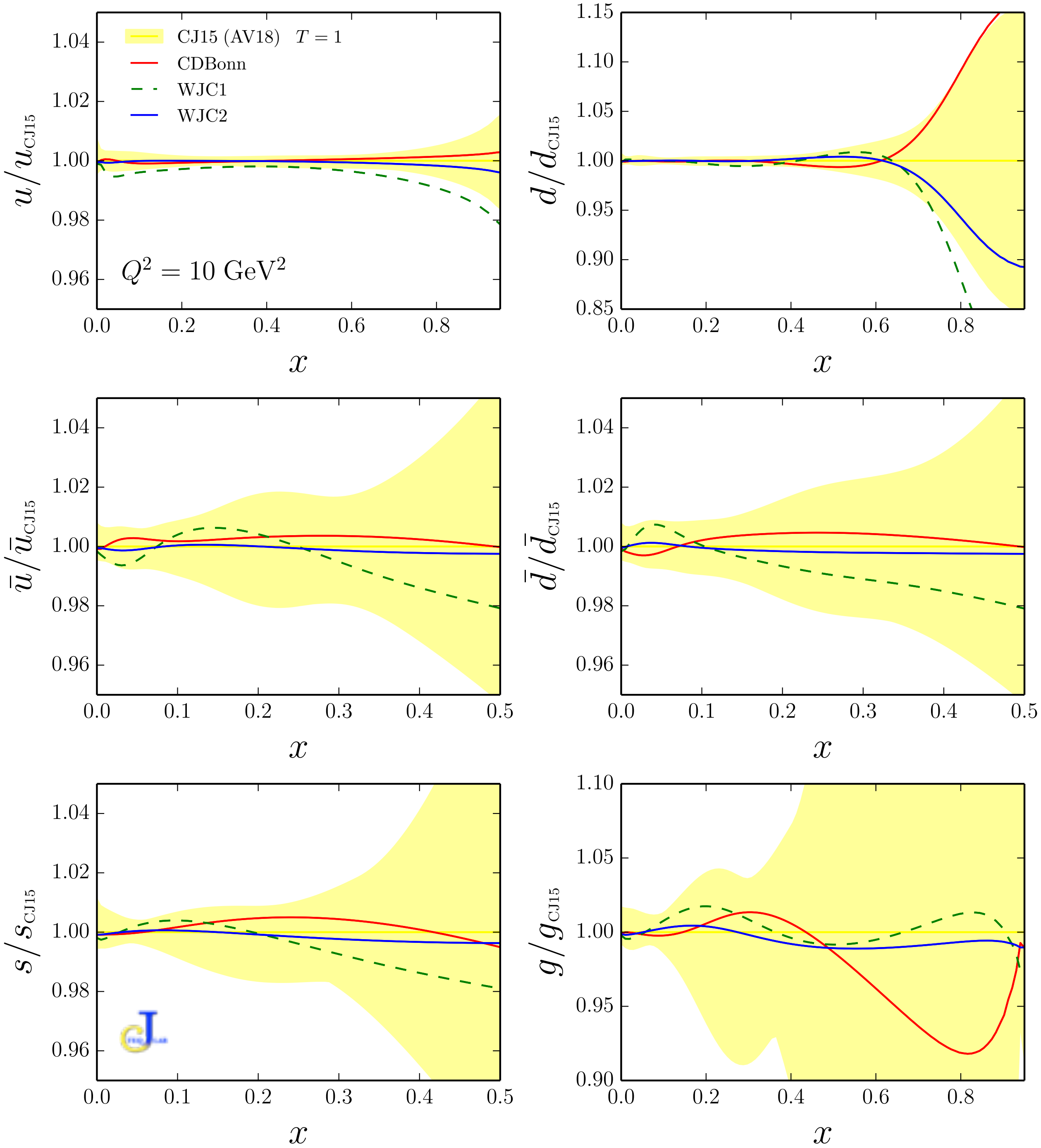


→ ratio has significant Q^2 dependence at low Q^2 from target mass effects

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



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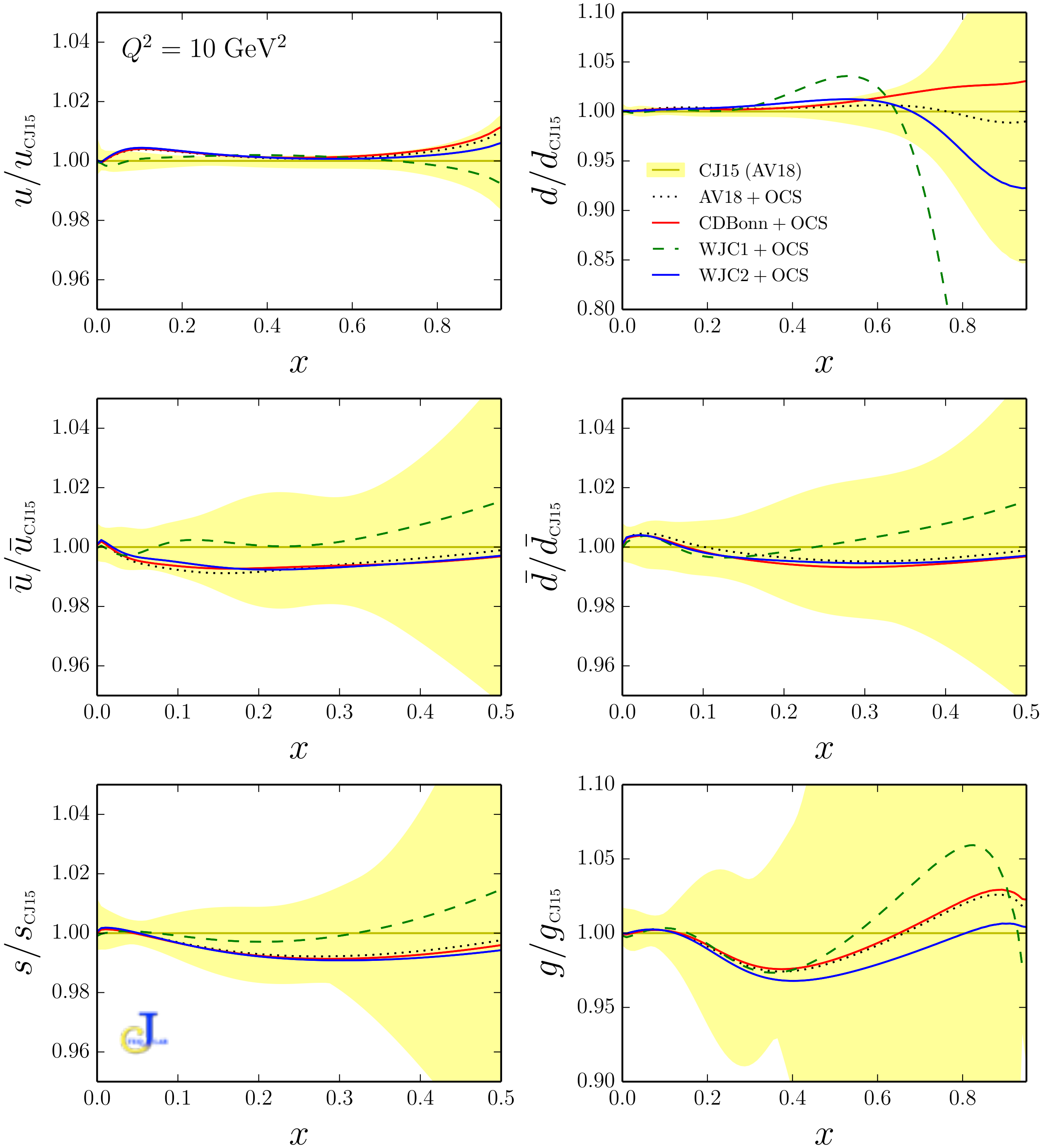
→ off-shell model dep. (*cf.* OCS) generally weak except for d PDF



Nuclear corrections & CJ15 PDFs

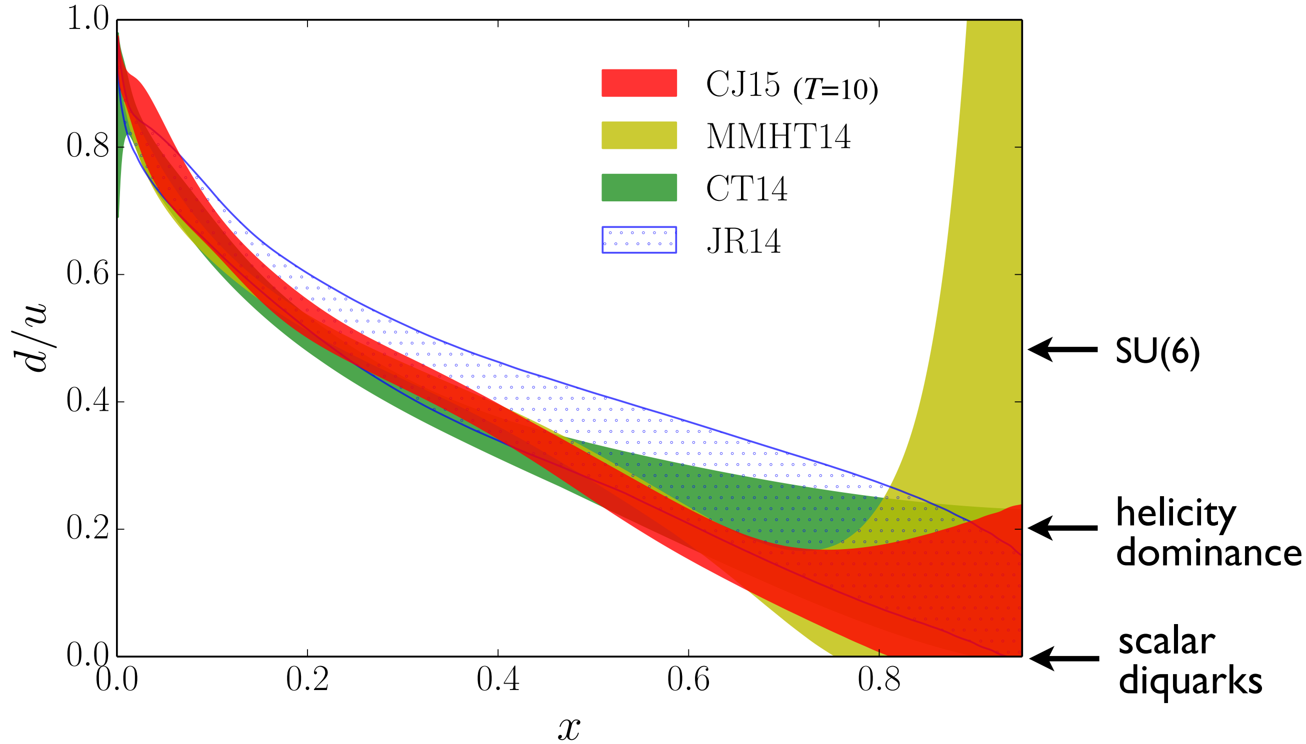
→ d/u ratio at high x of interest for nonperturbative models of nucleon

→ more flexible parametrization

$$d \rightarrow d + b\,x^c\,u$$

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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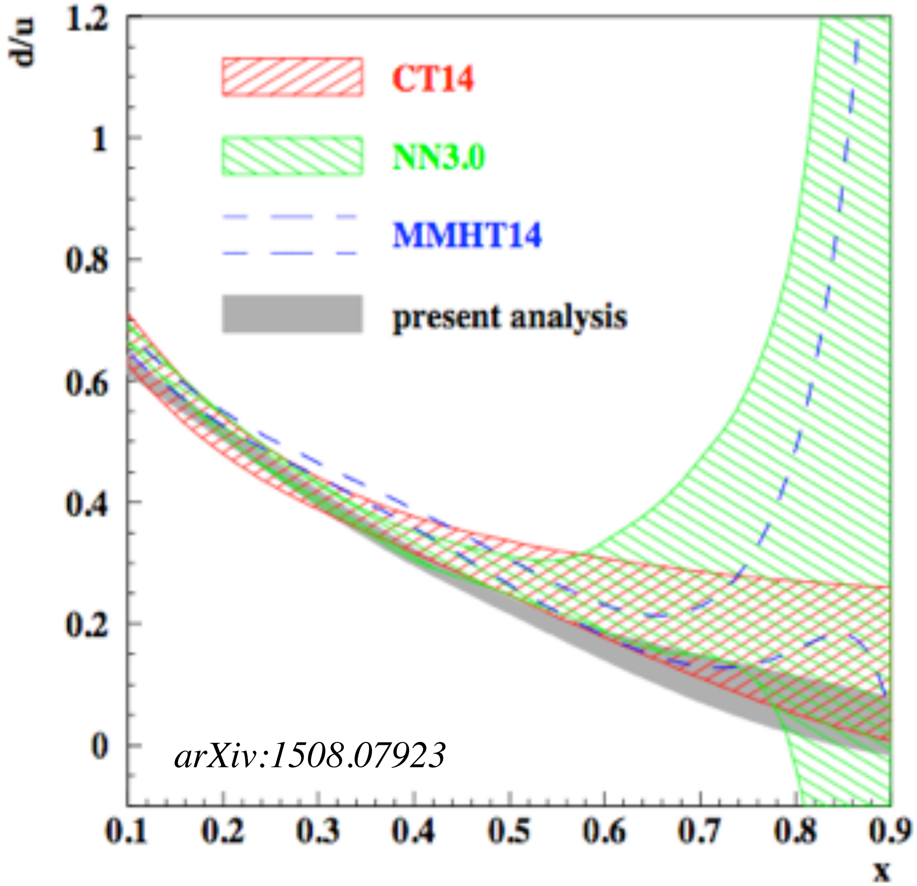
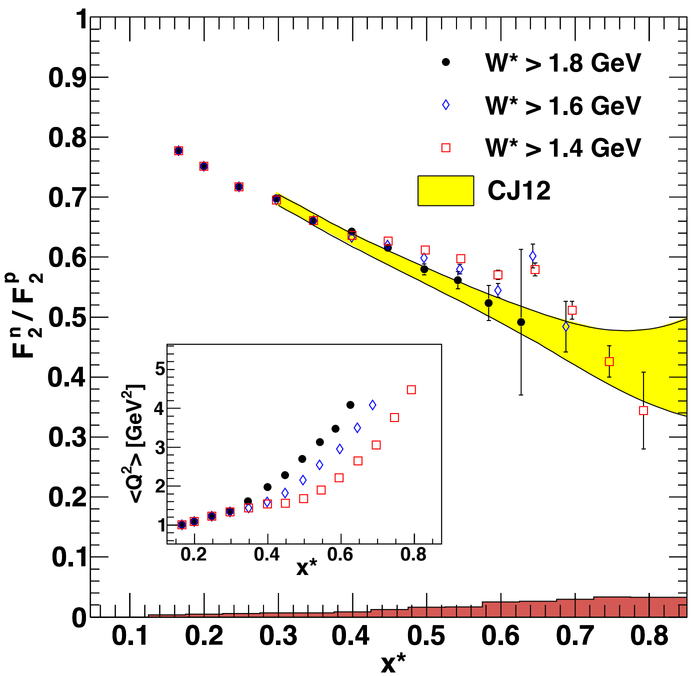


ABMP15: includes new lepton asymmetries, K–P nuclear corrections

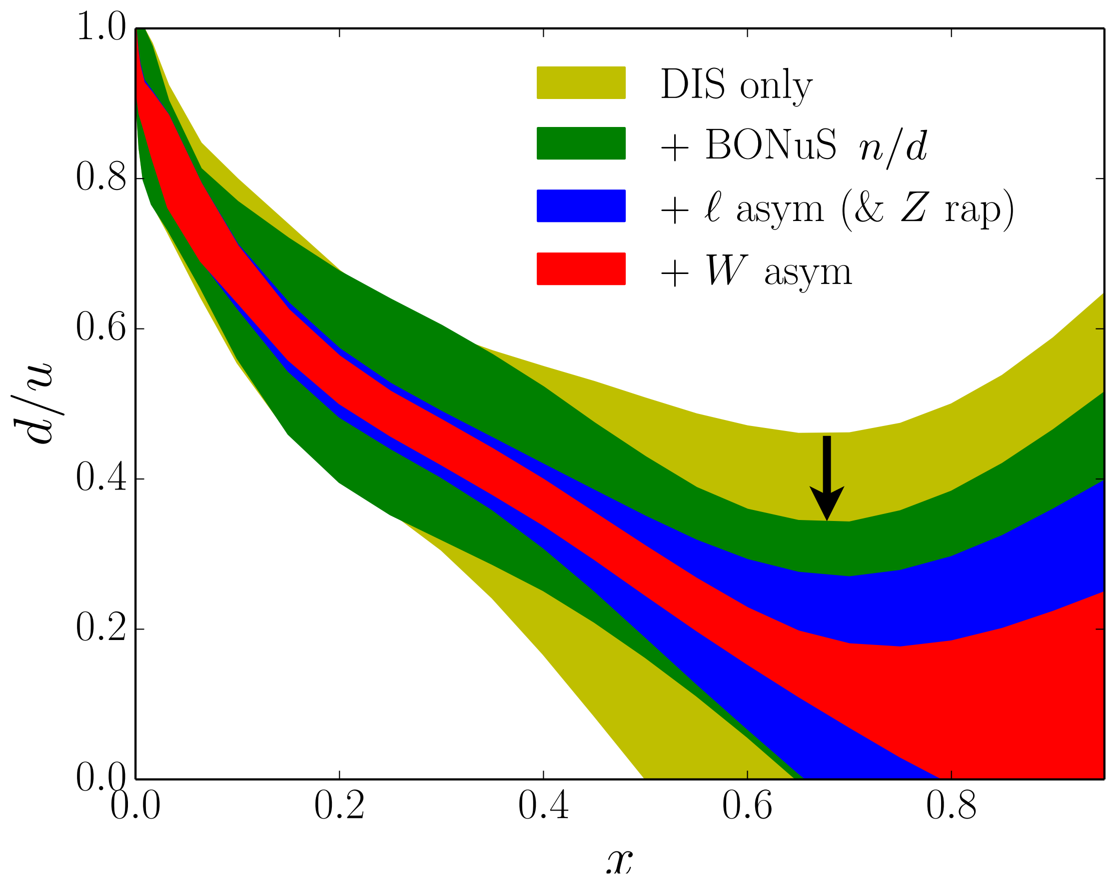
Effect of data sets of d/u

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

BONuS: spectator proton tagging in semi-inclusive ed DIS



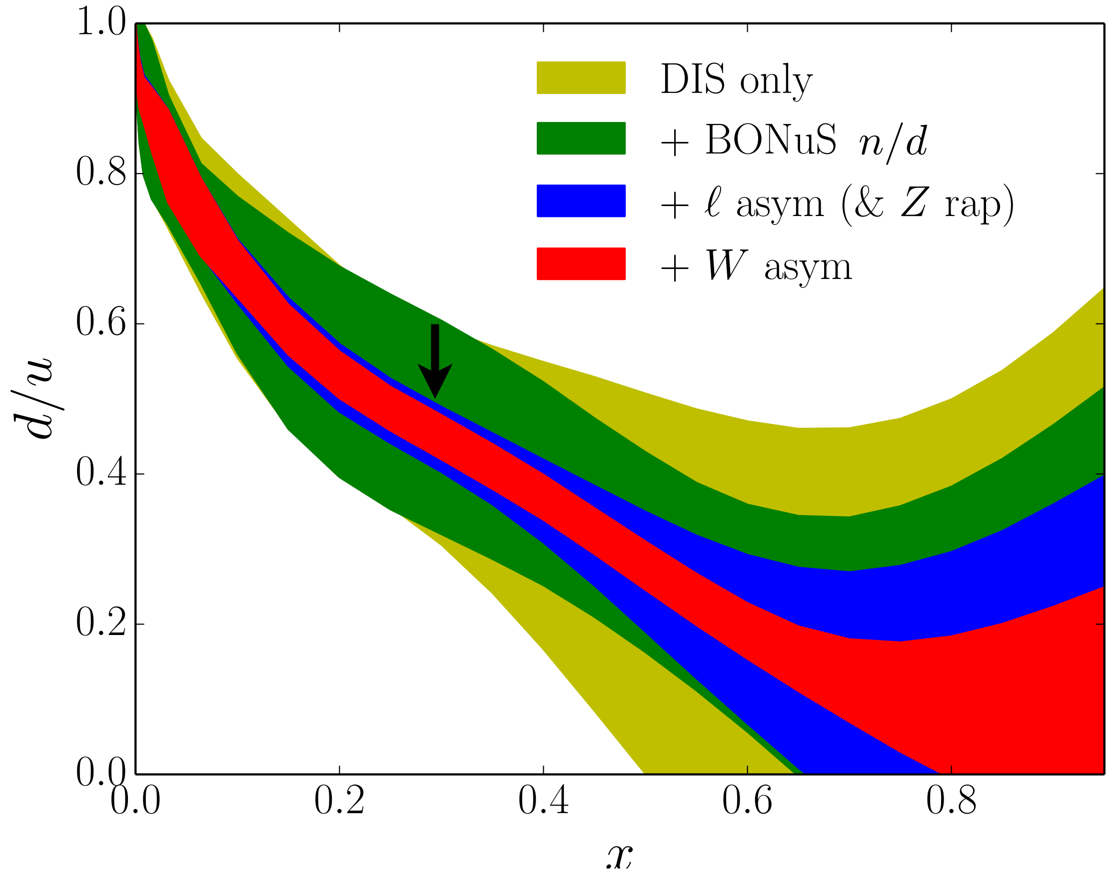
Baillie et al.
*PRL **108**, 142001 (2012)*

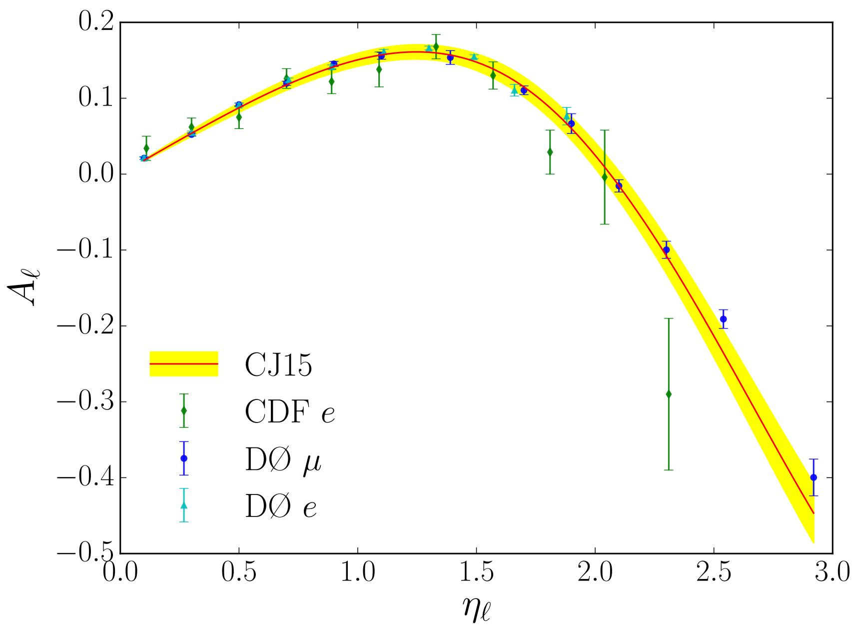


Effect of data sets of d/u

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

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





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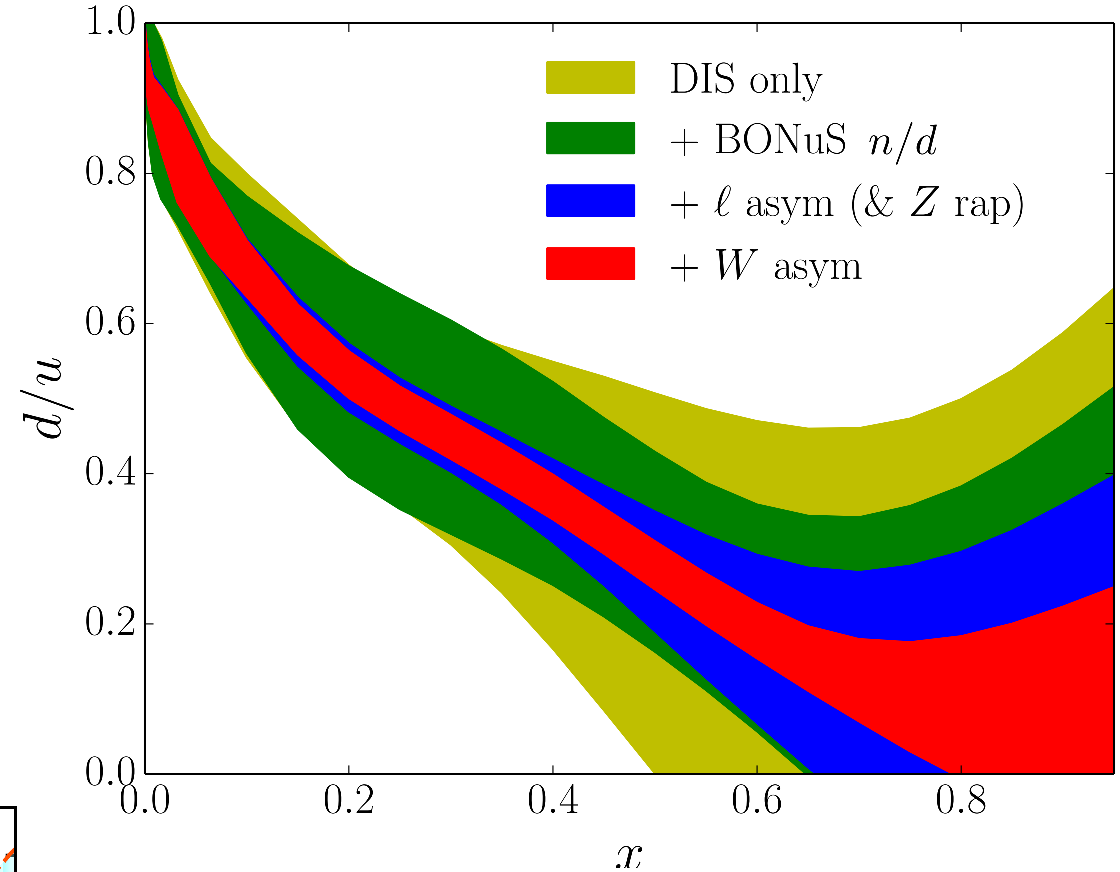

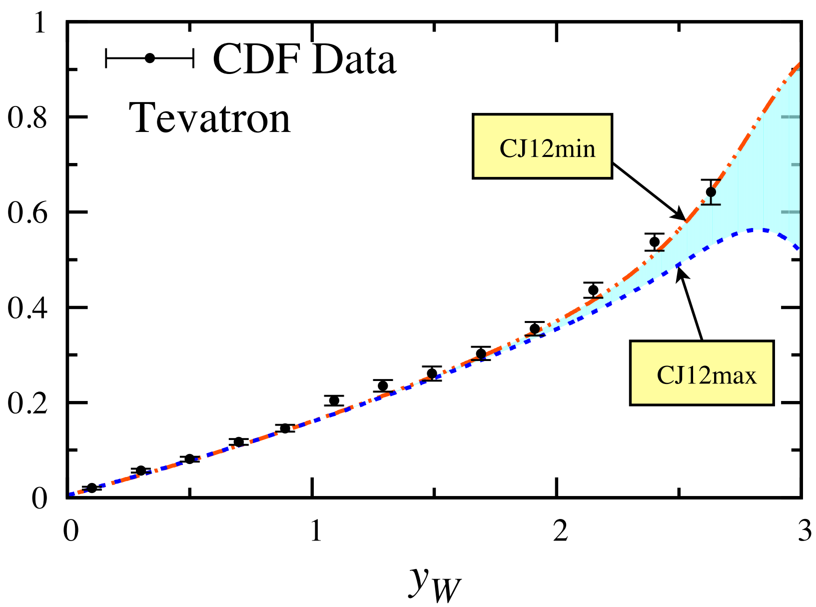

→ W asymmetry at large W rapidity more sensitive to d/u at high x

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

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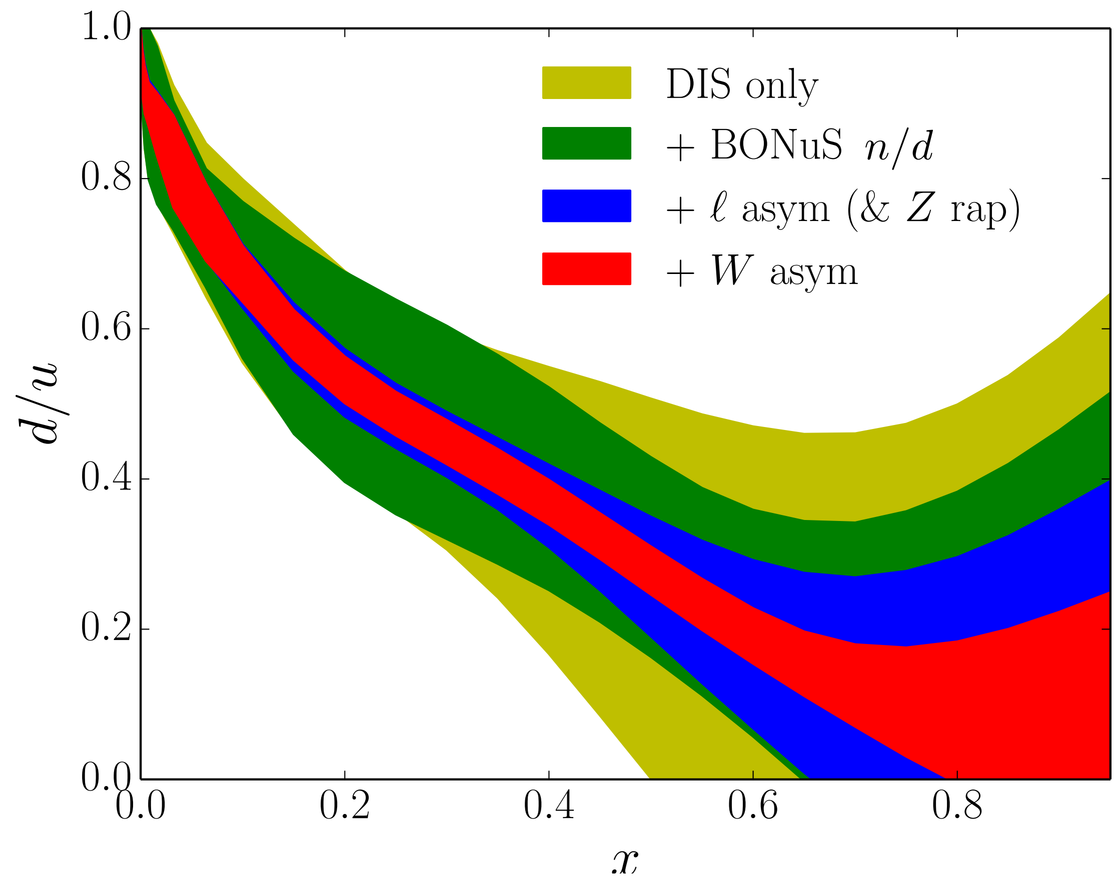

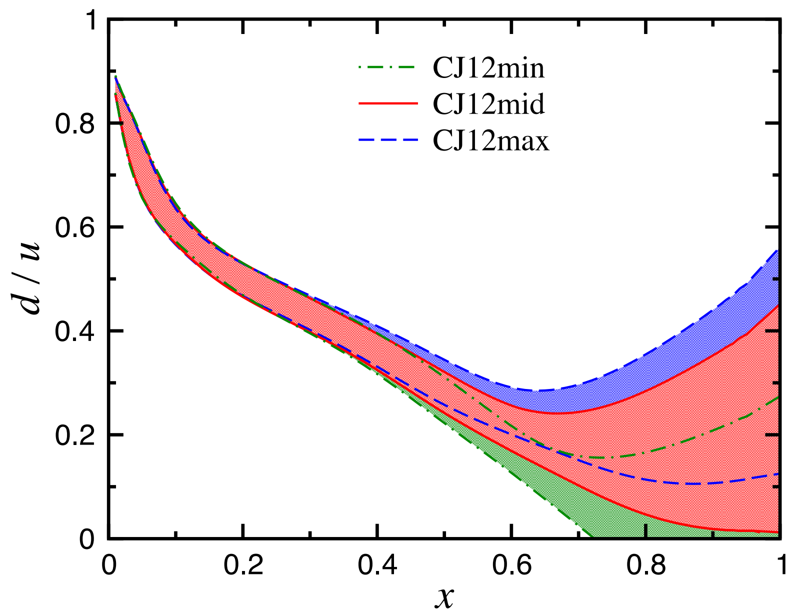

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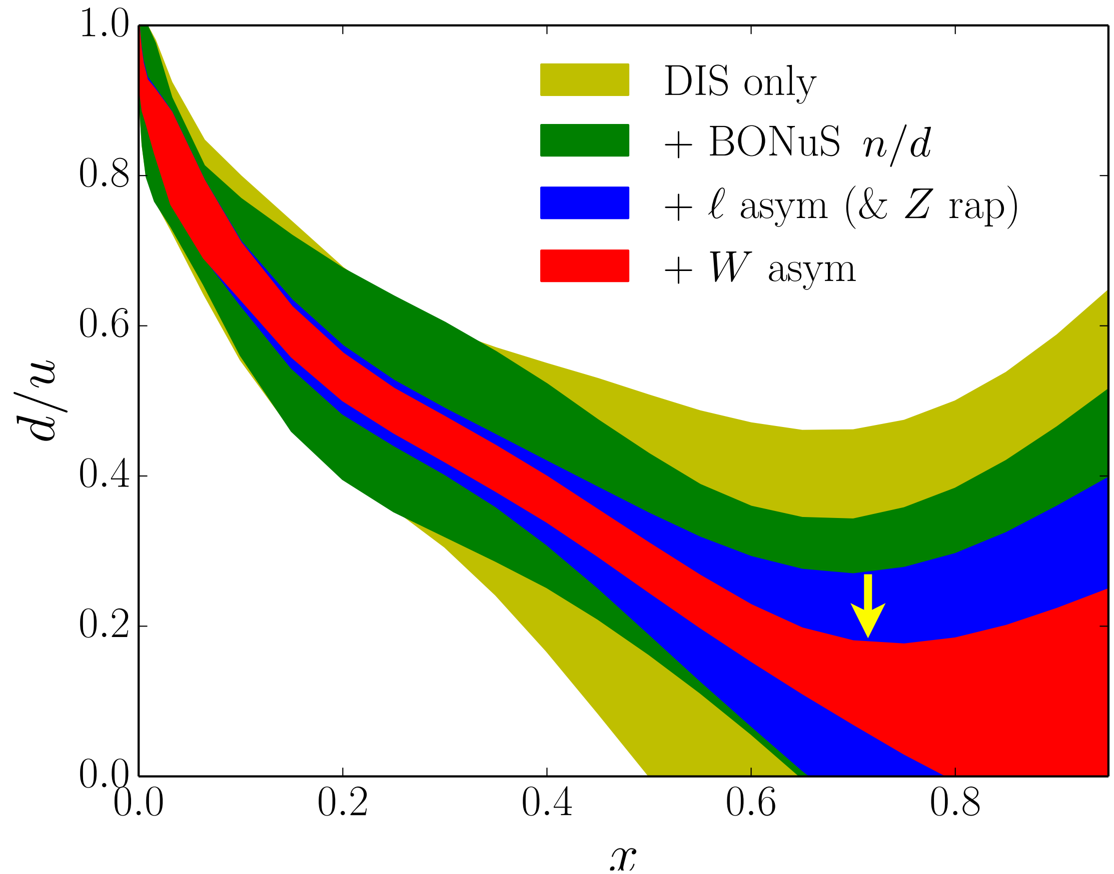
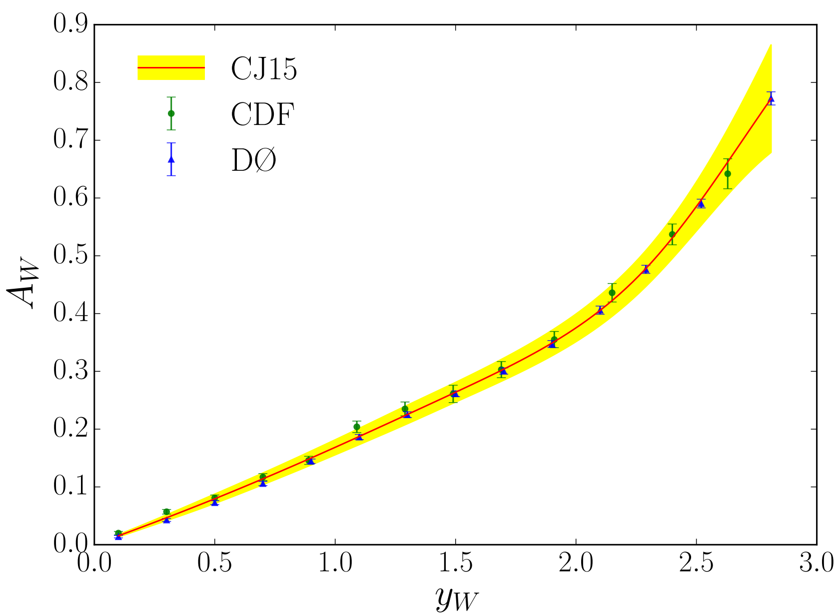




→ W asymmetry at large W rapidity more sensitive to d/u at high x

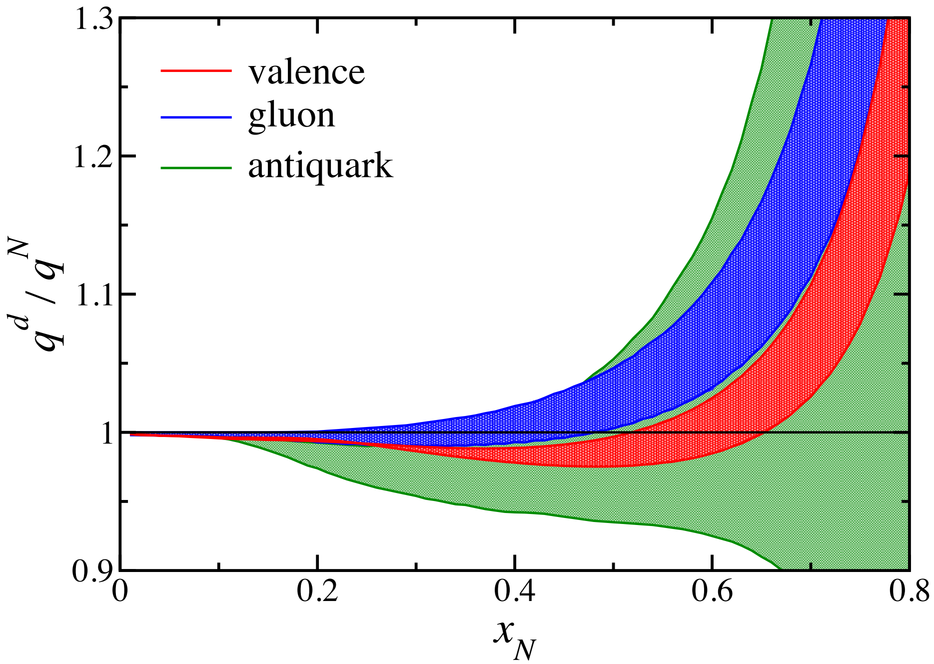
→ new D0 data reduce uncertainties at $x \sim 0.6 - 0.7$, strongly favor models with small (but nonzero) nuclear corrections

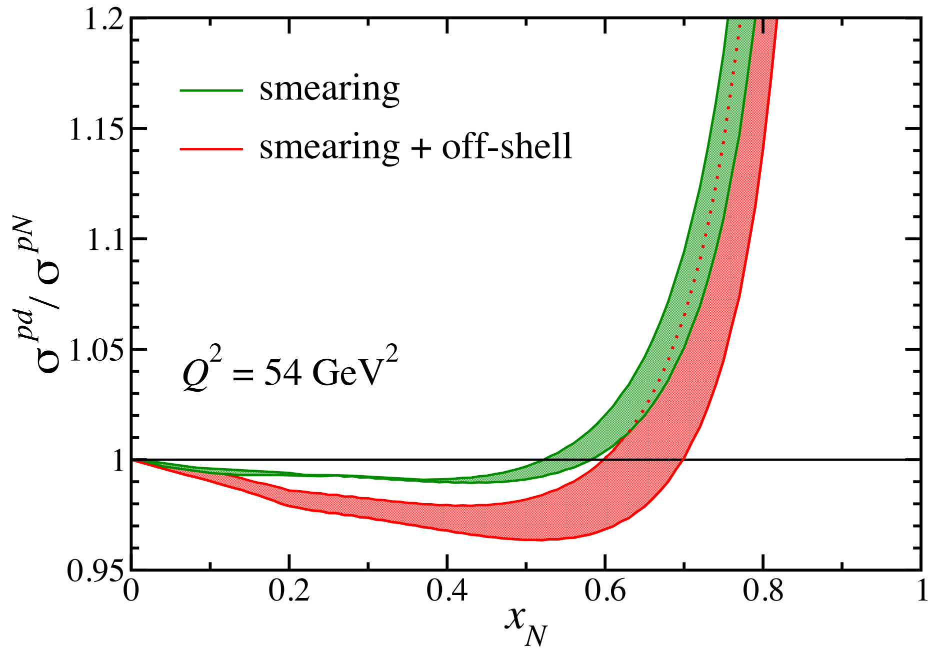
Light antiquark sea

- 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

  $\longrightarrow$ requires nuclear modifications in antiquark and gluon PDFs

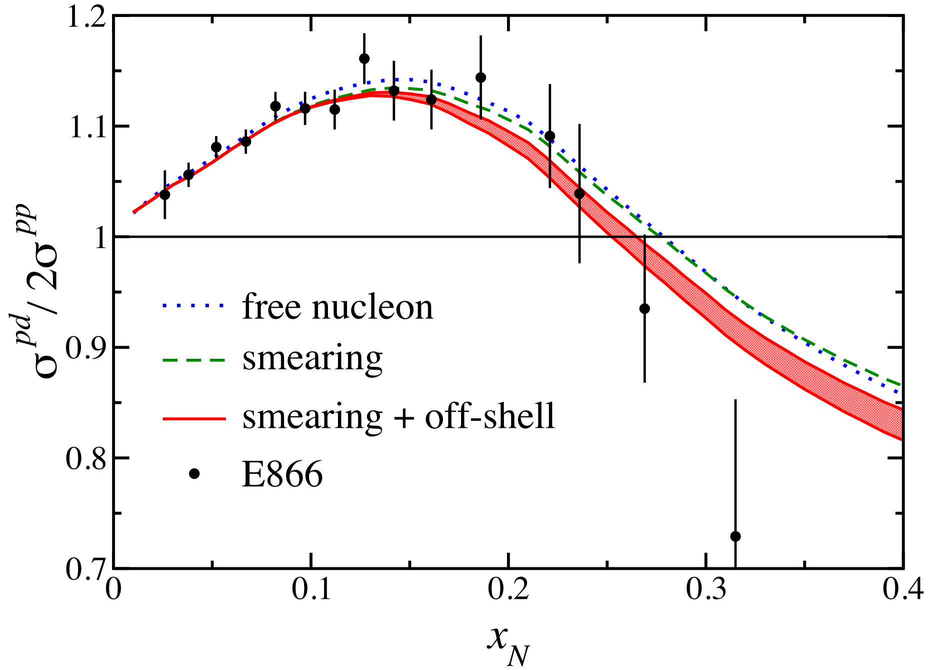




*Ehlers et al., PRD **90**, 014010 (2014)*

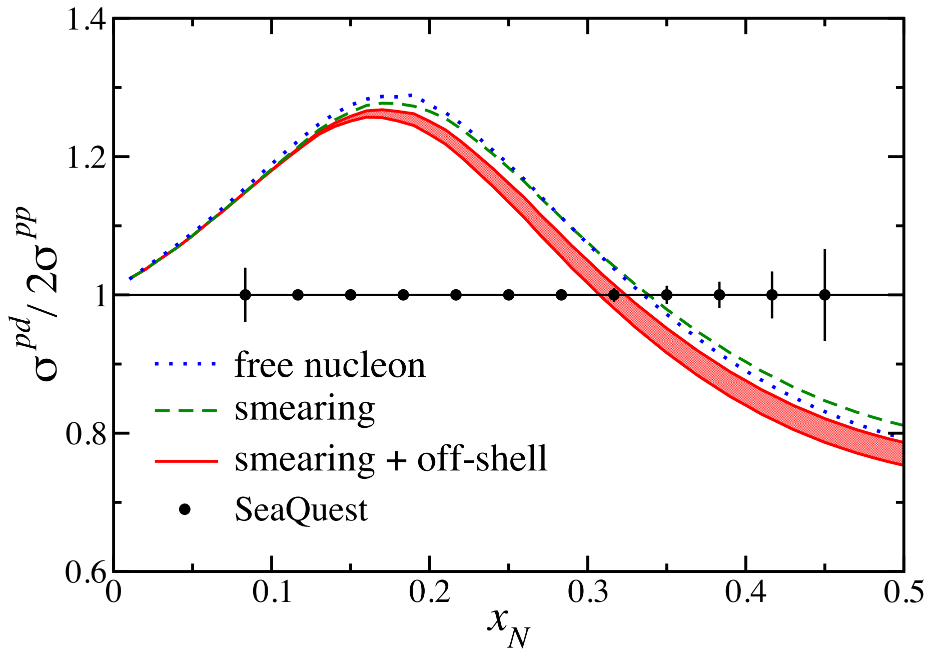
Light antiquark sea

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



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

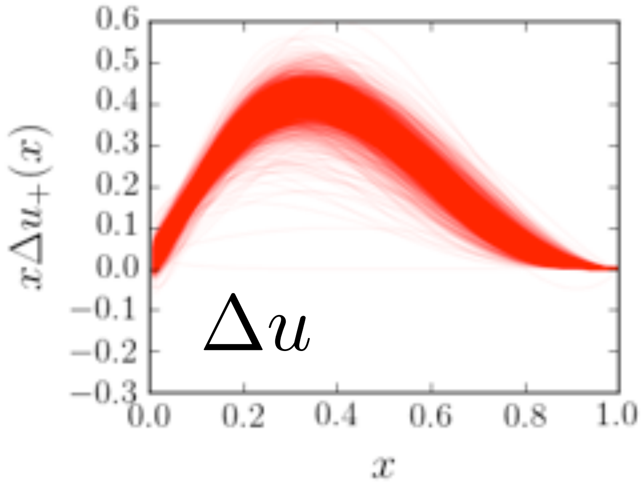
→ relevant for possible sign change of $\bar{d} - \bar{u}$ at high x ?

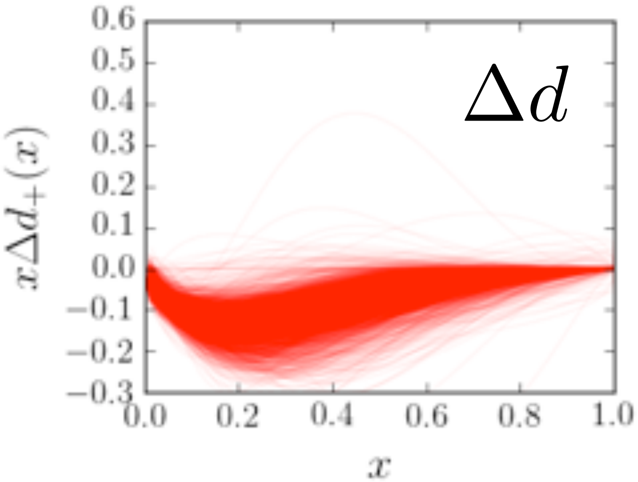


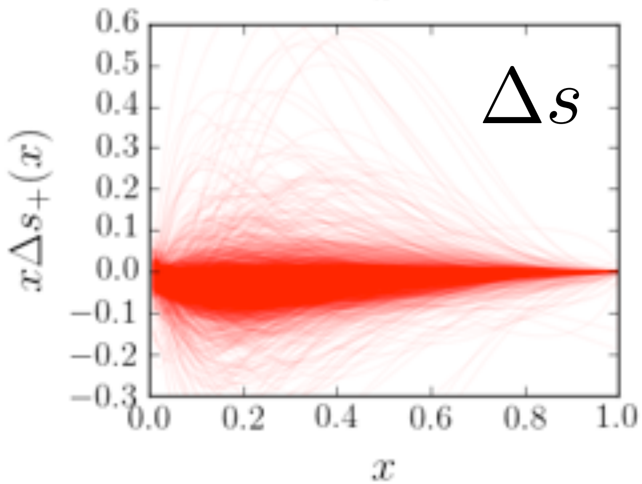
Summary & outlook

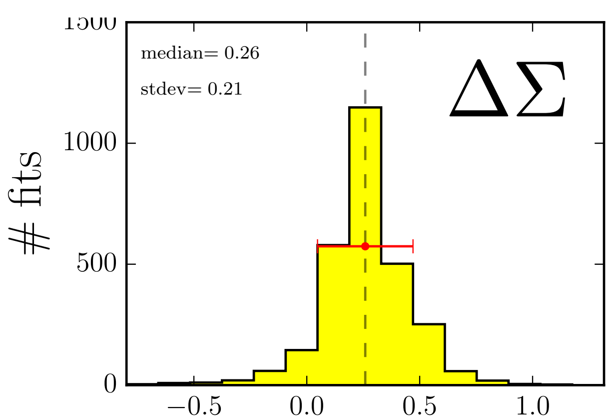
- New CJ15 PDFs will be released soon (~ autumn 2015)
  - → constraints on large-x PDFs from new data on lepton & W-asymmetries; first JLab F_2^n data
  - → reduced nuclear uncertainties on d quark *cf.* CJ12, with smaller d/u ratio for $x \to 1$ (smaller nuclear corrections)
  - → treatment of nuclear corrections in deuteron extended to sea quarks and gluons
    (important for pd Drell-Yan cross sections for $\bar{q}$, and for F_L)

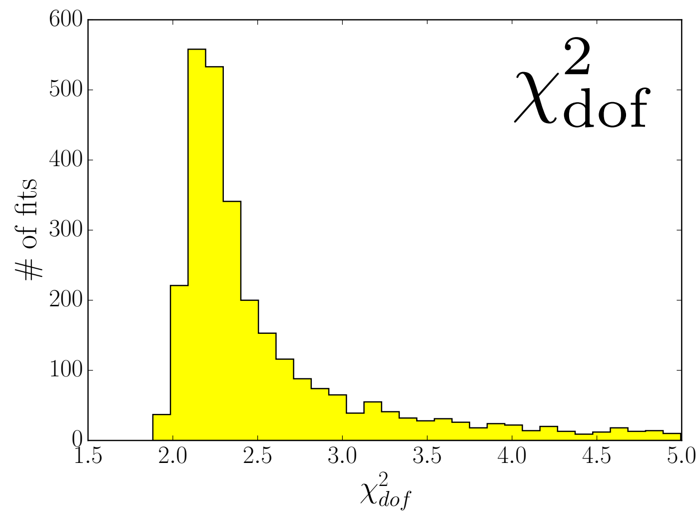
- Future direction: minimize input parameter bias through Monte Carlo analysis
  - → explore parameter space through MC sampling
  - → no ambiguity in "tolerance criteria" (or assumptions about Gaussian errors)
  - → cross validation (random data partition) & bootstrap (data resampling)











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