DIS 2015, Southern Methodist University
April 28, 2015

New CTEQ–Jefferson Lab (CJ) analysis of parton distribution functions

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Jefferson Lab

CTEQ-JLab (CJ) collaboration: http://www.jlab.org/CJ

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Outline

- CJ PDFs – motivations and goals

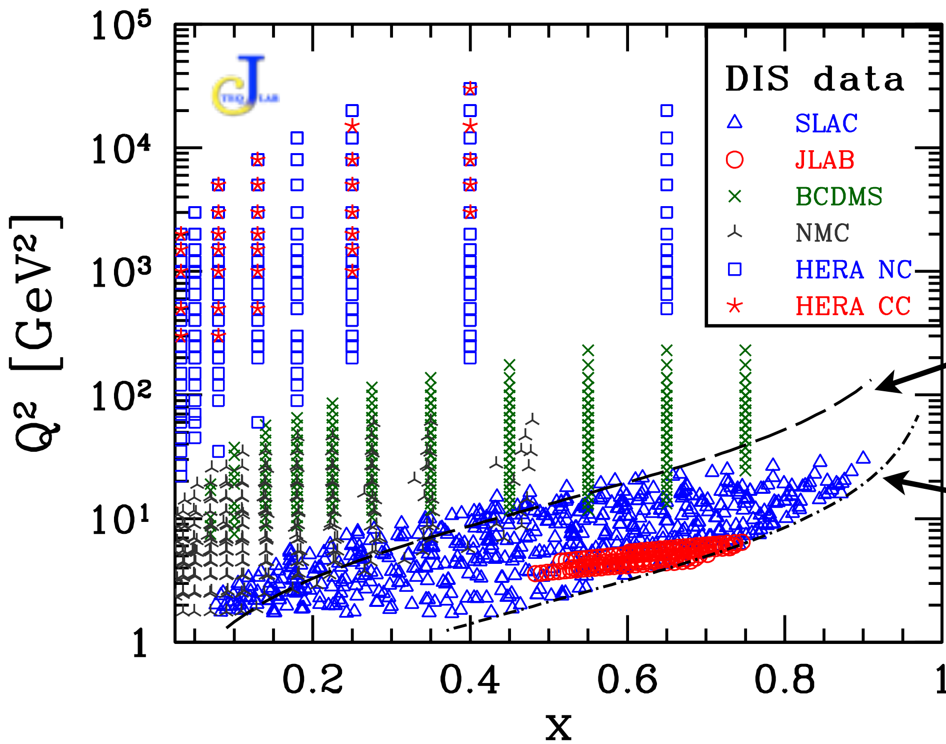
- New developments since CJ12
  - → more complete treatment of nuclear corrections
  - → impact of new W asymmetry data on d/u ratio
  - → inclusion of JLab (BONuS) data
  - → analysis of $\bar{d} - \bar{u}$ at large x
  - → S-ACOT scheme for heavy quarks

- Future plans

- 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:
$Q^2 > 4\ \text{GeV}^2, \quad W^2 > 12.25\ \text{GeV}^2$

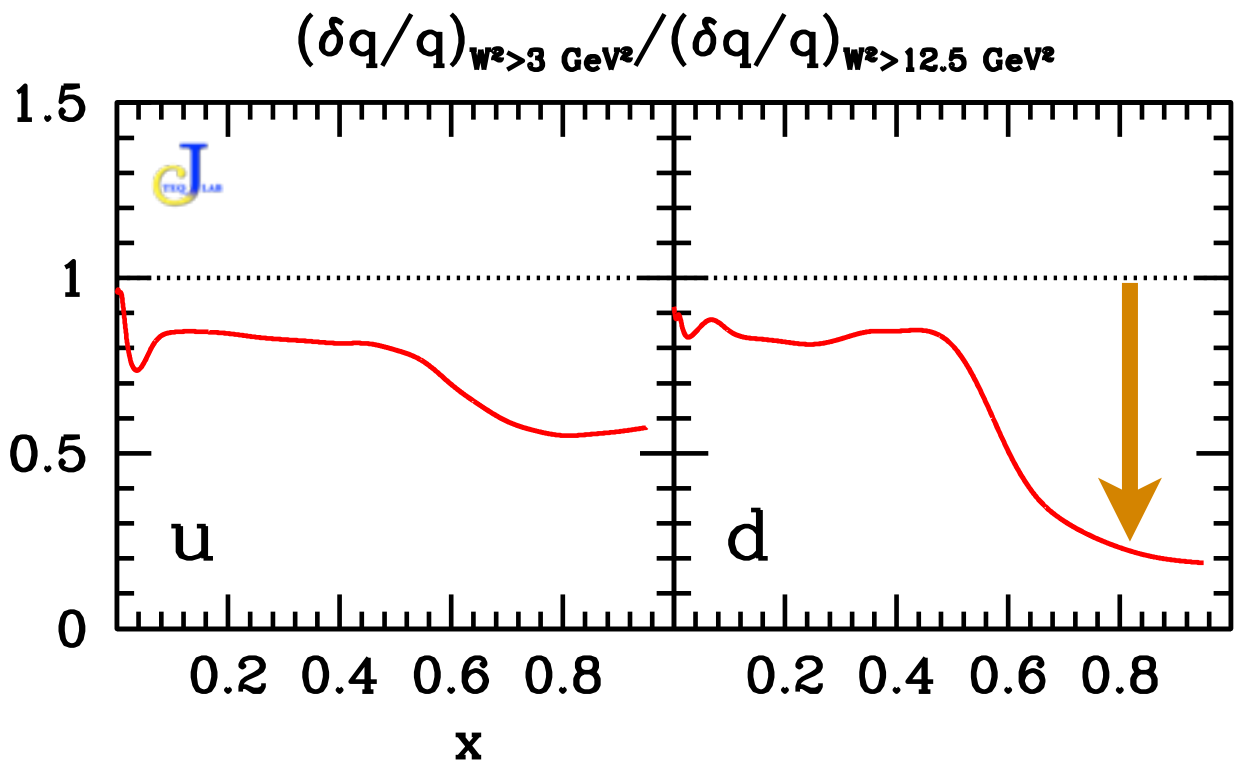
weak cut:
$Q^2 > m_c^2\ , \quad W^2 > 3\ \text{GeV}^2$

→ 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)

  → include high-x region ($x > 0.4$)

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



→ significant error reduction at high x

- 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 (standard deuteron wave functions), nucleon off-shell (stronger model dependence)

- Dependence on parametric form

  → d/u ratio in $x \to 1$ limit

Target mass corrections

- Operator product expansion

→ inverse Mellin transform (+ generalized binomial theorem)

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

massless limit function $F_2^{(0)} \equiv \lim_{M/Q\to 0} F_2$

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

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

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

- Collinear factorization

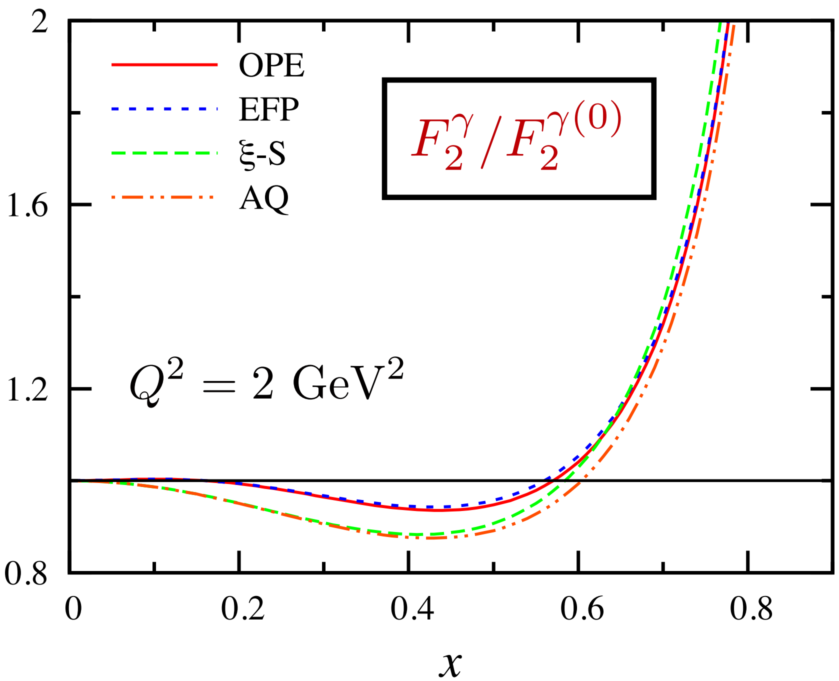
→ diagrammatic approach [to $\mathcal{O}(1/Q^2)$ only]

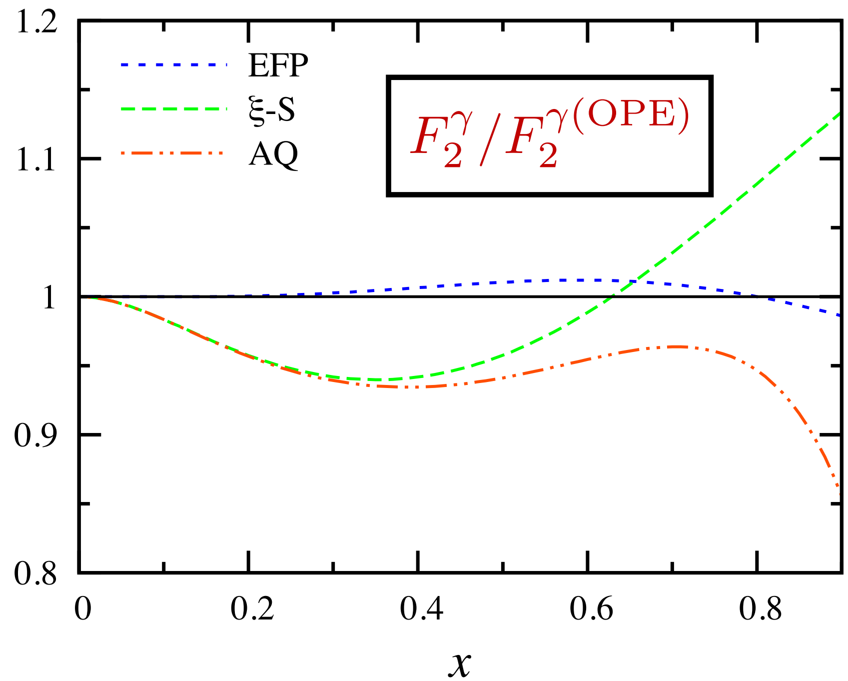
$$F_2^{\rm EFP}(x,Q^2) = \frac{1}{\rho^2} F_2^{(0)}(\xi,Q^2) + \frac{3\xi(\rho^2-1)}{\rho^2(1+\rho)} h(\xi,Q^2)$$

$$= F_2^{\rm OPE}(x,Q^2) + \mathcal{O}(1/Q^4)$$

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

Target mass corrections





→ threshold problem $F_2^{\mathrm{TMC}}(x=1, Q^2) \sim F_2^{(0)}(\xi_0, Q^2) > 0$

(non-matching partonic & hadronic thresholds)

→ various remedies, *e.g.* term-wise expansion

$$F_2(x, Q^2) = x^2 \sum_{j=0}^{\infty} \mu^j \frac{(-x)^j}{j!} \frac{\partial^{2+j}}{\partial x^{2+j}} \left[x^{2j} g(x)\right]$$

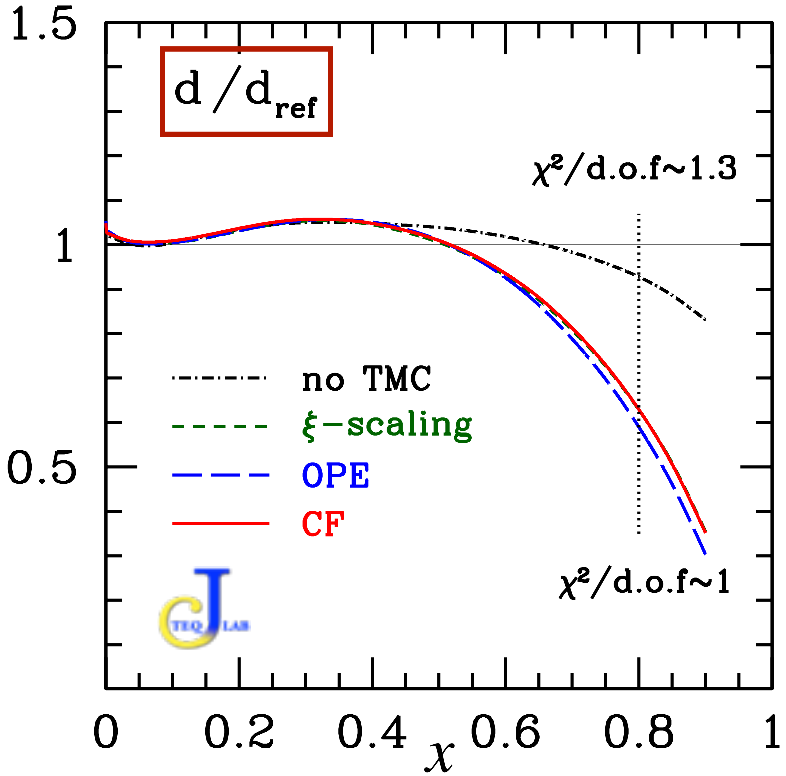
satisfies $M^{\mathrm{CN}}(F_i^{\mathrm{LT}}) = M^{\mathrm{Nacht}}(F_2^{\mathrm{LT+TMC}})$

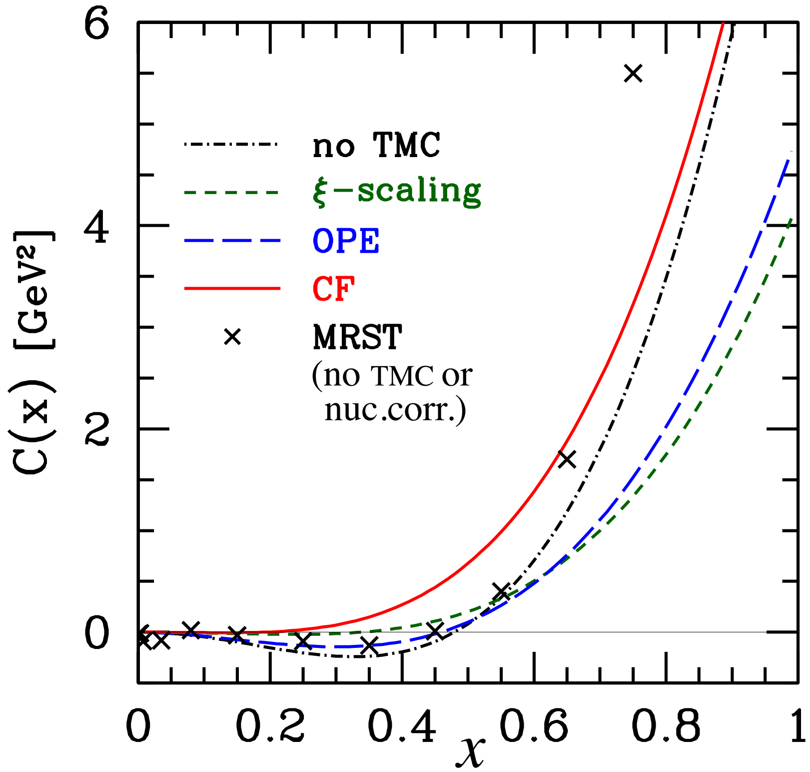
Steffens et al.
*PRC **86**, 065208 (2012)*

Higher twist corrections

- Parametrized phenomenologically, *e.g.*

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



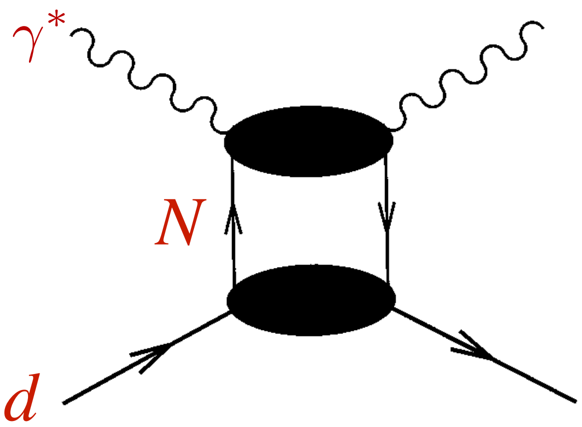


→ stable leading twist when *both* TMCs and HTs included

→ extraction of HTs depends on TMC prescription...

Nuclear corrections

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



N=p+n

$$F_2^d(x,Q^2) = \int_x dy\; f(y,\gamma)\; F_2^N(x/y,Q^2)$$
$$+\; \delta^{(\mathrm{off})} F_2^d$$

nucleon momentum distribution in d ("smearing function")

off-shell correction

→ y = momentum fraction of d carried by N

→ at finite Q^2, smearing function depends also on parameter

$$\gamma = |\mathbf{q}|/q_0 = \sqrt{1 + 4M^2x^2/Q^2}$$

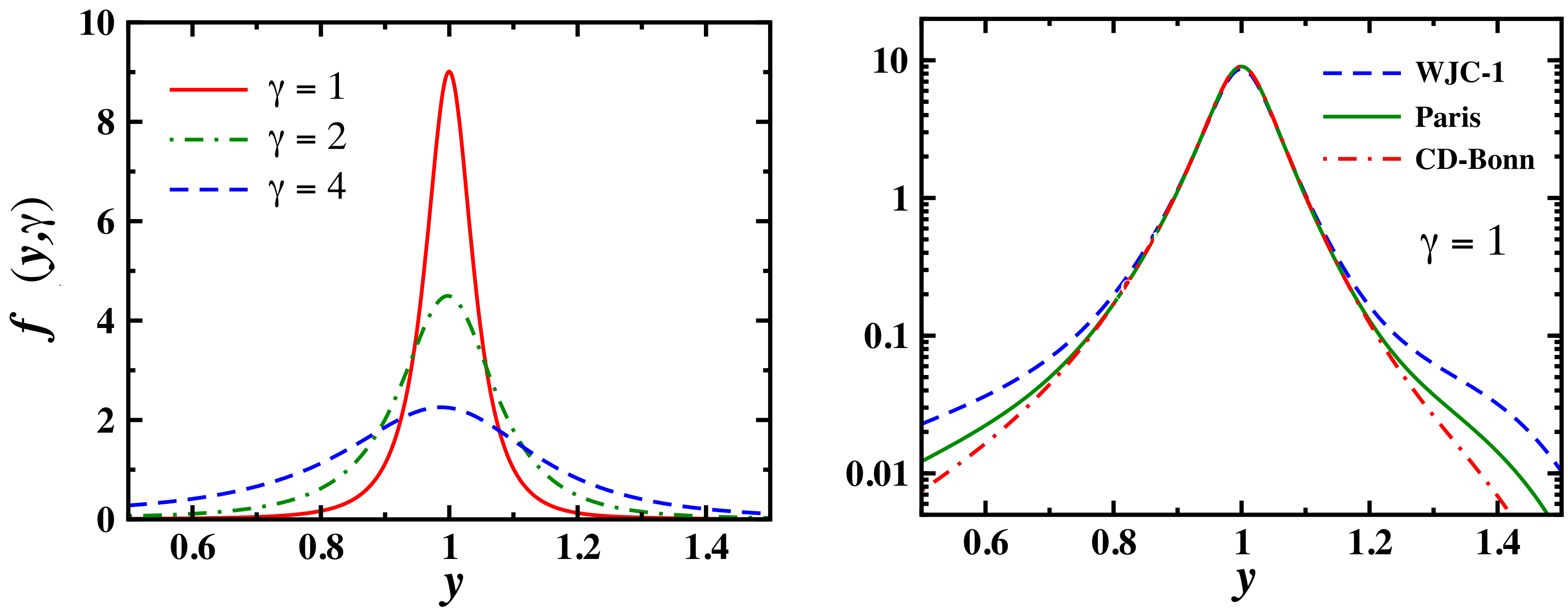
Nuclear corrections

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

$$f(y,\gamma) = \int \frac{d^3p}{(2\pi)^3}\, |\psi_d(p)|^2\, \delta\left(y - 1 - \frac{\varepsilon + \gamma p_z}{M}\right)$$
$$\times \frac{1}{\gamma^2}\left[1 + \frac{\gamma^2 - 1}{y^2}\left(1 + \frac{2\varepsilon}{M} + \frac{\vec{p}^2}{2M^2}(1 - 3\hat{p}_z^2)\right)\right]$$

$\psi_d(p) = d$ wave function

$$\varepsilon = \varepsilon_d - \frac{\vec{p}^2}{2M}$$



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

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

Nuclear corrections

- Nucleon off-shell correction to quark PDF

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

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

→ quark "spectator" off-shell model

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

applied to q_v, $\bar{q}$ & g

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

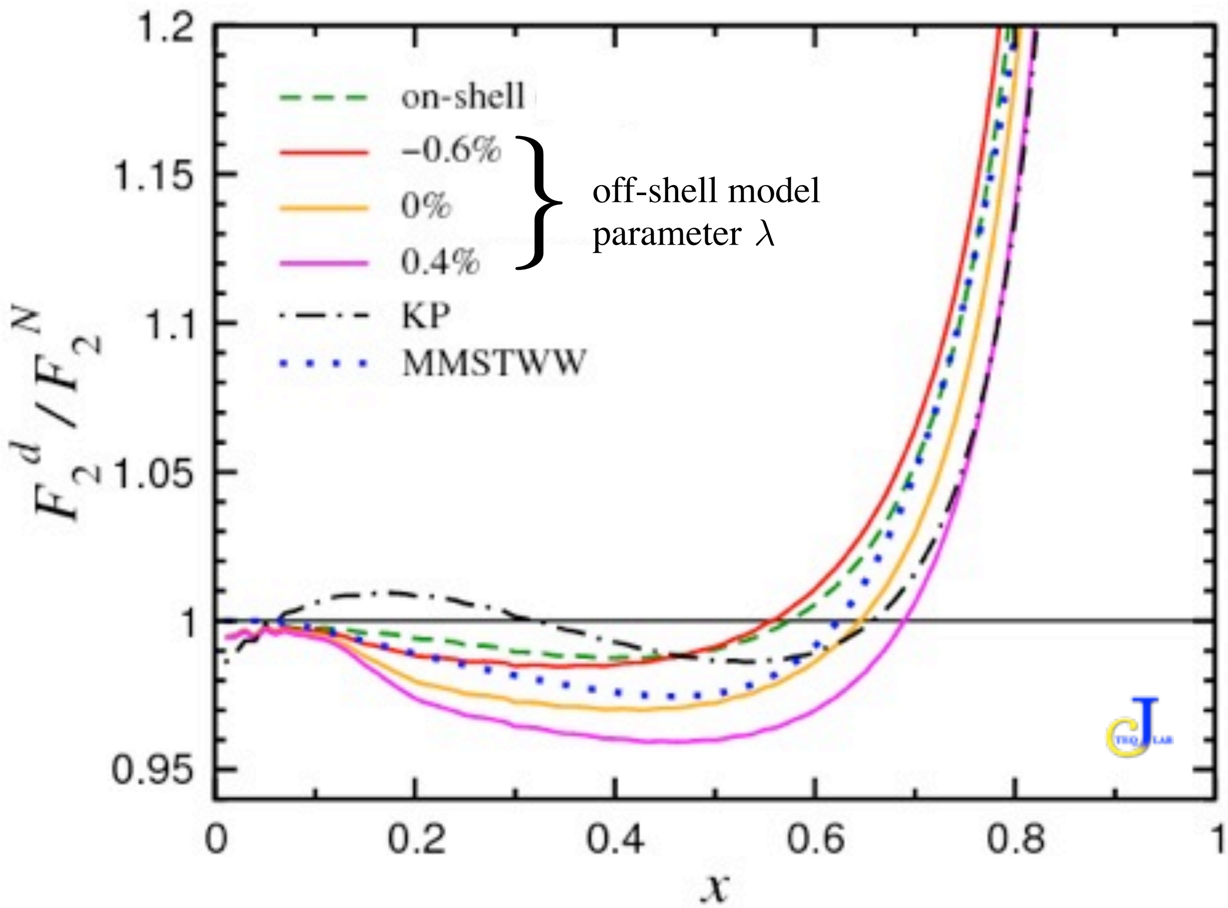
→ scale parameter $\Lambda(p^2)$ suppresses large-p^2 contributions

→ off-shell "rescaling" parameter $\lambda = \dfrac{\partial \log \Lambda^2}{\partial p^2}$ varied in fit to minimize χ^2

*Kulagin, Petti, NPA **765**, 126 (2006)*
*Owens et al., PRD **87**, 094012 (2013)*

Nuclear corrections

- Nuclear EMC ratio in deuterium

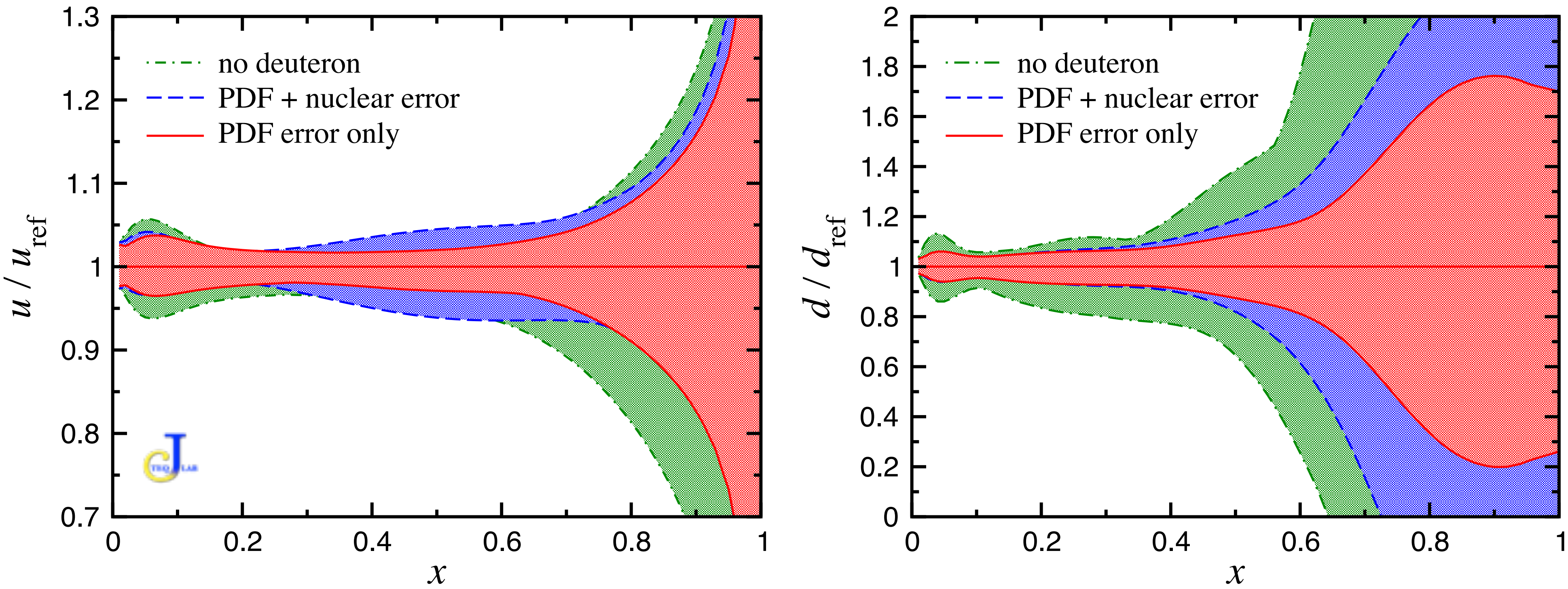


→ larger off-shell effects for larger λ, and for KP model

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

Nuclear corrections

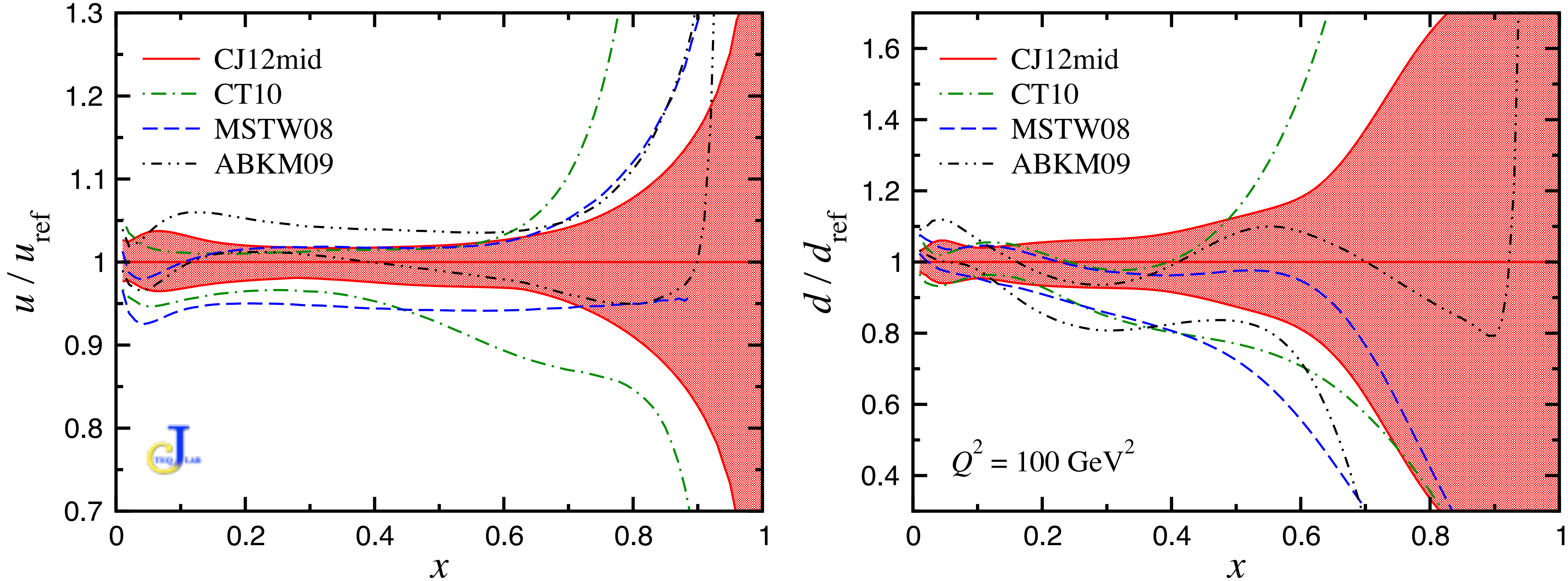
- Effect of nuclear corrections on PDF uncertainties



→ larger nuclear uncertainties for d than u PDFs at high x

Nuclear corrections

- Effect of nuclear corrections on PDF uncertainties



→ *increase* in PDF error from more realistic treatment of nuclear corrections

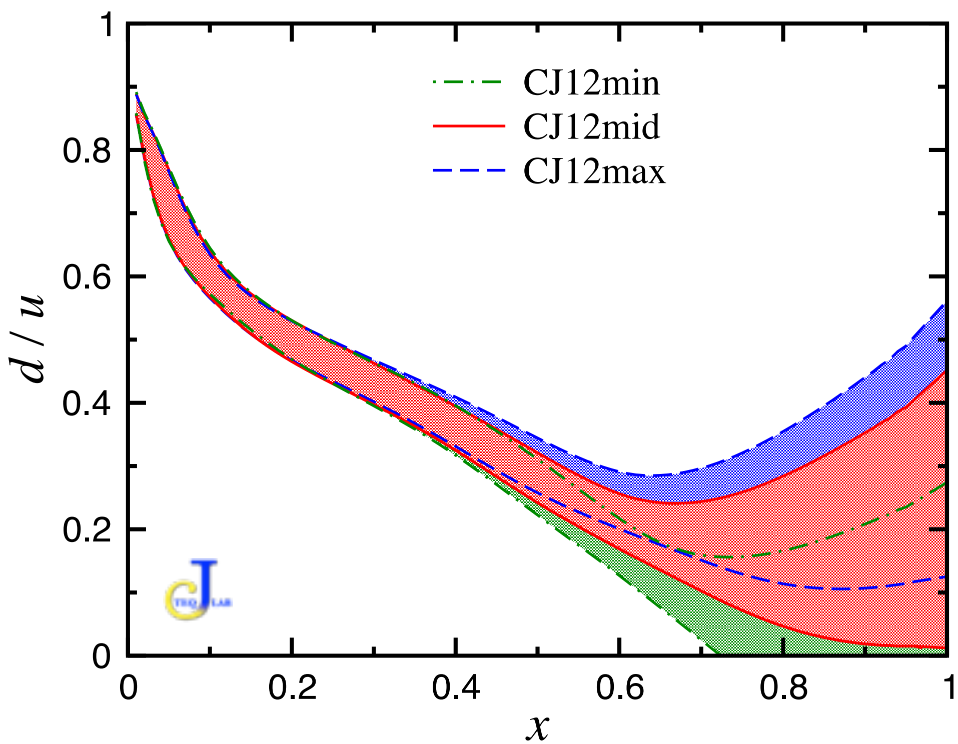
→ *reduction* of error from larger database

Nuclear corrections

- In CJ12, considered 3 sets of PDFs corresponding to different amounts of nuclear corrections
  - CJ12min: WJC-1 + mild off-shell $(\lambda = 0.3\%)$
  - CJ12mid: AV18 + medium off-shell $(\lambda = 1.2\%)$
  - CJ12max: CD-Bonn + large off-shell $(\lambda = 2.1\%)$

off-shell parameter λ range motivated by Q^2 rescaling model of nuclear EMC effect

Close, Jaffe, Roberts, Ross (1988)



Owens et al., PRD ***87****, 094012 (2013)*

- with same functional form for
  $u \,\&\, d \sim x^{\alpha}(1-x)^{\beta}\,(1+\epsilon\sqrt{x}+\eta\, x)$
  most PDF fits obtain either 0 or ∞ for $x \to 1$ limit

- more flexible parametrization for $x \to 1$ behavior

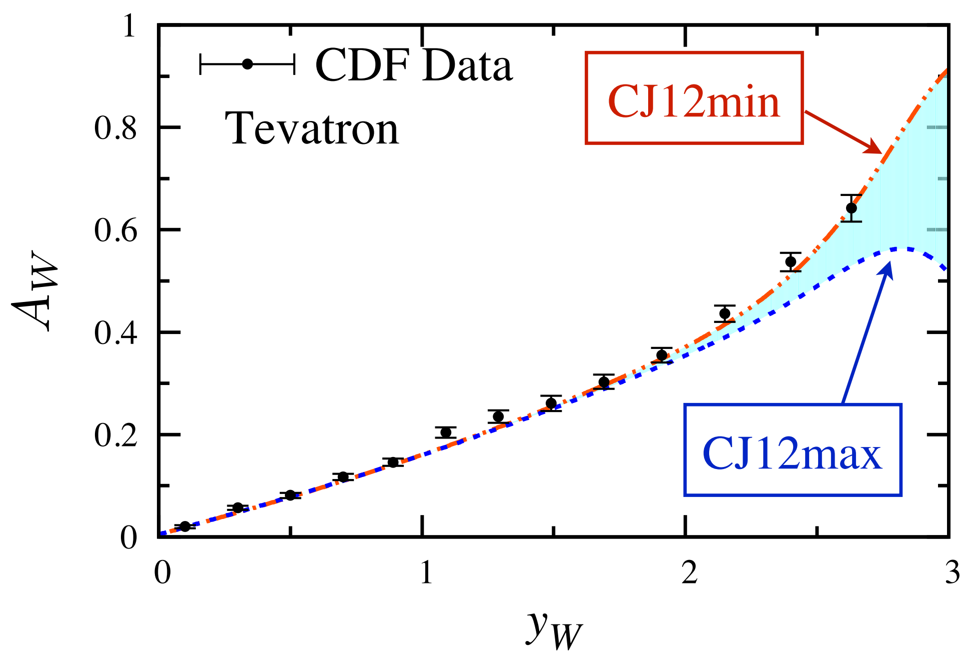
$$d \;\to\; d + a\, x^{b}\, u$$

allows finite, nonzero $x = 1$ limit

Constraints from W asymmetries

- $W^{\pm}$ asymmetry at large W-boson rapidity y_W is sensitive to d/u PDF ratio at high x

- Earlier CDF W-asymmetry data indicated preference for smaller nucleon off-shell corrections



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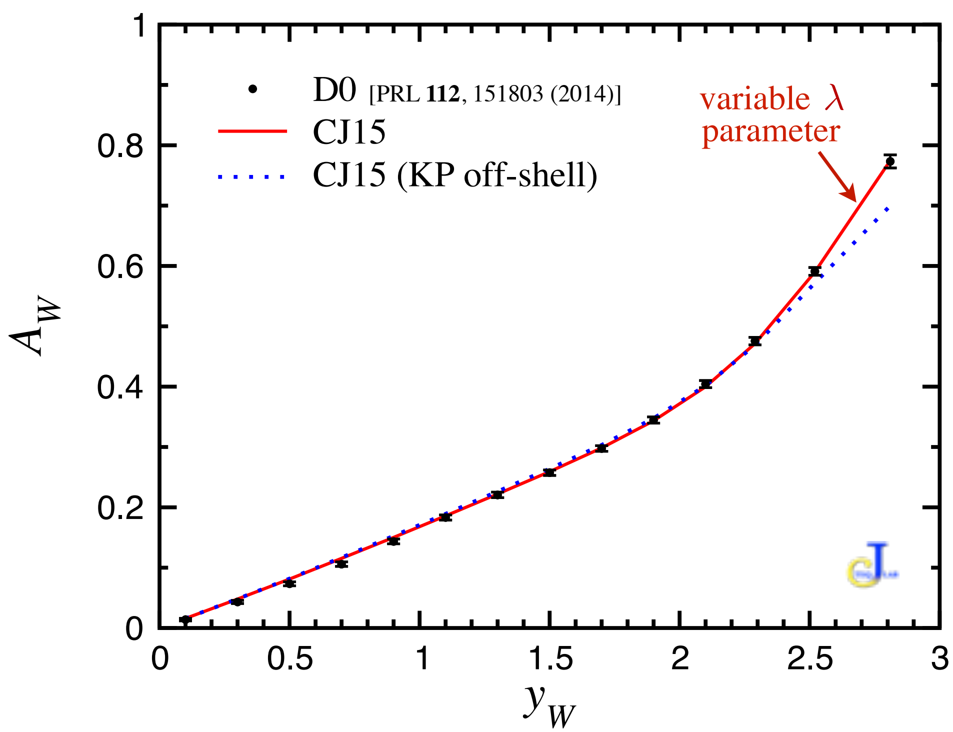
- New (2014) D0 W-asymmetry data have even greater discriminating power between nuclear models



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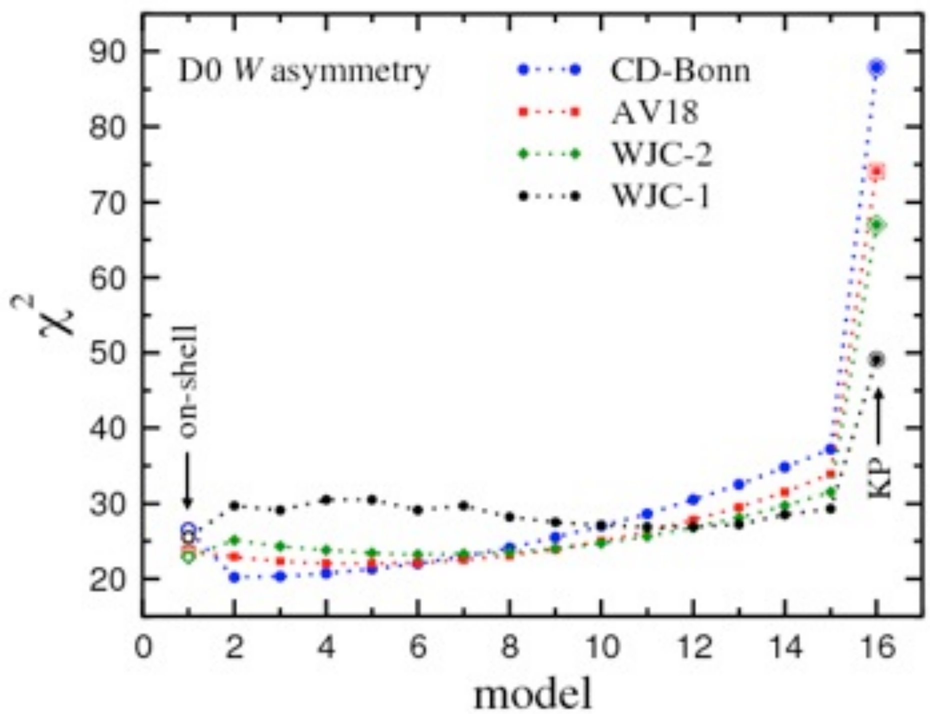

- disfavors KP off-shell model

- prefers smaller d PDF

models 2–15:
$\lambda = \{-0.9\%, -0.8\%, ..., +0.4\%\}$

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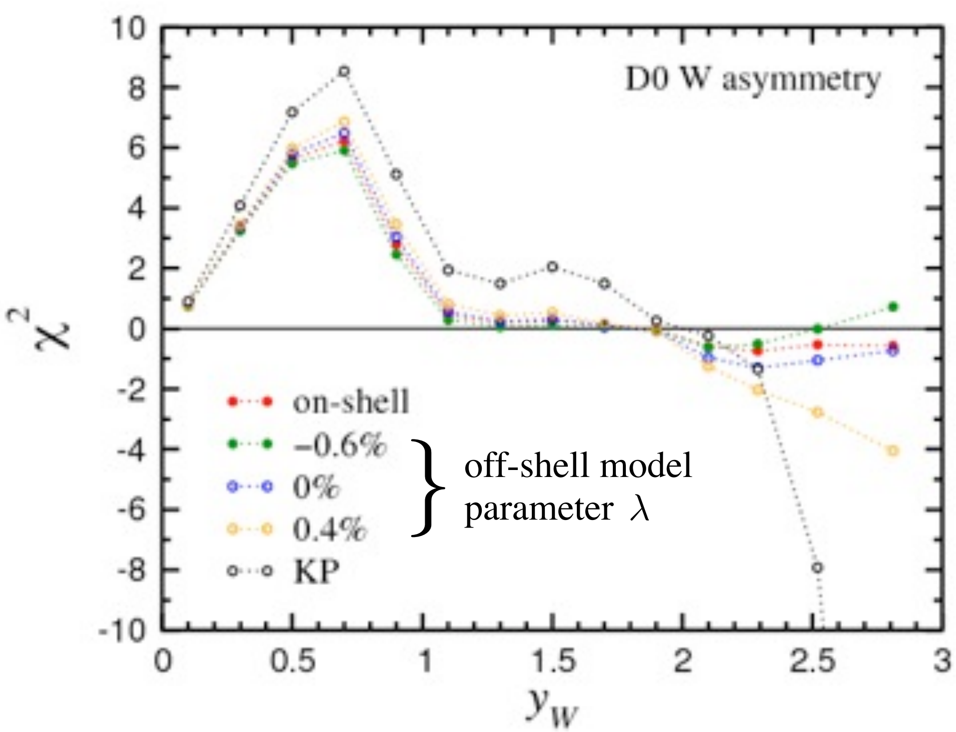

- disfavors KP off-shell model

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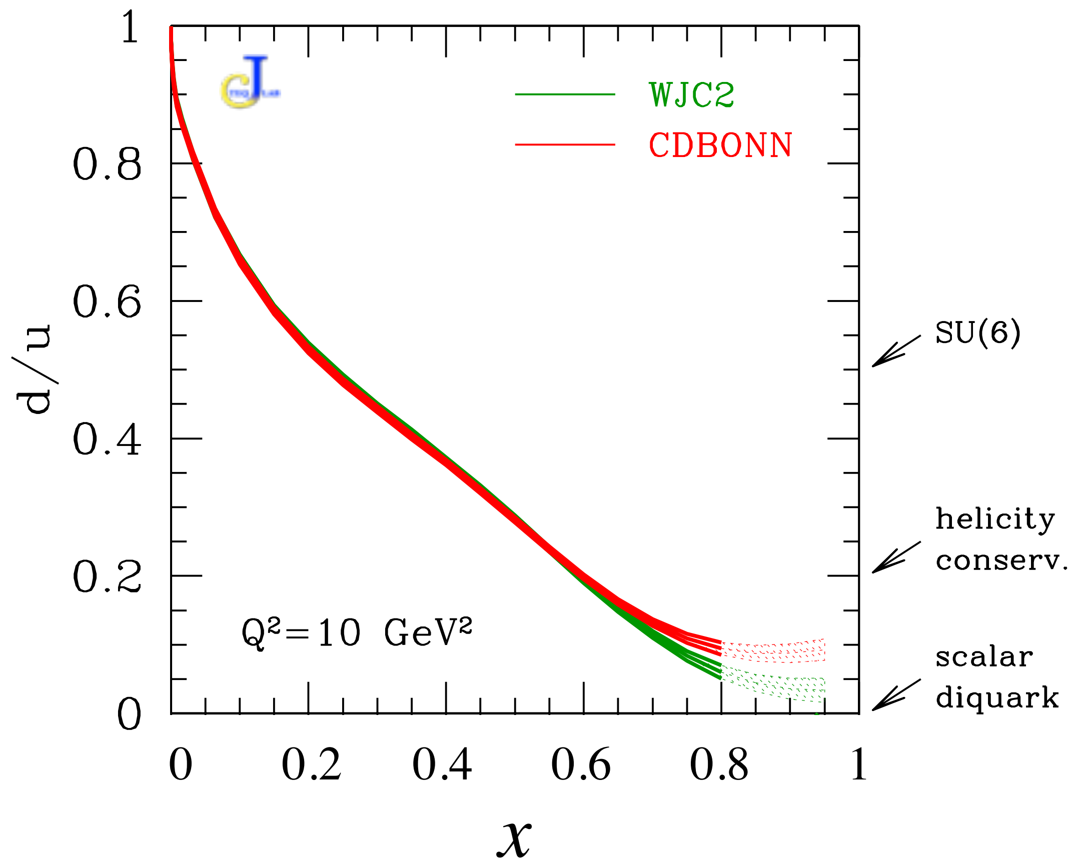
CJ15 PDFs

- Reduced nuclear uncertainty on d PDF at high x

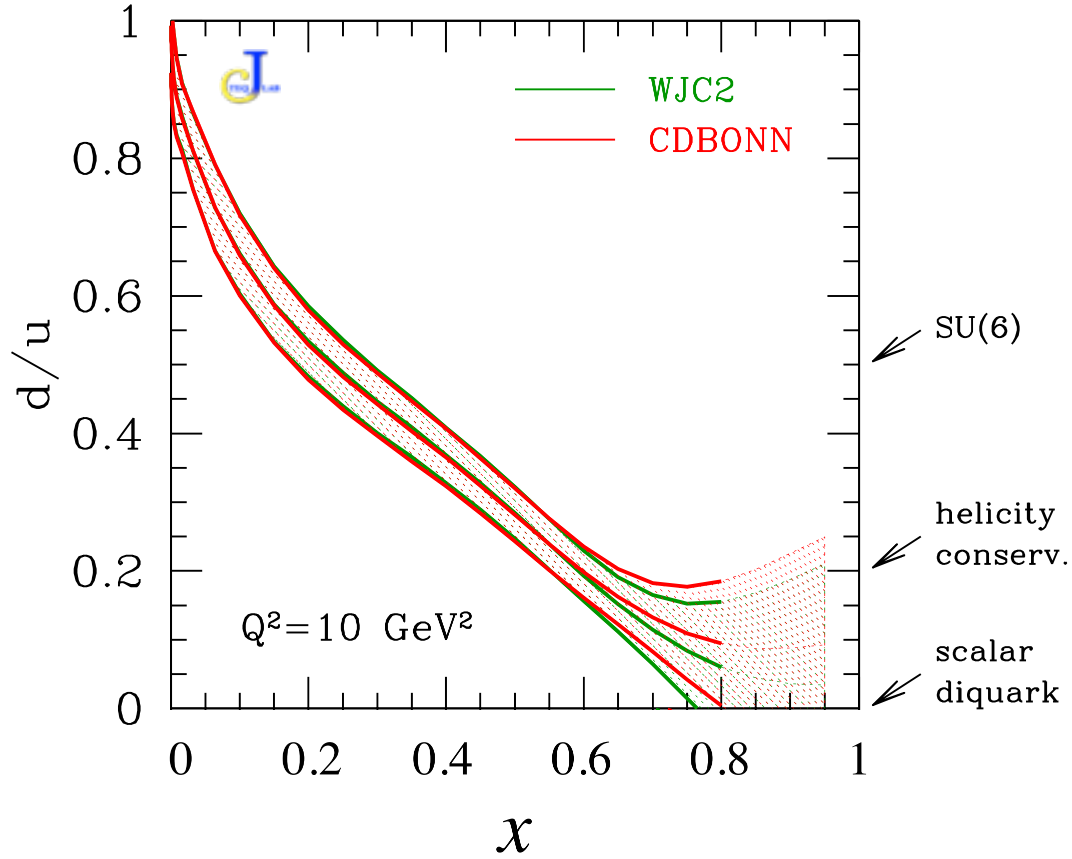


Tolerance $\Delta\chi^2 = 1$

note: λ a fit parameter

CJ15 PDFs

- Reduced nuclear uncertainty on d PDF at high x



Tolerance $\Delta\chi^2 = 100$

$d/u \rightarrow 0.07$
± 0.17 (PDF)
± 0.04 (nucl)
in $x \rightarrow 1$ limit

cf. $d/u \rightarrow 0.22$
± 0.20 (PDF)
± 0.10 (nucl)
in CJ12

CJ15 PDFs

Global χ^2 values

data set	# pts	WJC2	CD-Bonn	AV18	WJC1
BcdF2pCor	351	444.8	440.2	444.3	453.5
BcdF2dCor	254	293.9	294.5	294.8	294.5
slac_p	564	439.9	453.3	450.7	446.8
slac_d	582	380.7	385.7	389.4	396.0
jl00106F2p	136	163.3	167.1	168.5	168.9
jl00106F2d	136	124.4	126.3	126.2	126.3
NmcF2pCor	275	407.2	405.8	405.8	407.0
NmcRatCor	189	174.1	176.1	177.1	181.7
H_nc_el_c	145	113.4	112.9	113.3	113.8
H_nc_ps_c	408	544.7	545.1	545.5	546.6
H_cc_el_c	34	19.1	19.1	19.1	19.1
H_cc_ps_c	34	31.8	32.5	32.2	31.7
BNS_F2nd	191	217.0	216.3	213.4	211.5
e605	119	91.2	93.1	93.2	92.2
e866pp06xf	121	137.6	139.0	138.6	137.6
e866pd06xf	129	132.8	133.4	133.3	133.0
e866rat	15	6.0	10.4	10.4	8.5
cdfLasy05	11	10.6	10.7	10.6	10.5
d0Lasy_e08	12	30.0	31.7	29.9	28.4
CDF_Wasy	13	16.0	14.5	16.0	18.2
D0_Wasy	14	26.6	26.0	28.0	33.0
d0Lasy13	10	35.4	34.7	35.1	34.8
CDF_Z	28	27.9	27.5	27.4	27.9
D0_Z	28	15.7	15.6	15.6	15.7
d0run2cone	110	21.2	22.1	21.8	21.4
CDFrun2jet	72	15.8	15.0	15.1	15.3
d0_gamjet1	16	6.2	6.5	6.4	6.4
d0_gamjet2	16	15.6	16.1	16.0	15.9
d0_gamjet3	12	25.6	25.0	25.1	25.5
d0_gamjet4	12	12.9	13.0	13.1	13.1
TOTAL	4037	3981.2	4008.9	4015.8	4034.6
TOTAL+norm		3991.4	4018.8	4025.9	4045.6

slac_d: +15.3

BONuS F_2^n/F_2^d → BNS_F2nd: − 5.5

D0_Wasy: + 6.4

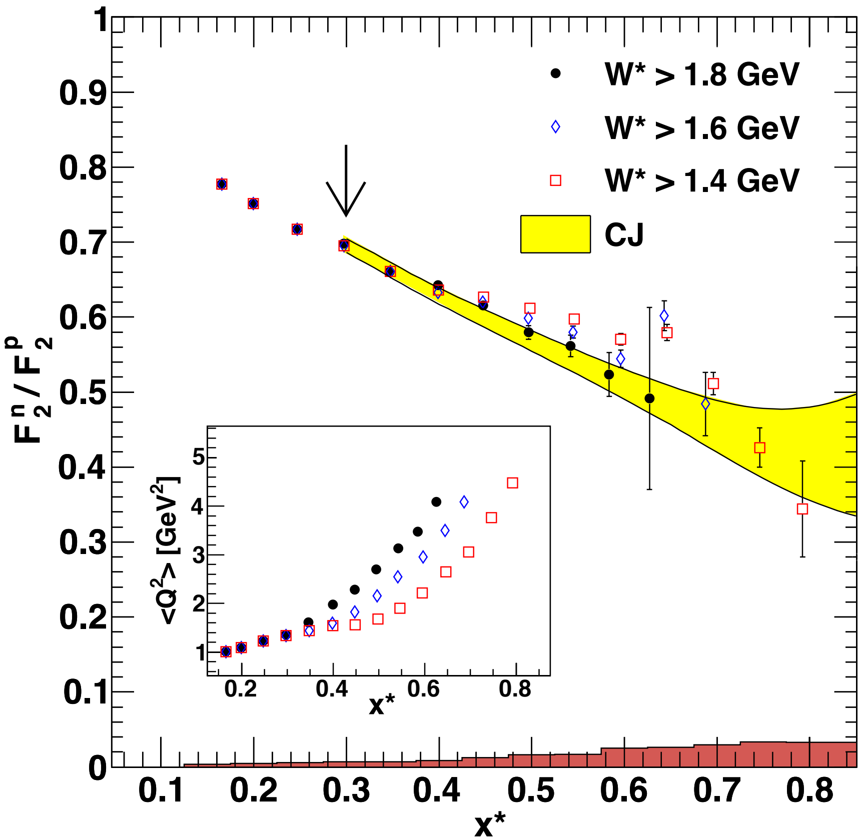
essentially equivalent fits

$\chi^2/N_{\rm dat} = 0.99 \ldots 1.00$ → TOTAL+norm

$\lambda = -0.6 \pm 0.3\%$ (WJC2), $-0.2 \pm 0.5\%$ (CD-Bonn), $0.1 \pm 0.9\%$ (AV18), $0.5 \pm 1.3\%$ (WJC1)

New JLab free neutron data

- New BONuS data (spectator proton tagging in semi-inclusive deuteron DIS) on F_2^n/F_2^d included for first time in global PDF fits



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

→ minimal uncertainties from nuclear corrections

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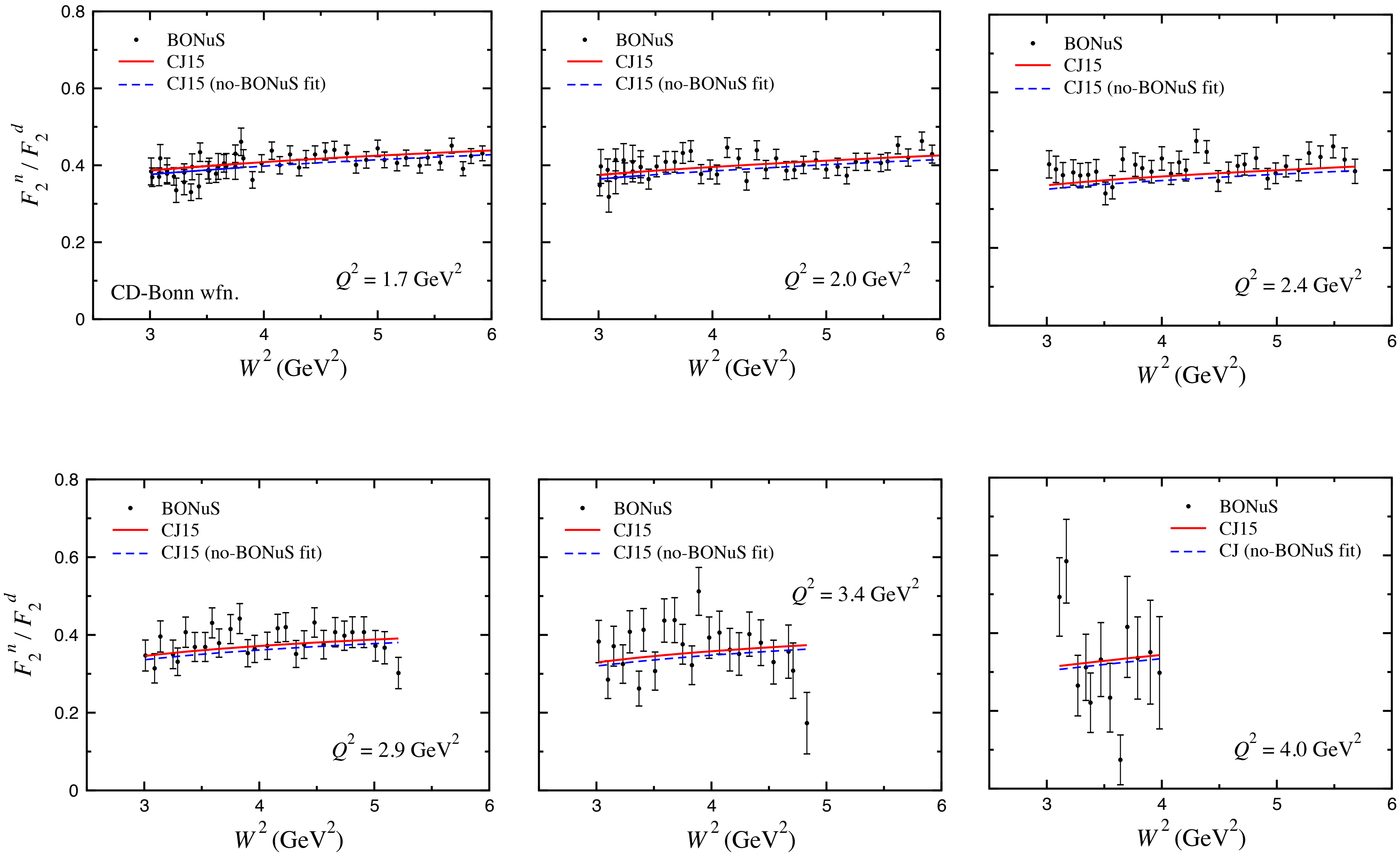
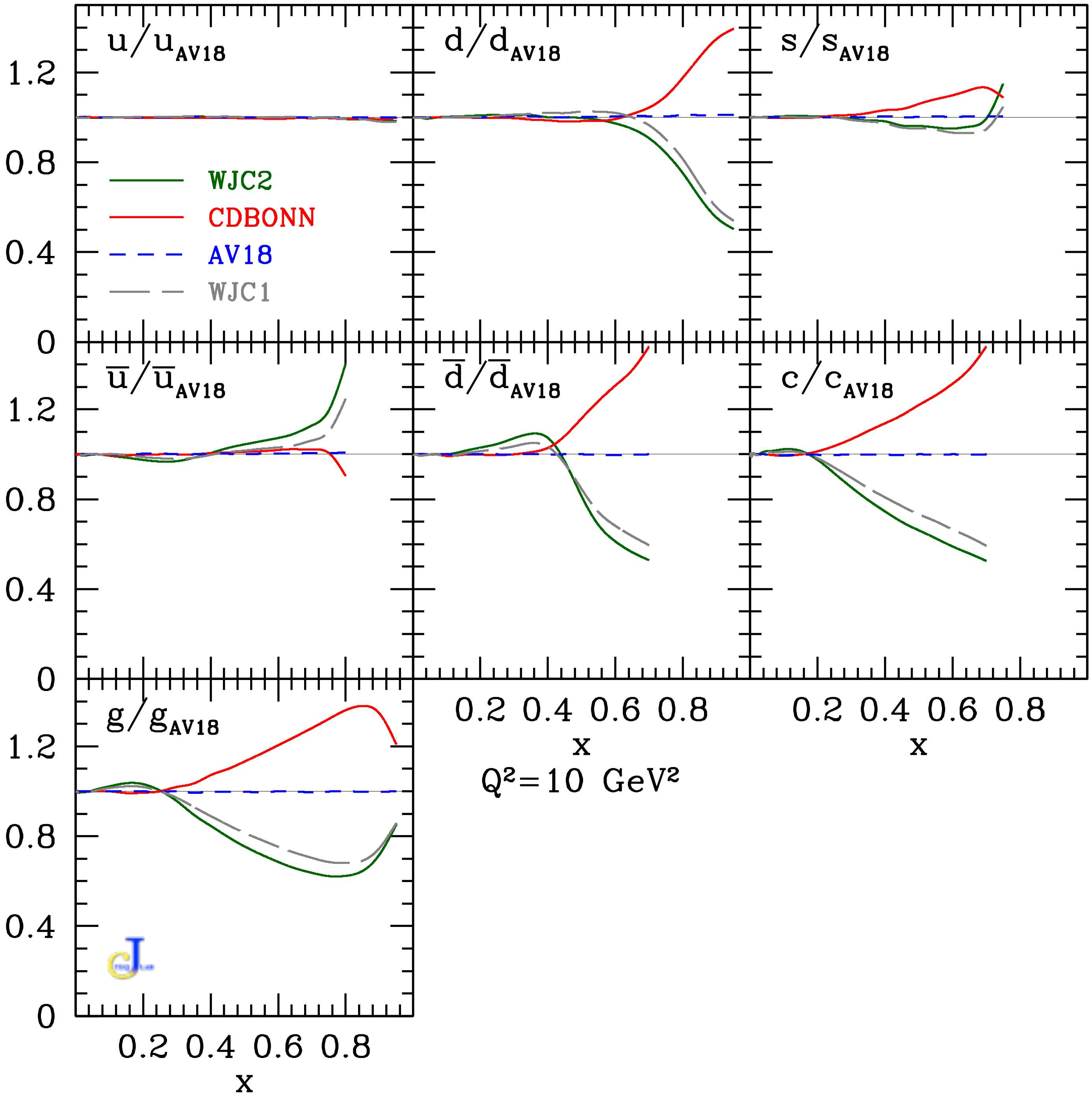


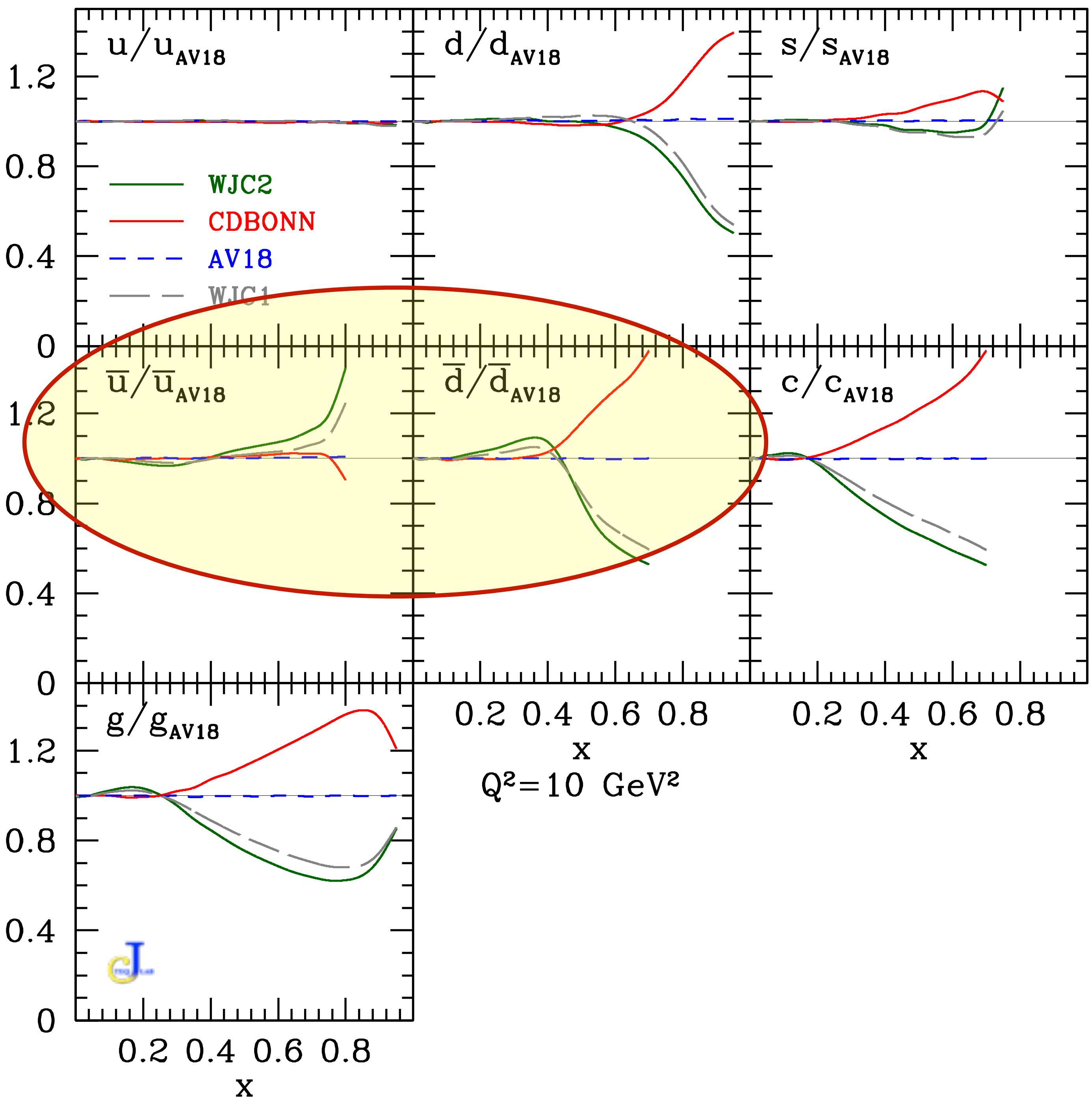
→ slight preference for larger neutron F_2 (hence d-quark)

CJ15



u/u_AV18
d/d_AV18
s/s_AV18
ū/ū_AV18
d̄/d̄_AV18
c/c_AV18
g/g_AV18
WJC2
CDBONN
AV18
WJC1
0
0.4
0.8
1.2
0.2 0.4 0.6 0.8
x
Q²=10 GeV²

CJ15



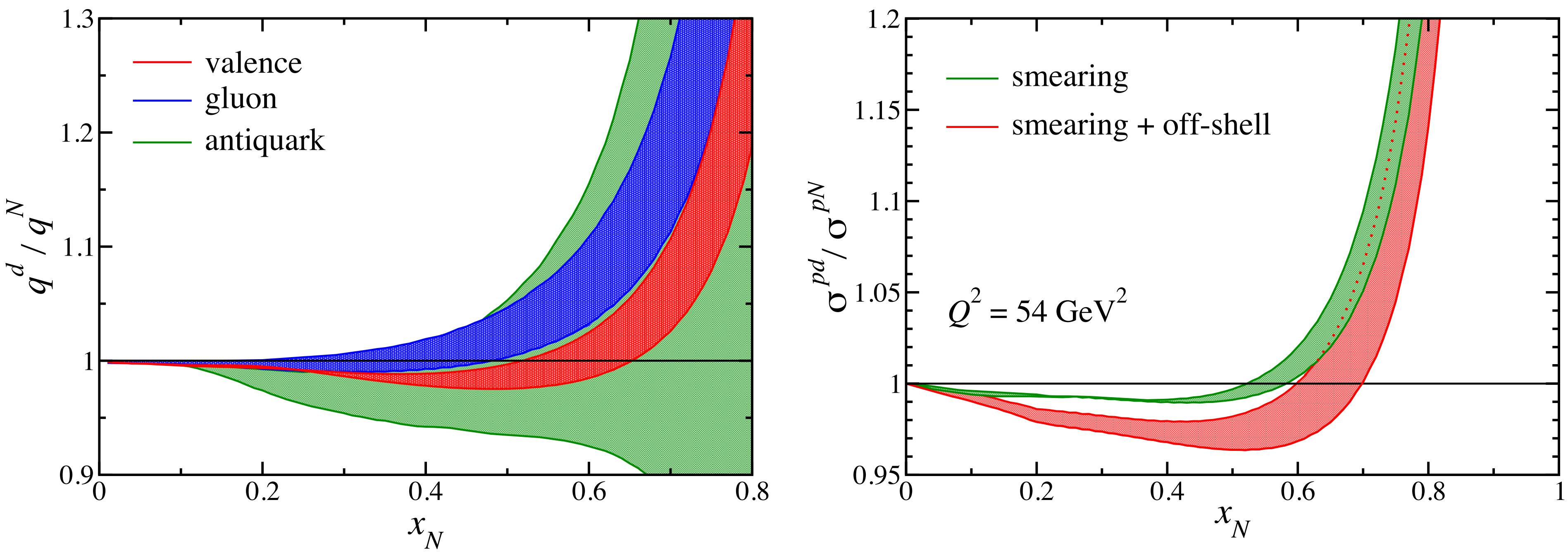
u/u_AV18
d/d_AV18
s/s_AV18
ū/ū_AV18
d̄/d̄_AV18
c/c_AV18
g/g_AV18
WJC2
CDBONN
AV18
WJC1
1.2
0.8
0.4
0
0.2 0.4 0.6 0.8
x
Q²=10 GeV²

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

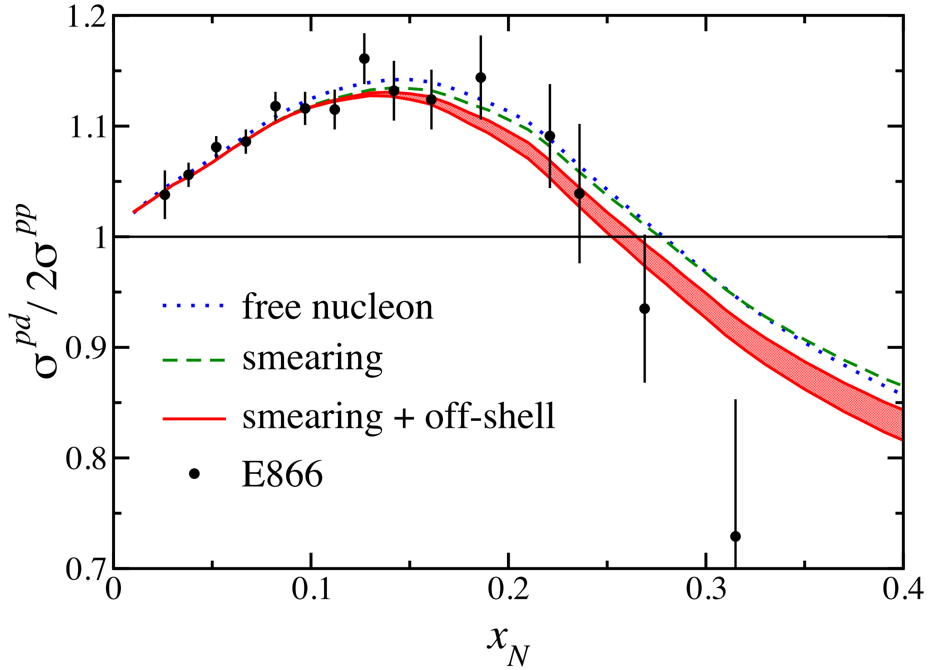
  → requires nuclear modifications in antiquark and gluon PDFs



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

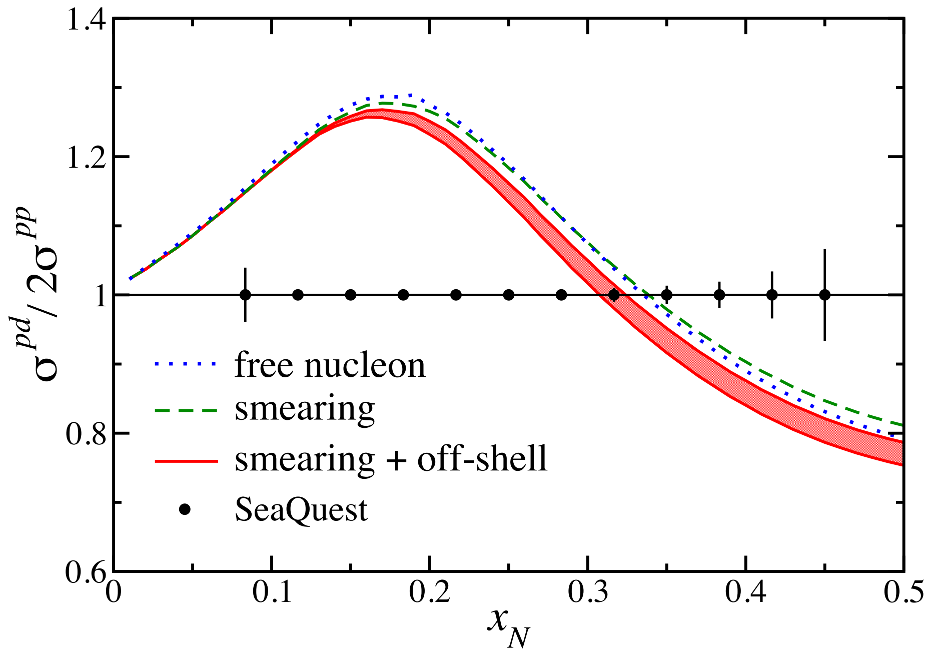
Light antiquark sea

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



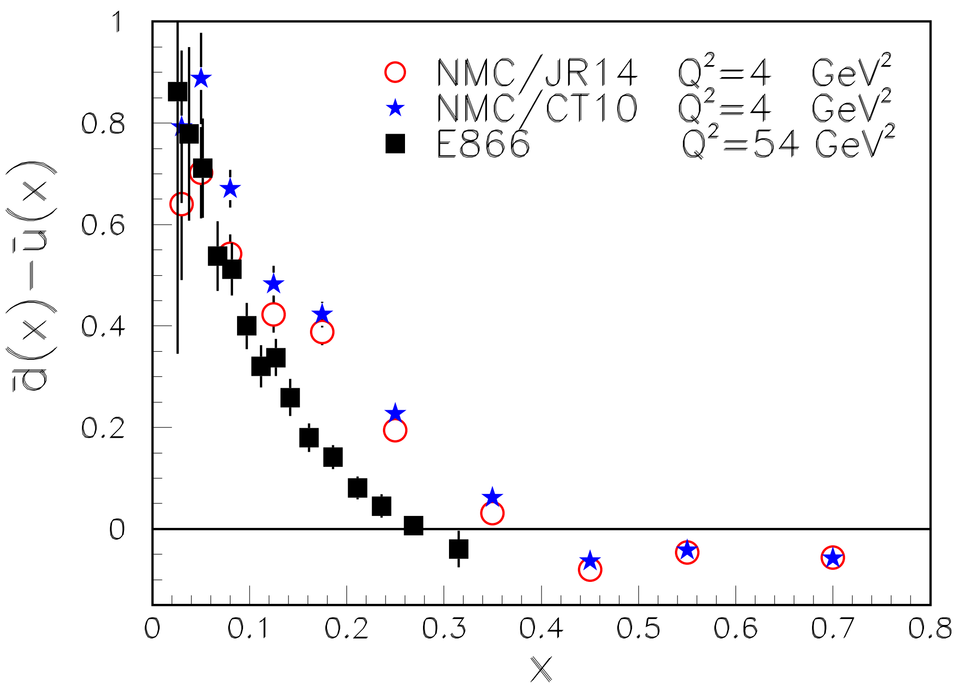
- More important effects expected at E906/SeaQuest kinematics at $x > 0.2$

→ could affect possible change of sign of $\bar{d} - \bar{u}$ at high x



Light antiquark sea

- Interesting recent speculation suggesting sign change in $\bar{d} - \bar{u}$ already evident in NMC $F_2^p - F_2^n$ data!



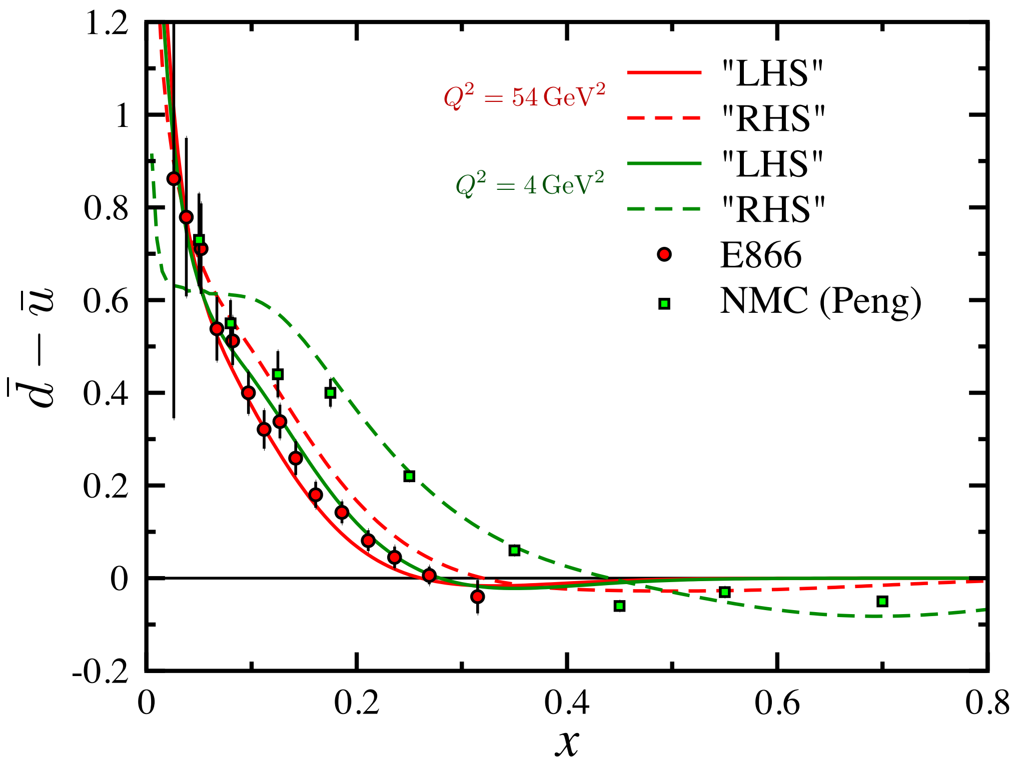
*Peng et al., PLB **736**, 411 (2014)*

→ based on leading order relation

$$\bar{d} - \bar{u} = \frac{1}{2}(u_v - d_v) - \frac{3}{2x}(F_2^p - F_2^n)$$

Light antiquark sea

- However, higher order and Q^2 evolution effects *not* negligible



$$\text{“LHS”} = \bar{d} - \bar{u}$$

$$\text{“RHS”} = \frac{1}{2}(u_v - d_v) - \frac{3}{2x}(F_2^p - F_2^n)$$

at NLO

→ negative "RHS" from NMC data at $x > 0.4$ consistent with zero "LHS" $(\bar{d} - \bar{u})$ at NLO

→ dangerous to draw physics conclusions from LO analysis

Outlook

- New CJ15 PDFs will be available soon (~ summer 2015)
  - → include constraints on large-x PDFs from new D0 W-asymmetry data, and first JLab F_2^n data
  - → reduced nuclear uncertainties on d quark *cf.* CJ12, with smaller d/u ratio in $x \to 1$ (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)

- Upcoming analysis will fit all available cross section data rather than extracted structure functions
  - → provide baseline set of (all-x) PDFs in anticipation of upcoming JLab 12 GeV data at high x
  - → better constraints on calculations of large invariant mass observables at LHC