4th Workshop of the APS Topical Group on Hadronic Physics
Anaheim, CA, April 27, 2011

New parton distributions from large-x, low-Q^2 data

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Outline

- Why are high-momentum (large x) quarks in the nucleon important?

- Extraction of neutron structure from inclusive data
  - → nuclear effects & d/u PDF ratio
  - → Q^2 dependence

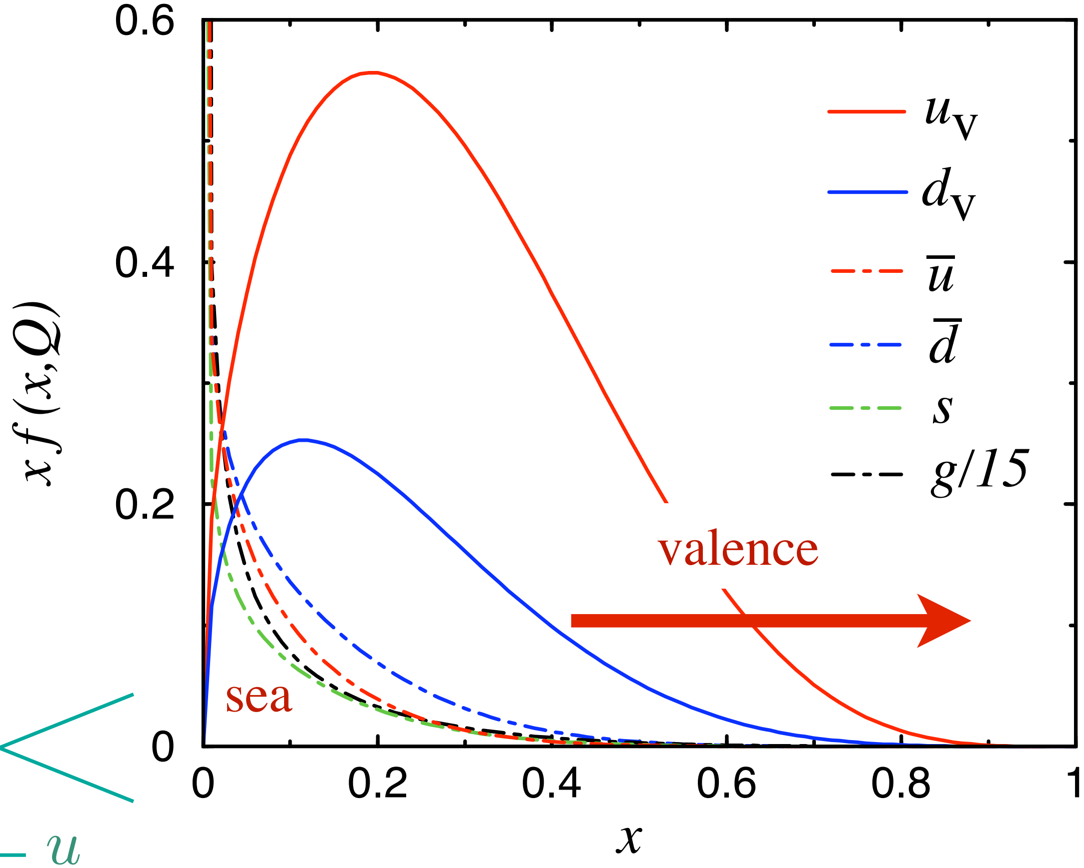
- New global "CJ" (CTEQ–Jefferson Lab) analysis
  - → first foray into high-x, low-Q^2 region
  - → surprising new results for d quark

- Future plans

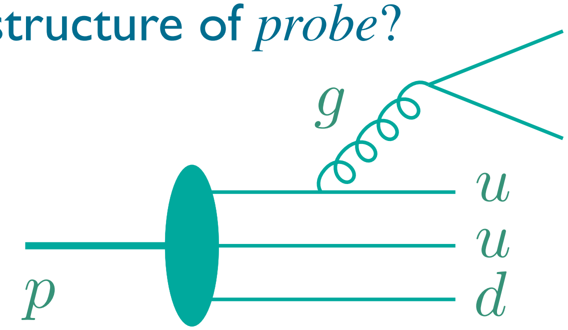
Why are PDFs at large x interesting?

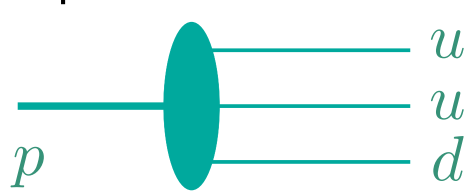
- Most direct connection between quark distributions and nonperturbative structure of nucleon is via *valence* quarks

  → most cleanly revealed at $x > 0.4$



structure of *hadron*
or structure of *probe*?





Why are PDFs at large x interesting?

- Most direct connection between quark distributions and nonperturbative structure of nucleon is via *valence* quarks

- Predictions for $x \to 1$ behavior of $e.g.$ d/u ratio

  → scalar diquark dominance: $d/u = 0$ *Feynman (1972)*

  → hard gluon exchange: $d/u = 1/5$ *Farrar, Jackson (1975)*

  → SU(6) symmetry: $d/u = 1/2$

- Needed to understand backgrounds in searches for *new physics* beyond the Standard Model at LHC or in ν oscillation experiments

  → DGLAP evolution feeds low x, high Q^2 from high x, low Q^2

- At large x, valence u and d distributions extracted from p and n structure functions, $e.g.$ at LO

$$\frac{1}{x}F_2^p \approx \frac{4}{9}u_v + \frac{1}{9}d_v$$

$$\frac{1}{x}F_2^n \approx \frac{4}{9}d_v + \frac{1}{9}u_v$$

$\longrightarrow$ u quark distribution well determined from *proton*

$\longrightarrow$ d quark distribution requires *neutron* structure function

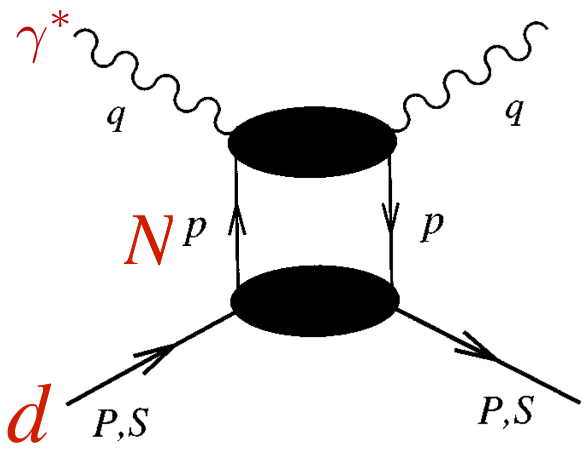
- No *free* neutron targets

$\longrightarrow$ nuclear effects (nuclear binding, Fermi motion, shadowing) obscure neutron structure information

Nuclear effects
in the deuteron

Nuclear "impulse approximation"

→ incoherent scattering from individual nucleons in d (good approx. at $x >> 0$)



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

$N=p+n$

nucleon momentum distribution in d ("smearing function")

off-shell correction

→ $y = p\cdot q/P\cdot q$ light-cone momentum fraction of d carried by N

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

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

N momentum distribution in d

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

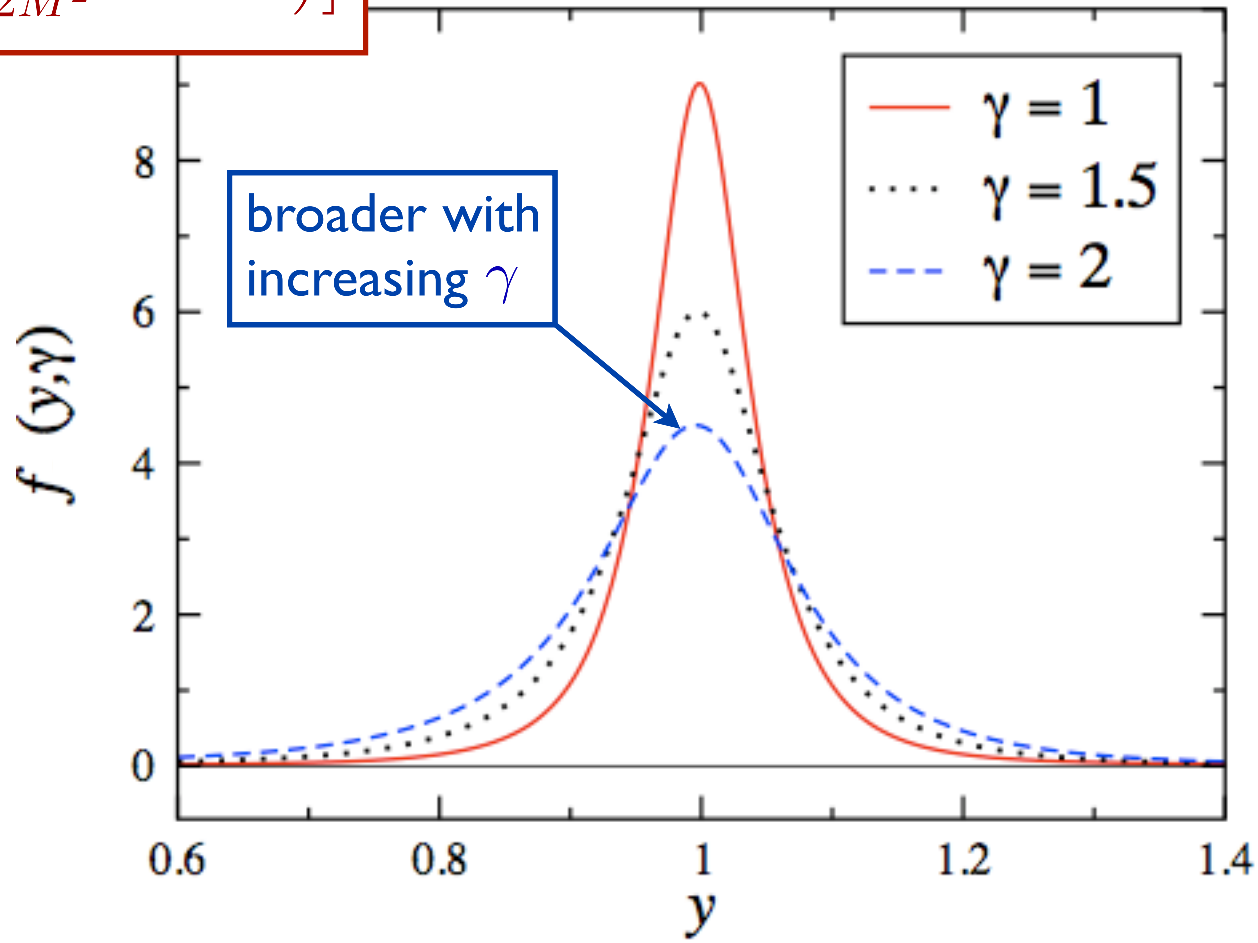
weak binding approximation (WBA): expand in powers of $|\vec{p}|/M$

→ deuteron wave function $\psi_d(p)$

→ deuteron separation energy

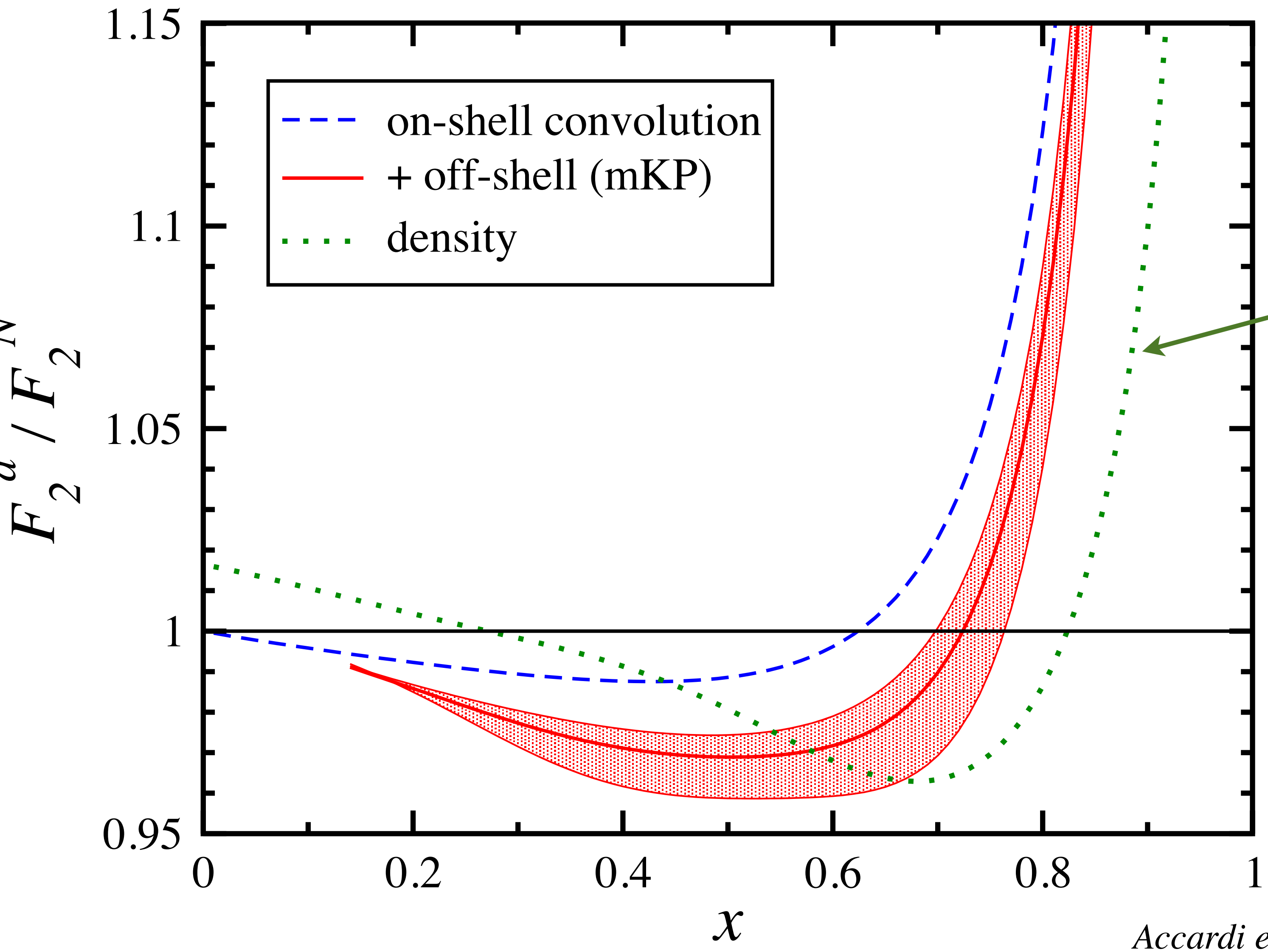
$$\varepsilon = \varepsilon_d - \frac{\vec{p}^{\,2}}{2M}$$

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



Kahn, WM, Kulagin, PRC ***79****, 035205 (2009)*

"EMC effect" in deuteron



nuclear density

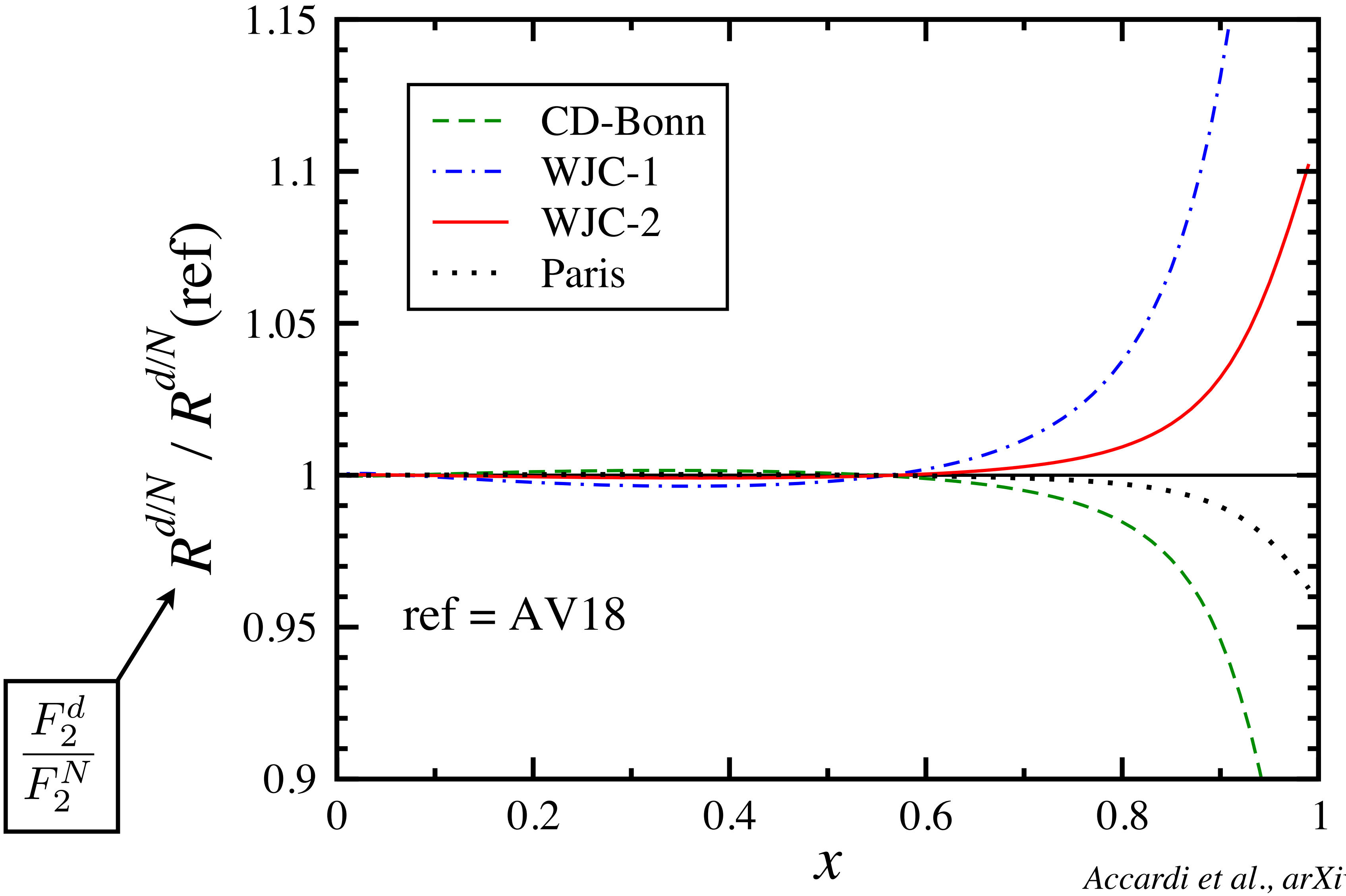
$$\frac{F_2^d}{F_2^N} - 1 \approx \frac{1}{4}\left(\frac{F_2^{\rm Fe}}{F_2^d} - 1\right)$$

assumes EMC effect scales with density; extrapolated from Fe → deuterium

Accardi et al., arXiv:1101.1234

→ $\approx$ 2–4% depletion at $x \sim 0.4$–0.6, depending on model

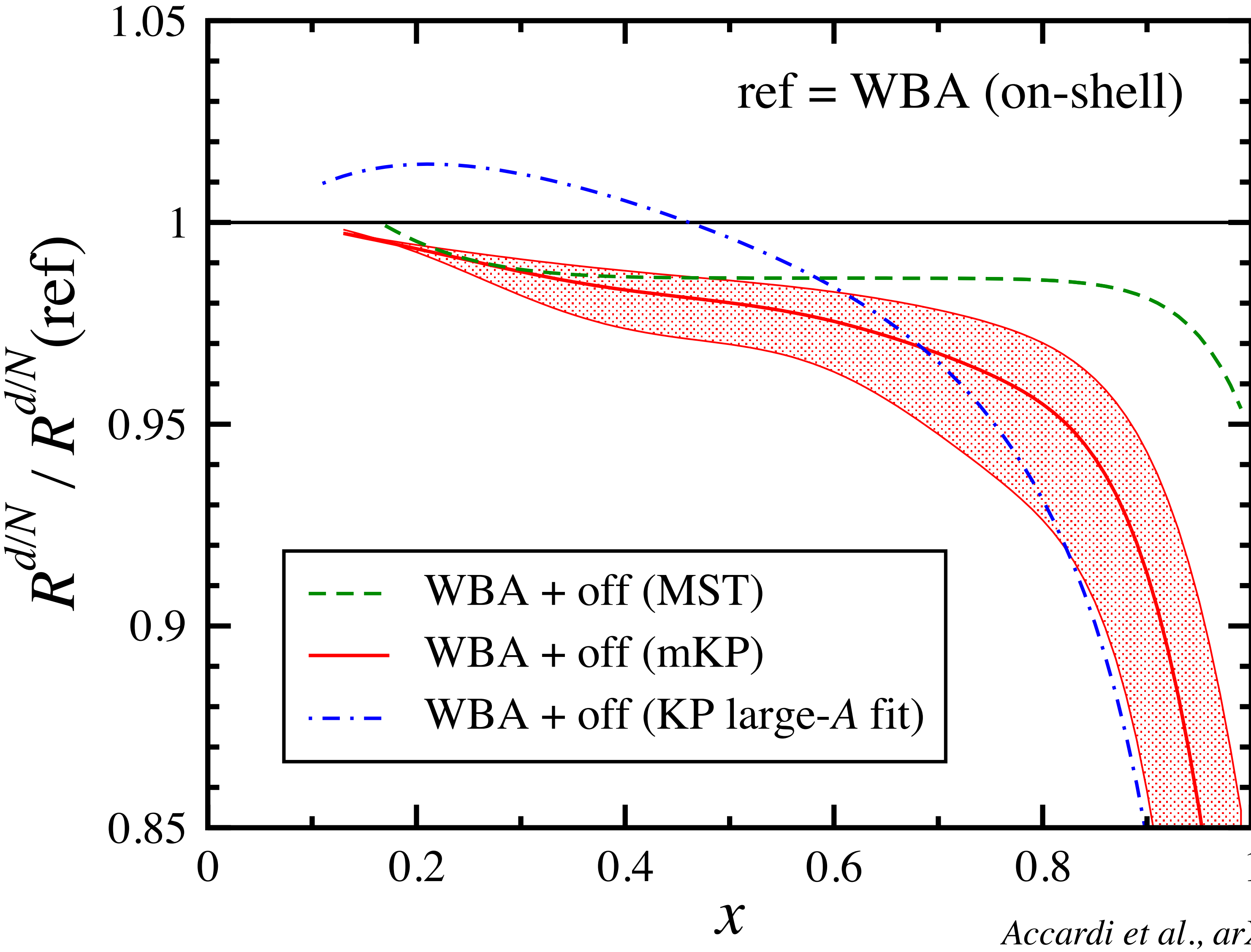
Model dependence: *NN* interaction at short distances



Accardi et al., arXiv:1101.1234

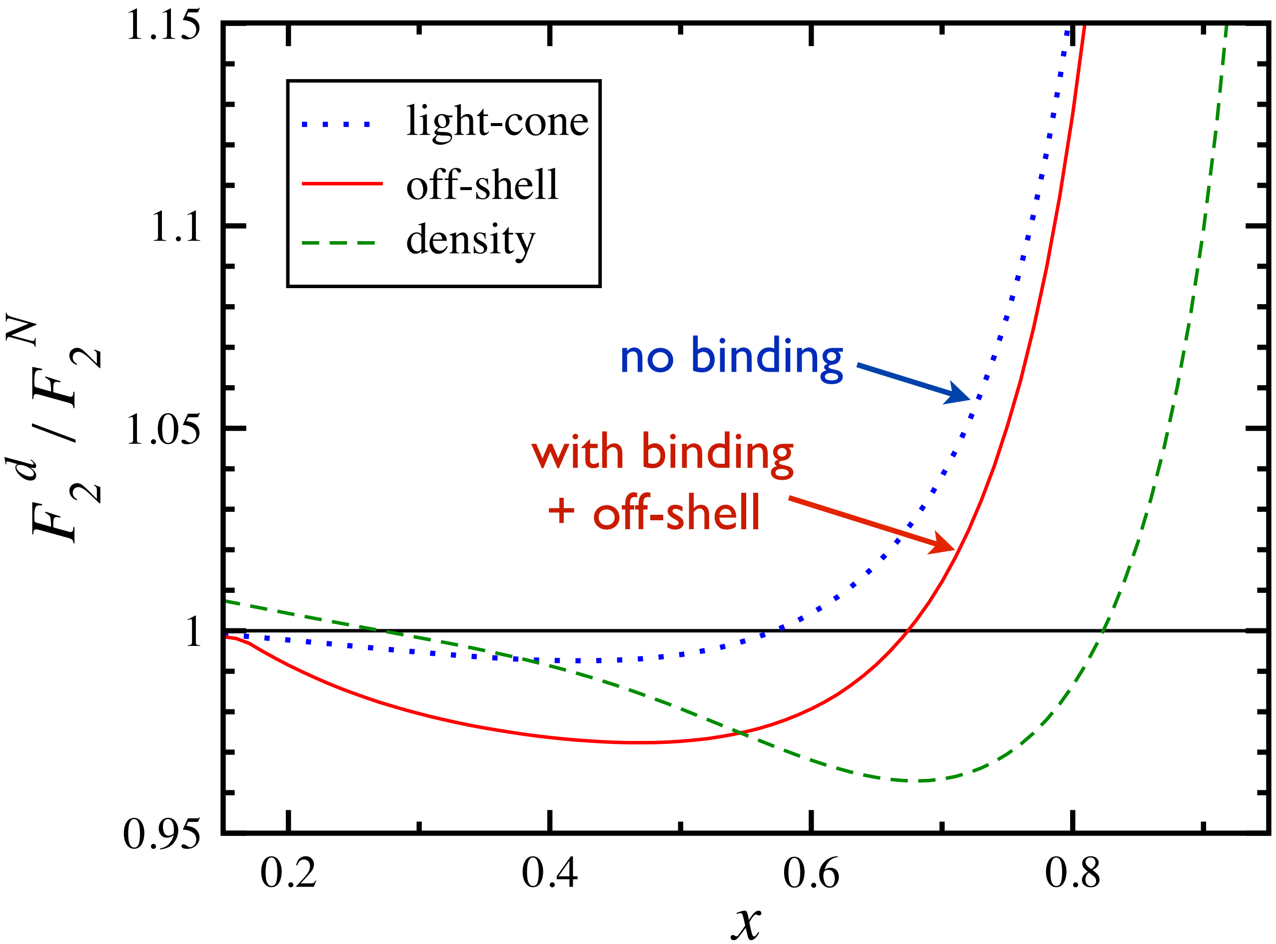
→ high x probes large-y tail of momentum distribution

Model dependence: nucleon off-shell corrections



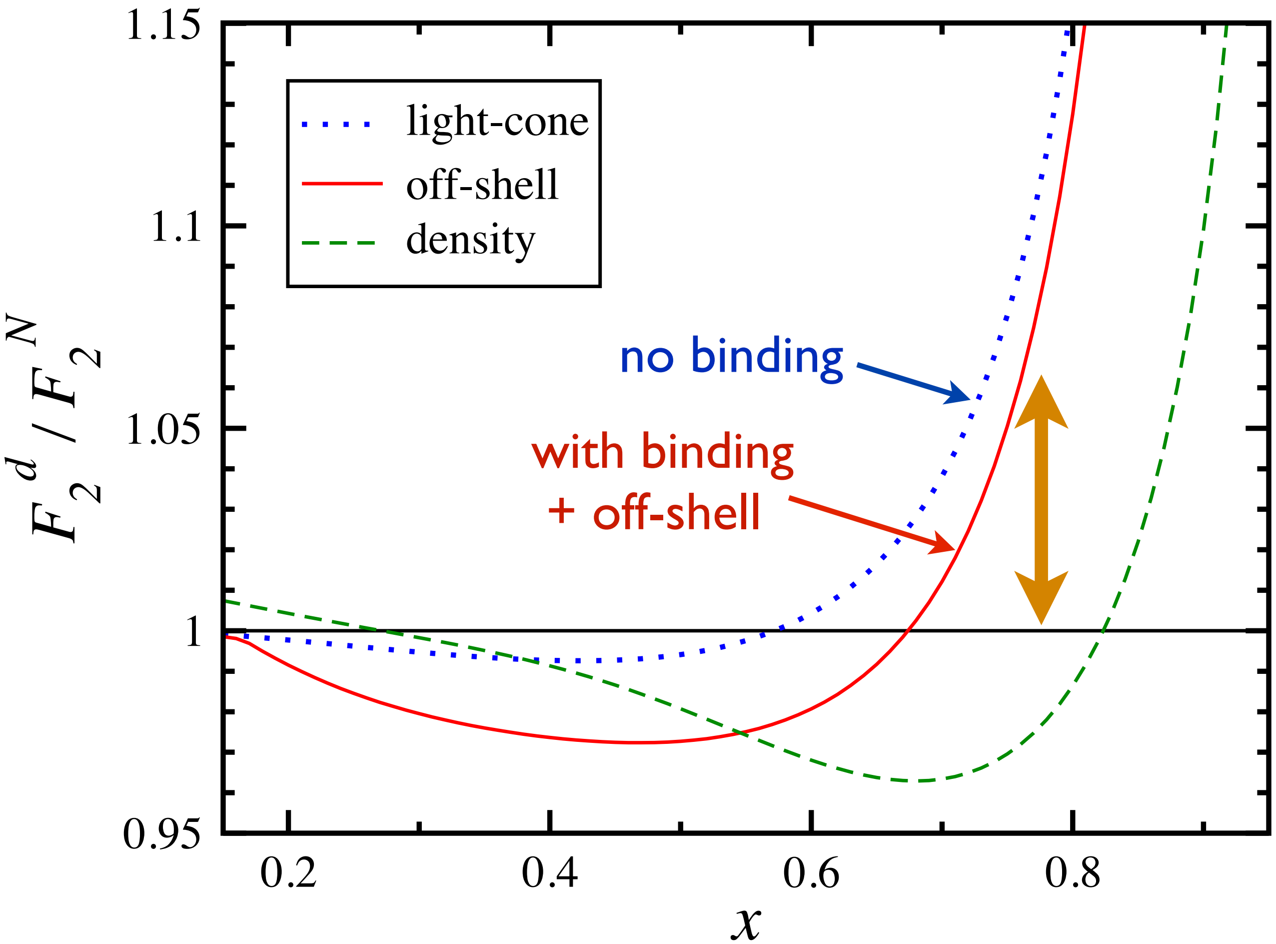
Accardi et al., arXiv:1101.1234

→ additional few % suppression at large x



→ $\sim 2\text{–}3\%$ reduction of F_2^d/F_2^N at $x \sim 0.5\text{–}0.6$ with steep rise for $x > 0.6\text{–}0.7$

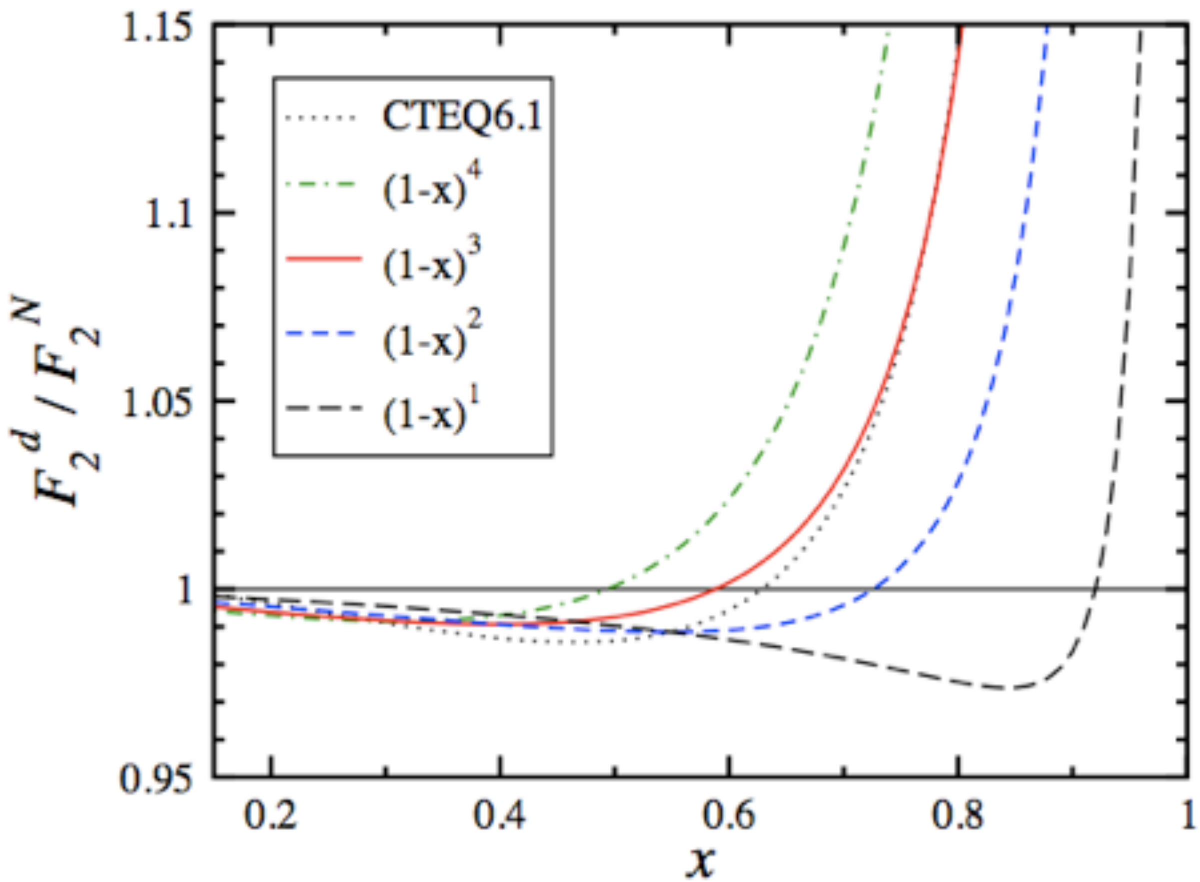
→ larger EMC effect at $x \sim 0.5\text{–}0.6$ with binding + off-shell corrections *cf.* light-cone



→ using off-shell model, will get *larger* neutron *cf. light-cone* model

→ but will get *smaller* neutron *cf. no nuclear effects* or *density* model

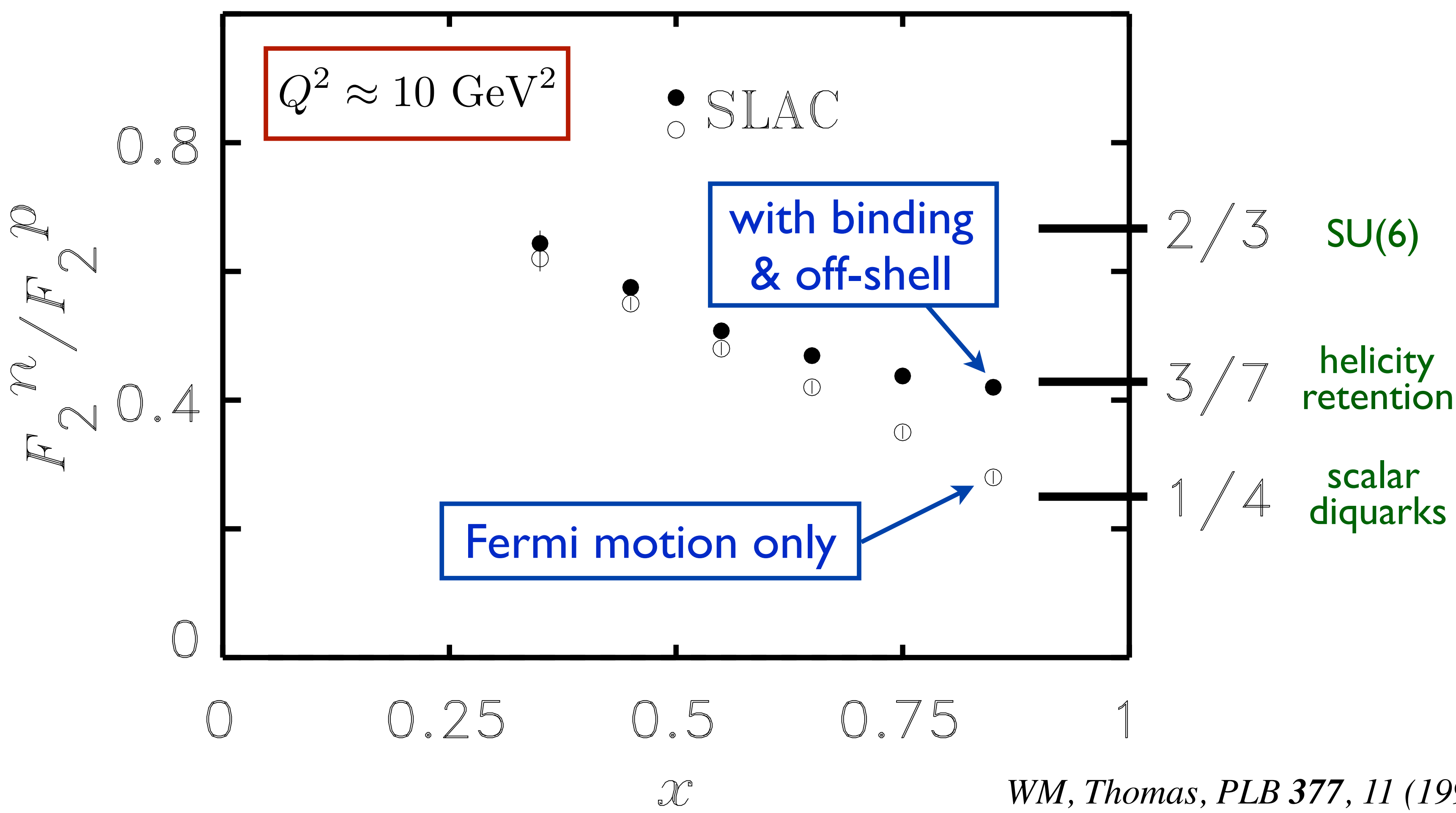
 WARNING 



→ EMC ratio depends also on *input nucleon* SFs; need to *iterate* when extracting F_2^n

Extraction of neutron SF from inclusive data

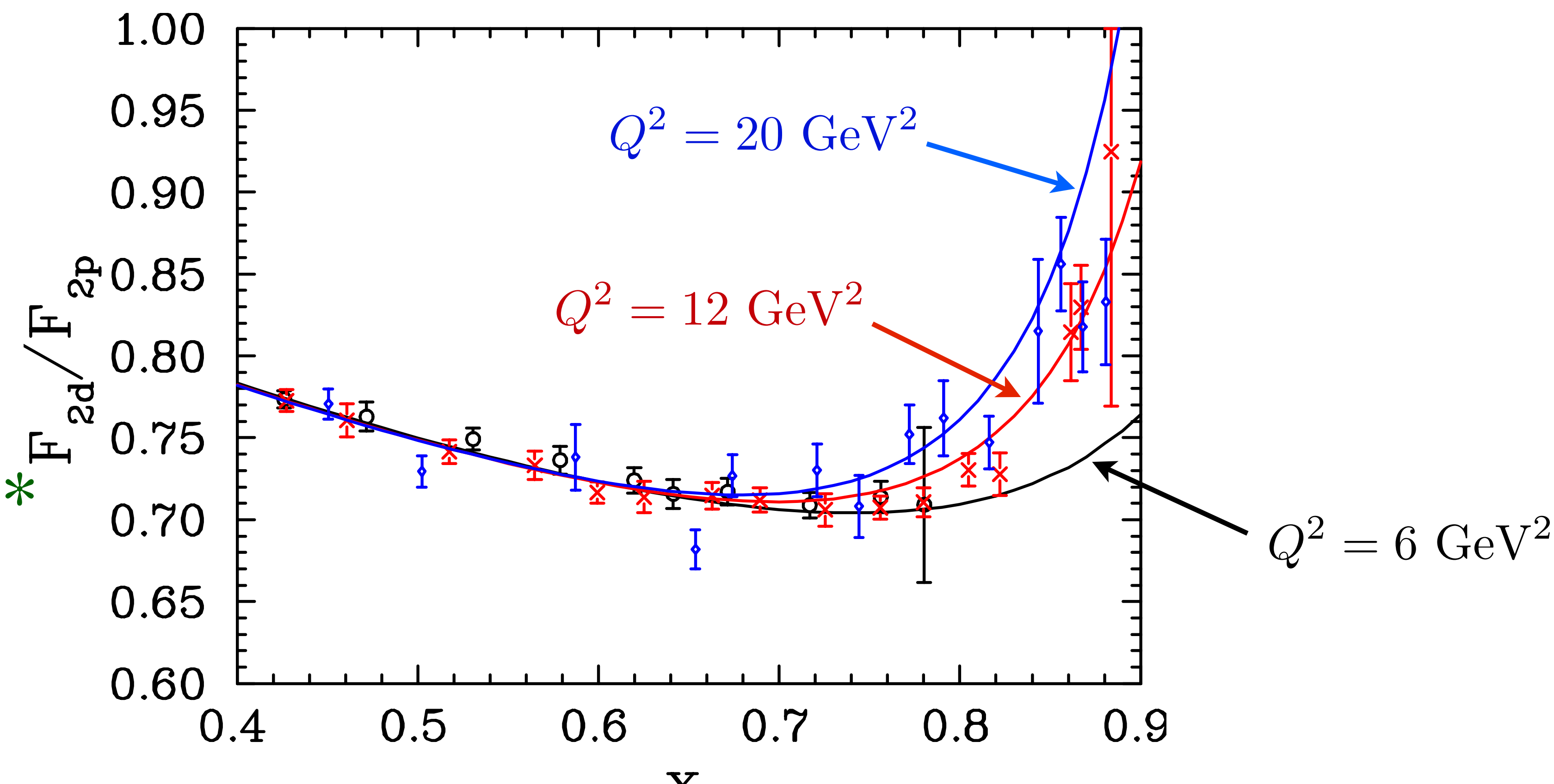
Impact of nucleon off-shell corrections (+ iteration)



WM, Thomas, PLB ***377****, 11 (1996)*

→ without EMC effect in d, F_2^n underestimated at large x

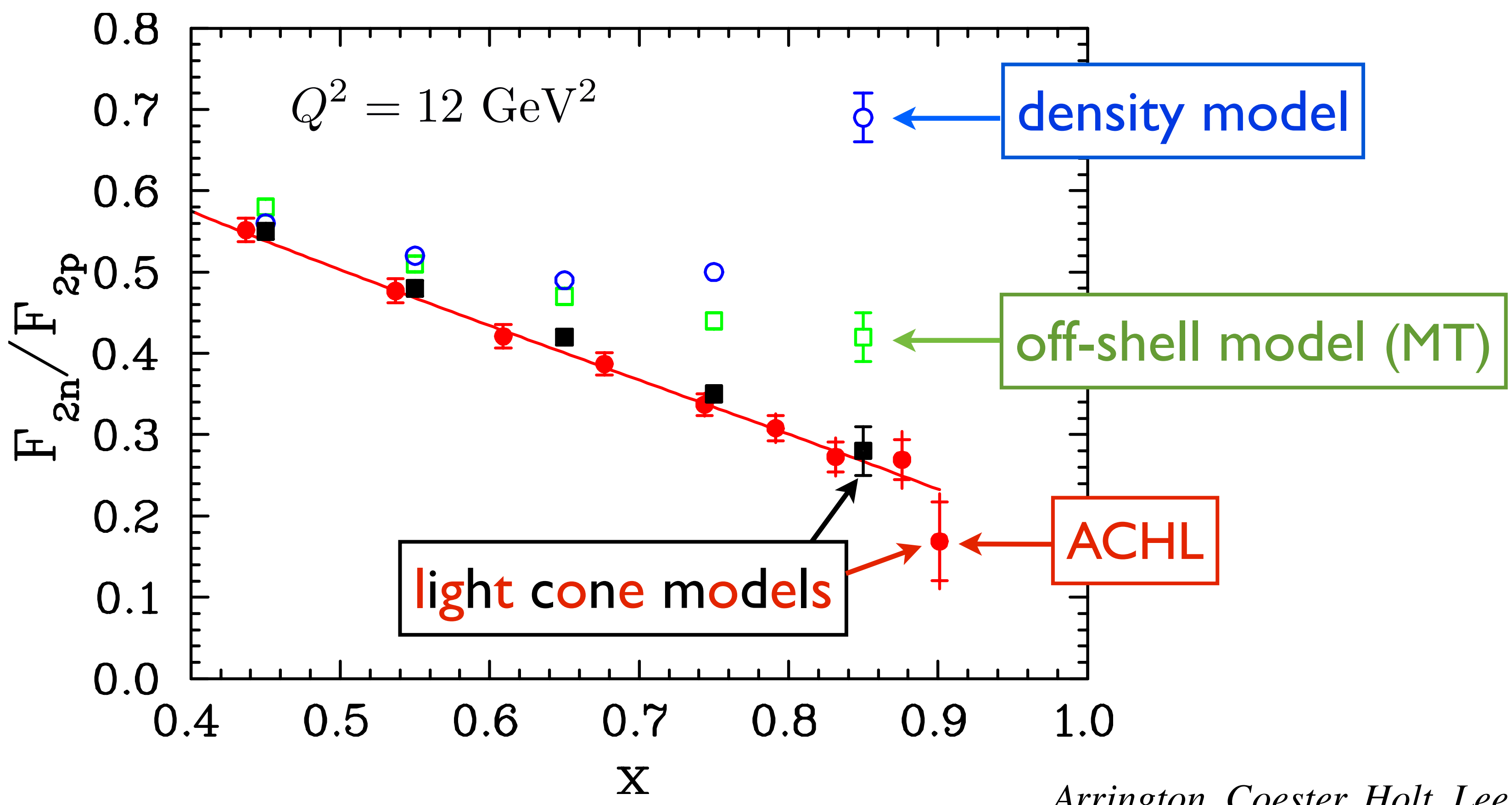
■ Important to account for Q^2 dependence of data at large x



Arrington, Coester, Holt, Lee
JPG ***36,*** *025005 (2009)*

* F_2^d computed using smearing ratios $S_N = F_2^{N/d}/F_2^N$ in light-cone model

■ Important to account for Q^2 dependence of data at large x

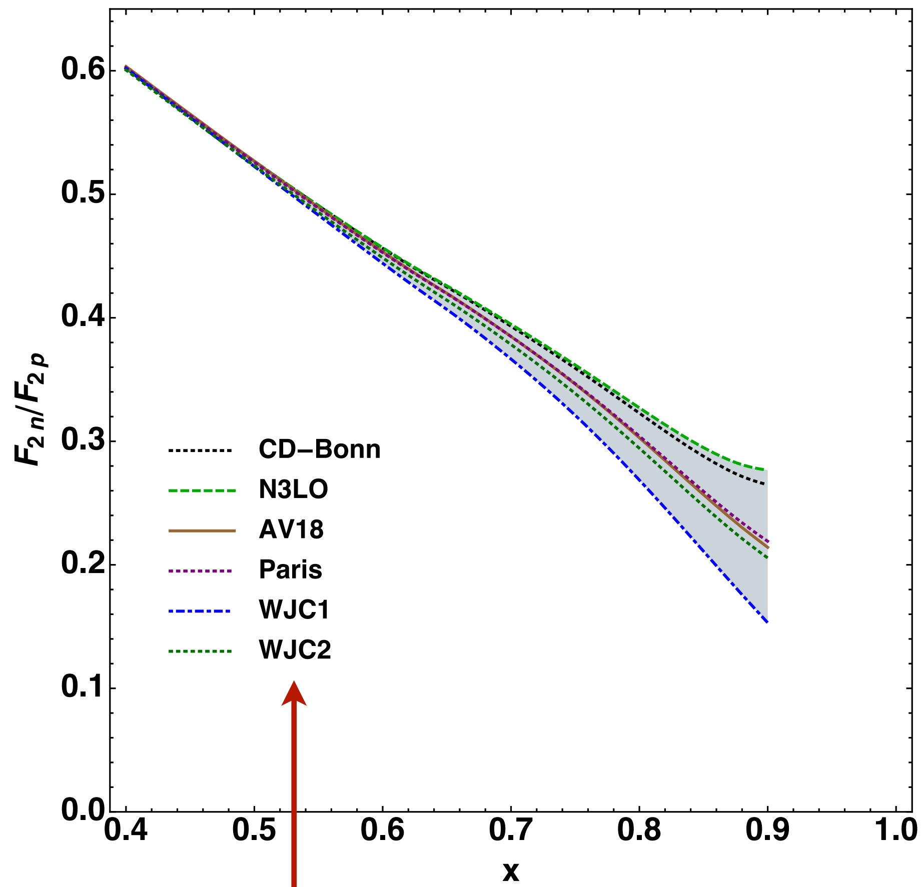


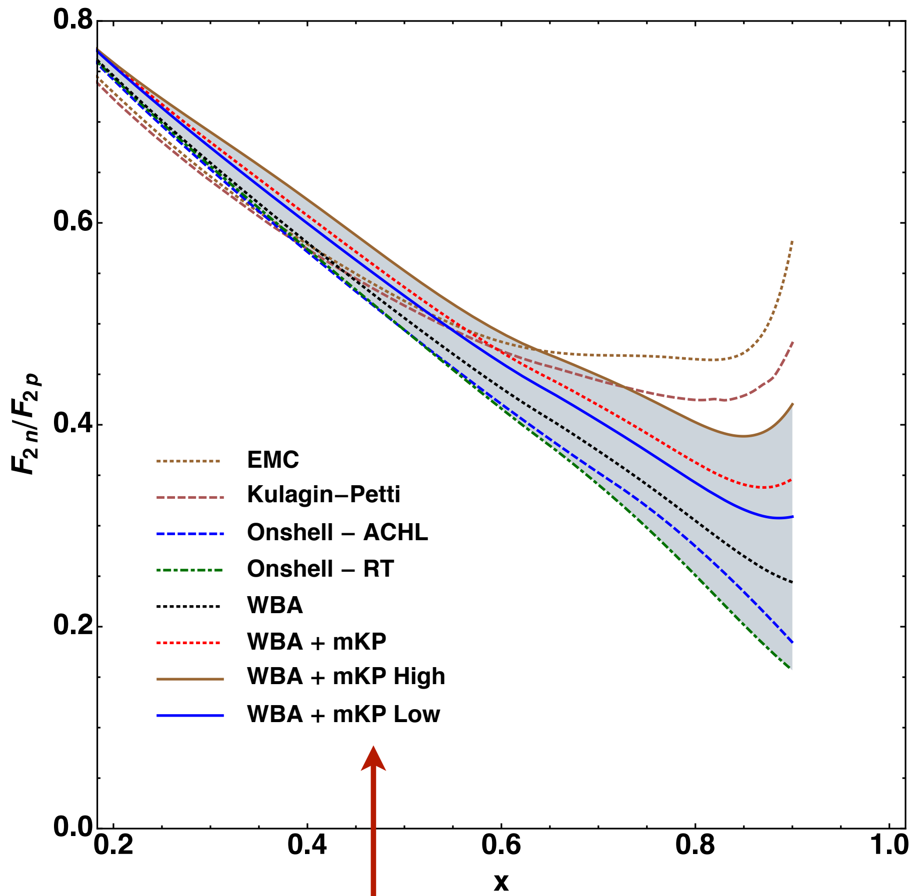
Arrington, Coester, Holt, Lee
JPG ***36****, 025005 (2009)*

→ nuclear model dependence consistent with earlier findings

(*NB*: F_2^n/F_2^p ratio here *not* constrained by $1/4$ PDF-positivity bound)

Deuteron model dependence explored in subsequent analysis



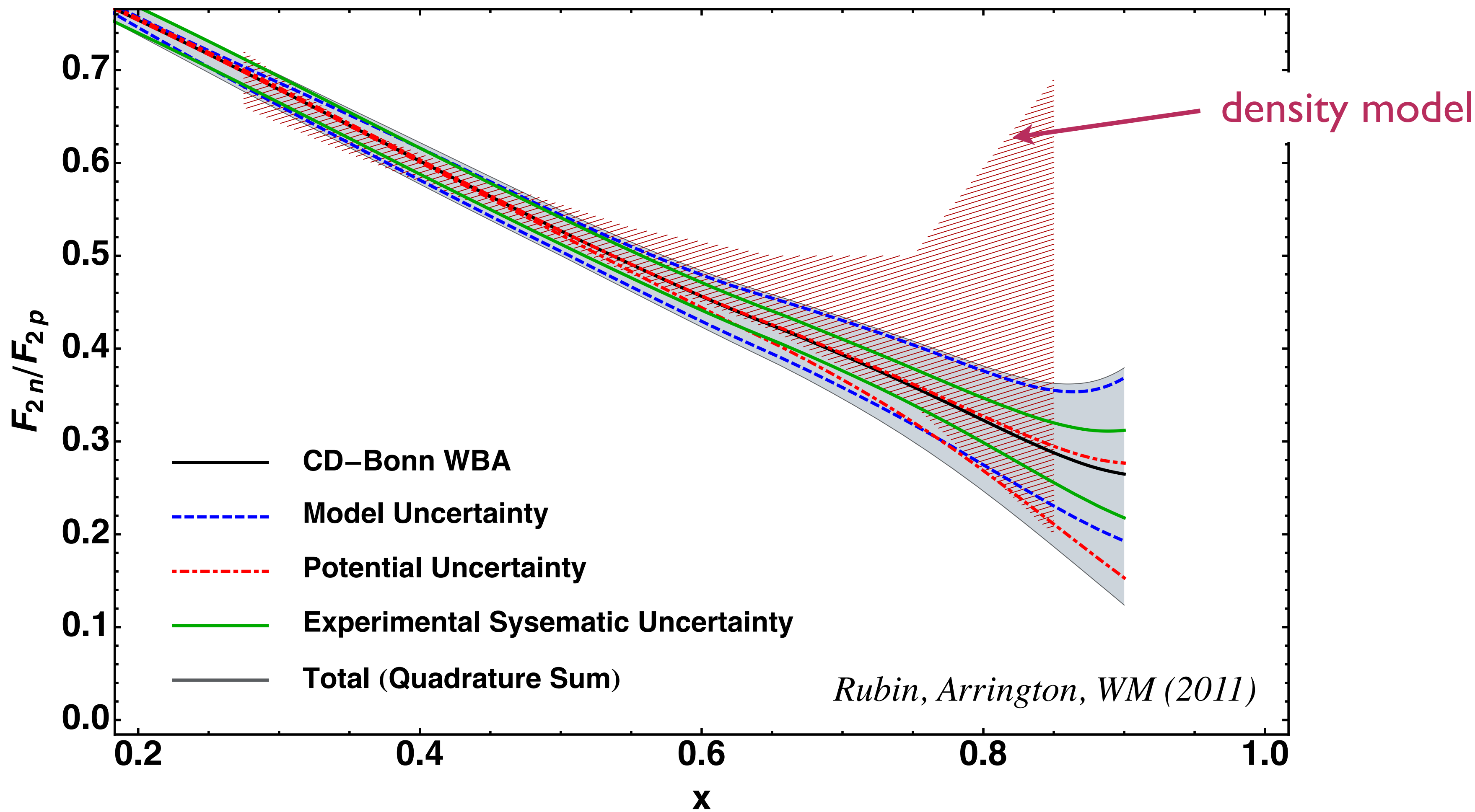


deuteron wave function dependence

nucleon on-shell / off-shell model dependence

Rubin, Arrington, WM (2011)

Deuteron model dependence explored in subsequent analysis



→ total uncertainty band smaller than "full" range of models (including *e.g.* density model)

→ significant *cf.* usual assumptions made in global PDF analyses

New global analysis:
"CJ" (CTEQ-JLab) collaboration

A. Accardi, E. Christy, C. Keppel, S. Malace,
W. Melnitchouk, P. Monaghan, J. Morfin, J. Owens, L. Zhu

Accardi et al., Phys. Rev. D ***81****, 034016 (2010)*
Accardi et al., arXiv:1101.1234, to appear in PRD

- Next-to-leading order (NLO) analysis of expanded set of *proton* and *deuterium* data, including large-x, low-Q^2 region

  → also include new CDF & D0 W-asymmetry, and E866 DY data

- Systematically study effects of Q^2 & W *cuts*

  → as low as $Q \sim m_c$ and $W \sim 1.7$ GeV

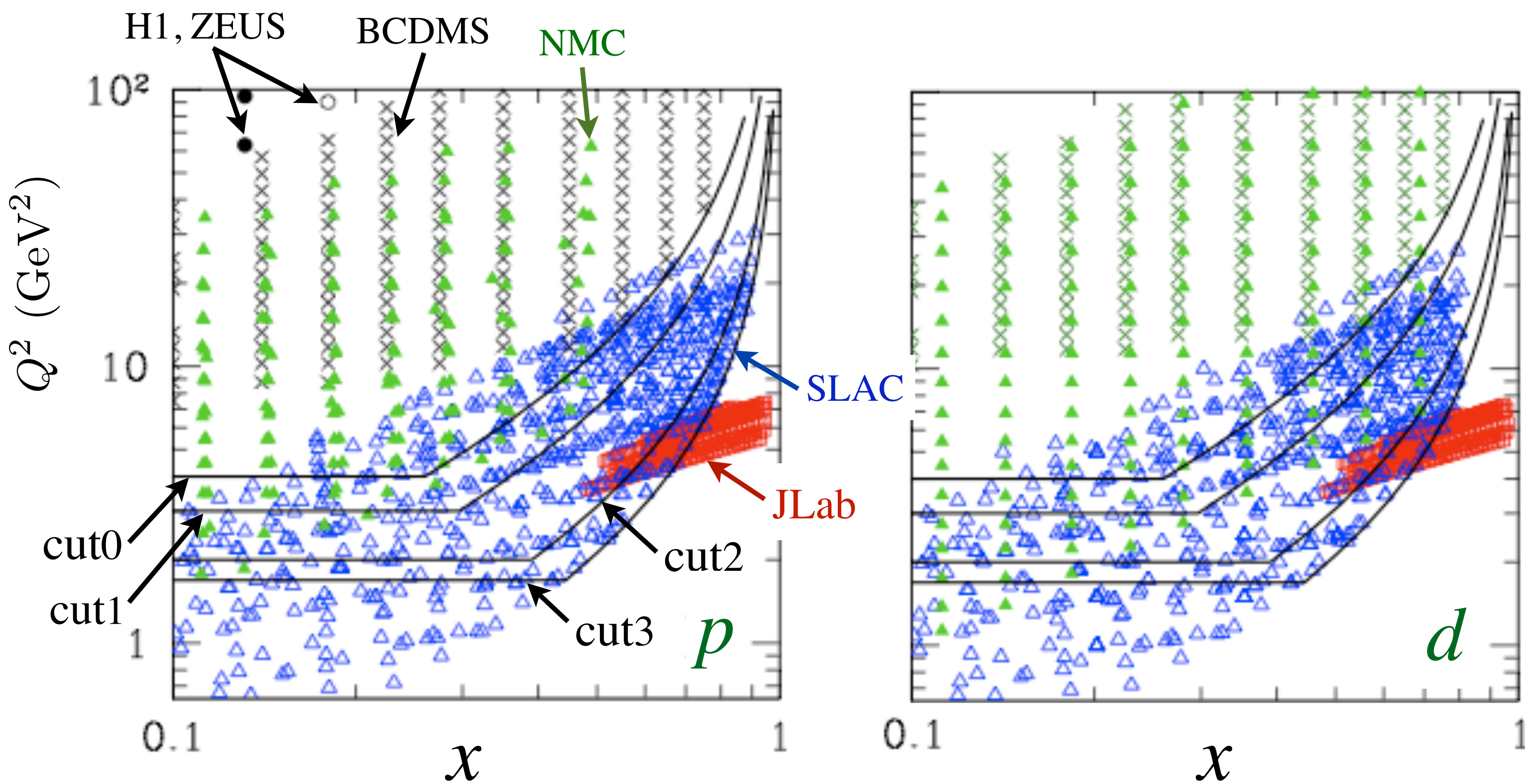
- Include subleading $1/Q^2$ corrections

  → target mass corrections & dynamical higher twists

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

  → most global analyses assume *free* nucleons; some use density model, a few assume Fermi motion only

Kinematic cuts



cut0: $Q^2 > 4\ \mathrm{GeV}^2, \quad W^2 > 12.25\ \mathrm{GeV}^2$

cut1: $Q^2 > 3\ \mathrm{GeV}^2, \quad W^2 > 8\ \mathrm{GeV}^2$

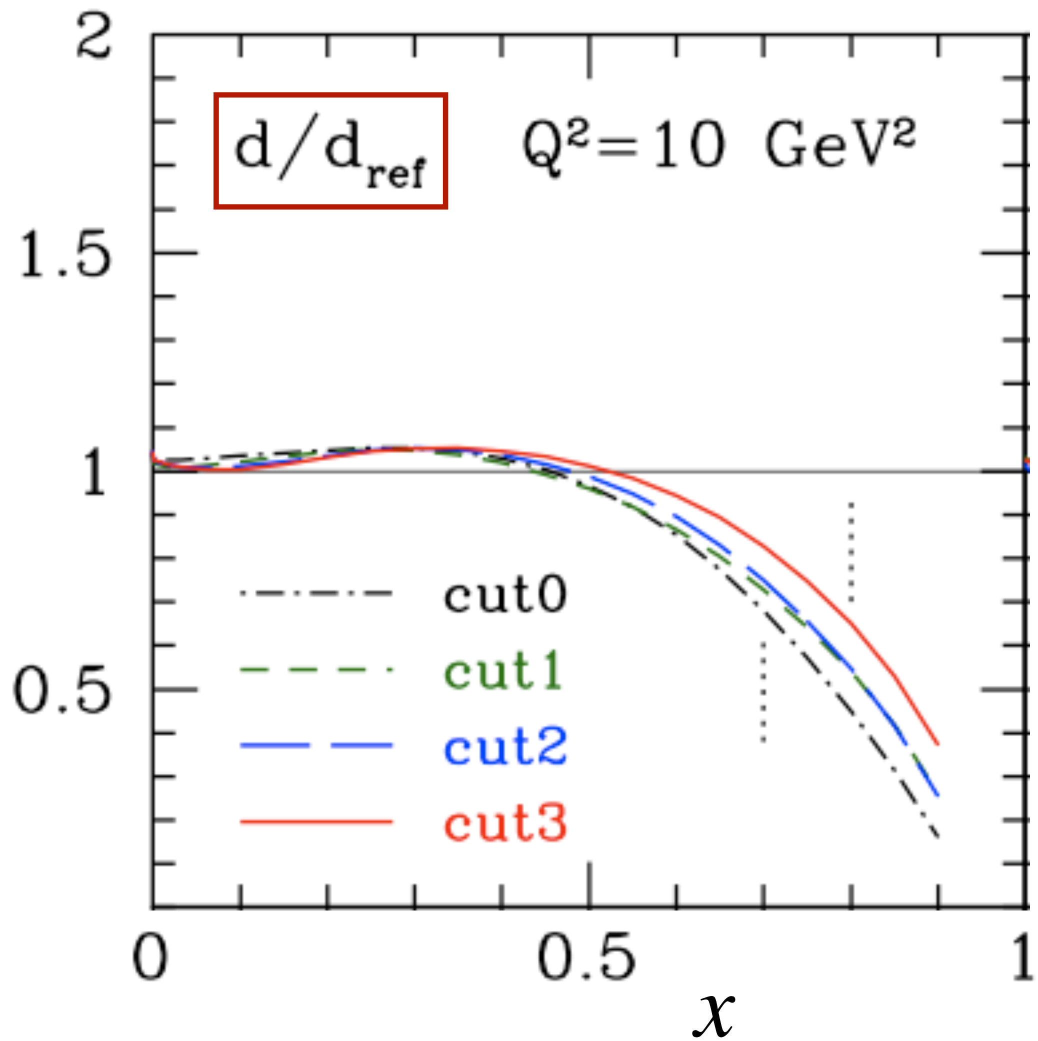
cut2: $Q^2 > 2\ \mathrm{GeV}^2, \quad W^2 > 4\ \mathrm{GeV}^2$

cut3: $Q^2 > m_c^2\ , \quad W^2 > 3\ \mathrm{GeV}^2$

factor 2 increase in DIS data from cut0 $\longrightarrow$ cut3

Effect of Q^2 & W cuts

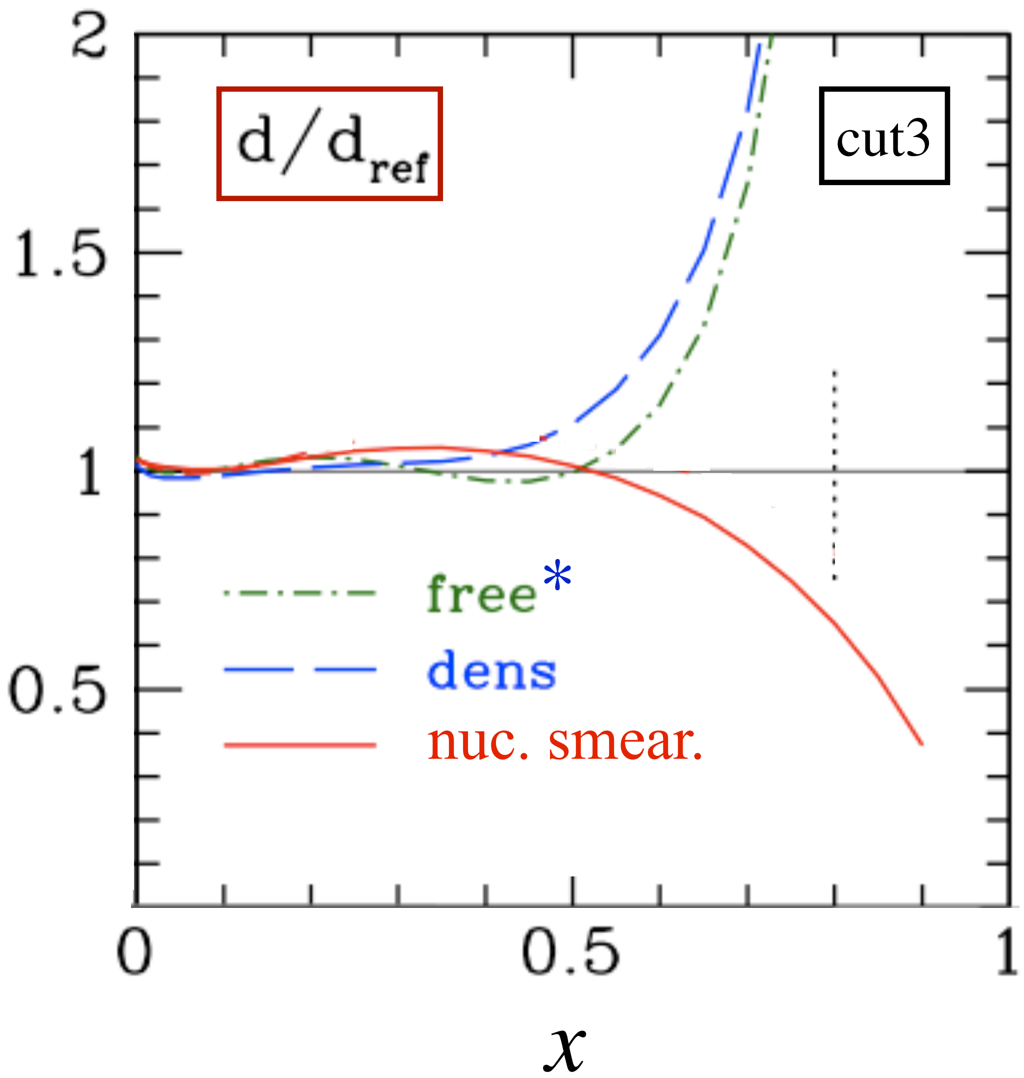
- Systematically reduce Q^2 and W cuts
- Fit includes TMCs, HT term, nuclear corrections



→ *stable* with respect to cut reduction

→ d quark suppressed by $\sim 50\%$ for $x > 0.5$ (driven by nuclear corrections)

Nuclear corrections



* assumes $F_2^d = F_2^p + F_2^n$ as in CTEQ6.1 and most other global fits

→ *increased* d quark for no nuclear effects

(compensates for nuclear smearing in deuteron → increased F_2^d)

→ *decreased* d quark for nuclear smearing models

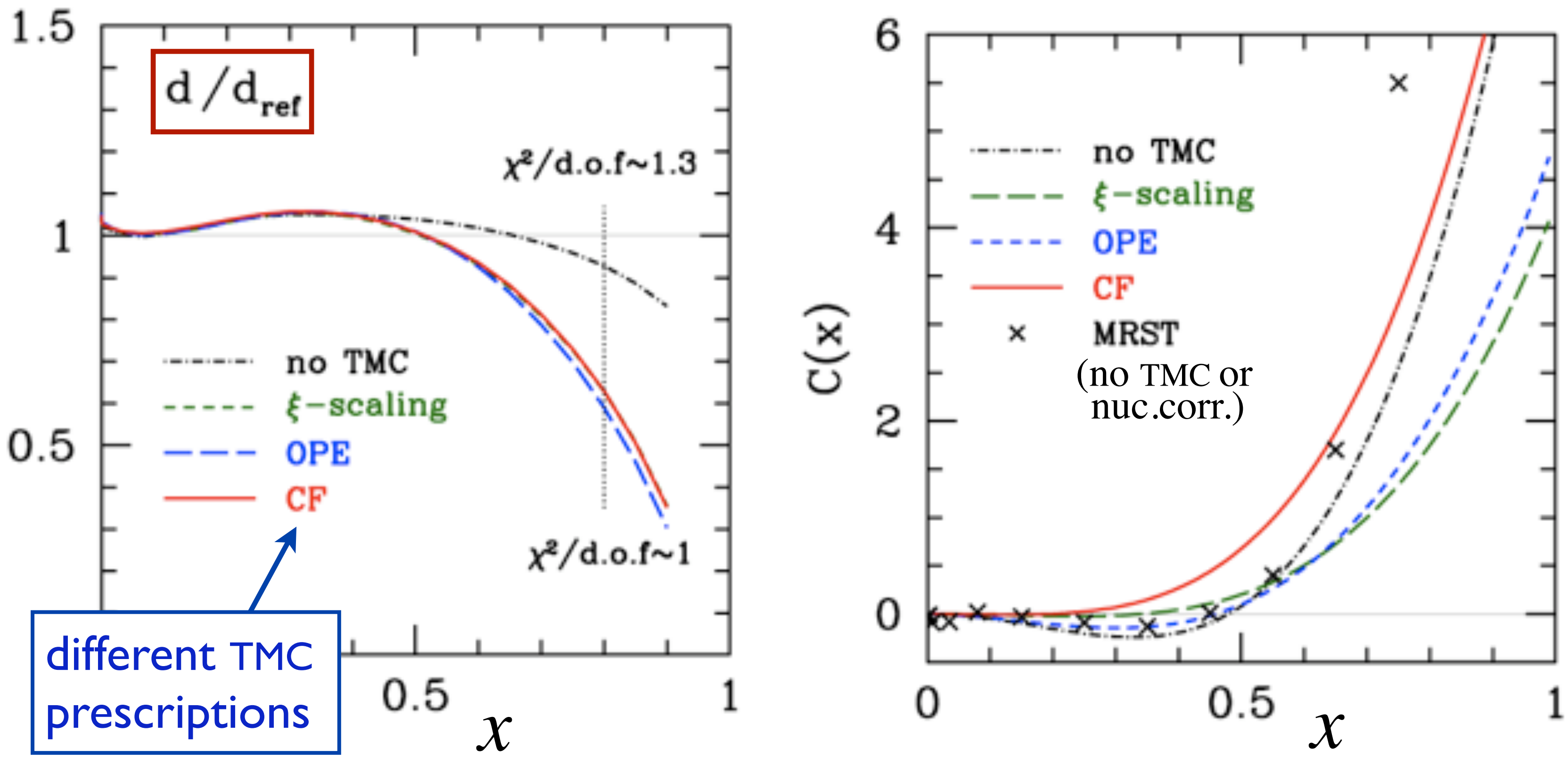
↓

$F_2^d/F_2^N > 1$ for $x \sim 0.6$–0.8 while $F_2^d/F_2^N < 1$ for "free" and "density" models

$F_2^d/F_2^N \uparrow \leftrightarrow F_2^n/F_2^p \downarrow$

$\leftrightarrow d/u \downarrow$

Effect of $1/Q^2$ corrections

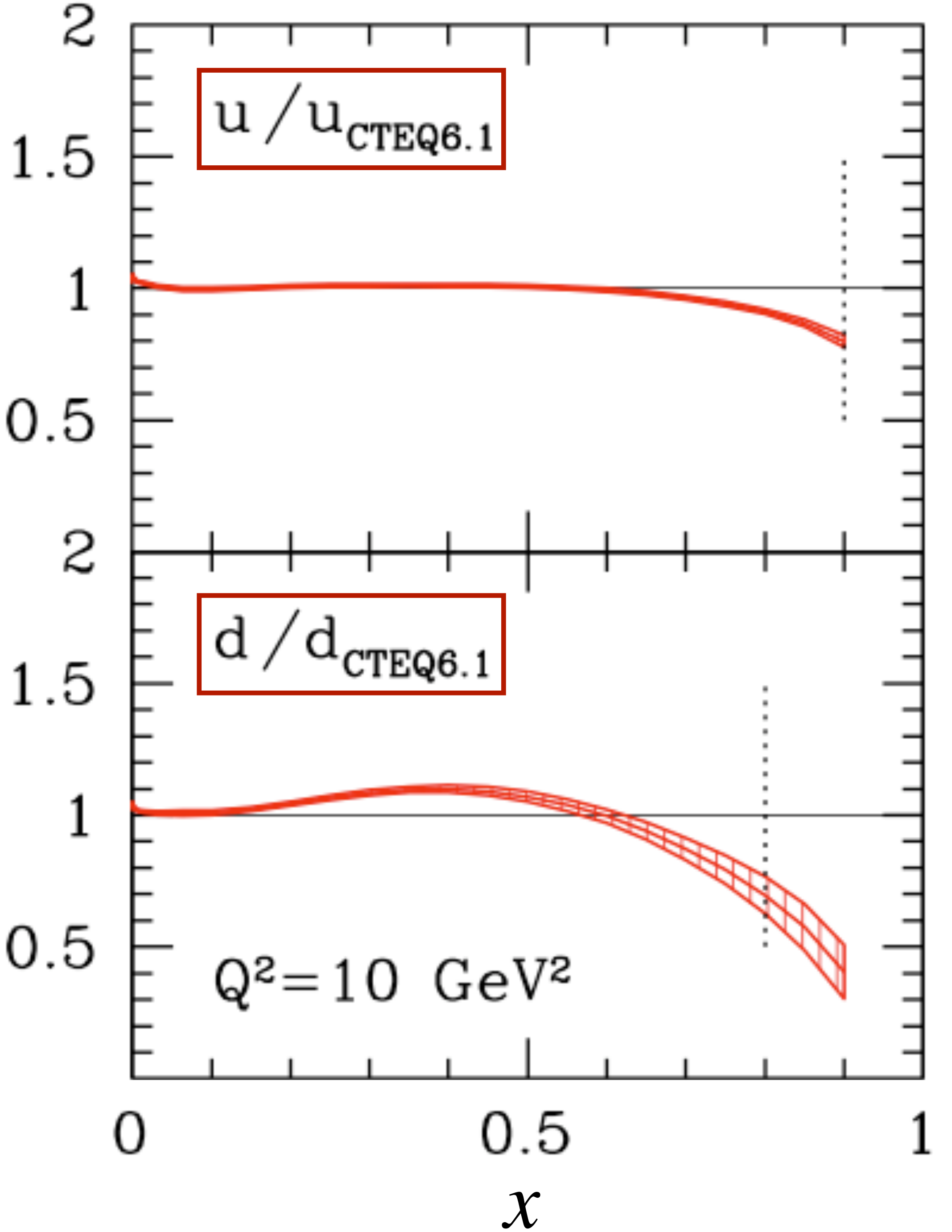


→ $1/Q^2$ correction $F_2 = F_2^{\rm LT}\left(1 + \frac{C(x)}{Q^2}\right)$, $\quad C(x) = c_1 x^{c_2}(1 + c_3 x)$

→ important interplay between TMCs and higher twist:
HT alone *cannot* accommodate full Q^2 dependence

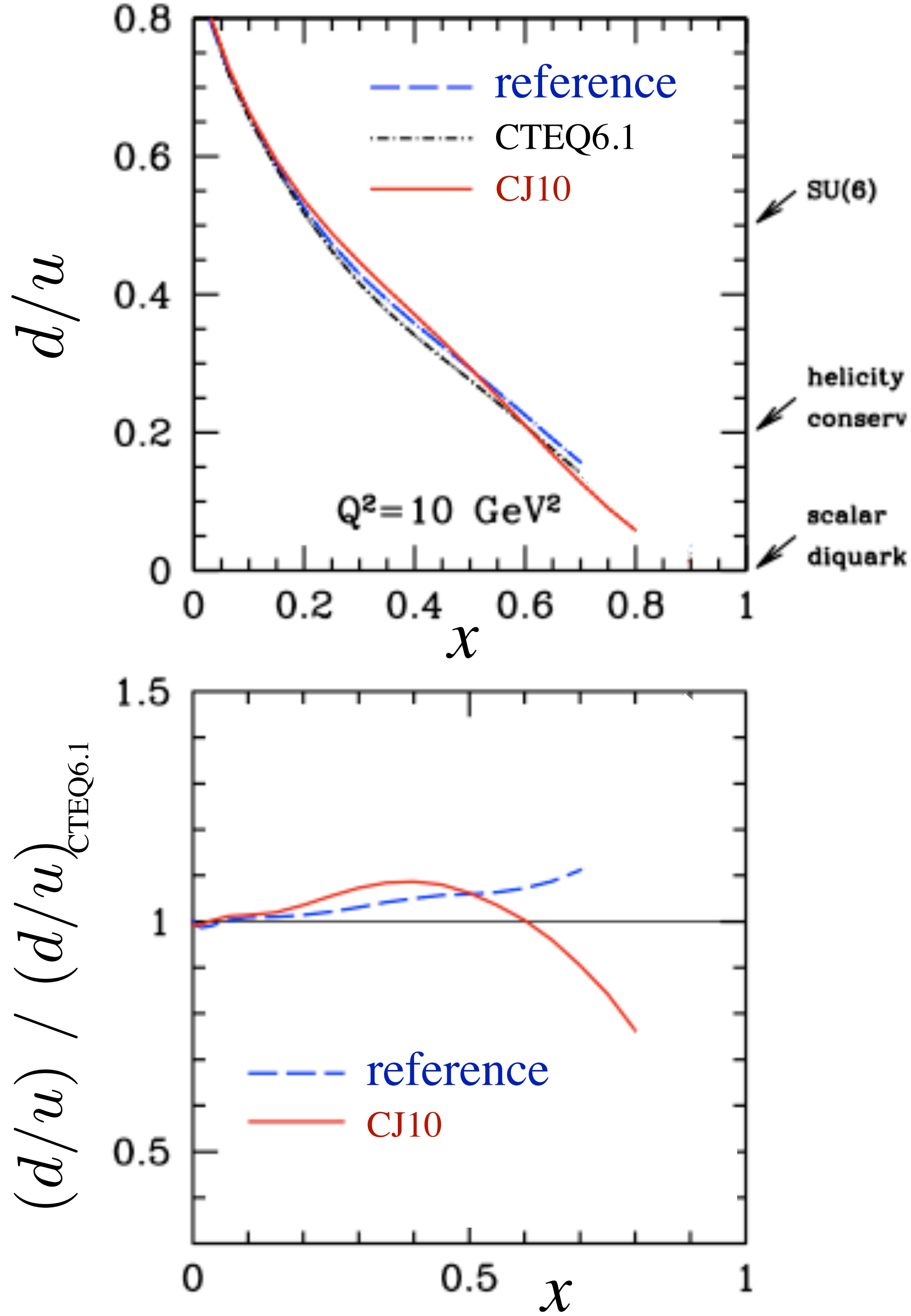
→ stable leading twist when *both* TMCs and HTs included

CJ10 PDF results



→ full fits favors smaller d/u ratio

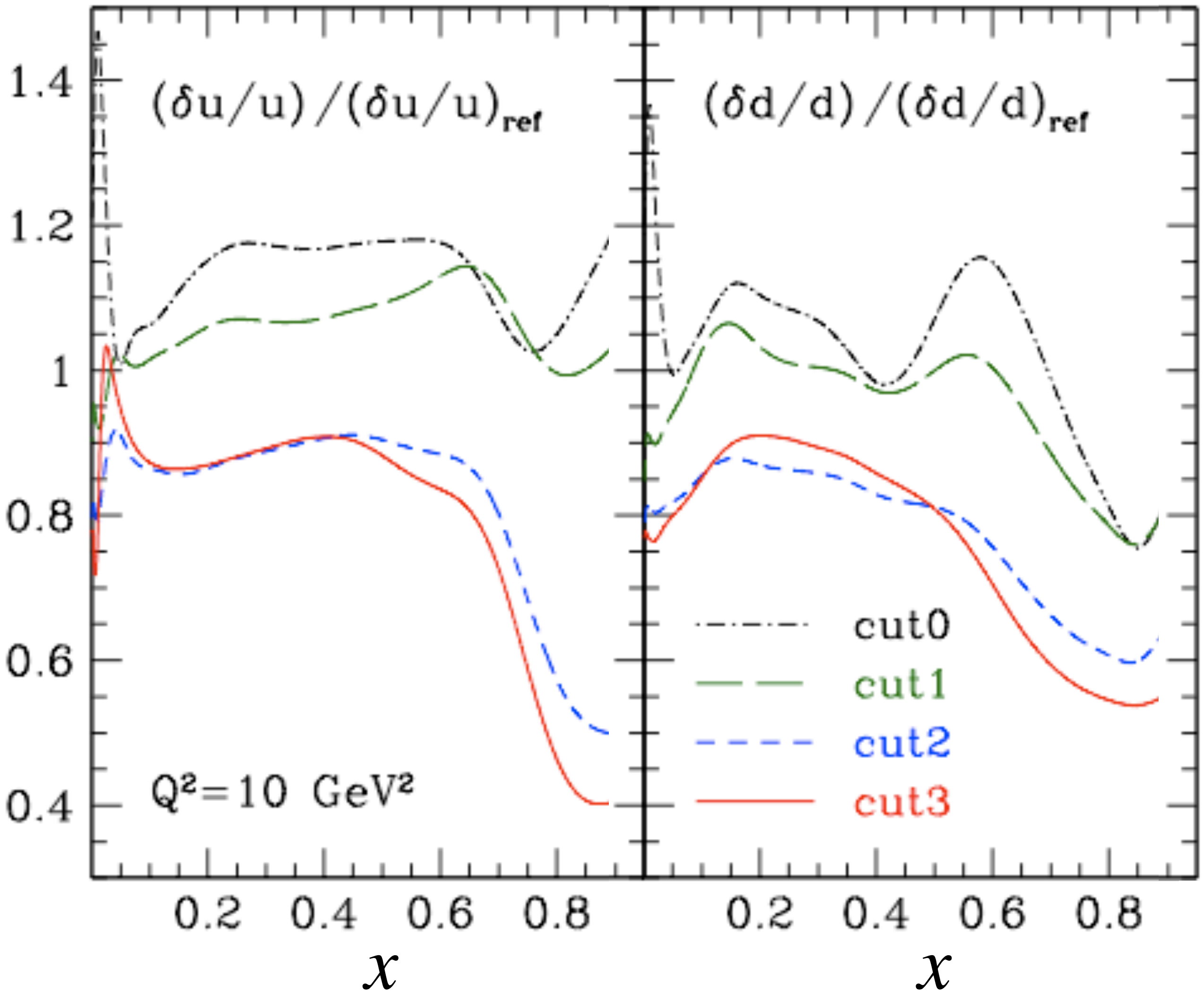
CJ10 PDF results



→ full fits favors smaller d/u ratio

→ dominance of non-pQCD physics
(*cf.* hard g exchange)

CJ10 PDF results



→ full fits favors smaller d/u ratio

→ dominance of non-pQCD physics (*cf.* hard g exchange)

→ significantly *reduced errors* with weaker cuts

New CJ11 PDF analysis

- Explore dependence of PDF fits on deuteron wave functions and nucleon off-shell corrections

  → use only "high-precision" wave functions (AV18, CD-Bonn, WJC-1, WJC-2)

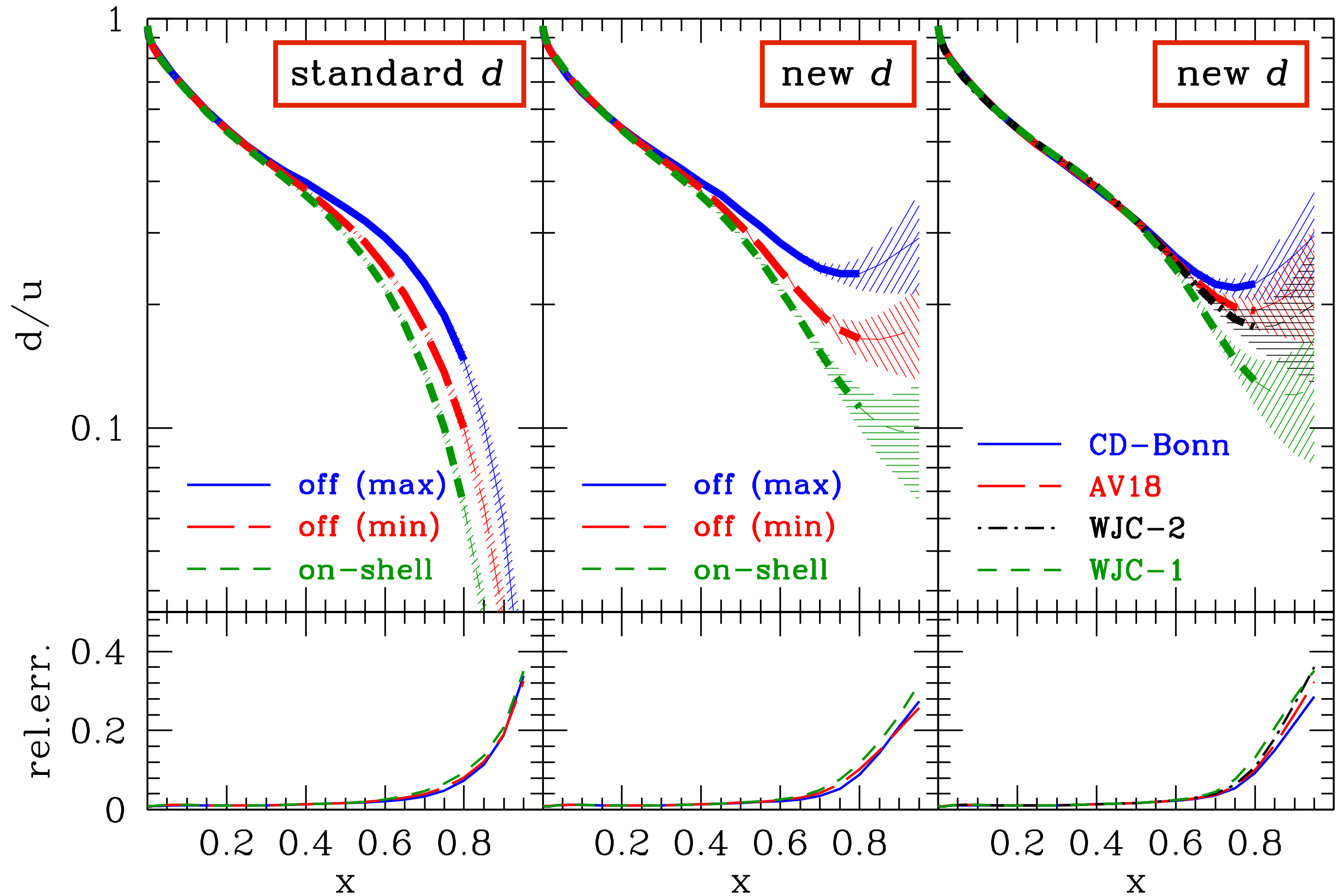
  → off-shell model bounds given by upper & lower limits of "mKP" model parameters

- Dependence of d/u ratio on d quark parametrization

  → allow for finite, nonzero ratio in $x = 1$ limit

$$d(x, Q^2) \rightarrow d(x, Q^2) + a\, x^b\, u(x, Q^2)$$

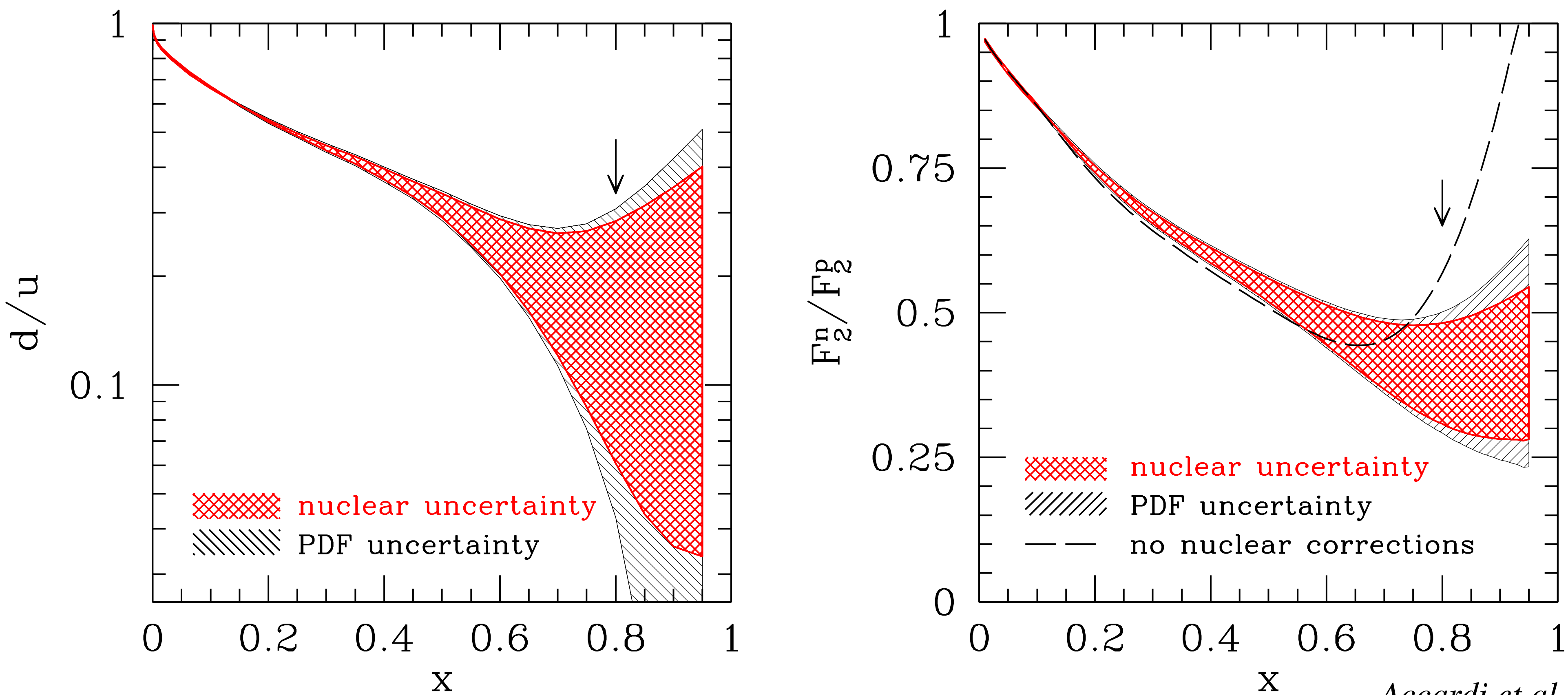
New CJ11 PDF analysis



Accardi et al.
arXiv:1101.1234

→ dramatic <u>increase</u> in d PDF in $x \to 1$ limit with more flexible parametrization

New CJ11 PDF analysis



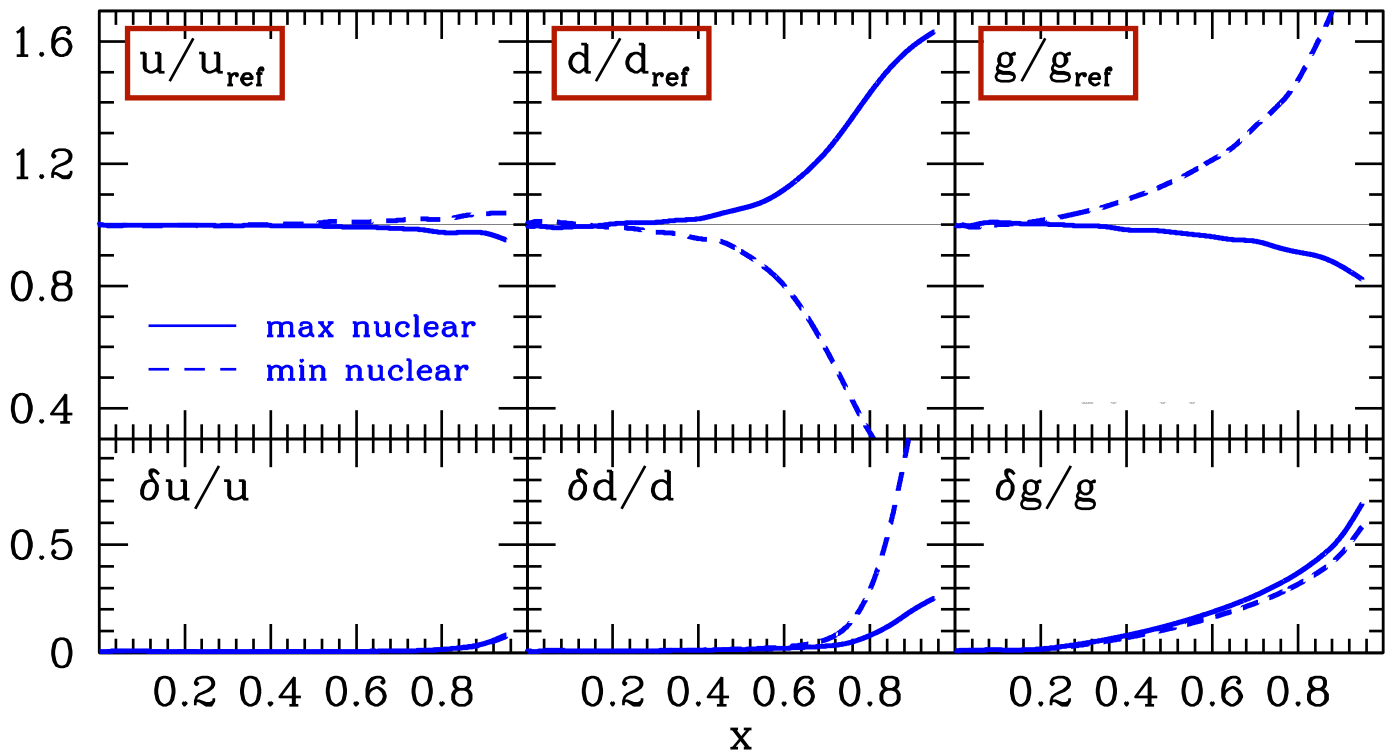
Accardi et al.
arXiv:1101.1234

→ combined nuclear correction uncertainties sizable at $x > 0.5$

→ $x \to 1$ limiting value depends critically on deuteron model

→ n/p ratio smaller at large x *cf.* no nuclear corrections fit

New CJ11 PDF analysis



Accardi et al.
arXiv:1101.1234

→ very little effect on u quark PDF
(tightly constrained by DIS & DY proton data)

→ gluon PDF anticorrelated with d quark
(g compensates for smaller d quark contribution in jet data)

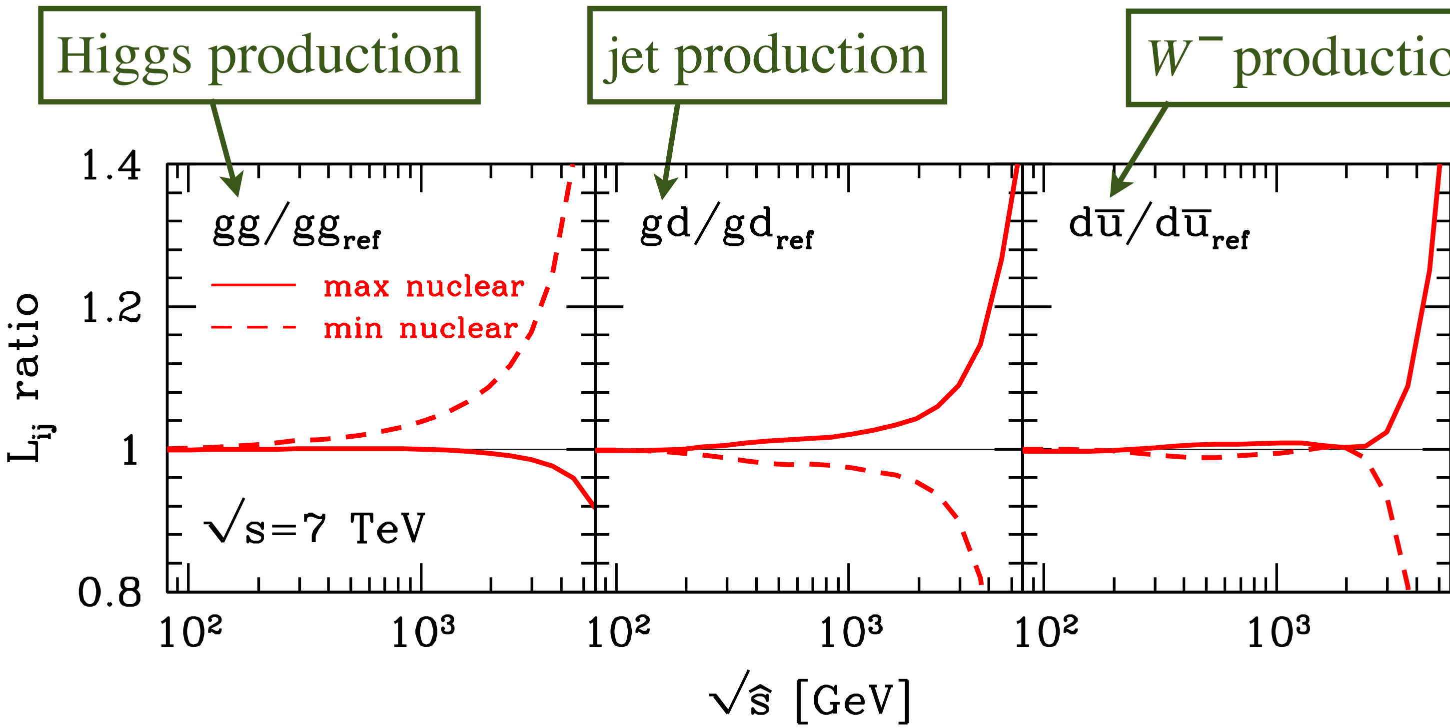
→ uncertainty in d feeds into larger uncertainty in g at high x

New CJ11 PDF analysis

- Impact on parton "luminosities" at colliders

$$L_{ij} = \frac{1}{s\,(1+\delta_{ij})} \int_{\hat{s}/s}^{1} \frac{dx}{x}\, f_i(x,\hat{s})\, f_j(\hat{s}/xs,\hat{s}) \;+\; (i \leftrightarrow j)$$

$s\;(\hat{s})$ = hadronic (partonic) c.m. energy squared



Accardi et al.
arXiv:1101.1234

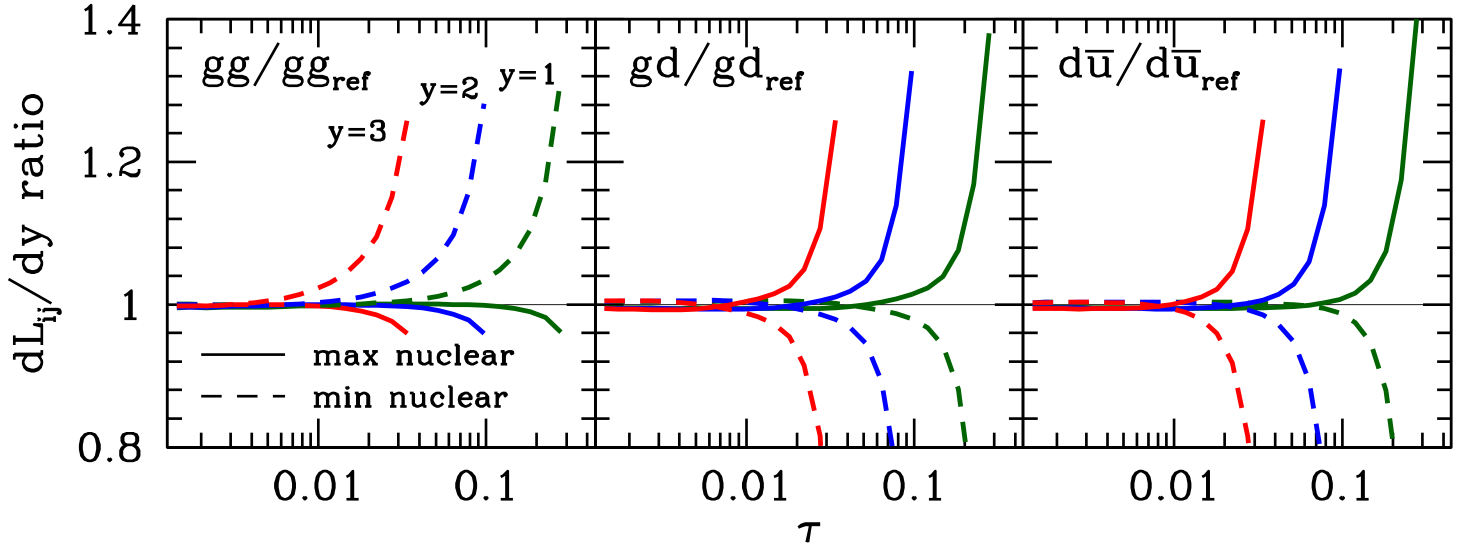
→ nuclear uncertainties important for $\sqrt{\hat{s}} \gtrsim 1\ \mathrm{TeV}$ mass range

New CJ11 PDF analysis

- Impact on differential parton luminosities

$$\frac{dL_{ij}}{dy} = \frac{1}{s\,(1+\delta_{ij})}\, f_i(x_1,\hat{s})\, f_j(x_2,\hat{s}) \;+\; (i \leftrightarrow j)$$

$$x_{1,2} = \tau\, e^{\pm y}, \quad \tau = \sqrt{\hat{s}/s} \;\; \text{for rapidity } y$$



Accardi et al.
arXiv:1101.1234

→ greater sensitivity to high-x region at *larger rapidities*

Future methods of determining d/u

- $e\ d \to e\ p_{\rm spec}\ X^*$ — semi-inclusive DIS from d

  "BoNuS"

  $\longrightarrow$ tag "spectator" protons

  (see talk session 9, 18:05)

- $e\ ^3{\rm He}(^3{\rm H}) \to e\ X^*$ — ^{3}He-tritium mirror nuclei

  "MARATHON"

- $e\ p \to e\ \pi^{\pm}\ X^*$ — semi-inclusive DIS as flavor tag

- $e^{\mp}\ p \to \nu(\bar\nu)X$

  $\nu(\bar\nu)\ p \to l^{\mp}\ X$

  $p\ p(\bar p) \to W^{\pm}X, Z^0\ X$

  $\vec e_L(\vec e_R)\ p \to e\ X^*$

  "PVDIS / SOLID"

  } weak current as flavor probe

* planned for JLab at 12 GeV

Summary & outlook

- New frontiers explored at large momentum fractions x

  $\longrightarrow$ dedicated global PDF analysis (CJ collaboration)

- Stable leading twist PDFs obtained for $W^2 > 3\ \mathrm{GeV}^2$ and $Q^2 \gtrsim 1.5\ \mathrm{GeV}^2$ including nuclear and $1/Q^2$ corrections

  $\longrightarrow$ new set of "CJ11" PDFs & structure functions released soon

  $\longrightarrow$ include lower-W^2 data

  $\longrightarrow$ explore consequences for colliders (*e.g.* LHC)

- Further constraints will require new experiments uniquely sensitive to d quark PDF (see *BoNuS* talk – session 9, 18:05)

- Extend methodology to *spin-dependent* global PDF analysis

  $\longrightarrow$ dedicated JLab (theory/experiment) postdoc from Jan. 2012 (Pedro Jimenez-Delgado)

The End