Department of Energy
United States of America

Jefferson Lab Pizza Seminar
Oct. 19, 2011

Quarks at the extreme: nucleon structure at large x

Wally Melnitchouk

Jefferson Lab

Outline

- How do we see quarks (with large momentum fractions x) in the nucleon, and why are they important?

- Extraction of neutron structure from inclusive data
  - → nuclear effects & d/u ratio

- New global "CJ" (CTEQ–Jefferson Lab) analysis
  - → first serious foray into high-x, low-Q^2 region
  - → implications of PDF uncertainties for high-energy colliders

- Future experiments

high momentum
Looking for ^ quarks in the nucleon
is like looking for the Mafia in Sicily –

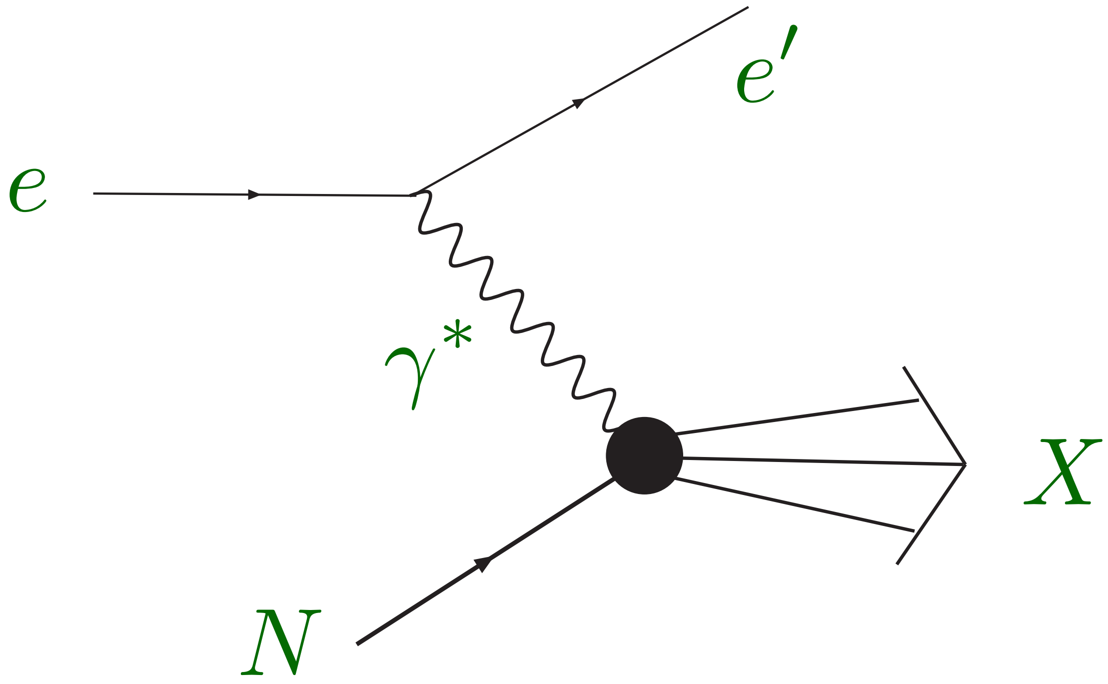
everybody *knows* they're there,
but it's hard to find the evidence!

Anonymous

"QUARKS. NEUTRINOS. MESONS. ALL THOSE DAMN PARTICLES YOU CAN'T SEE. THAT'S WHAT DROVE ME TO DRINK. BUT NOW I CAN SEE THEM."

Electron scattering

- Inclusive cross section for $e\,N \longrightarrow e\,X$

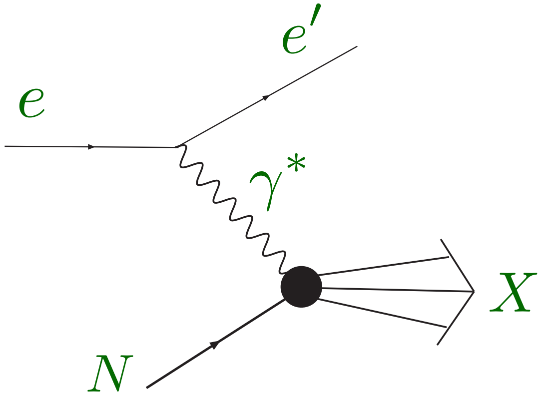


hadronic
debris

$\longrightarrow$ one-photon exchange approximation

Electron scattering

- Inclusive cross section for $e\,N \longrightarrow e\,X$



$$\frac{d^2\sigma}{d\Omega dE'} = \frac{4\alpha^2 E'^2 \cos^2\frac{\theta}{2}}{Q^4}\left(2\tan^2\frac{\theta}{2}\frac{F_1}{M} + \frac{F_2}{\nu}\right)$$

$$\left.\begin{array}{l} \nu = E - E' \\ Q^2 = \vec{q}^{\,2} - \nu^2 = 4EE'\sin^2\dfrac{\theta}{2} \end{array}\right\} \boxed{x = \frac{Q^2}{2M\nu}}$$

"Bjorken scaling variable"

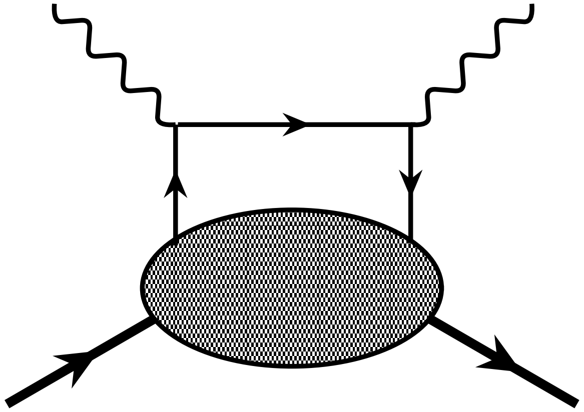
- Structure functions F_1 , F_2

⟶ contain all information about structure of nucleon

- Parton model

→ scatter from individual quarks (“*partons*”) in nucleon

$$F_2(x,Q^2) = x \sum_q e_q^2\, q(x,Q^2) \qquad (q{=}u,d,s\ldots)$$



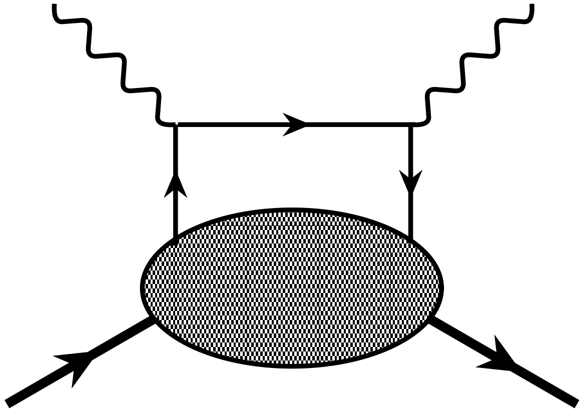
→ $q\,(x,Q^2)$ = probability to find quark type “q” in nucleon, carrying (light-cone) momentum fraction x

$$x = \frac{p_q^+}{p_N^+} = \frac{p_q^0 + p_q^z}{p_N^0 + p_N^z}$$

Parton model

- → scatter from individual quarks (“*partons*”) in nucleon

$$F_2(x, Q^2) = x \sum_q e_q^2 \, q(x, Q^2) \qquad (q{=}u,d,s\ldots)$$



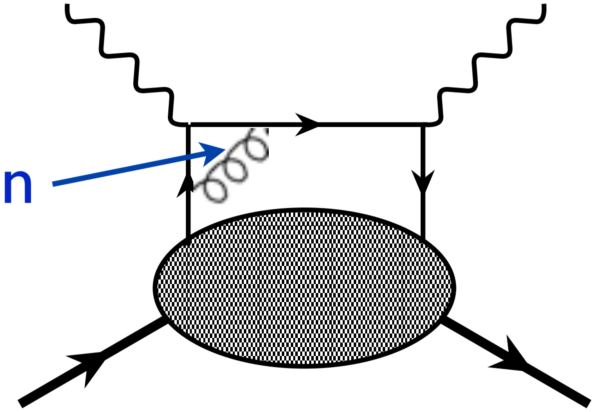
- → $q\,(x,Q^2)$ = probability to find quark type “q” in nucleon, carrying (light-cone) momentum fraction x

- → at large Q^2, “Callan-Gross relation” $F_2 = 2x\,F_1$

Parton model

- → scatter from individual quarks (“*partons*”) in hadron

$$F_2(x, Q^2) = x \sum_q e_q^2 \, q(x, Q^2) \qquad (q=u,d,s\ldots)$$

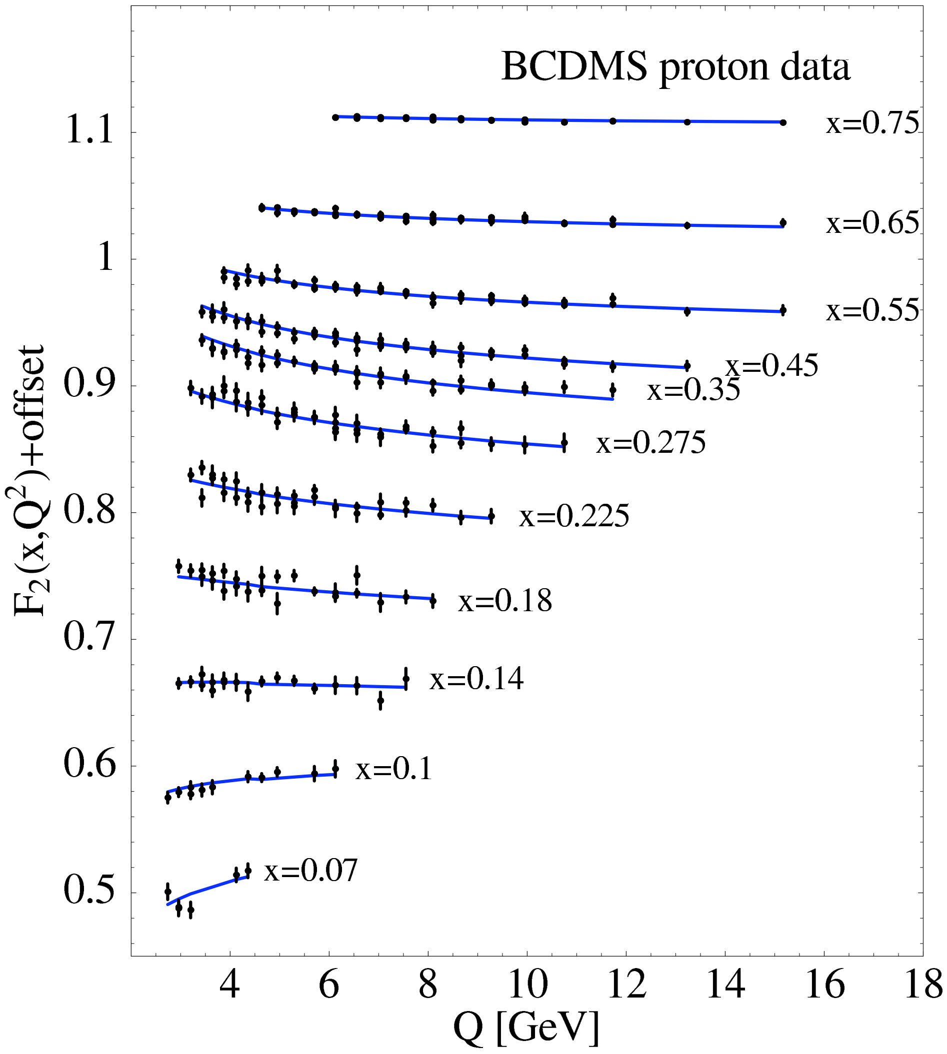


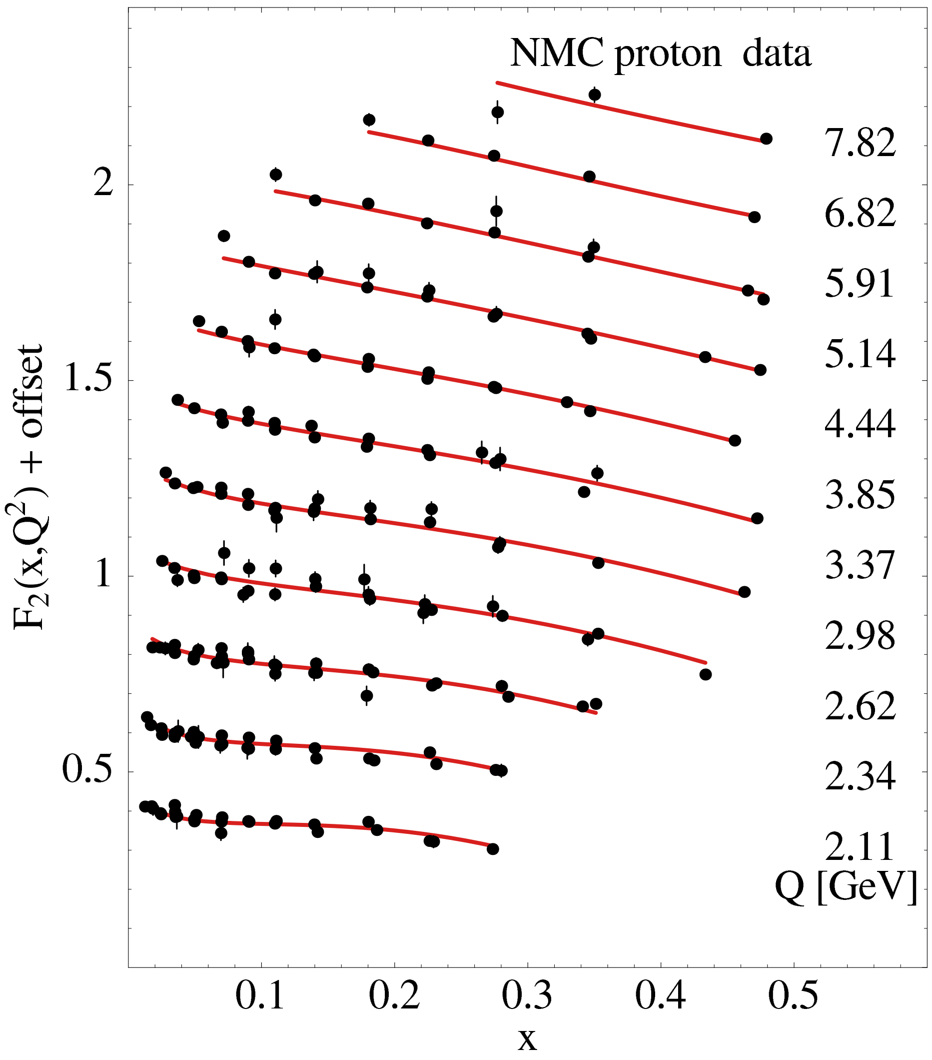
gluon radiation

- → at finite energy, Q^2 dependence given by (perturbatively calculable) QCD evolution equations

$$F_2 \to F_2(x, \log Q^2)$$

Structure function data





Lai et al., Eur. Phys. J. C12 (2000) 375

→ log Q^2 dependence observed in data

Parton distribution functions (PDFs)

- PDFs extracted in global QCD analyses (CTEQ, MSTW, ...) of structure function data from e, μ & ν scattering
  (also from lepton-pair & W-boson production in hadronic collisions)

  → determined over large range of x and Q^2

- Provide basic information on structure of QCD bound states

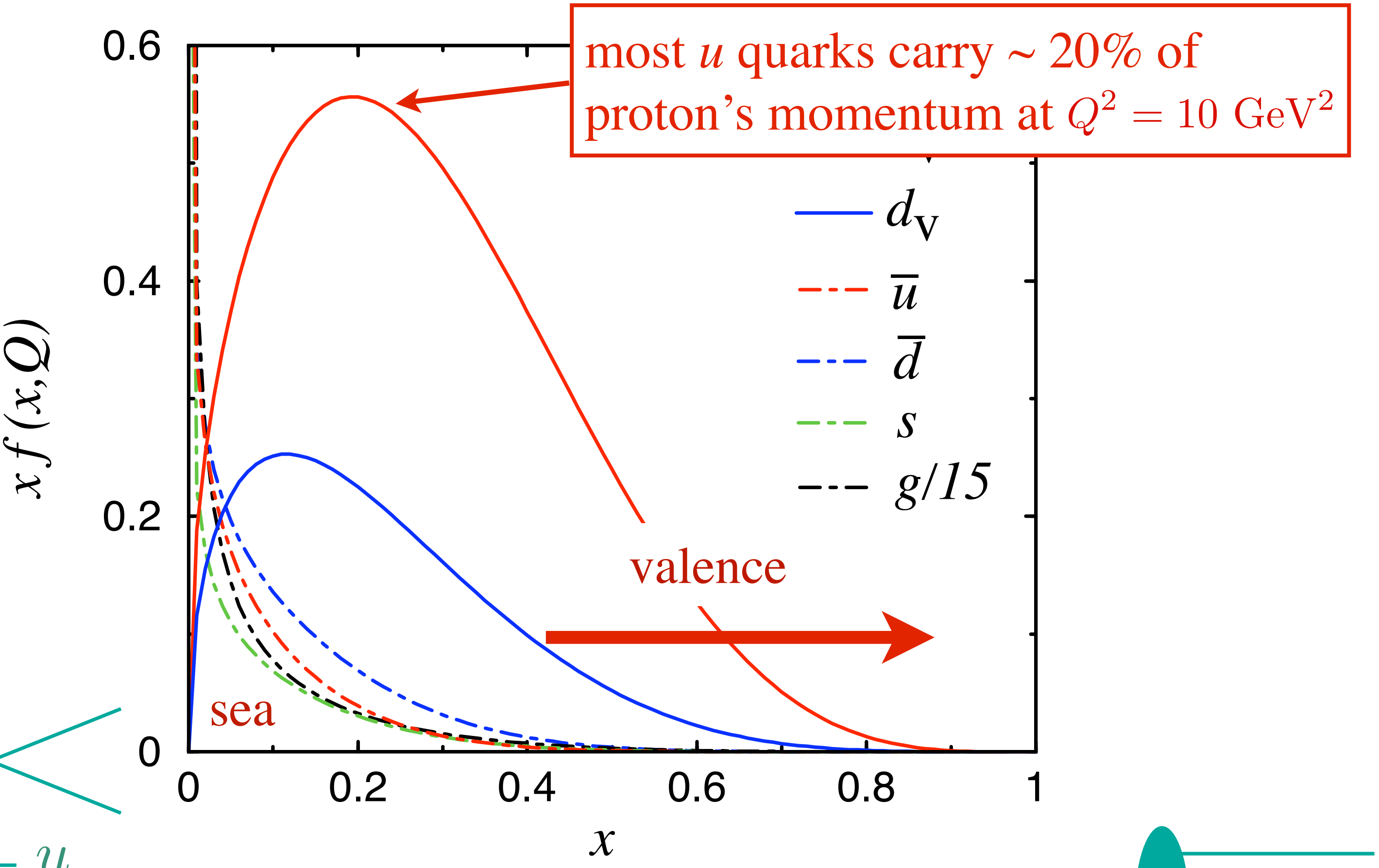
- Needed to understand backgrounds in searches for physics *beyond the Standard Model* in high-energy colliders *e.g.* the LHC

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

Why are PDFs at large x interesting?

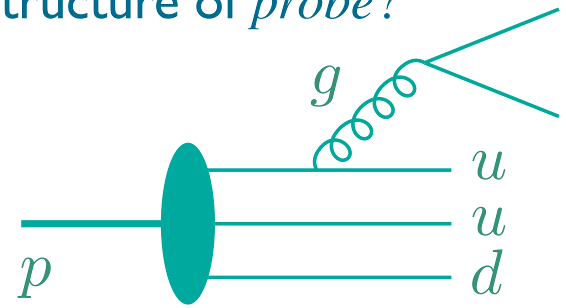
- Most direct connection between quark distributions and models of nucleon structure is via *valence* quarks

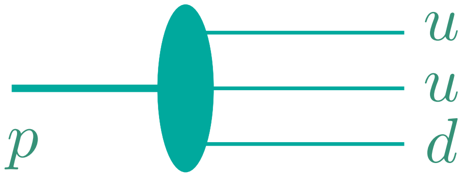
  → most cleanly revealed at $x > 0.4$



most u quarks carry ~ 20% of proton's momentum at $Q^2 = 10\ \mathrm{GeV}^2$

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





Valence quarks

- At large x, valence u and d distributions extracted from p and n structure functions

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

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

- u quark distribution well determined from *proton* data
- d quark distribution requires *neutron* structure function

$$\longrightarrow \qquad \frac{d}{u} \approx \frac{4 - F_2^n / F_2^p}{4 F_2^n / F_2^p - 1}$$

Valence quarks

- Ratio of d to u quark distributions particularly sensitive to quark dynamics in nucleon

- SU(6) spin-flavor symmetry

proton wave function

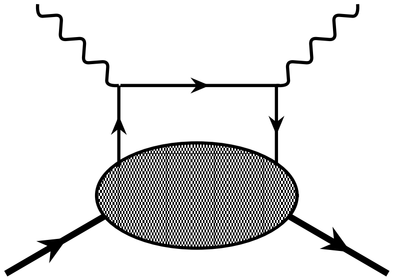
$50\%\ \ S{=}0\ \ (qq)$
$50\%\ \ S{=}1\ \ (qq)$

$$p^{\uparrow} = -\frac{1}{3} d^{\uparrow}(uu)_1 - \frac{\sqrt{2}}{3} d^{\downarrow}(uu)_1 + \frac{\sqrt{2}}{6} u^{\uparrow}(ud)_1 - \frac{1}{3} u^{\downarrow}(ud)_1 + \frac{1}{\sqrt{2}} u^{\uparrow}(ud)_0$$

interacting quark

spectator diquark

diquark spin



Valence quarks

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proton wave function

$$p^{\uparrow} = -\frac{1}{3} d^{\uparrow}(uu)_1 - \frac{\sqrt{2}}{3} d^{\downarrow}(uu)_1 + \frac{\sqrt{2}}{6} u^{\uparrow}(ud)_1 - \frac{1}{3} u^{\downarrow}(ud)_1 + \frac{1}{\sqrt{2}} u^{\uparrow}(ud)_0$$

50% S=0 (qq)
50% S=1 (qq)

→ $u(x) = 2\ d(x)$ for all x

→ $$\frac{F_2^n}{F_2^p} = \frac{2}{3}$$

Valence quarks

- But SU(6) symmetry is *broken*

e.g. $\boxed{\text{scalar diquark dominance}}$

$M_\Delta > M_N \quad \Longrightarrow \quad (qq)_1$ has larger energy than $(qq)_0$

$\Longrightarrow$ *scalar diquark* dominant in $x \to 1$ limit

since only u quarks couple to *scalar* diquarks

$$\rightarrow \quad \frac{d}{u} \to 0$$

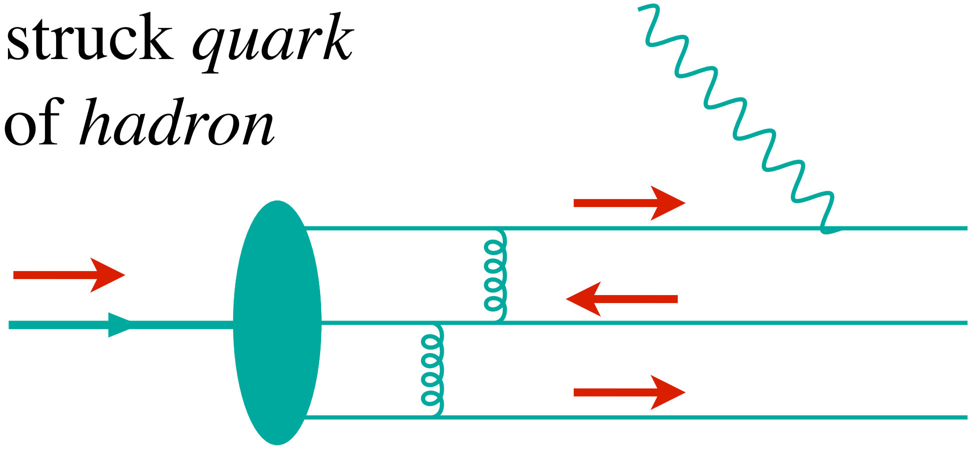
$$\rightarrow \quad \frac{F_2^n}{F_2^p} \to \frac{1}{4}$$

Feynman 1972, Close 1973, Close/Thomas 1988

Valence quarks

- Alternatively, SU(6) can be broken by **hard gluon exchange**

helicity of struck *quark*
= helicity of *hadron*



$$q^{\uparrow} \gg q^{\downarrow}$$

$\Longrightarrow$ *helicity-zero diquark* dominant in $x \to 1$ limit

$$\rightarrow \quad \frac{d}{u} \to \frac{1}{5}$$

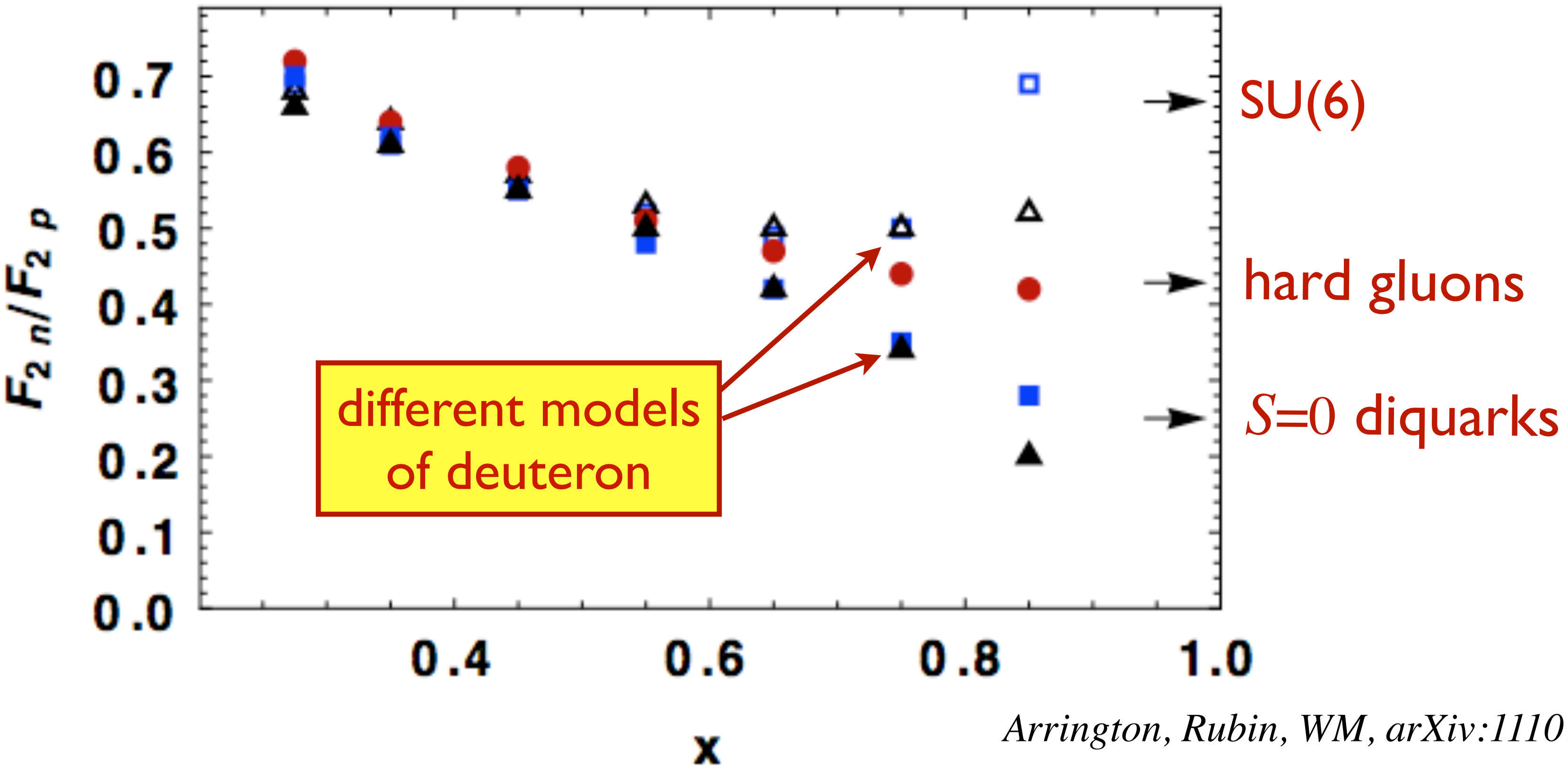
$$\rightarrow \quad \frac{F_2^n}{F_2^p} \to \frac{3}{7}$$

Farrar, Jackson 1975

Deuteron corrections

- Absence of free neutron targets

→ use *deuterons* (weakly bound state of p and n)



different models of deuteron

SU(6)

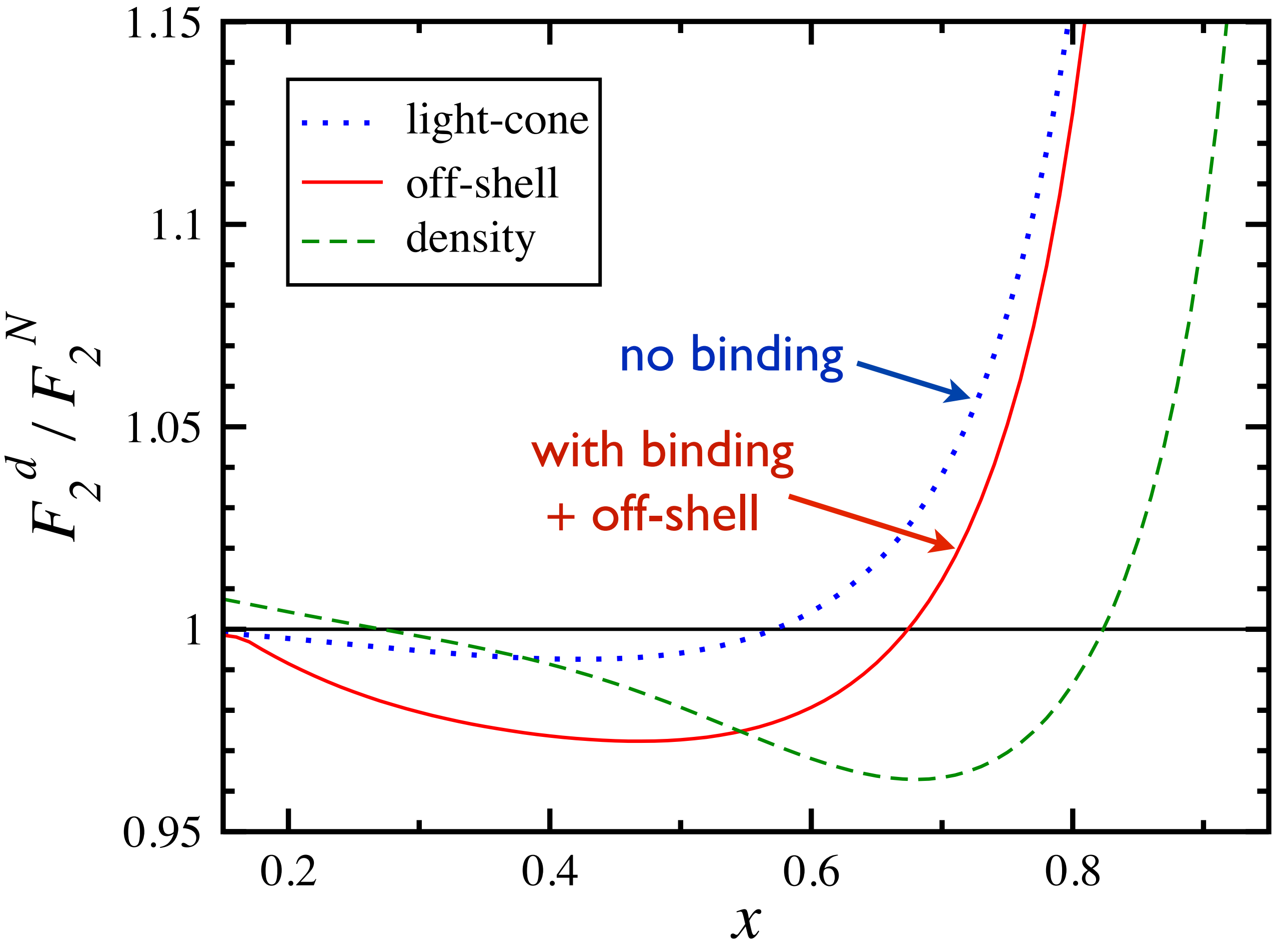
hard gluons

S=0 diquarks

Arrington, Rubin, WM, arXiv:1110.3362

→ deuteron model dependence obscures free neutron structure information at large x

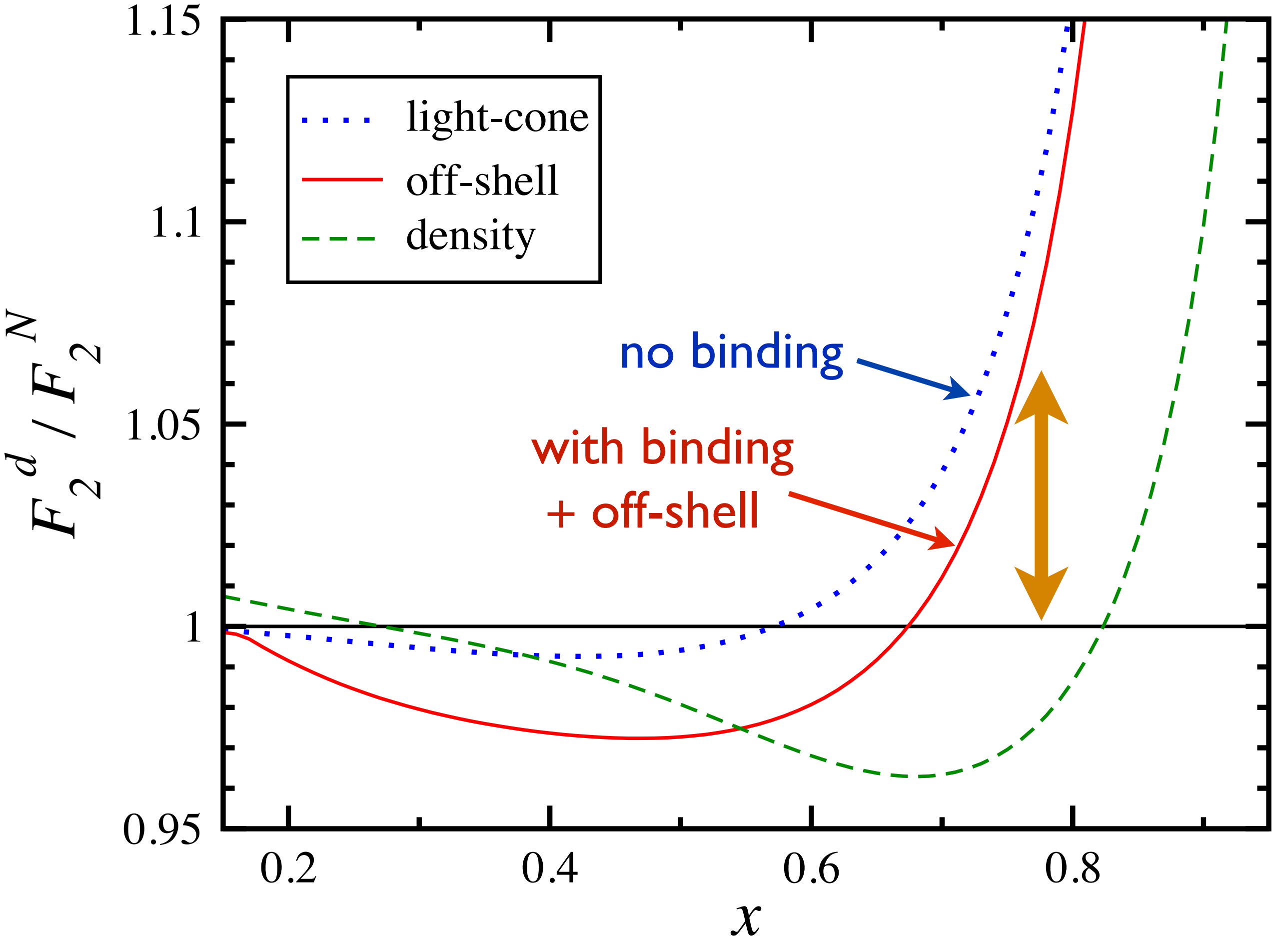
Deuteron corrections



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

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

Deuteron corrections



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

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

New global PDF analysis:

CTEQ-JLab collaboration

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

Accardi et al., Phys. Rev. D ***81****, 034016 (2010)* **"CJ10"**

Accardi et al., Phys. Rev. D ***84****, 014008 (2011)* **"CJ11"**

- 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

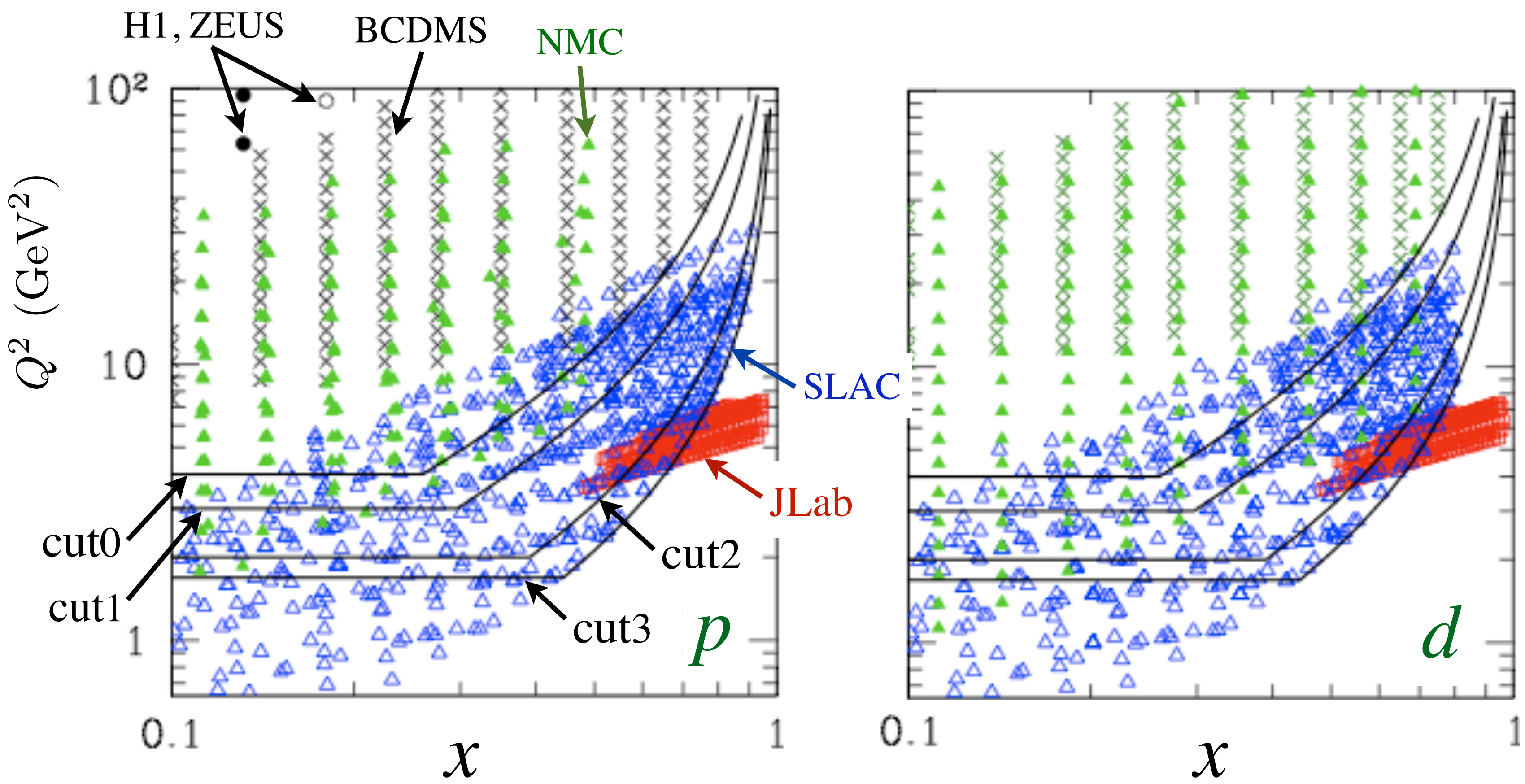
- Include subleading $1/Q^2$ corrections

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

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

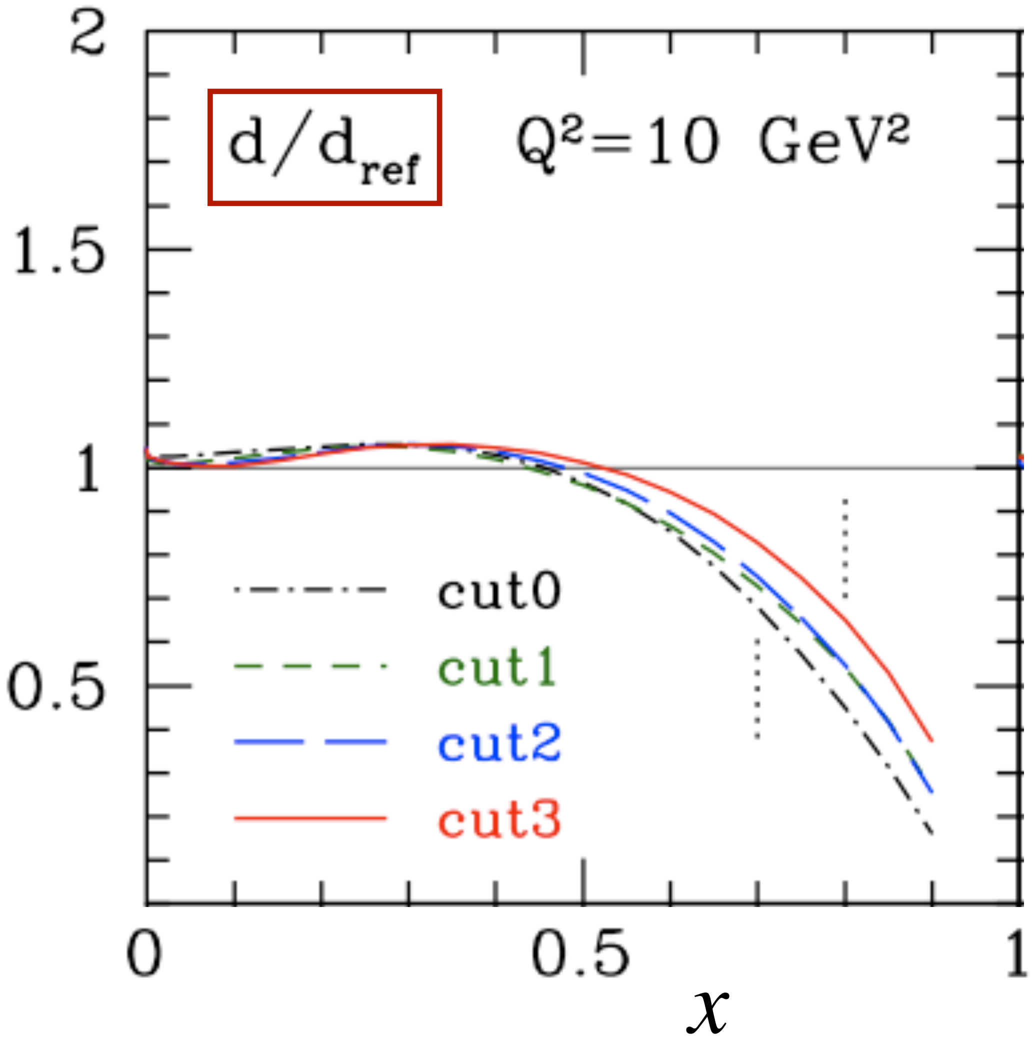
cut2: $Q^2 > 2\ \text{GeV}^2, \quad W^2 > 4\ \text{GeV}^2$

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

factor 2 increase
in DIS data from
cut0 ⟶ cut3

Effect of Q^2 & W cuts

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

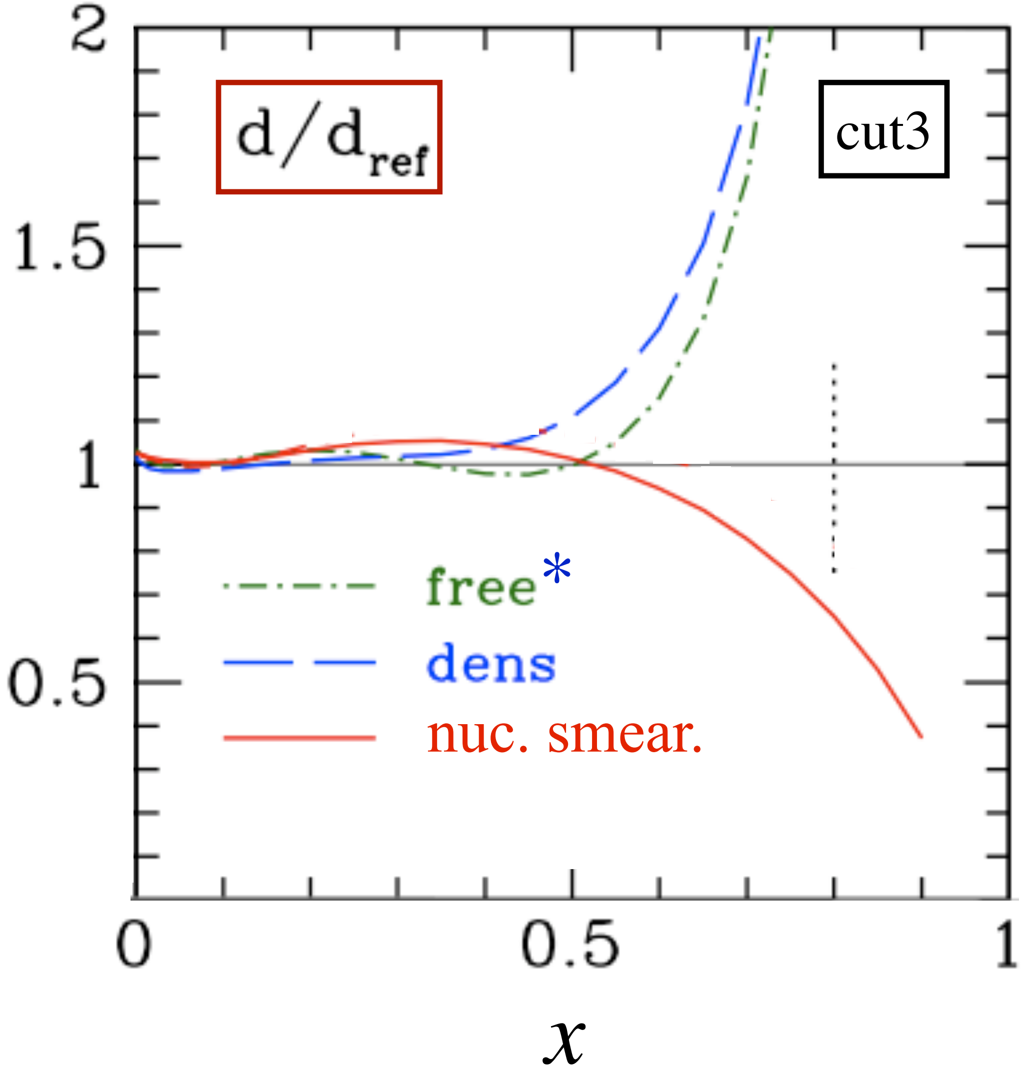


→ *stable* with respect to cut reduction

→ d quark suppressed by $\sim 50\%$ for $x > 0.5$

(driven by nuclear corrections)

Nuclear corrections



→ *increased* d quark for no nuclear effects

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

→ *decreased* d quark for nuclear smearing models

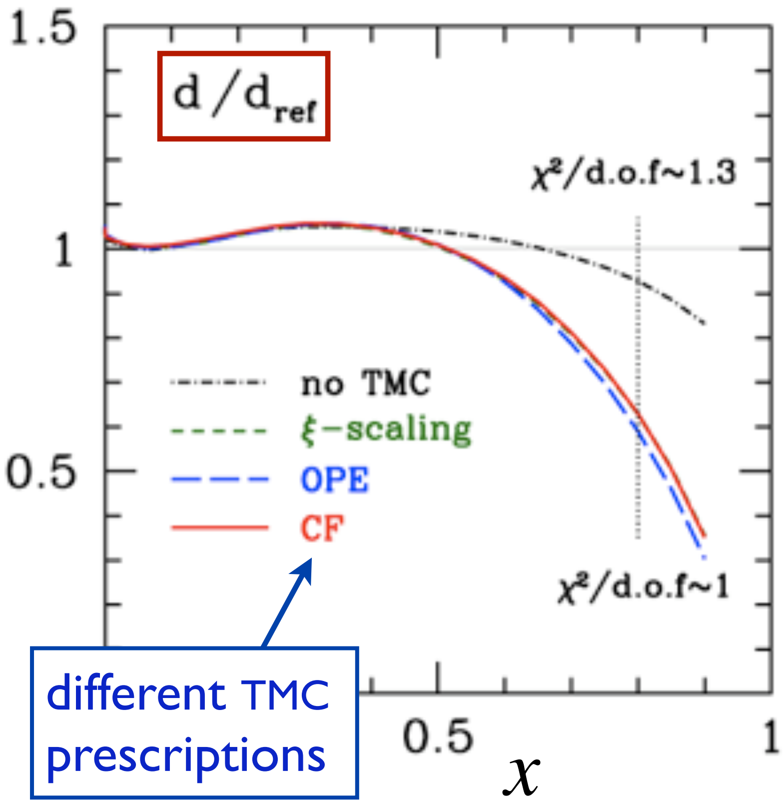
↓

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

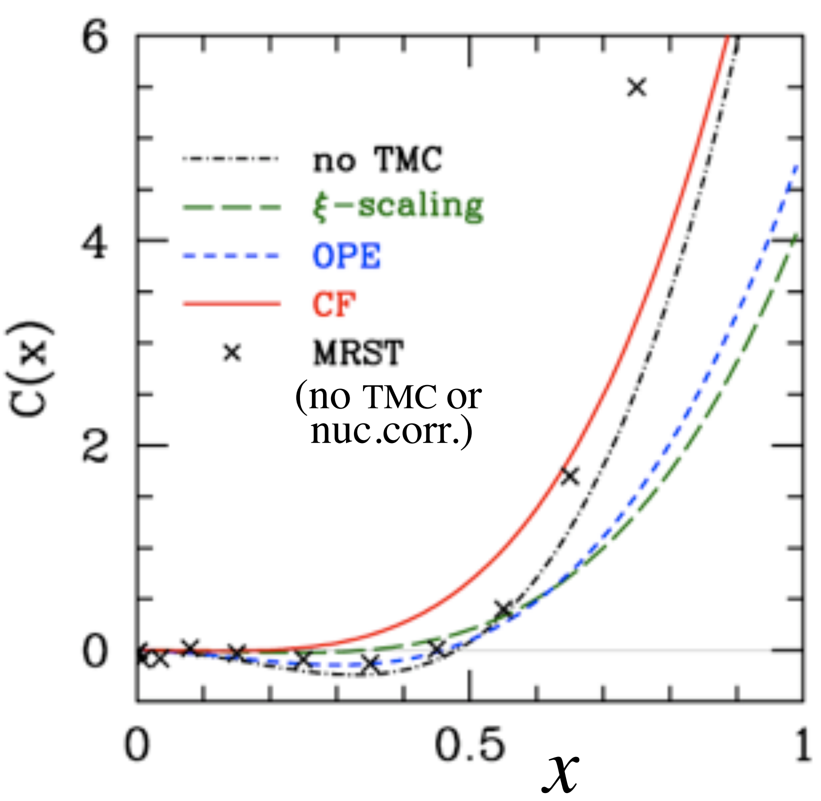
$$\boxed{\begin{array}{l} F_2^d/F_2^N \uparrow \;\leftrightarrow\; F_2^n/F_2^p \downarrow \\ \qquad\qquad\;\;\leftrightarrow\; d/u \downarrow \end{array}}$$

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

Effect of $1/Q^2$ corrections



different TMC prescriptions

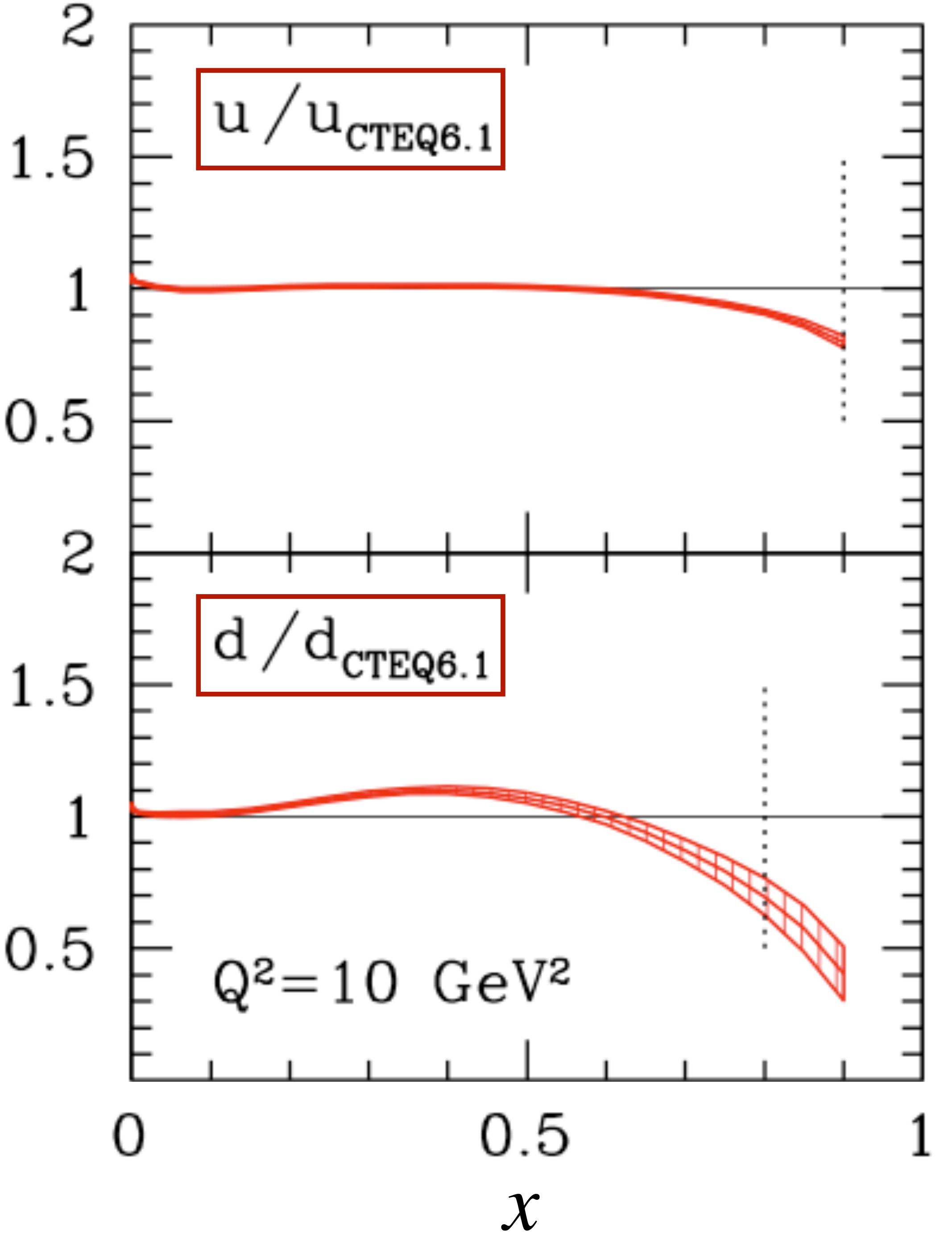


→ $1/Q^2$ correction $F_2 = F_2^{\rm LT}\left(1 + \frac{C(x)}{Q^2}\right), \quad C(x) = c_1 x^{c_2}(1 + c_3 x)$

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

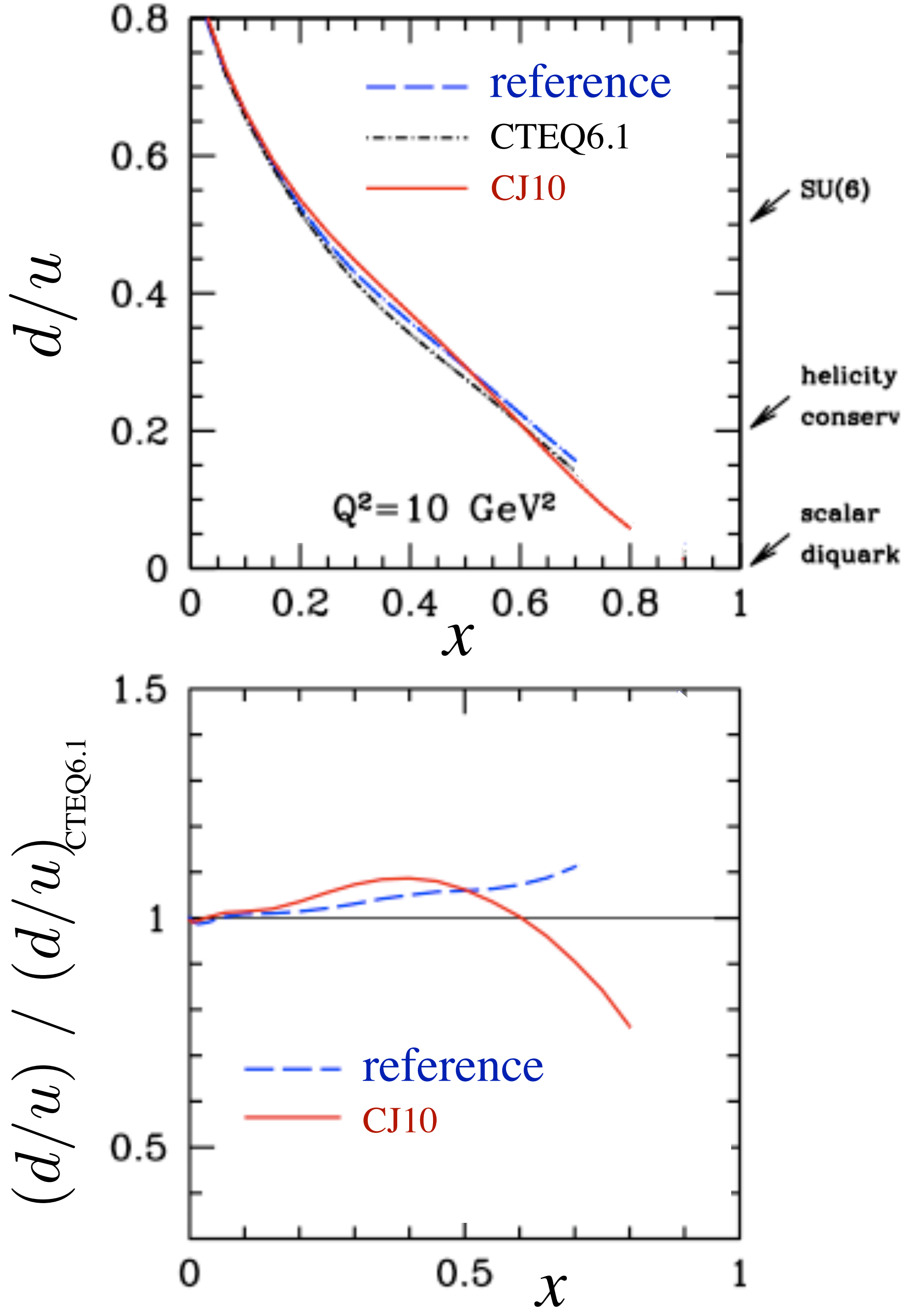
→ stable leading twist when *both* TMCs and HTs included

CJ10 PDF results



→ full fits favors smaller d/u ratio

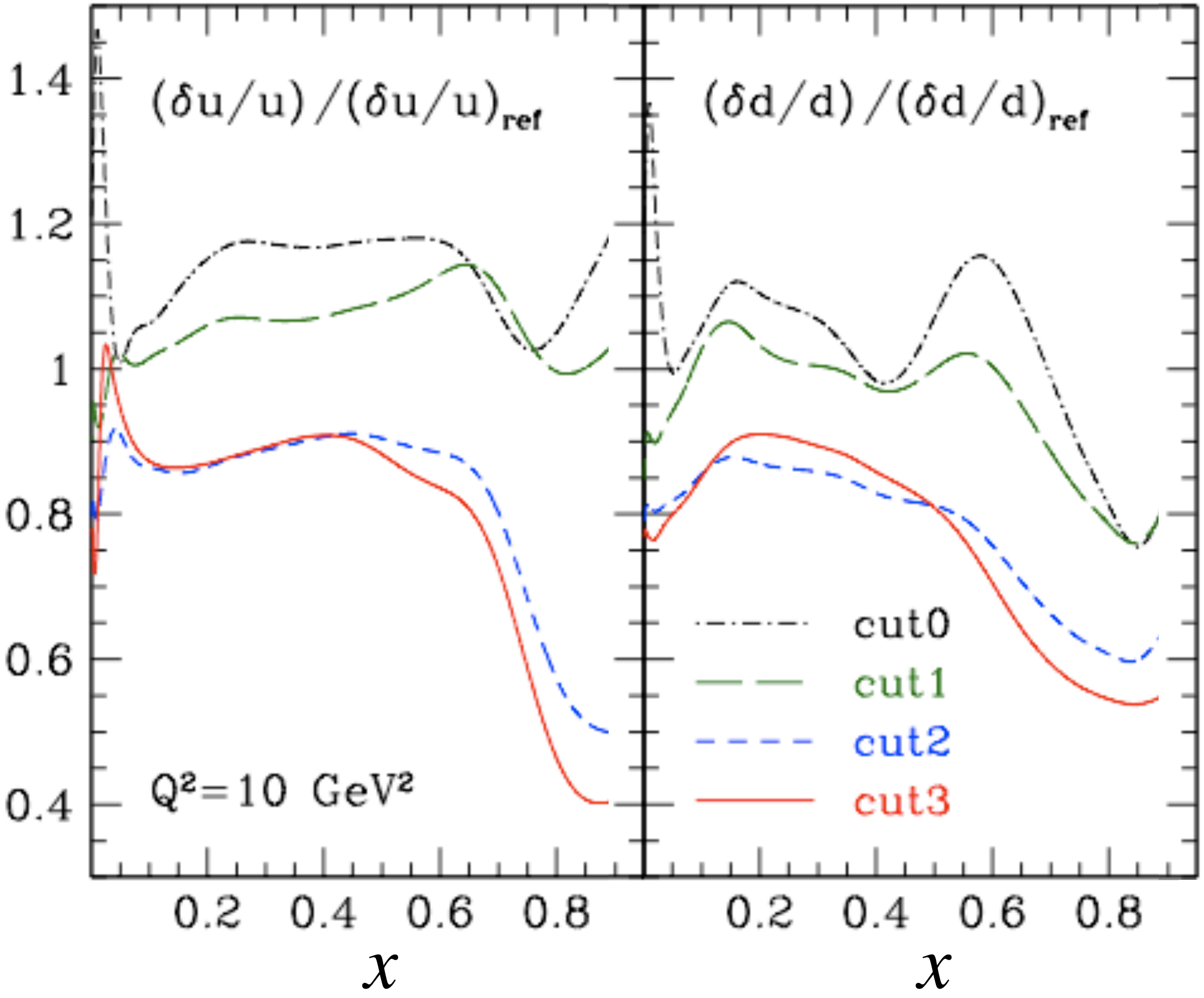
CJ10 PDF results



→ 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)

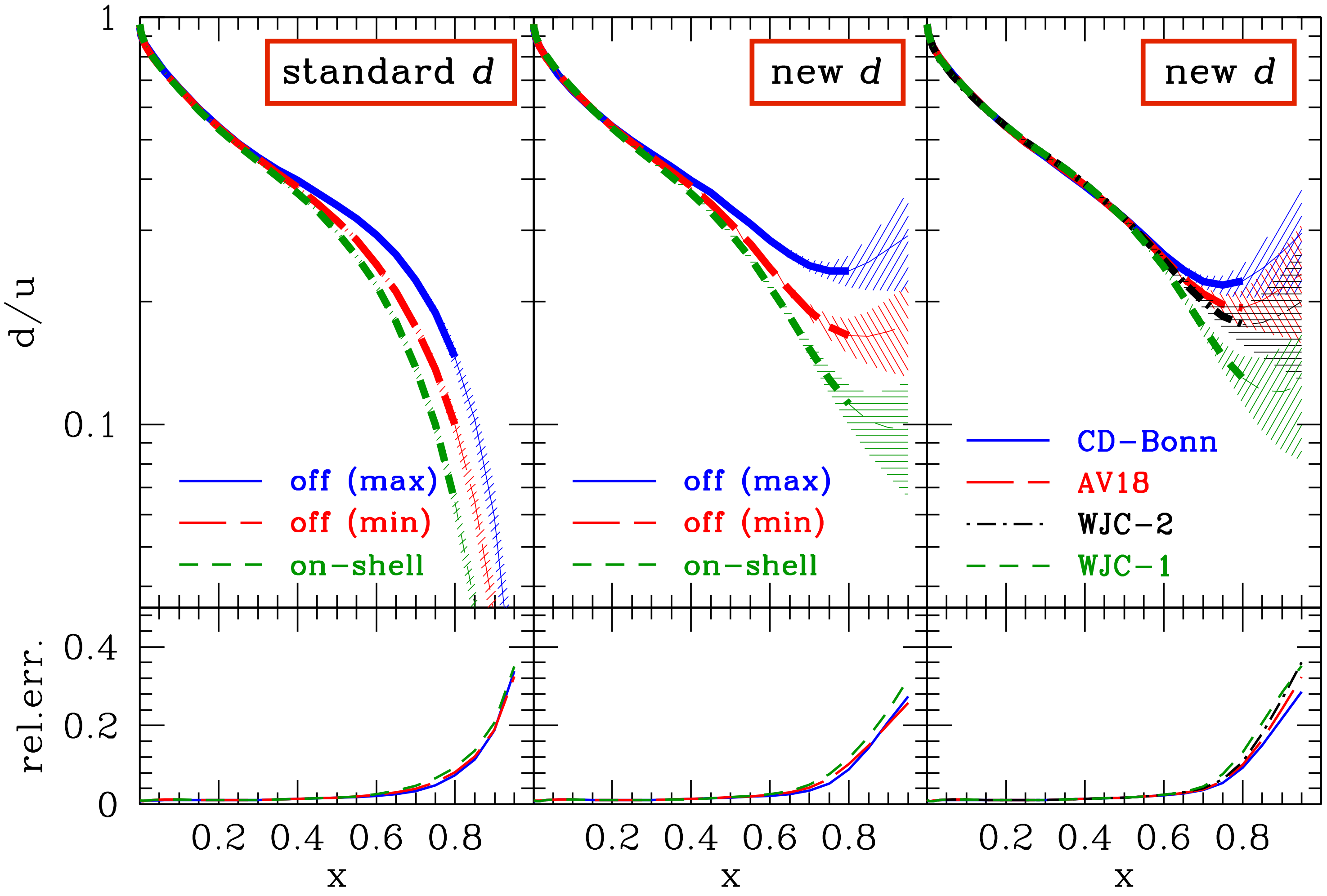
  → model nucleon off-shell correction with reasonable range of parameters

- Dependence of d/u ratio on d quark parametrization

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

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

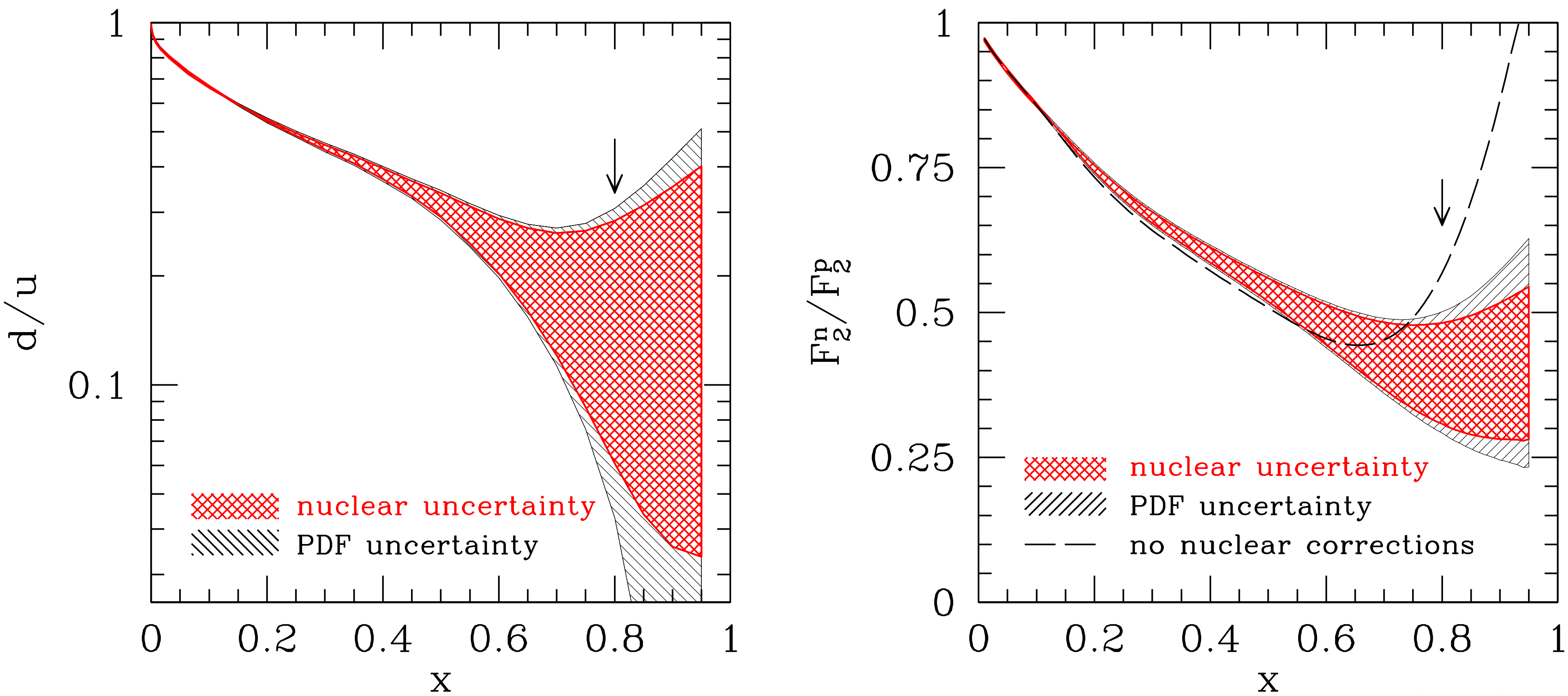
New CJ11 PDF analysis



Accardi et al.
PRD ***84****, 014008 (2011)*

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

New CJ11 PDF analysis



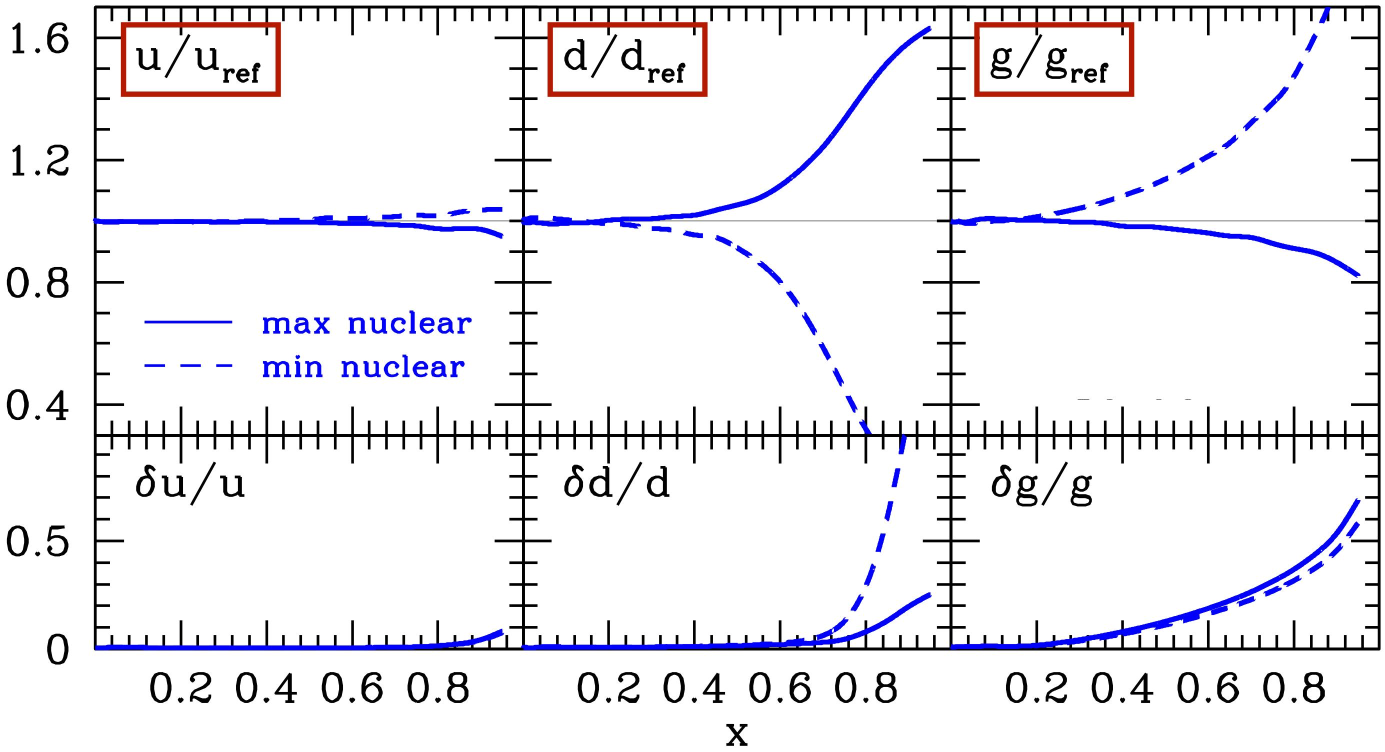
Accardi et al.
*PRD **84**, 014008 (2011)*

→ 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.
PRD ***84****, 014008 (2011)*

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

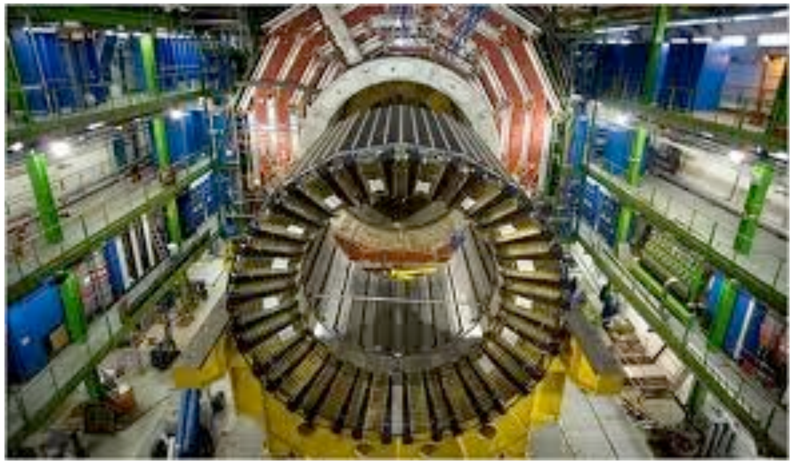
→ gluon PDF anticorrelated with d quark
(g compensates for smaller d quark contribution in jet data)

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

Implications for high-energy colliders

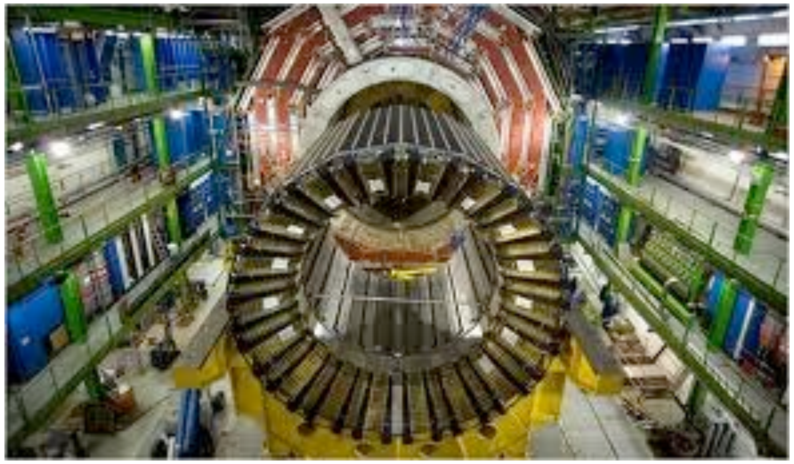
(Tevatron, LHC)

Large Hadron Collider (CERN): discovery of *Higgs boson*, new physics beyond the Standard Model?



→ pp collisions at $\sqrt{s} = 7 \ \mathrm{TeV}$

Large Hadron Collider (CERN): discovery of *Higgs boson*, new physics beyond the Standard Model?



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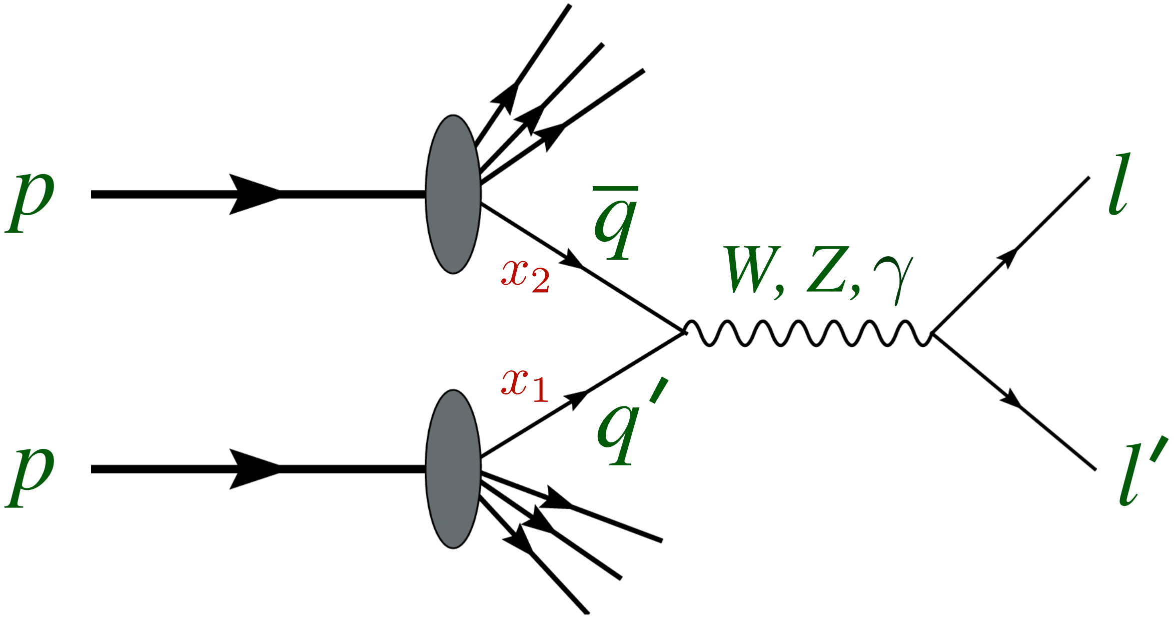

W boson asymmetries

- Large-x PDF uncertainties affect observables at large rapidity y, defined as

$$x_{1,2} = \frac{M}{\sqrt{s}}\, e^{\pm y}$$

$e.g.\ W^{\pm}$ asymmetry

$$A_W(y) = \frac{\sigma_{W^+} - \sigma_{W^-}}{\sigma_{W^+} + \sigma_{W^-}}$$

$$\approx \ \frac{d(x_2)/u(x_2) - d(x_1)/u(x_1)}{d(x_2)/u(x_2) + d(x_1)/u(x_1)} \qquad [x_1 \gg x_2]$$

where

$$\sigma_{W^+} \equiv \frac{d\sigma}{dy}(pp \to W^+X) = \frac{2\pi G_F}{3\sqrt{2}} x_1 x_2 \left(u(x_1)\bar{d}(x_2) + \cdots\right)$$

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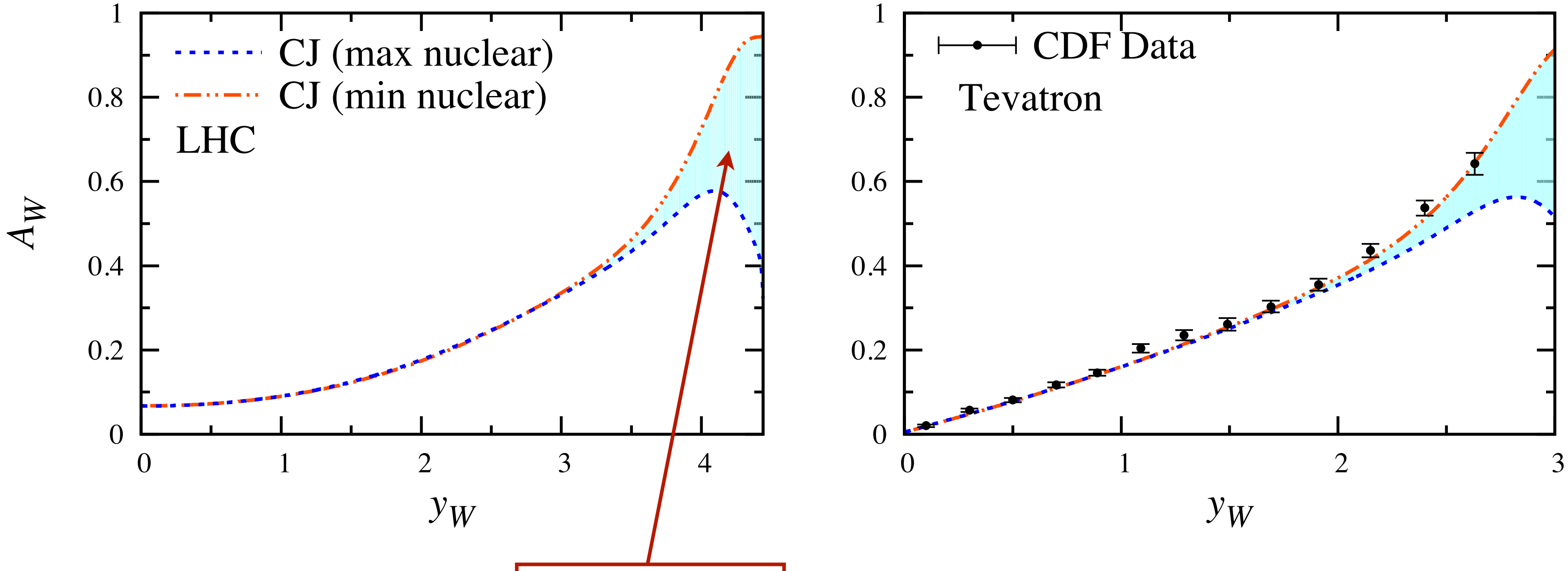


sensitive to d at high x

Brady, Accardi, WM, Owens (2011)

Heavy W', Z' boson production

- Some extensions of Standard Model predict heavy versions of W, Z bosons

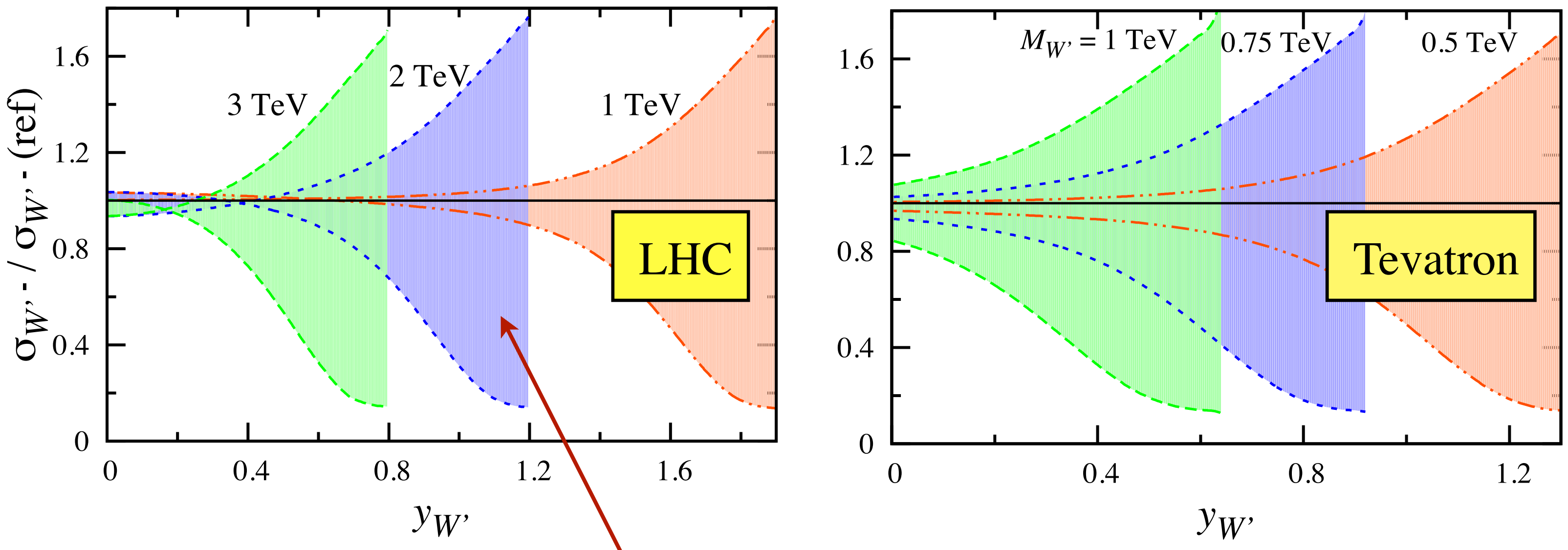
→ current limits $M_{W'} > 2.15\ \mathrm{TeV}\,,\ M_{Z'} > 1.83\ \mathrm{TeV}$
(assuming Standard Model couplings)

Heavy W', Z' boson production

- Some extensions of Standard Model predict heavy versions of W, Z bosons

- Observation of new physics signal requires accurate determination of QCD backgrounds, which depend on PDFs!

$e.g.$ for W'^{-} production



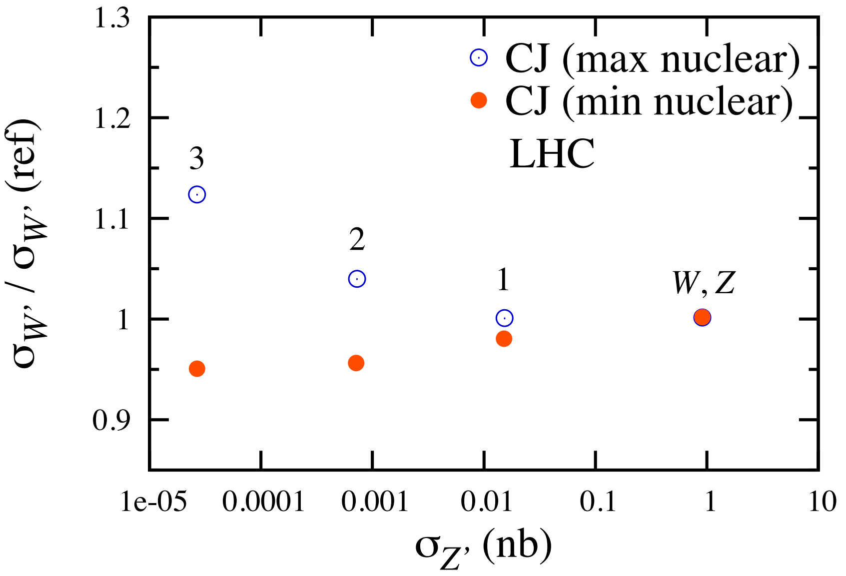
increasing uncertainty at large y

Heavy W', Z' boson production

- Some extensions of Standard Model predict heavy versions of W, Z bosons

- Observation of new physics signal requires accurate determination of QCD backgrounds, which depend on PDFs!

$e.g.$ integrated W' cross section



→ uncertainties in high-x PDFs could affect interpretation of experiments searching for new particles

Future plans

Future plans for determining d/u

- $e\ d \rightarrow e\ p_{\mathrm{spec}}\ X^{*}$

  "BoNuS"

  semi-inclusive DIS from d

  → tag "spectator" protons

- $e\ {}^{3}\mathrm{He}({}^{3}\mathrm{H}) \rightarrow e\ X^{*}$

  "MARATHON"

  ^{3}He-tritium mirror nuclei

- $e\ p \rightarrow e\ \pi^{\pm}\ X^{*}$

  semi-inclusive DIS as flavor tag

- $$\left.\begin{array}{l} e^{\mp}\ p \rightarrow \nu(\bar{\nu}) X \\ \nu(\bar{\nu})\ p \rightarrow l^{\mp}\ X \\ p\ p(\bar{p}) \rightarrow W^{\pm} X, Z^{0}\ X \\ \vec{e}_L(\vec{e}_R)\ p \rightarrow e\ X^{*} \end{array}\right\}$$

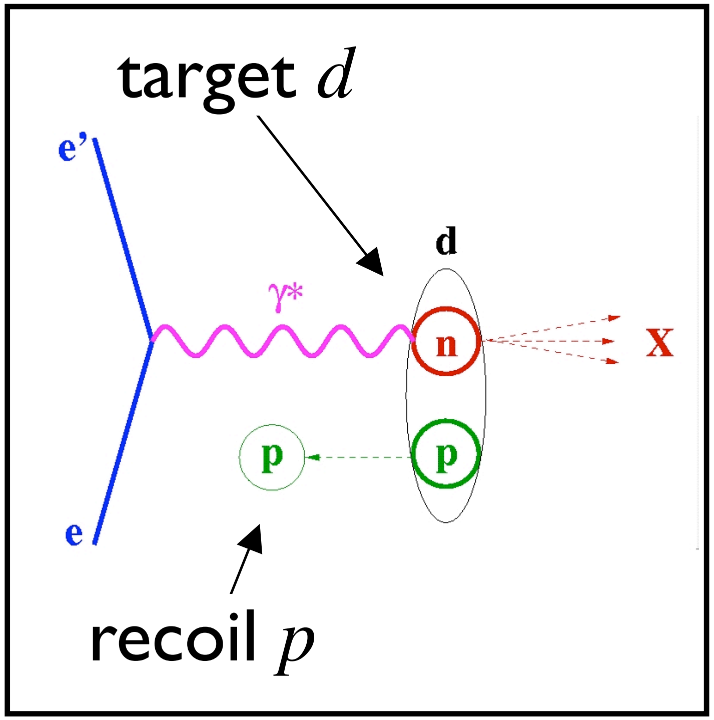
  weak current
  as flavor probe

  "PVDIS / SOLID"

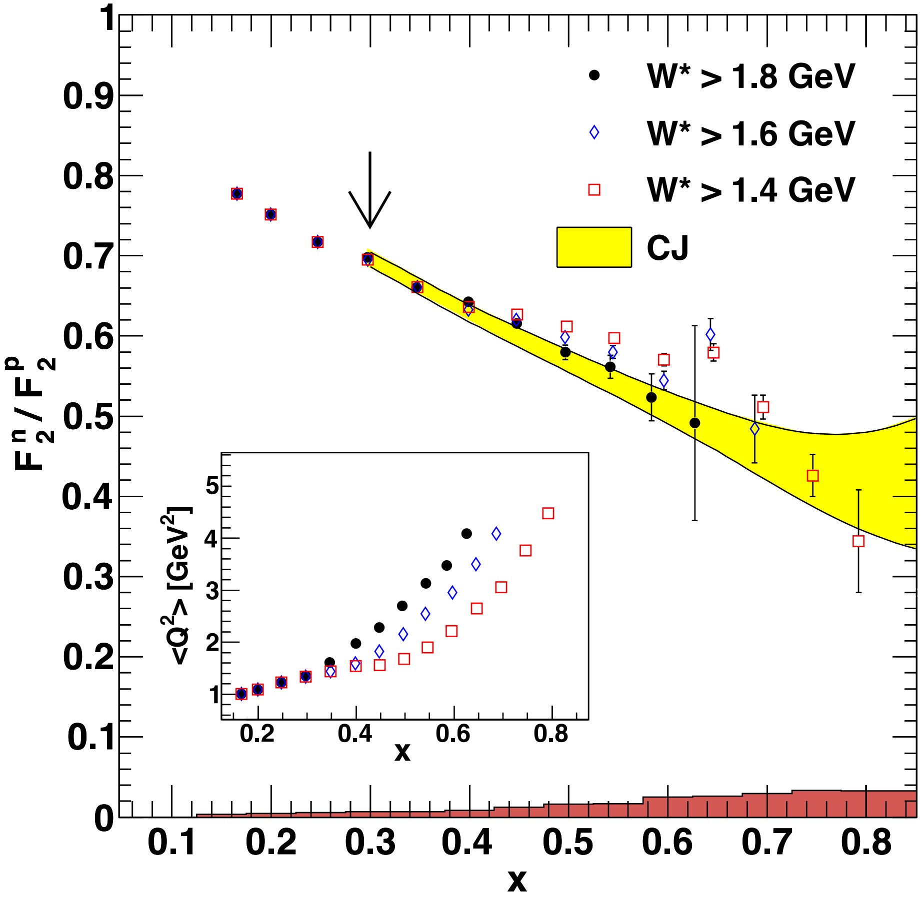
* planned for JLab at 12 GeV

BoNuS: slow spectator tagging

$$e\ d \rightarrow e\ p\ X$$



"6 GeV" JLab data



Baillie et al., arXiv:1110.2770

slow backward p

→ neutron nearly on-shell

→ minimize rescattering

→ 12 GeV experiment will extend range to $x \sim 0.8$

Bueltmann et al., Expt. E12-10-102

MARATHON: DIS from ^{3}He / ^{3}H

- Extract *n/p* ratio from measured ^{3}He / ^{3}H ratio

$$\frac{F_2^n}{F_2^p} = \frac{2\mathcal{R} - F_2^{^3\mathrm{He}}/F_2^{^3\mathrm{H}}}{2F_2^{^3\mathrm{He}}/F_2^{^3\mathrm{H}} - \mathcal{R}}$$

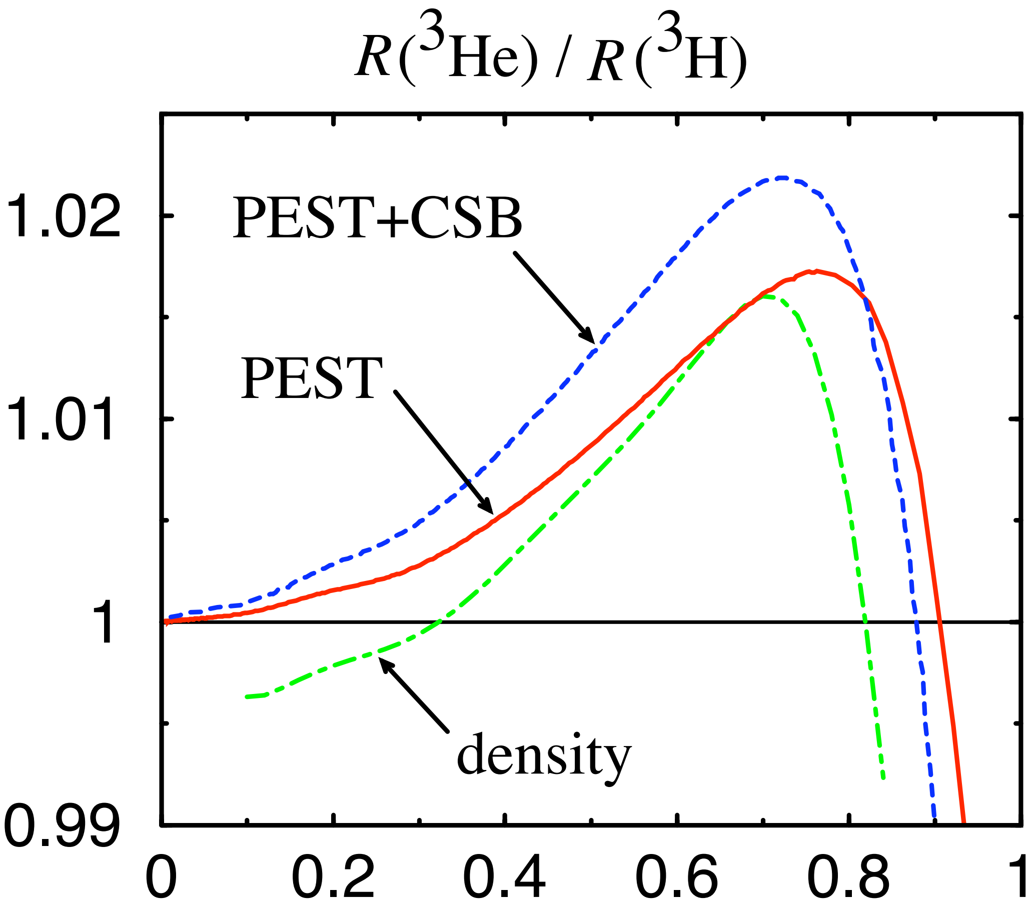
where ratio of "EMC ratios" $\mathcal{R} = \dfrac{R(^3\mathrm{He})}{R(^3\mathrm{H})}$

$$R(^3\mathrm{He}) = \frac{F_2^{^3\mathrm{He}}}{2F_2^p + F_2^n}\ ; \quad R(^3\mathrm{H}) = \frac{F_2^{^3\mathrm{H}}}{F_2^p + 2F_2^n}$$

→ main theoretical input

MARATHON: DIS from ^{3}He / ^{3}H

- Extract n/p ratio from measured ^{3}He / ^{3}H ratio

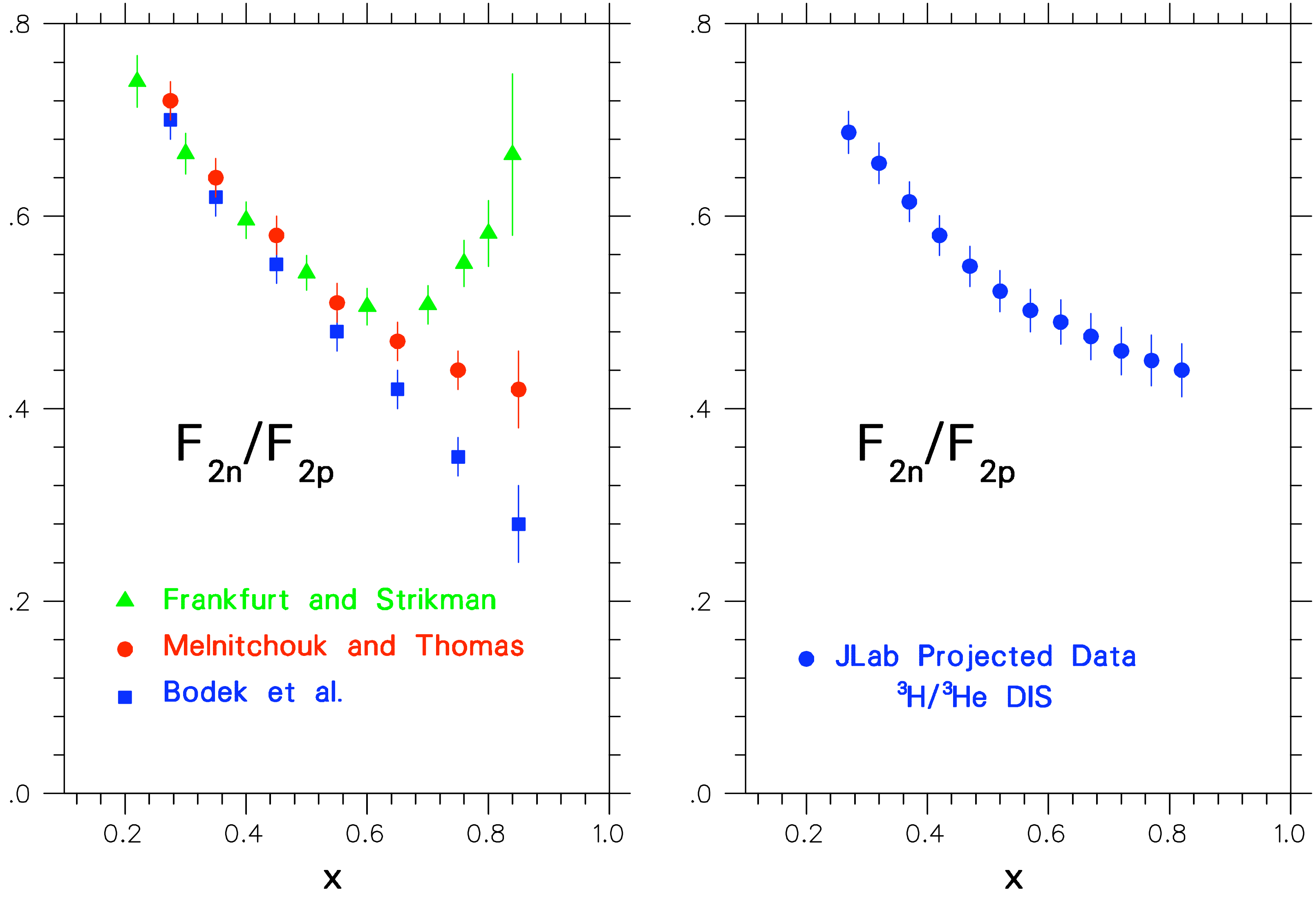


*Afnan et al., PRC **68**, 035201 (2003)*

→ nuclear effects cancel to < 1%

MARATHON: DIS from ^{3}He / ^{3}H

- Expected uncertainties of 12 GeV experiment



Petratos et al., Expt. E12-10-103

Summary

- New frontiers explored at large momentum fractions x

  $\longrightarrow$ dedicated global PDF analysis by CJ collaboration

- Current large uncertainties on d quark PDF

  $\longrightarrow$ impede knowledge about quark-gluon dynamics at large x

  $\longrightarrow$ affect possible signals of new physics at colliders

- Model independent constraints expected from new experiments at $12\ \mathrm{GeV}$ uniquely sensitive to d quarks

- Plan extension to *spin-dependent* global PDF analysis

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

The End