CSSM, University of Adelaide
Nov. 18, 2011

New parton distributions from high-x data:
implications for JLab to the LHC

Wally Melnitchouk

Jefferson Lab

Outline

- *Preliminaries*: electron scattering and parton distributions

- Why are large-x quarks in the nucleon important (and problematic)?

  → d/u PDF ratio, neutron structure & nuclear corrections

- New global "CJ" (CTEQ–Jefferson Lab) analysis

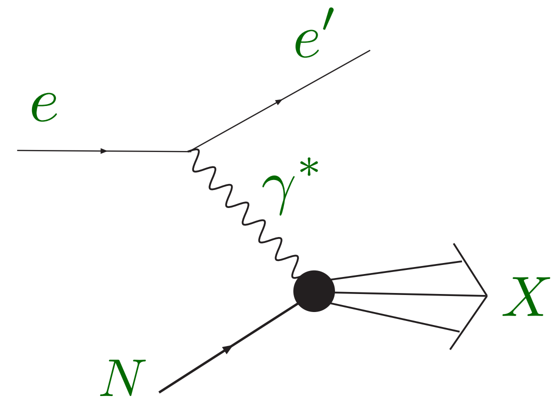
  → first serious foray into high-x, low-Q^2 region

  → implications of PDF uncertainties for LHC physics

- Outlook

Electron scattering

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



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

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

"Bjorken scaling variable"

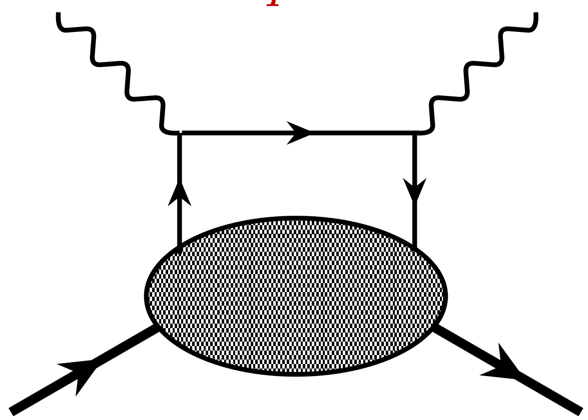
- Structure functions F_1 , F_2

$\longrightarrow$ contain all information about structure of nucleon

Parton model

→ scatter from individual quarks (*"partons"*) in hadron

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



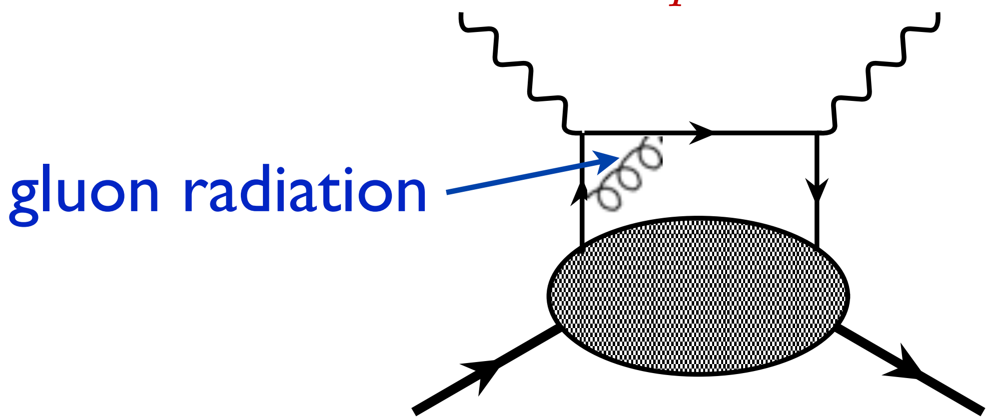
→ $q\,(x, Q^2)$ = probability to find quark type "q" in nucleon, carrying (light-cone) momentum fraction x

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

Parton model

→ scatter from individual quarks ("*partons*") in hadron

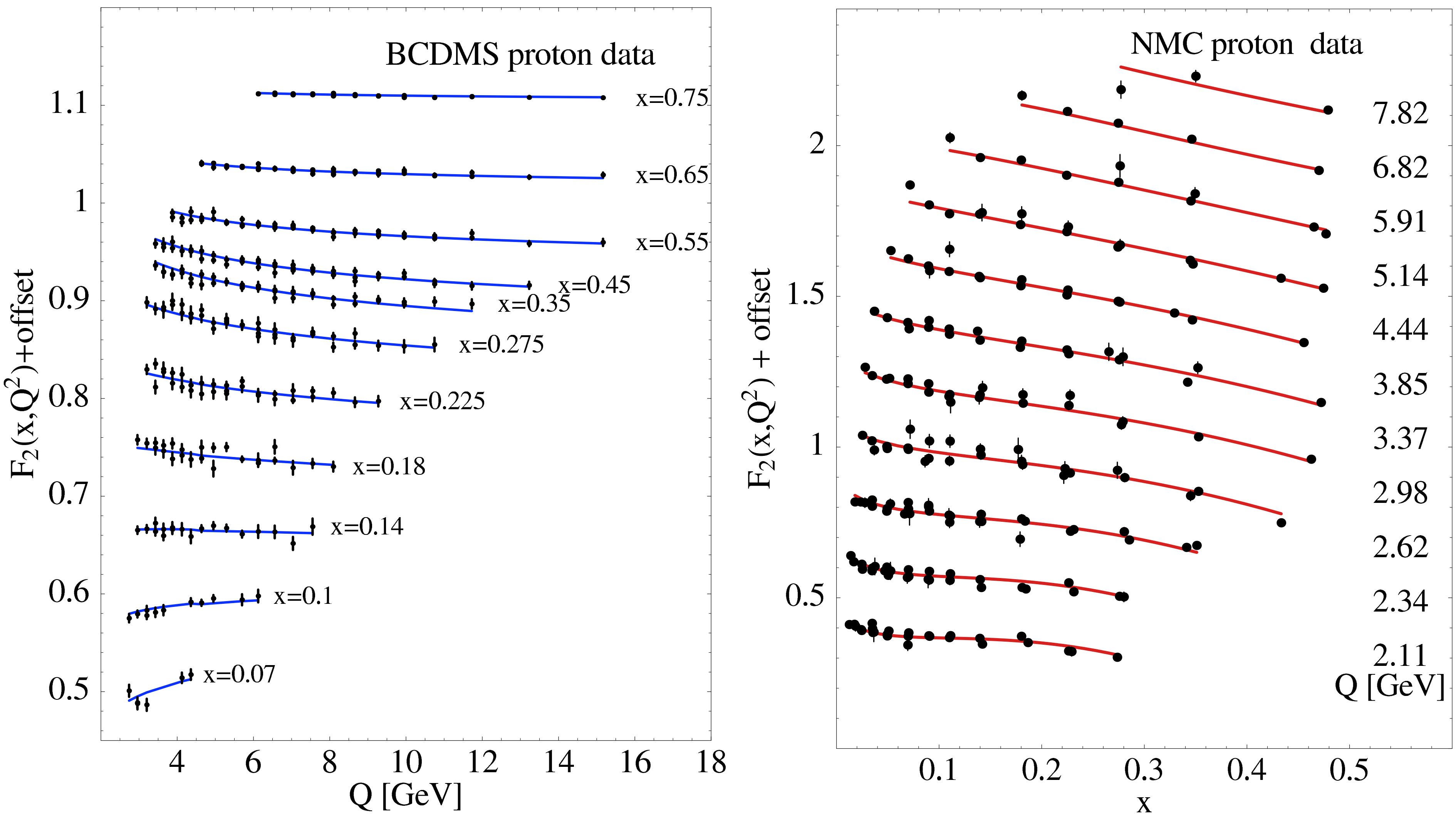
$$F_2(x,Q^2) = x \sum_q e_q^2 \, q(x,Q^2) \qquad (q=u,d,s\ldots)$$



→ Q^2 dependence given by (perturbatively calculable) QCD evolution equations (→ $\log Q^2$ behavior)

→ at large Q^2, "Callan-Gross relation" $F_2 \approx 2x\, F_1$

Structure function data



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

→ log Q^2 behavior confirmed experimentally

(important early confirmation of pQCD!)

Why are PDFs at *large x* important?

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

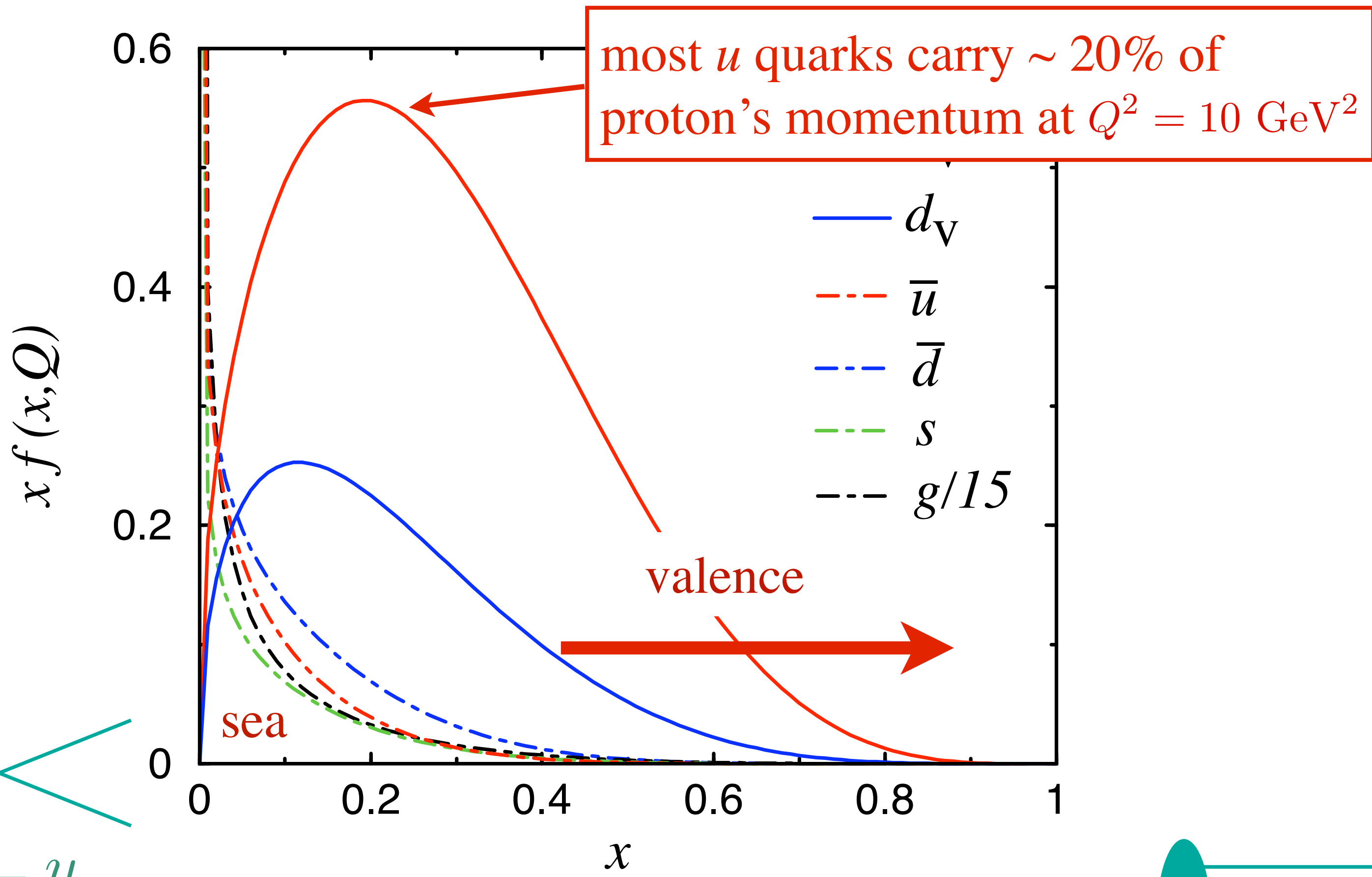
- Needed to understand backgrounds in searches for physics *beyond the Standard Model* in high-energy colliders *e.g.* the LHC

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

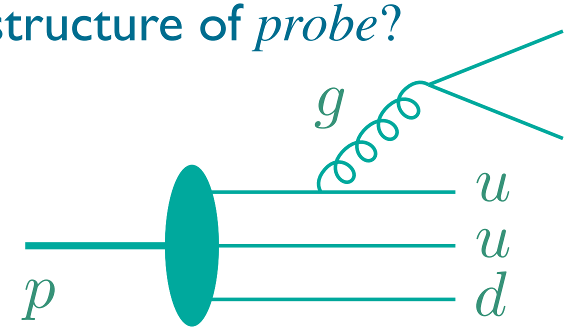
Large-x PDFs

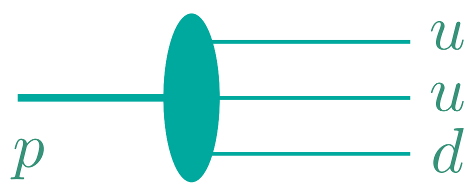
- Most direct connection between quark distributions and models of nucleon structure is via *valence* quarks

  → most cleanly revealed at $x > 0.4$



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





Large-x PDFs

- 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 quark models

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

- SU(6) spin-flavor symmetry

proton wave function

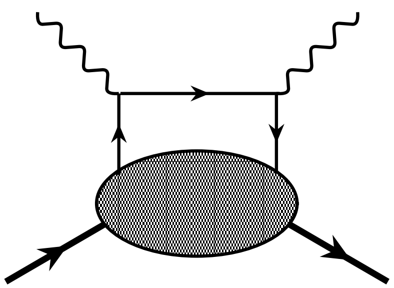
$$p^{\uparrow} = -\frac{1}{3}d^{\uparrow}(uu)_1 - \frac{\sqrt{2}}{3}d^{\downarrow}(uu)_1 + \frac{\sqrt{2}}{6}u^{\uparrow}(ud)_1 - \frac{1}{3}u^{\downarrow}(ud)_1 + \frac{1}{\sqrt{2}}u^{\uparrow}(ud)_0$$

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

interacting quark

spectator diquark

diquark spin



Valence quark models

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

- SU(6) spin-flavor symmetry

<u>proton wave function</u>

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

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 quark models

- But SU(6) symmetry is *broken*

e.g. scalar diquark dominance

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

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

since only u quarks couple to *scalar* diquarks

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

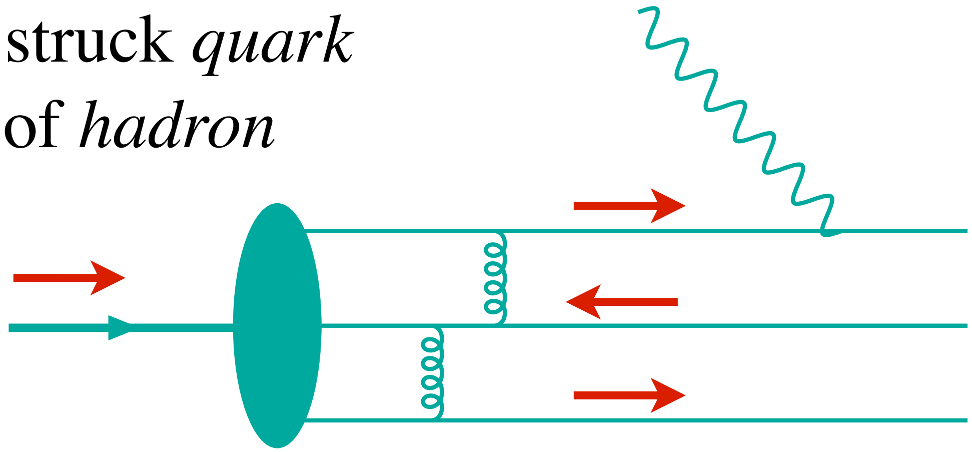
$\rightarrow \quad \frac{F_2^n}{F_2^p} \to \frac{1}{4}$

Feynman 1972, Close 1973, Close/Thomas 1988

Valence quark models

- 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

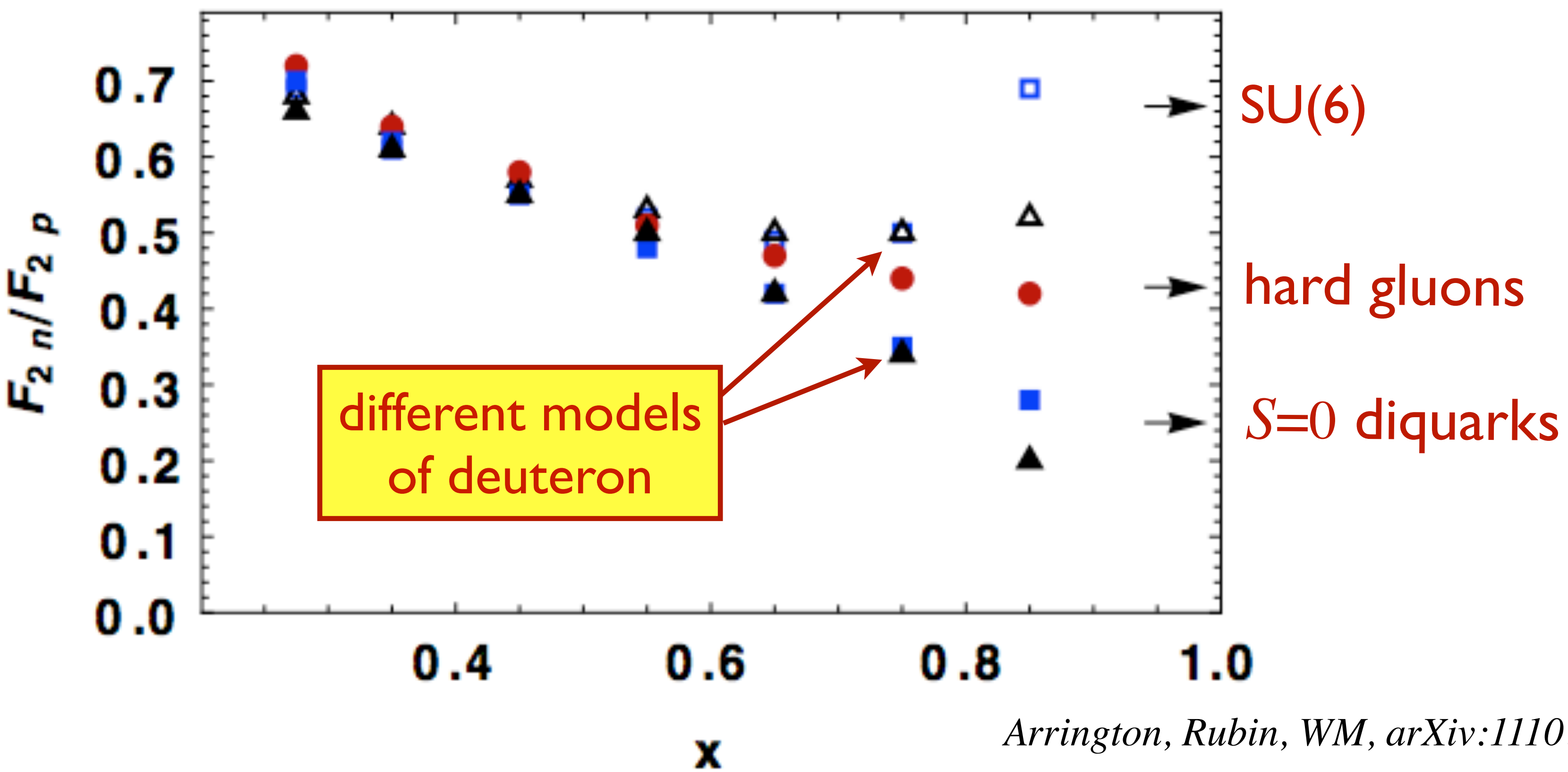
➔ $\dfrac{d}{u} \to \dfrac{1}{5}$

➔ $\dfrac{F_2^n}{F_2^p} \to \dfrac{3}{7}$

Farrar, Jackson 1975

Deuteron corrections

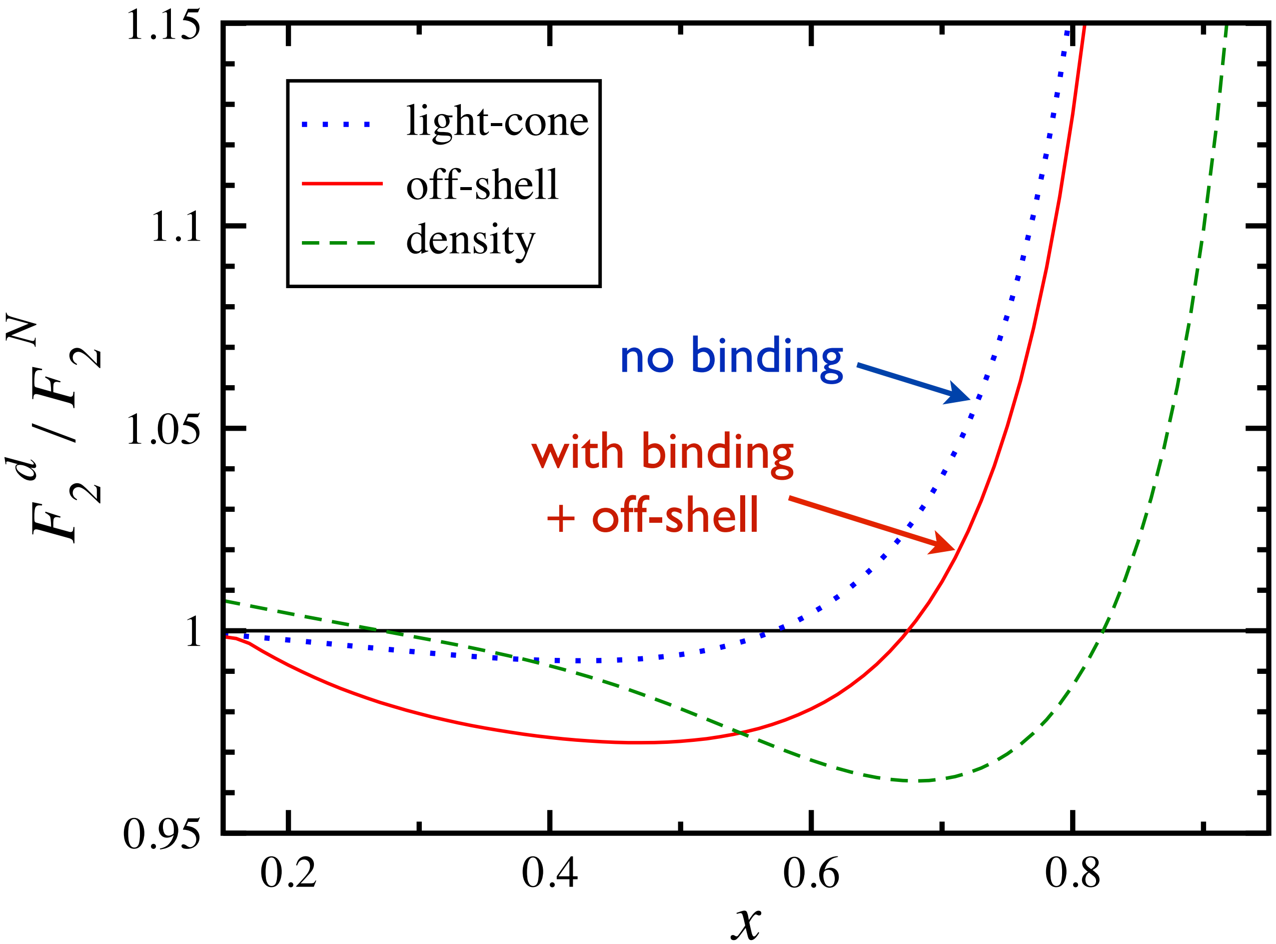
- Absence of free neutron targets
  → use *deuterons* (weakly bound state of p and n)



Arrington, Rubin, WM, arXiv:1110.3362

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

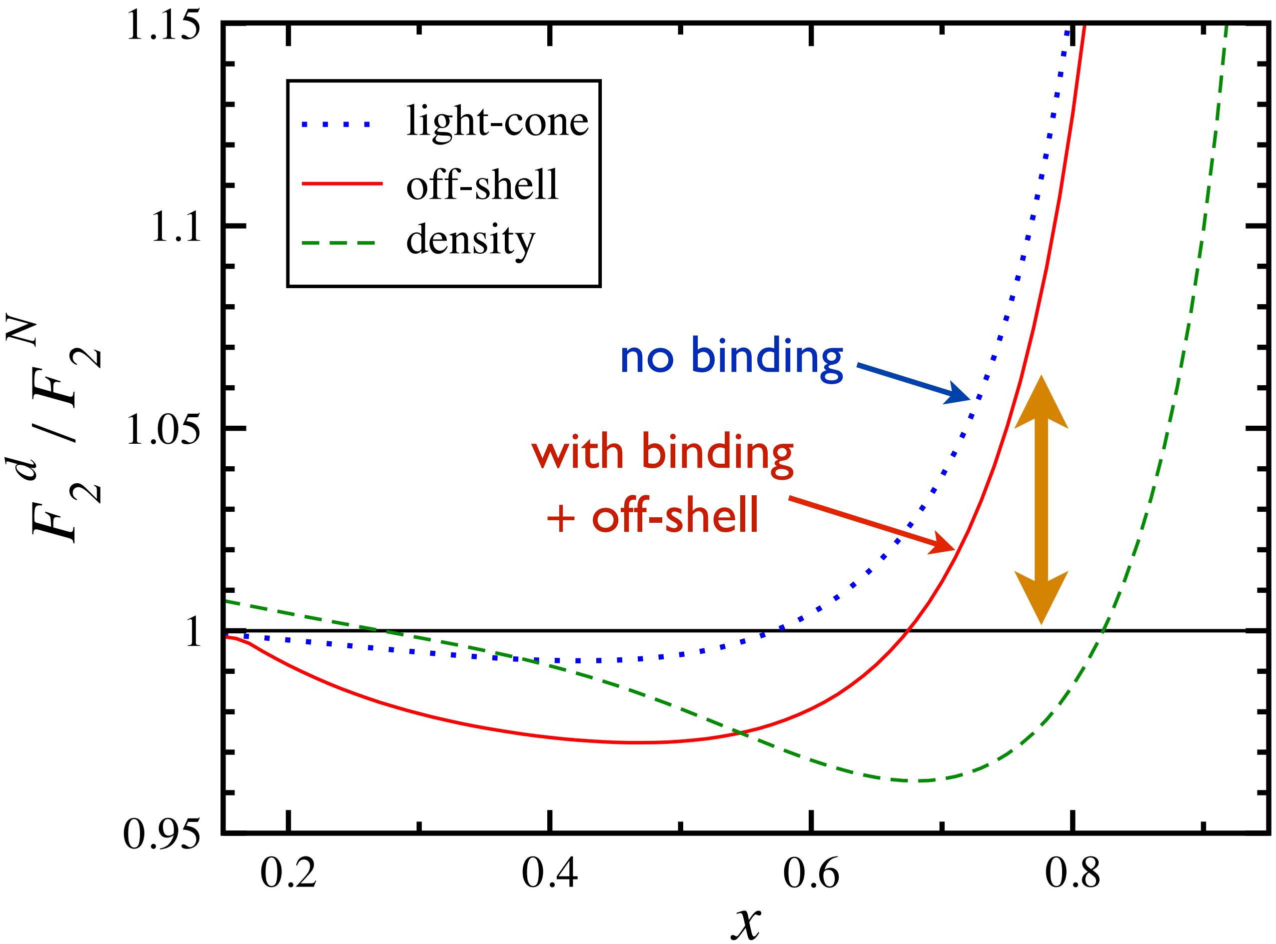
Deuteron corrections



→ ~ 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)* **"CTEQ6X/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

- 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

- Include subleading $1/Q^2$ corrections

  → target mass corrections & dynamical higher twists

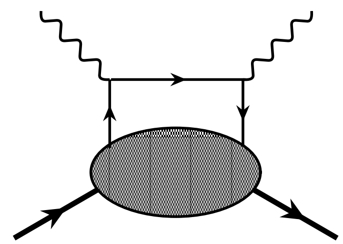
Higher twists

- $1/Q^2$ expansion of structure function moments

$$M_n(Q^2) = \int_0^1 dx\ x^{n-2}\ F_2(x,Q^2)\ = A_n^{(2)} + \frac{A_n^{(4)}}{Q^2} + \frac{A_n^{(6)}}{Q^4} + \cdots$$

matrix elements of operators with specific "twist" (= dimension − spin)

→ twist = 2 corresponds to single-quark scattering



e.g. $\bar{\psi}\,\gamma_\mu\,\psi$

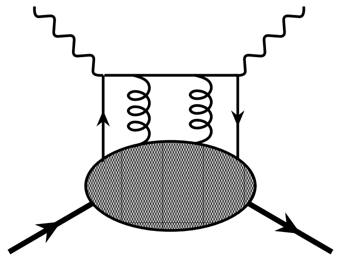
Higher twists

- $1/Q^2$ expansion of structure function moments

$$M_n(Q^2) = \int_0^1 dx\; x^{n-2}\; F_2(x,Q^2) \;= A_n^{(2)} + \frac{A_n^{(4)}}{Q^2} + \frac{A_n^{(6)}}{Q^4} + \cdots$$

matrix elements of operators with specific "twist" (= dimension − spin)

→ twist > 2 reveals long-range multi-parton correlations



$e.g.\;\; \bar\psi\, \widetilde{F}_{\mu\nu}\gamma_\nu\, \psi$

- phenomenologically important at large x and low Q^2

→ parametrize x dependence by

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

Target mass corrections

- Kinematical corrections arising from derivative operators

  $e.g.\ \bar{\psi}\,\gamma_\mu\, D_{\mu_1}\cdots D_{\mu_n}\,\psi$ ➞ twist = 2!

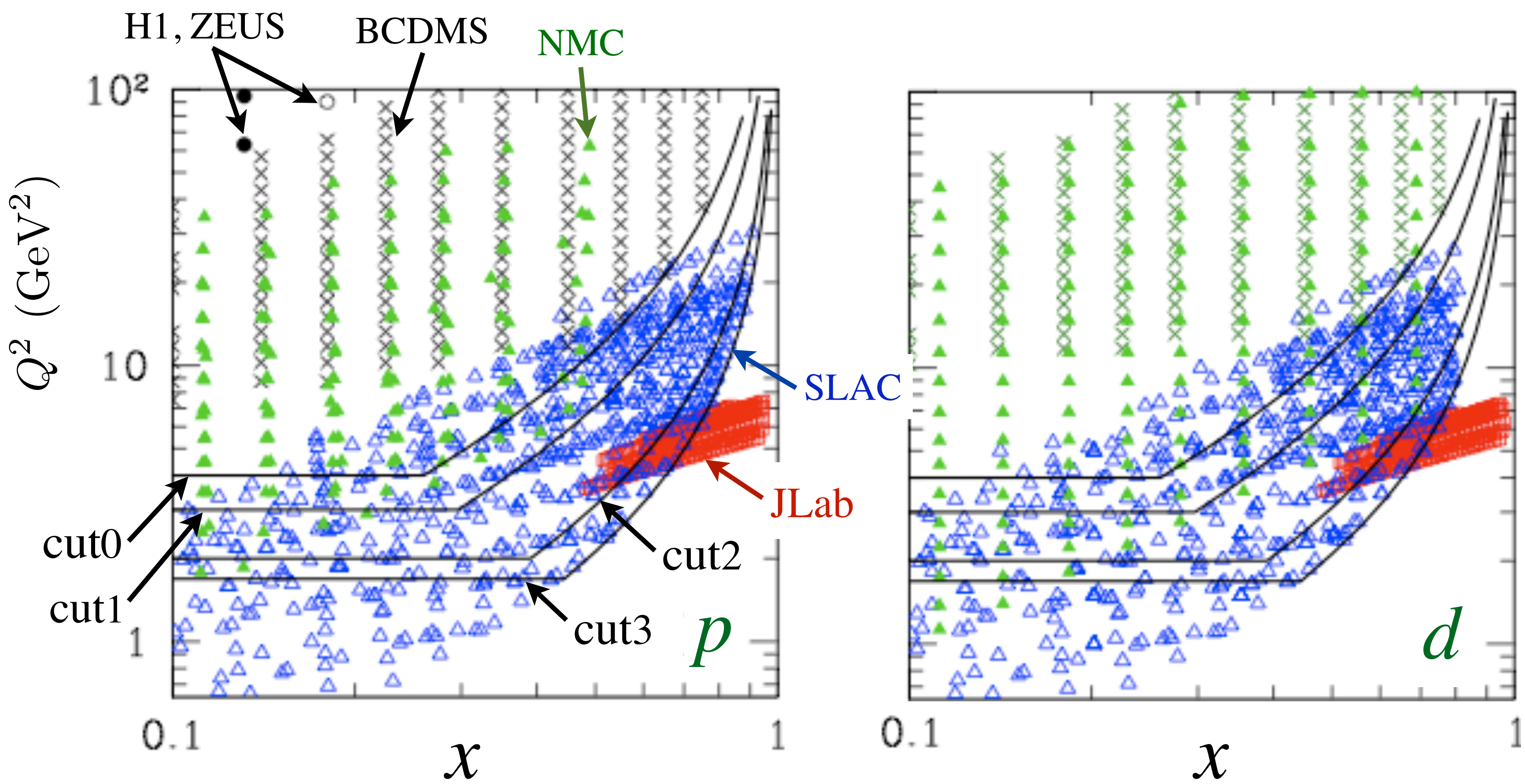
  ⟶ give rise to corrections $\sim\ Q^2/\nu^2 = 4M^2x^2/Q^2$
  (hence "target mass")

  ⟶ target mass corrected structure function

$$F_2^{\rm TMC}(x,Q^2) = \frac{x^2}{\xi^2\gamma^3}F_2^{(0)}(\xi,Q^2) + \frac{6M^2x^3}{Q^2\gamma^4}\int_\xi^1 du\,\frac{F_2^{(0)}(u,Q^2)}{u^2} + \frac{12M^4x^4}{Q^4\gamma^5}\int_\xi^1 dv(v-\xi)\,\frac{F_2^{(0)}(v,Q^2)}{v^2}$$

- $F_2^{(0)}$ = structure function in massless (Bjorken) limit
- new "Nachtmann" scaling variable $\xi = \dfrac{2x}{1+\sqrt{1+4M^2x^2/Q^2}}$

Kinematic cuts



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

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

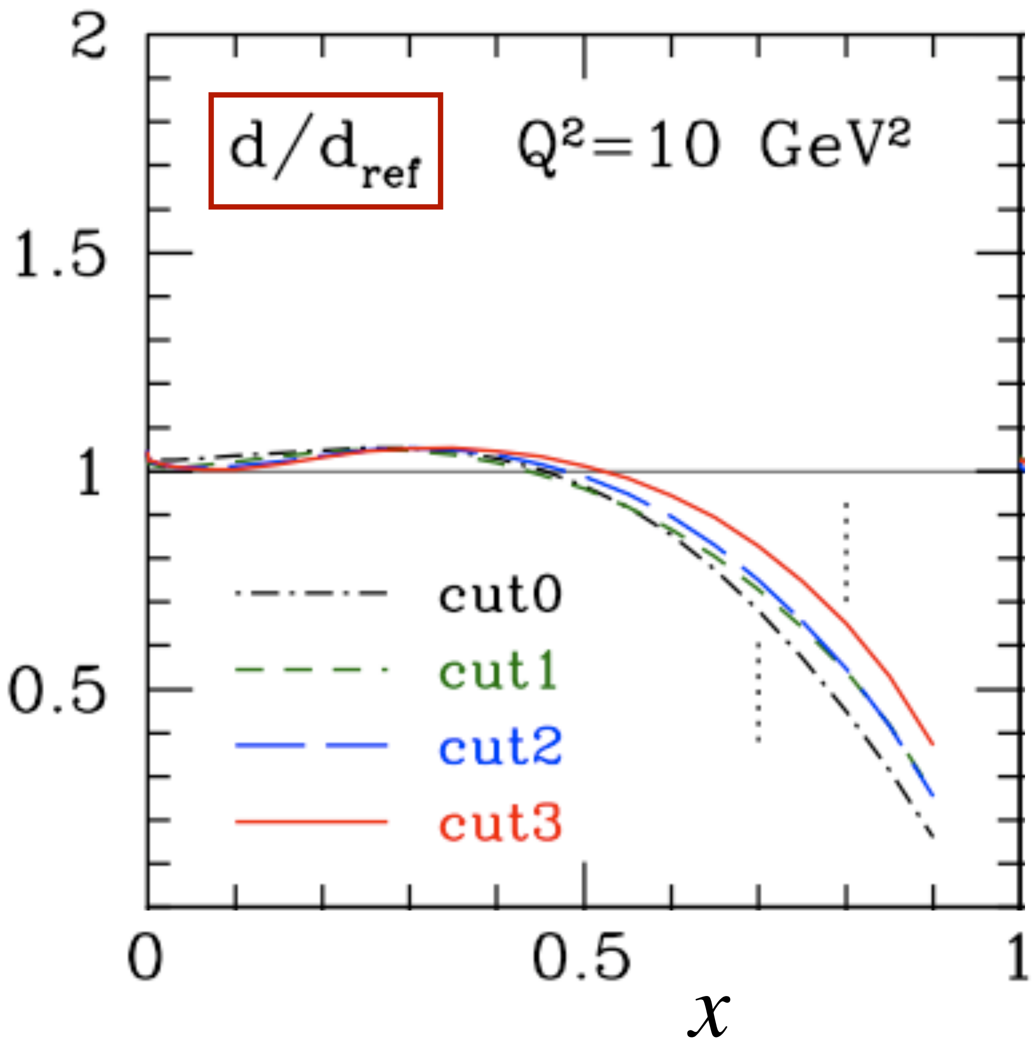
cut2: $Q^2 > 2\ \mathrm{GeV}^2, \quad W^2 > 4\ \mathrm{GeV}^2$

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

factor 2 increase in DIS data from cut0 → cut3

Kinematic cuts

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

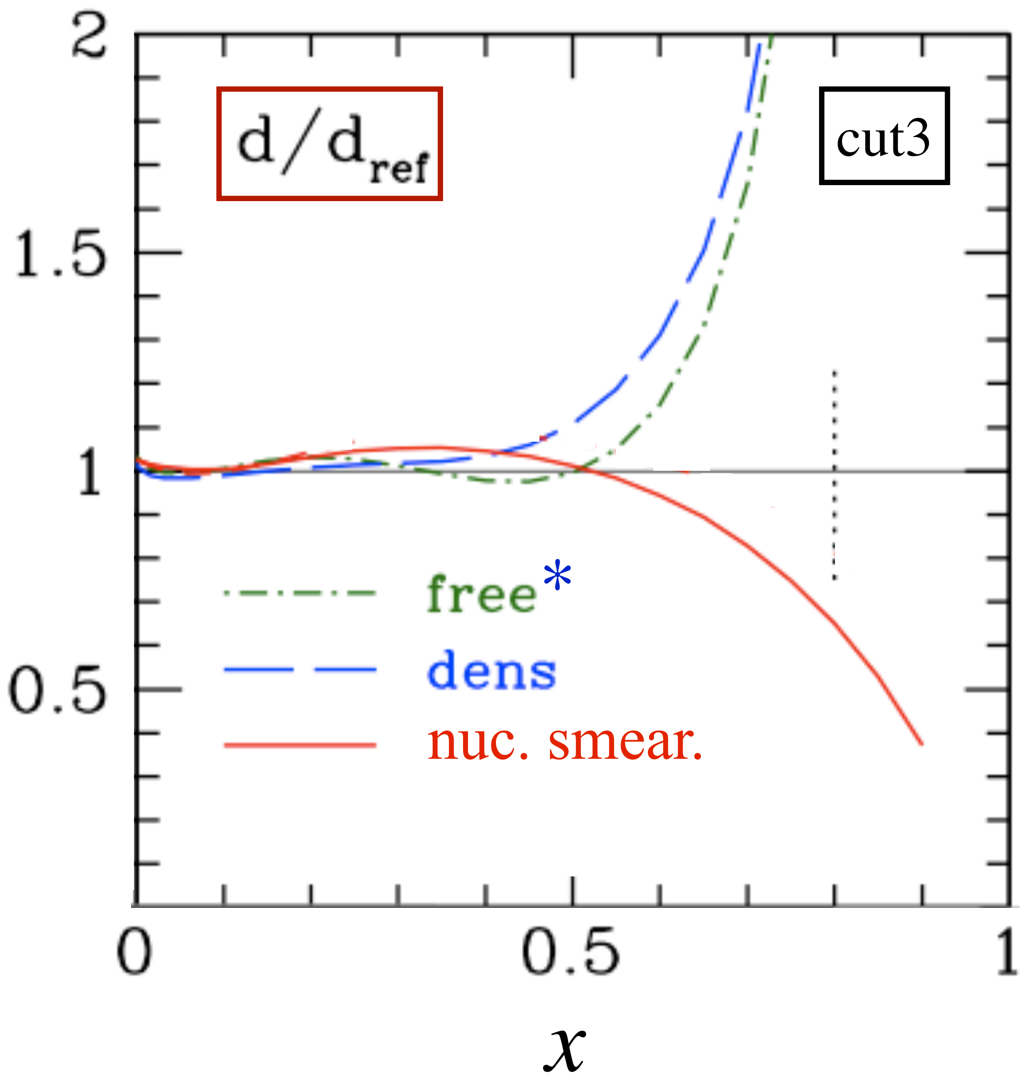


→ *stable* with respect to cut reduction

→ 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

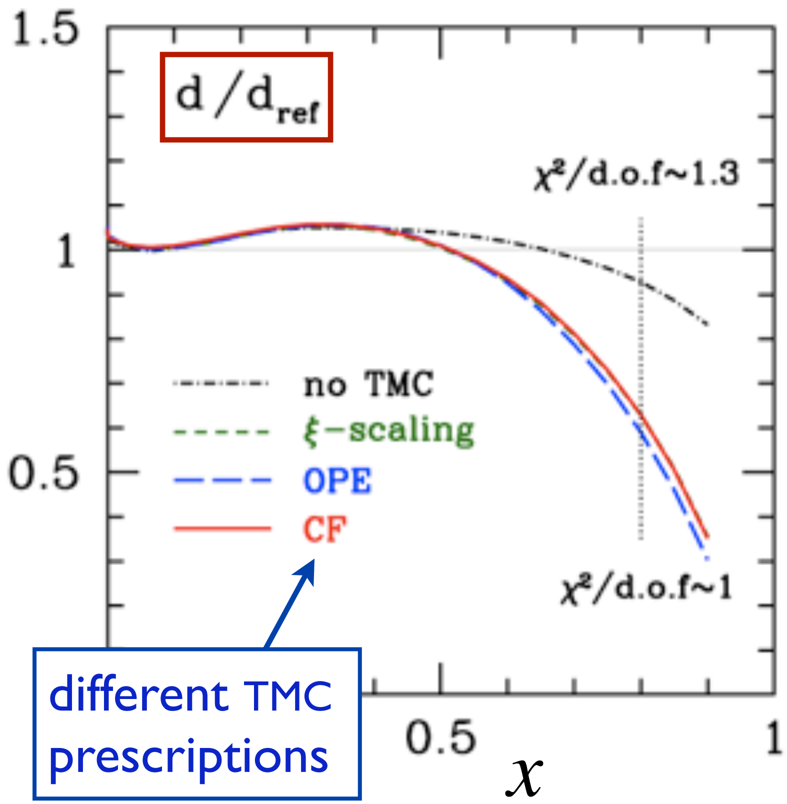
↓

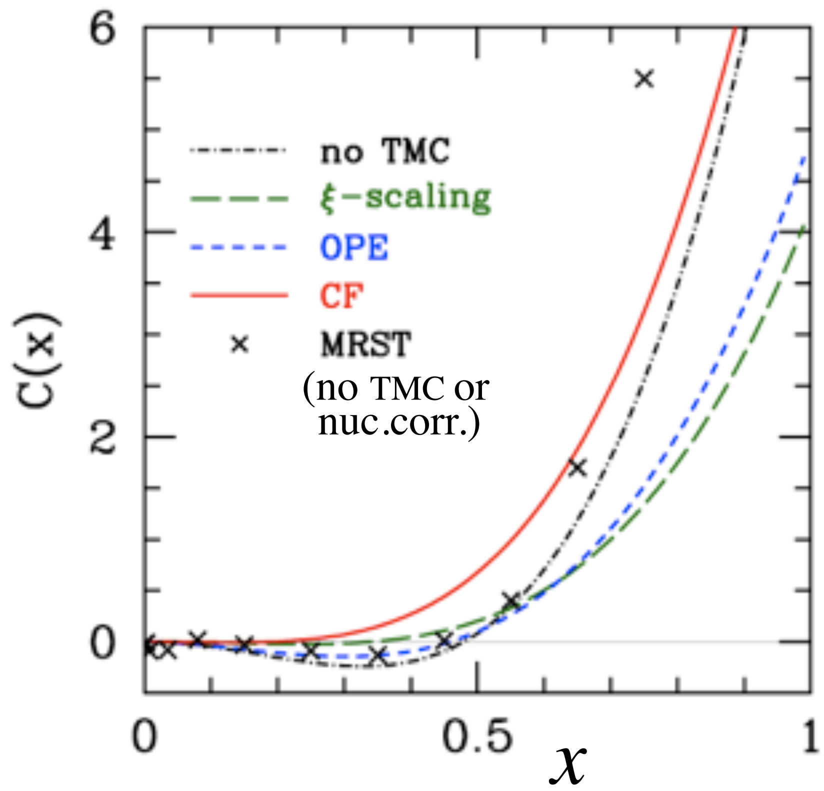
$F_2^d/F_2^N > 1$ for $x \sim 0.6$–0.8 while $F_2^d/F_2^N < 1$ for "free" and "density" models

F_2^d/F_2^N ↑ ⟷ F_2^n/F_2^p ↓

⟷ d/u ↓

Effect of $1/Q^2$ corrections



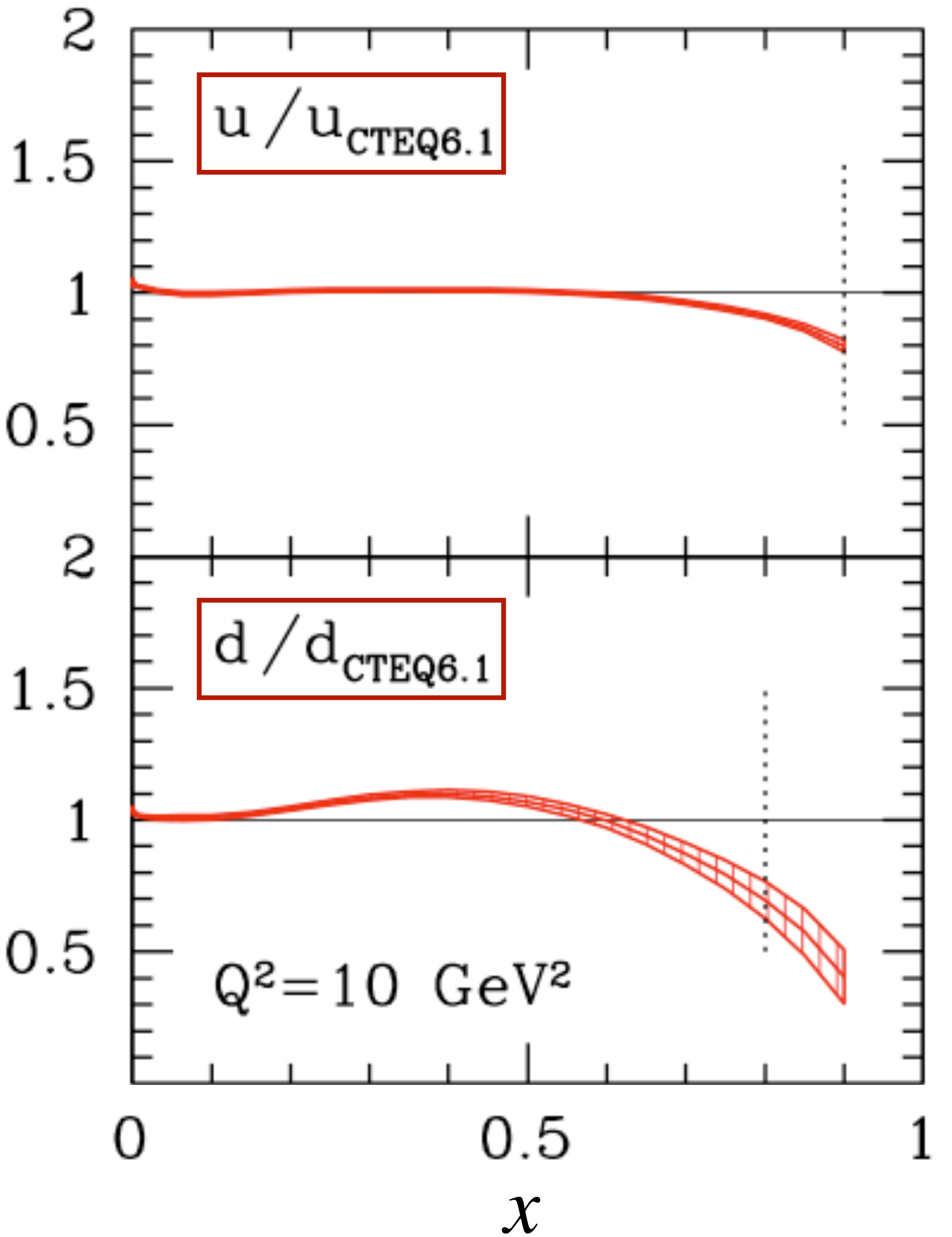


→ $1/Q^2$ correction $F_2 = F_2^{\rm LT}\left(1 + \dfrac{C(x)}{Q^2}\right)$, $C(x) = c_1 x^{c_2}(1 + c_3 x)$

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

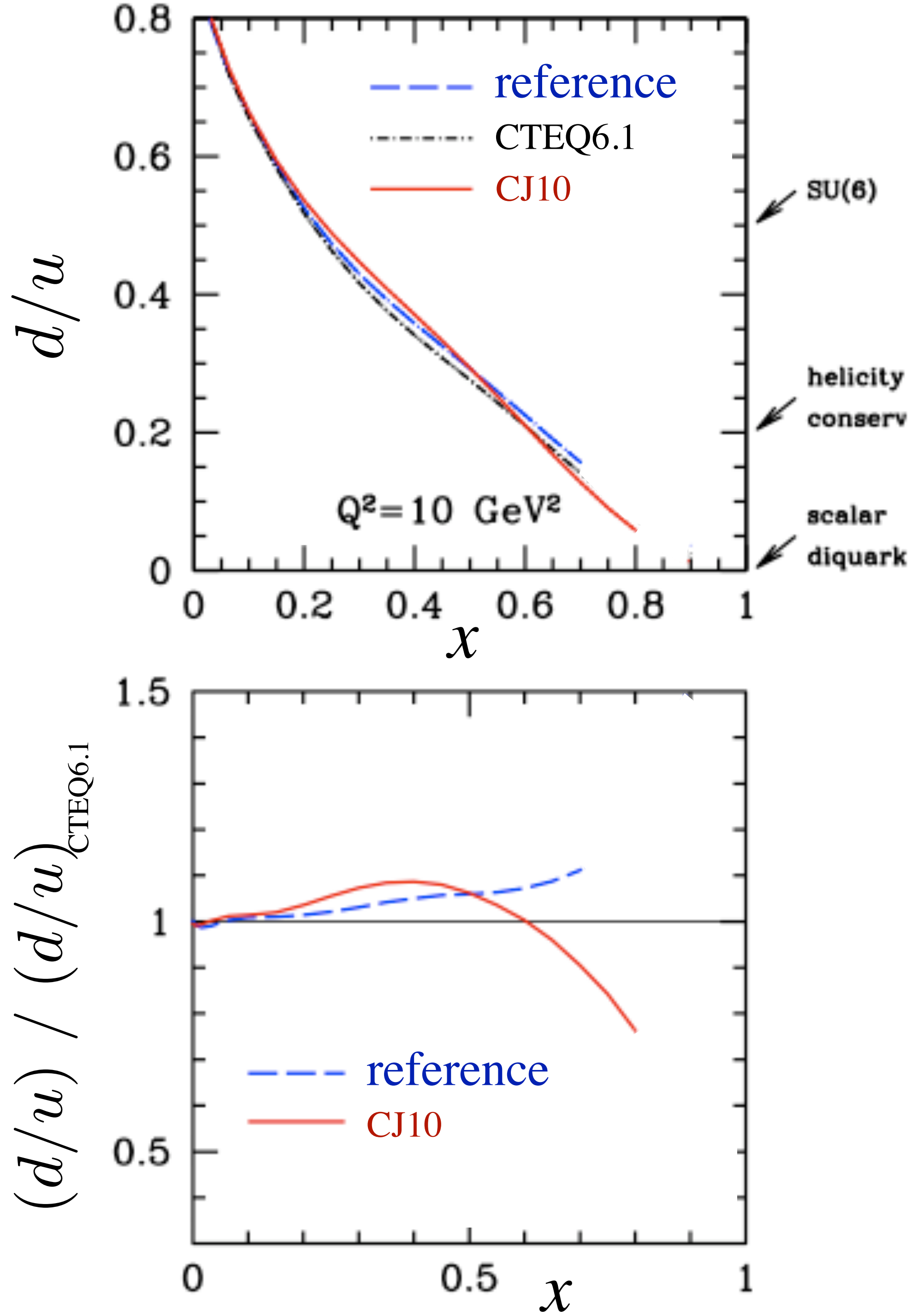
→ stable leading twist when *both* TMCs and HTs included

CJ10 PDF results



→ full fits favors smaller d/u ratio

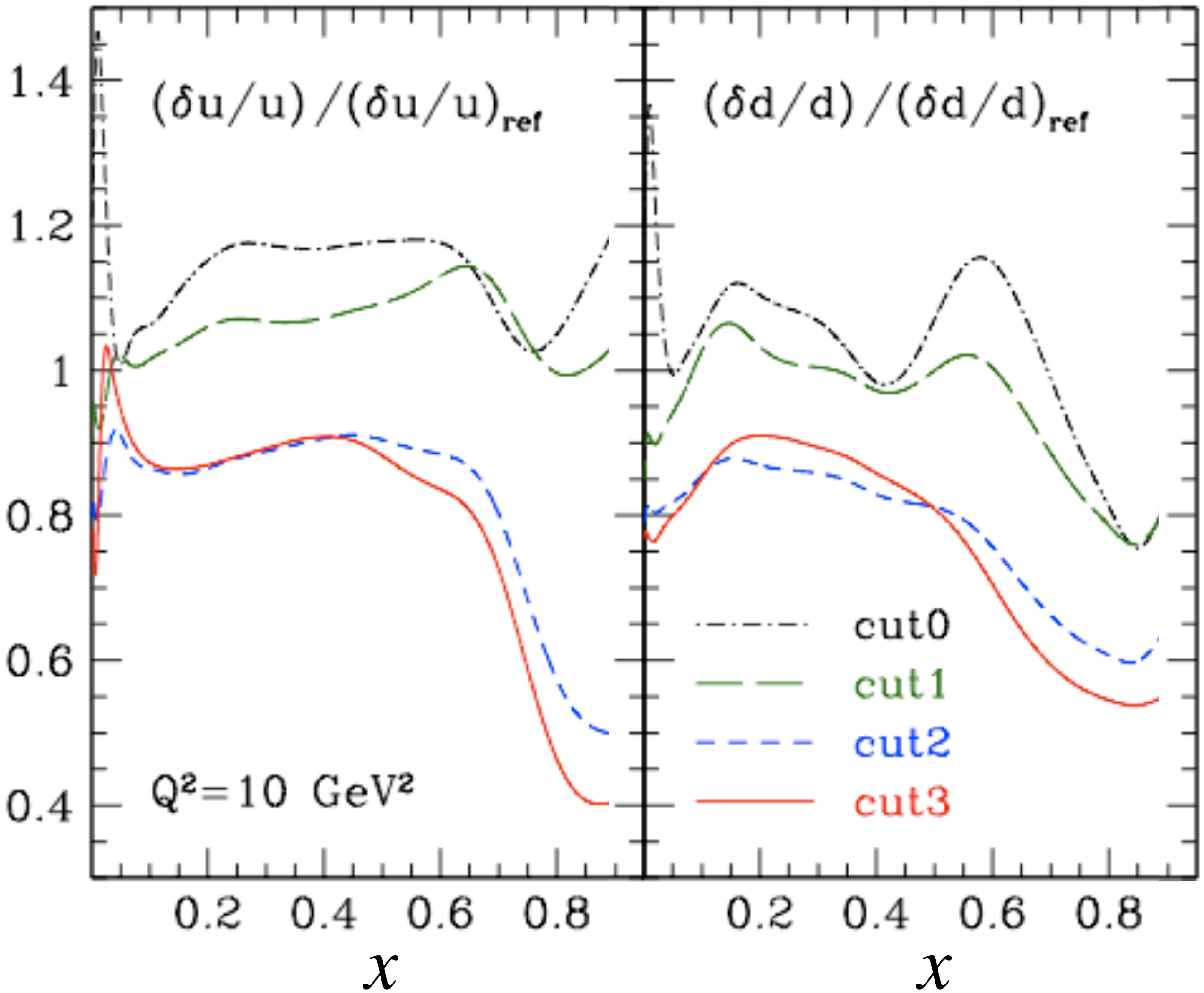
CJ10 PDF results



→ 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)

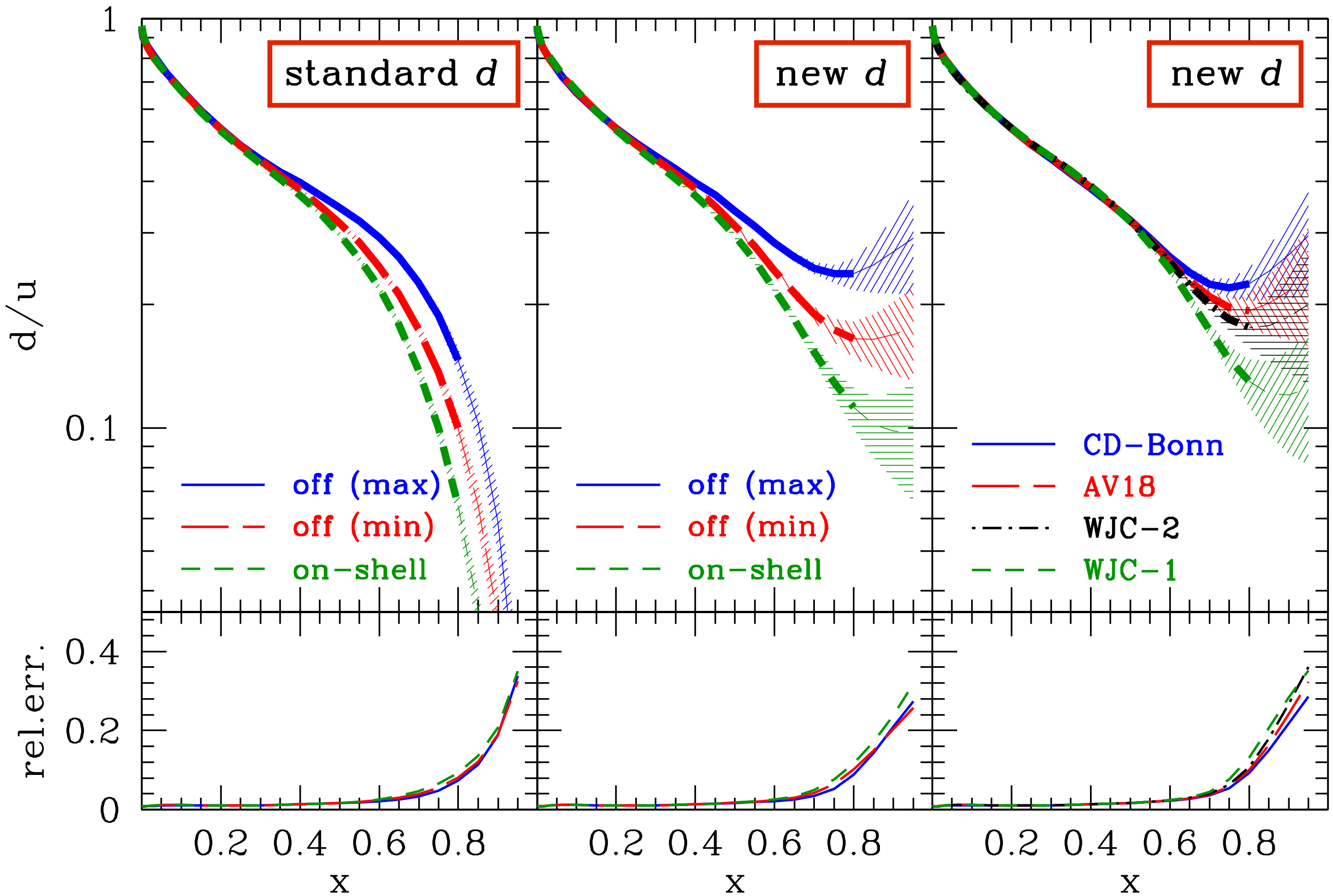
  → model nucleon off-shell correction with reasonable range of parameters

- Dependence of d/u ratio on d quark parametrization

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

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

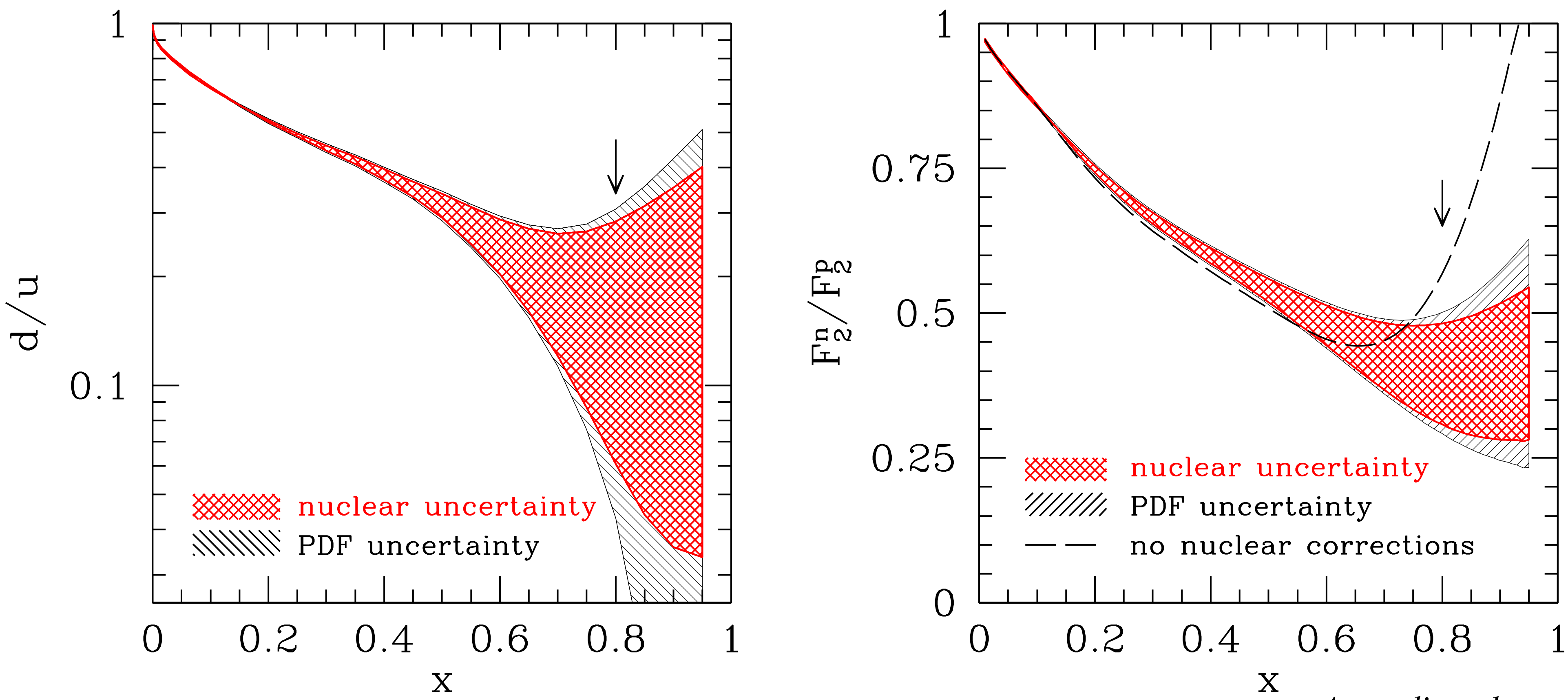
New CJ11 PDF analysis



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

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

New CJ11 PDF analysis



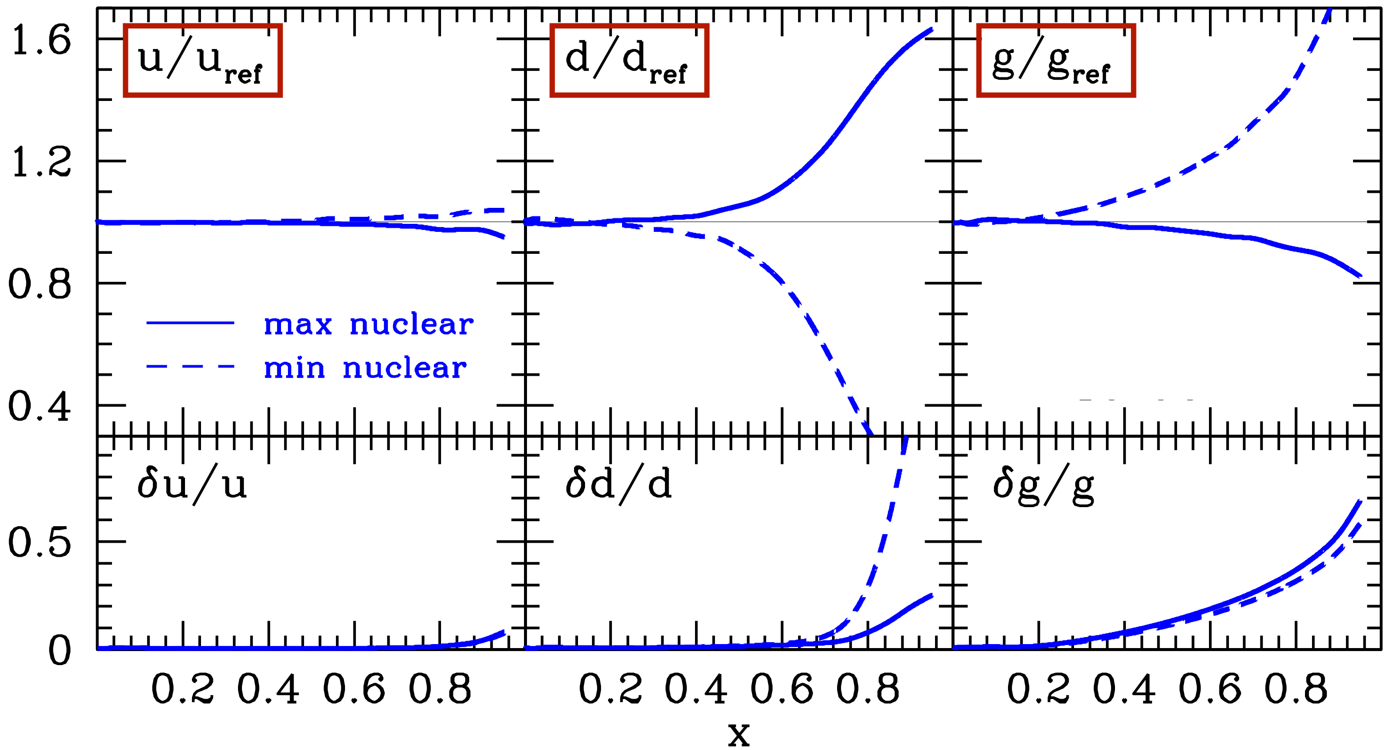
Accardi et al.
PRD ***84****, 014008 (2011)*

→ 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)

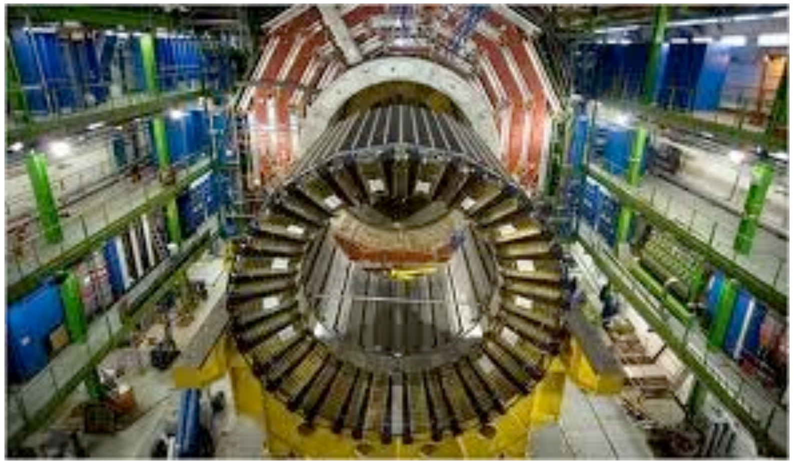
→ gluon PDF anticorrelated with d quark
(g compensates for smaller d quark contribution in jet data)

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

Implications for high-energy colliders

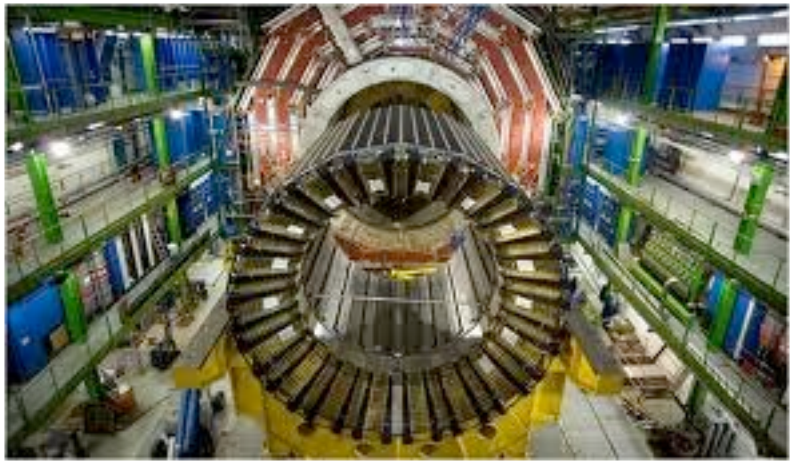
(Tevatron, LHC)

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

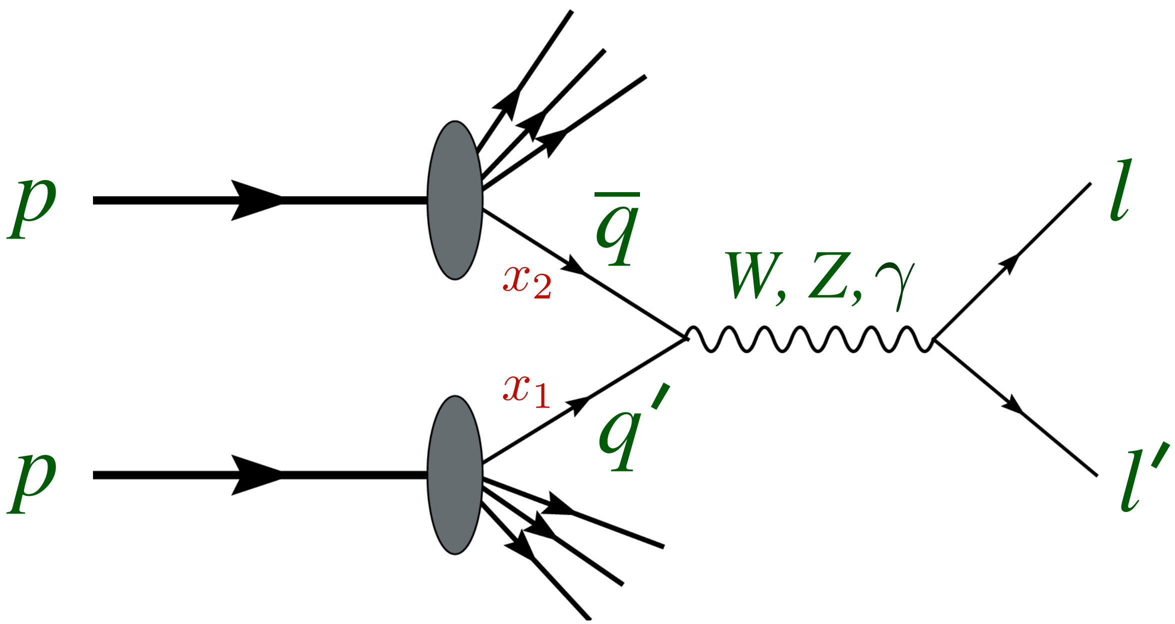


→ pp collisions at $\sqrt{s} = 7\ \mathrm{TeV}$

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



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

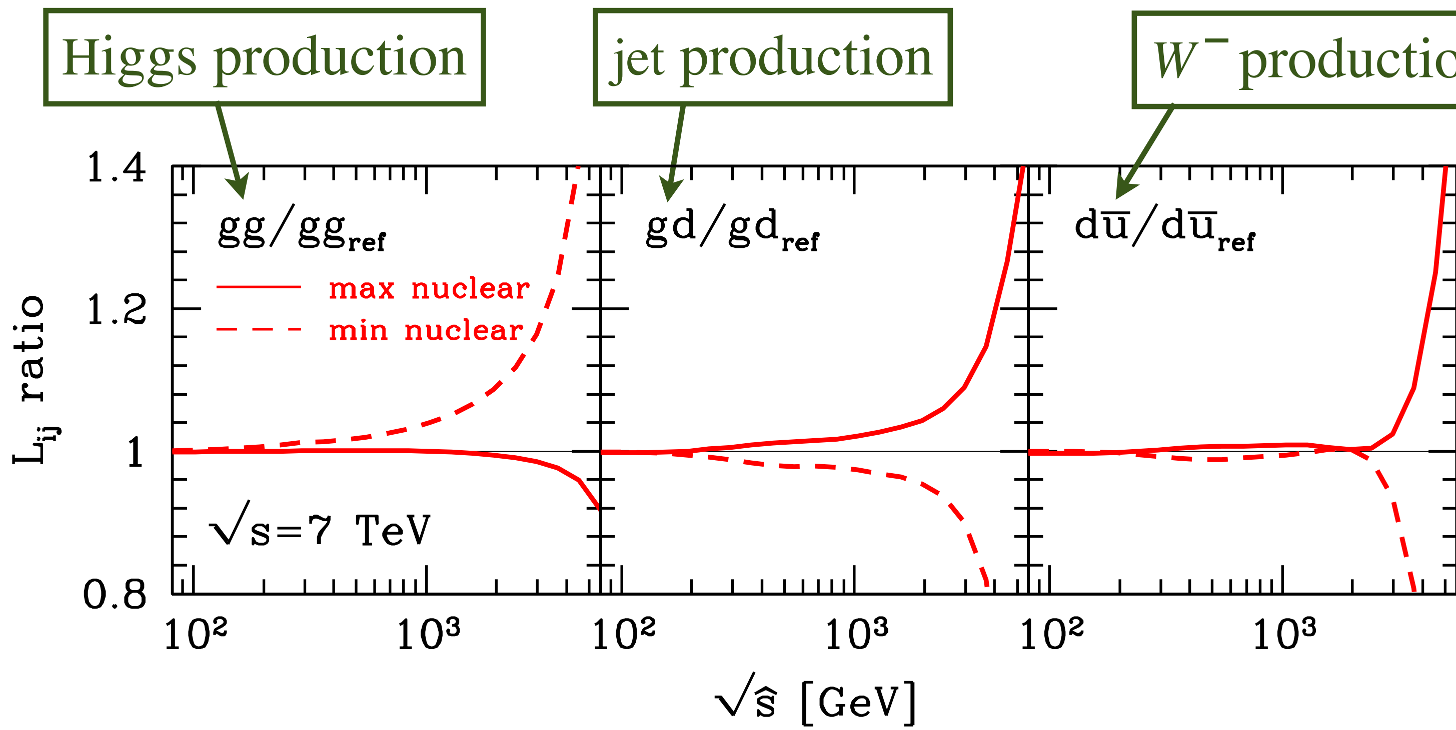


Parton luminosities

- Impact of CJ11 PDFs 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

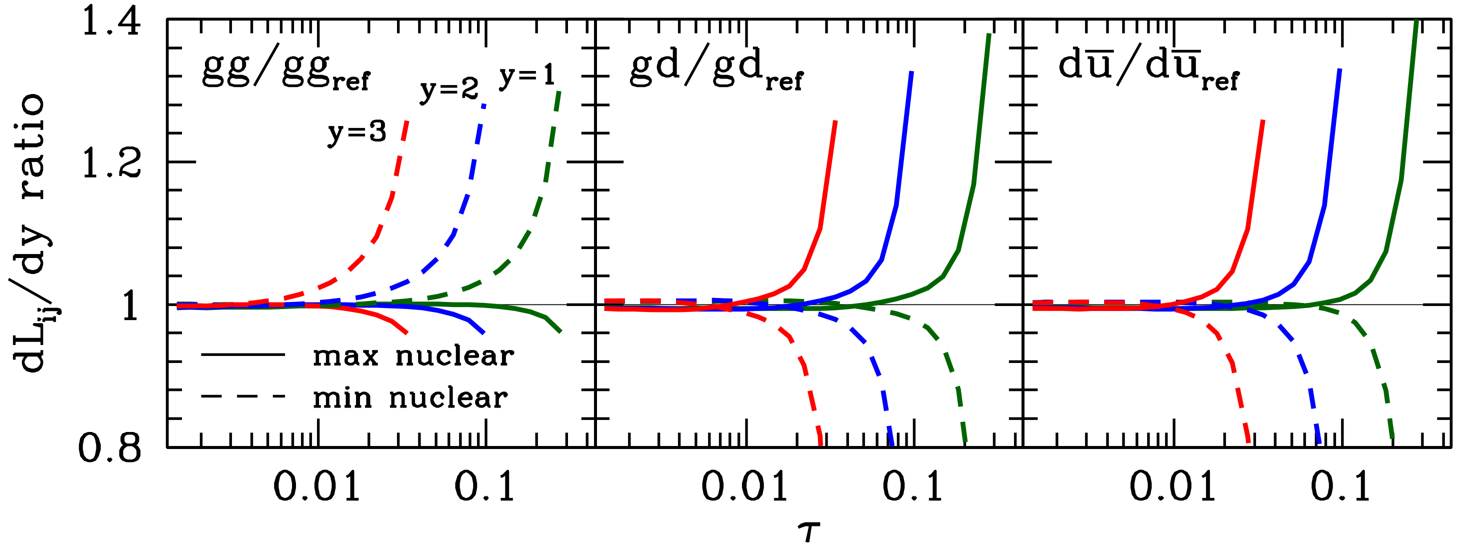
→ nuclear uncertainties important for $\sqrt{\hat{s}} \gtrsim 1$ TeV mass range

Parton luminosities

- Impact of CJ11 PDFs 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*

W boson asymmetries

- Large-x PDF uncertainties affect observables at large *rapidity* y, with

$$y = \frac{1}{2}\ln\left(\frac{E+p_z}{E-p_z}\right) \rightarrow \boxed{x_{1,2} = \frac{M}{\sqrt{s}}\,e^{\pm y}}$$

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

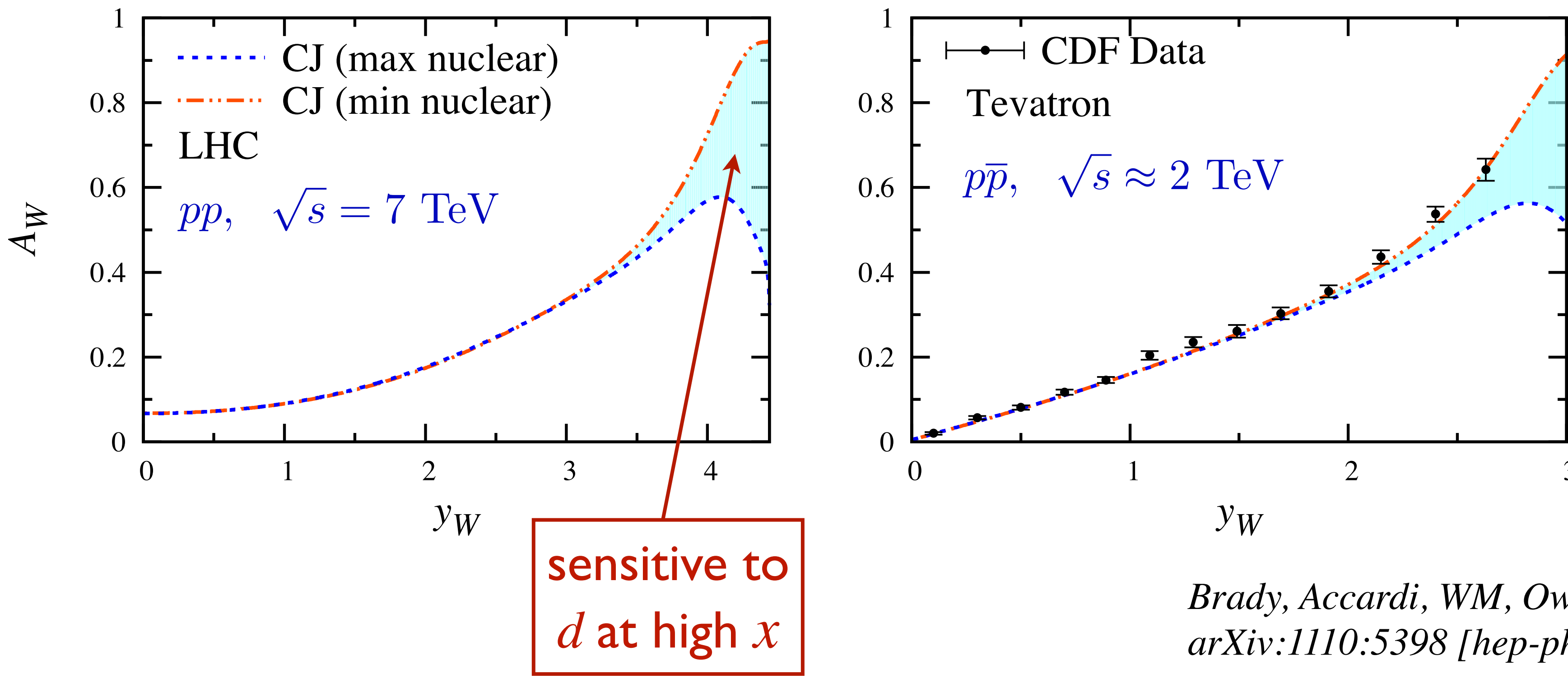
$$\sigma_{W^+} \equiv \frac{d\sigma}{dy}(pp \to W^+X) = \frac{2\pi G_F}{3\sqrt{2}} x_1 x_2 \left(u(x_1)\bar{d}(x_2) + \cdots\right)$$

W boson asymmetries

- Large-x PDF uncertainties affect observables at large *rapidity* y, with

$$y = \frac{1}{2}\ln\left(\frac{E+p_z}{E-p_z}\right) \rightarrow \boxed{x_{1,2} = \frac{M}{\sqrt{s}}\, e^{\pm y}}$$

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



Brady, Accardi, WM, Owens
arXiv:1110:5398 [hep-ph]

Heavy Z', W' boson production

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

$\longrightarrow$ Sequential Standard Model (SSM)
... assume same couplings as SM W, Z bosons

$\longrightarrow$ Grand Unified Theories *e.g.* E_6 *London, Rosner (1986)*

$$\mathrm{E}_6 \to \mathrm{SO}(10) \times \mathrm{U}(1)_\chi \to \mathrm{SU}(5) \times \mathrm{U}(1)_\psi \times \mathrm{U}(1)_\chi$$

$\longrightarrow$ more exotic scenarios, *e.g.*

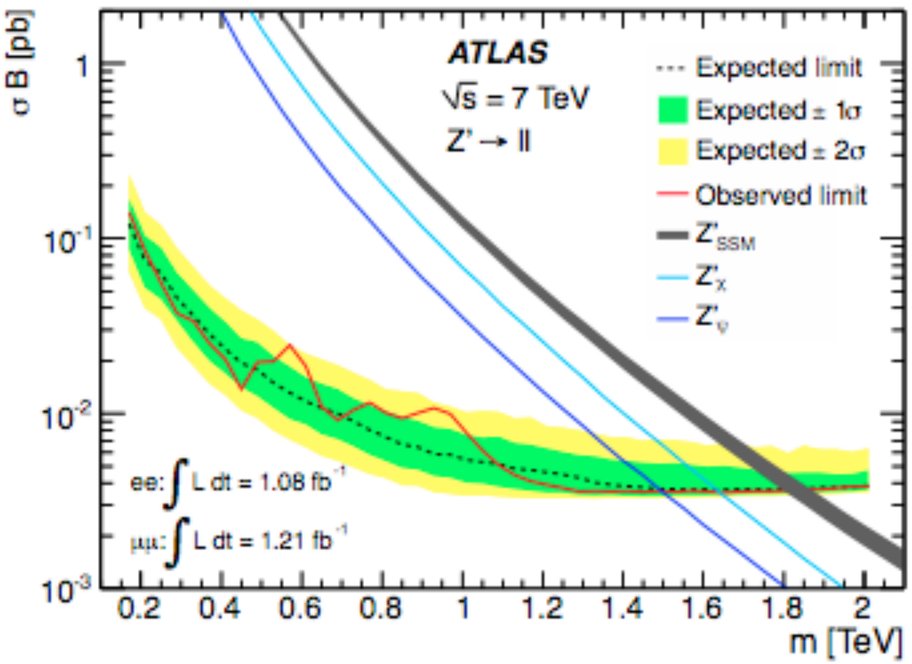
- scalar excitations in R-parity violating supersymmetric models *Hewett, Rizzo (1998)*
- spin-1 Kaluza-Klein excitations of SM bosons in presence of extra dimensions *Antoniadis (1990)*
- spin-2 excitations of the graviton *Randall, Sundrum (1999)*

Heavy Z', W' boson production

- Current limits on masses (for SSM; lower for other models)

$$\longrightarrow \quad M_{Z'} > 1.83\ \text{TeV}$$

$$M_{W'} > 2.15\ \text{TeV}$$ ATLAS @ LHC



arXiv:1108.1582 [hep-ex]

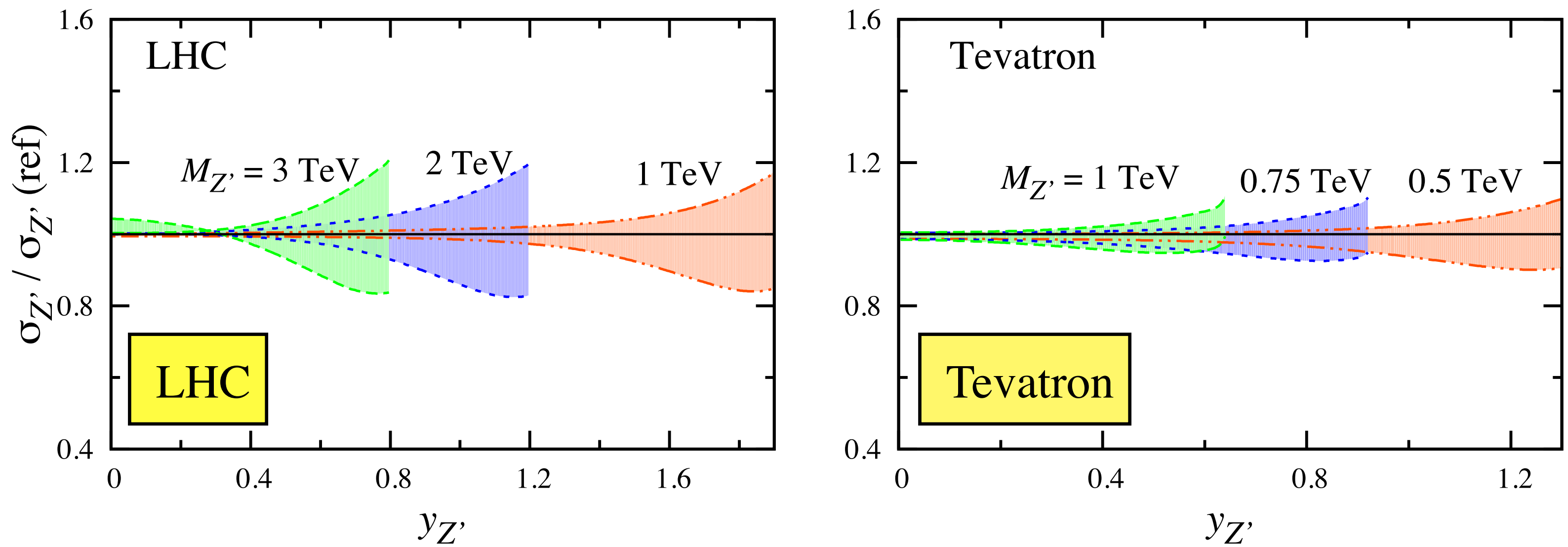
Heavy Z', W' boson production

- Observation of new physics signals requires accurate determination of QCD backgrounds — depend on PDFs!
  (since $x_{1,2} \sim M_{Z',W'}$, large-x uncertainties scale with mass)

  - for Z' production

couplings similar for u and d

$$\frac{d\sigma^{pp}}{dy} \sim \sum_q \left[(g_V^q)^2 + (g_A^q)^2 \right] \Big(q(x_1)\bar{q}(x_2) + \bar{q}(x_1)q(x_2) \Big)$$



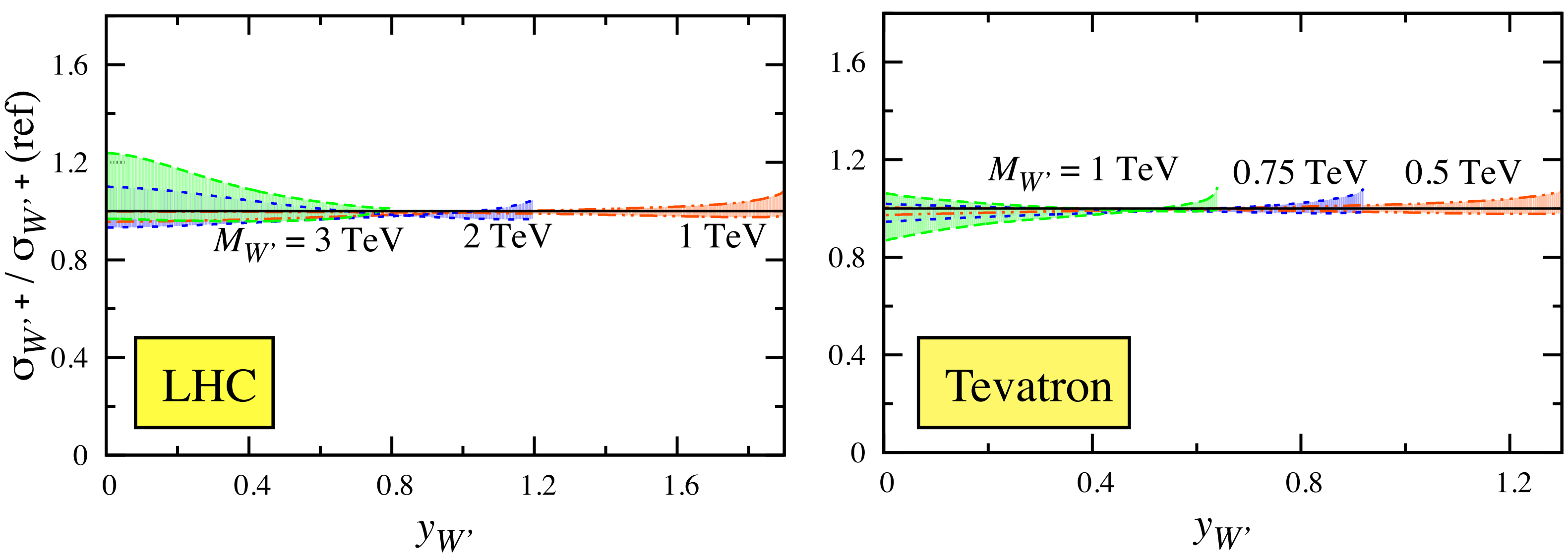
→ dominated by $u * \bar{u}$
– rel. small uncertainties

→ dominated by $u * u$
– well constrained

Heavy Z', W' boson production

- Observation of new physics signals requires accurate determination of QCD backgrounds — depend on PDFs!
  (since $x_{1,2} \sim M_{Z',W'}$, large-x uncertainties scale with mass!)

- for W'^{+} production



→ large y: dominated by $u * \bar{d}$ – well constrained

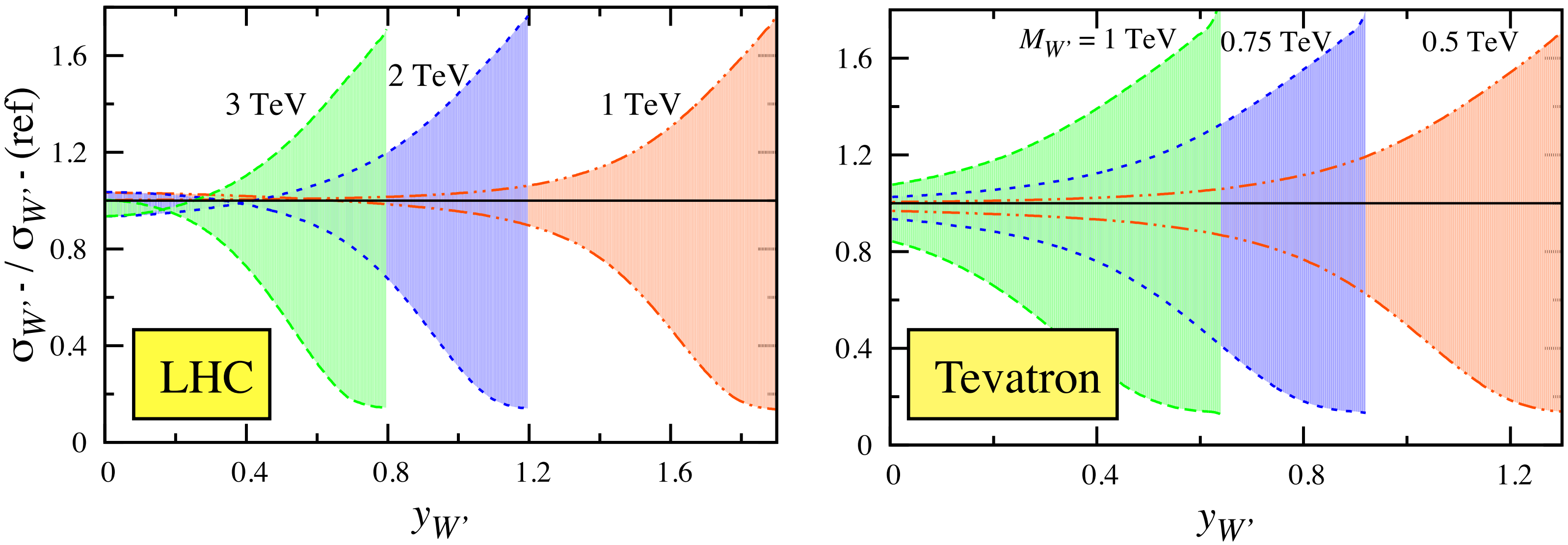
→ small y: uncertainty from $\bar{d}$ at $x \sim 0.3–0.4$

→ dominated by $u * d$ – well constrained

Heavy Z', W' boson production

- Observation of new physics signals requires accurate determination of QCD backgrounds – depend on PDFs!
  (since $x_{1,2} \sim M_{Z',W'}$, large-x uncertainties scale with mass!)

  - for W'^- production



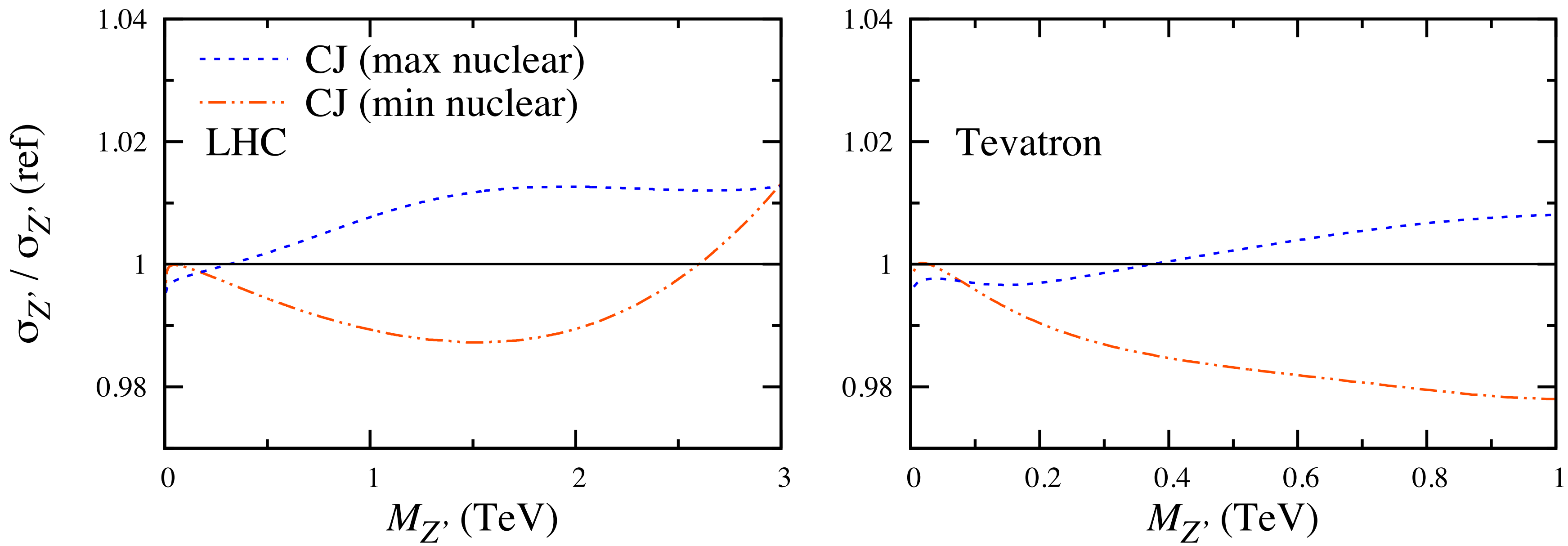
$\longrightarrow$ dominated by $d * \bar{u}$ $\longrightarrow$ dominated by $d * u + u * d$

$> 100\%$ uncertainties at large y !

Heavy Z', W' boson production

- Observation of new physics signals requires accurate determination of QCD backgrounds — depend on PDFs!
  (since $x_{1,2} \sim M_{Z',W'}$, large-x uncertainties scale with mass!)

  - for integrated Z' cross section
    → dominated by contributions from small y

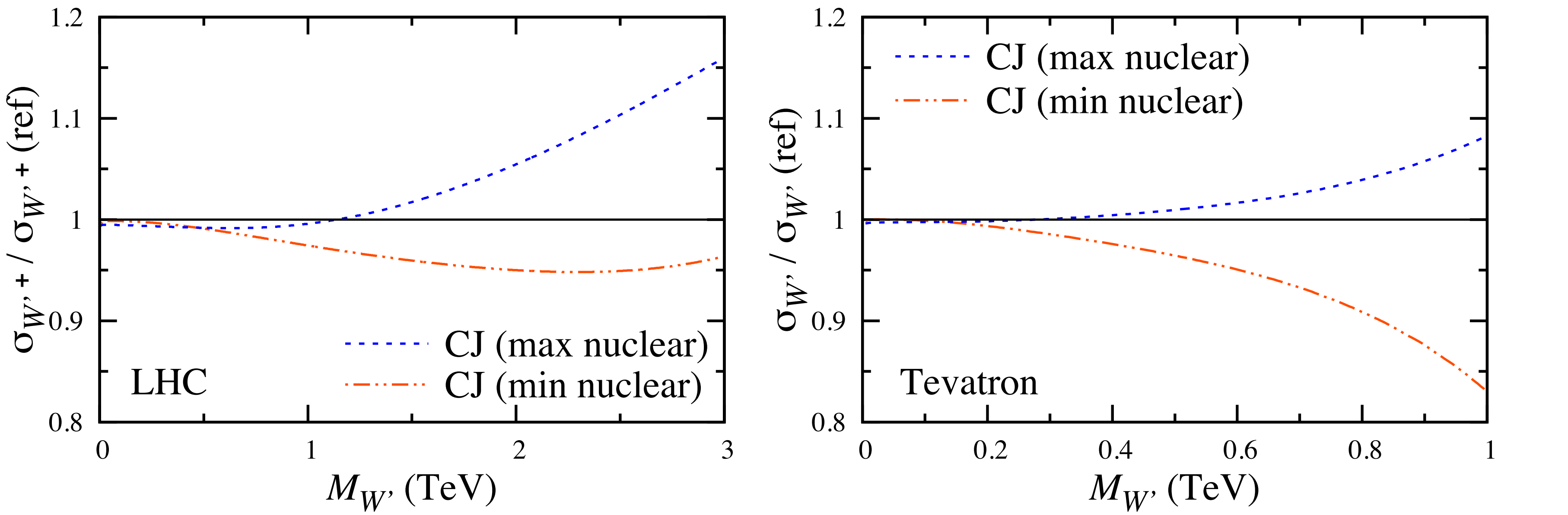


→ increasing uncertainties for large $M_{Z'}$ from antiquark PDFs at high x

Heavy Z', W' boson production

- Observation of new physics signals requires accurate determination of QCD backgrounds — depend on PDFs!
  (since $x_{1,2} \sim M_{Z',W'}$, large-x uncertainties scale with mass!)

  - for integrated W' cross section
    → dominated by contributions from small y

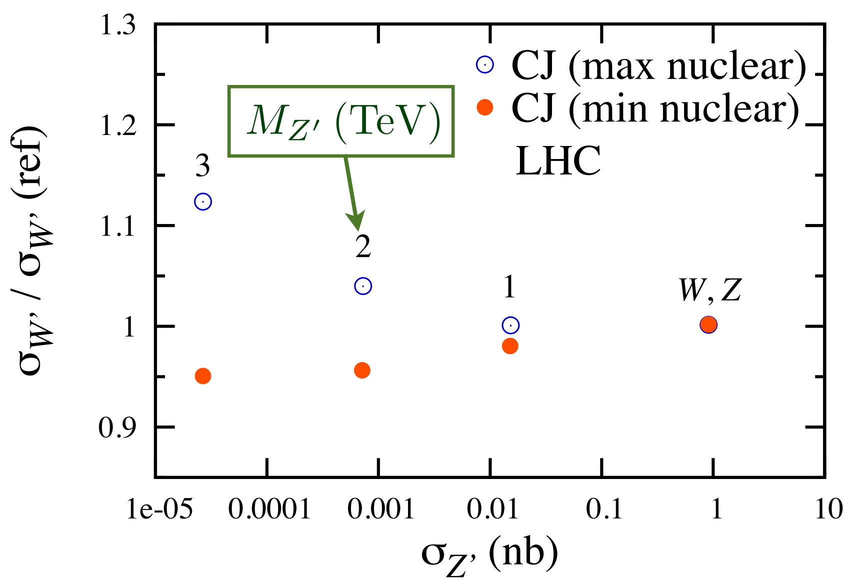


→ increasing uncertainties for large $M_{Z'}$ from antiquark PDFs at high x

Heavy Z', W' boson production

- Observation of new physics signals requires accurate determination of QCD backgrounds — depend on PDFs!
  (since $x_{1,2} \sim M_{Z',W'}$, large-x uncertainties scale with mass!)

  - for integrated Z' & W' cross sections



→ increasing sensitivity to high-x PDF uncertainties
– could affect interpretation of experimental searches

Outlook

Future plans for determining d/u

- $e\ d \to e\ p_{\rm spec}\ X^*$ — semi-inclusive DIS from d
  "BoNuS" — $\to$ tag "spectator" protons

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

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

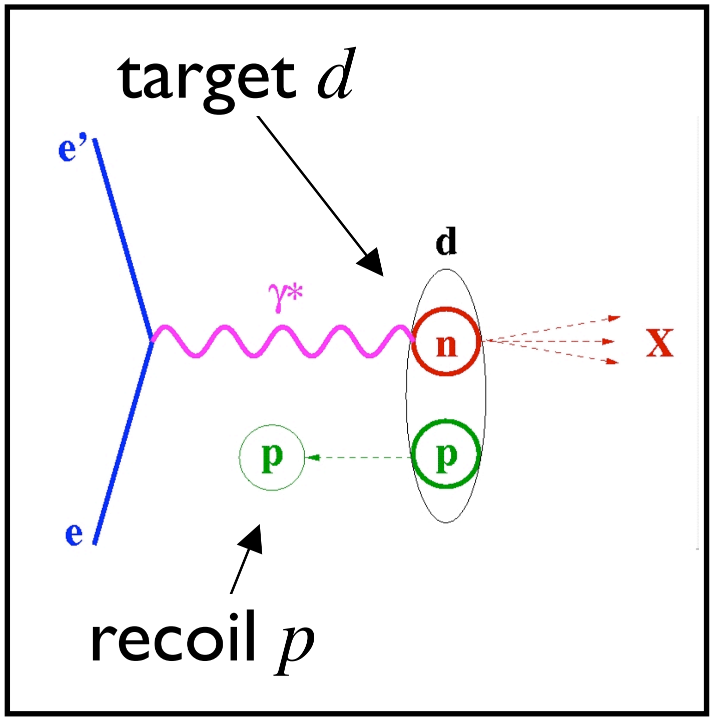
- $e^\mp\ p \to \nu(\bar\nu) X$
  $\nu(\bar\nu)\ p \to l^\mp\ X$
  $p\ p(\bar p) \to W^\pm X, Z^0\ X$
  $\vec e_L(\vec e_R)\ p \to e\ X^*$
  "PVDIS / SOLID"

  } weak current as flavor probe

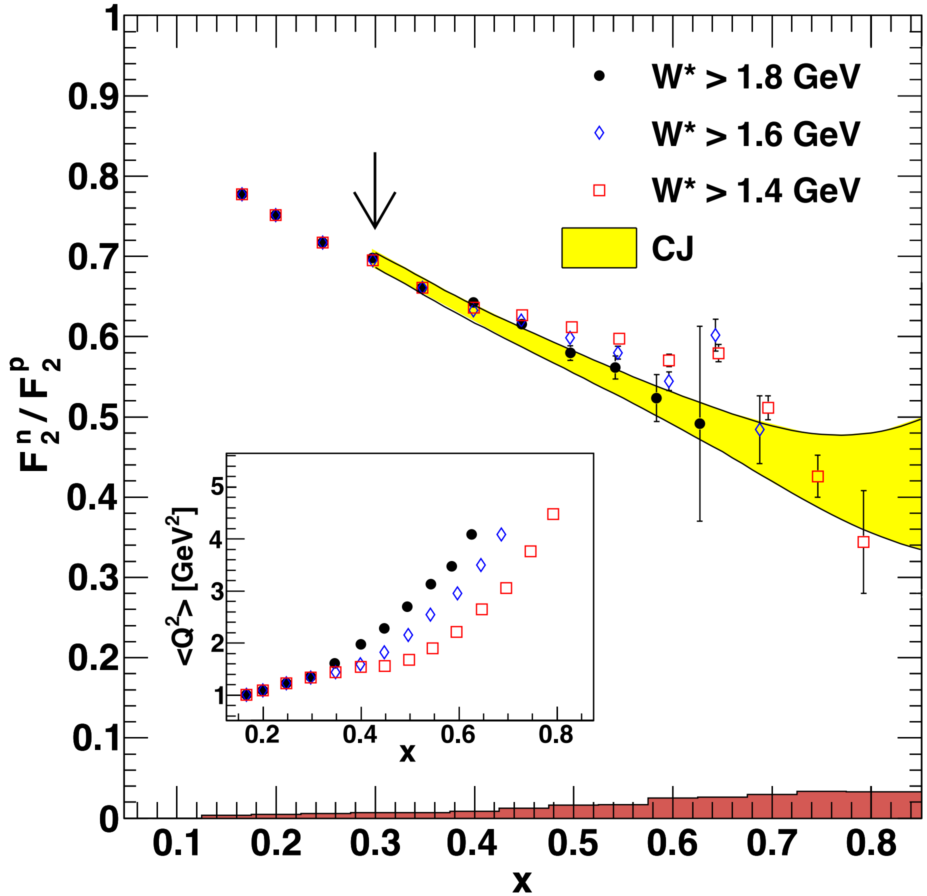
* planned for JLab at 12 GeV

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

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

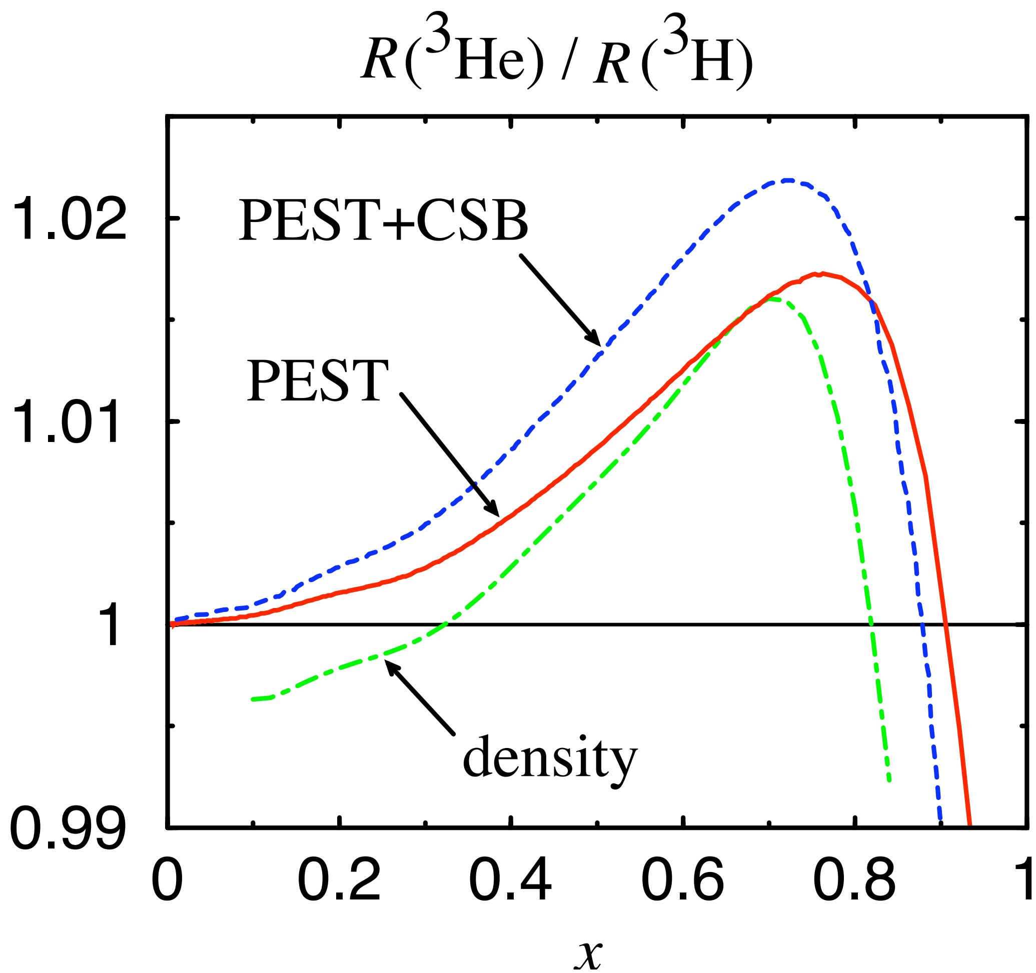
where ratio of "EMC ratios" $\mathcal{R} = \dfrac{R(^3\mathrm{He})}{R(^3\mathrm{H})}$

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

$\longrightarrow$ main theoretical input

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

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

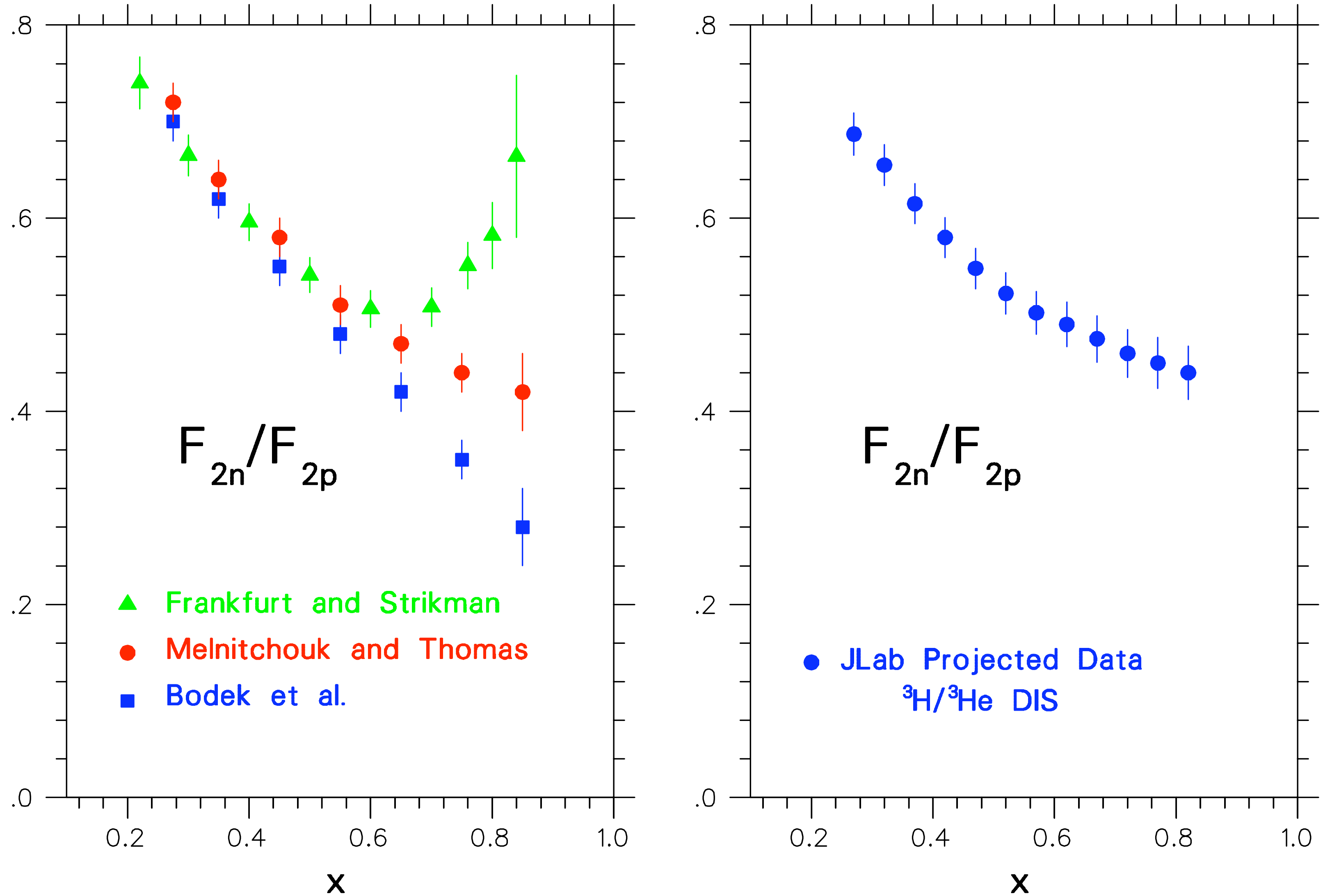


*Afnan et al., PRC **68**, 035201 (2003)*

→ nuclear effects cancel to < 1%

MARATHON: DIS from ^3He / ^3H

- Expected uncertainties of 12 GeV experiment



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

Summary

- New frontiers explored at large momentum fractions x

  → dedicated global PDF analysis by CJ collaboration

- Current large uncertainties on d quark PDF

  → impede knowledge about quark-gluon dynamics at large x

  → affect possible signals of new physics at the LHC

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

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

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

The End