CEEM, Indiana University
February 10, 2012

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

Wally Melnitchouk

Jefferson Lab

Outline

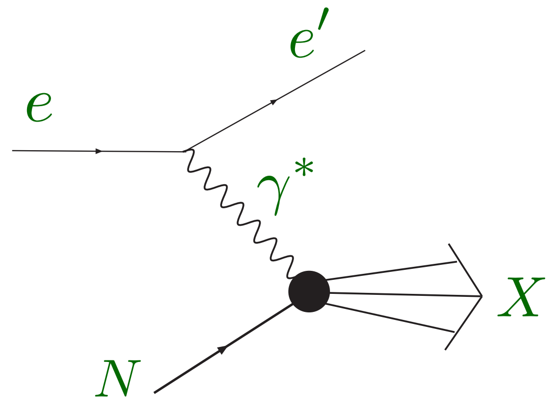
- Why are large-x quarks in the nucleon important (and problematic)?
  - ⟶ d/u PDF ratio, neutron structure & nuclear corrections

- 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 & structure functions

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



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

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

Bjorken scaling variable

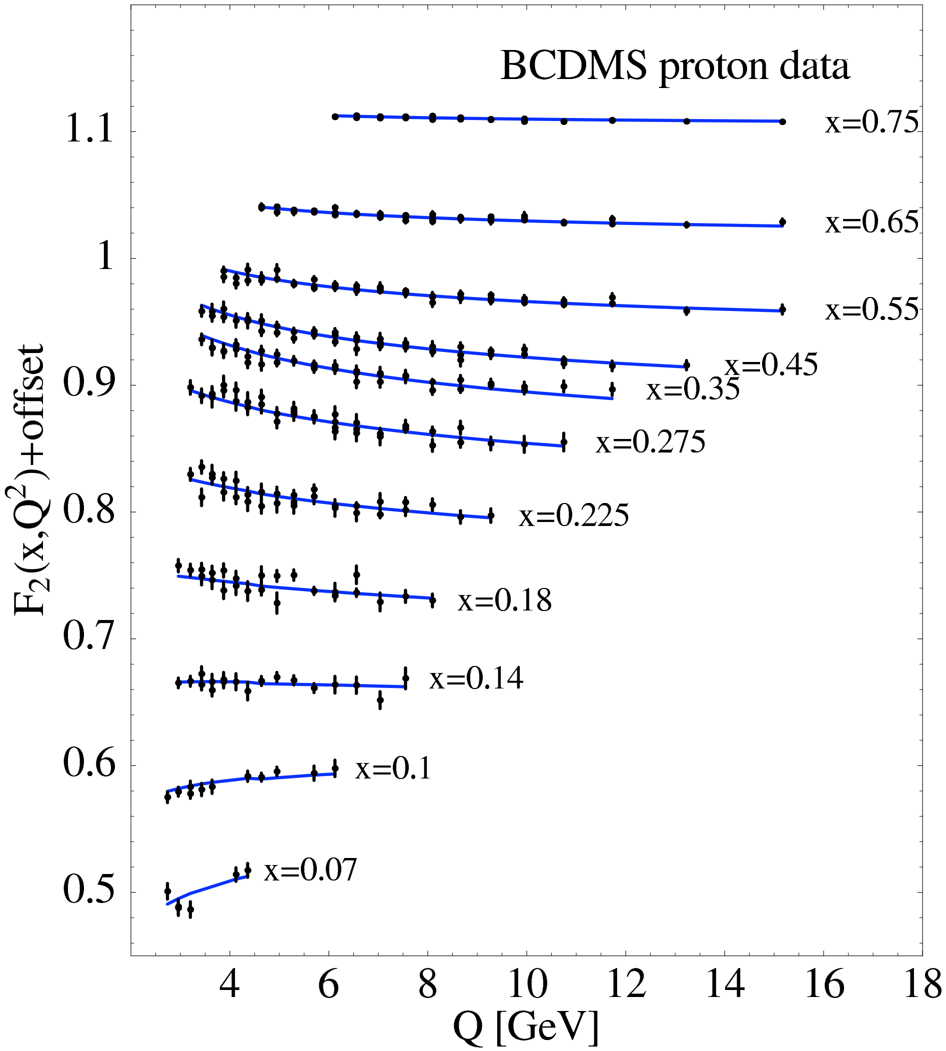
- Structure functions F_1 , F_2

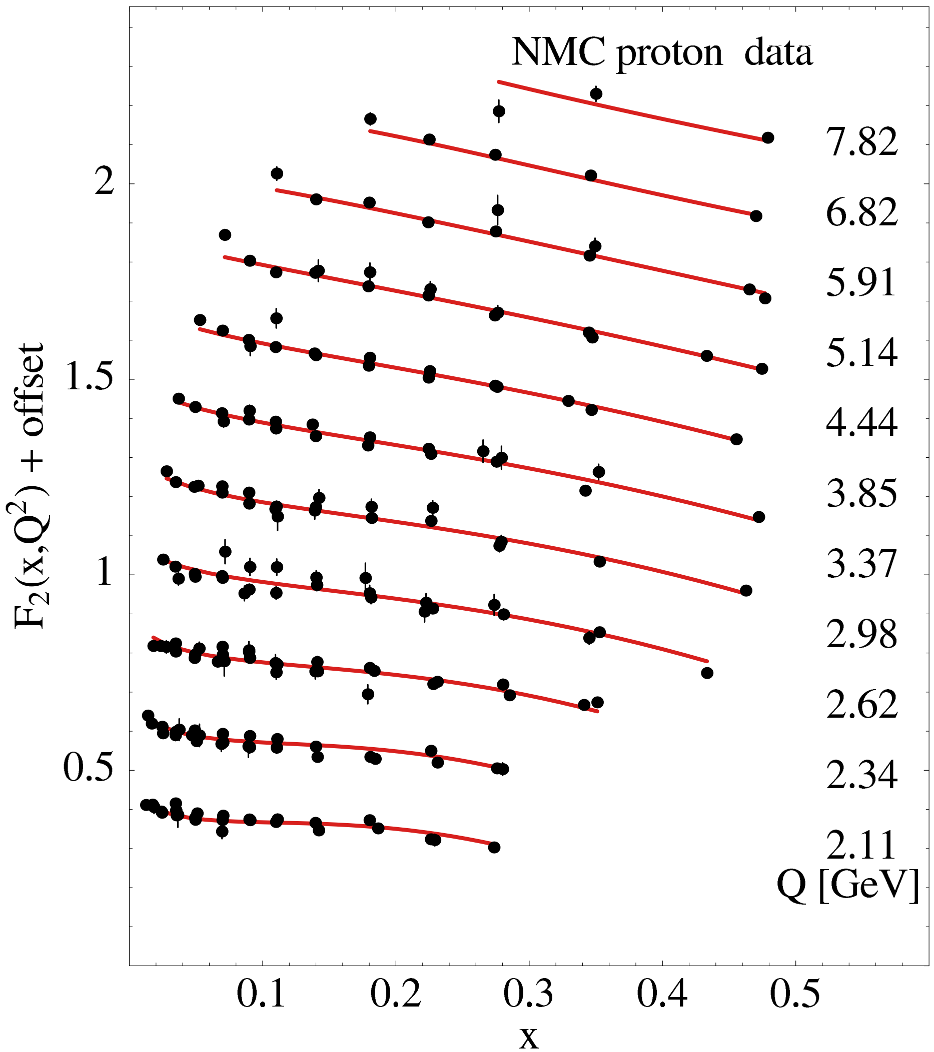
→ contain all information about structure of nucleon
$e.g.$ at leading order (parton model)

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

$q(x,Q^2) =$ probability (in infinite momentum frame & light-cone gauge) to find quark q with (light-cone) momentum fraction x

Electron scattering & structure functions





*Lai et al., EPJC **12** (2000) 375*

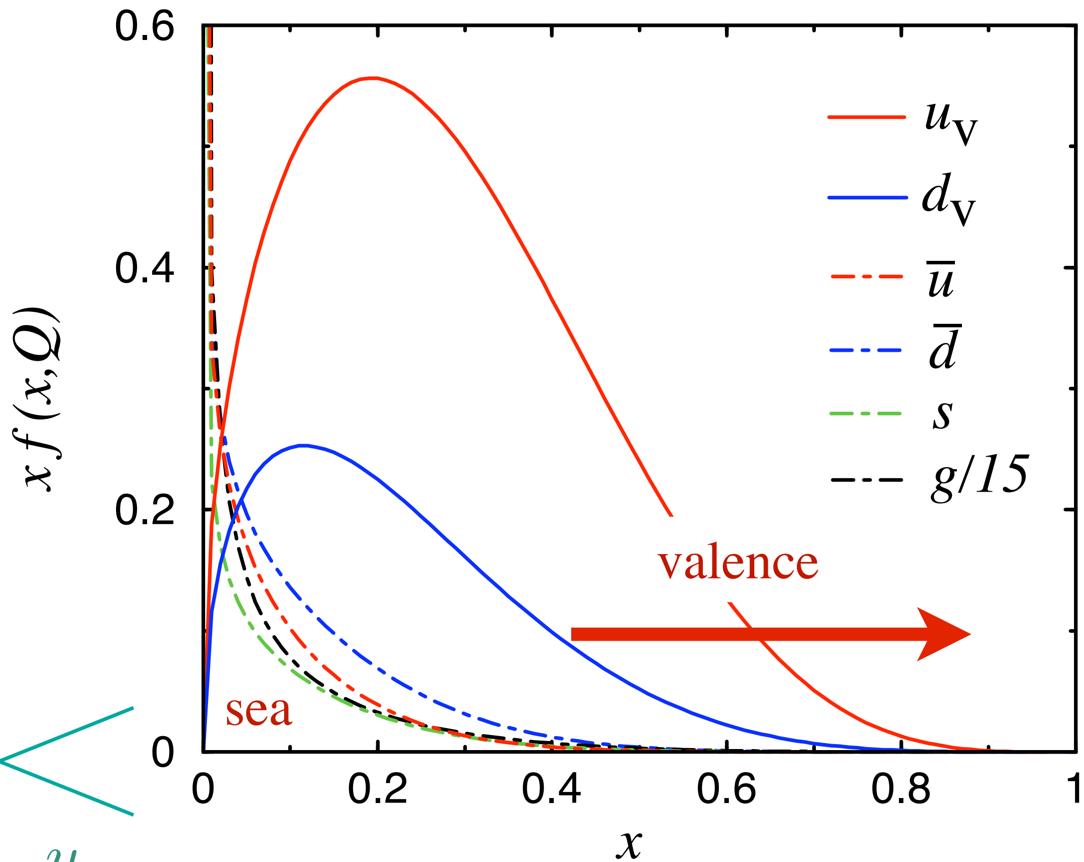
→ predicted log Q^2 scaling violations confirmed experimentally
(important early confirmation of QCD!)

Why are PDFs at *large x* important?

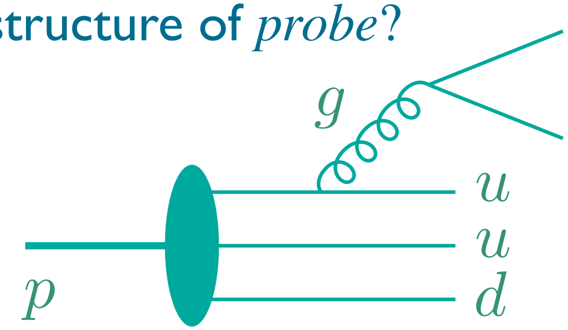
Large-x PDFs

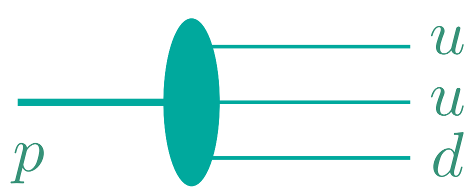
- Most direct connection between quark distributions and models of nucleon structure is via *valence* quarks

  → most cleanly revealed at $x > 0.4$



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





Large-x PDFs

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

  → most cleanly revealed at $x > 0.4$

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

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

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

  → Q^2 evolution feeds *high* x, *low* Q^2 to *low* x, *high* Q^2 where *e.g.* Higgs, SUSY most likely to produce signals

Large-x PDFs

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

- SU(6) spin-flavor symmetry

proton wave function

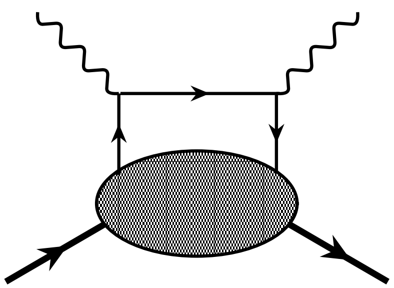
$$p^{\uparrow} = -\frac{1}{3}d^{\uparrow}(uu)_1 - \frac{\sqrt{2}}{3}d^{\downarrow}(uu)_1 + \frac{\sqrt{2}}{6}u^{\uparrow}(ud)_1 - \frac{1}{3}u^{\downarrow}(ud)_1 + \frac{1}{\sqrt{2}}u^{\uparrow}(ud)_0$$

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

interacting quark

spectator "diquark"

diquark spin



Large-x PDFs

- 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

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

Large-x PDFs

- But SU(6) symmetry is broken

e.g. scalar diquark dominance

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

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

since only u quarks couple to *scalar* diquarks

→ $\dfrac{d}{u} \to 0$

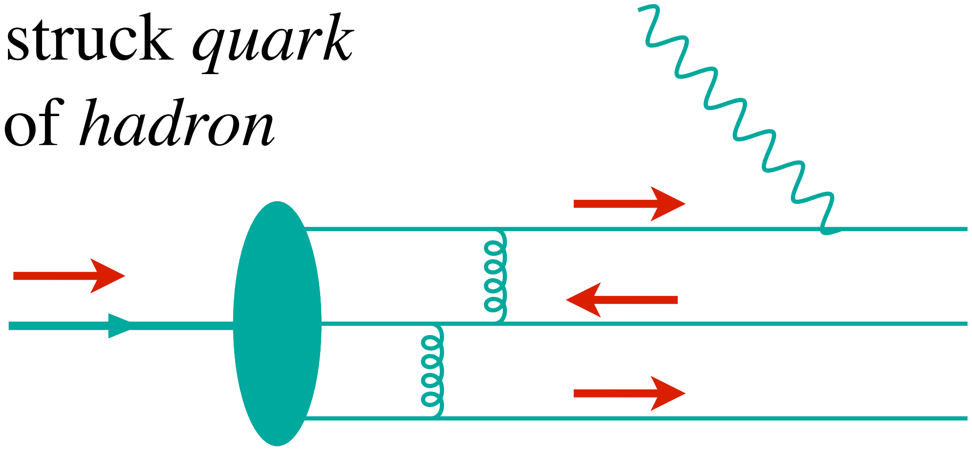
→ $\dfrac{F_2^n}{F_2^p} \to \dfrac{1}{4}$

Feynman (1972), Close (1973), Close/Thomas (1988)

Large-x PDFs

- 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)

Large-x PDFs

- Nonperturbative & perturbative QCD predictions for d/u ratio in $x \to 1$ limit:

  - $d/u \to 1/2$ SU(6) symmetry
  - $d/u \to 0$ $S = 0$ qq dominance
  - $d/u \to 1/5$ $S_z = 0$ qq dominance
  - $d/u \to \dfrac{4\,\mu_n^2/\mu_p^2 - 1}{4 - \mu_n^2/\mu_p^2}$ local quark-hadron duality* ($\mu_{p,n}$ magnetic moments)

*see e.g. WM, Ent, Keppel Phys. Rep. **406**, 127 (2005)*

*structure function at $x \to 1$ given by elastic form factor at $Q^2 \to \infty$

Large-x PDFs

- Nonperturbative & perturbative QCD predictions for $\Delta q/q$ ratio in $x \to 1$ limit:

  - $\Delta u/u \to 2/3$
 $\Delta d/d \to -1/3$ — SU(6) symmetry
  - $\Delta u/u \to 1$
 $\Delta d/d \to -1/3$ — $S = 0$ qq dominance
  - $\Delta u/u \to 1$
 $\Delta d/d \to 1$ — $S_z = 0$ qq dominance <u>*or*</u> local duality

$\longrightarrow$ sign of d quark polarization is uncertain!

Deuteron corrections

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

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

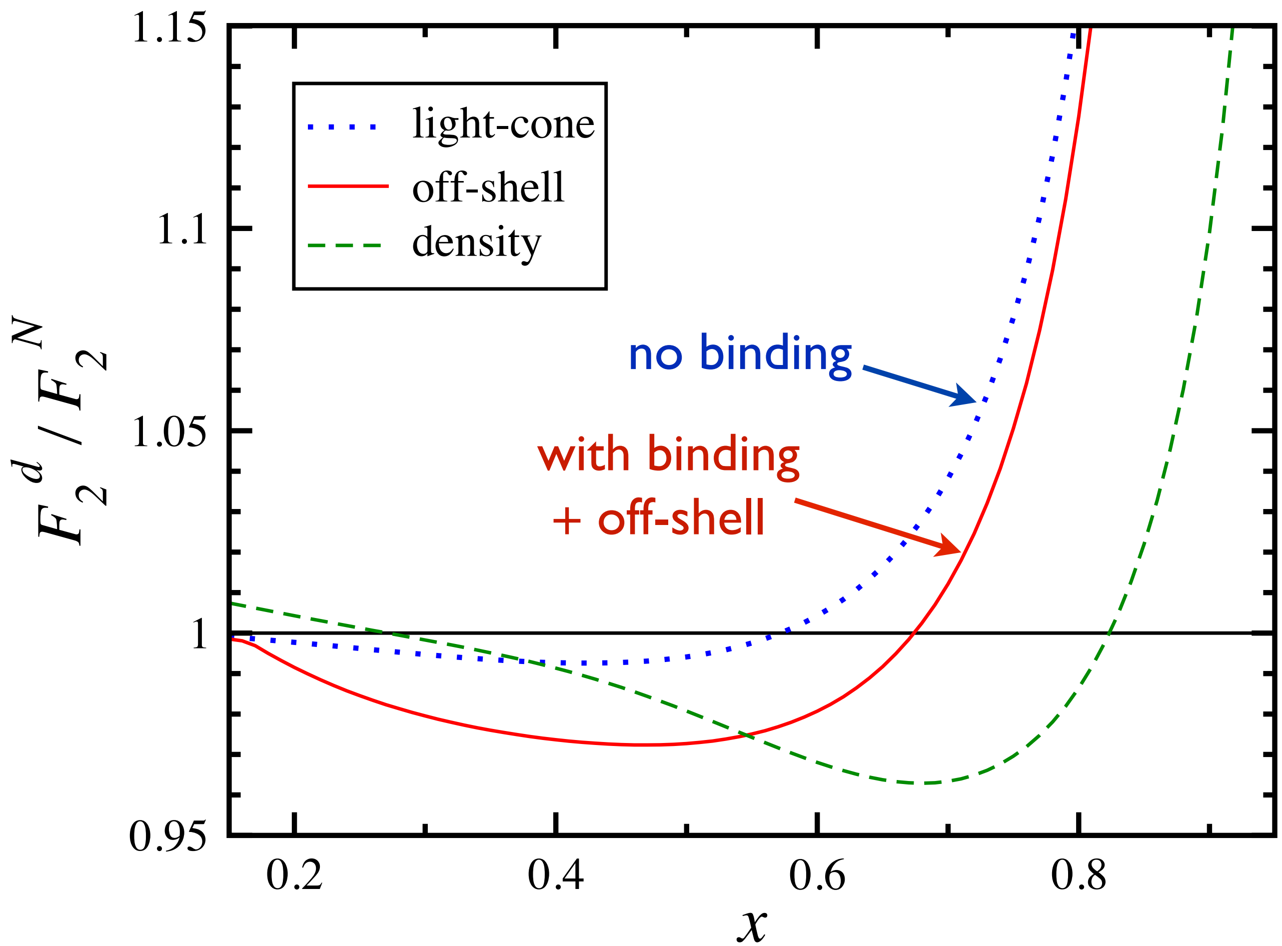
- Absence of free neutron targets

$\longrightarrow$ use *deuterons* (weakly bound state of p and n)

$\longrightarrow$ must account for nuclear effects in deuteron

$$F_2^d \neq F_2^p + F_2^n$$

Deuteron corrections

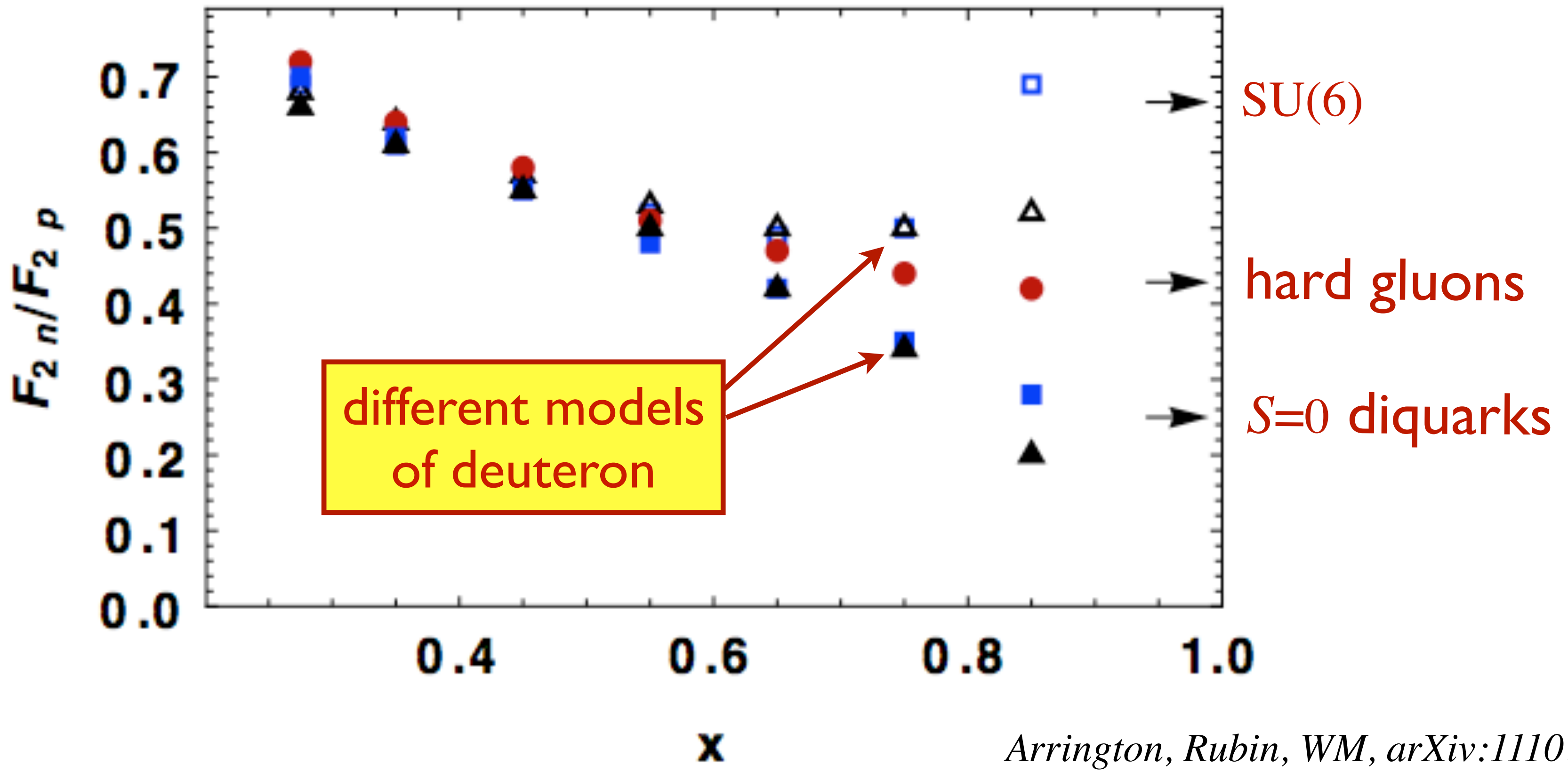


WM, Thomas
PLB ***377****, 11 (1996)*

→ $\sim 2\text{–}3\%$ 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

Deuteron corrections



Arrington, Rubin, WM, arXiv:1110.3362

→ significant deuteron model uncertainty at large x (short-range NN interaction)

→ obscures free neutron structure information

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

A. Accardi, J. Owens, WM (theory)
E. Christy, C. Keppel, P. Monaghan, L. Zhu (expt.)

- Next-to-leading order (NLO) analysis of expanded set of *proton* and *deuterium* data, including large-x, low-Q^2 region
  - $\longrightarrow$ also include new CDF & D0 W-asymmetry, and E866 DY data
- Systematically study effects of Q^2 & W *cuts*
  - $\longrightarrow$ as low as $Q \sim m_c$ and $W \sim 1.7$ GeV
- Correct for *nuclear* effects in the deuteron (binding + off-shell)
  - $\longrightarrow$ most global analyses assume *free* nucleons; some use density model, a few assume Fermi motion only
- Include subleading $1/Q^2$ corrections
  - $\longrightarrow$ target mass corrections & dynamical higher twists
- Dependence on choice of PDF parametrization

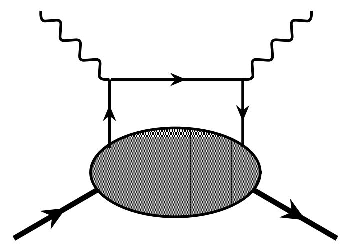
Higher twists

- $1/Q^2$ 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. $\bar{\psi}\,\gamma_\mu\,\psi$

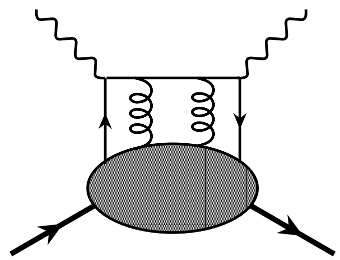
Higher twists

- $1/Q^2$ 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!

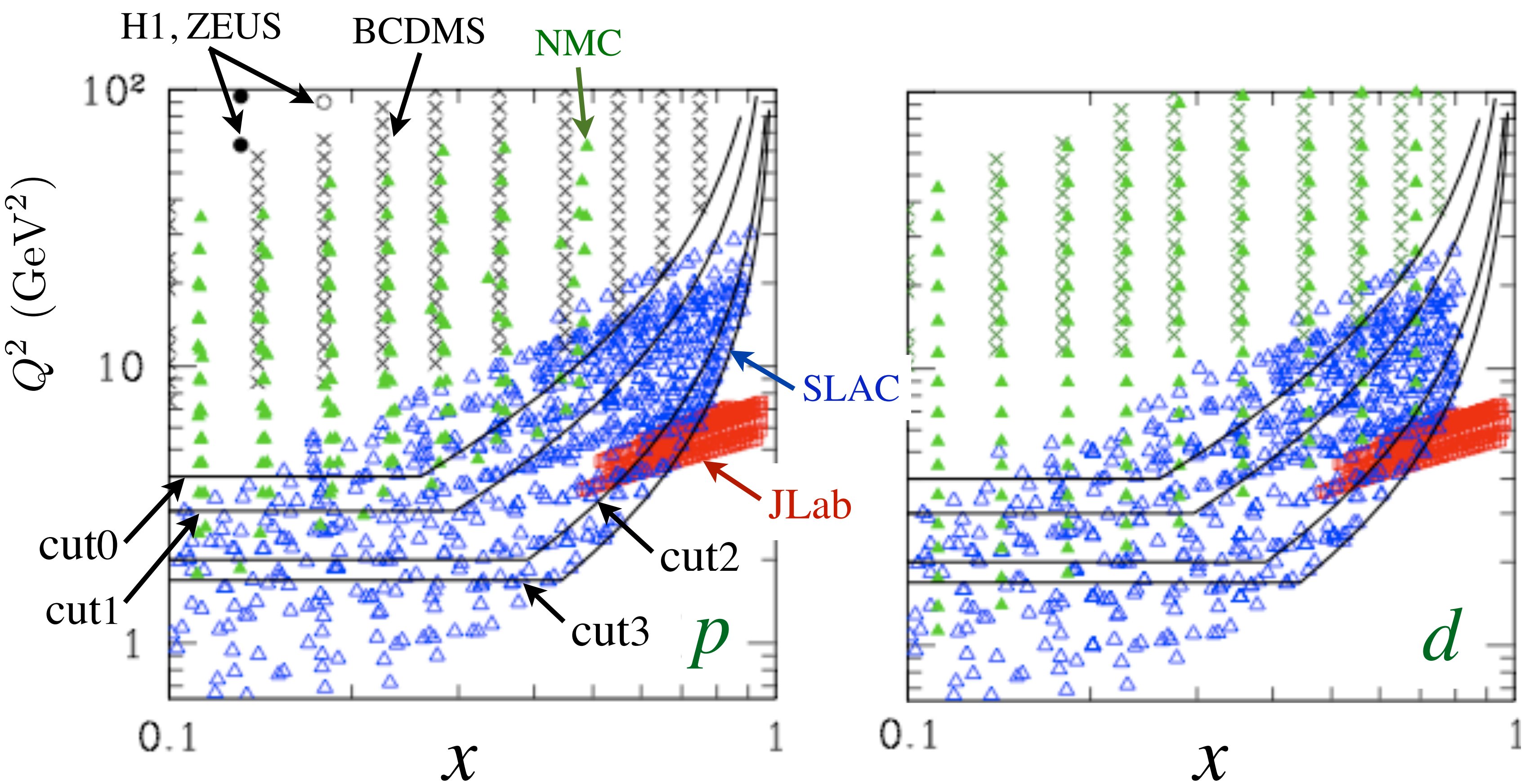
→ give rise to corrections $\sim\ Q^2/\nu^2 = 4M^2x^2/Q^2$
(hence "target mass")

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

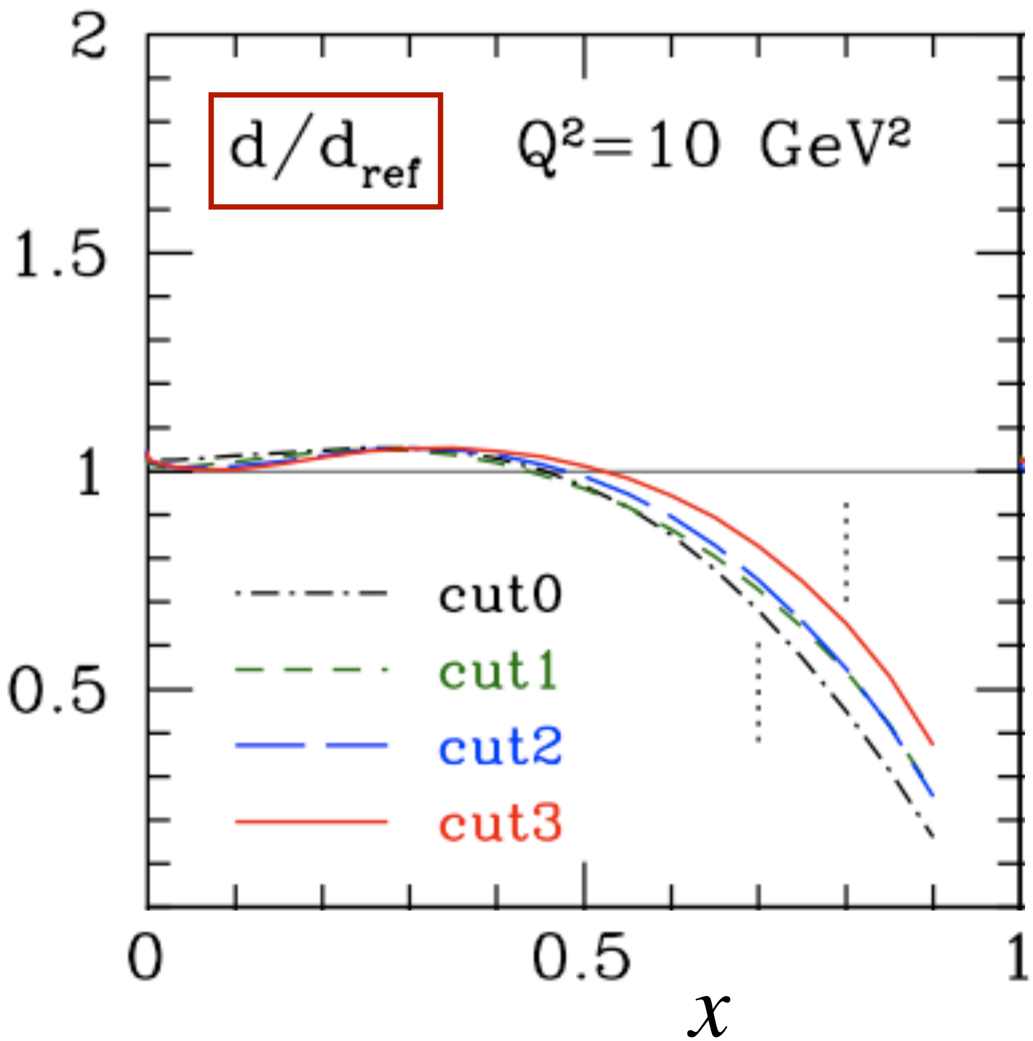
cut2: $Q^2 > 2\ \mathrm{GeV}^2, \quad W^2 > 4\ \mathrm{GeV}^2$

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 & W cuts
- Fit includes TMCs, HT term, nuclear corrections

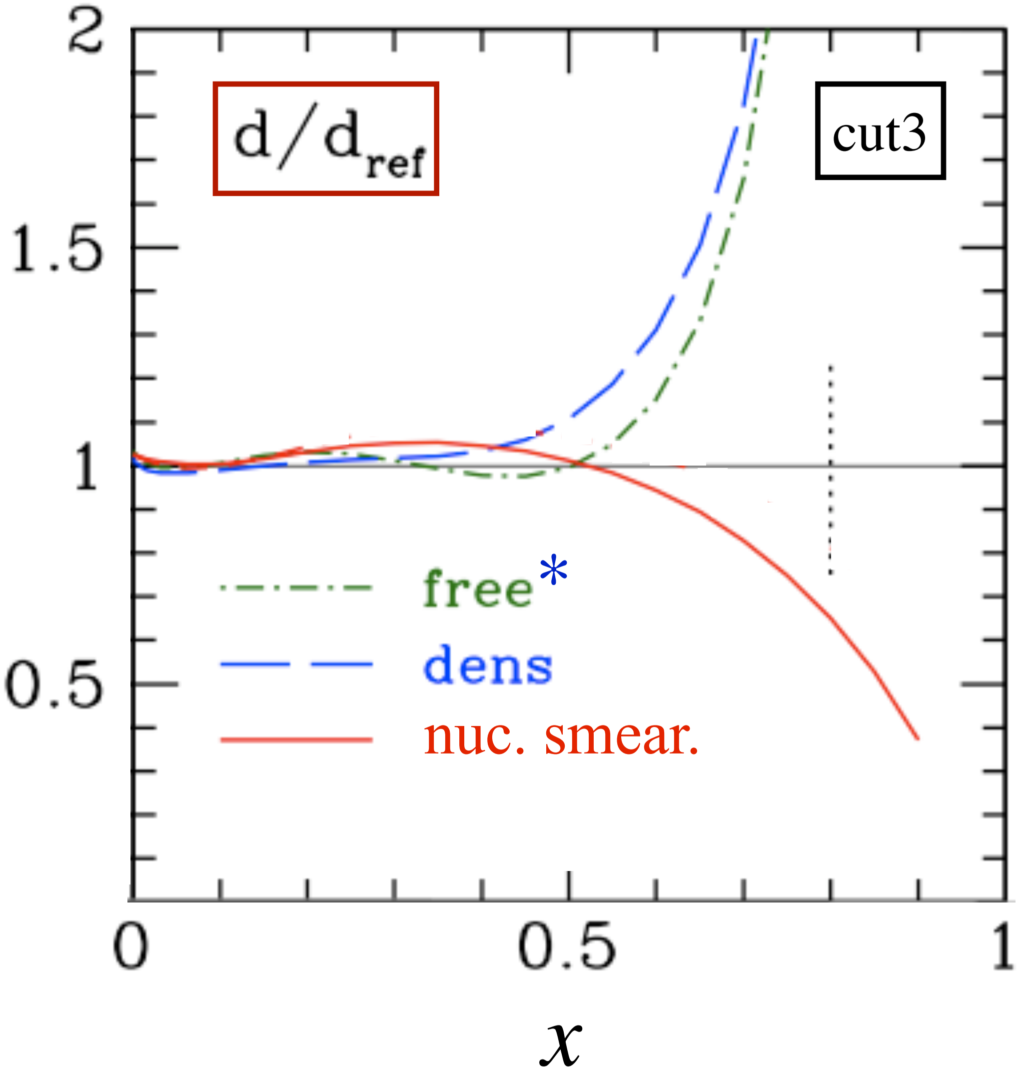


→ *stable* with respect to cut reduction

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

*Accardi et al., PRD **81**, 034016 (2010)*

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

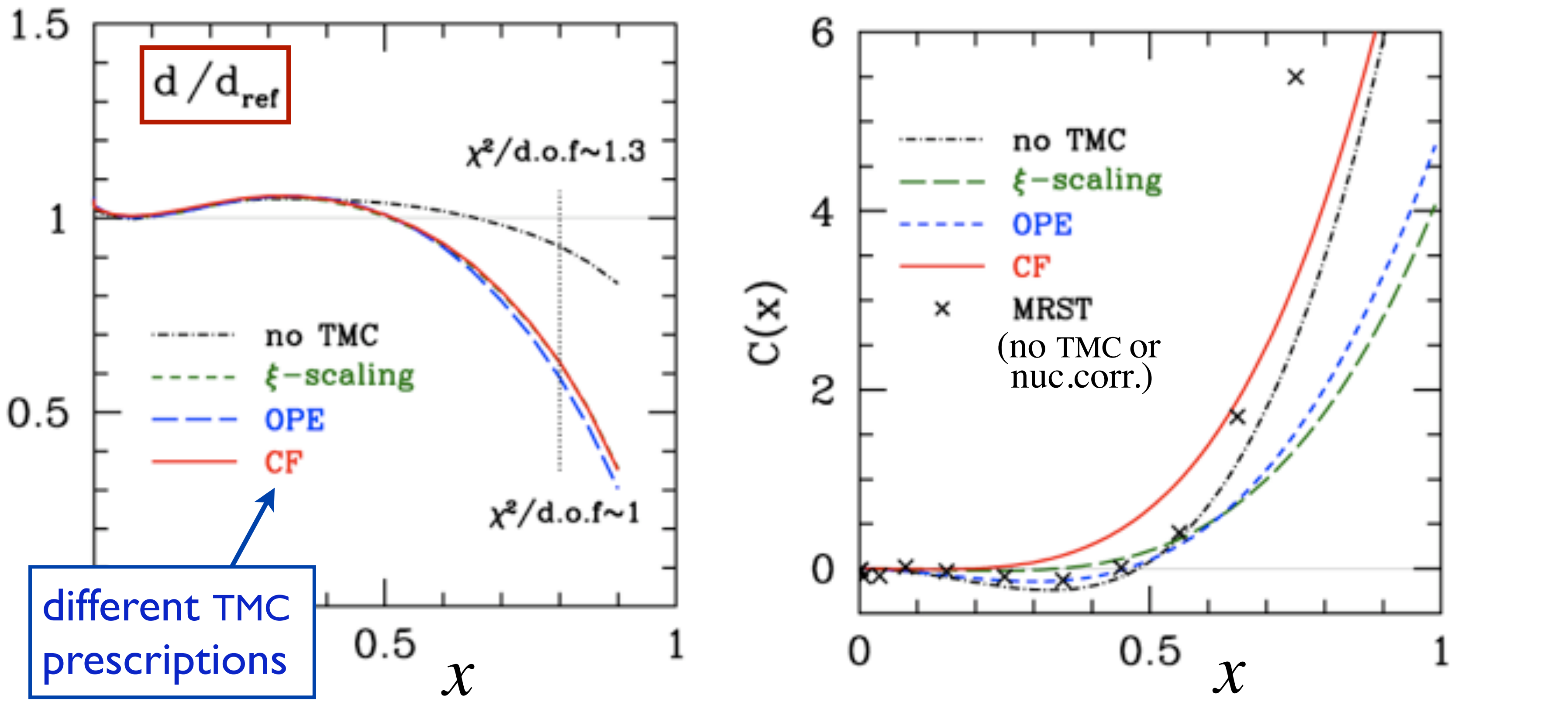
↓

$F_2^d / F_2^N > 1$ for $x \sim 0.6\text{–}0.8$ 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

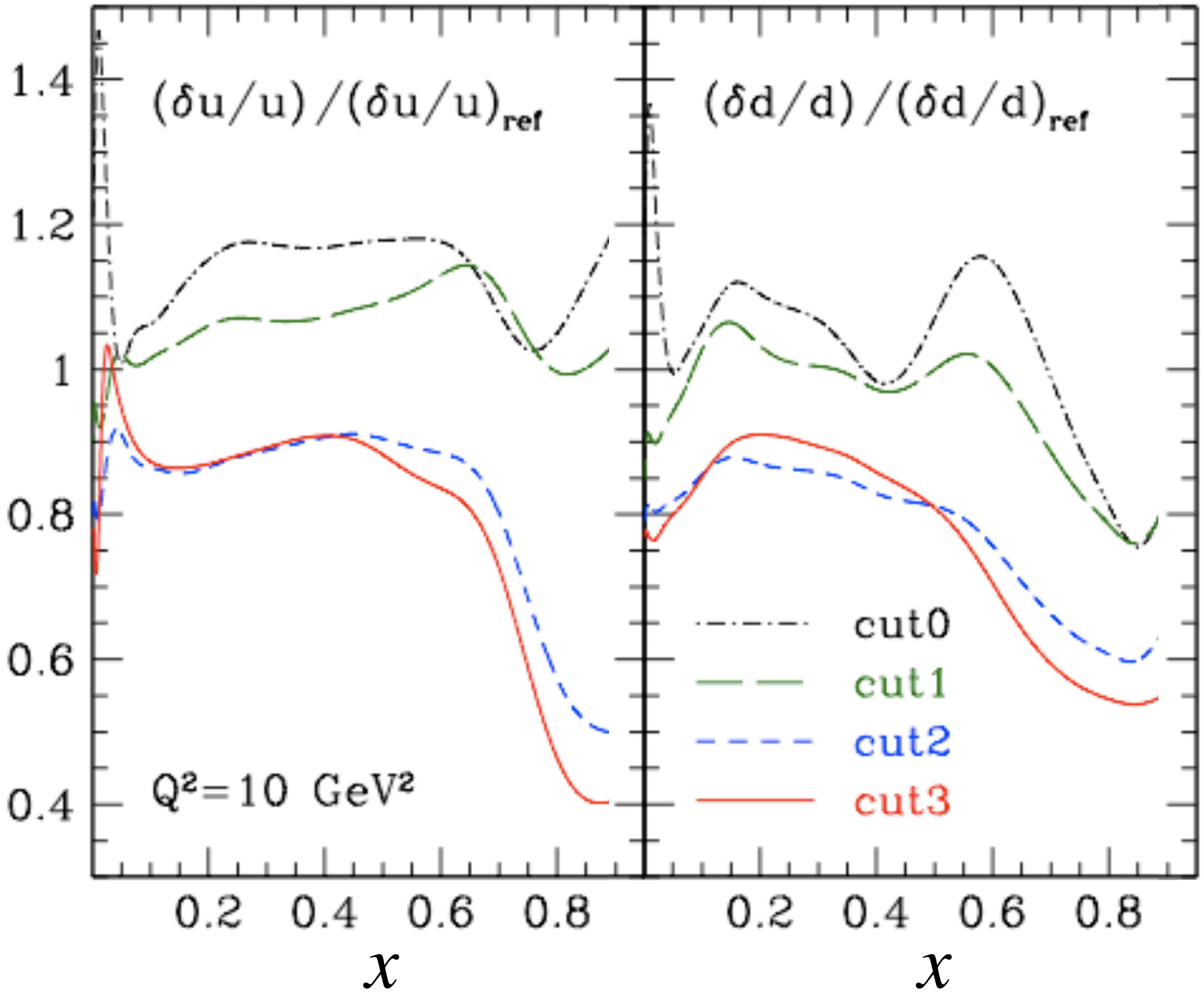


→ $1/Q^2$ correction $F_2 = F_2^{\rm LT}\left(1 + \frac{C(x)}{Q^2}\right), \quad C(x) = c_1 x^{c_2}(1 + c_3 x)$

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

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

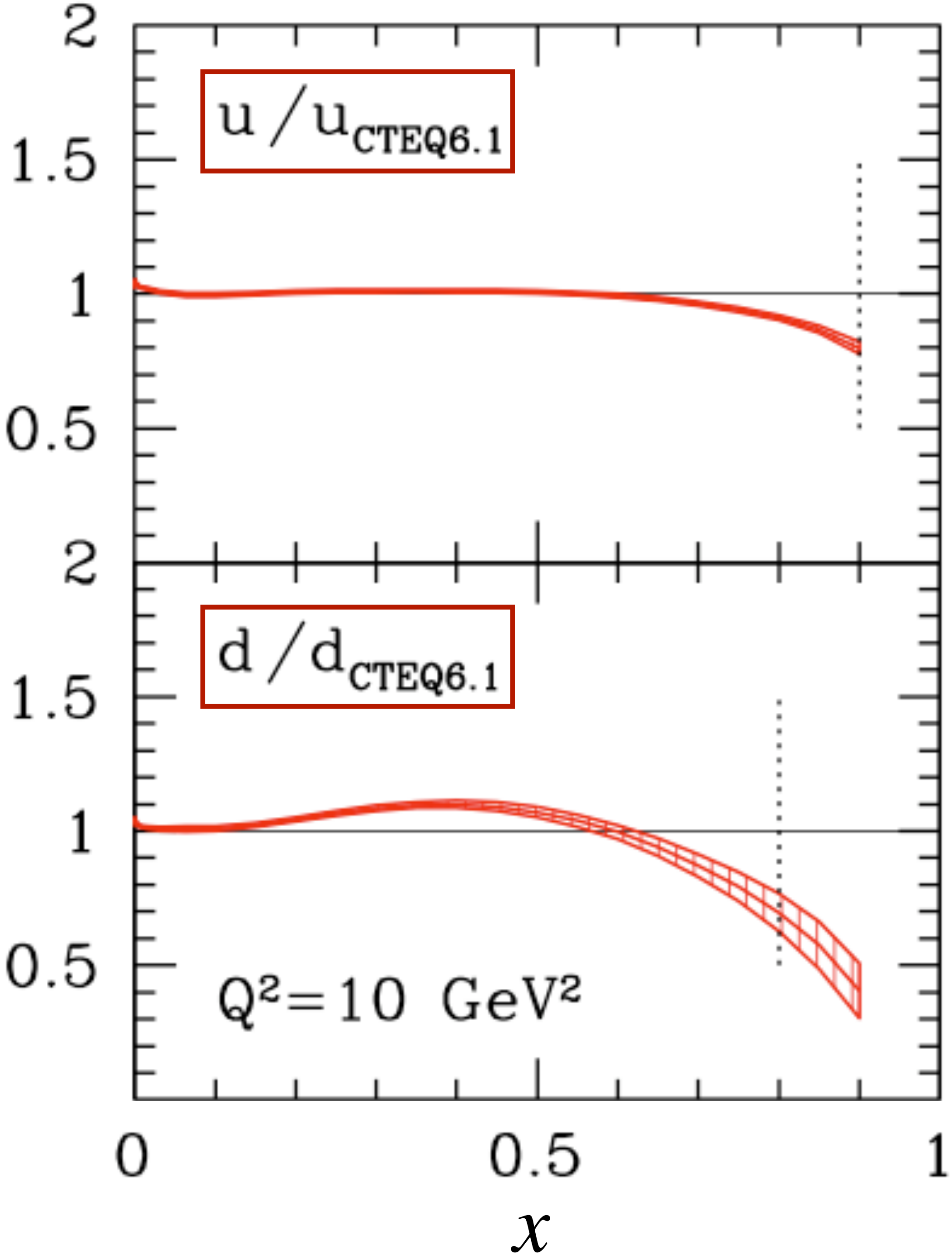
CJ10 PDF results



Accardi et al.
PRD ***81****, 034016 (2010)*

→ larger database with weaker cuts leads to significantly *reduced errors*, esp. at large x

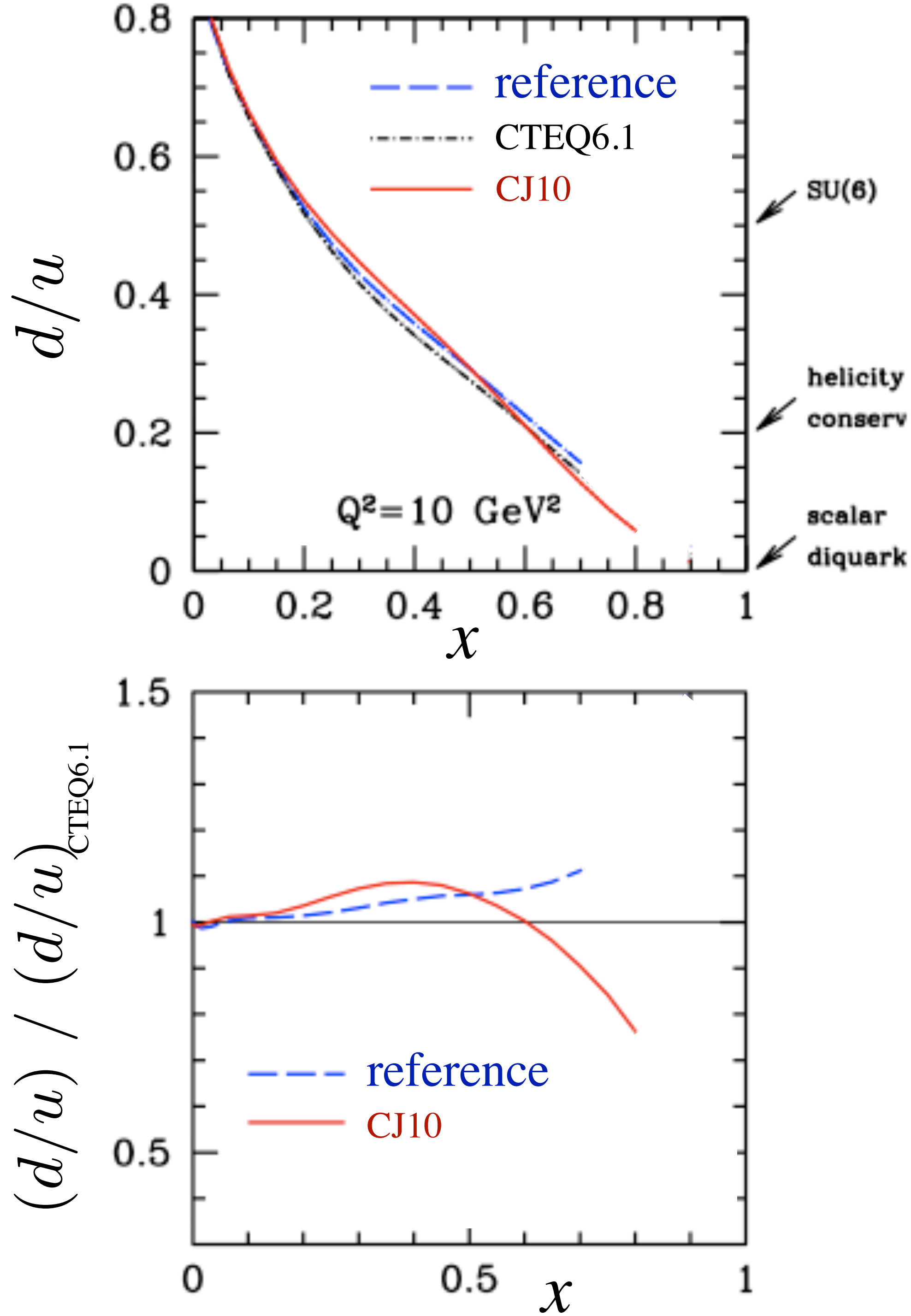
CJ10 PDF results



→ full fit appears to favor smaller d/u ratio

Accardi et al., PRD ***81****, 034016 (2010)*

CJ10 PDF results



→ full fit appears to favor smaller d/u ratio

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

→ how robust is this result?

Accardi et al., PRD ***81****, 034016 (2010)*

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)

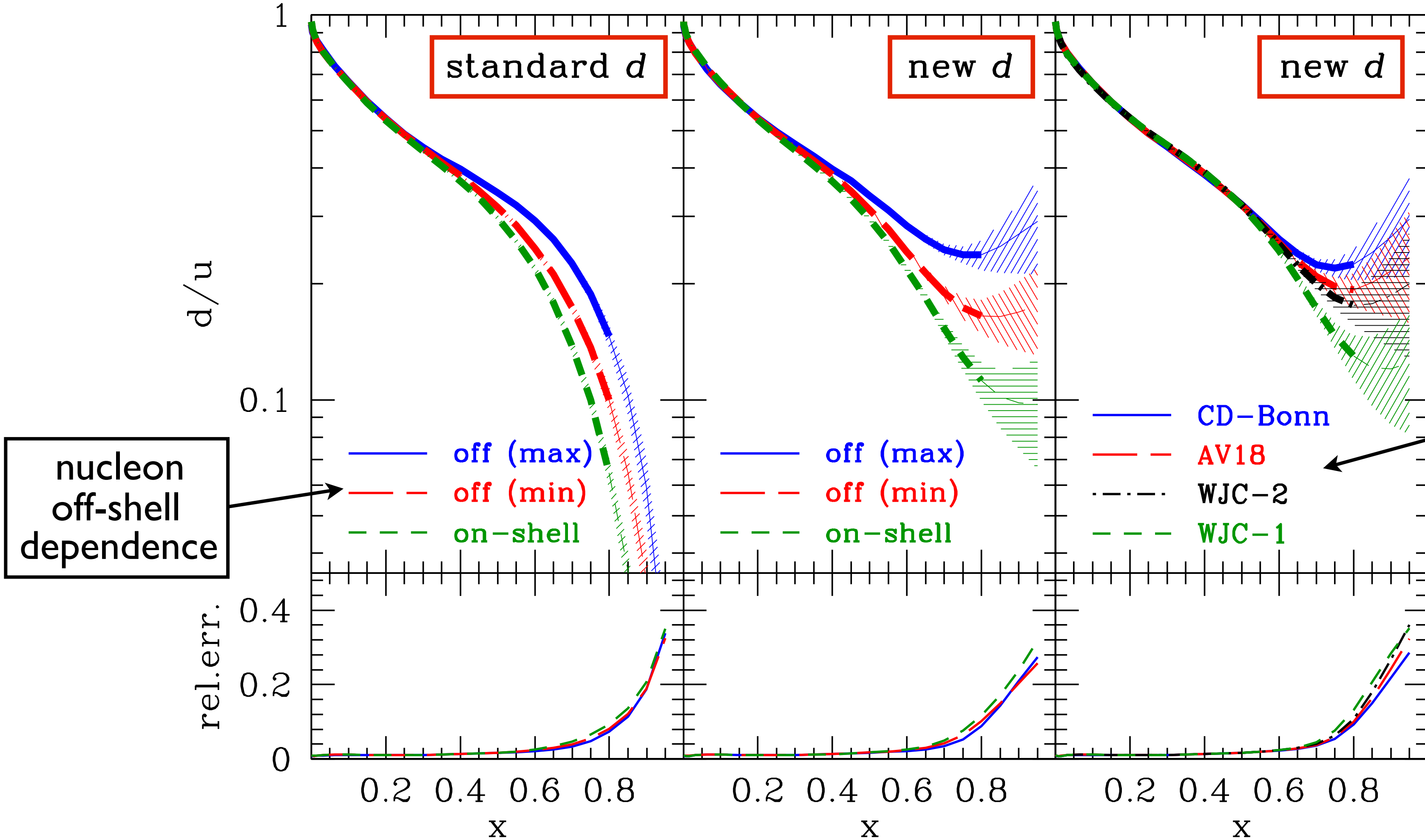
  → model nucleon off-shell correction with reasonable range of parameters

- Dependence of d/u ratio on choice of parametrization

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

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

CJ global analysis

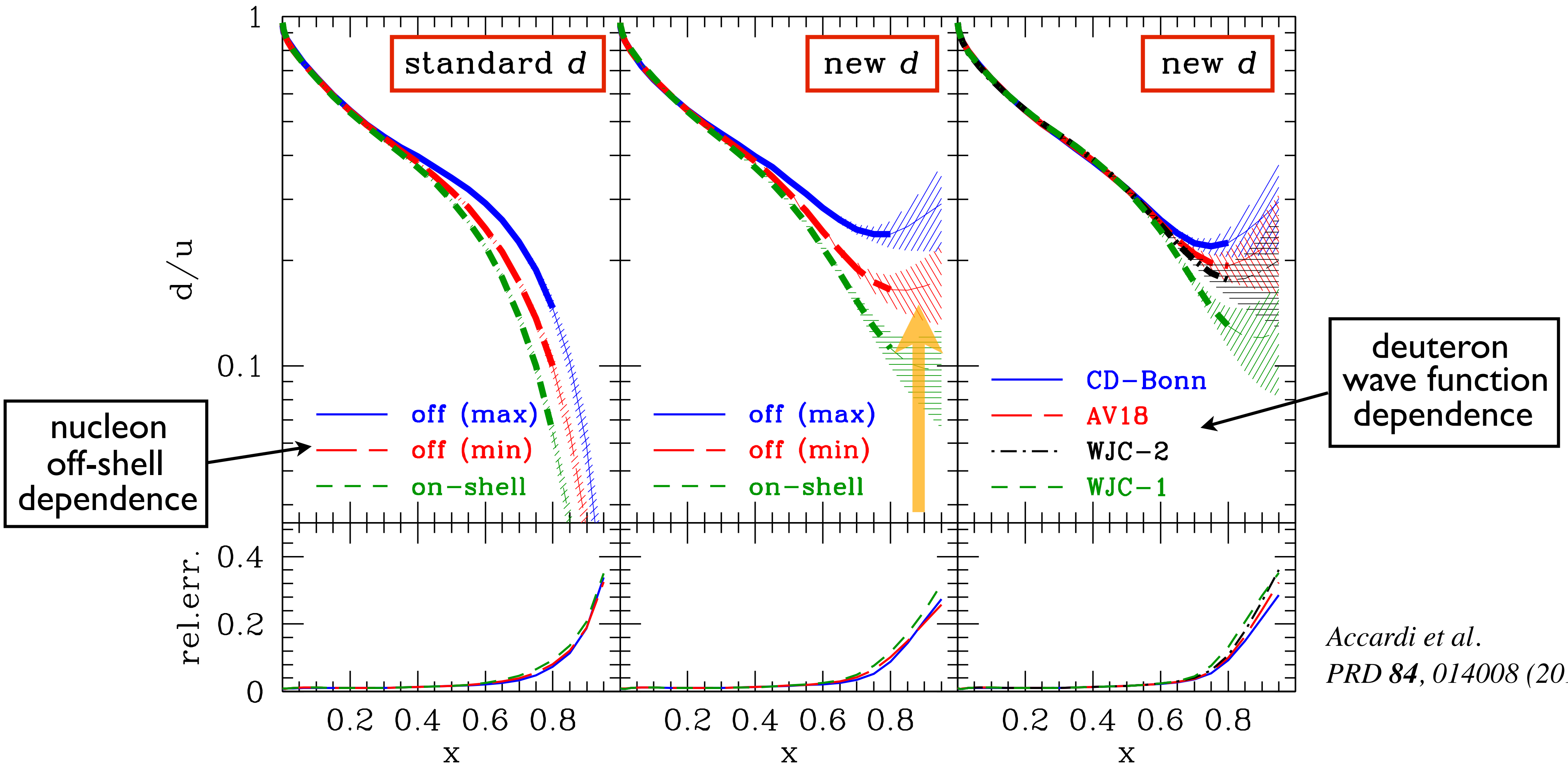


Accardi et al.
*PRD **84**, 014008 (2011)*

→ large nuclear correction uncertainties at $x > 0.5$

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

CJ global analysis

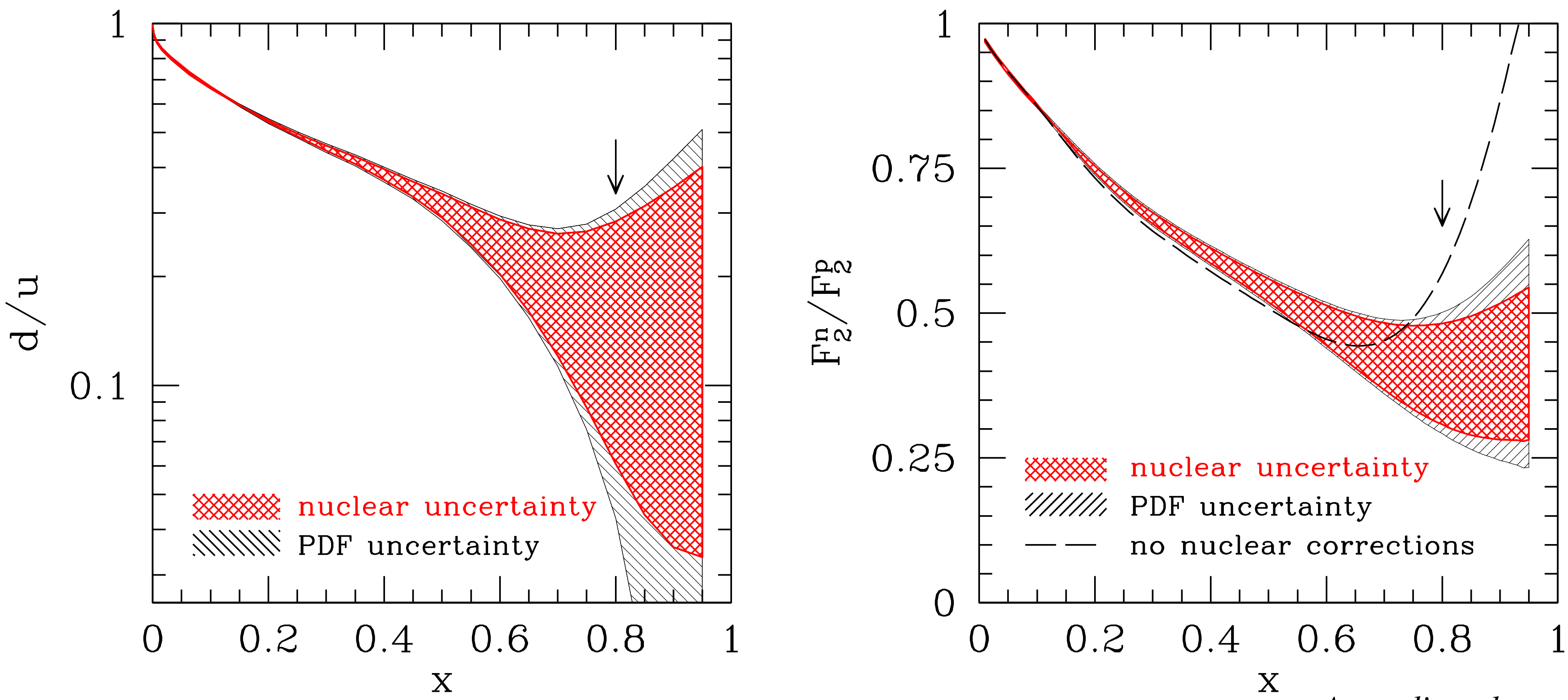


Accardi et al.
PRD ***84****, 014008 (2011)*

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

(range ~ 0 – 0.4)

New CJ11 PDF analysis



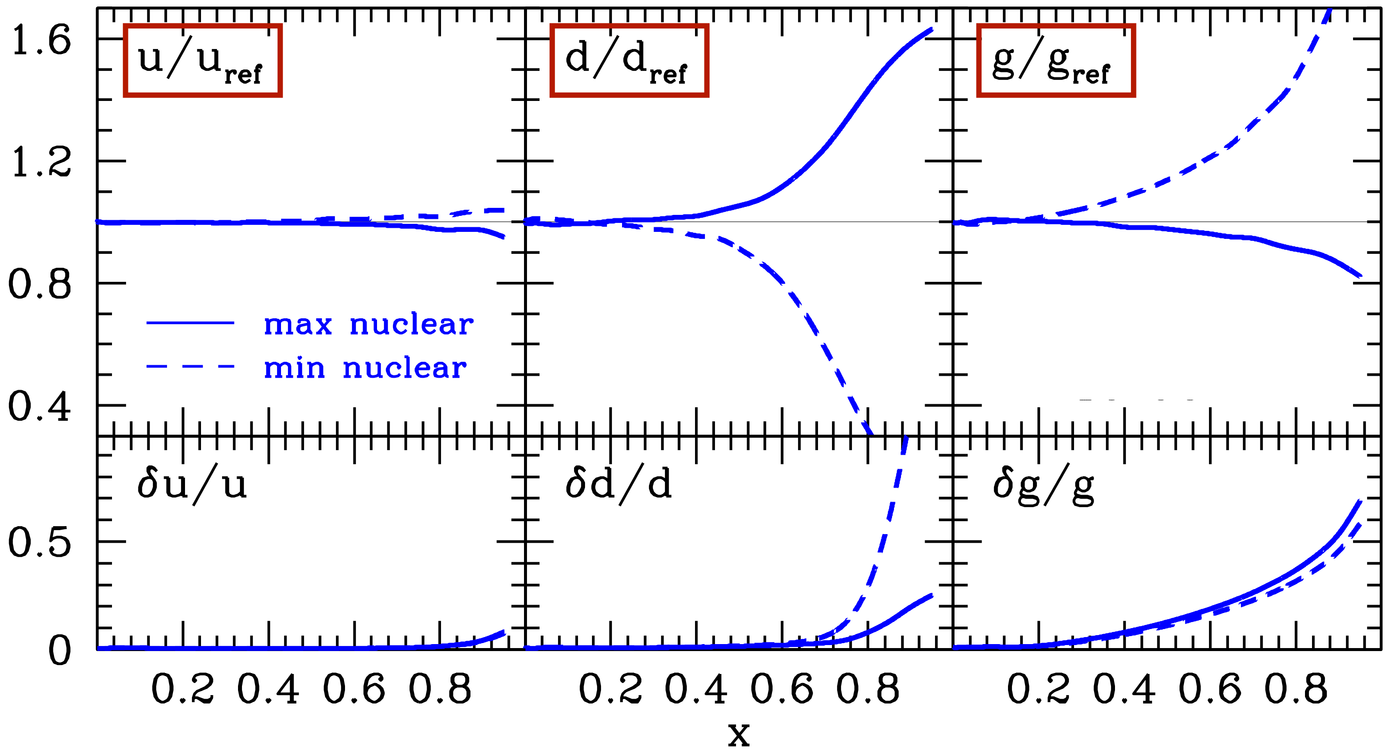
Accardi et al.
*PRD **84**, 014008 (2011)*

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

→ $x \rightarrow 1$ 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)

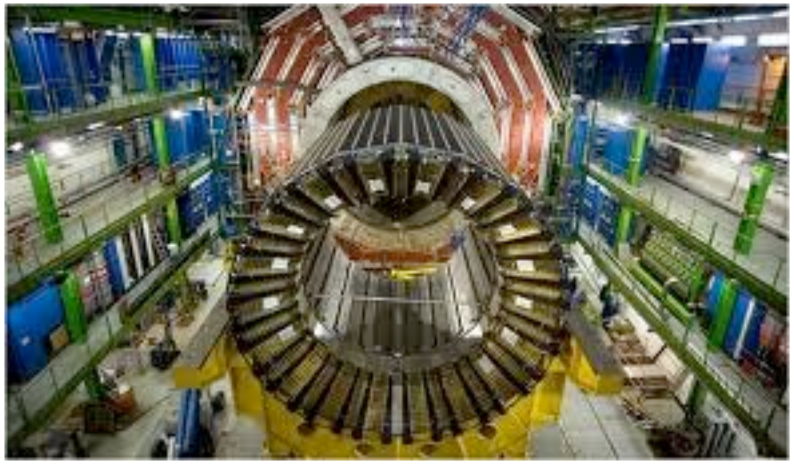
→ gluon PDF anticorrelated with d quark
(g compensates for smaller d quark contribution in jet data)

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

Implications for high-energy colliders

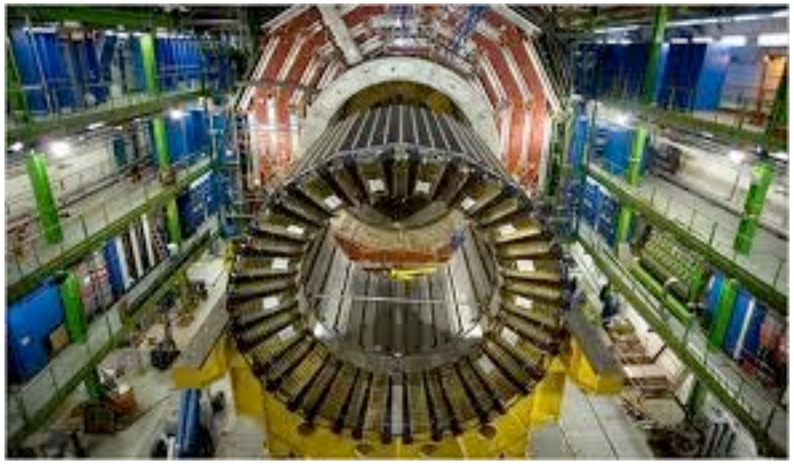
(Tevatron, LHC)

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

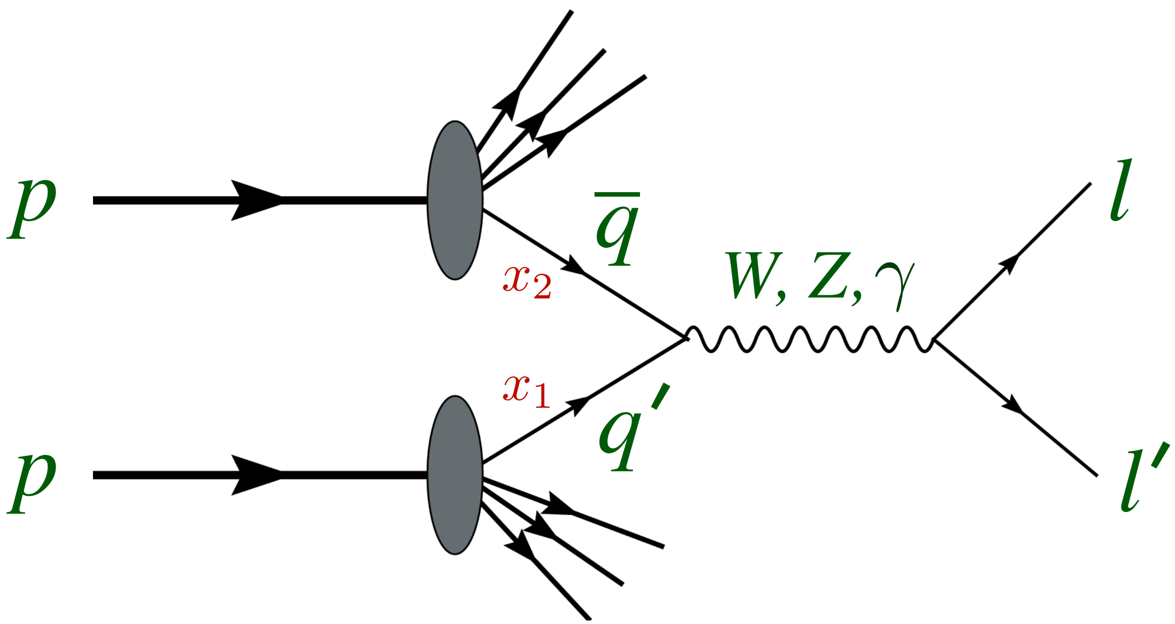


→ pp collisions at $\sqrt{s} = 7$ TeV

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



→ pp collisions at $\sqrt{s} = 7$ TeV

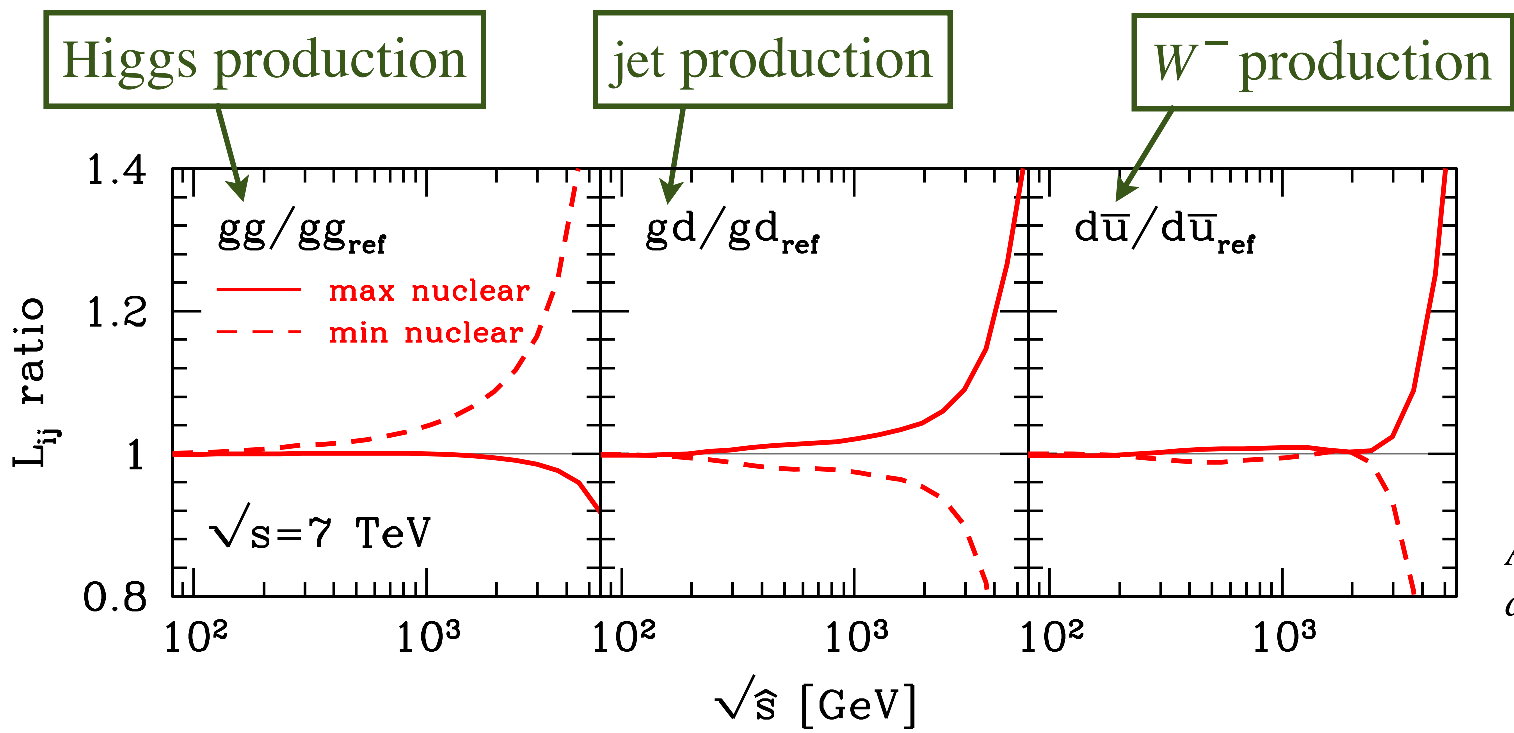


Parton luminosities

- 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

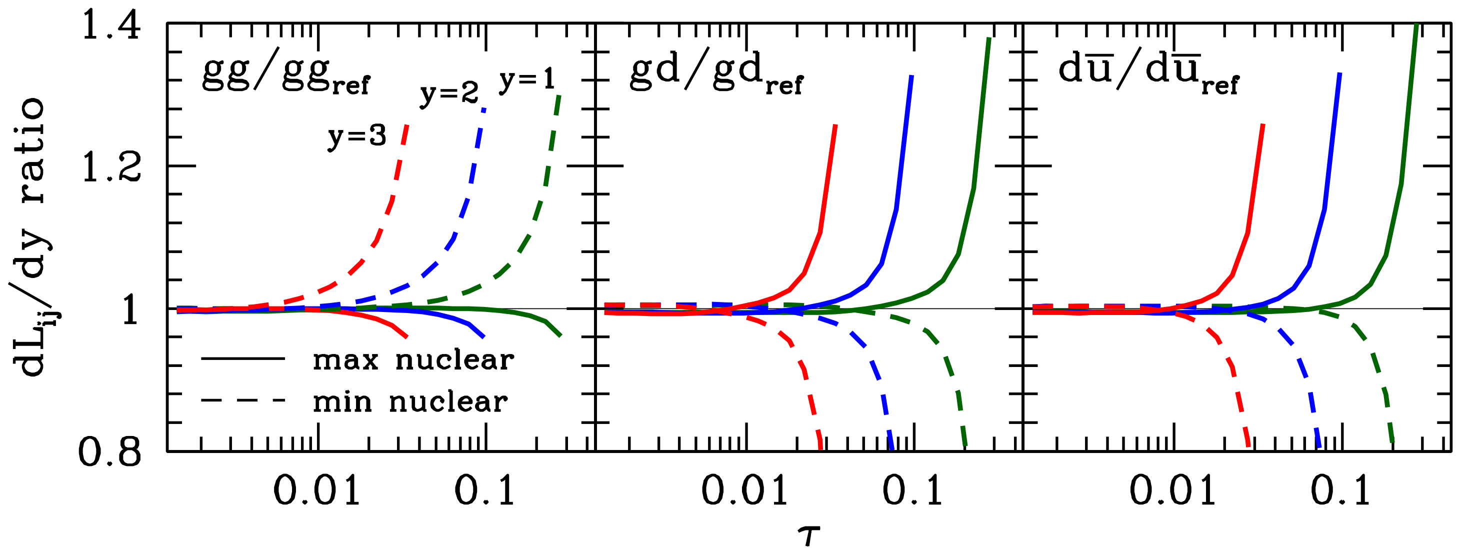
→ nuclear uncertainties important for $\sqrt{\hat{s}} \gtrsim 1$ TeV mass range

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

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

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

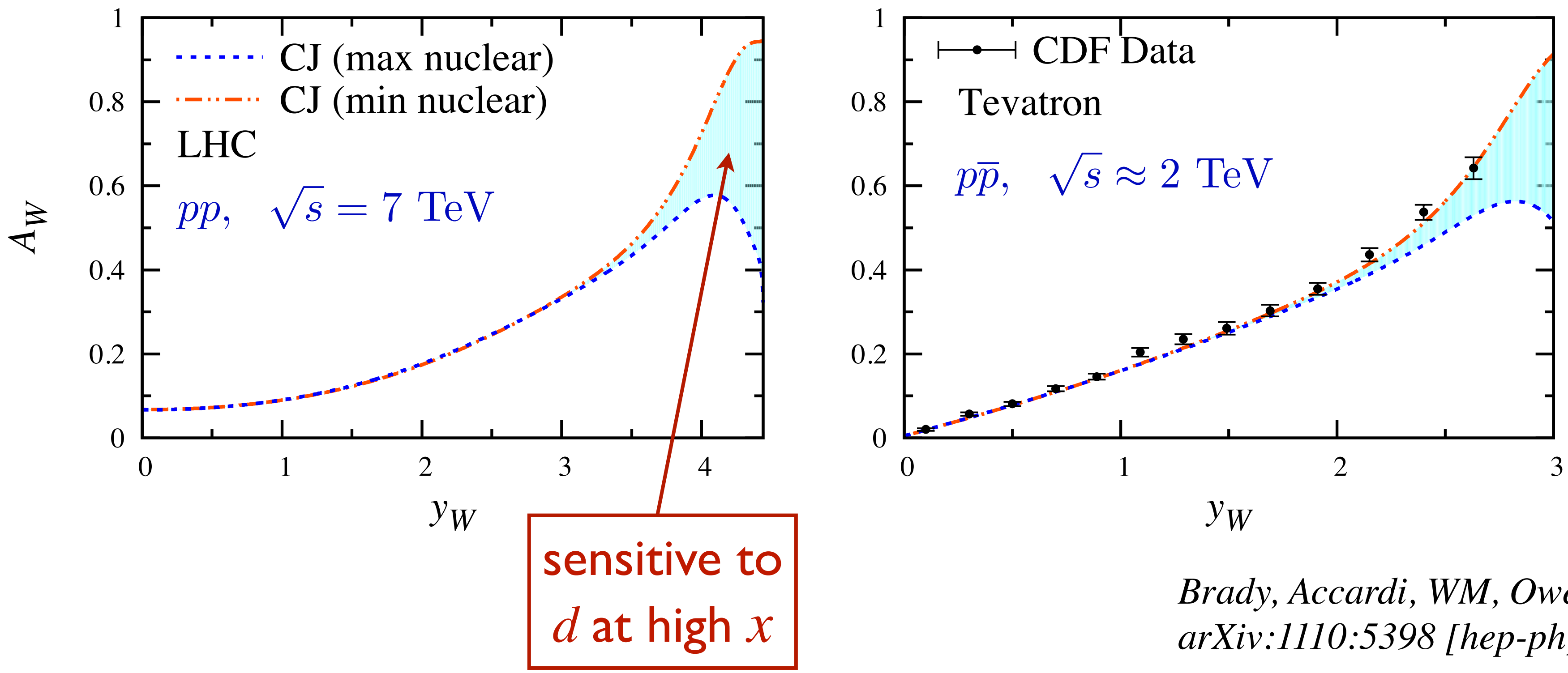
$$\sigma_{W^+} \equiv \frac{d\sigma}{dy}(pp \to W^+ X) = \frac{2\pi G_F}{3\sqrt{2}} x_1 x_2 \left(u(x_1) \bar{d}(x_2) + \cdots \right)$$

W boson asymmetries

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

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

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

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

→ Grand Unified Theories *e.g.* E_6 — *London, Rosner (1986)*

$$E_6 \to SO(10) \times U(1)_\chi \to SU(5) \times U(1)_\psi \times U(1)_\chi$$

→ more exotic scenarios, *e.g.*

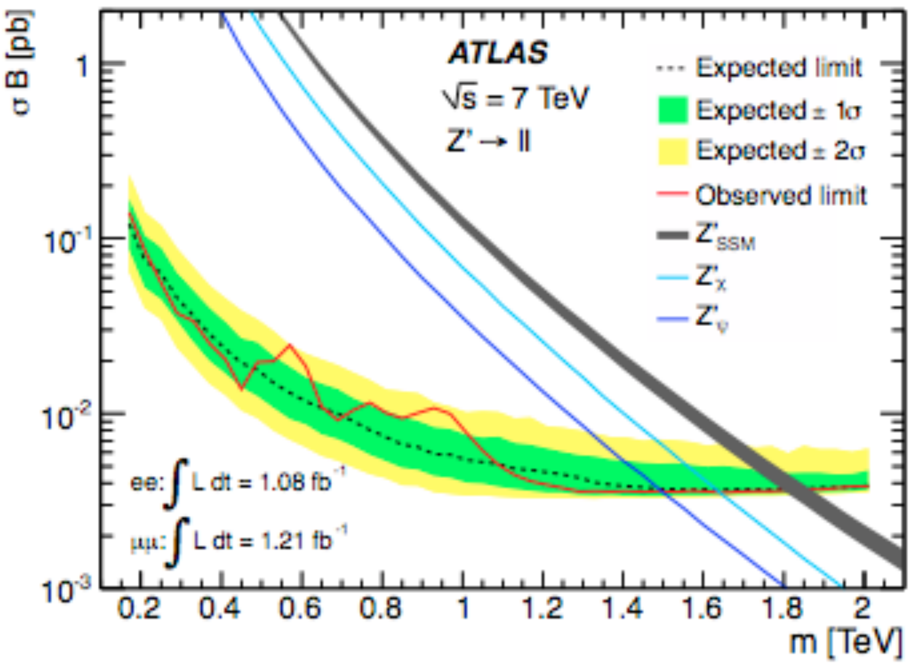
- scalar excitations in R-parity violating supersymmetric models — *Hewett, Rizzo (1998)*
- spin-1 Kaluza-Klein excitations of SM bosons in presence of extra dimensions — *Antoniadis (1990)*
- spin-2 excitations of the graviton — *Randall, Sundrum (1999)*

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]

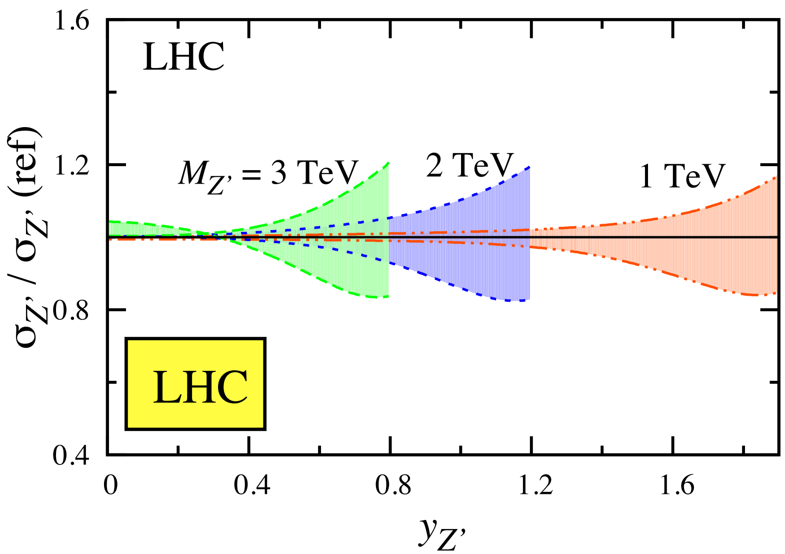
Heavy Z', W' boson production

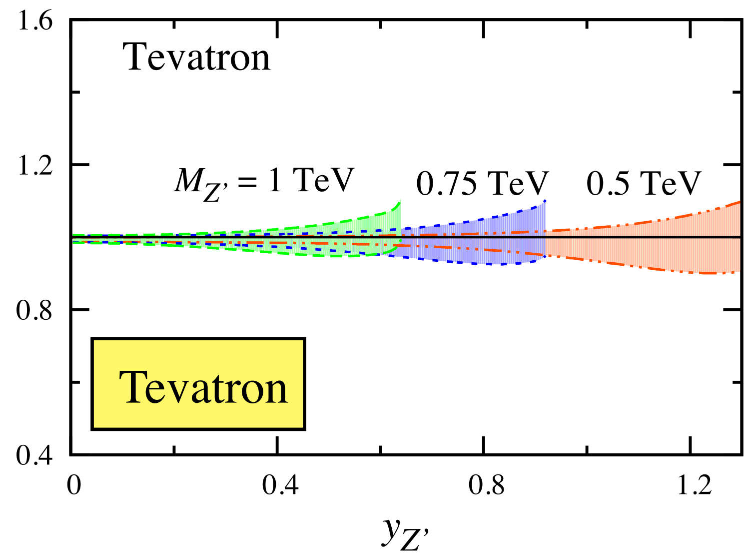
- Observation of new physics signals requires accurate determination of QCD backgrounds — depend on PDFs!
  (since $x_{1,2} \sim M_{Z',W'}$, large-x uncertainties scale with mass)

  - for Z' production

couplings similar for u and d

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





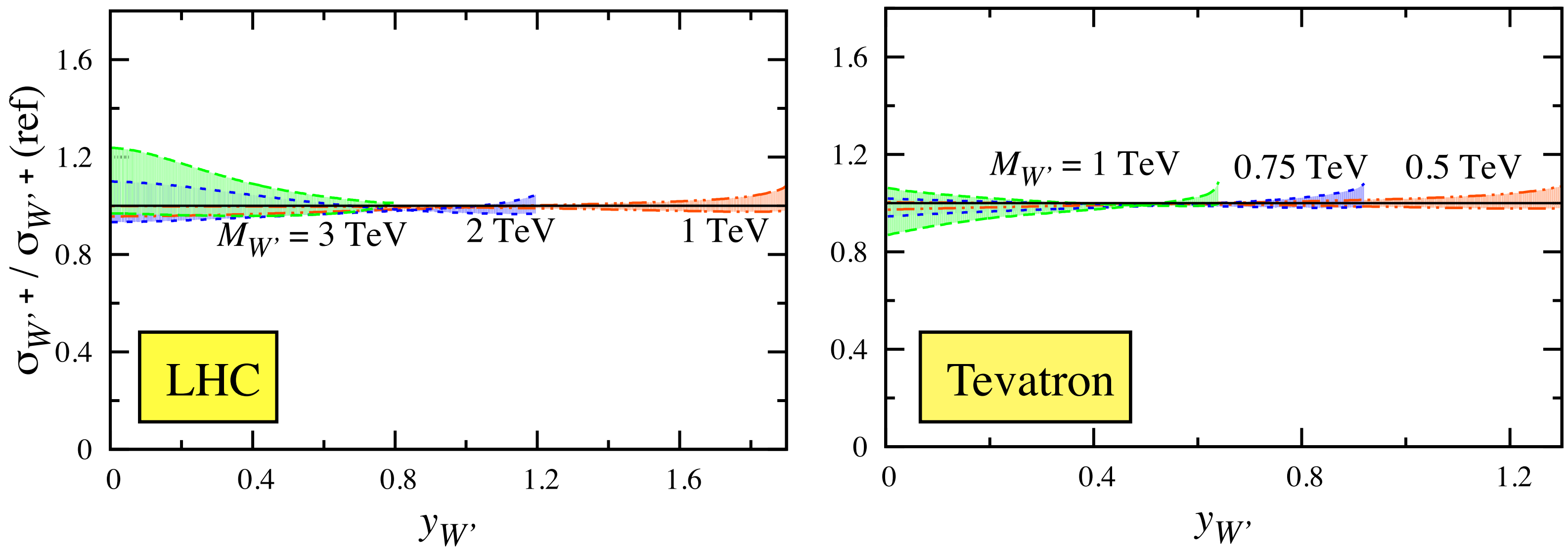
→ dominated by $u * \bar{u}$
– rel. small uncertainties

→ 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

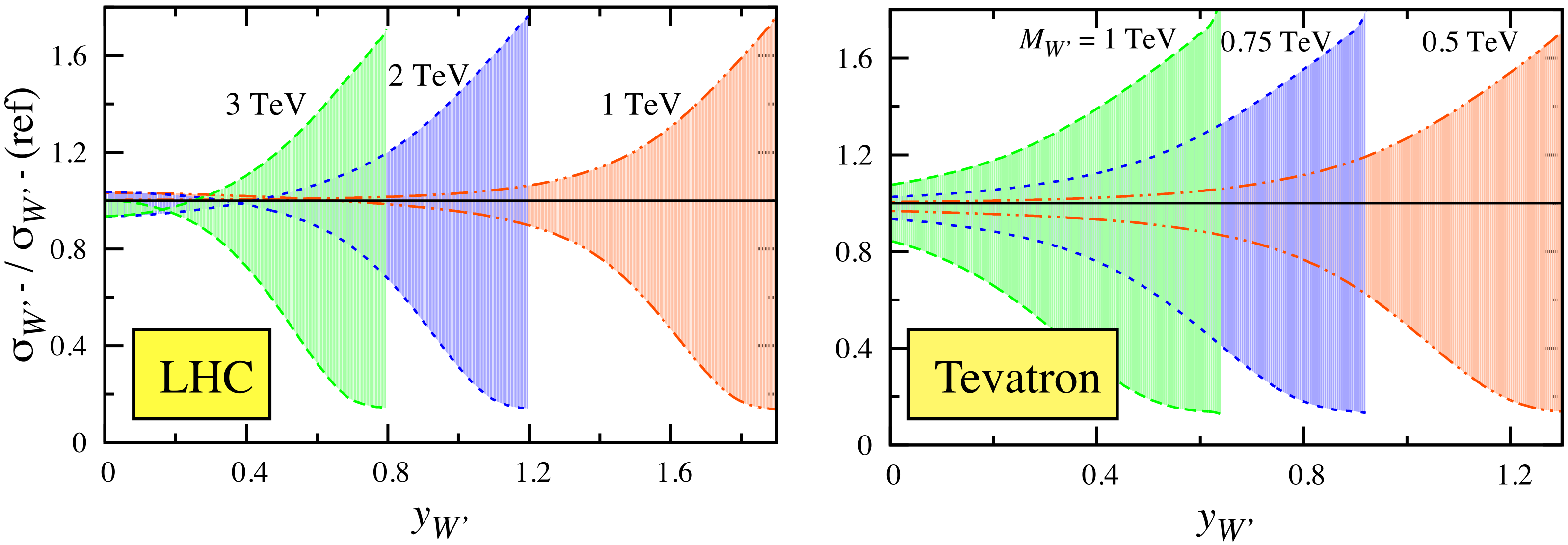
→ small y: uncertainty from $\bar{d}$ at $x \sim 0.3$–0.4

→ 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



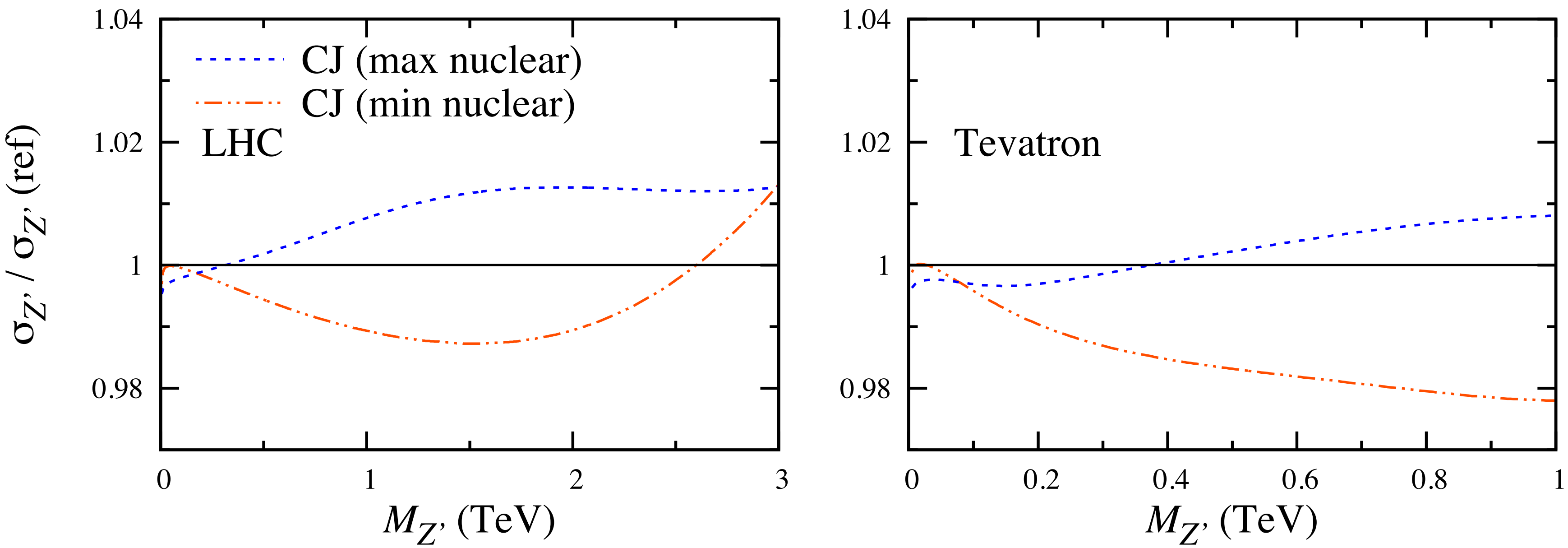
$\longrightarrow$ dominated by $d * \bar{u}$ $\longrightarrow$ dominated by $d * u + u * d$

$> 100\%$ 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

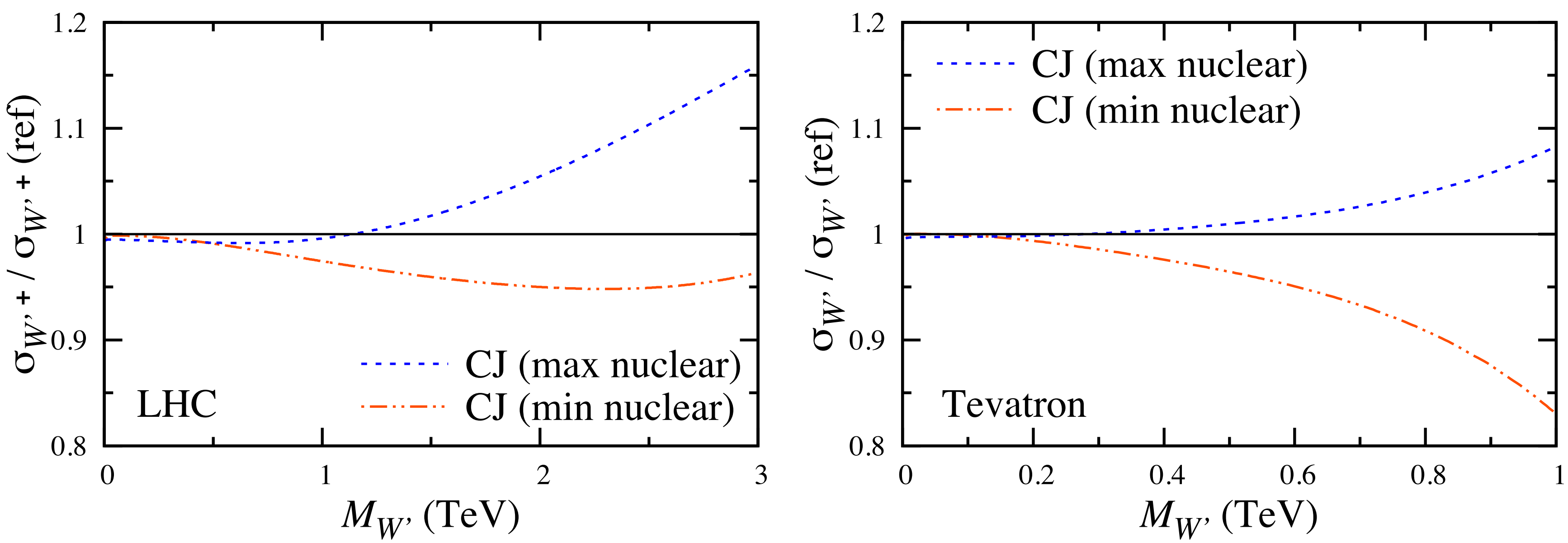


→ increasing uncertainties for large $M_{Z'}$ from antiquark PDFs at high x

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

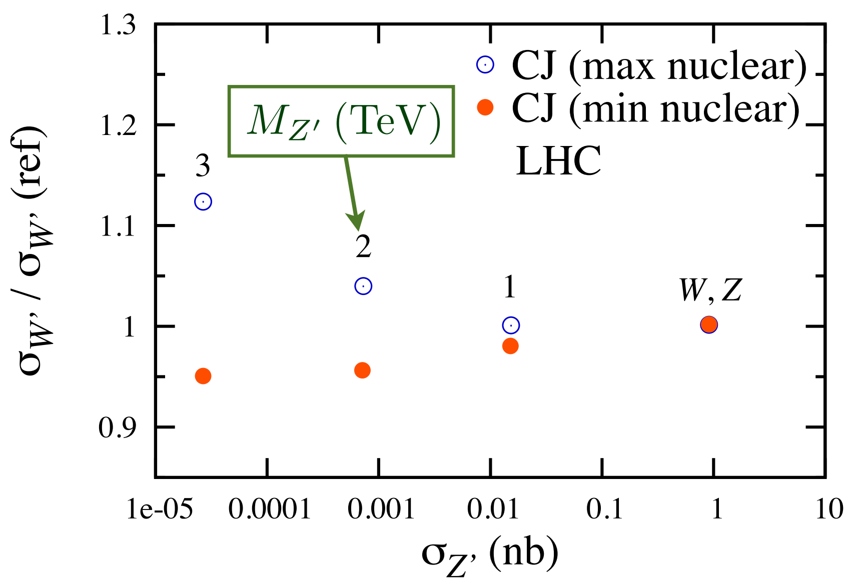


→ increasing uncertainties for large $M_{Z'}$ from antiquark PDFs at high x

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

Outlook

- Nuclear correction uncertainties expected to be resolved with new experiments at JLab−$12\ \mathrm{GeV}$ uniquely sensitive to d quarks (up to $x \sim 0.85$)

  → "spectator" protons tagged in SIDIS from deuterium
  $e\ d \to e\ p_{\mathrm{spec}}\ X$ ("BoNuS")

  → DIS from ^{3}He-tritium mirror nuclei
  $e\ ^3\mathrm{He}(^3\mathrm{H}) \to e\ X$ ("MARATHON")

  → PVDIS from protons
  $\vec{e}_L(\vec{e}_R)\ p \to e\ X$ ("SOLID")

- Constraints from W production in pp collisions at high (lepton & W boson) rapidities

  → CDF & D0 at Fermilab, LHCb at CERN

Outlook

- New JLab−12 GeV precisions measurements of A_1^n & A_1^p hope to constrain $\Delta d/d$ up to $x \sim 0.8$
  → new (non-inclusive DIS) experiments to reduce nuclear dependence

- Parametrization dependence of $x \to 1$ limit may be eliminated through *e.g.* "neural network" PDFs
  → thus far applied mainly to unpolarized PDFs

- New global analysis of *spin-dependent* PDFs dedicated to large-x, moderate-Q^2 region
  → JLab Angular Momentum ("JAM") collaboration*
  → initial focus on helicity PDFs; later expand scope to TMDs

* JAM collaboration: P. Jimenez-Delgado, A. Accardi, WM (theory) + JLab Halls A, B, C (expt.)

The End