

CJ PDFs and Impact of Nuclear Corrections on d/u

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Hampton U. and Jefferson Lab

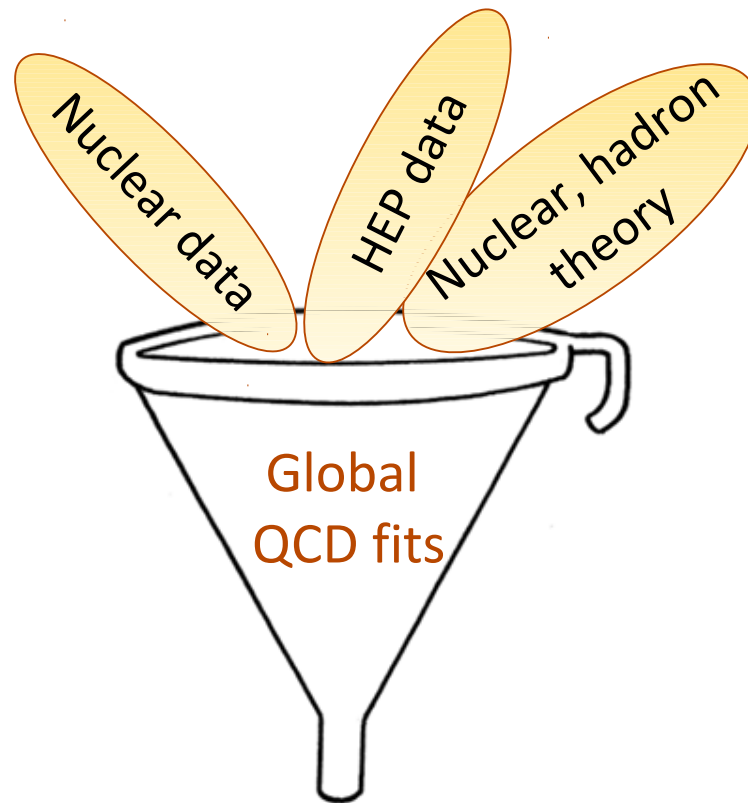
QCD @ LHC
Michigan State U.
August 22, 2012

“The coherence provided by QCD means that insights [into hadron structure] may arise from unexpected quarters.

It is more than ever advisable to take a broad view that integrates across hadronic physics, and to connect with the rest of subatomic physics.”

C. Quigg, 2011

“The Future of Hadrons: The Nexus of Subatomic Physics”
Talk at “Hadron 2011”, arXiv:1109.5814



In-medium protons and neutrons

New physics

Overview

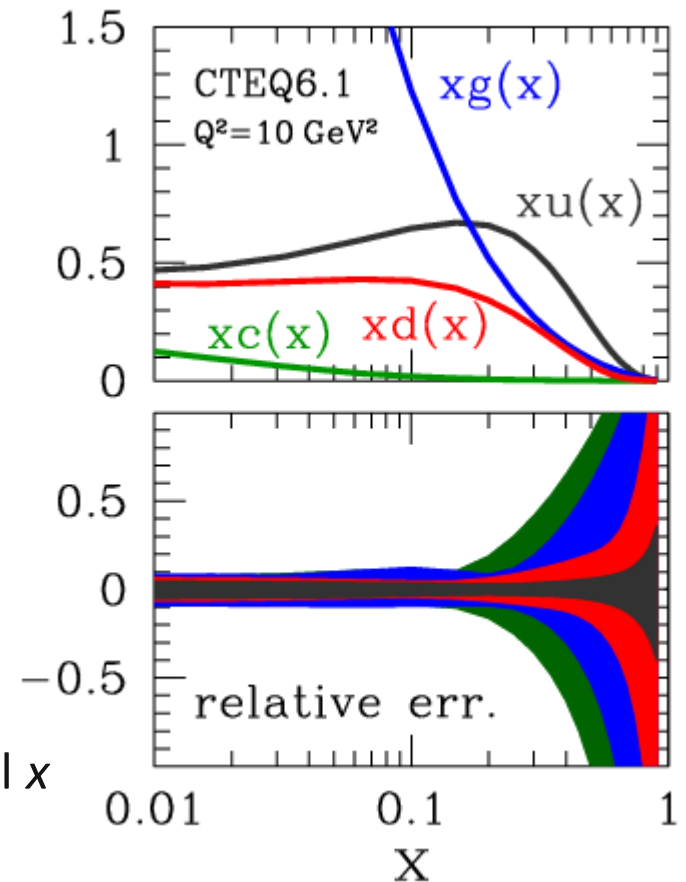
- **Why large x ?**
- **The CTEQ-JLab fits**
 - TMCs, HTs, nuclear corrections, d -quark parametrization
- **Applications**
 - d/u ratio extrapolated to $x=1$
 - Parton luminosities, W' and Z' production
- **Constraining nuclear corrections**
 - Jefferson Lab data
 - Tevatron, LHC data (!?)
 - ...and more...

Why large x ?

□ Large (experimental) uncertainties in Parton Distribution Functions (PDFs)

□ Precise PDFs at large x are needed, *e.g.*,

- Non-perturbative nucleon structure:
 - $d/u, \Delta u/u, \Delta d/d$ at $x \rightarrow 1$
- at LHC, Tevatron
 - New physics as excess on QCD
 - large p_T spectra \Leftrightarrow large x PDF
 - Forward physics
- At RHIC:
 - Spin structure of the nucleon at small x
- Neutrino oscillations, ...



Valence quarks at large x

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

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

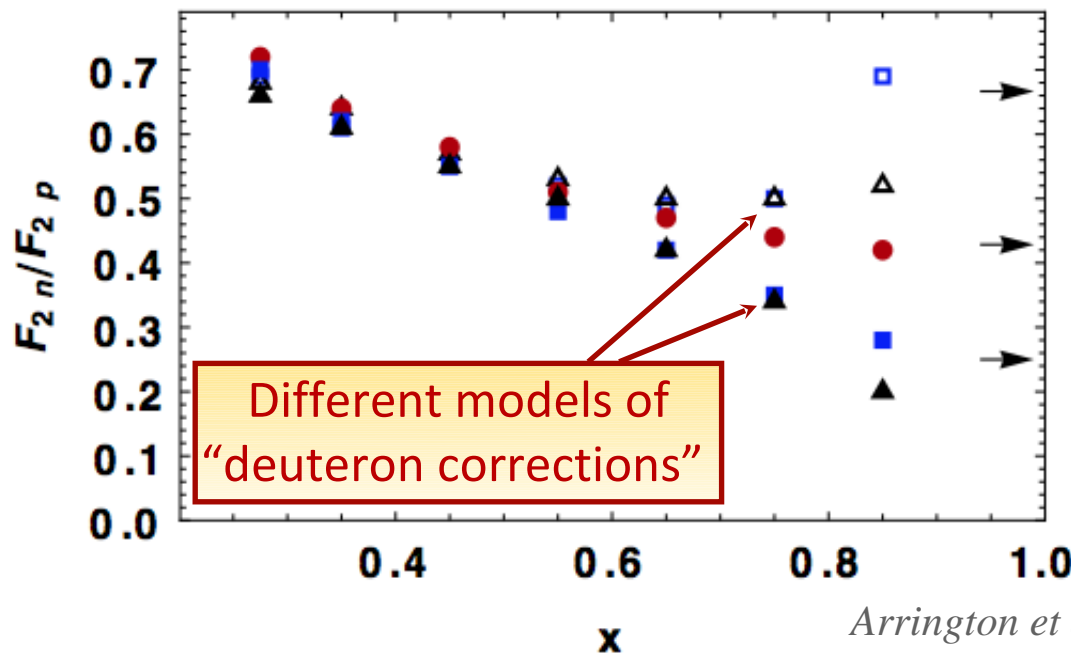
$$F_2^n \approx \frac{1}{9}u_v + \frac{4}{9}d_v$$

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

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

But... deuteron corrections!

- Absence of free neutron targets
⇒ use deuterons (weakly bound p and n)



Non-perturbative proton models

SU(6) spin-flavor

hard gluon exchange

S=0 diquark dominance

- Deuteron model dependence obscures free neutron at large x
 - We will see quantitatively how much

Large x at colliders - new physics searches

Remember, $x = \frac{M}{\sqrt{s}} e^y$

Examples:

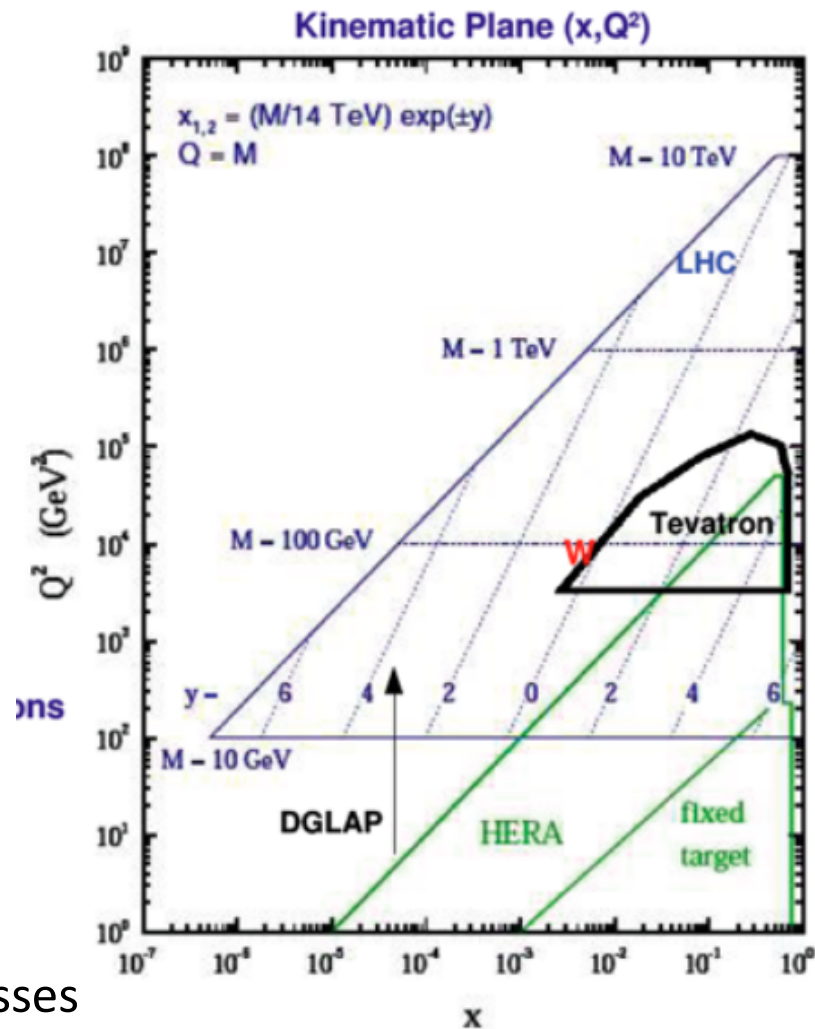
- Z' production $M'_Z \gtrsim 1 \text{ TeV}$
- W at forward rapidity: $y > 2$

$$x > 0.1 \text{ (LHC)}$$

$$x > 0.5 \text{ (Tevatron)}$$

Precise large-x PDFs needed to:

- reduce QCD background
- optimize searches involving large masses
- precisely characterize new particle properties



The CTEQ-JLab fits

The CTEQ-JLab collaboration

Collaborators:

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

Goals:

- Global QCD fits of unpolarized PDFs focused on large x
- Improve the PDF experimental precision (“PDF errors”) by enlarging the fitted data set
- Include all relevant large- x / small- Q^2 theory corrections
- ***Quantitatively evaluate theoretical systematic errors***
- ***Use PDFs as tools for nuclear and particle physics***

Papers:

- A.Accardi et al., Phys.Rev.D81 (2010) 034016 **“CJ10”**
- A.Accardi et al., Phys.Rev.D84 (2011) 014008 **“CJ11”**
- New fit in preparation with latest data

Available
on request

Public release planned

Global QCD fits of Parton Distribution Functions

data

- DIS: p, d
- p+p(pbar) \rightarrow l+l-, W $^{\pm}$
- p+p(pbar) \rightarrow jets, γ +jet

theory

- pQCD at NLO
- Factorization & universality
- **Large-x, low- Q^2 , nuclear corr.**

fits

- Parametrize PDF at Q_0 , evolve to Q
- Minimize χ^2

PDFs

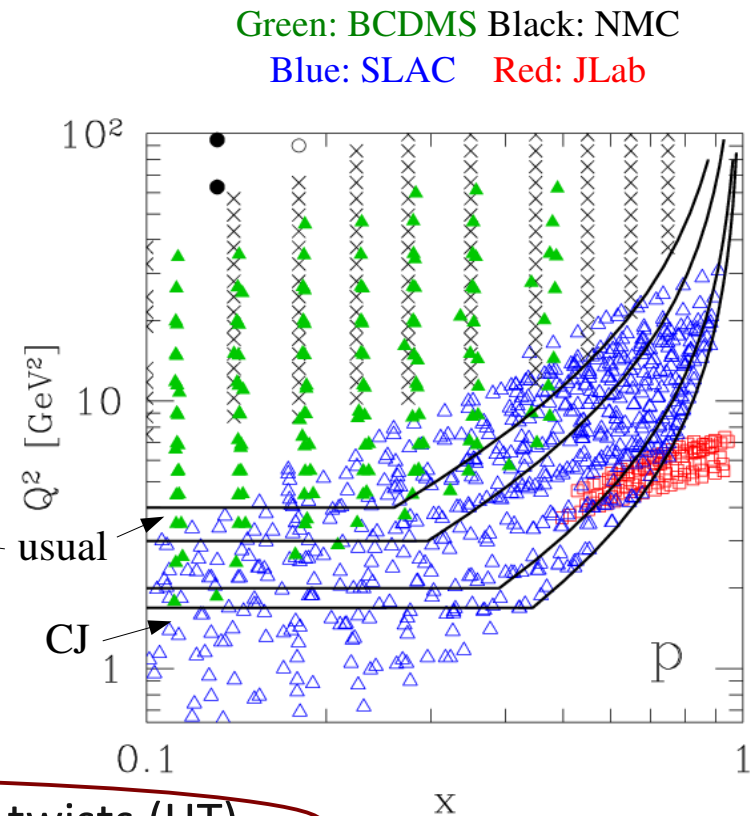
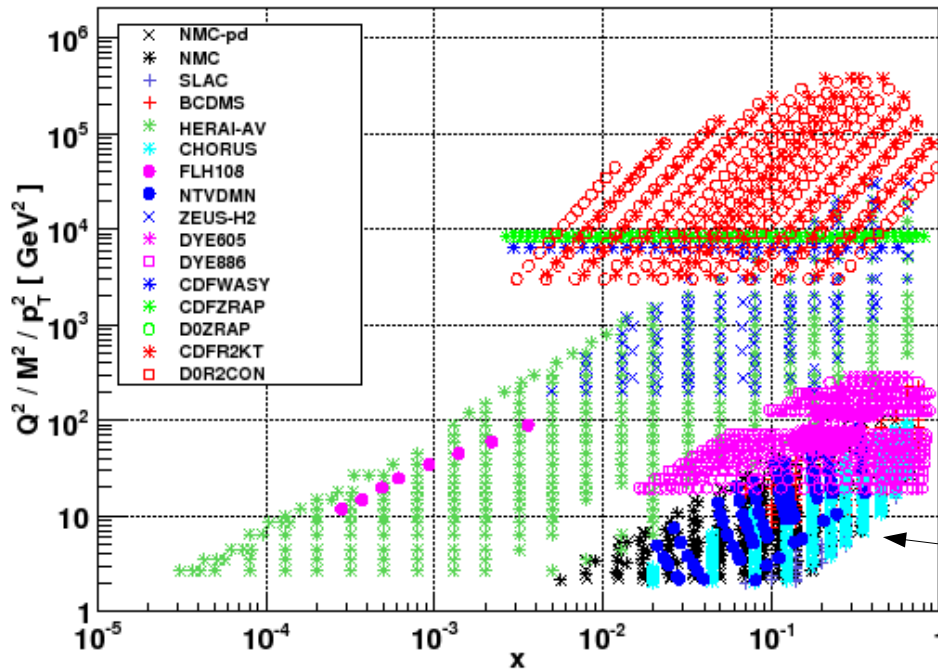
$F_2(n)$

W, Z / W', Z', Higgs

(or any other "hard" observable)

Large-x, small- Q^2 corrections

NNPDF2.0 dataset



1/ Q^{2n} suppressed:

- Target mass corrections (TMC), higher-twists (HT)
- Current jet mass, quark mass, large-x QCD evol.

included in CJ fits

Non-suppressed

- Nuclear corrections, threshold resum., parton recomb.

CJ10 fits: results in a nutshell

summary: Accardi, AIP Conf.Proc. 1374 (2011) 383

□ Standard cuts:

- PDF insensitive to TMC, HT
- Nuclear corrections not negligible (but usually neglected...)

□ Looser kinematic cuts

- PDFs stable as cut is varied about the largest allowed
- Substantial reduction in “experimental” PDF errors

□ Stability w.r.t. TMCs

- The fitted HT term compensates for differences in TMC models
 - Leading-twist PDFs have little systematic error (good!)
 - HT term has $\approx 50\%$ uncert. (not so good, if you care for this...)
- TMC theory uncertainty can be improved:

Brady, Accardi, Hobbs, Melnitchouk, PRD 84, 074008 (2011)

CJ11 fits: results in a nutshell

summary: Accardi, AIP Conf.Proc. 1374 (2011) 383

□ New d -quark parametrization

$$d'(x) = d(x) + \alpha x^\beta u(x)$$

- Allows d/u to be non-zero at $x = 1$
- Produces dramatic increase in d PDF in $x \rightarrow 1$ limit

□ Large sensitivity to nuclear model

- The d -quark at $x > 0.5$ is almost fully correlated to nuclear correction model
- ***Very large theoretical uncertainty***

Nuclear corrections - theoretical uncertainty

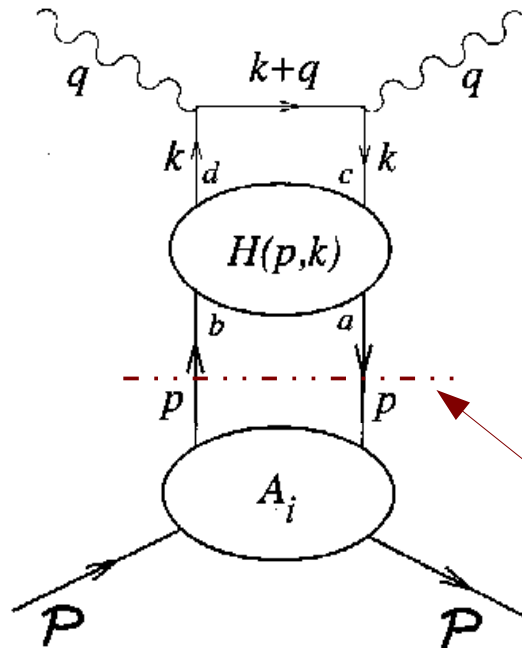
$$F_{2d}(x_B, Q^2) = \int_{x_B}^A dy \mathcal{S}_A(y, \gamma) F_2^{TMC+HT}(x_B/y, Q^2) \left(1 + \frac{\delta^{off} F_2(x)}{F_2(x)} \right)$$

Free nucleon str.fn.

“Smearing function”

Calculated from nuclear wave-function:

- CD-Bonn } non-relativistic
- AV18 } non-relativistic
- WJC-2 } relativistic
- WJC-1 } relativistic



Off-shell correction

Models (little theory guidance):

- Melnitchouk & C. (MST)
- Kulagin-Petti (KP) fits of A/d ratios
- modified KP model

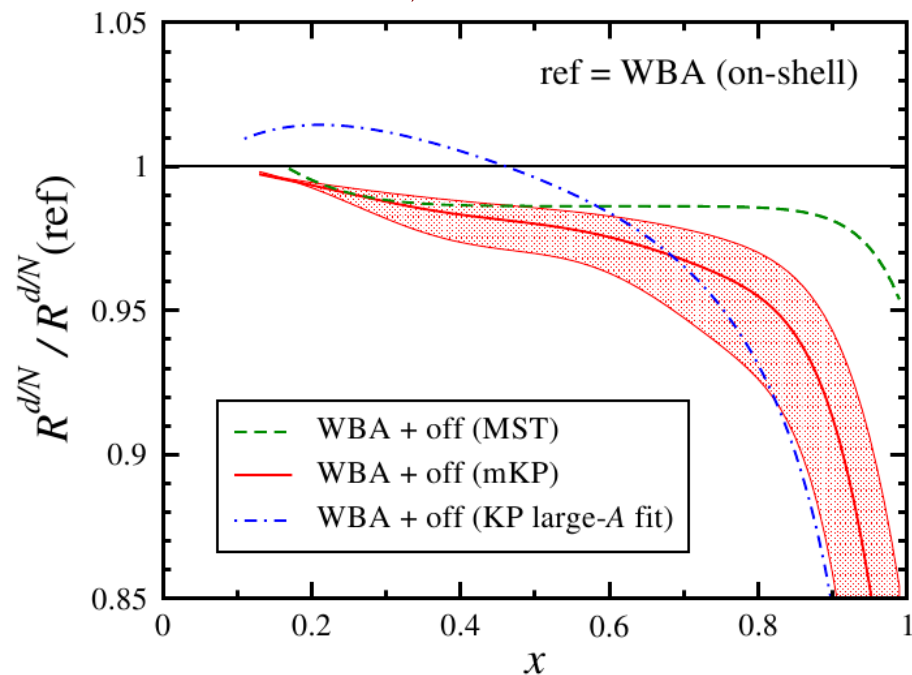
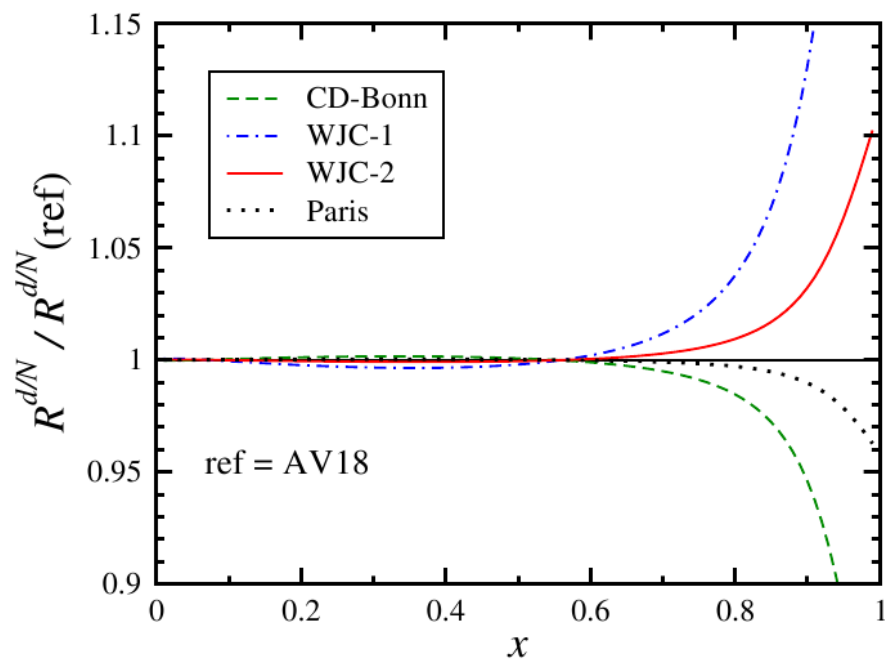
Low-energy factorization issues

- Renormalization of nuclear operators
- Lorentz vs. gauge invariance, FSI, ...

Nuclear corrections - theoretical uncertainty

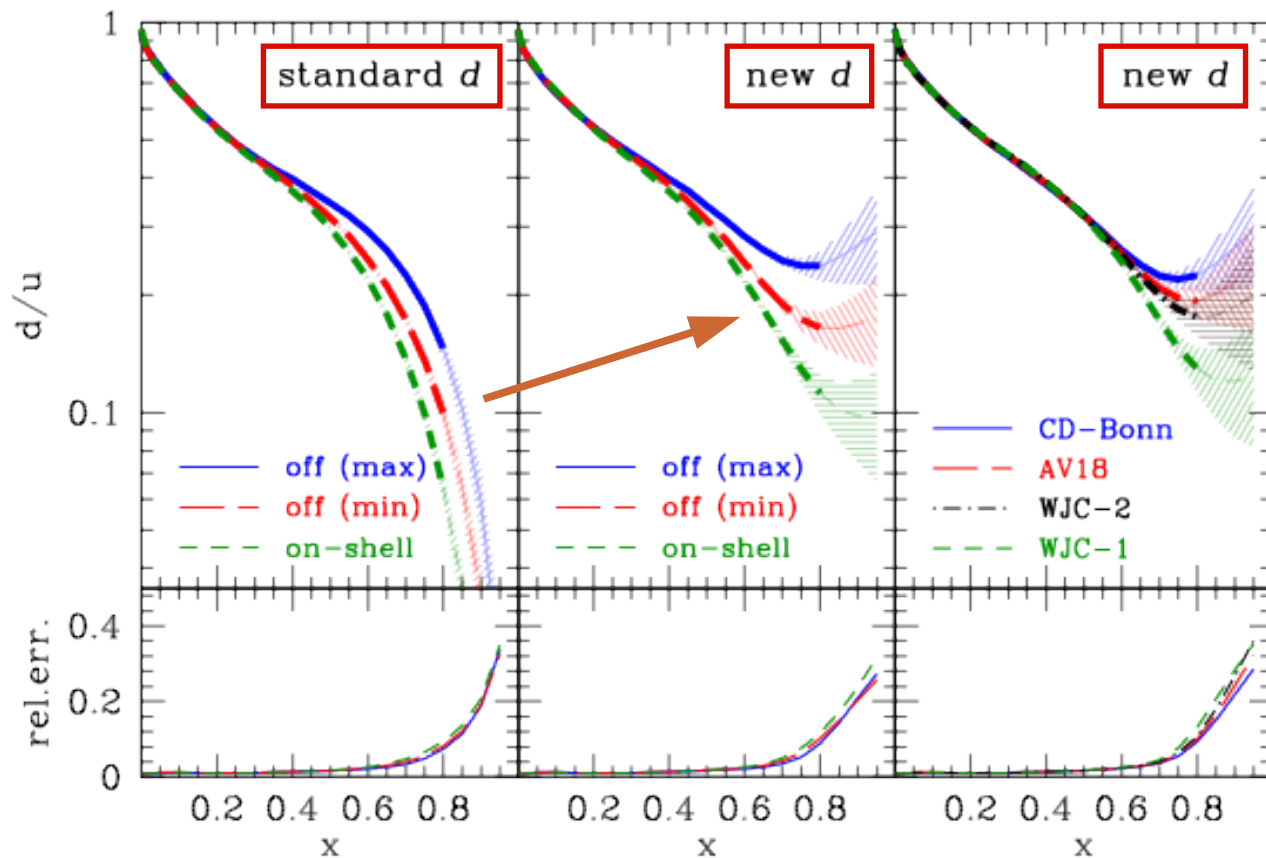
$$F_{2d}(x_B, Q^2) = \int_{x_B}^A dy \mathcal{S}_A(y, \gamma) F_2^{TMC+HT}(x_B/y, Q^2) \left(1 + \frac{\delta^{off} F_2(x)}{F_2(x)} \right)$$

Free nucleon str.fn.



CJ fits: effect of d -quark parametrization

Accardi et al. PRD 84, 014008 (2011)

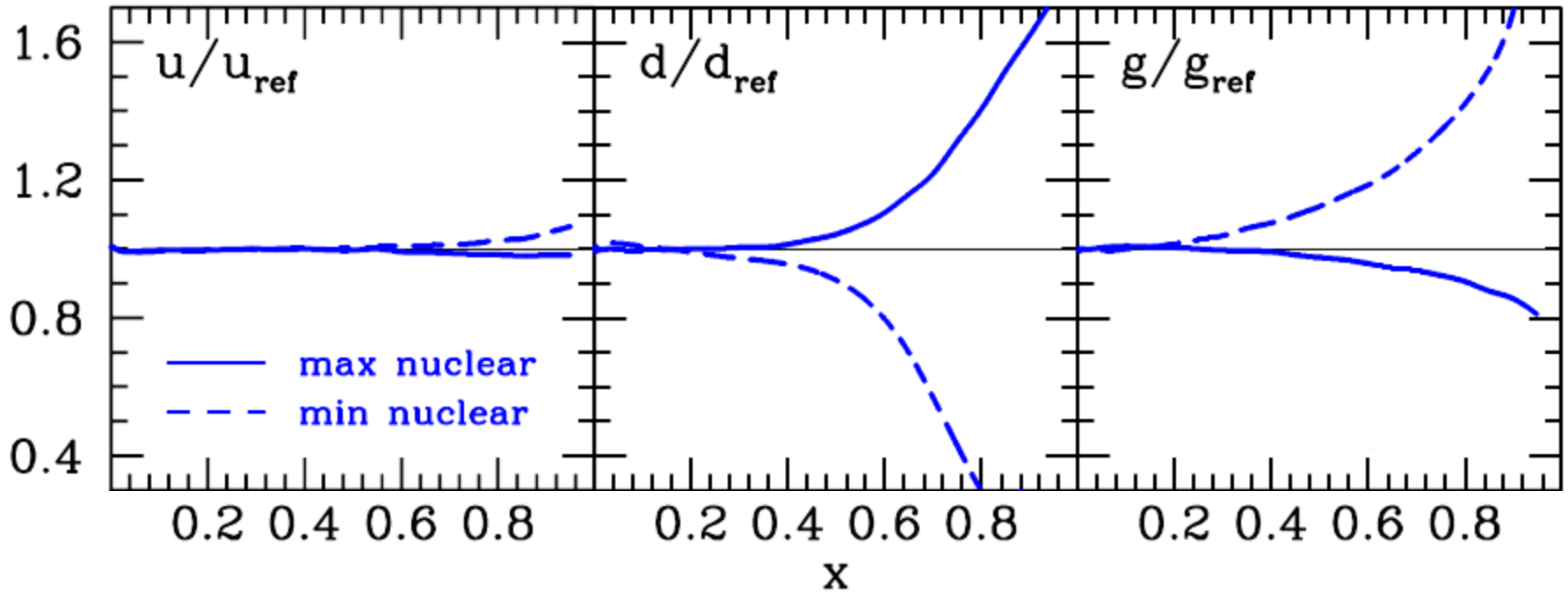


- Dramatic increase in d PDF as $x \rightarrow 1$ with more flexible parametrization

$$d'(x) = d(x) + \alpha x^\beta u(x)$$

CJ fits: nuclear model systematic error

Accardi et al. PRD 84, 014008 (2011)



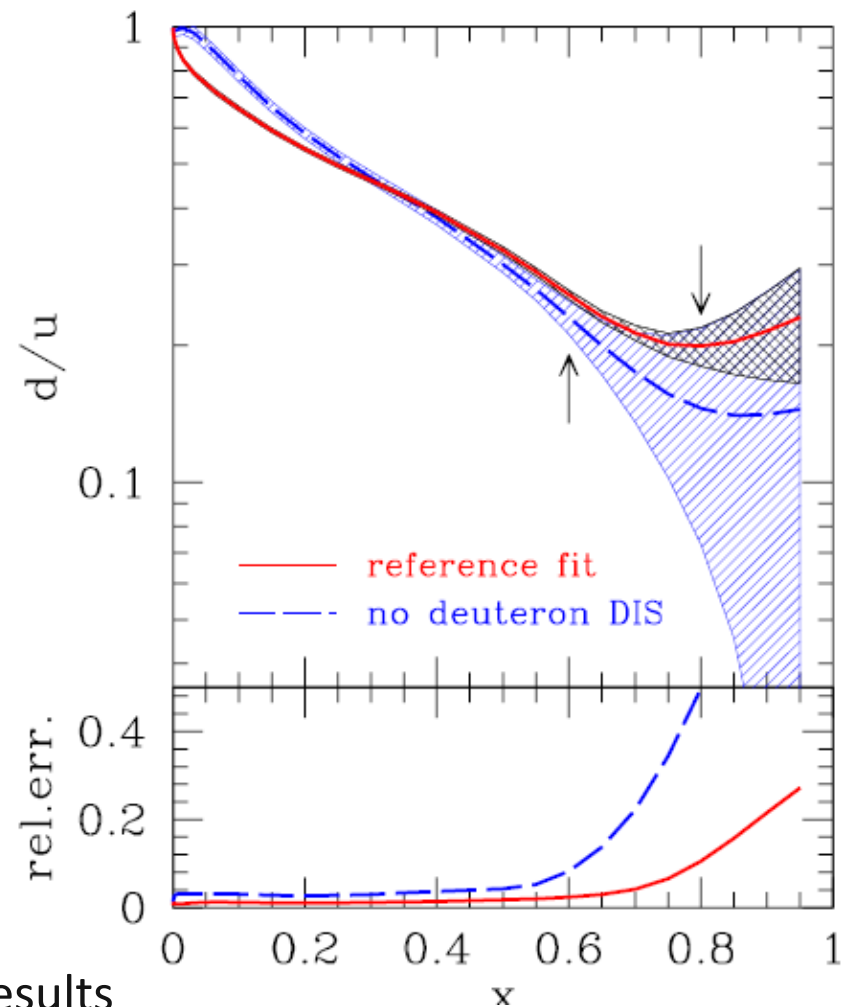
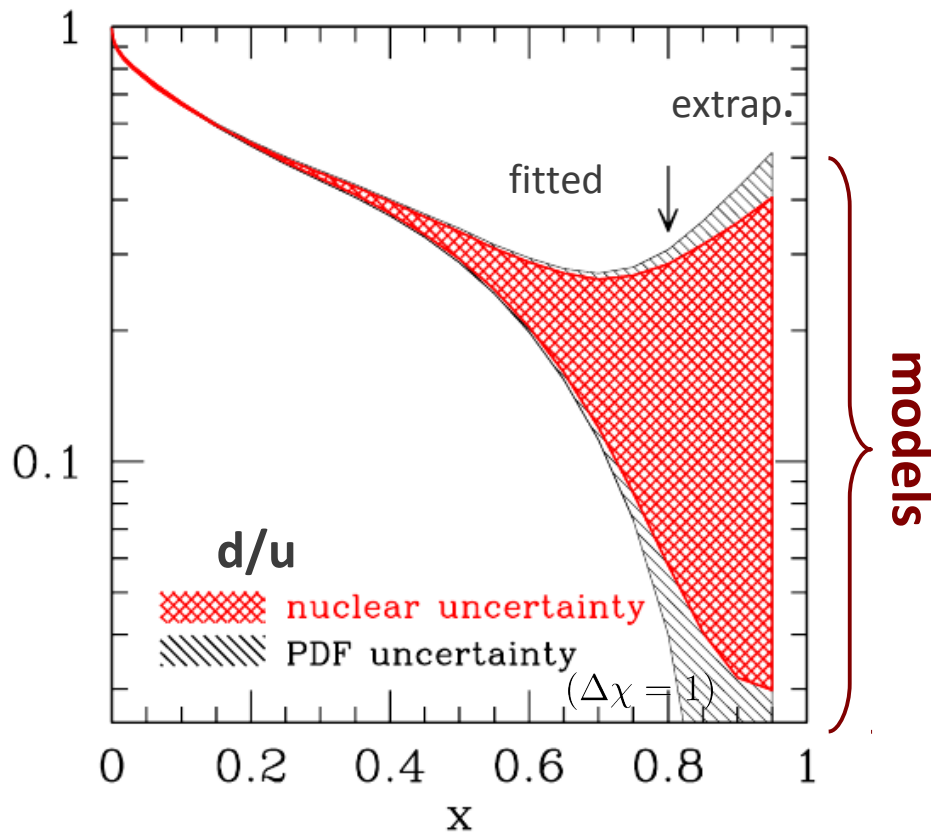
Large sensitivity to nuclear corrections model

- *d-quarks*: directly, due to corrections applied to $F_2(d)$
- *gluons*: due to correlation with d-quarks induced by jet data

Application:
The d/u ratio at $x \rightarrow 1$

The CTEQ-JLab d/u

Accardi et al. PRD 84, 014008 (2011)



Large nuclear uncertainty:

- Covers all non-perturbative model results
- Eats away improved statistics from low- W^2 data

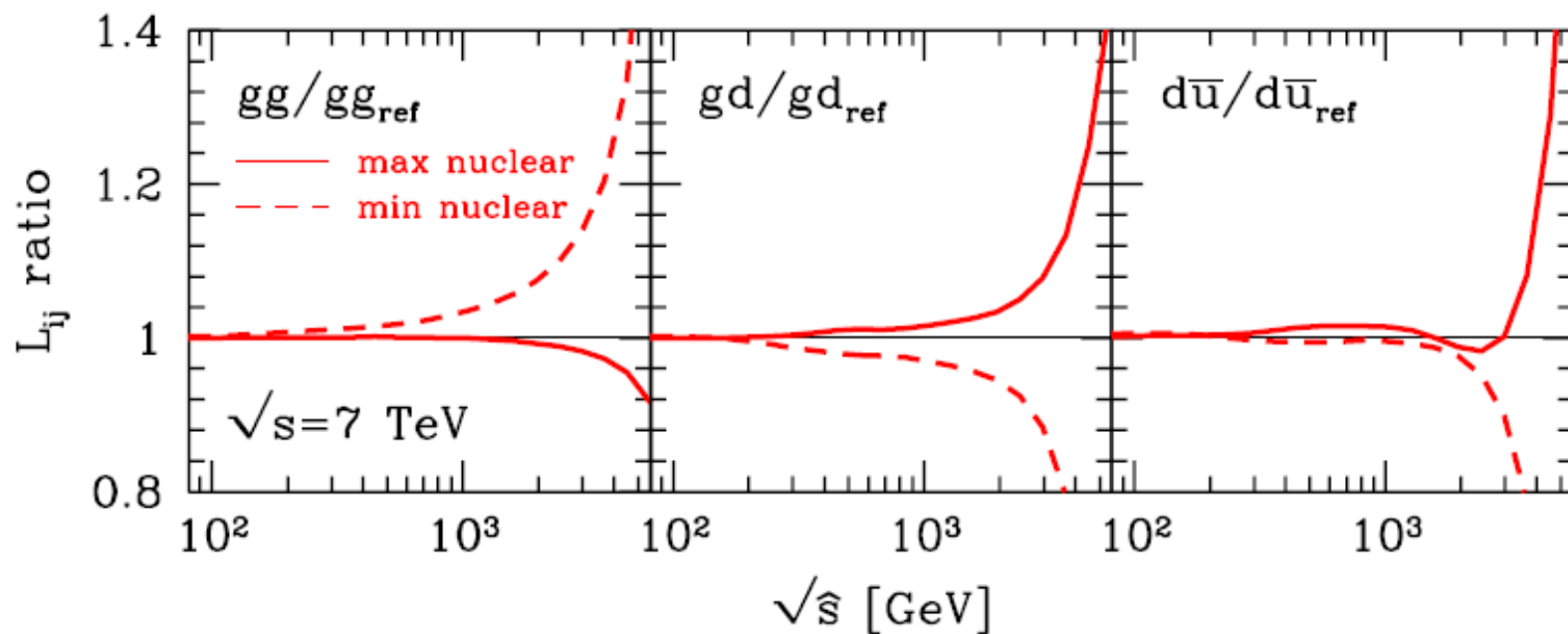
**Application:
Parton Luminosities
 W', Z' bosons**

Parton luminosities

Accardi et al. PRD 84, 014008 (2011)

- Large- x PDF uncertainties affect total cross sections for objects of large mass $\hat{s} = (p_1 + p_2)^2 = x_1 x_2 s$

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



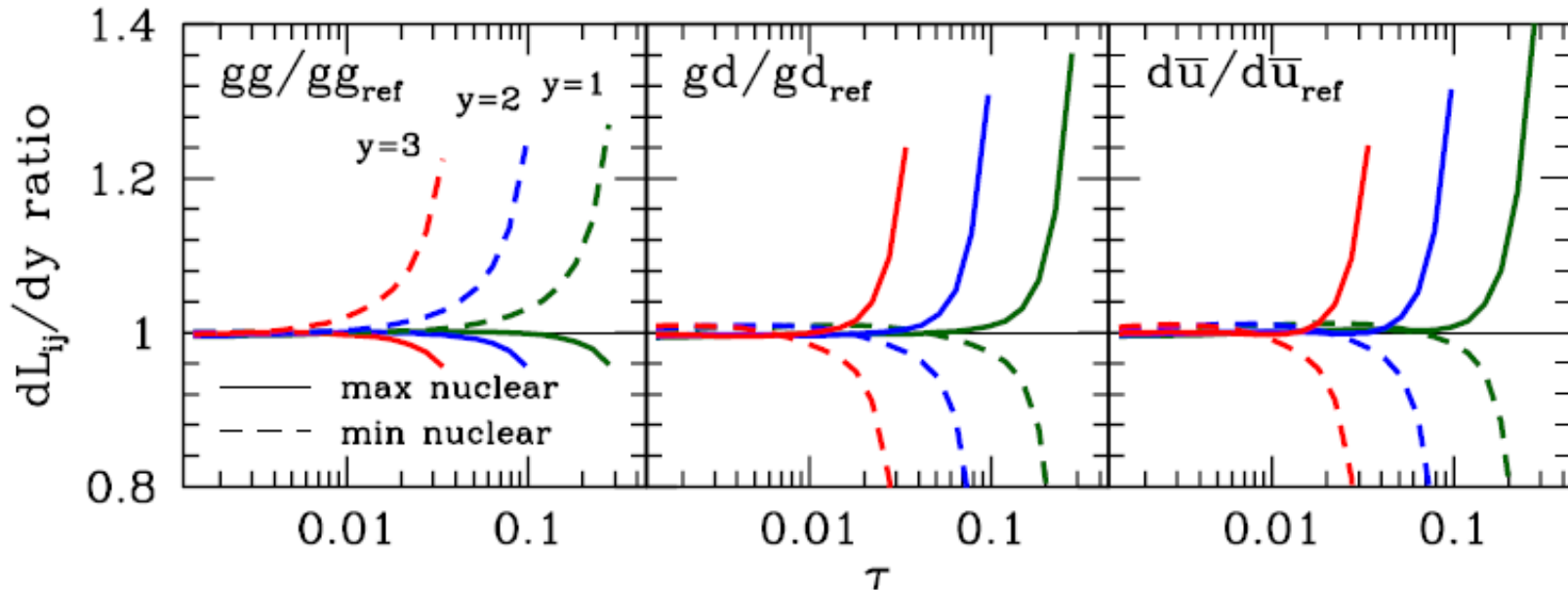
Parton luminosities

Accardi et al. PRD 84, 014008 (2011)

□ ... or large rapidity:

$$\frac{dL_{ij}}{dy} = \frac{1}{s(1 + \delta_{ij})} \left[f_i(\tau e^y, \hat{s}) f_j(\tau e^{-y}, \hat{s}) + (i \leftrightarrow j) \right]$$

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

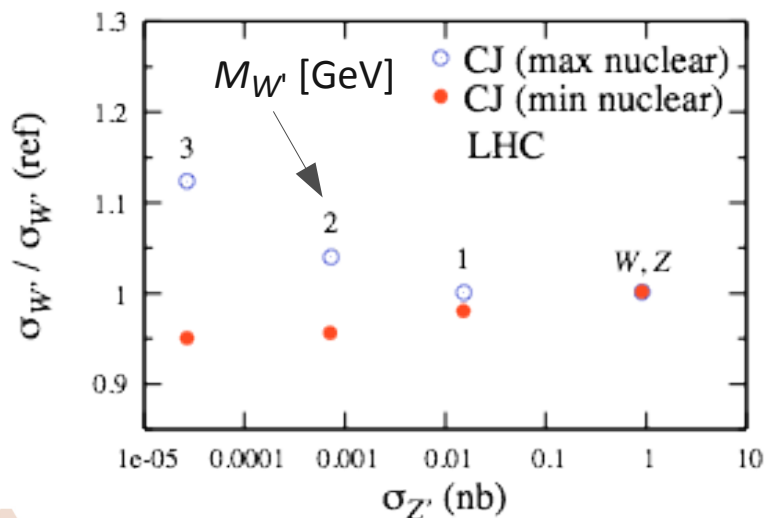


(Note: ratios are largely independent of s)

Heavy W' and Z' boson production

Brady, Accardi, Melnitchouk, Owens, JHEP 1206 (2012) 019

- Some extensions of Standard Model predict heavy versions of W , Z bosons
 - current limits $M_{W'} > 2.1$ TeV, $M_{Z'} > 1.8$ TeV
(assuming Standard Model couplings)
- Observation of new physics signal requires accurate determination of QCD backgrounds, which depend on PDFs!
- Example: total cross sections ($M_{W'} / M_{Z'}$ fixed)



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

Constraining nuclear corrections

Need data to constrain nuclear corrections!

□ Data minimally sensitive to nuclear corrections

- DIS with slow spectator proton (BONUS, BONUS12)
 - Quasi-free neutrons
- DIS with fast spectator (DeepX)
 - Off-shell neutrons – but large, poorly controlled FSI
- $^3\text{He}/^3\text{H}$ ratios (MARATHON)

JLab

□ Data on free (anti)protons, sensitive to d or g

- $e+p: F_L$, parity-violating DIS **JLab, HERA** (e^+p vs. e^-p)
- $\nu+p, \bar{\nu}+p$ **Minerva ???**
- $p+p, p+\bar{p}$ at large positive rapidity
 - W charge asymmetry, Z rapidity distribution

**Tevatron: D0, CDF??
LHCb?? RHIC ??
AFTER@LHC**

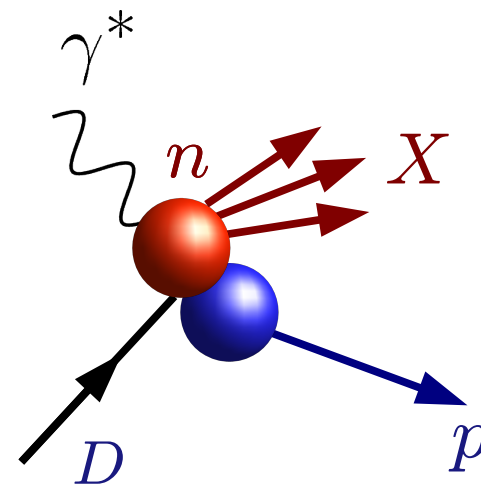
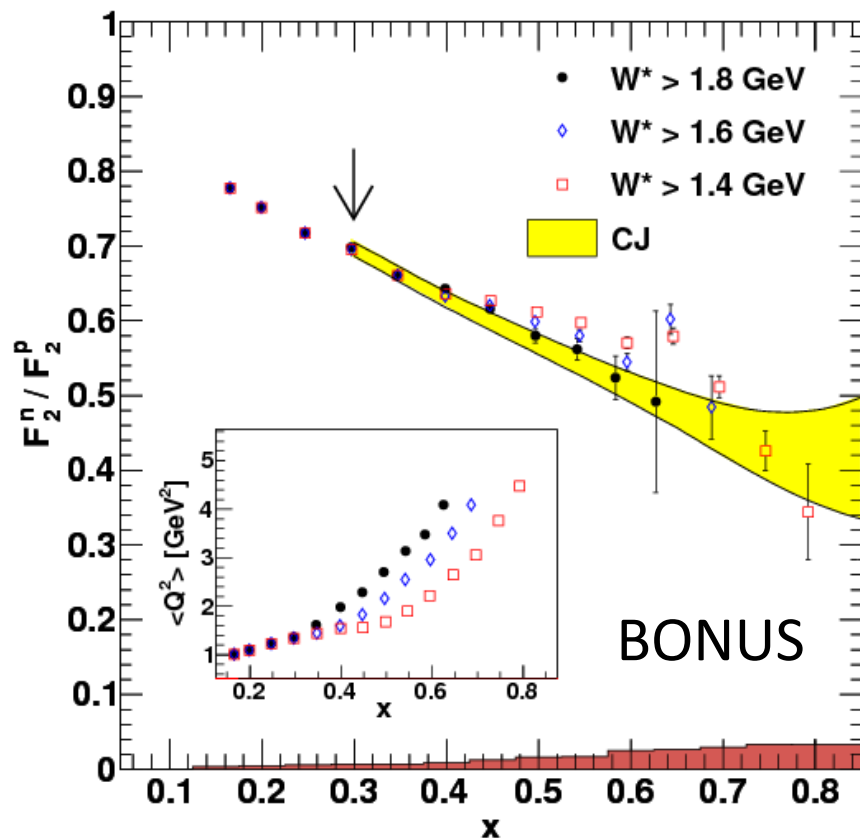
□ Cross-check data

- $p+d$ at large negative rapidity – dileptons; W, Z
 - Sensitive to nuclear corrections, cross-checks $e+d$

**RHIC ??
AFTER@LHC**

Quasi-free neutrons from BONUS

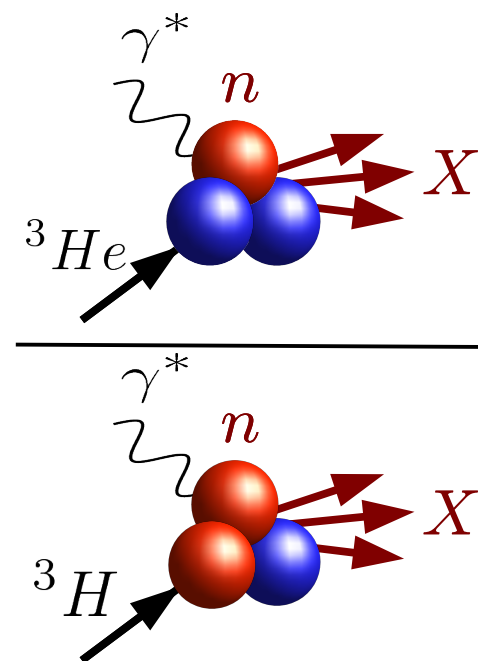
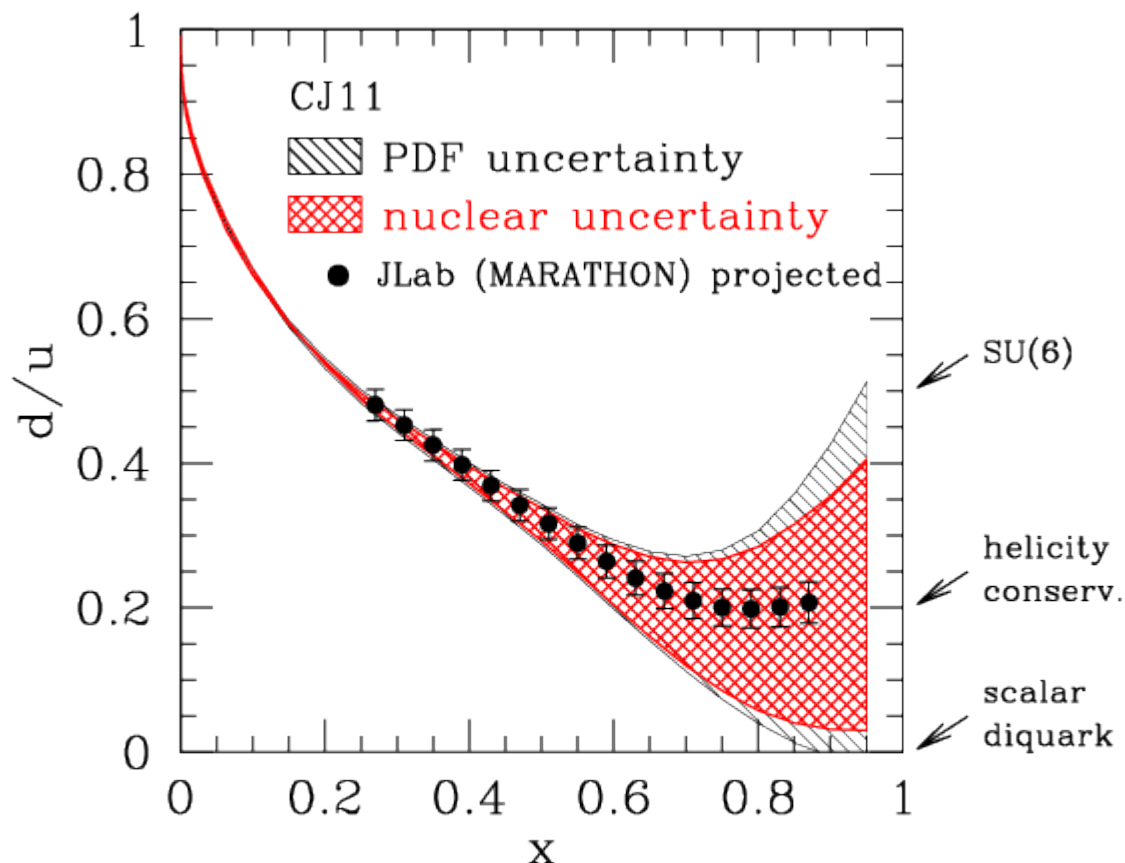
N.Baillie et al., PRL 108 (2012) 199902



- DIS data (black disks) too uncertain at $x > 0.5$
 - Need to wait for BONUS12 / MARATHON

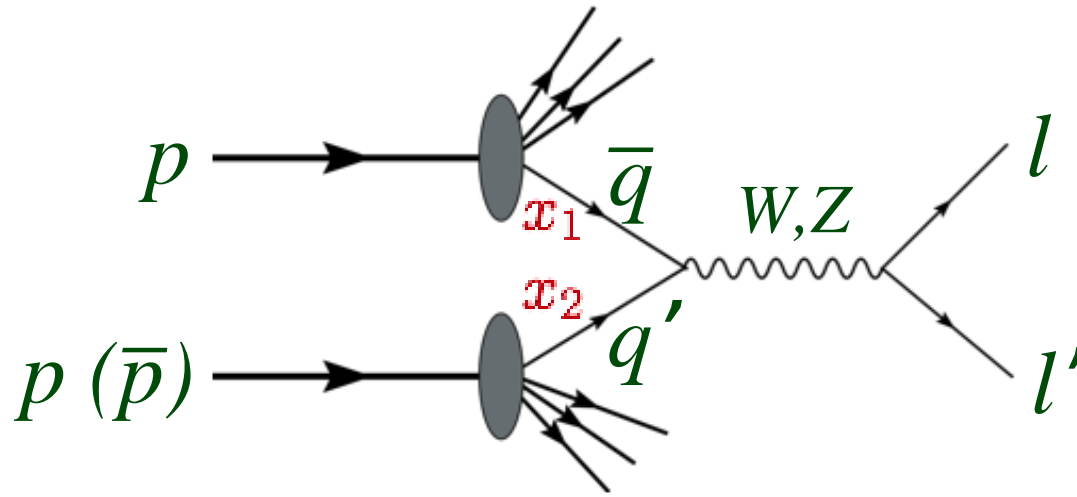
Quasi-free neutrons from MARATHON

Approved JLAB12 experiment



□ Nuclear corrections largely cancel in the ratio of $^3\text{He}/^3\text{H}$ cross sections

W,Z production



- Example: W and decay lepton charge asymmetry at large rapidity

$$A_W(y) = \frac{\sigma(W^+) - \sigma(W^-)}{\sigma(W^+) + \sigma(W^-)} \approx \frac{d/u(x_2) - d/u(x_1)}{d/u(x_2) + d/u(x_1)} \quad [x_1 \gg x_2]$$

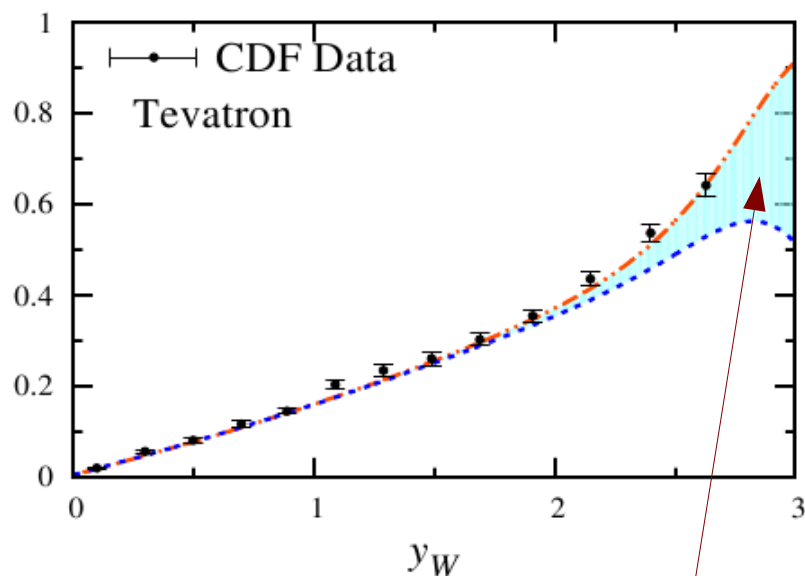
$$A_l(y) = A_W \otimes B_{W \rightarrow l}(y)$$

W charge asymmetry at Tevatron

Brady, Accardi, Melnitchouk, Owens, JHEP 1206 (2012) 019

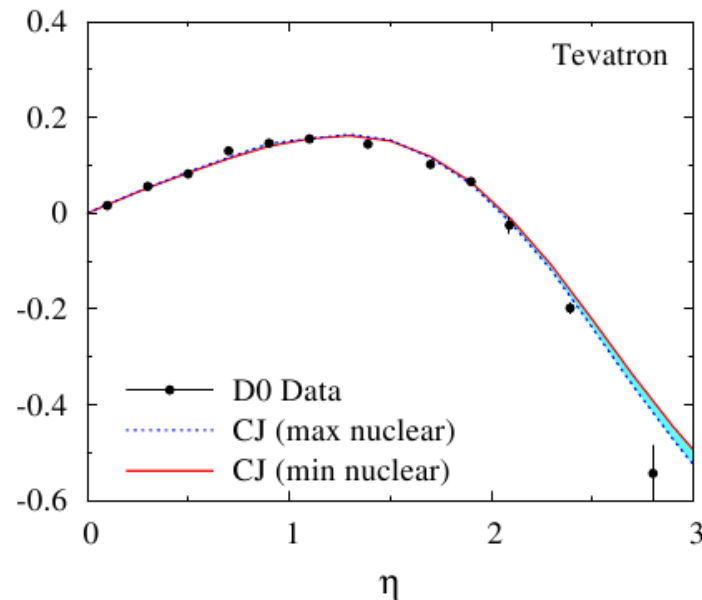
Directly reconstructed W:

- highest sensitivity to large x



From decay lepton $W \rightarrow l + \nu$:

- smearing in x



sensitive to
 d at high x

Can constrain
Nuclear models!

❑ Too little large- x sensitivity in lepton asymmetry:

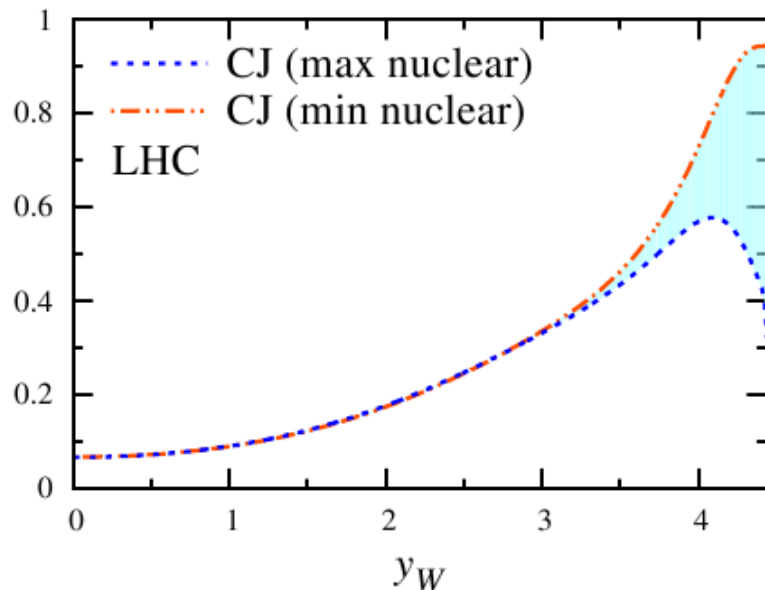
— need reconstructed W (but: correlation to PDF used in exp. analysis...)

W charge asymmetry at LHC

Brady, Accardi, Melnitchouk, Owens, *JHEP* 1206 (2012) 019

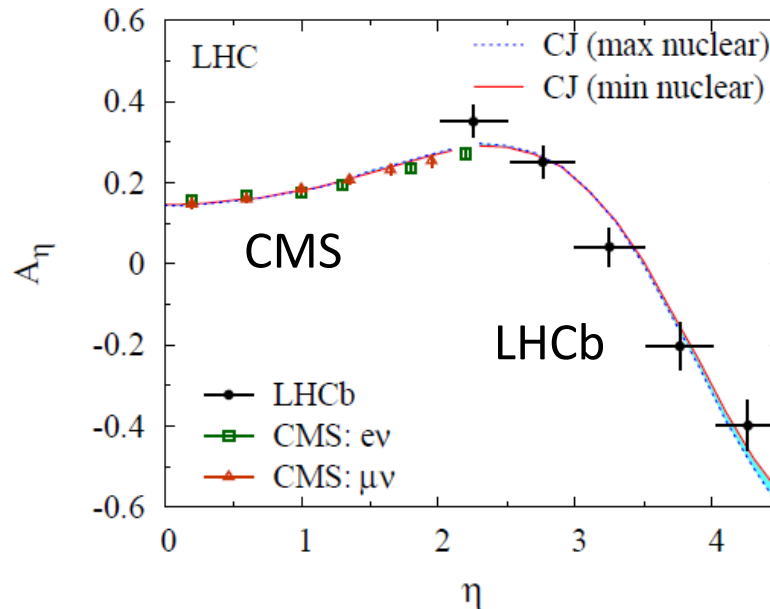
Directly reconstructed W:

➤ highest sensitivity to large x



From decay lepton $W \rightarrow l+\nu$:

➤ smearing in x

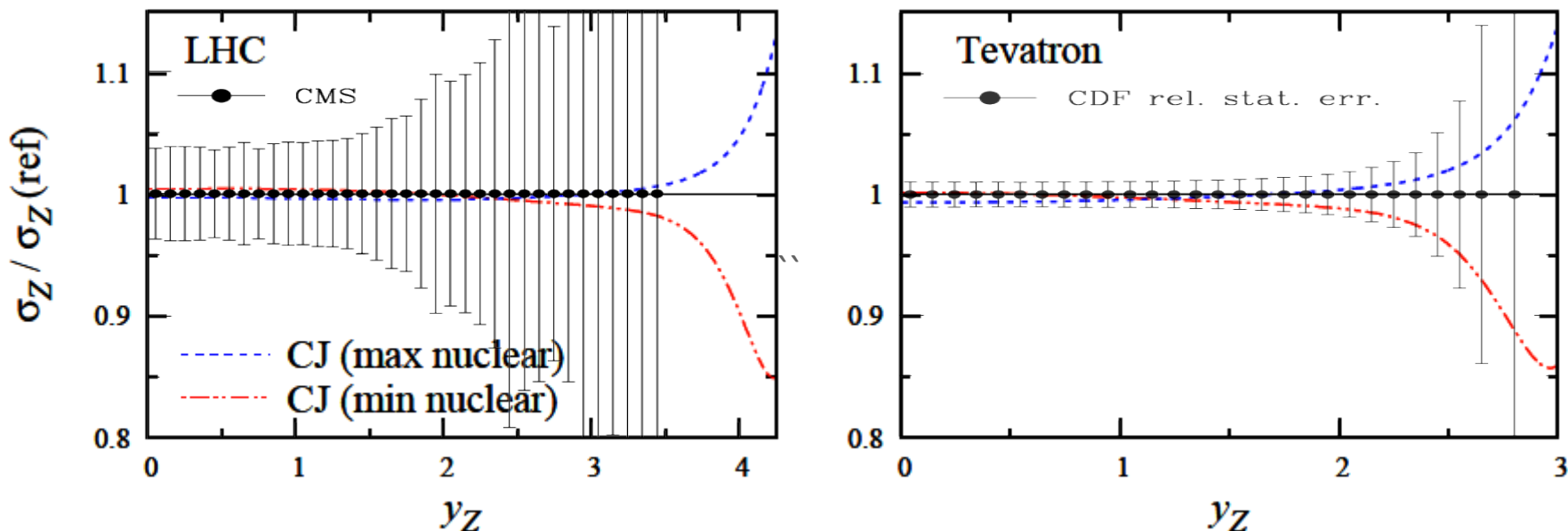


❑ Would be nice to reconstruct W at LHCb

- Definitely needs more statistics
- Is it at all possible?? (too many holes in detector?)
- Systematics in W reconstruction?
- **What about RHIC, AFTER@LHC?**

Z rapidity distribution

Brady, Accardi, Melnitchouk, Owens, *JHEP* 1206 (2012) 019

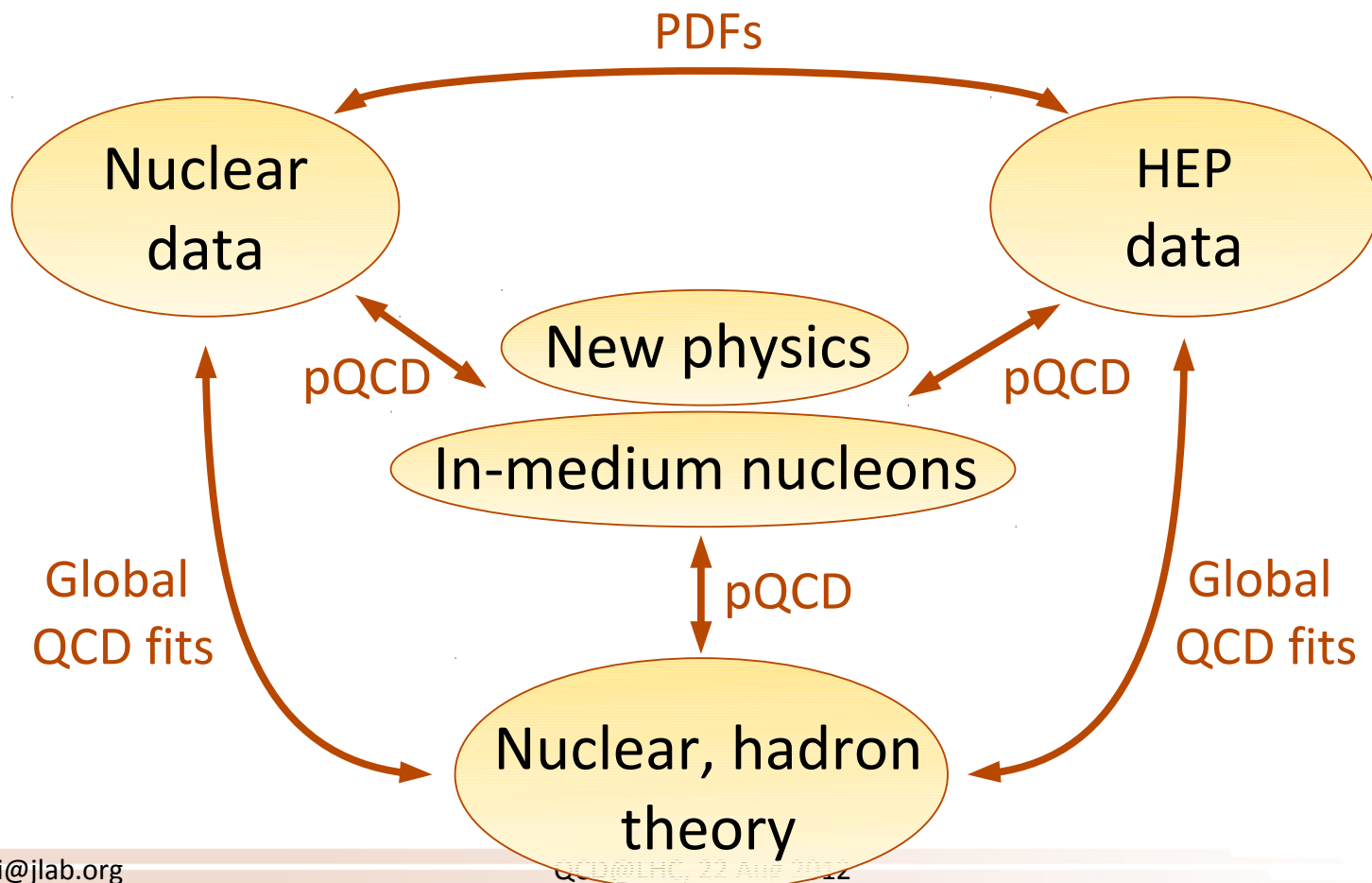


- ❑ Direct Z reconstruction is unambiguous in principle, but:
 - Needs better than 5-10% precision at large rapidity
 - Experimentally achievable?
 - At LHCb? RHIC? AFTER@LHC?
 - Was full data set used at Tevatron?

Summary

□ Ongoing CTEQ-JLab global fits attacking large-x PDFs:

- integrate across hadronic physics
- connect with rest of subatomic physics



Plans

□ In preparation / near future

- Fits with latest data (HERA combined, LHC @ 7 TeV)
- Correlated errors where available; tensions between data sets
- Public release of PDF + error sets (and accompanying software)
- LHC / RHIC / E906 phenomenology
- Will be ready to fully exploit JLab 12 GeV upgrade, next generation exp's

□ Longer term

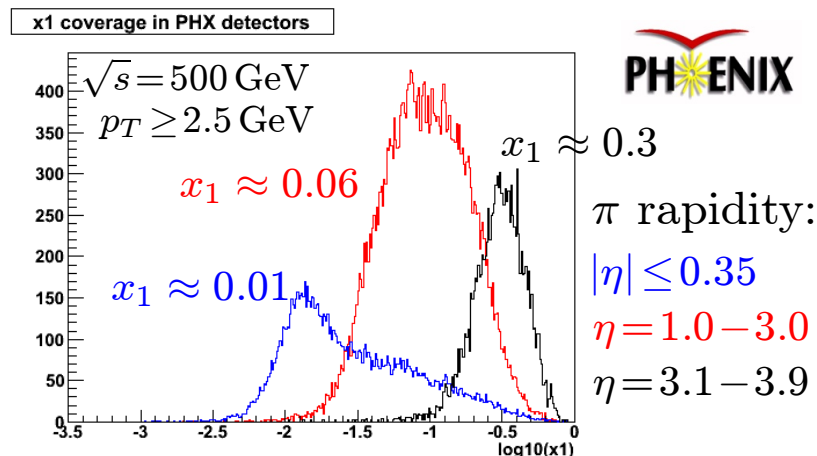
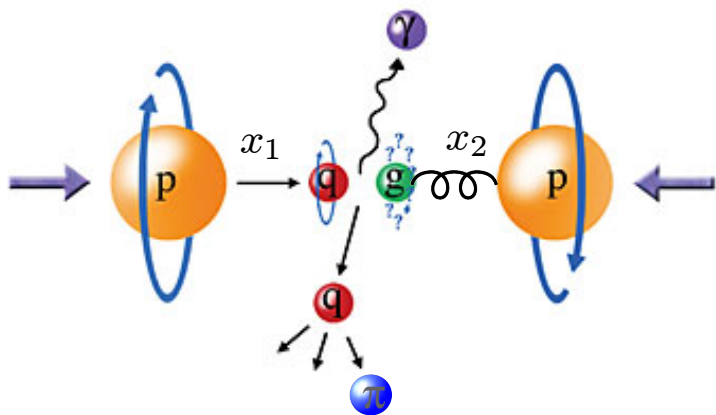
- F_L / σ data on deuterium (large-x gluons); heavy quarks
- large-x resummation, jet mass corrections, quark-hadron duality
- better off-shell corrections, extend to gluons
- Integration to MCFM generator
- Monte Carlo PDF errors

Backup slides

Small x gluons at colliders: hadronic structure

- Gluon spin at small x at RHIC requires particle production at large y

$$\sigma(\vec{p}\vec{p} \rightarrow \pi^0 X) \propto \Delta q(x_1) \Delta g(x_2) \hat{\sigma}^{qg \rightarrow qg} D_q^{\pi^0}(z)$$



$$x_1 \sim \frac{p_T}{\sqrt{s}} e^y \quad x_2 \sim \frac{p_T}{\sqrt{s}} e^{-y}$$

- Precise large-x PDFs needed:
 - to measure smallest-x gluon helicity

Valence quarks at large x

□ d/u quark ratio particularly sensitive to quark dynamics in nucleon

□ **SU(6) spin-flavor symmetry**

– proton wave function

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

interacting
quark

spectator
diquark

diquark spin

Valence quarks at large x

□ d/u quark ratio 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% $(qq)_1$ 50% $(qq)_0$, $u = 2d$ at all x

$$\frac{d}{u} = \frac{1}{2} \implies \frac{F_2^n}{F_2^p} = \frac{2}{3}$$

Valence quarks at large x

Broken SU(6) : scalar diquark dominance

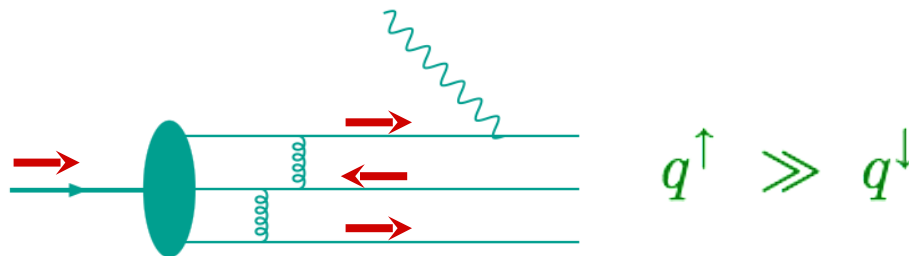
- $M_{\Delta} > M_N \Rightarrow (qq)_1$ has larger energy than $(qq)_0$
- But only u quark couples to scalar diquark:

$$\frac{d}{u} \rightarrow 0 \quad \Longrightarrow \quad \frac{F_2^n}{F_2^p} \rightarrow \frac{1}{4}$$

*Feynman 1972, Close 1973
Close/Thomas 1988*

Broken SU(6) : hard gluon exchange

- helicity of struck quark = helicity of struck hadron



$$\frac{d}{u} \rightarrow \frac{1}{5} \quad \Longrightarrow \quad \frac{F_2^n}{F_2^p} \rightarrow \frac{3}{7}$$

Farrar, Jackson, 1975

The mKP off-shell nucleon model

Accardi et al. PRD 84, 014008 (2011)

- Nucleon at large x = valence quark + spectator diquark

$$q_v(x, p^2) = \int ds \int_{-\infty}^{k_{\max}^2} dk^2 D_{q/N}(s, k^2, x, p^2)$$

Nucleon virtuality

diquark
inv. mass squared

Quark virtuality

- Quark spectral function, with spectator diquark

$$D_{q/N} \approx \delta(s - s_0) \Phi(k^2, \Lambda(p^2)) \quad [s_0 = 2.1 \text{ GeV}^2 \text{ from fits}]$$

Cutoff scale

- Physical interpretation: nucleon size changes with p^2 : $R_N \sim 1/\Lambda$

The mKP off-shell nucleon model

Accardi et al. PRD 84, 014008 (2011)

- Expand $F_2(N)$ to first order in virtuality:

$$F_2^N(x, Q^2, p^2) = F_2^N(x, Q^2) \left(1 + \delta f_2(x, Q^2) \frac{p^2 - M^2}{M^2} \right)$$

- In the mKP model

$$\delta f_2 = c + \frac{\partial \log q_v}{\partial x} x(1-x) \frac{(1-\lambda)(1-x)M^2 + \lambda s_0}{(1-x)^2 M^2 - s_0}$$

- Only 1 free parameter

$$\lambda = \left. \frac{\partial \log \Lambda^2}{\partial \log p^2} \right|_{p^2=M^2} = -2(\delta R_N / R_N)(\delta p^2 / M^2)$$

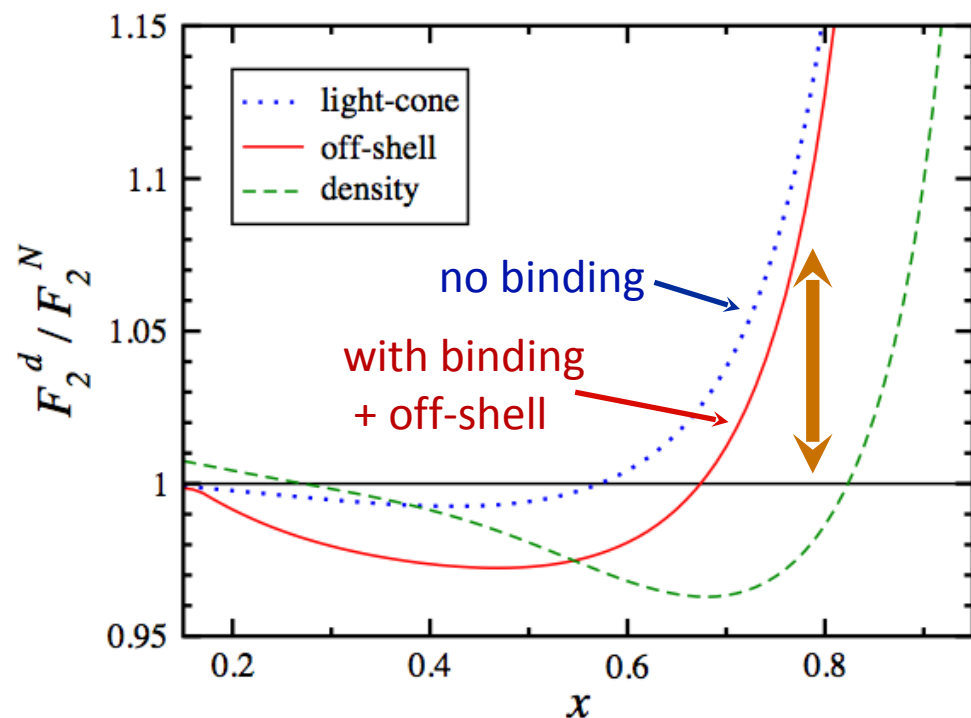
Physical interpretation:
nucleon size changes with p^2 : $R_N \sim 1/\Lambda$

$$\delta p^2 = \langle p^2 - M^2 \rangle$$

$$\int d^4 p (p^2 - M^2) \mathcal{S}_d(y)$$

Nuclear corrections

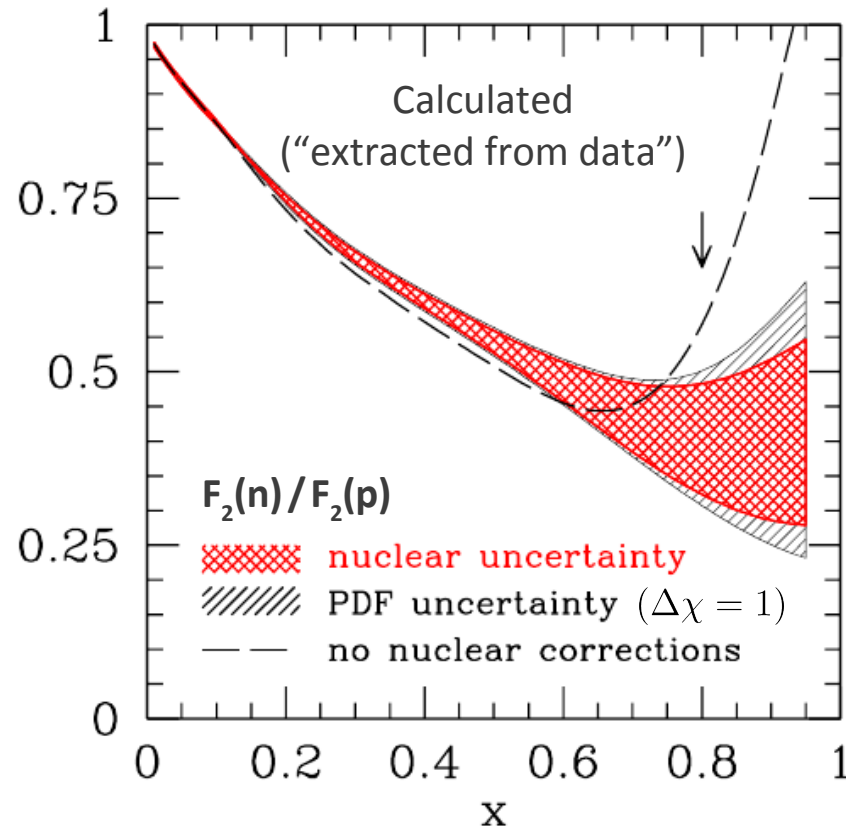
$$F_{2d}(x_B, Q^2) = \int_{x_B}^A dy \mathcal{S}_A(y, \gamma) F_2^{TMC+HT}(x_B/y, Q^2) \left(1 + \frac{\delta^{off} F_2(x)}{F_2(x)} \right)$$



- Using off-shell model, obtains *larger neutron* (larger d) than light-cone model
- But smaller *neutron* (larger d) than no nuclear effects or density model

The CTEQ-JLab $F_2(n) / F_2(p)$

Accardi et al. PRD 84, 014008 (2011)



- Well behaved extrapolation for each nuclear model
 - however, beware of remaining PDF “parametrization bias”
- Needs some realistic nuclear corrections, or obtains non-sense results