Large-x connections nuclear and particle physics

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Hampton U. - Nuclear Physics Seminar
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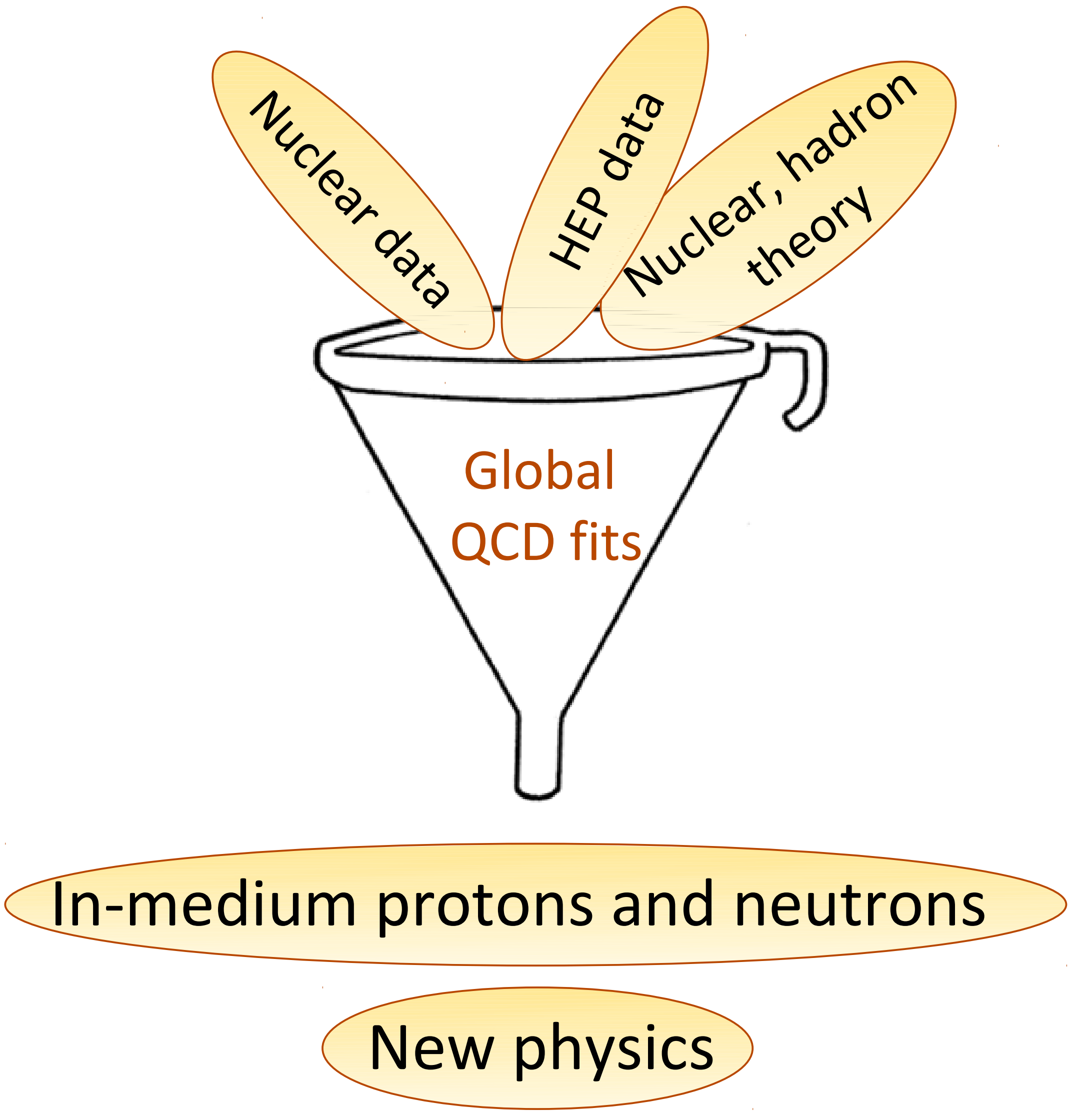
"The coherence provided by QCD means that insights [into hadron structure] may arise from unexpected quarters.

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


Nuclear data
HEP data
Nuclear, hadron theory
Global QCD fits
In-medium protons and neutrons
New physics

Overview

– **Why large *x*?**

– **The CTEQ-JLab fits**
  - TMCs, HTs, nuclear corrections, *d*-quark parametrization

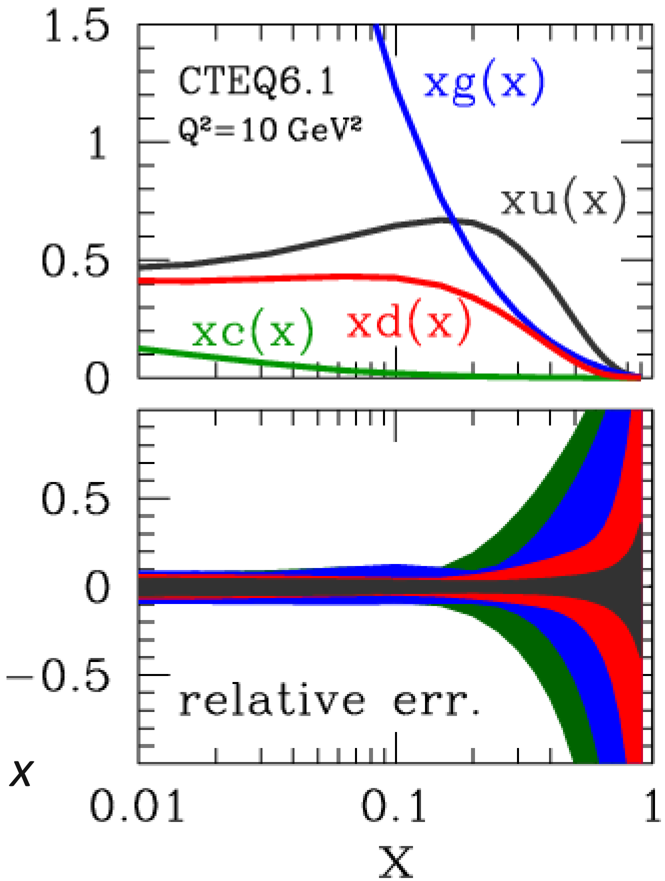
– **Applications**
  - *d*/*u* ratio extrapolated to *x*=1
  - Parton luminosities, *W'* and *Z'* production

– **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 $x \to 1$
  - at LHC, Tevatron
    - New physics as excess on QCD large p_T spectra ⇔ 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

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

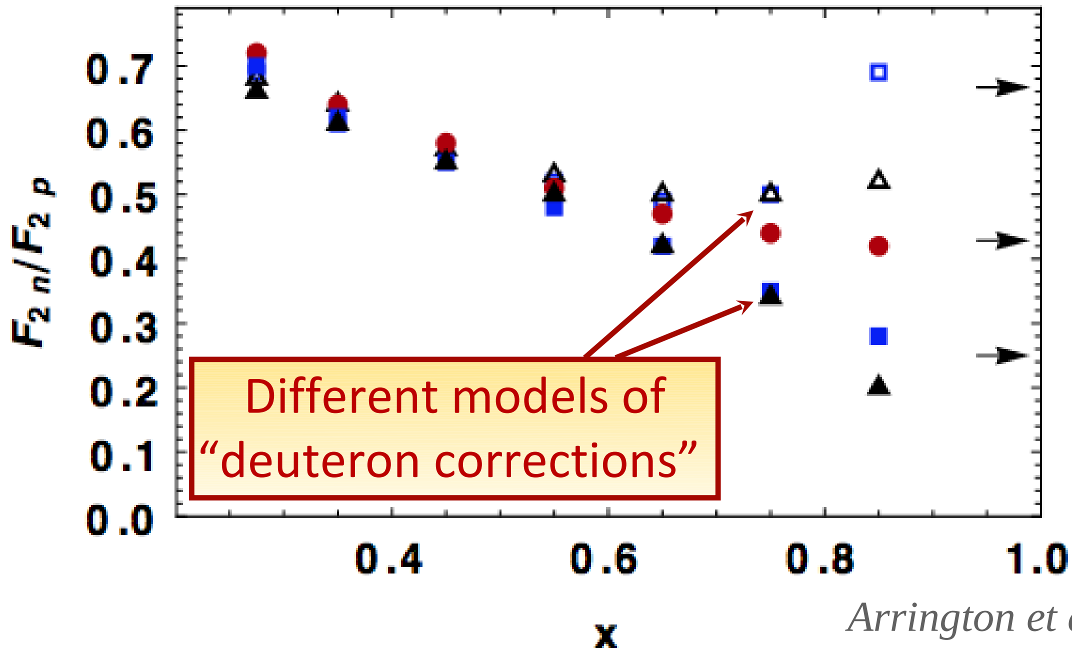
  - *u* quark distribution well determined from proton data
  - *d* quark distribution requires neutron structure function

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

But… deuteron corrections!

- Absence of free neutron targets
  $\Rightarrow$ use deuterons (weakly bound *p* and *n*)

Non-perturbative proton models



SU(6) spin-flavor

hard gluon exchange

S=0 diquark dominance

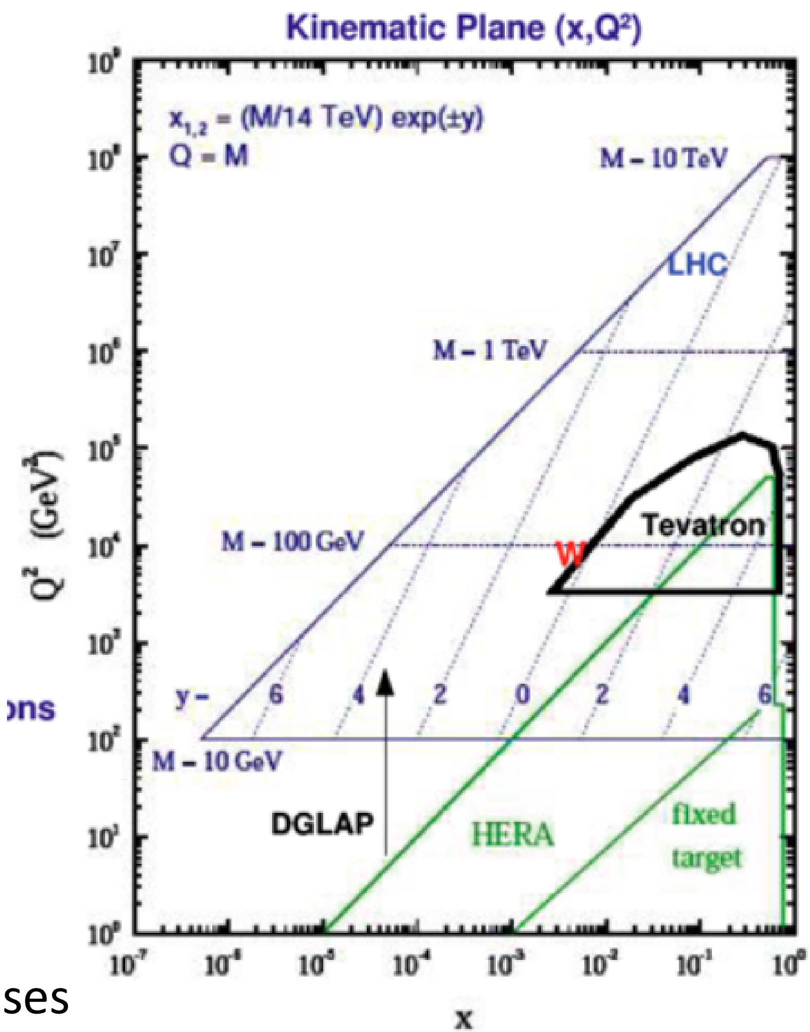
Arrington et al. arXiv:1110.3362

- 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 $M_Z' \gtrsim 1$ 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”** ← Available on request
  - New fit in preparation with latest data ← 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

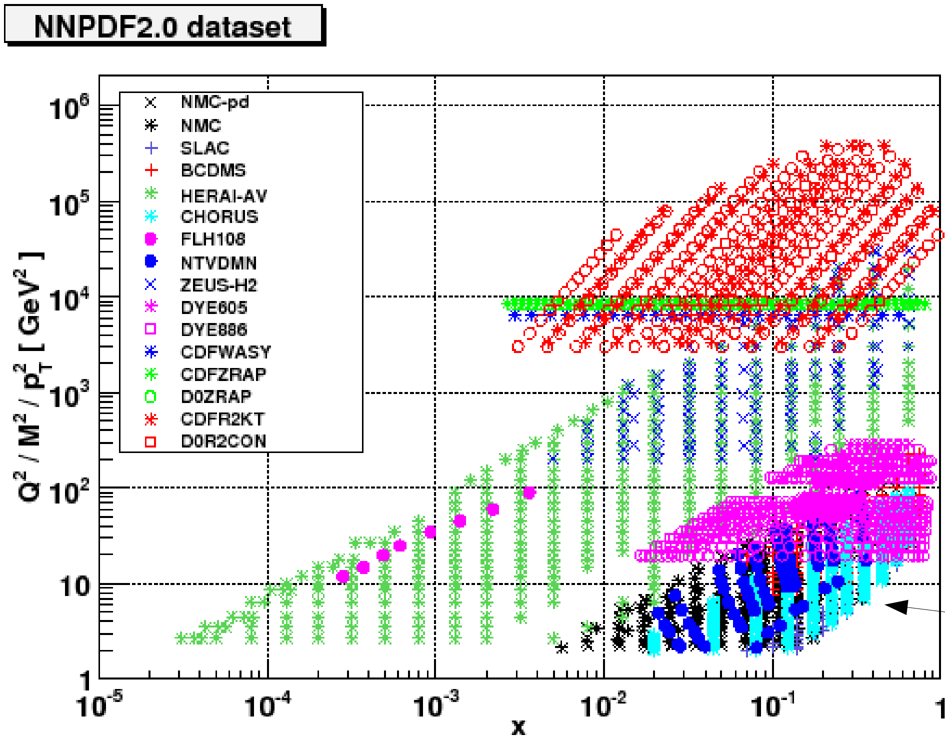
PDFs

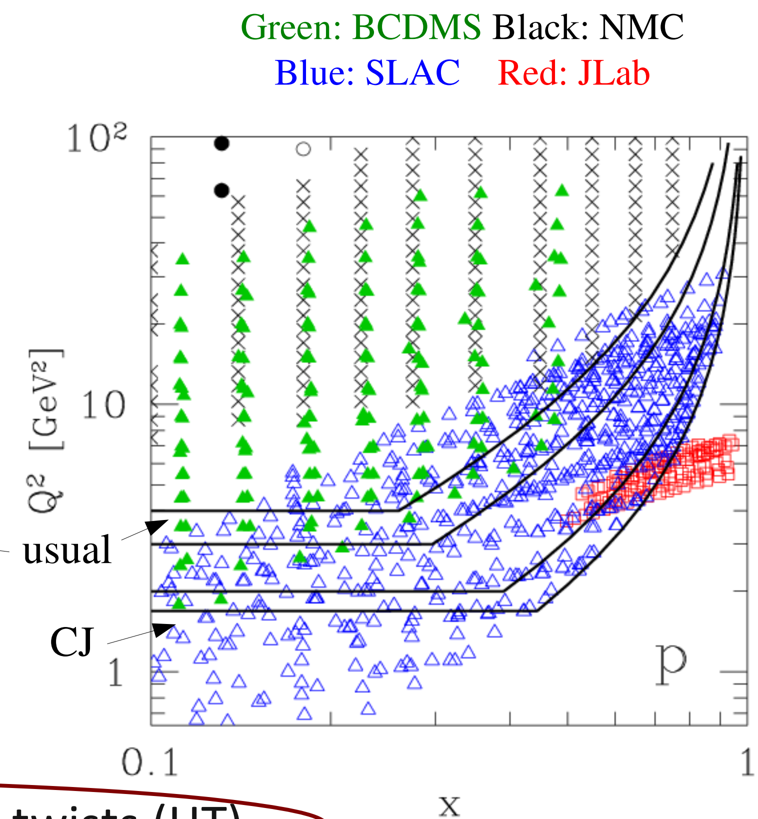
$F_2(n)$

W, Z / W',Z', Higgs

(or any other "hard" observable)

Large-x, small-Q^2 corrections





- **1/Q^{2n} suppressed:**
  - Target mass corrections (TMC), higher-twists (HT)
  - Current jet mass, quark mass, large-*x* QCD evol.
- **Non-suppressed**
  - Nuclear corrections, threshold resum., parton recomb.

included in CJ fits

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 ≈ 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 $x \to 1$ 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"

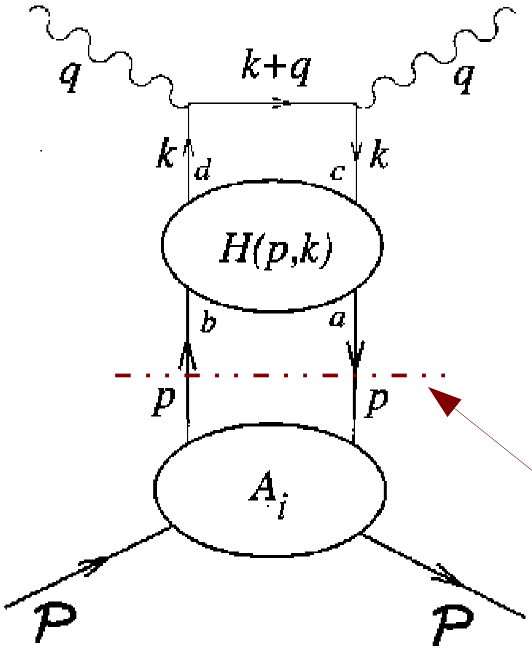
Calculated from nuclear wave-function:

- CD-Bonn
- AV18

} non-relativistic

- WJC-2
- 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

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

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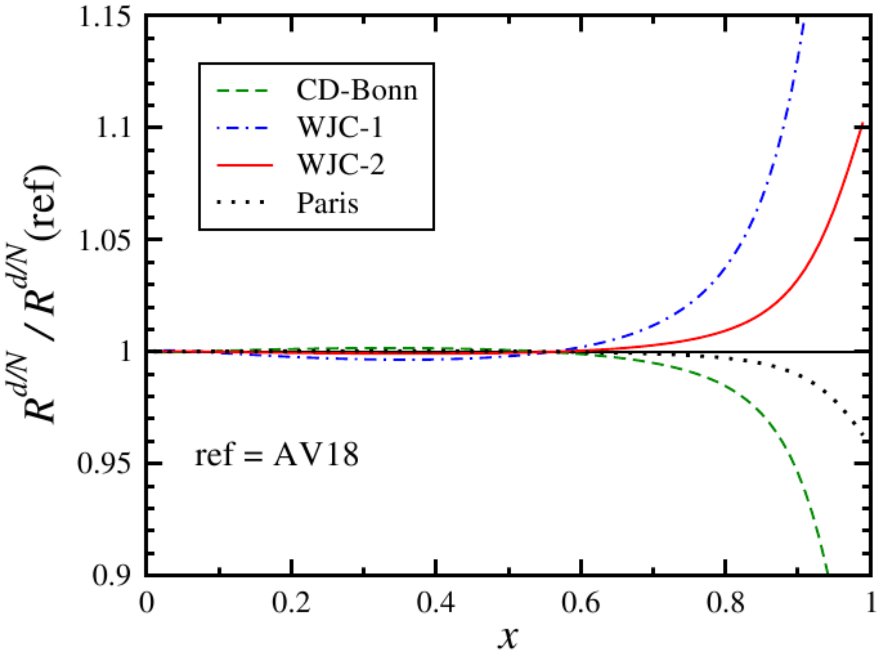
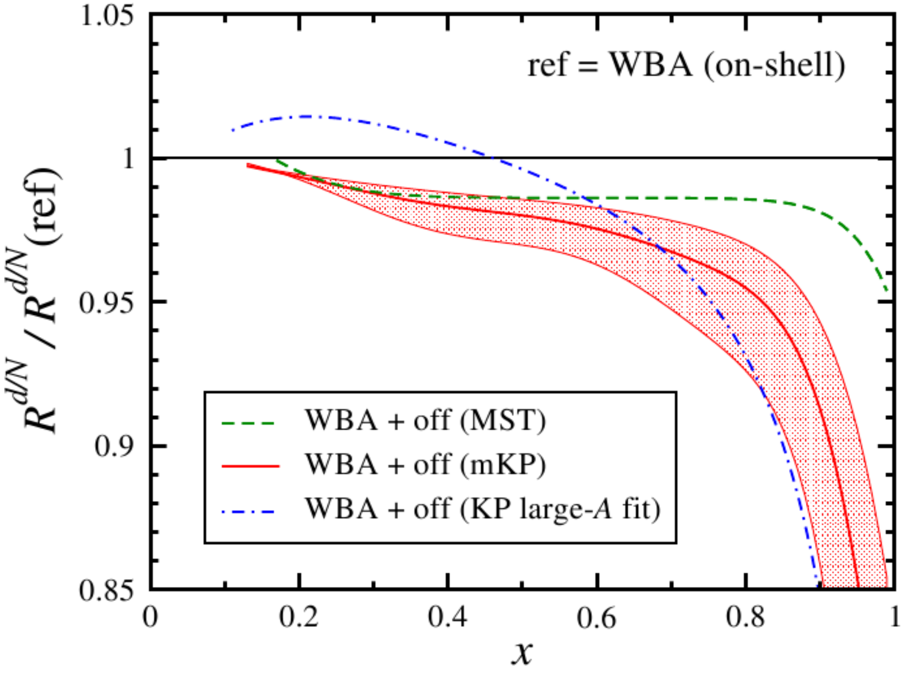
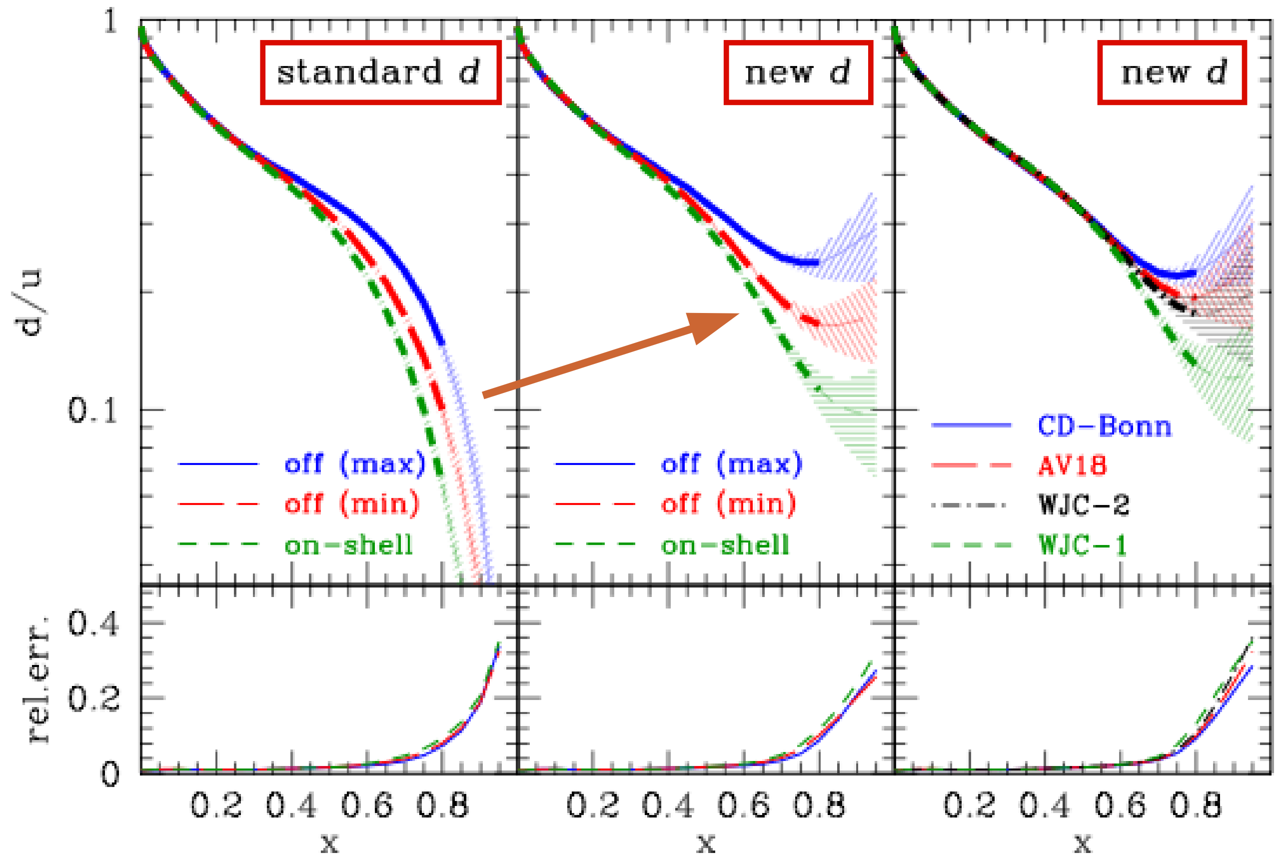




CJ fits: effect of *d*-quark parametrization

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

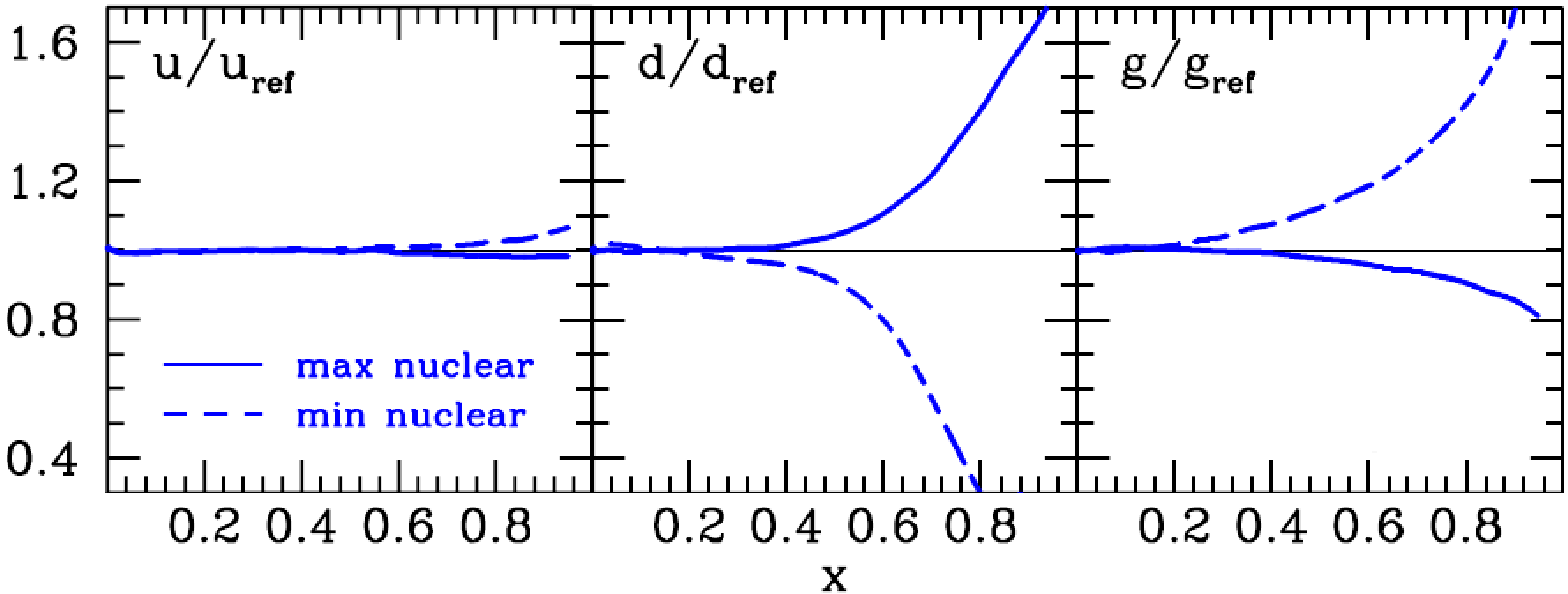


- **Dramatic increase in *d* PDF as x ⟶ 1** with more flexible parametrization

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

CJ fits: nuclear model systematic error

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

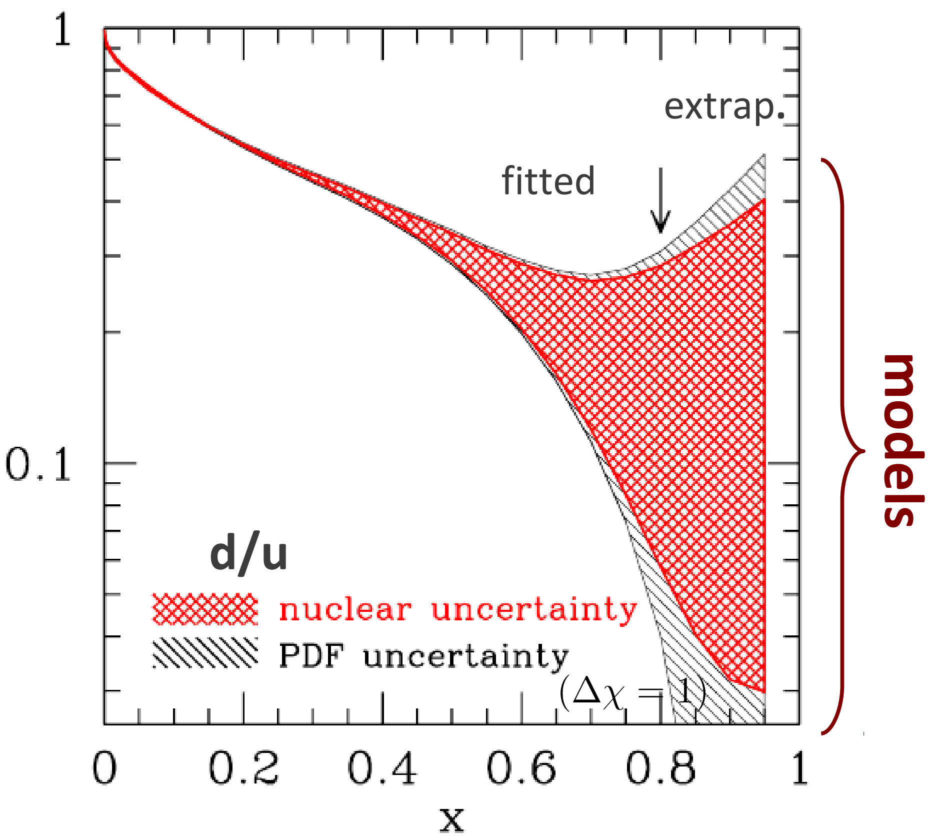


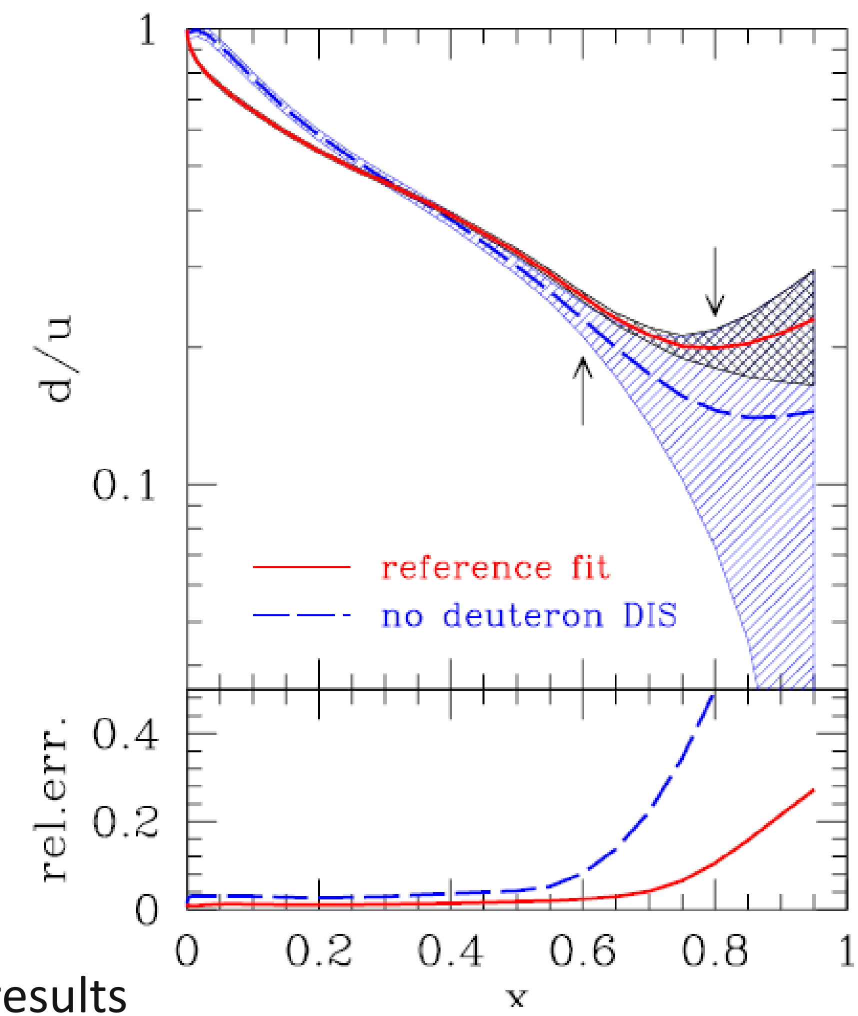
- **Large sensitivity to nuclear corrections model**
  - *d-quarks*: directly, due to corrections applied to $F_2(d)$
  - *gluons:* due to correlation with d-quarks induced by jet data

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

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

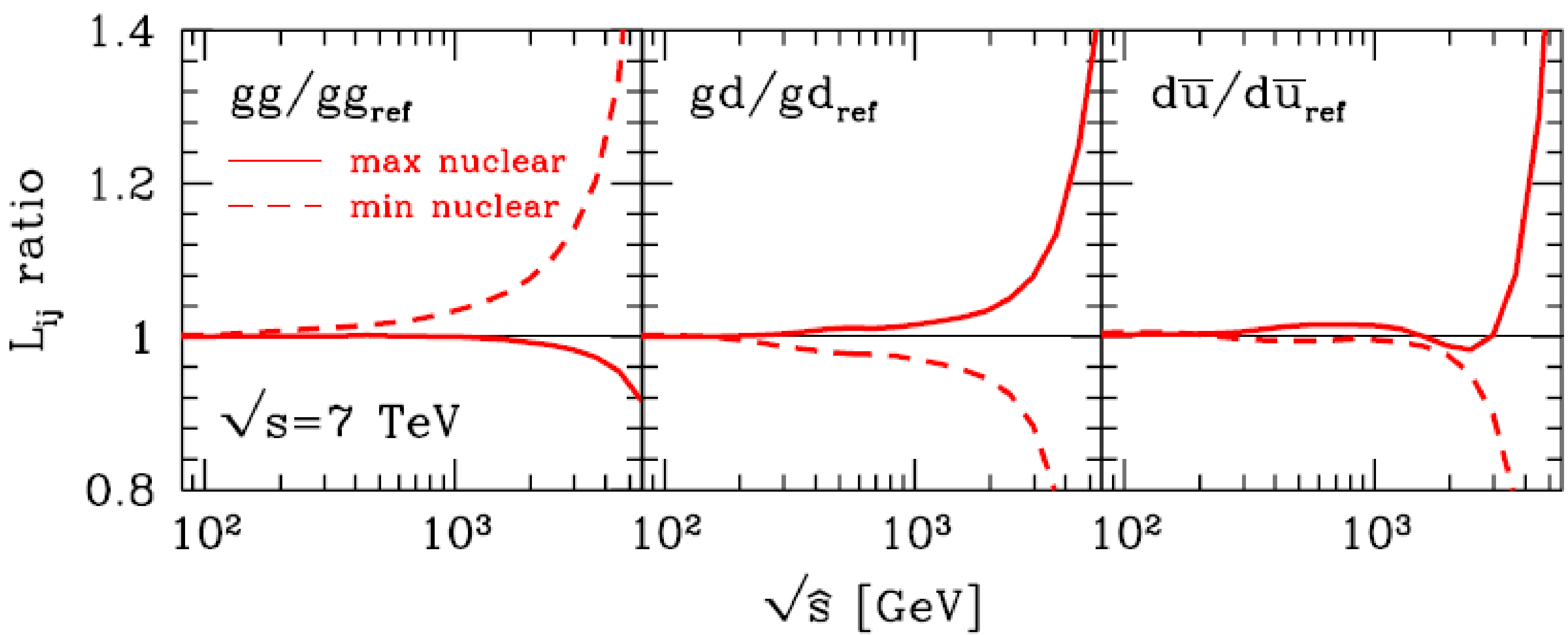
Application:
Parton Luminosities
W',Z' bosons

Parton luminosities

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

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

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



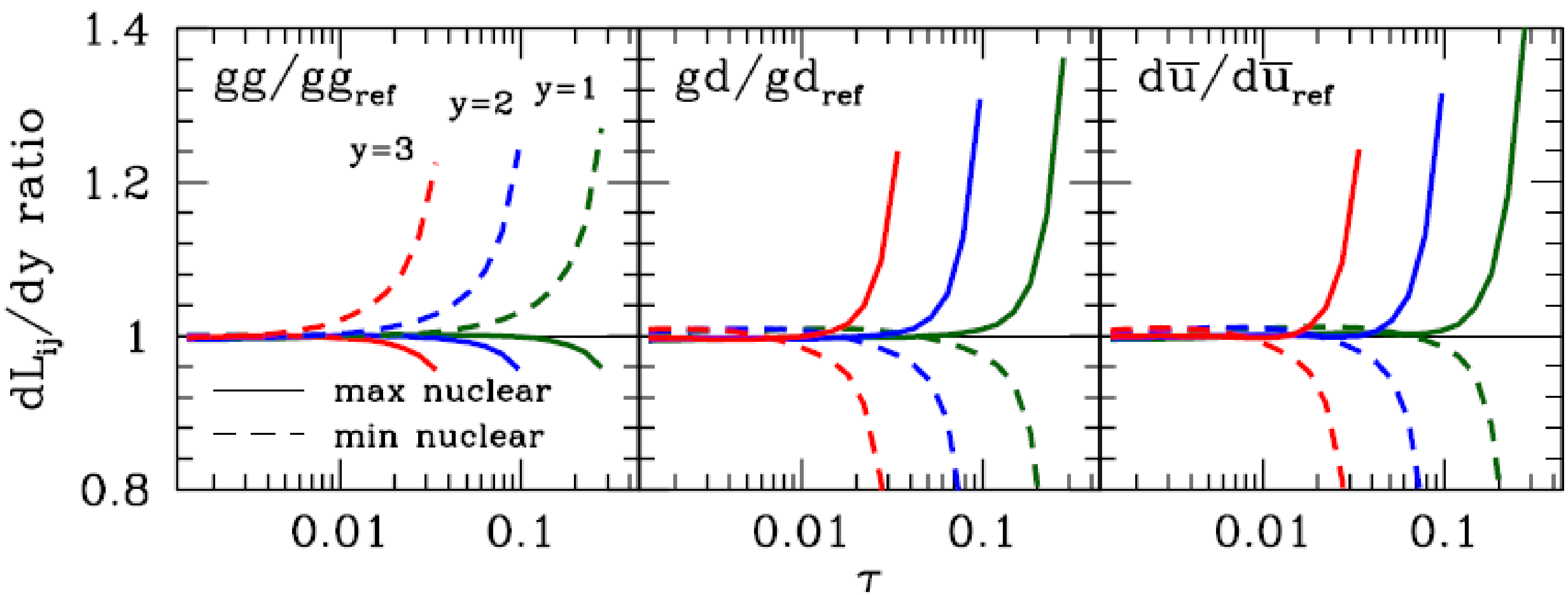
Parton luminosities

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

- … or large rapidity:

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

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



(Note: ratios are largely independent of *s*)

Heavy *W'* and *Z'* boson production

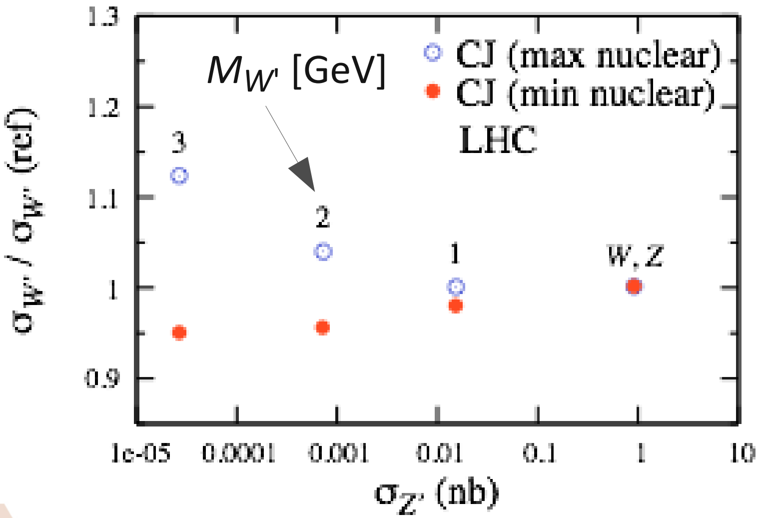
Brady, Accardi, Melnitchouk, Owens, JHEP 1206 (2012) 019

- 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}He/^{3}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)*
  - ν+*p*, $\bar{\nu}$+*p* **Minerva ???**
  - *p+p*, *p+*$\bar{p}$ at large positive rapidity
    - *W* charge asymmetry, *Z* rapidity distribution

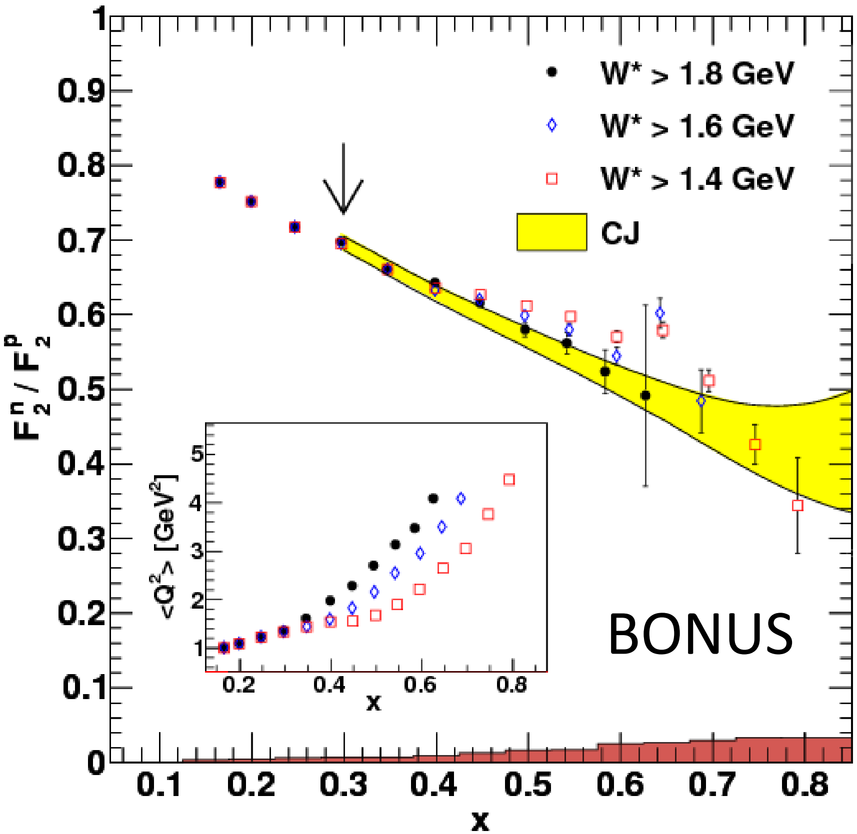
Tevatron: D0, CDF??
LHCb?? RHIC ??
AFTER@LHC

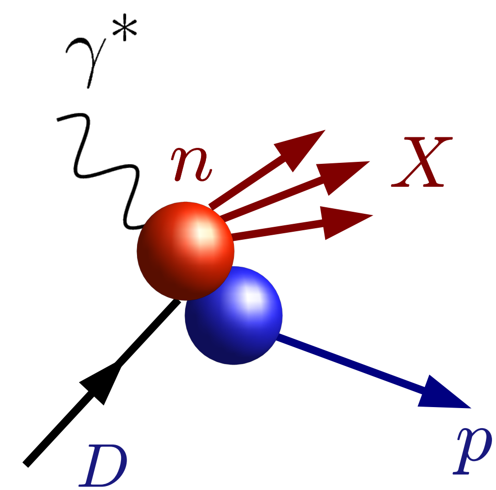
- **Cross-check data**
  - *p+d* at large negative rapidity – dileptons; *W*, *Z*
    - Sensitive to nuclear corrections, cross-checks *e+d*

RHIC ??
AFTER@LHC

Quasi-free neutrons from BONUS

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

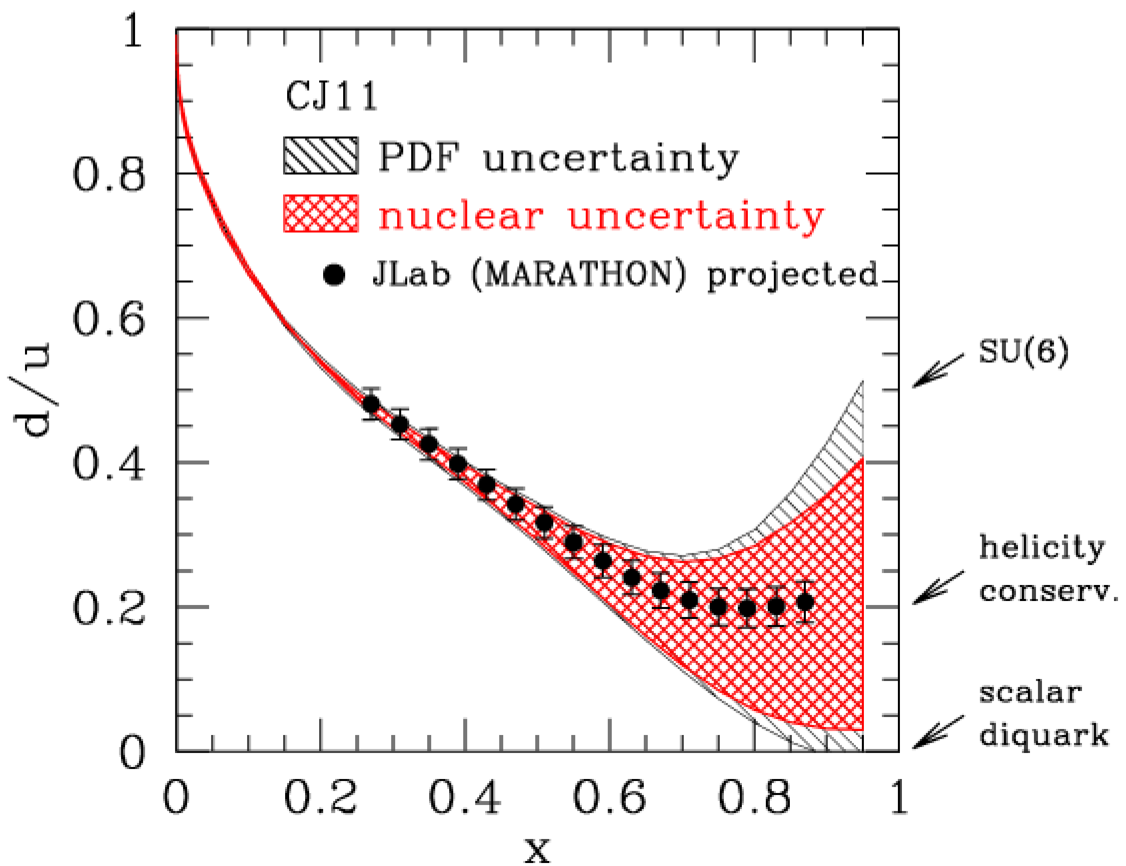


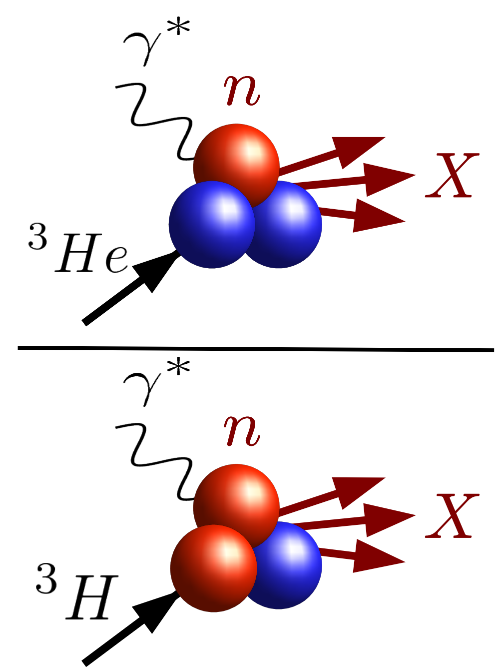


- DIS data (black disks) too uncertain at $x > 0.5$
  - Need to wait for BONUS12 / MARATHON

Quasi-free neutrons from MARATHON

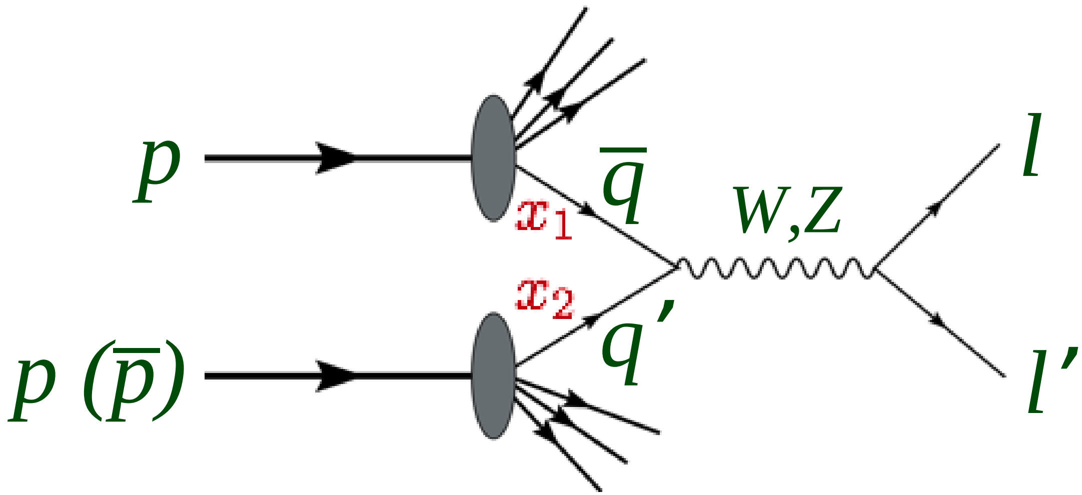
Approved JLAB12 experiment





- Nuclear corrections largely cancel in the ratio of $^3He/^3H$ cross sections

W,Z production



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

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

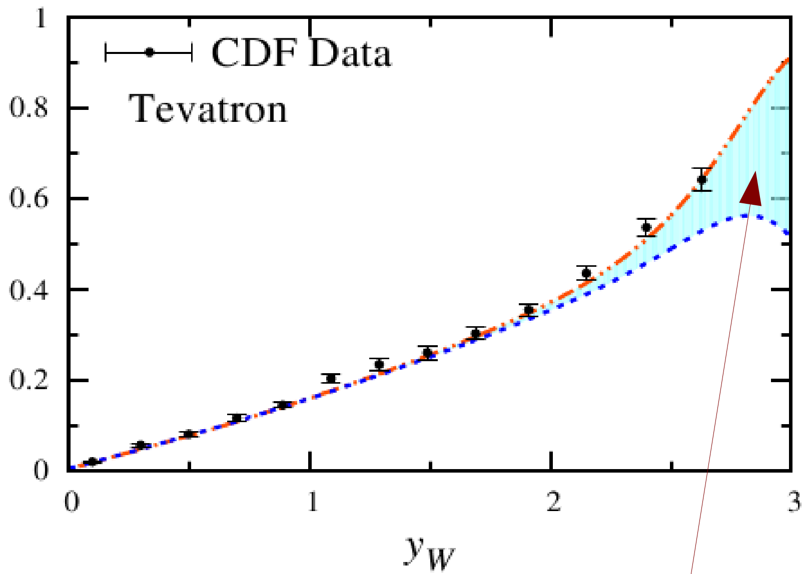
$$A_l(y) = A_W \otimes B_{W\to l}(y)$$

W charge asymmetry at Tevatron

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

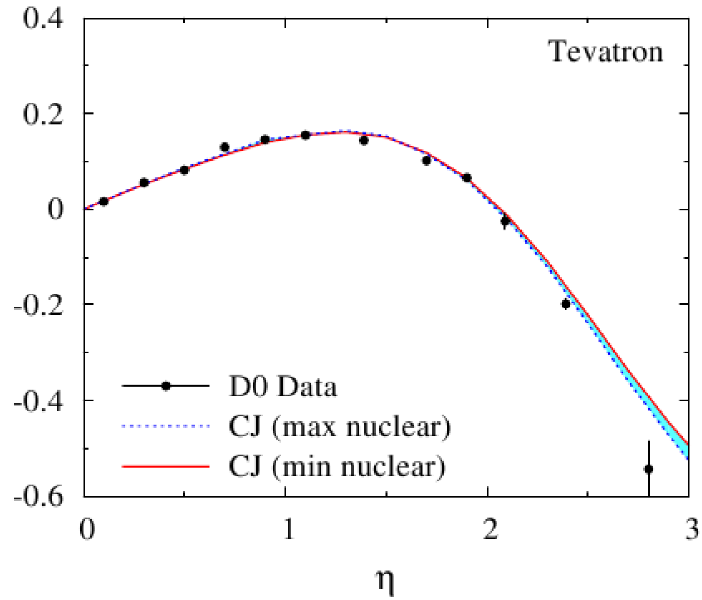
Directly reconstructed W:

- highest sensitivity to large *x*



From decay lepton W → l+ν:

- smearing in *x*



sensitive to *d* at high *x*

Can constrain Nuclear models!

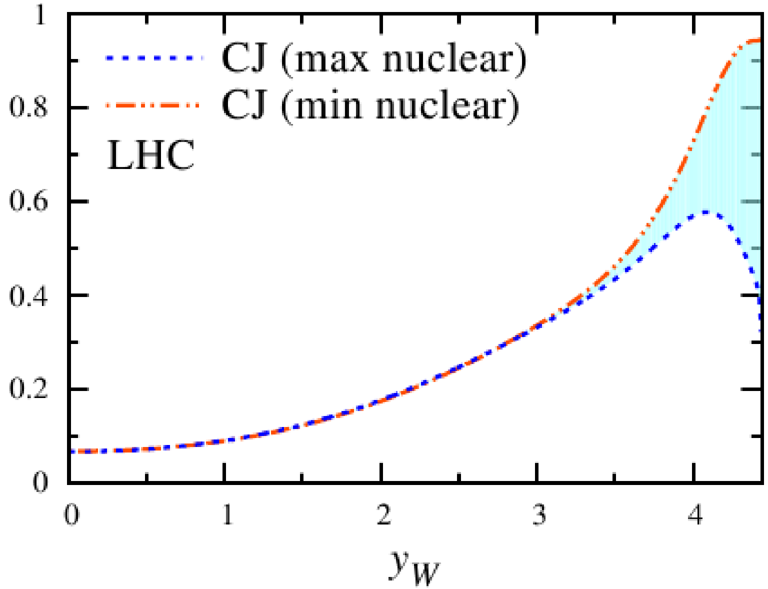
- Too little large-*x* sensitivity in lepton asymmetry:
  - **need reconstructed *W*** (but: correlation to PDF used in exp. analysis…)

W charge asymmetry at LHC

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

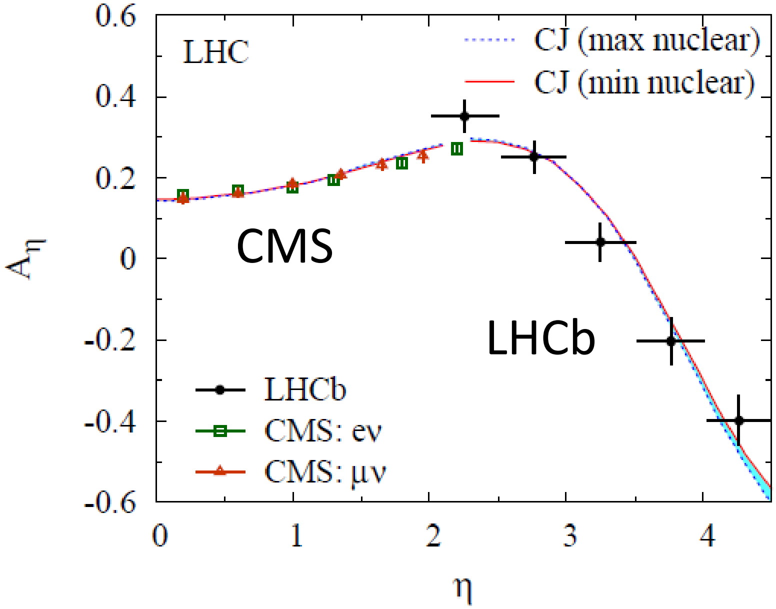
Directly reconstructed W:

- highest sensitivity to large *x*



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

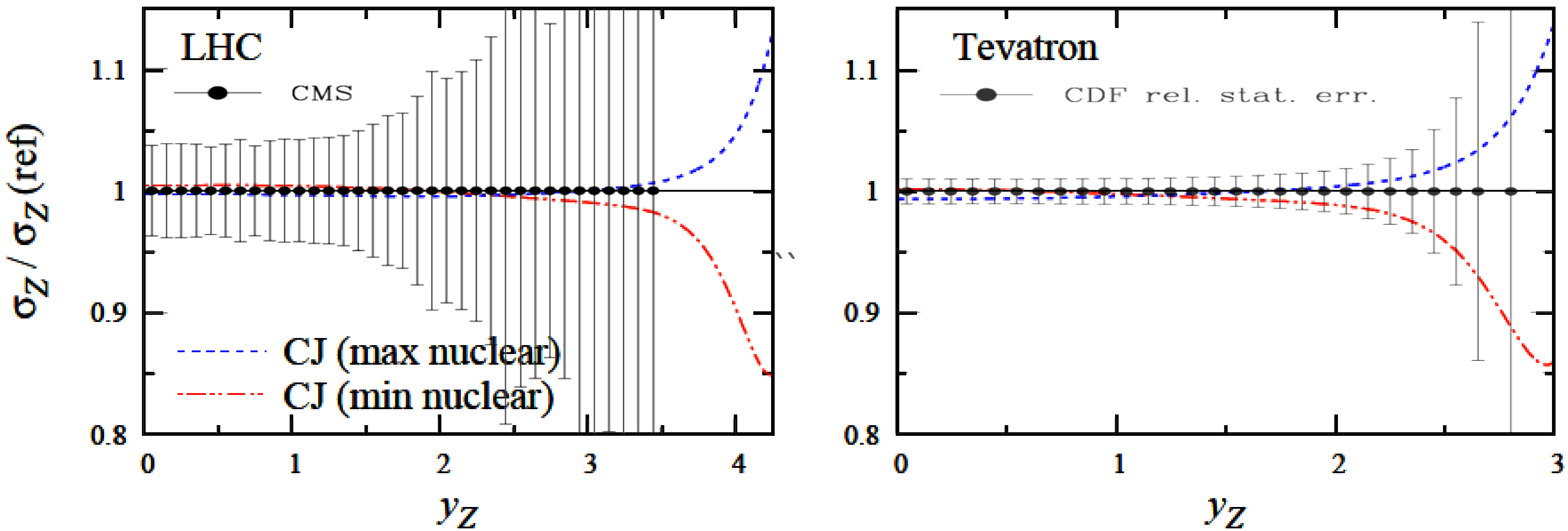
- smearing in *x*



- **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

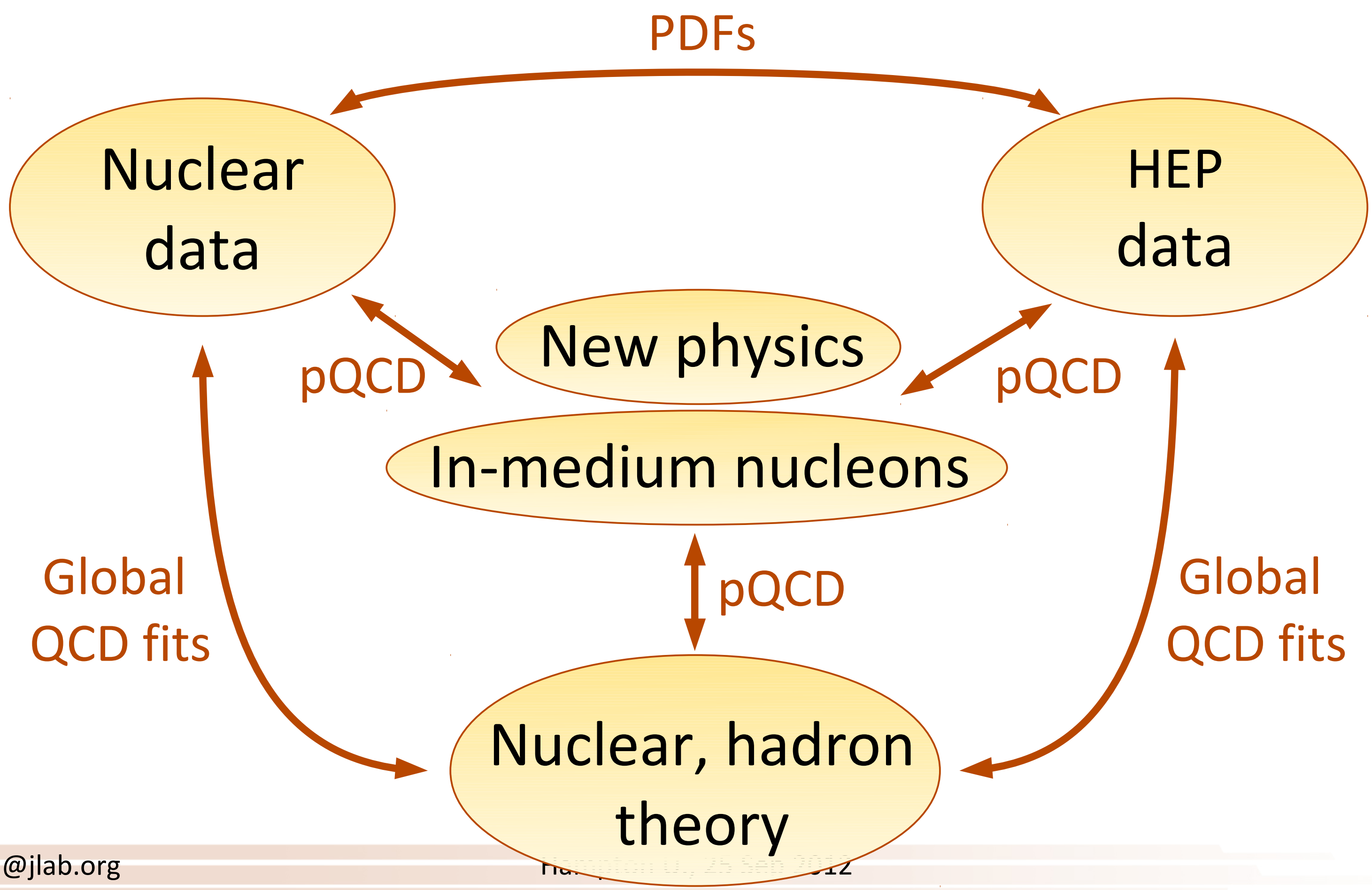
Brady, Accardi, Melnitchouk, Owens, JHEP 1206 (2012) 019



- 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

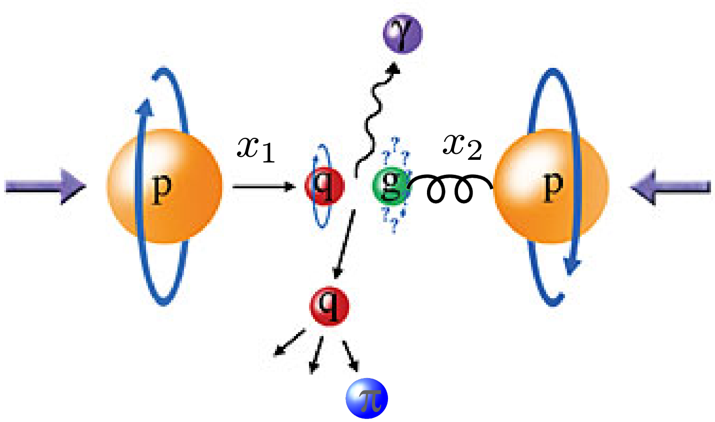
- **Longer term**
  - F_L / σ data on deuterium (large-*x* gluons); heavy quarks
  - large-*x* resummation, jet mass corrections, quark-hadron duality
  - better off-shell corrections, extend to gluons
  - Integration to MCFM generator
  - Monte Carlo PDF errors

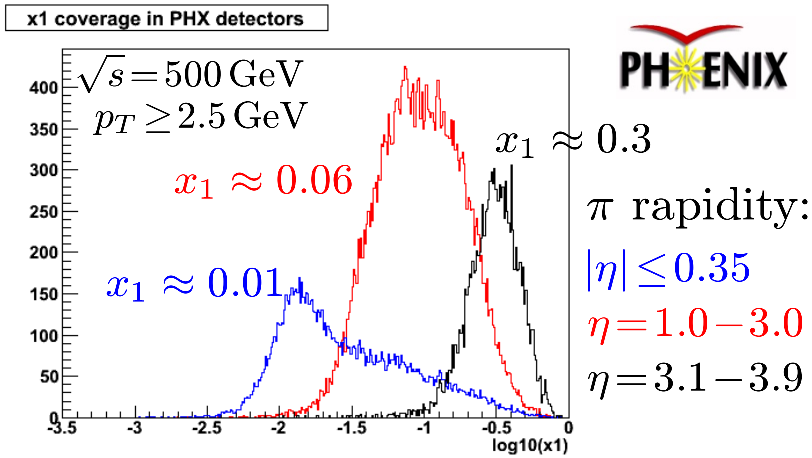
Backup slides

Small x gluons at colliders: hadronic structure

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

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





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

- 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

diquark spin

spectator diquark

Valence quarks at large x

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

\

  - 50% $(qq)_1$ 50% $(qq)_0$, $u = 2d$ at all x

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

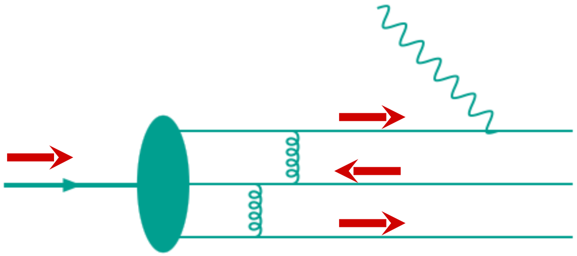
Valence quarks at large *x*

- **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:

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

Feynman 1972, Close 1973
Close/Thomas 1988

- **Broken SU(6) : hard gluon exchange**
  - helicity of struck quark = helicity of struck hadron



$$q^\uparrow \gg q^\downarrow$$

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

Farrar, Jackson, 1975

The mKP off-shell nucleon model

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

- Nucleon at large *x* = valence quark + spectator diquark

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

Nucleon virtuality

diquark inv. mass squared

Quark virtuality

  – Quark spectral function, with spectator diquark

$$D_{q/N} \approx \delta(s-s_0)\,\Phi(k^2,\Lambda(p^2))$$

[s_0 = 2.1 GeV^2 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

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

  – Only 1 free parameter

$$\lambda = \partial \log \Lambda^2/\partial \log p^2\big|_{p^2=M^2} \;=\; -2(\delta R_N/R_N)(\delta p^2/M^2)$$

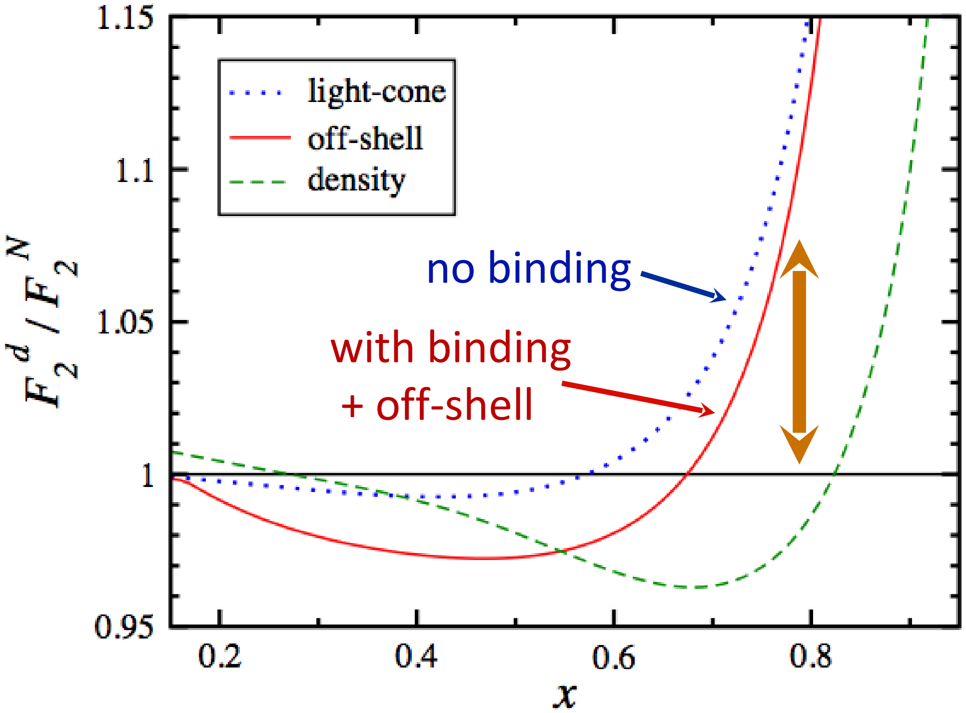
Physical interpretation:
nucleon size changes with p^2: $R_N \sim 1/\Lambda$

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

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

Nuclear corrections

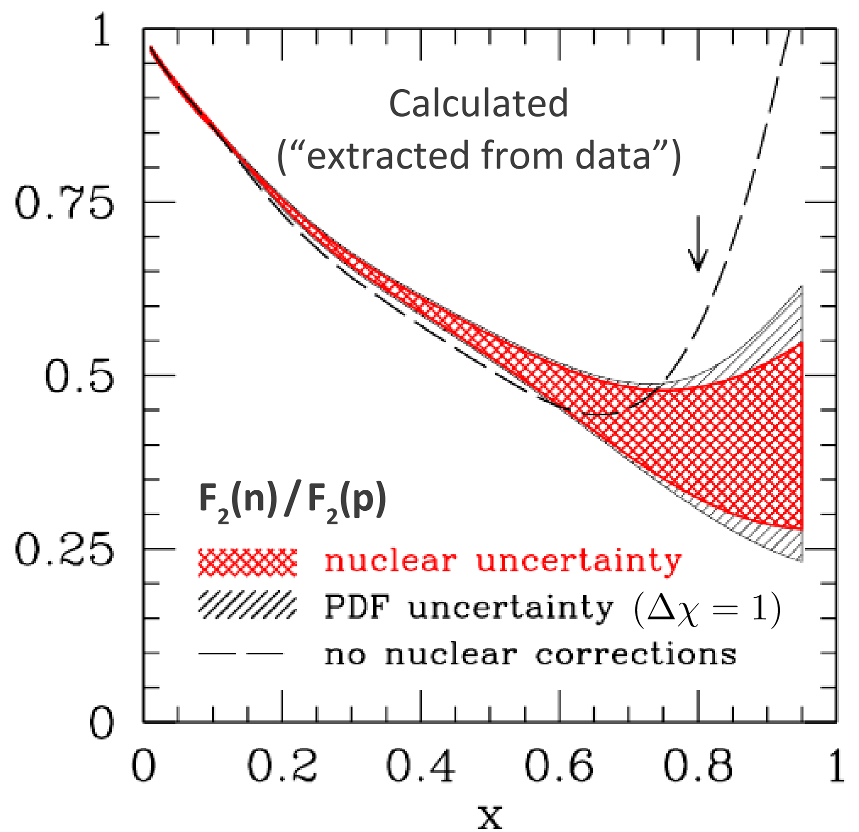
$$F_{2d}(x_B, Q^2) = \int_{x_B}^{A} dy\, \mathcal{S}_A(y,\gamma) F_2^{TMC+HT}(x_B/y, Q^2) \left(1 + \frac{\delta^{off} F_2(x)}{F_2(x)}\right)$$



- 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