Nucleon and nuclear structure at the EIC

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Overview

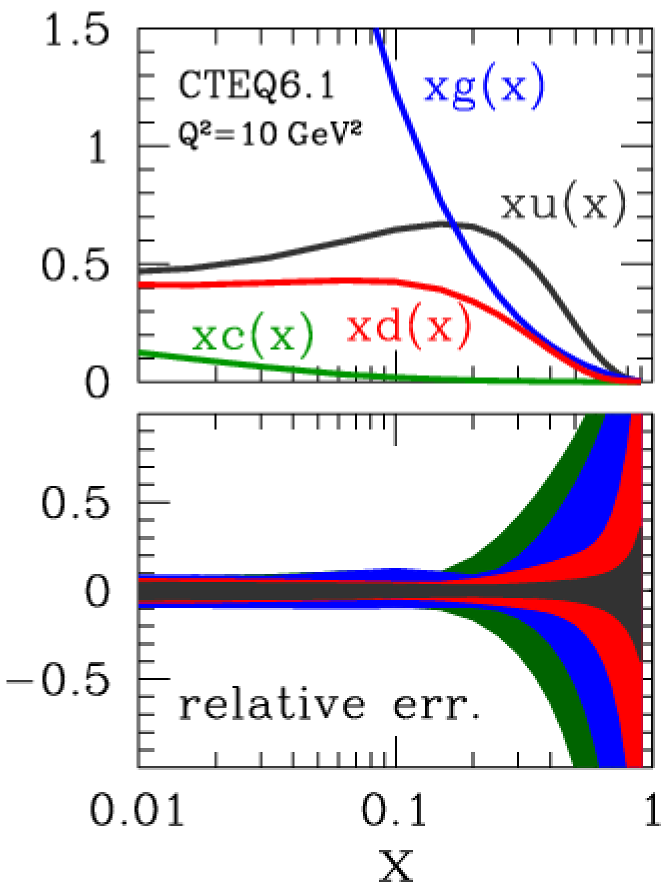
- **Protons and Deuterons: partons at large x**
  - *d*/*u* ratio extrapolated to *x*=1
  - *W'* and *Z'* production
- **Constraining nuclear uncertainties**
  - W,Z in proton collisons (!?)
  - JLab, EIC
- **From Deuterons to larger nuclei**
  - Inclusive DIS from small to large *x*
  - Jets at the EIC

Protons and Deuterons: partons at large x

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 $\Leftrightarrow$ large x PDF
    - Forward physics
  - At RHIC:
    - Polarized gluons at the smallest x
  - Neutrino oscillations, …



Valence quarks at large *x*

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

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

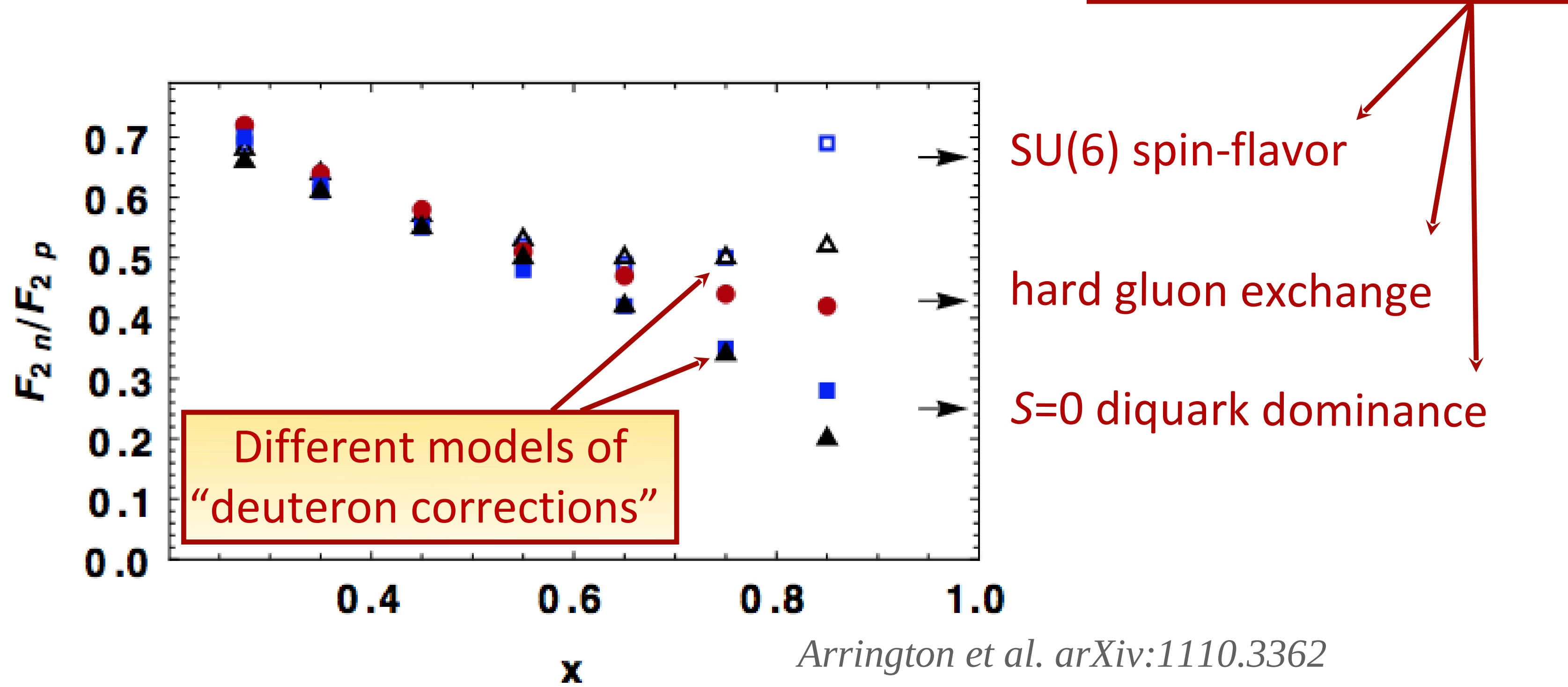
  – *u* quark distribution well determined from proton data
  – *d* quark distribution requires neutron structure function

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

But… deuteron corrections!

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

Non-perturbative proton models

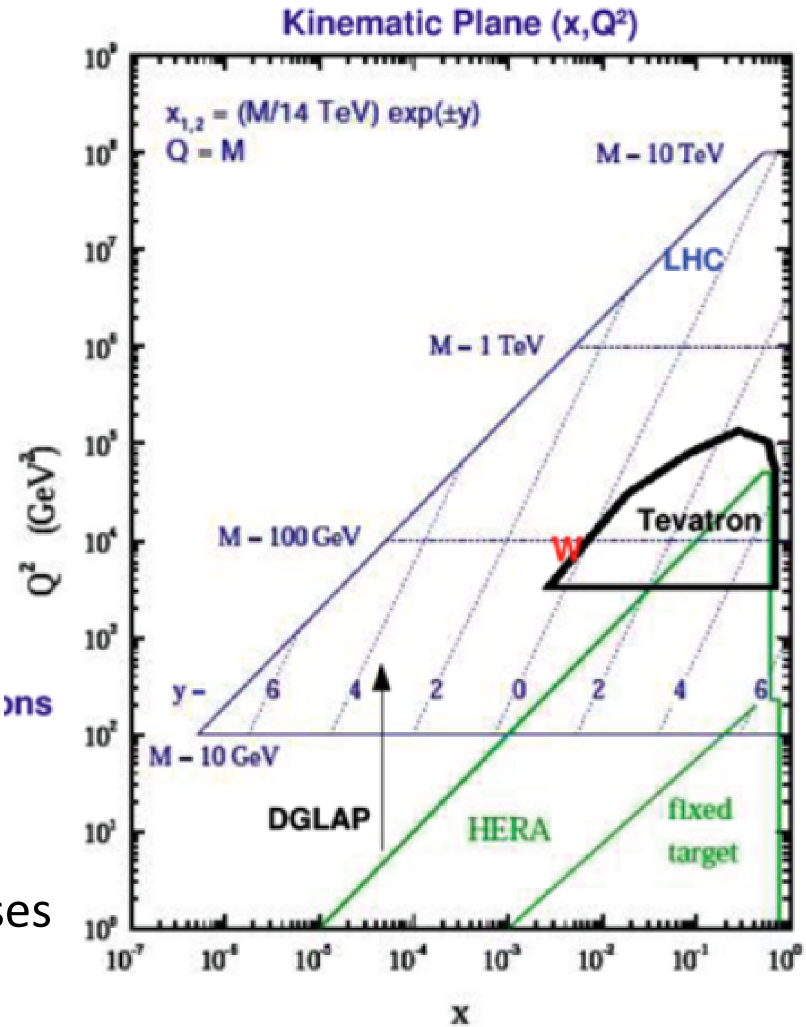


- Deuteron model dependence obscures free neutron at large *x*
  - We will see quantitatively how much

Large x at colliders - new physics searches

- Remember, $x = \frac{M}{\sqrt{s}} e^{y}$
- Examples:
  - Z' production $M'_Z \gtrsim 1\ \mathrm{TeV}$
  - W at forward rapidity: $y > 2$

$$x > 0.1\ \mathrm{(LHC)}$$
$$x > 0.5\ \mathrm{(Tevatron)}$$

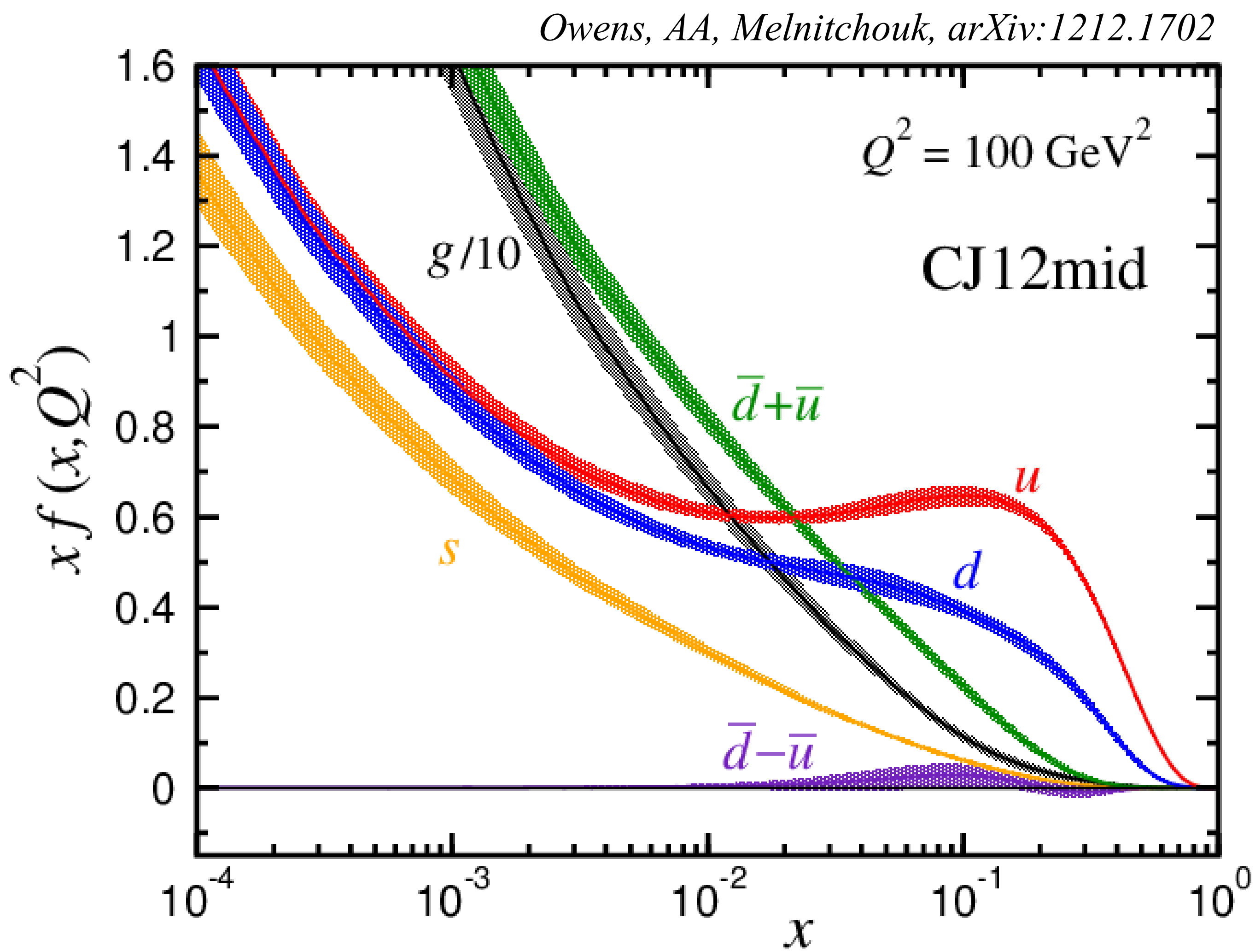


- Precise large-*x* PDFs needed to:
  - reduce QCD background
  - optimize searches involving large masses
  - precisely characterize new particles

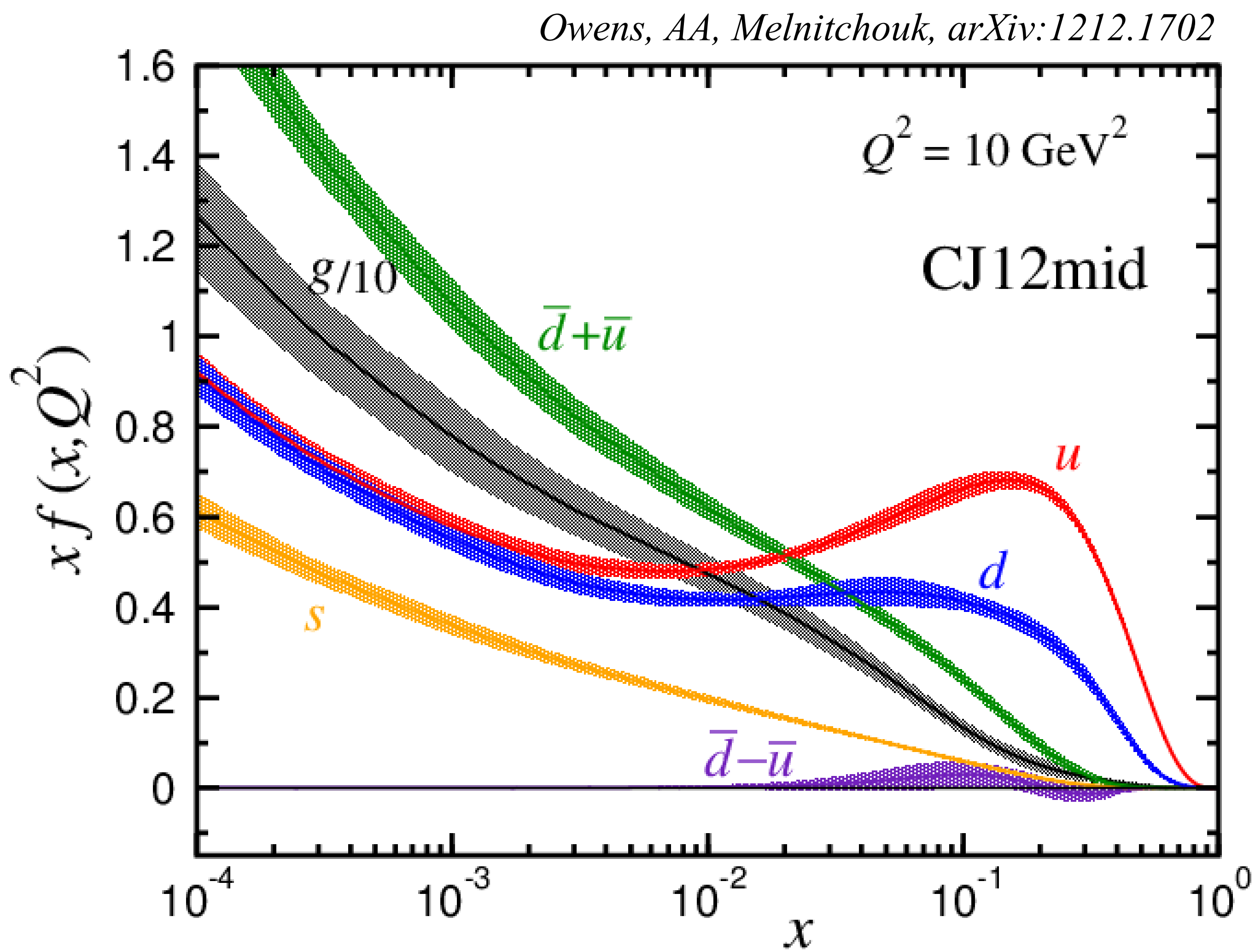
The CTEQ-JLab global fits

- **Collaborators:**
  - A.Accardi, E.Christy, C.Keppel, K.Kovarik, W.Melnitchouk, P.Monaghan, J.Owens
- **Goals:**
  - Improve llarge-x experimental precision (PDF errors) with larger DIS 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***
- **Public release: CJ12**
  - **Owens, Accardi, Melnitchouk, arXiv:1212.1702**
    - www.jlab.org/cj
    - In next LHAPDF release (soon to appear)

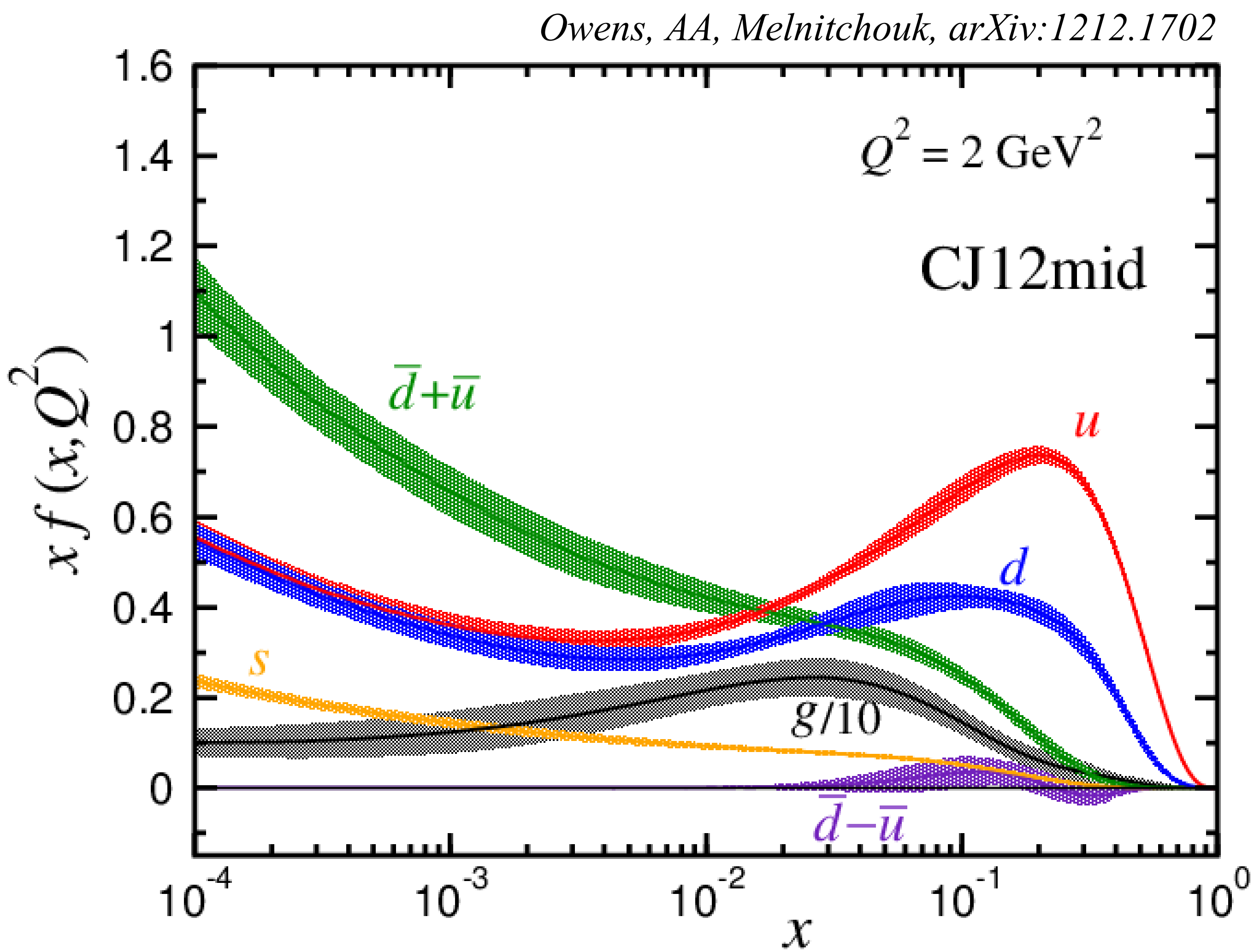
CJ12 parton distributions



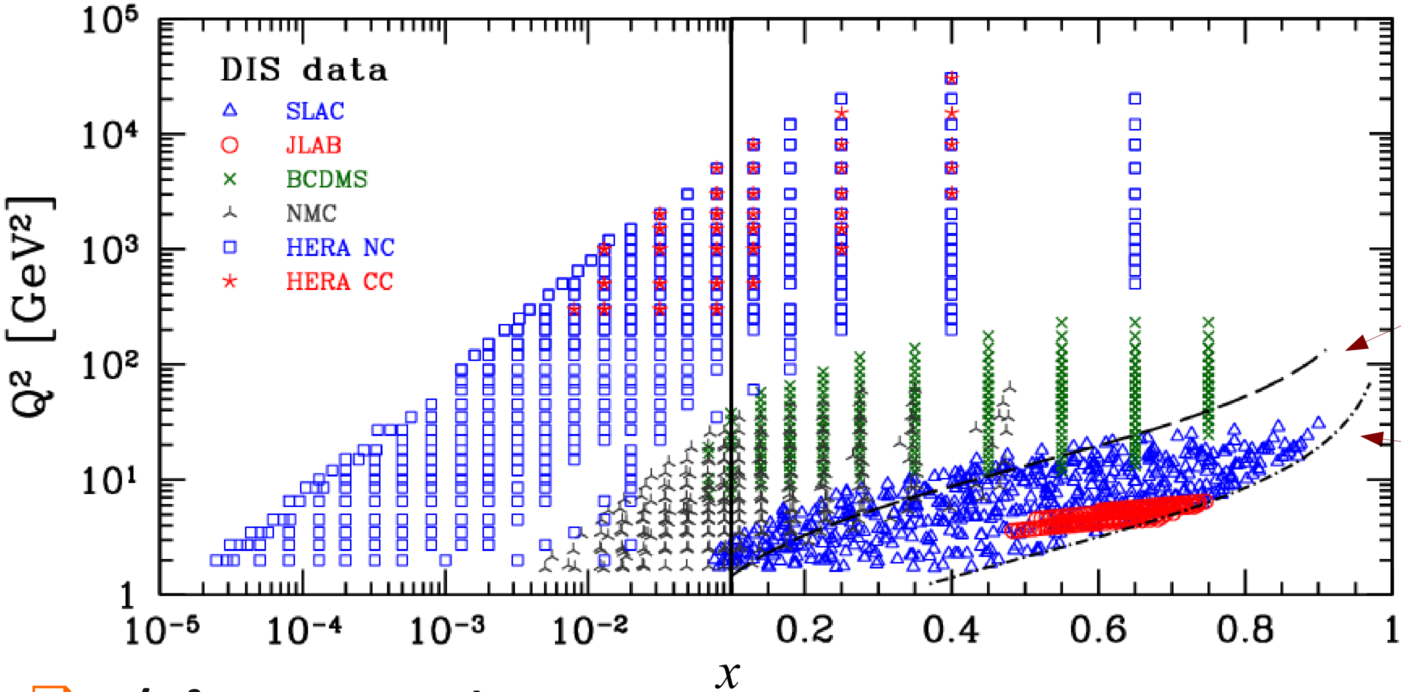
CJ12 parton distributions



CJ12 parton distributions



Large-x, small-Q^2 corrections



usual cut
$W^2 \gtrsim 14\ \mathrm{GeV}^2$

CJ12
$W^2 \gtrsim 3\ \mathrm{GeV}^2$

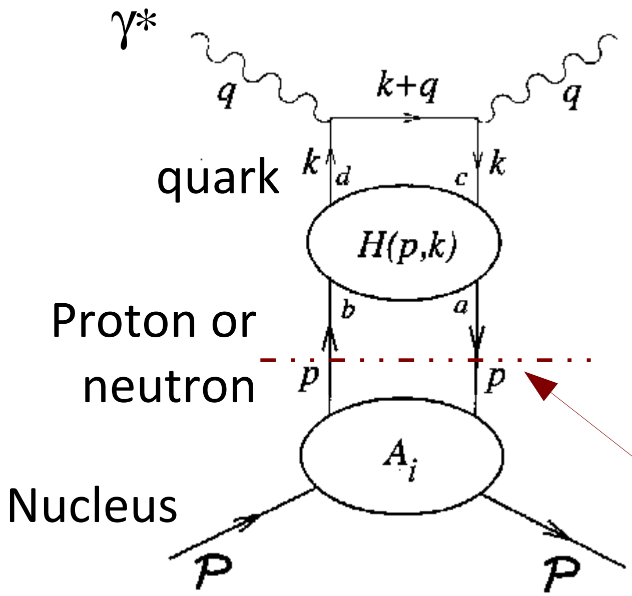
- **$1/Q^{2n}$ suppressed:**
  - Target mass corrections (TMC), higher-twists (HT)
  - Current jet mass, quark mass, large-*x* QCD evol.
- **Non-suppressed**
  - Nuclear corrections, threshold resum., parton recomb.
- **New d-quark parametrization:** $d'(x) = d(x) + \alpha x^\beta u(x)$

included in CJ fits

Deuteron corrections

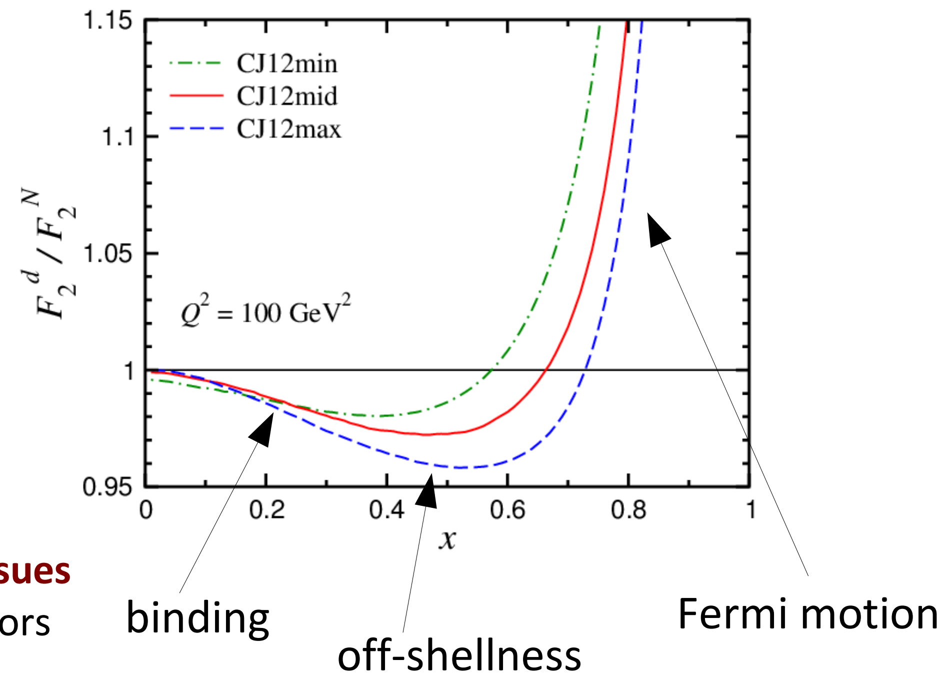
- No free neutron! Best proxy: Deuteron
  - Parton distributions (to be fitted)
  - nuclear wave function (AV18, CD-Bonn, WJC1, …)
  - Off-shell nucleon modification (model dependent)

Theoretical uncertainty



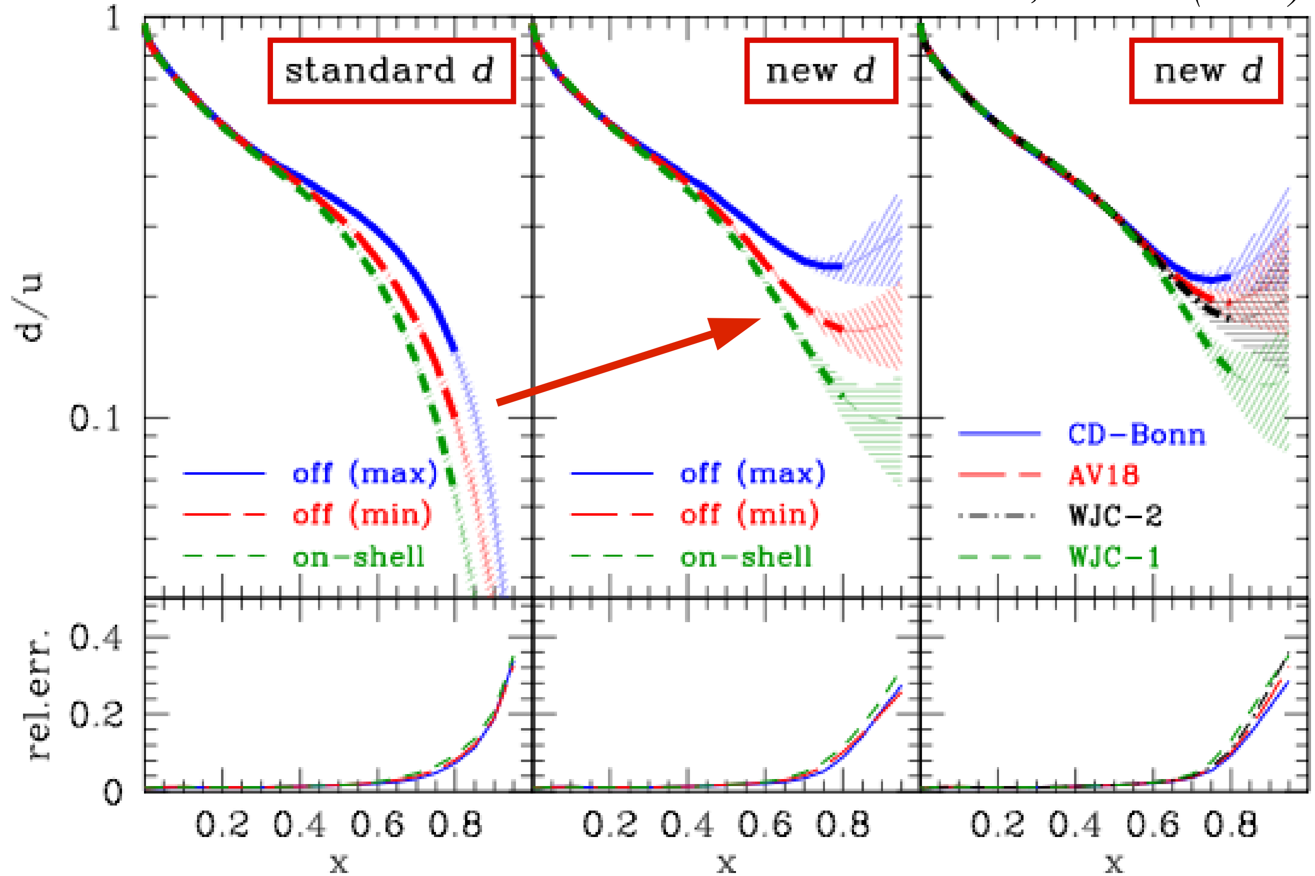
Low-energy factorization issues
- Renorm. of nuclear operators
- Gauge invariance, FSI, ...

Bound vs. free proton+neutron



CJ fits: new *d* quark, nuclear uncertainty

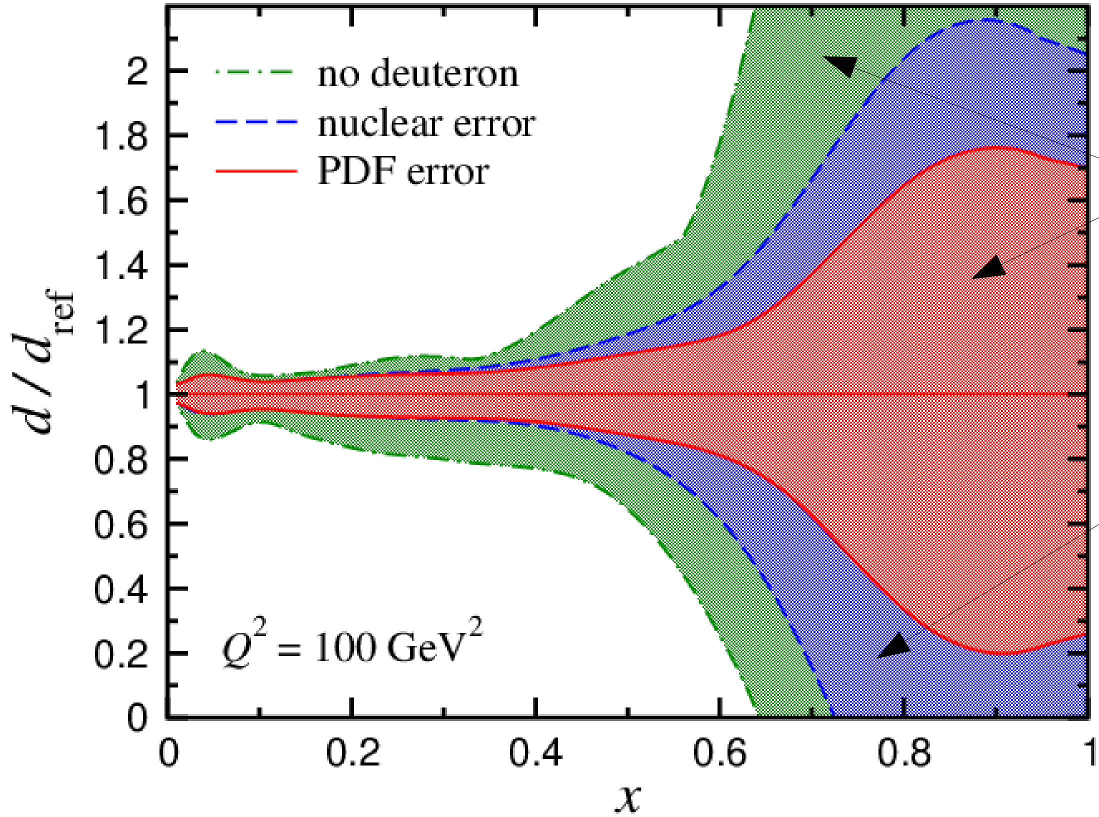
*Accardi et al. PRD **84**, 014008 (2011)*



- Dramatic increase in *d* quark with more flexible parametrization
  - Neglected in all other fits

CJ12 fits: nuclear and PDF uncertainty

Owens, Accardi, Melnitchouk, arXiv:1212.1702



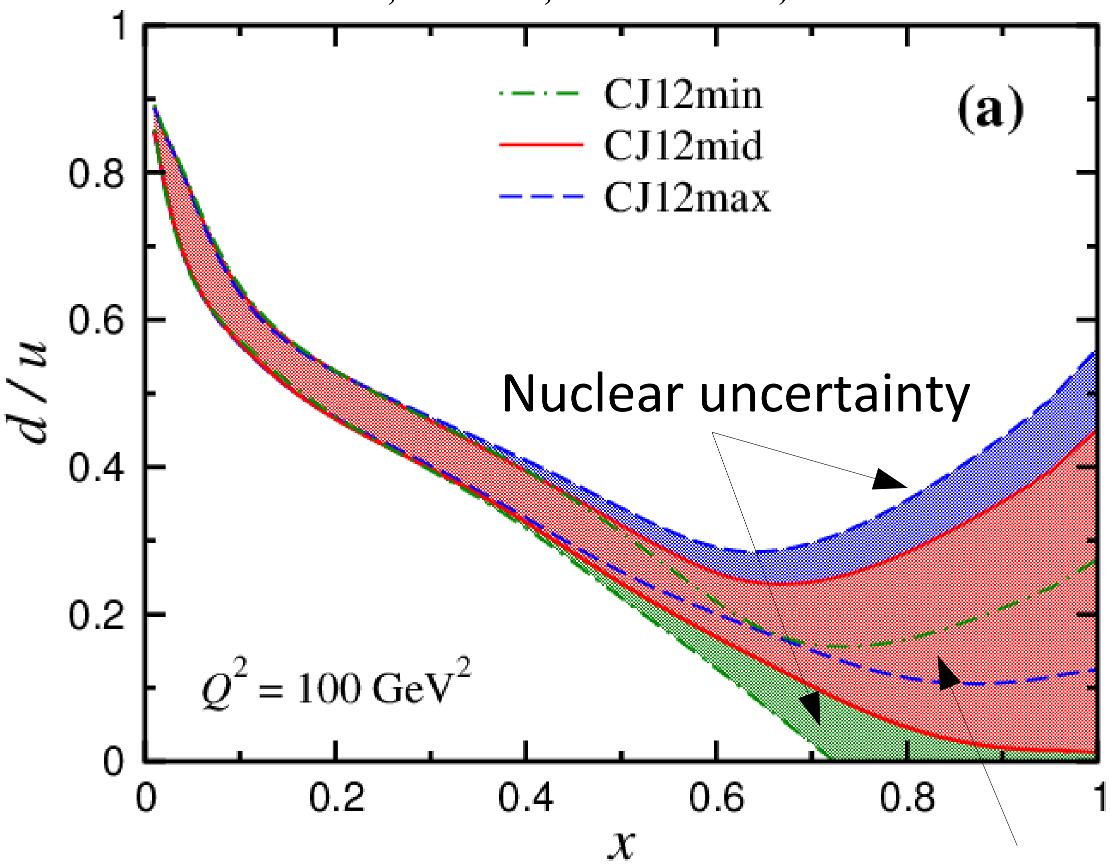
Largely reduced PDF errors (increased statistics)

Nuclear uncertainties (systematic)

- Large overall reduction in uncertainty with relaxed cuts

Applications: *d/u* ratio

Owens, Accardi, Melnitchouk, arXiv:1212.1702



"PDF" experimental uncertainty

Non-perturbative proton models

SU(6) spin-flavor

hard gluon exchange

S=0 diquark dominance

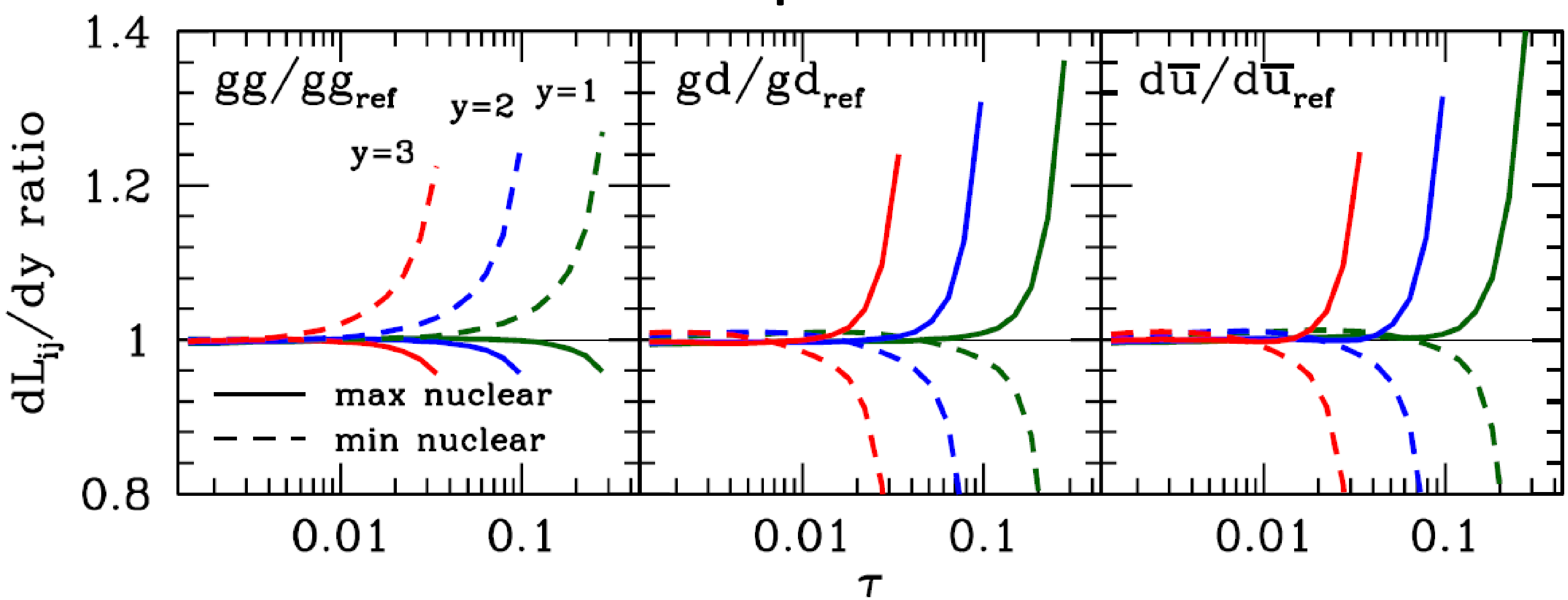
$$d/u \xrightarrow[x\to 1]{} 0.22 \pm 0.20\,(\mathrm{PDF}) \pm 0.10\,(\mathrm{nucl})$$

Applications: new physics at LHC

Accardi et al., PRD84 (2011) 014008

- Observation of new physics signal requires accurate determination of QCD background
- Uncertainties in large-*x* PDFs could affect interpretation of experiments searching for new particles

Differential parton luminosities

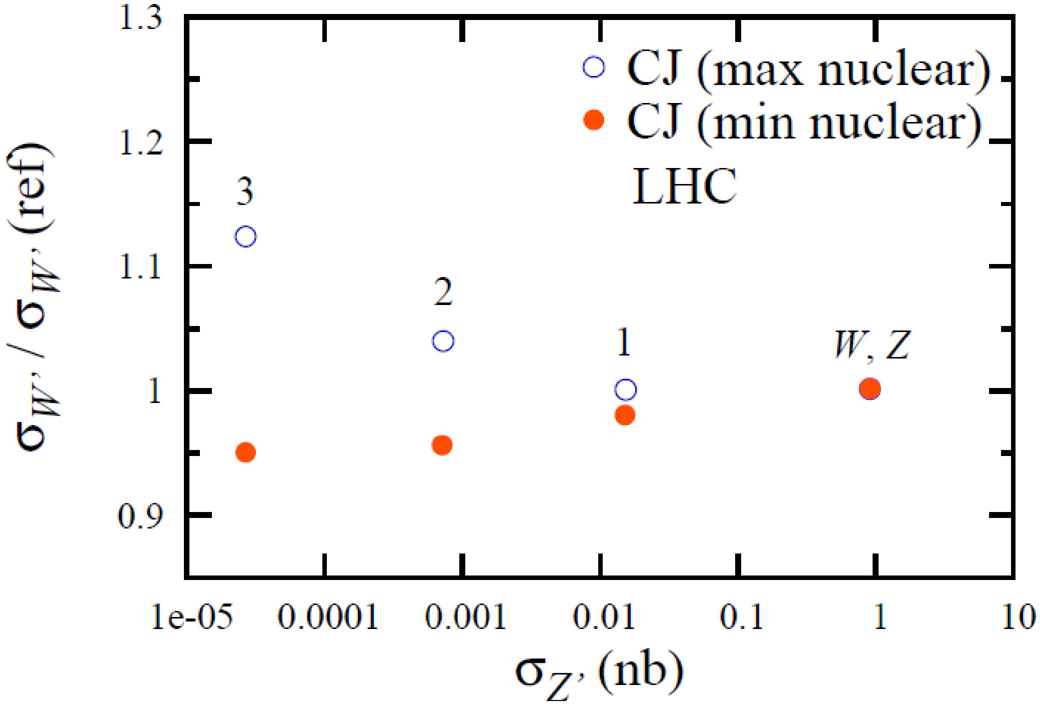


Applications: large mass searches at LHC

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

- Observation of new physics signal requires accurate determination of QCD backgrounds,
- uncertainties in large-*x* PDFs could affect interpretation of experiments searching for new particles

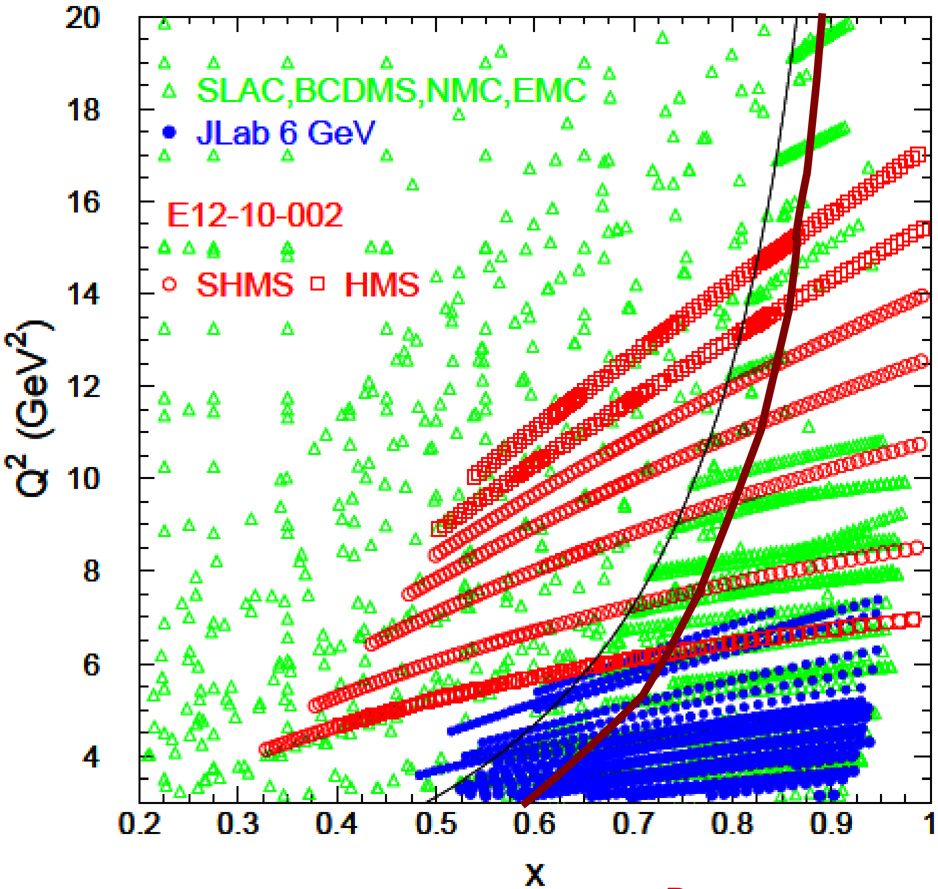
Example: W' and Z' total cross sections



Beating the experimental uncertainties

At JLab 12

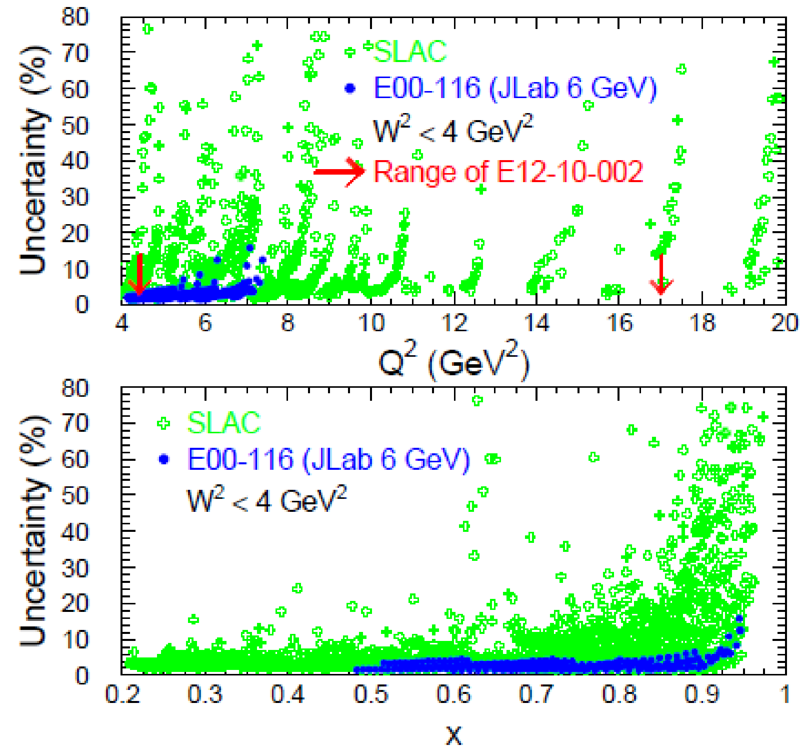
CJ cut: $W^2 > 3\ \mathrm{GeV}^2$



DIS region

Resonance region

Jlab12 experiment E12-10-002

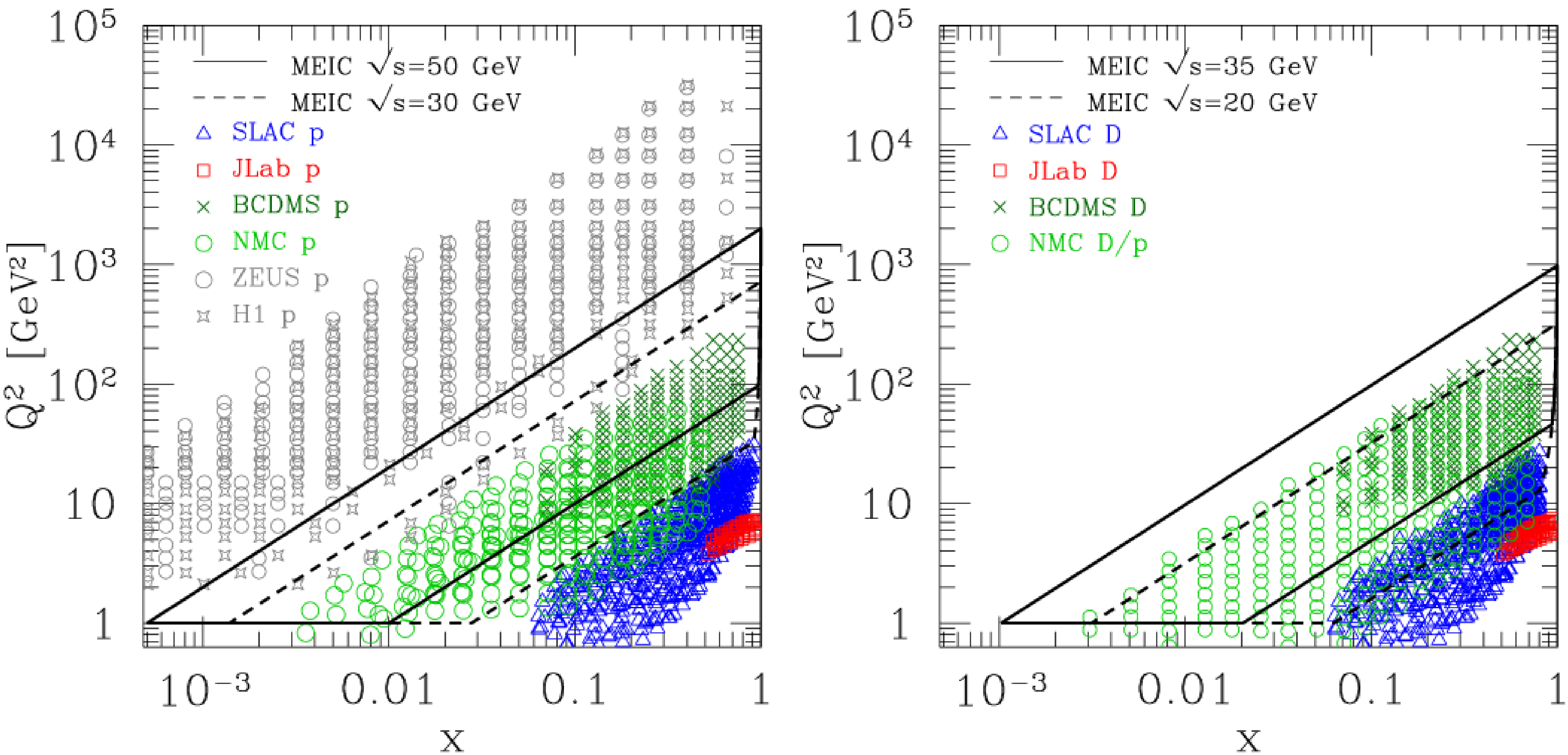


Goal @ 12 GeV: similar precision as E00-116 (@ 6 GeV)

EIC projections

- MEIC √s = 31 GeV (ca. 2010)

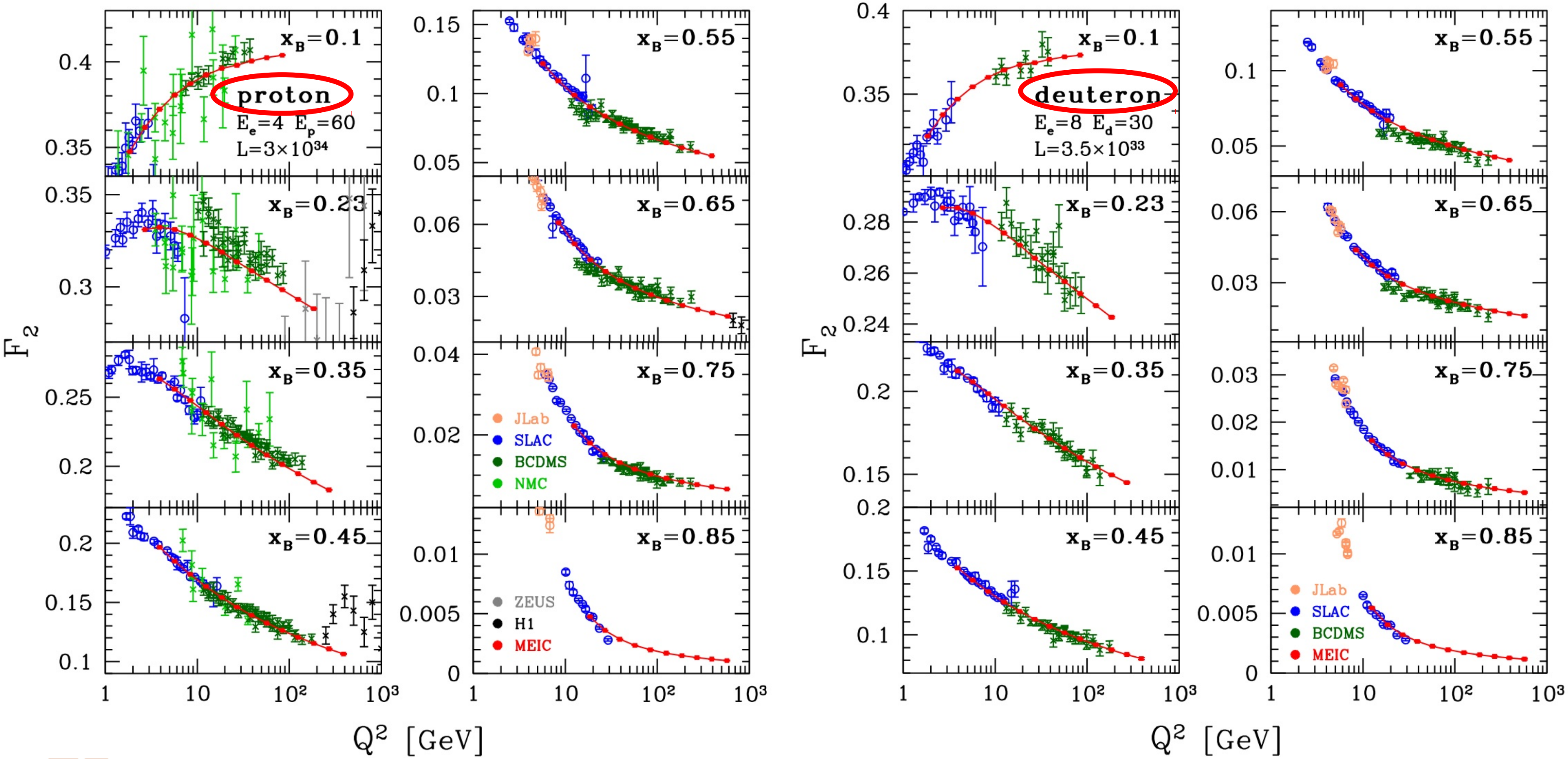
[Accardi, Ent, Keppel]



EIC projections

- MEIC √s = 31 GeV (ca. 2010)
  - Pseudo data using CTEQ-JLab "CTEQ6X" fits, L=230 (35) fb^{-1}

[Accardi, Ent, Keppel]



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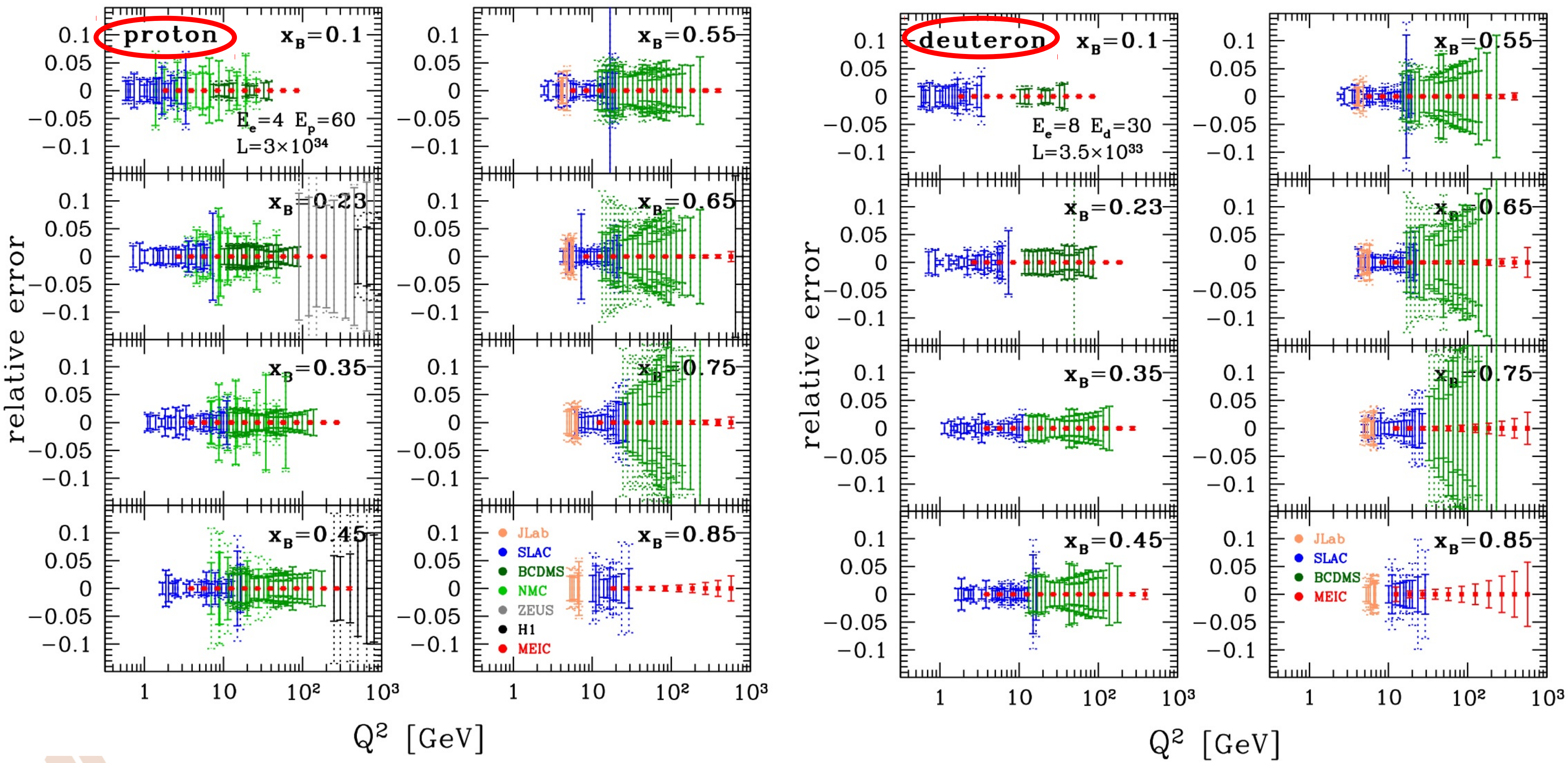
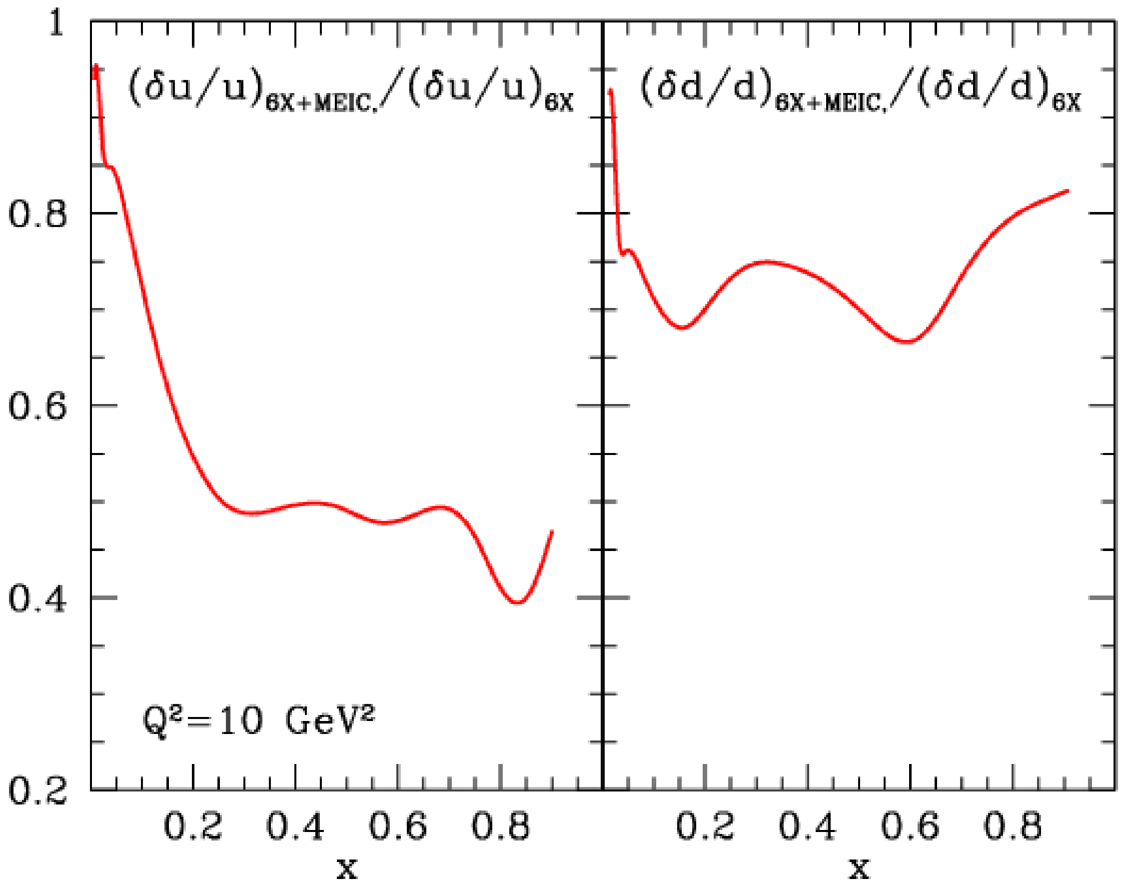


Impact of a new accelerator – the EIC

- Reduction in PDF errors

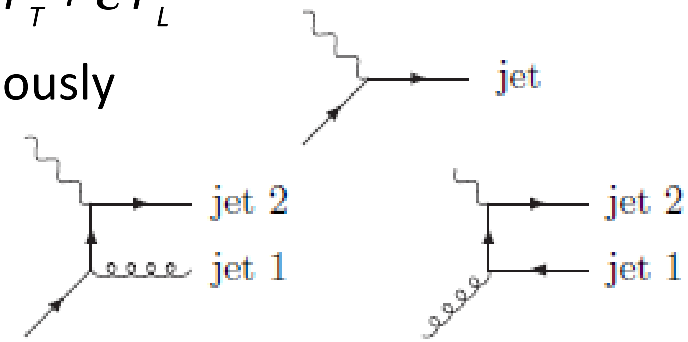
[Accardi, Ent, Keppel]

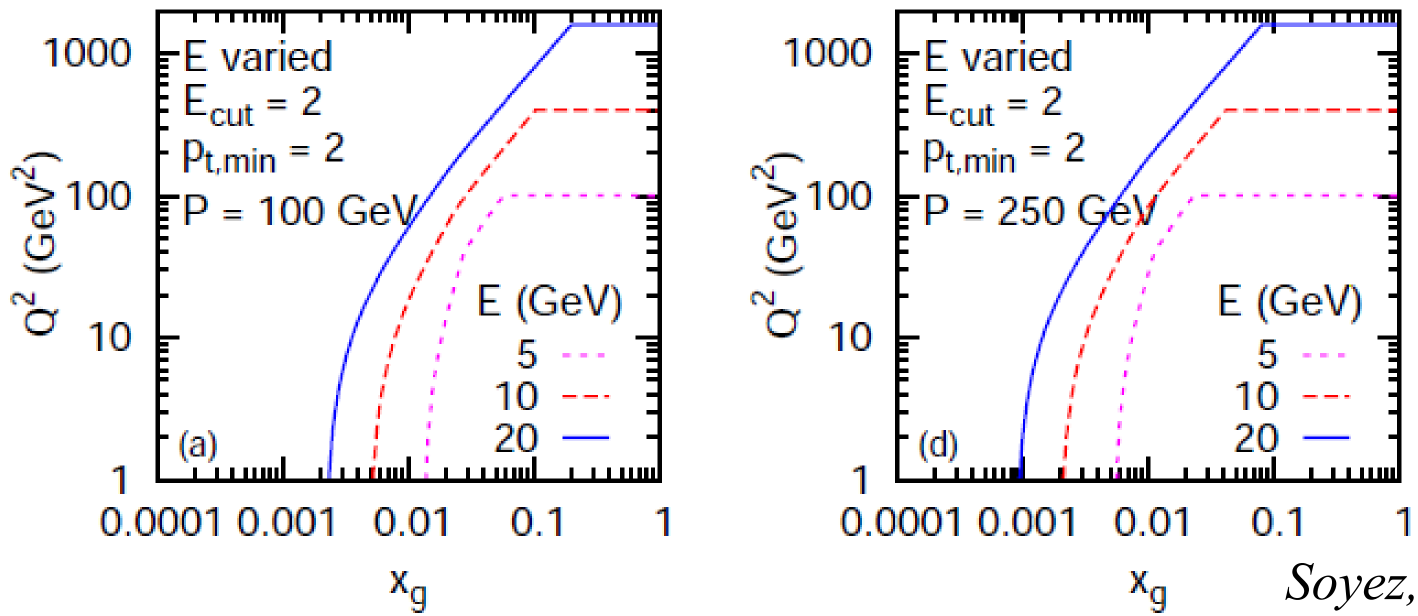


EIC - gluons: F_L and jets

(will evaluate this, see V.Radescu for LHeC)

- Large leverage in Q^2 $\Rightarrow$ reduction in gluon PDF errors
  - Driven by scaling violation, some from $\sigma = F_T + \varepsilon F_L$
  - Interplay with α_s , if this is fitted simultaneously
- DIS jets have different α_s dependence
  - Remove ambiguities





Soyez, INT report

Constraining the theoretical uncertainties

Constraining the nuclear uncertainty

- **DIS data minimally sensitive to nuclear corrections**
  - DIS with slow spectator proton (BONUS)
    - Quasi-free neutrons
  - DIS with fast spectator (DeepX)
    - Off-shell neutrons
  - ^{3}He/^{3}H ratios
- **Data on free (anti)protons, sensitive to *d***
  - *e+p*: parity-violating DIS **HERA** *(e^++p vs. e^-+p)*
  - ν+*p*, ν+*p* *(no experiment in sight)*
  - *p+p*, *p*+$\bar{p}$ at large positive rapidity
    - *W* charge asymmetry, *Z* rapidity distribution

Jlab12, EIC

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*

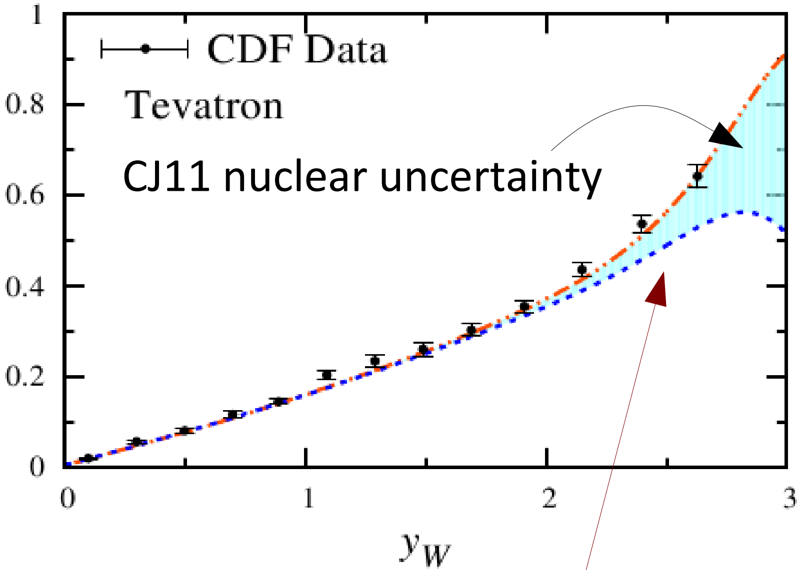
RHIC ??
AFTER@LHC

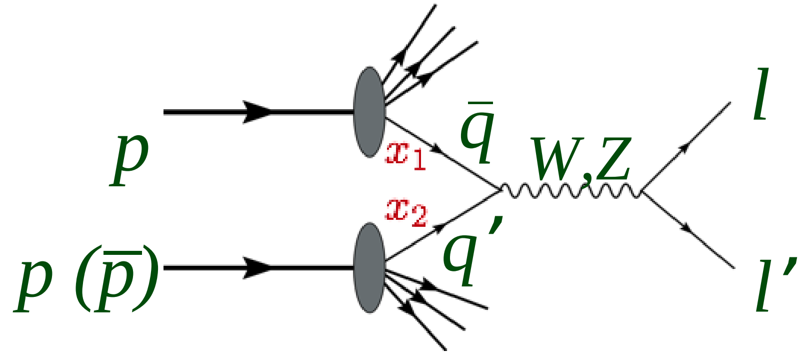
Use protons to study nuclei (!)

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

Directly reconstructed W:

- highest sensitivity to large *x*





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

$$\approx \frac{d/u(x_2) - d/u(x_1)}{d/u(x_2) + d/u(x_1)}$$

sensitive to *d* at high *x* → Can constrain Deuteron models!

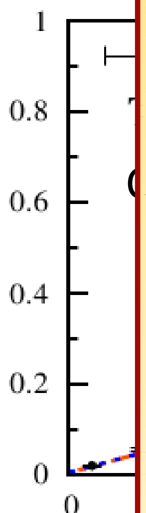
- Needs to be corroborated:
  - *W, Z* at RHIC, *Z* (and *W* ?) at LHC, *W* at DØ (??)
  - PVDIS at JLab 12, **CC @ EIC**

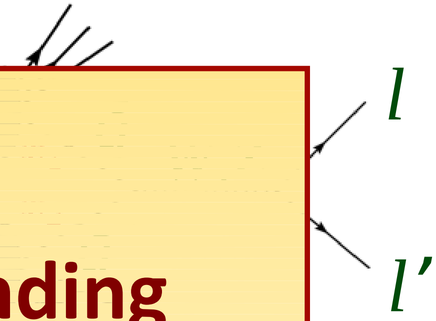
W charge asymmetry (p+p / p+pbar collisions)

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

Directly reconstructed W:

- high





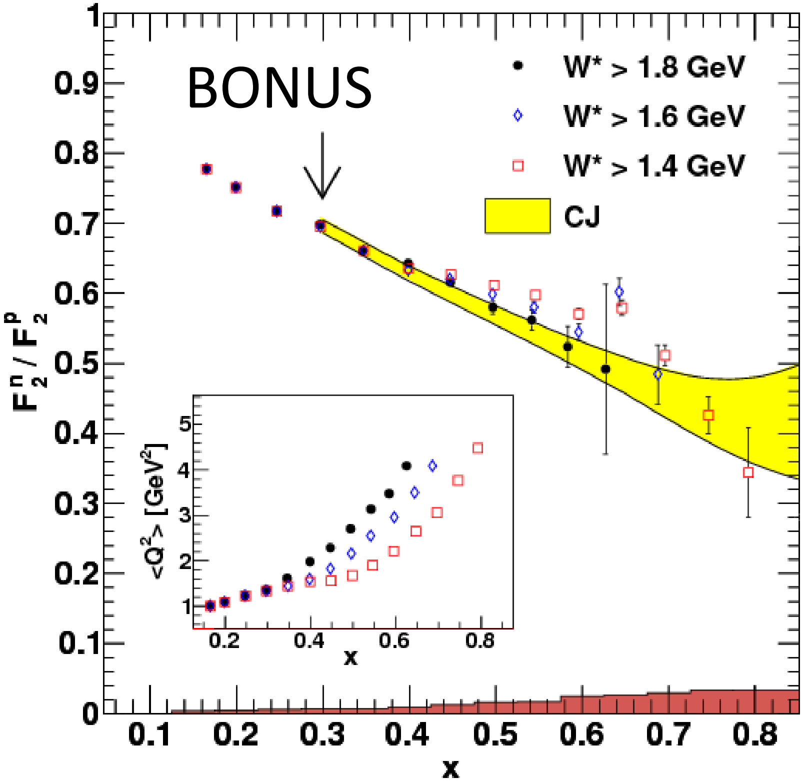
A new avenue for understanding high-energy processes on <u>nuclei</u>:

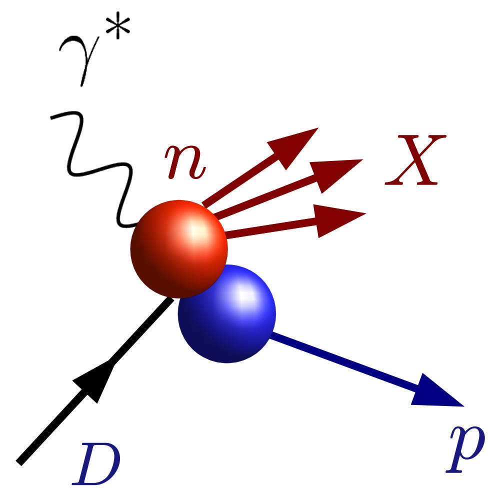
weak interactions on <u>proton targets</u> from JLab to the LHC!

- Nee
  - *W, Z* at RHIC, *Z* (and *W* ?) at LHC, *W* at DØ (??)
  - PVDIS at JLab 12, **CC @ EIC**

Spectator tagging at Jlab: quasi-free neutrons

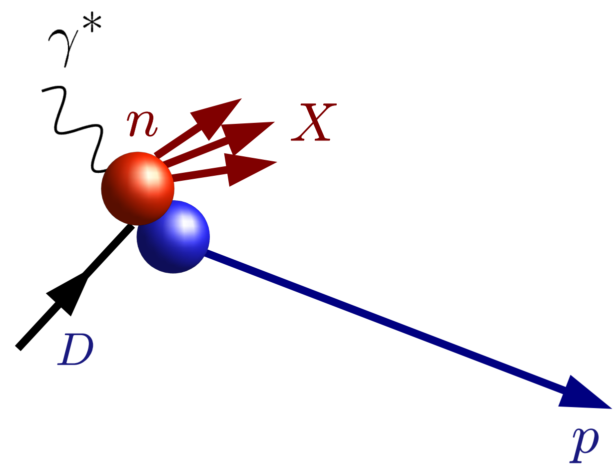
N.Baillie et al., PRL 108 (2012) 199902

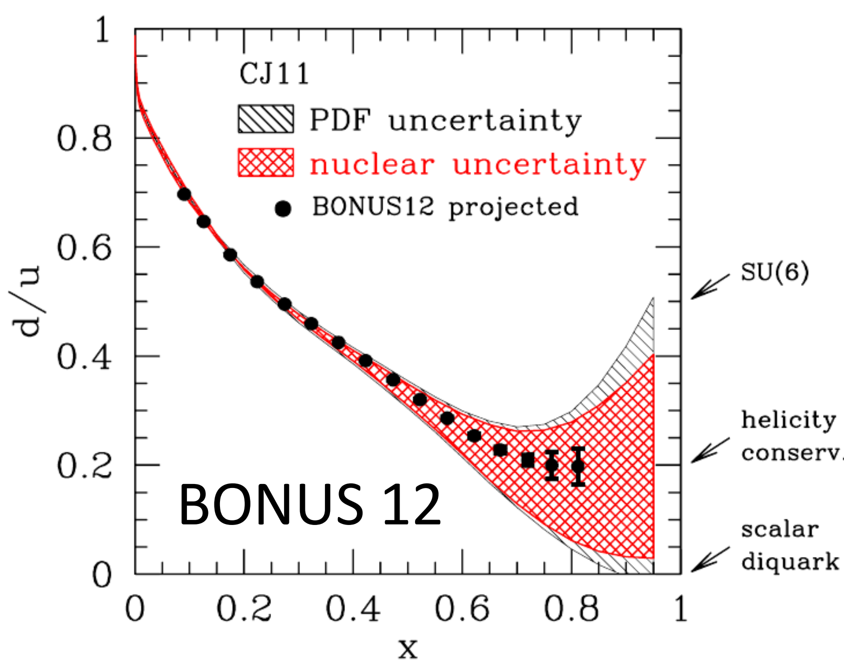


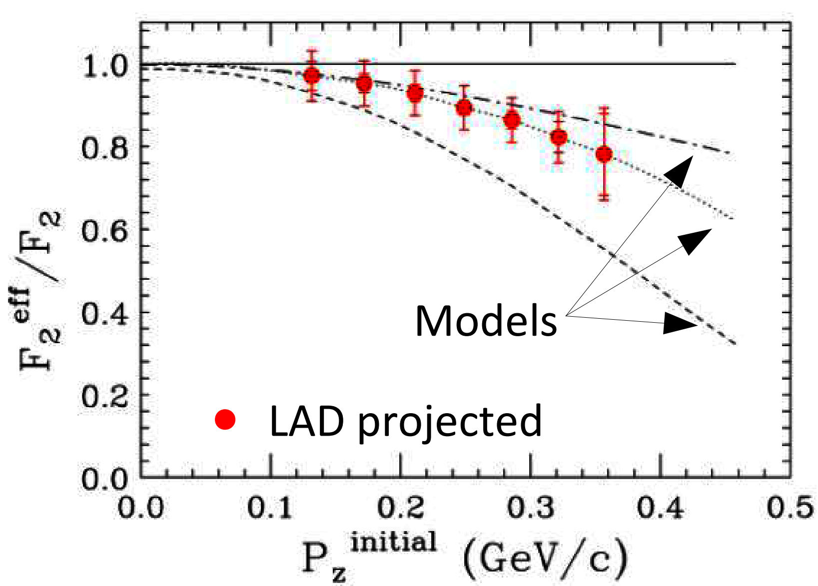


Spectator tagging at JLab12

- Neutron off-shellness depends on on spectator momentum:
  - Slow: nearly on-shell (BONUS12)
  - Fast: more and more off-shell (LAD)





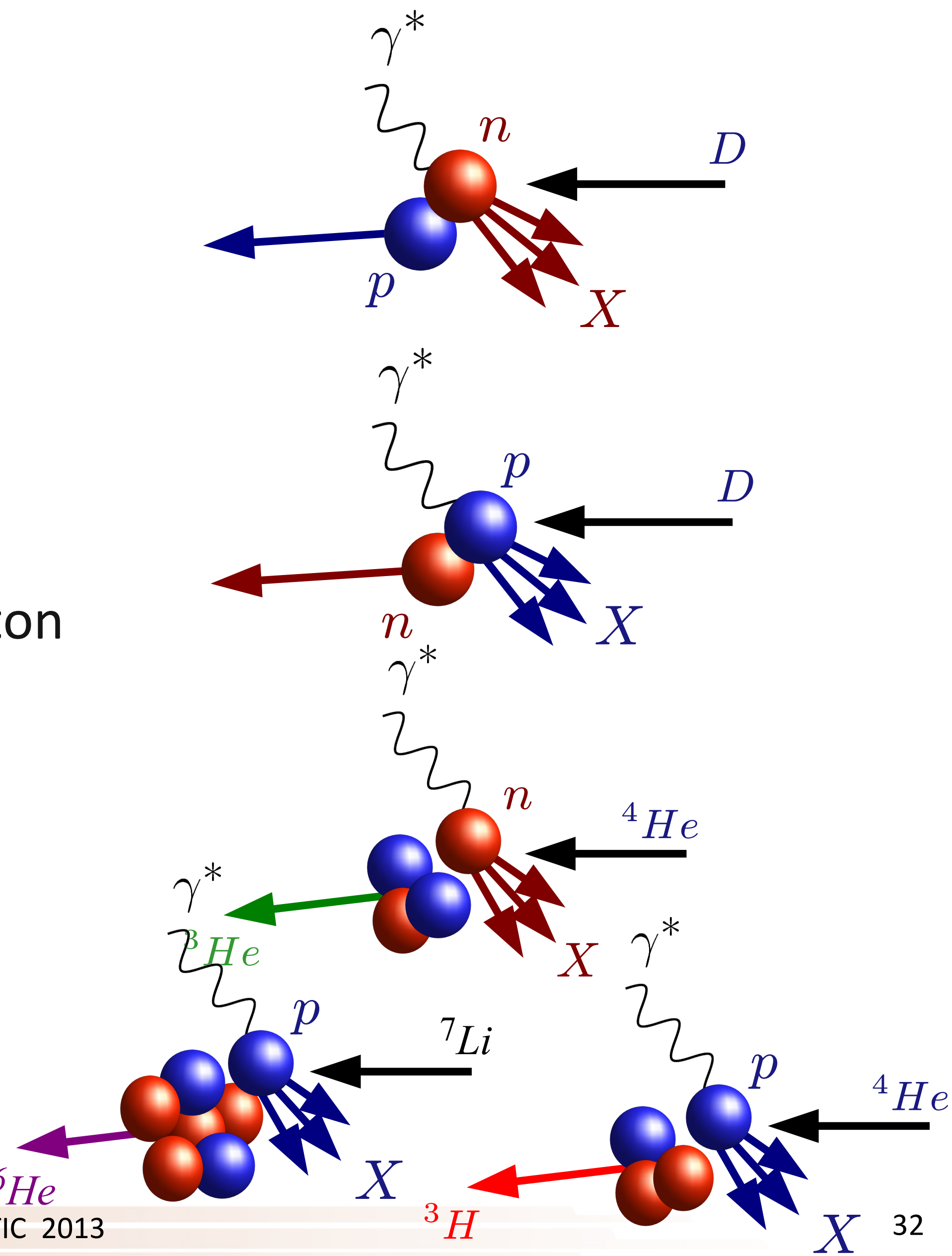


Spectator tagging at EIC: even better!

- measure **neutron F_2** in D target
  - flavor separation

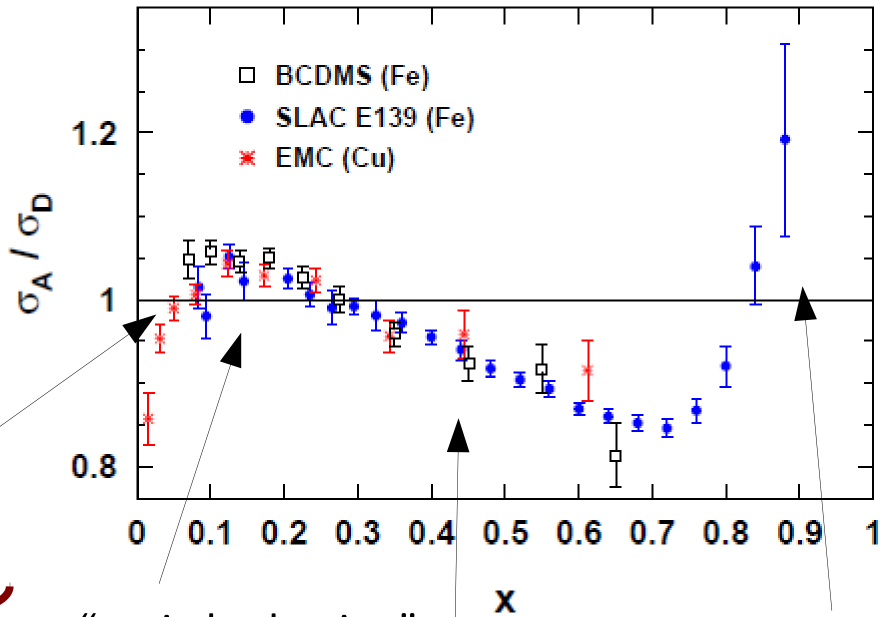
- measure **proton F_2** in D target
  - **Unique at colliders**
  - Compare off-shell to free proton

- **proton, neutron in light nuclei**
  - embedding in nuclear matter **(a piece of the EMC puzzle)**



From deuterons to nuclei

Nuclear to Deuteron ratio



Short-range correlations
6-quark bags
Other exotica ...

Shadowing
Saturation

"anti-shadowing"

Fermi-motion

EMC effect

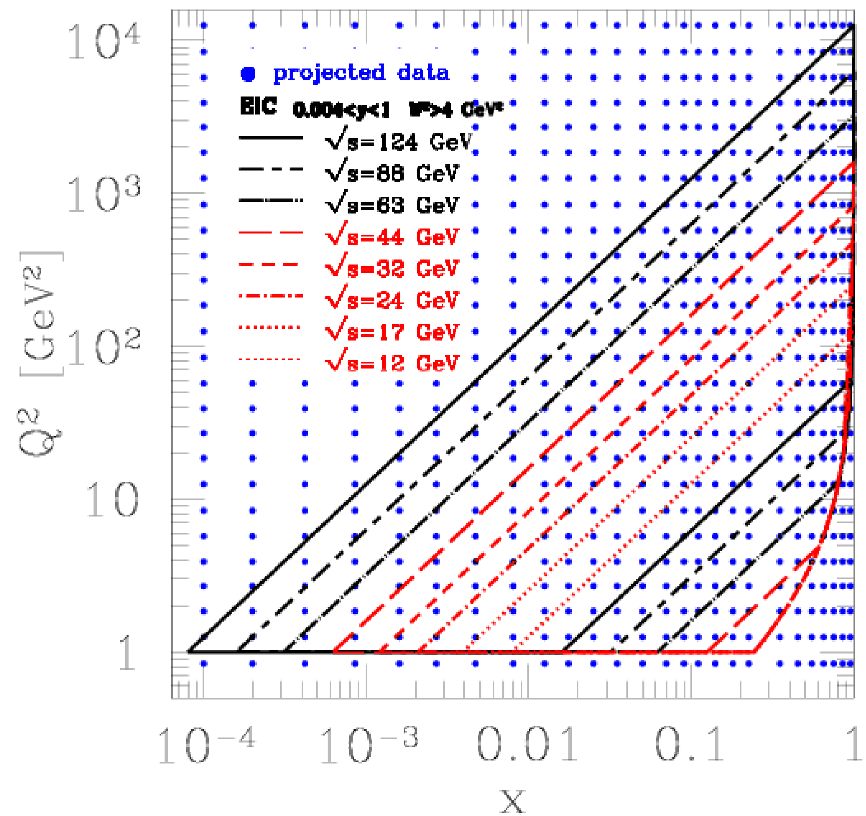
Can saturation be detected as deviation from DGLAP?

Can also use protons to study larger nuclei !!

Impact of the EIC

Accardi, Guzey, Rojo, INT report

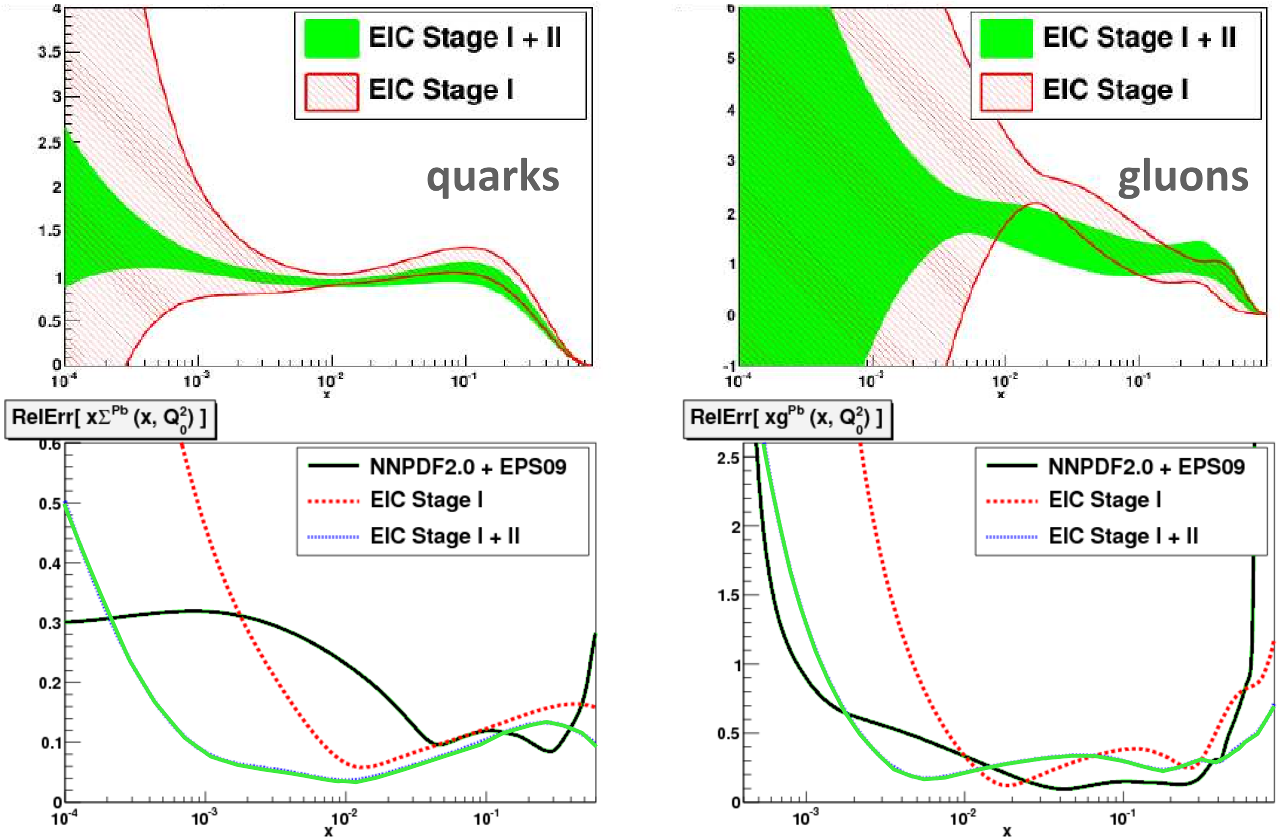
- **e+A collisions** – using NNPDF2.0 fits
  - QCD fit to EIC pseudo-data for Pb only
  - Assume energy scan
    L=4 fb^{-1} per energy setting
    $0.04 < y < 0.8$
  - $\sqrt{s}$ = 12, 17, 24, 32, 44 GeV
    (medium energy EIC – **stage I**)
  - $\sqrt{s}$ = 63, 88, 124 GeV
    (full energy EIC – **stage II**)



Impact of the EIC

Accardi, Guzey, Rojo, INT report

- **e+A collisions** – using NNPDF2.0 fits
  - With only 1 nucleus target, impact comparable to present day world data; <u>small *and* large *x*</u>

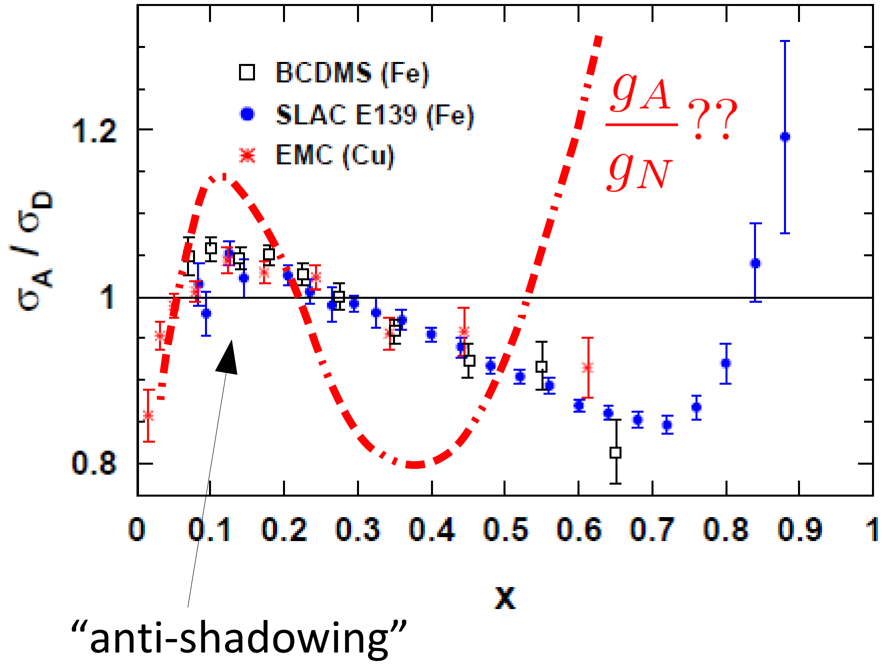


Gluons in nuclei - large *x*

- **Next to nothing known about large-x nuclear gluons**
  - Easily as revolutionary as quark EMC effect 30 years ago
  - In fact, indications that “anti-shadowing” resides in longitudinal

Guzey et al., PRC86 (2012) 045201

- **Needs**
  - Dedicated nuclear L/T separation at JLab 12 GeV
  - **Energy scan at EIC**

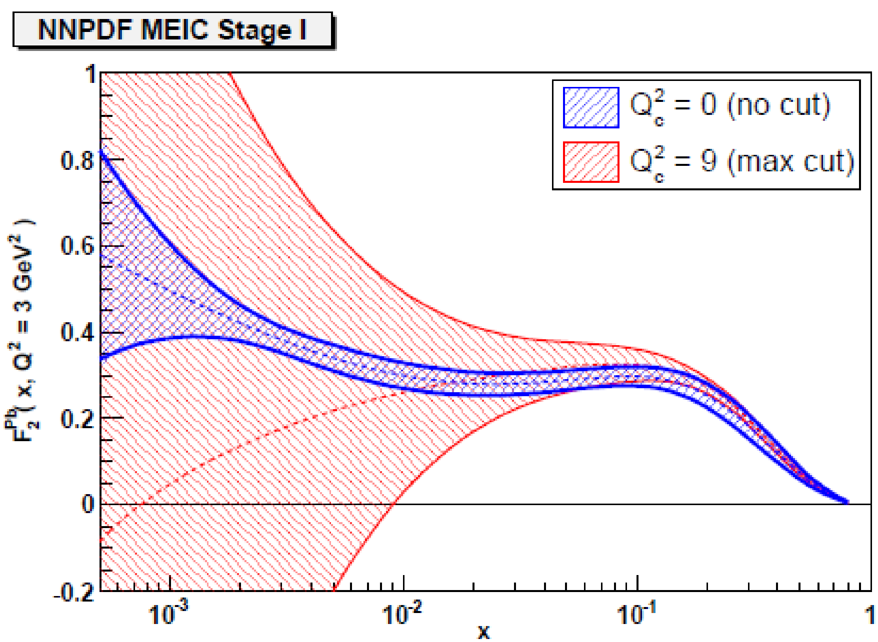


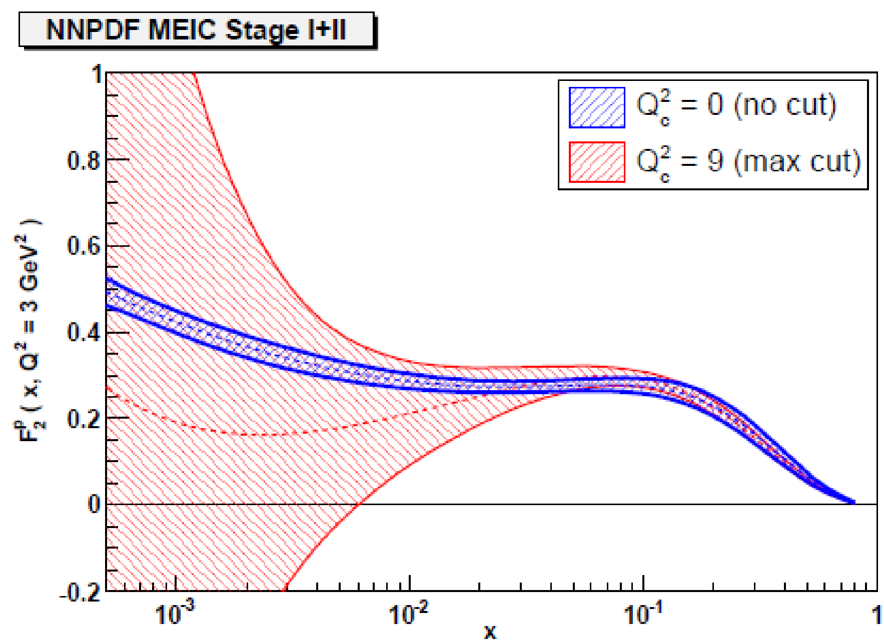
Gluons in nuclei - small *x*

Accardi, Guzey, Rojo, INT report

- **Can EIC detect (the approach) saturation as deviation from DGLAP?**
  - Cut data in saturation region $Q^2 < Q_0^2 (\frac{x_0}{x})^{1/3} A^{1/3}$ and refit
  - Systematic downward shift
  - Signal of saturation (marginal in stage I ?)
  - Needs detailed study of statistical significance

$= Q_c^2 x^{-1/3}$





Gluons in nuclei - the science matrix

Accardi, Lamont, Marquet, INT report

Deliverables	Observables	What we learn	Phase-I	Phase-II
integrated gluon distributions	$F_{2,L}$	nuclear wave.fn.; saturation, Q_s	gluons at $10^{-3} \lesssim x \lesssim 1$	explore sat. regime
k_T-dep. gluons; gluon correlations	di-hadron correlations	non-linear QCD evolution/universality	onset of saturation; Q_s	RG evolution

integrated gluon distributions	$F_{2,L}^c$, $F_{2,L}^D$	nuclear w.fn.; saturation, Q_s	early sat. onset challenge to measure	saturation regime
flavour separated nuclear PDFs	charged current & γZ str. fns.	EMC effect origin	full q_i separation at $0.01 \lesssim x \lesssim 1$	larger Q^2, smaller x

Good performance also at large *x*; similar for protons:

$\Rightarrow$ don't forget intrinsic charm 😉

Summary: the next 20 years

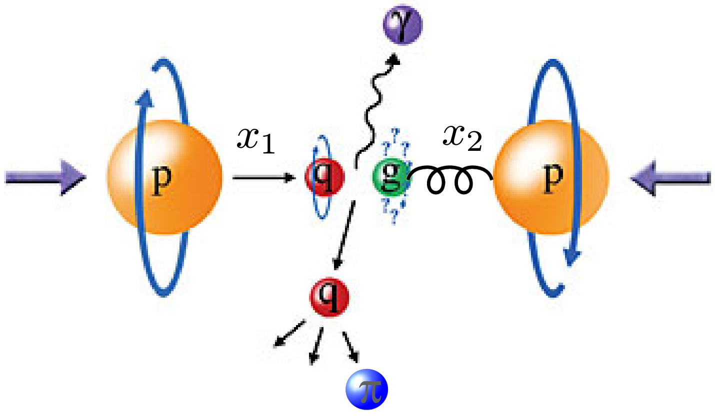
- **Global fits: new avenue to study nuclear physics with proton targets**
  - Deuteron corrections, EMC effect theory
- **The next 10 years: pushing the envelope of existing machines**
  - High-precision large-*x* quarks need **fixed target DIS(D) statistics**
  - Theory nuclear systematics will be minimized using proton data
    - W,Z at **RHIC, Tevatron, LHC**; tagging, PVDIS, ^{3}He/^{3}H ratio at **JLab12**
  - Start exploiting p vs. large A for understanding EMC effect
  - Revisit intrinsic charm fits
- **10-20 years from now**
  - **EIC** and/or **LHeC** likely to allow deuteron-free large-*x* PDF fits
    - CC DIS, jets, charm tagging on proton targets
  - High precision forward physics at LHC (**AFTER@LHC**, ...)
  - Use high precision p data to study nuclei in detail

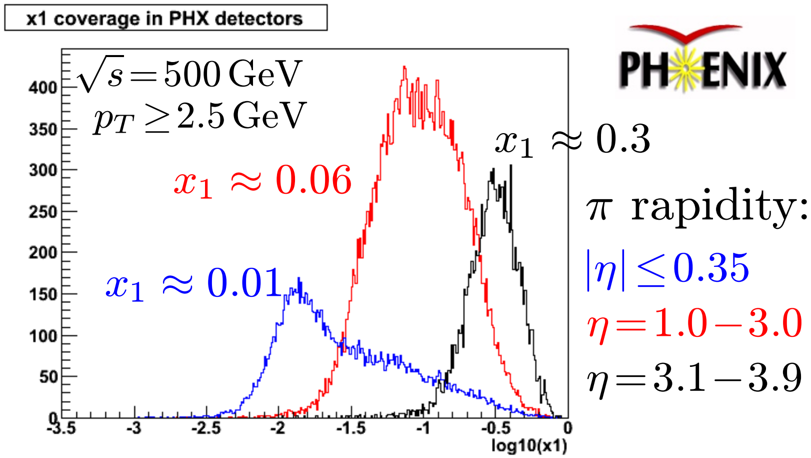
Backup slides

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

- *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

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

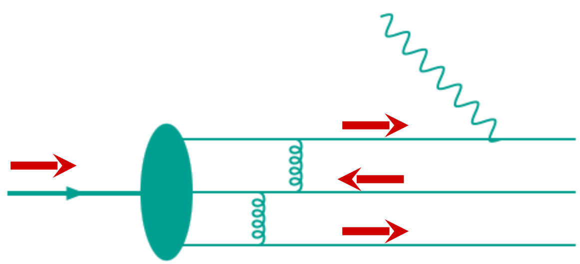
Valence quarks at large *x*

- **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

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)

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"

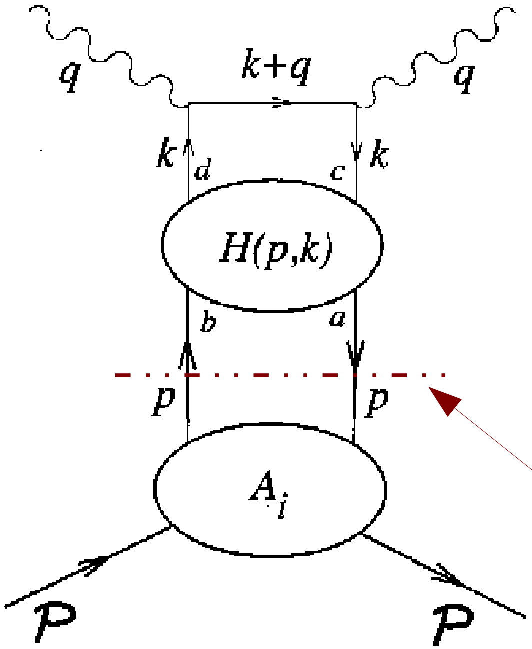
Calculated from nuclear wave-function:

- 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

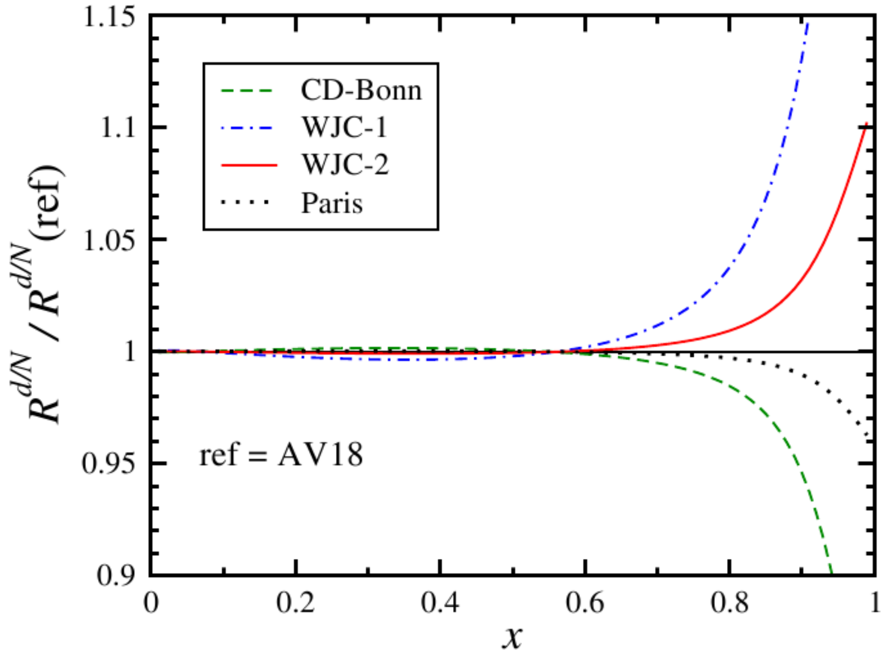
Low-energy factorization issues

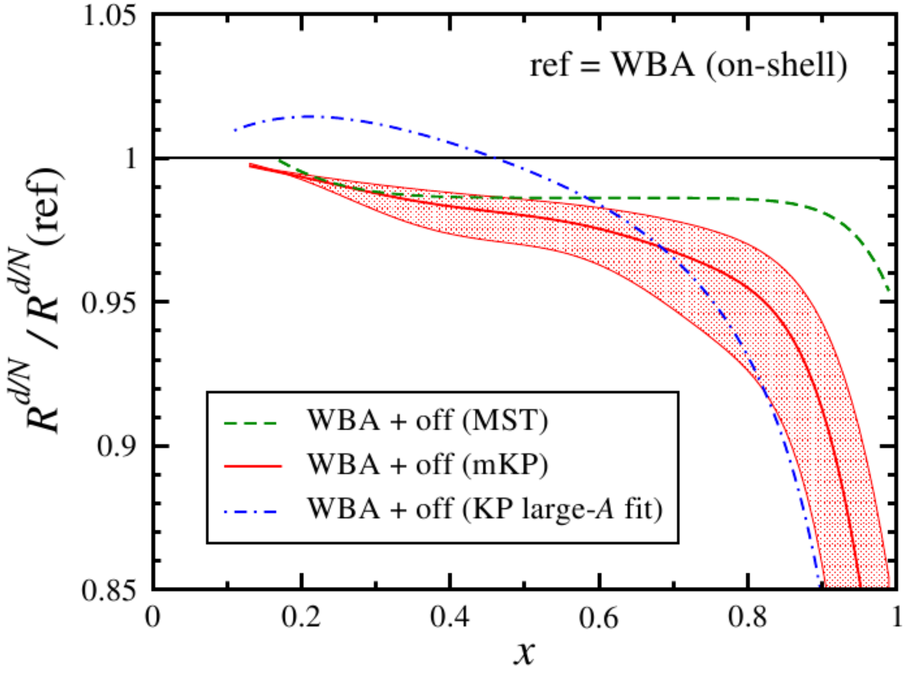
- Renormalization of nuclear operators
- Lorentz vs. gauge invariance, FSI, ...

Nuclear corrections - theoretical uncertainty

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

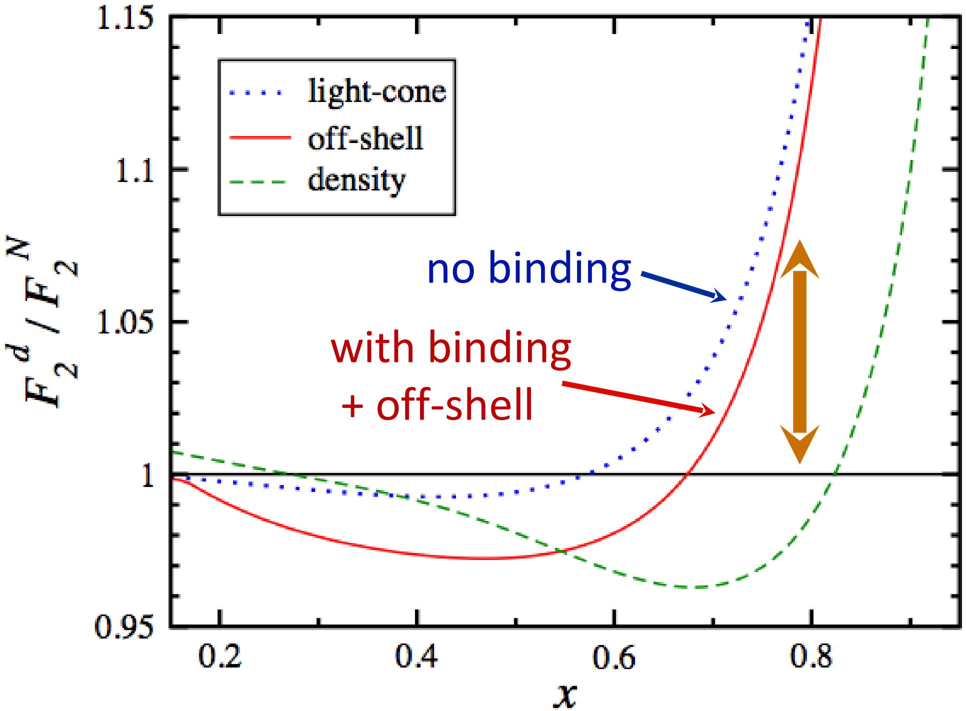
Free nucleon str.fn.





Nuclear corrections

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

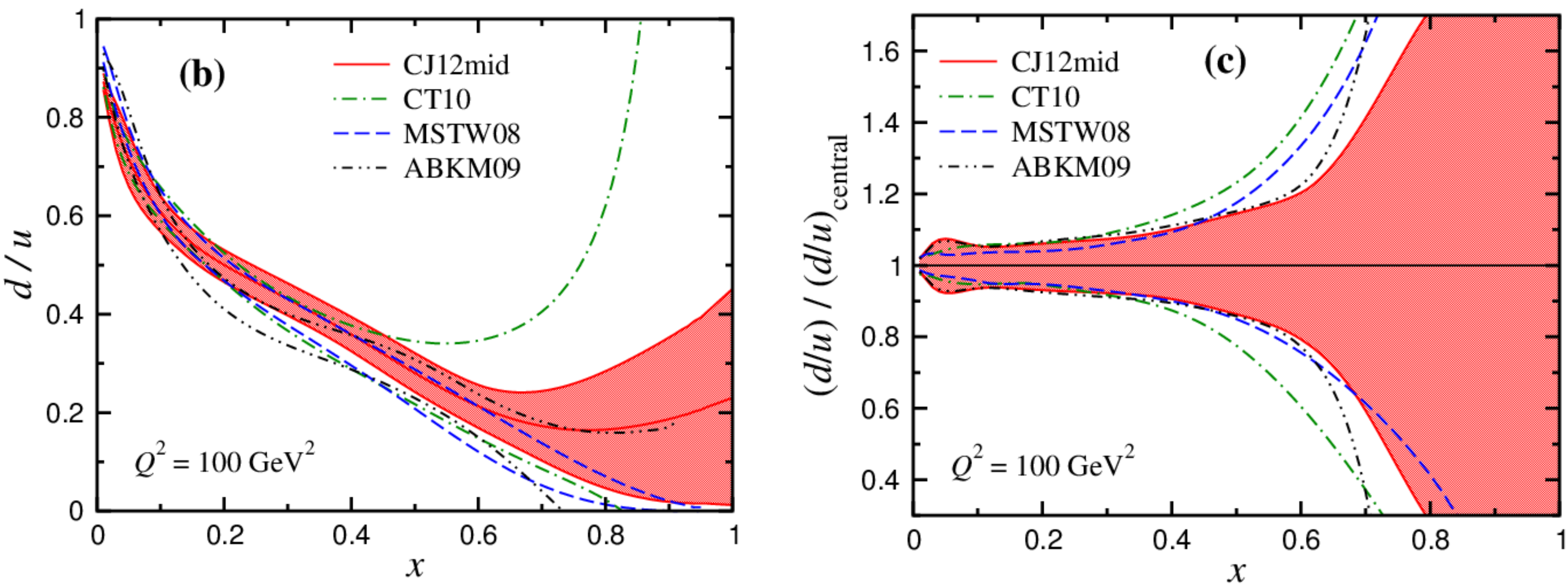


– Using off-shell model, obtains *larger neutron* (larger *d*) than light-cone model

– But smaller *neutron* (larger *d*) than no nuclear effects or density model

d/u ratio: CJ12 *vs.* others

Owens, Accardi, Melnitchouk, arXiv:1212.1702



The mKP off-shell nucleon model

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

- Nucleon at large x = valence quark + spectator diquark

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

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: $R_N \sim 1/\Lambda$

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

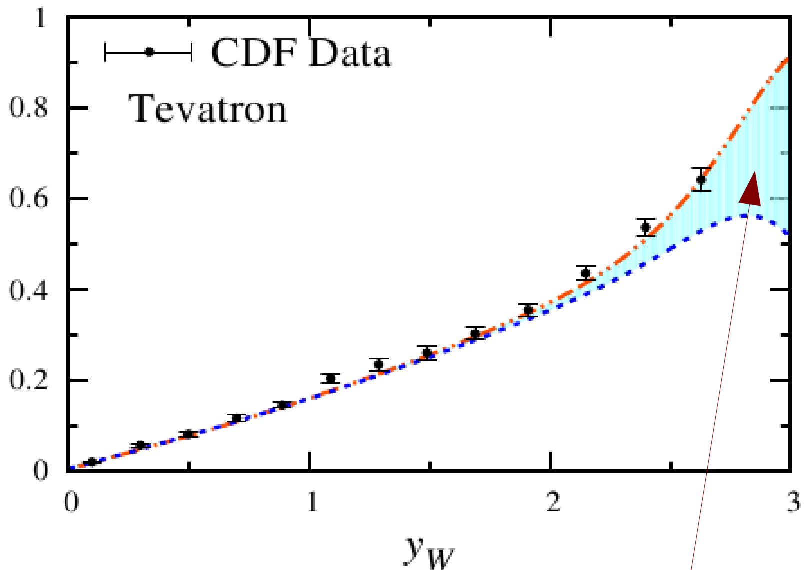
$$\int d^4p(p^2-M^2)\mathcal{S}_d(y)$$

W charge asymmetry at Tevatron

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

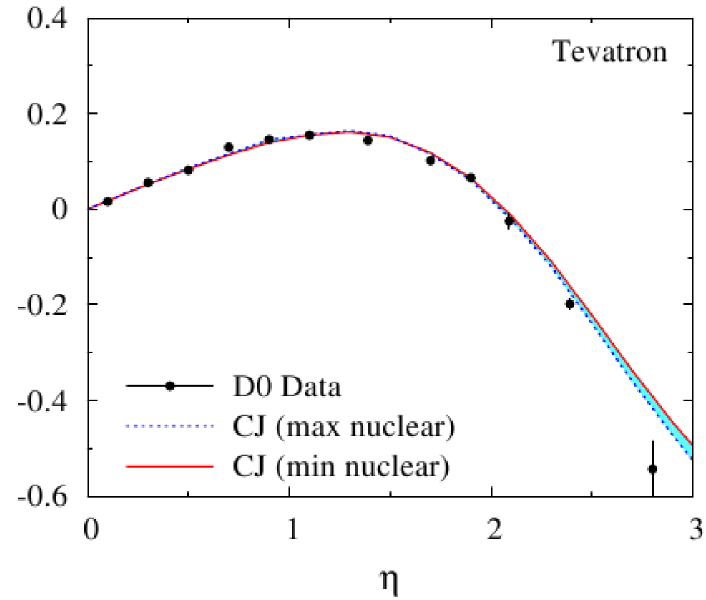
Directly reconstructed W:

- highest sensitivity to large *x*



From decay lepton W → l+ν:

- smearing in *x*



sensitive to *d* at high *x*

Can constrain Nuclear models!

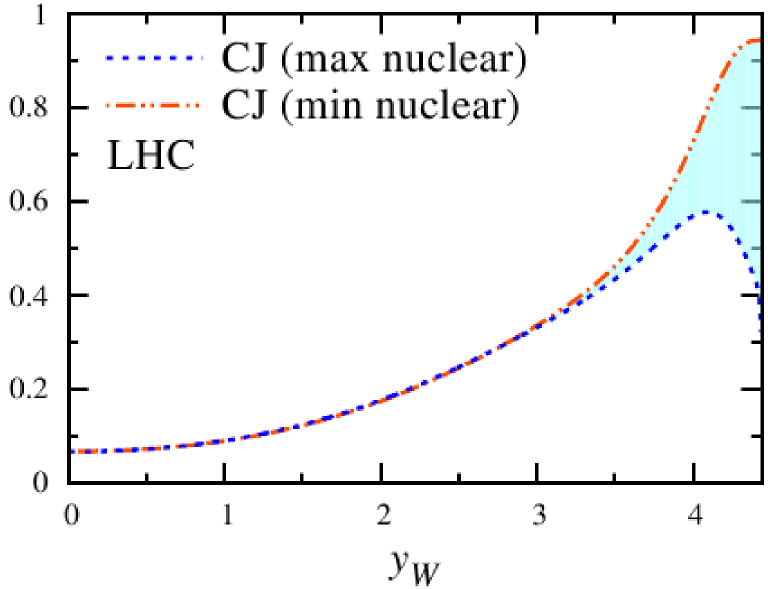
- Too little large-*x* sensitivity in lepton asymmetry:
  - **need reconstructed *W***

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 → l+ν:

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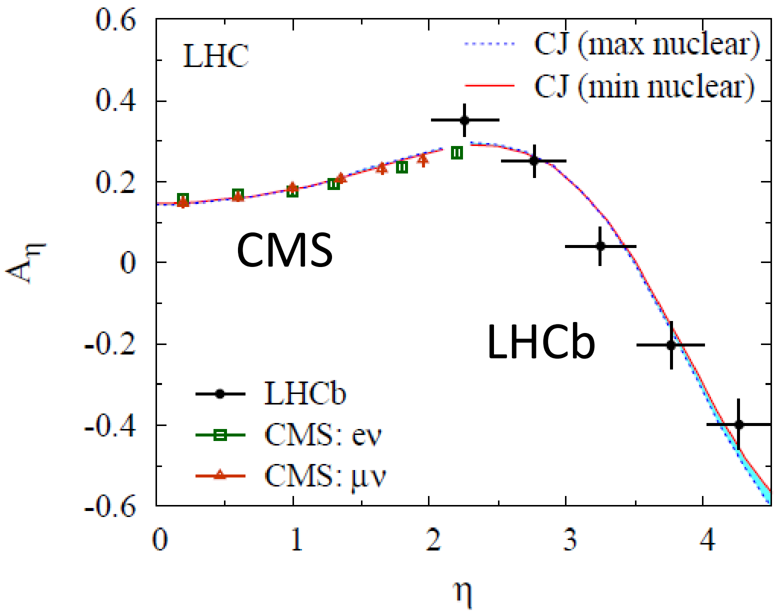
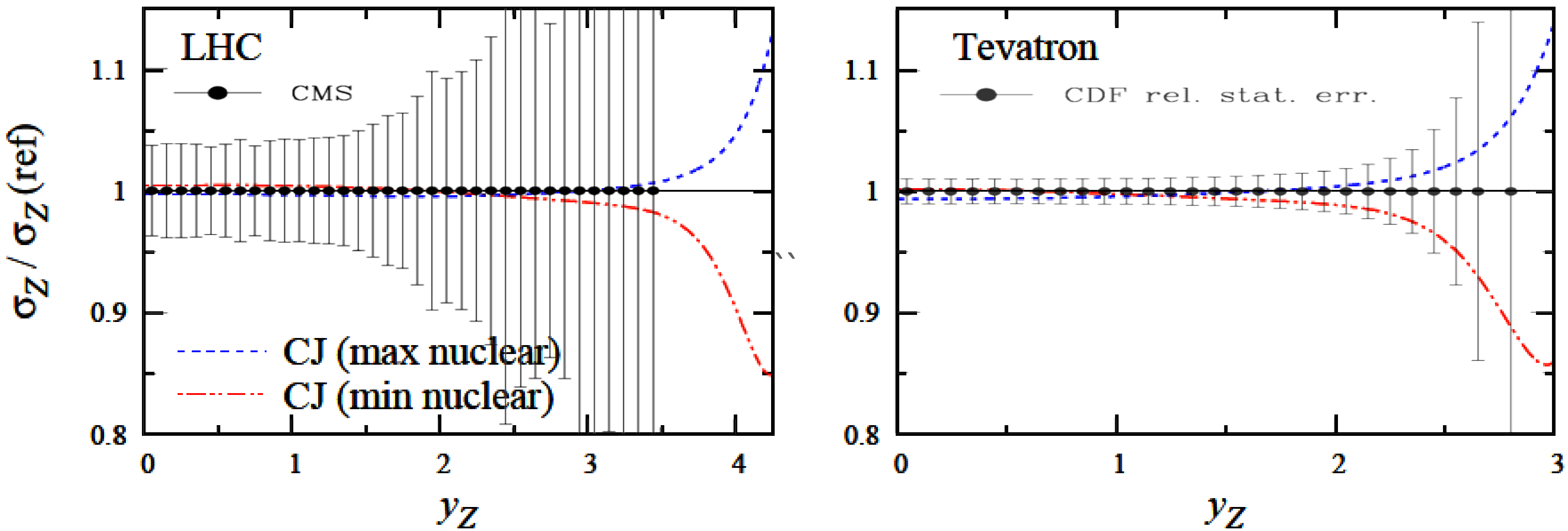


- **Would be nice to reconstruct *W* at LHCb**
  - Definitely needs more statistics
  - Is it at all possible?? (too many holes in detector?)
  - Systematics in *W* reconstruction?
  - **What about RHIC, AFTER@LHC?**

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?