Large-x partons from JLab to the LHC

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HAMPTON UNIVERSITY
THE STANDARD OF EXCELLENCE

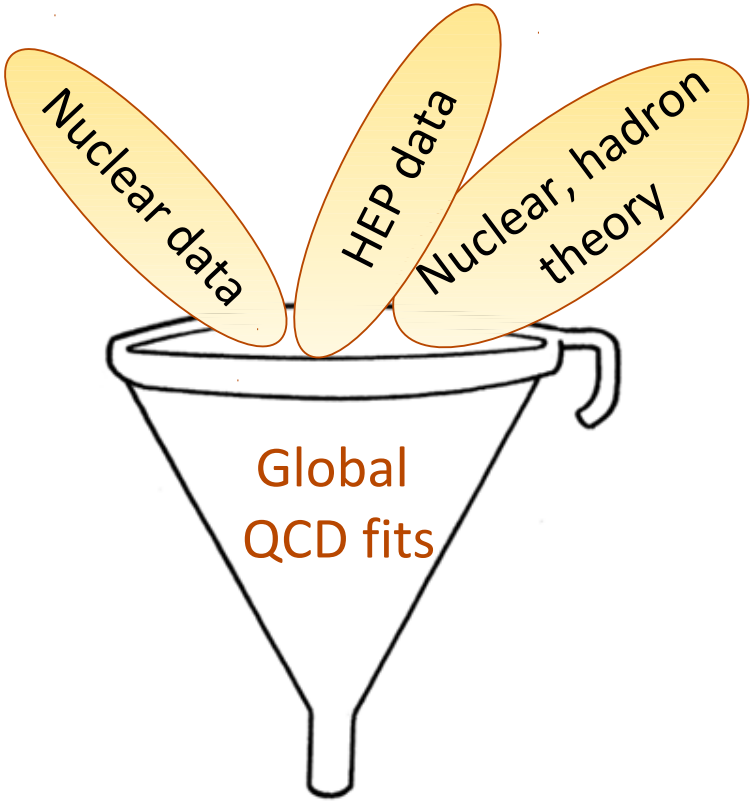
Jefferson Lab

"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



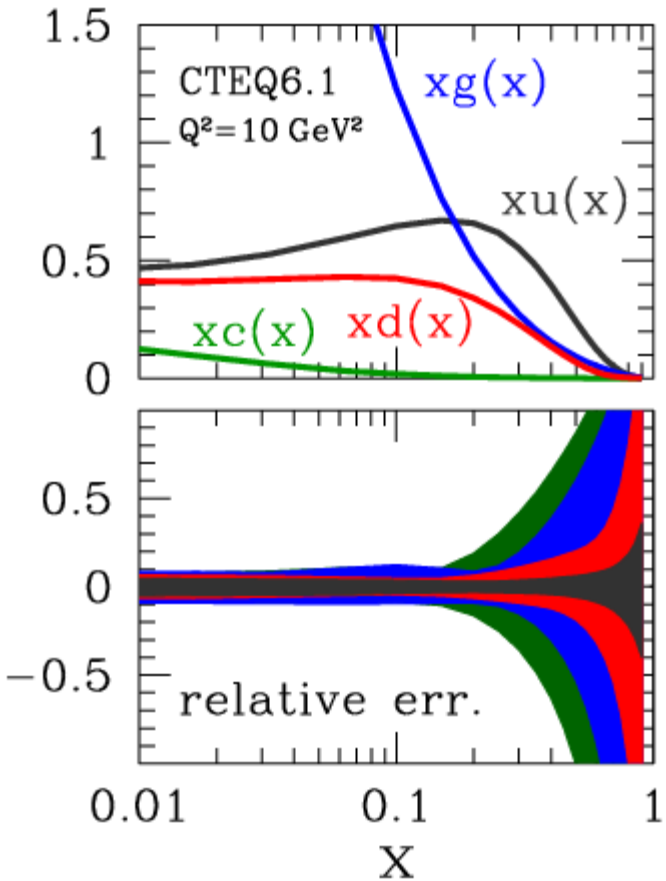
In-medium protons and neutrons

New physics

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 large p_T excess
    - High mass searches
    - 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

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

Valence quarks at large *x*

- Non-perturbative models:
  - **SU(6) spin-flavor symmetry:** $d/u \xrightarrow[x\to 1]{} 1/2$
  - **Broken SU(6) : hard gluon exchange:** $d/u \xrightarrow[x\to 1]{} 1/5$
  - **Broken SU(6) : scalar diquark dominance** $d/u \xrightarrow[x\to 1]{} 0$

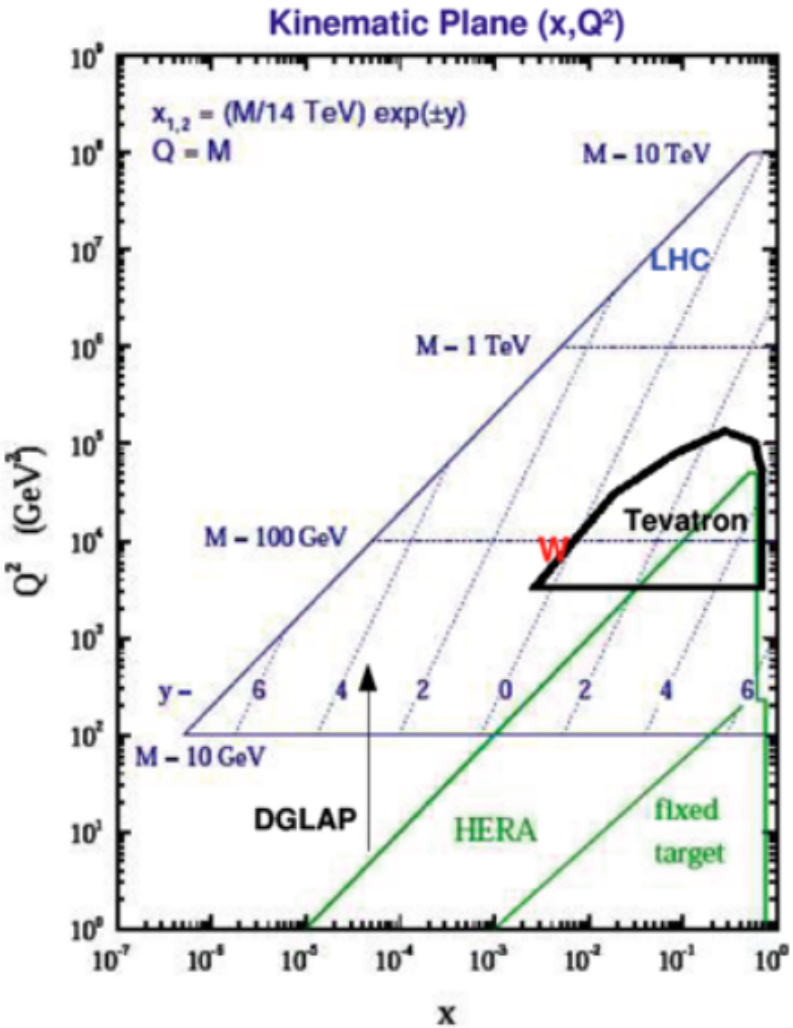
- No free neutron! Best proxy: Deuteron
  - But bound and off-shell nucleons, Fermi motion

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: $y > 2$

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

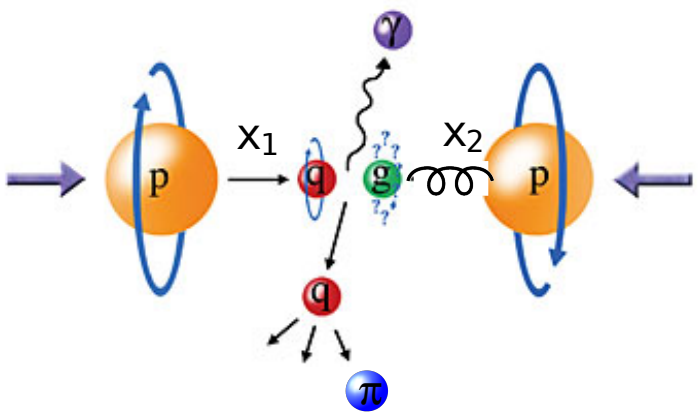
- **Precise large-*x* PDFs needed** to:
  - reduce QCD background
  - optimize searches involving large mass
  - precisely characterize new particles

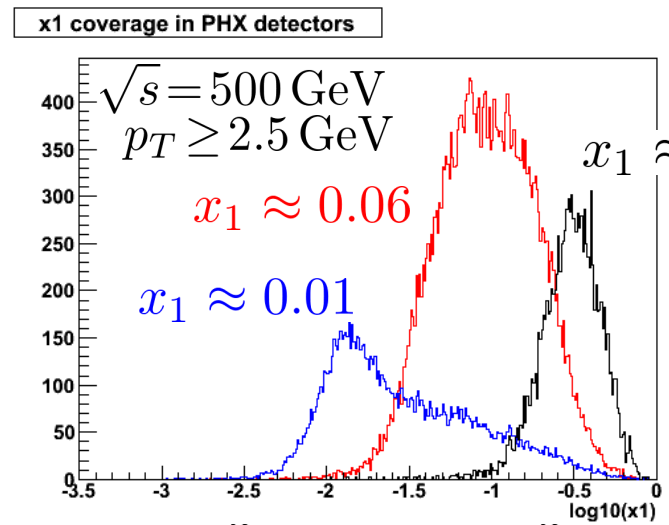


Large *x* at colliders - Gluon spin at small x

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

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





π rapidity:
$|\eta| \leq 0.35$
$\eta = 1.0 - 3.0$
$\eta = 3.1 - 3.9$

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

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

The CTEQ-JLab global fits

- **Collaborators:**
  - A.Accardi, E.Christy, C.Keppel, K.Kovarik, W.Melnitchouk, P.Monaghan, J.Owens
- **Goals:**
  - Improve large-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** (PRD to appear)
    - www.jlab.org/cj
    - Included in LHAPDF

The CTEQ-JLab global fits

- **Collaborators:**
  -
- **Goa**
  -
  -
  -
  -
- **Pu**
  -
    - Included in LHAPDF

set

ear)

Special advertisement section

JAM*:

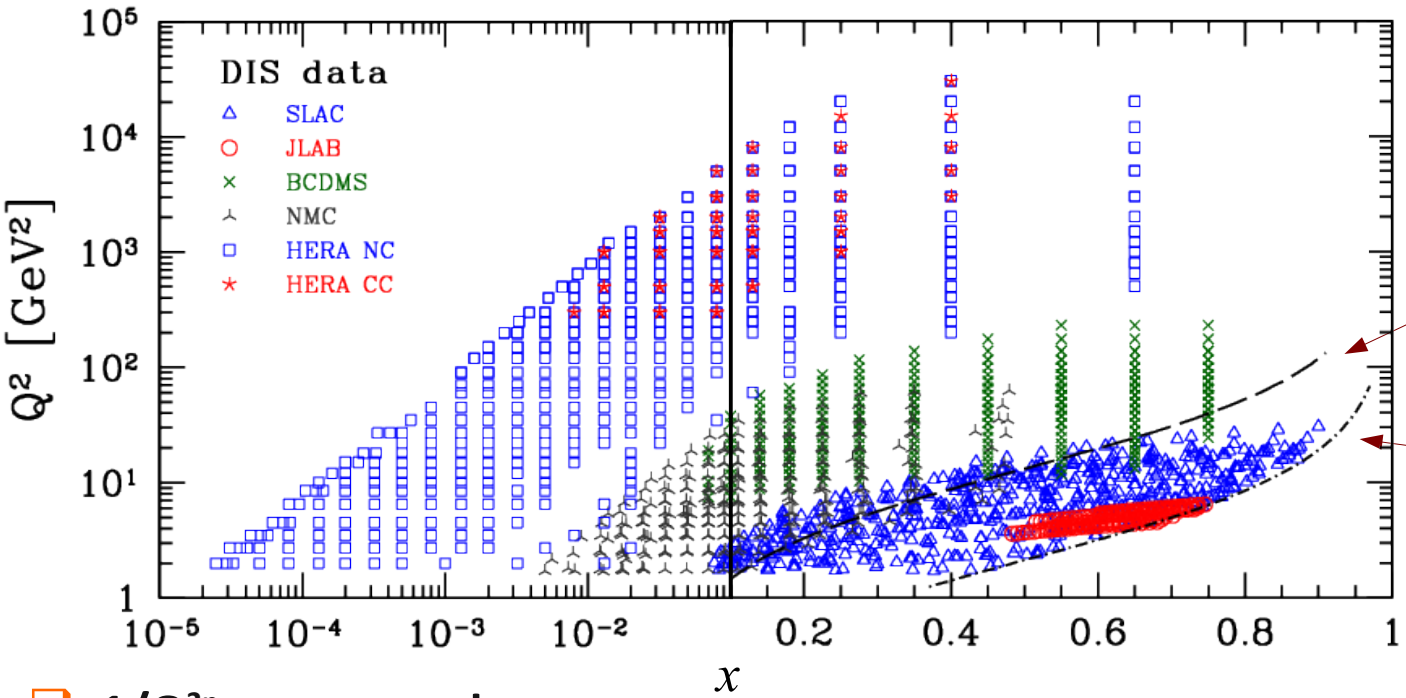
a new polarized PDF fit

(Accardi, talk at DIS2013)

But if you really insist it will only take an additional 15 minutes...

* Jefferson Lab Angular Momentum collaboration

Large-x, small-Q^2 corrections



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

Accardi et al.
PRD ***D81*** *(2010)*

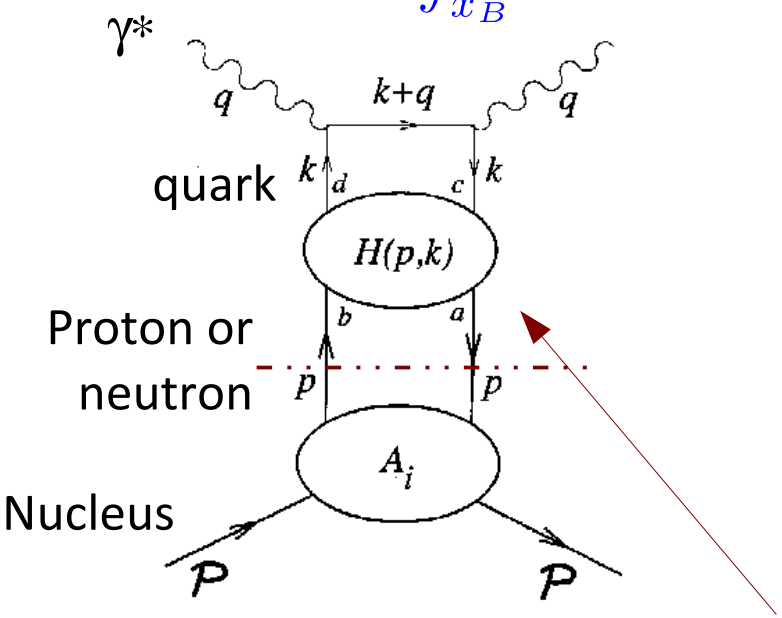
included in CJ fits

Deuteron corrections

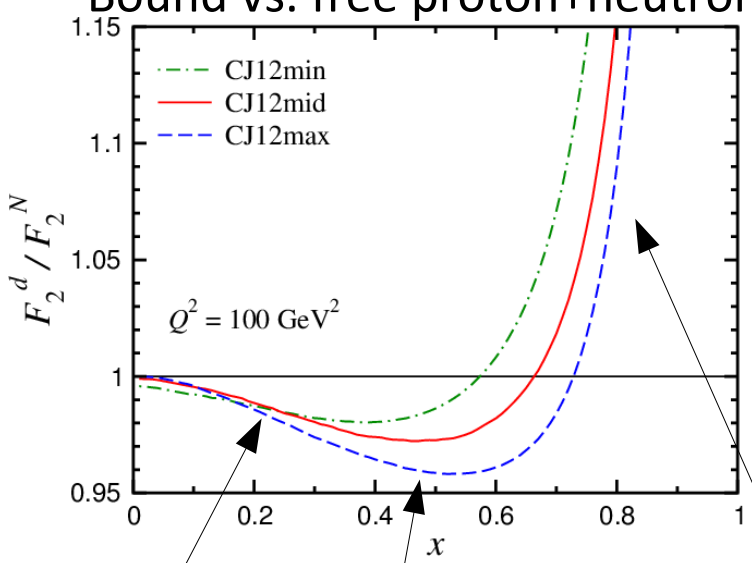
- No free neutron! Best proxy: Deuteron
  - Parton distributions (to be fitted)
  - nuclear wave function (AV18, CD-Bonn, WJC1, …)
  - Off-shell nucleon modification (model dependent)

  } Theoretical uncertainty

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



Bound vs. free proton+neutron



binding

off-shellness

Fermi motion

Low-energy factorization issues

- Renorm. of nuclear operators, gauge inv., FSI, …

Fit framework

- We concentrated on theory corrections, established a baseline fit
- Data
  - DIS: fixed target F_2, HERA combined σ
  - Drell-Yan, W asymmetry, Z rapidity distribution
  - Tevatron jets, γ + jets
- Parametrization (with *d*-quark and strange sea exception)

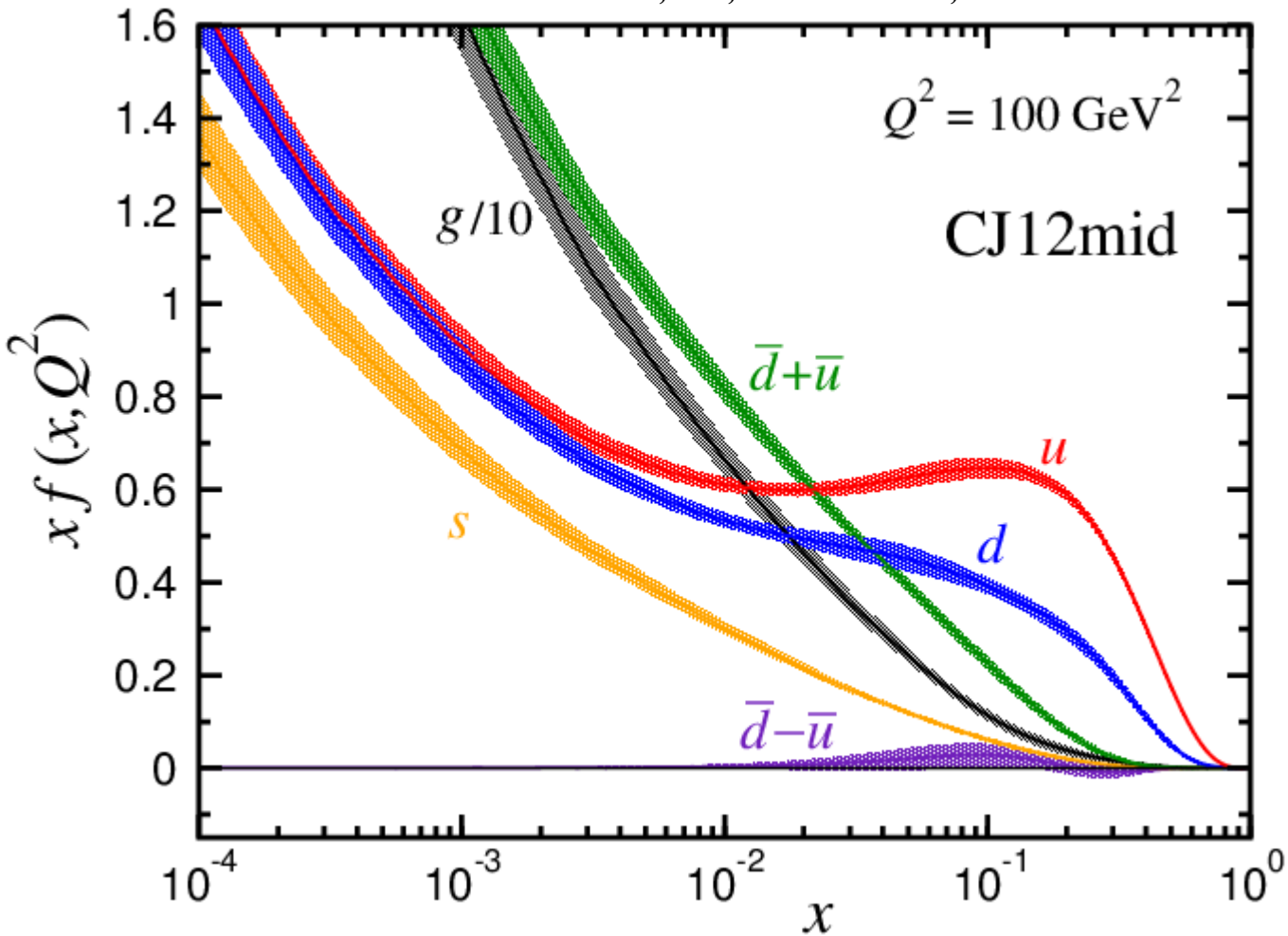
$$xf(x) = Nx^a(1-x)^b(1+c\sqrt{x}+dx)$$

$$F_2 = F_2^{LT}\left[\left(1+a_{HT}x_{HT}^b(x)(1+c_{HT}x)\right)/Q^2\right]$$

- Other
  - NLO, zero-mass VFN scheme (will upgrade to s-ACOT)
  - α_s = 0.118 (will be fitted in future releases)
  - Correlated errors, Hessian technique, tolerance T=10

CJ12 parton distributions

Owens, AA, Melnitchouk, arXiv:1212.1702



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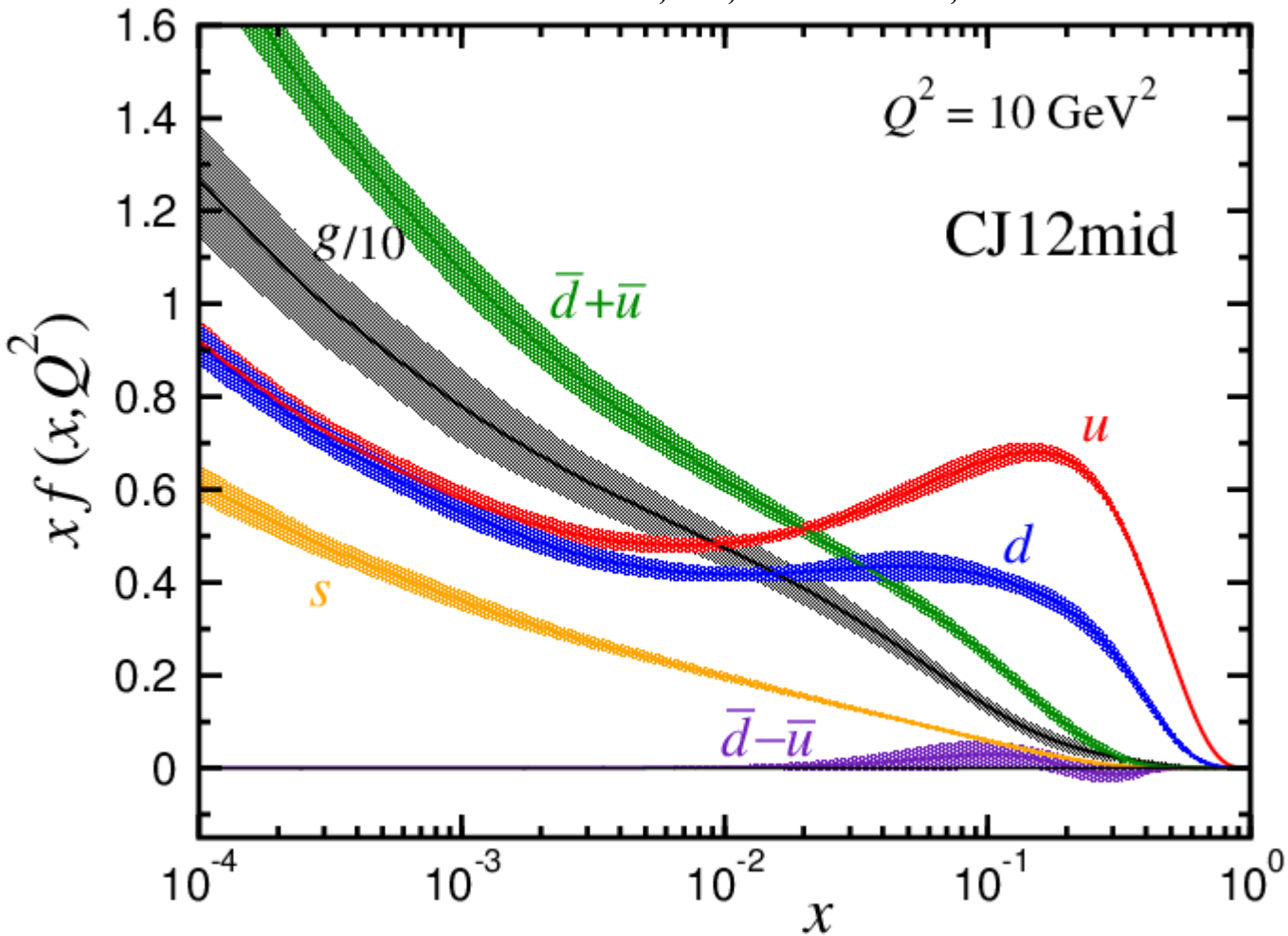

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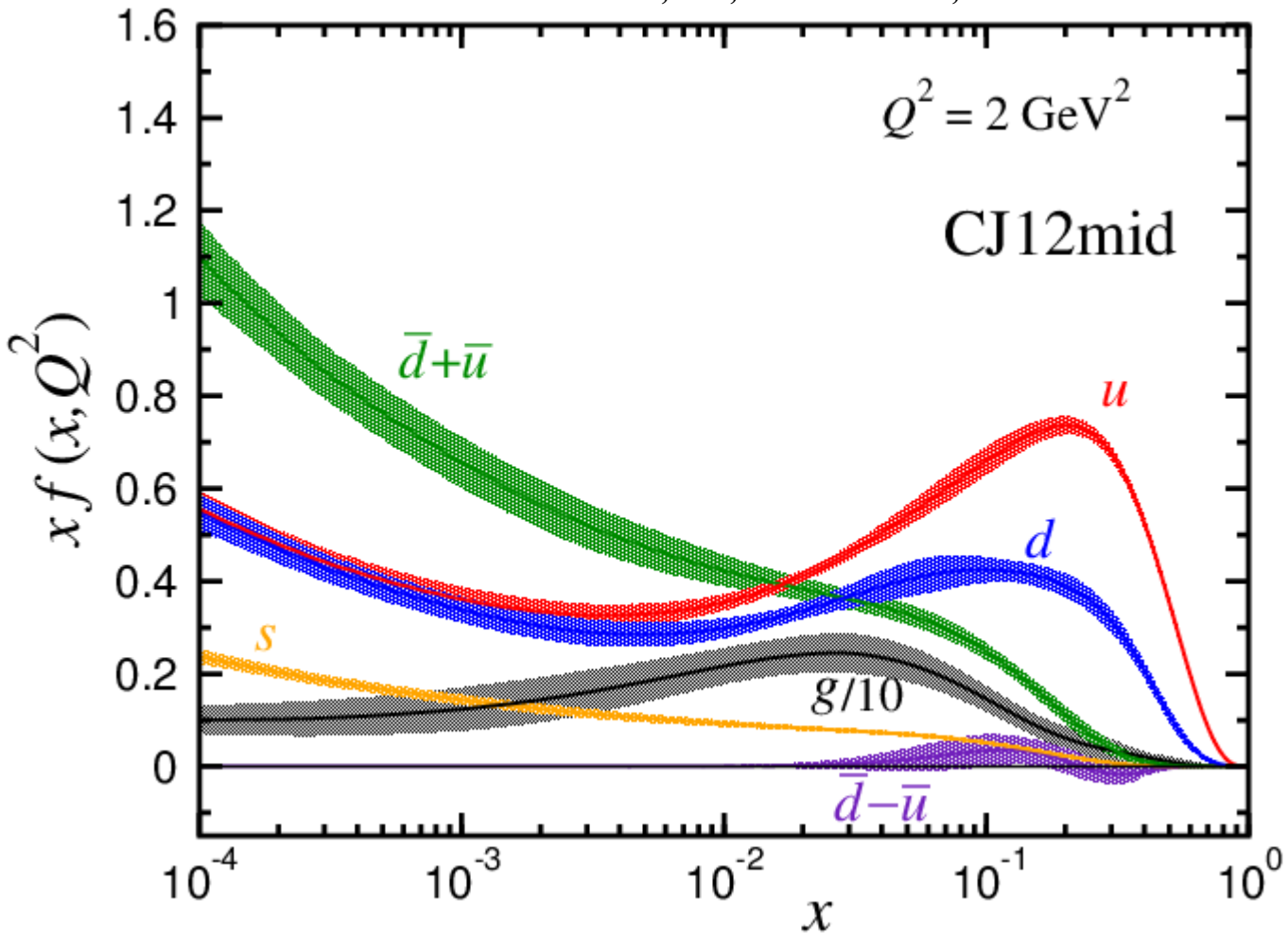
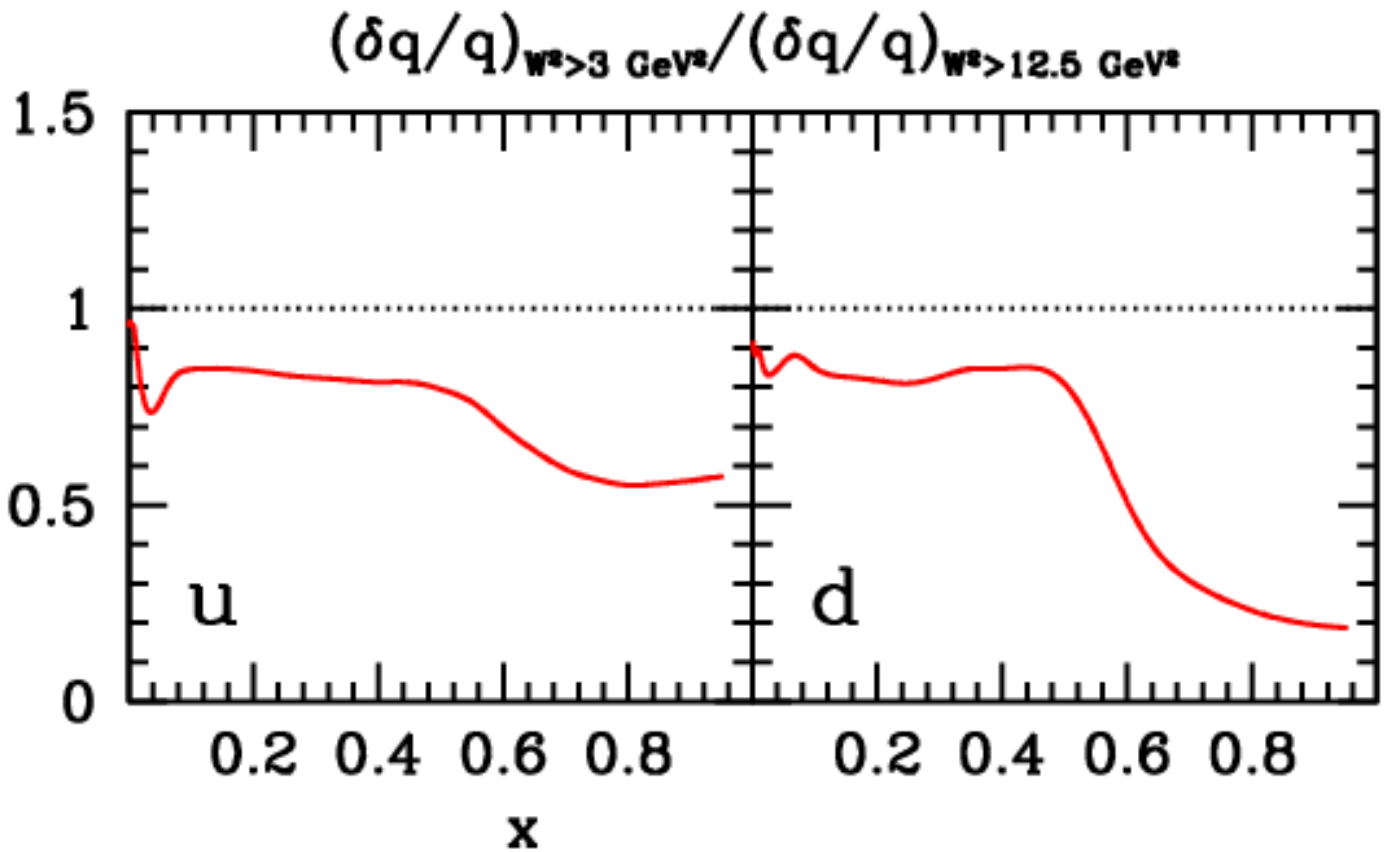


Statistical improvement



Theoretical uncertainties

Effect of theory corrections in a nutshell

- **New *d*-quark parametrization**

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

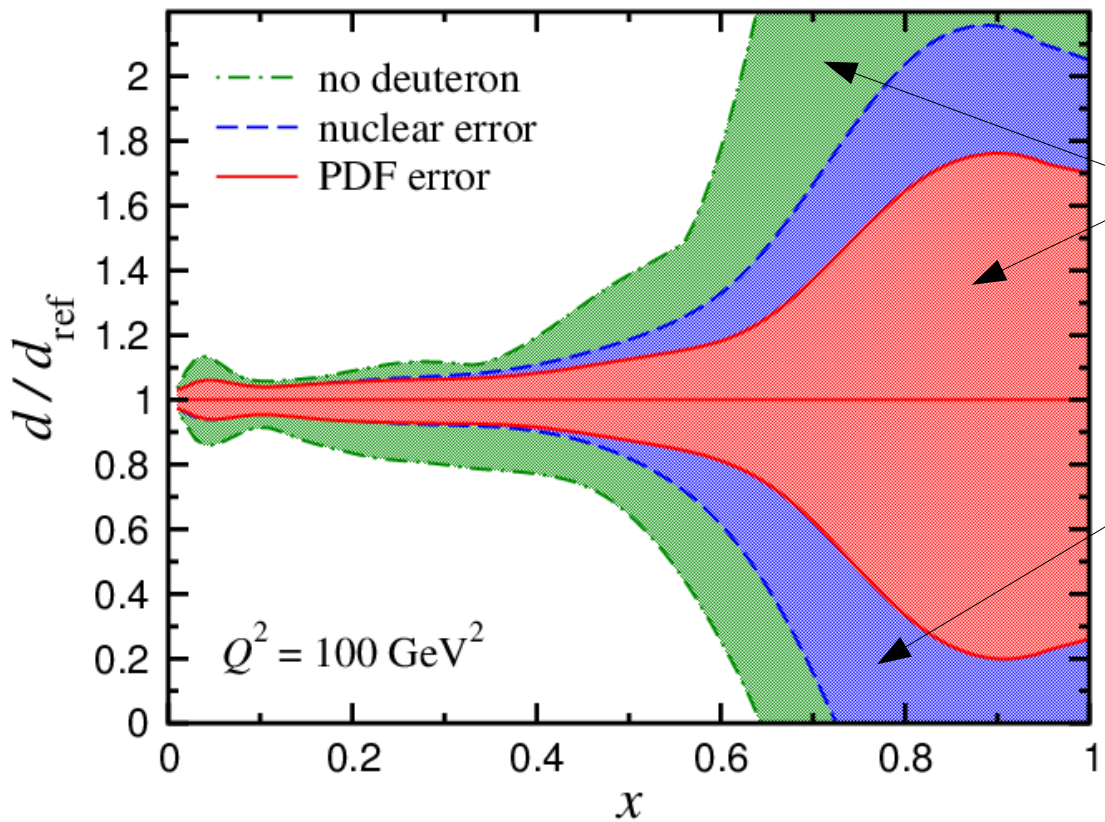
  - Allows d/u to be non-zero at $x = 1$ (as required in non-perturbative models)
  - Produces ***dramatic increase in d PDF in x → 1 limit***

- **Sensitivity to nuclear corrections**
  - *d*-quark at $x > 0.5$ almost fully correlated to nuclear model model: ***Very large theoretical uncertainty at large x***
  - Modest, non negligible impact also at $0.2 < x < 0.5$

Accardi et al. PRD81 (2010)
Ball et al. ArXiv:1303.1189 (2013)

CJ12 fits: nuclear and PDF uncertainty

Owens, Accardi, Melnitchouk, arXiv:1212.1702



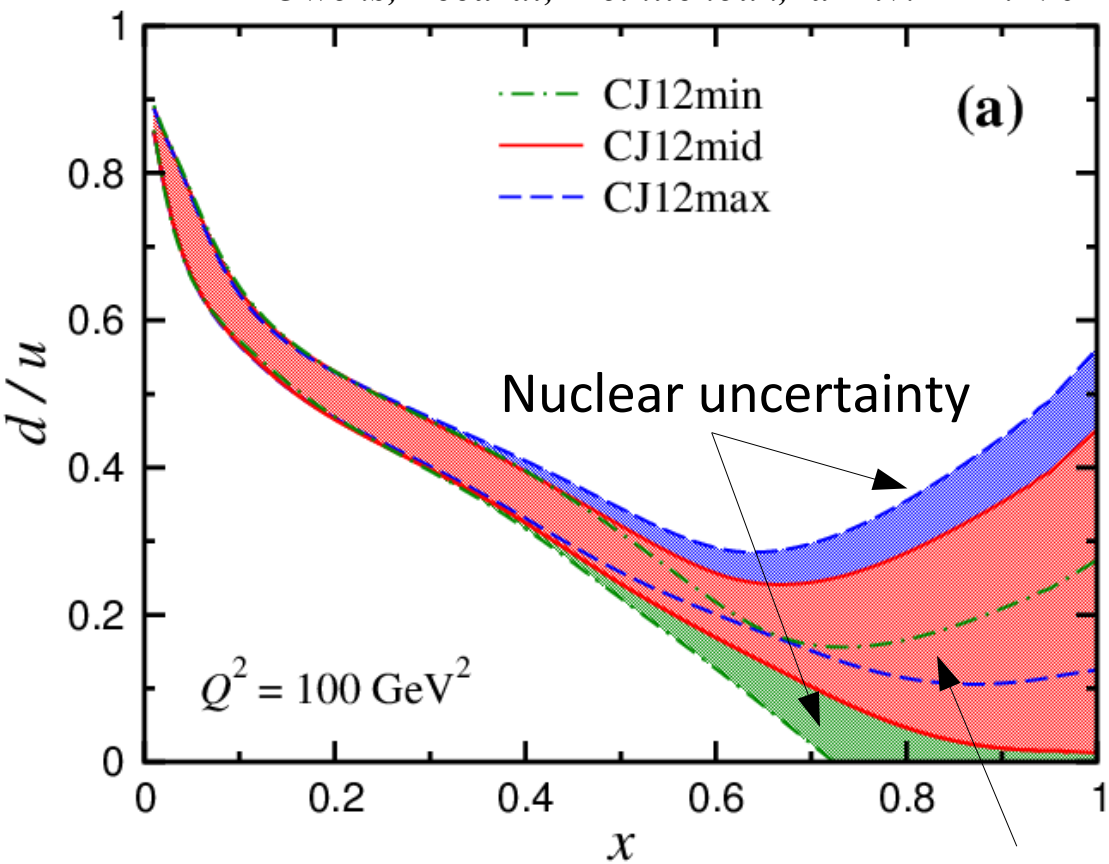
Largely reduced PDF errors (increased statistics)

Nuclear uncertainties (systematic)

- Large overall reduction in uncertainty with relaxed cuts

Applications: *d/u* ratio

Owens, Accardi, Melnitchouk, arXiv:1212.1702



Non-perturbative proton models

SU(6) spin-flavor

hard gluon exchange

S=0 diquark dominance

"PDF" experimental uncertainty

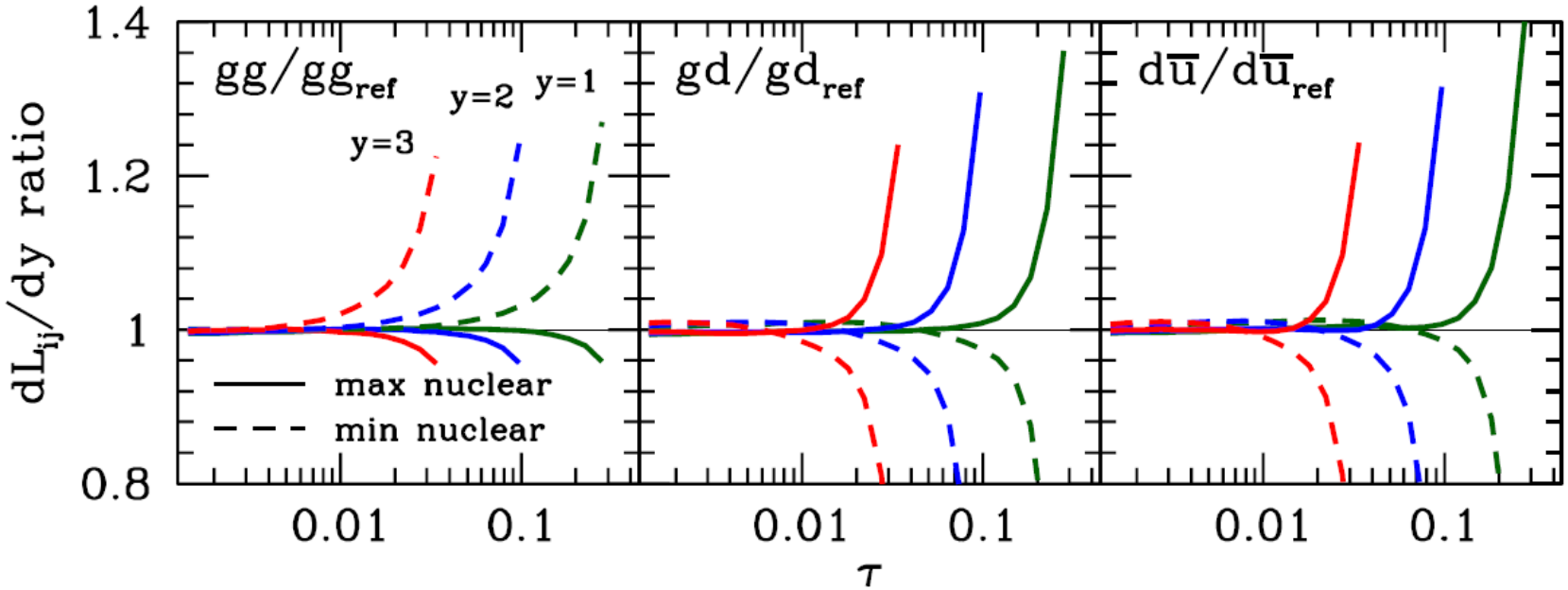
$$d/u \xrightarrow[x\to 1]{} 0.22 \pm 0.20\,(\mathrm{PDF}) \pm 0.10\,(\mathrm{nucl})$$

Applications: new physics at LHC

Accardi et al., PRD84 (2011) 014008

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

Differential parton luminosities

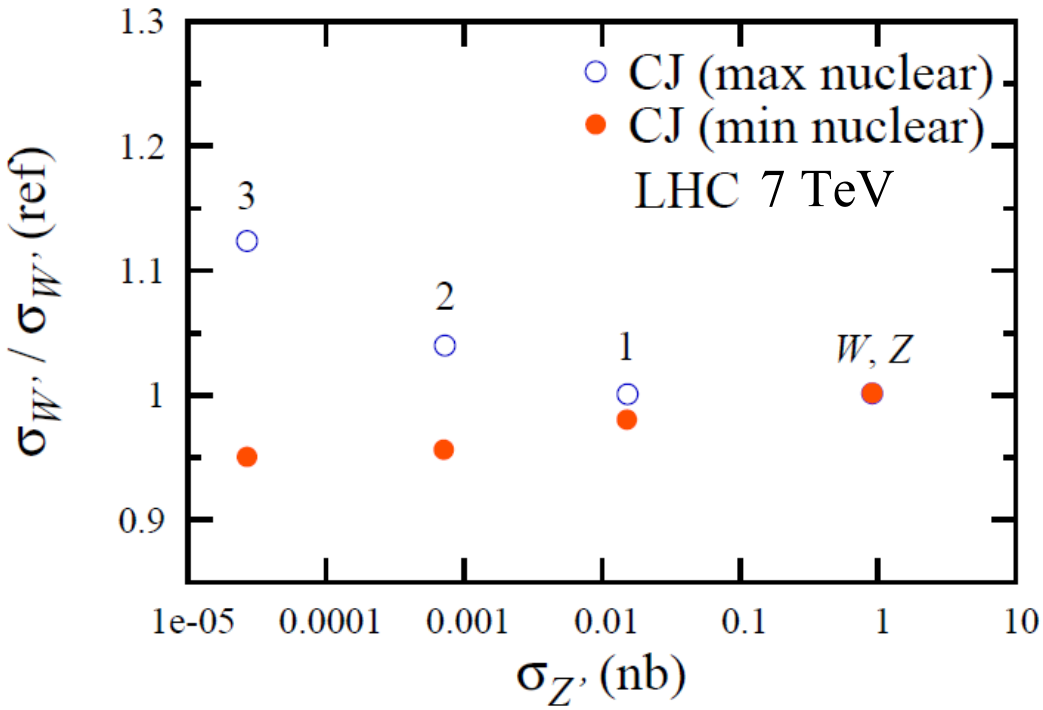


Applications: large mass searches at LHC

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

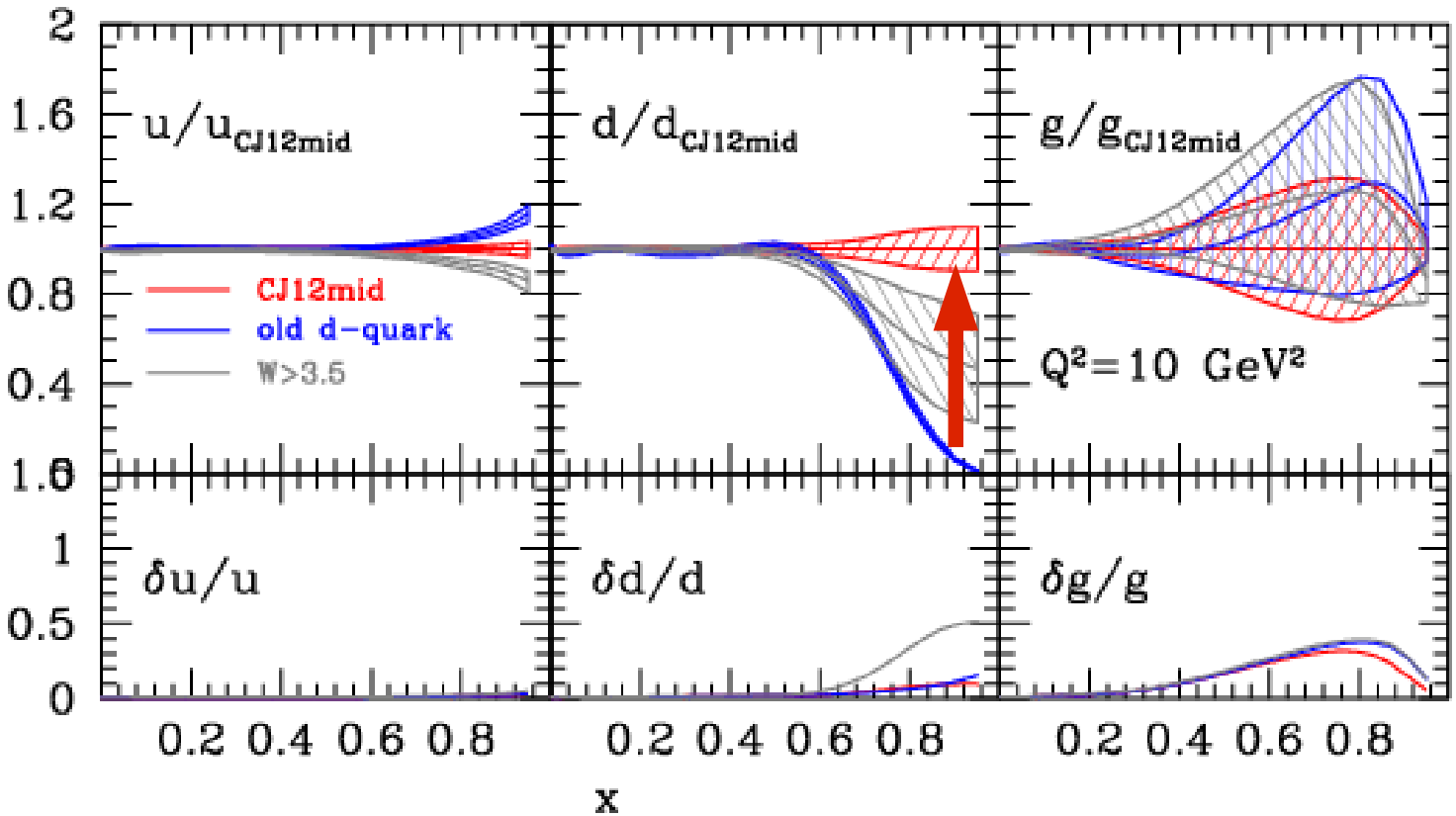
- New physics signal require accurate determination of QCD background
- Uncertainties in large-*x* PDFs could affect interpretation of experiments searching for new particles

Example: W' and Z' total cross sections



CJ12: old vs. new *d* quark

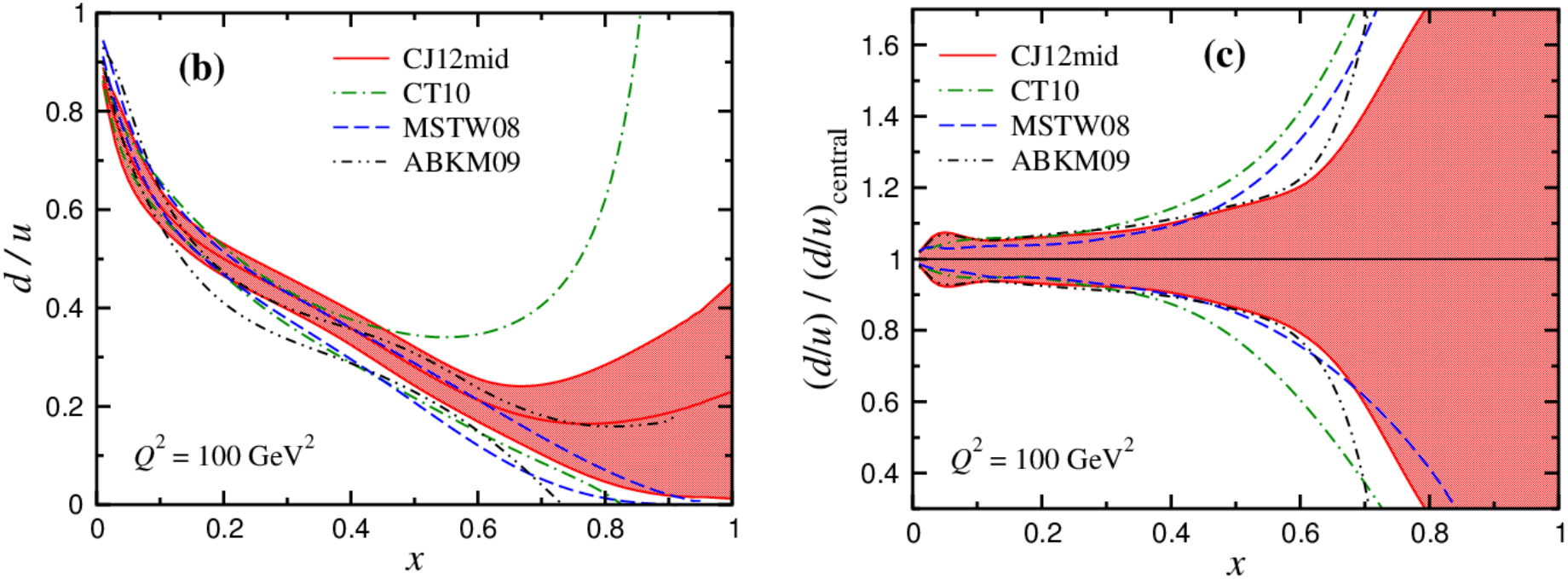
[here T=1 for clarity]



- Dramatic increase in *d* quark with more flexible parametrization
- Standard (old) d-quark: either $d/u \to 0$ or $d/u \to \infty$
  - ***Large bias, neglected in all other fits***

CJ12: old vs. new *d* quark

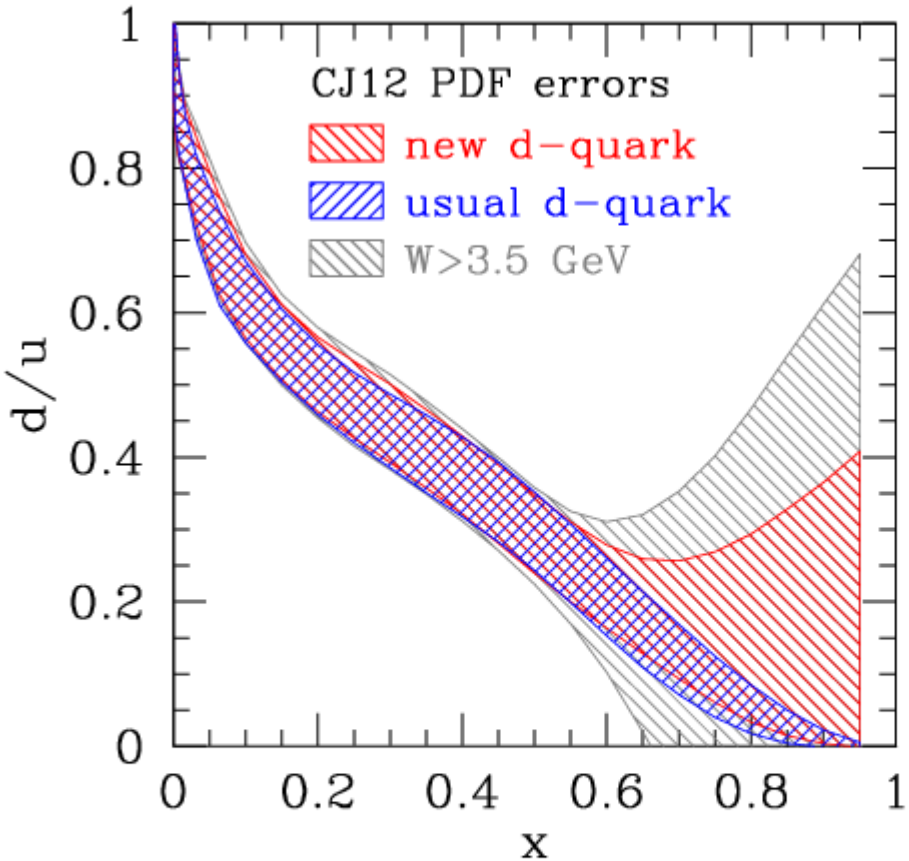
Owens, Accardi, Melnitchouk, arXiv:1212.1702

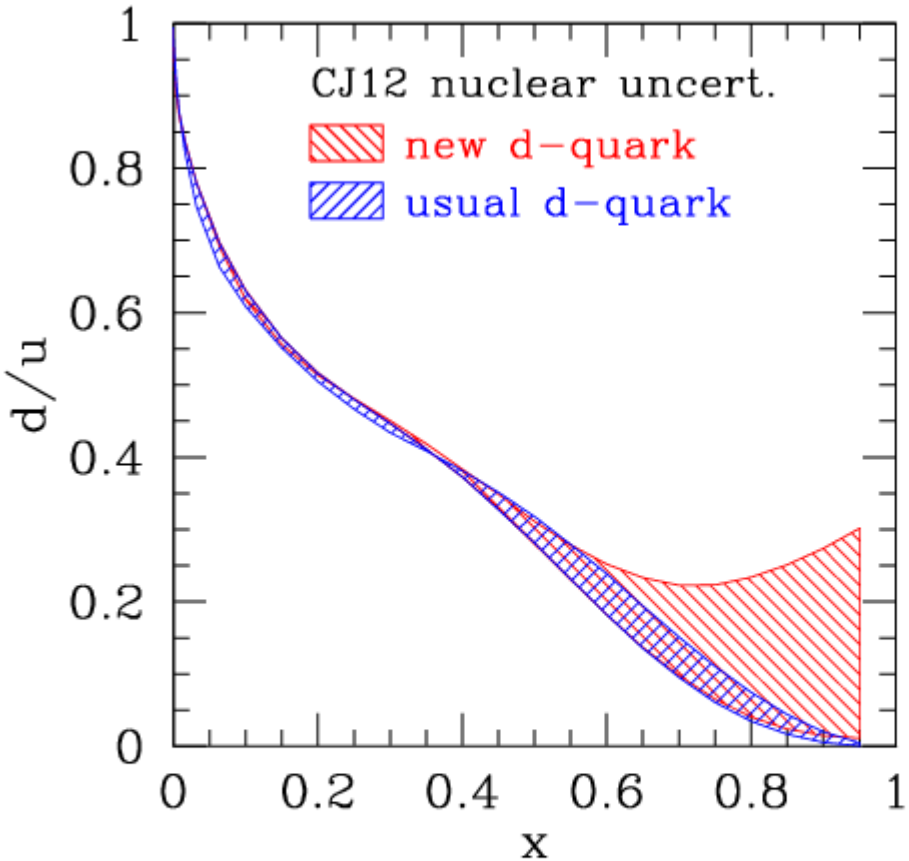


$$\frac{d'}{u} \longrightarrow \frac{a_d(1-x)^{b_d}}{a_u(1-x)^{b_u}} + \alpha \longrightarrow \begin{cases} \alpha & \text{if } b_d > a_d \\ \infty & \text{otherwise} \end{cases}$$

$$d \longrightarrow \begin{cases} 0 & \text{if } b_d > a_d \\ \infty & \text{otherwise} \end{cases}$$

CJ12: old vs. new *d* quark



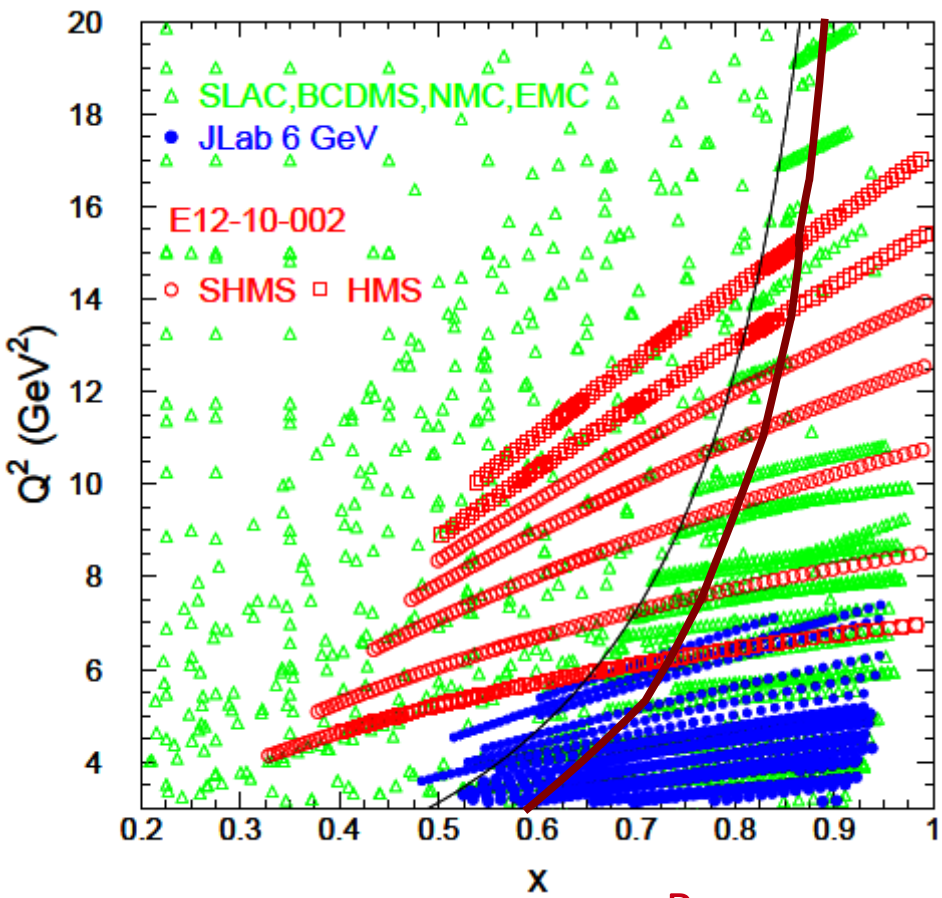


- ***Standard d-quark too stiff at x > 0.6***
  - Underestimates central value *and nuclear uncertainty*
  - Full unbiasing could be obtained in a NN analysis with low *W* cuts

Beating the experimental uncertainties

At JLab 12

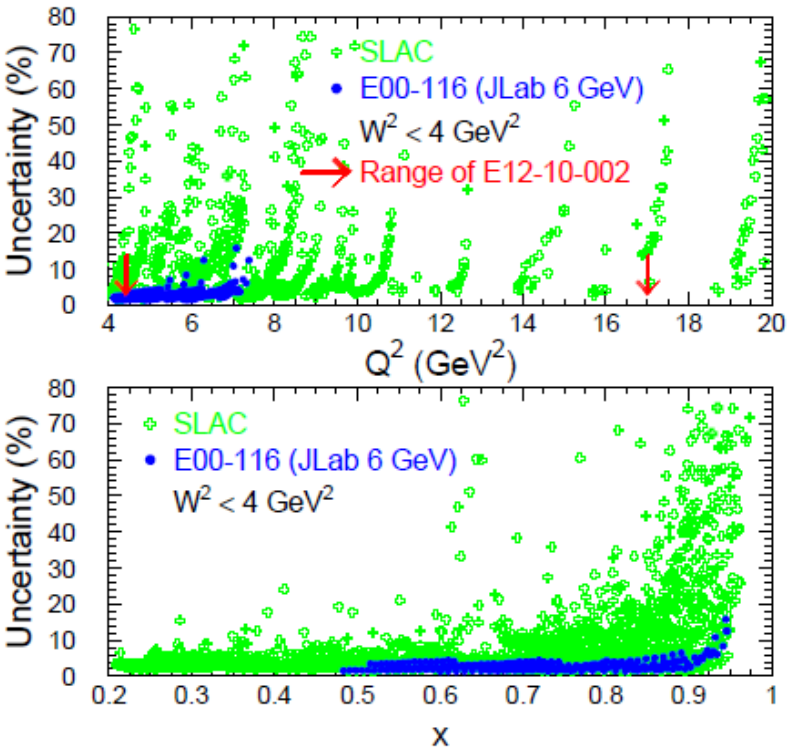
CJ cut: $W^2 > 3\ \mathrm{GeV}^2$



DIS region

Resonance region

Jlab12 experiment E12-10-002 (running in 2015)

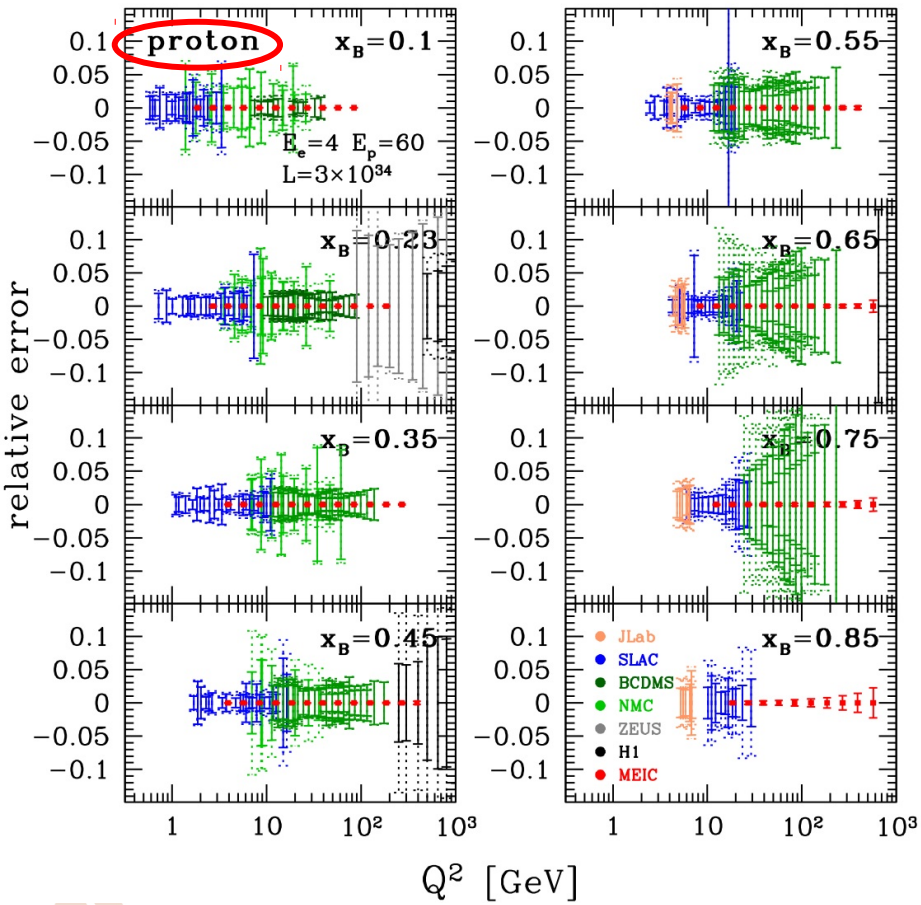


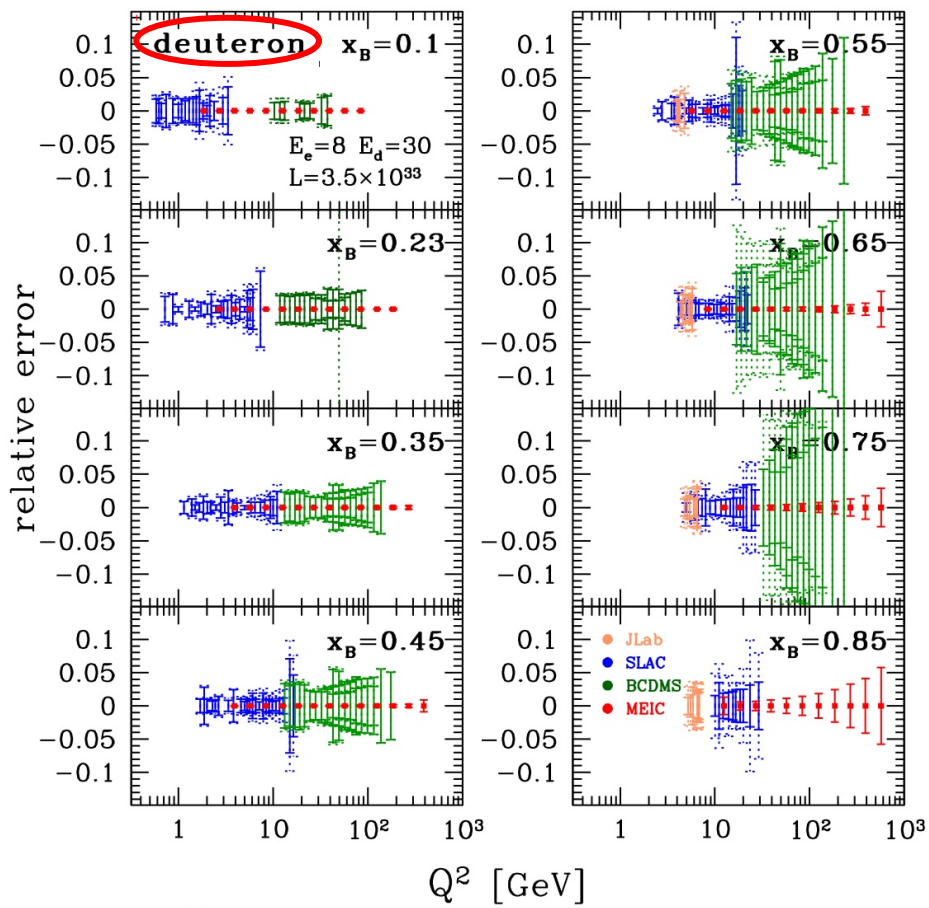
Goal @ 12 GeV: similar precision as E00-116 (@ 6 GeV)

At the EIC

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

[Accardi, Ent, Keppel]





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^+ vs. e^-)*, ***EIC, LHeC***
  - 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: CDF, D0(?)
LHCb(?) RHIC
AFTER@LHC

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

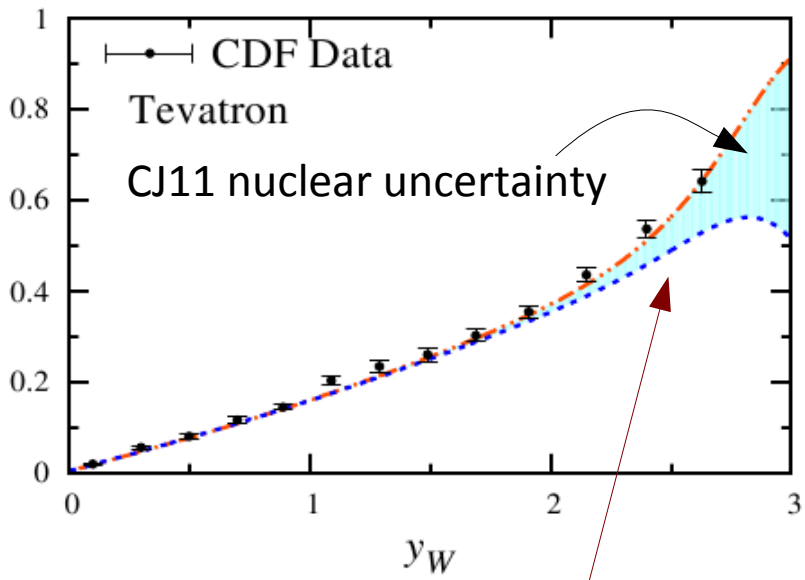
RHIC ??
AFTER@LHC

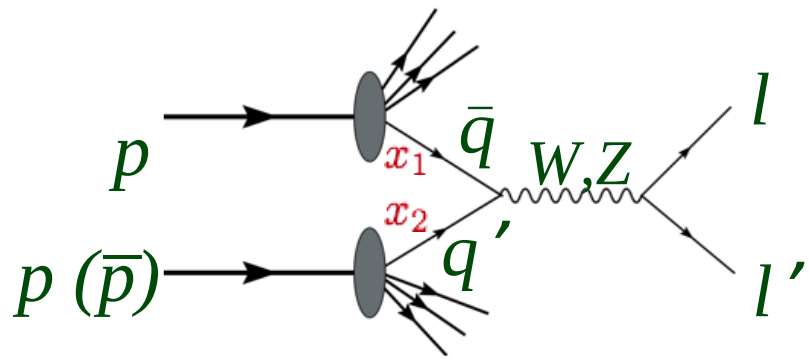
Use protons to study nuclei (!)

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!

See also MMSTWW, EPJ C73 (2013)

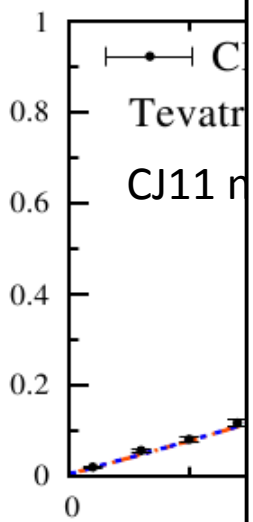
- Needs to be corroborated:
  - *W, Z* at RHIC, *Z* (and *W* ?) at LHC, *W* at DØ (??)
  - PVDIS at JLab 12, **CC @ EIC**

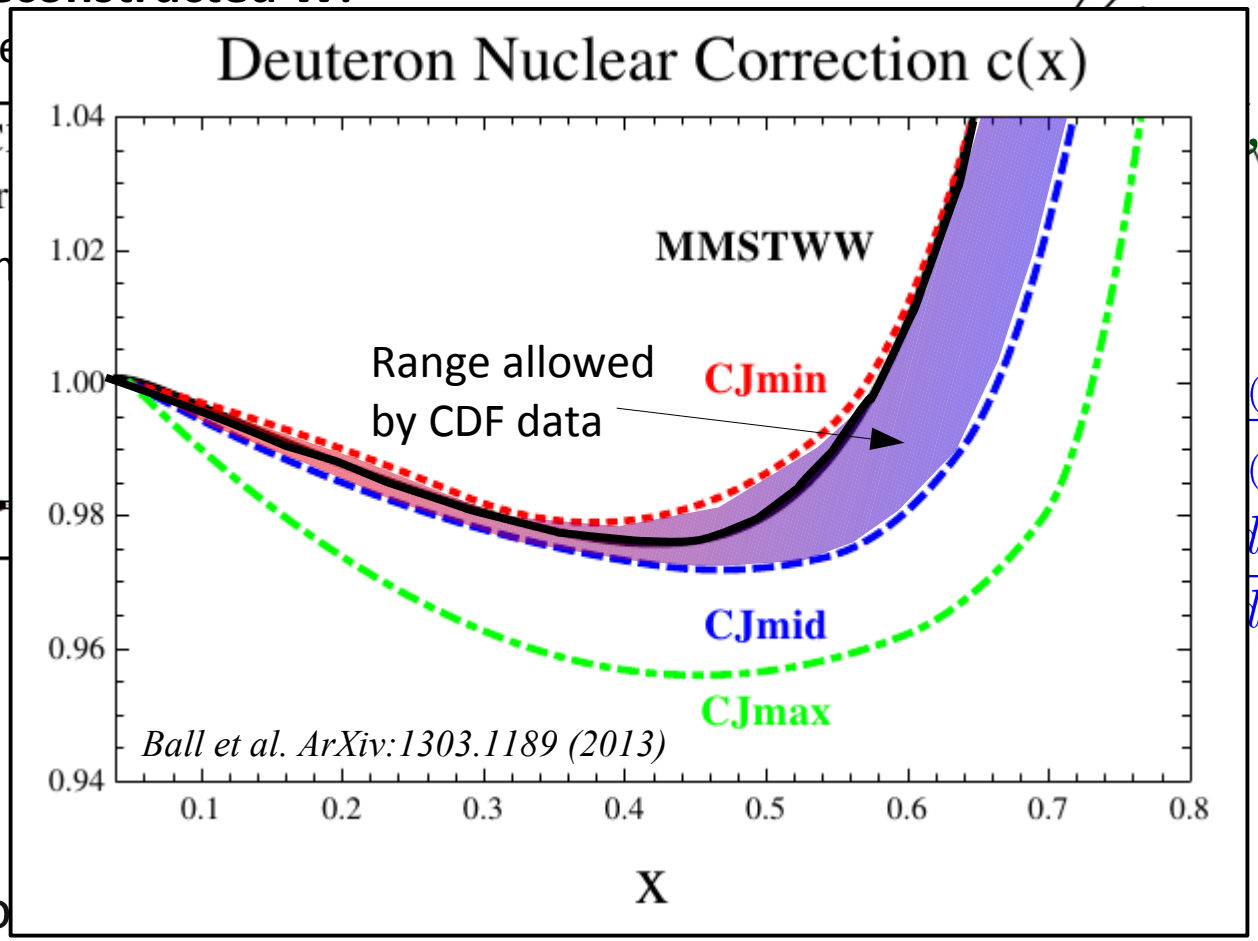
Use protons to study nuclei (!)

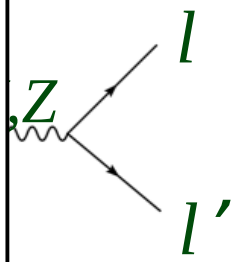
Brady, Accardi, Melnitchouk, Owens, JHEP 1206 (2012) 019

Directly reconstructed W:

- highest se







$$\frac{(W^-)}{(W^-)}$$

$$\frac{d/u(x_1)}{d/u(x_1)}$$

EPJ C73 (2013)

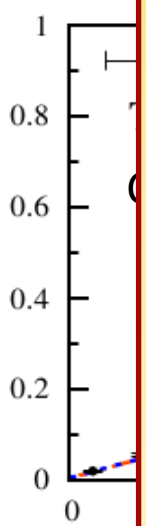
- Needs to
  - *W, Z* at RHIC, *Z* (and *W* ?) at LHC, *W* at DØ (??)
  - PVDIS at JLab 12, **CC @ EIC**

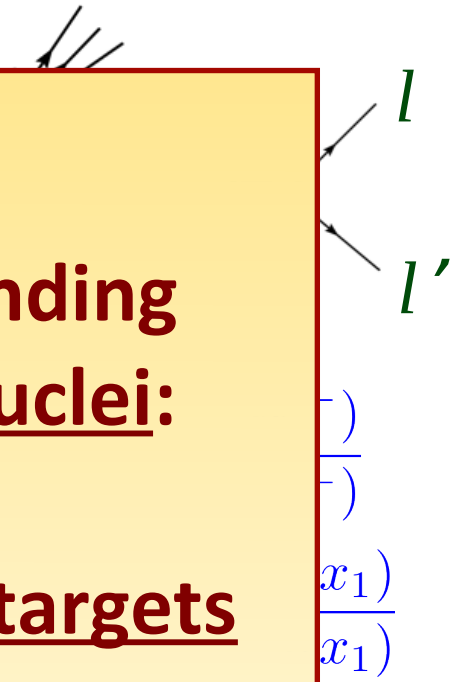
Use protons to study nuclei (!)

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

C73 (2013)

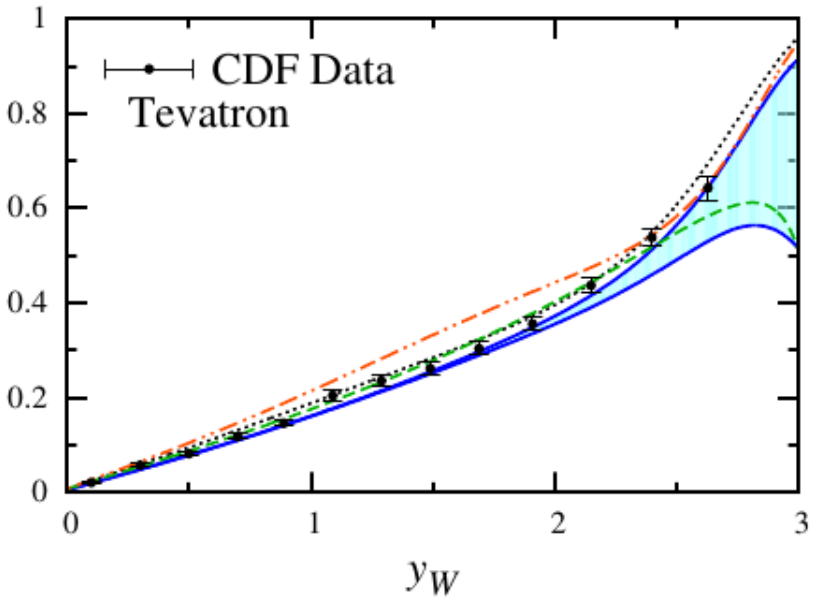
  - *W, Z* at RHIC, *Z* (and *W* ?) at LHC, *W* at DØ (??)
  - PVDIS at JLab 12, **CC @ EIC**

W charge asymmetry at Tevatron

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

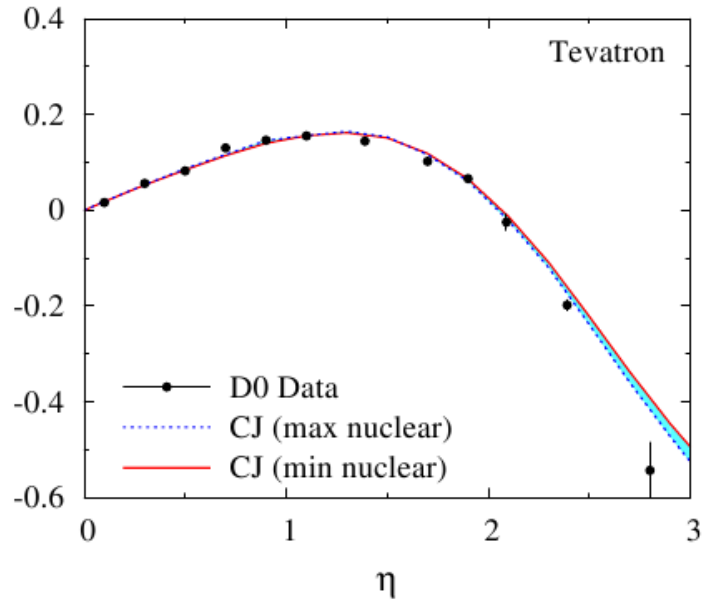
Directly reconstructed W:

- highest sensitivity to large *x*



From decay lepton W → l+ν:

- smearing in *x*



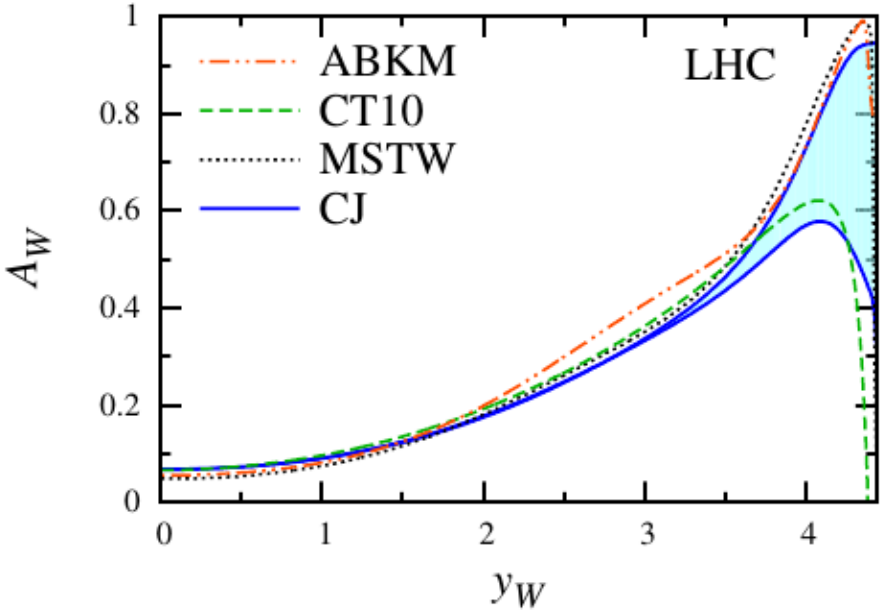
- Too little large-*x* sensitivity in lepton asymmetry:
  - **need reconstructed *W***

W charge asymmetry at LHC

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

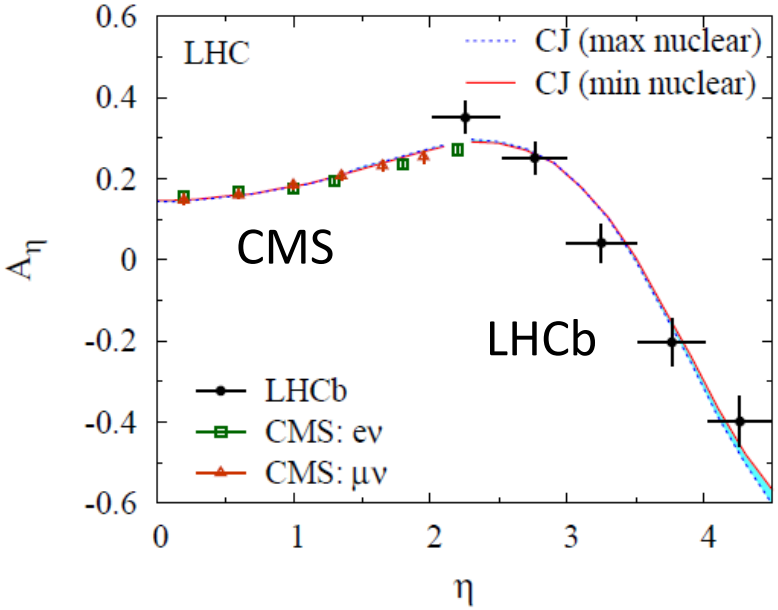
Directly reconstructed W:

- highest sensitivity to large *x*



From decay lepton W → l+ν:

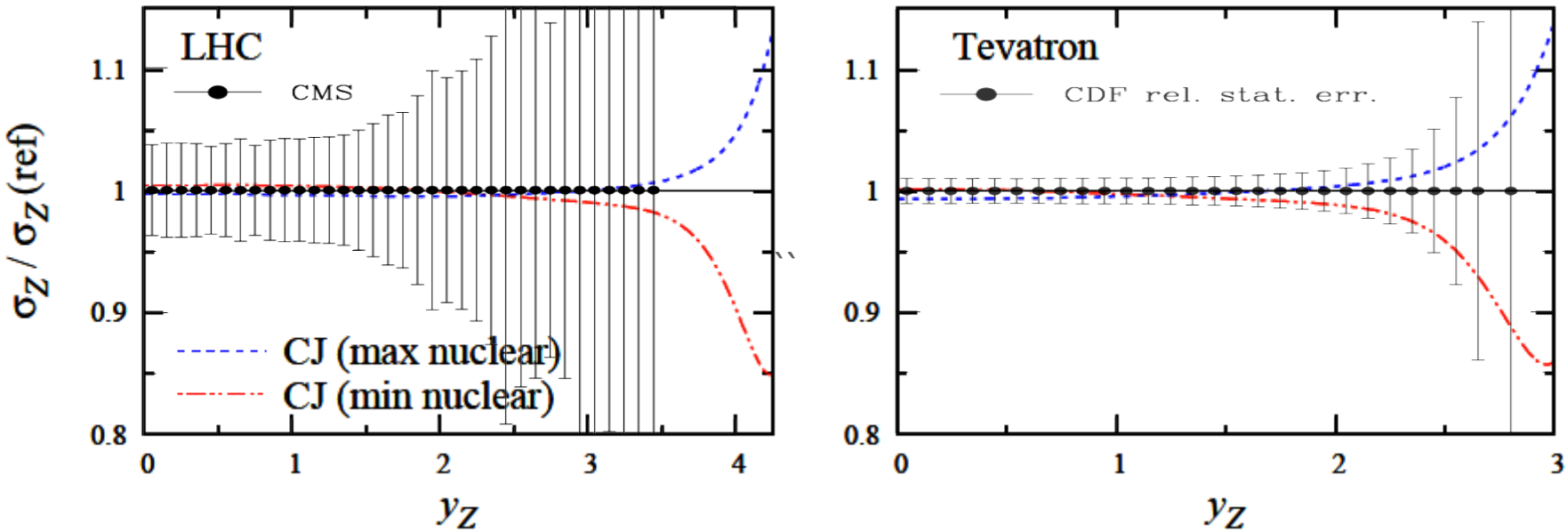
- smearing in *x*



- **Would be nice to reconstruct *W* at LHCb**
  - Does not seem feasible (too many holes in detector)
  - **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?

At RHIC: p+p collisions

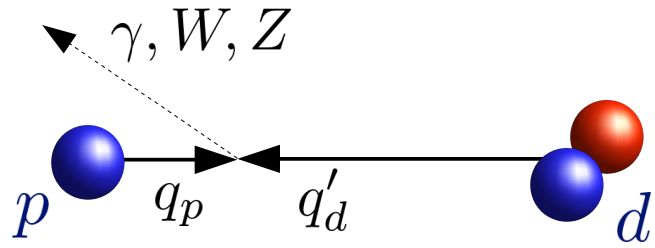
- **W reconstruction: an almost unique RHIC measurement**
  - Cross checks CDF measurements (tension with lepton asymmetry)
  - Energy systematics: 500 → 1960 GeV
  - Large x > 0.5 **needs 1.1 < *y* < 1.9**
  - Double differential in *y* <u>*and*</u> p_T ?
    - To understand better small p_T resummation
  - Hard/impossible at LHCb (large x)
  - Not a priority at ATLAS, CMS (small x)
    - Lepton asymmetry good substitute in this case

Possibly the hardest experimental requirement

- **Z reconstruction much easier**
  - Similar motivations, kinematics
  - Energy systematics: 500 → 1960 → 7000

At RHIC: p+d collisions

- **W,Z, dileptons at *negative* rapidity**
  (or d+p collisions)



  - Large x_A in nucleus
  - Large Q2 ==> no power corrections

  - Cross checks nuclear corrections in DIS assuming universality of "nuclear PDFs":

$$q_d(x,Q^2) = \int_{x_B}^{A} dy\, \mathcal{S}_A(y,\gamma=1) q(x,Q^2) \left(1 + \frac{\delta^{off} q(x)}{q(x)}\right)$$

(see also Kamano, Lee, PRD86 (2012) 094037
for a DY convolution formula analogous to the DIS one)

At RHIC: …and more…

- **Sea asymmetry at mid-rapidity**

Bourrelly, Soffer, NPB 423 (1994) 329
Peng, Jensen, PLB 354 (1995) 460

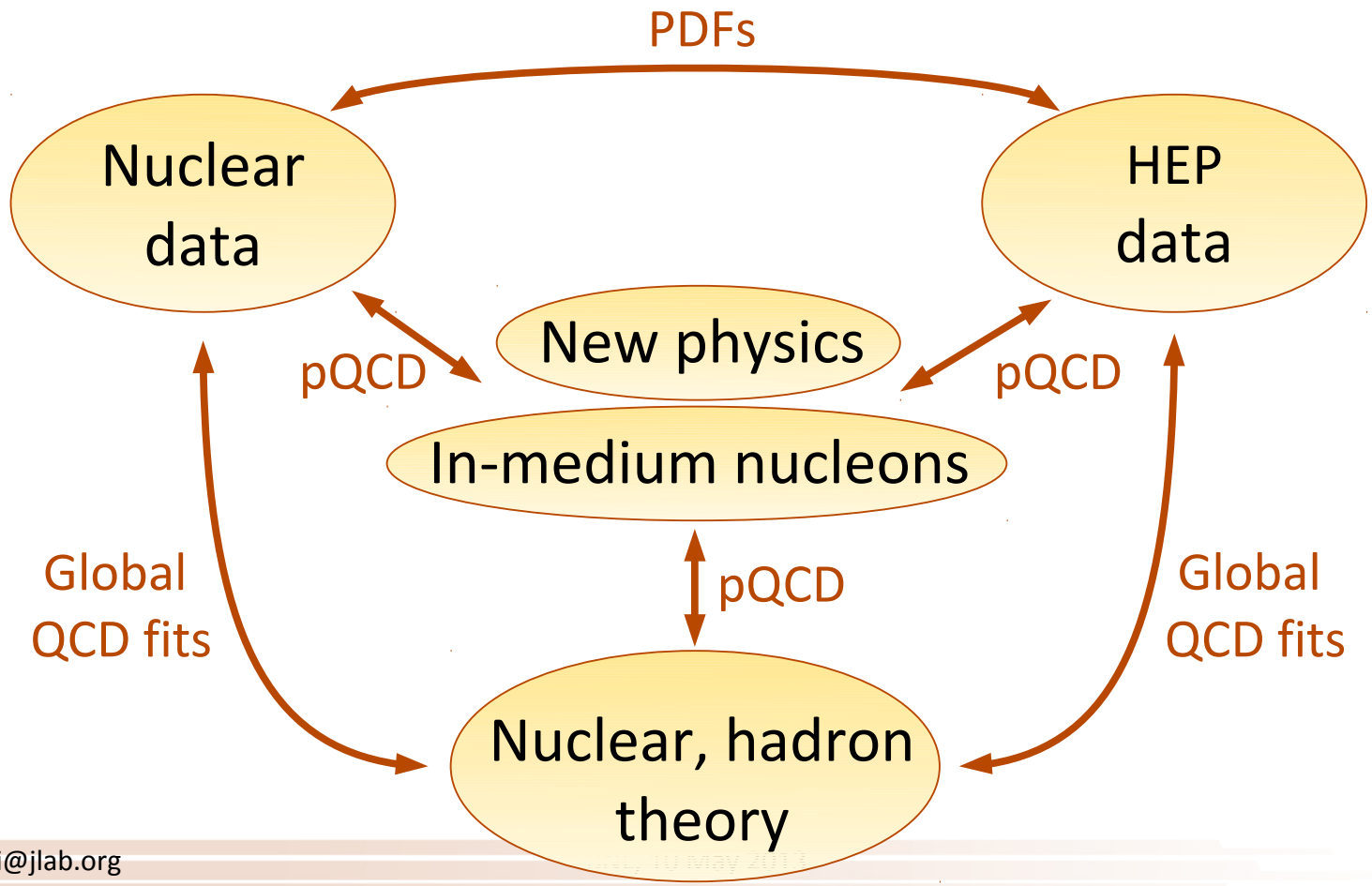
  - Measures $\bar{u}/\bar{d}$ at x = 0.06-0.45 (for -1 < y < 1)
  - Useful to compare p+p vs. p+n
  - Play W vs. Z production

- **Forward physics**

  - What to do with what you will measure forward?
    - Photons
    - Pions
    - …

Summary

- **CJ12 PDF global fits attacking large-*x* PDFs:**
  - integrate across hadronic physics from JLab to the LHC
  - connect with rest of subatomic physics



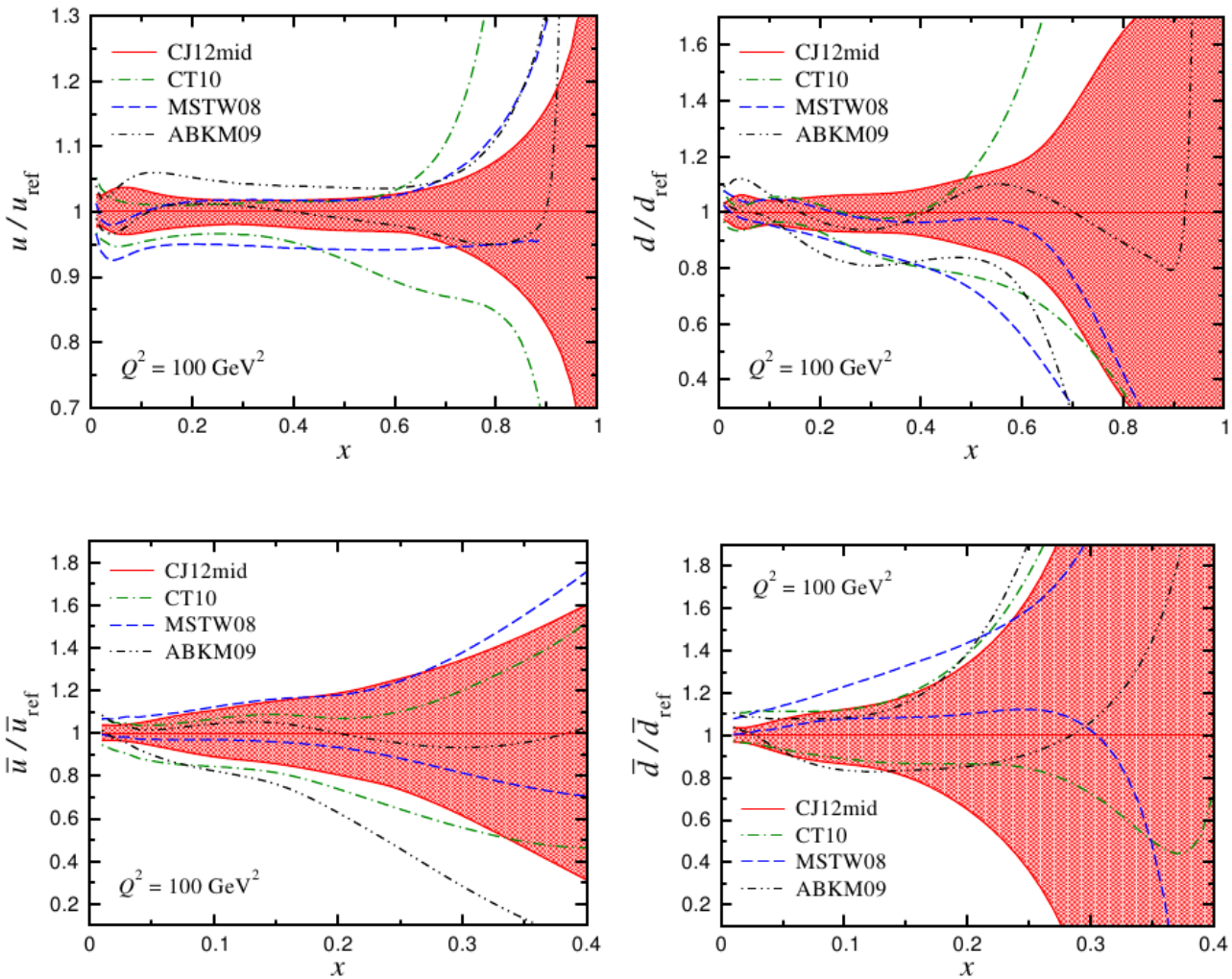
Summary – the next 20 years

- **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
- **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

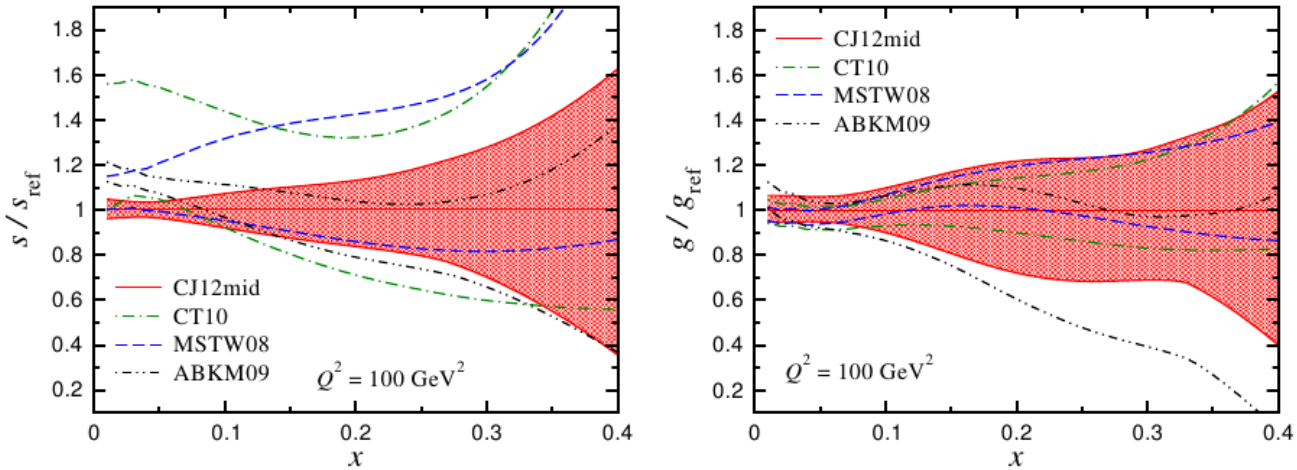
CJ12 *vs.* others

Owens, Accardi, Melnitchouk, arXiv:1212.1702



CJ12 *vs.* others

Owens, Accardi, Melnitchouk, arXiv:1212.1702



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

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

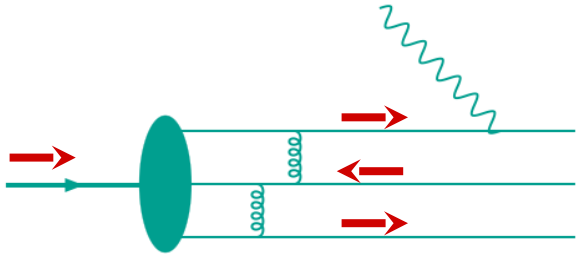
Valence quarks at large *x*

- **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



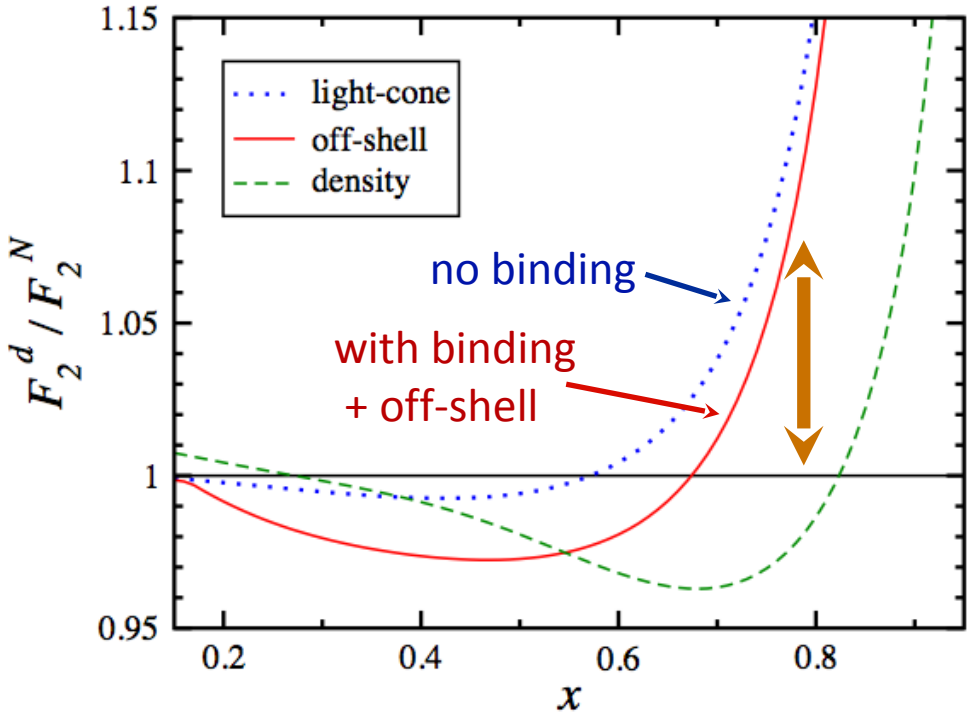
$$q^\uparrow \gg q^\downarrow$$

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

Farrar, Jackson, 1975

Nuclear corrections

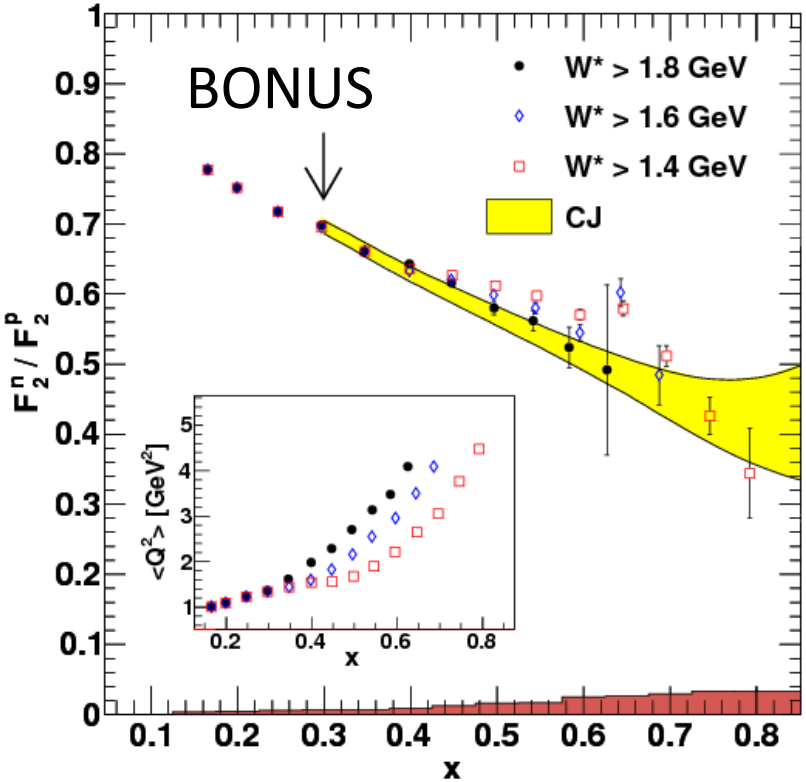
$$F_{2d}(x_B, Q^2) = \int_{x_B}^{A} dy\, \mathcal{S}_A(y,\gamma) F_2^{TMC+HT}(x_B/y, Q^2) \left(1 + \frac{\delta^{off} F_2(x)}{F_2(x)}\right)$$

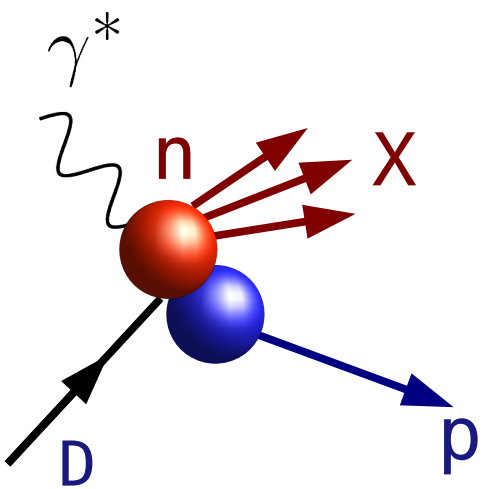


- Using off-shell model, obtains *larger neutron* (larger *d*) than light-cone model
- But smaller *neutron* (larger *d*) than no nuclear effects or density model

Spectator tagging at Jlab: quasi-free neutrons

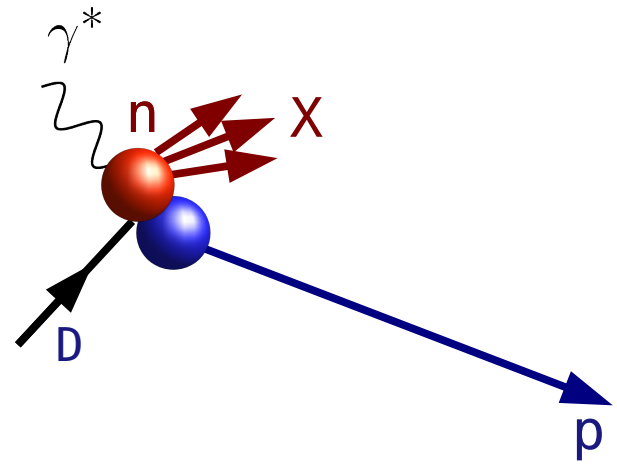
N.Baillie et al., PRL 108 (2012) 199902

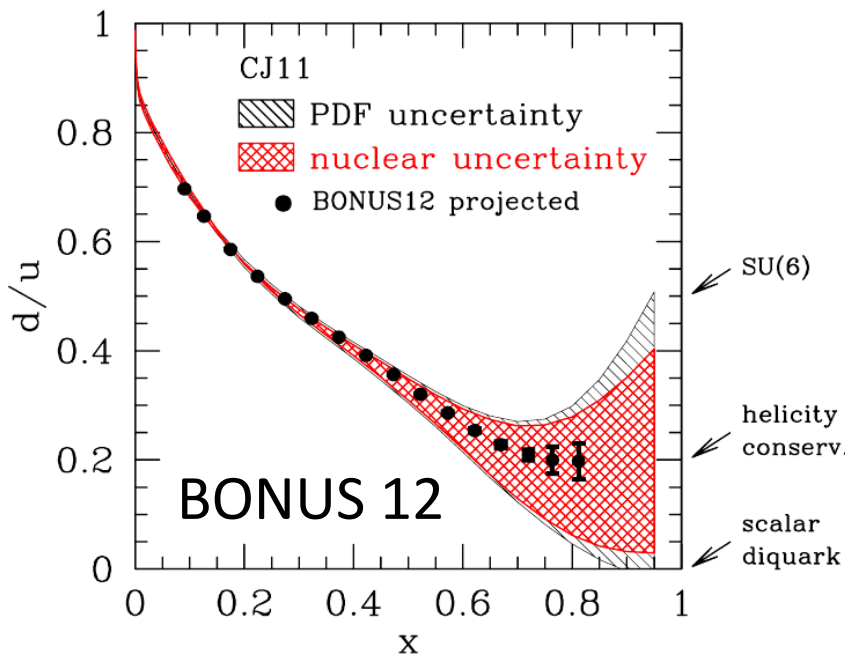


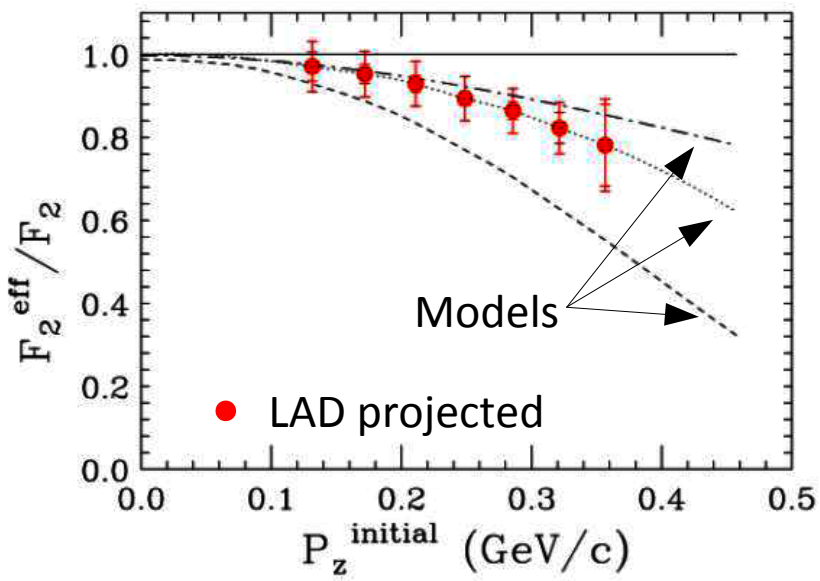


Spectator tagging at JLab12

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

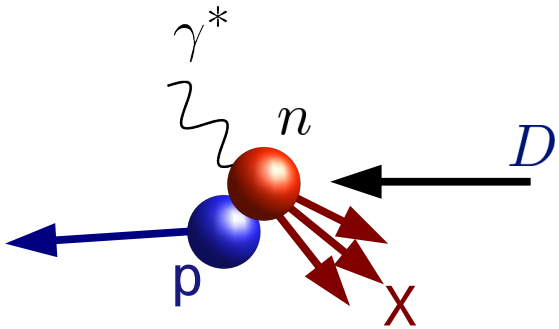




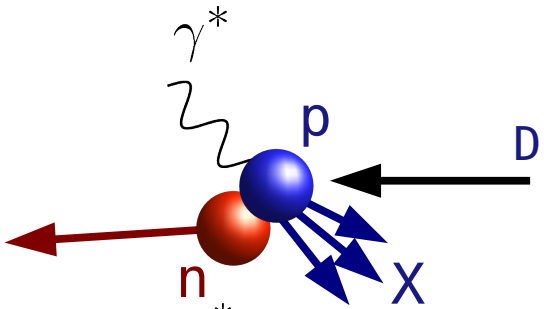
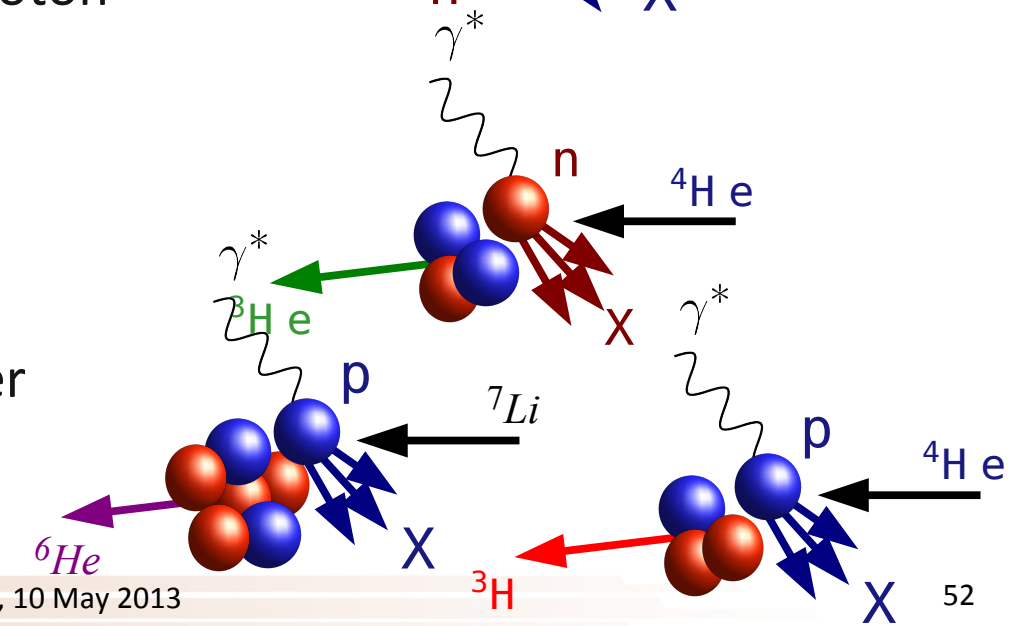


Spectator tagging at EIC: even better!

- 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)**