The CJ12 parton distributions

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DIS 2013

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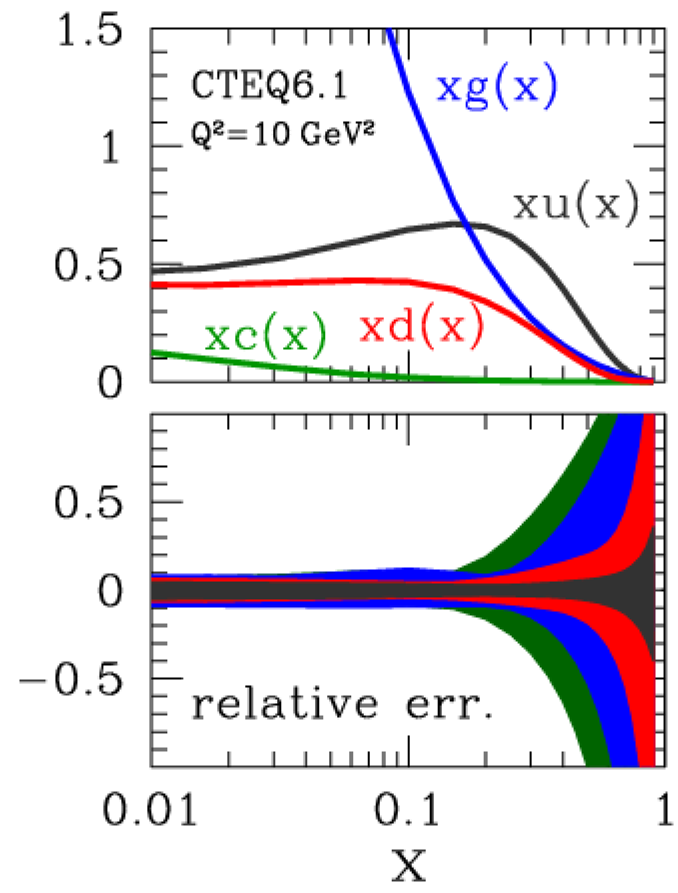
The CTEQ-JLab global fits

- **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** (soon in PRD)
    - www.jlab.org/cj
    - Included in LHAPDF

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 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

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

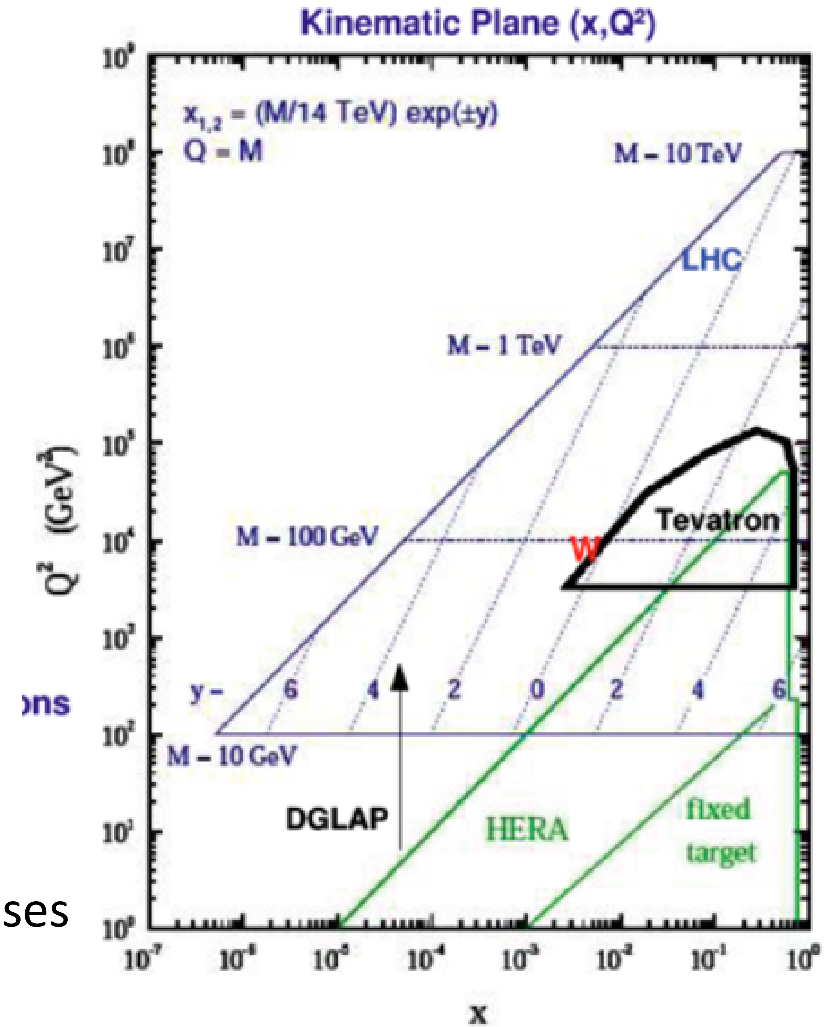
Valence quarks at large x

- 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

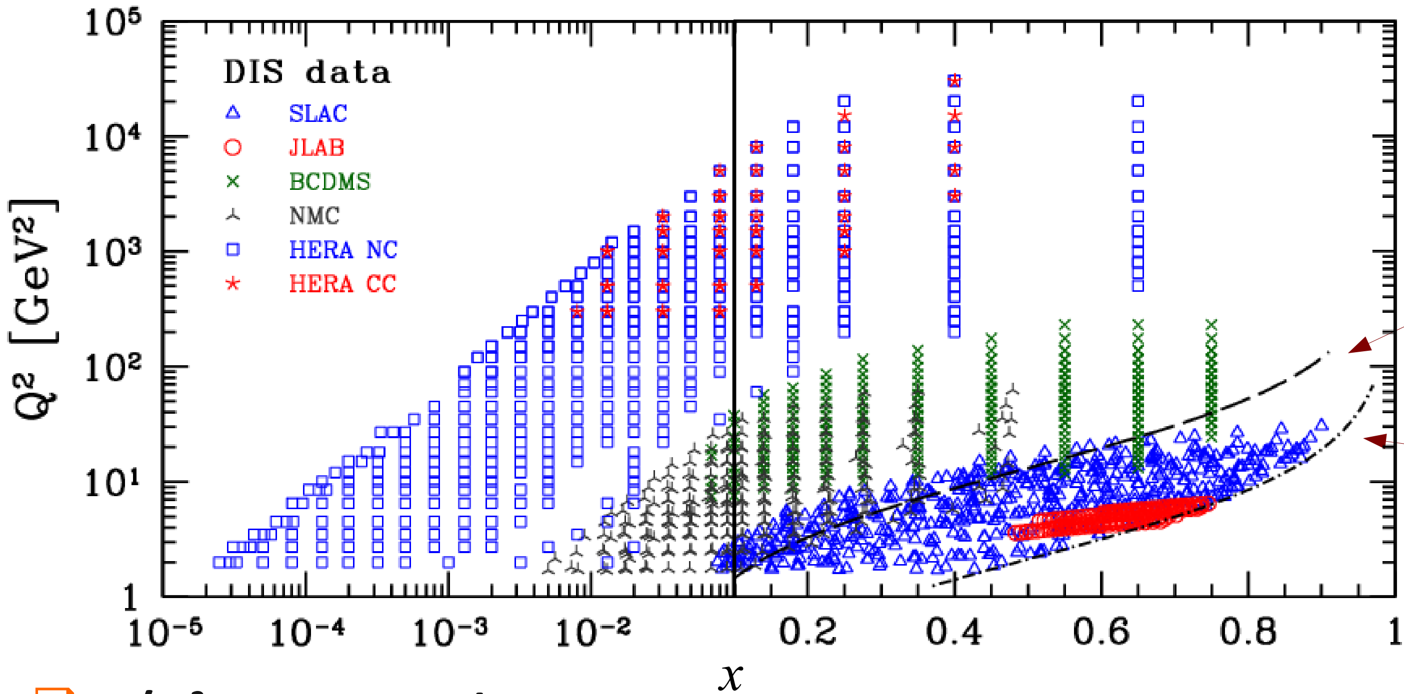
- Remember, $x = \frac{M}{\sqrt{s}} e^{y}$
- Examples:
  - Z' production $M'_Z \gtrsim 1 \text{ TeV}$
  - W at forward rapidity: $y > 2$

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



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

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.
- **New d-quark parametrization:** $d'(x) = d(x) + \alpha x^{\beta} u(x)$

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

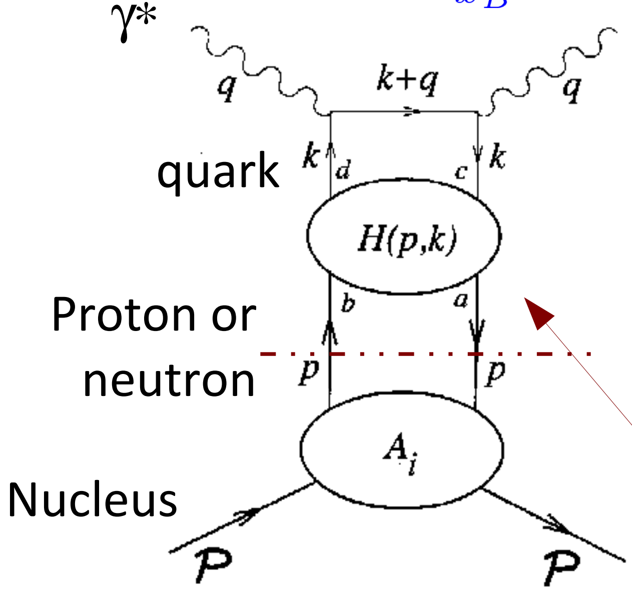
included in CJ fits

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

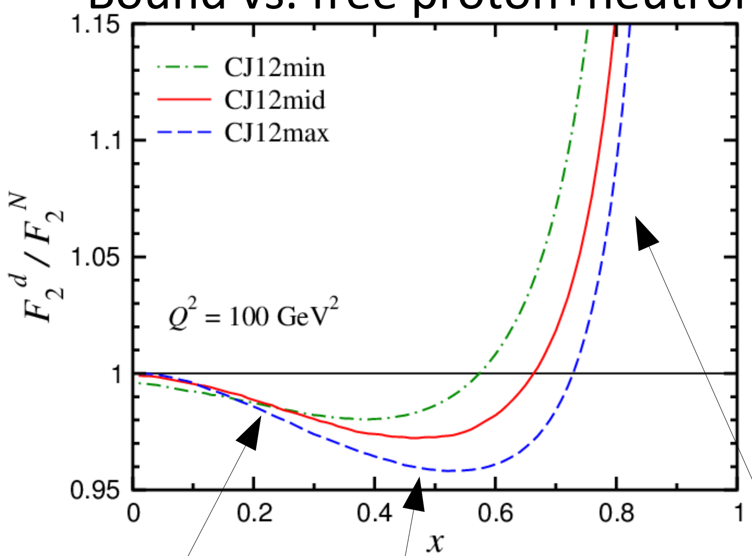
$$F_{2d}(x_B, Q^2) = \int_{x_B}^{A} dy\, \mathcal{S}_A(y,\gamma) F_2^{TMC+HT}(x_B/y, Q^2) \left(1 + \frac{\delta^{off} F_2(x)}{F_2(x)}\right)$$



Low-energy factorization issues

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

Bound vs. free proton+neutron



Fit framework

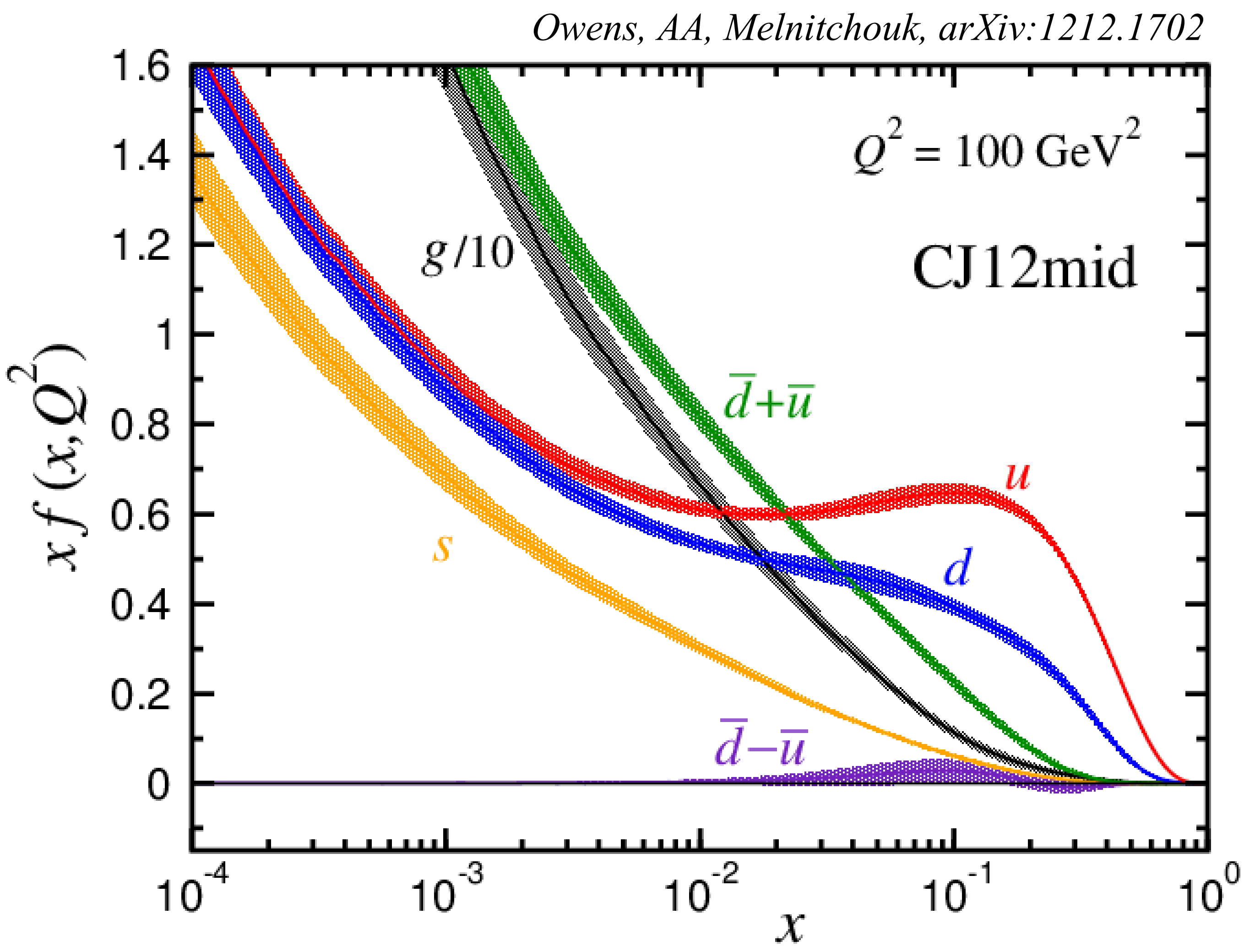
- We concentrated on theory corrections, established a baseline fit
- Data
  - DIS: fixed target F_2, HERA combined σ
  - Drell-Yan, W asymmetry, Z rapidity distribution
  - Tevatron jets, γ + jets
- Parametrization (with *d*-quark and strange sea exception)

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

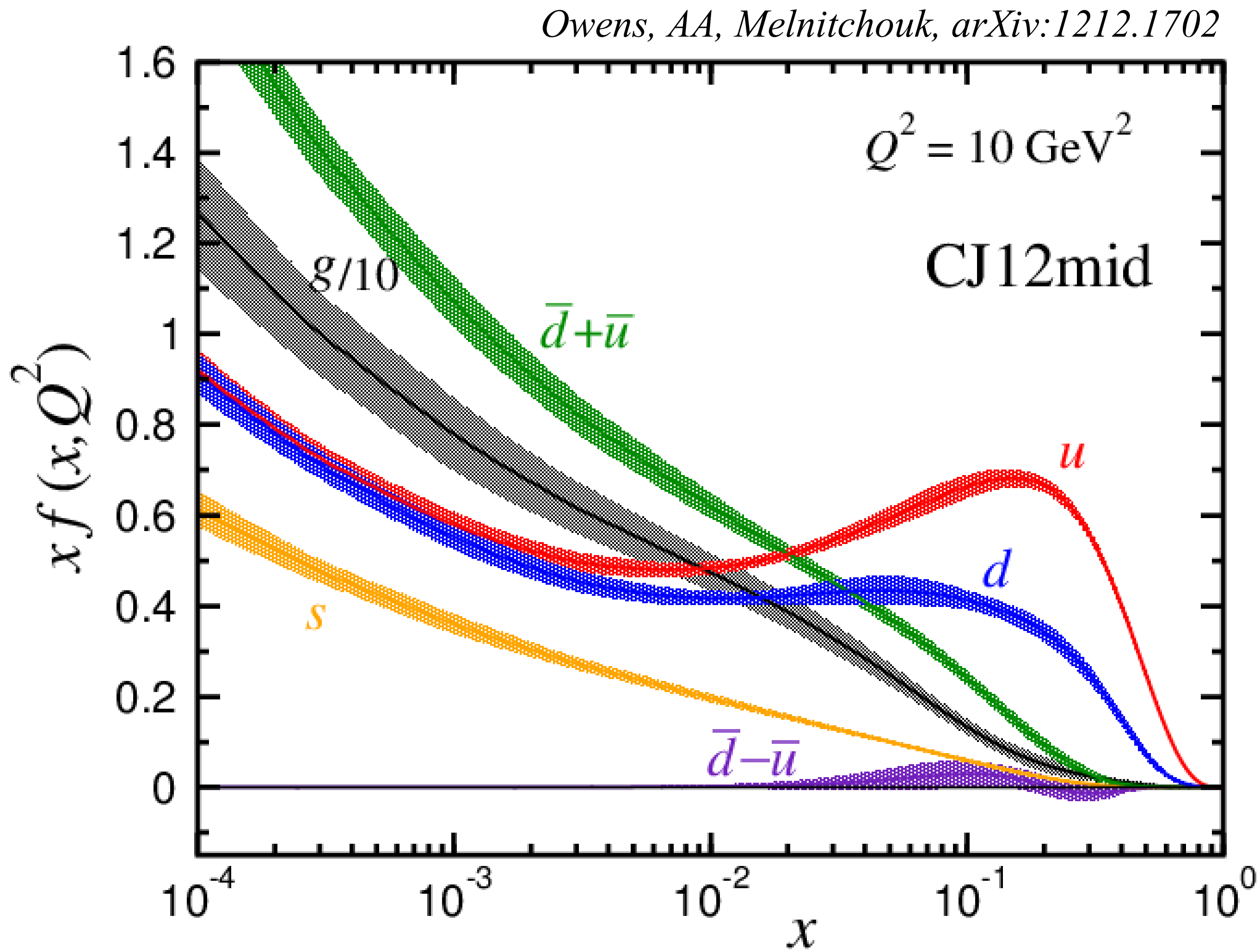
$$F_2 = F_2^{LT}\left[\left(1 + a_{HT}x_{HT}^b(x)(1+c_{HT}x)\right)/Q^2\right]$$

- 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

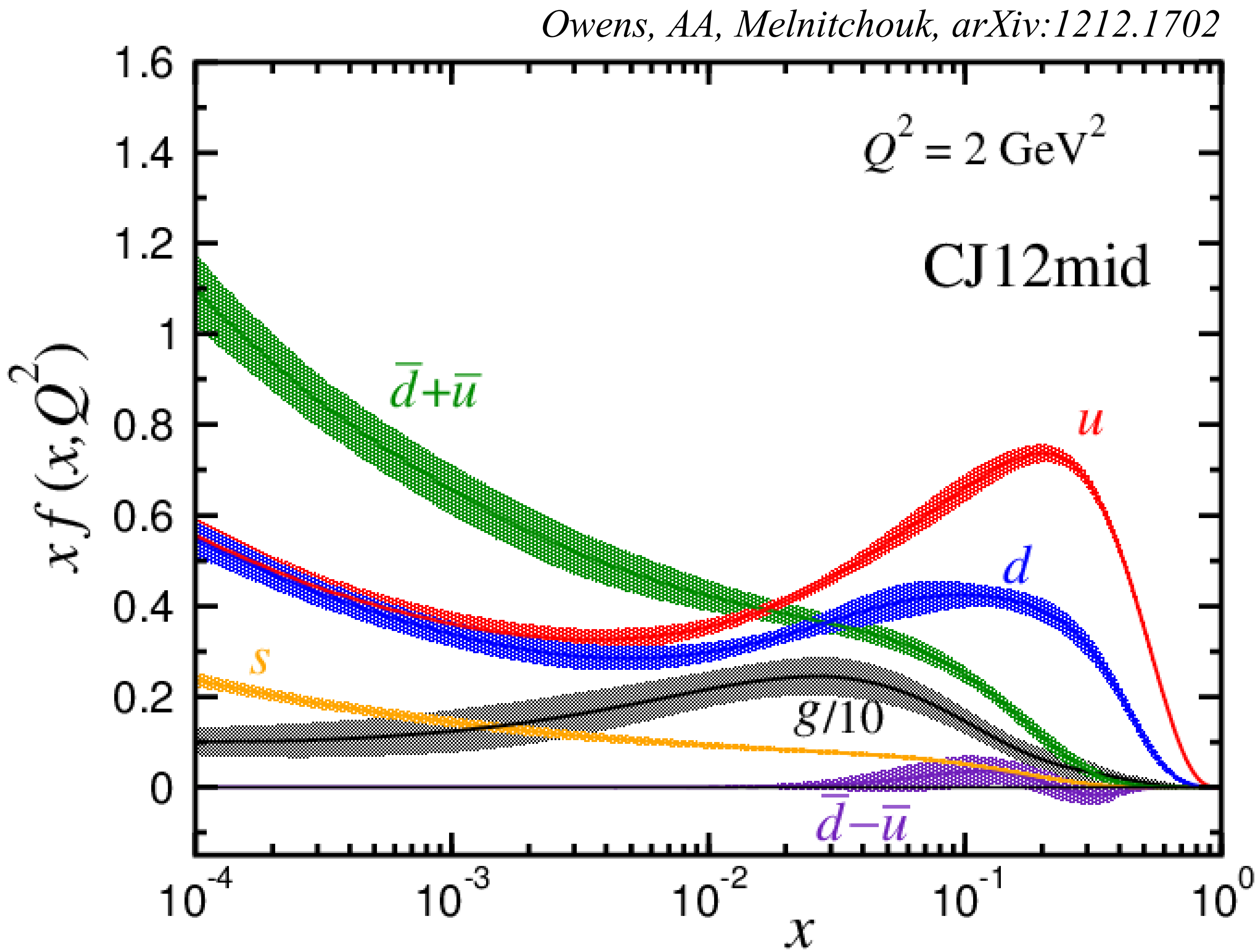
CJ12 parton distributions



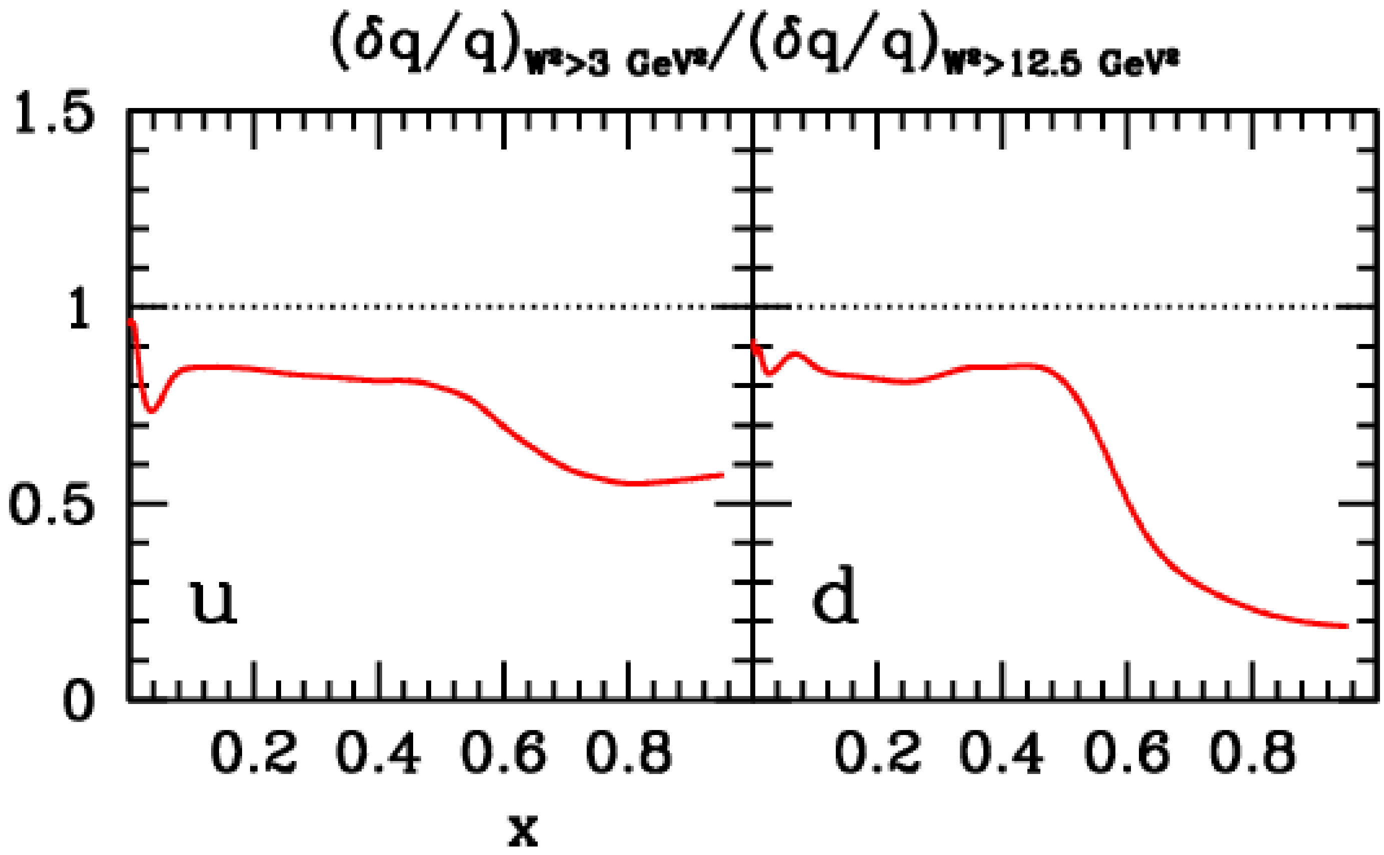
CJ12 parton distributions



CJ12 parton distributions



Statistical improvement



Theoretical uncertainties

Effect of theory corrections in a nutshell

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

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

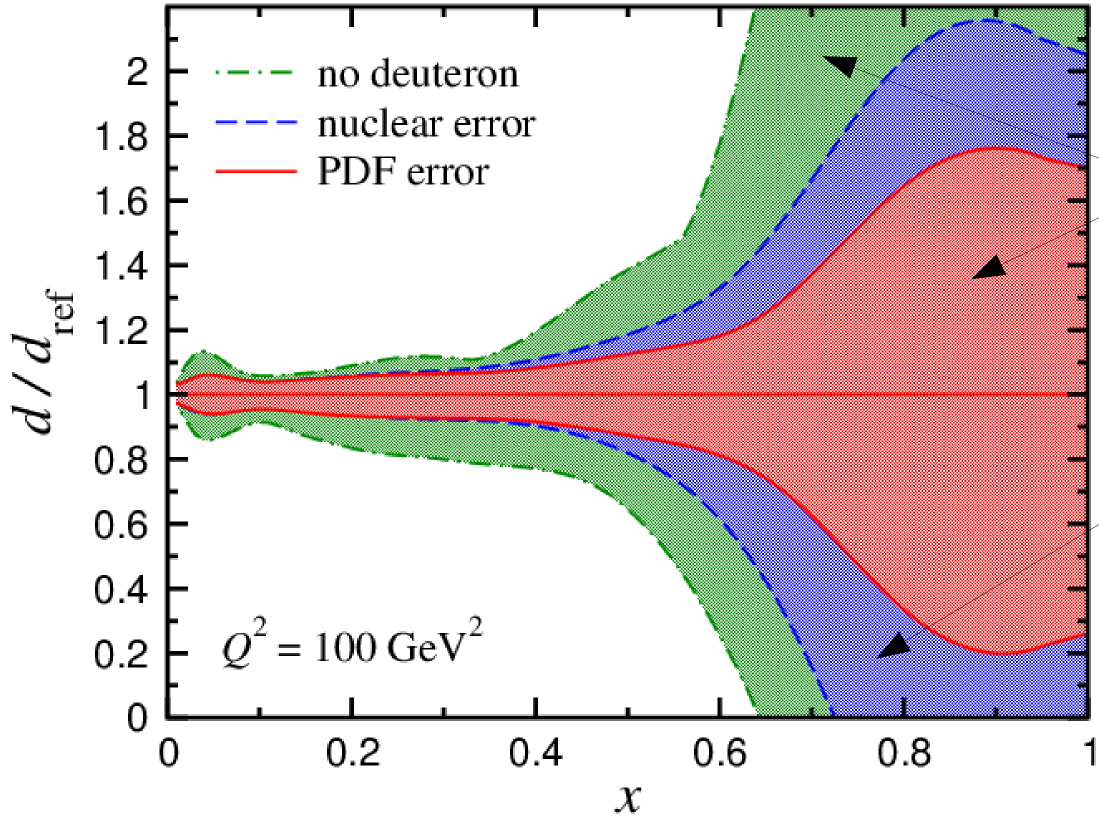
  - Allows d/u to be non-zero at $x = 1$
    (as required in non-perturbative models)
  - Produces ***dramatic increase in d PDF in x → 1 limit***

- **Sensitivity to nuclear corrections**
  - *d*-quark at $x > 0.5$ almost fully correlated to nuclear model model: ***Very large theoretical uncertain 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

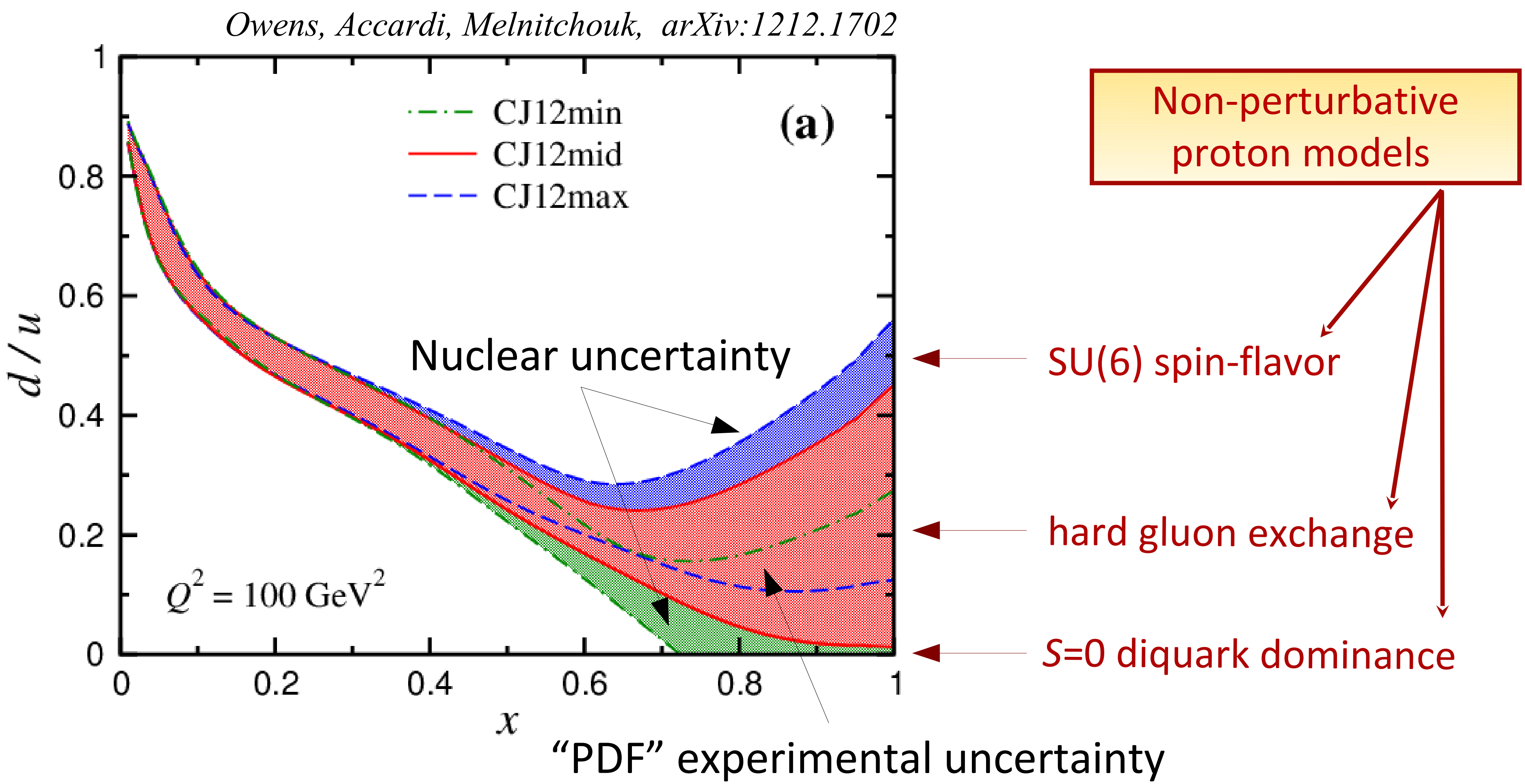


Largely reduced PDF errors (increased statistics)

Nuclear uncertainties (systematic)

- Large overall reduction in uncertainty with relaxed cuts

Applications: *d/u* ratio



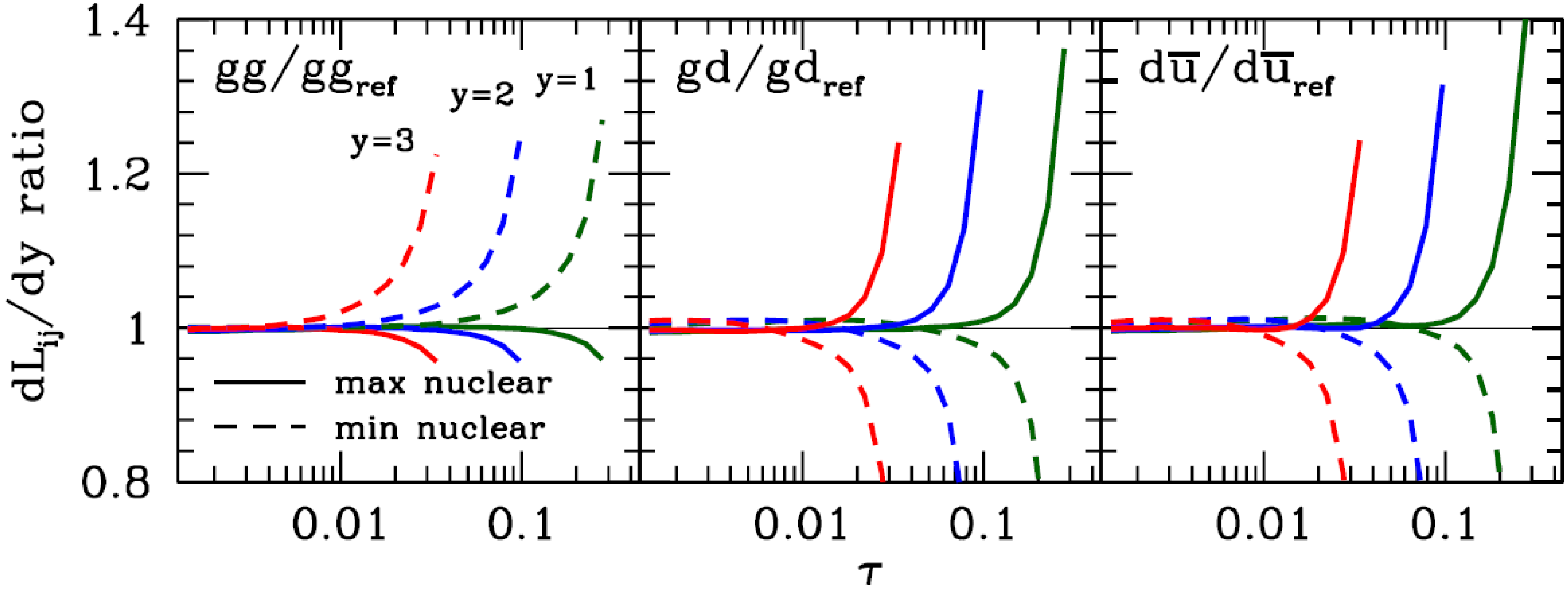
$$d/u \xrightarrow[x\to 1]{} 0.22 \pm 0.20\,(\mathrm{PDF}) \pm 0.10\,(\mathrm{nucl})$$

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

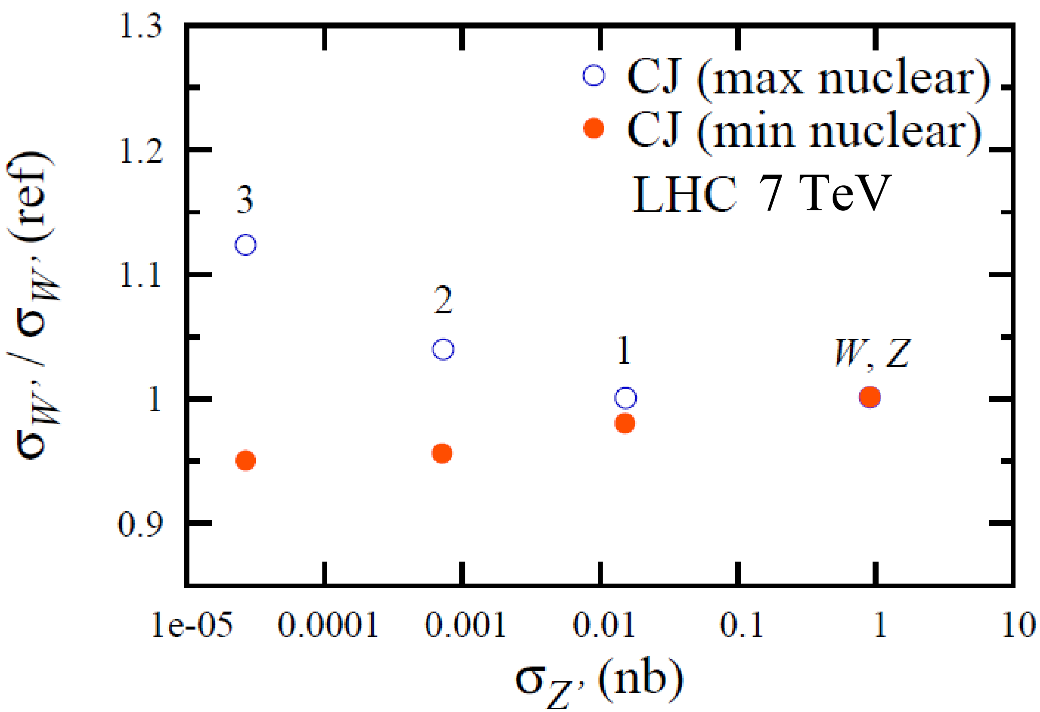


Applications: large mass searches at LHC

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

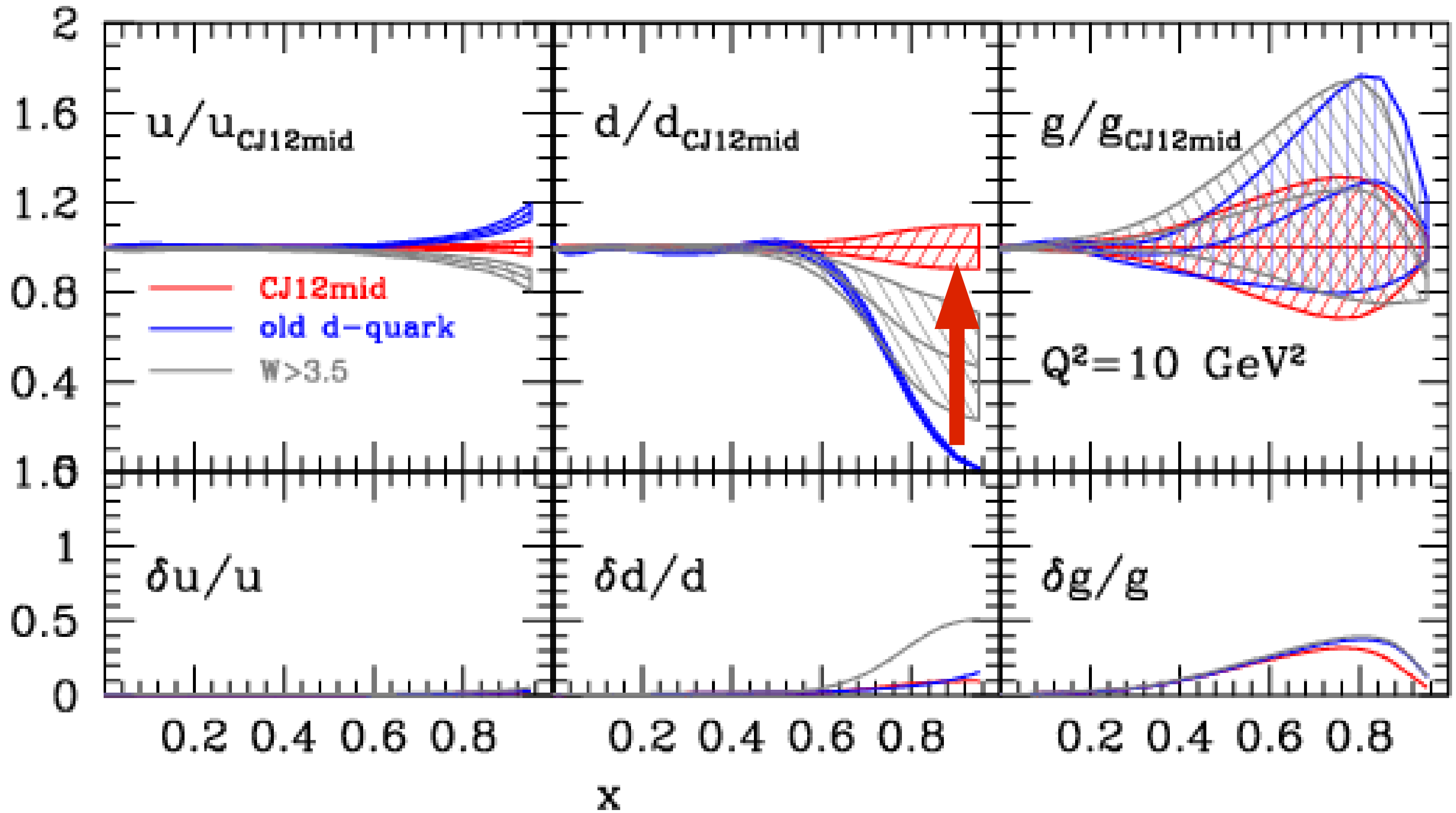
- New physics signal require accurate determination of QCD background
- Uncertainties in large-*x* PDFs could affect interpretation of experiments searching for new particles

Example: W' and Z' total cross sections



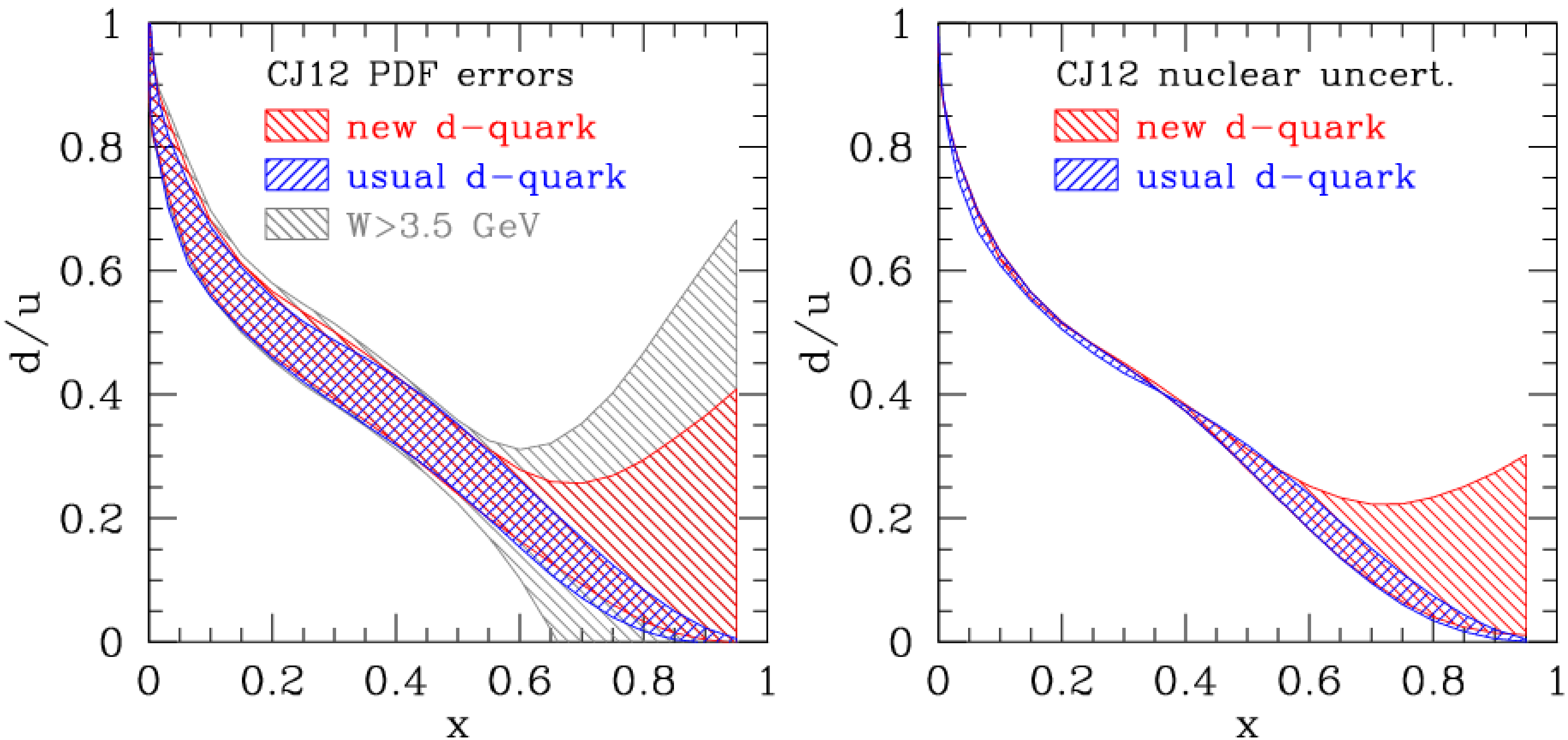
CJ12: old vs. new *d* quark

[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***

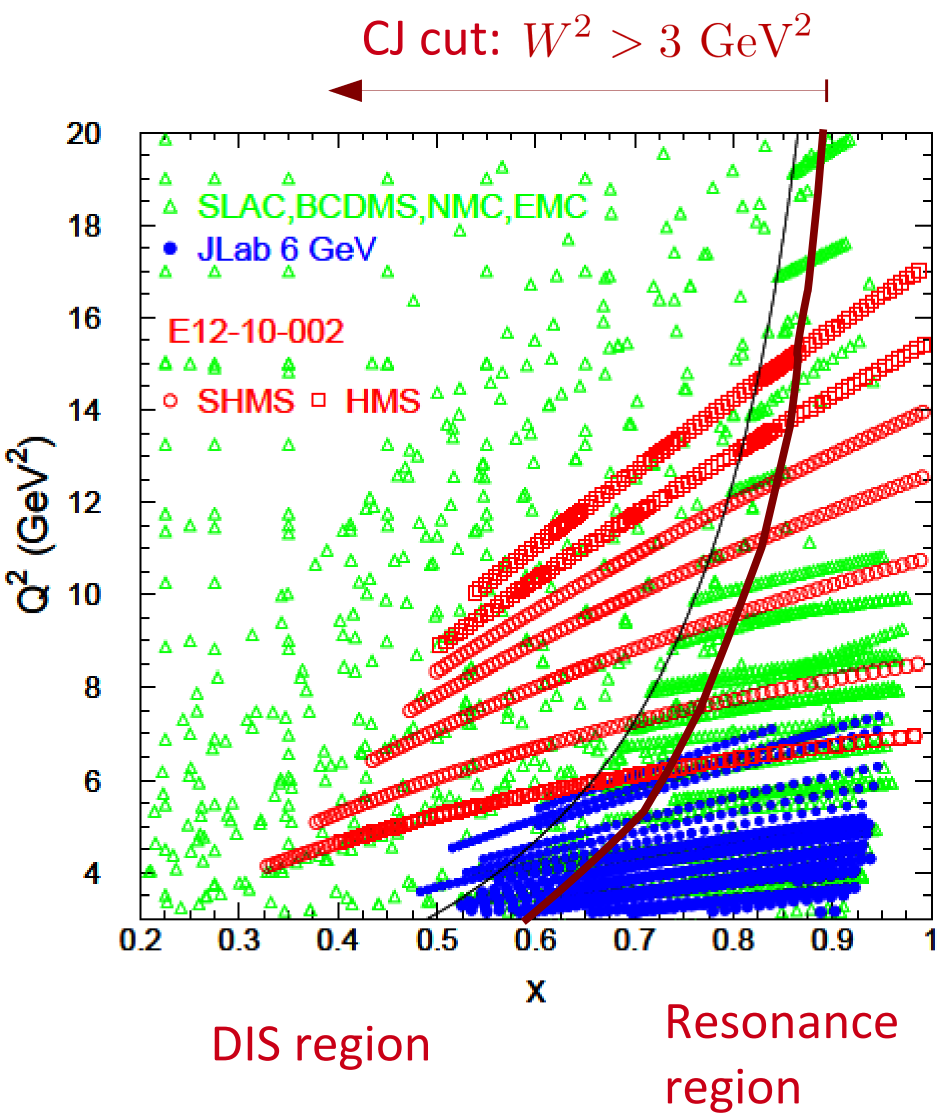
CJ12: old vs. new *d* quark



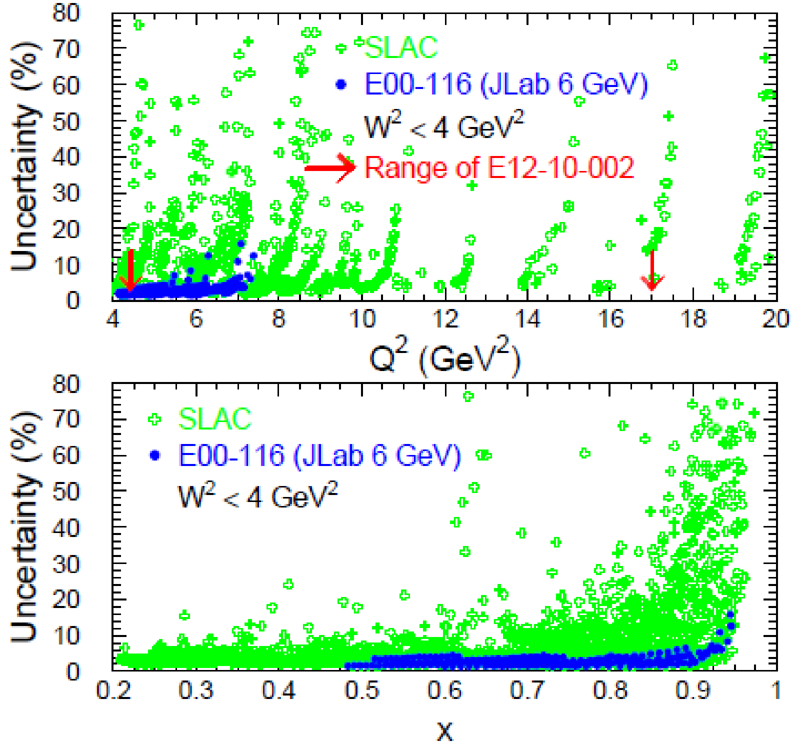
- ***Standard d-quark too stiff at x > 0.6***
  - Underestimates central value *and nuclear uncertainty*
  - Full unbiasing could be obtained in a NN analysis with low *W* cuts

Beating the experimental uncertainties

At JLab 12



Jlab12 experiment E12-10-002

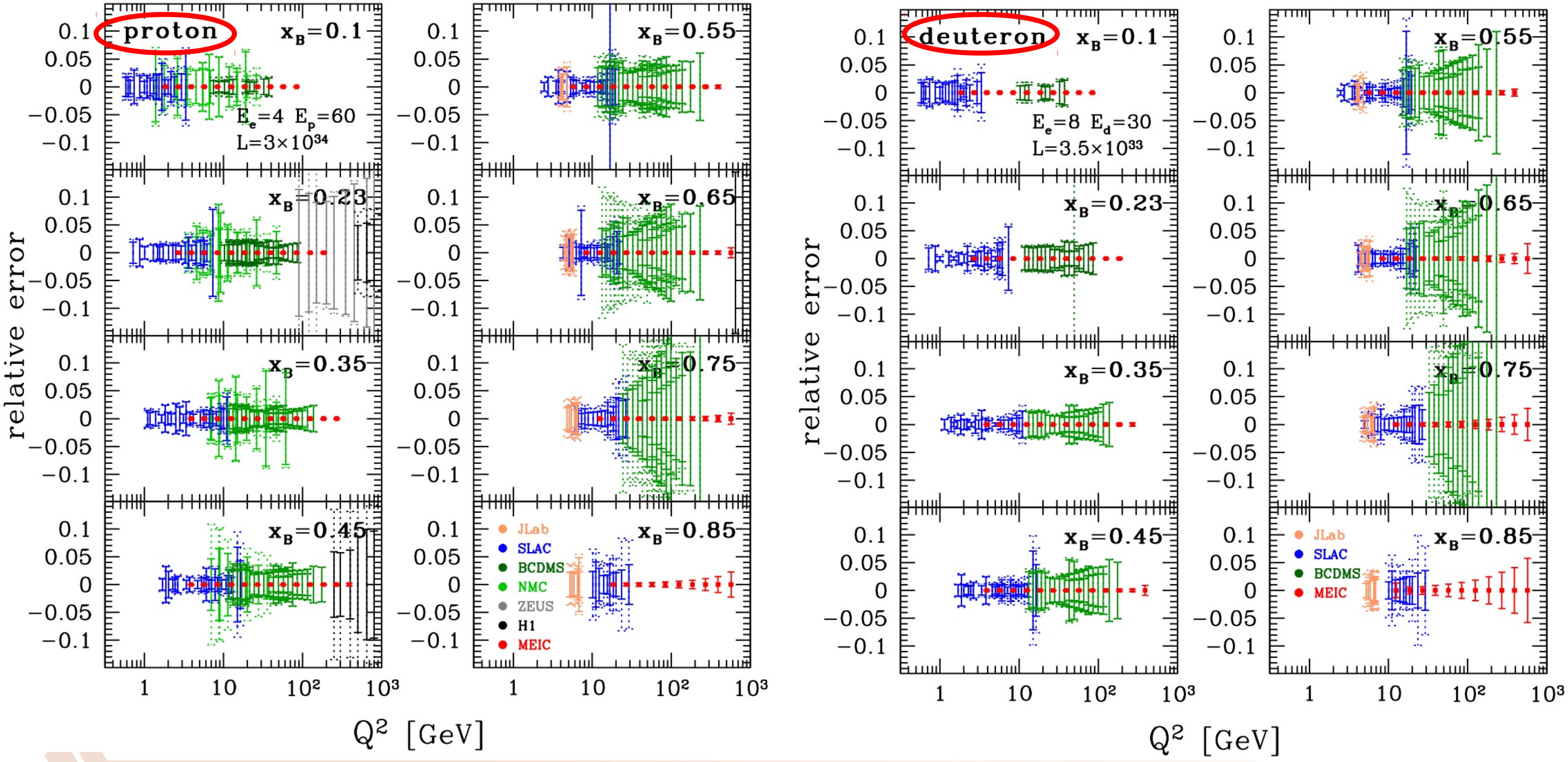


Goal @ 12 GeV: similar precision as E00-116 (@ 6 GeV)

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

Jlab12
[Keppel - Thursday]

- **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

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*

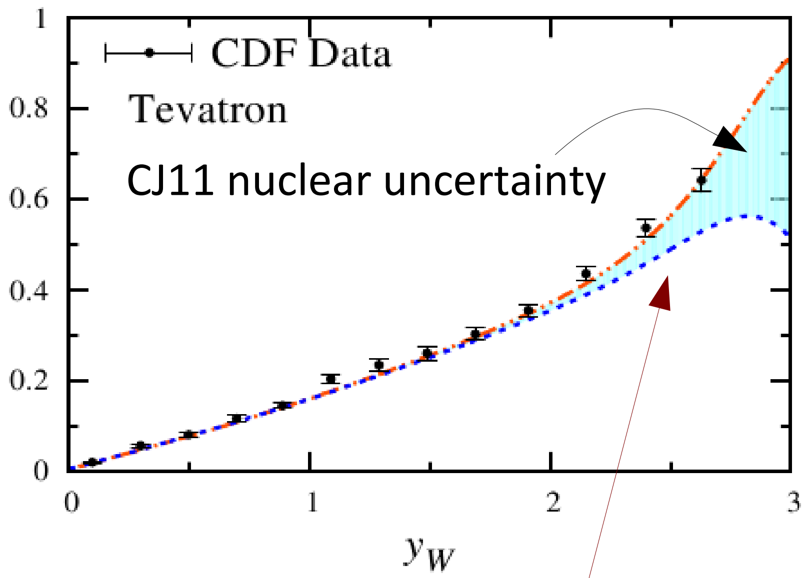
RHIC ??
AFTER@LHC

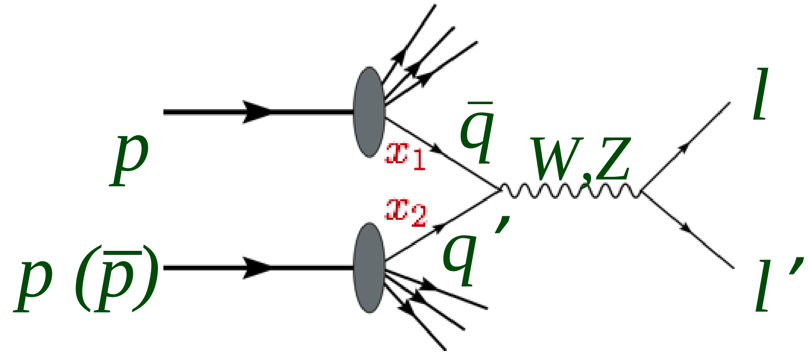
Use protons to study nuclei (!)

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!

See also MMSTWW, EPJ C73 (2013)

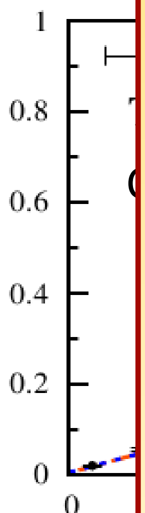
- Needs to be corroborated:
  - *W, Z* at RHIC, *Z* (and *W* ?) at LHC, *W* at DØ (??)
  - PVDIS at JLab 12, **CC @ EIC**

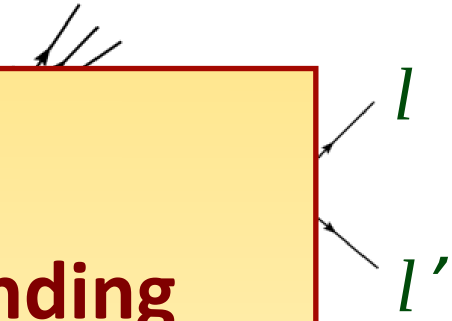
Use protons to study nuclei (!)

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

Directly reconstructed W:

- high





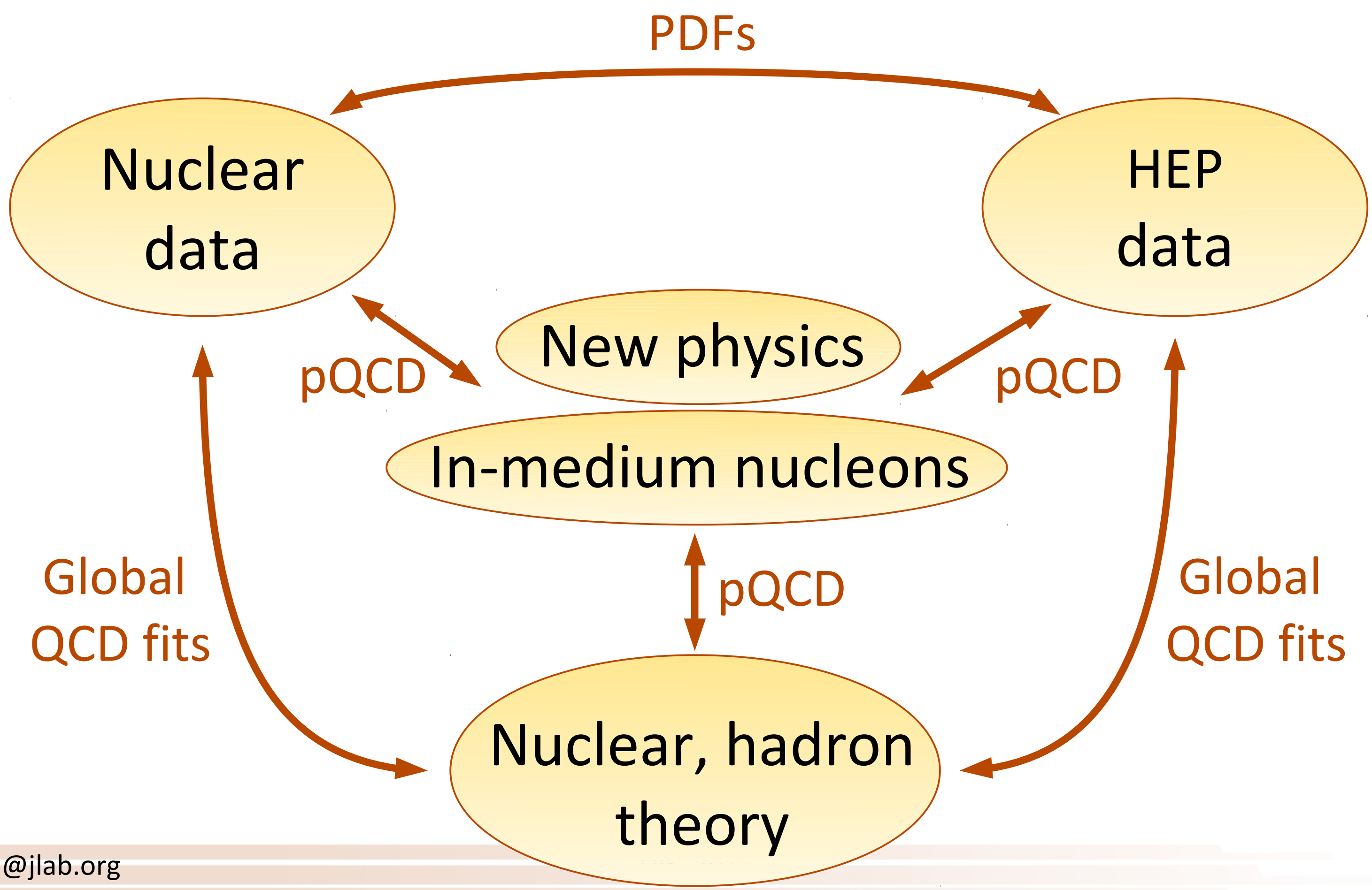
A new avenue for understanding high-energy processes on <u>nuclei</u>:

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**

Summary

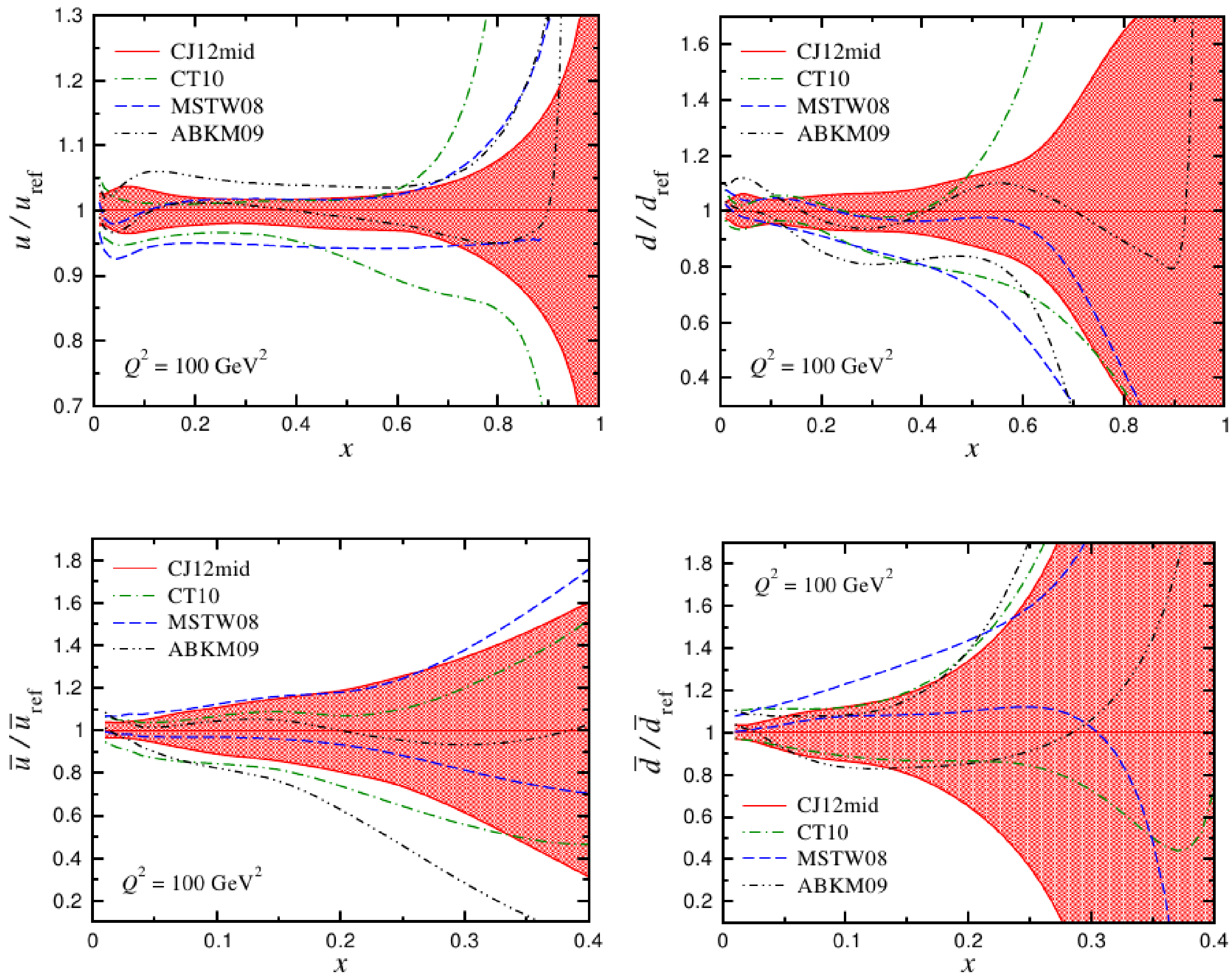
- **CJ12 PDF global fits attacking large-*x* PDFs:**
  - integrate across hadronic physics from JLab to the LHC
  - connect with rest of subatomic physics



Backup slides

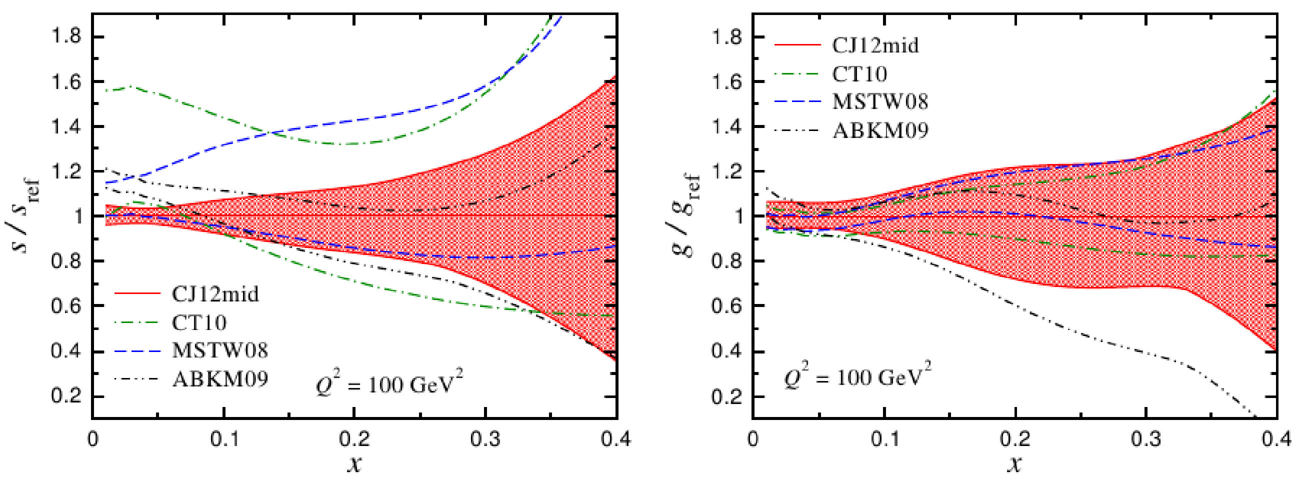
CJ12 *vs.* others

Owens, Accardi, Melnitchouk, arXiv:1212.1702



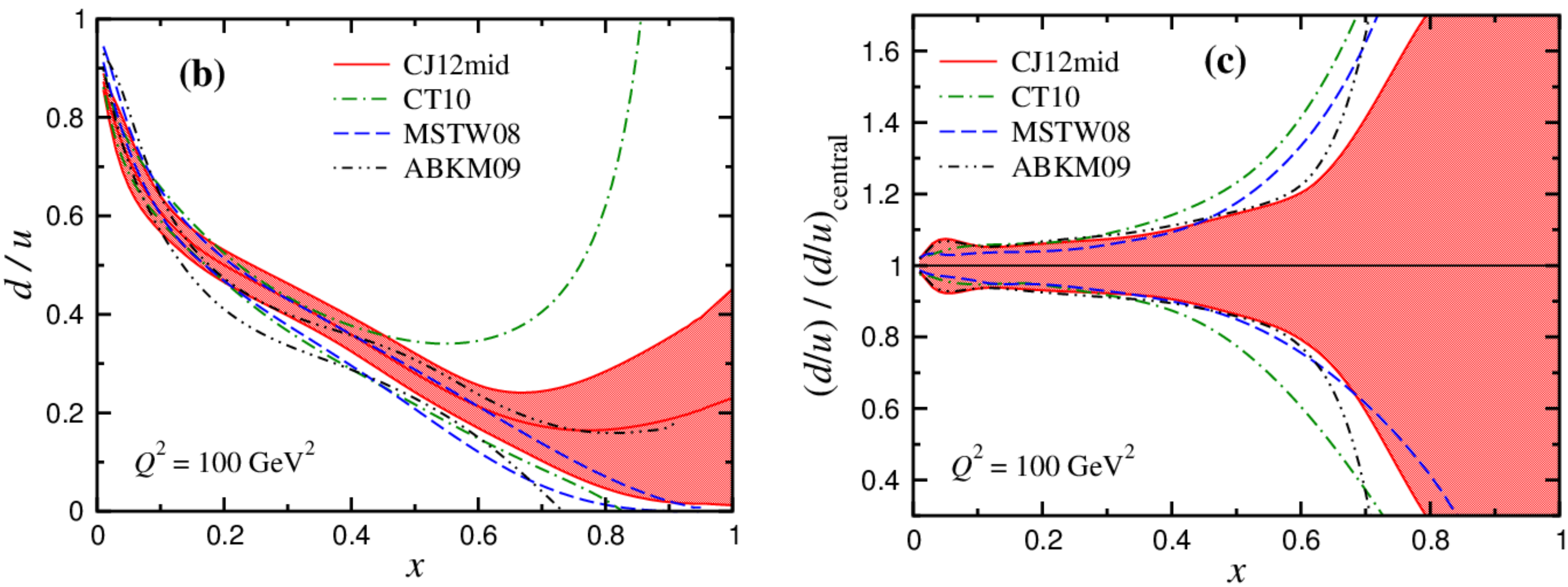
CJ12 *vs.* others

Owens, Accardi, Melnitchouk, arXiv:1212.1702



CJ12 *vs.* others – *d/u* ratio

Owens, Accardi, Melnitchouk, arXiv:1212.1702

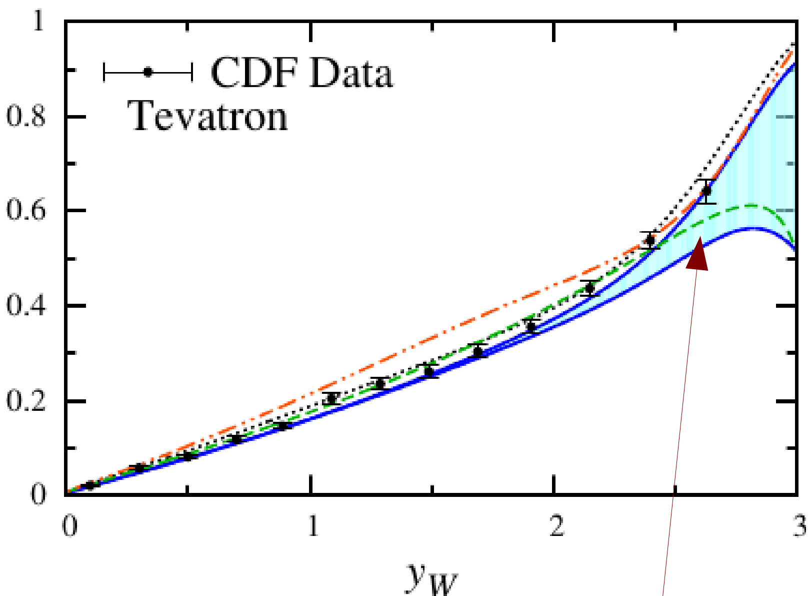


W charge asymmetry at Tevatron

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

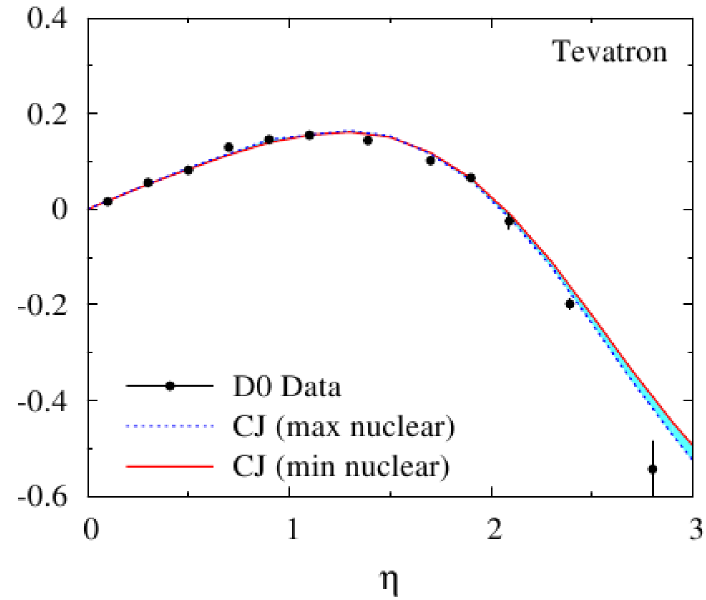
Directly reconstructed W:

- highest sensitivity to large *x*



From decay lepton W → l+ν:

- smearing in *x*



sensitive to *d* at high *x*

Can constrain Nuclear models!

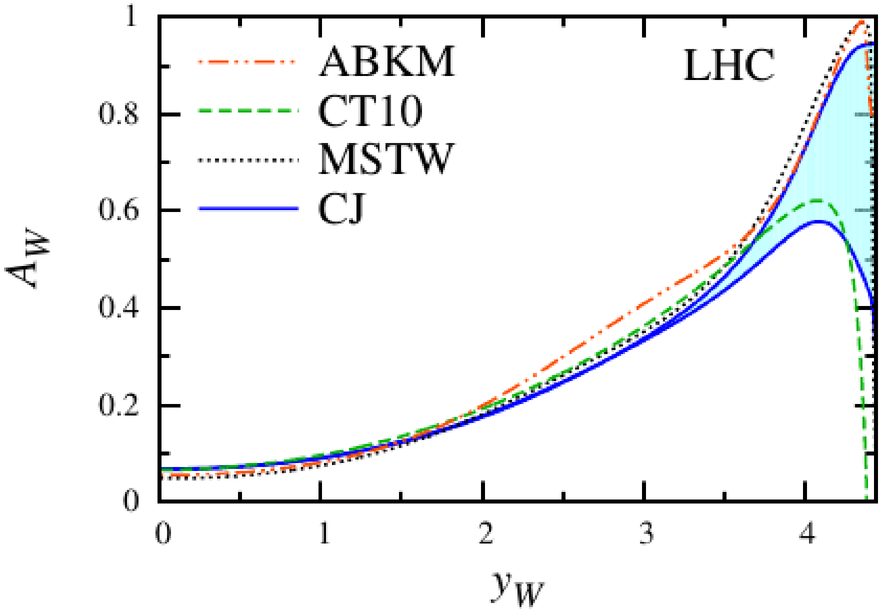
- Too little large-*x* sensitivity in lepton asymmetry:
  - **need reconstructed *W***

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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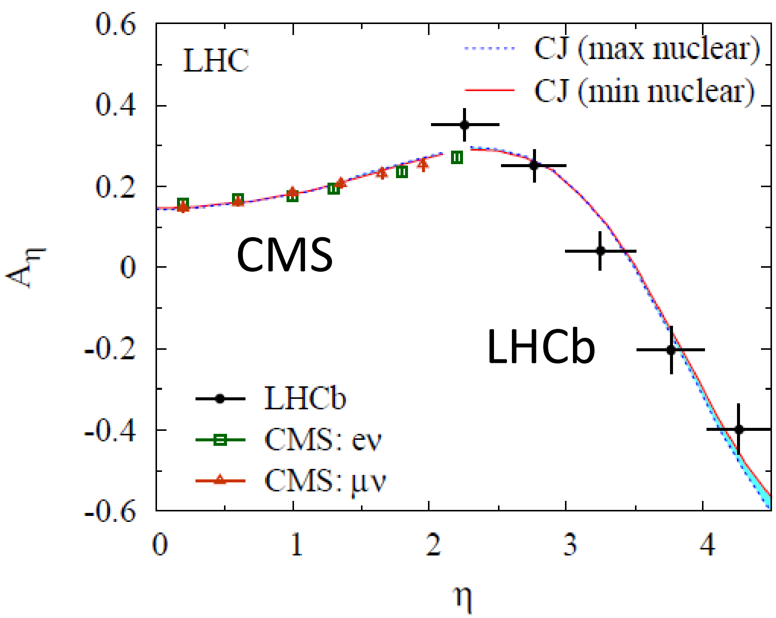
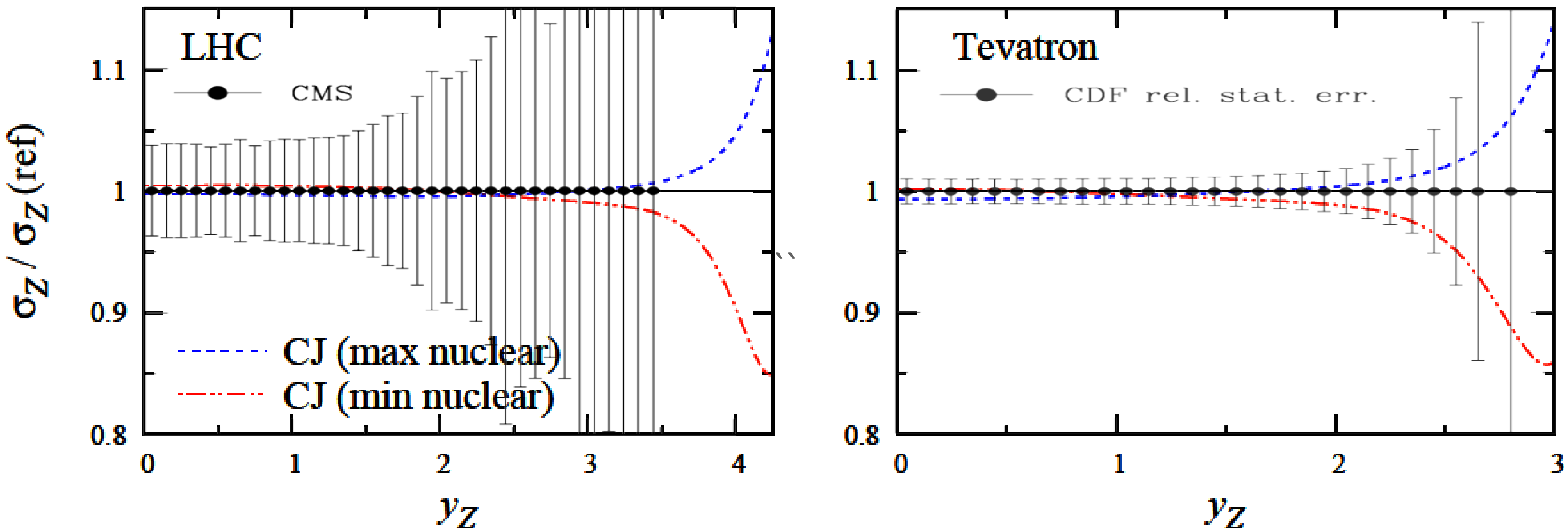


- **Would be nice to reconstruct *W* at LHCb**
  - Definitely needs more statistics
  - Is it at all possible?? (too many holes in detector?)
  - Systematics in *W* reconstruction?
  - **What about RHIC, AFTER@LHC?**

Z rapidity distribution

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

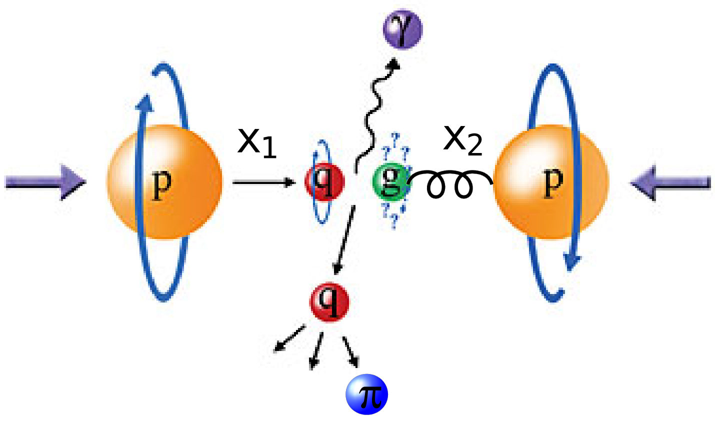


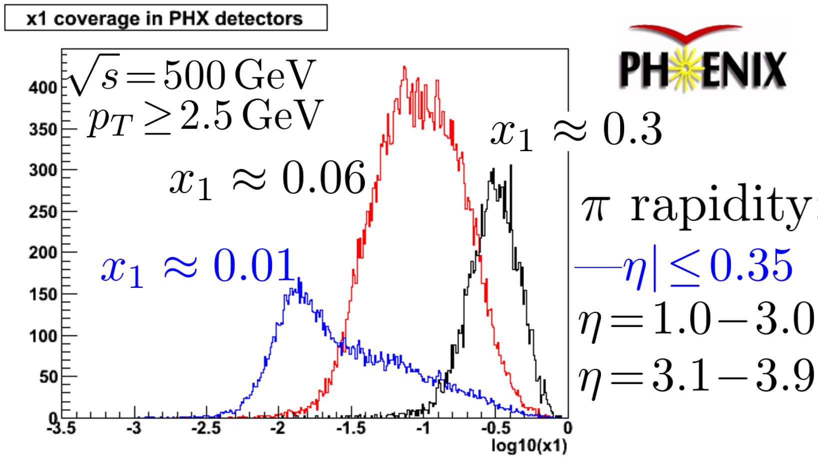
- Direct Z reconstruction is unambiguous in principle, but:
  - **Needs better than 5-10% precision at large rapidity**
  - Experimentally achievable?
    - At LHCb? RHIC? AFTER@LHC?
    - Was full data set used at Tevatron?

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

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

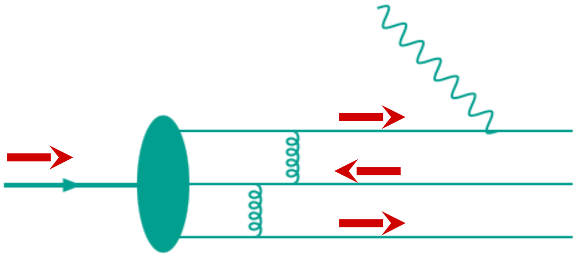
Valence quarks at large *x*

- **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



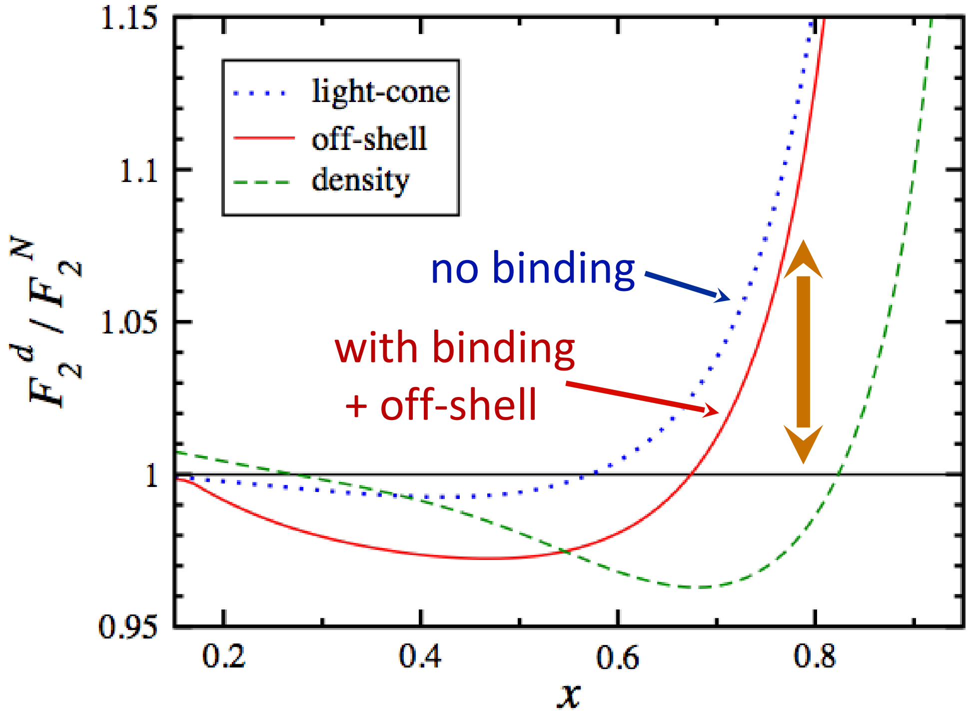
$$q^\uparrow \gg q^\downarrow$$

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

Farrar, Jackson, 1975

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