Parton Distribution Functions
- lecture 2 -

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Lecture 1 - recap

data

- DIS: p, d
- p+p(pbar) $\rightarrow$ l^+l^-, $W^\pm$, Z
- 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)

Lecture 2 - PDF uncertainties and Applications

- **PDF uncertainties**
  - Statistical, in detail
  - Theoretical, by examples
- **Comparison of PDFs**
  - PDFs, parton luminosities
- **LHC**
  - Standard candles, Higgs and t-tbar
  - PDF constraints from LHC data
- **Large-*x* connections**
  - Nuclear uncertainty, a new parametrization bias
  - d/u ratio, large mass searches at LHC
  - Using proton targets to constrain nuclear phsyics

PDF uncertainties

PDF uncertainties

- **Experimental ("PDF errors")**:
  - uncertainties in measured data propagate into the fitted PDFs
  - can be quantified adapting statistical methods: "PDF error bands"
  - Need to interpreted with care (We will see this in some detail)
- **Theoretical**
  - Several sources, cannot be quantified easily
    - Choice of data sets, kinematic cuts
    - Choice of χ^2 function
    - Parametrization bias
    - Truncation of pQCD series, scale choice, alpha strong
    - Heavy-quark scheme
    - Higher-twist, target mass effects
    - Nuclear corrections
    - …

(a few examples will be discussed later)

Hessian method

- PDF parameters denoted by $\{a_\mu\}$, $\mu = 1, \ldots, d$
- As a byproduct of the fitting process, one obtains the Hessian $H_{\mu\nu}$

$$H_{\mu\nu} \equiv \frac{1}{2} \frac{\partial^2 \chi^2}{\partial a_\mu \, \partial a_\nu}$$

  which is evaluated at the minimum of χ^2.

- To estimate the error on some observable $X(a)$, taking into account only the experimental errors which entered into the calculation of χ^2 one uses the "Master Formula"

$$(\Delta X)^2 = T \sum_{\mu,\nu} \frac{\partial X}{\partial a_\mu} (H^{-1})_{\mu\nu} \frac{\partial X}{\partial a_\nu}$$

"tolerance"

Representation of PDF uncertainties

Error PDFs

- Diagonalize the Hessian in parameter space
- Parameter eigenvectors define orthogonal directions in the functional PDF space
- A number of PDF error sets is provided:

$f^{(0)}$		Central value (best fit)
$f^{(i)}$	$i = 1, N_{par}$	Error PDFs (one for each orthogonal direction)

- Observables and their uncertainty are then calculated as *

$$X_0 = X[f^{(0)}]$$

$$\Delta X^2 = T \sum_{i}^{N_{par}} \left(X[f^{(i)}] - X_0 \right)^2$$

* NOTE: in CT10, tolerance is absorbed inside the error PDFs

Representation of PDF uncertainties

- **Monte-Carlo error set**
  - Construct a number *N* of PDF replicas by generating a multi-Gaussian distribution of parameter values:
    - One Gaussian per orthogonal direction
    - Centered on best fit parameter, width provided by the Hessian matrix
  - Observables and their uncertainty are then calculated as

$$X_0 = \frac{1}{N} \sum_1^N X[f^{(i)}]$$

$$\Delta X^2 = \frac{1}{N^2} \sum_1^N \left(X[f(i)] - X_0] \right)^2$$

  - Previous results recovered as $N \longrightarrow \infty$; *N*=50-100 suitable

Tolerance

- Open a textbook, $T=\Delta\chi=1$ means 67% confidence level

- But Hessian method works only if
  - all data sets are statistically compatible
  - Exp. errors are Gaussian...
  - ...and have not been underestimated (*e.g.*, by neglect of a source of systematics)

- Correct this by a larger tolerance factor so that most data (90%, 67% of them) fall inside the PDF error band
  - Fixed tolerance (T=10 for CTEQ6.1 and CJ12, T=7 for MRST)
  - "Dynamical tolerance" for each fit (MSTW08, CT10)

Monte Carlo method

- Generate N_{rep} replicas of the chosen data set
  - In each replica, randomize central data point within quoted errors
- Make a fit for each replica
- Obtain PDF errors from statistical analysis of all fit results

$$X_0 = \frac{1}{N} \sum_{1}^{N_{rep}} X[f^{(i)}]$$

$$\Delta X^2 = \frac{1}{N_{rep}^2} \sum_{1}^{N_{rep}} \left(X[f(i)] - X_0] \right)^2$$

- This method originally adopted by the NNPDF collaboration (Hessian not available in their case) but not limited to neural network based fits

Advantages of a Monte-Carlo representation of errors

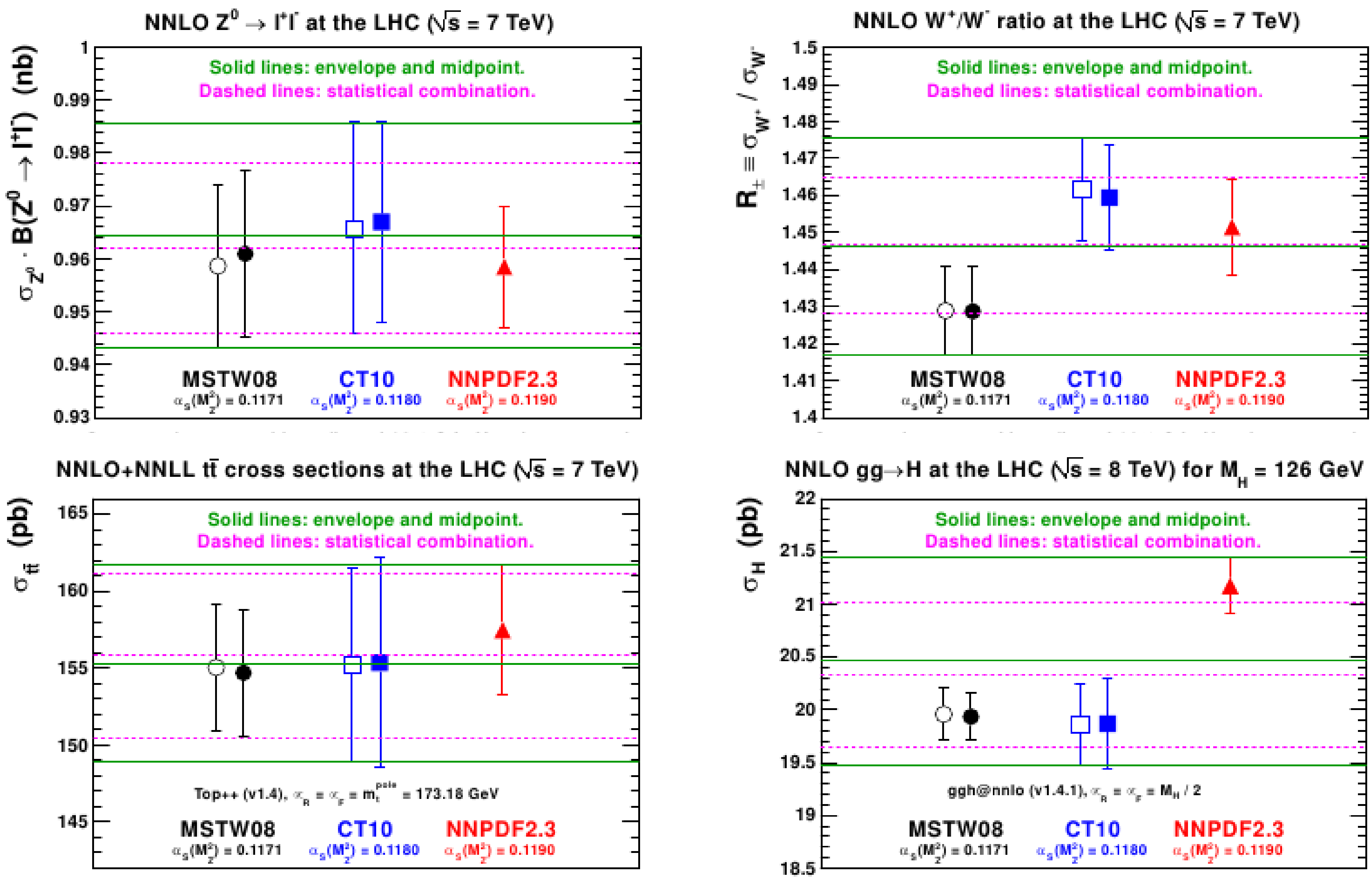
- "Monte-Carlo" error PDF sets (either by NNPDF or conventional Hessian methods) can be used in several ways

- **Bayseian reweighting:**
  - New data sets can be included by "reweighting" according to the previously obtained Monte Carlo PDFs
  - No need to perform new fits if N large enough

- **Combination of PDFs** from different groups
  - E.g., for equal a-priori weighting, take same number of Monte-Carlo PDFs from each group
  - Calculate X and ΔX as before

- Speed up uncertainty calculations in Monte-Carlo generators

Example: combination of CT10, NNPDF2.3, MSTW08



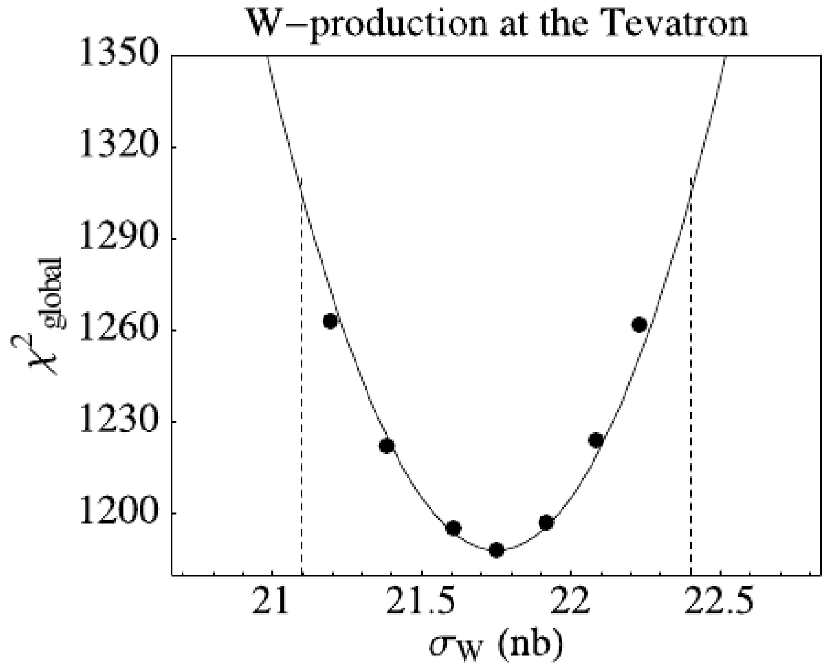
Open markers: usual best-fit and 68% C.L. Hessian uncertainty.
Closed markers: average and s.d. over random predictions.

Lagrange multiplier method

- Given an observable *X*, minimize a new function for fixed values of Lagrange multiplier λ

$$\Psi(\lambda,\{a\}) = \chi_g^2(\{a\}) + \lambda\big(X(\{a\}) - X_0\big)$$

  - Obtain a new set of parameters, A_{min}, and the pair $\{\chi_g^2(\lambda),\, X(\lambda)\}$
  - Repeat for many λ values, obtain $\chi_g^2(X)$
  - Chose a tolerance *T*, read off the PDF error Δ*X*



Comparison of PDFs

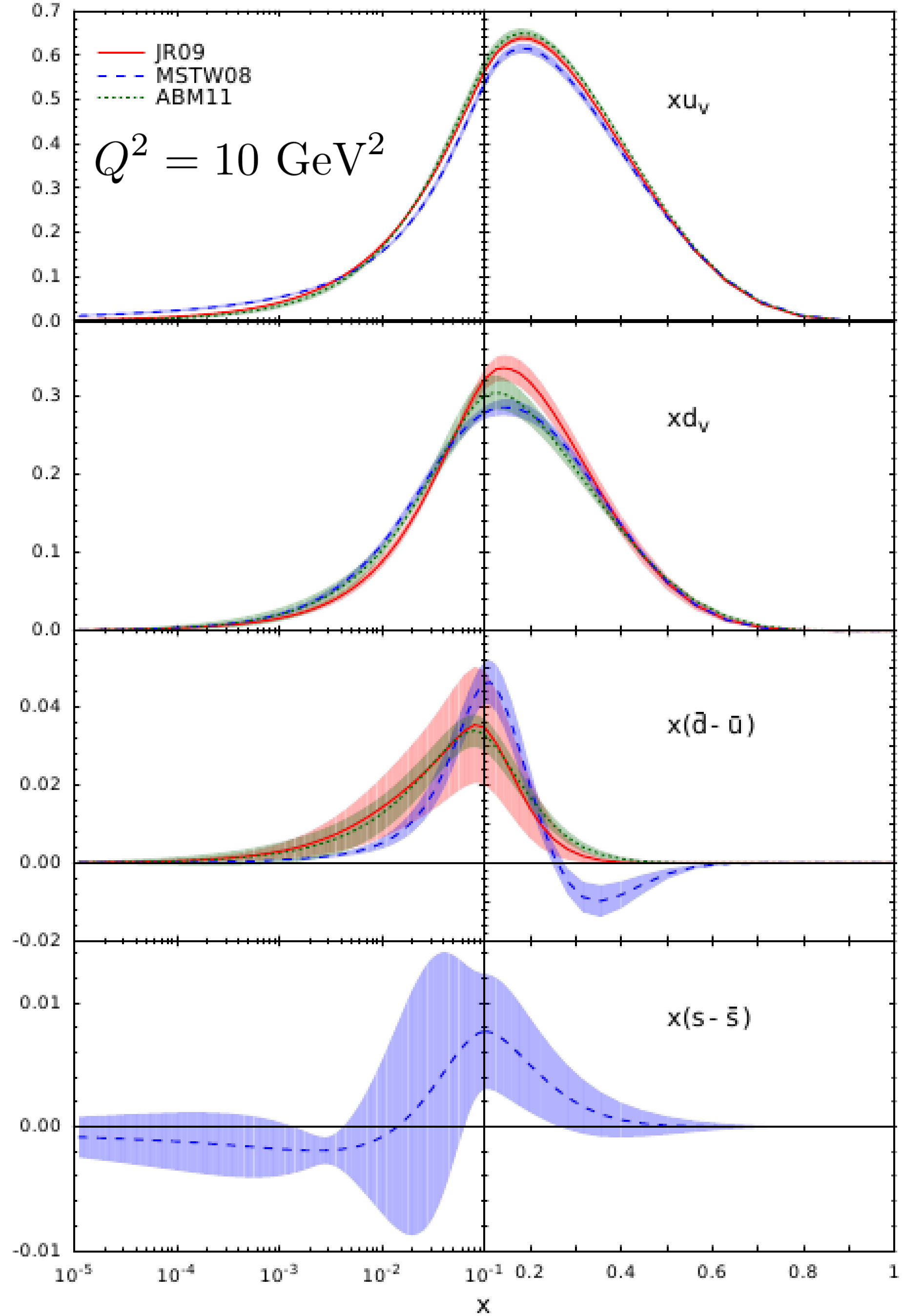
Some differences between PDF groups

	MSTW08	CT10	NNPDF2.3	HERAPDF1.5
PDFs	7	6	7	5
Params.	20+8	25	259	14
Heavy Q.	TR	ACOT	FONLL	TR
Statistics	Hess.+DT	Hess.+DT	MC	Hess.+par+modl
W^2_{min}	high	high	high	high
HT, TMC				
Nucl. corr.	explored		explored	
large-x d				

	ABM11	JR09	CJ12
PDFs	6	5	5
Params.	24	12	19+3
Heavy Q.	FFN	FFN	ZM
Statistics	Hess.	Hess.+T	Hess.+T
W^2_{min}	low	high	low
HT, TMC	✓		✓
Nucl. corr.	✓		✓
large-x d			✓

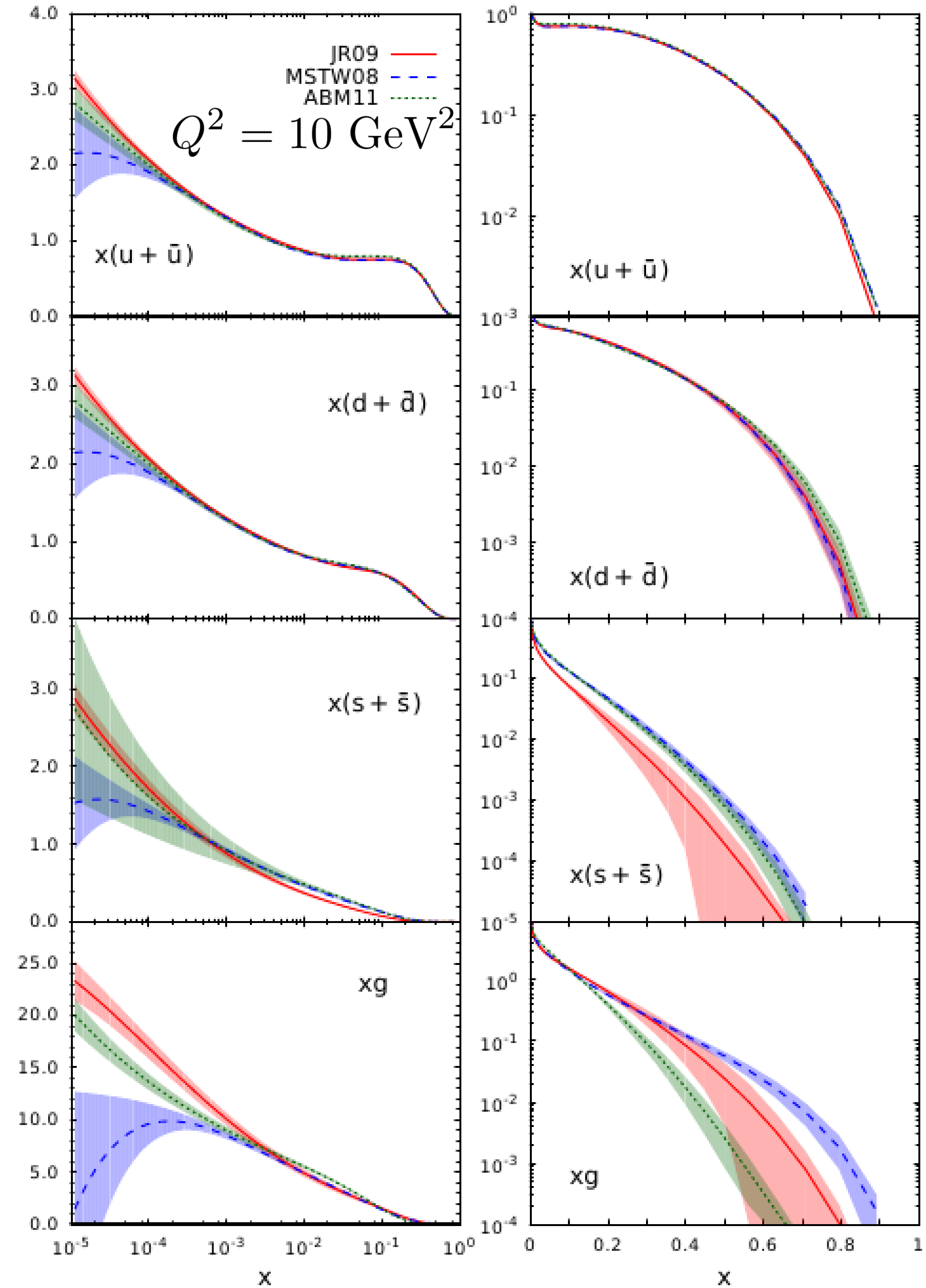
Non-singlet PDFs

- u_v well determined, some
- Uncertainties in d_V at medium-large x
  - See later for details
- $\bar{d} - \bar{u}$ well determined by DY data at x = 0.05–0.25
  - otherwise unconstrained
- $s - \bar{s}$ partially determined by EMC ν+A dimuon production
  - But large experimental, nuclear uncertainties
  - CJ12 omits these data altogether



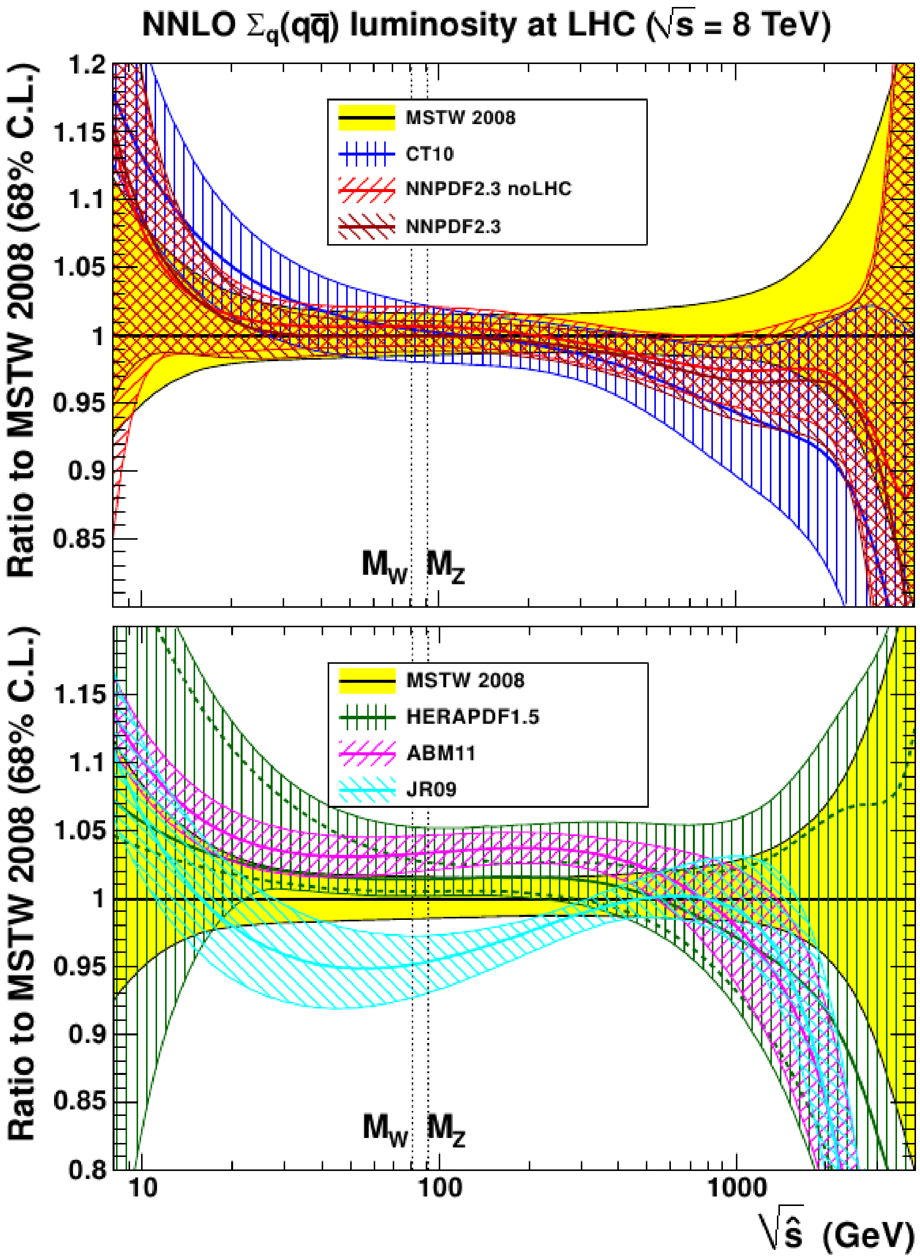
Singlet, gluon PDFs

- $u + \bar{u}$ and $d + \bar{d}$ dominant at large x
- $s + \bar{s}$ becomes comparable at small x
- *Gluons* dominate by far at small x



Parton luminosities: q - qbar

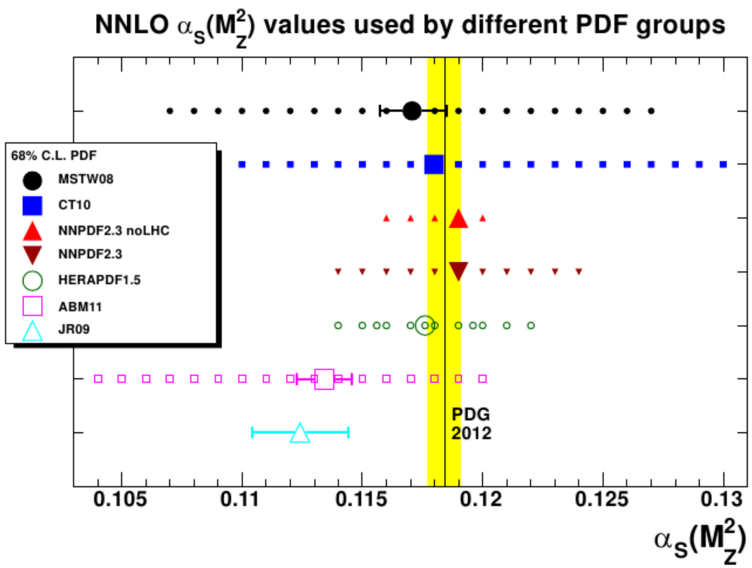
- Fairly good agreement between MSTW08, CT10, NNPDF2.3
  - "standard candles" under control
- But at variance with other sets... Due to choice of data?
  - ABM and JR have DIS+DY only
  - HERAPDF have HERA DIS only
- Uncertainties and spread of central values grow at large *x*
  - Limitation for large mass, forward rapidity observables

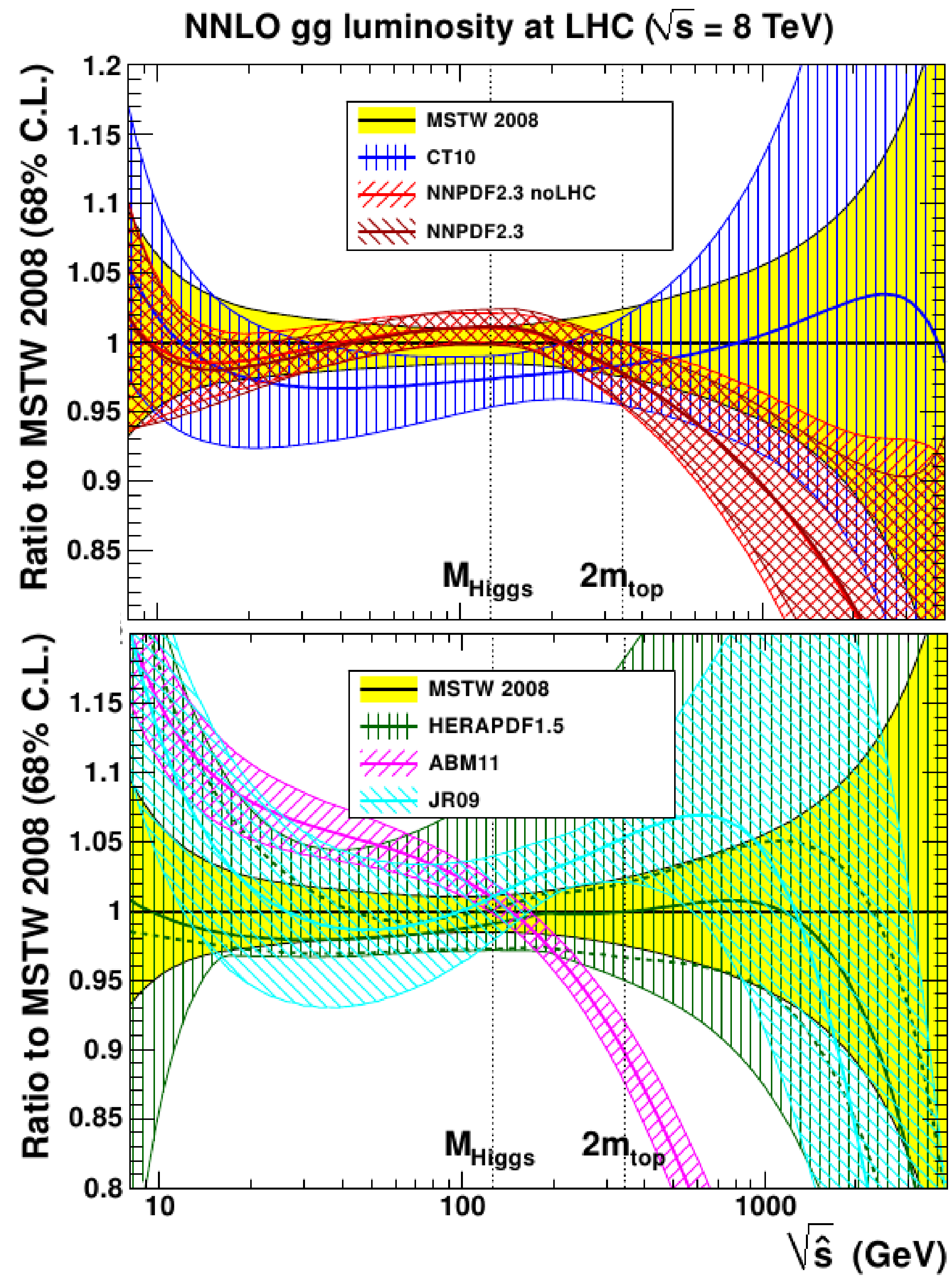


$$L^{ij} \equiv q_{i/A}(x_1)\bar{q}_{j/B}(x_2) + \{A \leftrightarrow B\}$$

Parton luminosities: g - g

- More variation
  - In particular in the region relevant to Higgs production
- HERAPDF has larger PDF errors
  - Due to use of HERA-only data
- Note: α_s varies with each PDF
  - Strongly correlated with gluons





$$L^{ij} \equiv q_{i/A}(x_1)\bar{q}_{j/B}(x_2) + \{A \leftrightarrow B\}$$

LHC

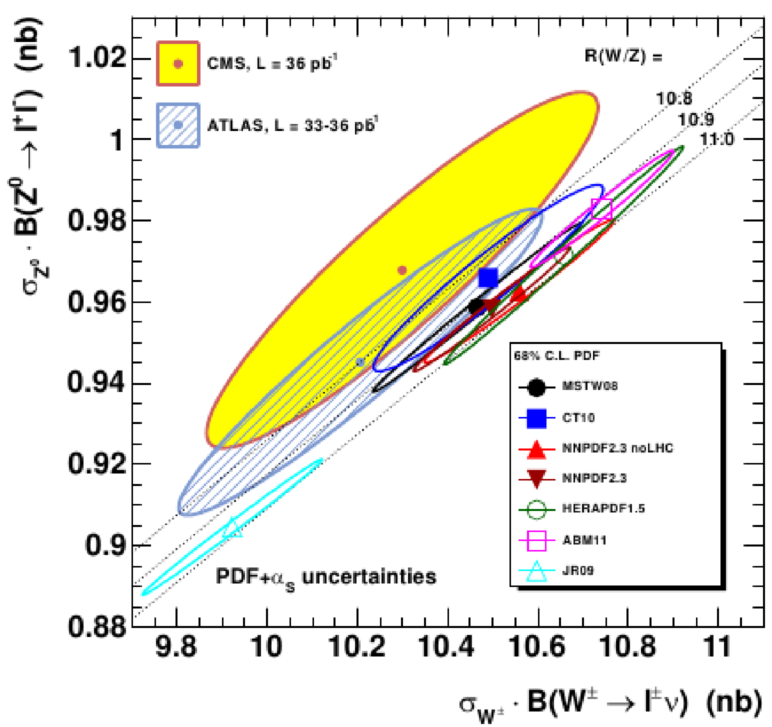
W and Z cross sections - a standard candle at the LHC

- Partonic cross section for inclusive W,Z production well-known
  - use to monitor parton luminosity reduce systematic in other cross sects.

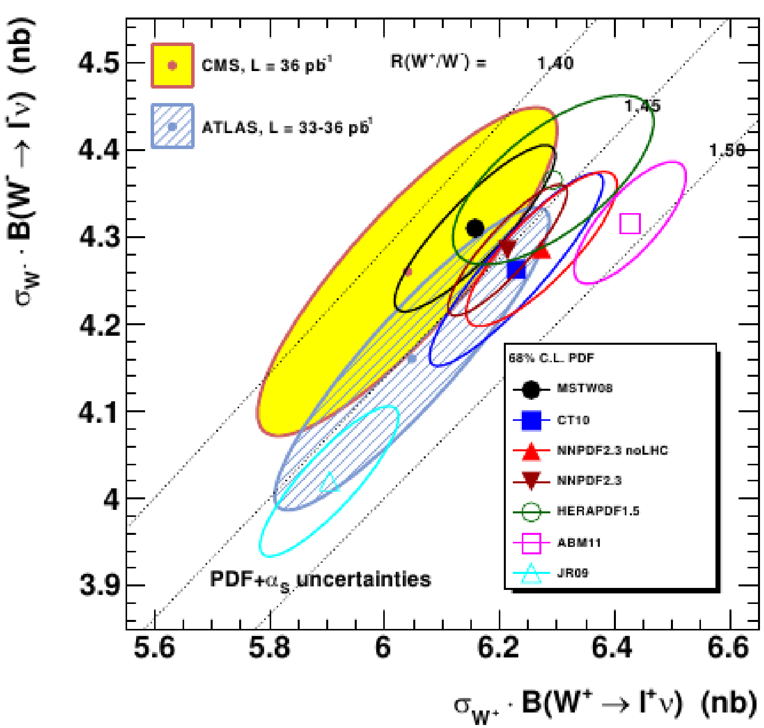
$$\sigma_X(s, M_X^2) = \int_\tau^1 \frac{dx}{x} \mathcal{L}(x)\, C\left(\frac{\tau}{x}, \alpha_s(M_X^2)\right)$$

$$\mathcal{L}(x) \equiv \int_x^1 \frac{dz}{z} f_{a/h_1}(z, M_X^2) f_{b/h_2}\left(\frac{x}{z}, M_X^2\right) \qquad \tau \equiv \frac{M_X^2}{s}$$

NNLO W and Z cross sections at the LHC ($\sqrt{s}$ = 7 TeV)

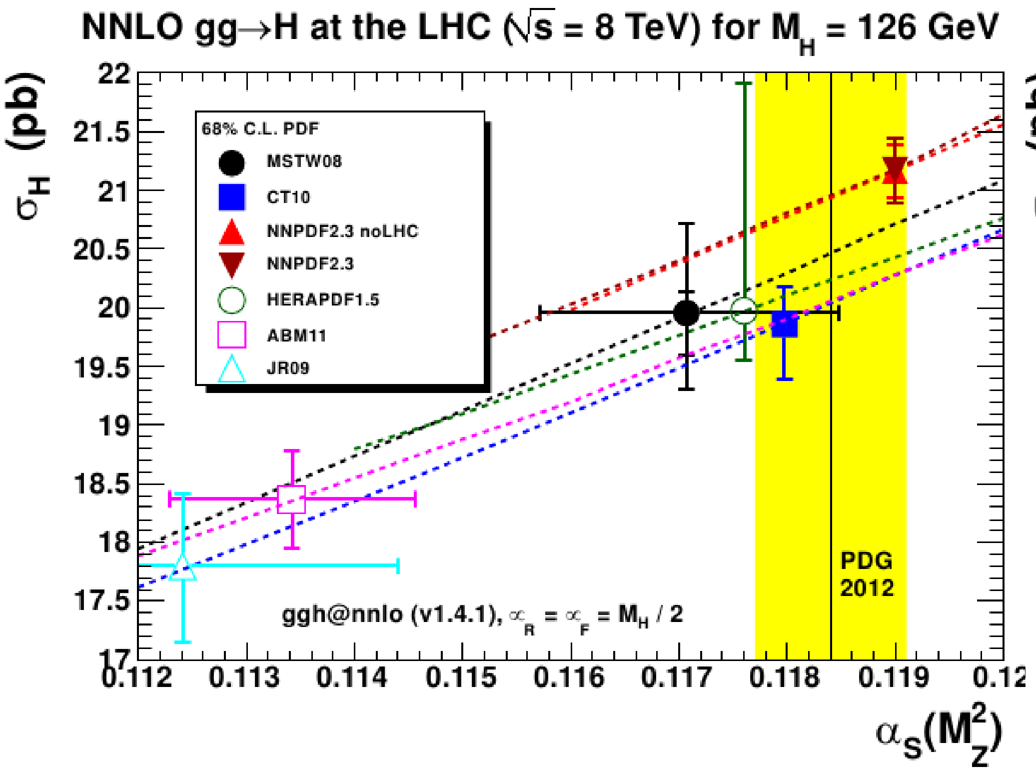


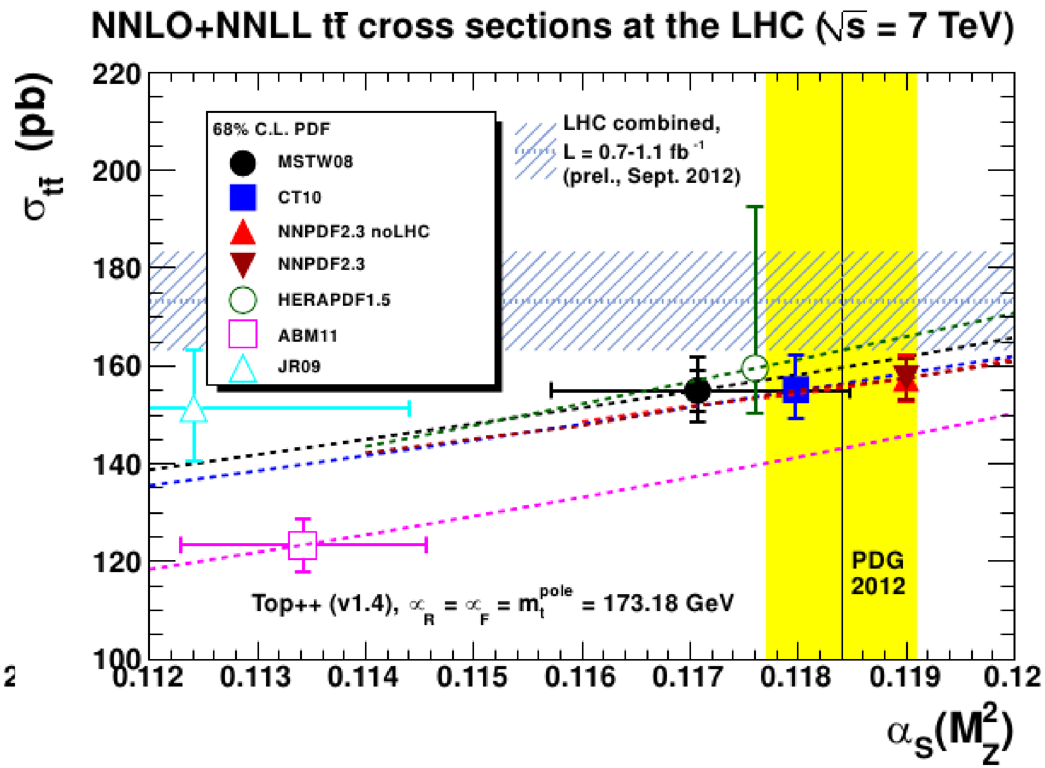
NNLO W+ and W- cross sections at the LHC ($\sqrt{s}$ = 7 TeV)



Higgs and t-tbar

- Sensitivity to gluons, alpha strong



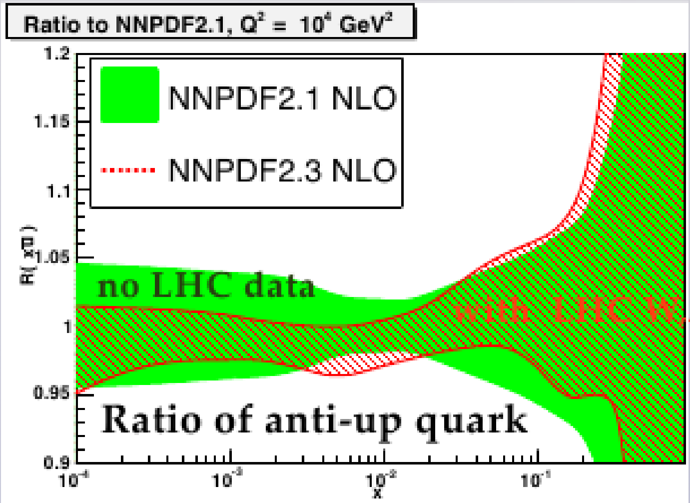


- Both *g-g* and *q-qbar lumi underestimated (also CJ12 for q-qbar)*
  - ***What are we missing***?

J.Rojo, DIS 2013

PDF sets with LHC data

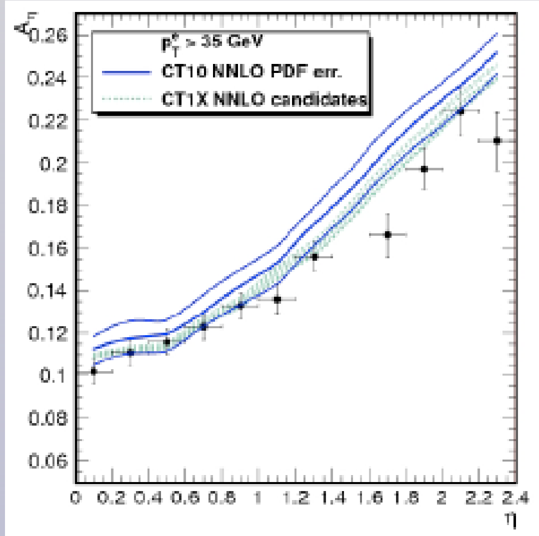
- A major improvement since DIS12 is **use of LHC data** on **jets and W,Z production** by the PDF groups
- **NNPDF2.3** is only publicly available PDF set that includes constrains from **LHC jet and W,Z data**, and other groups have presented **preliminary updates** quantifying the impact of LHC measurements



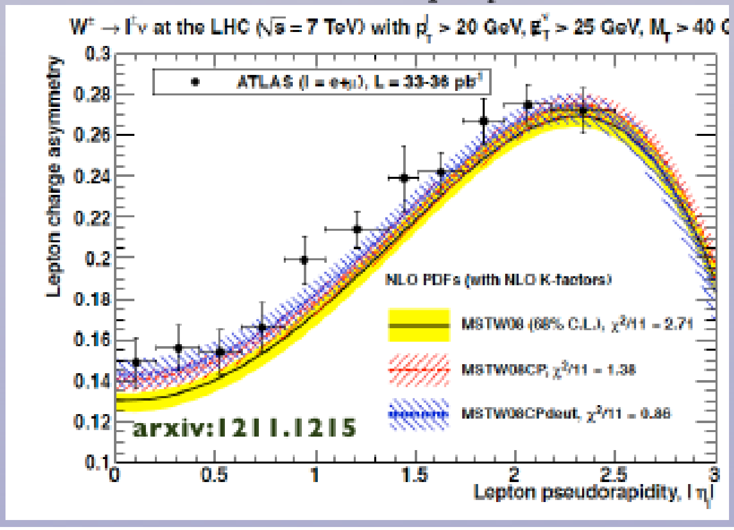
CT: studies of impact of LHC **jet and W,Z** production

Good overall agreement

Slightly **increased PDF errors** due to need of more flexible PDF param

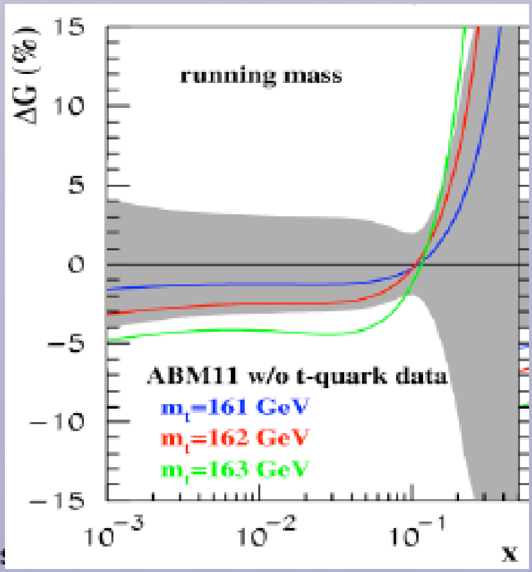


MSTW: poor description of **W asymmetry data** cured with a **more flexible input** parametrization



ABM: studied impact of LHC **top quark data** into gluon PDF (PDF4LHC, 19.04.13)

Also studies of impact of **W and Z data** at LHC (arxiv:1303.1073)



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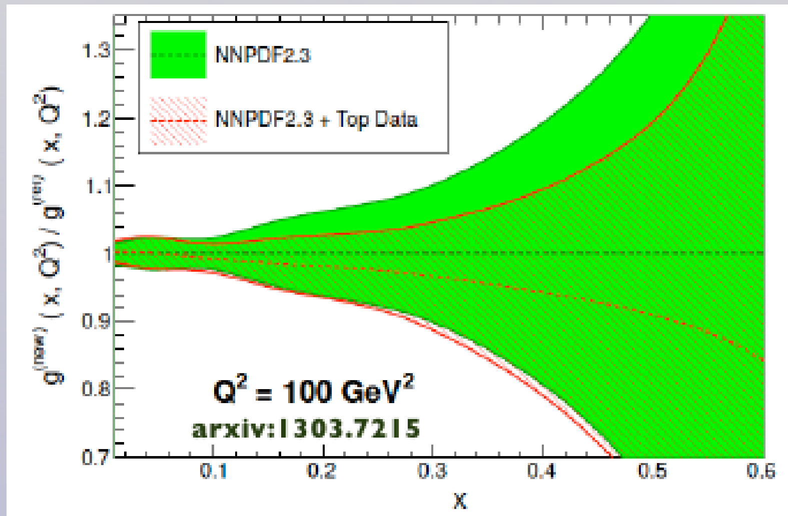
J.Rojo, DIS 2013

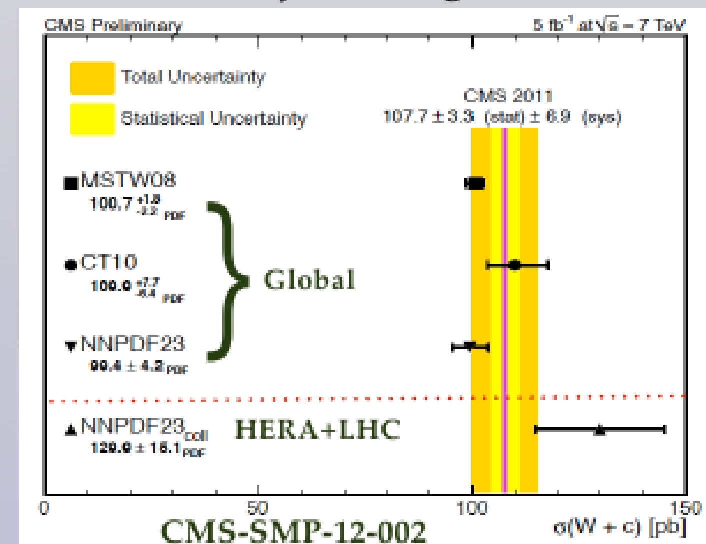
Experimental constraints

On top of traditional processes, like **jets** and **W, Z production**, a **wide range of new processes** that provide PDF information is now available at the **LHC** (see **Voica's** talk)

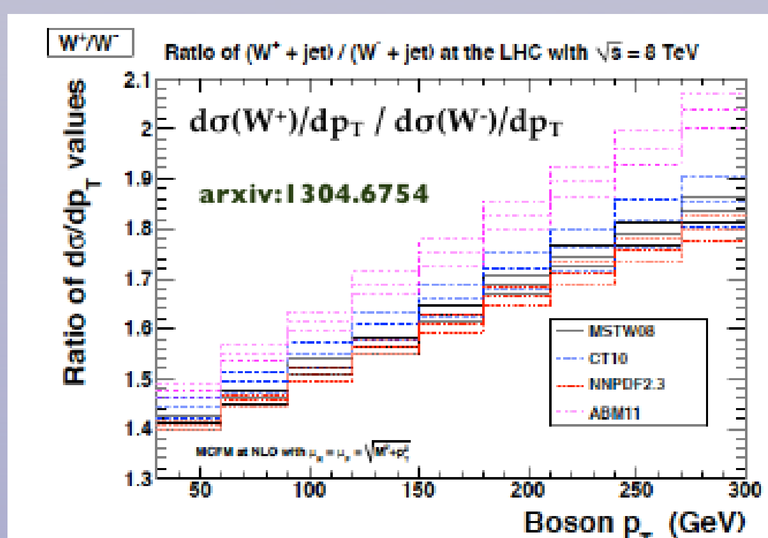
☑ **Top quarks:** constrain **large-x gluon**



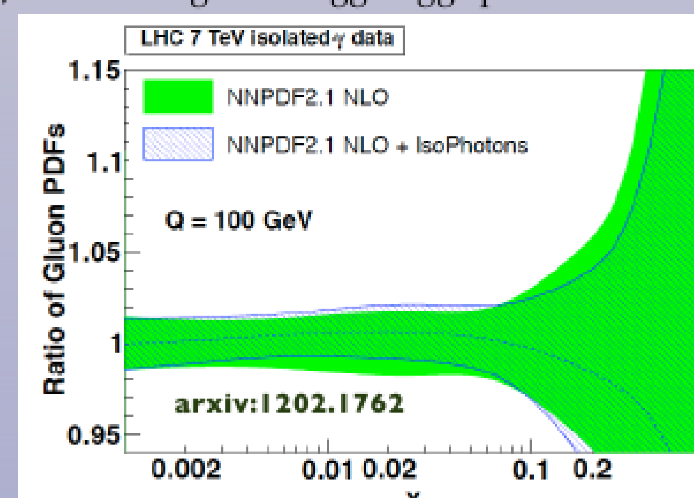
☑ **W+charm:** sensitivity to **strangeness**



☑ **high p_T W and Z: gluon** and on **d/u ratio**



☑ **Isolated photons:** complementary probe of the **gluon,** same x-range as for gg Higgs production



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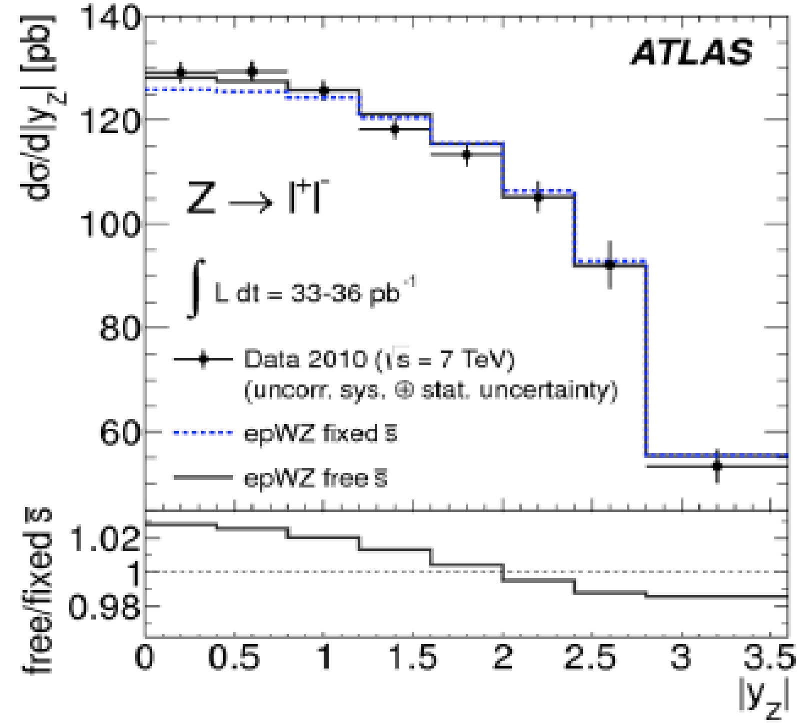
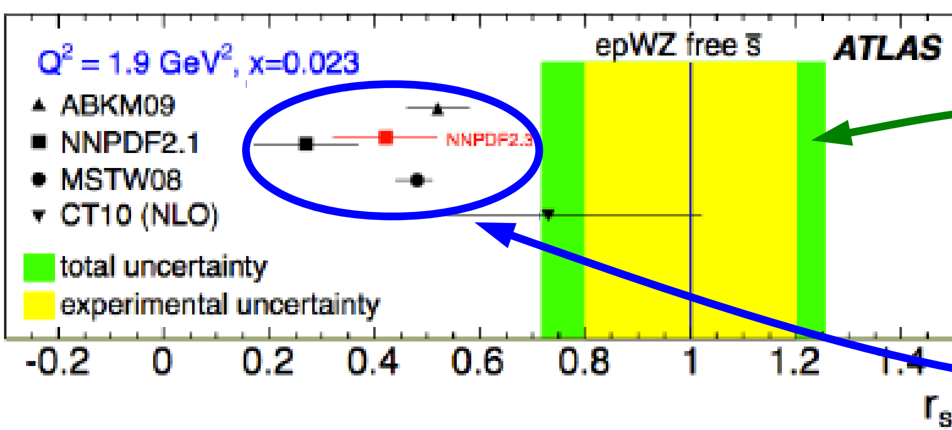
Radescu DIS 2013

Strange quark from W, Z measurements at ATLAS

- Strange quark is not so well constrained:
  - Neutrino dimuon data favours suppressed strange
- At LHC, Z cross sections together with y_Z shape may provide a constraint on s-quark density and it can be cross checked by W+charm data.
  - The results for NNLO fits to inclusive W, Z differential data with free and fixed **s:**
    - For W+ and W- there is little difference, helps to fix the normalisation.
    - For Z, the cross section is increased and the shape is modified.





$$r_s = 1.00 \pm 0.20_{\rm exp} \pm 0.07_{\rm mod}{}^{+0.10}_{-0.15}{}_{\rm par}{}^{+0.06}_{-0.07}{}_{\alpha_S} \pm 0.08_{\rm th.}$$

- ATLAS+HERA data
  $\Rightarrow$ flavor symmetric sea
- Above most others

Accardi CTEQ'13

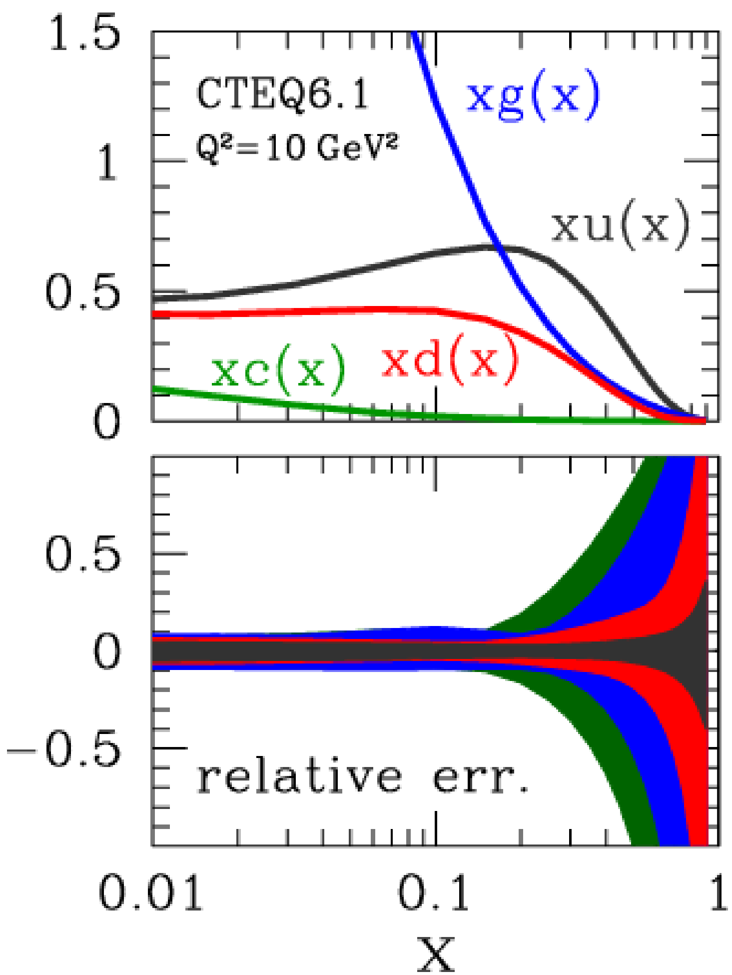
- Tension with ν+A dimuons?
- Nuclear suppression of charm?

Large x

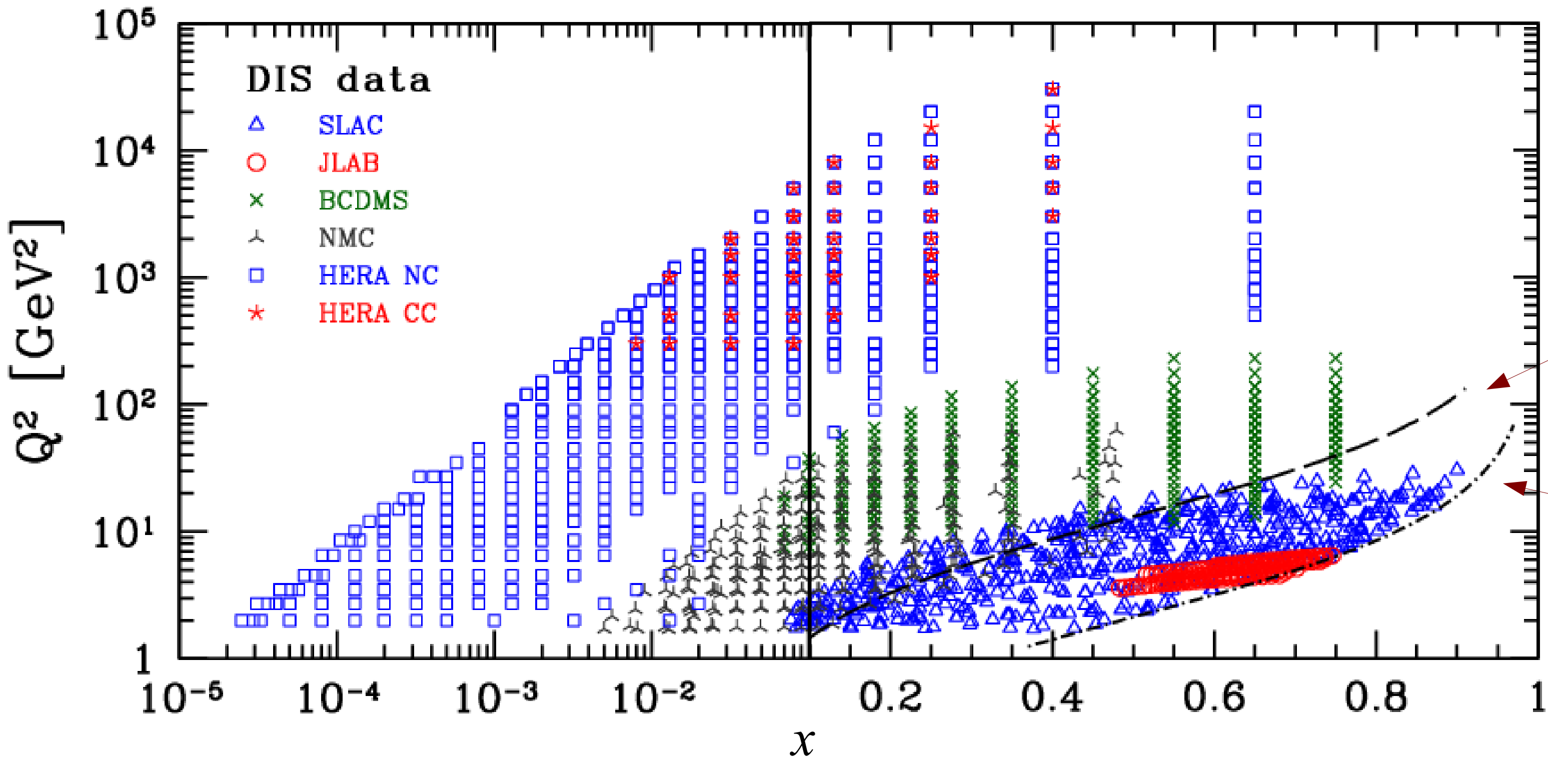
Why large x ?

- 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 large p_T excess
    - High mass searches
    - Forward physics
  - At RHIC:
    - Polarized gluons at the smallest *x*
  - Neutrino oscillations, …



Large-x, small-Q^2 corrections



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

CJ12, ABM11 $W^2 \gtrsim 3\ \mathrm{GeV}^2$

- **$1/Q^{2n}$ 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

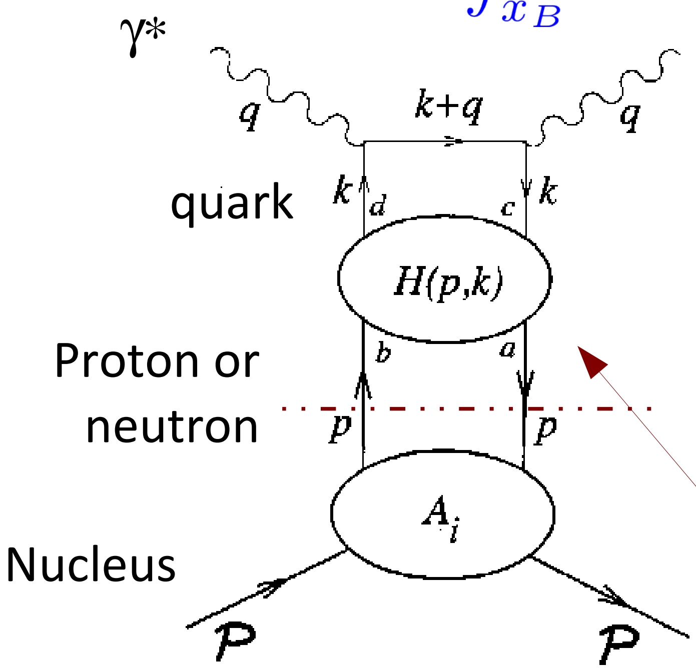
*Owens, Accardi, Melnitchouk PRD **D87** (2013)*

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

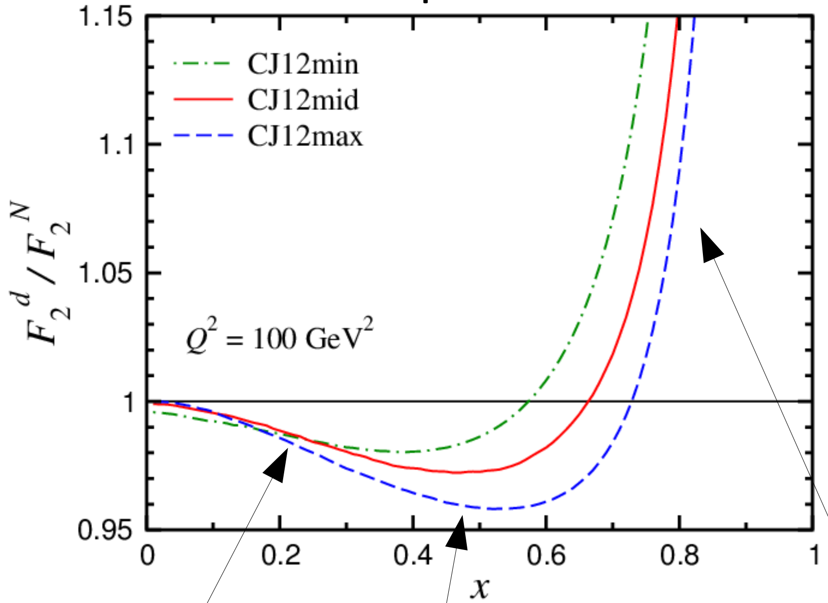
$$F_{2d}(x_B, Q^2) = \int_{x_B}^{A} dy\, \mathcal{S}_A(y,\gamma) F_2^{TMC+HT}(x_B/y, Q^2) \left(1 + \frac{\delta^{off} F_2(x)}{F_2(x)}\right)$$



Low-energy factorization issues

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

Bound vs. free proton+neutron



Effect of theory corrections in a nutshell

- **PDFs stable with respect to low W cut**
  - If TMC included and residual power correction ("HT") fitted

Accardi et al., PRD 81 (2010)

- **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***

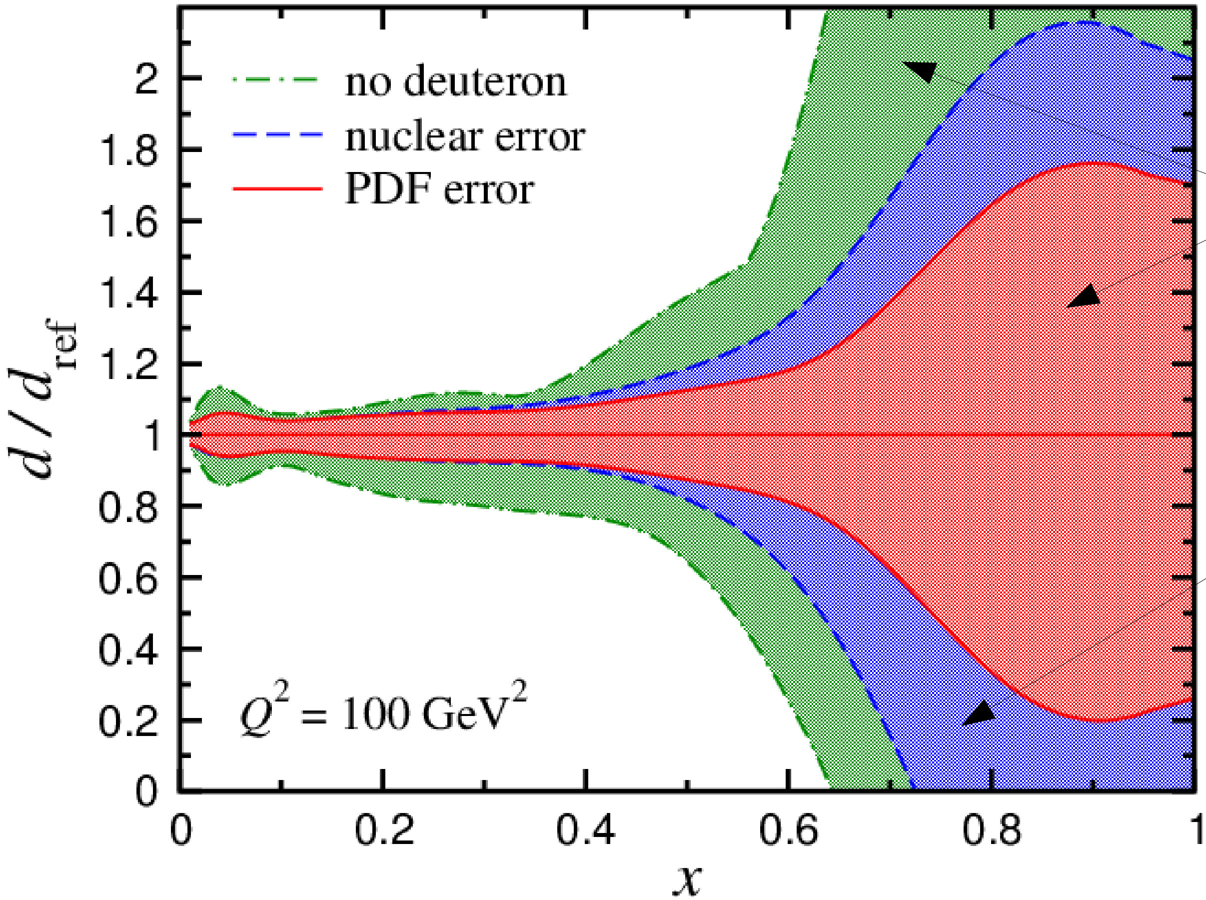
- **Sensitivity to nuclear corrections**
  - *d*-quark at $x > 0.5$ almost fully correlated to nuclear model model:
    Very large theoretical uncertainty at large x
  - Modest, non negligible impact also at $0.2 < x < 0.5$

Accardi et al. PRD81 (2010)

Ball et al. ArXiv:1303.1189 (2013)

CJ12 fits: nuclear and PDF uncertainty

*Owens, Accardi, Melnitchouk, PRD **87** (2013)*

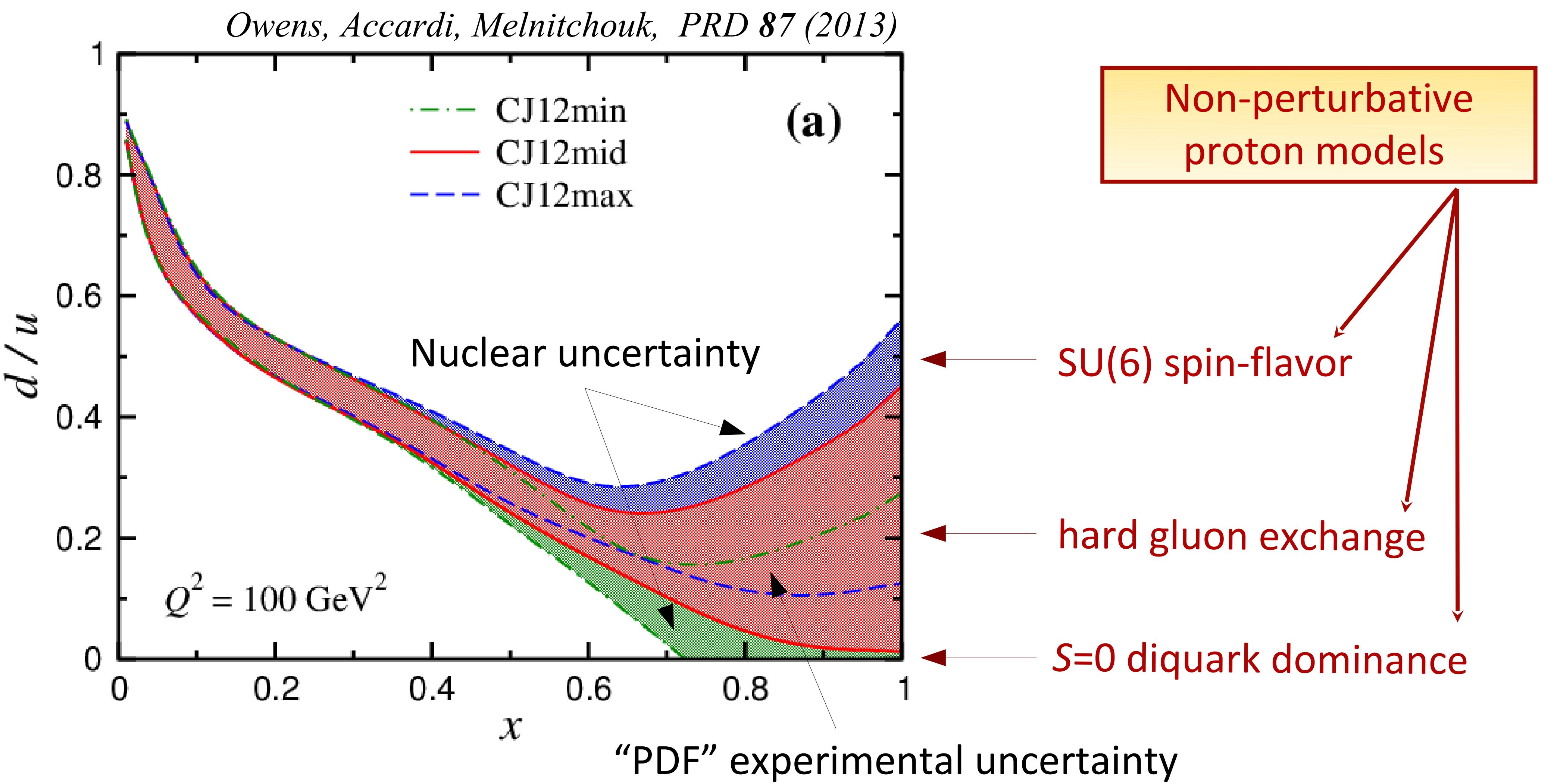


Largely reduced PDF errors (increased statistics)

Nuclear uncertainties (systematic)

- Large overall reduction in uncertainty with relaxed cuts

Applications: *d/u* ratio



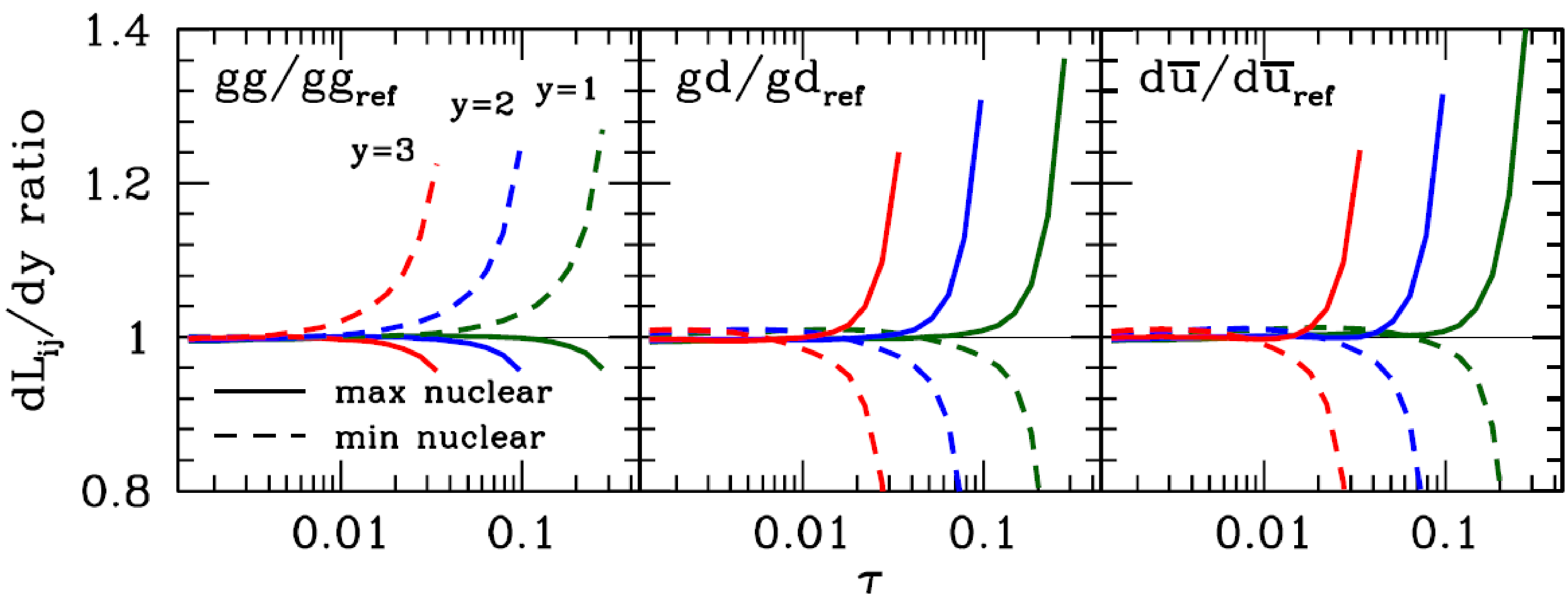
$$d/u \xrightarrow[x\to 1]{} 0.22 \pm 0.20\,(\mathrm{PDF}) \pm 0.10\,(\mathrm{nucl})$$

Applications: new physics at LHC

*Accardi et al., PRD **84** (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

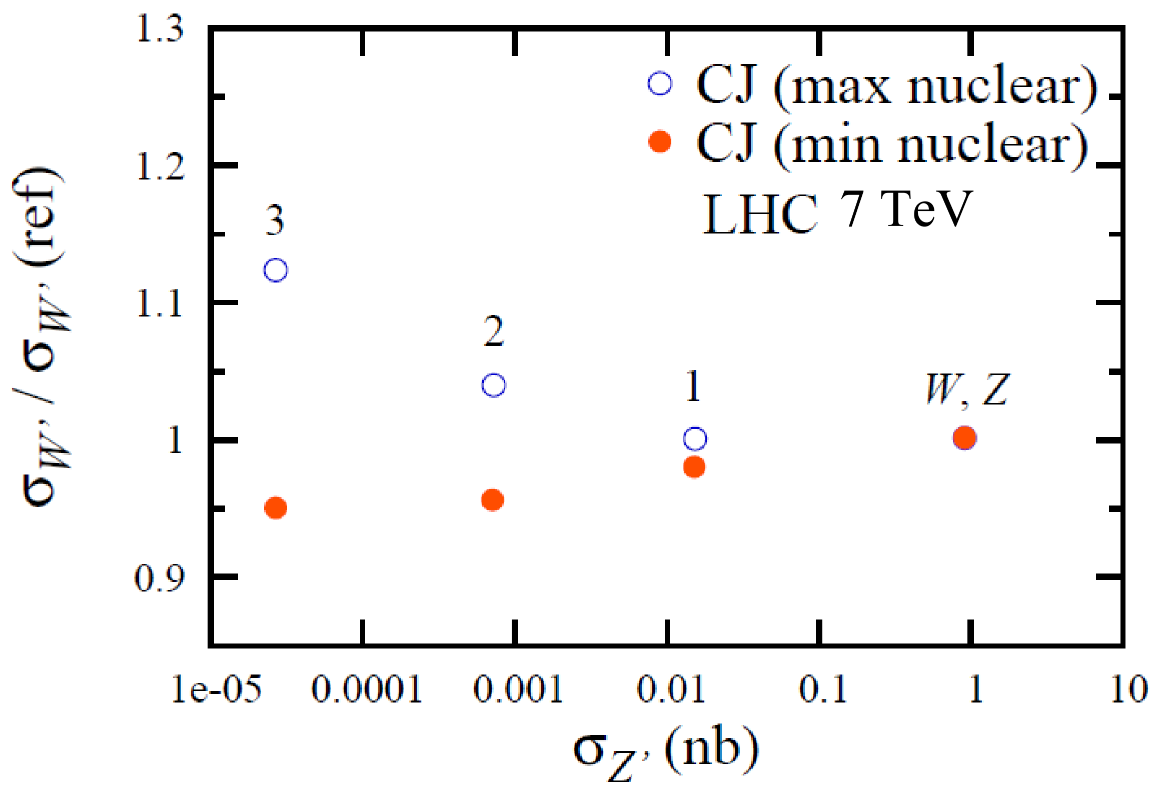


Applications: large mass searches at LHC

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

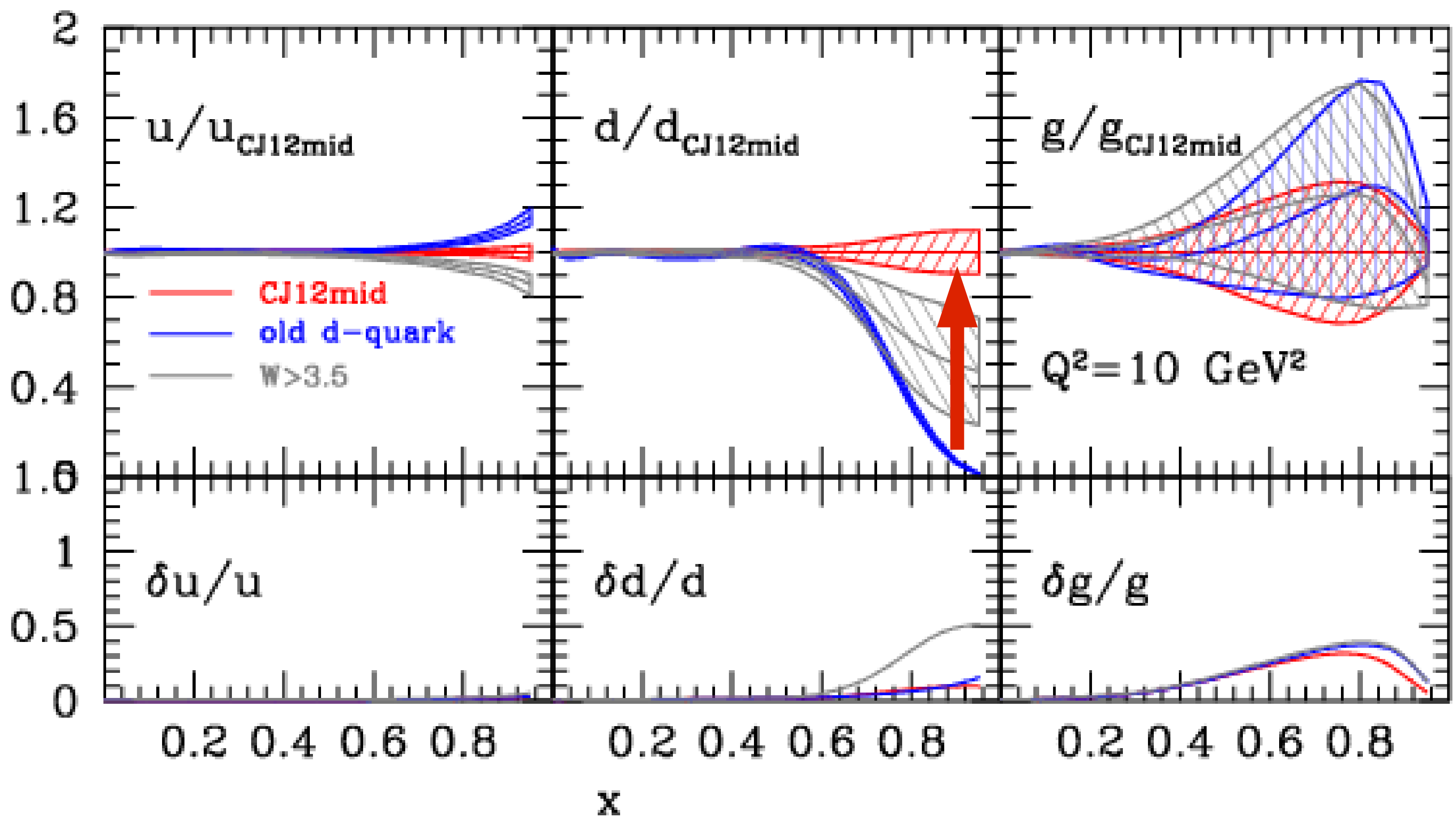
- New physics signal require accurate determination of QCD background
- Uncertainties in large-*x* PDFs could affect interpretation of experiments searching for new particles

Example: W' and Z' total cross sections



Large-x parametrization bias

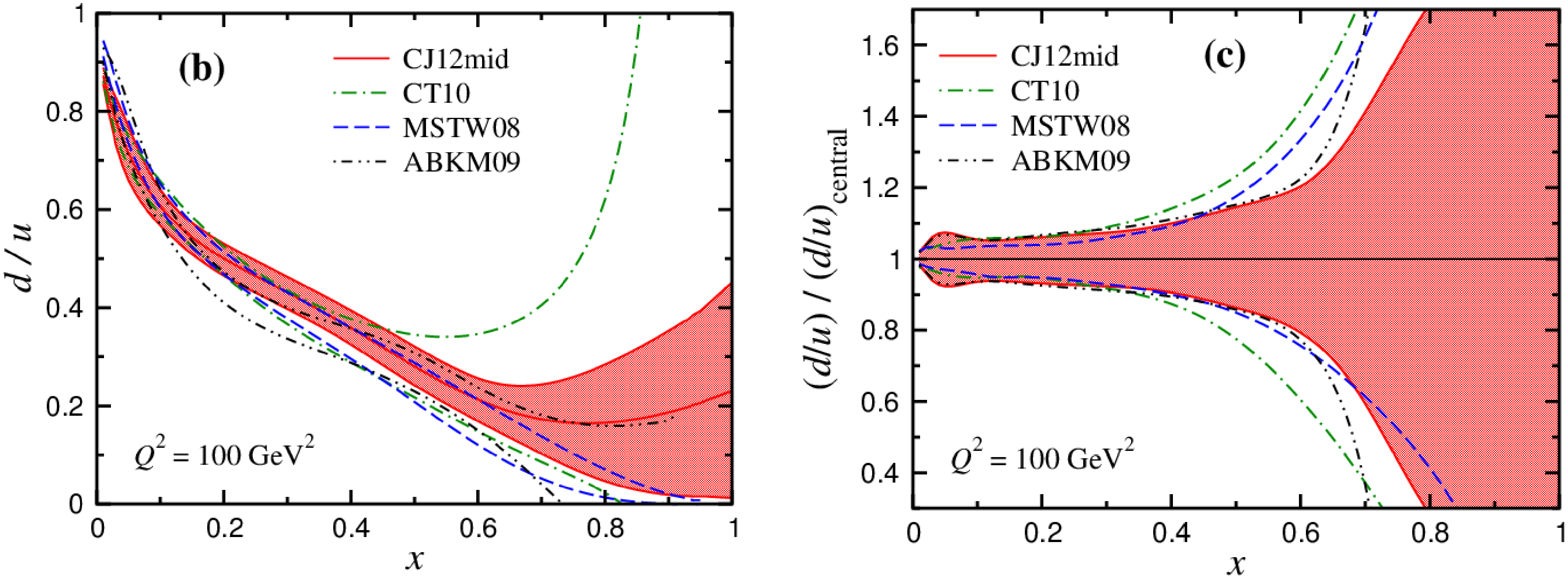
[here T=1 for clarity]



- 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***

Large-x parametrization bias

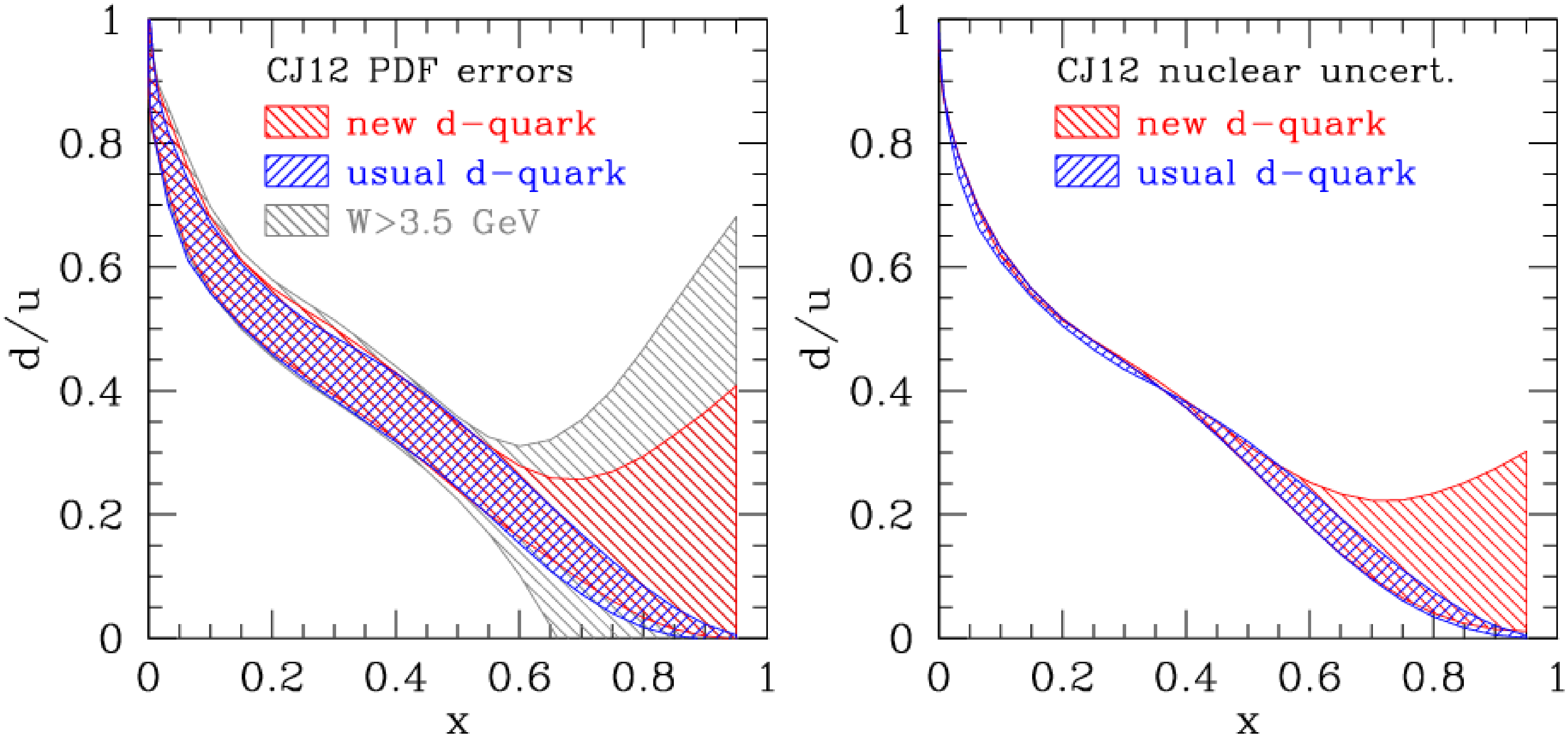
Owens, Accardi, Melnitchouk, arXiv:1212.1702



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

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

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

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
  - $^3He/^3H$ ratios
- **Data on free (anti)protons, sensitive to *d***
  - *e+p*: parity-violating DIS — **HERA** *(e⁺ vs. e⁻), **EIC, LHeC***
  - ν+*p*, $\bar{\nu}$+*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 negative rapidity – dileptons; *W, Z*
    - Sensitive to nuclear corrections, cross-checks *e+d*

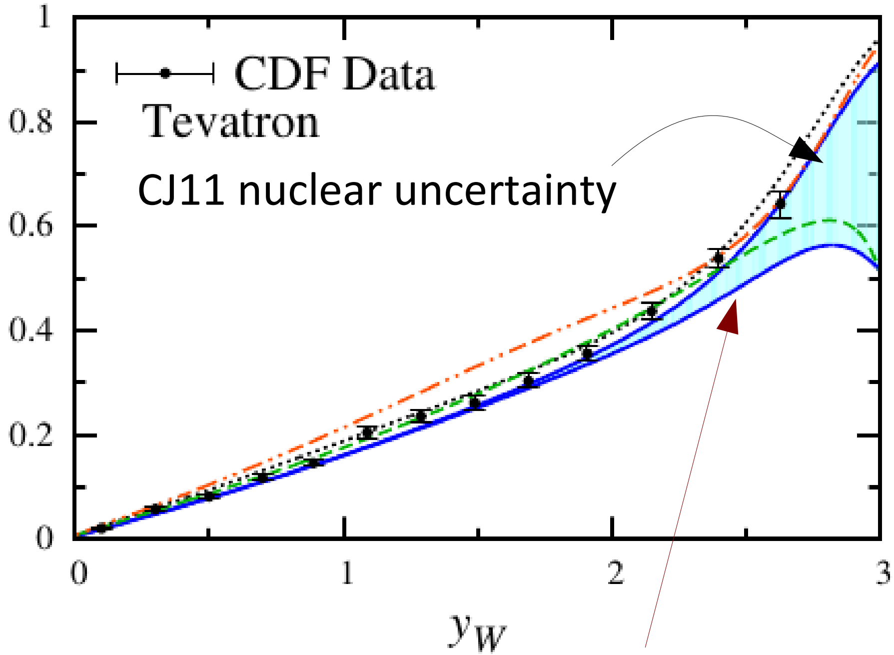
RHIC ??
AFTER@LHC

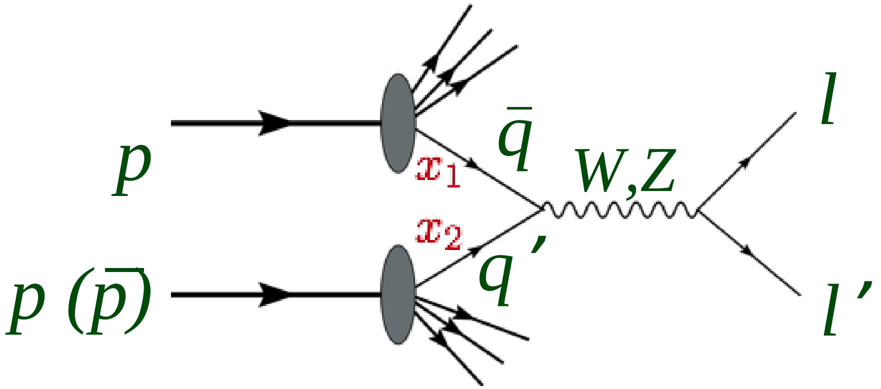
Use protons to study nuclei (!)

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)

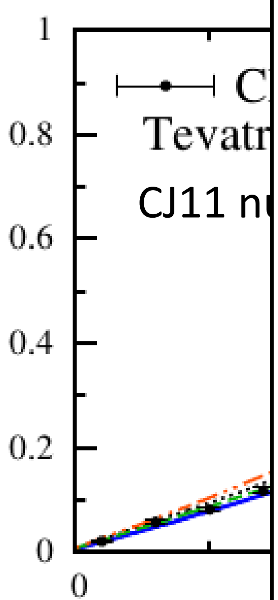
- Needs to be corroborated:
  - *W*, *Z* at RHIC, *Z* (and *W* ?) at LHC, *W* at DØ (??)
  - PVDIS at JLab 12, **CC @ EIC**

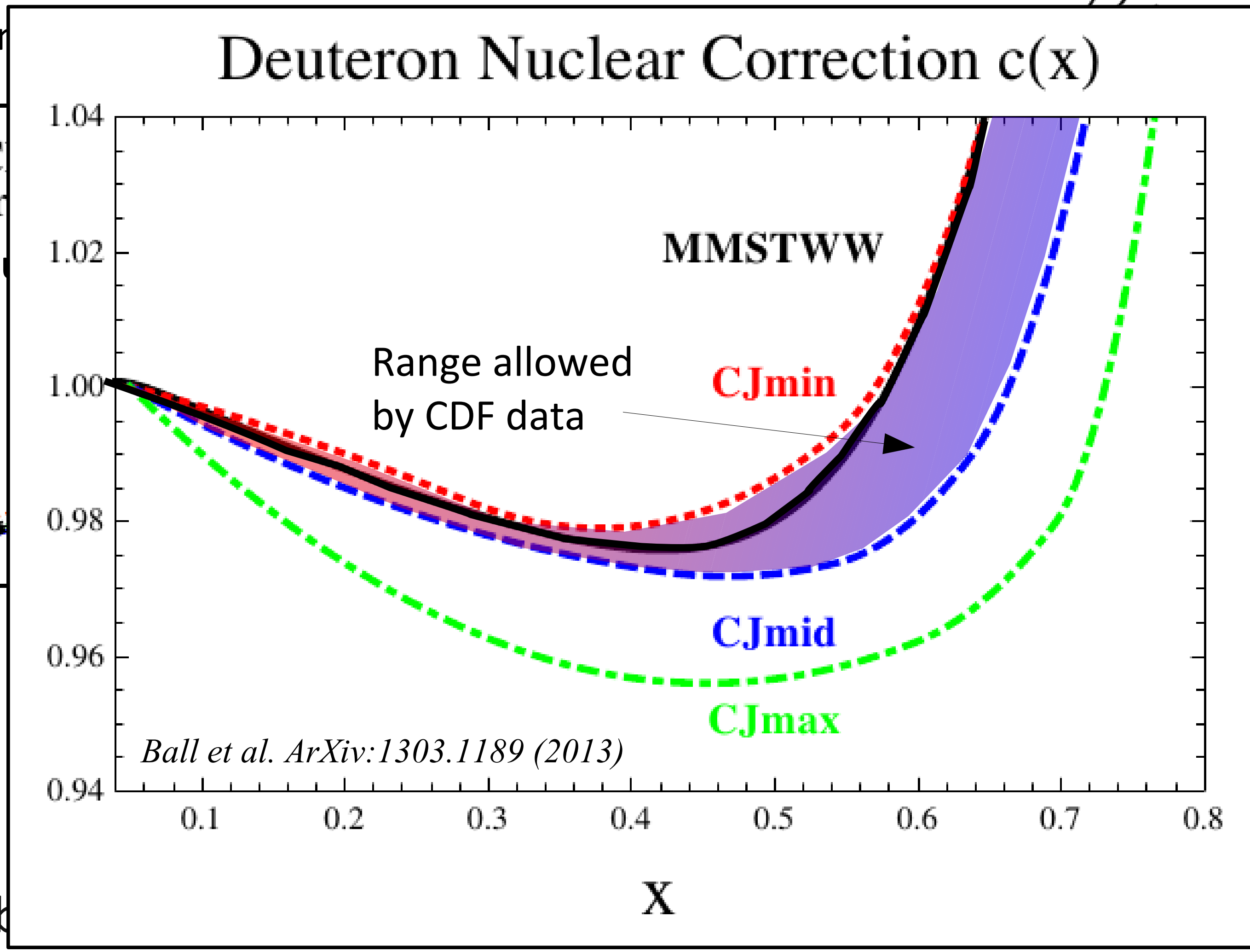
Use protons to study nuclei (!)

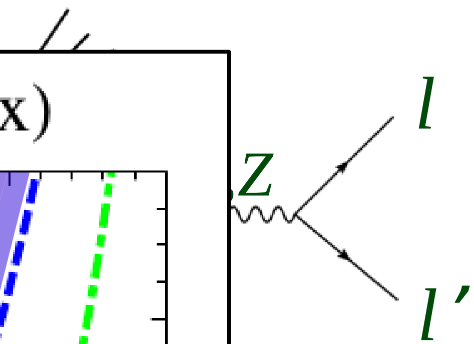
Brady, Accardi, Melnitchouk, Owens, JHEP 1206 (2012) 019

Directly reconstructed W:

- highest ser







(W^-) / (W^-)

$l/u(x_1)$ / $l/u(x_1)$

PJ C73 (2013)

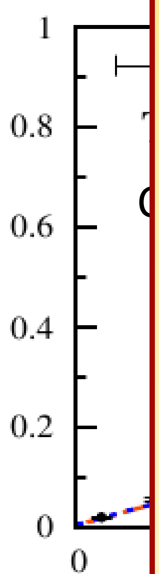
- Needs to b
  - *W*, *Z* at RHIC, *Z* (and *W* ?) at LHC, *W* at DØ (??)
  - PVDIS at JLab 12, **CC @ EIC**

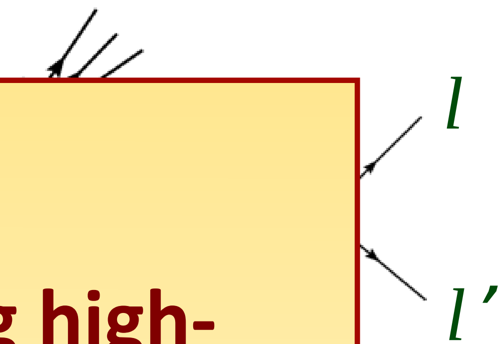
Use protons to study nuclei (!)

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

Directly reconstructed W:

- high…





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

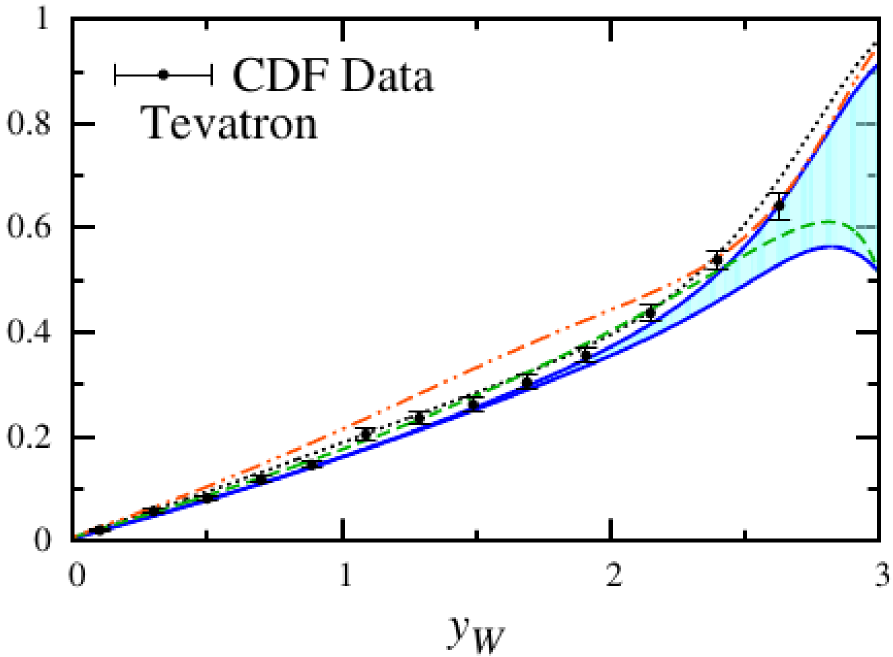
weak interactions on <u>proton targets</u> from JLab to the LHC!

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

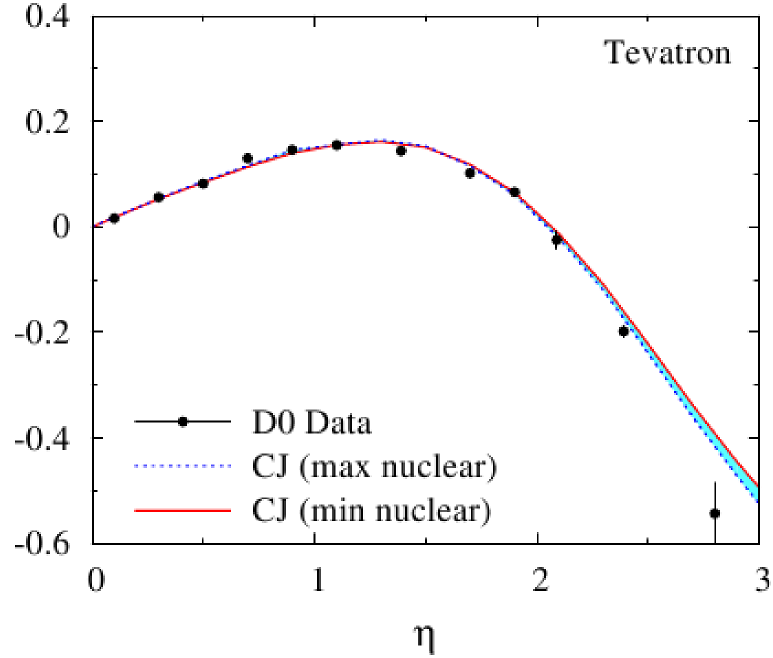
W charge asymmetry at Tevatron

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*



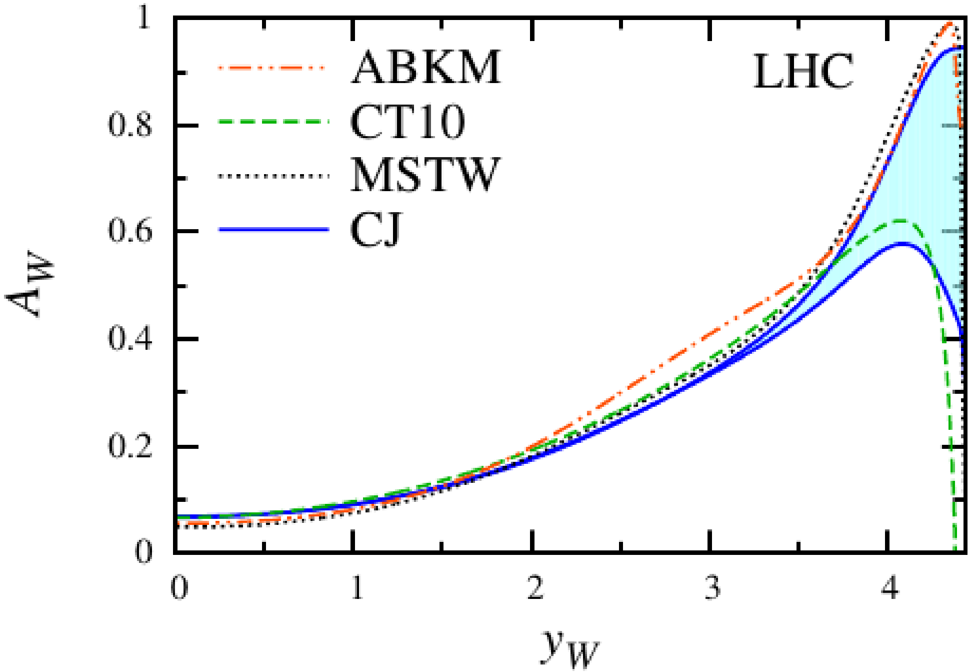
- Too little large-*x* sensitivity in lepton asymmetry:
  - **need reconstructed *W***

W charge asymmetry at LHC

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

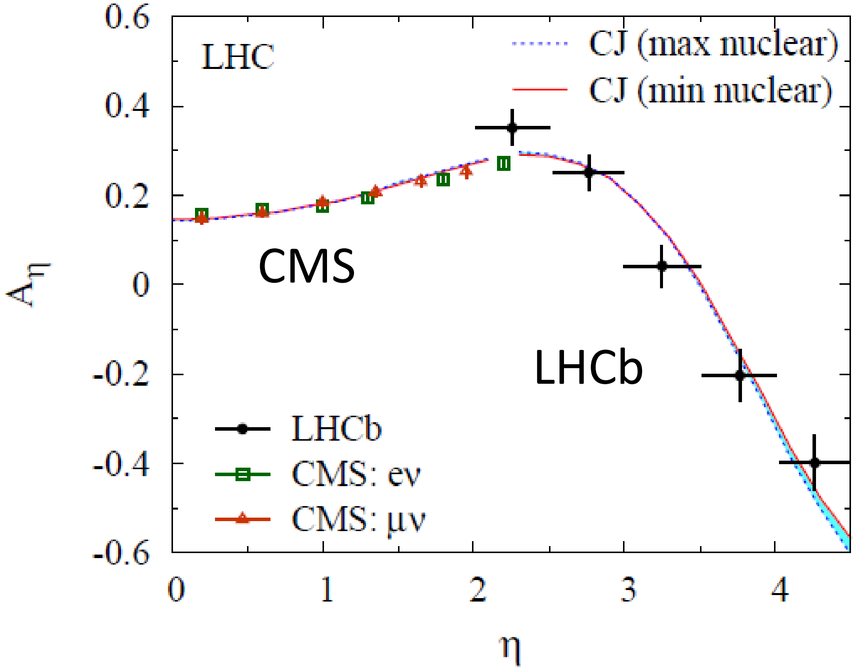
Directly reconstructed W:

- highest sensitivity to large *x*



From decay lepton W → l+ν:

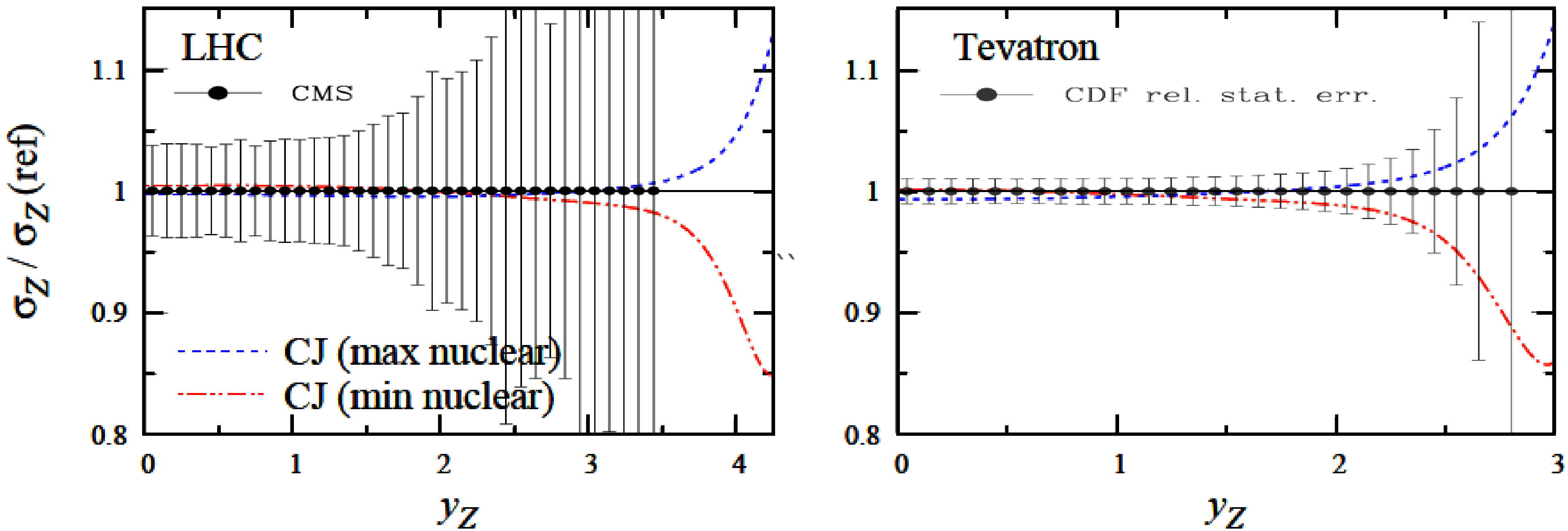
- smearing in *x*



- **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**
  - 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

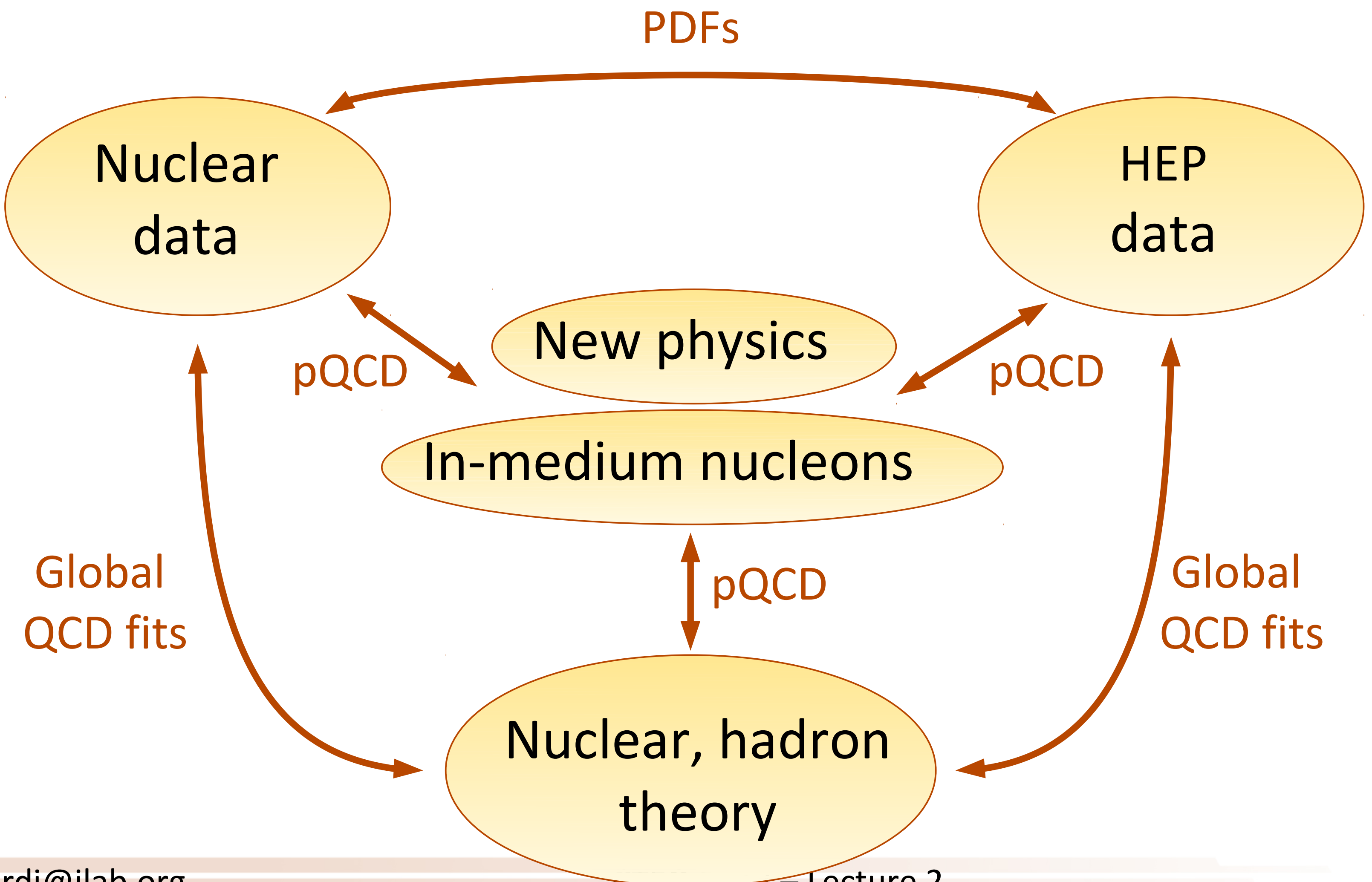
- **Z reconstruction much easier**
  - Similar motivations, kinematics
  - Energy systematics: 500 → 1960 → 7000

Final thoughts

- **Data -** extended kinematic range, precision needed
  - LHC, JLab12, E906/J-PARC, RHIC, EIC/LHeC
- **Large-*x*:** use nuclei to find new particles; use protons to study nuclear physics
- **Experimental PDF uncertainties**
  - use MC error representation, compare to Hessian + tolerance
- **Theoretical uncertainties** will be crucial
  - Need to be estimated, provided to users – not explored enough so far
- **Parametrization biases**
  - Use extended parametrizations; how to determine an optimal fit?
- **Perturbative order**
  - NNLO to be calculated for all relevant processes – where to stop?
  - Do we want/need PDFs with resummation?
- **Heavy quarks s**chemes to be extended beyond DIS
  - Intrinsic charm (hadron structure, new Higgs channels at large *y*)
- **Electroweak corrections** to PDFs as large as NNLO – need to include

Lecture 2 - recap

- **Global PDF fits as a tool for particle physics**
  - integrate across hadronic physics from JLab to the LHC
  - connect with rest of subatomic physics



Appendices

A1
Impact of a new accelerator

Impact of a new accelerator - the EIC

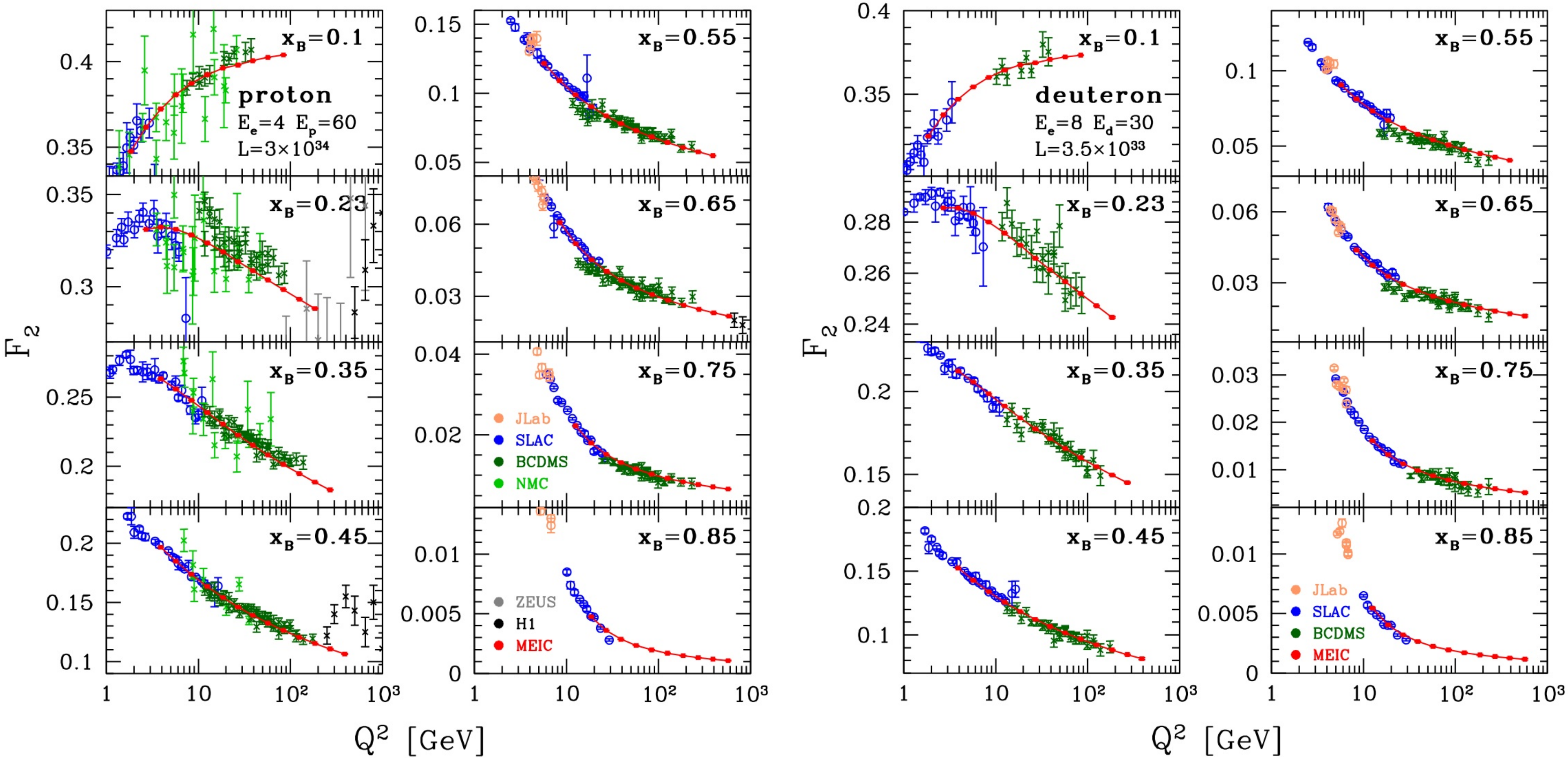
- **Questions**
  - What are the requirements in terms of energy, luminosity?
  - What physics do we expect to learn?
  - "Is it worthwhile building that accelerator?"

- **For example:**
  - Is a DIS cross section measurement at the EIC going to improve the PDF measurements?

- **This we can answer with a global fit:**
  - Generate pseudo-data
  - Include them in a global fit
  - Compare with old result

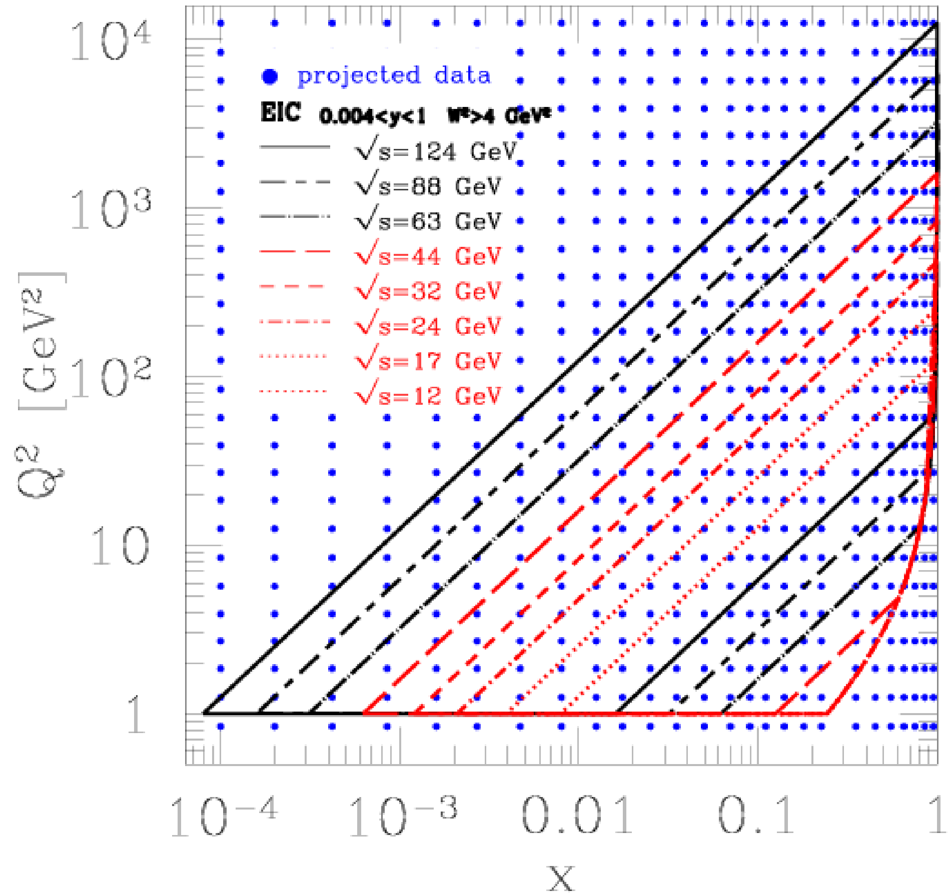
Impact of a new accelerator - the EIC

- **e+p collisions** – using CTEQ-JLab fits `[Accardi, Ent, Keppel]`
  - Pseudo data:



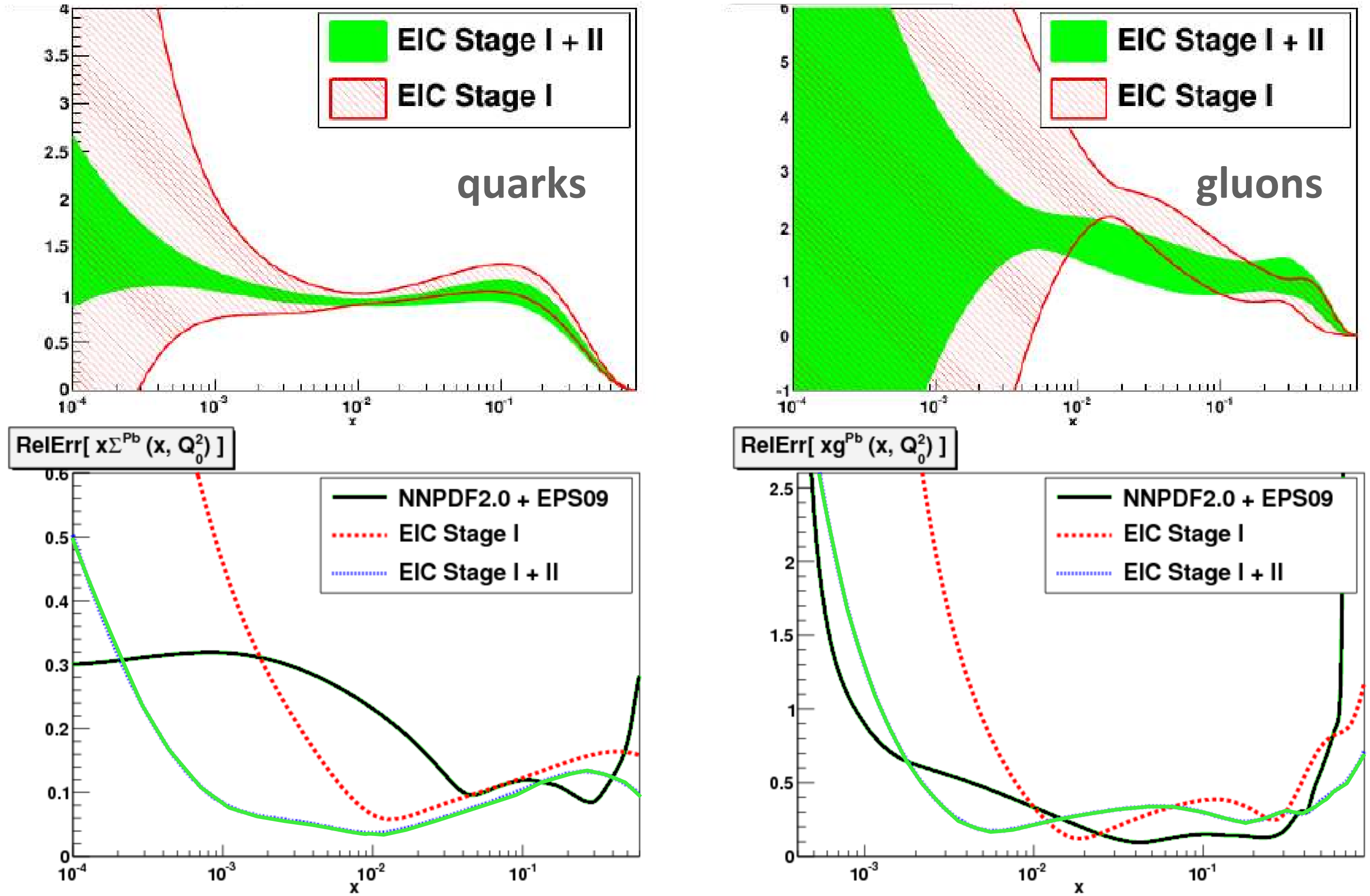
Impact of a new accelerator - the EIC

- **e+A collisions** – using NNPDF2.0 fits [Accardi, Guzey, Rojo]
  - 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 a new accelerator - the EIC

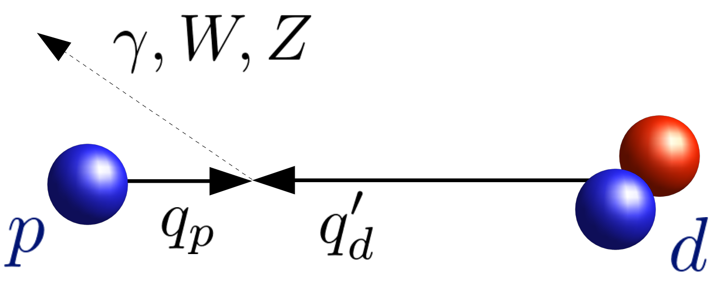
- **e+A collisions** – using NNPDF2.0 fits [Accardi, Guzey, Rojo]
  - With only 1 nucleus target, impact comparable to present day world data:



A2
Other large x observables

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

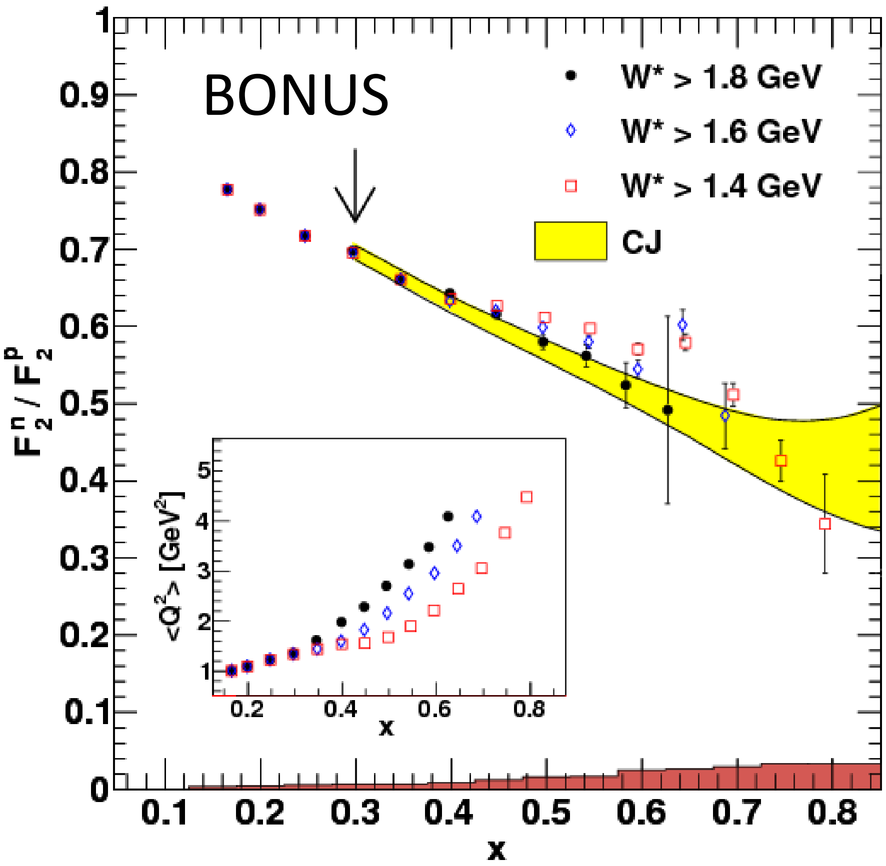
  – Measures $\bar{u}/\bar{d}$ at x = 0.06-0.45 (for -1 < y < 1)
  – Useful to compare p+p vs. p+n
  – Play W vs. Z production

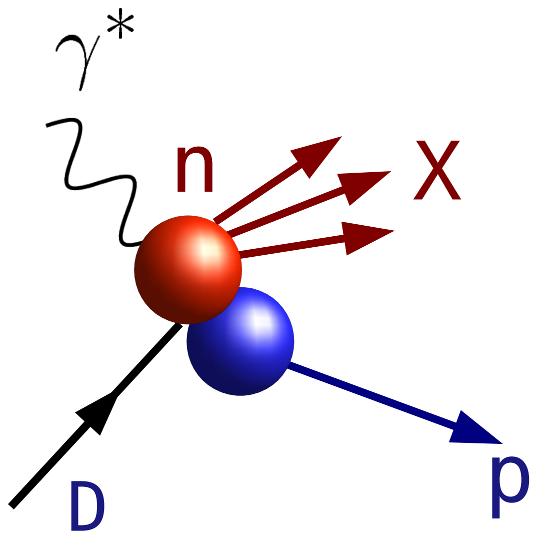
- **Forward physics**

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

Spectator tagging at Jlab: quasi-free neutrons

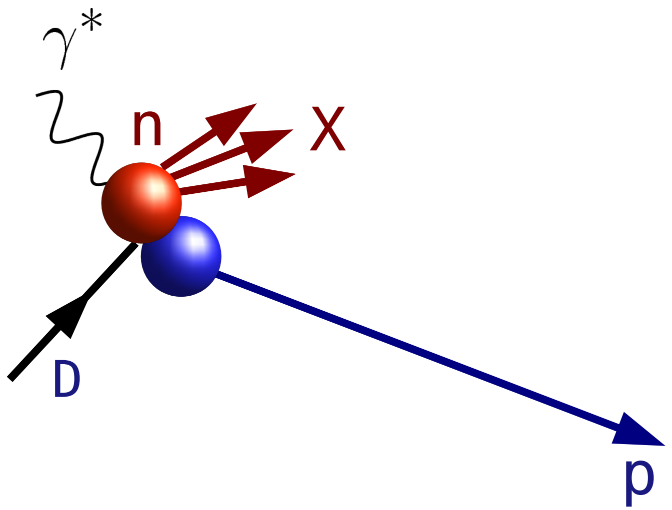
N.Baillie et al., PRL 108 (2012) 199902

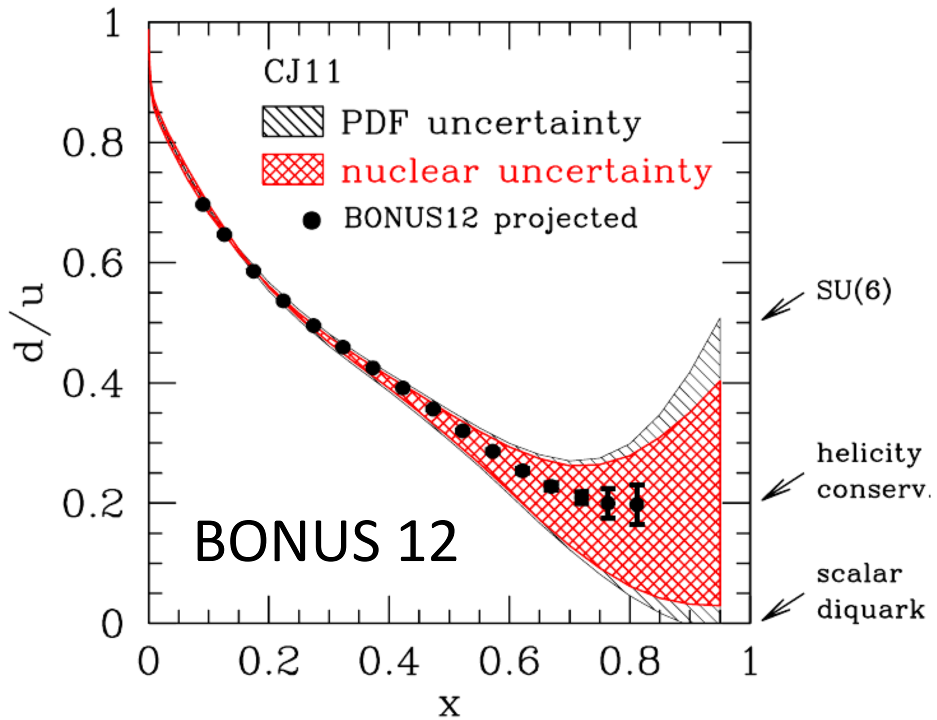


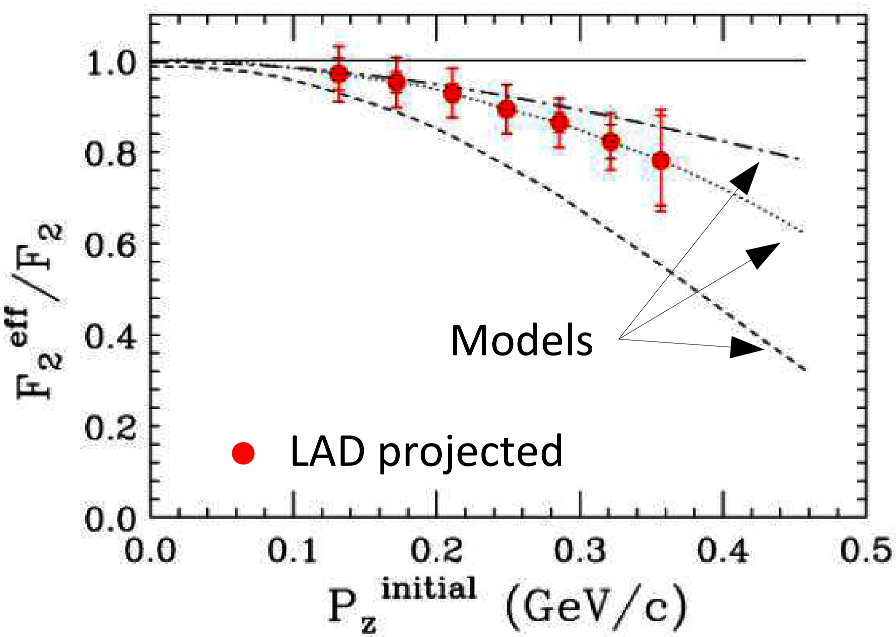


Spectator tagging at JLab12

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

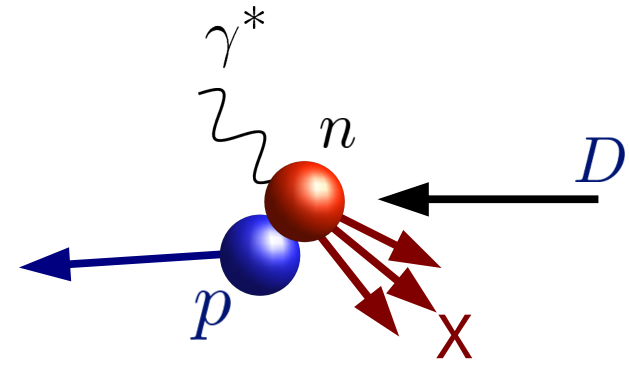




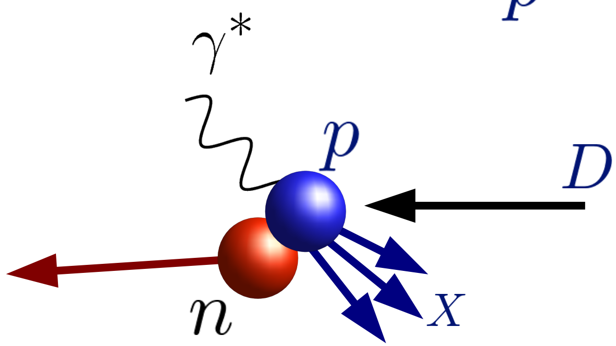


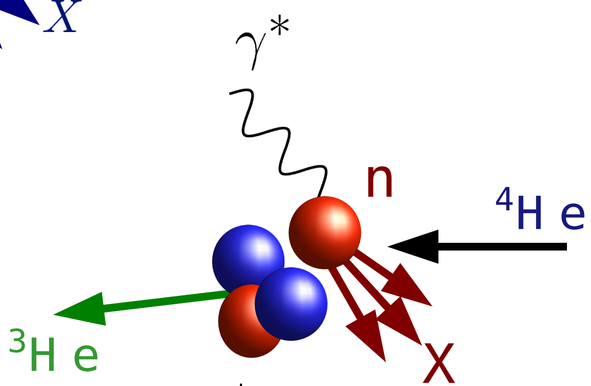
Spectator tagging at EIC: even better!

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

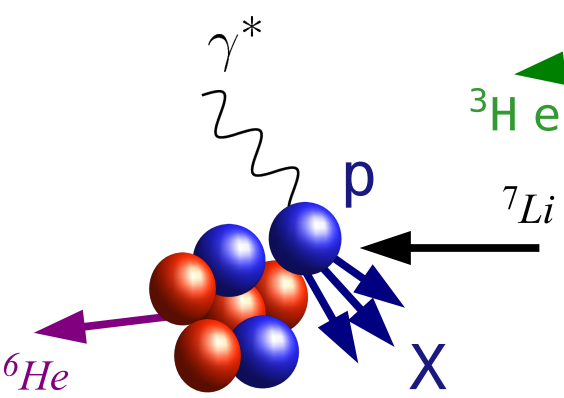


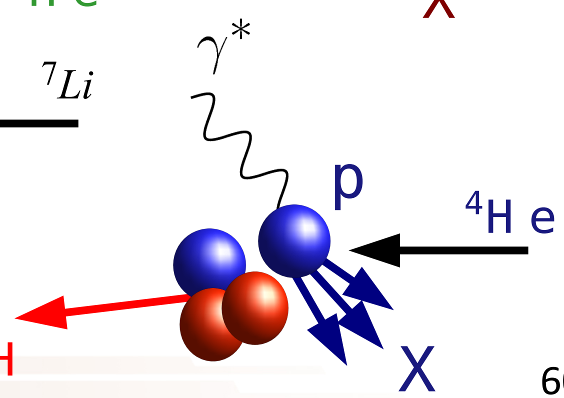
- measure **proton F_2** in D target
  - **Unique at colliders**
  - Compare off-shell to free proton





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

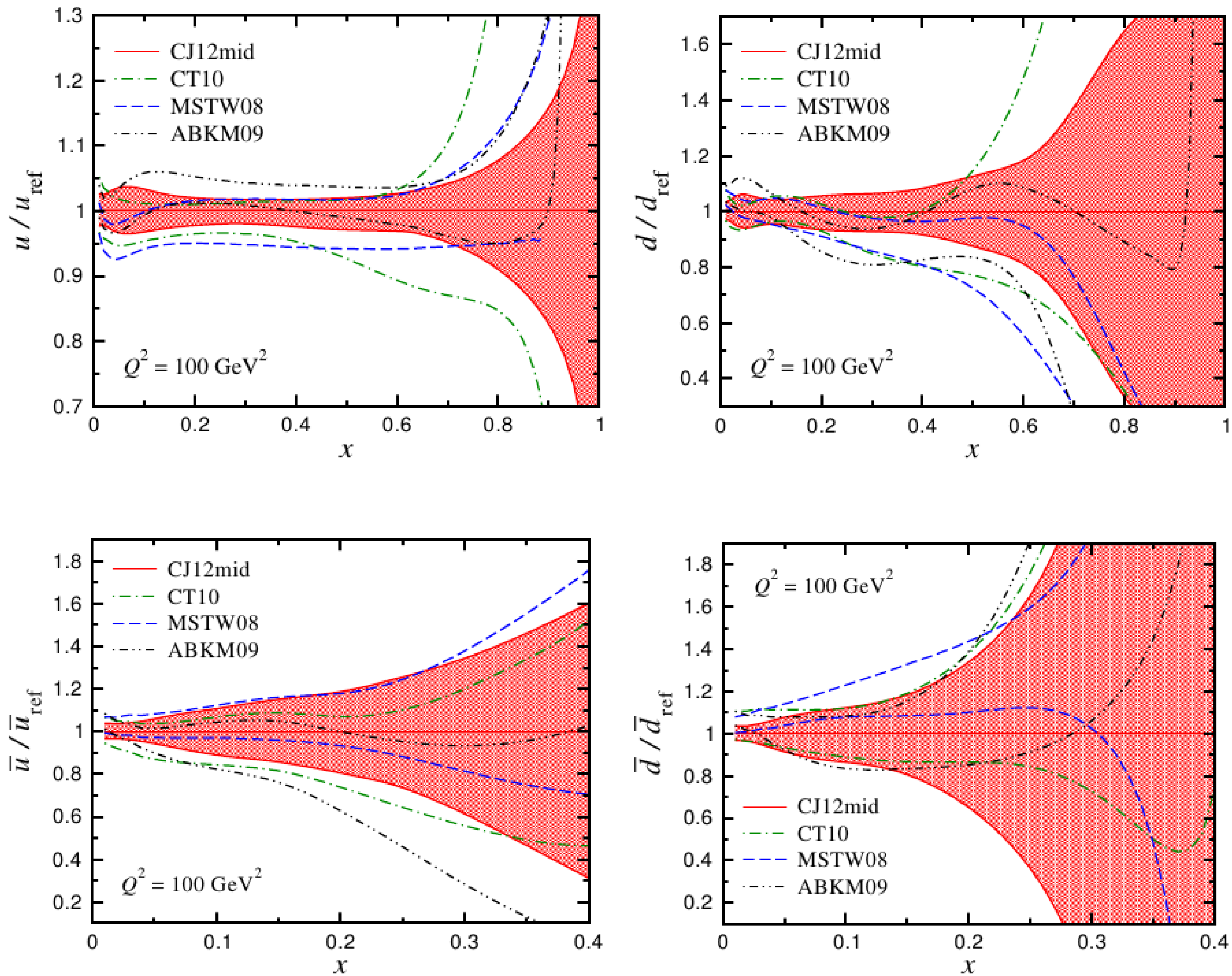




A3
CJ12 vs. others

CJ12 *vs.* others

Owens, Accardi, Melnitchouk, arXiv:1212.1702



CJ12 *vs.* others

Owens, Accardi, Melnitchouk, arXiv:1212.1702