Impact of Nuclear Corrections on Global Fits for Parton Distribution Functions

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Loopfest XII

Tallahassee, Florida
May 15, 2013

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Introduction

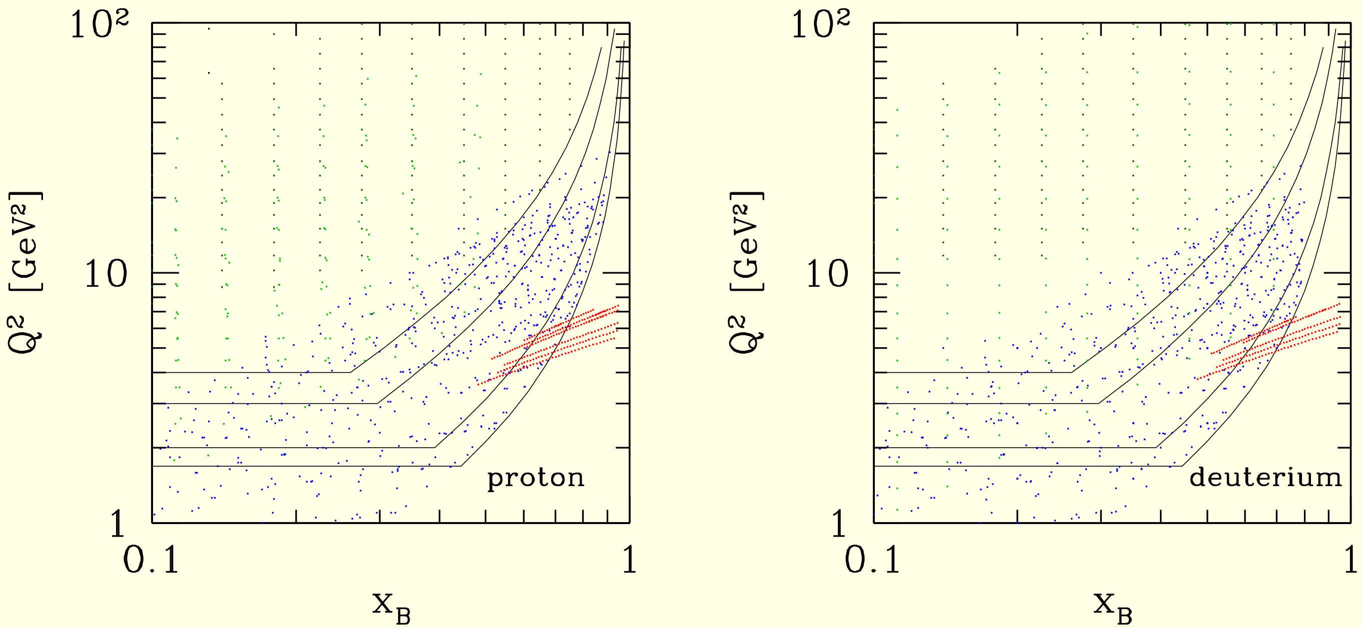
CTEQ/Jefferson Lab (CJ) Collaboration - Alberto Accardi, Eric Christy, Cynthia Keppel, Simona Malace, Wally Melnitchouk, Peter Monaghan, Jorge Morfín, JFO, and Lingyan Zhu

Goals:

- Overall goal - Quantify the uncertainty due to nuclear corrections needed when deuteron targets are used
- Extend PDF fits to larger values of x and lower values of Q
- Wealth of data from older SLAC experiments and newer JLAB experiments
- Improve the precision of the d PDF

Motivation

- Traditional global fits focus on leading twist PDFs convoluted with hard scattering partonic cross sections
- For DIS require cuts on Q and W to avoid regions with contributions from higher twist terms and target mass corrections
- $W^2 = m^2 + Q^2(\frac{1}{x} - 1)$ limits $x \leq \frac{Q^2}{W_{min}^2 - m^2 + Q^2}$
- Need large Q^2 in order to get near $x \approx 1$ with $W \geq W_{min}$
- Lower energy fixed target experiments - run out of Q
- Higher energy experiments - run out of statistics
- Typically use $Q^2 > 4$ GeV and $W^2 \gtrsim 12$ GeV
- When applied to existing DIS data sets this results in $x \lesssim .7$
- Some experiments, *e.g.*, neutrino oscillation searches, need PDFs at lower Q^2 and W^2



- Red = JLAB, Blue = SLAC, Green = BCDMS and NMC
- Four boundaries correspond to four sets of (Q^2, W^2) cuts: (4, 12.25), (3, 8), (2, 4), and (1.69, 3) GeV^2
- Top boundary is the one used in previous fits
- Lower boundary is the one currently used

Why go to larger x and smaller Q values?

- Existing PDFs are largely unconstrained, parametrization-dependent extrapolations beyond $x \approx 0.7$
- Large-x region is important for studies of massive particle production at forward rapidity values since

$$x_{1,2} = \frac{M}{\sqrt{s}} \exp(\pm y)$$

- Having PDFs at lower Q values is potentially important for neutrino oscillation experiments
- Intrinsic interest in the behavior of d/u as $x \to 1$ in order to probe the structure of the proton

Considerations when including large-x data

- Target mass corrections
- Higher twist contributions
- Nuclear corrections

Each is potentially important when going to large values of x

Target Mass Corrections

Have implemented both the standard Georgi-Politzer and Collinear Factorization formalisms in the fitting program

Higher Twist Parametrization

Parametrize the higher twist contribution by a multiplicative factor

$$F_2(data) = F_2(TMC)(1 + C(x)/Q^2)$$

where

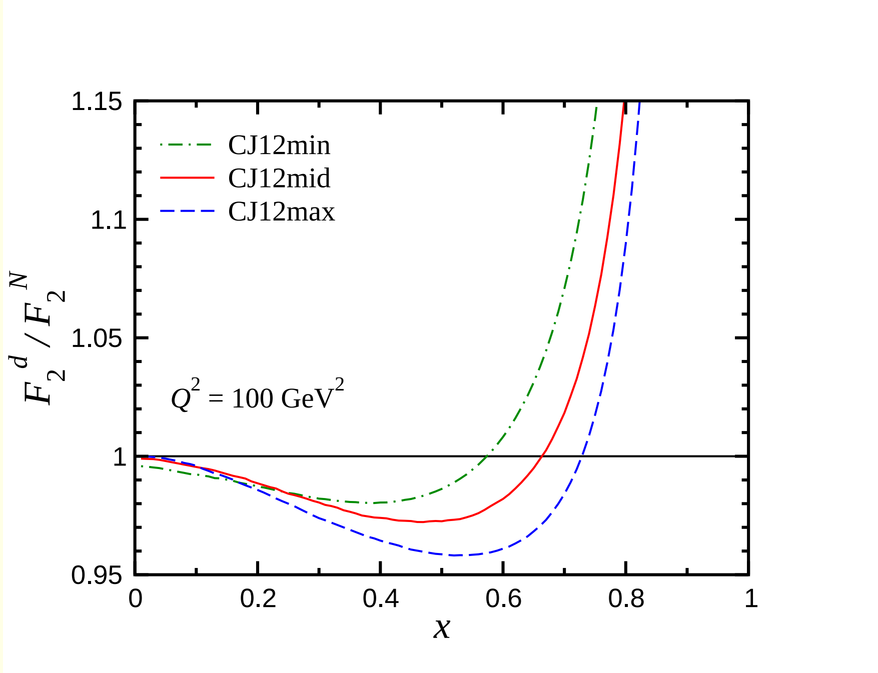
$$C(x) = a\,x^b(1 + c\,x)$$

Comments:

- Parametrization is sufficiently flexible to give a good fit to the data
- Resulting twist-2 PDFs are stable regarding the choice of the target mass correction formalism - the parametrized higher twist term compensates

Nuclear Corrections

- Fermi motion smearing done using the Weak Binding Approximation (WBA)
- Various choices of wavefunctions explored
- Range of offshell corrections included using a model by Kulagin and Petti, but with a range of parameter values (Wally Melnitchouk)
- Choose three sets of nuclear models corresponding different strengths of the off-shell corrections: min, mid, and max corrections



- Easy way to think about the effects of the nuclear corrections on the PDFs
- The deuterium data are divided by this ratio, yielding effectively the sum of neutron and proton data
- When the ratio is less than one the data are enhanced and the d PDF will increase
- Conversely, the d PDF will be reduced when the ratio is greater than one
- At large values of x CJ12min (CJ12max) will have the smallest (largest) d PDF

Information on the d PDF

DIS

- $F_2^p(x,Q^2) \sim 4u + d$
- $F_2^d(x,Q^2) \sim 5(u+d)$, but requires nuclear corrections

Lepton Pair Production

- $x_1 x_2 = \frac{M^2}{s}$ and $x_F = x_1 - x_2$
- Can get to large x_1 if high-x_F data are available
- E-866 reaches to $x_F \approx .8$
- $\sigma_{pp} \sim \overline{u}(x_2)[4u(x_1) + d(x_1)\overline{d}(x_2)/\overline{u}(x_2)]$
- $\sigma_{pn} \sim \overline{d}(x_2)[4u(x_1) + d(x_1)\overline{u}(x_2)/\overline{d}(x_2)]$
- At large $x_F, x_1 \gg x_2$
- To the extent that $\overline{u}(x_2) \simeq \overline{d}(x_2)$, which is roughly satisfied for small x_2, one is still sensitive to $4u + d$

W asymmetry

- $x_{1,2} = \frac{M_W}{\sqrt{s}} e^{\pm y}$
- W asymmetry directly sensitive to large x d/u at large y
- Effect is reduced if decay lepton asymmetry is used
- Newer data reach to $x \approx .8$, but the last bin is wide and the central value corresponds to $x \approx .57$

Vector boson production

- W and Z production are sensitive to different linear combinations of PDFs than for Drell-Yan pairs
- Potential constraints from data at high values of rapidity

Jet Data

- All parton pairs contribute, weighted by their respective subprocess cross sections
- Leads to an anticorrelation between the d PDF and the u and g PDFs

Neutrino Data

- Sensitive to different linear combinations of PDFs than charged lepton DIS, thereby giving flavor differentiation
- Dimuon data allow for the study of $s - \bar{s}$
- But, neutrino data require the use of nuclear corrections for heavy targets
- Have not included neutrino data since we only want to study the effects of deuterium corrections at this time
- Lacking constraints on $s, \bar{s}$ provided by neutrino dimuon data

Fitting Package

We are using my NLO DGLAP fitting package which I have continued to update and extend

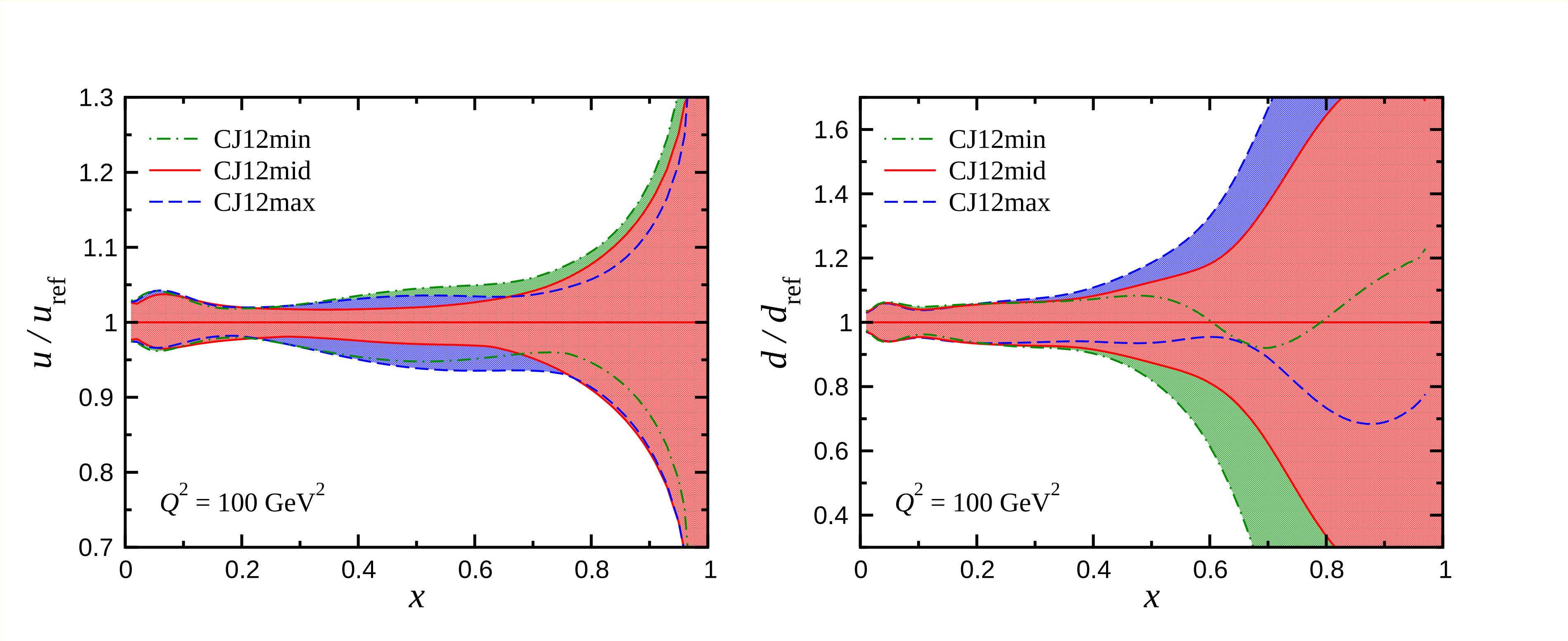
- Can fit DIS, Drell-Yan, W lepton asymmetry, W charge asymmetry, Z rapidity distribution, jets, and γ + jet
- Added PDF errors (Hessian method)
- Multiple TMC and HT terms added (Alberto Accardi)
- Correlated errors used when available
- Options for nuclear corrections added (Wally Melnitchouk, Alberto Accardi)

Data Sets

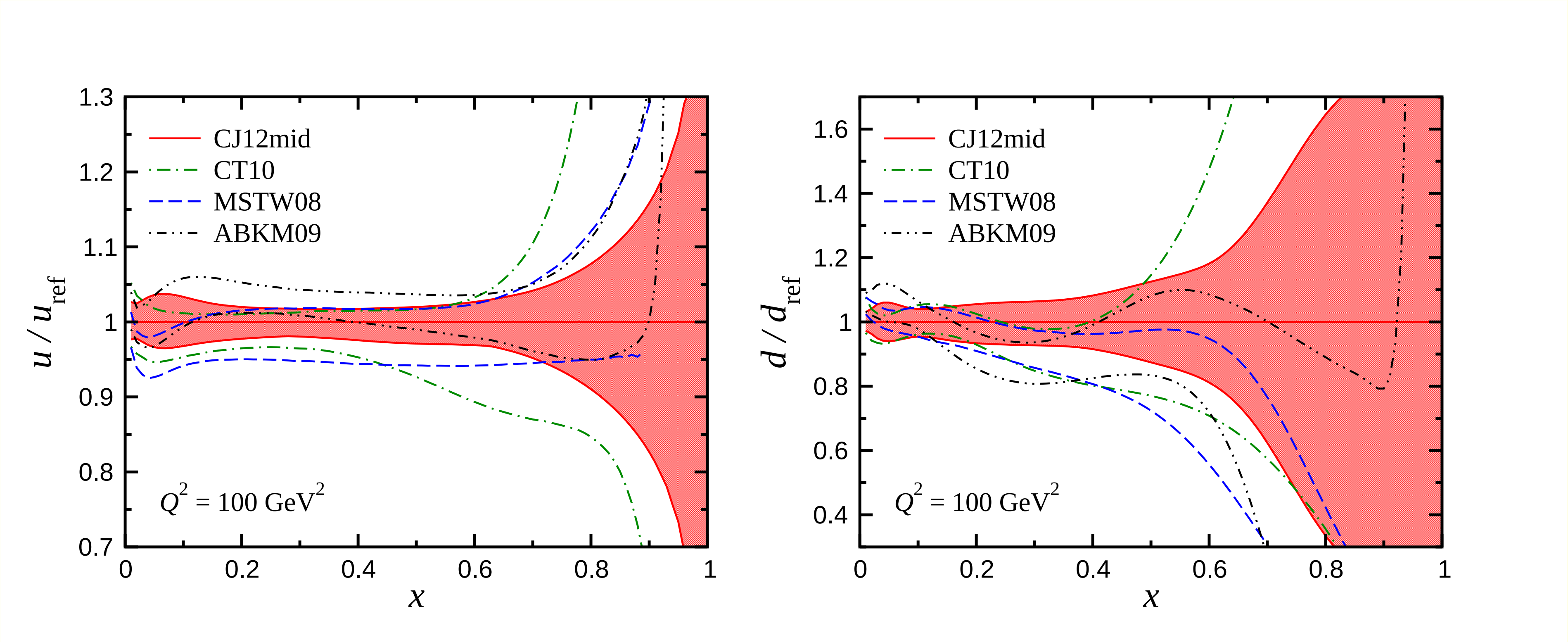
- BCDMS, SLAC, NMC, combined HERA (H1 and Zeus), and JLAB DIS data
- E-605 and E-866 lepton pair data
- CDF and D0 jet data
- W asymmetry and W-lepton asymmetry data
- Z rapidity distribution data
- DØ γ + jet data

Results

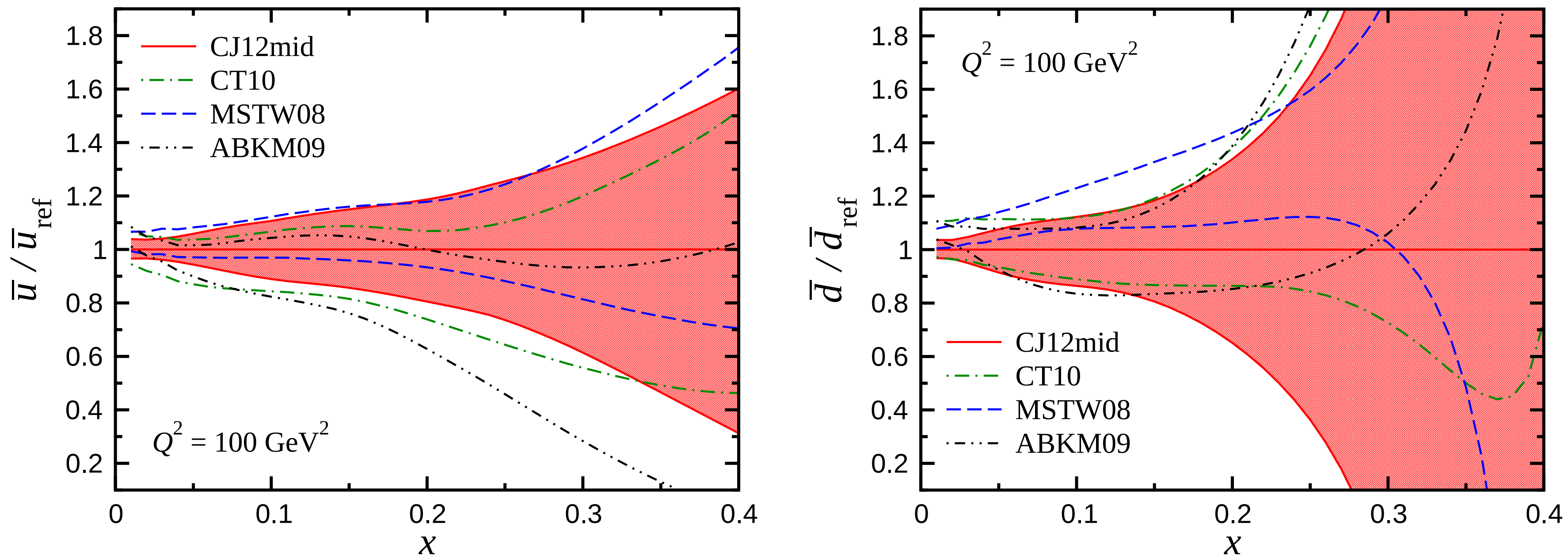
- Have produced three sets of PDFs with error sets: CJ12min, mid, and max corresponding to the three nuclear models discussed previously
- The different nuclear corrections have the largest effect on the d PDF
- Basically, the d PDF shifts to accommodate whatever nuclear model is used and the other PDFs adjust to compensate for the shift



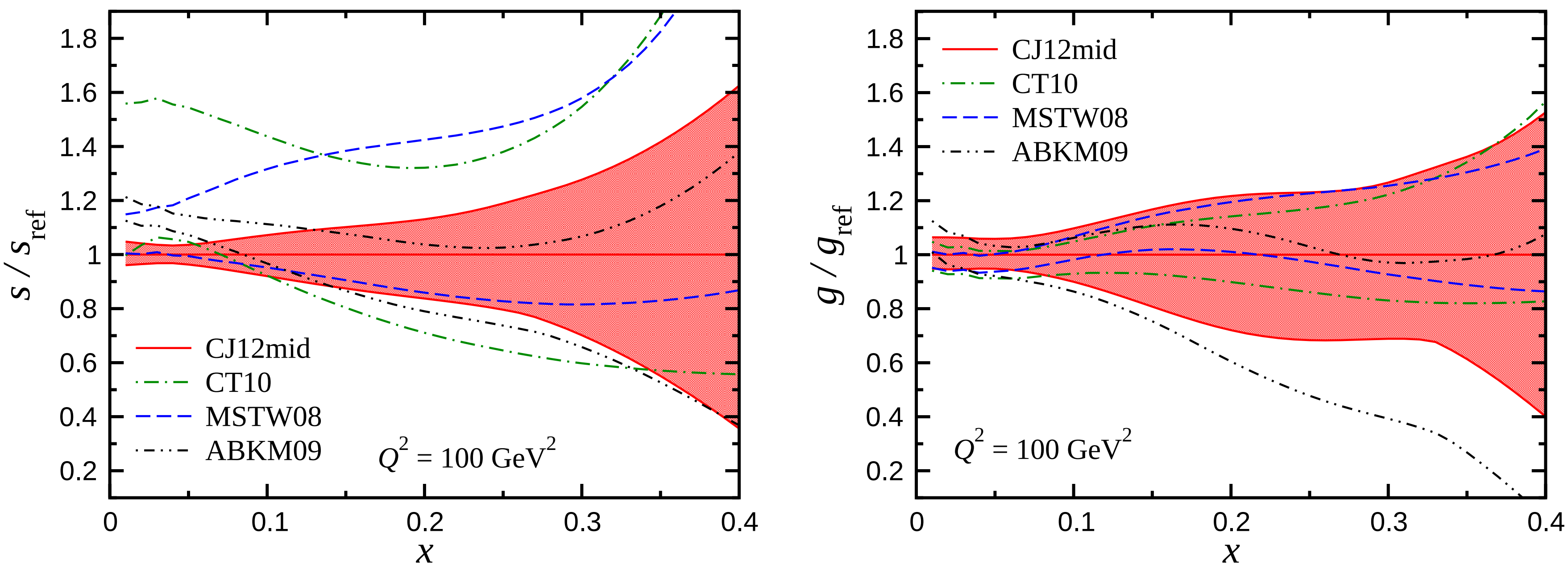
- CJ12min (max) has a smaller (larger) d PDF than CJ12 mid
- Less effect on the u PDF



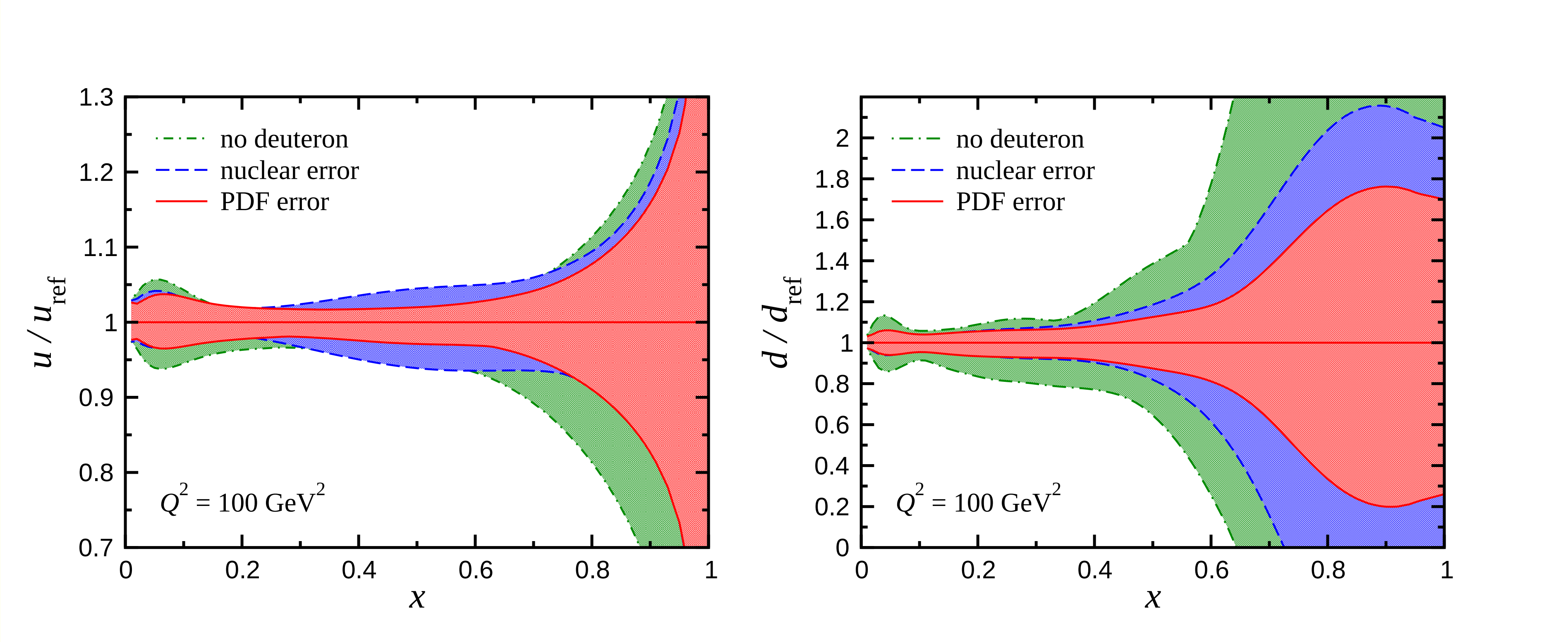
- Can see the effect of the additional DIS data by the decrease in the uncertainty bands for the u and d PDFs in the large-x region



- Results for the $\bar{u}$ and $\bar{d}$ PDFs are similar to other sets

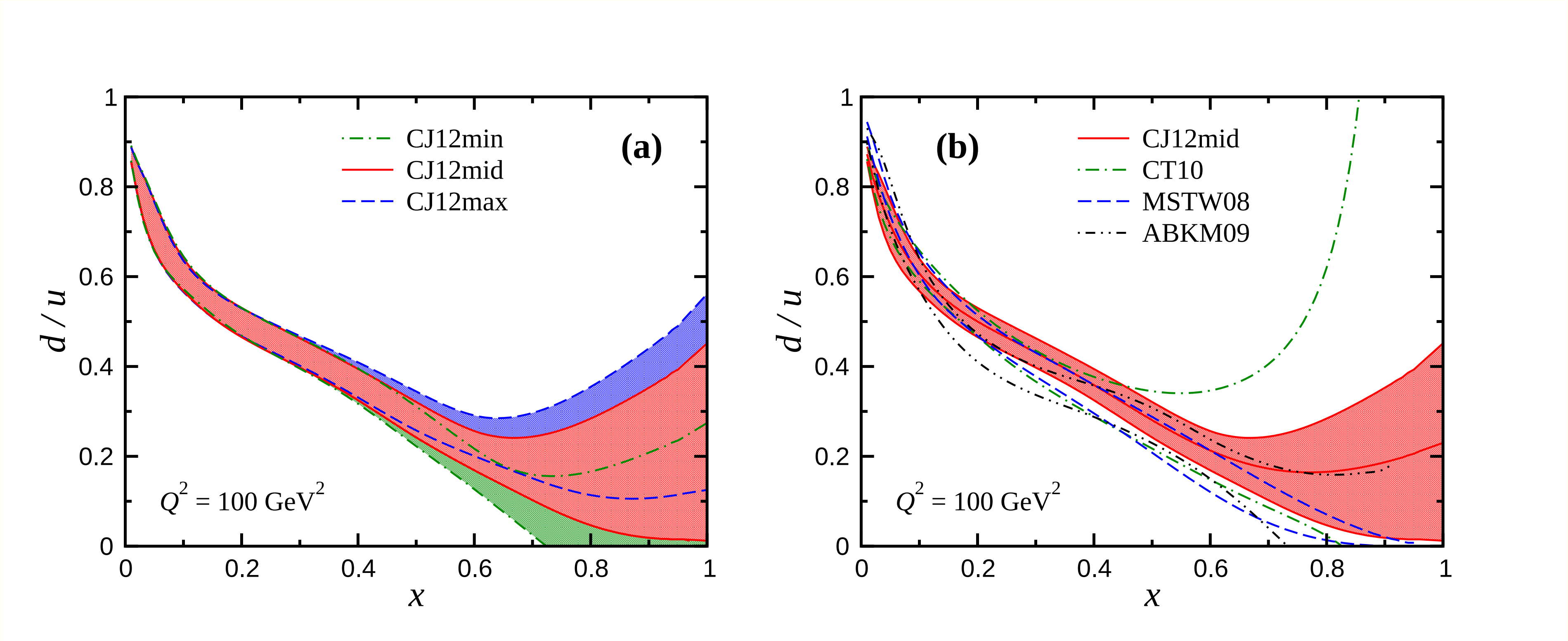


- Errors on the s PDF are small since $\kappa \equiv \frac{s+\bar{s}}{\bar{u}+\bar{d}}$ was fixed
- Results for the gluon are similar to other sets

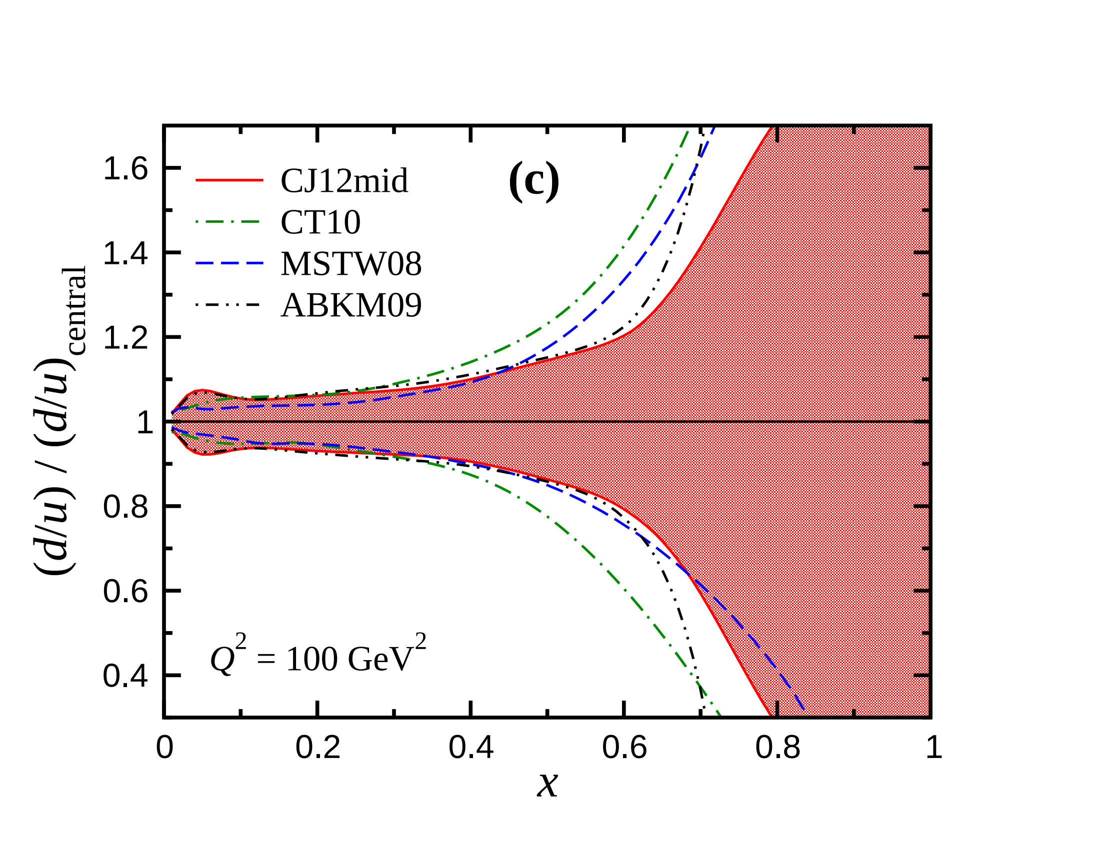


- u and d uncertainties showing standard PDF errors, nuclear uncertainties, and the effect of using no deuterium target data (note different scales on the two plots)
- Even with nuclear uncertainties, one is better off using the deuterium data

- Interesting to examine the d/u ratios
- Shows the effects of the nuclear models
- Our d parametrization
  - Use a modified parametrization where $d \rightarrow d + c_u \, u x^{b_u}$ so that $d/u \rightarrow c_u$ in the limit that $x = 1$
  - Standard parametrizations where d and u behave as $(1 - x)$ raised to individual powers give $d/u \rightarrow 0$ or ∞ as $x \rightarrow 1$.

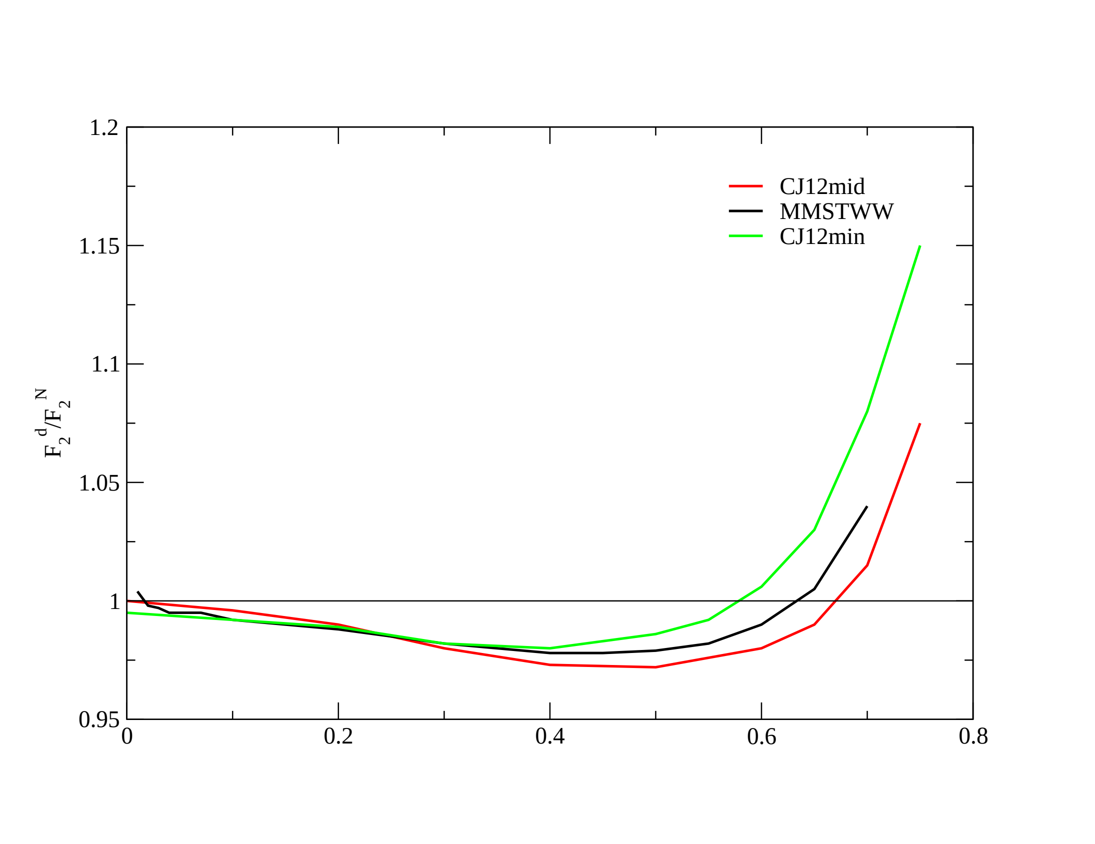


- With a conventional parametrization the error bands get very small as $x \to 1$ if $d/u \to 0$
- Conversely, the bands get large if the ratio goes to ∞ as $x \to 1$



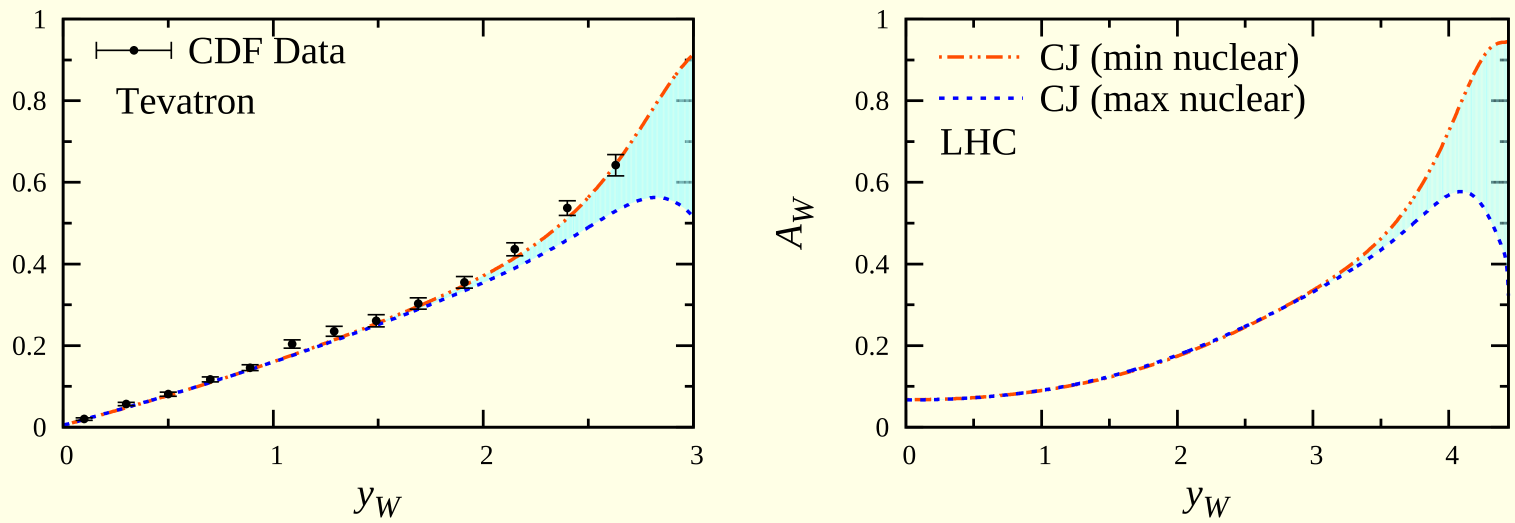
- However, the *relative* errors are comparable for each of the sets shown
- So, if you are interested in the behavior of d/u then a flexible parametrization should be used that allows d/u to go to a finite constant as $x \to 1$

Another Approach to Nuclear Corrections



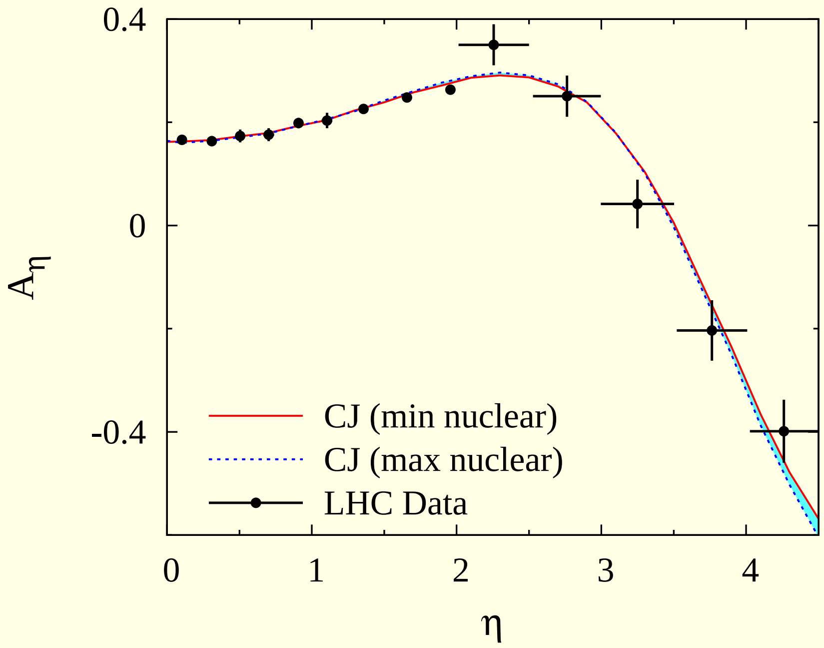
- Martin, Mathijssen, Stirling, Thorne, Watt, and Watt in arXiv: 1212.1215 parametrize the nuclear correction factor $\frac{F_2^d}{F_2^N}$
- Their result lies between those used in CJ12min and CJ12mid
- However, their ratio is Q^2 independent (ours are at $Q^2 = 100\text{GeV}^2$)

Selected Collider Results



- Figures by L. Brady from a paper showing the variations in vector boson production predictions at collider energies (L. Brady, A. Accardi, W. Melnitchouk, and JFO, arXiv:1110.5398[hep-ph])
- Variations in the nuclear corrections for deuterium cause the fitted d PDF to change, especially at large values of x
- This causes variations in the W asymmetry at large values of rapidity

W-Lepton Asymmetry at the LHC



- Plot made by L. Brady using MCFM with CJ PDFs
- Good agreement observed with CMS and LHCb data
- Nuclear variations not as pronounced since the V-A nature of the W decay reduces the reach in x for a given value of rapidity
- Nice cross check on the CJ PDFs

Summary and Conclusions

- Nuclear corrections - Fermi smearing and offshell corrections - have significant effects on the behavior of d PDF when it is constrained by deuterium DIS data
- Three PDF sets - CJ12min, mid, and max - have been made available
- These sets can be used to assess nuclear uncertainties on observables
- To further constrain the d PDF we need data which are sensitive to the d PDF while not being sensitive to nuclear corrections. This includes experiments such as MARATHON (DIS with H^3 He^3 mirror nuclei), BONUS (DIS on deuterium with a tagged spectator proton), and PVDIS (parity violating measurements with a deuterium target).
- Information on the d PDF obtained via methods which do not rely on nuclear corrections will then place constraints on nuclear correction models