Impact of low-energy data on global fits for PDFs

J.F. Owens

Physics Department, Florida State University

2011 Fall Meeting of the
APS Division of Nuclear Physics

Michigan State University, East Lansing, Michigan

October 26-29, 2011

Outline

- Introduction
  - Collaborators
  - Analysis Goals
- Motivation - why consider large-x, lower-Q^2 data?
- Procedures
  - Global fits
  - Target mass corrections
  - Higher twist contributions
  - Nuclear corrections
- Current results
- Next steps
- Conclusion and Outlook

Introduction

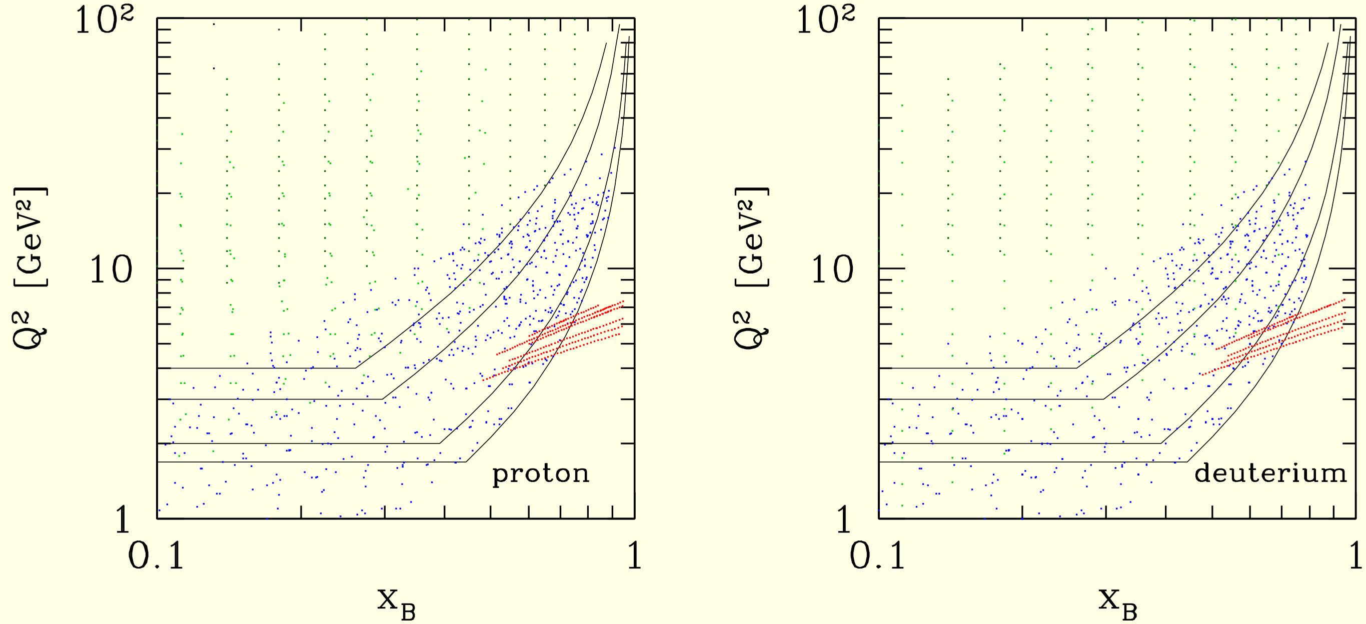
CTEQ/Jefferson Lab (CJ) Collaboration - Alberto Accardi, Eric Christy, Cynthia Keppel, Simona Malace, Wally Melnitchouk, Peter Monaghan, Jorge Morfín, JFO, and Lingyan Zhu

Goals:

- Overall goal - Improve the precision of the d PDF
- Extend PDF fits to larger values of x and lower values of Q
- Wealth of data from older SLAC experiments and newer JLAB experiments
- Study effects of different target mass correction methods
- Explore role of higher twist contributions
- Quantify the uncertainty due to nuclear corrections for deuteron targets
- Study the parametrization dependence of the results

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 $x \leq \frac{Q^2}{W^2_{min} - m^2 + Q^2}$
- 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 $Q > 2$ GeV and $W > 3.5$ GeV
- When applied to existing DIS data sets this results in $x \lesssim .7$



- 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

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

- Intrinsic interest in the behavior of d/u as $x \to 1$ in order to probe the structure of the proton

Question - how does one constrain PDFs in regions which are excluded by kinematic cuts?

- Use momentum sum rule and quantum number sum rules for PDFs
- Rely on evolution equations - high x, low Q feeds lower x, higher Q
- Both provide indirect constraints on the PDFs as one integrates over a larger region than is covered by data

But, one would also like a direct comparison - requires a lowering of the cuts on W and Q.

- Target mass corrections and higher twist contributions will become important
- Fermi motion smearing for deuterium targets becomes important at high x

DIS Target Mass Corrections

Several different methods available

- Standard Georgi-Politzer method
- Collinear Factorization
  - Jianwei Qiu and Alberto Accardi - arXiv:0805.1496 [hep-ph], JHEP 0807:090, 2008.
  - See also Jianwei's talk at the 2005 JLAB meeting/workshop on the CTEQ web page
- Naive TMC - to be defined below

Some comments on TMCs

- Nachtmann variable: $\xi = \frac{2x_B}{1+\sqrt{1+4x_B^2 m_N^2/Q^2}}$

  - In the standard GP formalism $\xi < 1$ when $x_B = 1$
  - Leads to non-zero structure functions at $x_B \geq 1$

- Collinear factorization gives structure functions as a convolution which respects the kinematic boundaries

$$F_{T,L}(x_B, Q^2, m_N^2) = \int_{\xi}^{\xi/x_B} \frac{dx}{x} h_{f|T,L}(\xi/x_B, Q^2)\phi_f(x, Q^2)$$

  where h_f is a parton-level helicity structure function and ϕ is the respective PDF

- Naive: $F_{T,L}(x_B, Q^2, m_n^2) = F_{T,L}(\xi, Q^2)$
- For a recent review of the phenomenology of these different TMCs, see L.T. Brady, A. Accardi, T.J. Hobbs, and W. Melnitchouk, arXiv:1108.4734, Phys. Rev. D84, 074008 (2011).

Higher Twist parametrization

Parametrize the higher twist contribution by a multiplicative factor

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

where

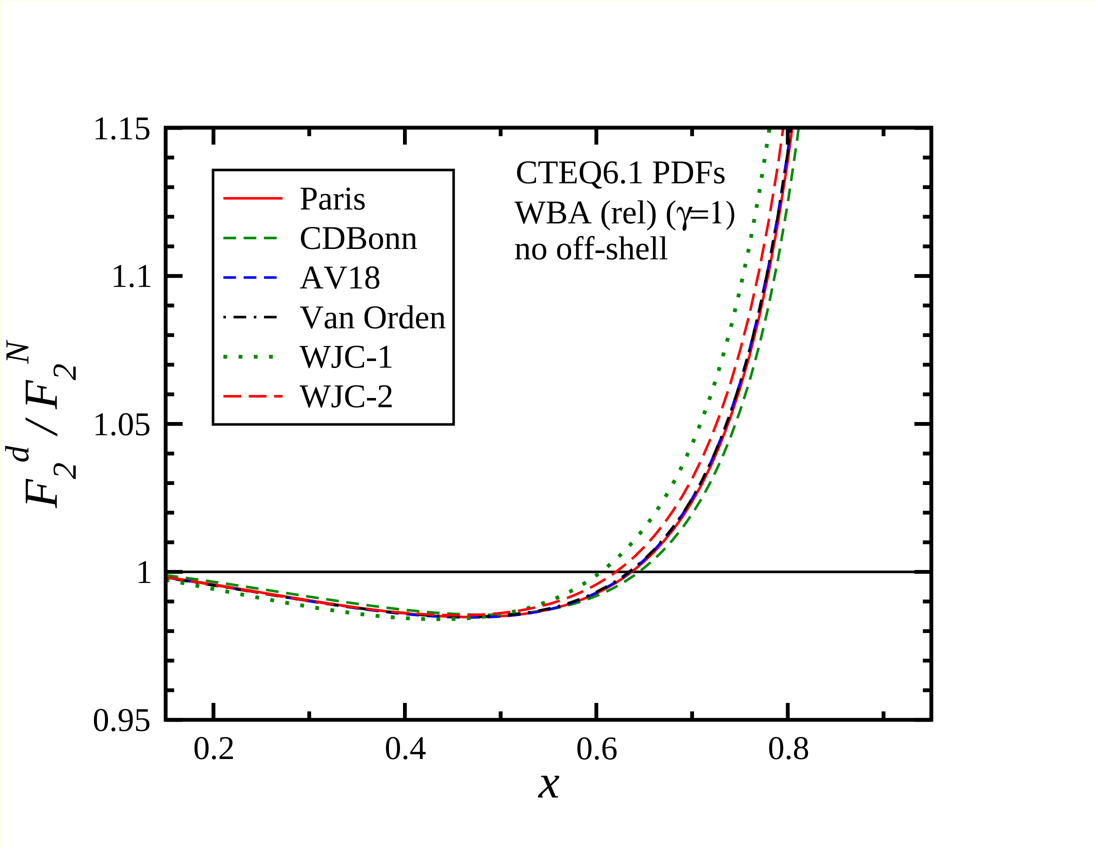
$$C(x) = a\,x^b(1 + c\,x + d\,x^2)$$

Comments:

- Parametrization is sufficiently flexible to give a good fit to the data
- Parameter d not really needed since for x near 1 there is not a lot of difference between x and x^2
- Differences in higher twist contributions for p or d can be included if/when required by data

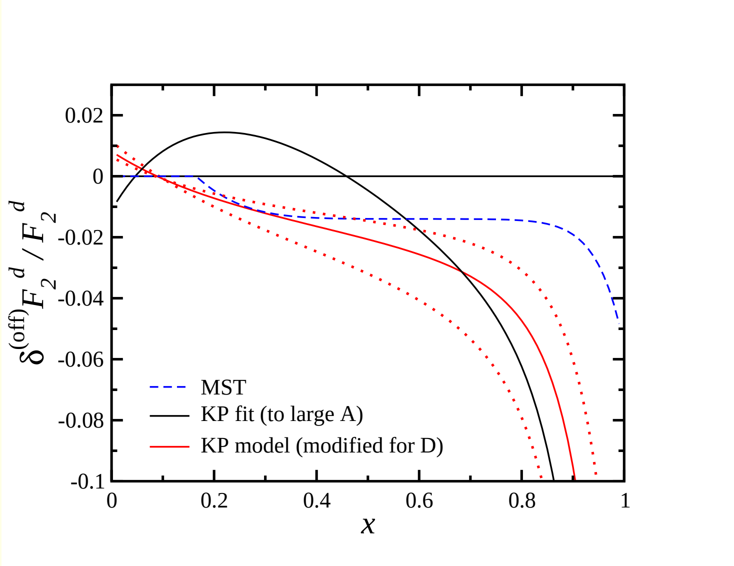
Nuclear Corrections

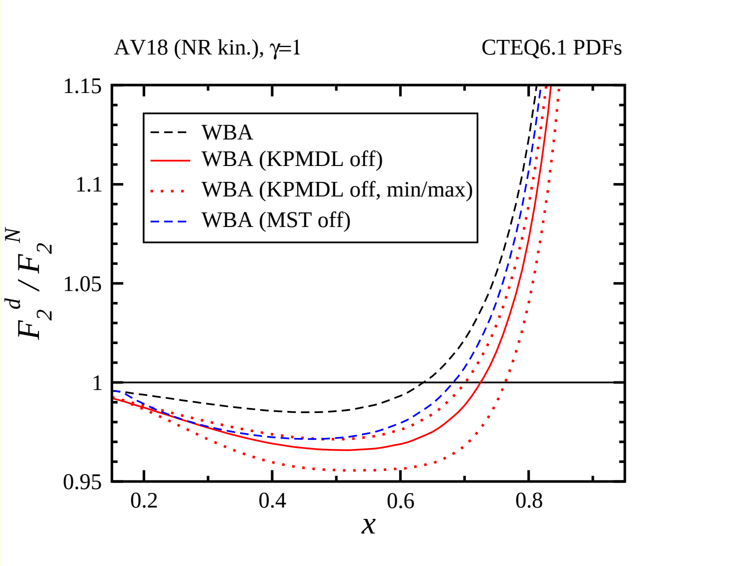
- Fermi motion smearing done using the Weak Binding Approximation (WBA)
- Various choices of wavefunctions explored



Offshell Corrections

- Start with a parametrization due to Kulagin and Petti which is fitted to data for a range of heavy nuclei
- Parameters were adjusted (Wally Melnitchouk) to provide a range of corrections representative of the average offshellness of nucleons in a deuteron





- 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

Previous analysis (Phys. Rev. **D81**:034016, 2010) showed the following

- Good fits could be obtained using the lower Q and W cuts on the DIS data
- Different target mass correction prescriptions gave equivalent fits as long as a simple parametrization of higher twist contributions was added
- Leading twist PDF was stable as the TMC prescription was varied

Residual questions:

- How do the results depend on the models used for the nuclear corrections for DIS data from deuterium targets (deuteron wavefunction, offshell corrections)?
- How do the results depend on the parametrization used for the 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 $x \approx .8$
- $\sigma_{pp} \sim \overline{u}(x_2)[4u(x_1) + d(x_1)\overline{d}(x_2)/\overline{u}(x_2)]$
- $\sigma_{pn} \sim \overline{d}(x_2)[4u(x_1) + d(x_1)\overline{u}(x_2)/\overline{d}(x_2)]$
- 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 $s - \overline{s}$
- 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

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, jets, and γ + jet
- W lepton asymmetry routine allows for a single p_T cut, but a generalization to allow for multiple p_T cuts has been developed
- Added PDF errors (Hessian method)
- Multiple TMC and HT terms added (Alberto Accardi)
- Some correlated errors added
- Options for nuclear corrections added (Wally Melnitchouk, Alberto Accardi)

Data Sets

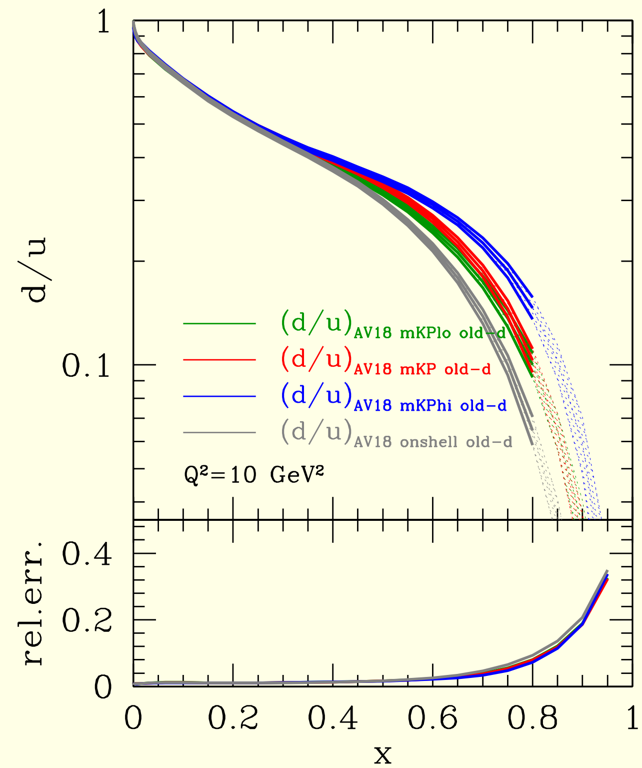
- BCDMS, SLAC, NMC, H1, Zeus, and JLAB DIS data
- E-605 and E-866 lepton pair data
- CDF and D0 jet data
- W asymmetry and W-lepton asymmetry data
- DØ γ + jet data
- Data sets similar to those used in CTEQ6.1 except CCFR removed, E-866 added, DØ γ + jet added, and some new W asymmetry data added

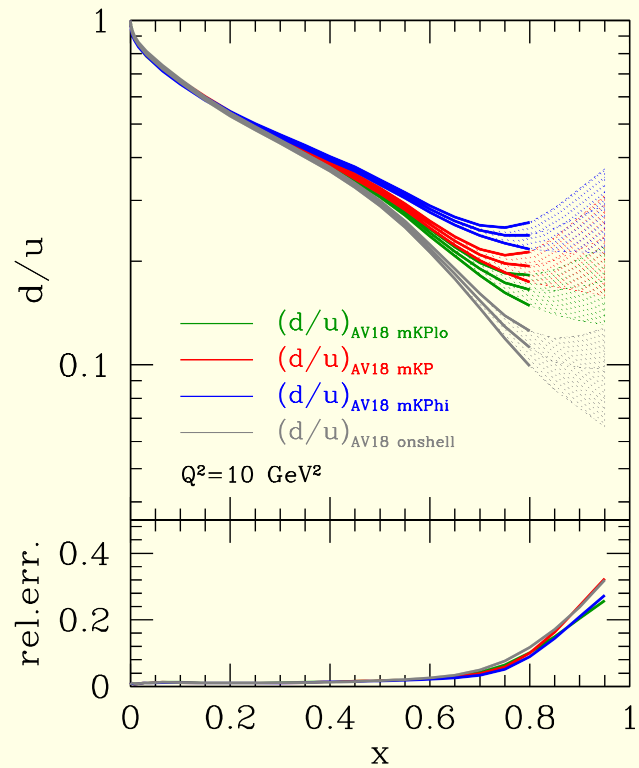
Results

- Summarize results by showing d/u ratios
  - The u PDF is already well constrained
  - 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

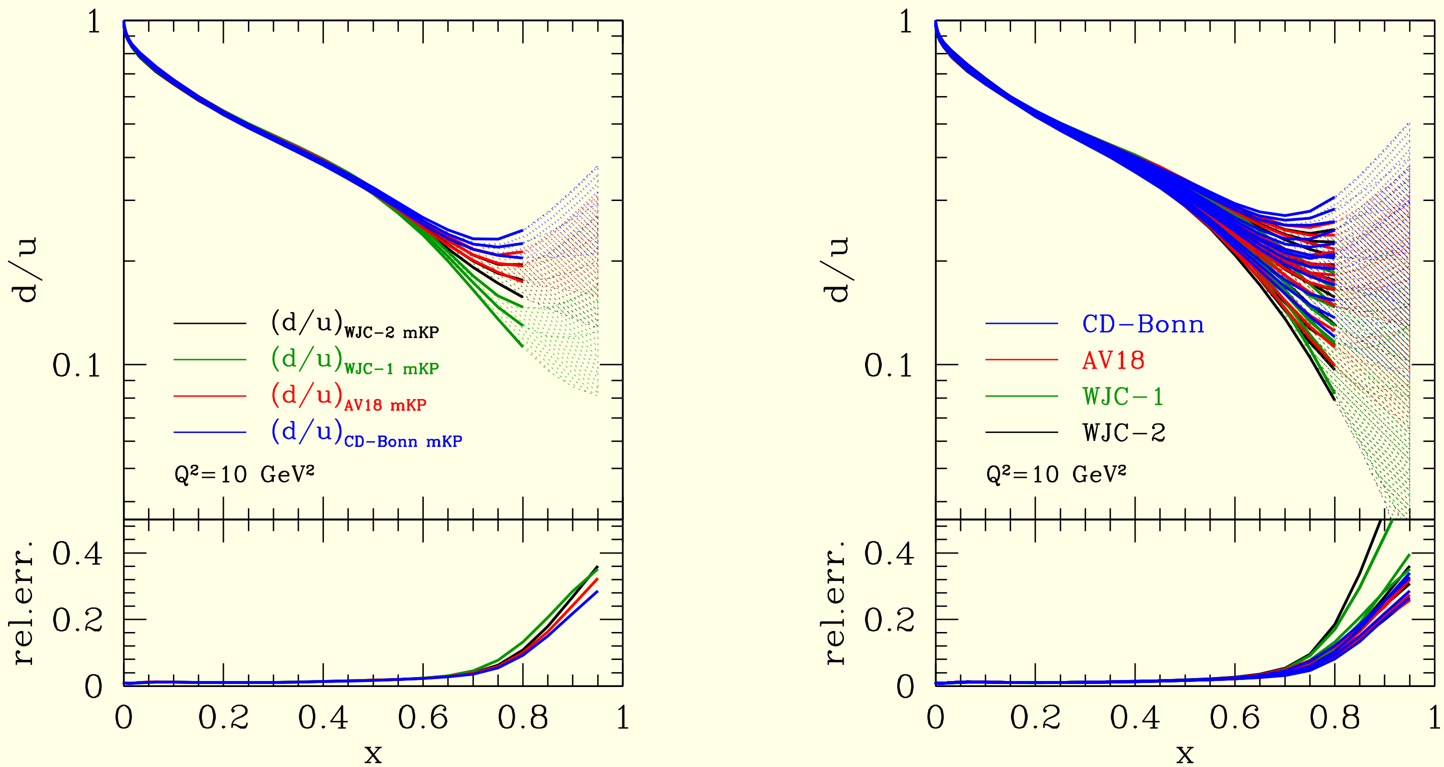
- Consider first a traditional parametrization where the d PDF vanishes as $x \to 1$
- Then, compare to a parametrization where $d \to d + c_u\, u x^{b_u}$ so that $d/u \to c_u$ in the limit that $x = 1$
- For clarity, the bands denote the PDF uncertainty resulting from the experimental errors with $\Delta\chi = 1$

Sample results obtained using the AV18 wavefunction



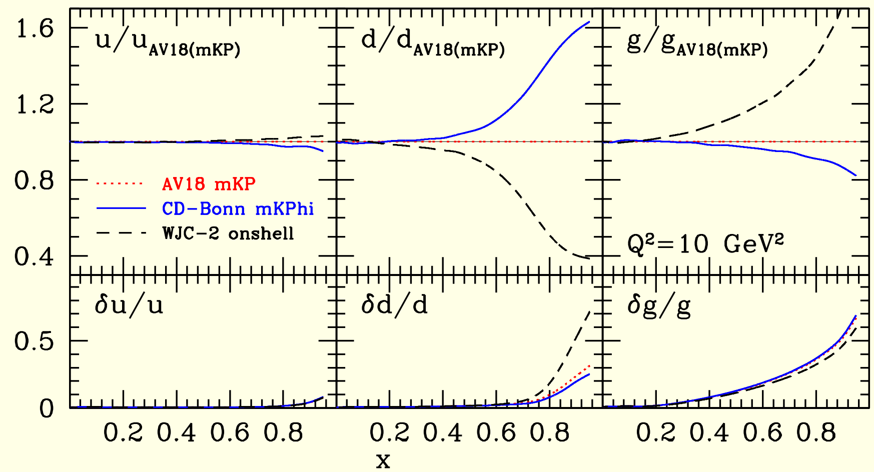


Either parametrization gives good fits, with a very slight chi square preference existing for the right-hand plots ($d/u \rightarrow c$ at $x = 1$)



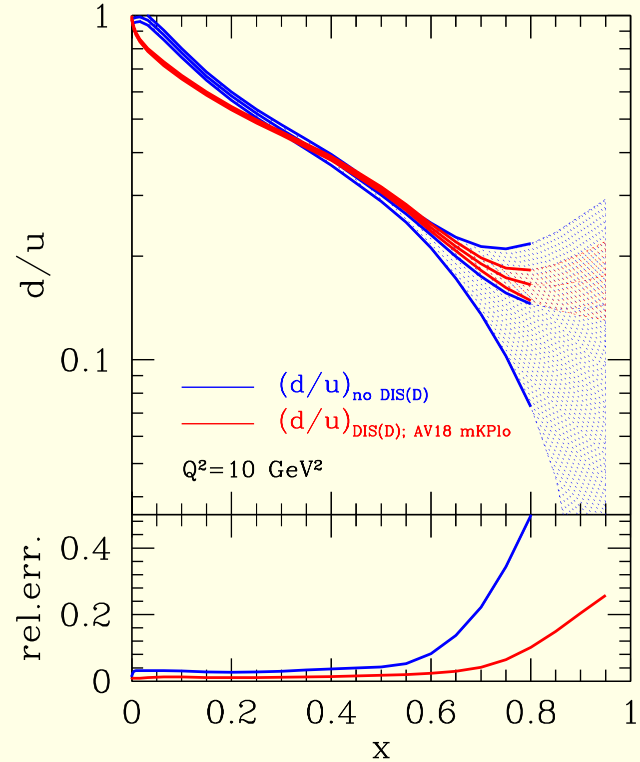
Left-hand plot shows the wavefunction dependence with a fixed offshell model while the right-hand plot shows the full effect of varying both the wavefunction and the offshell model

Compare the PDFs resulting from the upper and lower extremes of the d/u ratios shown on the previous slide



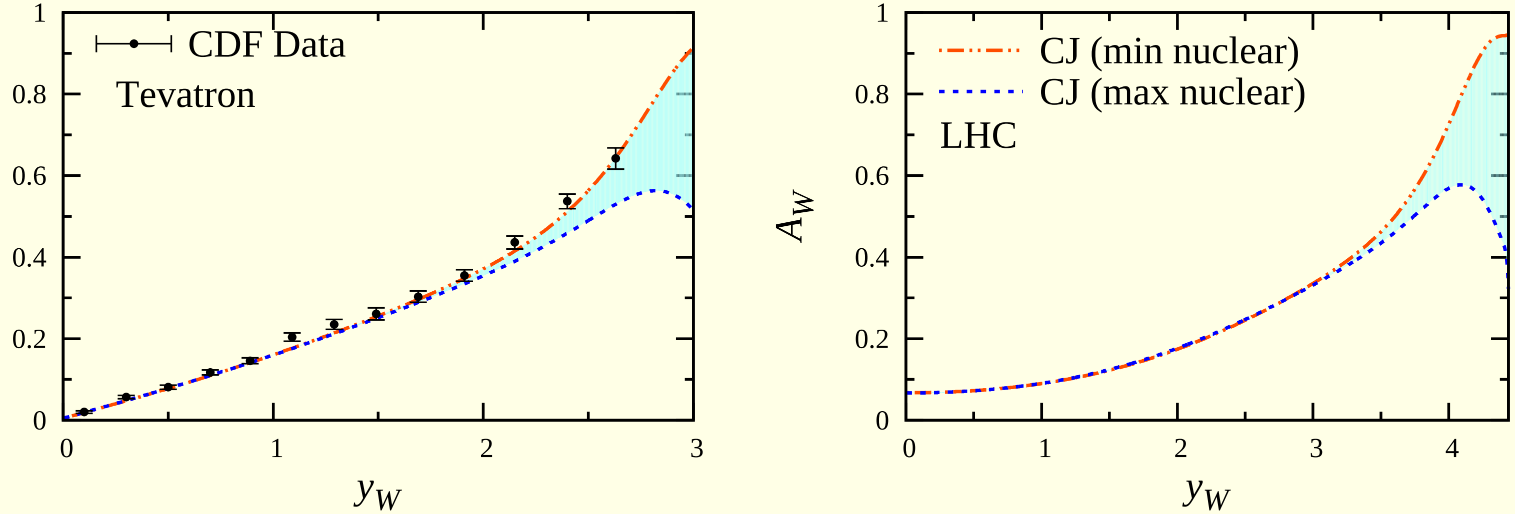
- Center panels show the d PDFs for the upper and lower extremes
- A very small shift (few percent) in the u PDF compensates
- Primarily because the DIS and Drell Yan data are sensitive to $4u + d = u(4 + d/u)$ in a region where d/u is already small
- Gluon PDF compensates the change in the d PDF for the jet data
- Uncertainty in the d PDF due to the variation of the nuclear corrections feeds into increased uncertainty in the large-x gluon PDF

The figure below shows the result of removing the deuterium DIS data from the fit.



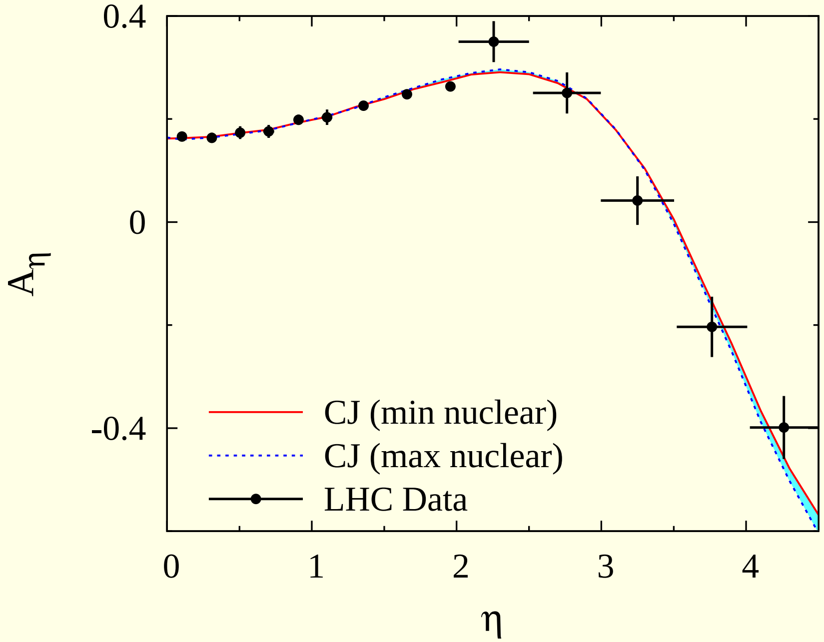
For a fixed choice of the nuclear models the uncertainty on the d PDF is decreased when the deuterium data are added

Selected Collider Results



- Figures by L. Brady from a paper in preparation showing the variations in vector boson production predictions at collider energies (L. Brady, A. Accardi, W. Melnitchouk, and JFO)
- 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

Next Steps

- Update data sets
  - Have added joint HERA data sets
  - Have added CDF and DØ Z rapidity distributions
  - Have added Run II CDF and DØ jet data
- Quantify the nuclear uncertainties
  - Currently have included a wide range of wavefunctions and off-shell corrections
  - But, the off-shell correction parameters depend, in principle on the wavefunction
  - Choose three representative wavefunctions and match the off-shell model parameters to them

Parametrization dependence

- Conventional parametrizations of PDFs are of the form

$$f(x) = a_0 x^{a_1} (1 - x)^{a_2} P(x)$$

  where $P(x)$ is often, though not always, a polynomial in x
- Different choices for P can lead to a wide range of extrapolations in regions not constrained by data
- Comparisons of different choices are in progress
- There is also the choice of the d parametrization as $x \to 1$

PDF Errors

- Software is being written to generate PDF error eigenvector parameter sets using the Hessian technique
- Will produce corresponding error PDF sets in tabular form
- Goal is to produce NLO PDF sets with errors for each of the three choices of nuclear corrections
- Aim to distribute sets in table form through LHAPDF, for example

Nuclear Corrections - what can be done?

- How can one resolve the dilemma posed by the fact that the d PDF simply adjusts to whatever nuclear model is used while the other PDFs are anticorrelated and vary in order to maintain good fits to the non-deuterium data?
- Need new data which constrain the d PDF but which are not sensitive to nuclear corrections
- Examples include the BONUS, MARATHON, and PVDIS experiments at Jefferson Lab
- Could also consider experiments done with proton targets such as ν and $\overline{\nu}$ p DIS data, perhaps from the Minerνa experiment. These will directly constrain the d/u ratio
- Another example - finer binning on W asymmetry data at high values of rapidity in order to get to large x values

If we knew the d/u ratio, then we could turn the problem around and use our fits to select the best model for the nuclear corrections

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
- Good descriptions of the data are easily obtained and the d PDF varies significantly, depending on the nuclear model choice
- Other PDFs are anticorrelated with the d PDF (mostly the u and gluon PDFs) so that the fits to all other data sets are essentially independent of the nuclear corrections
- 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, BONUS, and PVDIS. It also includes additional observables taken on proton targets.
- Information on the d PDF obtained via methods which do not rely on nuclear corrections will then place constraints on nuclear correction models