

PDFs, Nuclear Corrections, and the *d/u* Ratio

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more...

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Introduction

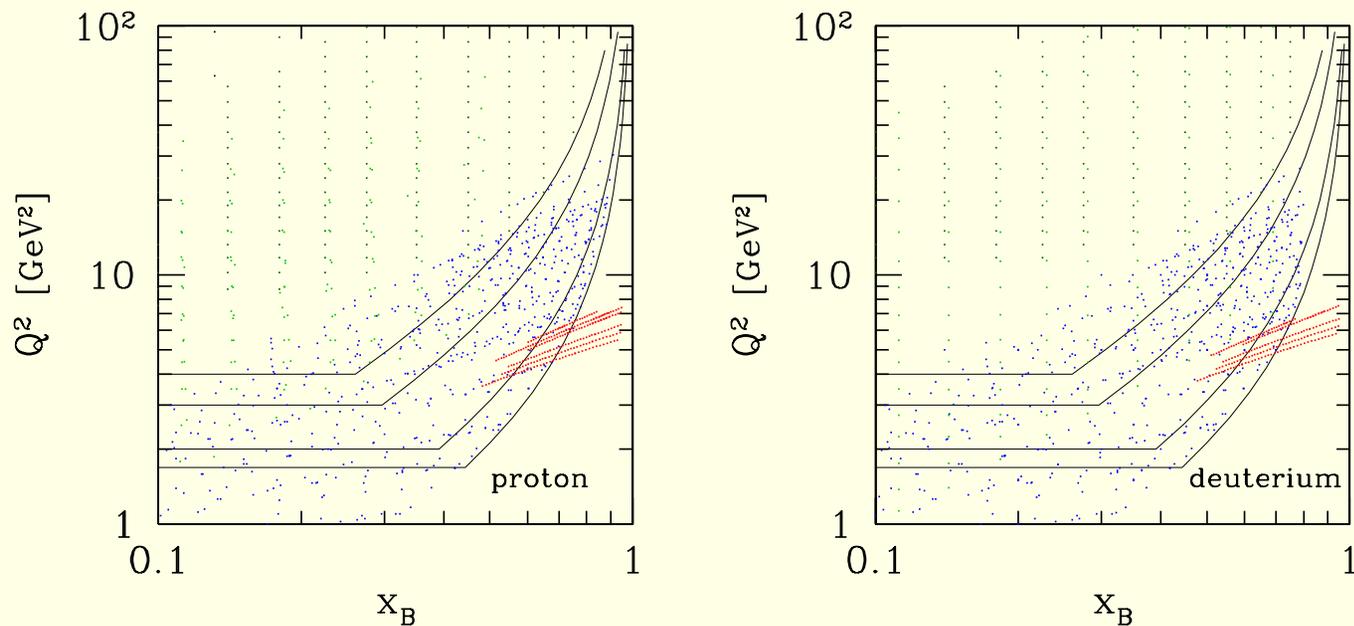
CTEQ/Jefferson Lab (CJ) Collaboration - Alberto Accardi, Eric Christy, Cynthia Keppel, Simona Malace, Wally Melnitchouk, Peter Monaghan, Jorge Morfín, JFO, and Lingyan Zhu

Goals:

- Overall goal - 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 $x \leq \frac{Q^2}{W_{min}^2 - m^2 + Q^2}$
- 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 $Q > 2$ 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) GeV²
- 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 $x \rightarrow 1$ 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
 - R.K. Ellis, W. Furmanski, and R. Petronzio, Nucl. Phys. **B212**, 29(1983)
 - 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, accepted for publication in Phys. Rev. D

Higher Twist parametrization

Parametrize the higher twist contribution by a multiplicative factor

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

where

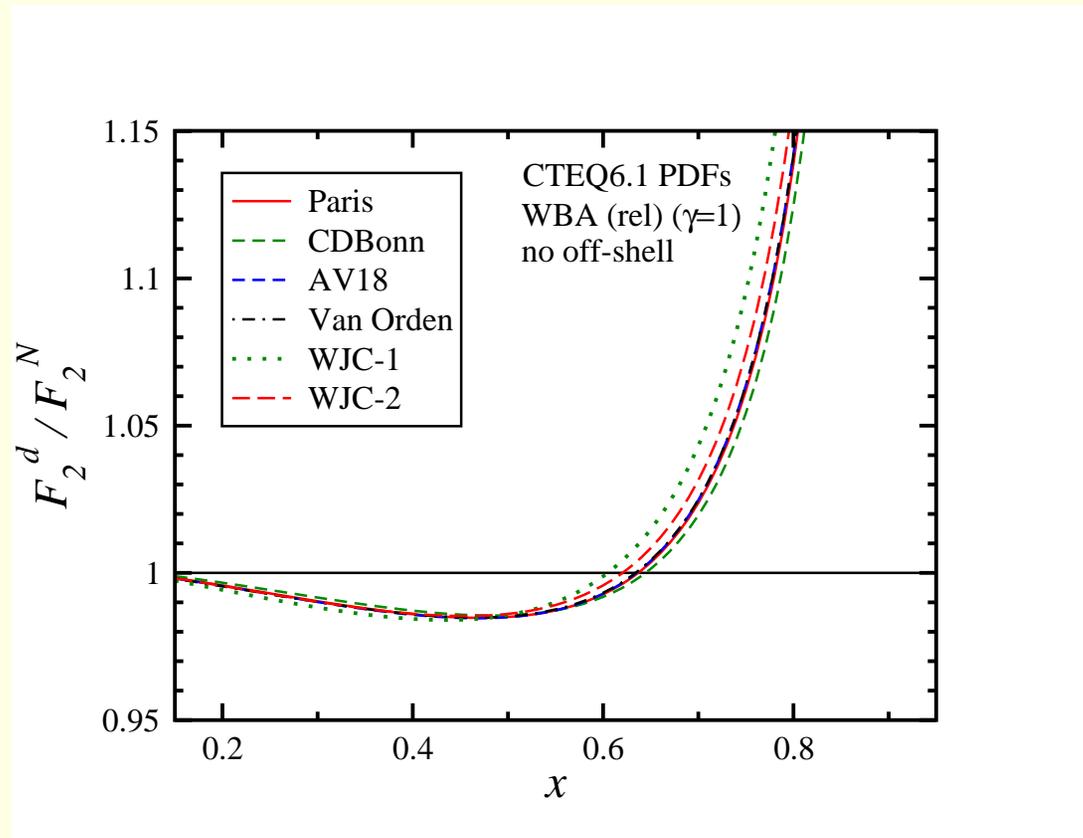
$$C(x) = a x^b (1 + c x + d x^2)$$

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

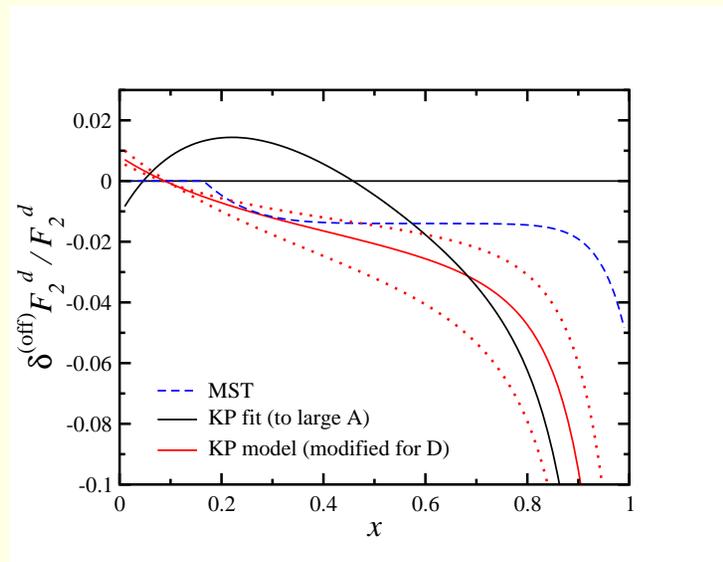
Nuclear Corrections

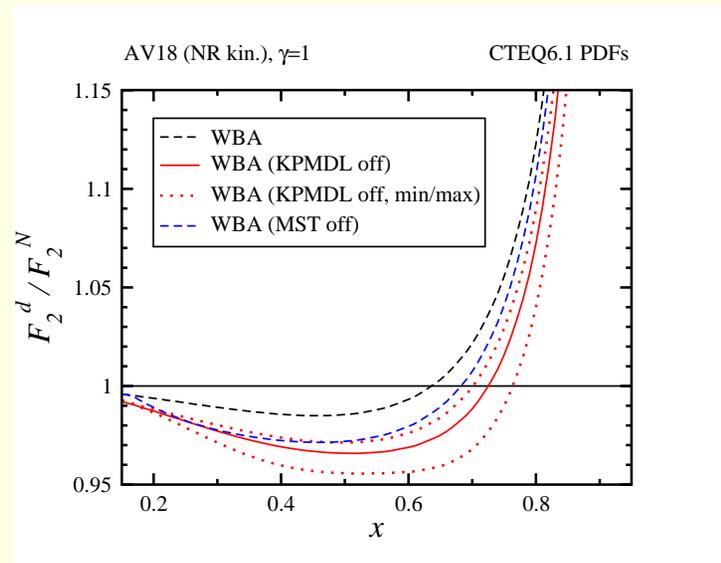
- Fermi motion smearing done using the Weak Binding Approximation (WBA)
- Various choices of wavefunctions explored



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 $x \approx .8$
- $\sigma_{pp} \sim \bar{u}(x_2)[4u(x_1) + d(x_1)\bar{d}(x_2)/\bar{u}(x_2)]$
- $\sigma_{pn} \sim \bar{d}(x_2)[4u(x_1) + d(x_1)\bar{u}(x_2)/\bar{d}(x_2)]$
- At large $x_F, x_1 \gg x_2$
- To the extent that $\bar{u}(x_2) \simeq \bar{d}(x_2)$, 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

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 $\gamma + \text{jet}$
- 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)

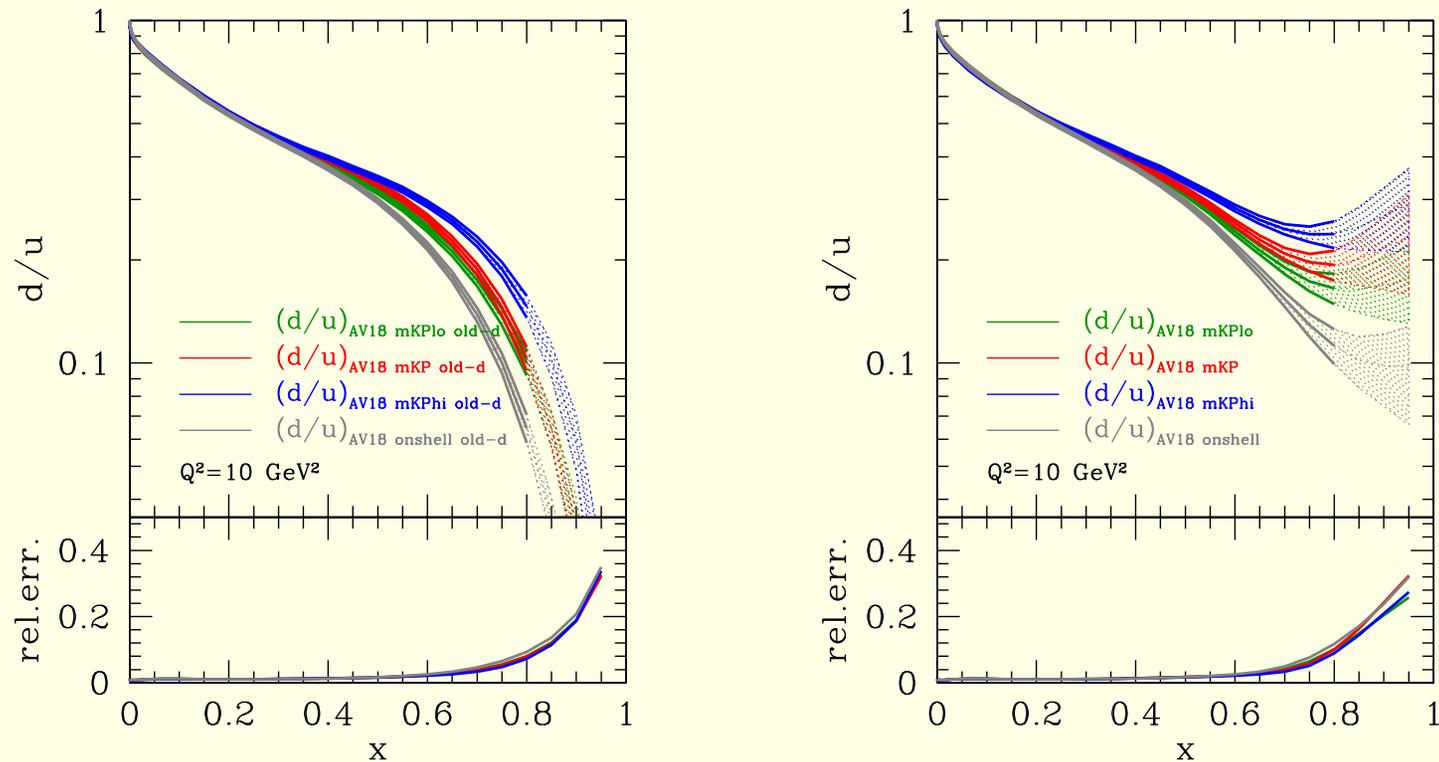
Data Sets

- 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
- $D\bar{0}$ $\gamma + \text{jet}$ data
- Data sets similar to those used in CTEQ6.1 except CCFR removed, E-866 added, $D\bar{0}$ $\gamma + \text{jet}$ added, and some new W asymmetry data added

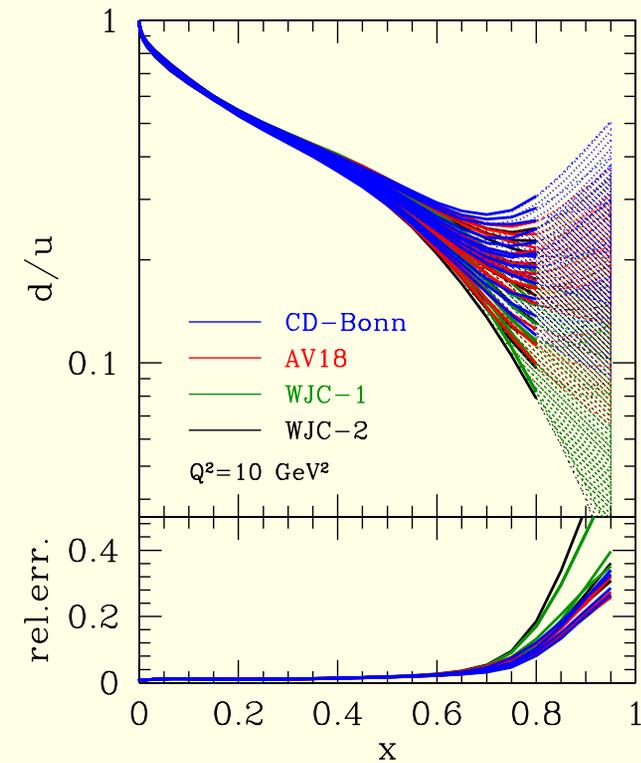
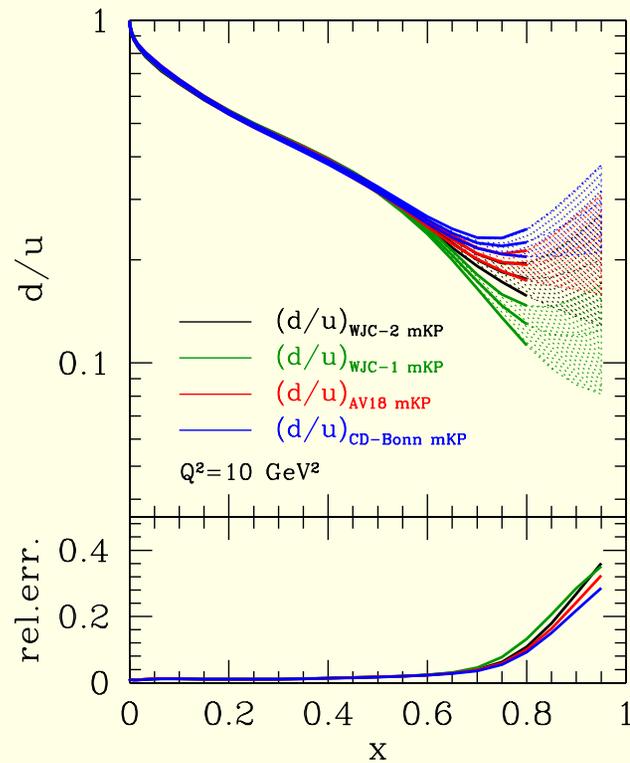
Results

- 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 $x \rightarrow 1$
- Then, compare to a parametrization where $d \rightarrow d + c_u ux^{b_u}$ so that $d/u \rightarrow c_u$ 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

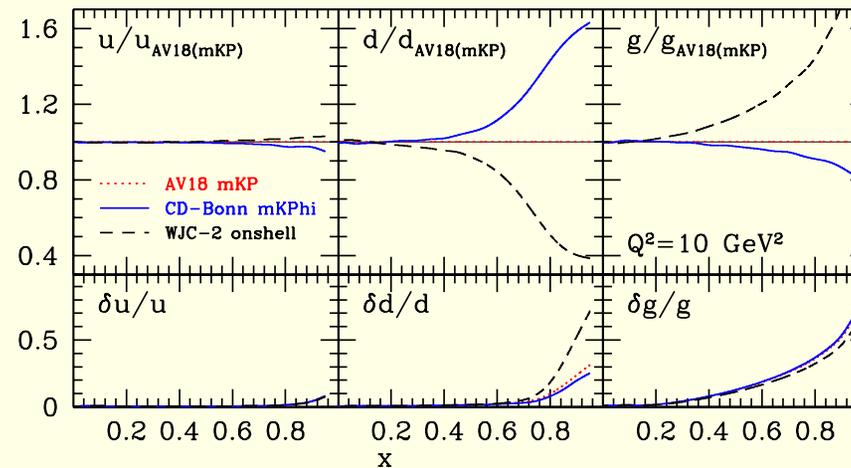


Either parametrization gives good fits, with a very slight chi square preference existing for the right-hand plots ($d/u \rightarrow c$ at $x = 1$)



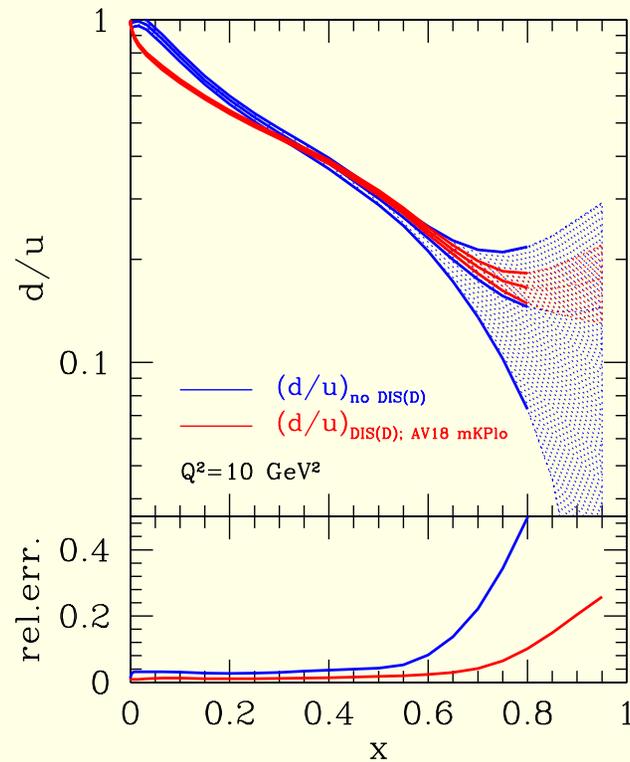
Left-hand plot shows the wavefunction dependence with a fixed offshell model while the right-hand plot shows the full effect of varying both the wavefunction and the offshell model

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



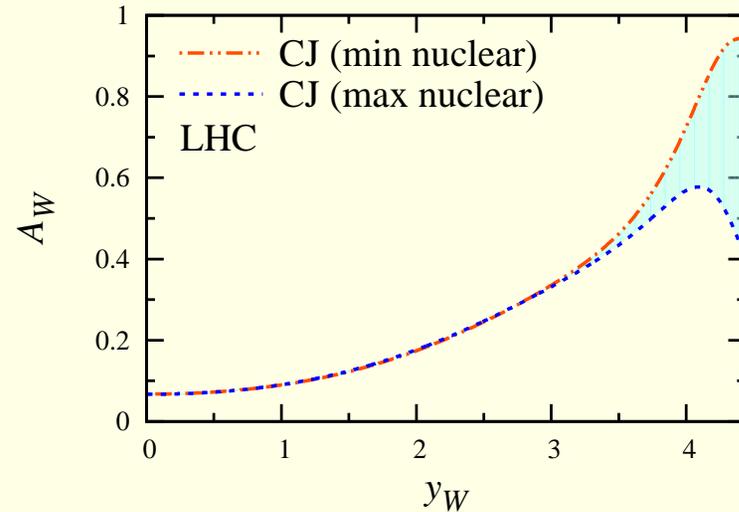
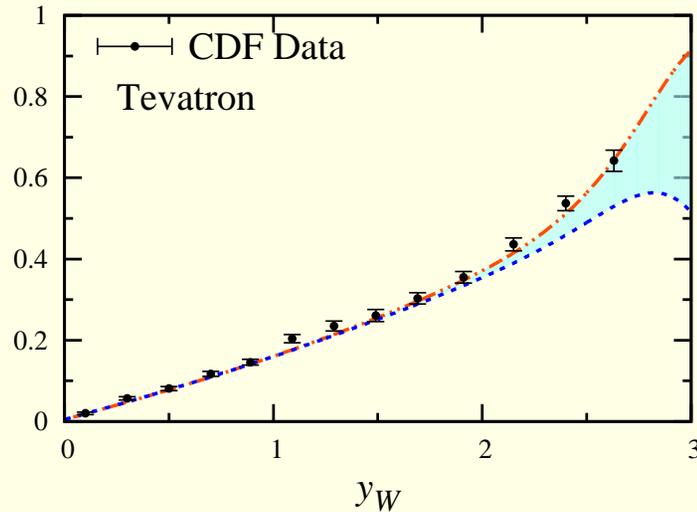
- Center panels show the d PDFs for the upper and lower extremes
- A very small shift (few percent) in the u PDF compensates
- Primarily because the DIS and Drell Yan data are sensitive to $4u + d = u(4 + d/u)$ in a region where d/u is already small
- Gluon PDF compensates the change in the d PDF for 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.



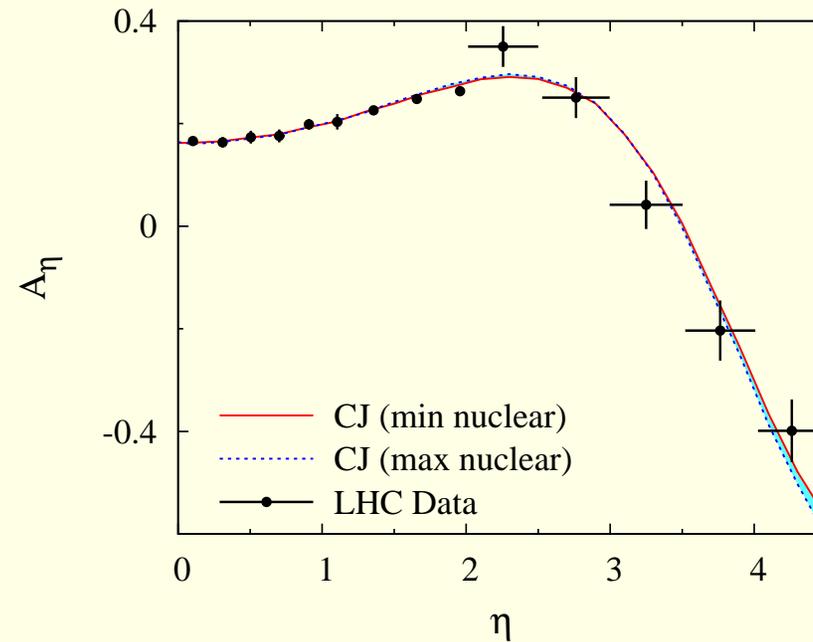
For a fixed choice of the nuclear models the uncertainty on the d PDF is decreased when the deuterium data are added

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. Melnitchuk, 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
 - Likely to reduce the nuclear correction uncertainty estimates

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 $x \rightarrow 1$

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 $\bar{\nu}$ p DIS data, perhaps from the Minerva 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