Uncertainties in Determining Parton Distributions at Large x: Results from the CTEQ-Jefferson Lab "CJ" Collaboration

Deep Inelastic Scattering 2012

Bonn

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CTEQ-Jefferson Lab "CJ" Collaboration and Goals

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New parton distributions from large-x and low-Q^2 data
Phys. Rev. D81:034016 (2010)
Uncertainties in determining parton distributions at large x
Phys. Rev. D84:014008 (2011)

Initial Goals:

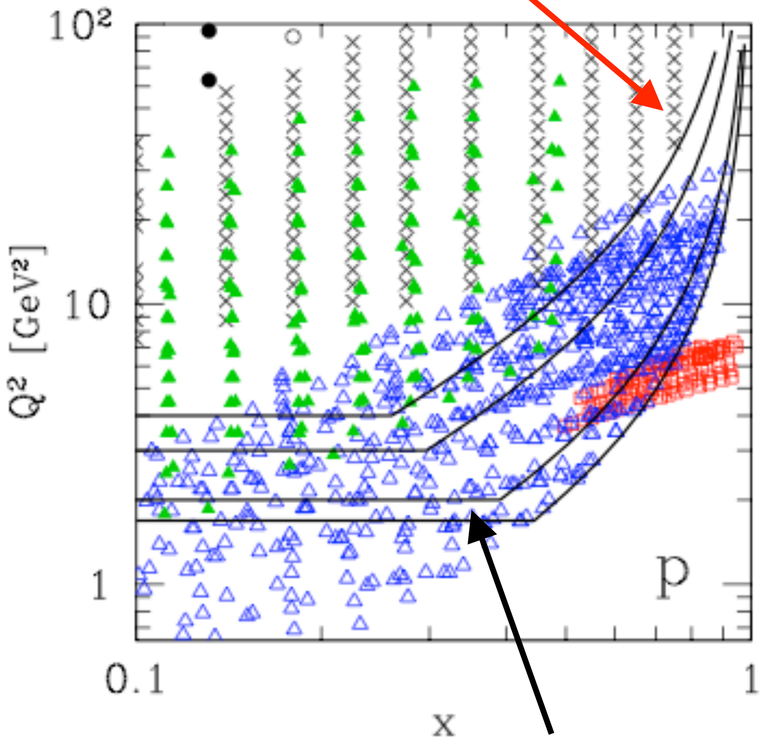
- Extend CTEQ PDF global fit to larger values of x and lower values of Q
- Incorporate data from older SLAC and newer JLab, Drell-Yan, jets, gamma+jet
- See if PDF errors can be reduced using new data

BUT:

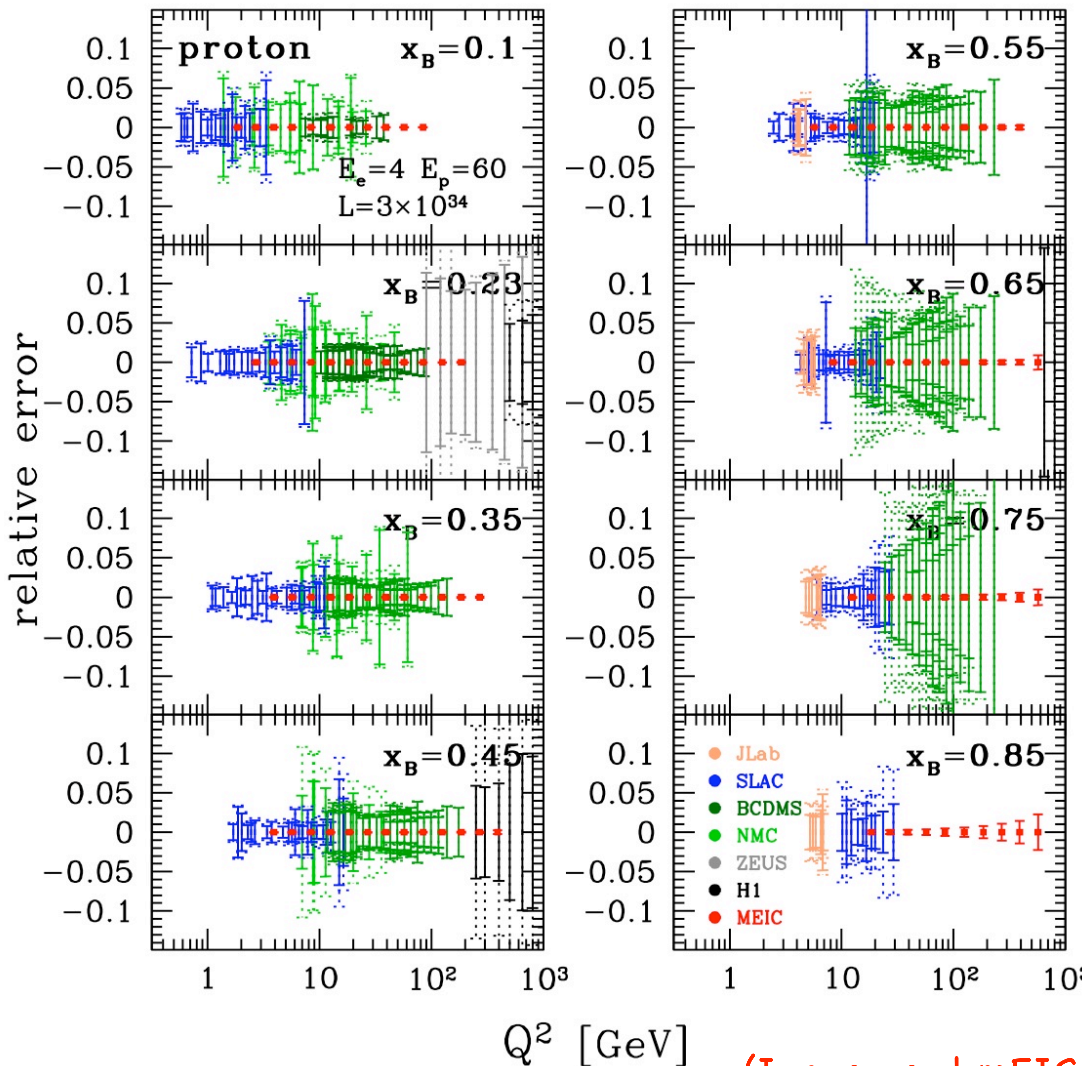
- Conventional cuts are in "safe" region for issues such as higher twist, target mass - will now need to take these into account
- *Will also need deuteron nuclear corrections*

Typical W, Q cuts are VERY restrictive….

Current $Q^2 > 4$ GeV^2, $W^2 >$ 12.25 GeV^2, cuts



Reduced CJ cuts



Typical cuts essentially include no data above x~0.75

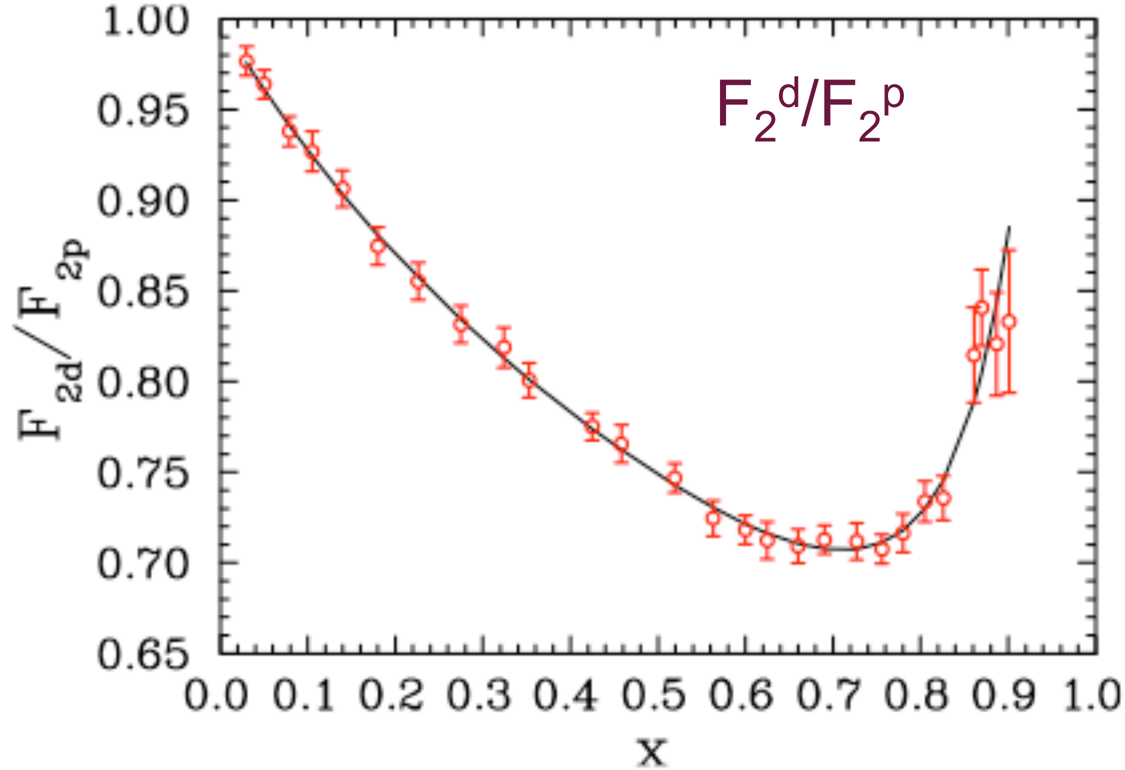
(Ignore red mEIC data points.)

<u>What large x data that is used has large uncertainty</u>

Moreover, *neutron* structure is typically derived from deuterium target data by subtracting proton

.....but.....

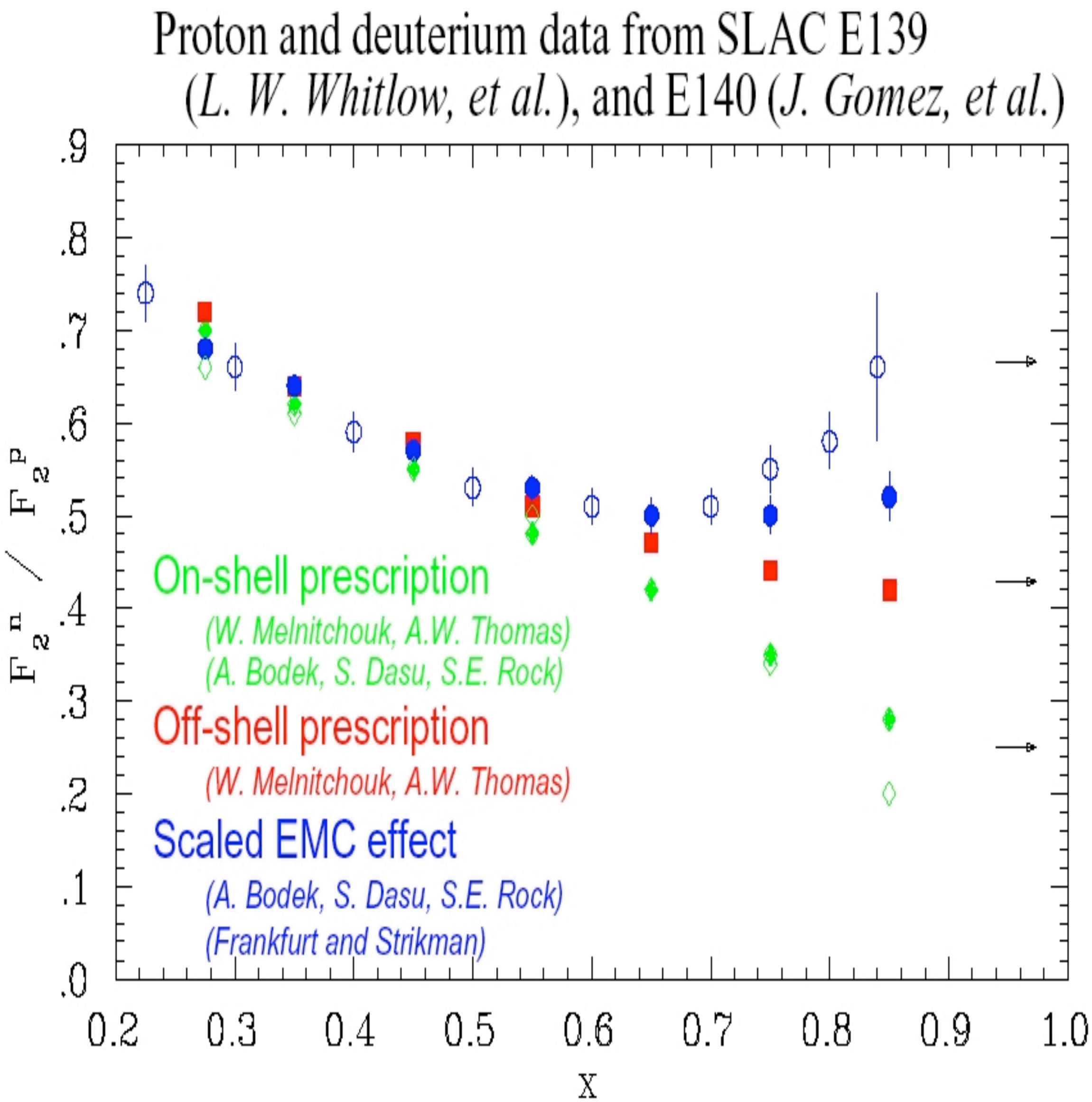
Large uncertainty in unfolding nuclear effects (Fermi motion, off-shell effects, deuteron wave function,coherent scattering, final state interactions, nucleon structure modification ("EMC"-effect)……………..



SLAC data

The deuteron is a nucleus….

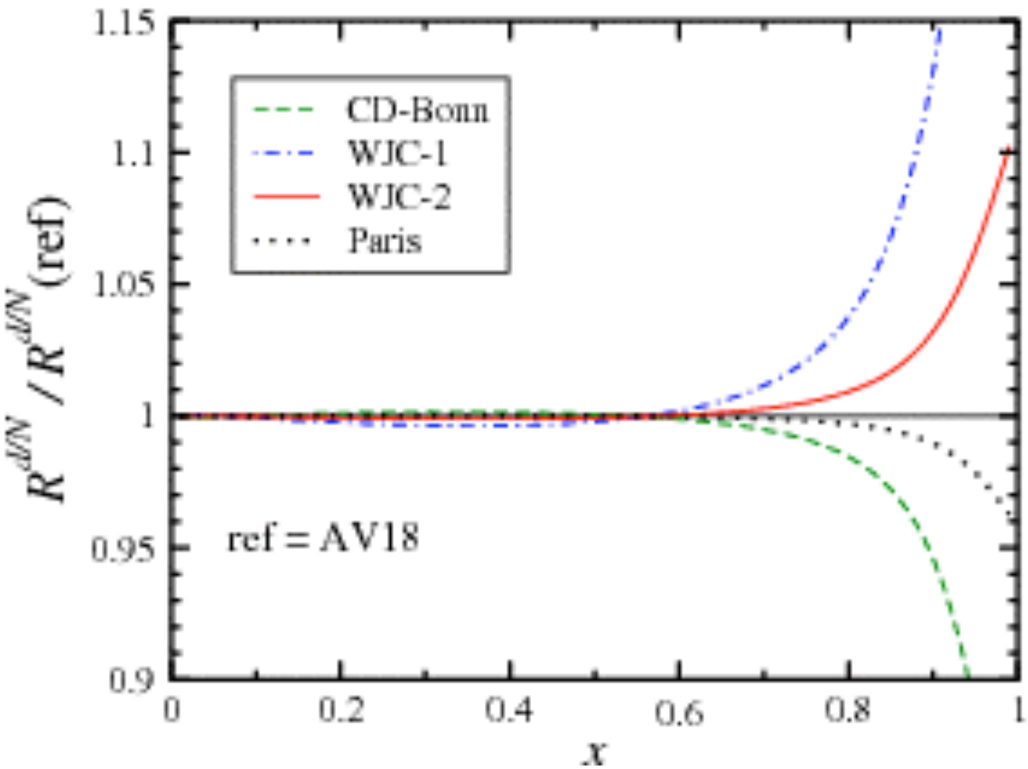
This is a major obstacle….



$0.2 < F_2^n/F_2^p < 0.8$?!?!

Large x - Large Nuclear Effects

Deuteron wave function model dependence



R – ratio of deuteron and nucleon F_2 structure functions

- Even simple "Fermi Smearing" leads to significant dependence on D wave function
- Different models for off-shell and "EMC" effects lead to large additional variations
- Contributions from MEC, Δ (1232) and "exotic" degrees of freedom unknown
- FSI?

(Large) Range in Theory

	F_2^n/F_2^p	d/u
SU(6)	2/3	1/2
Scalar Diquark	1/4	0
H-P Quark Model	1/4	0
pQCD	3/7	1/5
Counting Rules	3/7	1/5

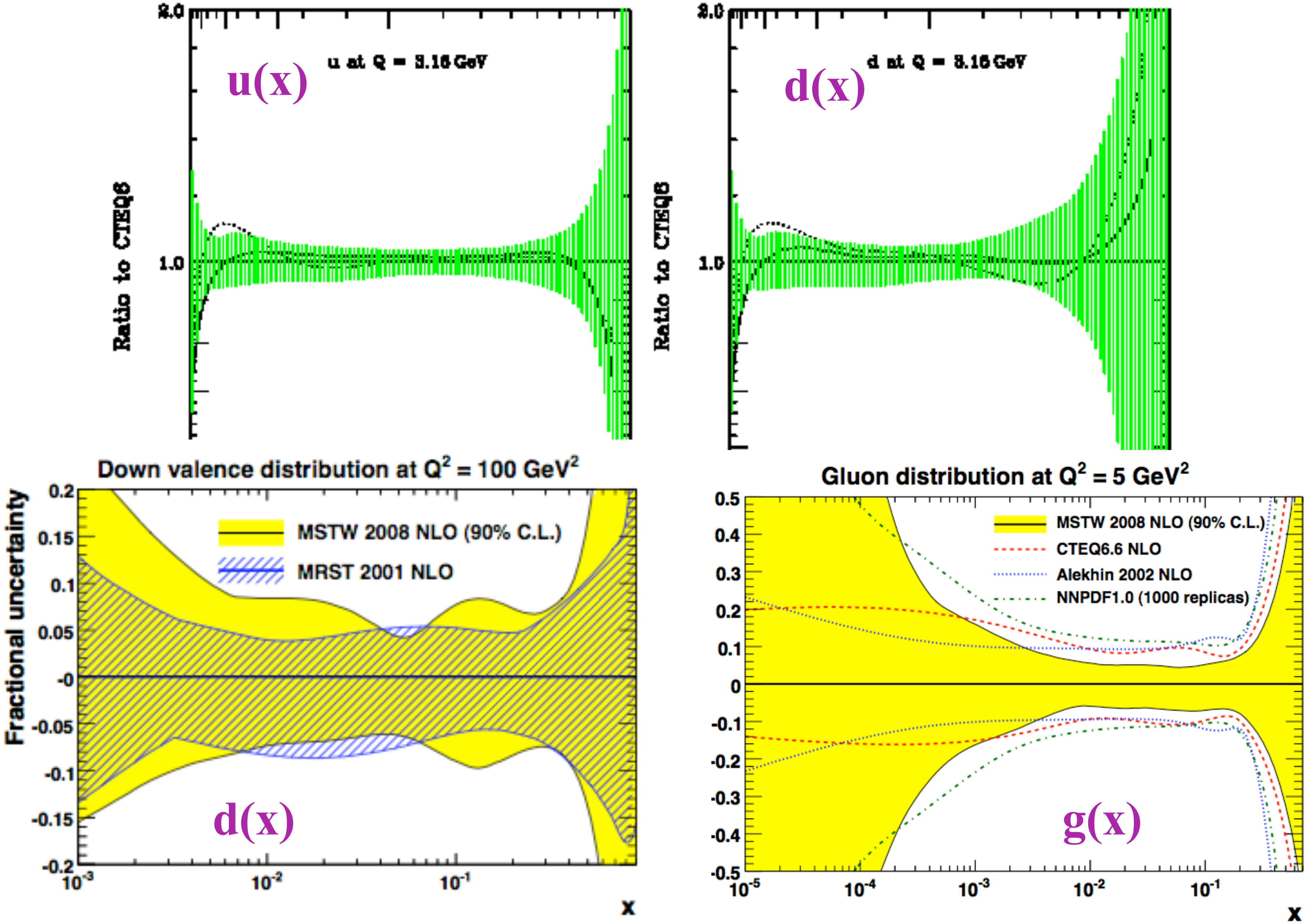
Review Articles :

Isgur, Phys. Rev. D59, 34013 (1999)
Brodsky et al., Nucl. Phys. B441, 197 (1995)
Melnitchouk and Thomas, Phys. Lett. B377, 11 (1996)

$$0.25 < F_2^n/F_2^p < 0.75 \quad ?!$$

(Large) Range in Data (due to nuclear corrections in deuterium)

Translates Directly to Large x Valence pdf Uncertainties



Target Mass Corrections - *There are options!*

A Review of Target Mass Corrections, Ingo Schienbein et al., J.Phys.G 35:053101 (2008)

- Nachtmann variable $\xi = 2x\left[1 + (1 + 4M^2x^2/Q^2)^{1/2}\right]$
- **Standard Georgi-Politzer** (OPE)
  [Georgi, Politzer 1976; see review by Schienbein et al. 2007]
  - leads to non-zero structure functions at x_B>1 (!)
- **Collinear Factorization** **
  [Accardi, Qiu, JHEP 2008; Accardi, Melnitchouk 2008]
  Structure fns as convolutions of parton level structure fns and PDF

$$F_{T,L}(x_B, Q^2, m_N) = \sum_f \int_{\xi}^{\frac{\xi}{x_B}} \frac{dx}{x}\, h^f_{T,L}\left(\frac{\xi}{x}, Q^2\right) \varphi_f(x, Q^2)$$

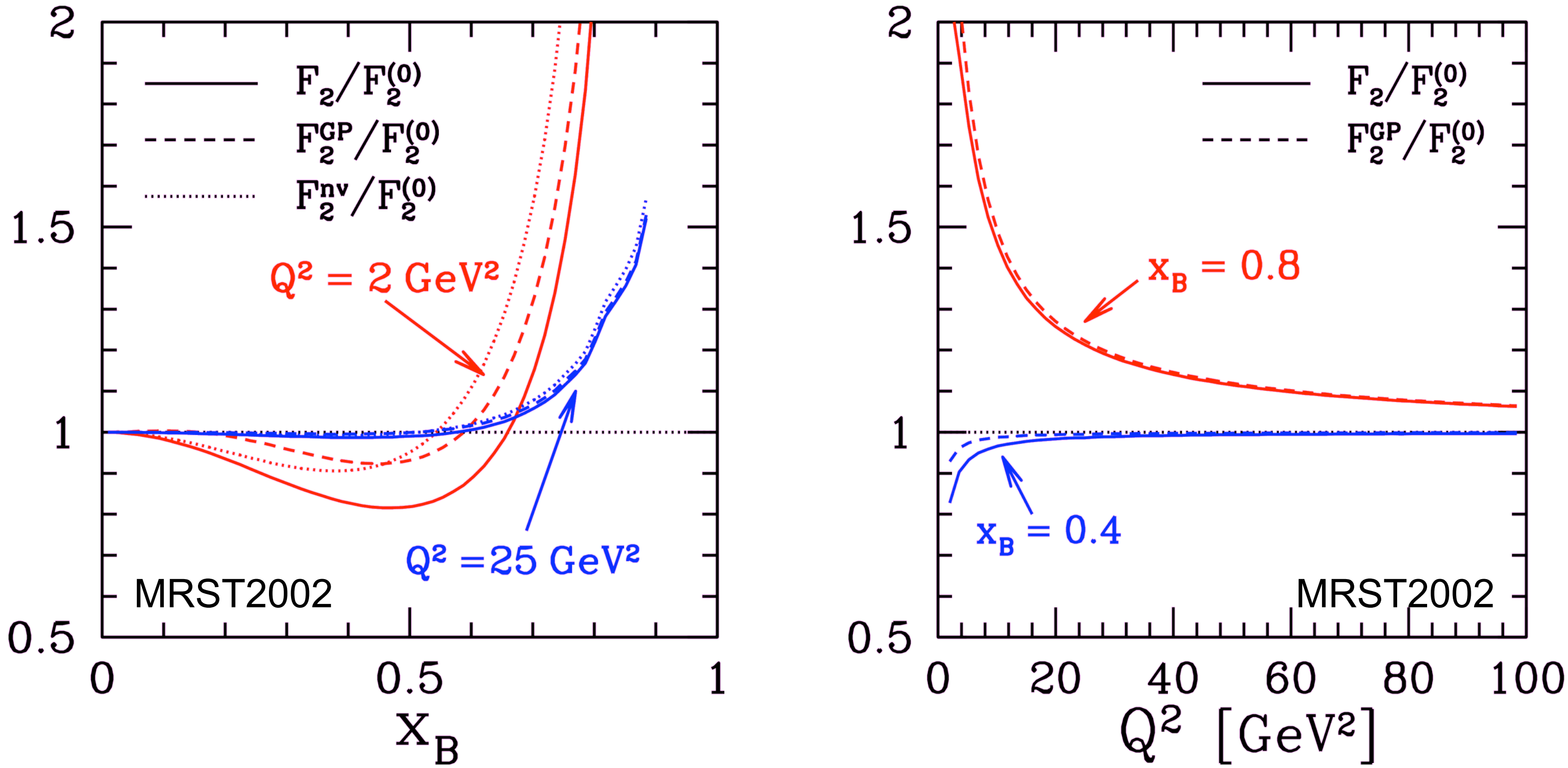
  - respects kinematic boundaries
- **Naïve CF**, uses x_{max}= 1
  [Aivazis et al '94; Kretzer,Reno '02]

$$F^{nv}_{T,L}(x_B, Q^2, m_N) \equiv F^{(0)}_T(\xi, Q^2)$$

  - leads to non-zero structure functions at x_B>0 (!)

Target mass corrections – F_2 at NLO

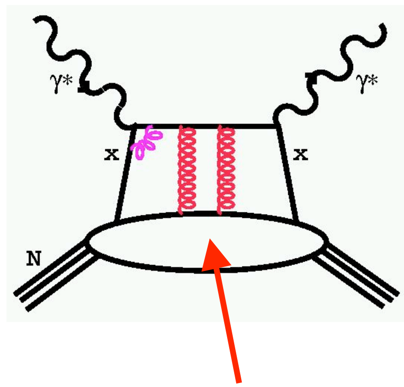
Accardi, Qiu JHEP '08



Crucial at low Q^2, large x

Crucial *even at high Q^2* at high x – not taken into account in current pdf analyses

Higher-Twist Parameterization



Parameterize the higher-twist contributions by a multiplicative factor:

$F_2(\text{data}) = F_2(\text{TMC})\ (1+C(x)/Q^2)$

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

SIMPLE parametrization is sufficiently flexible to give good fits to data *(except when no TMCs are included)*

C(x) includes dynamical higher twist, TMC model uncertainty (jet mass corrections), NNLO (power-like at small Q)

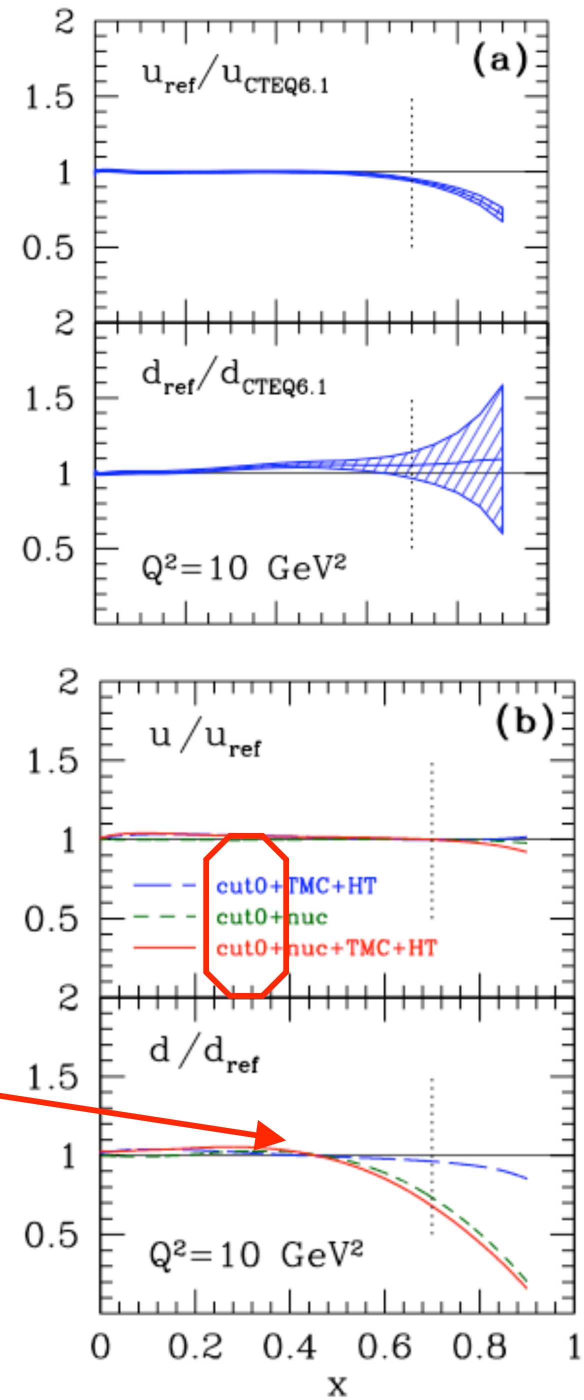
Global Fitting

We are using Jeff Owens' (CTEQ) NLO DGLAP fitting package

- Fit DIS *(including SLAC and JLab!)* proton and deuteron, E866 Drell-Yan, CDF, D0 W lepton asymmetry, jets (and D0 γ+jet), H1, ZEUS
- First, compare "Reference Fit" to CTEQ6.1 parameterization of PDFs at Q^2=1.69 GeV^2

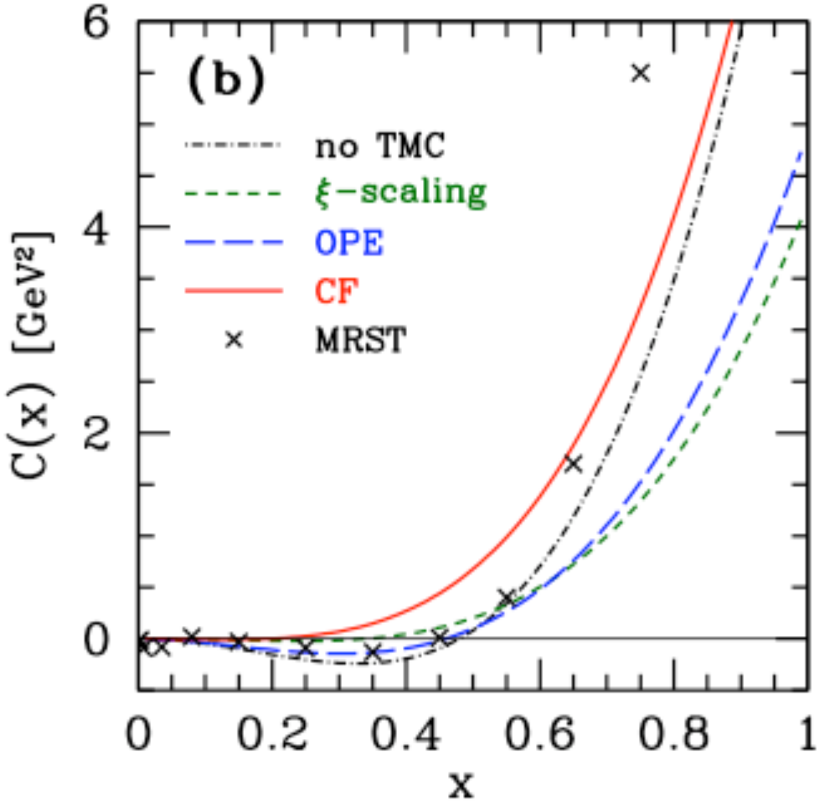
  u-quark suppression, d-quark enhancement - mainly due to E866 DY and SLAC DIS data

- Next: Systematically reduce Q, W (x) cuts:
- Multiple TMC terms, Higher-twist contributions by a multiplicative factor
- Nuclear corrections for deuteron targets added - no such things as a safe cut above x~0.5!
- PDF errors computed by the Hessian method, with $\Delta\chi^2$=1



Results - higher twist

Extracted higher-twist term depends on the type of TMC used



- $Q^2 > 1.69$ GeV^2 and $W^2 > 3$ GeV^2 (referred to as "cut03")
- lower cuts $\Rightarrow x_B < 0.85$ compared to $x_B < 0.65$ in CTEQ/MRST
- curves have small errors on HT coefficients *a*, *b*, and *c*

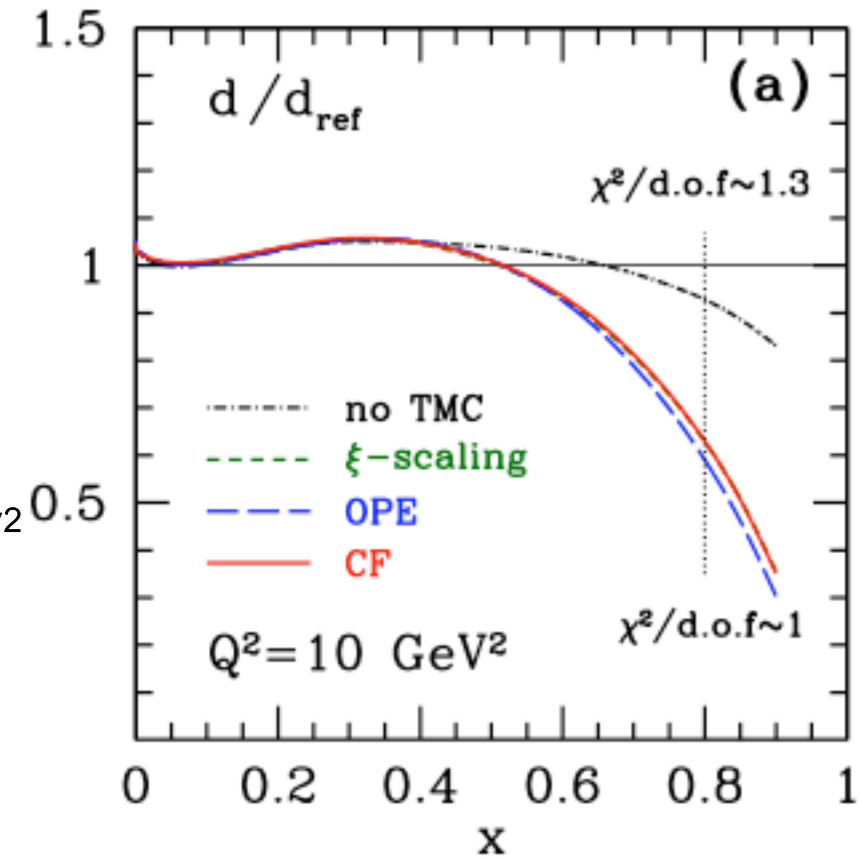
Results - Good News!

- **Extracted twist-2 PDF *nearly insensitive* to choice of TMC!**
  - fitted HT function compensates the TMC
  - except when no TMC is included

- **Largest effect on *d*-quark**

- $Q^2 > 1.69$ GeV^2, $W^2 > 3$ GeV^2 (referred to as 'cut03')

- plots relative to fit with
  - $Q^2 > 4$ GeV^2, $W^2 > 12.25$ GeV^2 (“cut00” ≡ CTEQ6.1 cuts)
  - no TMC, no HT, no nuclear correction



Deuteron Nuclear Corrections

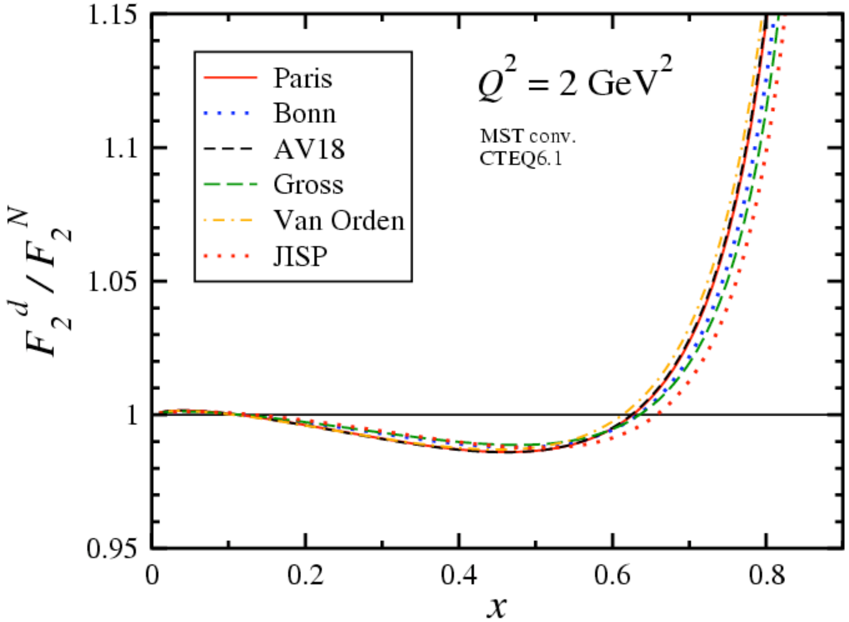
Nucleon Smearing Model, Fermi motion and binding energy [Phys. Rev. C79:035205 (2009)]

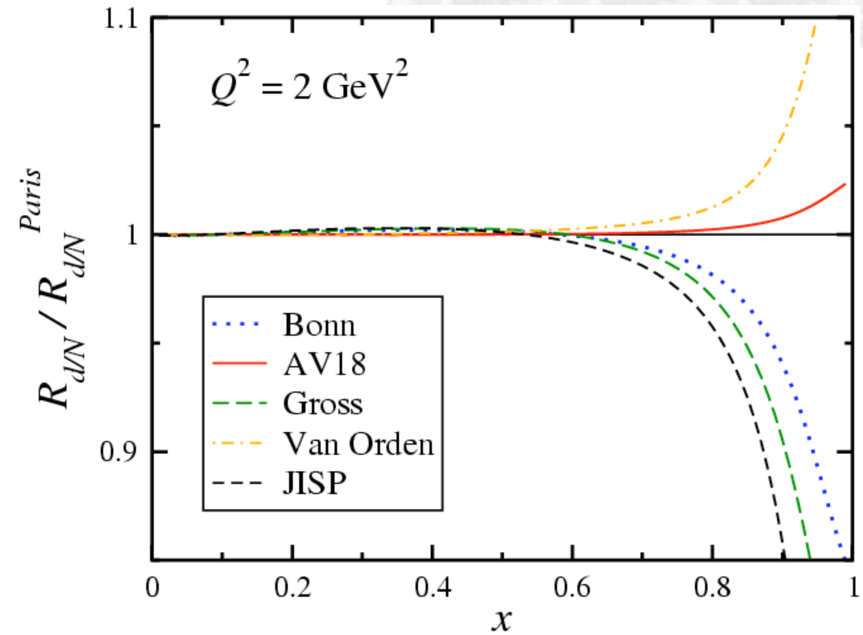
Important to go beyond Bjorken limit, allows finite-Q^2 corrections, can include off-shell corrections in S_A

$$F_{2A}(x_B) = \int_{x_B}^{A} dy S_A(y, \gamma, x_B) F_2^{TMC}(x_B/y, Q^2)$$

$$\gamma = \sqrt{1 + 4x_B^2 m_N^2/Q^2}$$

$$\frac{x_B}{y} = -\frac{q^2}{2p_N \cdot q}$$





LEFT Deuteron to nucleon structure function ratio, using CTEQ6.1 nucleon PDFs and various smearing functions

RIGHT The same, relative to that for the Paris wave functions. The effects are of the order of 5% at x ~ 0.8.

Offshell Corrections, Relativity

• Start with a parametrization due to Kulagin and Petti which is fitted to data for a range of heavy nuclei

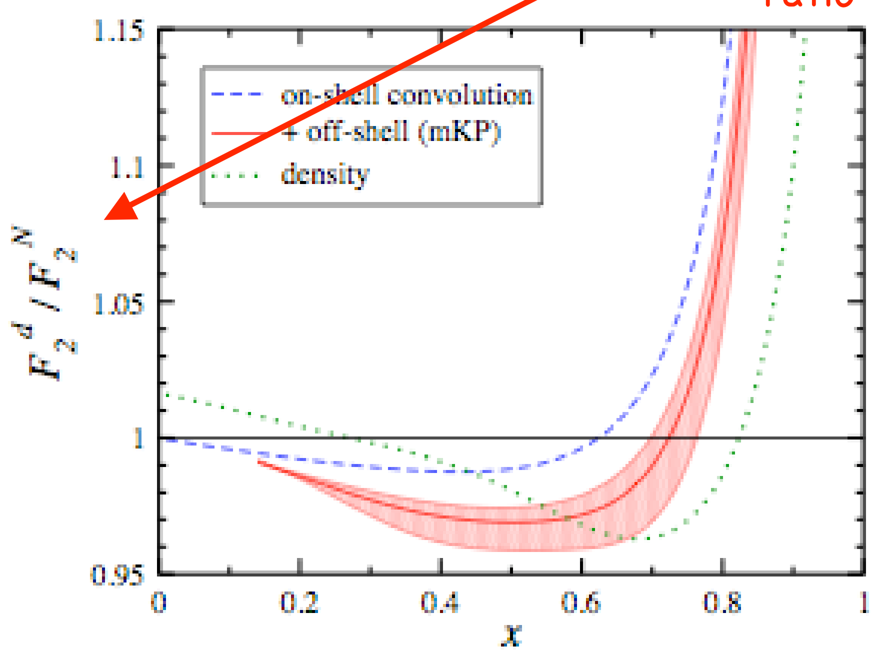
• Parameters were adjusted (Wally Melnitchouk) to provide a range of corrections representative of the average offshellness of nucleons in a deuteron

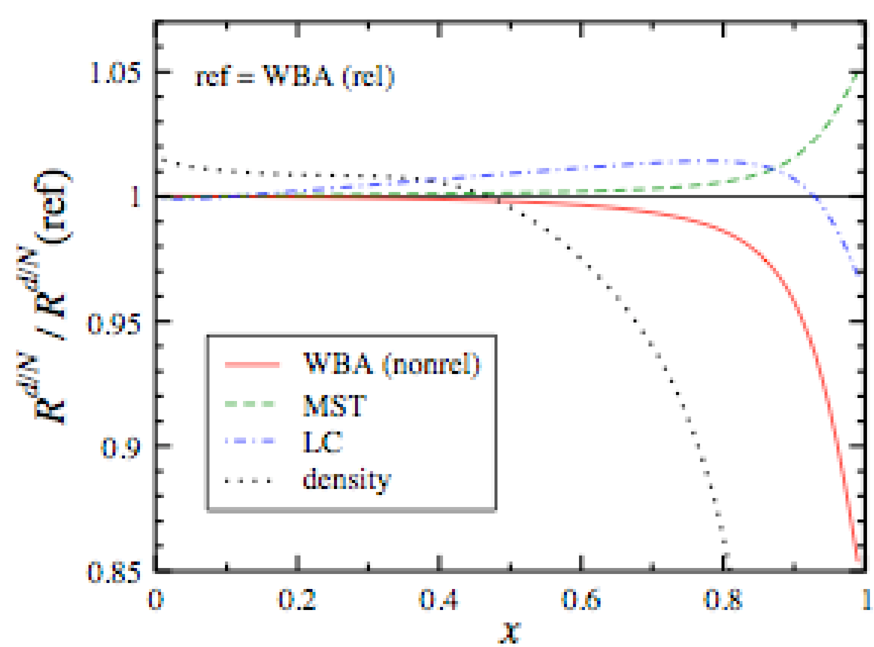
• Dynamical effects of relativity require model dependent assumptions, kinematics straightforward

Deuterium data divided by this ratio:

ratio < 1 d enhanced

ratio > 1 d decreased

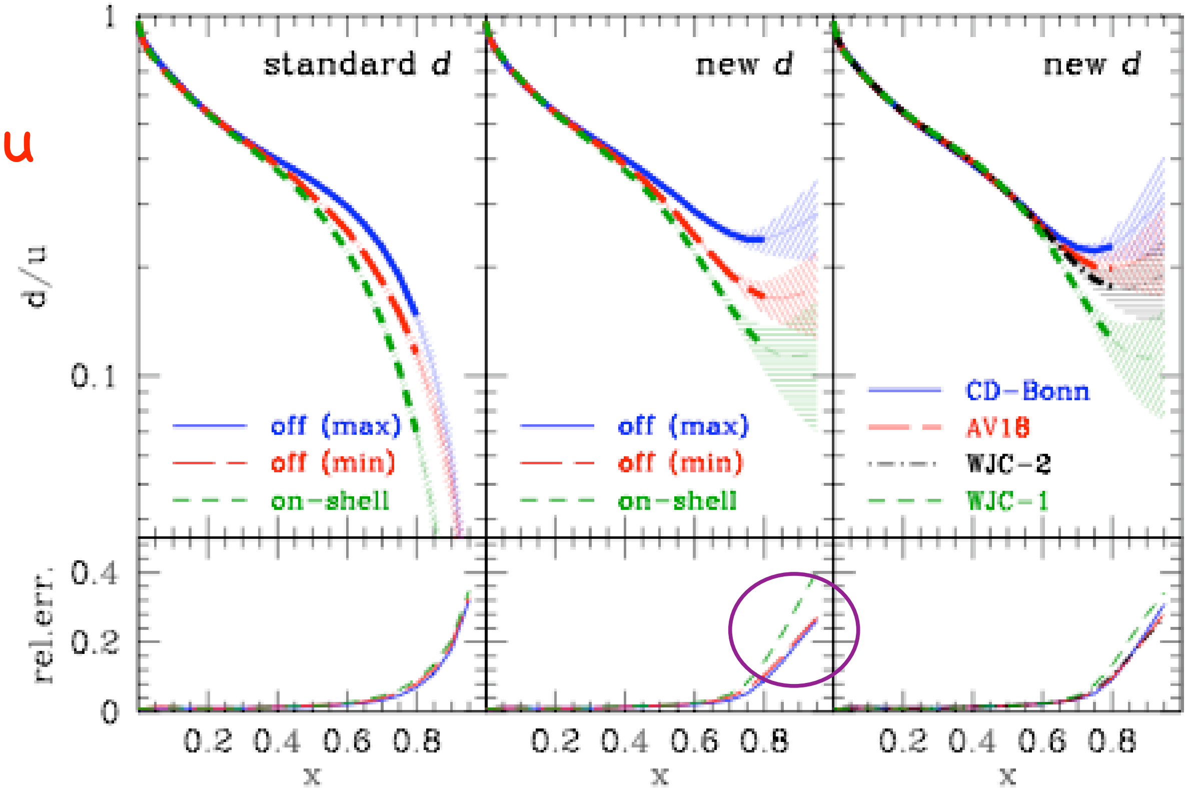




Evaluate nuclear (deuterium) corrections by showing d/u ratios

- The u PDF is already well constrained
- The different nuclear corrections have the largest effect on the d PDF

d/u

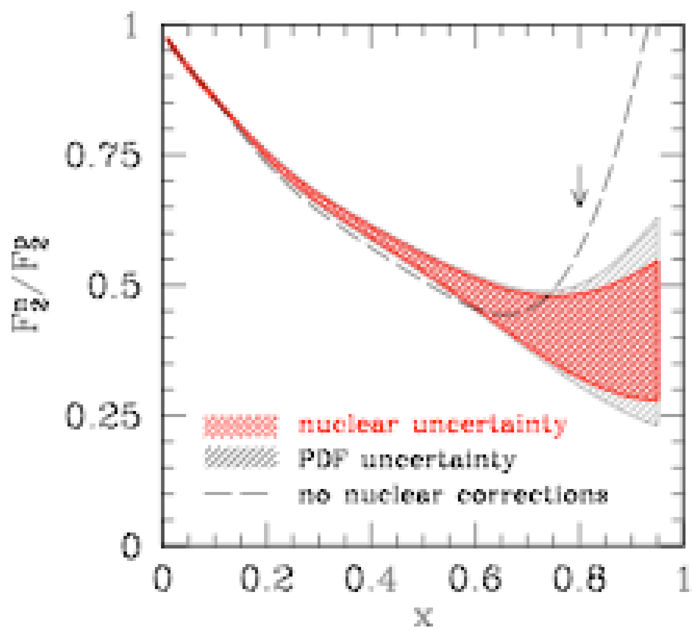


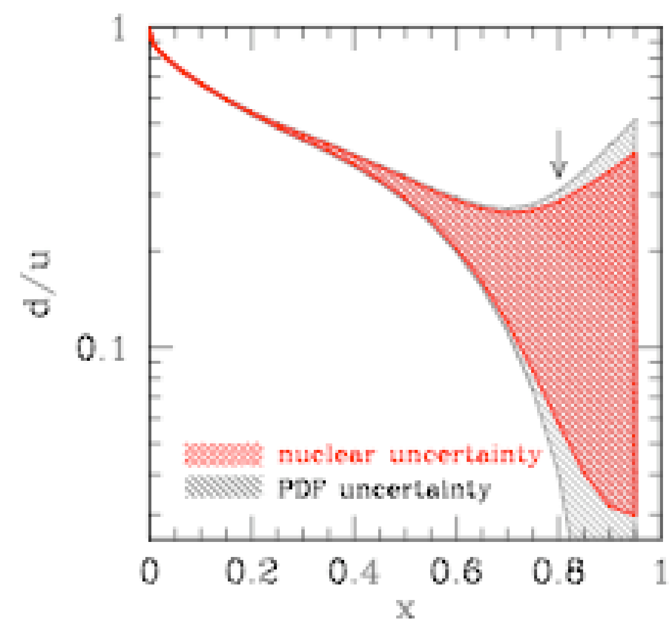
- Standard d-quark parameterization (d -> 0 as x -> 1)
- AV18 wave function
- Range of off-shell models

- Modified d-quark parameterization (d/u -> c as x -> 1)
- AV18 wave function
- Range of off-shell models

- Modified d-quark parameterization
- Fixed off-shell
- Range of deuteron wave functions

F_2^n/F_2^p d/u





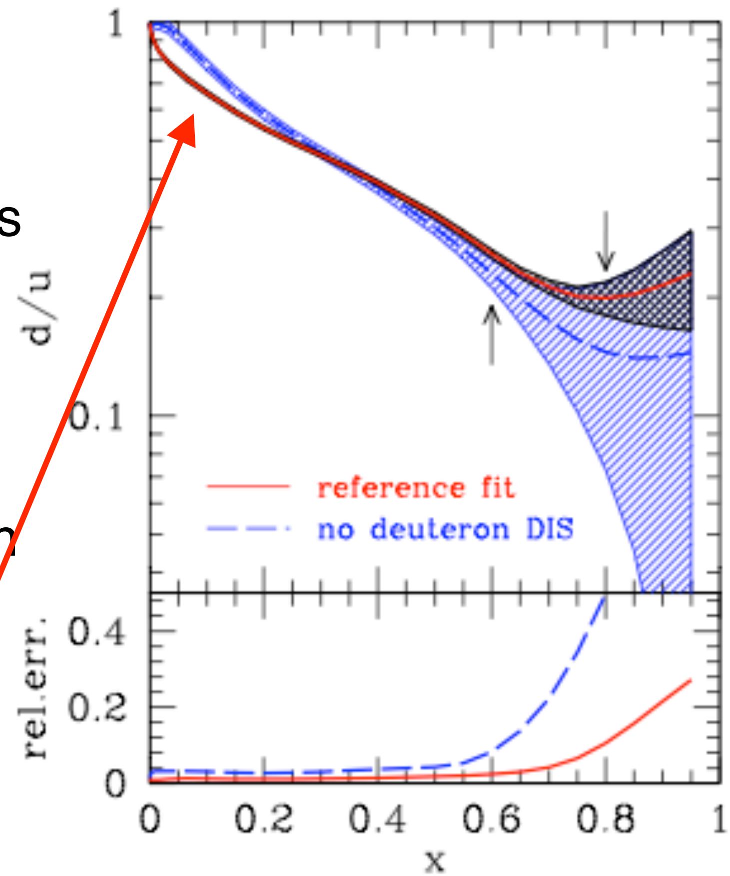
- Resulting uncertainty bands for d/u and F_2^n/F_2^p

  - nuclear corrections dominant

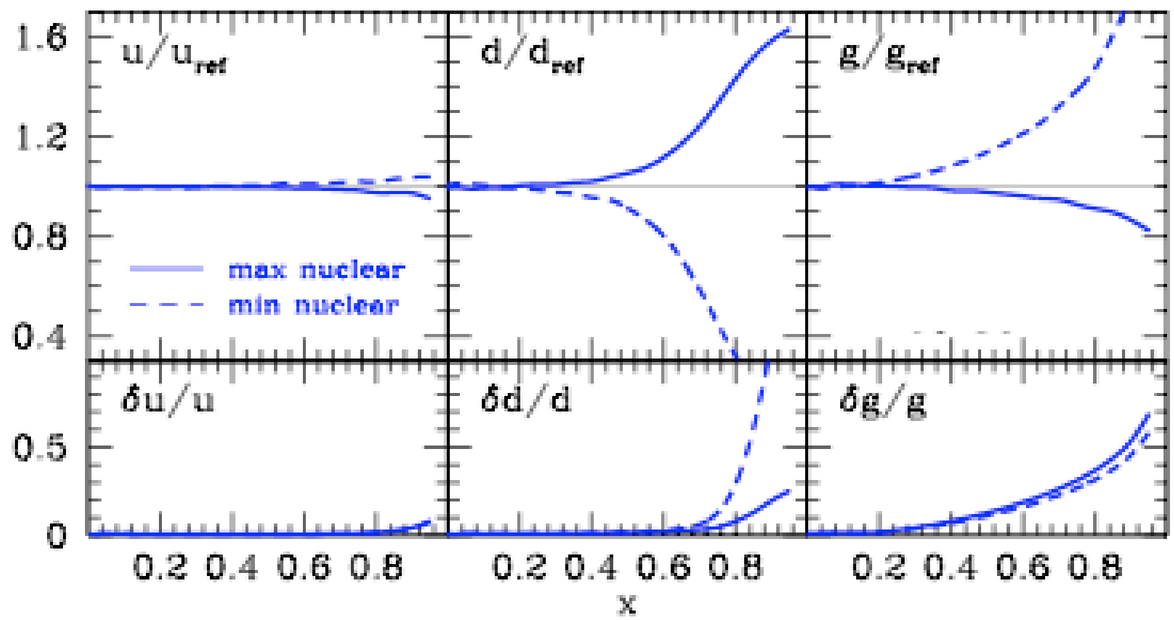
- F_2^n/F_2^p ratio is bounded below at 1/4
- Resulting uncertainty in the structure function ratio is reduced relative to that for the d/u ratio

No deuterium data study....

- Solid curve utilizes all the data, uncertainties given by the cross-hashed band
- Dashed curve results from removing all the deuterium DIS data sets, uncertainties given by the diagonal-hashed band
- Arrows indicate the extrapolation region of each fit
- Removal of the deuterium data results in a significant *increase* in the d/u ratio at *low* values of x! Shadowing models only differ ~1% - don't account for this.
- CDF W asymmetry data and the D0 lepton asymmetry data seem collectively to prefer a somewhat larger d/u ratio than is favored by the deuterium DIS data in the region below x ~ 0.2. *Under study!*



Study extreme results...

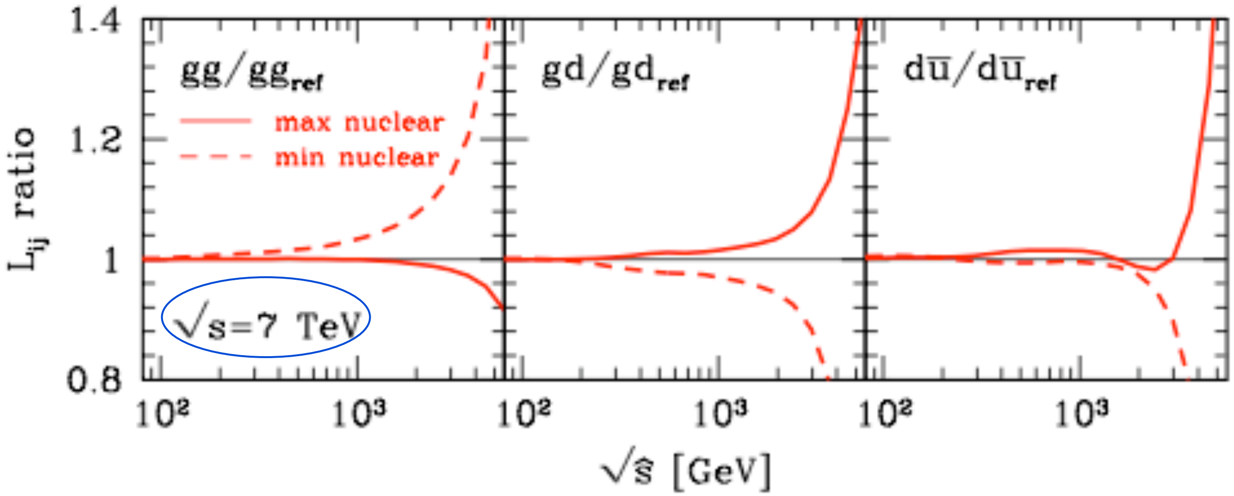


The extremes of variation of the u,d, gluon PDFs, relative to reference PDFs using different deuterium nuclear corrections

- reference PDFs use smearing function with AV18 deuteron wave function and mKP off-shell corrections

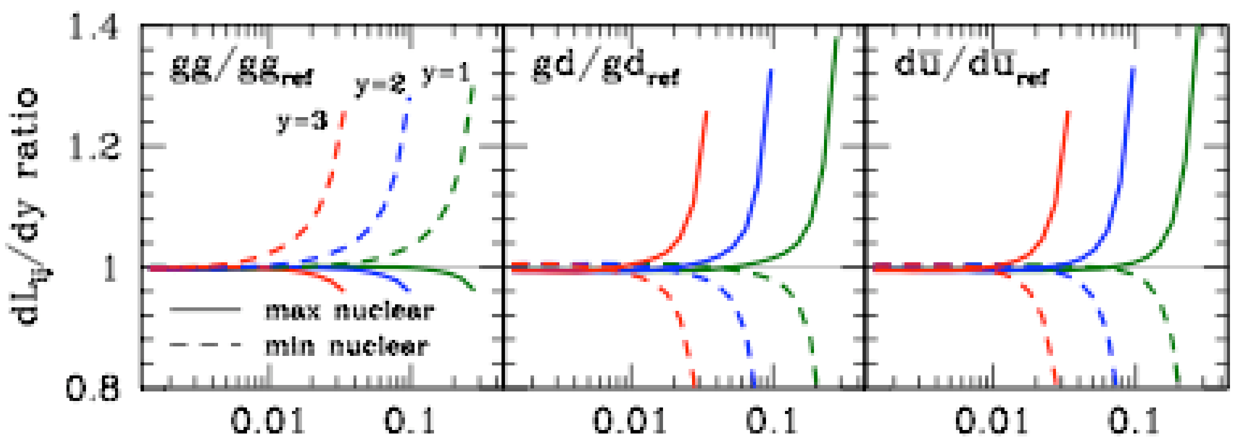
Since the u PDF is already well constrained, a variation in the d PDF is compensated by a significant and anti-correlated shift in the gluon PDF.

Implications for Collider Experiments



Uncertainty induced by nuclear corrections extends to rather small scales $\sqrt{\hat{s}}$, and grows quickly above 5–10% as $\sqrt{\hat{s}}$ exceeds 1 TeV.

fixed rapidity y = 1, 2, 3



$\tau = Q^2/S$

Larger rapidity = more sensitive to large-x region for a given mass. For example, nuclear uncertainty becomes relevant at rapidity larger than 2 for W production at the Tevatron.

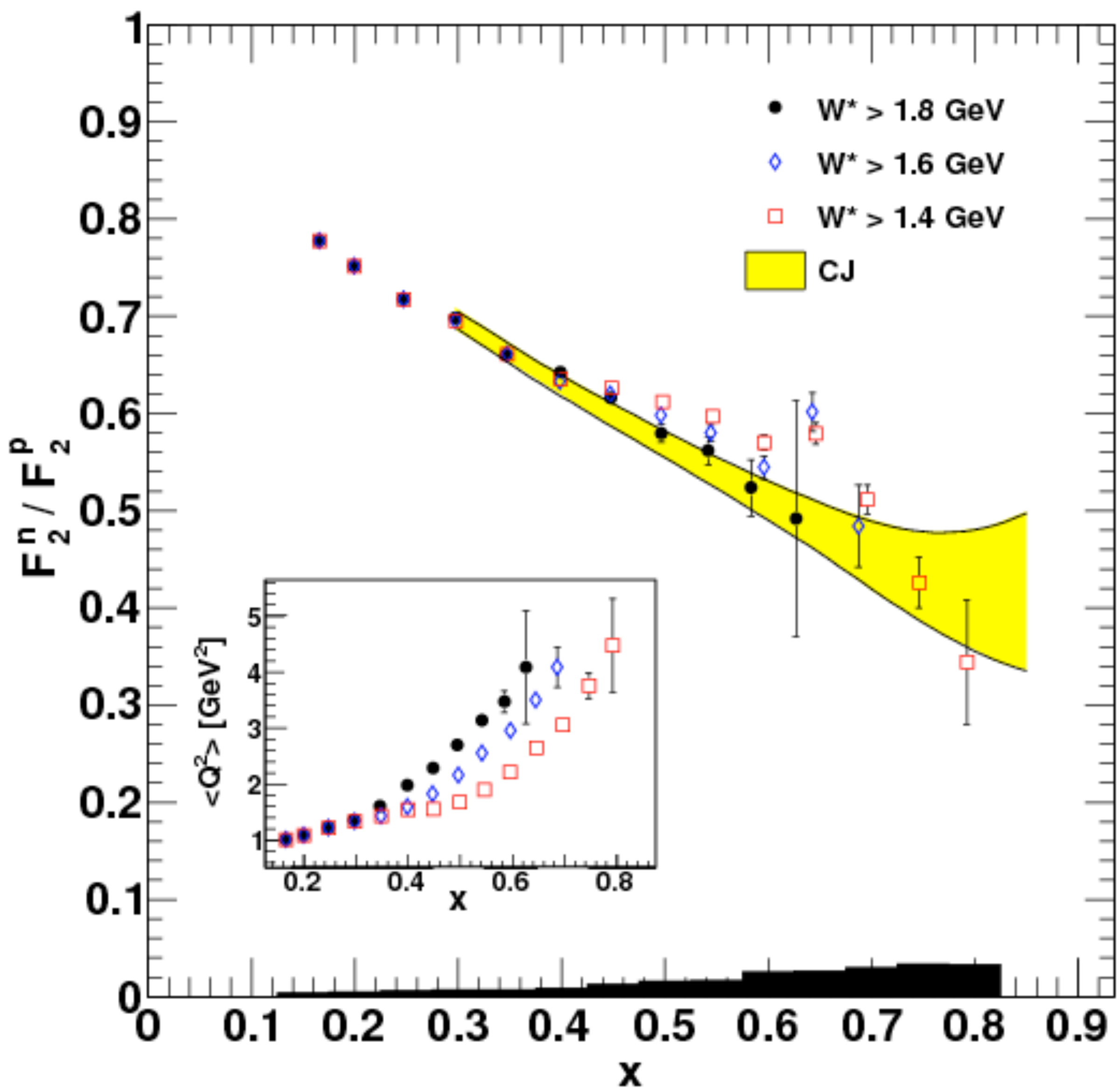
The gg, gd, du luminosities impact the main channel(s) for Higgs production, jet production, "standard candle" cross section for W^- production, respectively.

Status and Discussion

- Good fits may be obtained using lower Q and W cuts on the DIS data
- Different target mass correction prescriptions yield equivalent PDF fits as long as a simple parametrization of higher twist contributions is added, *leading twist PDF stable*
- 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)
- 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, PVDIS, MINERvA.

  Continuing effort….
- Working now with cross section (not structure function) data – improve F_L (gluon) sensitivity, reduce systematic uncertainty
- Public PDF release with uncertainties en route!

Extracted F_2^n/F_2^p (BONUS Experiment - accepted to PRL)



- BONUS actually measures (n/d)*(d/p)

- tagged kinematics creates near-free neutron target:

$P_{spectator} < 90$ MeV/c

$\theta_{spectator} < 90$

- Different Q^2 ranges for different x, W