

# **CTEQ6X: a global analysis of large-x PDFs**

**Alberto Accardi**

Hampton U. & Jefferson Lab

MENU 2010, William & Mary  
2 June 2010



# Outline

- ◆ Why large- $x$  ?
- ◆ Up and down: the CTEQ6X fit
- ◆ Constraining d-quarks at large  $x$
- ◆ Quark-hadron duality
- ◆ Conclusions

**Why large x ?**

# Why large $x$ ?

- ✚ Large (experimental) uncertainties in quark and gluon PDF at  $x > 0.5$
- ✚ Precise PDF at large  $x$  are needed, e.g.,
  - ✚ at LHC, Tevatron
    - 1) New physics as excess on QCD large  $p_T$  spectra  $\Leftrightarrow$  large  $x$  PDF
    - 2) Luminosity monitoring at large mass –  $Z, W$  cross-sections
  - ✚ Non-perturbative nucleon structure –  $d/u, \Delta u/u, \Delta d/d$  at  $x \rightarrow 1$
  - ✚ Spin structure of the nucleon *at small  $x$*
  - ✚ Neutrino oscillations

# Why large $x$ ...and low $Q^2$ ?

→ JLab and SLAC have precision DIS data at large  $x$  , BUT low  $Q^2$

→ need of theoretical control over

- 1) higher twist  $\propto \Lambda^2/Q^2$
  - 2) target mass corrections (TMC)  $\propto x_B^{-2} m_N^{-2}/Q^2$
  - 3) nuclear corrections
  - 4) quark-hadron duality
  - 5) jet mass corrections (JMC)  $\propto m_j^{-2}/Q^2$
  - 6) heavy-quark mass corrections  $\propto m_Q^{-2}/Q^2$
  - 7) large- $x$  resummation
  - 8) large- $x$  DGLAP evolution
  - 9) parton recombination at large  $x$
  - 10) perturbative stability at low- $Q^2$
  - 11) ...
- }
- this talk

# **Up and down: the CTEQ6X fit**

Accardi, Christy, Keppel, Melnitchouk, Monaghan, Morfín, Owens,  
Phys. Rev. D 81, 034016 (2010)

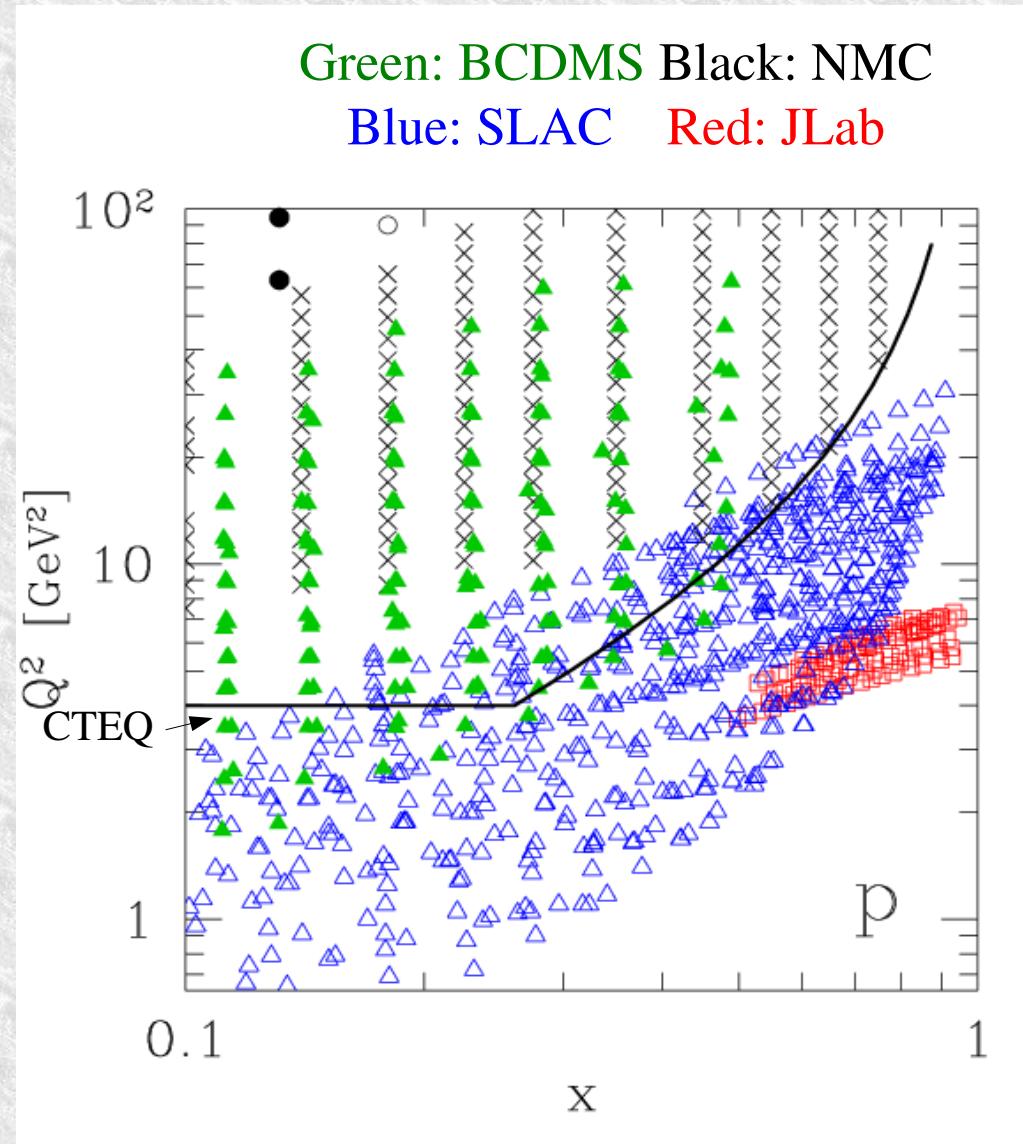
**(a JLab/HU/CTEQ collaboration)**

# CTEQ6X vs. CTEQ

## CTEQ

$$Q^2 \geq 4 \text{ GeV}^2 \quad W^2 \geq 12.25 \text{ GeV}^2$$

- not so large  $x$ , not too low  $Q^2$
- hope  $1/Q^2$  corrections not large



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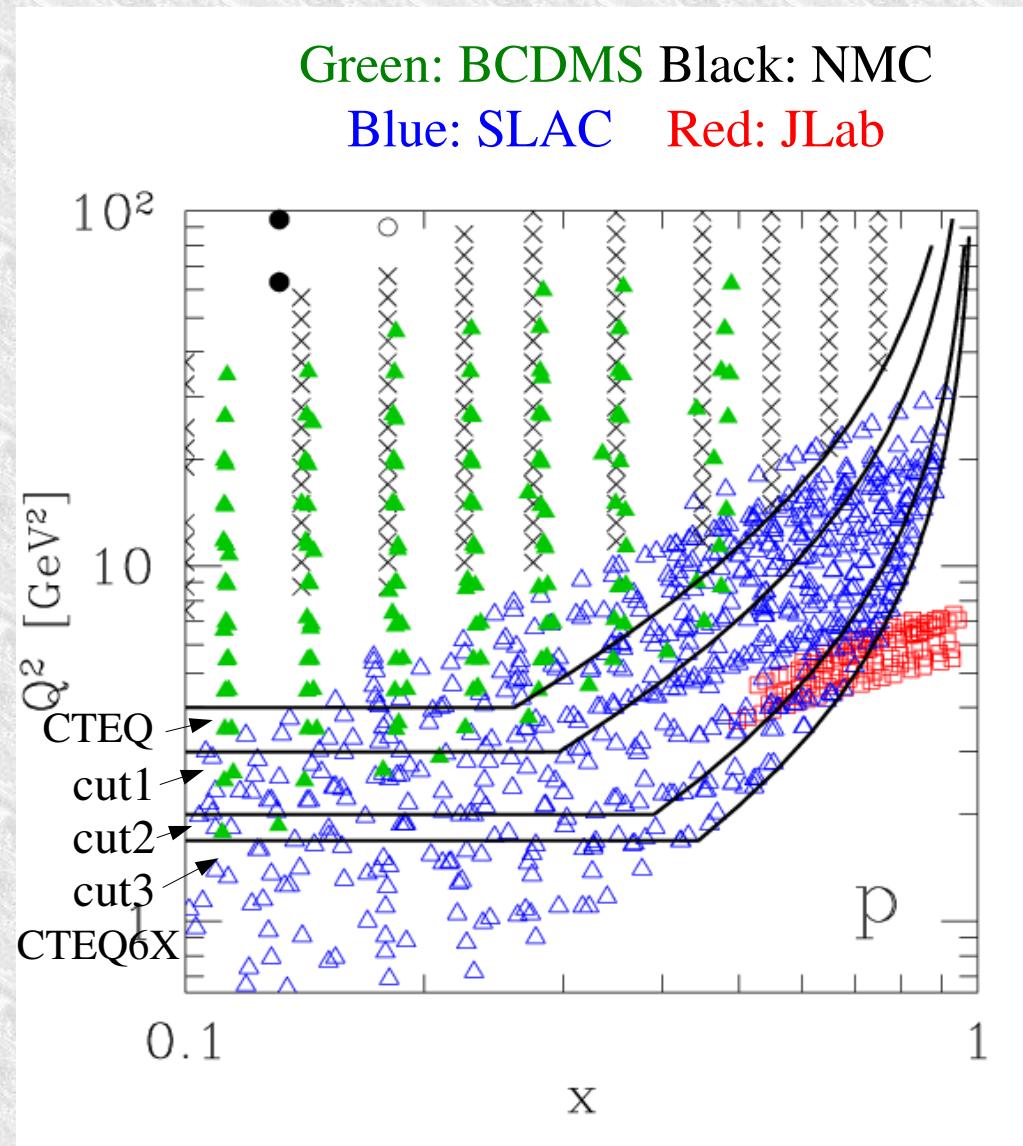
- + not so large  $x$ , not too low  $Q^2$
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## CTEQ6X

- + TMC, HT, deuteron corrections
- + Progressively lower the cuts:

	$Q^2$ [GeV $^2$ ]	$W^2$ [GeV $^2$ ]
CTEQ $\equiv$ cut0	4	12.25
cut1	3	8
cut2	2	4
cut3	1.69	3

- + Better large- $x$ , low- $Q^2$  coverage



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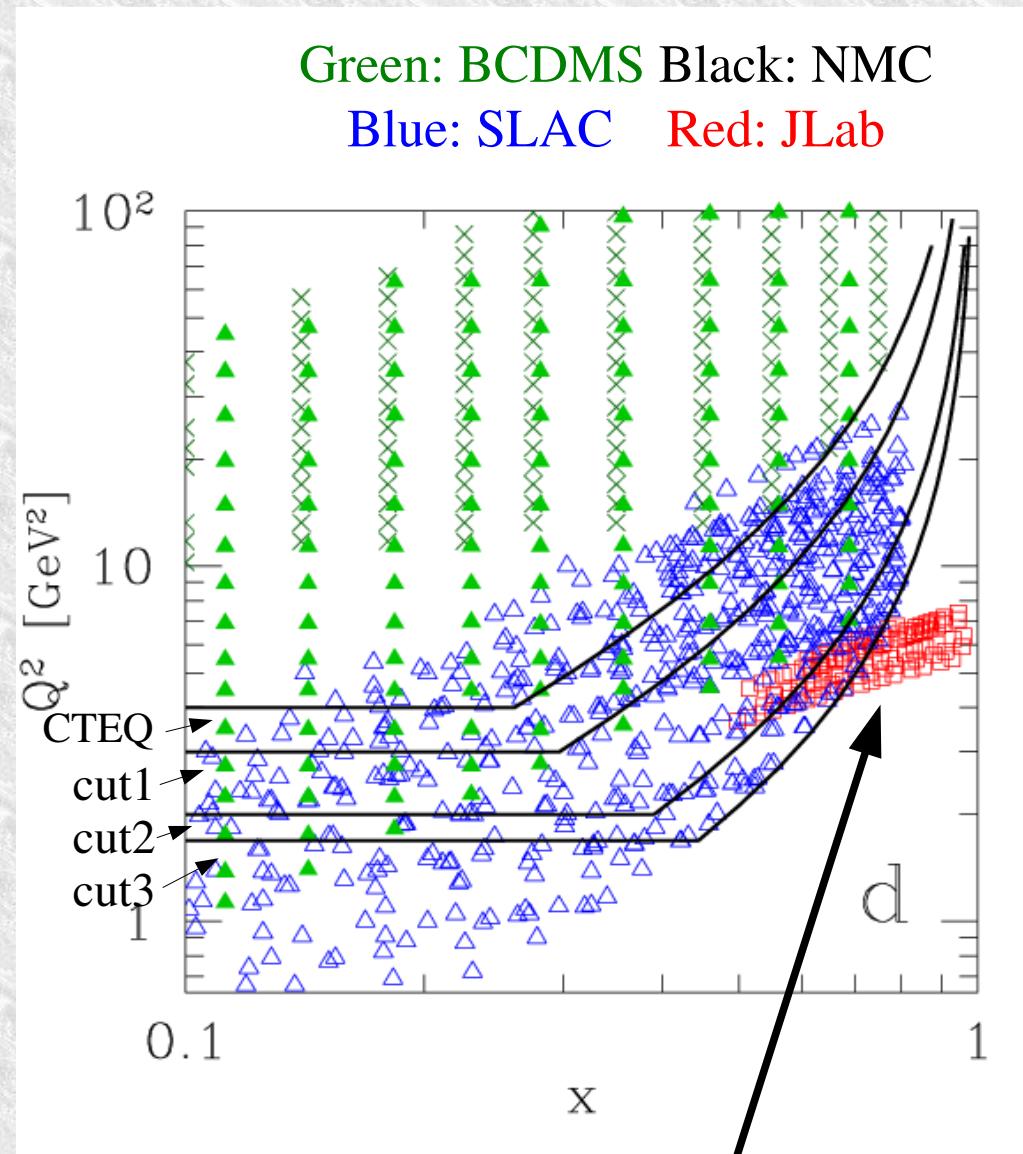
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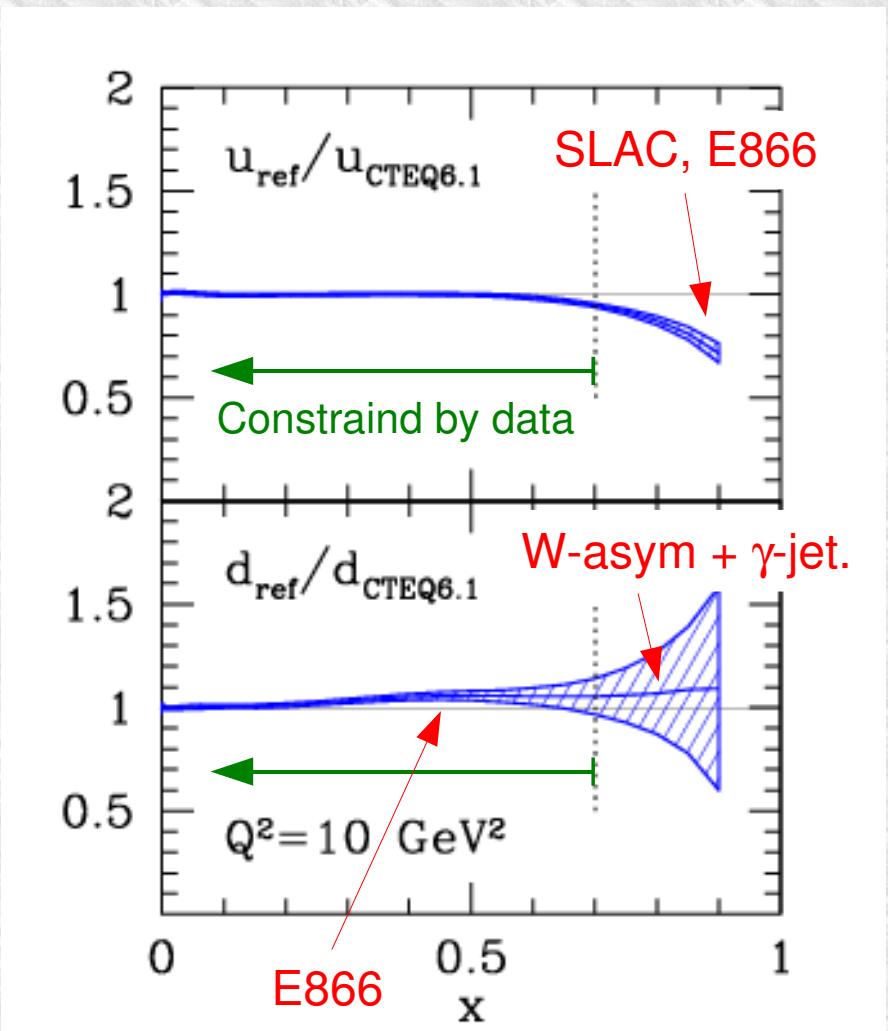
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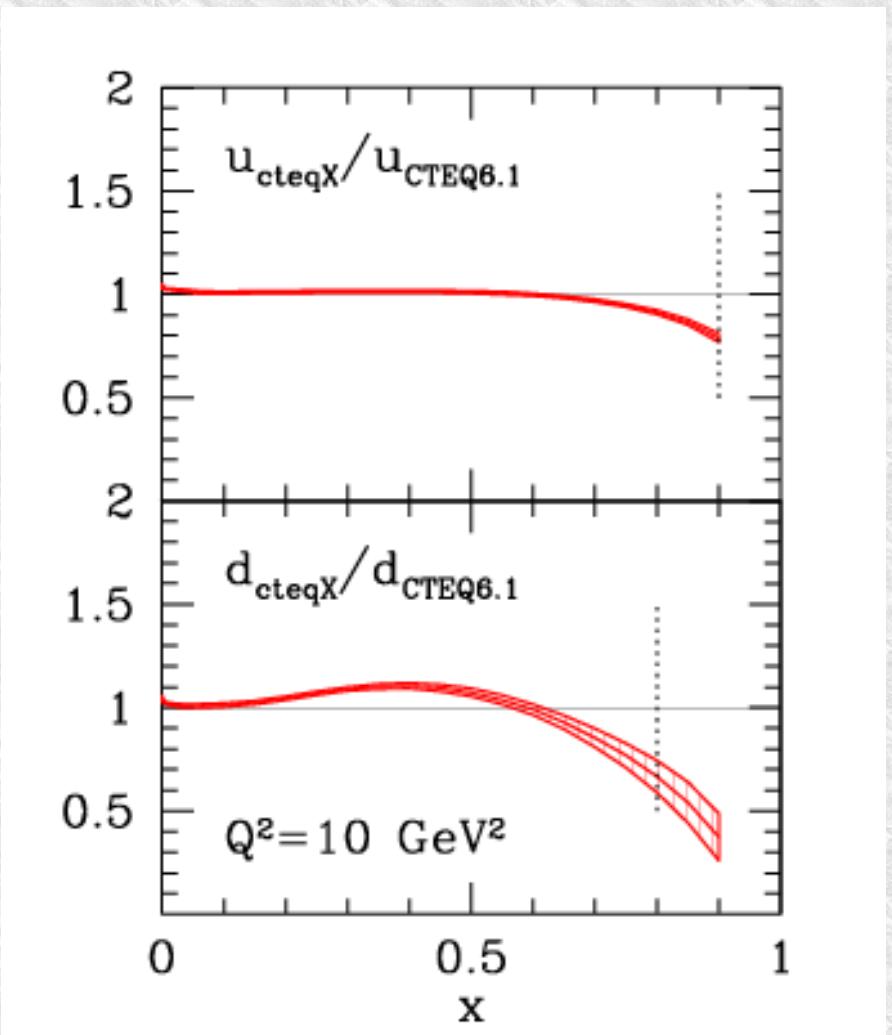
# Reference fit



- ◆ Reference fit:
  - ✚ cut0, no corrections
  - ✚ PDF errors with  $\Delta\chi=1$

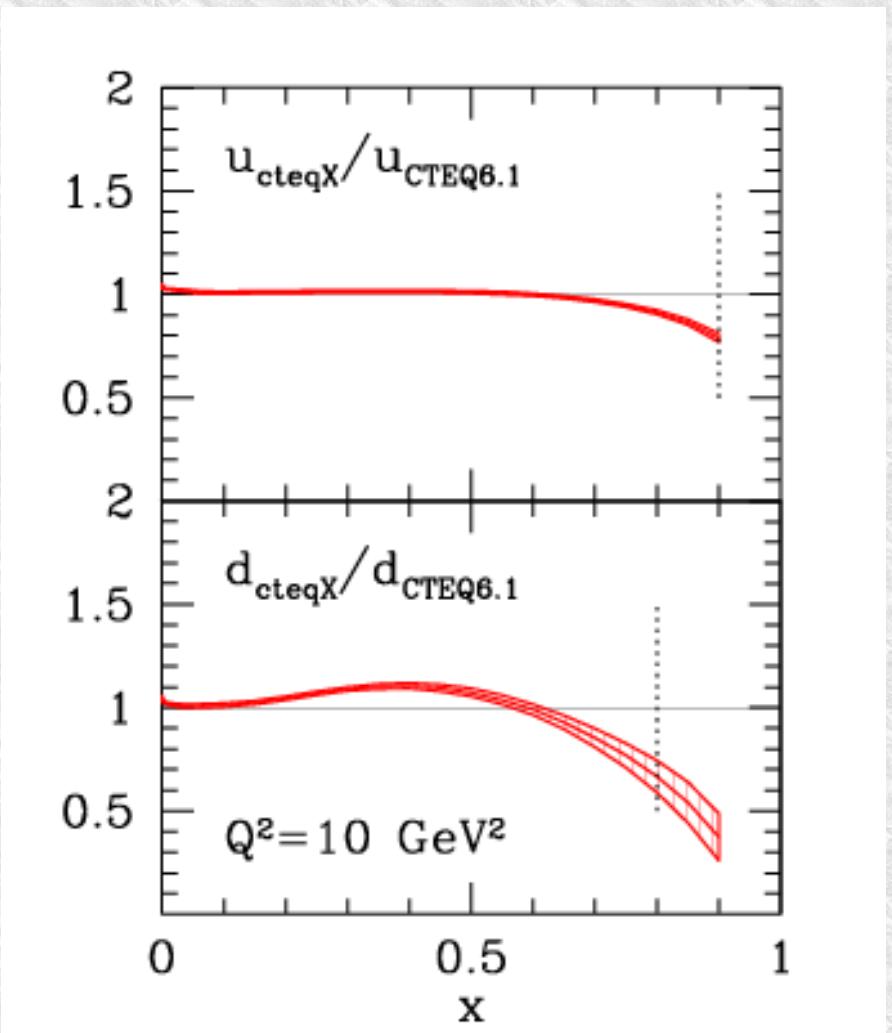
	data	CTEQ6.1
DIS	(JLab)	NO
	SLAC	NO
	NMC	✓
	BCDMS	✓
	H1	✓
	ZEUS	✓
DY	E605	✓
	E866	NO
W	CDF '98 ( $\ell$ )	✓
	CDF '05 ( $\ell$ )	NO
	D0 '08 ( $\ell$ )	NO
	D0 '08 ( $e$ )	NO
	CDF '09 ( $W$ )	NO
jet	CDF	✓
	D0	✓
$\gamma+\text{jet}$	D0	NO

# CTEQ6X fit



- ◆ CTEQ6X fit:
  - ✚ cut3, TMC+HT
  - ✚ deuteron corrections
  - ✚ extended x-range
- ◆ TMC, HT compensate each other
- ◆ u-quark vs. CTE6.1:
  - ✚ almost unchanged
- ◆ d-quark vs. CTEQ6.1
  - ✚ due to deuteron corrections
- ◆ Reduced PDF errors
  - ✚ about 30-50%

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# Deuterium corrections

- ◆ Nuclear Smearing Model

[Kahn et al., PRC79(2009)  
Accardi,Qiu,Vary, *in preparation*]

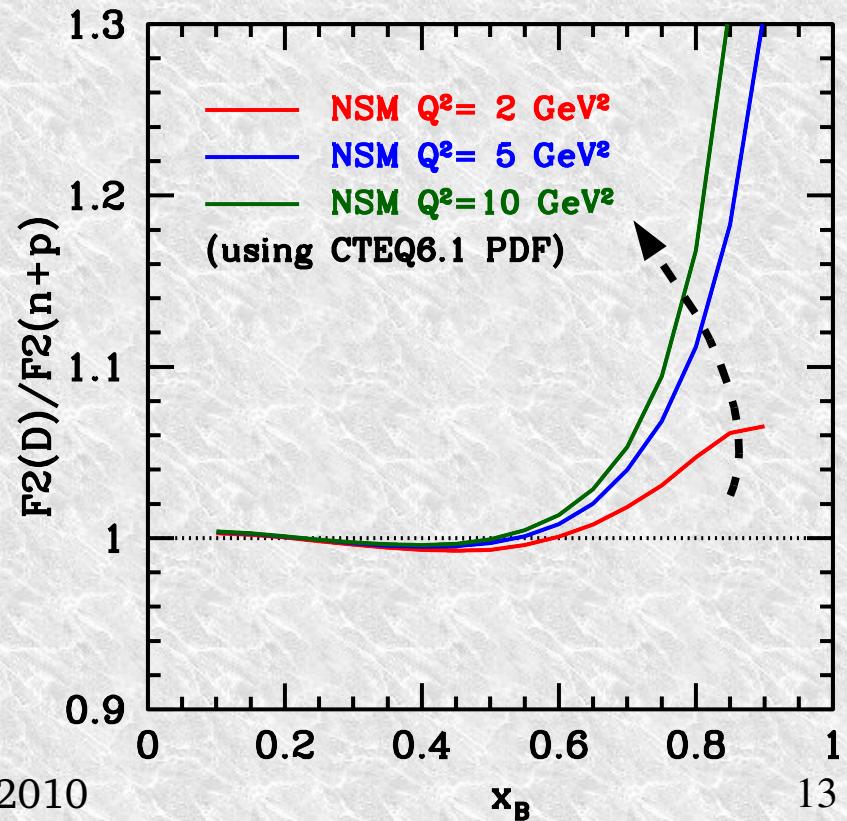
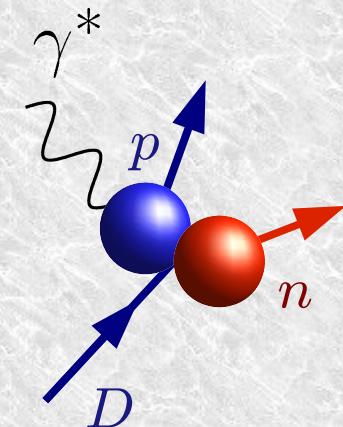
- ◆ nucleon Fermi motion and binding energy
- ◆ use non-relativistic deuteron wave-function
- ◆ finite- $Q^2$  corrections

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

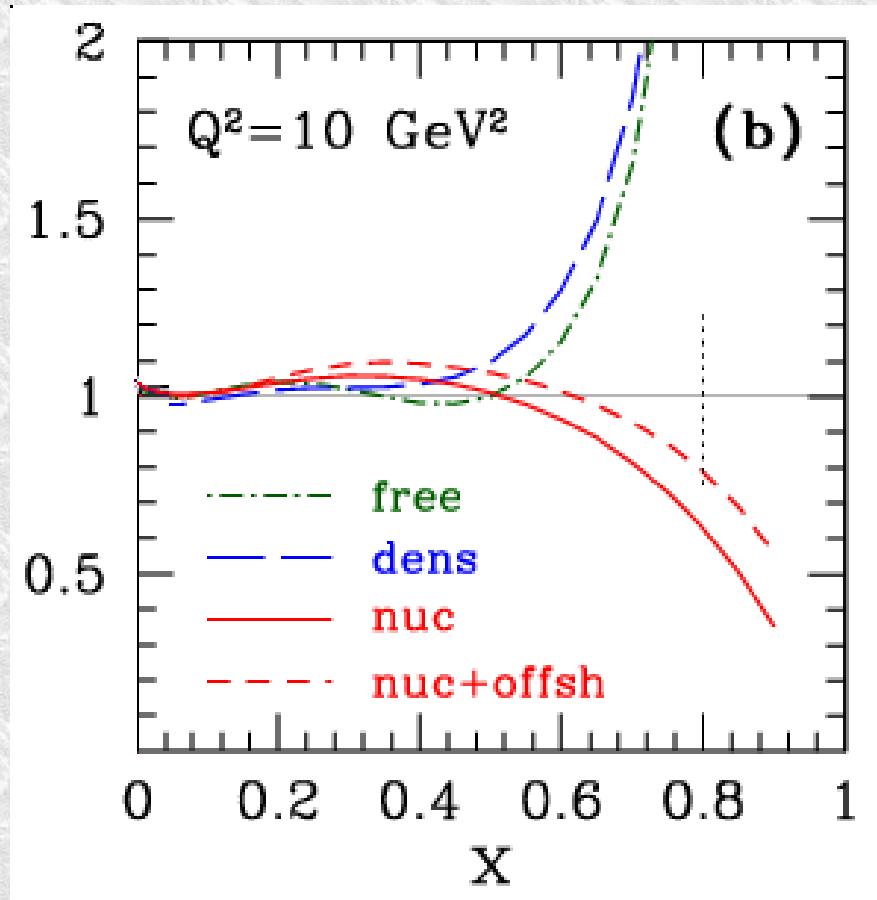
$$\gamma = \sqrt{1 + 4x_B^2 m_N^2 / Q^2}$$

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

- ◆ off-shell effects can be included in  $S_A$



# Deuterium corrections

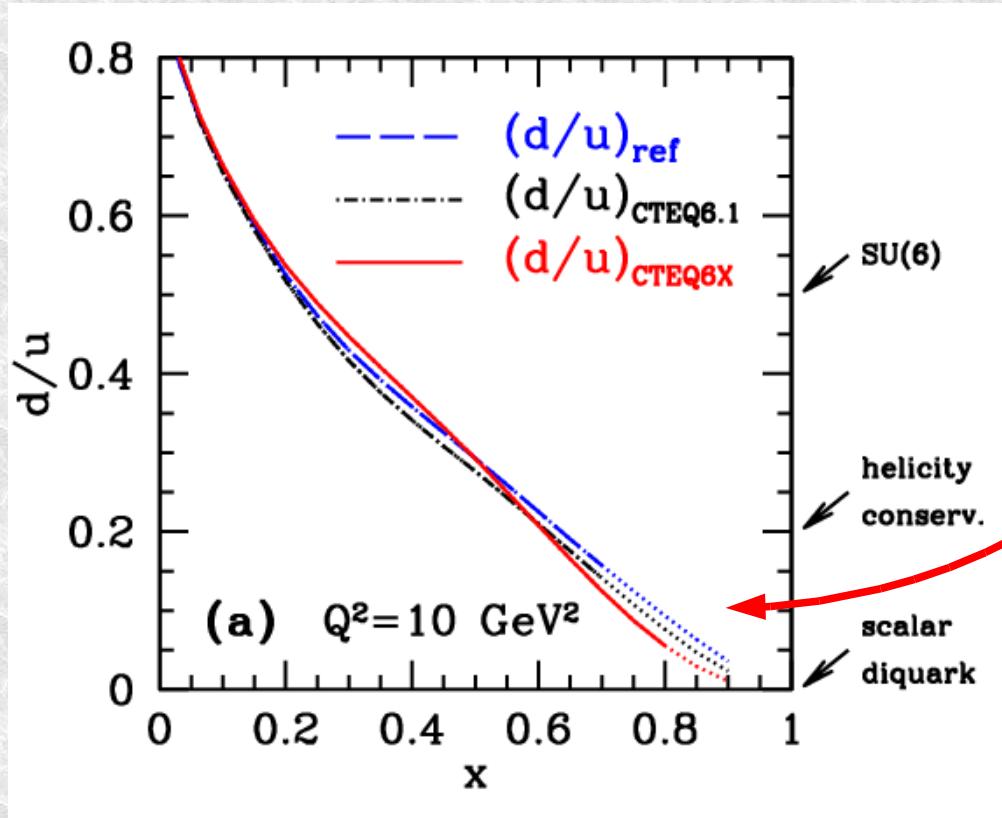


- ◆  $d$ -quarks are very sensitive to deuterium corrections
- ◆ Off-shell corrections completely absorbed by the  $d$ -quark

free = free p+n  
dens = density model corrections  
nuc = WBA smearing model  
offsh = off-shell corrections

[Melnitchouk et al., '94]

# Impact on d/u limit



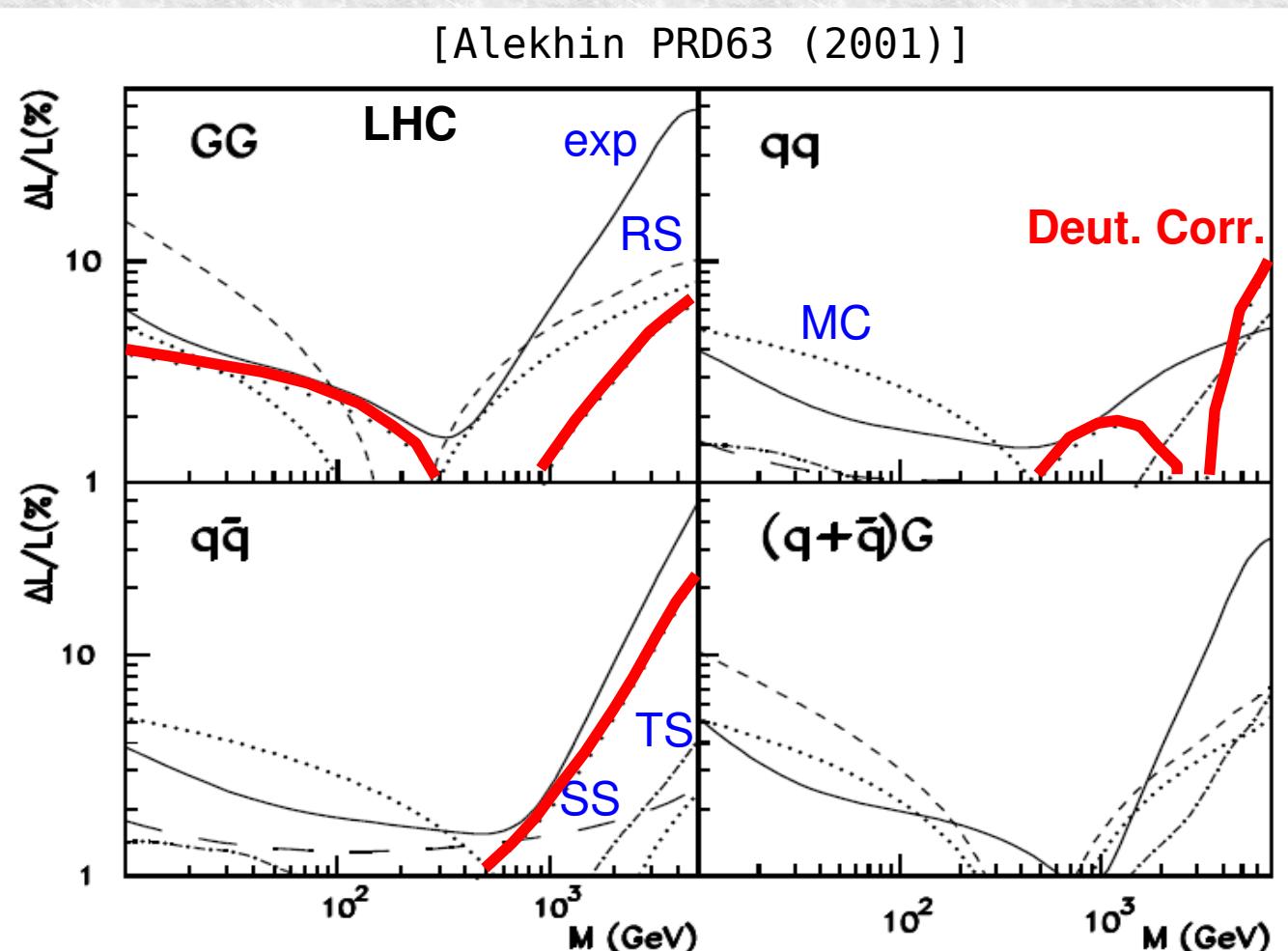
## NOTE:

$d/u$  constrained to  $\rightarrow 0$   
by CTEQ parametrization  
at  $Q_0^2 = 1.69 \text{ GeV}^2$

- Allow  $d/u$  to be finite at  $x=1$ : new parametrization at  $Q_0$
- Limit completely correlated to nuclear correction:  $d/u \xrightarrow{x \rightarrow 1} c \approx 0 - 2$
- HUGE theoretical uncertainty!

# Impact on LHC

- Parton luminosities:  $L_{i,j}(M) = \frac{1}{S} \int_{M^2/s}^1 \frac{dx}{x} q_i(x, M^2) q_j(M^2/(xs), M^2)$
- Nuclear model uncertainty  $\sim 10\%$  at large  $x$ :
  - dominates Z cross-sections used as luminosity monitor



exp = experimental  
 RS = renorm. scale  
 MC = charm mass  
 TS = charm threshold  
 SS = strangeness suppr.

**d-quarks at large x**

# Free nucleon targets

- ◆ Constraints on large- $x$   $d$ -quarks from

- ✚  $p+p(\bar{p})$  : DY at large  $x_F$

$$pp(\bar{p}) \longrightarrow \mu^+ \mu^- X$$

- ✚  $p+p(\bar{p})$  : W-asymmetry at large rapidity [D0 and CDF]

$$pp(\bar{p}) \longrightarrow W^\pm X$$

- ✚  $\nu+p$  and  $\nu\bar{p}+p$

- WA21 already has data

- (but hard to reconstruct cross-sections from published “quark distributions”)

- MINERvA with a hydrogen target

$$\nu(\bar{\nu}) p \longrightarrow l^\pm X$$

- ✚ Parity Violating DIS \*

- L/R electron asymmetry  $\Rightarrow \gamma/Z$  interference  $\propto d/u$

$$\vec{e}_L(\vec{e}_R) p \longrightarrow e X$$

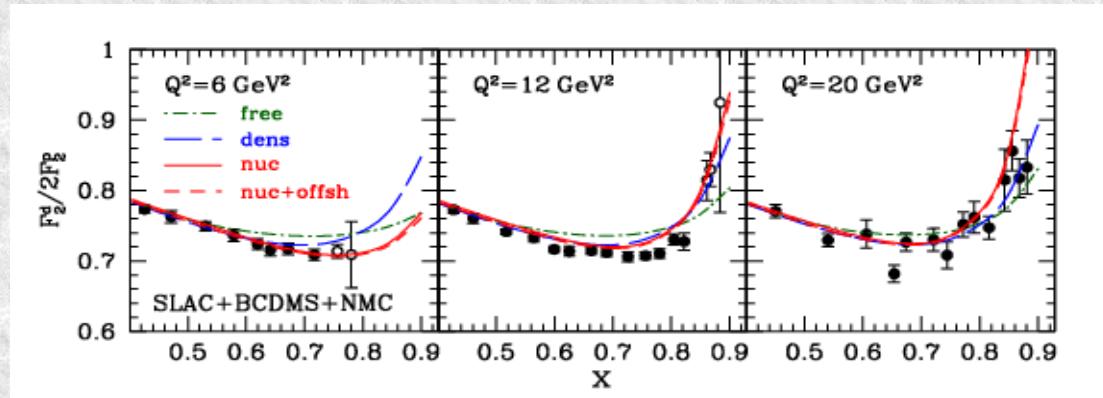
- ✚ Charged current structure functions [H1 and ZEUS]

$$e p \longrightarrow \nu X$$

\* planned for Jlab at 12 GeV

# Constraining the nuclear corrections

- ◆  $Q^2$  dependence of  $D/p$  ratios at large  $x$

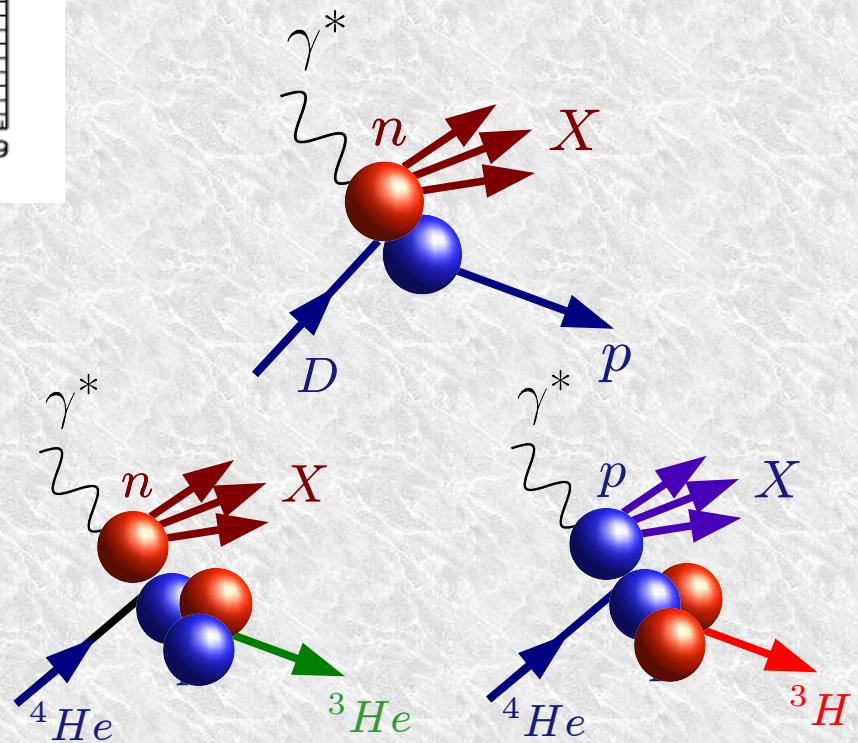


- ◆ Quasi-free nucleon targets <sup>\*</sup>  
[BONUS, E94-102 and EG6 at JLab 6 GeV]

$$e A \rightarrow e (A - 1) X$$

- ◆  ${}^3\text{He}$  -  ${}^3\text{H}$  mirror nuclei <sup>\*</sup>

$$\frac{{}^3\text{H}}{{}^3\text{He}} \approx \frac{n}{p} \frac{2 + p/n}{2 + n/p}$$



<sup>\*</sup> planned for Jlab at 12 GeV

# **Quark-hadron duality**

# Proton

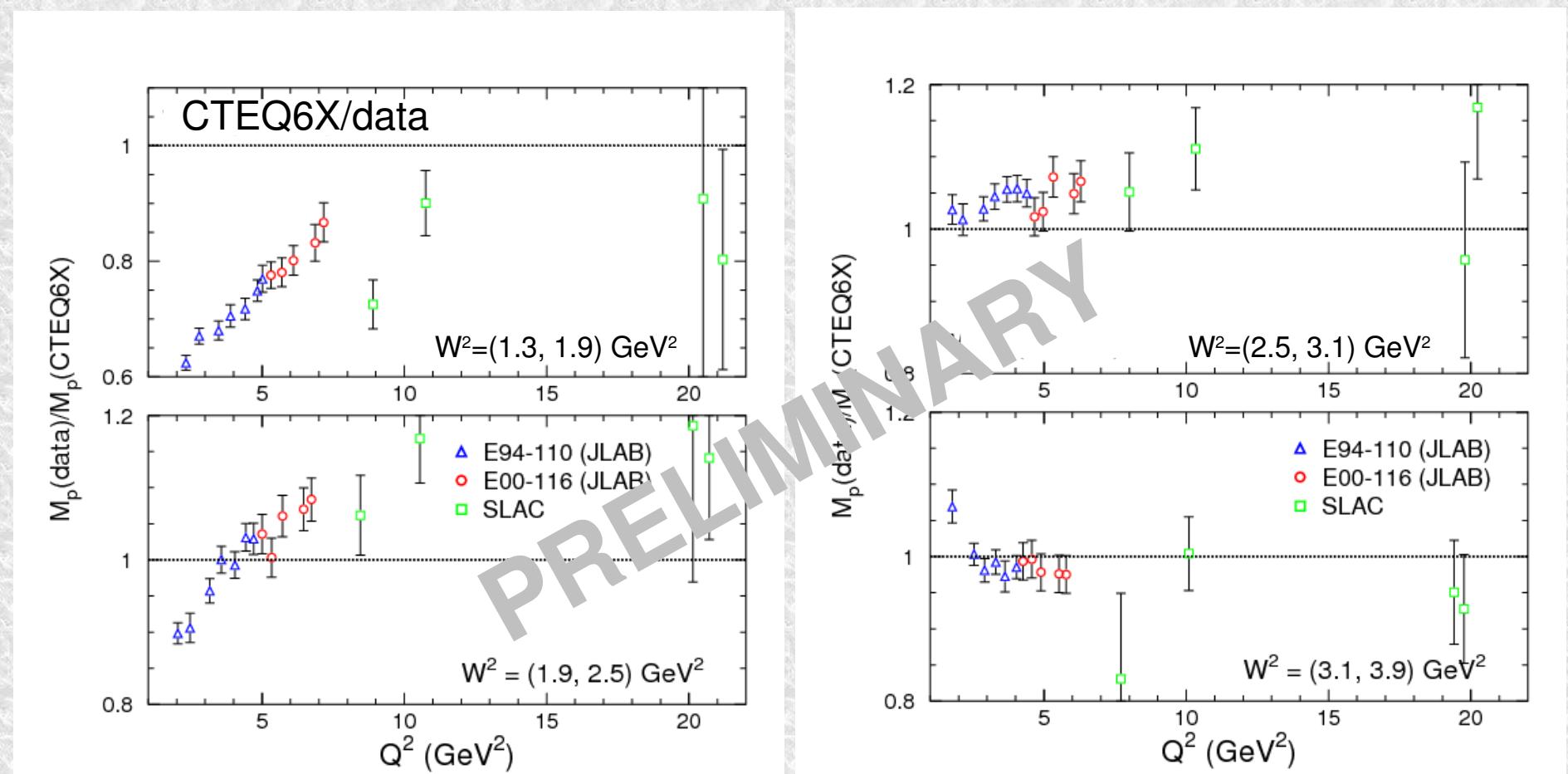
[Accardi, Malace, in preparation]

- Truncated moments, plotted at an “average”  $x$

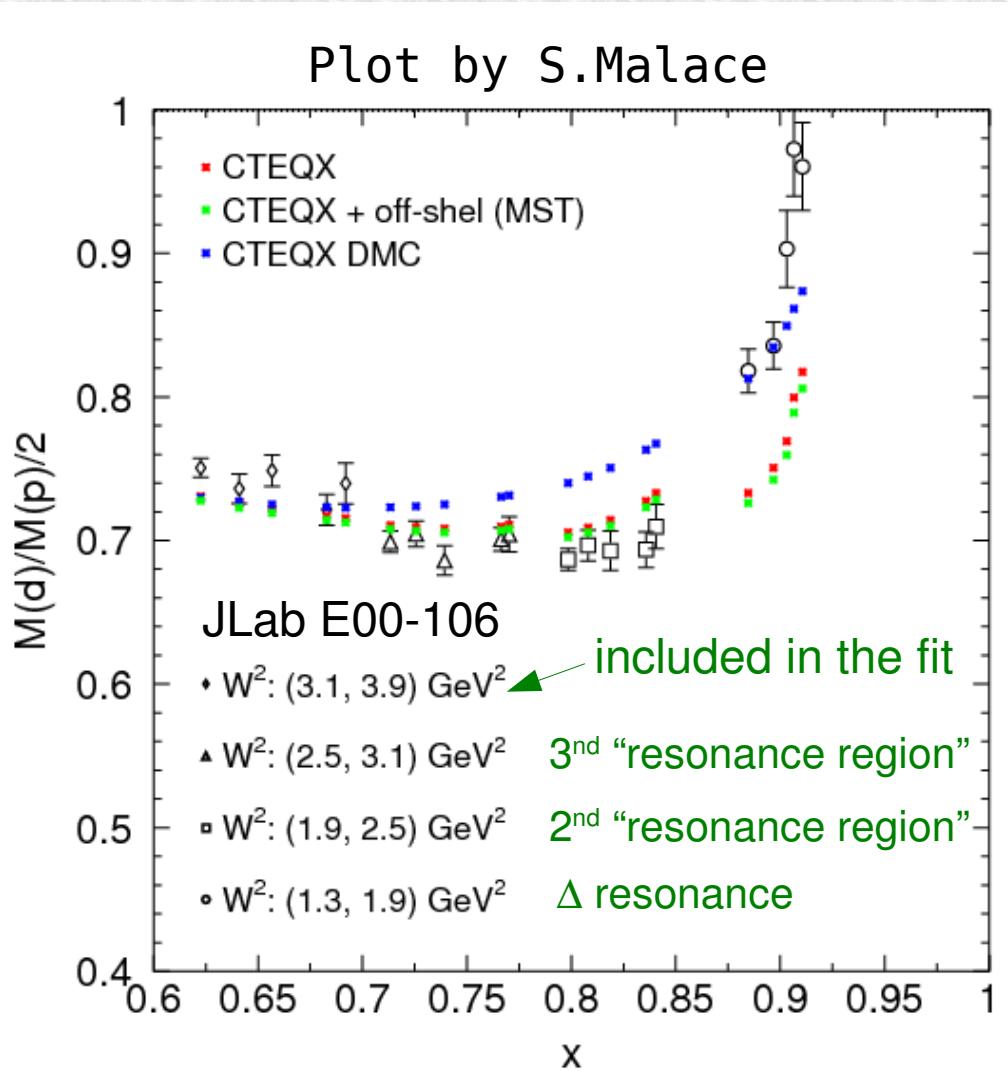
Malace et al, PRC80, 035207, 2009

$$M = \int_{W=[W_m, W_M]} dx F_2(x)$$

- Quark-hadron duality works to less than 5% up to  $\Delta$  region*



# Deuteron at JLab 6 GeV...



- ✚  $Q^2$  runs with  $x$ 
  - smearing has correct shape
  - Density Model disfavored
- ✚ Too small  $Q^2$  leverage for further constraining d-quarks

# ...and at the 12 GeV upgrade

Jlab E10-002 experiment, Malace, Niculescu, Keppel, spokespersons.

Precision measurements of the  $F_2$  structure function at large  $x$  in the resonance region and beyond

S.P. Malace (Spokesperson), M. Paolone, and S. Strauch  
*University of South Carolina, Columbia, South Carolina 29208*

I.M. Niculescu (Spokesperson) and G. Niculescu  
*James Madison University, Harrisonburg, Virginia 22807*

A. Accardi, I. Albayrak, O. Ates, E. Christy, C. Jackson, C. Keppel (Spokesperson),  
M. Kohl, Y. Li, P. Monaghan, A. Pushkarnamari, J. Taylor, T. Walton, and J. Williams  
*Hampton University, Hampton, Virginia 23668*

R. Ent, H. Fenker, D. Gaskell, M.K. Jones, D. Meekins, P. Solvignon, A. Smith, and L. Tang  
*Thomas Jefferson National Accelerator Facility, Newport News, Virginia 23606*

A. Asaturyan, A. Mkrtchyan, H. Mkrtchyan, V. Ter-Antonyan, and S. Zhamkochyan  
*Yerevan Physics Institute, Yerevan, Armenia*

G. Gossiaux  
*University of Regina, Regina, Saskatchewan, Canada, S4S 0A2*

S. Danagolian  
*North Carolina A&T State University, Greensboro, North Carolina 27411*

P. Markowitz  
*Florida International University, University Park, Florida 33199*

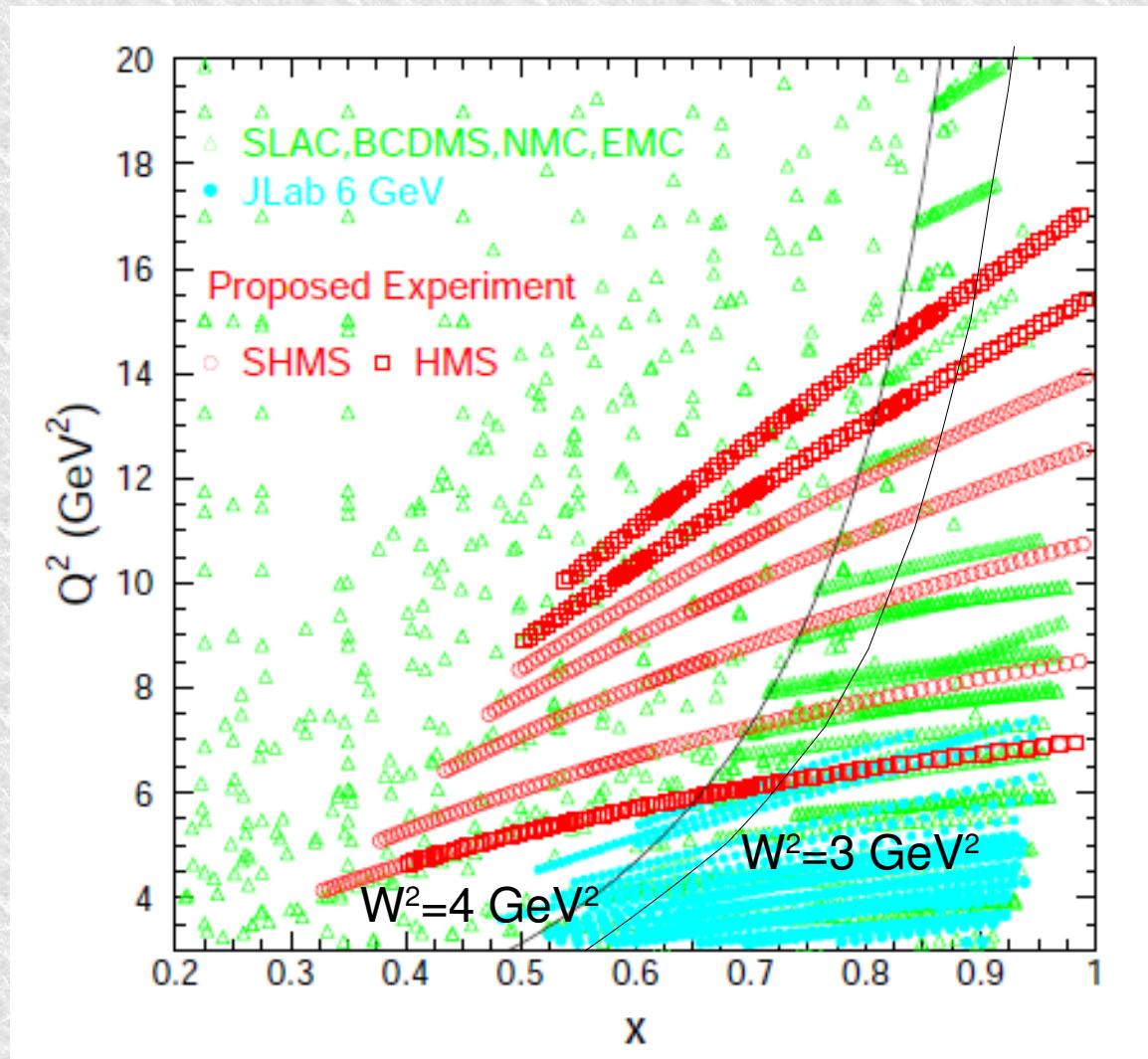
A. Daniel  
*Ohio University, Athens, Ohio 45701*

T. Horn  
*Catholic University of America, Washington DC 20064*  
(Dated: December 11, 2009)

JLab12 experiment 10-002

# ...and at the 12 GeV upgrade

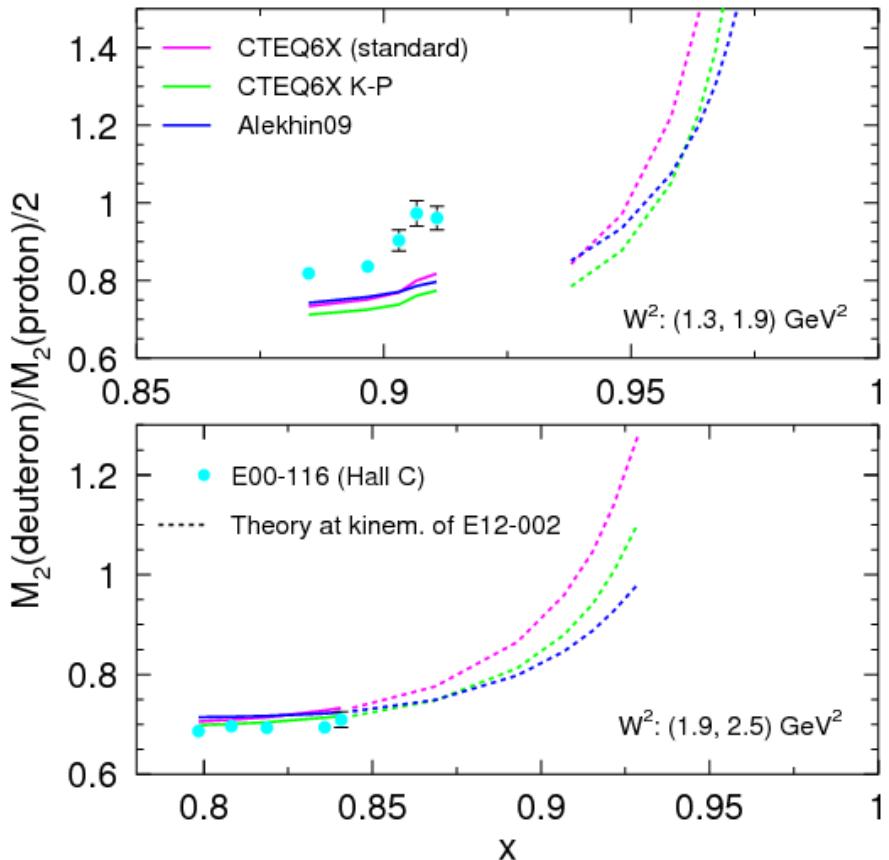
Jlab E10-002 experiment, Malace, Niculescu, Keppel, spokespersons.



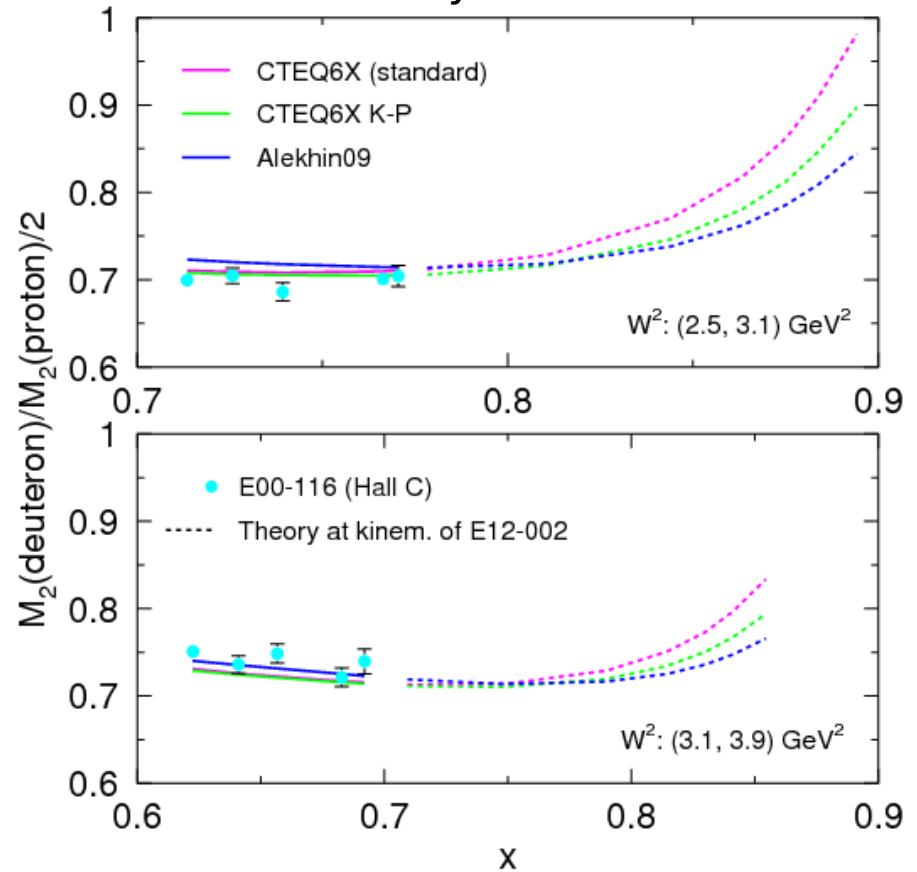
# ...and at the 12 GeV upgrade

Jlab E10-002 experiment, Malace, Niculescu, Keppel, spokespersons.

Plot by S.Malace



Plot by S.Malace



*Enough  $Q^2$  leverage for constraining the d-quark*

# Conclusions

- ★ Large-x, low-Q<sup>2</sup> region manageable in global PDF fits
- ★ Large, dominant nuclear corrections uncertainty
- ★ Need data on free nucleons, large-x
  - scarce for now, deuteron unavoidable

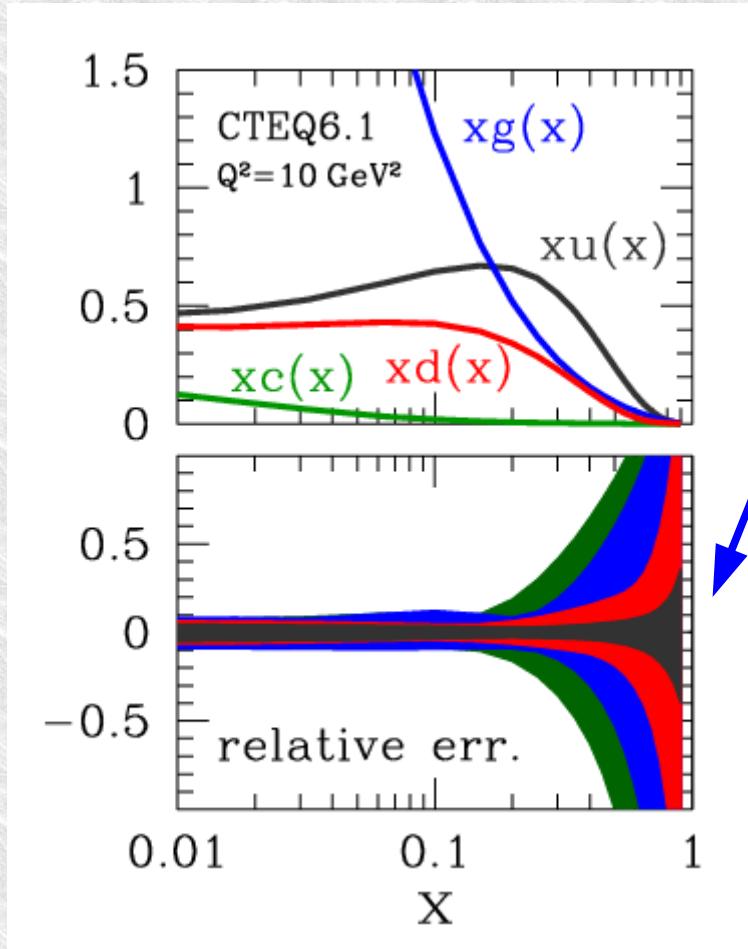
In the near future...

- ★ Nuclear corrections systematics [CTEQ-X, in preparation]
  - effects on d/u ratio, LHC, Drell-Yan
- ★ Applications to quark-hadron duality [Accardi, Malace, in prep.]
  - use resonance region data in global PDF fits?
- ★ Applications to spectator-tagged DIS [Accardi, Melnitchouk]

# **BACKUP SLIDES**

# Why large $x$ ?

- Large uncertainties in quark and gluon PDF at  $x > 0.4$  – e.g., CTEQ6.1



- PDF errors
  - propagation of exp. errors into the fit
  - statistical interpretation
  - reduced by enlarging the data set
- Theoretical errors
  - often poorly known
  - difficult to quantify
  - can be dominant

# Why large $x$ ?

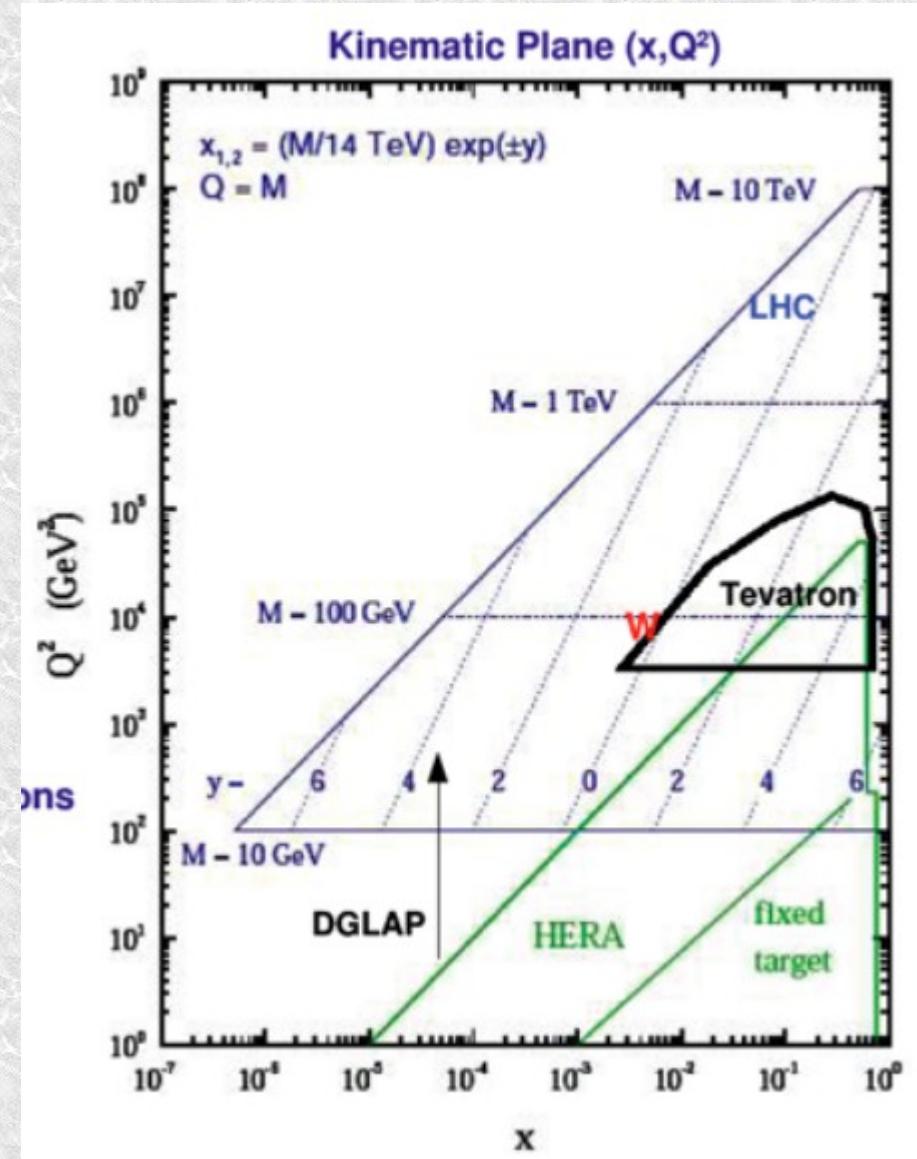
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- ◆ Precise PDF at large  $x$  are needed, e.g.,
  - ◆ at LHC, Tevatron
    - 1) DGLAP evolution feeds large  $x$ , low  $Q^2$  into lower  $x$ , large  $Q^2$
    - 2) New physics as excess on QCD large- $p_T$  spectra  $\Leftrightarrow$  large  $x$  PDF
  - ◆ Example: Z' production

$$M_{Z'} \gtrsim 200 \text{ GeV} \quad x = \frac{m_T}{\sqrt{s}} e^y$$

$$x \geq 0.02 \text{ (LHC)}, \quad 0.1 \text{ (Tevatron)}$$

but recent work raises the bar:

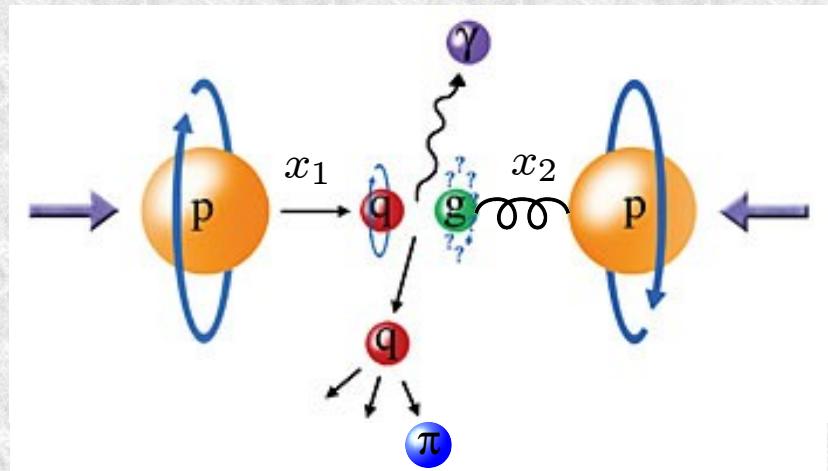
$$M_{Z'} \gtrsim 900 \text{ MeV}$$



# Why large $x$ ?

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- Precise PDF at large  $x$  are needed, e.g.,
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    - New physics as excess on QCD large  $p_T$  spectra  $\Leftrightarrow$  large  $x$  PDF
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  - spin structure of the nucleon – most spin at large- $x$ , but also, e.g.,

$$\sigma(p\vec{p} \rightarrow \pi^0 X) \propto \Delta q(x_1) \Delta g(x_2) \hat{\sigma}^{qg \rightarrow qg} \otimes D_q^{\pi^0}(z)$$

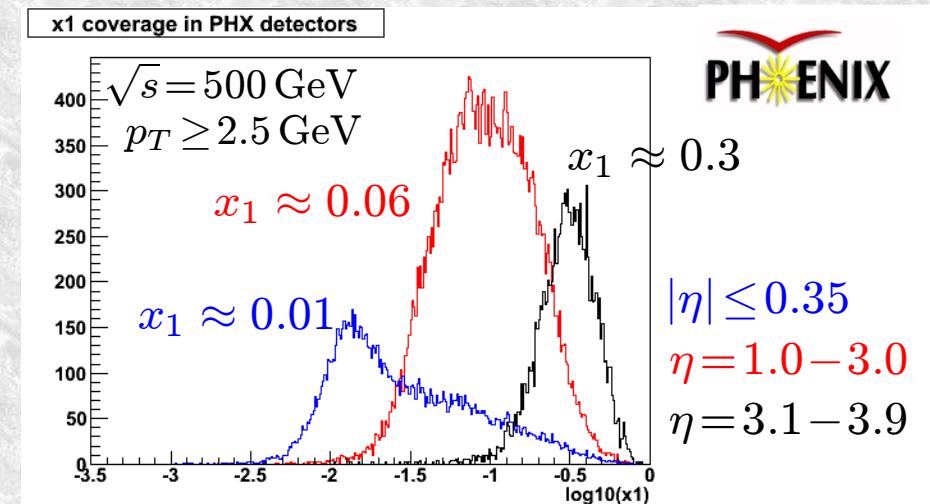
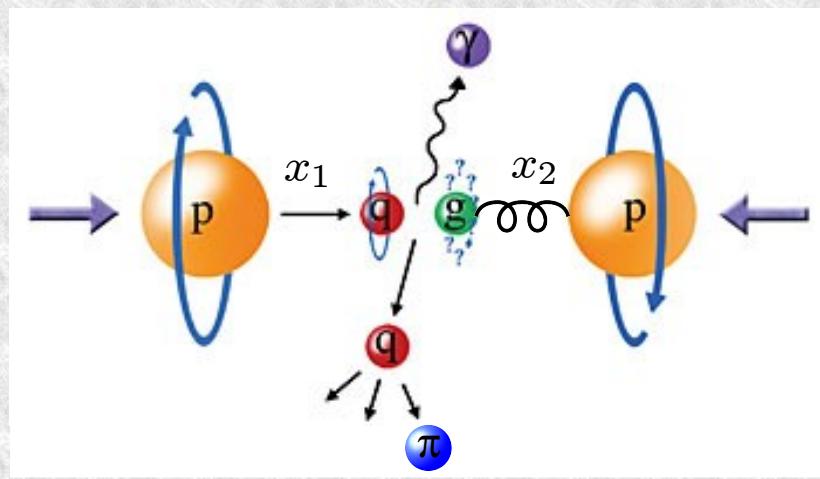


$$x_1 \sim \frac{p_T}{\sqrt{s}} e^y$$
$$x_2 \sim \frac{p_T}{\sqrt{s}} e^{-y}$$

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# Target mass corrections

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

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

- ◆ respects kinematic boundaries

- ◆  $\xi$ -rescaling, uses  $x_{\max} = 1$  [Aivazis et al '94; Kretzer,Reno '02]

$$F_{T,L}^{nv}(x_B, Q^2, m_N) \equiv F_T^{(0)}(\xi, Q^2)$$

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

# “Higher-Twists” parametrization

- ◆ Parametrize by a multiplicative factor:

$$F_2(\text{data}) = F_2(\text{TMC}) \times \left(1 + \frac{C(x_B)}{Q^2}\right)$$

with

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

- ◆ Important:  $C(x_B)$  includes
  - ◆ dynamical higher-twists (parton correlations)
  - ◆ all uncontrolled power corrections:
    - ✓ TMC model uncertainty, Jet Mass Corrections
    - ✓ NNLO corrections (power-like at small  $Q$ )
    - ✓ ...

# Deuterium corrections

- ◆ Nuclear Smearing Model

[Kahn et al., PRC79(2009)  
Accardi,Qiu,Vary, *in preparation*]

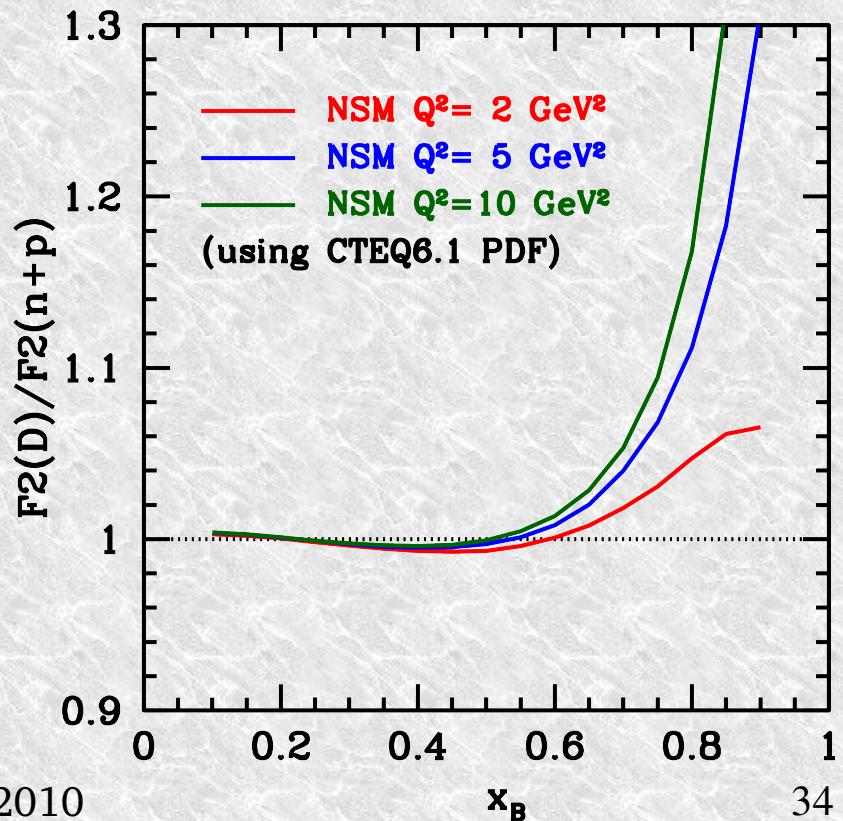
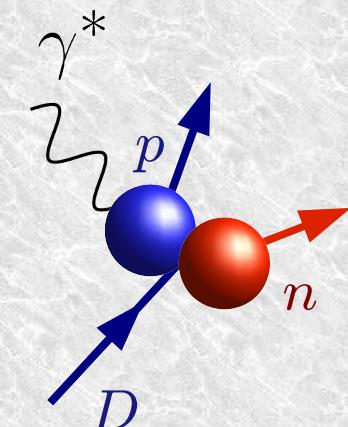
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- ◆ use non-relativistic deuteron wave-function
- ◆ finite- $Q^2$  corrections

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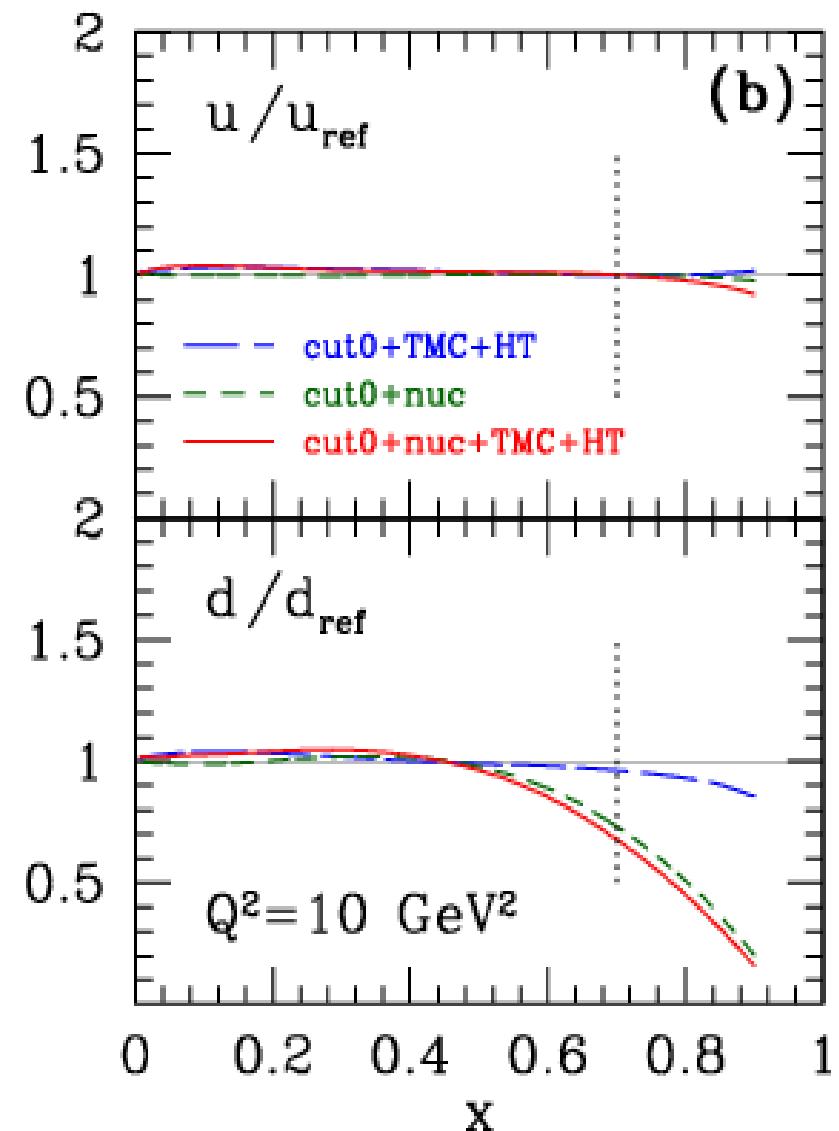
$$\frac{x_B}{y} = -\frac{q^2}{2p_N \cdot q}$$

- ◆ off-shell effects can be included in  $S_A$

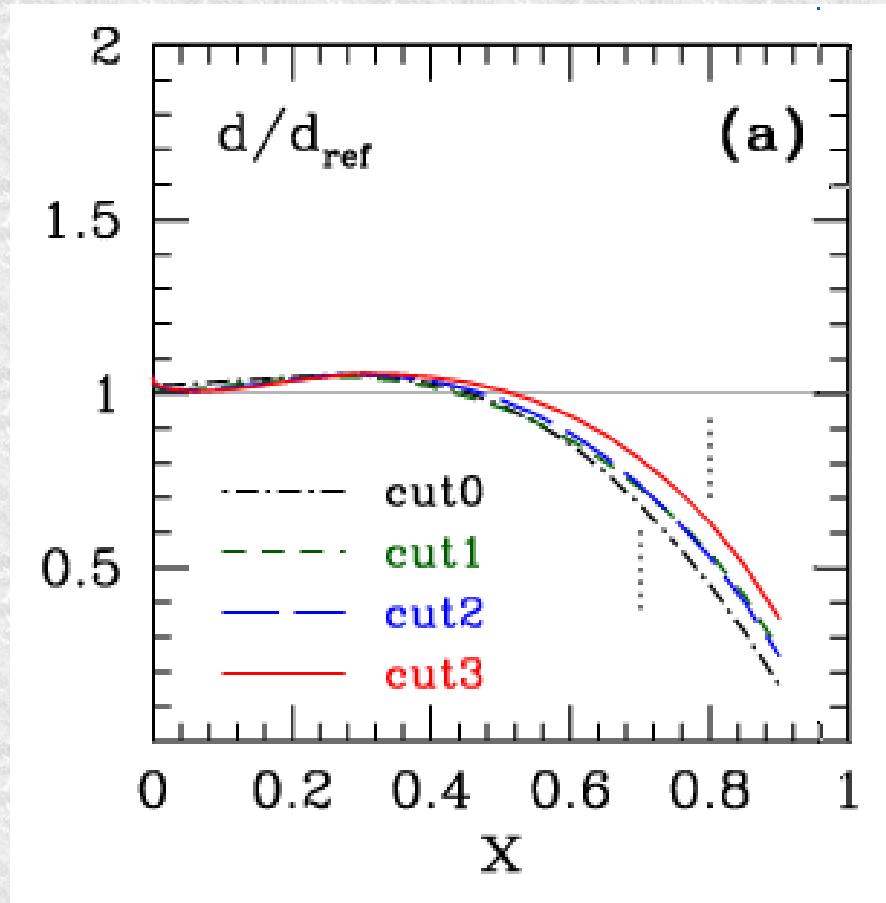


# Effects of corrections on reference fit

- Apply the theoretical corrections one at a time
- 2 important lessons:
  - cut0 removes TMC+HT (as desired)**
  - nuclear corrections are large starting from  $x > 0.5$  !!**  
("safe cuts" aren't safe everywhere)

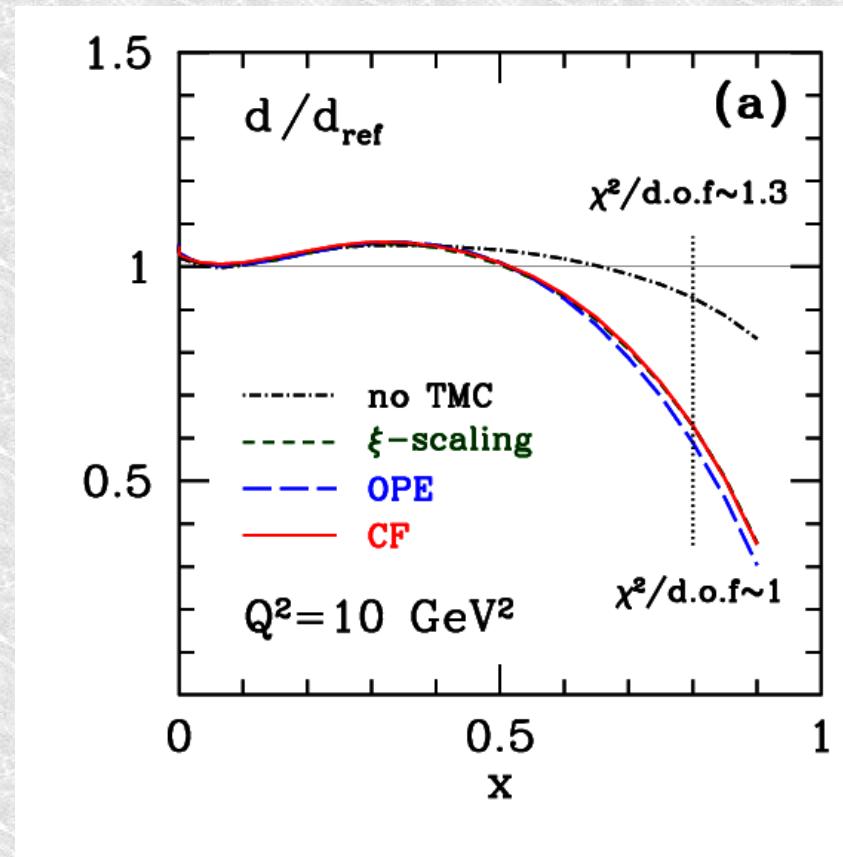


# Stability of the d-quark fit



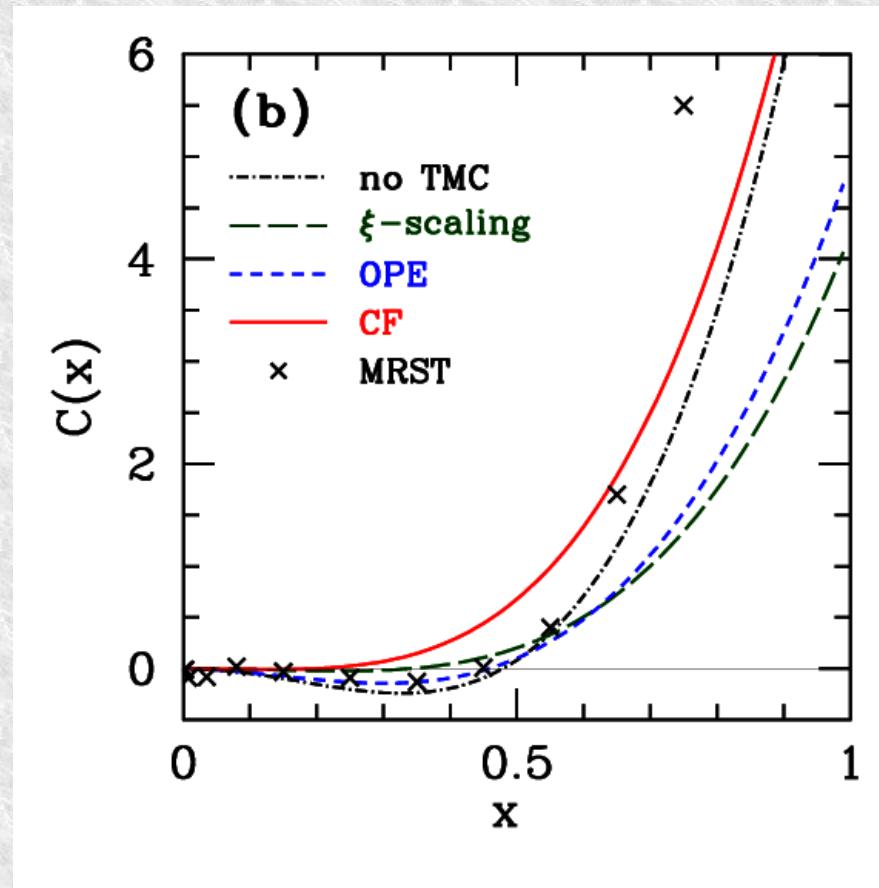
- Relatively stable against kinematic cuts, but
  - the d-quark suppression is lessened by the less restrictive cuts
  - effect still sizable at  $x=0.5$ – $0.7$  in the nominal range of validity of cut0

# TMC vs HT



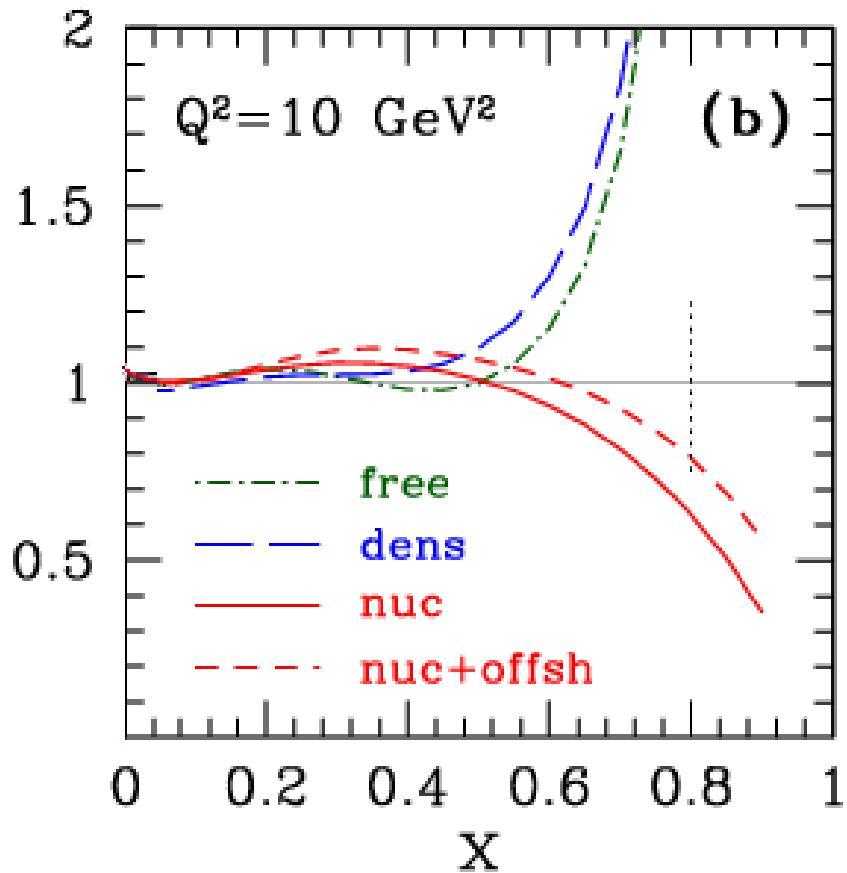
- ◆ Extracted twist-2 PDF much less sensitive to choice of TMC
  - ✚ fitted HT function compensates the TMC
  - ✚ except when no TMC is included
- ◆ Inclusion of TMC allow for economical HT parametrization (3 params)

# TMC vs HT



- Extracted higher-twist term depends on the type of TMC used
  - $Q^2 > 1.69 \text{ GeV}^2$  and  $W^2 > 3 \text{ GeV}^2$  (referred to as “cut03”)
  - lower cuts  $\Rightarrow x_B < 0.85$  compared to  $x_B < 0.7$  in CTEQ/MRST
  - No evidence for negative HT

# Off-shell corrections



$$F_2^p = \frac{4}{9}x u \left(1 + \frac{d}{4u}\right) \quad \text{no corrections}$$

$$F_2^d = \frac{5}{9}x u \left(1 + \frac{d}{u}\right). \quad \text{O.S. corrections}$$

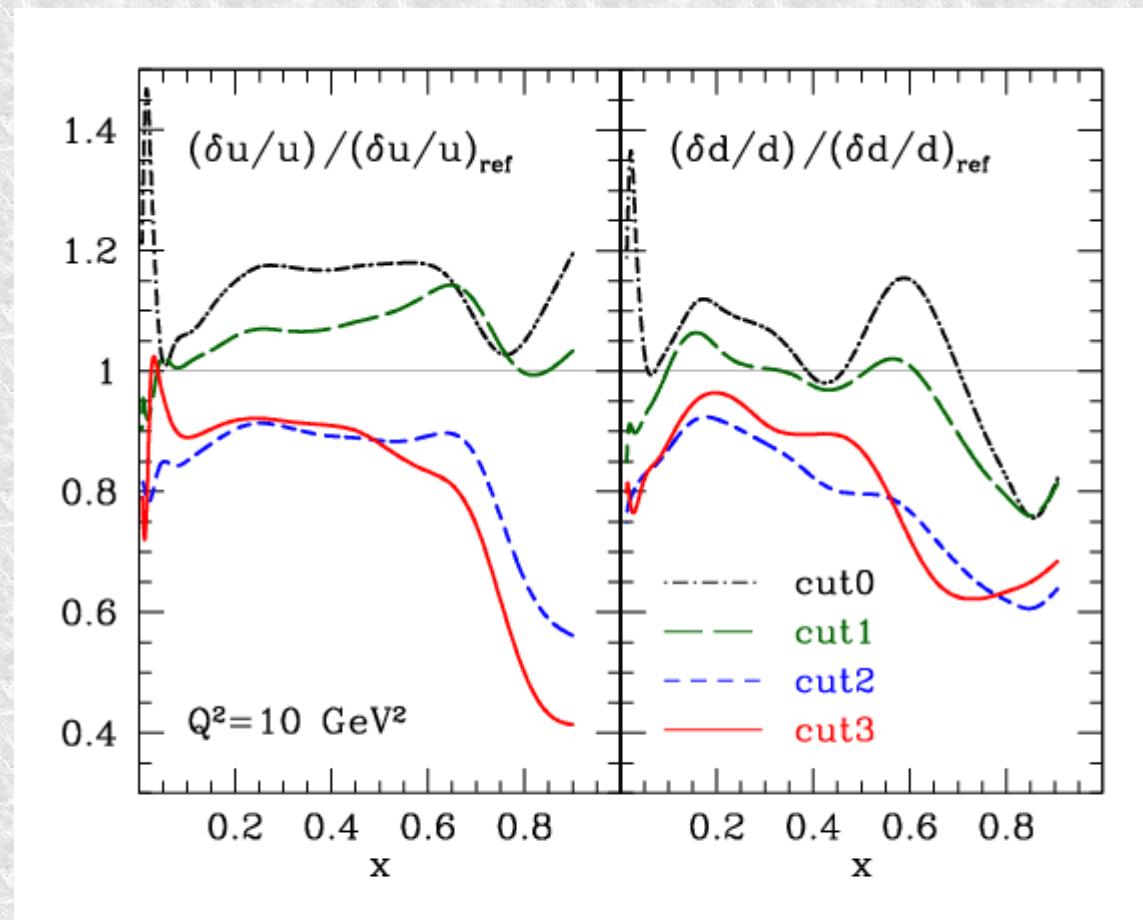
$$\frac{\delta d}{d} = \frac{4}{3} \frac{\delta F_2^d}{F_2^d} \left(1 + \frac{1}{d/u}\right).$$

1.5% on  $F_2^d \Rightarrow 40\%$  on  $d$ -quark !!!

- ◆ d-quark is strongly correlated to choice of Off-Shell correction !
- ◆ on-shell or mild off-shell correction  $\Rightarrow$  d-quark suppression
- ◆ might as well be enhanced...
- ◆ Need to constrain the models ! – see later

# Experimental uncertainties: PDF errors

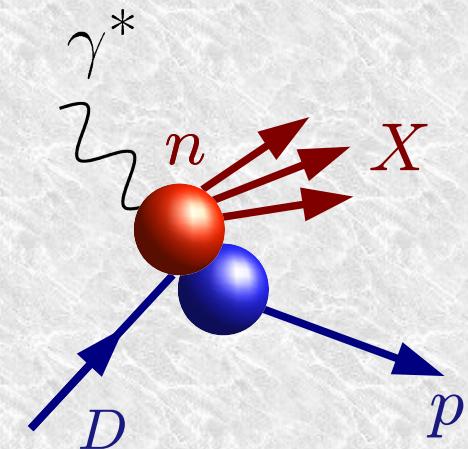
- PDF errors at large  $x$  are reduced by lowering the cuts
  - Note: these are exp. errors propagated in the fit
  - nuclear correction uncertainty for d-quarks likely larger than this!



# Quasi-free nucleon targets

BONUS and E94-102 experiments at JLab

- ◆ DIS on deuterium with tagged proton
- ◆ tagged proton momentum is measured
- ◆ neutron off-shellness can be reconstructed



- ◆ Study the off-shell dependence of  $F_2(n)$  and quark PDFs

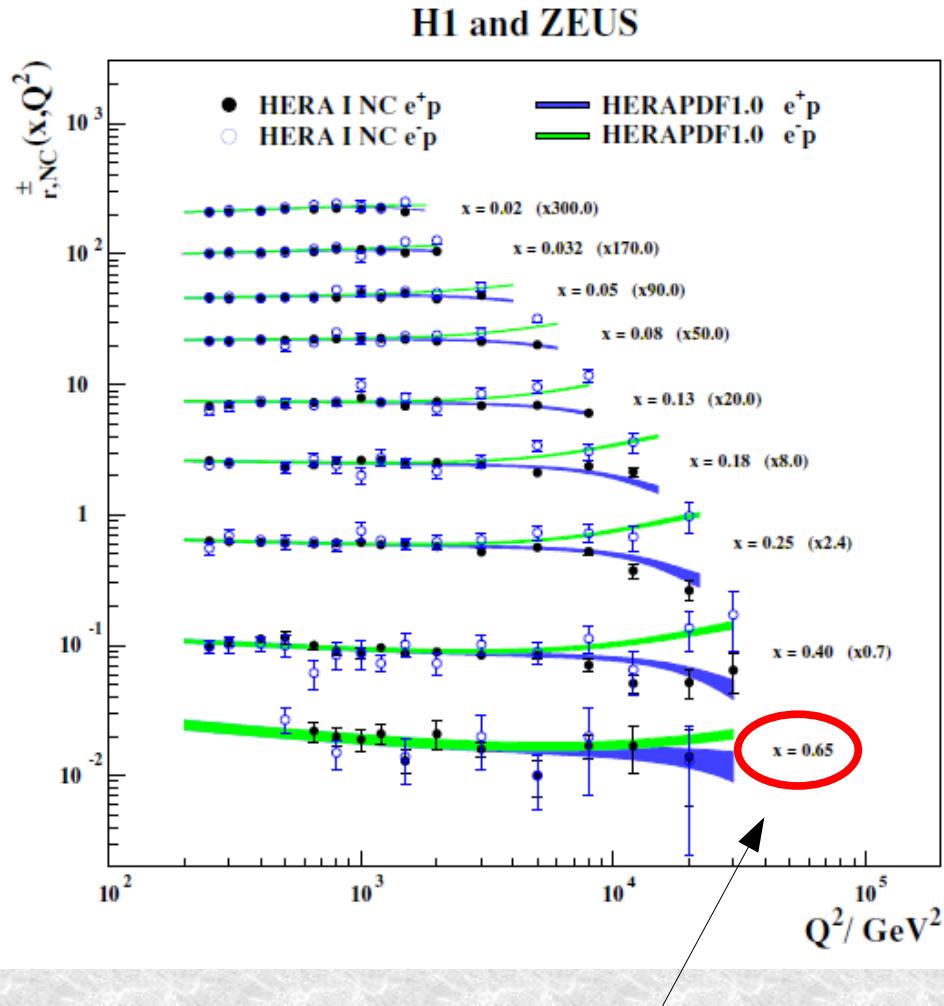
$$q \equiv q_D(x, Q^2, p^2)$$

- ◆ Extrapolate to a free neutron target  $p^2 \rightarrow M_n^2$

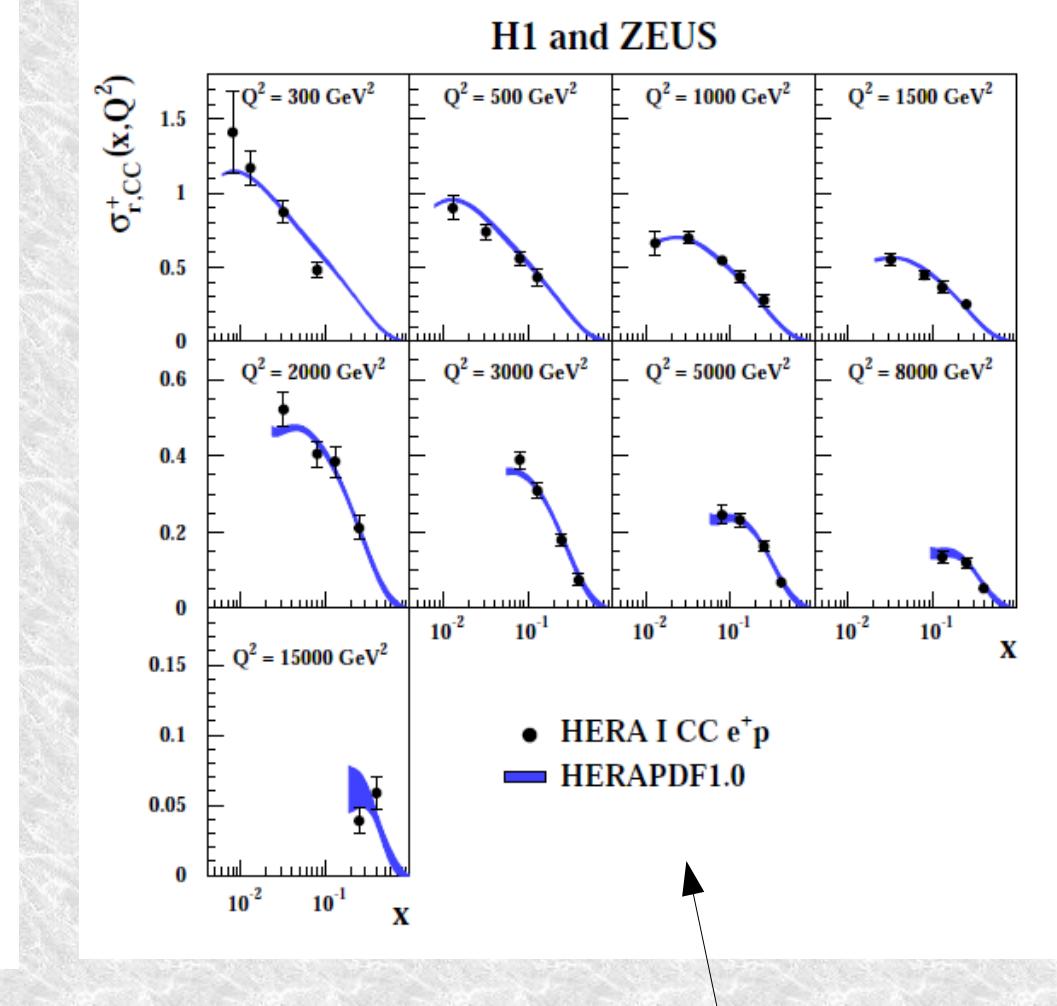
# HERA combined data

[JHEP 1001, 2010]

- H1 and ZEUS combined data on  $e^+p$  and  $e^-p$  collisions, NC & CC



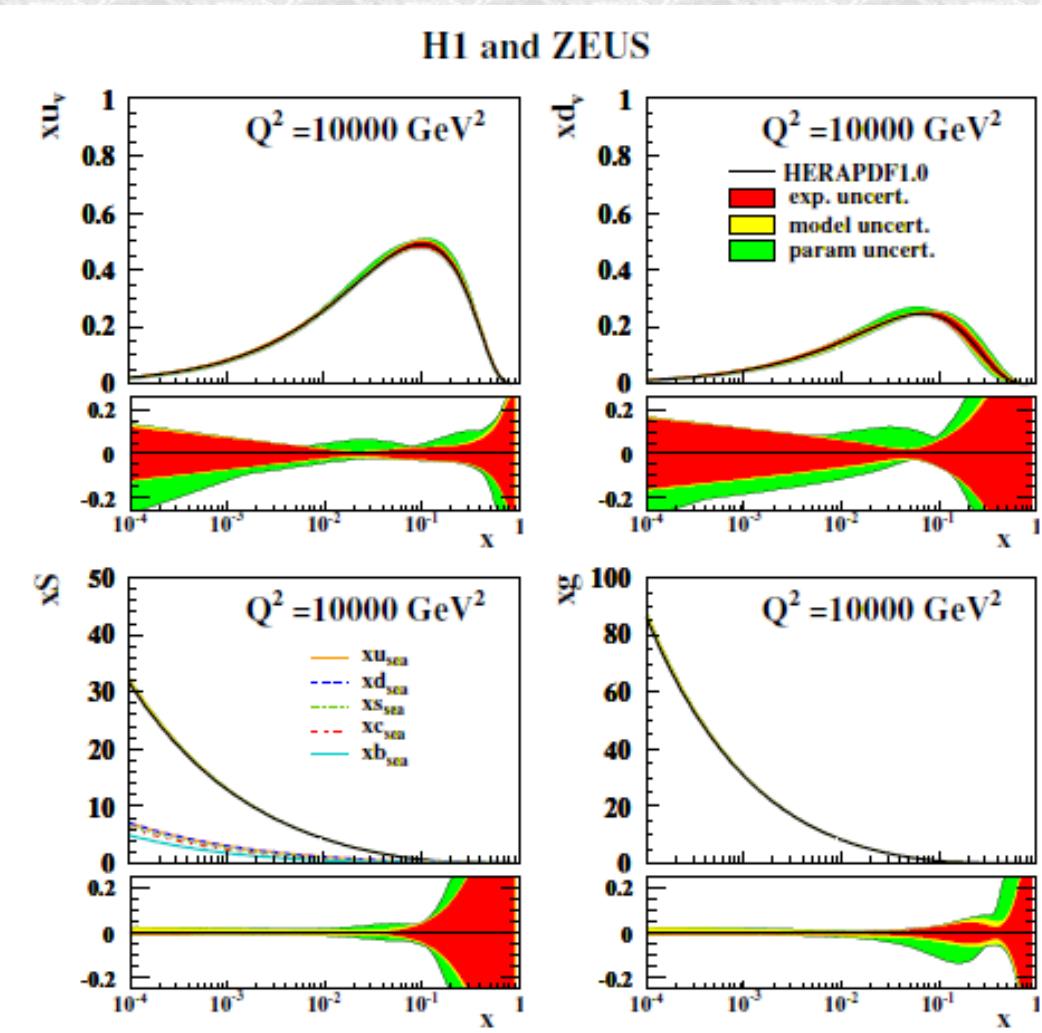
Reaches into the critical  $x$  range



Too limited  $x$  coverage

# HERA combined data

[JHEP 1001, 2010]



- These data alone insufficient for  $d$ -quark at large  $x$
- combine with deuterium data, cross check nuclear corrections