CTEQ6X: large-x PDFs

Alberto Accardi
Hampton U. & Jefferson Lab

CTEQ meeting
20-21 November 2009

Outline

- **Why large x (and low-Q^2)**

- **The CTEQ6X fits at large x**
  - Target Mass Corrections
  - Higher Twist and power corrections
  - Nuclear Corrections
  - Experimental errors

- **Future Plans**

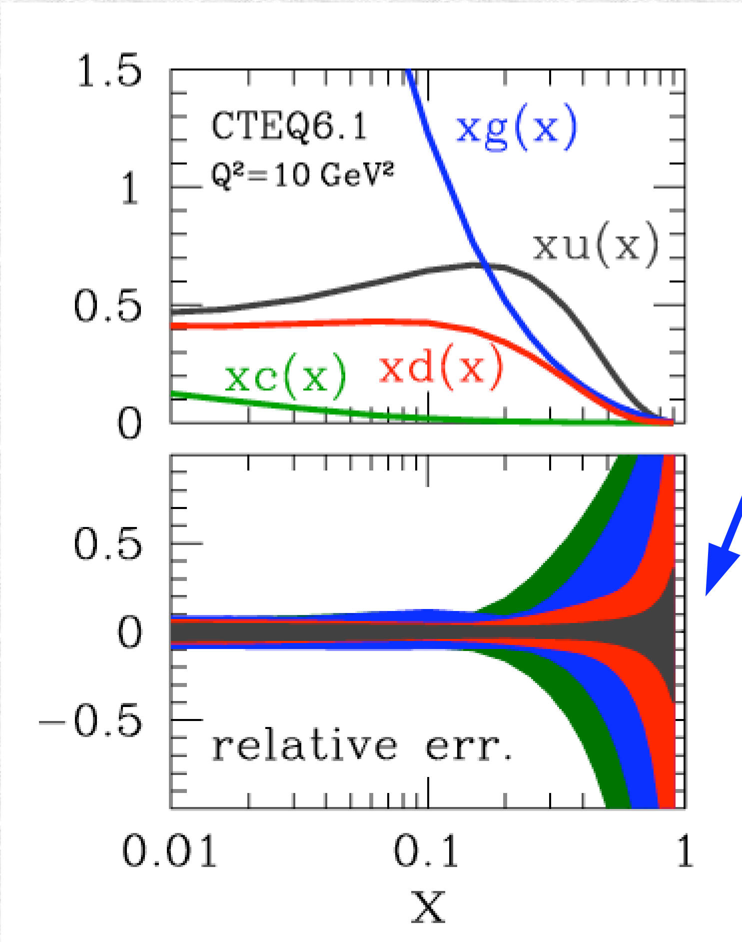
Based on:

Accardi, Cristy, Keppel, Melnitchouk, Monaghan, Morfin, Owens, arXiv:0911.2254

Why large-x, low-Q^2?

Why large x_B and low Q^2 ?

- 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_B and low Q^2 ?

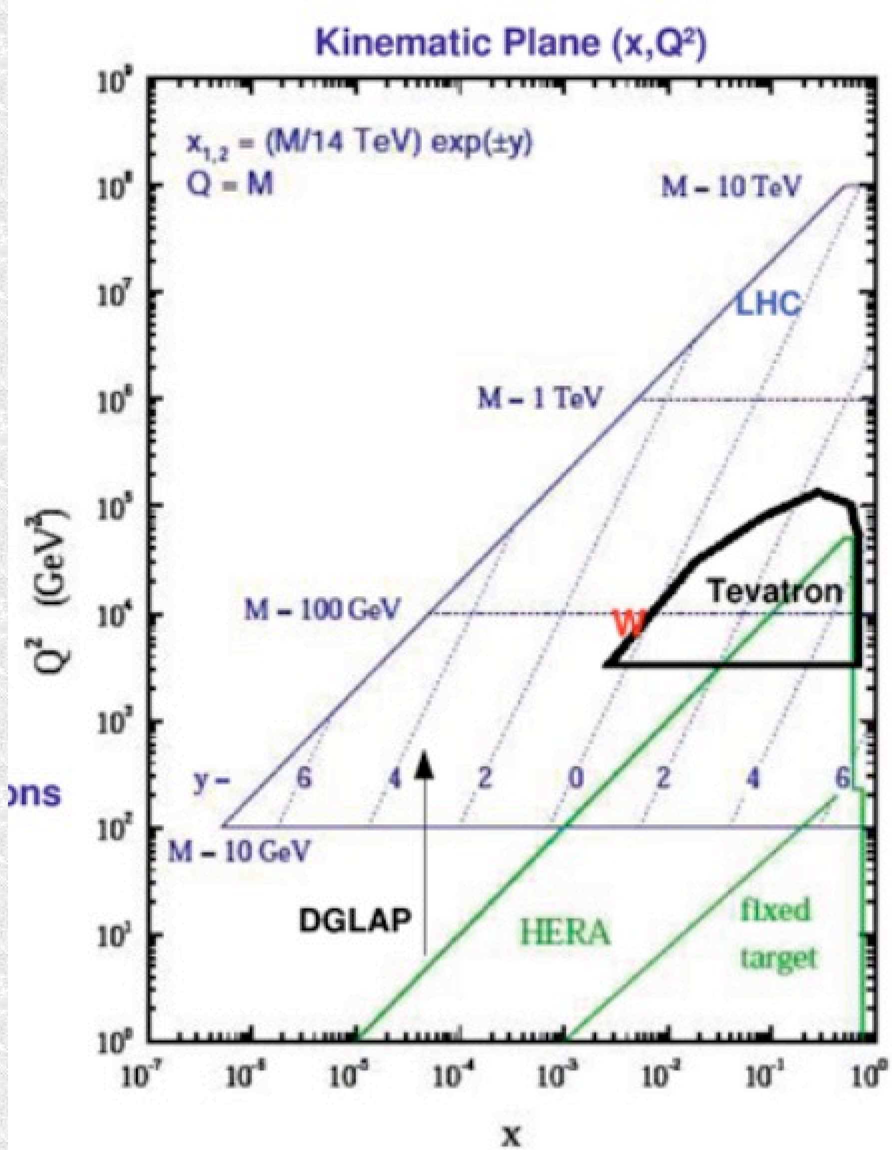
- Large uncertainties in quark and gluon PDF at $x > 0.4$
- Precise PDF at large x are needed, e.g.,
  - at LHC, Tevatron
    1) DGLAP evolution feeds large x, low Q^2 into lower x, large Q^2
    2) New physics as excess in large-p_T spectra ⇔ large x PDF
  - Example 1: Z' production

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

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

but recent work raises the bar:

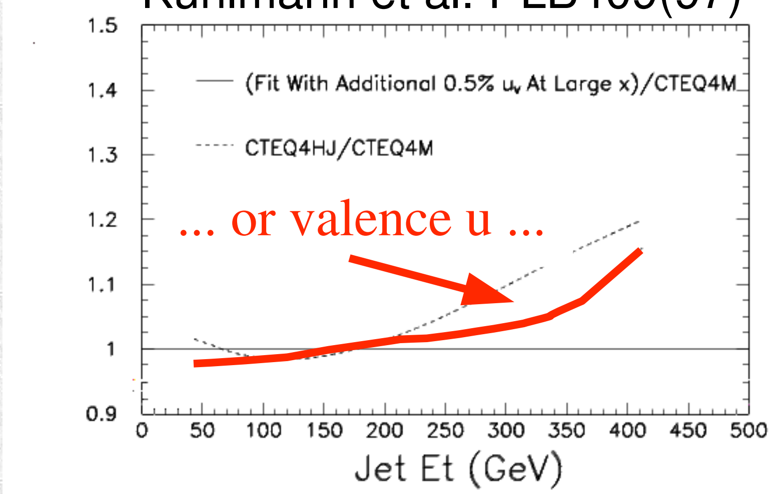
$$M_{Z'} \gtrsim 900\ \mathrm{GeV}$$



Why large x_B and low Q^2 ?

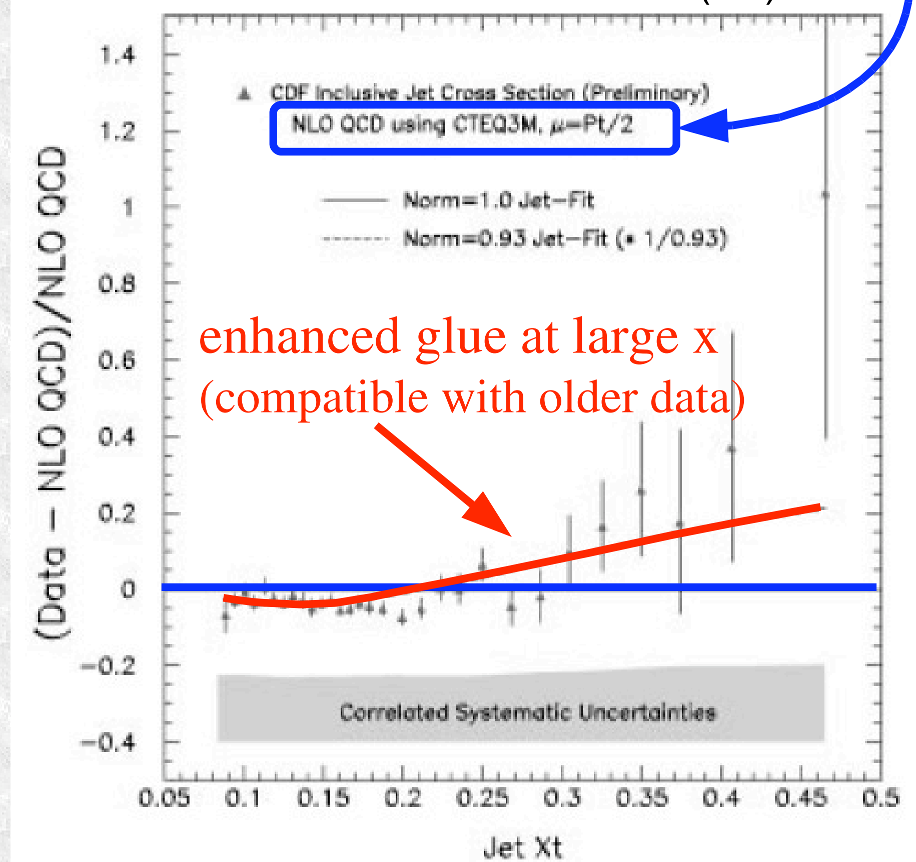
- Large uncertainties in quark and gluon PDF at $x > 0.4$
- Precise PDF at large x are needed, e.g.,
  - at LHC, Tevatron
    1) DGLAP evolution feeds large x, low Q^2 into lower x, large Q^2
    2) New physics as excess in large-p_T spectra $\Leftrightarrow$ large x PDF
  - Example 2: 1996 CDF p_T excess

Kuhlmann et al. PLB409(97)



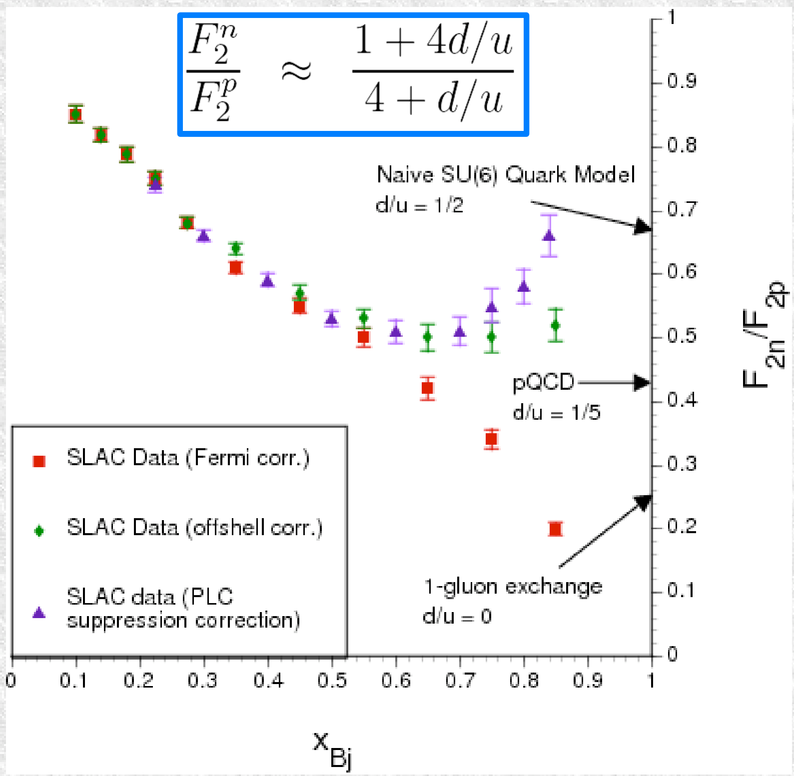
NLO state of the art at the time

Kuhlmann et al. PLB476(00)



Why large x_B and low Q^2 ?

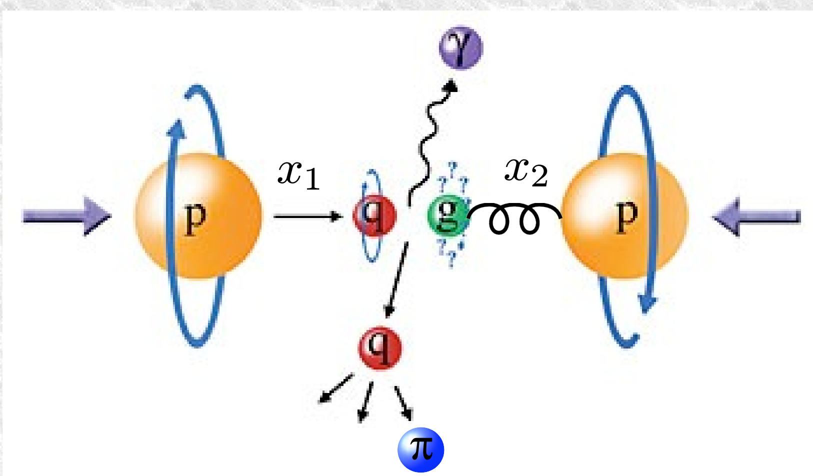
- Large uncertainties in quark and gluon PDF at $x > 0.5$
- Precise PDF at large x are needed, e.g.,
  - at LHC, Tevatron
    1) New physics as excess in large p_T spectra $\Leftrightarrow$ large x PDF
    2) DGLAP evolution feeds large x, low Q^2 into lower x, large Q^2
  - non-perturbative nucleon structure $\Leftrightarrow$ d/u ratio at $x=1$



Why large x_B and low Q^2 ?

- Large 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 in large p_T spectra $\Leftrightarrow$ large x PDF
    2) DGLAP evolution feeds large x, low Q^2 into lower x, large Q^2
  - non-perturbative nucleon structure
  - spin structure of the nucleon – most spin at large-x, but also, e.g.,

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



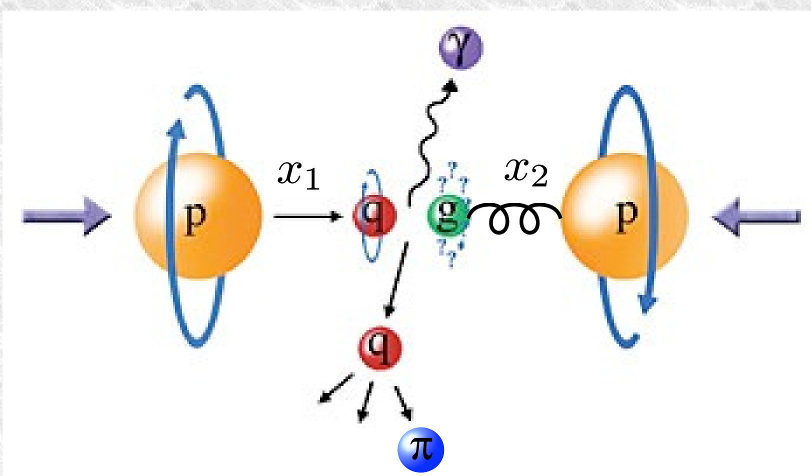
$$x_1 \sim \frac{p_T}{\sqrt{s}} e^{y}$$

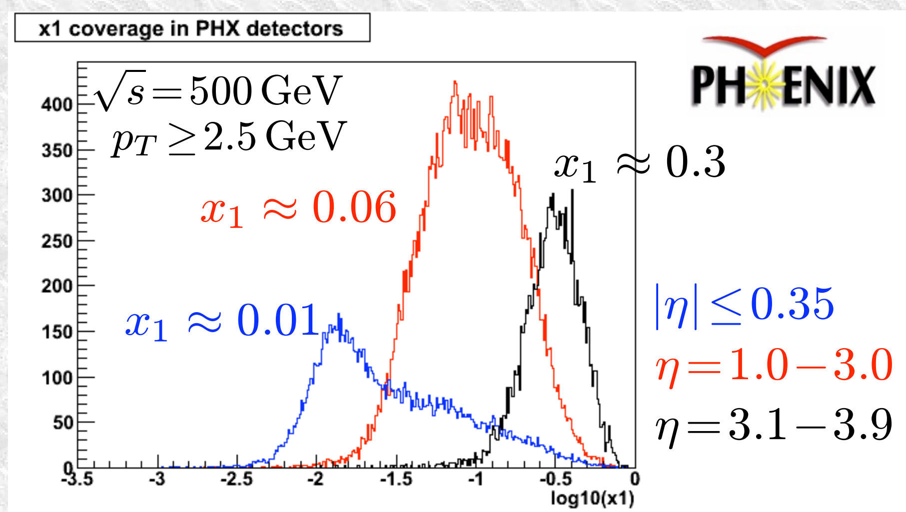
$$x_2 \sim \frac{p_T}{\sqrt{s}} e^{-y}$$

Why large x_B and low Q^2 ?

- Large 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 in large p_T spectra $\Leftrightarrow$ large x PDF
    2) DGLAP evolution feeds large x, low Q^2 into lower x, large Q^2
  - non-perturbative nucleon structure
  - spin structure of the nucleon – most spin at large-x, but also, e.g.,

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





Why large x_B and low Q^2 ?

- Large 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 in large p_T spectra $\Leftrightarrow$ large x PDF
    2) DGLAP evolution feeds large x, low Q^2 into lower x, large Q^2
  - non-perturbative nucleon structure
  - spin structure of the nucleon
  - neutrino physics

Why large x_B and low Q^2 ?

- Jlab and SLAC have precision DIS data at **large x_B , 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

    } **this talk** (items 1–3)

    4) jet mass corrections (JMC) $\propto m_j^2/Q^2$
    5) large-x resummation
    6) large-x DGLAP evolution
    7) parton recombination at <u>large</u> x
    8) quark-hadron duality
    9) perturbative stability at low-Q^2
    10) …

- An Electron-Ion Collider (EIC) will be able to explore **large x_B *and* Q^2**

The CTEQ6X global fits

Collaboration and goals

- **JLab / Florida State U. / Fermilab collaboration**
  - A. Accardi, E. Christy, C. Keppel, W. Melnitchouk, P. Monaghan, J. Morfín, J. Owens
  - weekly phone meetings
  - e-log for discussions and results
  - CVS repository for fitting code

- Initial Goals:
  - Extend PDF global fits to larger values of x_B and lower values of Q
  - Wealth of data from older SLAC and newer Jlab, DY, γ+jet
  - see if PDF errors can be reduced using new JLAB data

Global fit details

- We are using **Jeff Owens' NLO DGLAP fitting package**
  - use CTEQ6.1 parametrization of PDFs at $Q_0 = 1.3$ GeV
  - Can fit DIS, Drell-Yan, W asymmetry, jets, γ+jet
  - statistical and systematic errors added in quadrature
  - PDF errors computed by the Hessian method, $\Delta\chi^2 = 1$

- **New in this work:**
  - γ+jet
  - Multiple TMC and HT terms
  - Higher-twist contributions by a multiplicative factor
  - Nuclear corrections for deuteron targets

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

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

  - respects kinematic boundaries

- **ξ-scaling**, uses $x_{\max} = 1$ [Aivazis et al '94; Kretzer,Reno '02]

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

  - leads to non-zero structure functions at $x_B > 1$ (!)

"Higher-Twists" parametrization

- Parametrize by a multiplicative factor:

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

with

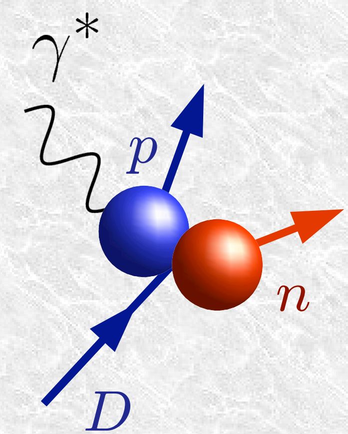
$$C(x_B) = a\, x^b\, (1 + c\, x)$$

  - parametrization is sufficiently flexible to give good fits to data
  - c parameter allows negative HT at small x_B

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

Deuterium corrections

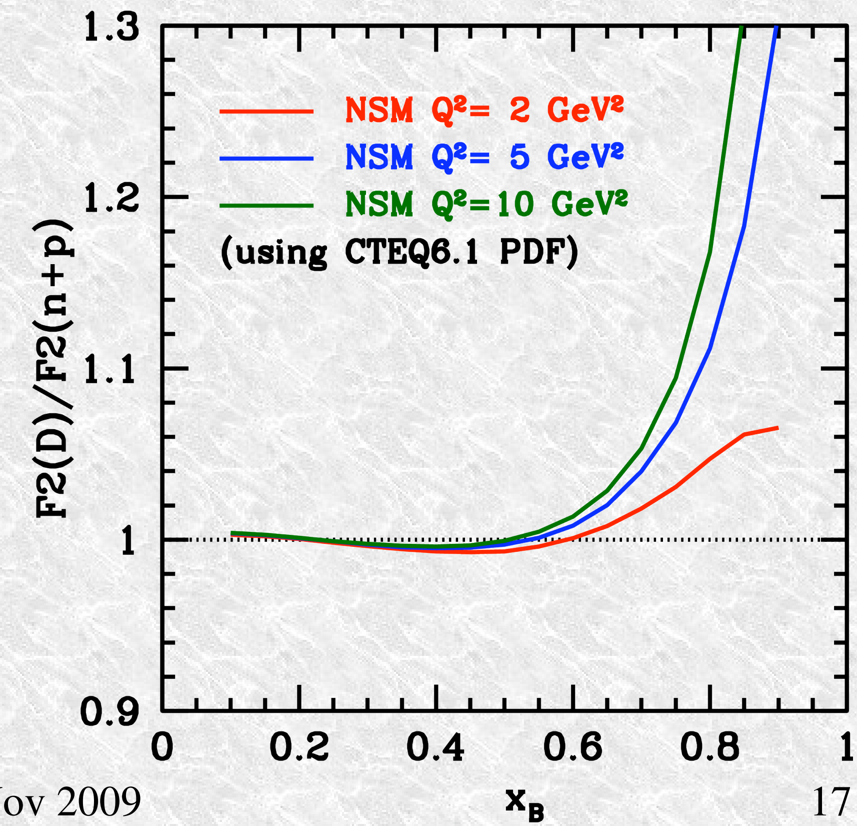
- Nuclear Smearing Model [Kahn et al., arXiv:0809.4308 Accardi et al., *in preparation*]
  - nucleon Fermi motion and binding energy
  - use non-relativistic deuteron wave-function
  - finite-Q^2 corrections (very important!)



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

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

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



- off-shell effects can be included in S_A

CTEQX vs. CTEQ

- **CTEQ**

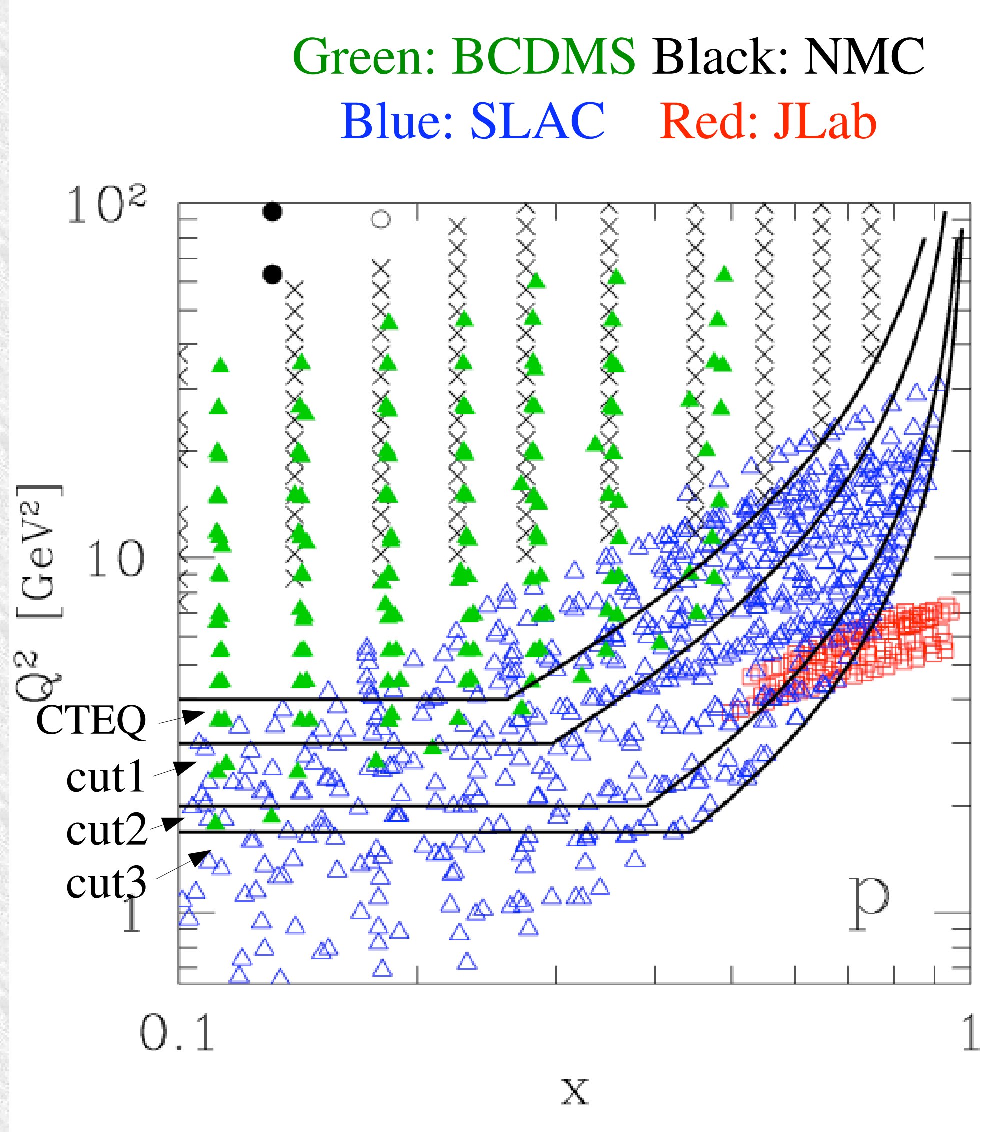
  $Q^2 \geq 4\ \mathrm{GeV}^2 \quad W^2 \geq 12.25\ \mathrm{GeV}^2$

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

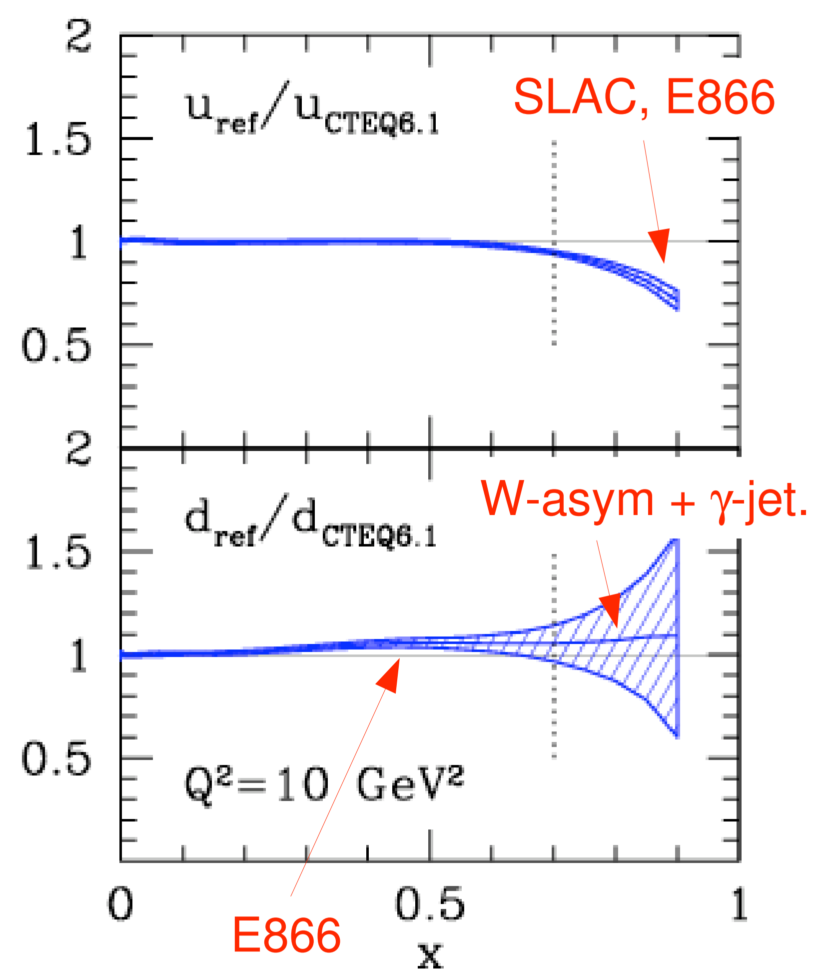
- **CTEQ6X**
  - **TMC, HT, deuteron corrections**
  - Progressively lower the cuts:

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

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



Reference fit vs. CTEQ6.1

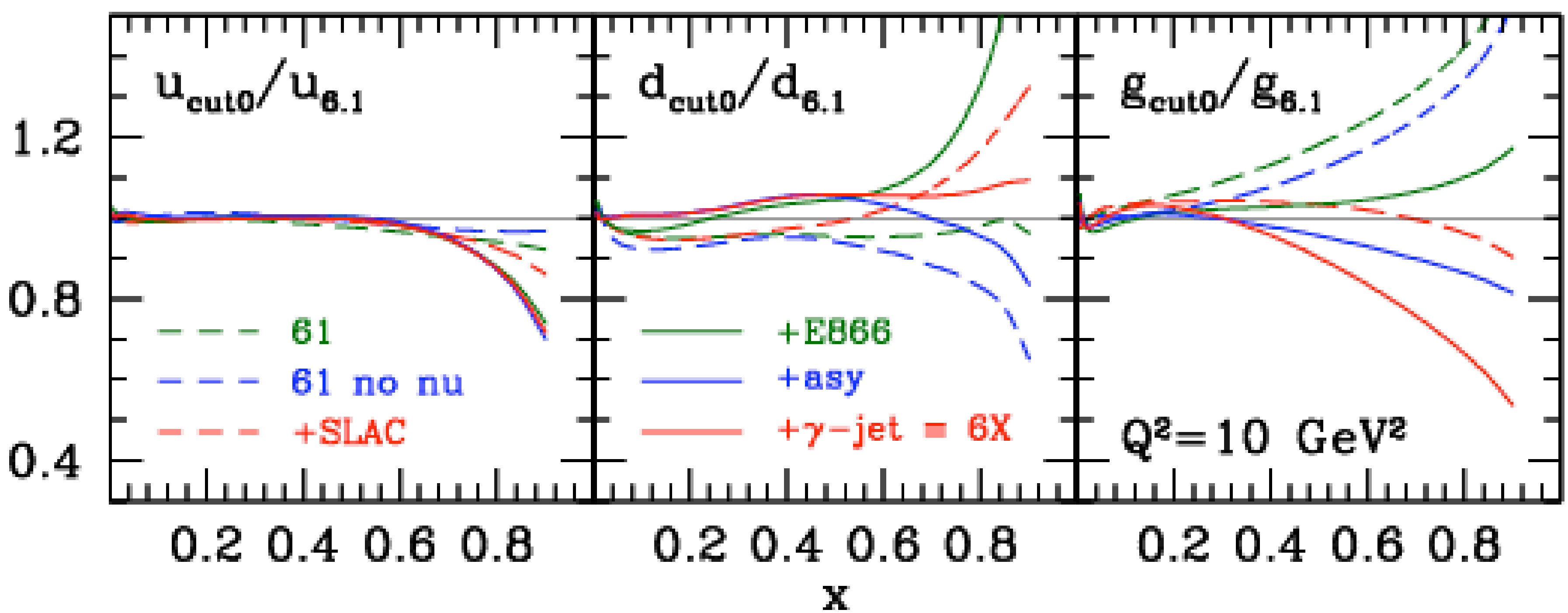


- **Reference fit:** cut0, no corrections

	data	CTEQ6.1
DIS	(JLab)	NO
	SLAC	NO
	NMC	√
	BCDMS	√
	H1	√
	ZEUS	√
DY	E605	√
	E866	NO
W	CDF '98 (ℓ)	√
	CDF '05 (ℓ)	NO
	D0 '08 (ℓ)	NO
	D0 '08 (e)	NO
	CDF '09 (W)	NO
jet	CDF	√
	D0	√
γ+jet	D0	NO

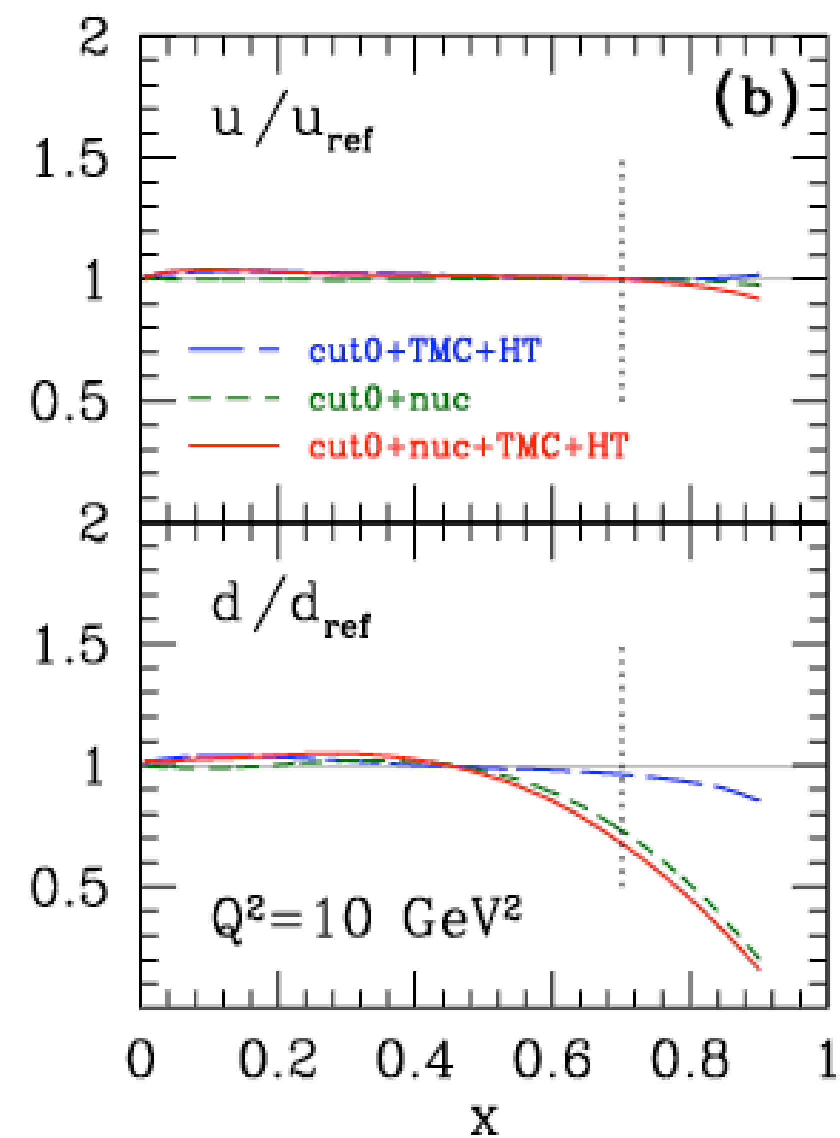
From CTEQ6.1 to our reference fit

- The lines show our fit to data sets interpolating 6.1 and 6X
  - minor differences lack of correlated error treatment un our code

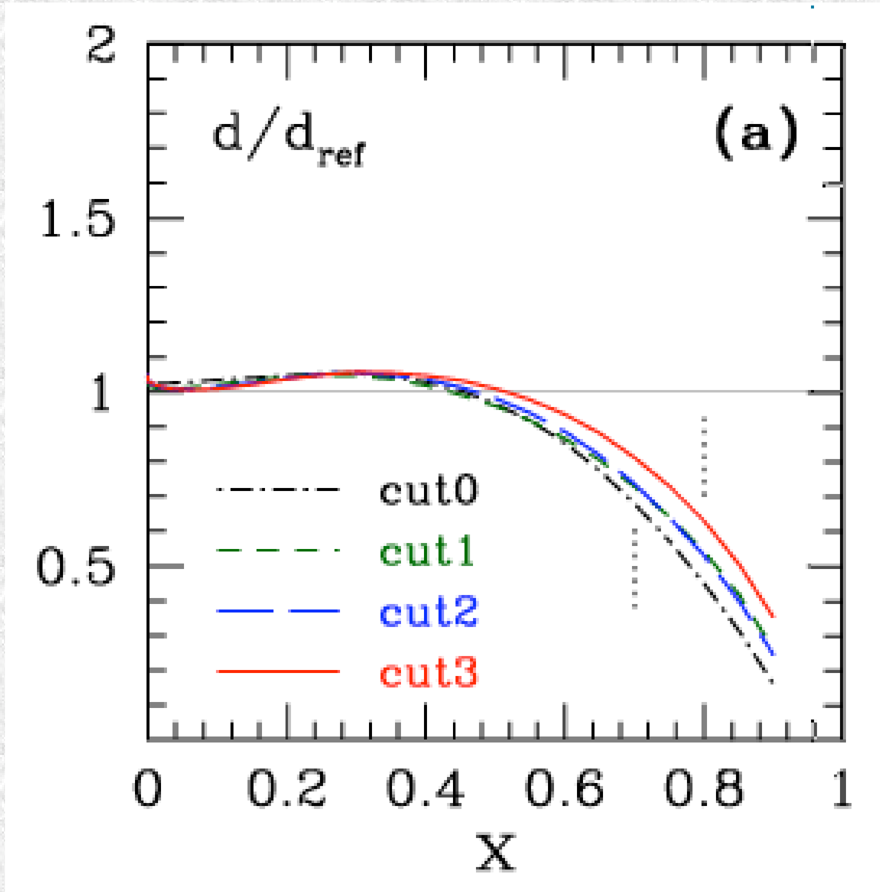


Effects of corrections on reference fit

- 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)

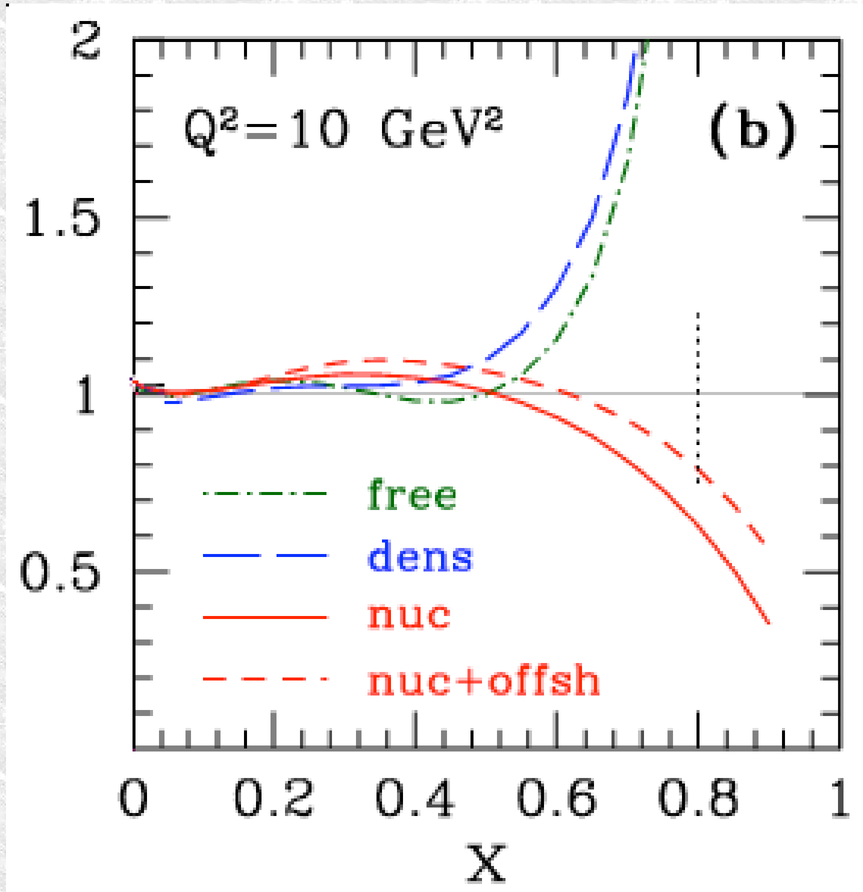


Stability of the d-quark fit



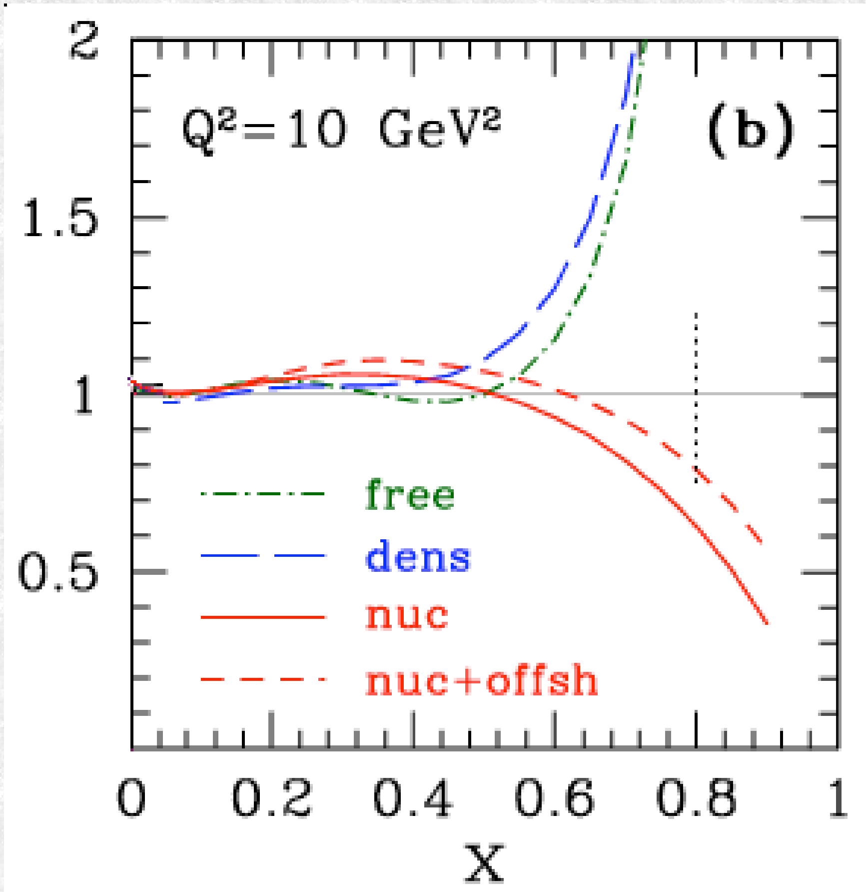
- **Relatively stable against kinematic cuts**, but
  - the d-quark suppression is lessened by the less restrictive cuts
  - effect still sizable at x=0.5–0.7 in the nominal range of validity of cut0

Nuclear corrections



- ***d*-quarks are very sensitive to deuterium corrections**
  - “density model” unreliable for deuterium, large x
  - sensitivity to off-shell corrections [MST = Melnitchouk et al., '94]

Off-shell corrections



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

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

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

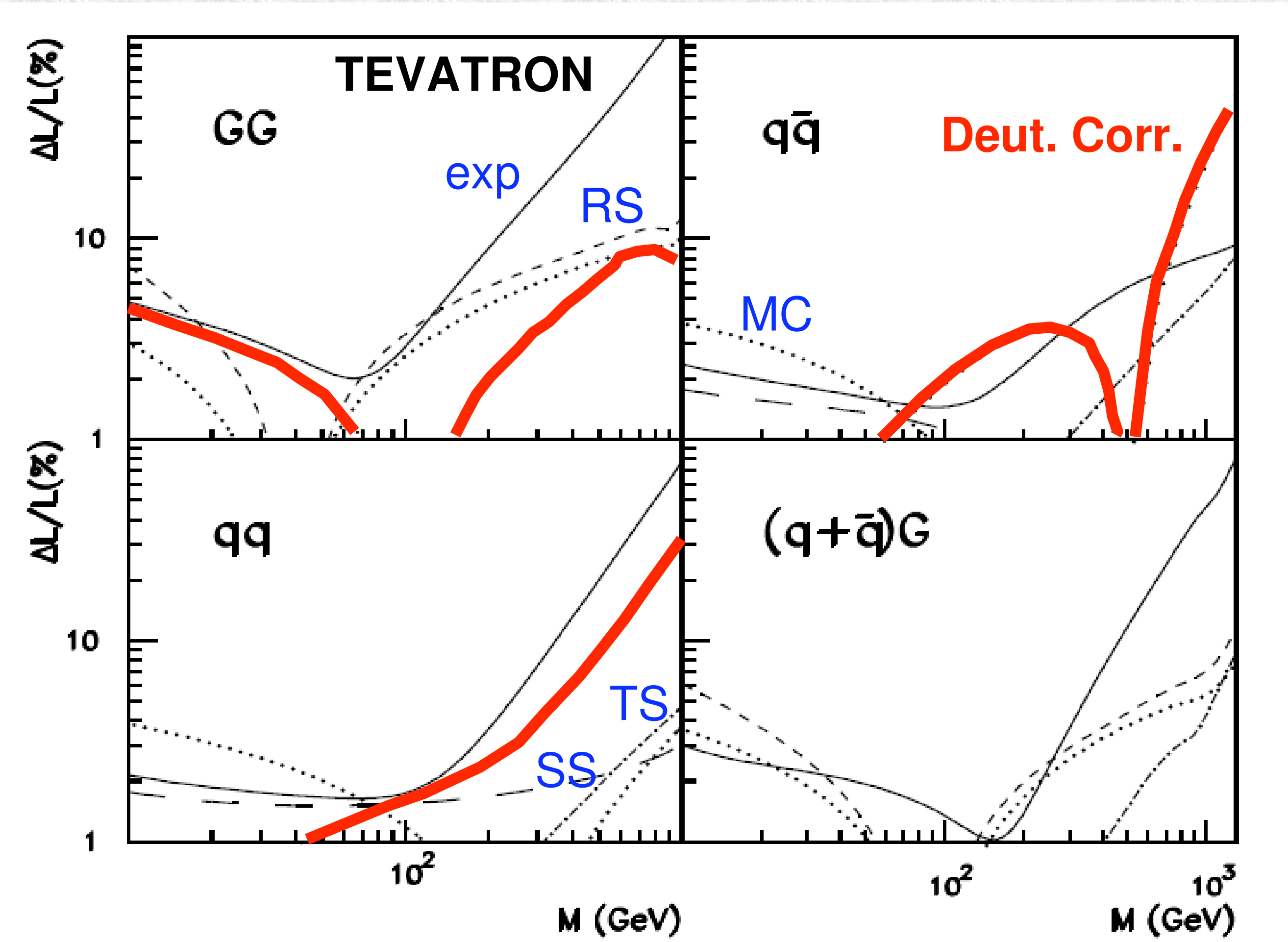
1.5% on F_2^d ⇒ 40% on *d*-quark !!!

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

Impact on Tevatron / LHC

- Parton luminosities [Alekhin PRD63 (2001)]

$$L_{i,j}(M) = \frac{1}{S}\int_{M^2/s}^{1} \frac{dx}{x} q_i(x, M^2) q_j(M^2/(xs), M^2)$$

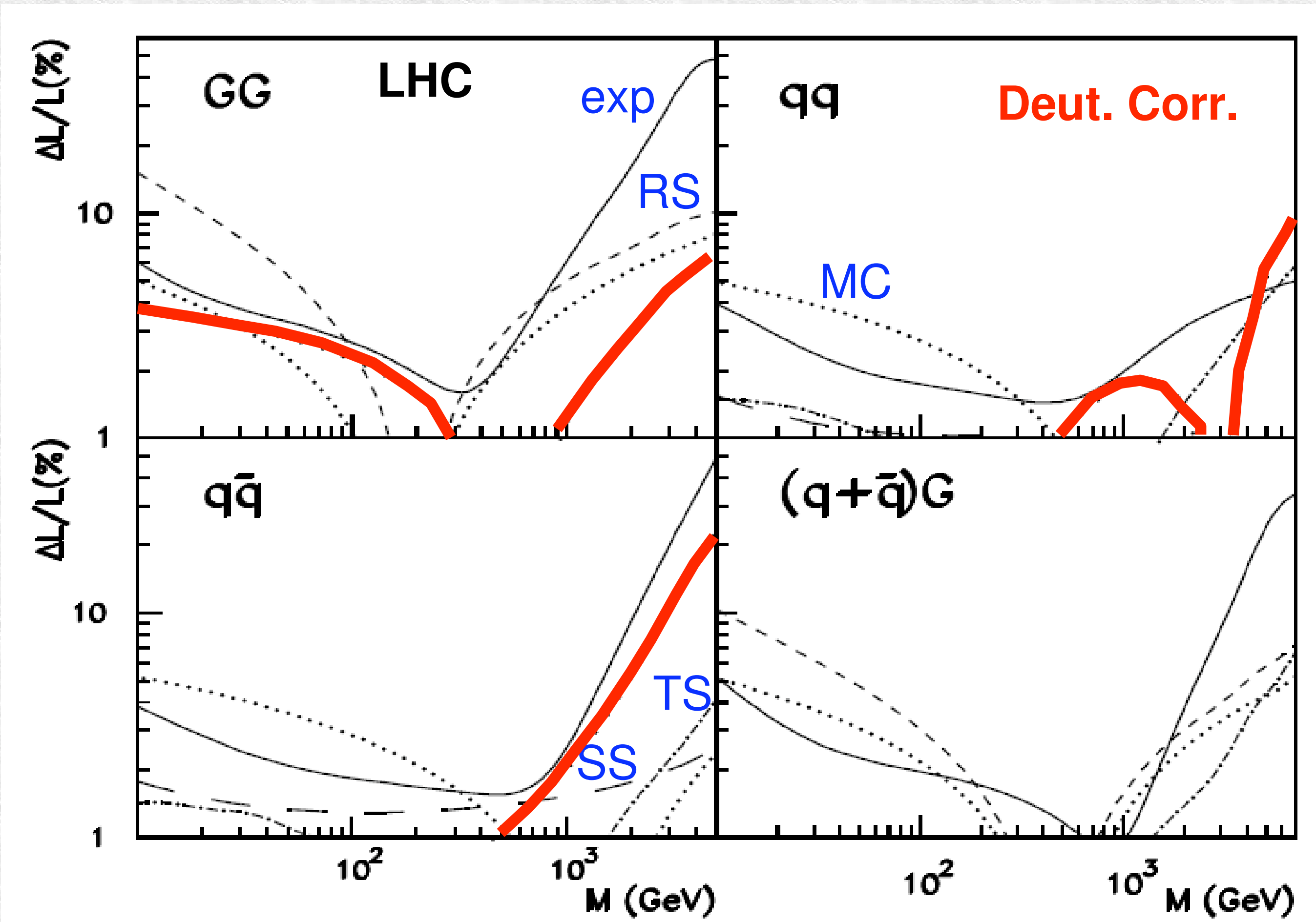


exp = experimental
RS = renorm. scale
MC = charm mass
TS = charm threshold
SS = strangeness suppr.

Impact on Tevatron / LHC

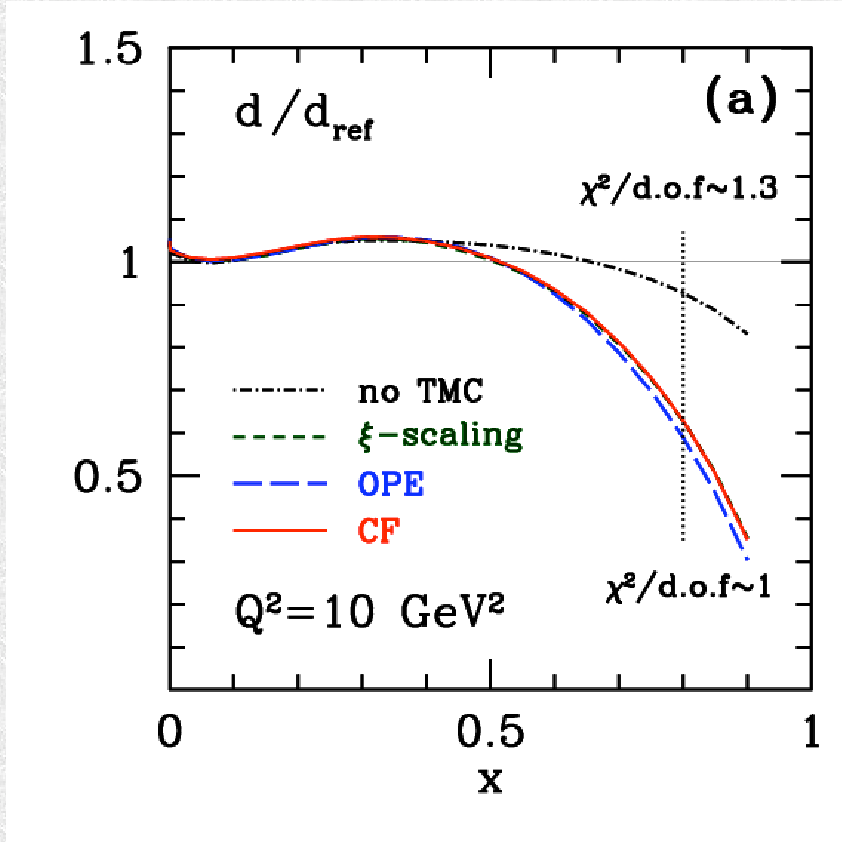
- Parton luminosities [Alekhin PRD63 (2001)]

$$L_{i,j}(M) = \frac{1}{S}\int_{M^2/s}^{1} \frac{dx}{x} q_i(x, M^2) q_j(M^2/(xs), M^2)$$



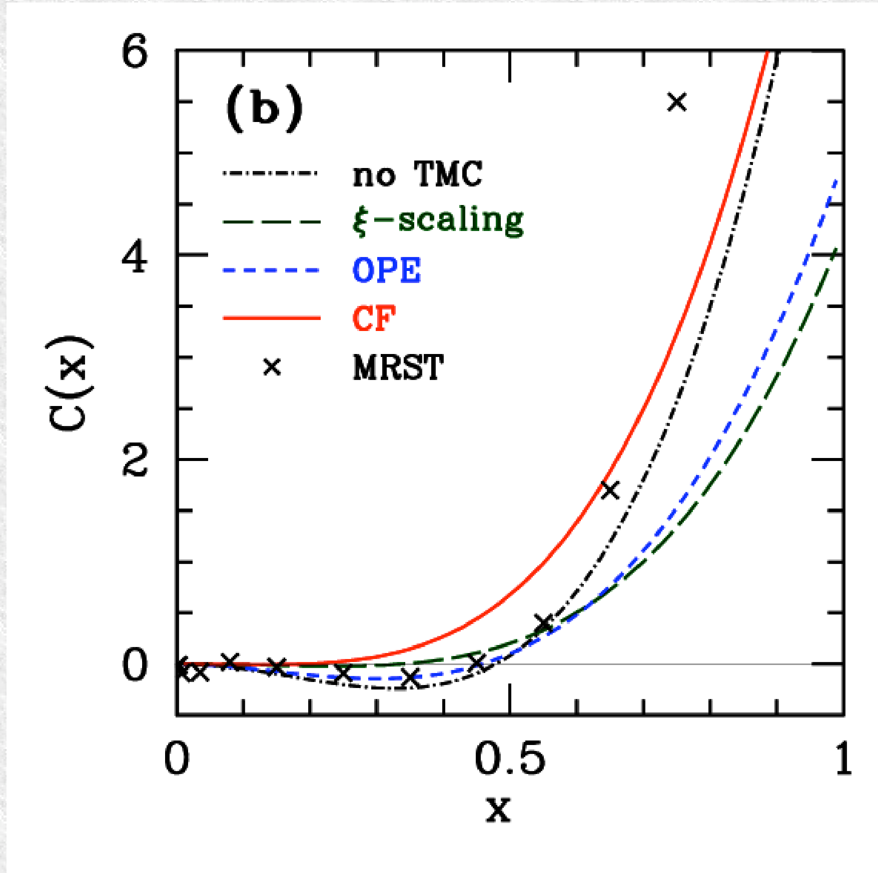
exp = experimental
RS = renorm. scale
MC = charm mass
TS = charm threshold
SS = strangeness suppr.

TMC vs HT



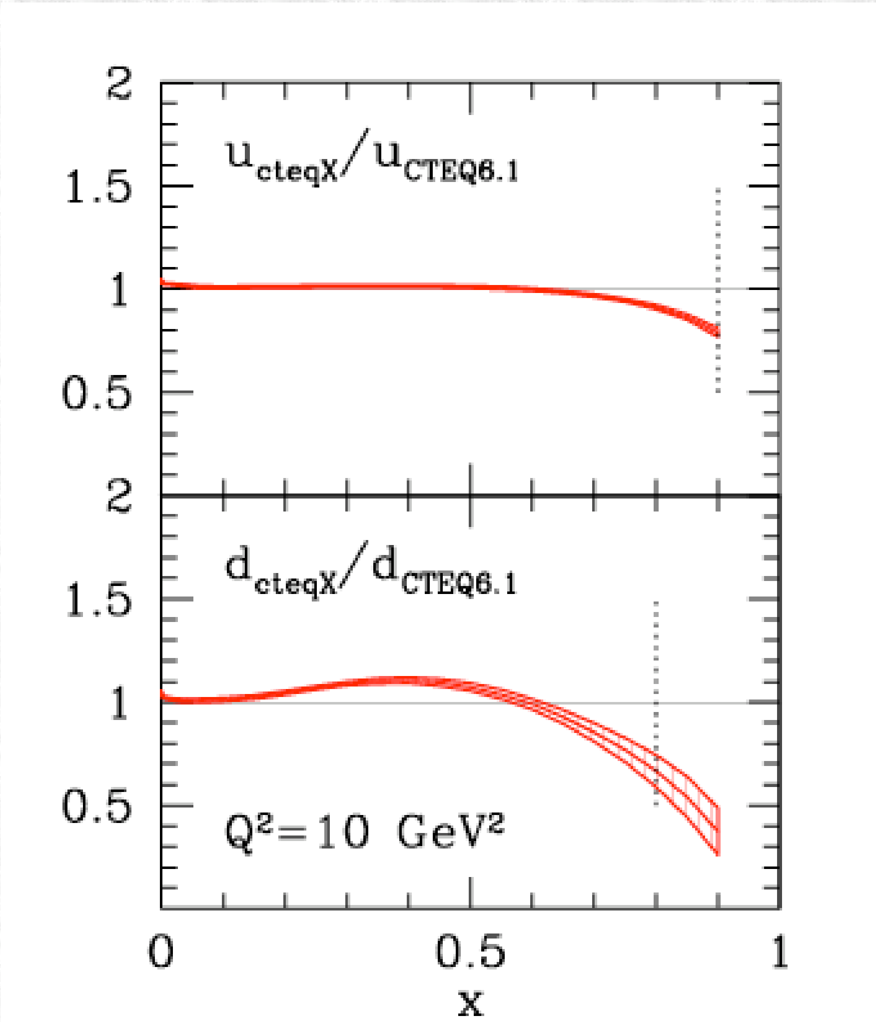
- **Extracted twist-2 PDF much less sensitive to choice of TMC**
  - fitted HT function compensates the TMC
  - except when no TMC is included
- **Inclusion of TMC allow for economical HT parametrization** (3 params)

TMC vs HT



- **Extracted higher-twist term depends on the type of TMC used**
  - $Q^2 > 1.69$ GeV^2 and $W^2 > 3$ 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

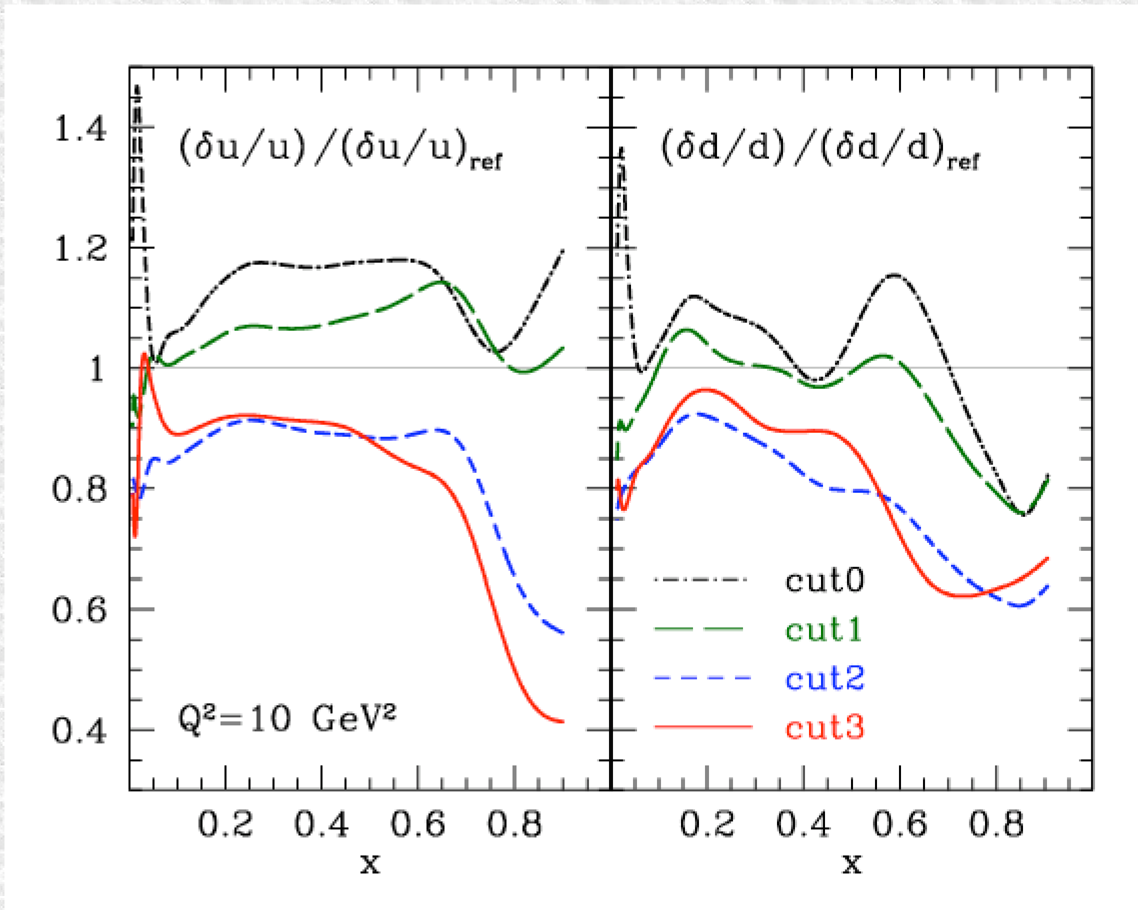
Summary: CTEQ6X vs CTEQ6.1



- **cteqX fit:**
  - cut3
  - TMC+HT
  - deuteron corrections
- **u-quark:**
  - almost unchanged
- **d-quark:**
  - suppressed at large x
- **reduced errors**

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!



Summary

- **Suppressed d/u ratio at large x** compared to CTEQ6.1
  - HT+TMC:
    - stable twist-2
    - economical higher-twist parametrization
  - Extended data set – reduced PDF errors
- **Nuclear corrections**
  - essential for deuterium at $x_B > 0.6$
  - Very large effect on d-quark:
    - need to constrain theory models

Plans for the future

- Collaborators: you are invited to join us!
  - join forces with the nuclear PDF group?
- Longer paper
  - nuclear corrections vs d/u at $x \to 1$
  - theoretical errors estimate
  - HT(p) vs HT(n)
  - fit of off-shell corrections ??
- Future fits
  - F_L or DIS cross-section data
  - BONUS / EG6 data (quasi-free neutrons)
- Longer term: use large-*x* techniques in full-*x* CTEQ fit

Outlook:

d-quarks at large x

d-quarks at large x

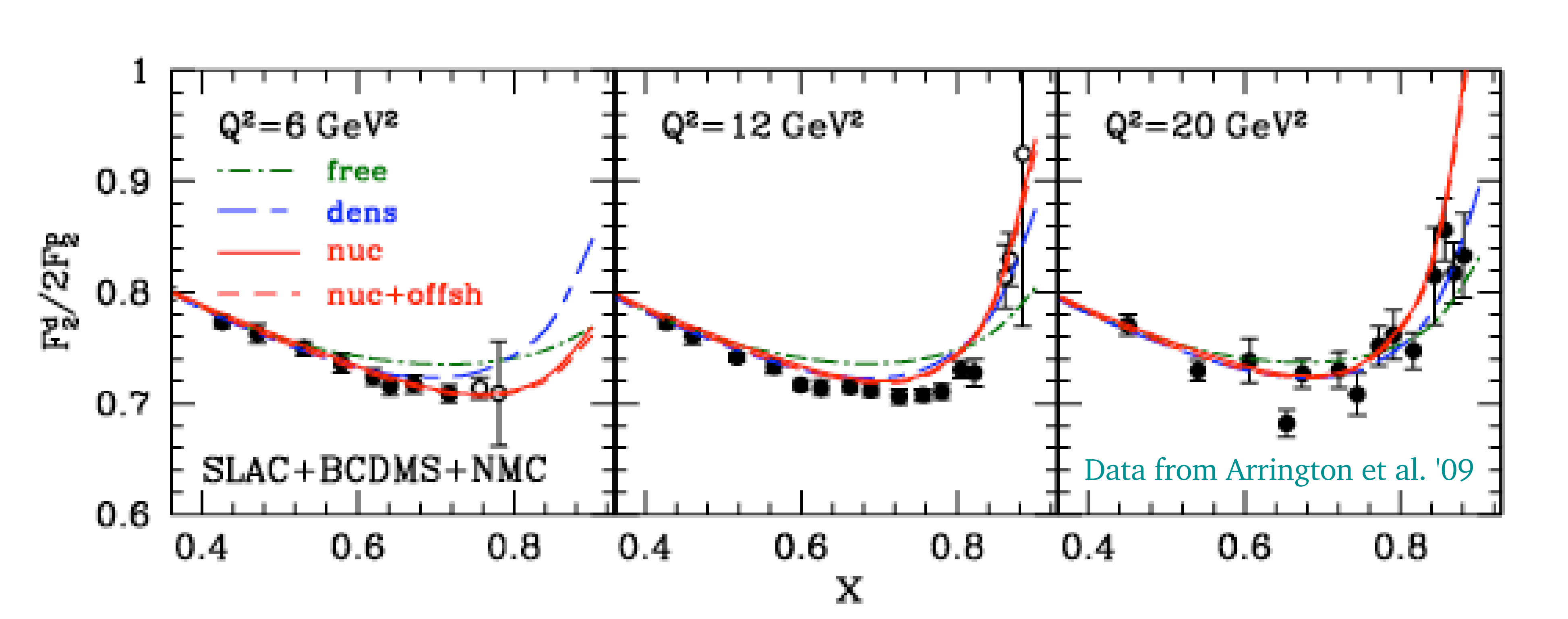
- **Large theoretical undertainties on *d*-quark at large x**
  - coming from deuteron corrections
    (no deuteron ⇒ d unconstrained at large x)
  - unavoidable at the moment: model dependent

- **How to progress?**
  - Avoid them
    - Free nucleon targets
  - Constrain them
    - Q^2 dependence of D/p ratio up to Q^2 =30-40 GeV^2
    - Use quasi-free nucleon targets

Free nucleon targets

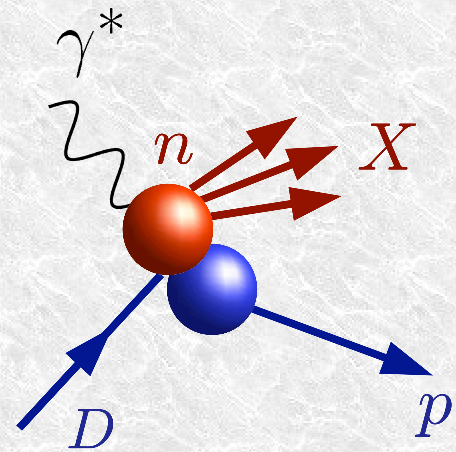
- Constraints on large-x d-quarks from
  - $p+pbar$:
    - DY at large x_F
  - $p+p$:
    - W-asymmetries at large rapidity
  - ν+p and ν-*bar*+p :
    - WA21 already has data
      (but need to reconstruct cross-sections from
      published “quark distributions”... very hard) [w/ L.Y.Zhu]
    - MINERνA with a hydrogen target [E.Christy, L.Y.Zhu]

D/p ratios



- **Strong Q^2 dependence of nuclear smearing**
  - **to be checked by higher precision data up to larger Q^2**
  - off-shell corrections don't sensibly change the result (but do change the *d*-quark)

Quasi-free nucleon targets - BONUS



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

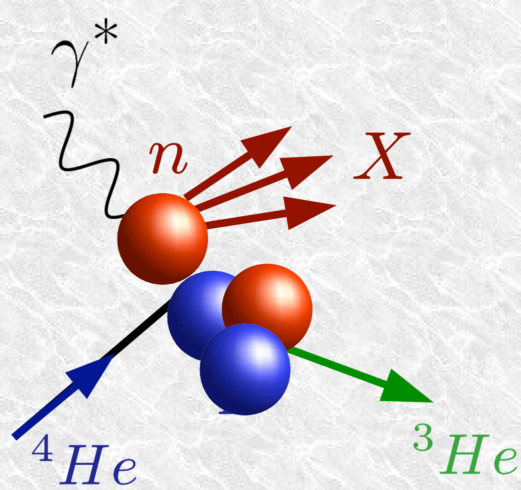
- Study the <u>off-shell dependence</u> of $F_2(n)$ and quark PDFs

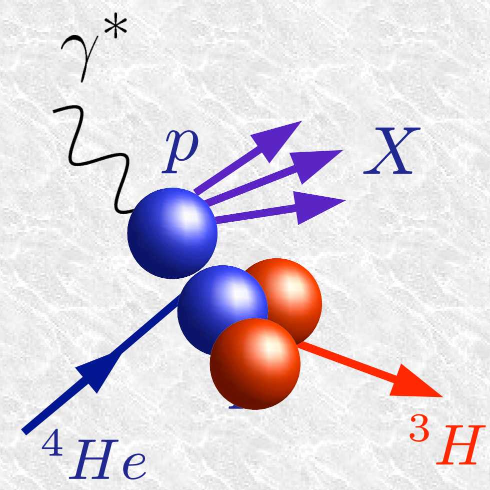
$$q \equiv q_D(x, Q^2, p^2)$$

- <u>Extrapolate</u> to a free neutron target $p^2 \to {M_n}^2$

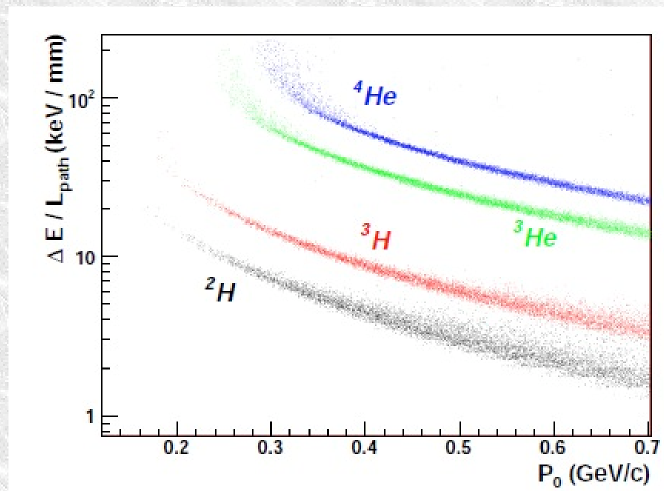
Quasi-free nucleon targets - EG6

- DIS on ^{4}He with tagged ^{3}He or ^{3}H
  - neutron & proton off-shellness reconstructed



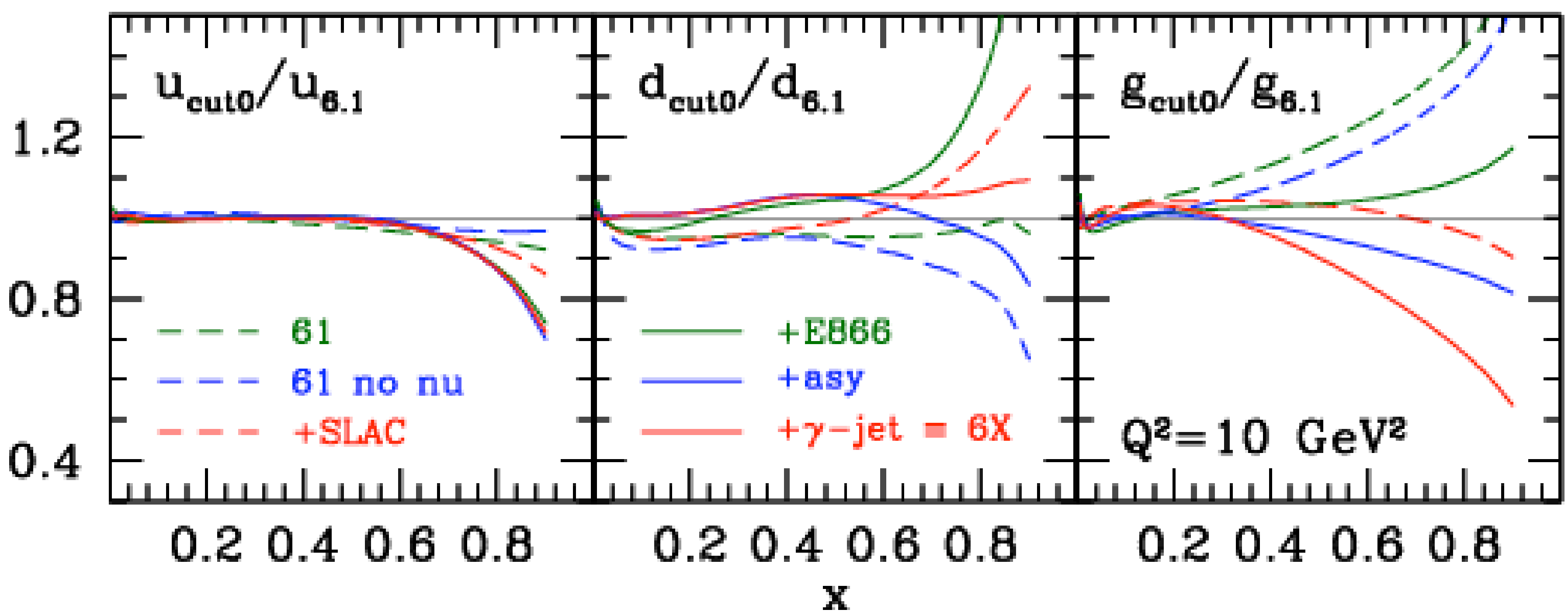


- Study the off-shell dependence of $F_2(n)$ & $F_2(p)$
- Compare off-shell $F_2(n/D)$ to $F_2(n/^4He)$
  - any nuclear dependence?
- Extrapolate to a free proton target $p^2 \rightarrow M_n{}^2$
  - and CHECK the extrapolation procedure

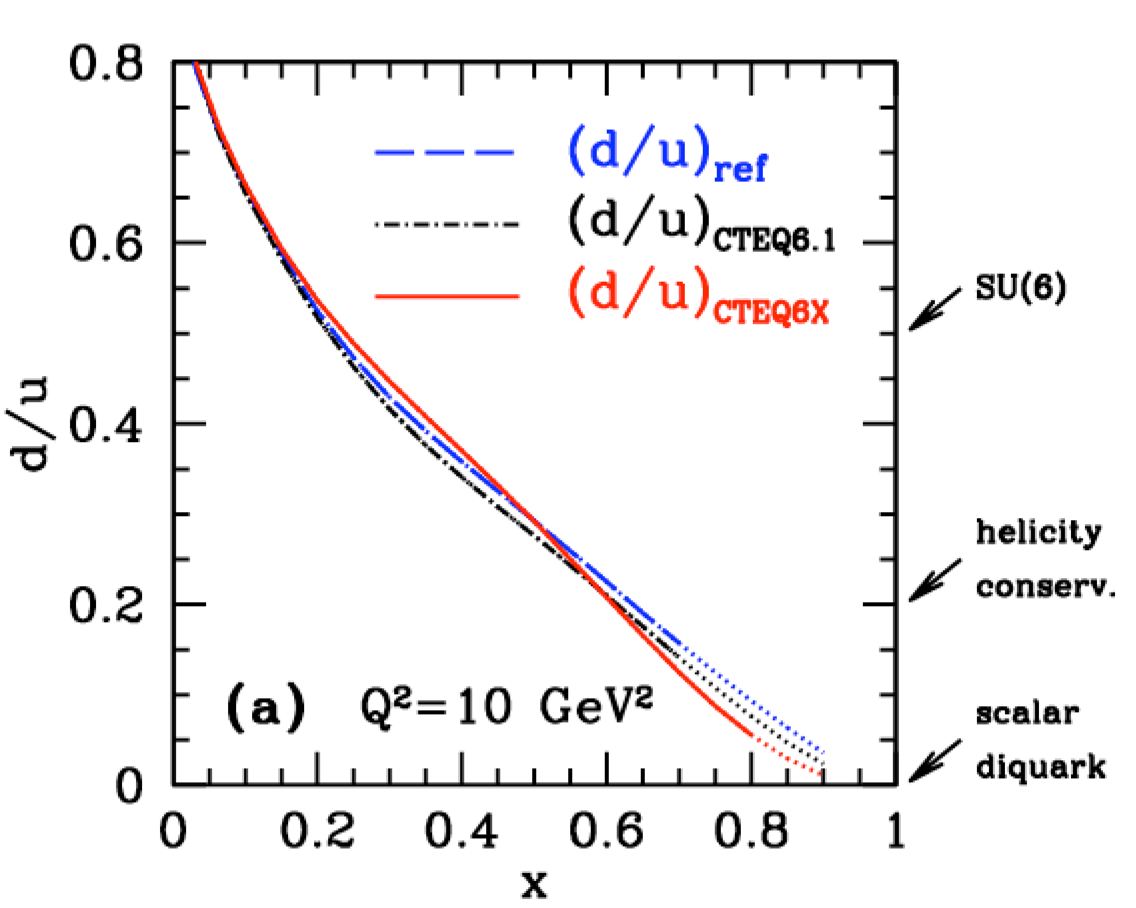


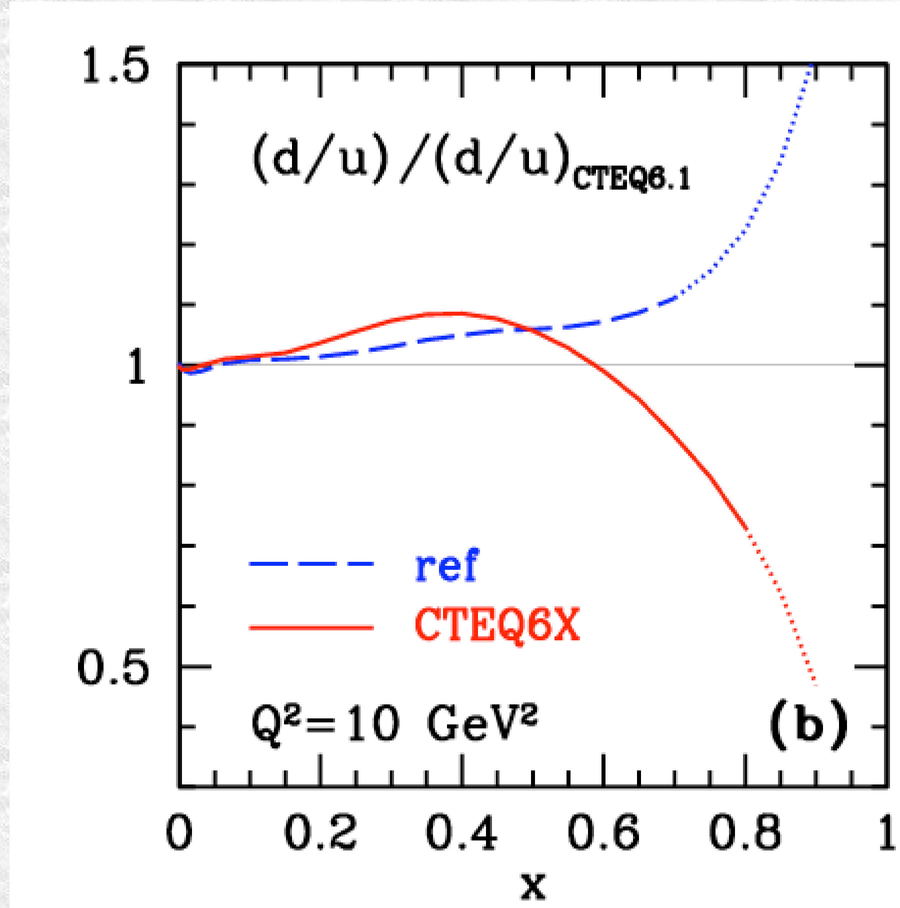
From CTEQ6.1 to our reference fit

- The lines show our fit to data sets interpolating 6.1 and 6X
  - minor differences lack of correlated error treatment un our code



d/u ratio





- NOTE: at $x \to 1$the CTEQ6.1 parametrization constrains

$$d/u \to 0 \quad \text{or} \quad d/u \to \infty$$

  - we are working on free d/u fits