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New global analysis of PDFs
– *exploring the large-x domain*

Wally Melnitchouk

"CTEQX"

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Outline

- Why is nucleon structure at large x important?

- Navigating the large-x landscape
  - $\longrightarrow$ nuclear corrections
  - $\longrightarrow$ target mass corrections & higher twists

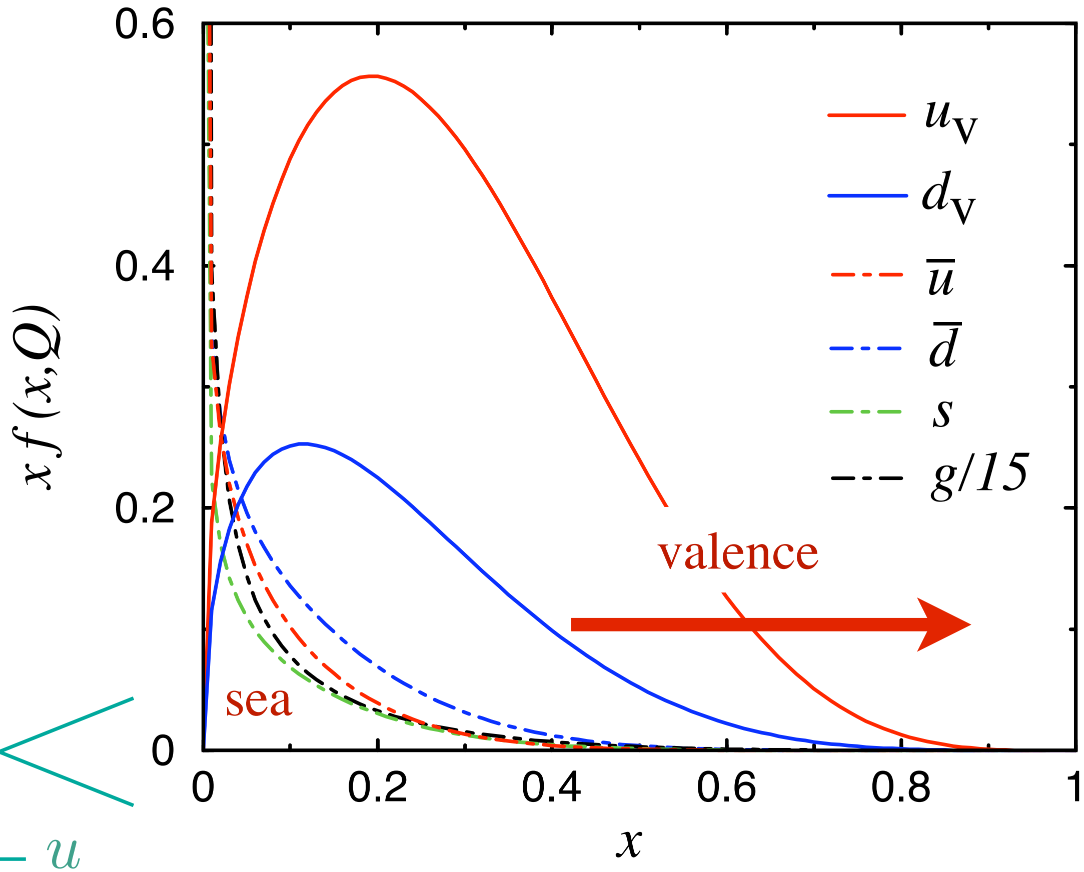
- New global analysis (CTEQX)
  - $\longrightarrow$ first foray into high-x, low-Q^2 region
  - $\longrightarrow$ surprising new results for d/u

- Future experimental constraints

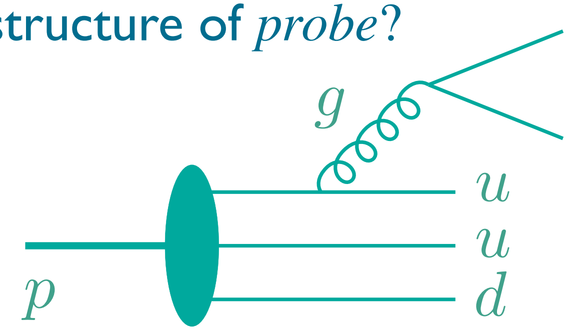
Why are PDFs at large x interesting?

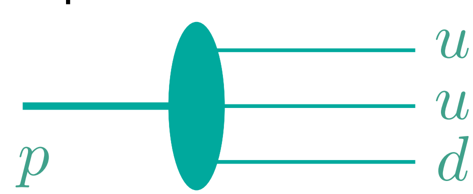
- Most direct connection between quark distributions and nonperturbative structure of nucleon is via *valence* quarks

→ most cleanly revealed at $x > 0.4$



structure of *hadron*
or structure of *probe*?





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- Most direct connection between quark distributions and nonperturbative structure of nucleon is via *valence* quarks

- Predictions for $x \to 1$ behavior of *e.g.* d/u ratio
  - → scalar diquark dominance: $d/u = 0$ *Feynman (1972)*
  - → hard gluon exchange: $d/u = 1/5$ *Farrar, Jackson (1975)*
  - → SU(6) symmetry: $d/u = 1/2$

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- Needed to understand backgrounds in searches for *new physics* beyond the Standard Model at LHC, ν oscillation experiments, astrophysics applications
  - ⟶ DGLAP evolution feeds low x, high Q^2 from high x, low Q^2

- At large x, valence u and d distributions extracted from p and n structure functions, *e.g.* at LO

$$\frac{1}{x}F_2^p \approx \frac{4}{9}u_v + \frac{1}{9}d_v$$

$$\frac{1}{x}F_2^n \approx \frac{4}{9}d_v + \frac{1}{9}u_v$$

- u quark distribution well determined from *proton*

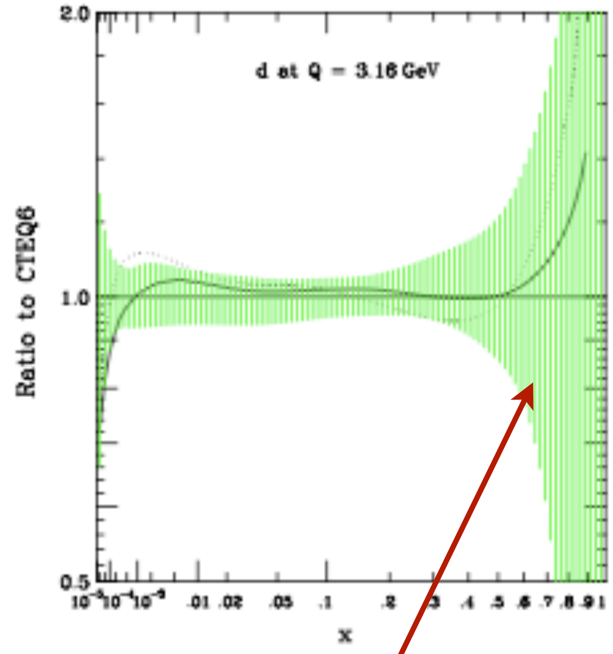
- d quark distribution requires *neutron* structure function

$$\Longrightarrow \quad \frac{d}{u} \approx \frac{4 - F_2^n/F_2^p}{4F_2^n/F_2^p - 1}$$

- No **FREE** neutron targets

  (neutron half-life ~ 12 mins)

  ➡ use deuteron as "effective" neutron target



large uncertainty beyond $x \sim 0.5$

- **BUT** deuteron is a nucleus

  ➡ $F_2^d \neq F_2^p + F_2^n$

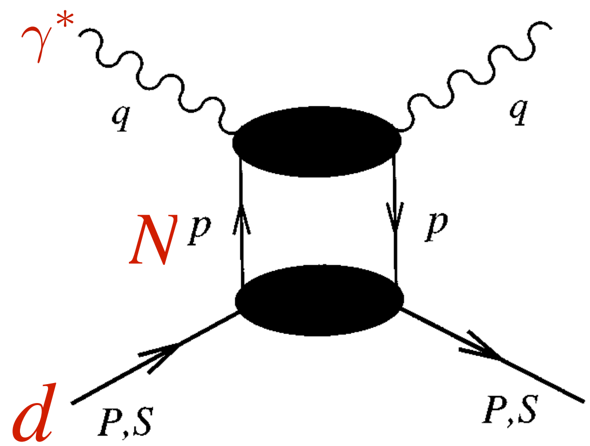
  ➡ nuclear effects (nuclear binding, Fermi motion, shadowing) *obscure neutron structure* information

  ➡ need to correct for "nuclear EMC effect"

Large-x landscape:
nuclear effects in the deuteron

- nuclear "impulse approximation"

→ incoherent scattering from individual nucleons in d
(good approx. at $x >> 0$)



$$F_2^d(x,Q^2) = \int_x dy\ f(y,\gamma)\ F_2^N(x/y,Q^2) + \delta^{(\mathrm{off})} F_2^d$$

N=p+n

nucleon momentum distribution in d ("smearing function")

off-shell correction (~1%)

→ $y = p\cdot q/P\cdot q$ light-cone momentum fraction of d carried by N

→ at finite Q^2, smearing function depends also on parameter

$$\gamma = |\mathbf{q}|/q_0 = \sqrt{1+4M^2x^2/Q^2}$$

N momentum distributions in d

- weak binding approximation (WBA): expand amplitudes to order $\vec{p}^2/M^2$

$$f(y,\gamma) = \int \frac{d^3p}{(2\pi)^3}\; |\psi_d(p)|^2\; \delta\left(y - 1 - \frac{\varepsilon + \gamma p_z}{M}\right)$$

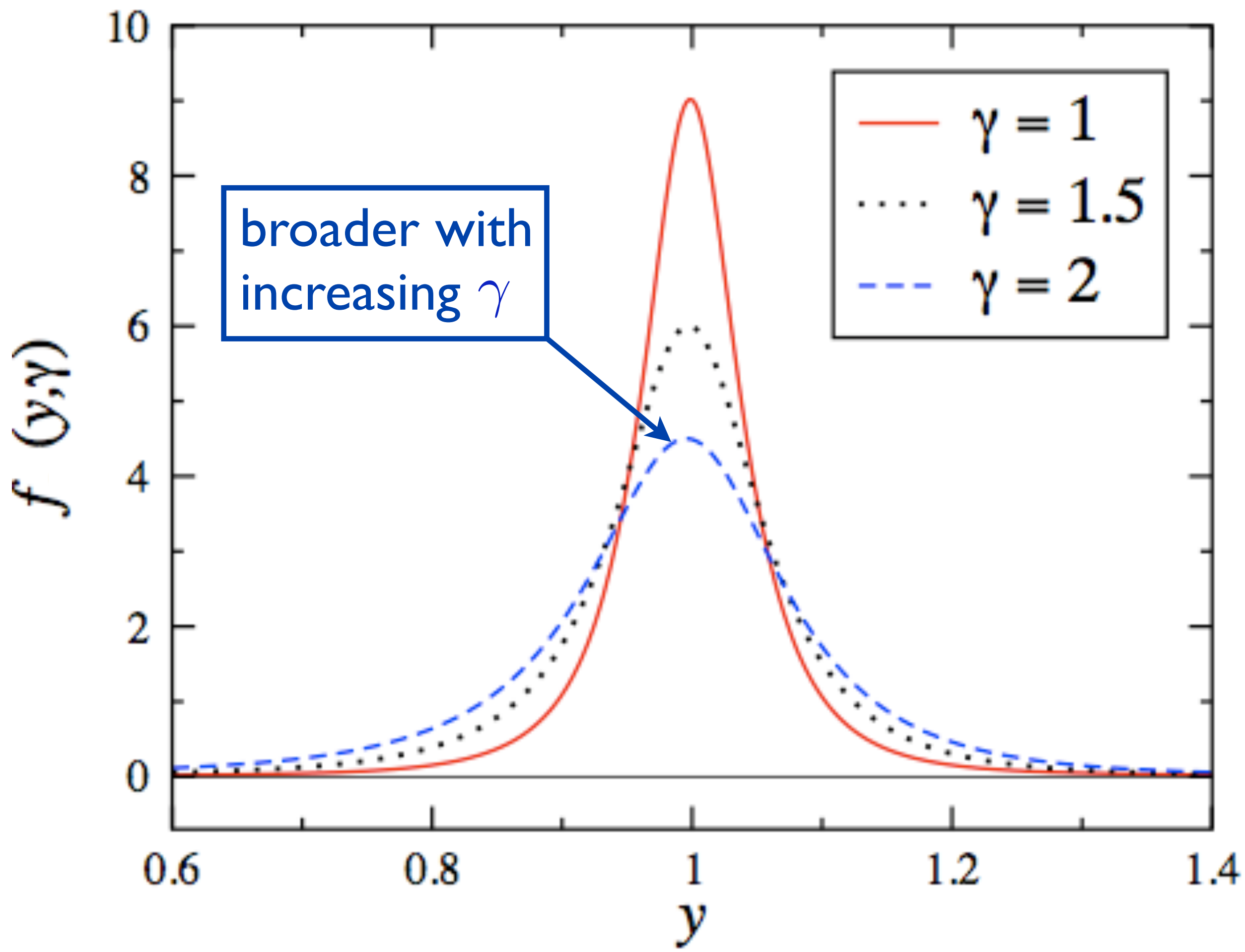
$$\times \frac{1}{\gamma^2}\left[1 + \frac{\gamma^2 - 1}{y^2}\left(1 + \frac{2\varepsilon}{M} + \frac{\vec{p}^2}{2M^2}(1 - 3\hat{p}_z^2)\right)\right]$$

→ deuteron wave function $\psi_d(p)$

→ deuteron separation energy $\varepsilon = \varepsilon_d - \dfrac{\vec{p}^2}{2M}$

→ approaches usual nonrelativistic momentum distribution in $\gamma \to 1$ limit

N momentum distributions in d



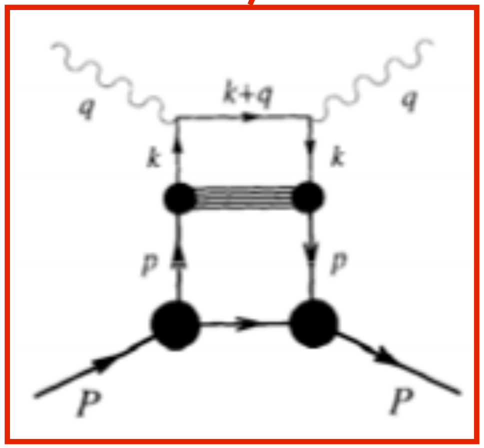
Kahn, WM, Kulagin (2009)

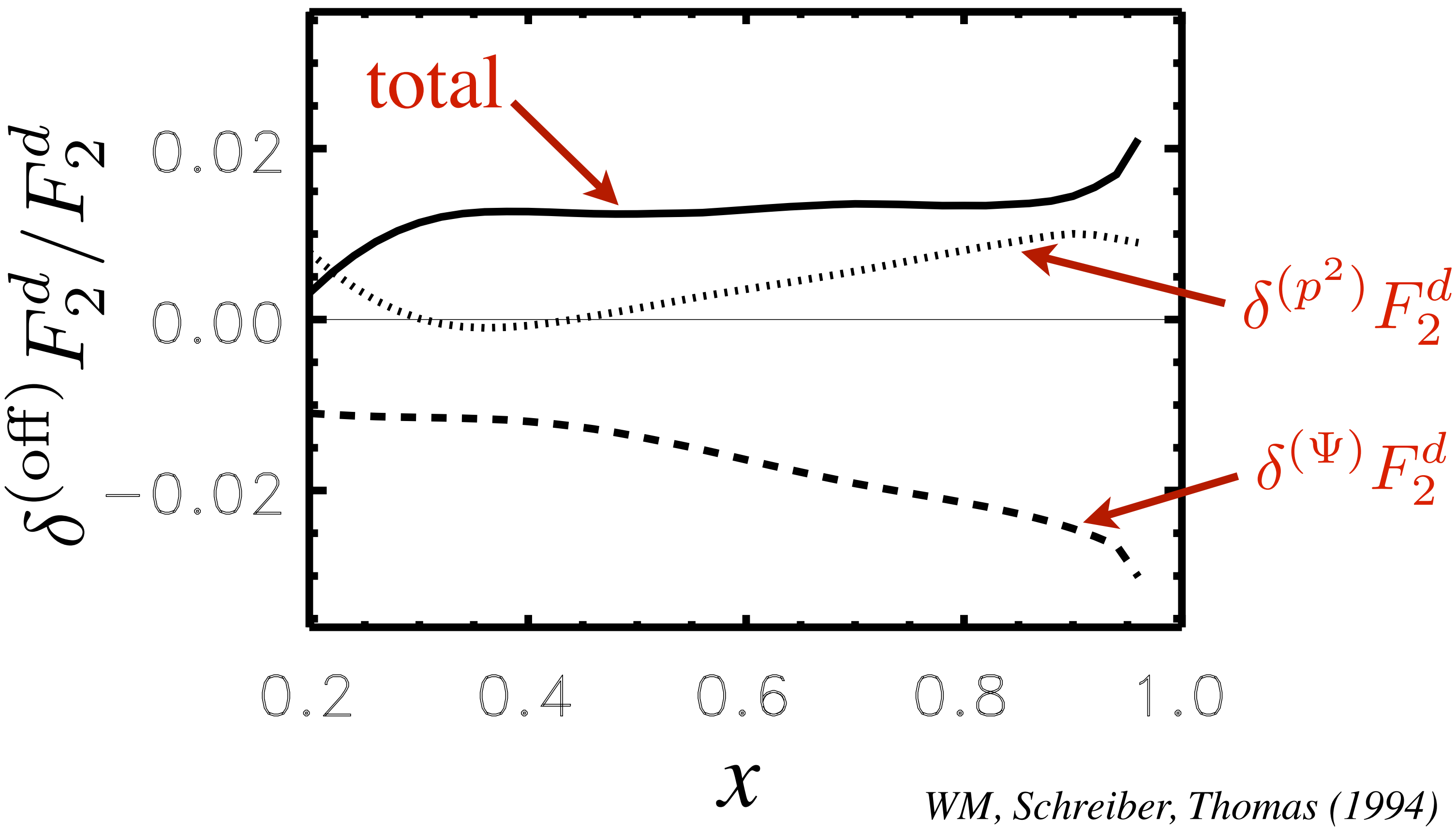
→ for most kinematics $\gamma \lesssim 2$

Off-shell correction

$\delta^{(\text{off})} F_2^d \;\rightarrow\; \delta^{(\Psi)} F_2^d$ negative energy components of ψ_d

$\rightarrow\; \delta^{(p^2)} F_2^d$ off-shell N structure function

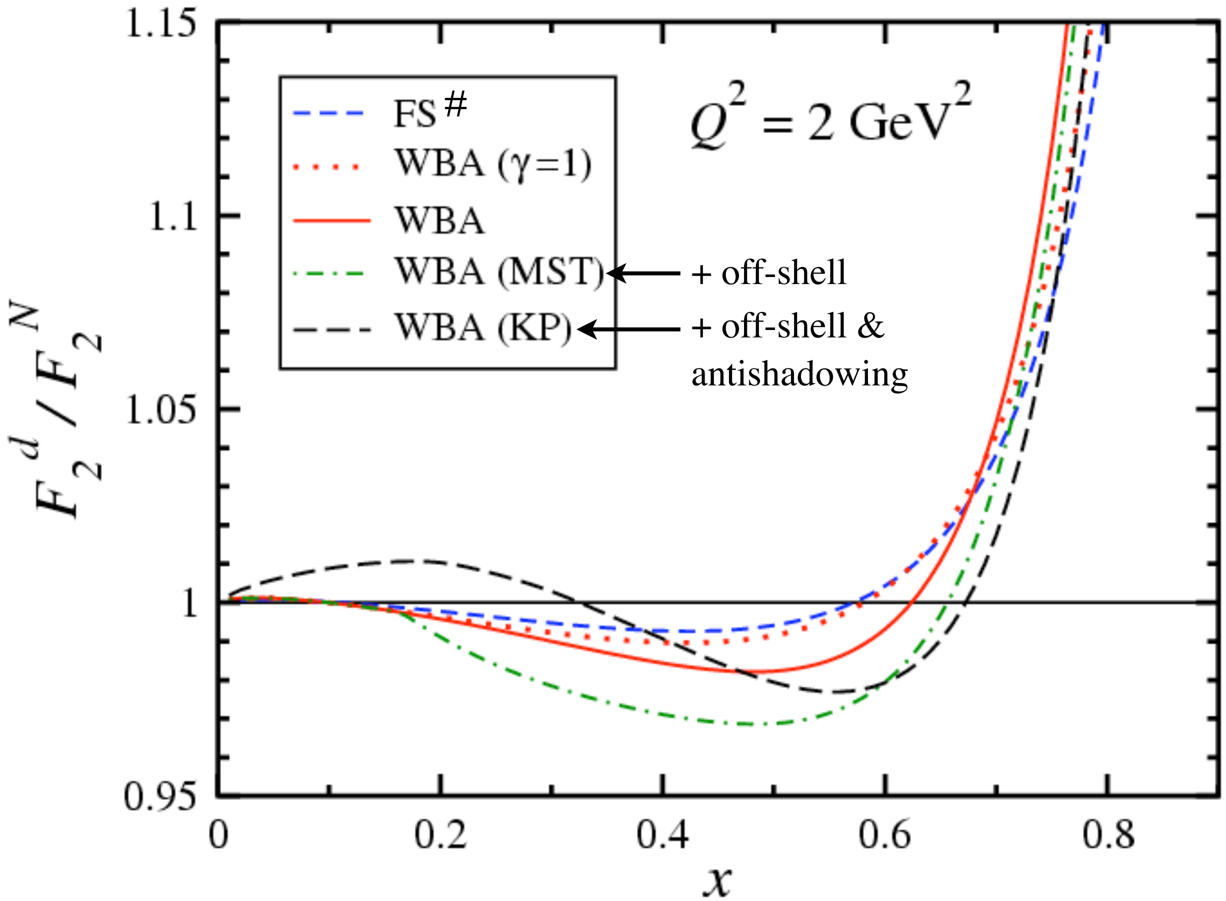




WM, Schreiber, Thomas (1994)

$\rightarrow\; \leq 1-2\ \%$ effect

EMC effect in deuteron



Frankfurt-Strikman "light-cone" model (no binding)

→ ~ 2–3% reduction of d/N ratio at $x \sim 0.5$–0.6 with steep rise for $x > 0.6$

→ can significantly affect neutron extraction

Large-*x* landscape:
target mass & higher twist corrections

Target mass corrections

- Additional corrections from *kinematical* Q^2/ν^2 effects

  $\longrightarrow$ "target mass corrections" (TMC), since $x = Q^2/2M\nu$

- Important at large x and low Q^2

  $\longrightarrow$ new "Nachtmann" scaling variable

$$\xi = \frac{2x}{1 + \sqrt{1 + 4M^2x^2/Q^2}}$$

Baumik, Greenberg (1971)
Nachtmann (1973)

$\longrightarrow$ but *not unique* – depends on formalism
($e.g.$ OPE, collinear factorization)

Operator product expansion

→ n-th Cornwall-Norton moment of F_2 structure function

$$M_2^n(Q^2) = \int dx\ x^{n-2}\ F_2(x,Q^2)$$
$$= \sum_{j=0}^{\infty} \left(\frac{M^2}{Q^2}\right)^j \frac{(n+j)!}{j!(n-2)!} \frac{A_{n+2j}}{(n+2j)(n+2j-1)}$$

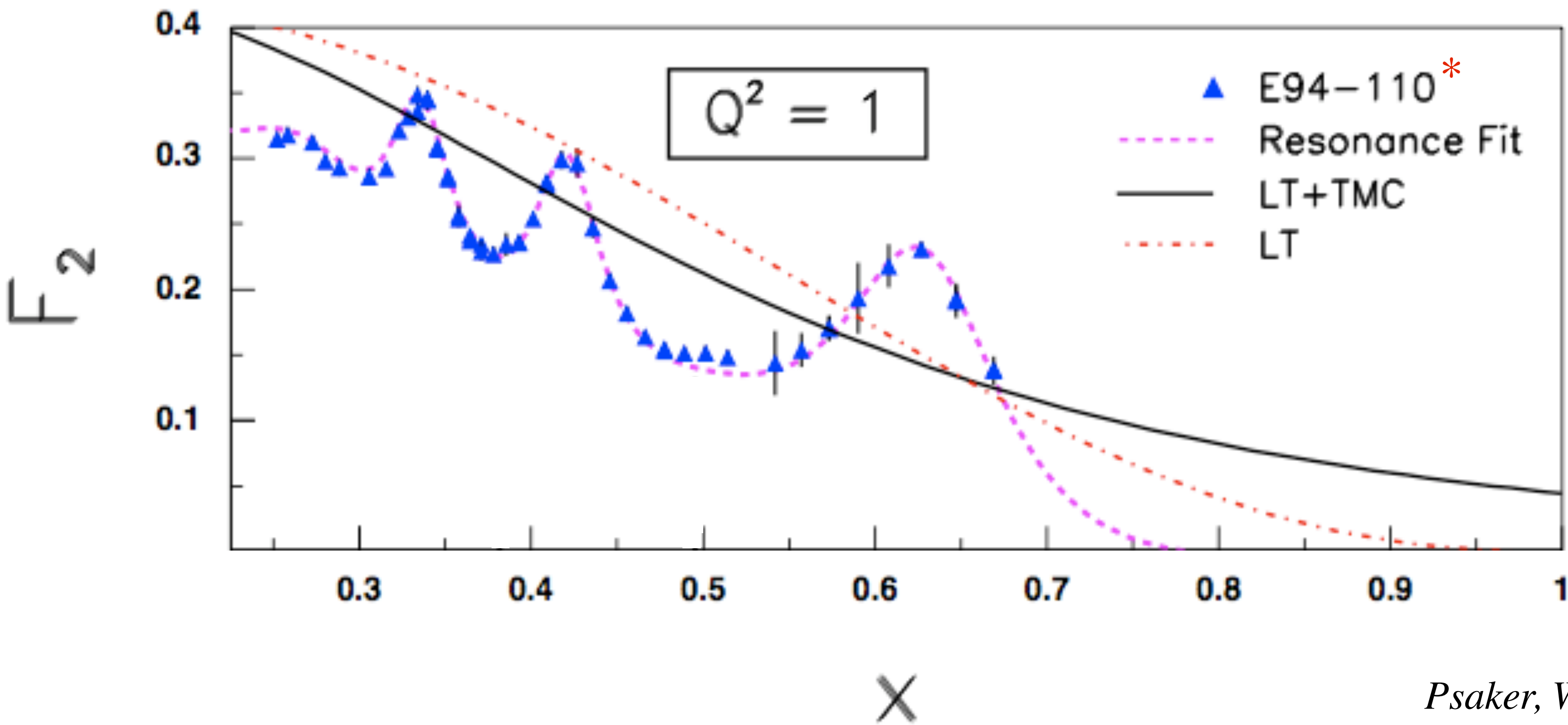
→ take inverse Mellin transform

$$F_2^{\rm OPE}(x,Q^2) = \frac{x^2}{\xi^2\gamma^3} F_2^{(0)}(\xi,Q^2) + \frac{6M^2x^3}{Q^2\gamma^4} \int_\xi^1 du \frac{F_2^{(0)}(u,Q^2)}{u^2}$$
$$+ \frac{12M^4x^4}{Q^4\gamma^5} \int_\xi^1 dv (v-\xi) \frac{F_2^{(0)}(v,Q^2)}{v^2}$$

Georgi, Politzer (1976)

where $F_2^{(0)}$ is structure function in massless (Bjorken) limit

Target mass corrections

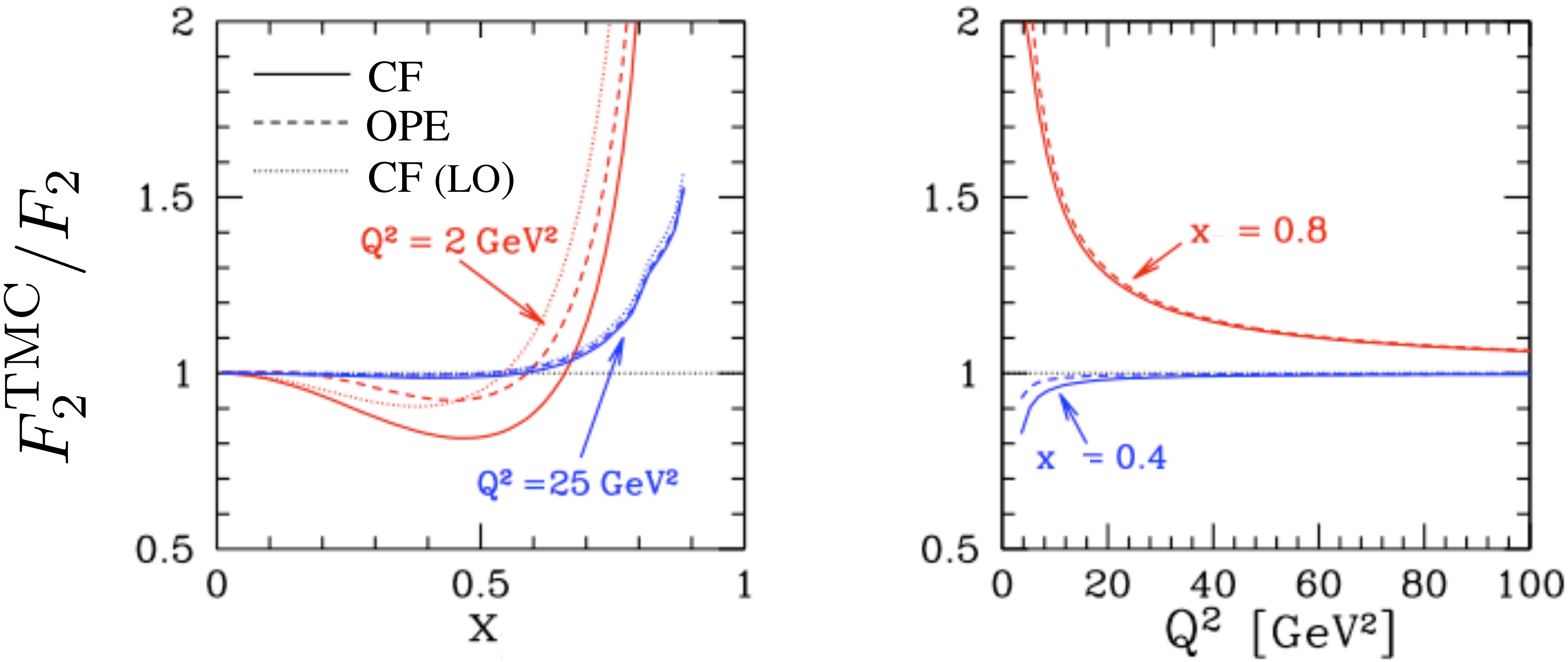


* JLab Hall C

Psaker, WM et al. (2008)

→ TMC important for verification of quark-hadron duality

Target mass corrections



Accardi, Qiu (2008)

→ TMC important at large *x even for large* Q^2

Collinear factorization

→ work directly in *momentum* space at partonic level (avoids need for Mellin transform)

→ expand parton momentum k around its *on-shell* and *collinear* component $(k_\perp^2 \to 0)$

Ellis, Furmanski, Petronzio (1983)

$$F_{T,L}(x,Q^2) = \sum_q \int_\xi^{\xi/x} \frac{dy}{y}\, C^q_{T,L}\left(\frac{\xi}{y},Q^2\right) q(y,Q^2)$$

Accardi, Qiu (2008)

avoids unphysical $x > 1$ region

→ at leading order

$$F_2^{\rm CF}(x,Q^2) = \frac{x}{\xi\gamma^2}\, F_2^{(0)}(\xi,Q^2)$$

$$\approx \frac{\xi\gamma}{x}\, F_2^{\rm OPE}(x,Q^2)$$

Kretzer, Reno (2004)

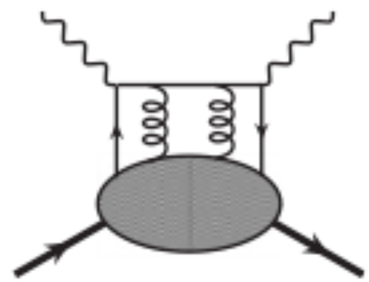
Higher twists

- $1/Q^2$ expansion of structure function moments

$$M_n(Q^2) = \int_0^1 dx\ x^{n-2}\ F_2(x,Q^2)\ = A_n^{(2)} + \frac{A_n^{(4)}}{Q^2} + \frac{A_n^{(6)}}{Q^4} + \cdots$$

matrix elements of operators with specific "twist" (= dimension − spin)

→ twist > 2 reveals long-range mulit-parton correlations



- phenomenologically important wherever TMCs important

→ parametrize x dependence by

$$F_2(x,Q^2) = F_2^{\rm LT}(x,Q^2)\left(1 + \frac{C(x)}{Q^2}\right)$$

New global analysis
(“CTEQX”)

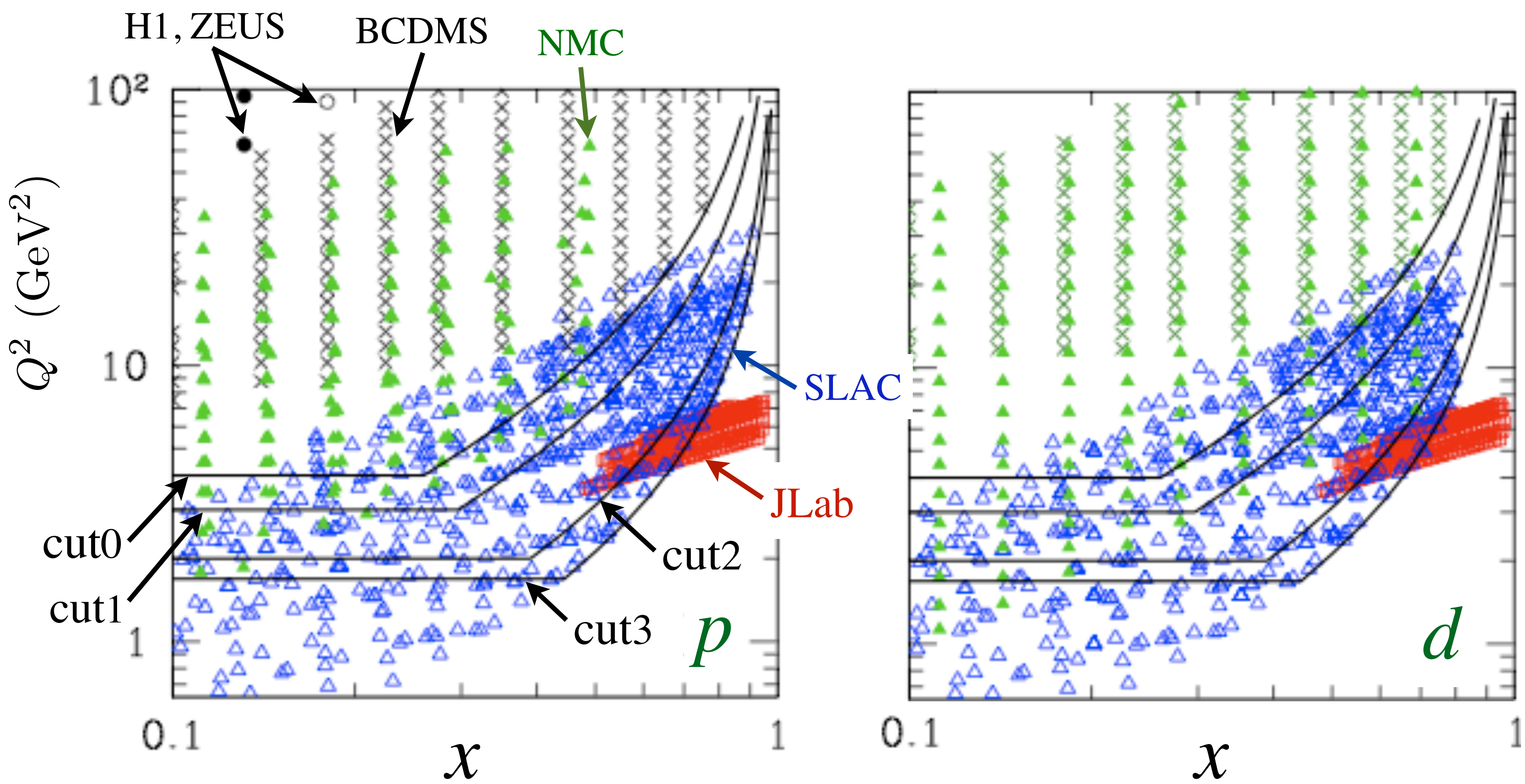
- Next-to-leading order analysis of expanded set of *proton* and *deuterium* data, including large-x, low-Q^2 region

- Systematically study effects of Q^2 & W *cuts*
  - ⟶ as low as $Q \sim m_c$ and $W \sim 1.7$ GeV

- Include subleading $1/Q^2$ corrections
  - ⟶ target mass corrections
  - ⟶ dynamical higher twists

- Correct for *nuclear* effects in the deuteron

Kinematic cuts



cut0: $Q^2 > 4\ \mathrm{GeV}^2, \quad W^2 > 12.25\ \mathrm{GeV}^2$

cut1: $Q^2 > 3\ \mathrm{GeV}^2, \quad W^2 > 8\ \mathrm{GeV}^2$

cut2: $Q^2 > 2\ \mathrm{GeV}^2, \quad W^2 > 4\ \mathrm{GeV}^2$

cut3: $Q^2 > m_c^2\ , \quad W^2 > 3\ \mathrm{GeV}^2$

Data points

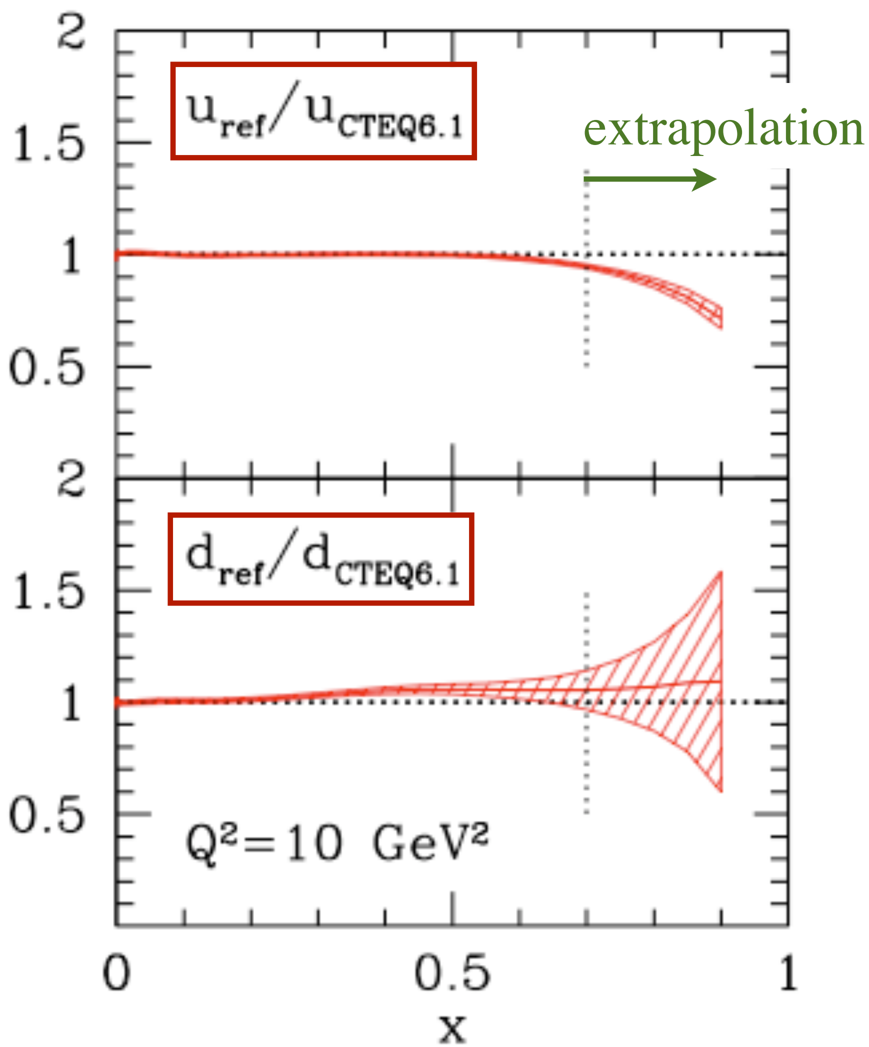
factor 2 increase
from cut0 → cut3

			Total		Deuterium		
			cut0	cut3	cut0	cut3	CTEQ6.1
DIS	*JLab	[39]	–	272	–	136	
	#SLAC	[40]	206	1147	104	582	
	NMC	[41]	324	464	123	189	√
	BCDMS	[42]	590	605	251	254	√
	H1	[43]	230	251	–	–	√
	ZEUS	[44]	229	240	–	–	√
νA DIS	CCFR	[45],[46]	–	–	–	–	√
DY	E605	[47]	119		–		√
	#E866	[48]	375		191		
W asymmetry	CDF '98 (ℓ)	[49]	11		–		√
	#CDF '05 (ℓ)	[50]	11		–		
	#D0 '08 (ℓ)	[51]	10		–		
	#D0 '08 (e)	[52]	12		–		
	#CDF '09 (W)	[53]	13		–		
jet	CDF	[54]	33		–		√
	D0	[55]	90		–		√
γ+jet	#D0	[56]	56		–		
	TOTAL		2408	3709	569	1161	

* only L–T separated data used at low Q^2

new data sets in CTEQX fit

Effect of new data on "standard" fits



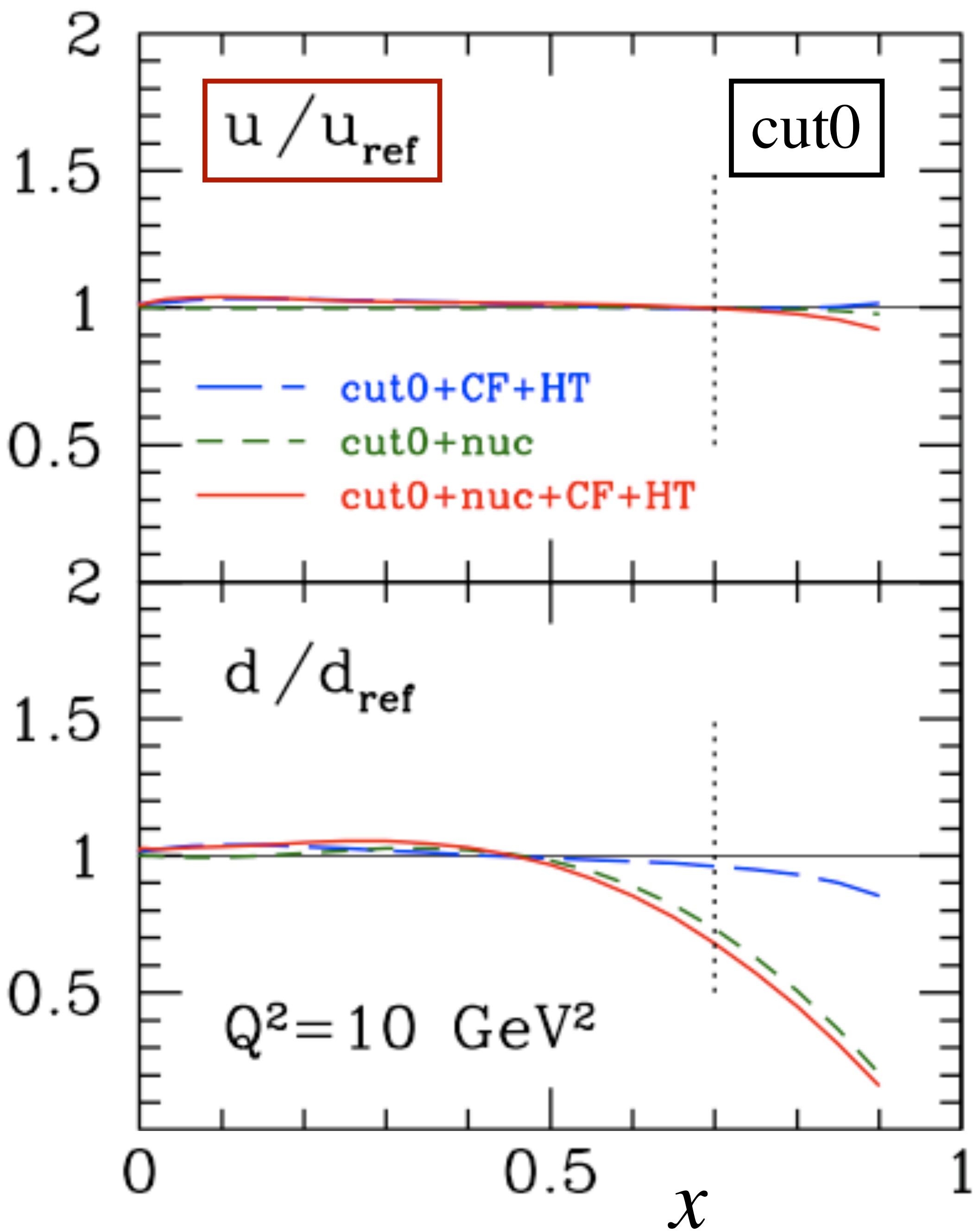
→ "cut0" (as in CTEQ6.1)

→ no nuclear or $1/Q^2$ corrections

→ no significant effect in measured region

→ u suppression at large x due to E866 DY data

Effect on "reference" fit from $1/Q^2$ and nuclear corrections



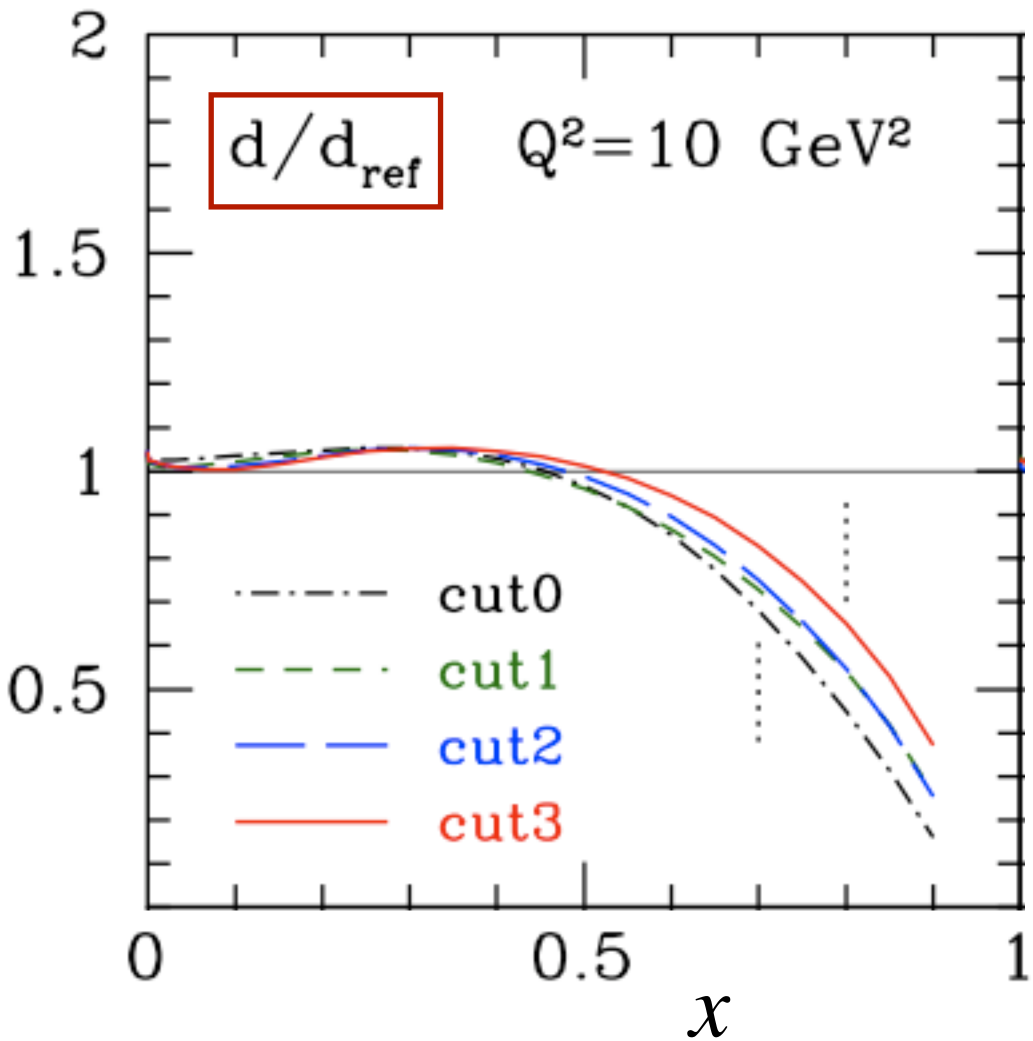
→ cut0 limits significant change to u quark

→ profound effect on d quark from nuclear corrections in deuteron

→ must include deuteron corrections for $x > 0.5$ *even for standard cuts*

Effect of Q^2 & W cuts

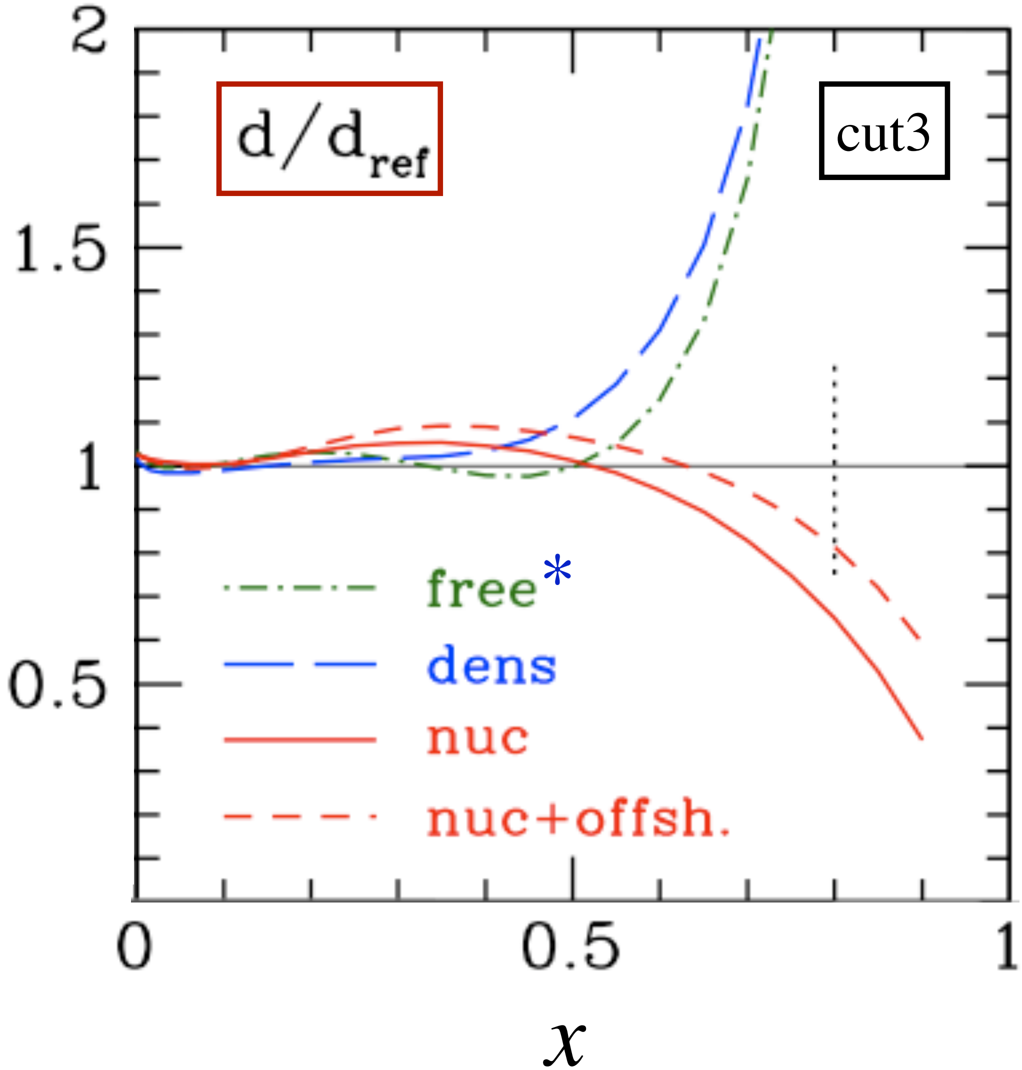
- Systematically reduce Q^2 and W cuts
- Fit includes TMCs (CF), HT term, nuclear corrections (WBA)



→ stable with respect to cut reduction

→ d quark suppressed by $\sim 50\%$ for $x > 0.5$ (driven by nuclear corrections)

Nuclear corrections



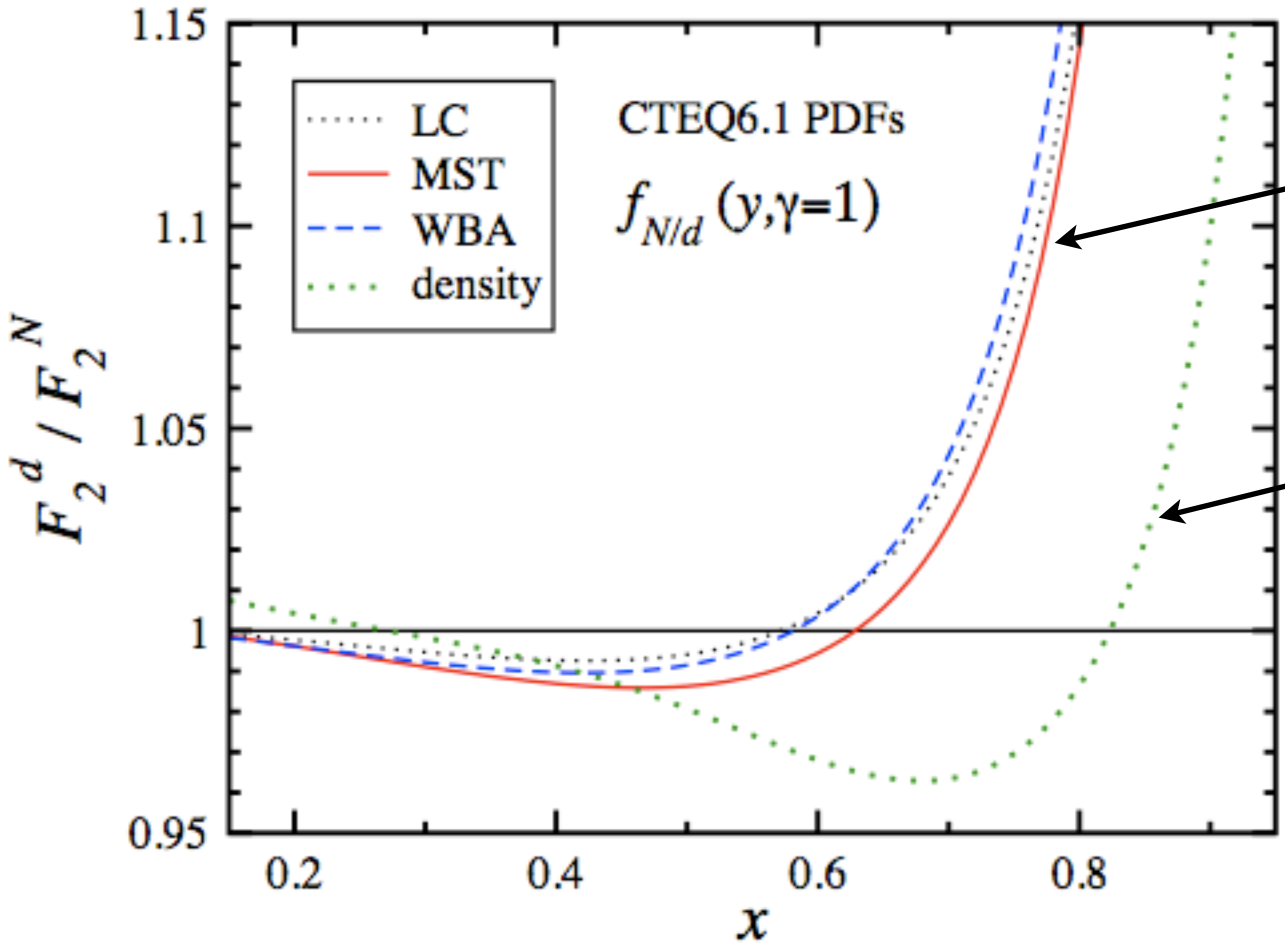
→ *increased d* quark for no nuclear effects
(or nuclear density model)

→ *decreased d* quark for nuclear smearing models

→ modest increase with off-shell correction
(larger EMC effect)

* assumes $F_2^d = F_2^p + F_2^n$ as in CTEQ6.1 and most other global fits

Nuclear corrections



nuclear smearing
(microscopic deuteron wave functions)

nuclear density *

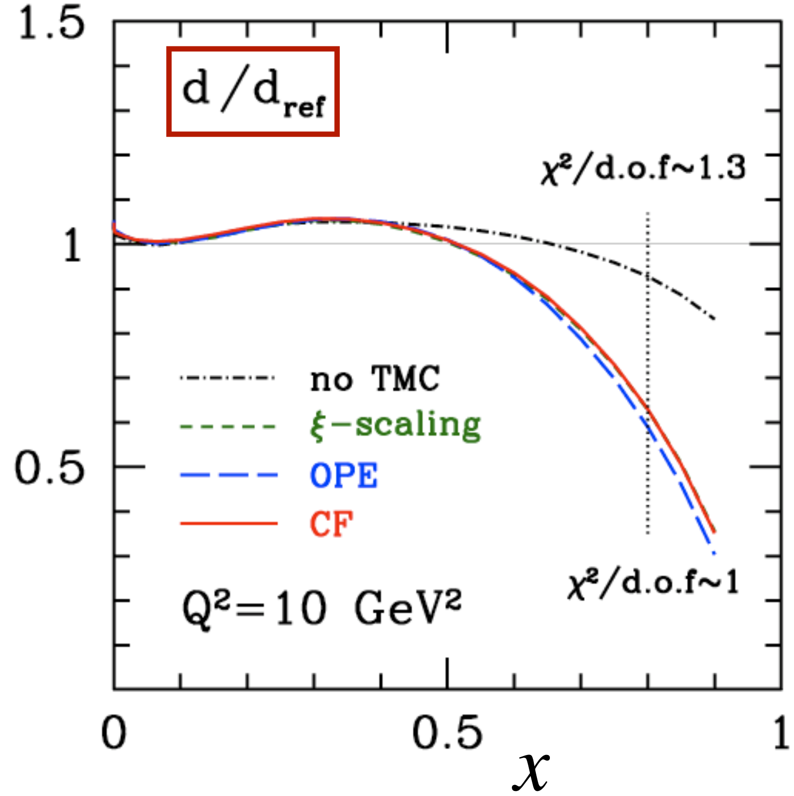
$$\frac{F_2^d}{F_2^N} - 1 \approx \frac{1}{4}\left(\frac{F_2^{\rm Fe}}{F_2^d} - 1\right)$$

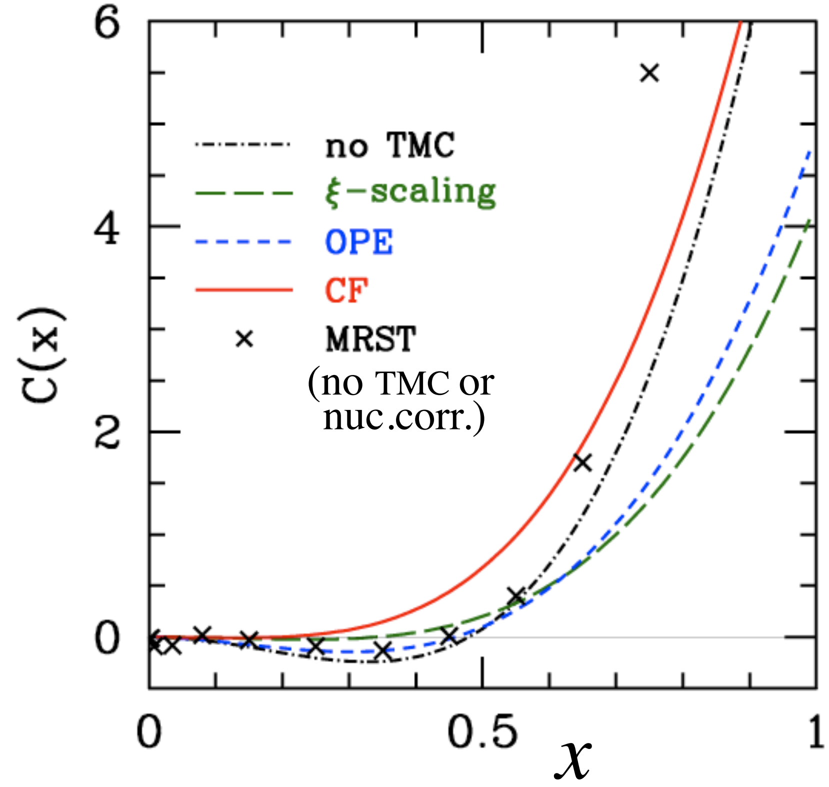
* assumes EMC effect scales with density; extrapolated from Fe $\longrightarrow$ deuterium

$\longrightarrow$ large differences with "free" for $x > 0.6$

$\longrightarrow$ definition of density for deuteron is problematic

Effect of $1/Q^2$ corrections





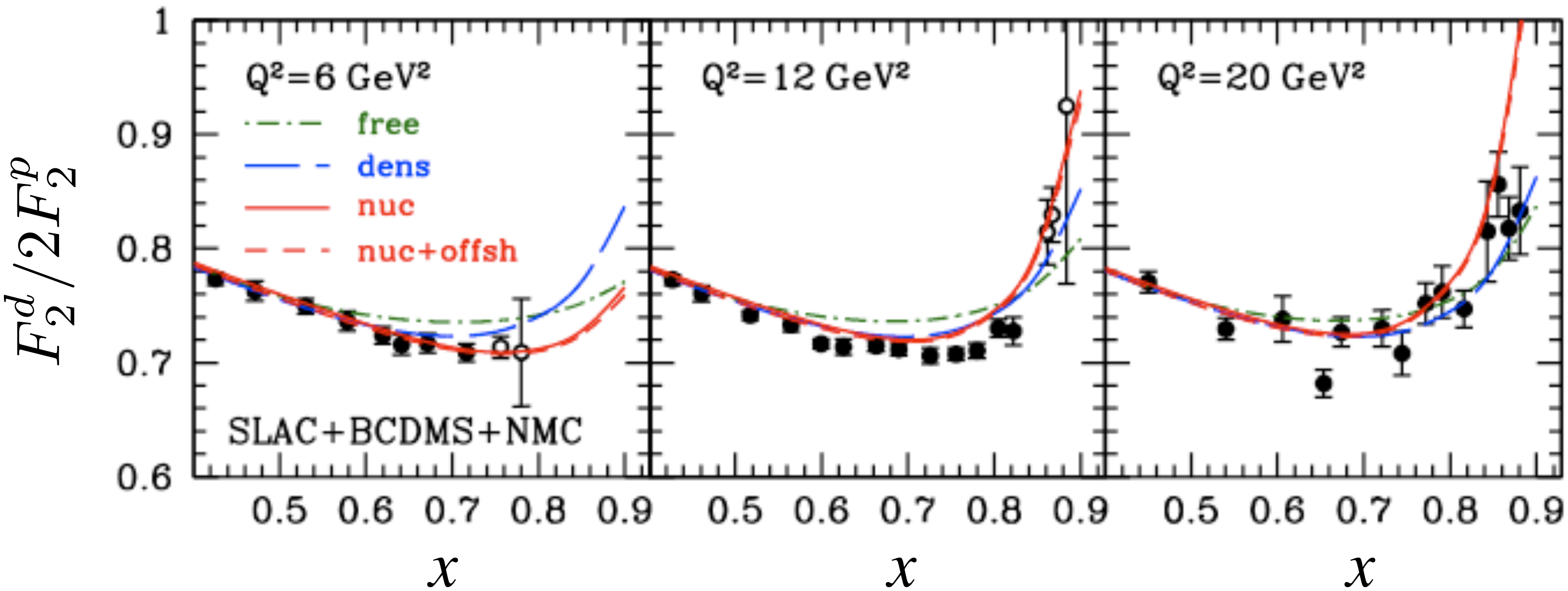
→ $1/Q^2$ HT coefficient parametrized as $C(x) = c_1 x^{c_2}(1 + c_3 x)$

→ important interplay between TMCs and higher twist: HT alone *cannot* accommodate full Q^2 dependence

→ stable leading twist when *both* TMCs and HTs included

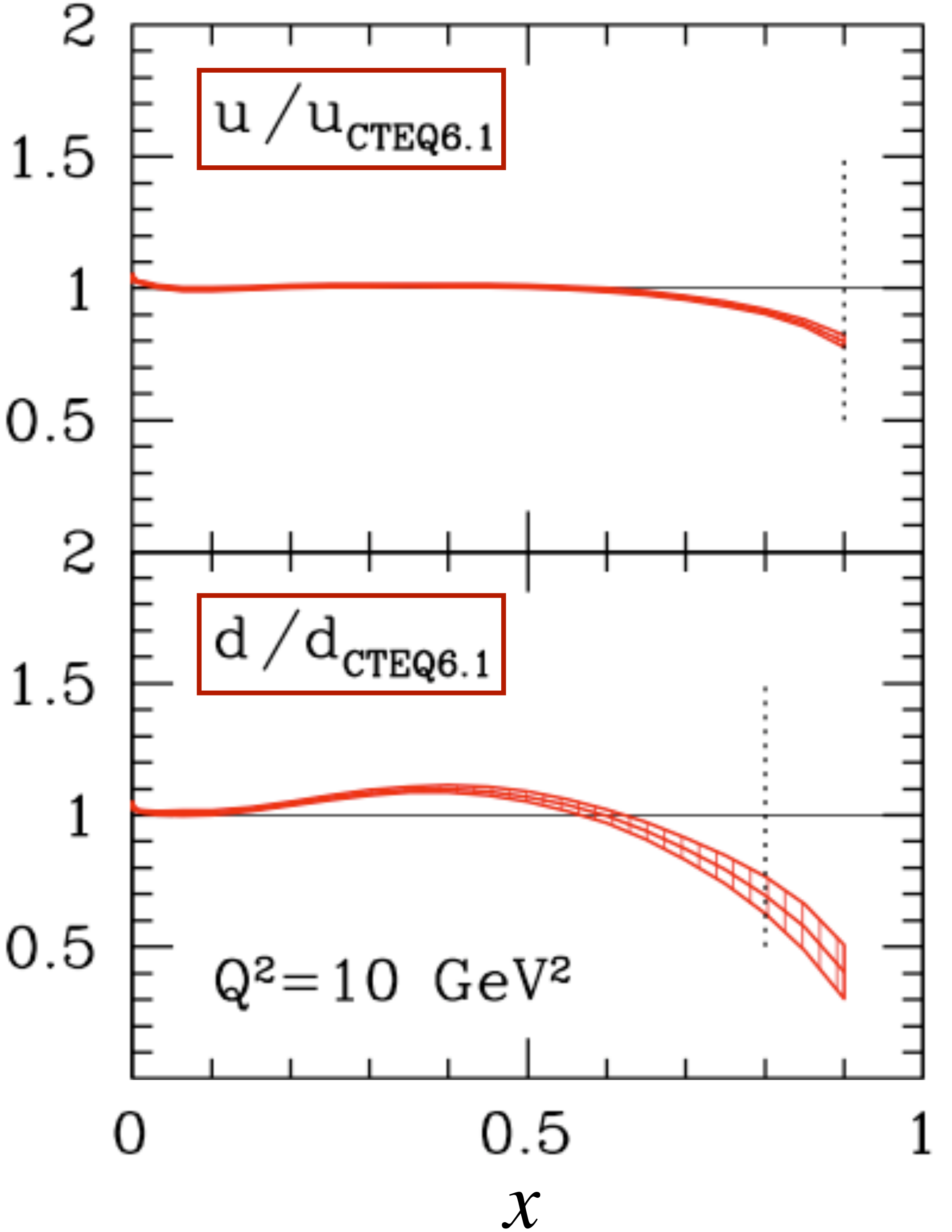
Deuteron / proton ratio

- Consistency check of fit with F_2^d/F_2^p ratio (not used in fit)



→ fits without nuclear smearing in deuteron overestimate data at intermediate x, do not reproduce rise at large x

Final PDF results



→ full fits favors *smaller d/u* ratio

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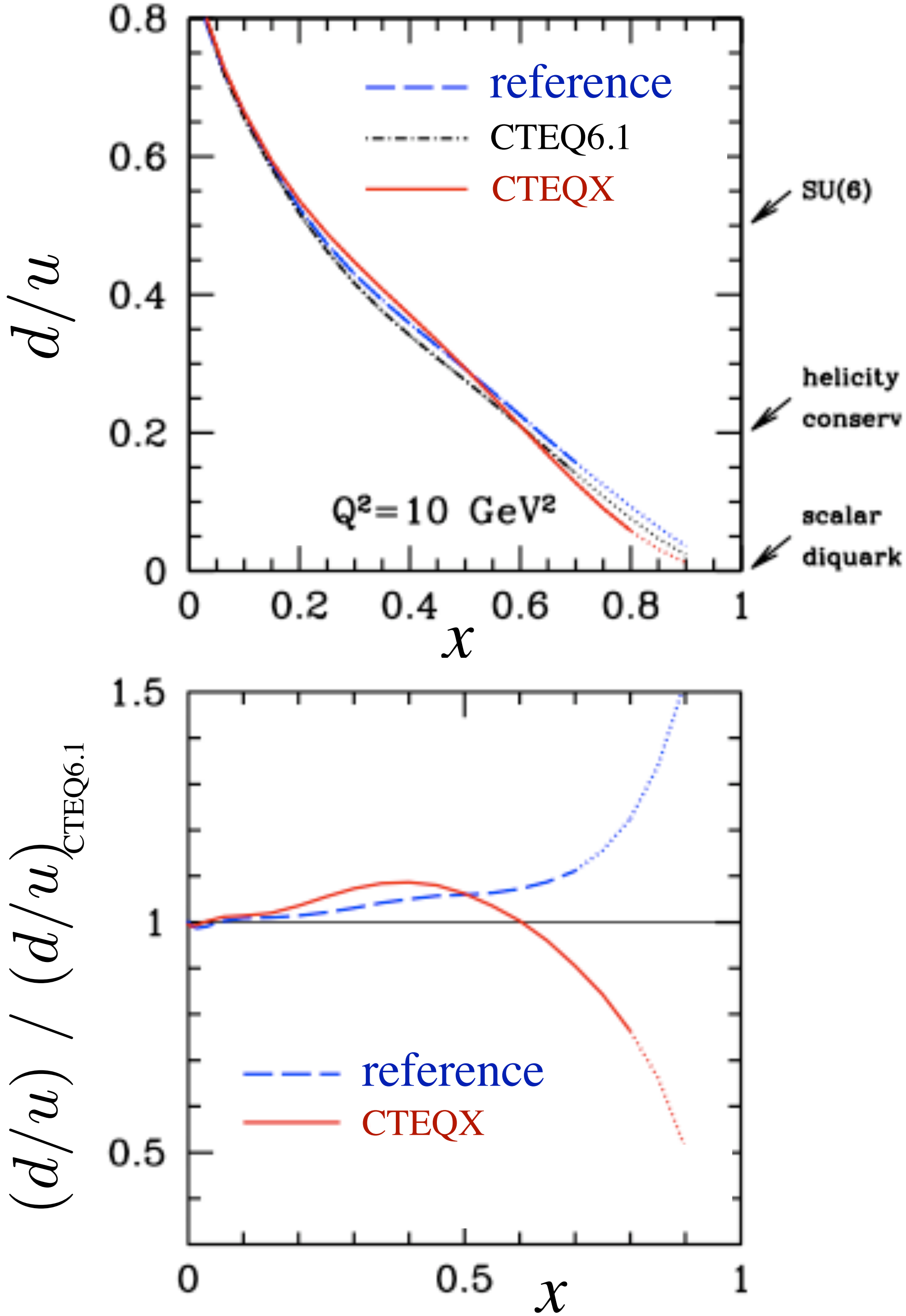

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→ dominance of non-pQCD physics (*cf.* hard *g* exchange)

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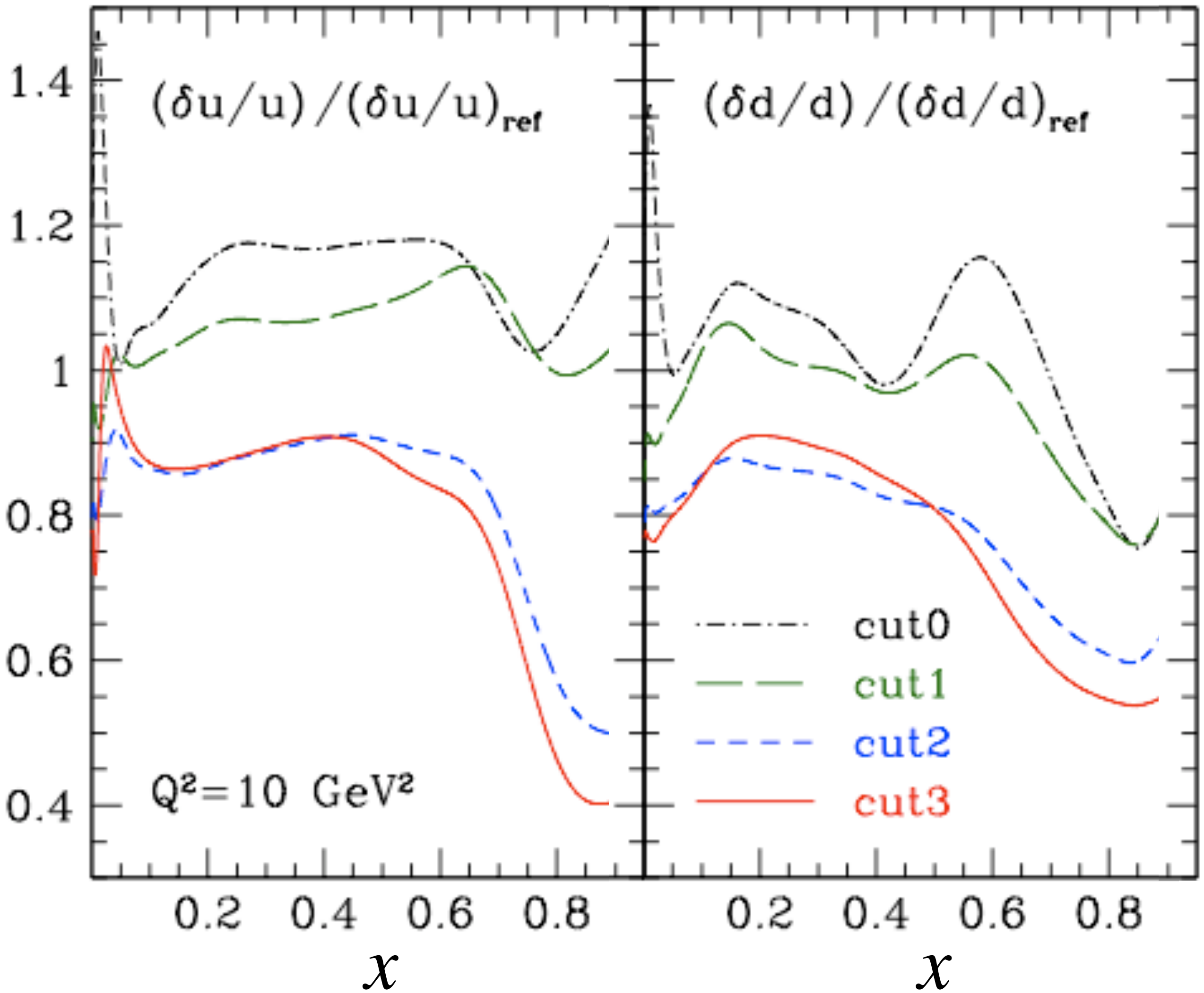

→ full fits favors *smaller d/u* ratio

→ dominance of non-pQCD physics (*cf.* counting rules)

→ significantly *reduced errors* with weaker cuts

“Cleaner” methods of determining d/u

- $e\ d \rightarrow e\ p_{\rm spec}\ X^*$ semi-inclusive DIS from d
  $\longrightarrow$ tag “spectator” protons

- $e\ {}^3{\rm He}({}^3{\rm H}) \rightarrow e\ X^*$ ^{3}He-tritium mirror nuclei

- $e\ p \rightarrow e\ \pi^{\pm}\ X^*$ semi-inclusive DIS as flavor tag

- $e^{\mp}\ p \rightarrow \nu(\bar{\nu}) X$
  $\nu(\bar{\nu})\ p \rightarrow l^{\mp}\ X$
  $p\ p(\bar{p}) \rightarrow W^{\pm} X$
  $\vec{e}_L(\vec{e}_R)\ p \rightarrow e\ X^*$
  } weak current as flavor probe

*planned for JLab at 12 GeV

Summary & Outlook

- New global PDF analysis (CTEQX) including high-x, low-Q^2 data
- *Stable leading twist* PDFs obtained with TMC, higher twist and nuclear corrections (valid to $x \sim 0.8$)

  $\longrightarrow$ opens door to study of nucleon structure over large kinematic domain
- Results suggest smaller d/u ratio for $x > 0.6$
- *Future*: explore effects of

  $\longrightarrow$ jet mass corrections, W^2 evolution, quark-hadron duality
- Extend analysis to *spin-dependent* PDFs ("SpinTEQ")

The End