Achievements and Future Directions in Subatomic Physics:
Workshop in Honour of Tony Thomas's 60th Birthday
CSSM Adelaide, 15-19 February 2010

Nucleon Structure at Large x

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Outline

- Why is nucleon structure at large x important?

- Navigating the large-x landscape
  - $\longrightarrow$ nuclear effects & d/u PDF ratio
  - $\longrightarrow$ subleading $1/Q^2$ corrections

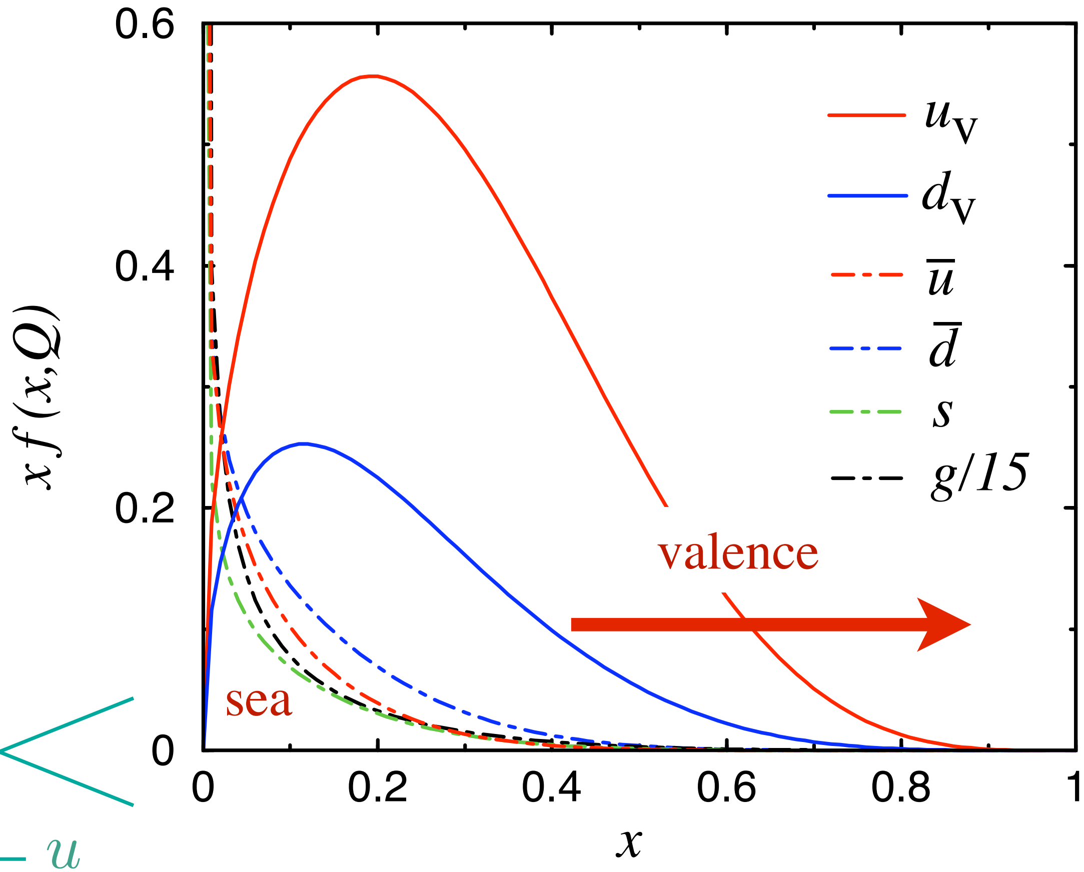
- New global analysis ("CTEQX")
  - $\longrightarrow$ first foray into high-x, low-Q^2 region
  - $\longrightarrow$ surprising new results for d quark

- Future experimental constraints

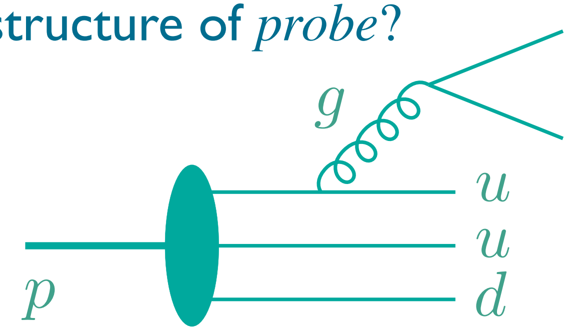
Why are PDFs at large x interesting?

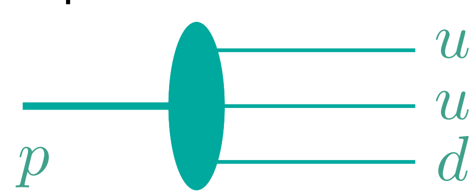
- Most direct connection between quark distributions and nonperturbative structure of nucleon is via *valence* quarks

  → most cleanly revealed at $x > 0.4$



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





Why are PDFs at large x interesting?

- 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

  $\longrightarrow$ scalar diquark dominance: $d/u = 0$ *Feynman (1972)*

  $\longrightarrow$ hard gluon exchange: $d/u = 1/5$ *Farrar, Jackson (1975)*

  $\longrightarrow$ 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 or in ν oscillation experiments

  $\longrightarrow$ 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*

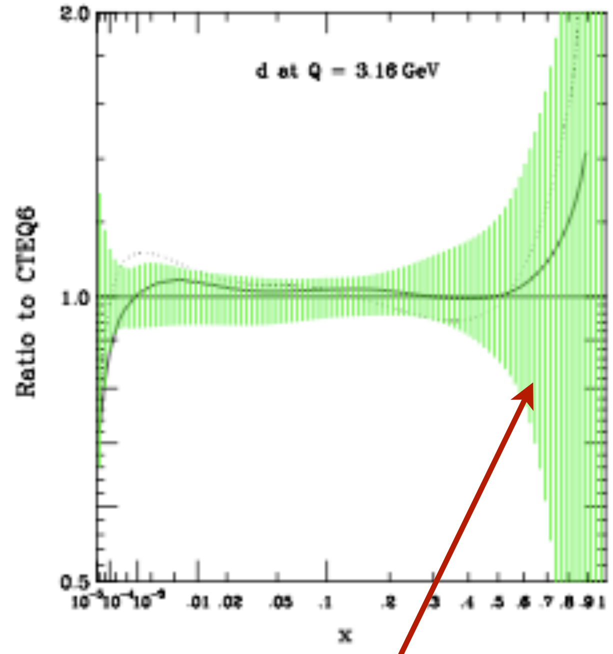
- d quark distribution requires *neutron* structure function

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

- 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

  ➡ $F_2^d \neq F_2^p + F_2^n$

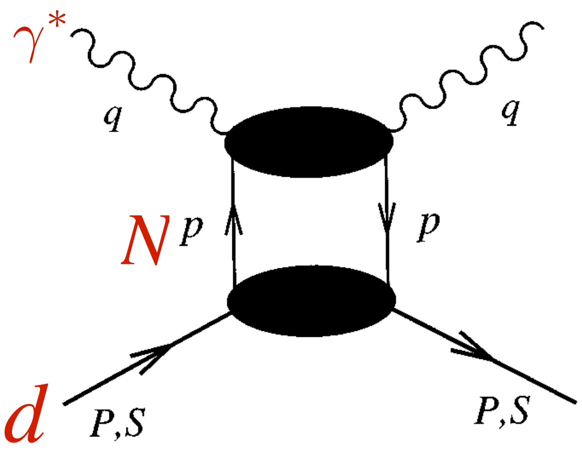
  ➡ nuclear effects (nuclear binding, Fermi motion, shadowing) *obscure neutron structure* information

  ➡ 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 $x >> 0$)



$N=p+n$

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

nucleon momentum distribution in d ("smearing function")

off-shell correction

→ $y = p\cdot q / P\cdot q$ 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

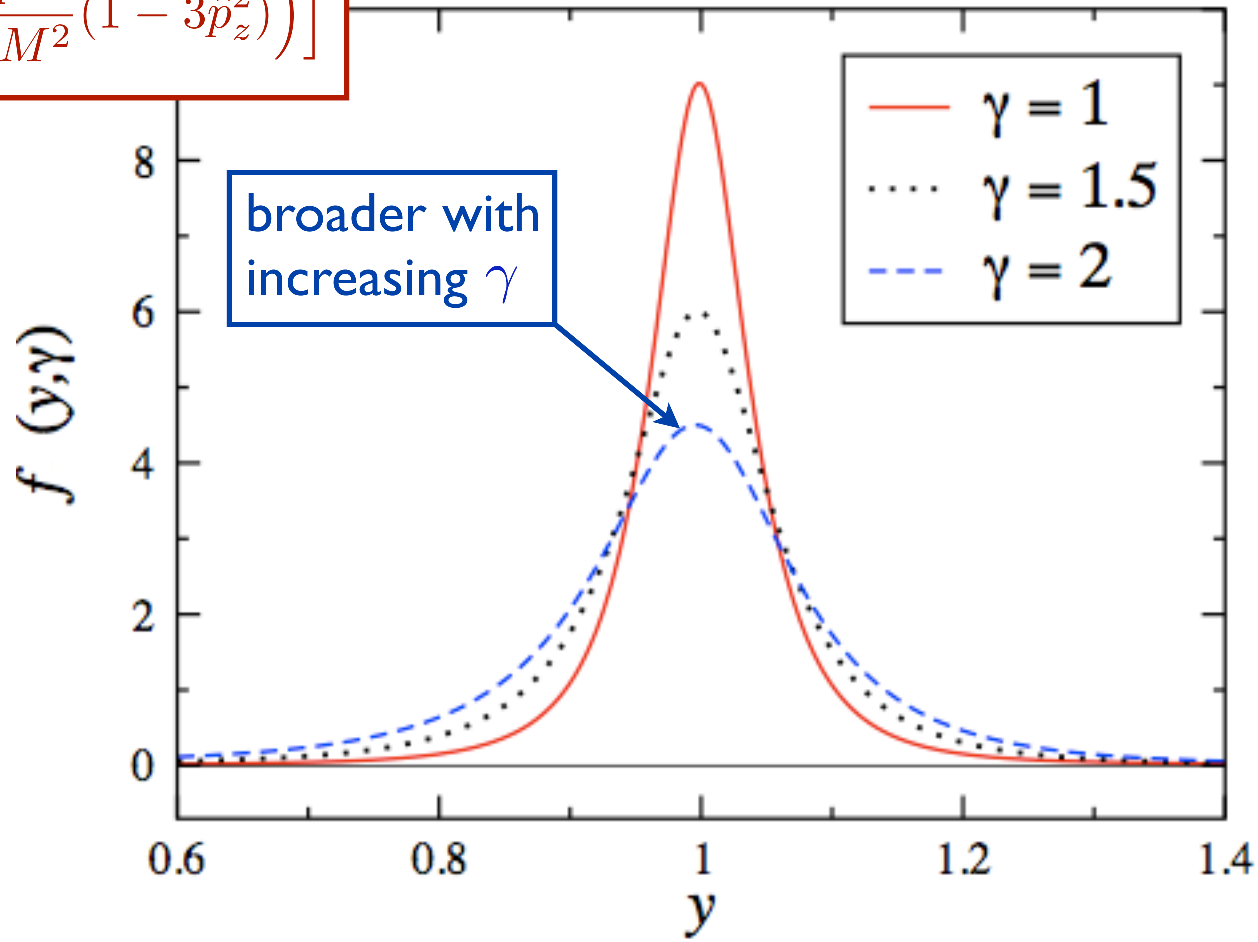
$$f(y,\gamma) = \int \frac{d^3p}{(2\pi)^3} \; |\psi_d(p)|^2 \; \delta\Big(y - 1 - \frac{\varepsilon + \gamma p_z}{M}\Big)$$
$$\times \frac{1}{\gamma^2}\Big[1 + \frac{\gamma^2 - 1}{y^2}\Big(1 + \frac{2\varepsilon}{M} + \frac{\vec{p}^{\,2}}{2M^2}(1 - 3\hat{p}_z^2)\Big)\Big]$$

→ deuteron wave function $\psi_d(p)$

→ deuteron separation energy

$$\varepsilon = \varepsilon_d - \frac{\vec{p}^{\,2}}{2M}$$

→ effectively more smearing for larger x or lower Q^2



Off-shell nucleons

- relativistic calculation required development of formalism for DIS from *off-shell nucleons*

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Deep-inelastic scattering from off-shell nucleons

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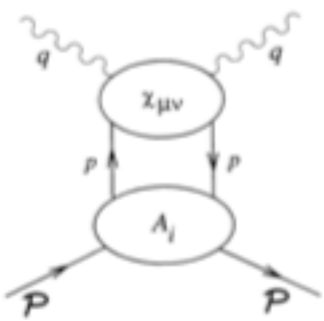
(Received 24 June 1993)

We derive the general structure of the hadronic tensor required to describe deep-inelastic scattering from an off-shell nucleon within a covariant formalism. Of the large number of possible off-shell structure functions we find that only three contribute in the Bjorken limit. In our approach the usual ambiguities encountered when discussing problems related to off shellness in deep-inelastic scattering are not present. The formulation therefore provides a clear framework within which one can discuss the various approximations and assumptions which have been used in earlier work. As examples, we investigate scattering from the deuteron, nuclear matter, and dressed nucleons. The results of the full calculation are compared with those where various aspects of the off-shell structure are neglected, as well as with those of the convolution model.

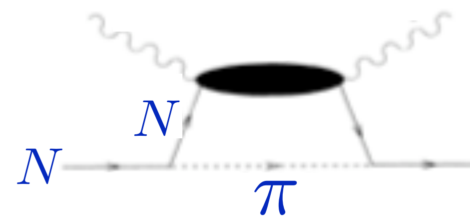


$$M_T\ W_T^A(\mathcal{P},q) = \frac{1}{4\pi^2}\int \frac{dy\ dp^2}{(p^2-M^2)^2}\left\{A_0(p,\mathcal{P})\ \chi_T^0(p,q) + p\cdot A_1(p,\mathcal{P})\ \chi_T^1(p,q) + q\cdot A_1(p,\mathcal{P})\ \chi_T^2(p,q)\right\}$$

Off-shell nucleons

- relativistic calculation required development of formalism for DIS from *off-shell nucleons*

→ original motivation was for computing pion cloud corrections to nucleon PDFs ($\bar{d}/\bar{u}$ ratio)!



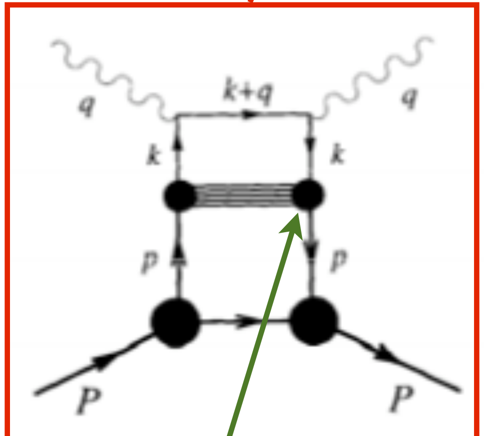
→ identify conditions under which usual convolution model of nuclear structure functions holds:
in general these are *not* satisfied in relativistic framework

→ but can isolate (dominant) convolution component, with (small & model-dependent) off-shell corrections

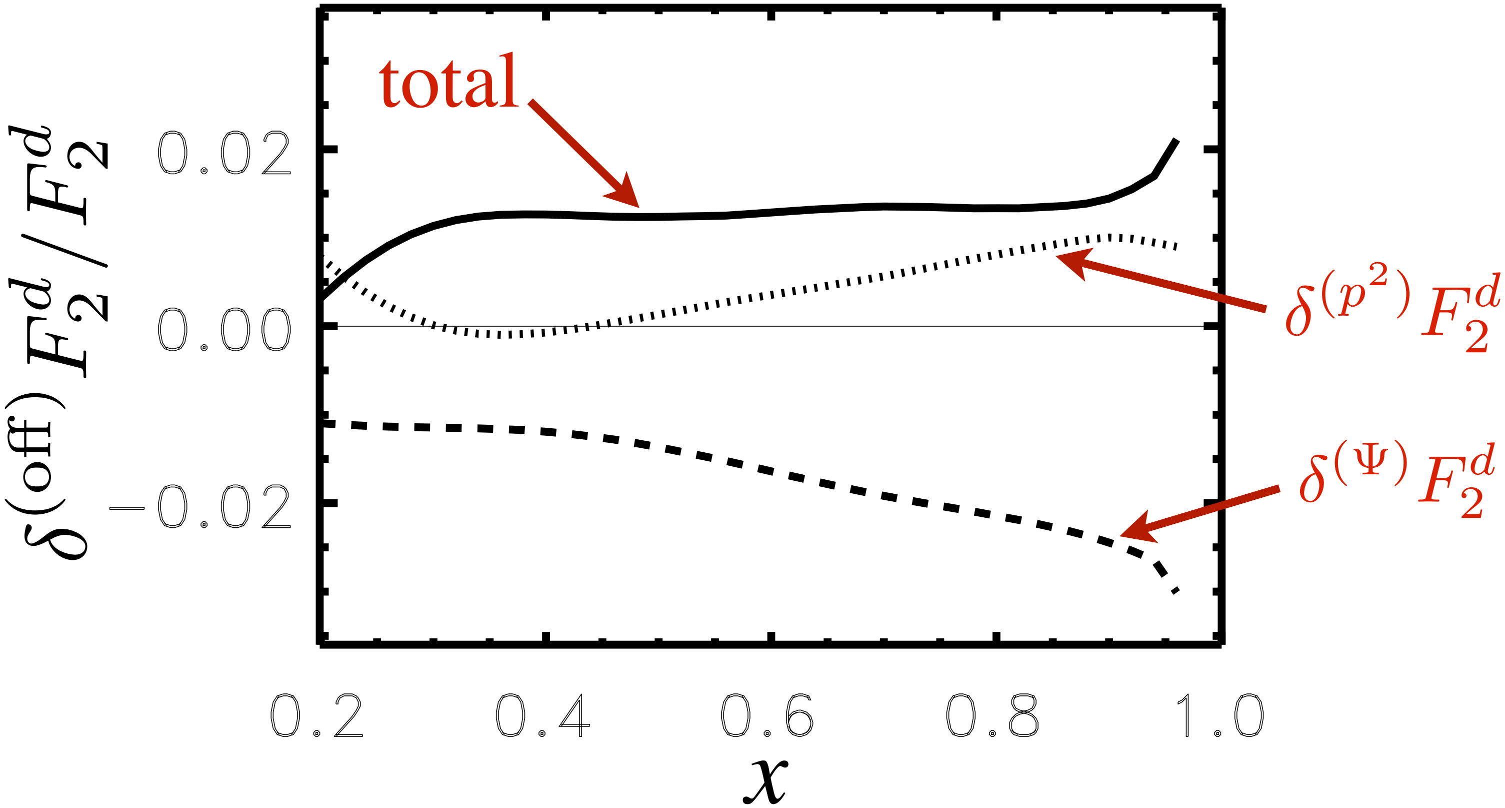
Off-shell nucleons

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

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

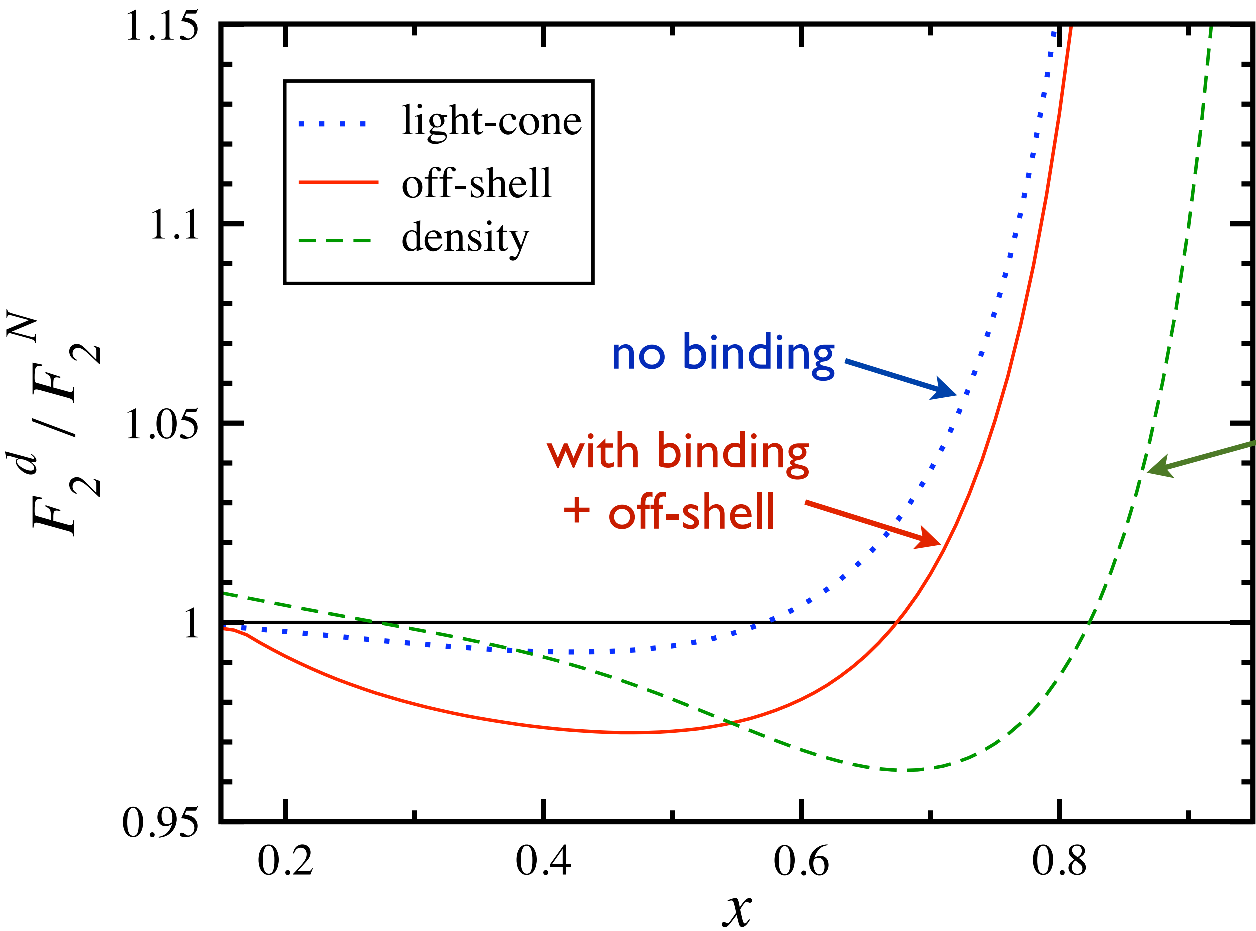


quark-diquark vertex functions



$\longrightarrow\; \lesssim 1 - 2\%$ **effect**

EMC effect in deuteron



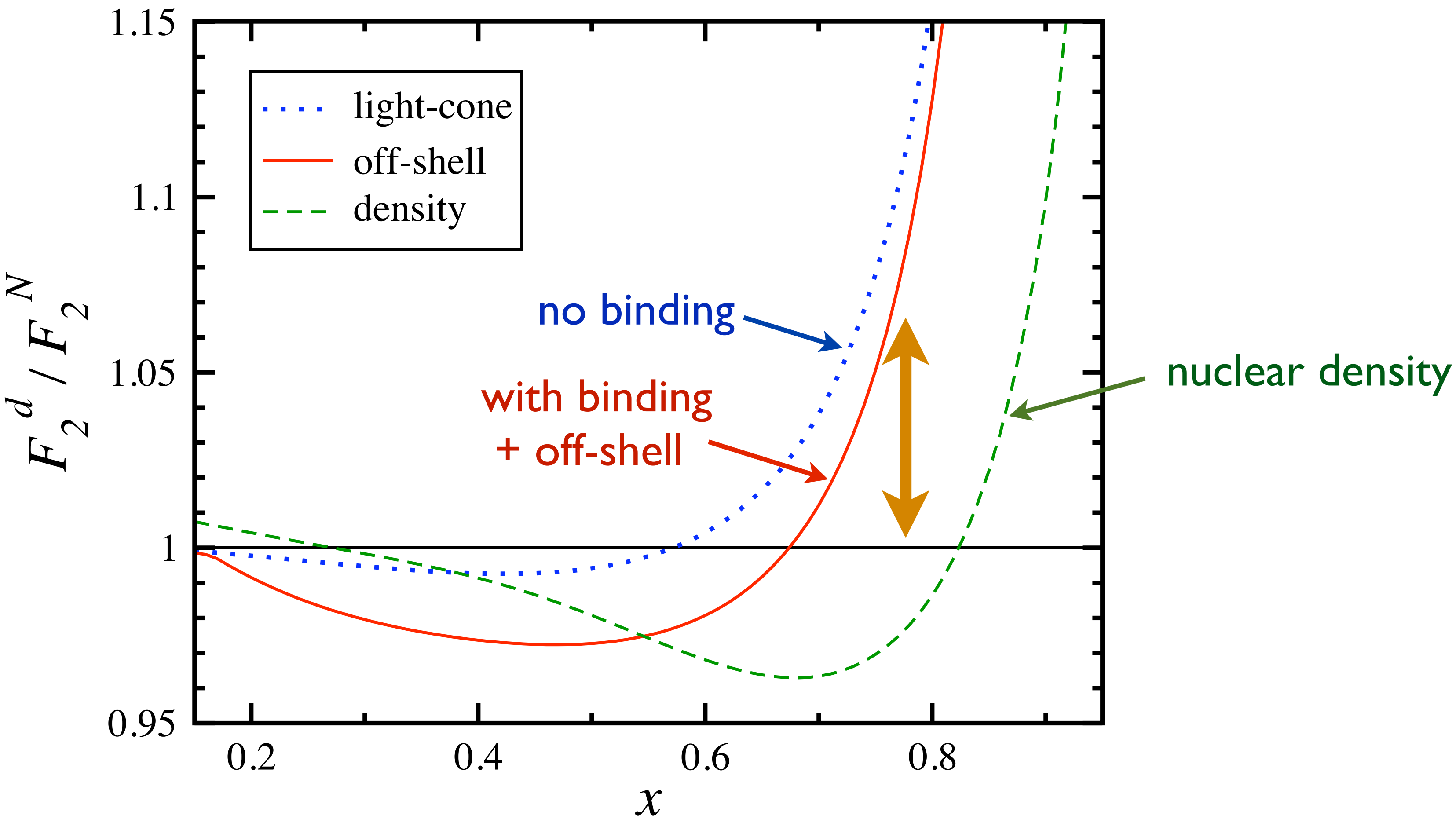
$$\frac{F_2^d}{F_2^N} - 1 \approx \frac{1}{4}\left(\frac{F_2^{\mathrm{Fe}}}{F_2^d} - 1\right)$$

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

→ ~ 2–3% reduction of F_2^d / F_2^N at $x \sim 0.5$–0.6 with steep rise for $x > 0.6$–0.7

→ larger EMC effect at $x \sim 0.5$–0.6 with binding + off-shell corrections *cf.* light-cone

EMC effect in deuteron

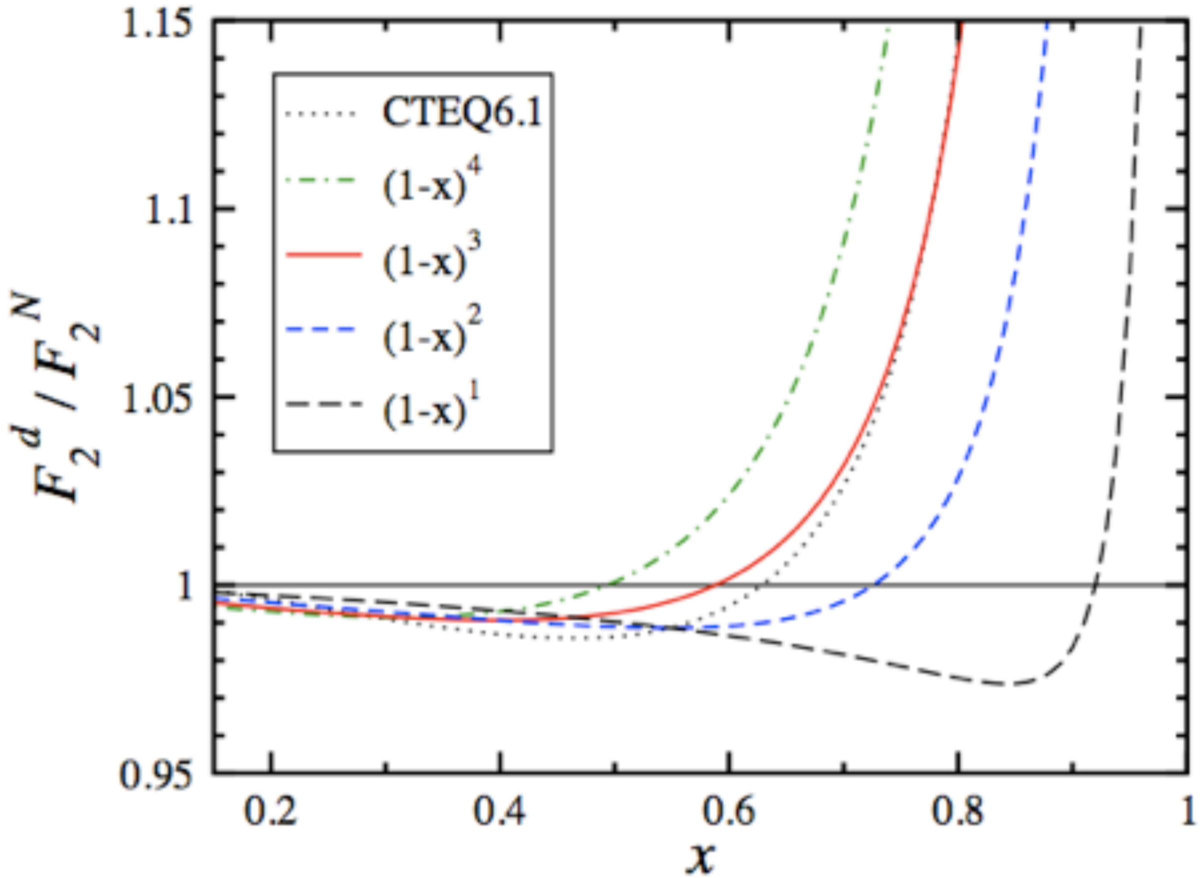


→ using off-shell model, will get *larger* neutron *cf. light-cone* model

→ but will get *smaller* neutron *cf. no nuclear effects* or *density* model

EMC effect in deuteron

⚠ WARNING



→ EMC ratio depends also on *input nucleon* SFs; need to *iterate* when extracting F_2^n

Large-x landscape:

subleading $1/Q^2$ *corrections*

Target mass corrections

- At fixed final state hadron mass $W^2 = M^2 + Q^2(1-x)/x$ larger x corresponds to smaller Q^2

→ need to account for kinematical *target mass corrections* arising from Q^2/ν^2 terms in the OPE $(x = Q^2/2M\nu)$

→ gives rise to new *Nachtmann* scaling variable

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

- Target mass corrected structure function (leading twist)

$$F_2(x,Q^2) = \frac{x^2}{\xi^2\gamma^3}\underbrace{F_2^{(0)}(\xi,Q^2)}_{\text{massless limit function}} + \frac{6M^2x^3}{Q^2\gamma^4}\int_\xi^1 du\,\frac{F_2^{(0)}(u,Q^2)}{u^2} + \frac{12M^4x^4}{Q^4\gamma^5}\int_\xi^1 dv(v-\xi)\frac{F_2^{(0)}(v,Q^2)}{v^2}$$

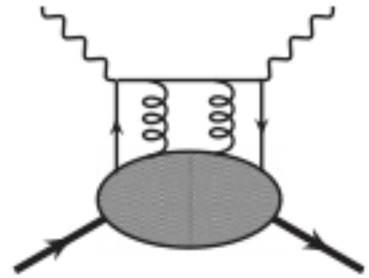
Higher twists

- $1/Q^2$ 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")

<u>Joint CTEQ-JLab collaboration</u>

A. Accardi, E. Christy, C. Keppel,
W.M., P. Monaghan, J. Morfin, J. Owens

*Accardi et al., Phys. Rev. D **81**, 034016 (2010)*

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

  $\longrightarrow$ also include new CDF & D0 W-asymmetry, and E866 DY data

- Systematically study effects of Q^2 *& W cuts*

  $\longrightarrow$ as low as $Q \sim m_c$ and $W \sim 1.7$ GeV

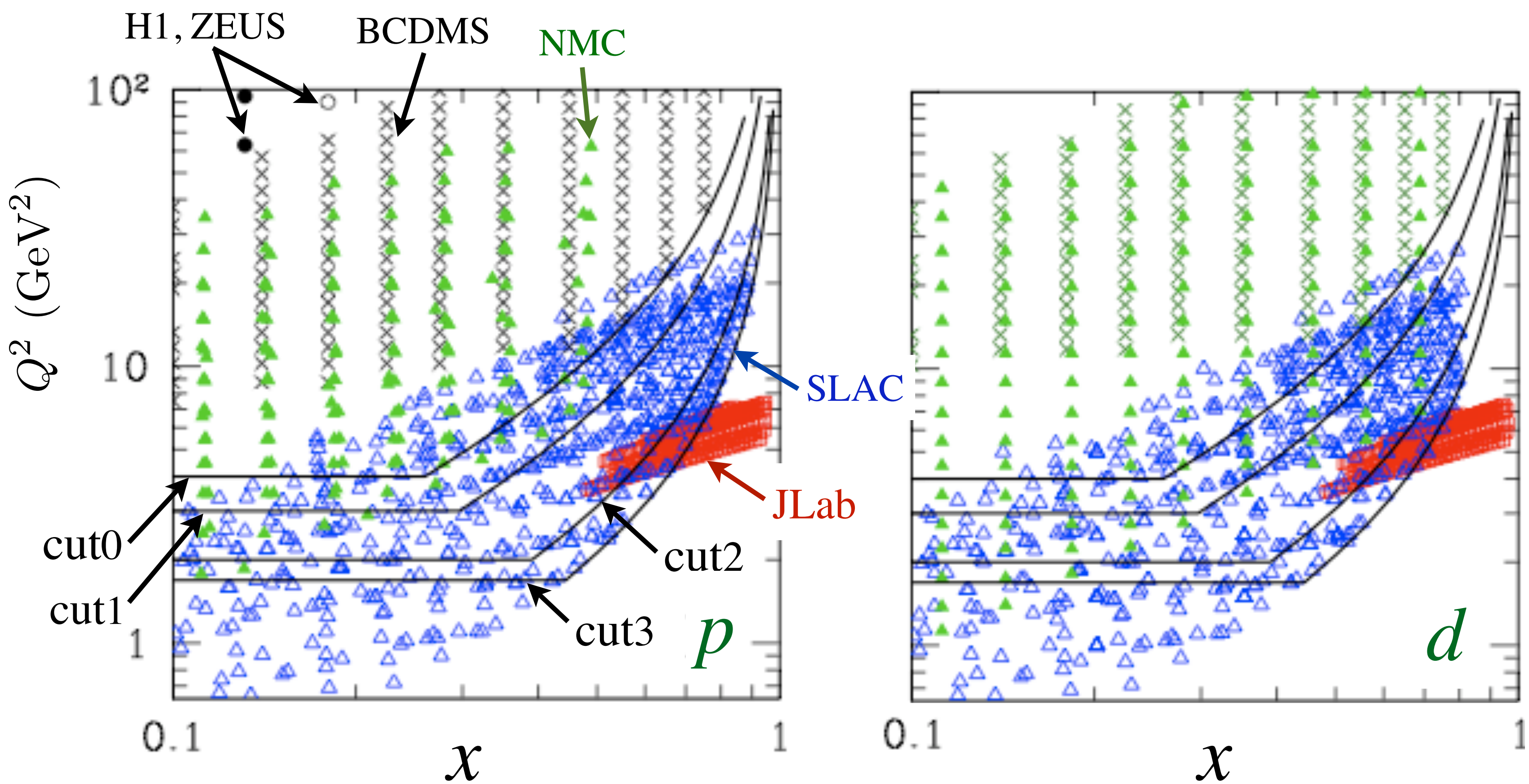
- Include subleading $1/Q^2$ corrections

  $\longrightarrow$ target mass corrections & dynamical higher twists

- Correct for *nuclear* effects in the deuteron (binding + off-shell)

  $\longrightarrow$ most global analyses assume *free* nucleons; some use density model, a few assume Fermi motion only

Kinematic cuts



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

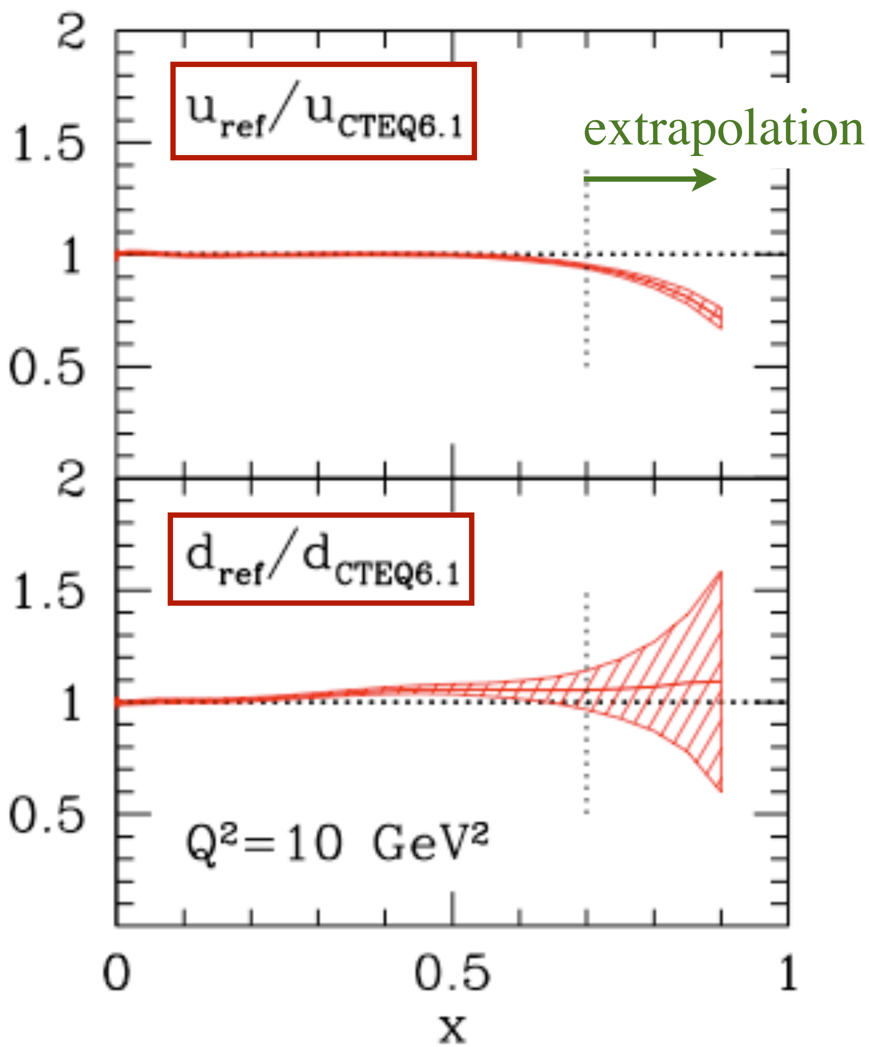
cut1: $Q^2 > 3\ \mathrm{GeV}^2, \quad W^2 > 8\ \mathrm{GeV}^2$

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

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

factor 2 increase in DIS data from cut0 $\rightarrow$ cut3

Effect of new data on "standard" fits (cut0)

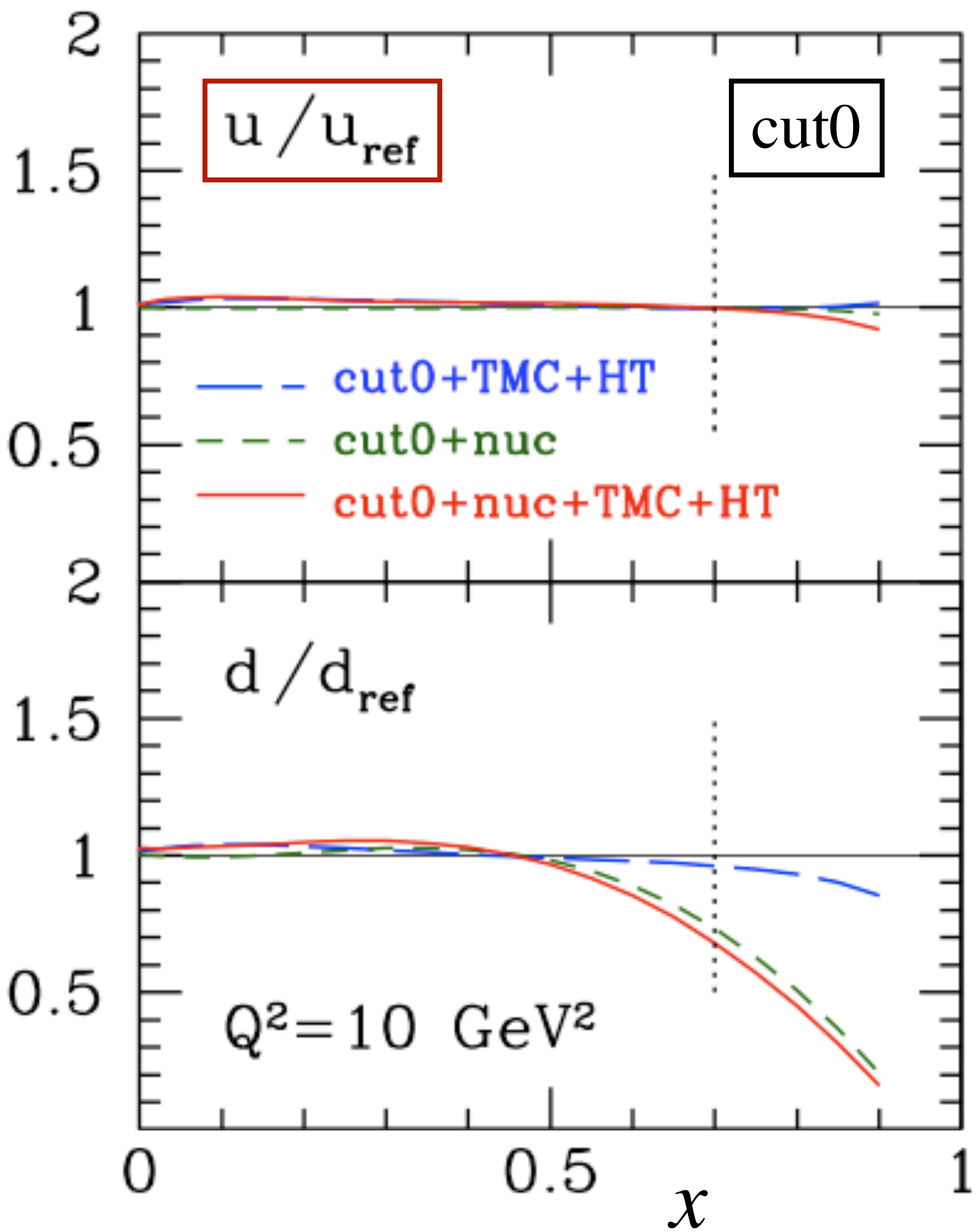


→ *no* nuclear or $1/Q^2$ corrections

→ no significant effect in measured region

→ u suppression at large x due to E866 DY data

Effect on "reference" fit (cut0) from $1/Q^2$ and nuclear corrections



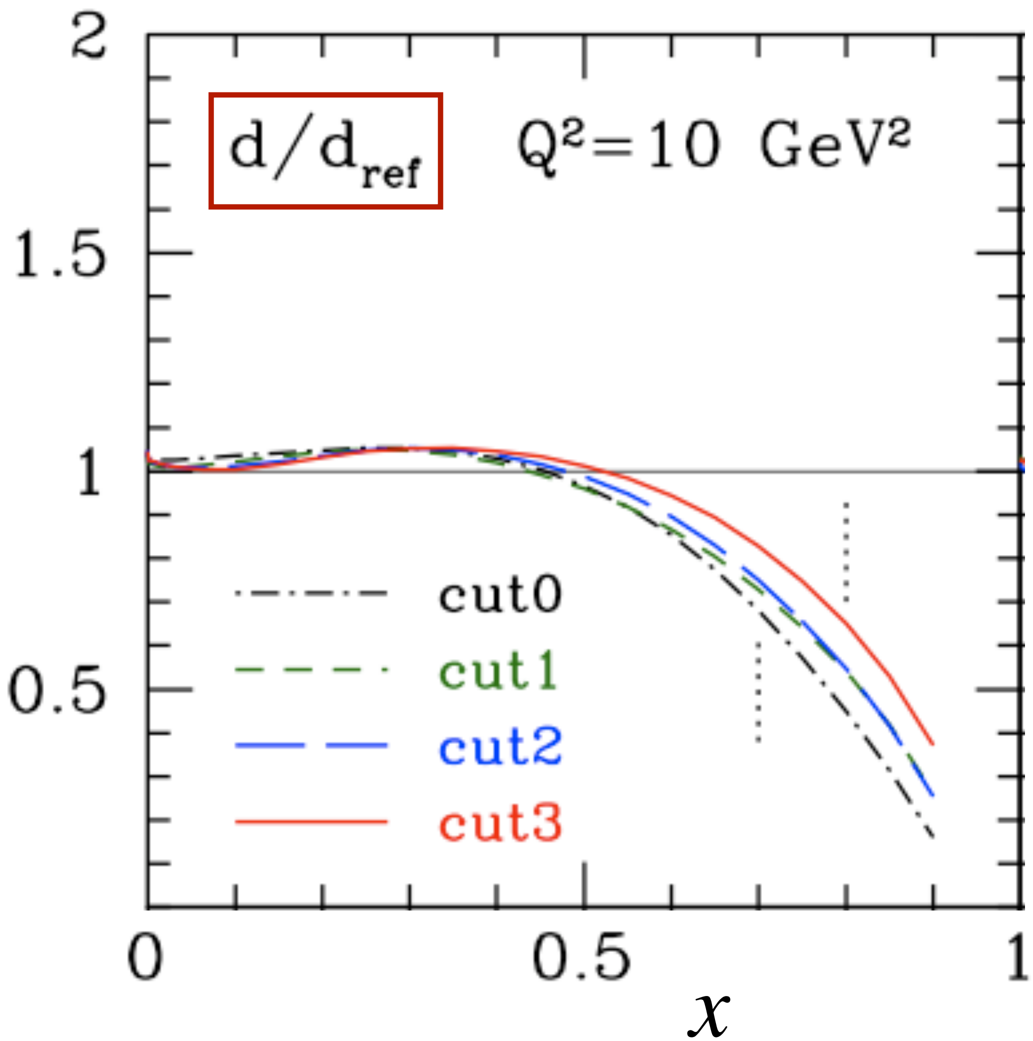
→ cut0 limits significant change to u quark

→ 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

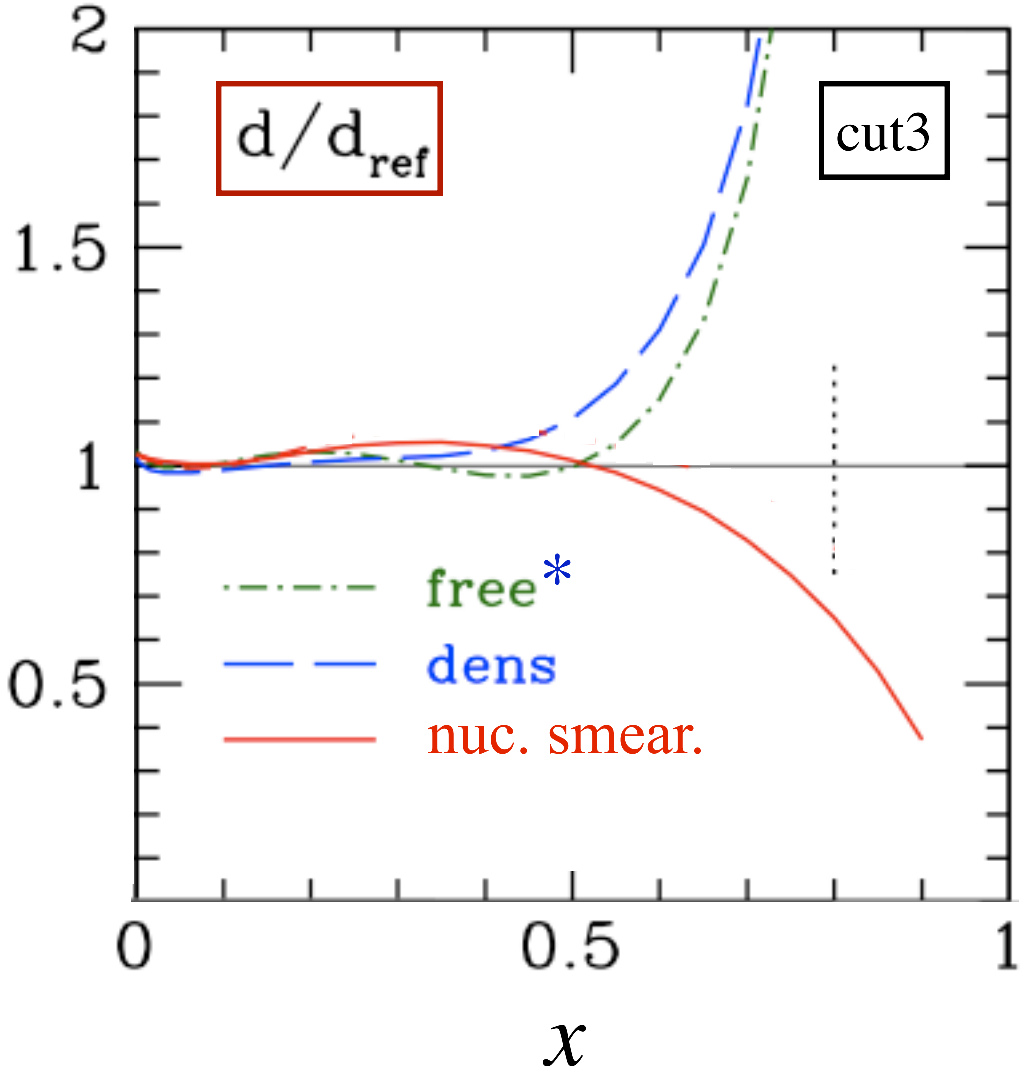
- Systematically reduce Q^2 and W cuts
- Fit includes TMCs, HT term, nuclear corrections



→ stable with respect to cut reduction

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

Nuclear corrections



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

→ *increased* d quark for no nuclear effects

(compensates for nuclear smearing in deuteron → increased F_2^d)

→ *decreased* d quark for nuclear smearing models

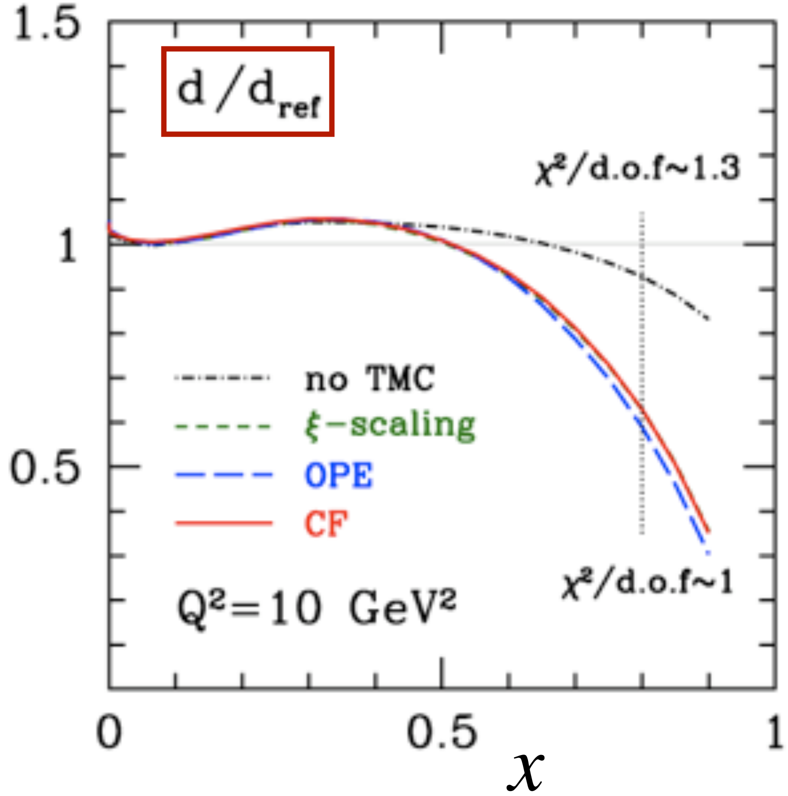
↓

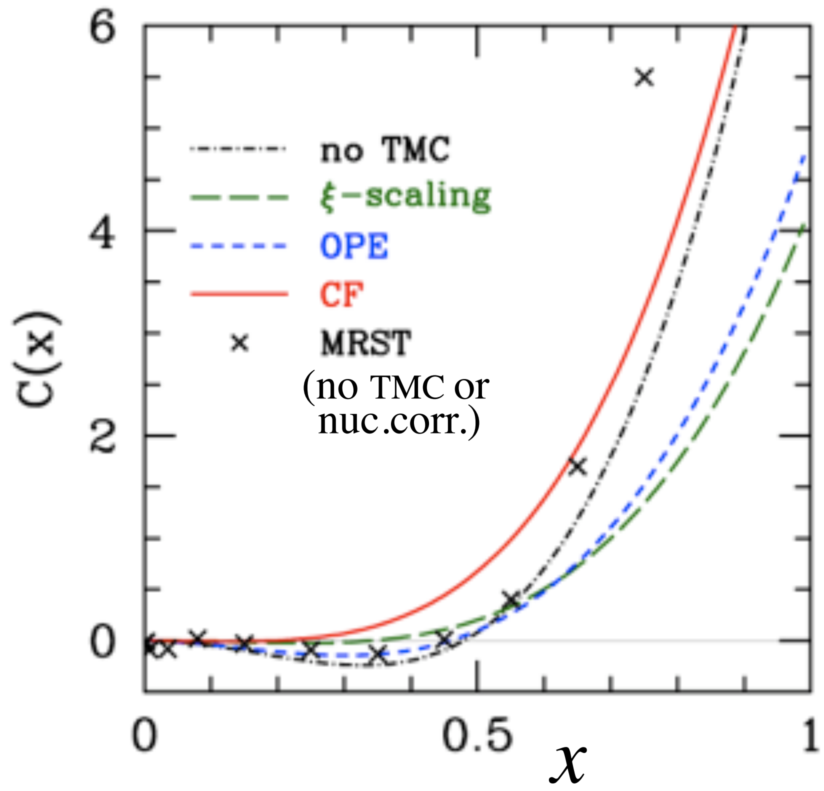
$F_2^d/F_2^N > 1$ for $x \sim 0.6–0.8$ while $F_2^d/F_2^N < 1$ for "free" and "density" models

$F_2^d/F_2^N \uparrow \leftrightarrow F_2^n/F_2^p \downarrow$

$\leftrightarrow d/u \downarrow$

Effect of $1/Q^2$ corrections





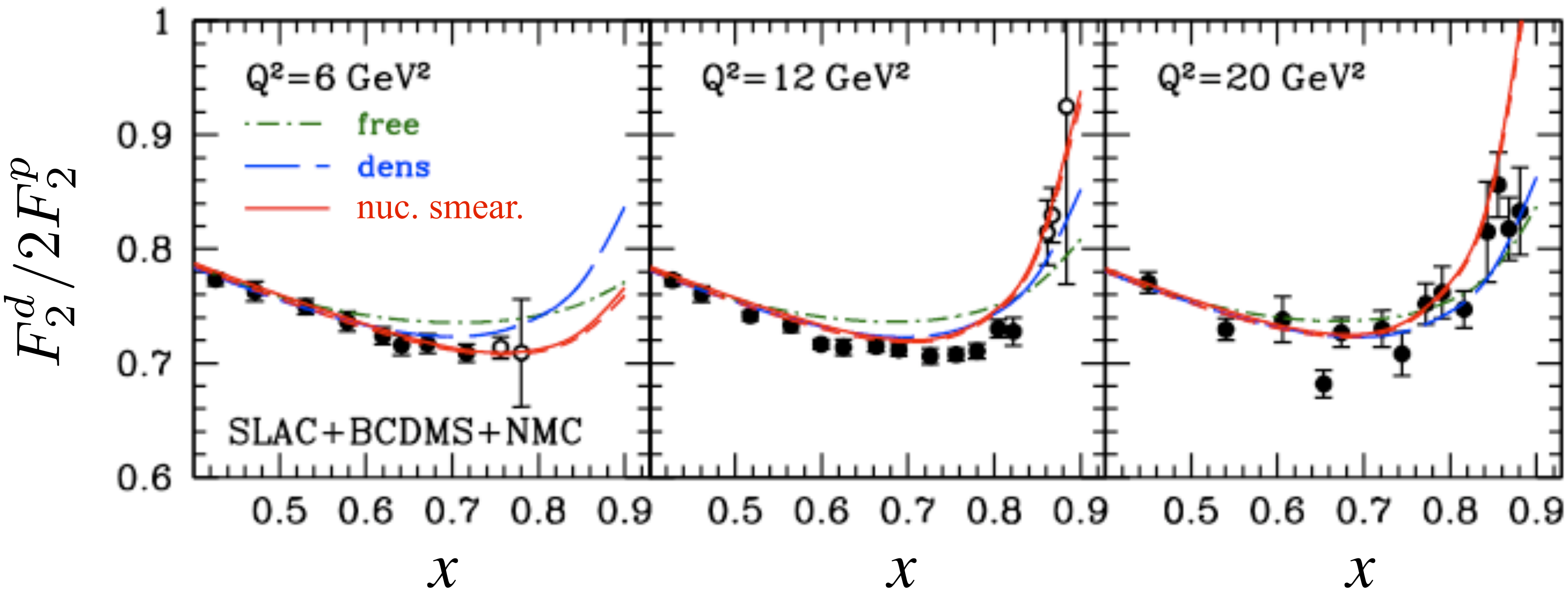
→ $1/Q^2$ HT coefficient parametrized as $C(x) = c_1 x^{c_2}(1 + c_3 x)$

→ 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

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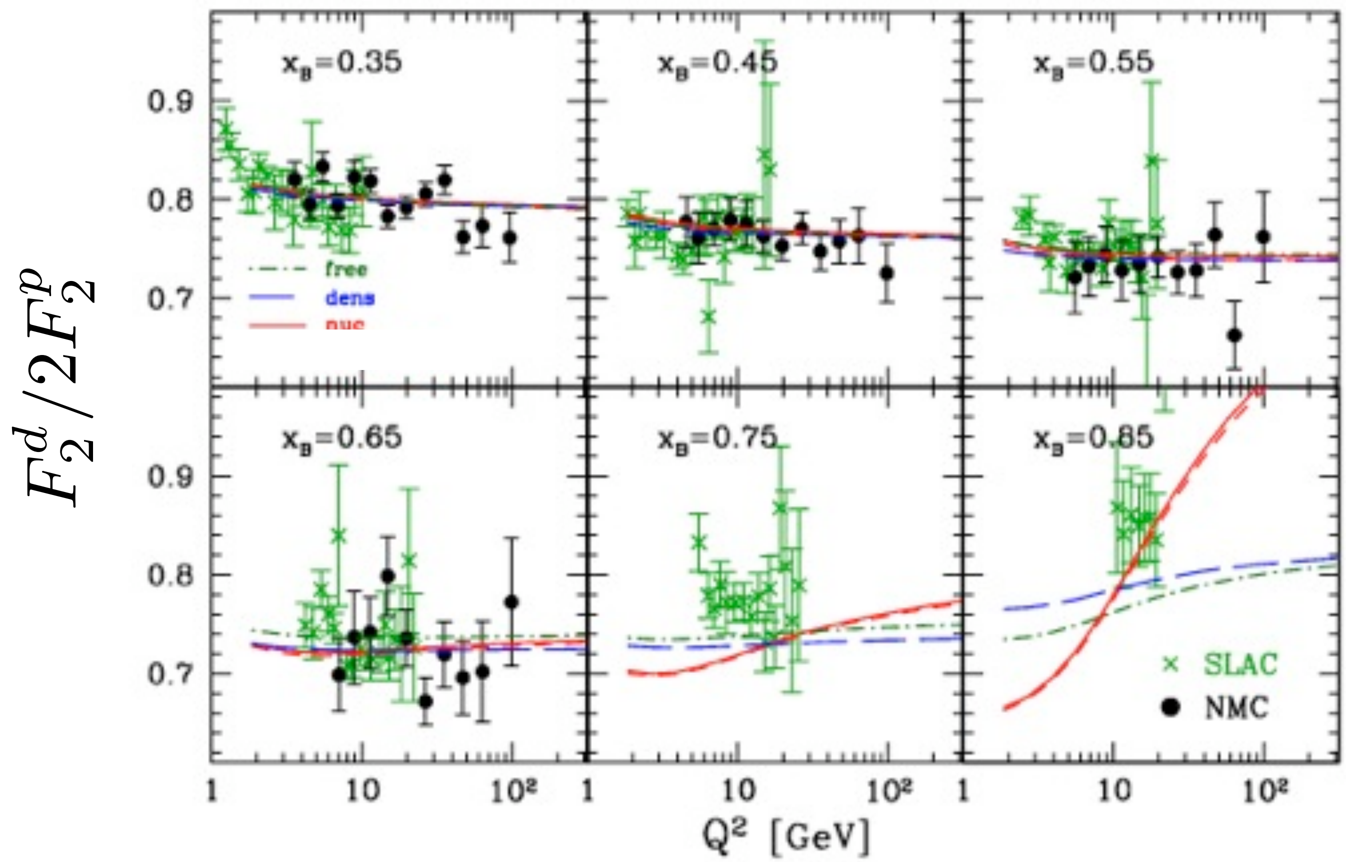

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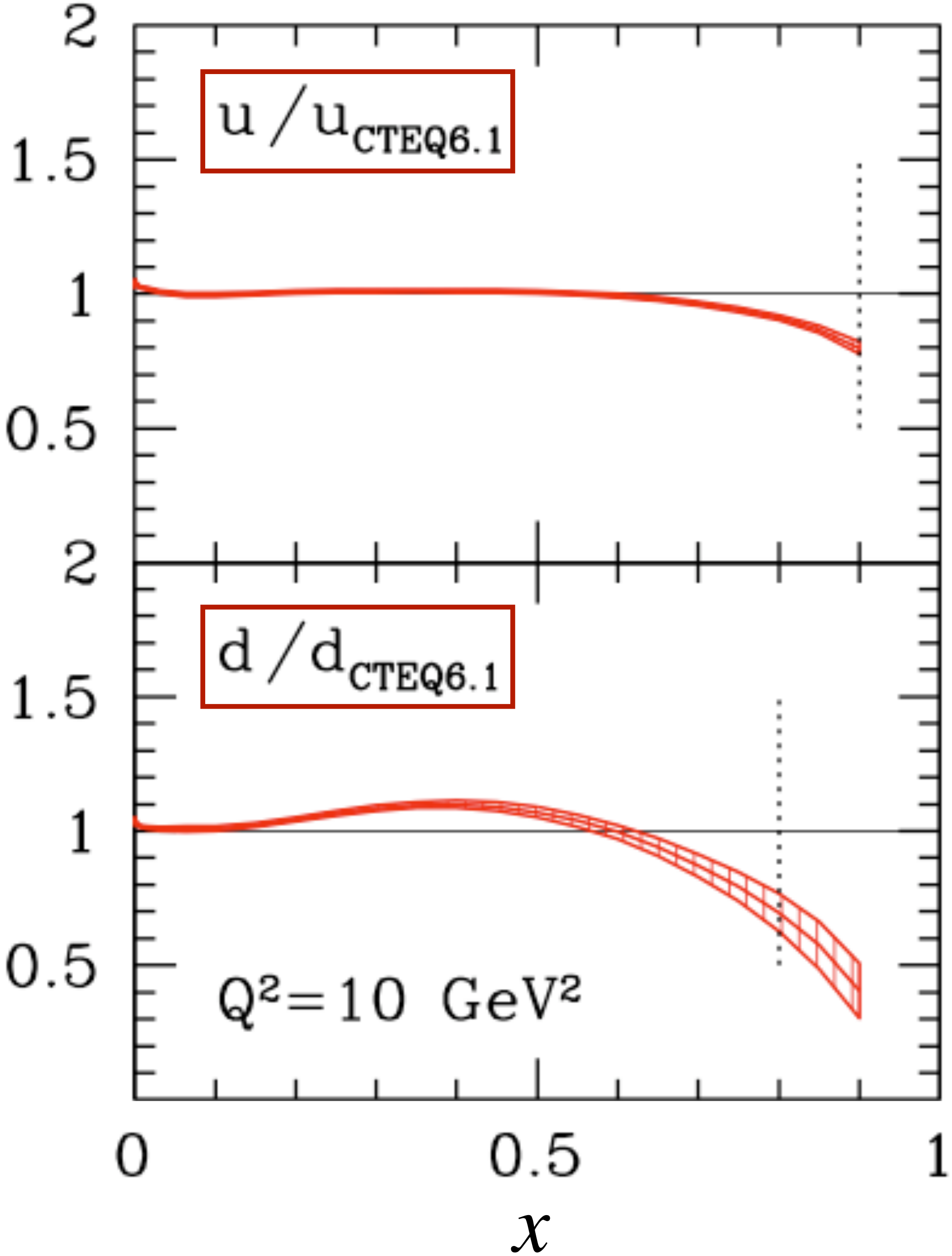
Final PDF results



→ full fits favors *smaller d/u* ratio

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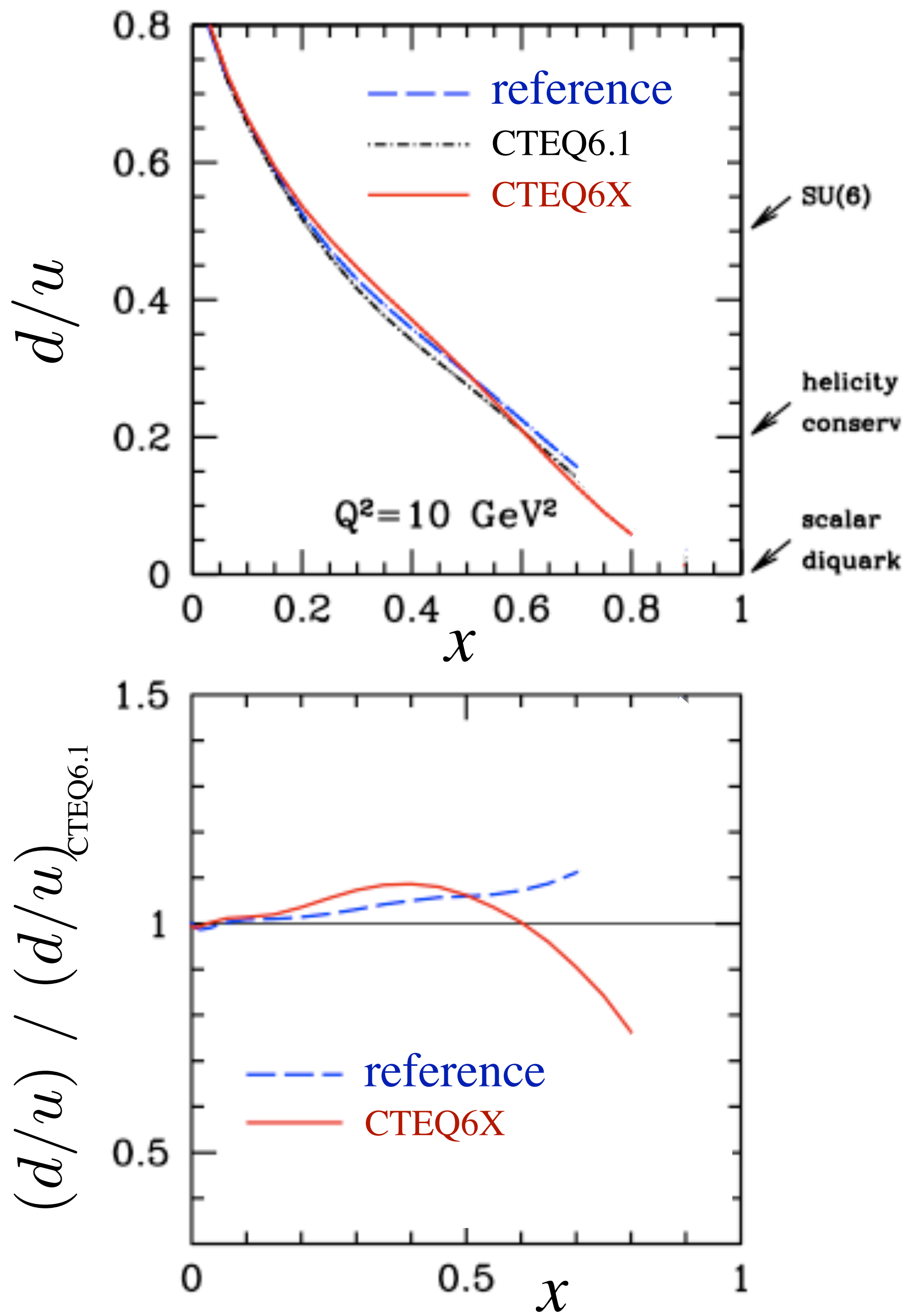
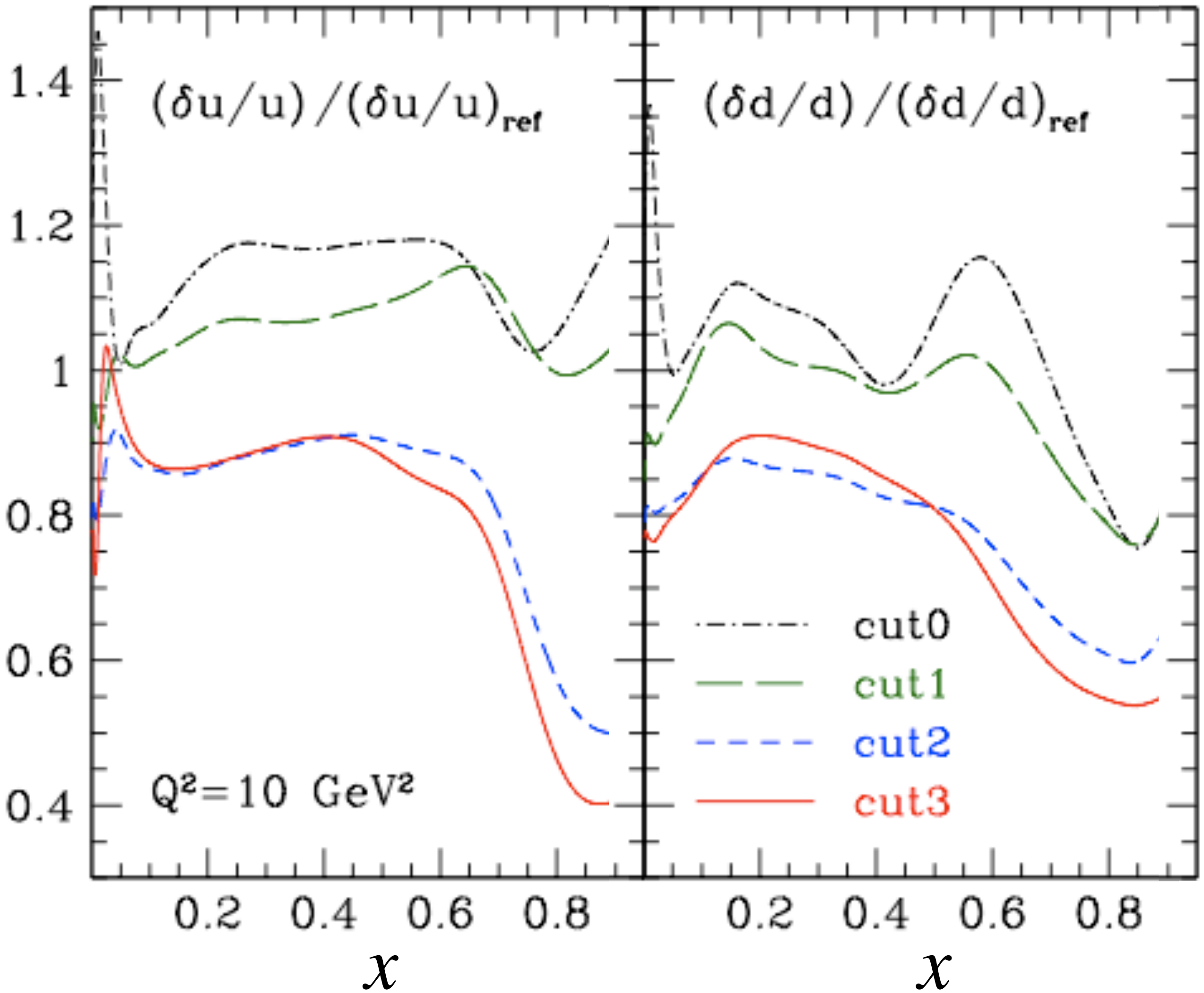


→ full fits favors *smaller* d/u ratio

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

Final PDF results



→ full fits favors *smaller* *d/u* ratio

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

→ significantly *reduced errors* with weaker cuts

Future experimental constraints

“Cleaner” methods of determining d/u

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

- $e\ {}^3\mathrm{He}({}^3\mathrm{H}) \to e\ X^*$ — ^{3}He-tritium mirror nuclei

- $e\ p \to e\ \pi^\pm\ X^*$ — semi-inclusive DIS as flavor tag

- $$\left.\begin{array}{l} e^\mp\ p \to \nu(\bar\nu) X \\ \nu(\bar\nu)\ p \to l^\mp\ X \\ p\ p(\bar p) \to W^\pm X \\ \vec{e}_L(\vec{e}_R)\ p \to e\ X^* \end{array}\right\}$$ weak current as flavor probe

*planned for JLab at 12 GeV

PHYSICAL REVIEW C **68**, 035201 (2003)

Deep inelastic scattering from $A=3$ nuclei and the neutron structure function

I. R. Afnan,[1] F. Bissey,[2] J. Gomez,[3] A. T. Katramatou,[4] S. Liuti,[5] W. Melnitchouk,[3] G. G. Petratos,[4] and A. W. Thomas[6]

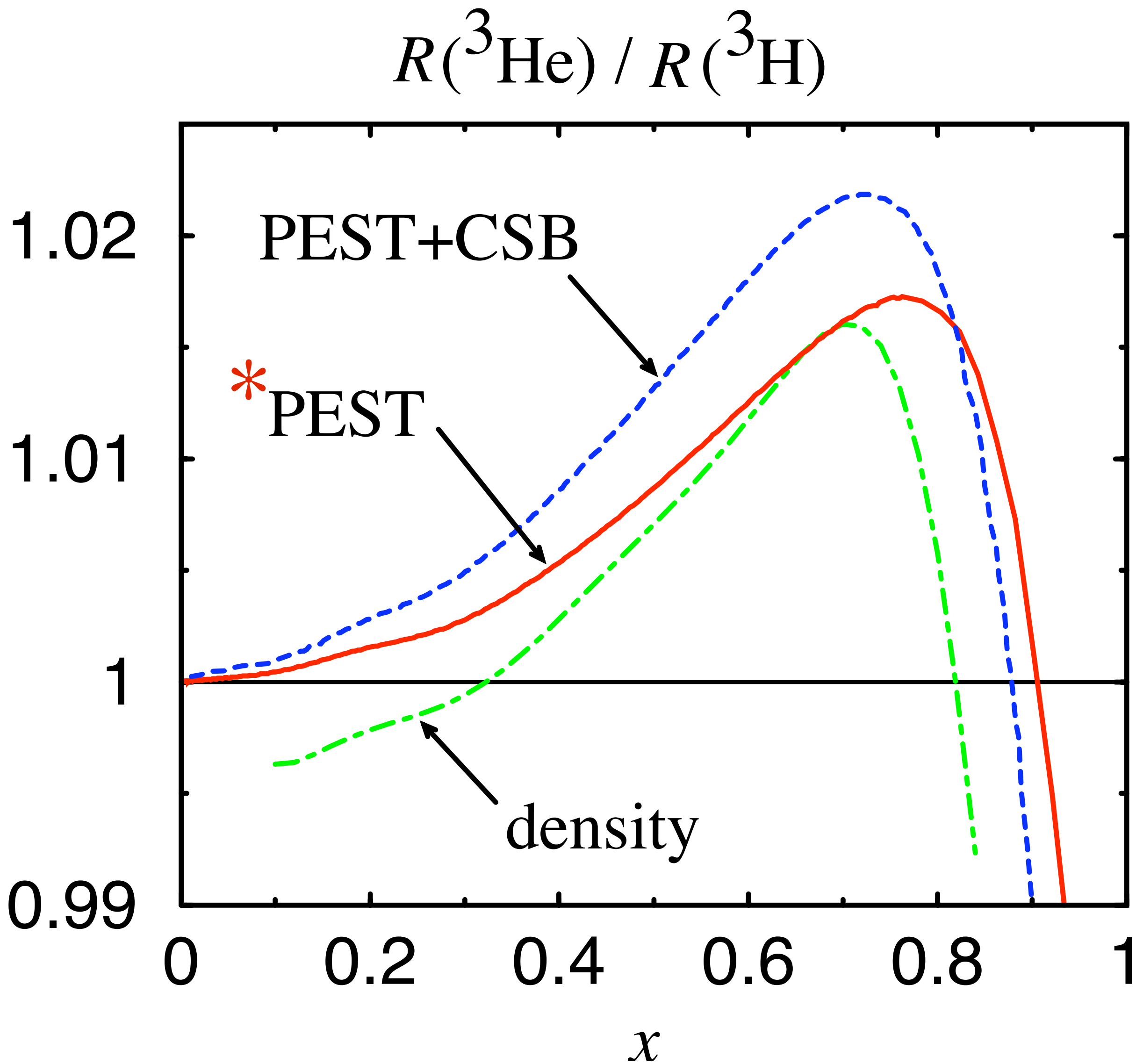
- EMC ratios for A=3 mirror nuclei

$$R(^3\mathrm{He}) = \frac{F_2^{^3\mathrm{He}}}{2F_2^p + F_2^n} \qquad R(^3\mathrm{H}) = \frac{F_2^{^3\mathrm{H}}}{F_2^p + 2F_2^n}$$

- Extract n/p ratio from measured ^{3}He-^{3}H ratio

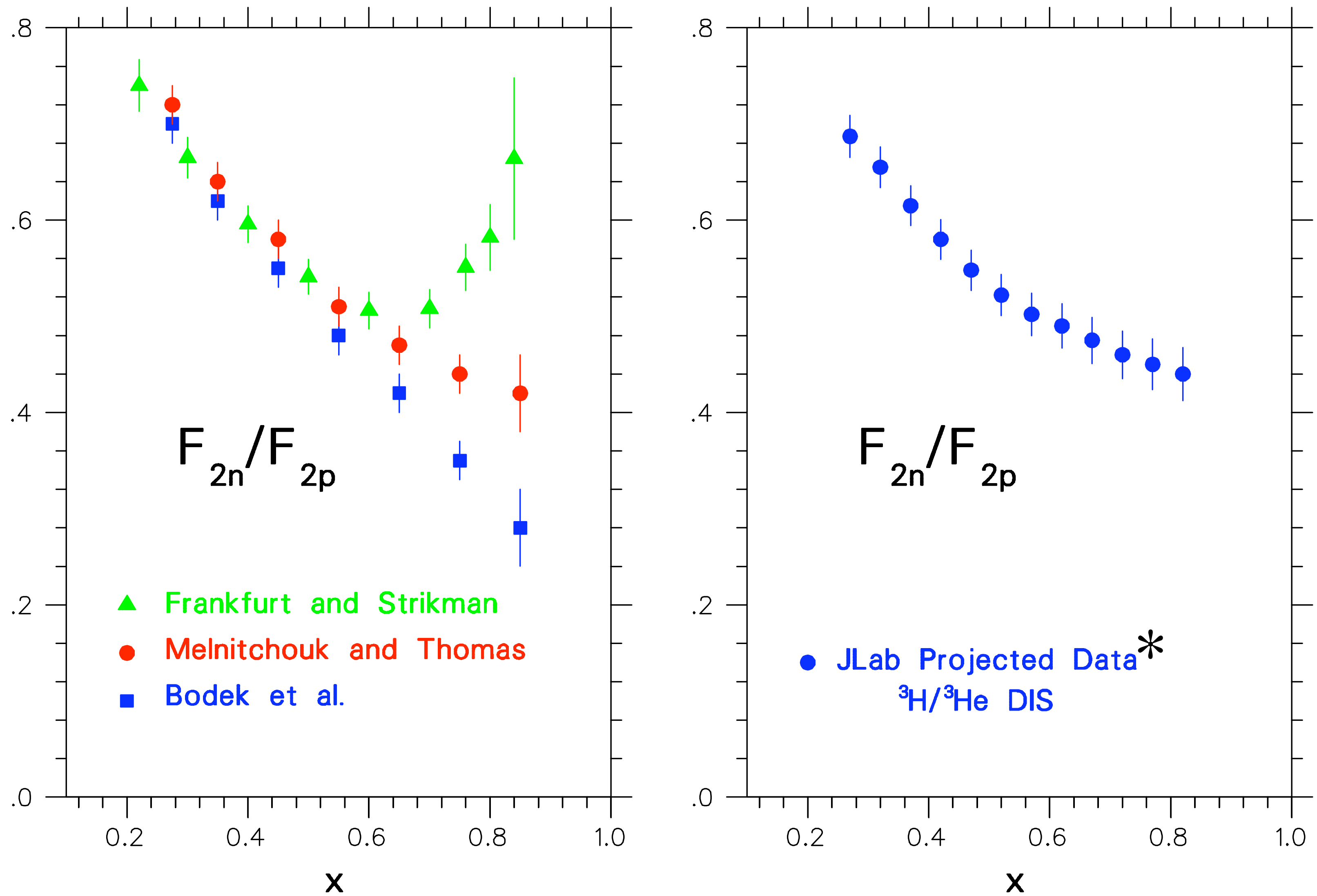
$$\frac{F_2^n}{F_2^p} = \frac{2\mathcal{R} - F_2^{^3\mathrm{He}}/F_2^{^3\mathrm{H}}}{2F_2^{^3\mathrm{He}}/F_2^{^3\mathrm{H}} - \mathcal{R}} \qquad \mathcal{R} = \frac{R(^3\mathrm{He})}{R(^3\mathrm{H})}$$

theory input



* Ernst-Shakin-Thaler separable approx. to Paris potential

→ nuclear effects cancel to < 1% level



*theoretical uncertainty integrated into total error

Summary & outlook

- New frontiers explored at large momentum fractions x

  $\longrightarrow$ dedicated global PDF analysis (CTEQX)

- *Stable* leading twist PDFs obtained for $x \lesssim 0.8$ and $Q^2 \gtrsim 1.5$ GeV^2 provided nuclear and subleading $1/Q^2$ corrections included

  $\longrightarrow$ 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

  $\longrightarrow$ W^2 evolution at large x, quark-hadron duality

  $\longrightarrow$ extend analysis to *spin-dependent* PDFs (larger portion of data at low Q^2)

Summary & outlook

- Work with Tony on nuclear effects & large-x structure functions was a few years ahead of its time

  → important role of nuclear corrections in global PDF fits now being realized

  → helped to motivate large-x experimental program at JLab with 12 GeV

  → relevant two papers:

  WM, Schreiber, Thomas, "DIS from off-shell nucleons", PRD49, 1183 (1994)

  WM, Thomas, "Neutron / proton structure function ratio at large x", PLB377, 11 (1996)

  now have ~200 citations between them

- Thank you, Tony, for all your contributions to this and all our other work together – "*Многая Лiта!*"