Los Alamos National Lab.
April 5, 2010

High-Momentum Quarks in the Nucleon

Wally Melnitchouk

Jefferson Lab

Outline

- Why are high-momentum (large x) quarks in the nucleon important?

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

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

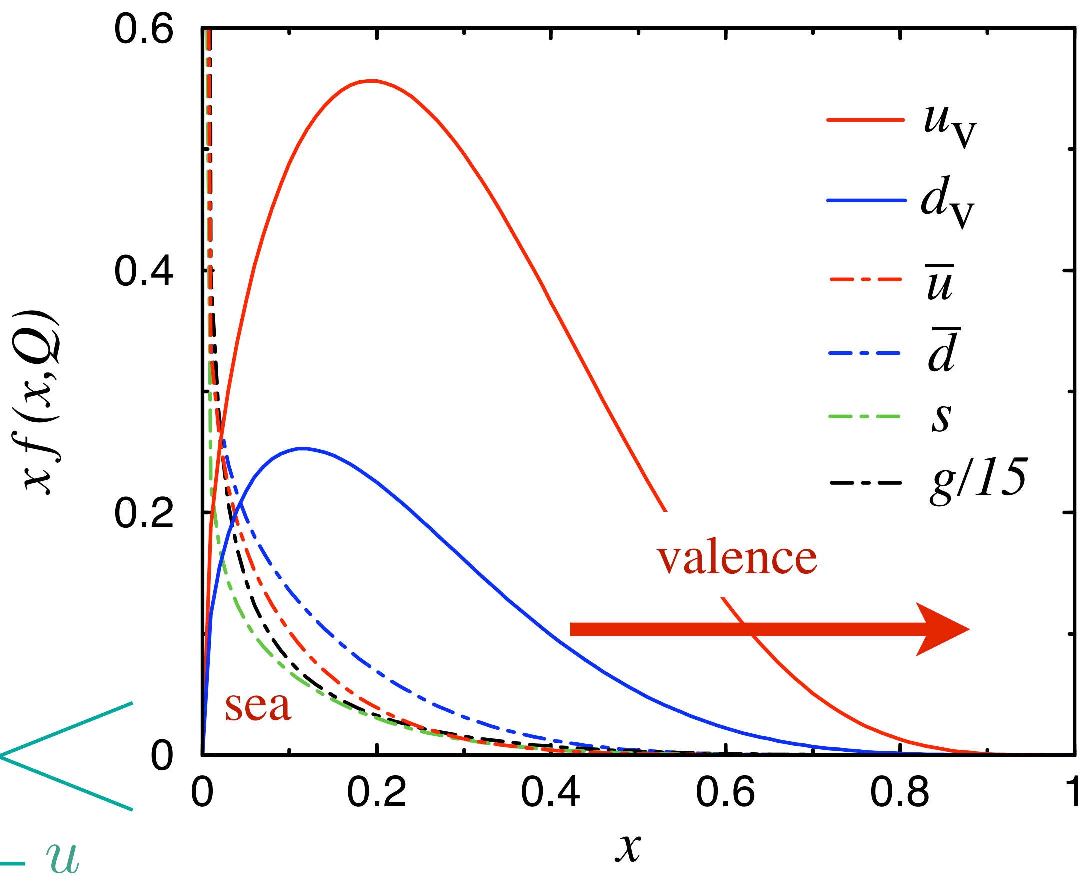
- Extension to SIDIS
  - → target and hadron mass corrections

- Summary

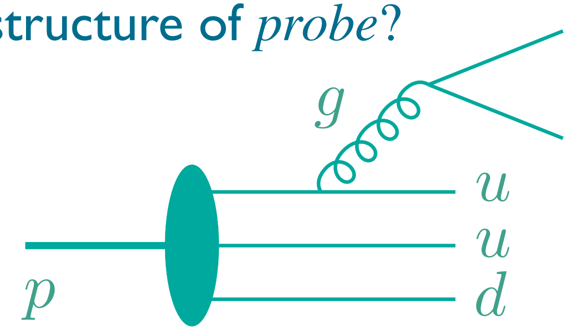
Why are PDFs at large x interesting?

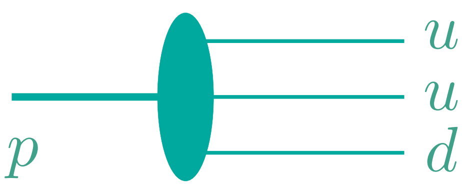
- Most direct connection between quark distributions and nonperturbative structure of nucleon is via *valence* quarks

  → 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
  - $\longrightarrow$ 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

  → 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

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

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

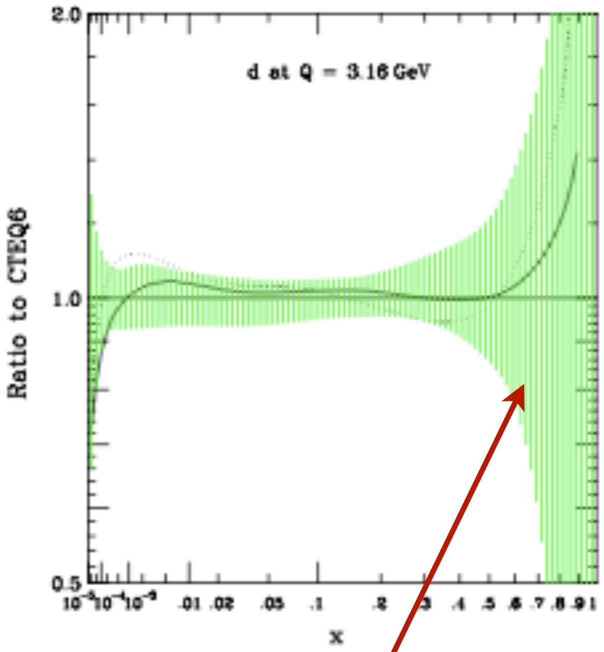
- u quark distribution well determined from *proton*
- d quark distribution requires *neutron* structure function

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

- 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"

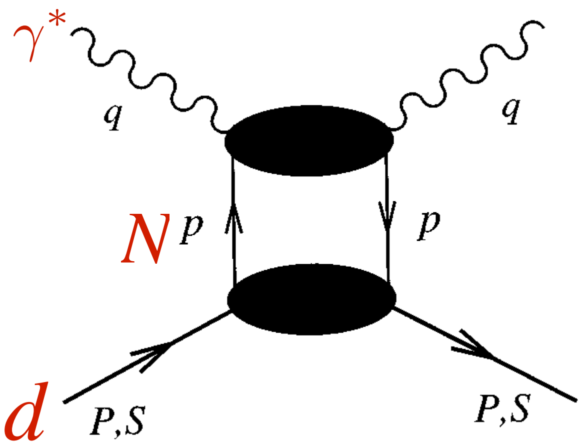
Large-x landscape:
nuclear effects in the deuteron

- 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

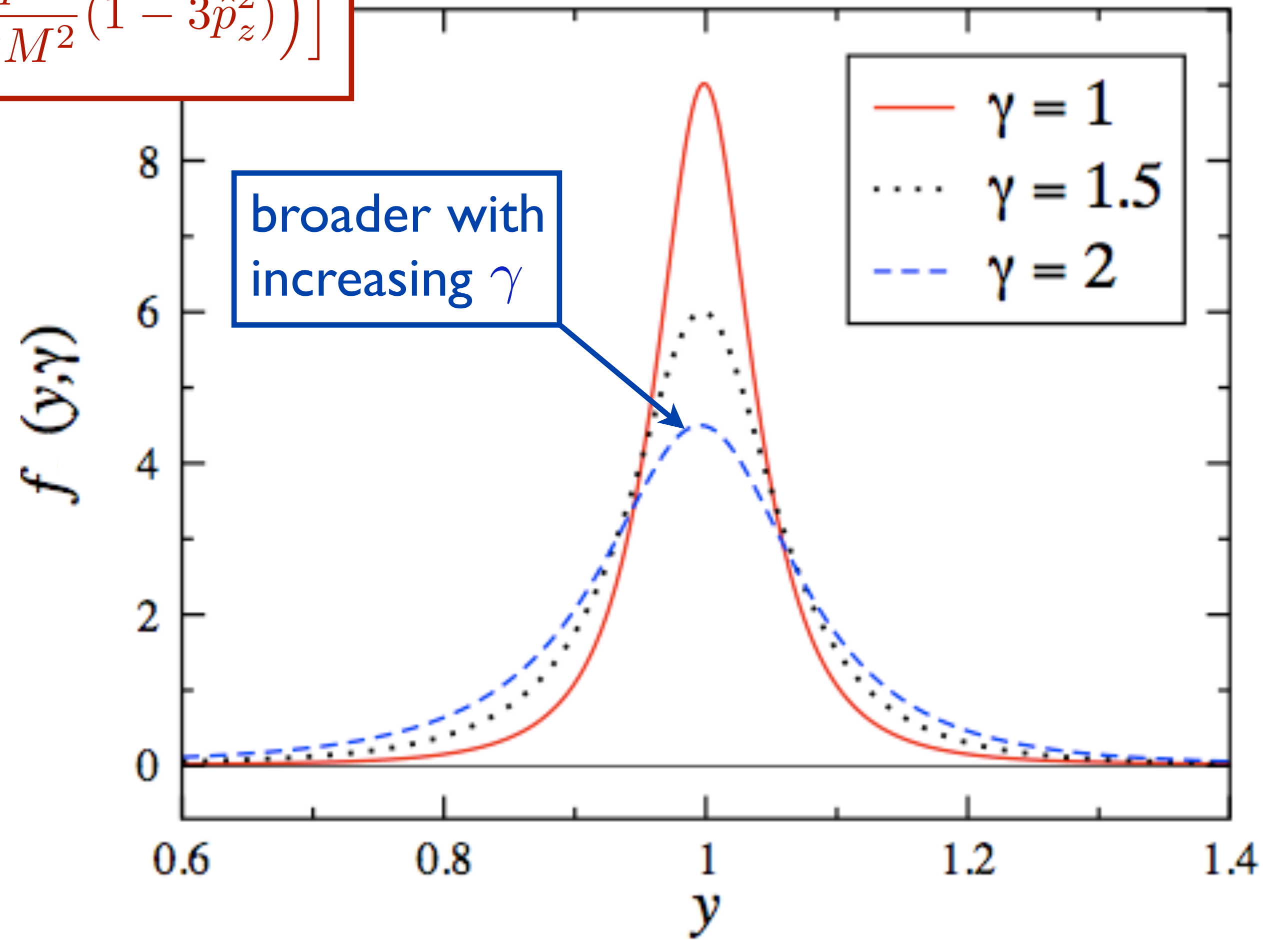
$$f(y,\gamma) = \int \frac{d^3p}{(2\pi)^3}\ |\psi_d(p)|^2\ \delta\Big(y - 1 - \frac{\varepsilon + \gamma p_z}{M}\Big)$$
$$\times \frac{1}{\gamma^2}\Big[1 + \frac{\gamma^2 - 1}{y^2}\Big(1 + \frac{2\varepsilon}{M} + \frac{\vec{p}^{\,2}}{2M^2}(1 - 3\hat{p}_z^2)\Big)\Big]$$

→ deuteron wave function $\psi_d(p)$

→ deuteron separation energy

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

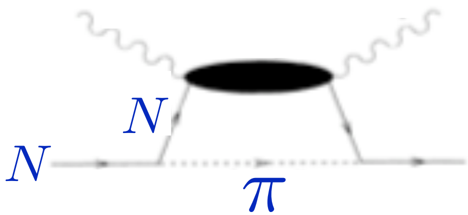
→ effectively more smearing for larger x or lower Q^2



Off-shell nucleons

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

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



PHYSICAL REVIEW D VOLUME 49, NUMBER 3 1 FEBRUARY 1994

Deep-inelastic scattering from off-shell nucleons

W. Melnitchouk*
Department of Physics and Mathematical Physics, University of Adelaide, Adelaide, South Australia 5005

A. W. Schreiber
Paul Scherrer Institut, Würenlingen und Villigen, CH-5232 Villigen PSI, Switzerland

A. W. Thomas
Department of Physics and Mathematical Physics, University of Adelaide, Adelaide, South Australia 5005
(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.

$$M_T\, W_T^A(P,q) = \frac{1}{4\pi^3}\int \frac{dy\, dp^2}{(p^2-M^2)^2}\Big\{A_0(p,P)\,\chi_T^0(p,q) + \not{p}\cdot A_1(p,P)\,\chi_T^1(p,q) + \not{q}\cdot A_2(p,P)\,\chi_T^2(p,q)\Big\}$$

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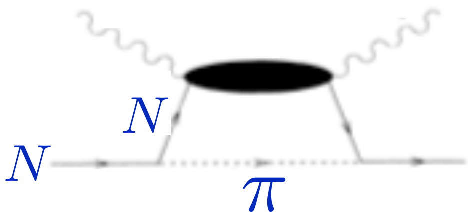


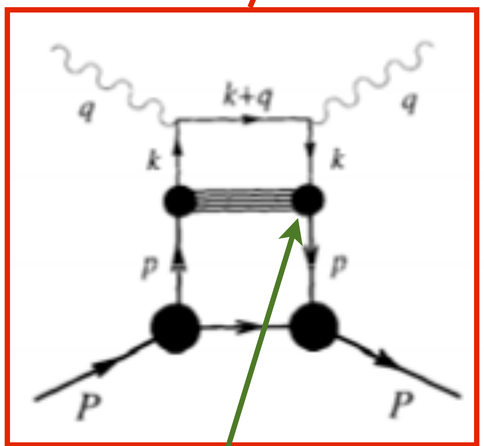
  → identify conditions under which usual convolution model of nuclear structure functions holds:
  in general these are *not* satisfied in relativistic framework

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

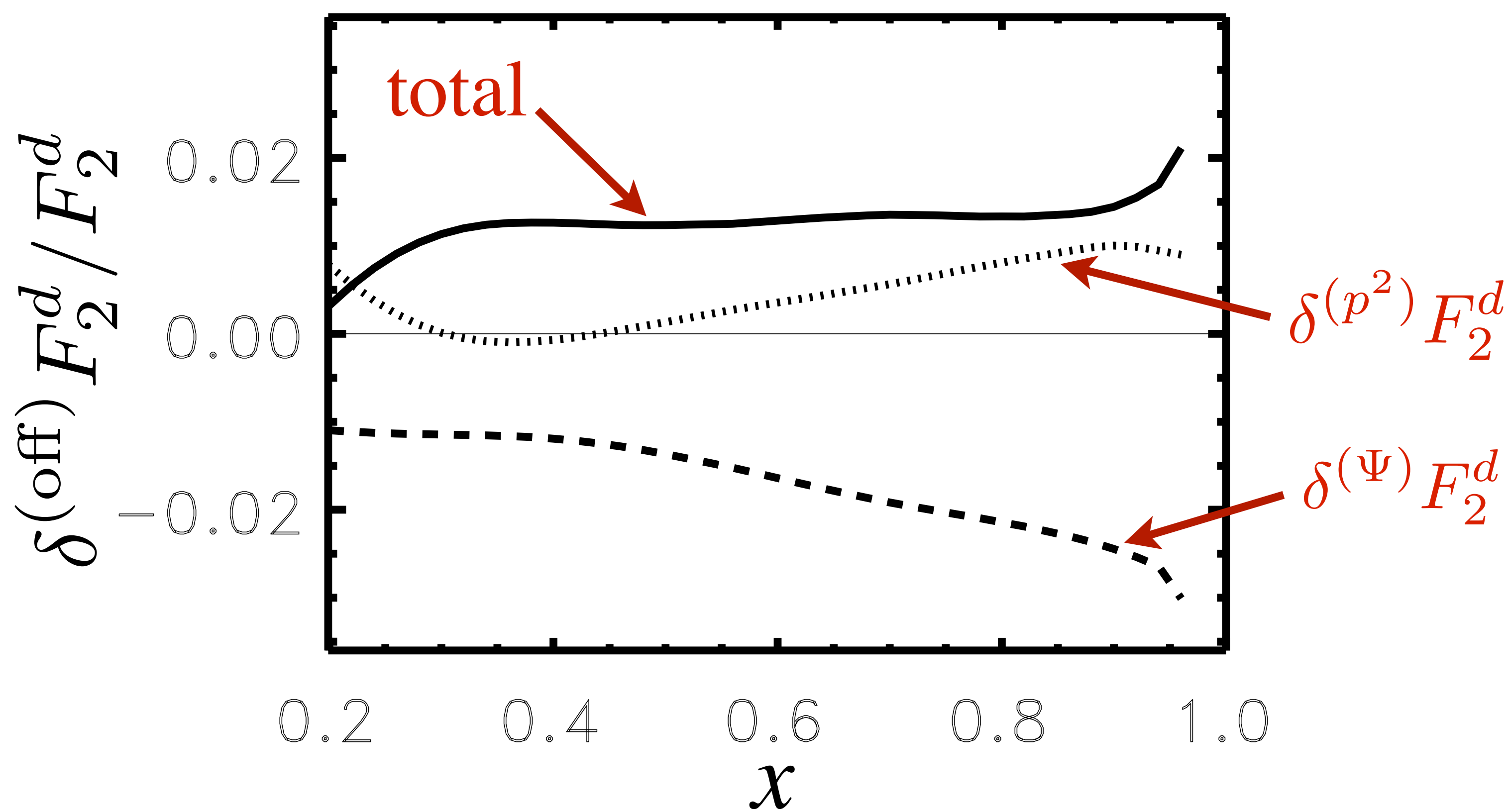
Off-shell nucleons

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

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

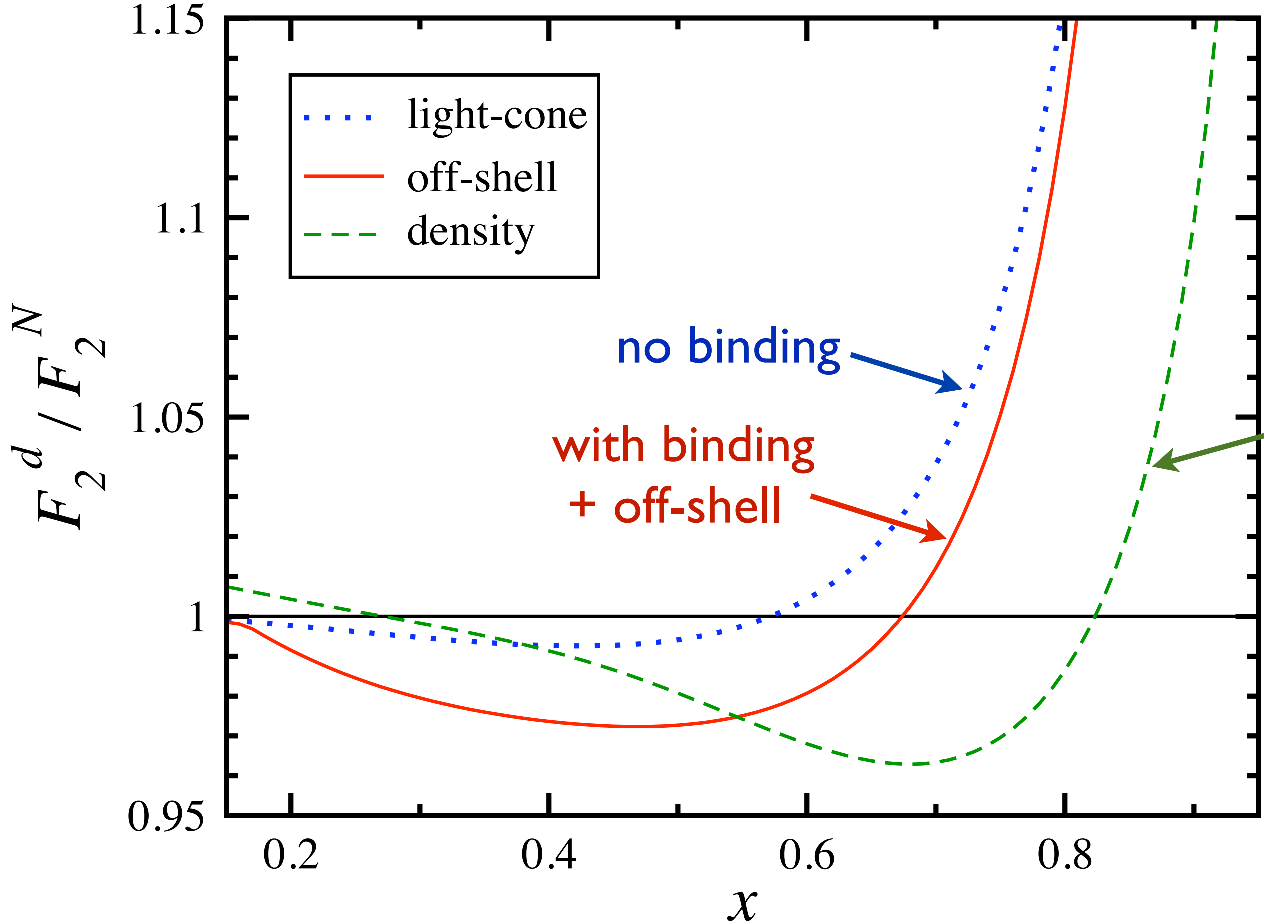


quark-diquark
vertex functions



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

EMC effect in deuteron



nuclear density

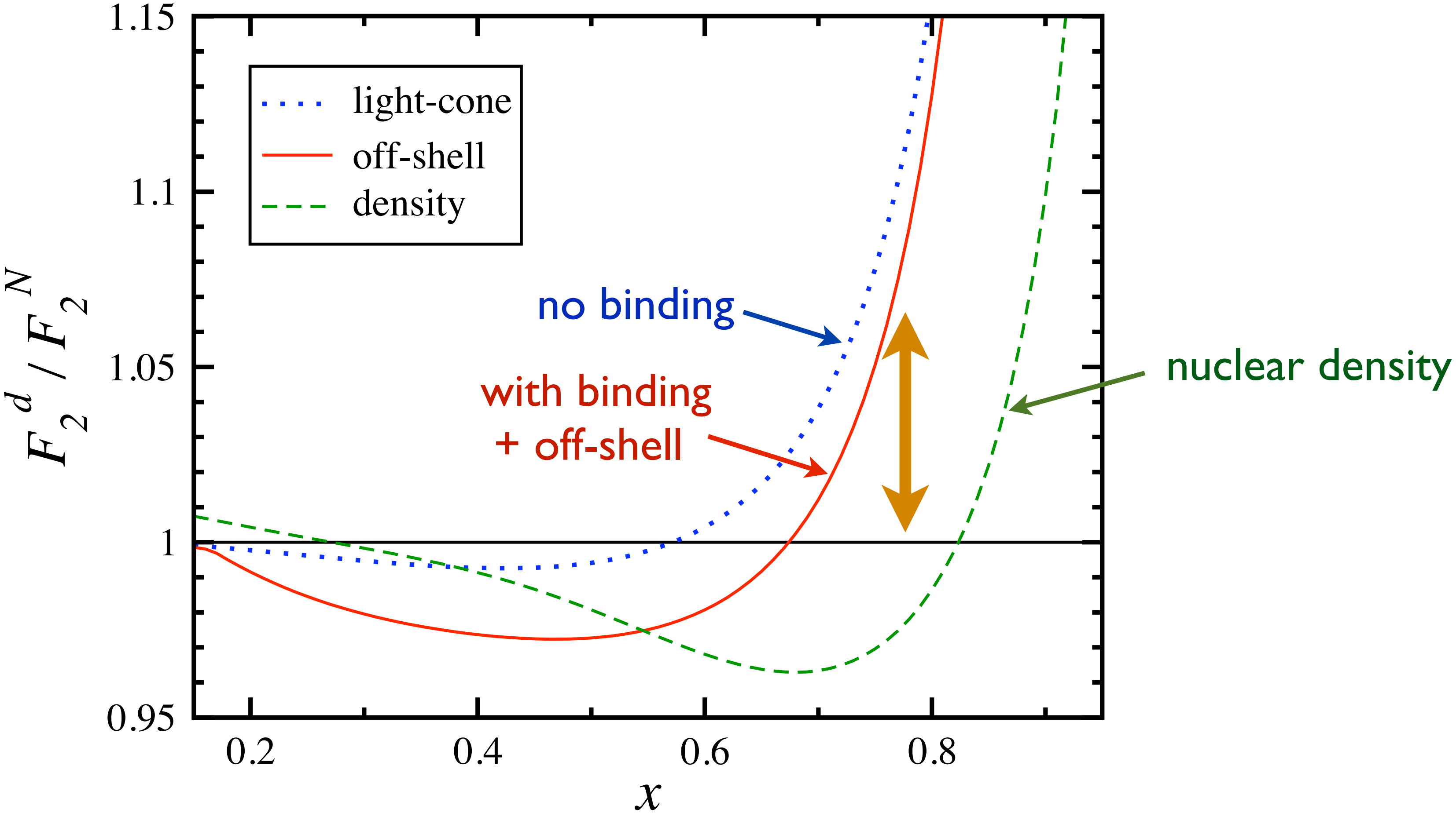
$$\frac{F_2^d}{F_2^N} - 1 \approx \frac{1}{4}\left(\frac{F_2^{\rm Fe}}{F_2^d} - 1\right)$$

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

$\longrightarrow$ ~ 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

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

EMC effect in deuteron

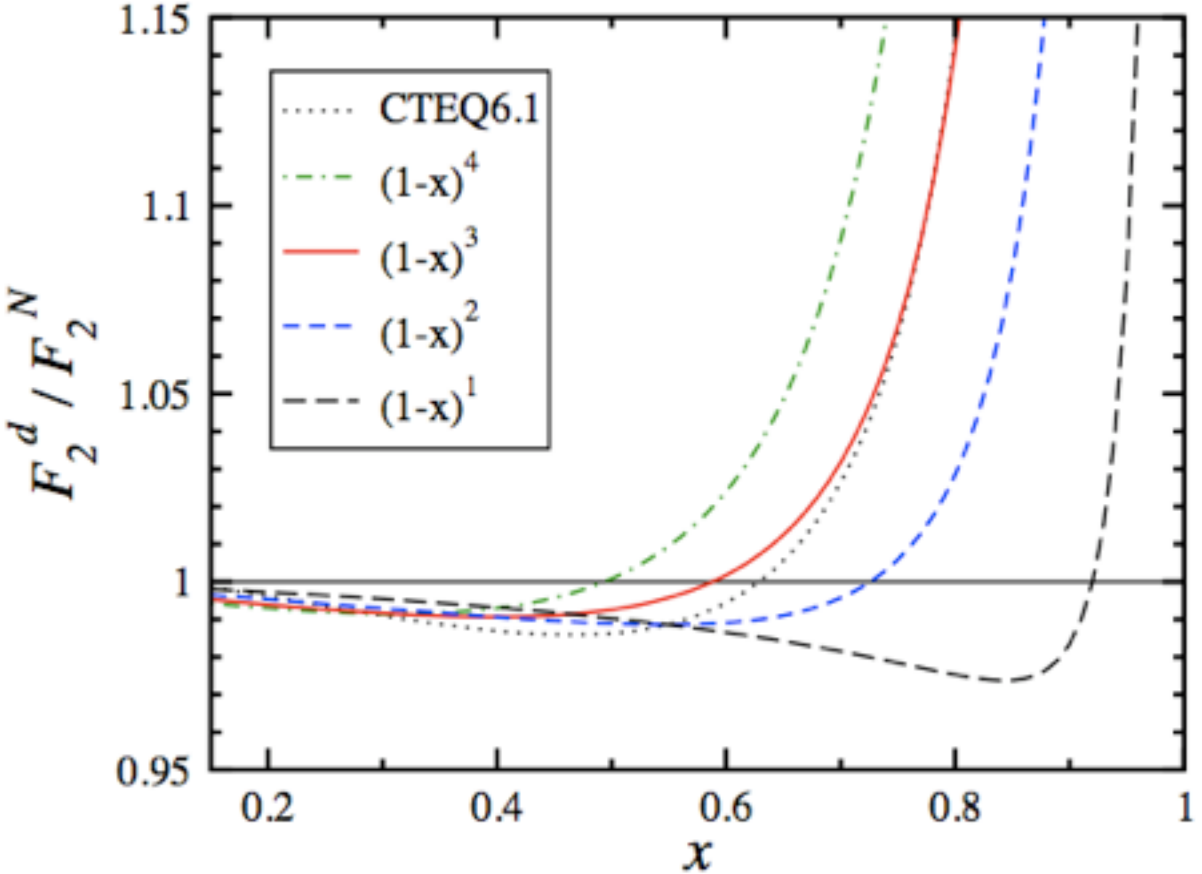


→ using off-shell model, will get *larger* neutron *cf. light-cone* model

→ 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

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

  $\longrightarrow$ gives rise to new *Nachtmann* scaling variable

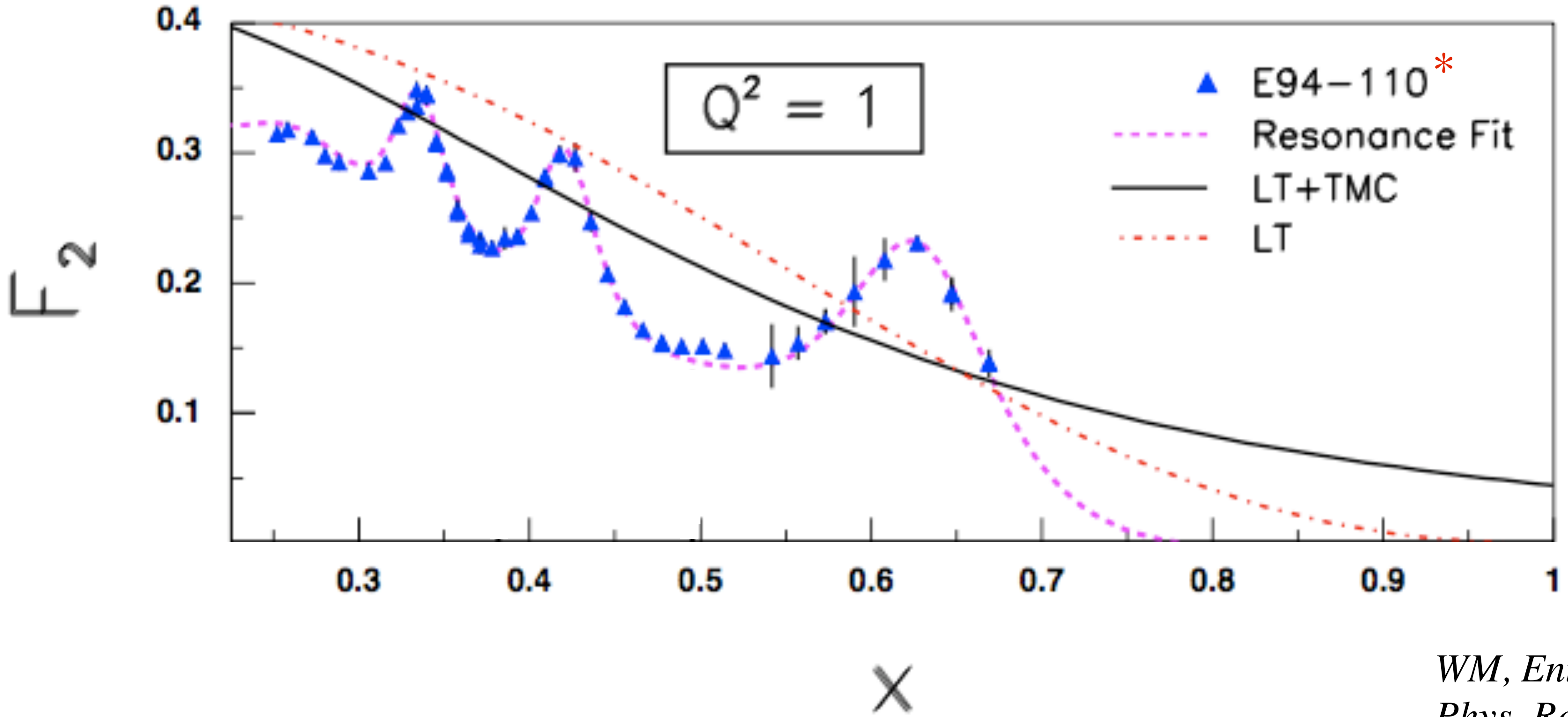
$$\boxed{\xi = \frac{2x}{1+\sqrt{1+4M^2x^2/Q^2}}}$$

- Target mass corrected structure function (leading twist)

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

massless limit function

Target mass corrections



* JLab Hall C

WM, Ent, Keppel
Phys. Rept. (2005)

→ TMC important for verification of quark-hadron duality

Target mass corrections

- *But* TMCs not unique: *e.g.* in 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

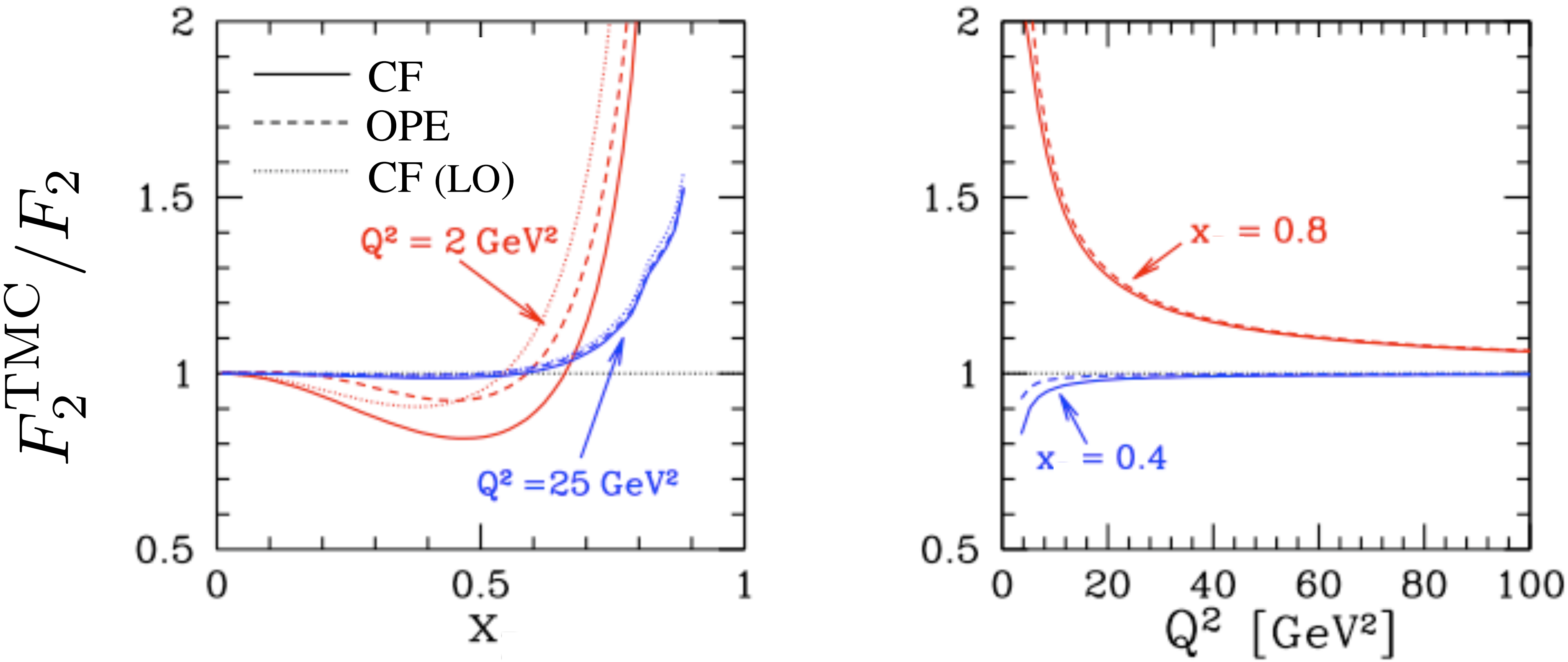
→ at leading order

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

Kretzer, Reno (2004)

Target mass corrections

- *<u>But</u>* TMCs not unique: *e.g.* in collinear factorization



Accardi, Qiu (2008)

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

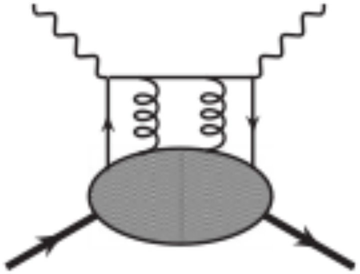
Higher twists

- $1/Q^2$ 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

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

New global analysis ("CTEQX")

Joint CTEQ-JLab collaboration
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 *proton* and *deuterium* 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

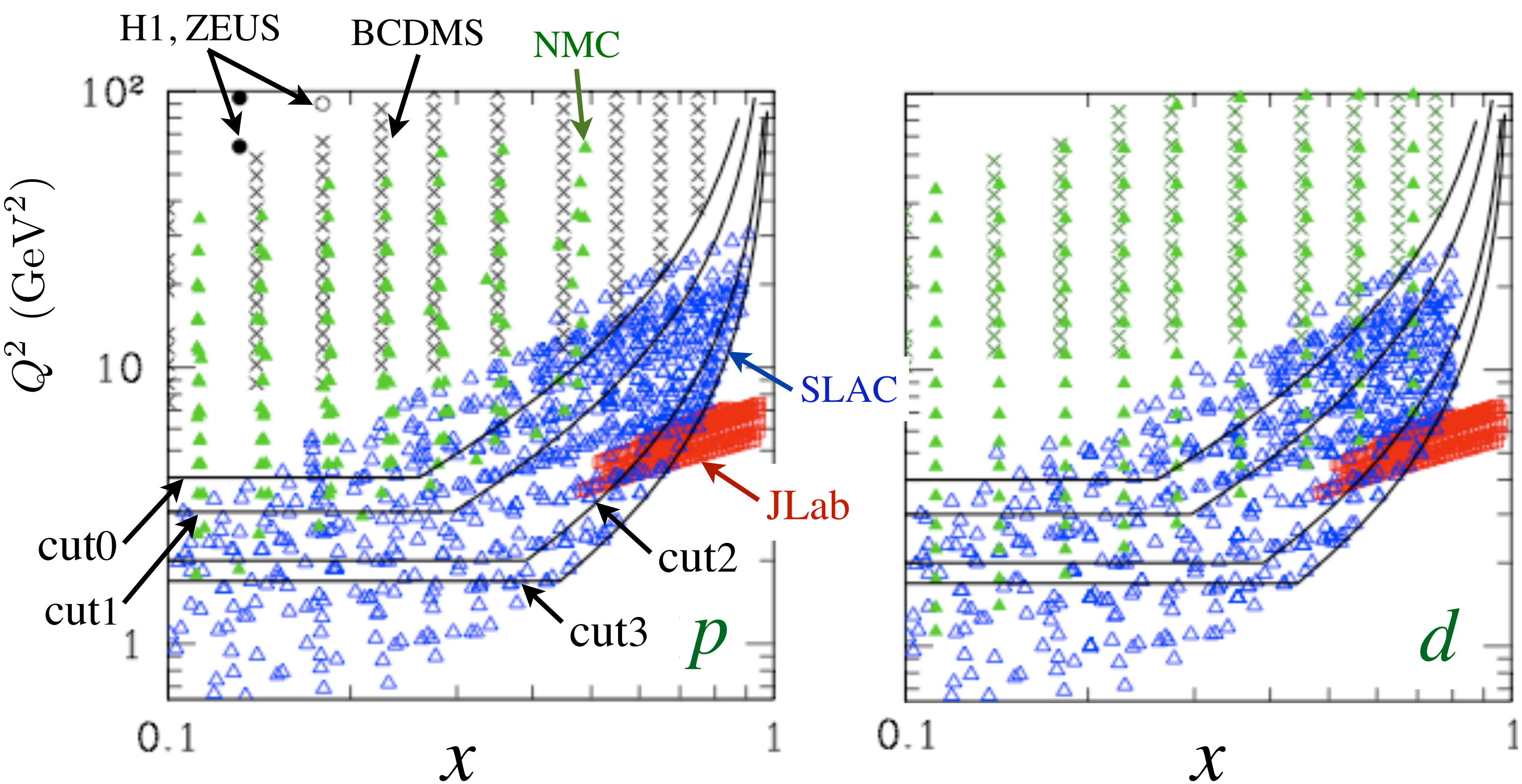
- Include subleading $1/Q^2$ corrections

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

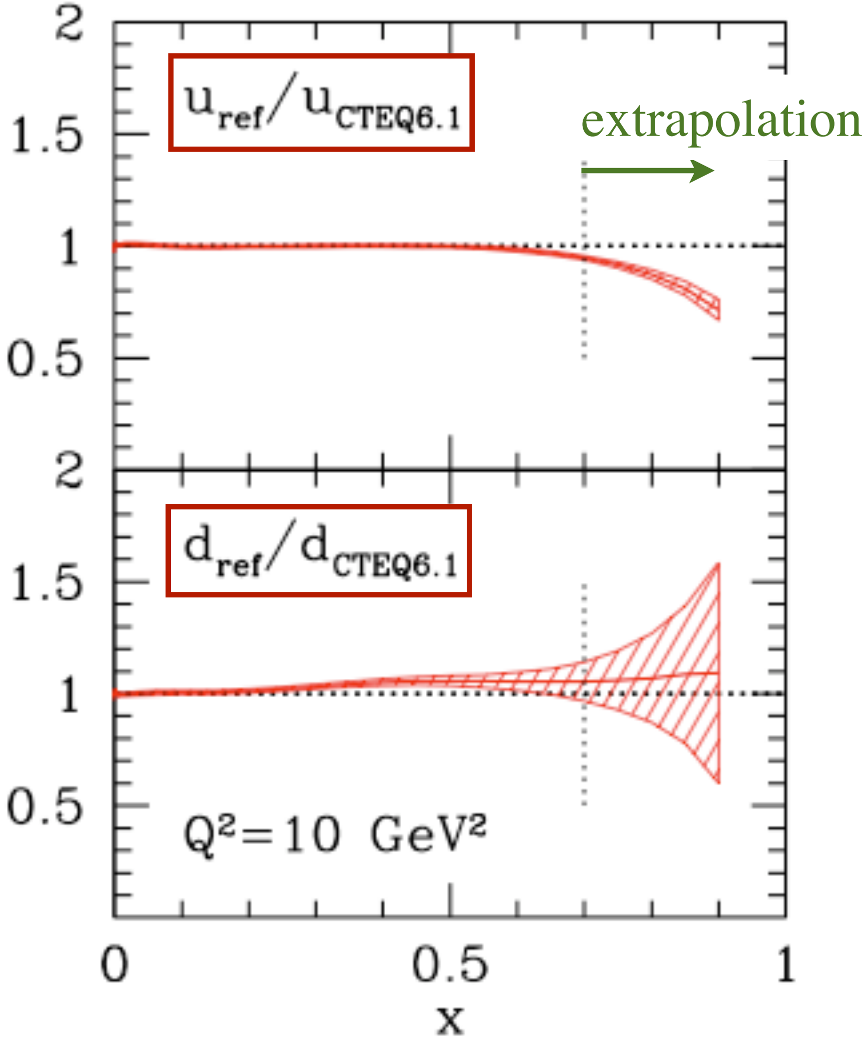
cut1: $Q^2 > 3\ \mathrm{GeV}^2, \quad W^2 > 8\ \mathrm{GeV}^2$

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 $\longrightarrow$ cut3

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

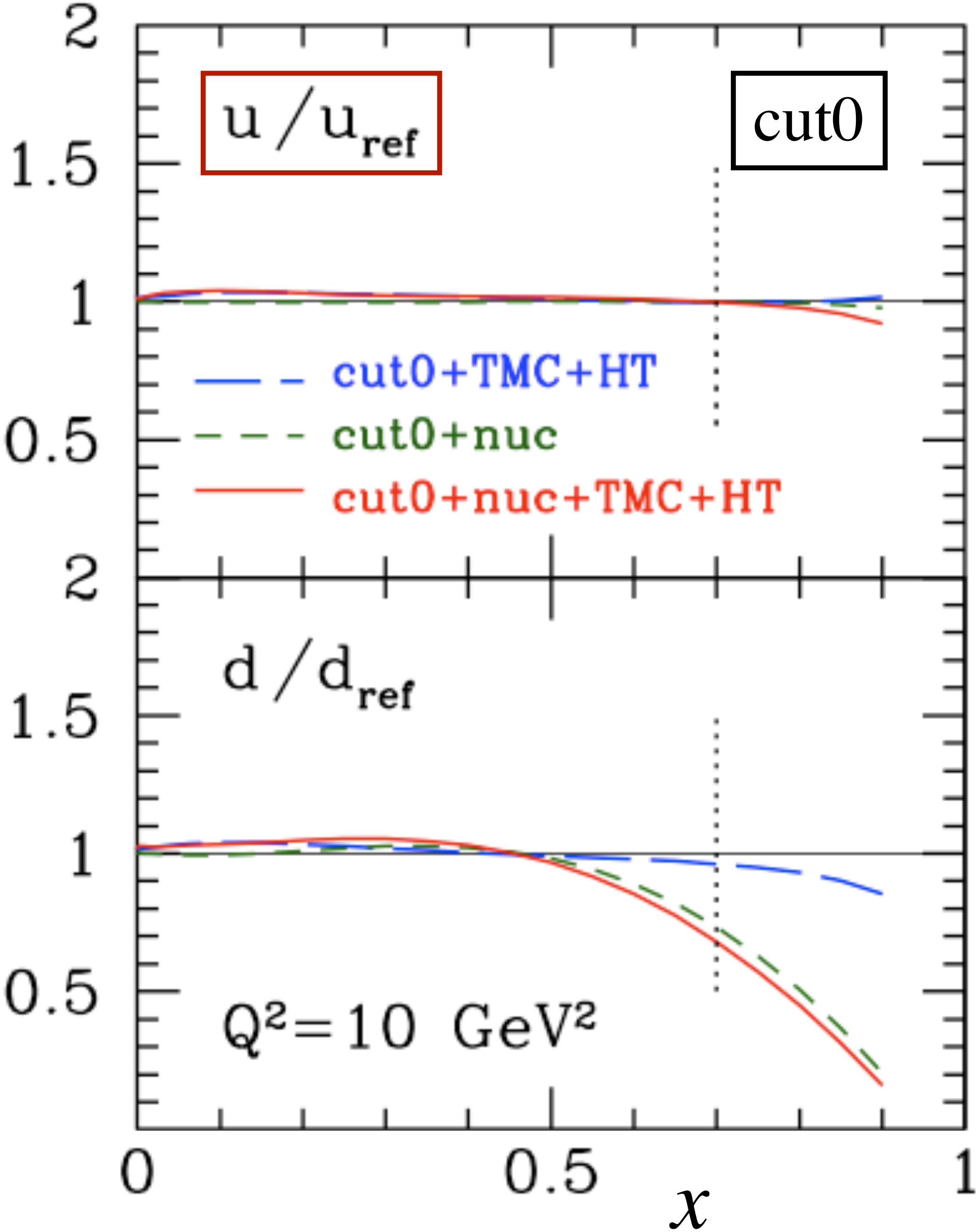


→ *no* nuclear or $1/Q^2$ corrections

→ 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



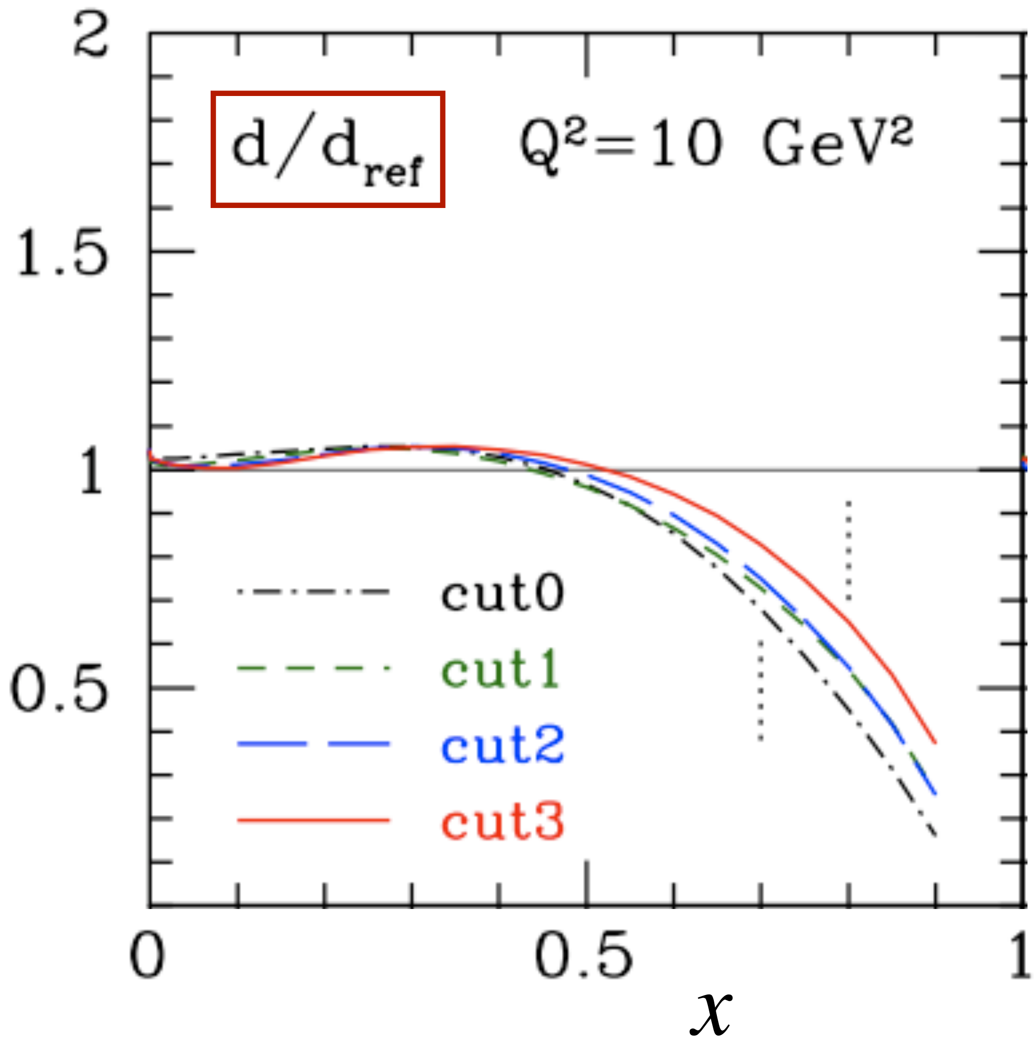
→ cut0 limits significant change to u quark

→ 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

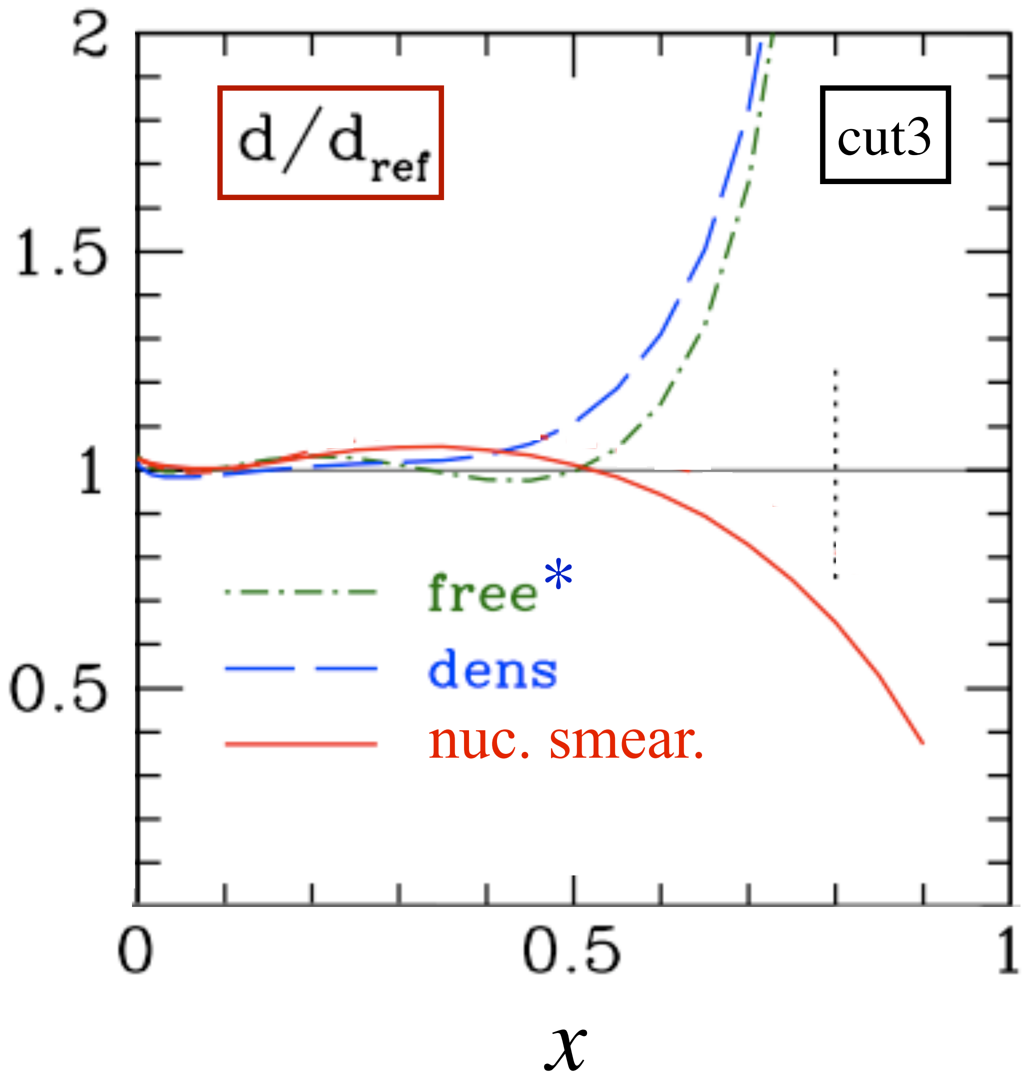
- Systematically reduce Q^2 and W cuts
- Fit includes TMCs, HT term, nuclear corrections



→ stable with respect to cut reduction

→ d quark suppressed by ~ 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)

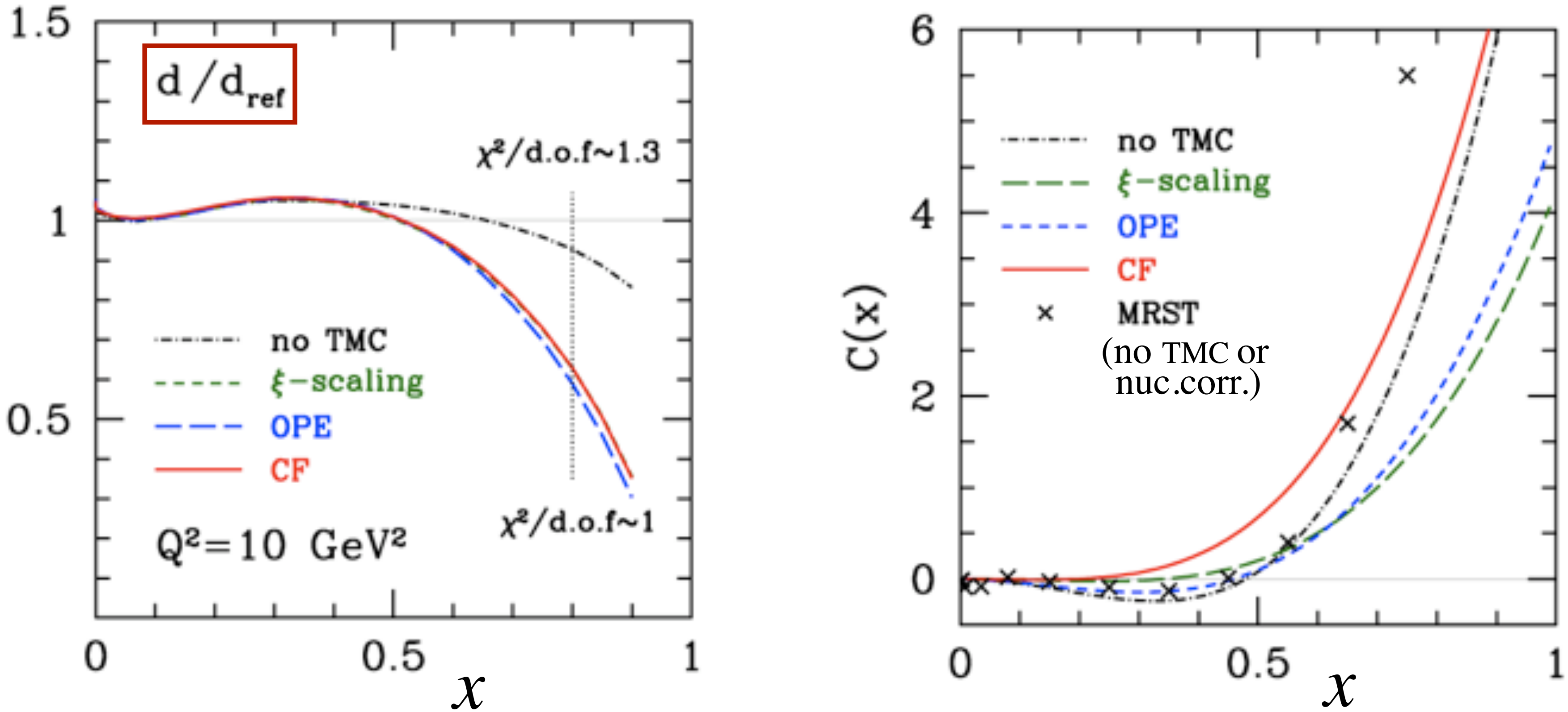
→ *decreased* d quark for nuclear smearing models

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

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

$\leftrightarrow \quad d/u \downarrow$

Effect of $1/Q^2$ corrections



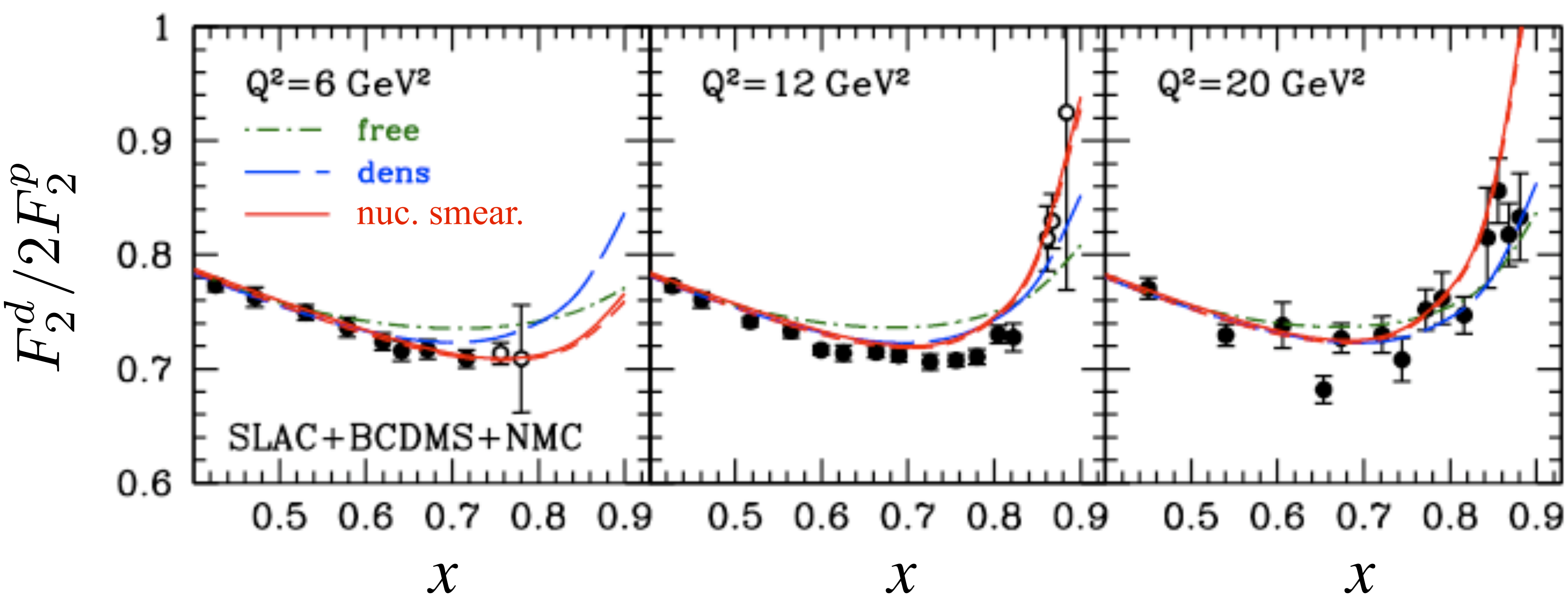
→ $1/Q^2$ HT coefficient parametrized as $C(x) = c_1 x^{c_2}(1 + c_3 x)$

→ 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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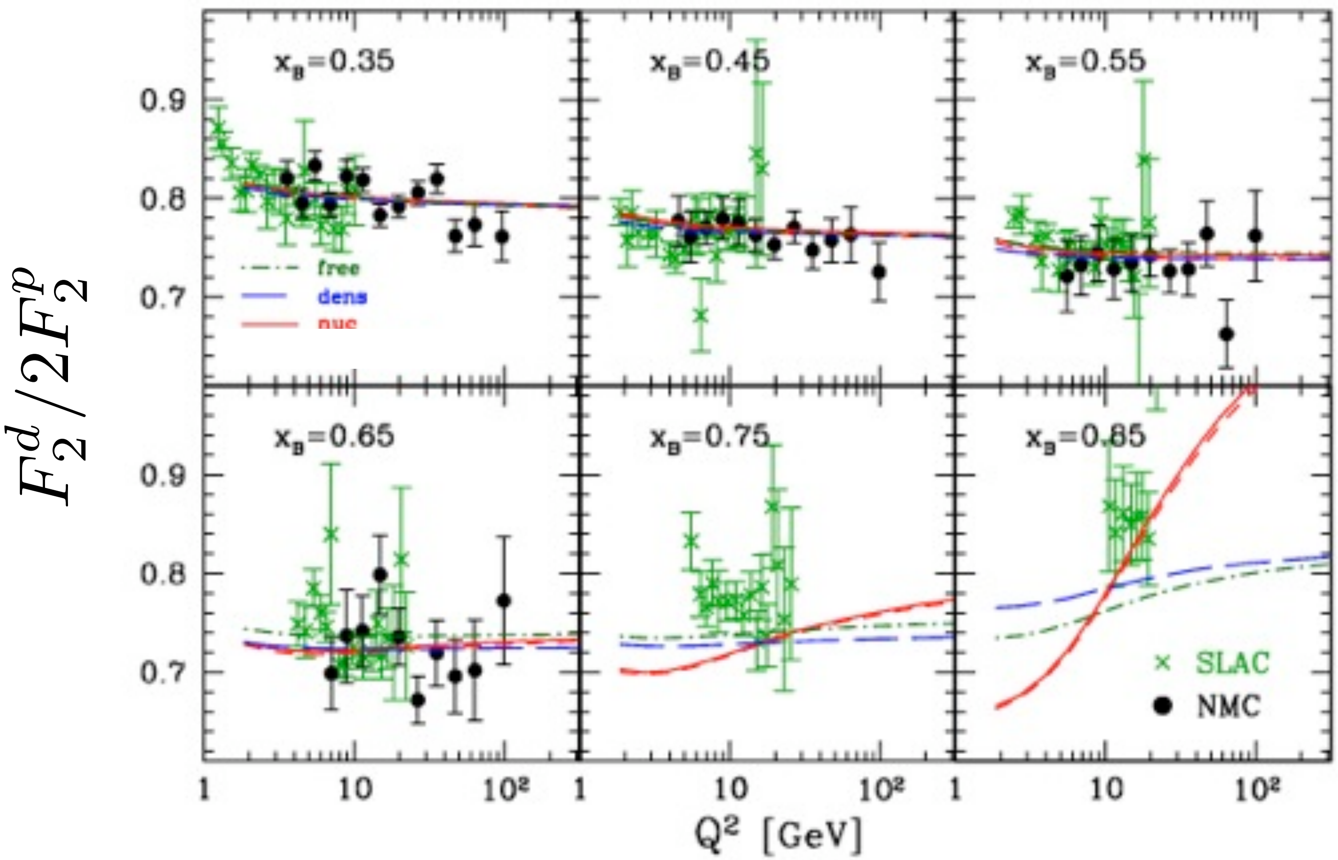

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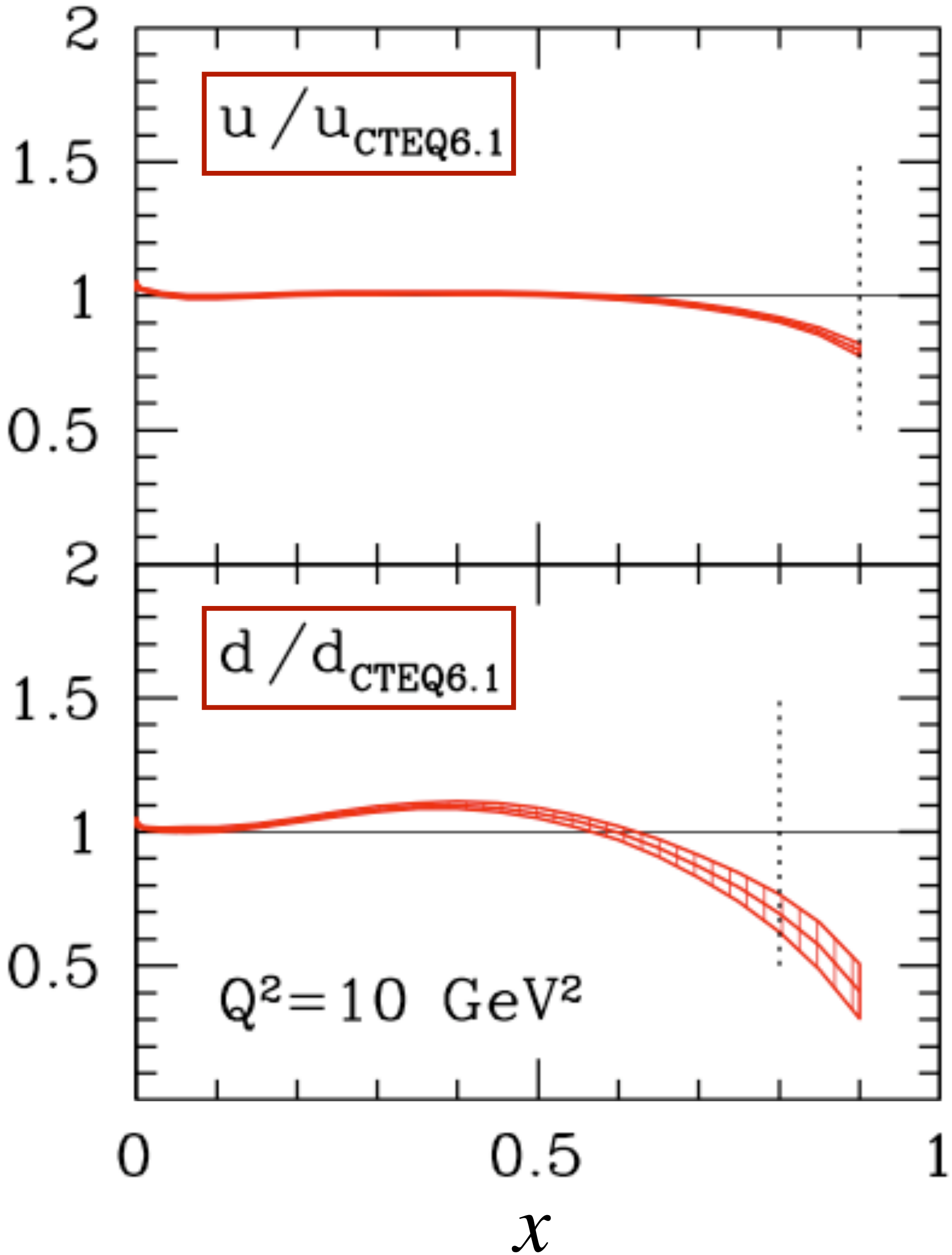
Final PDF results



→ full fits favors *smaller* d/u ratio

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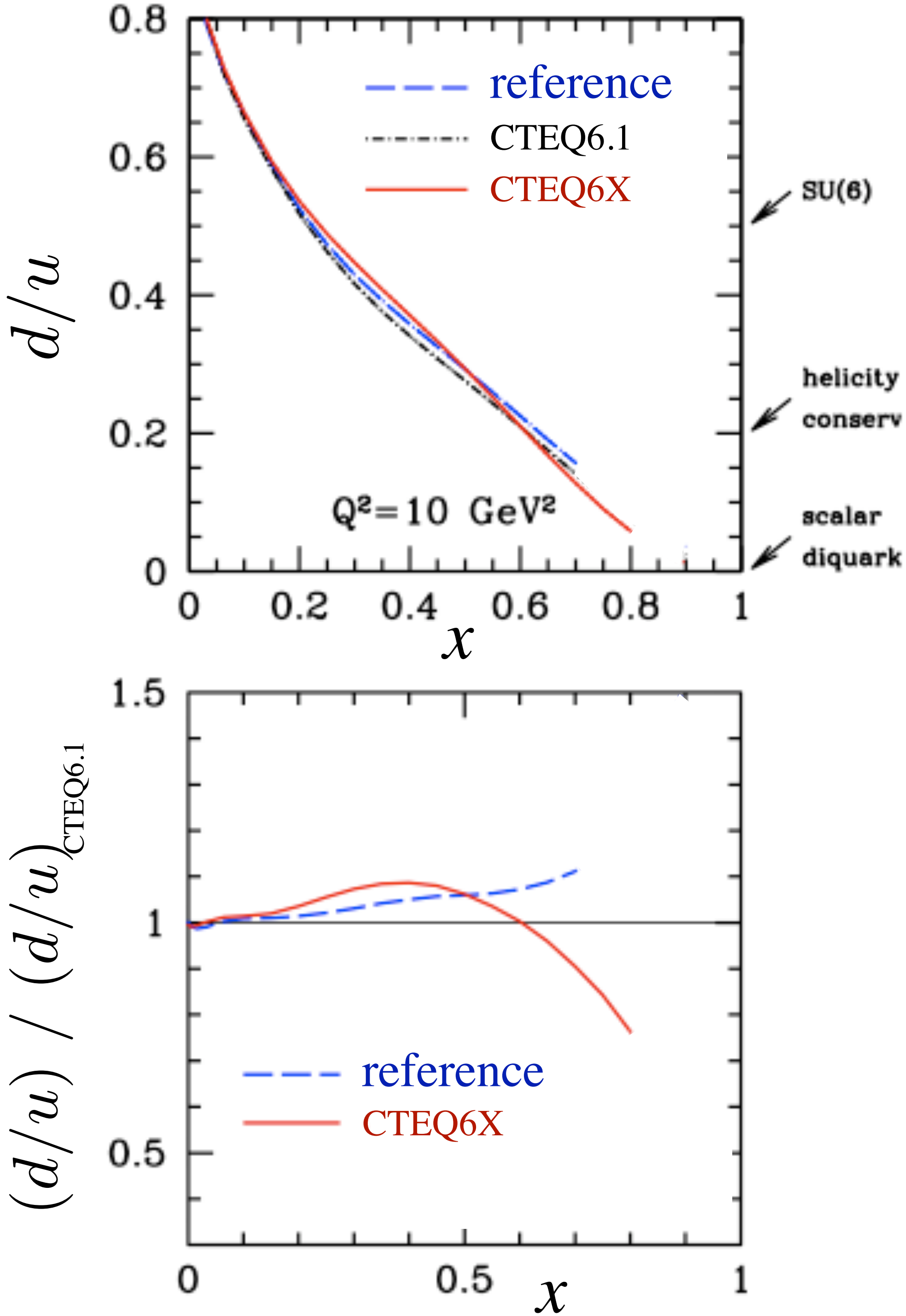

→ full fits favors *smaller* d/u ratio

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

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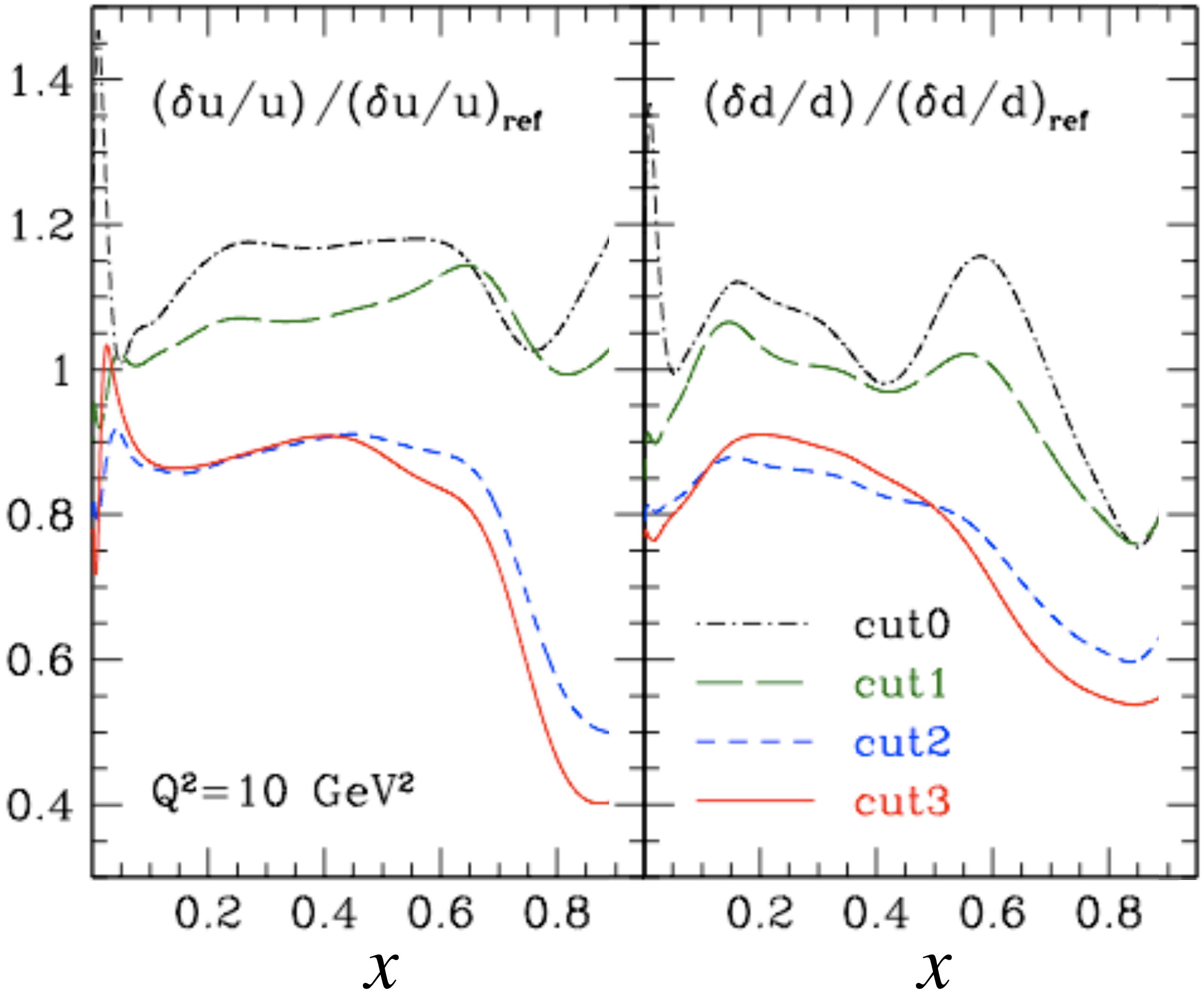


→ full fits favors <u>*smaller*</u> *d/u* ratio

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

→ significantly *reduced errors* with weaker cuts

Future methods of determining d/u

- $e\ d \to e\ p_{\rm spec}\ X^*$ — semi-inclusive DIS from d
  $\longrightarrow$ tag "spectator" protons
- $e\ {}^3\mathrm{He}({}^3\mathrm{H}) \to e\ X^*$ — ${}^3\mathrm{He}$-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

Semi-inclusive DIS:
hadron mass corrections

Hobbs, Accardi, Melnitchouk, JHEP ***11****, 084 (2009)*

- Semi-inclusive DIS offers tremendous opportunity for determining

  → spin-flavor decomposition of nucleon PDFs
  ($e.g.\ d/u,\ \bar{d}/\bar{u},\ \Delta\bar{d} - \Delta\bar{u}$)

  → new distributions, not accessible in inclusive DIS
  ($e.g.$ transversity, Sivers function, etc)

- In parton model cross section has simple factorization

$$\frac{d\sigma}{dx\, dQ^2\, dz_h} \sim \sum_q e_q^2\, q(x, Q^2)\, D_q^h(z_h, Q^2)$$

  ★ D_q^h quark ⟶ hadron fragmentation function

  ★ $z_h = \frac{p_h \cdot p}{q \cdot p} \to \frac{E_h}{\nu}$ fractional energy of produced hadron
  (at large Q^2)

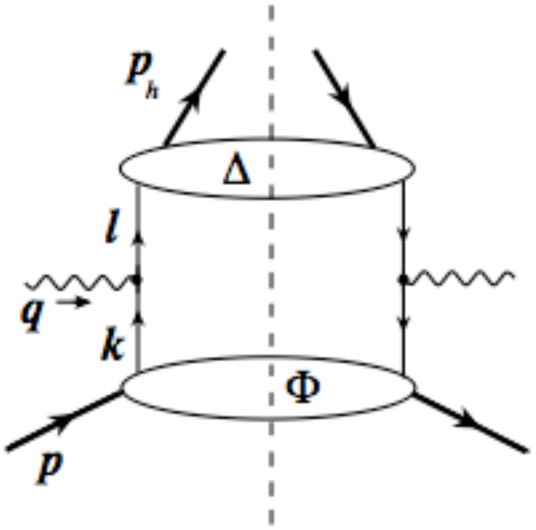
- At finite Q^2 parton model expression can have important corrections arising from

  → $x - z_h$ factorization breaking

  → subleading M^2/Q^2 & m_h^2/Q^2 *hadron mass corrections* (HMC)

- SIDIS kinematics

$$
\begin{aligned}
p^\mu &= p^+\,\bar{n}^\mu + \frac{M^2}{2p^+}\,n^\mu \\
q^\mu &= -\xi p^+\,\bar{n}^\mu + \frac{Q^2}{2\xi p^+}\,n^\mu \\
p_h^\mu &= \frac{\xi m_h^2}{\zeta_h Q^2} p^+\,\bar{n}^\mu + \frac{\zeta_h Q^2}{2\xi p^+}\,n^\mu + p_{h\perp}^\mu
\end{aligned}
$$



n^μ, $\bar{n}^\mu$ light-cone unit vectors

"*(p,q)*" collinear frame: p, q in same plane as $n, \bar{n}$

- In (p,q) frame cross section becomes

$$\frac{d\sigma}{dx\, dQ^2\, dz_h} \sim \sum_q e_q^2\, q(\xi_h, Q^2)\, D_q^h(\zeta_h, Q^2)$$

- ★ $\xi_h = \xi\left(1 + \frac{m_h^2}{\zeta_h Q^2}\right)$ ★ $\zeta_h = \frac{z_h}{2}\frac{\xi}{x}\left(1 + \sqrt{1 - \frac{4x^2 M^2 m_h^2}{z_h^2 Q^4}}\right)$

$\longrightarrow$ *hadron* mass dependence in quark *distribution* function

$\longrightarrow$ factorization breakdown (but quantifiable)

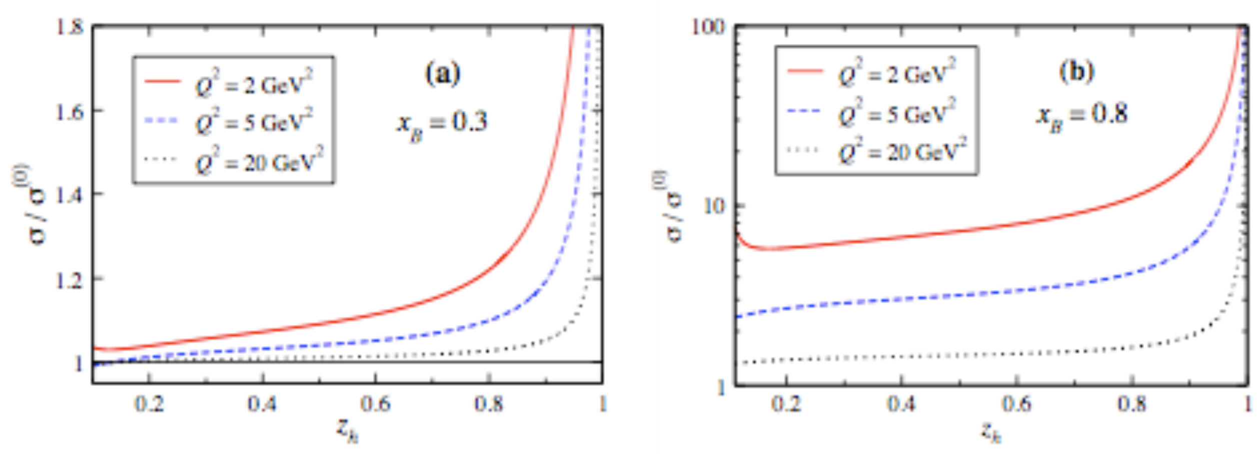
- Finite-Q^2 constraints on scaling variables

- ★ $x \le \frac{1}{(m_h^2 + 2Mm_h^2)/Q^2}$ N+h exclusive threshold

- ★ $z_h \ge 2xMm_h/Q^2$

- ★ $\xi M^2/(1-\xi)Q^2 \ \le\ \zeta_h\ \le\ 1 + \xi M^2/Q^2$

- Ratio $\sigma/\sigma^{(0)}$ of corrected to uncorrected (massless limit) $\pi^+ + \pi^-$ cross sections

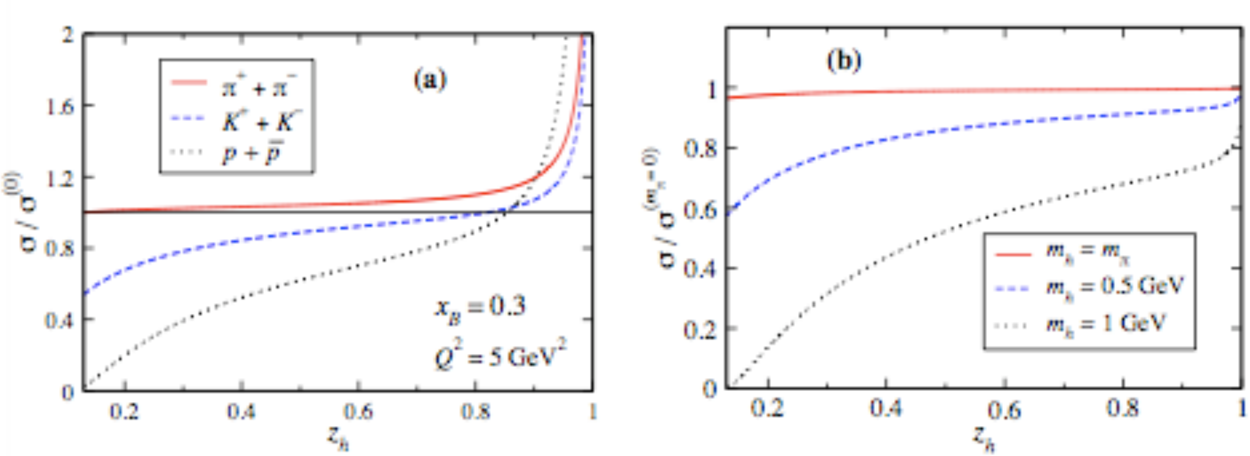


→ use CTEQ6L PDFs and KPP fragmentation functions

→ dramatic rise as $z_h \to 1$, more pronounced at low Q^2

→ order of magnitude larger effect at large x
(mostly due to TMC in PDF)

■ Flavor and mass dependence of $\sigma/\sigma^{(0)}$

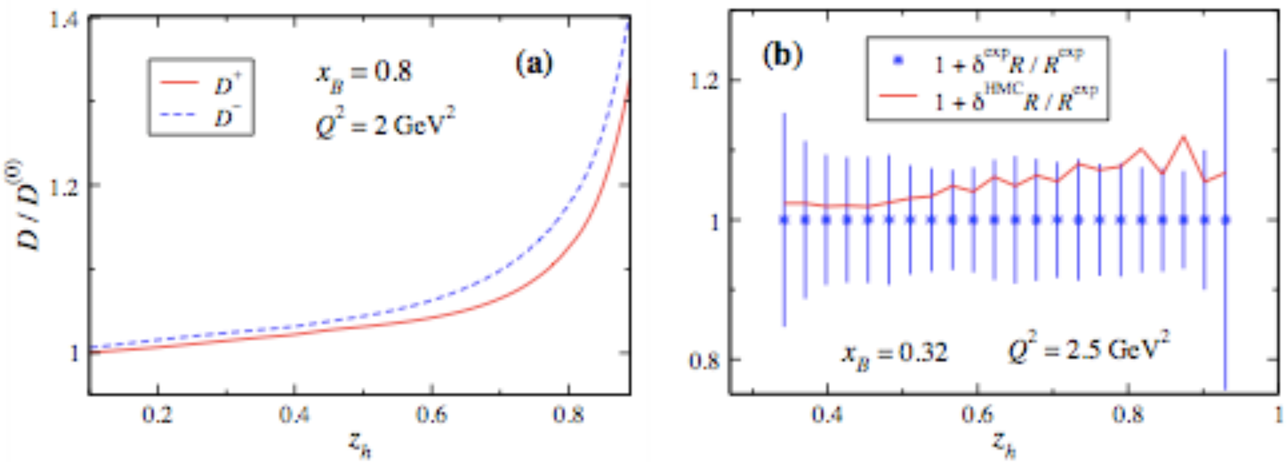


→ downward correction at small z_h for heavier hadrons driven by suppression of PDF from $(1 + m_h^2/\zeta_h Q^2)$ factor in $\xi_h\ (> \xi)$

→ reshuffling of HMC hierarchy at large z_h reflects larger (negative) slope of K and p fragmentation functions

→ effect small for π but significant for masses $\sim 1\ \mathrm{GeV}$, even at $Q^2 \sim$ several GeV^2

Hadron mass corrections to fragmentation functions



JLab E00-108

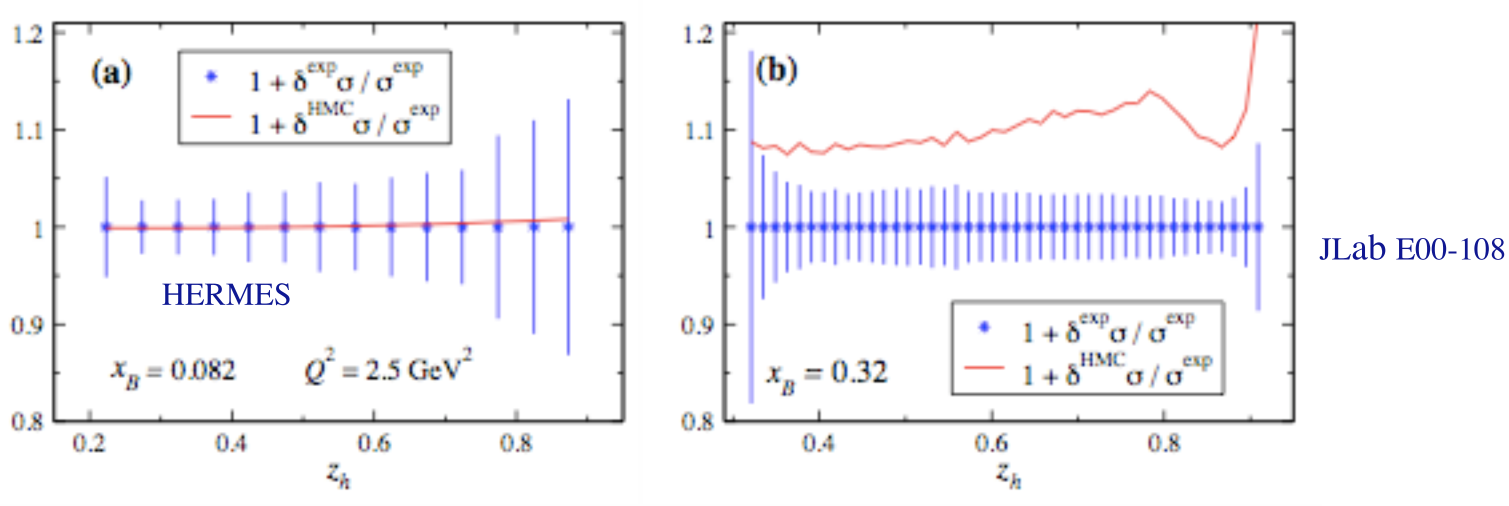
→ HMC larger for *unfavored* fragmentation function D^- than for *favored* D^+ because of steeper fall-off with z_h

$$\frac{D(\zeta_h)}{D(z_h)} \approx 1 + \frac{D'(z_h)}{D(z_h)} \, (\zeta_h - z_h)$$

→ effect on $R = D^- / D^+$ illustrated by comparison of $\delta^{\rm HMC} R = (D^- / D^+) - (D^- / D^+)^{(0)}$ with experimental error

→ correction at $z_h \gtrsim 0.6$ comparable to JLab E00-108 uncertainty

Hadron mass corrections to SIDIS *charged hadron* cross sections



→ HMC to (mostly π) cross section negligible for small x (*e.g.* HERMES)

→ significant corrections to cross sections at larger x (*e.g.* JLab)

→ to avoid HMC need smaller x or larger Q^2 ...
or include HMC in data analysis!

Summary

- 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 $Q^2 \gtrsim 1.5\ \mathrm{GeV}^2$ 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 $x > 0.6$

  $\longrightarrow$ further constraints will require novel new experiments

- Derivation of HMCs in SIDIS using collinear factorization

  $\longrightarrow$ modified fragmentation variable, corrections to $x - z_h$ factorization

  $\longrightarrow$ effects largest for heavier hadrons (K, p)