QCD Bound States: Methods & Properties
Argonne National Lab
June 15, 2009

Nucleon structure at large x – *recent developments*

Wally Melnitchouk

Jefferson Lab

Outline

- Why is nucleon structure at large x important?
  - $\longrightarrow$ d/u ratio

- 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

Quark distributions at large x

Parton distributions functions (PDFs)

- provide basic information on structure of QCD *bound states*

- extracted in global analyses of structure function data from electron, muon & neutrino scattering
  (also from Drell-Yan & W production in hadronic collisions)

- needed to understand backgrounds in searches for *new physics* beyond the Standard Model in high-energy colliders, neutrino oscillation experiments, ...

  $\longrightarrow$ DGLAP evolution feeds low x, high Q^2 from high x, low Q^2

$$\frac{dq(x,t)}{dt} = \frac{\alpha_s(t)}{2\pi} \int_x^1 \frac{dy}{y} \left[P_{qq}\left(\frac{x}{y}\right) q(y,t) + P_{qg}\left(\frac{x}{y}\right) g(y,t) \right]$$

$$t = \log Q^2 / \Lambda^2_{\rm QCD}$$

recent PDF parameterization

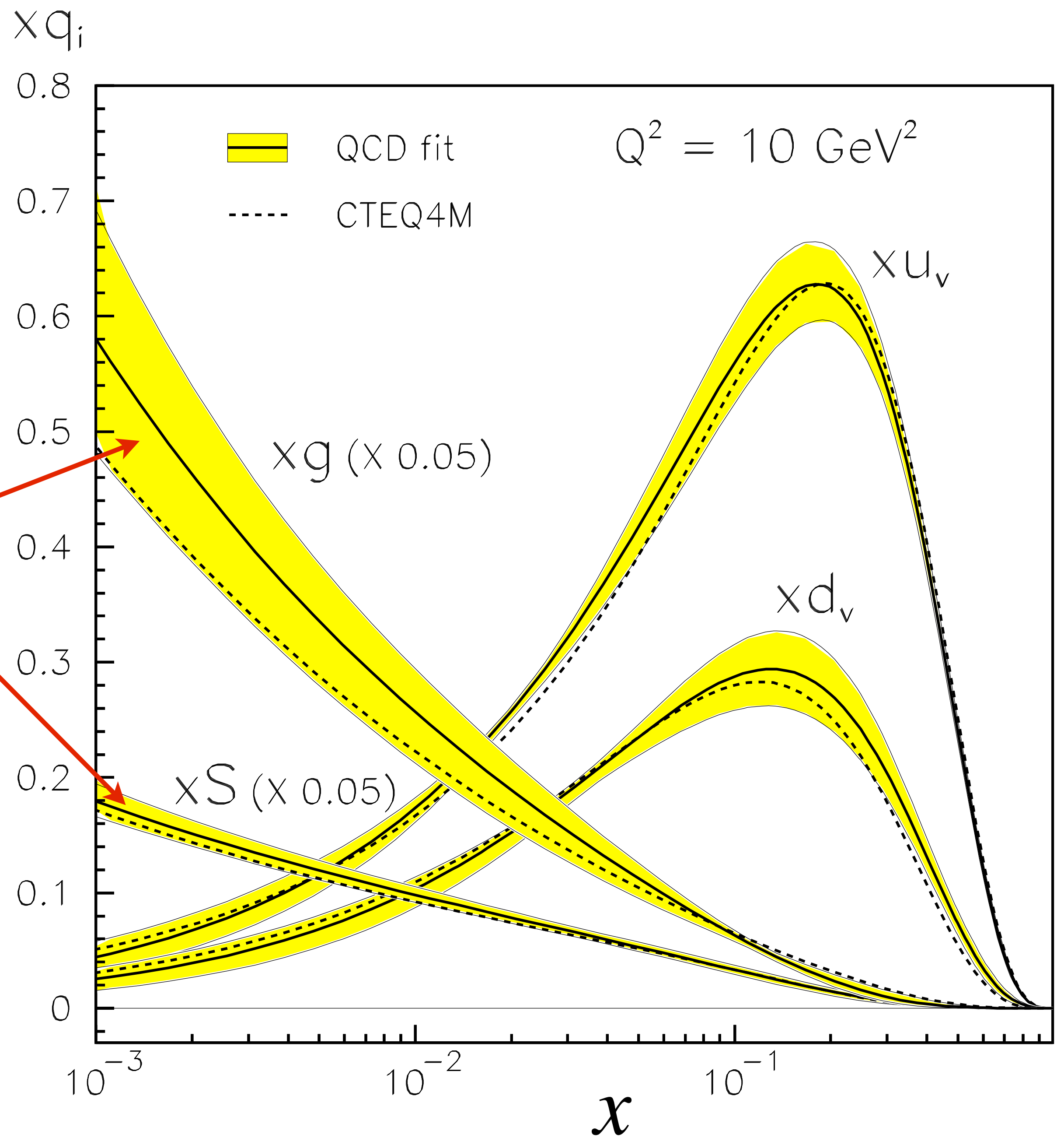
virtual "sea" of $q\bar{q}$ pairs & gluons at small x

↓

structure of *hadron*

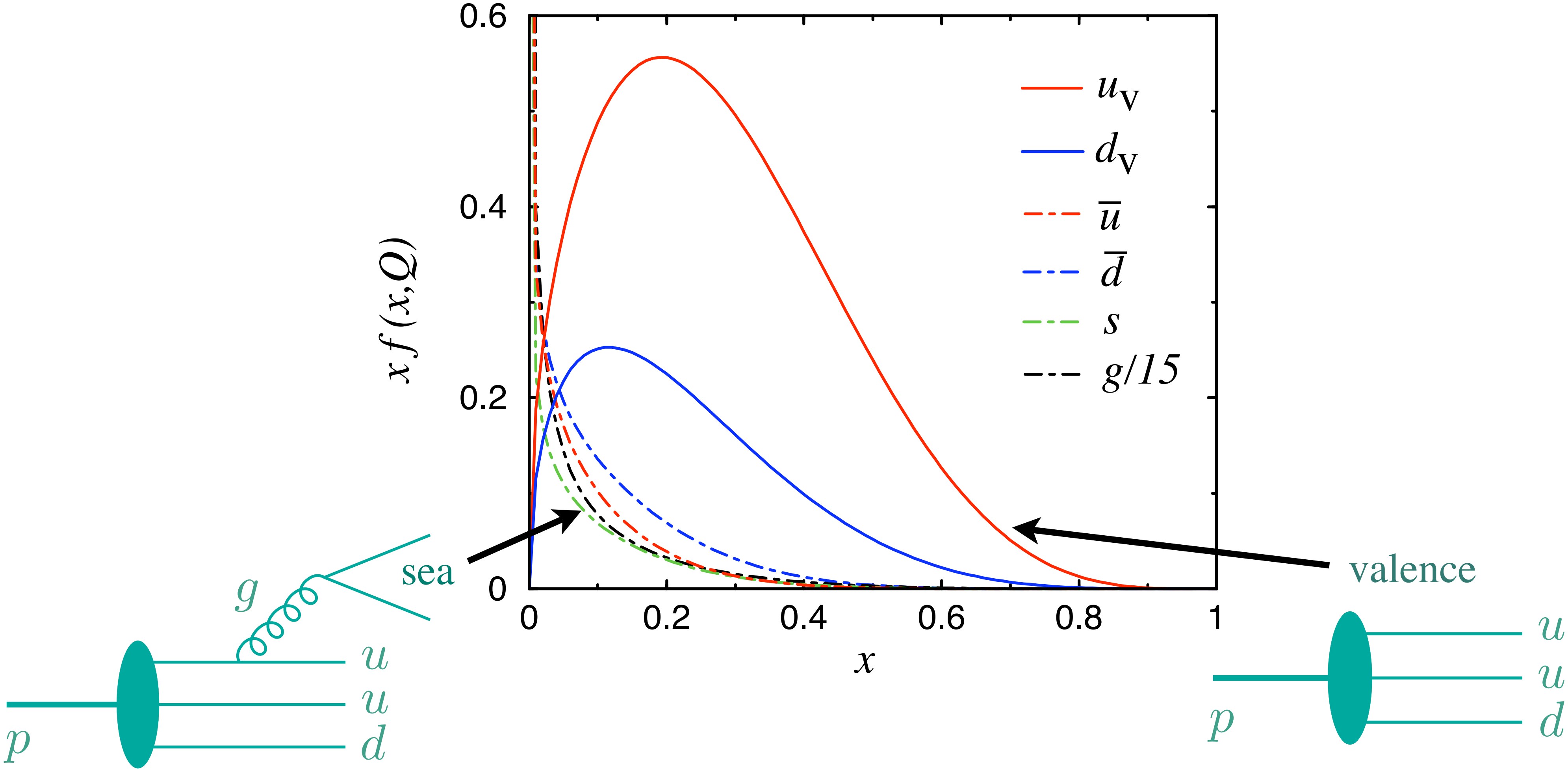
or

structure of *probe*?



Valence quarks

- Most direct connection between quark distributions and models of the nucleon is through *valence* quarks
- Nucleon structure at large x dominated by valence quarks



Valence quarks

- At large x, valence u and d distributions extracted from p and n structure functions

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

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

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

- u quark distribution well determined from p

- d quark distribution requires n structure function

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

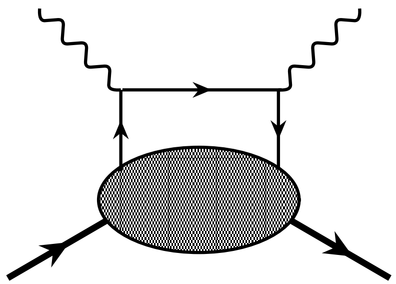
Valence quarks

- Ratio of d to u quark distributions particularly sensitive to quark dynamics in nucleon

- <u>SU(6) spin-flavor symmetry</u>

proton wave function

$$p^{\uparrow} = -\frac{1}{3}d^{\uparrow}(uu)_1 - \frac{\sqrt{2}}{3}d^{\downarrow}(uu)_1 + \frac{\sqrt{2}}{6}u^{\uparrow}(ud)_1 - \frac{1}{3}u^{\downarrow}(ud)_1 + \frac{1}{\sqrt{2}}u^{\uparrow}(ud)_0$$



interacting quark

spectator diquark

diquark spin

Valence quarks

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proton wave function

$$p^{\uparrow} = -\frac{1}{3} d^{\uparrow} (uu)_1 - \frac{\sqrt{2}}{3} d^{\downarrow} (uu)_1 + \frac{\sqrt{2}}{6} u^{\uparrow} (ud)_1 - \frac{1}{3} u^{\downarrow} (ud)_1 + \frac{1}{\sqrt{2}} u^{\uparrow} (ud)_0$$

$\longrightarrow$ $u(x) = 2\ d(x)$ for all x

$\longrightarrow$ $\dfrac{F_2^n}{F_2^p} = \dfrac{2}{3}$

Valence quarks

- scalar diquark dominance

$M_\Delta > M_N \quad \Longrightarrow \quad (qq)_1$ has larger energy than $(qq)_0$

$\Longrightarrow$ scalar diquark dominant in $x \to 1$ limit

Valence quarks

- scalar diquark dominance

$$M_\Delta > M_N \quad \Longrightarrow \quad (qq)_1 \text{ has larger energy than } (qq)_0$$

$$\Longrightarrow \quad \text{scalar diquark dominant in } x \to 1 \text{ limit}$$

since only u quarks couple to scalar diquarks

$$\longrightarrow \quad \frac{d}{u} \to 0$$

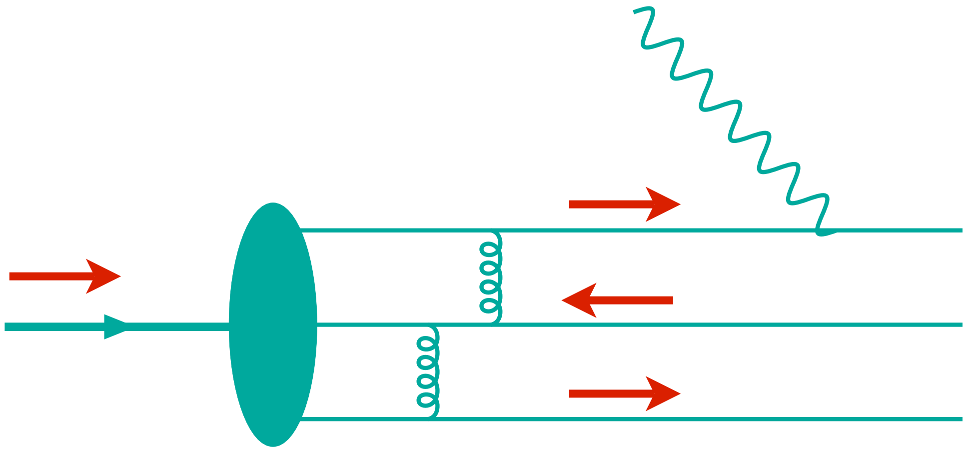
$$\longrightarrow \quad \frac{F_2^n}{F_2^p} \to \frac{1}{4}$$

Feynman 1972, Close 1973, Close/Thomas 1988

Valence quarks

- <u>hard gluon exchange</u>

  at large x, helicity of struck quark = helicity of hadron



$$q^{\uparrow} \gg q^{\downarrow}$$

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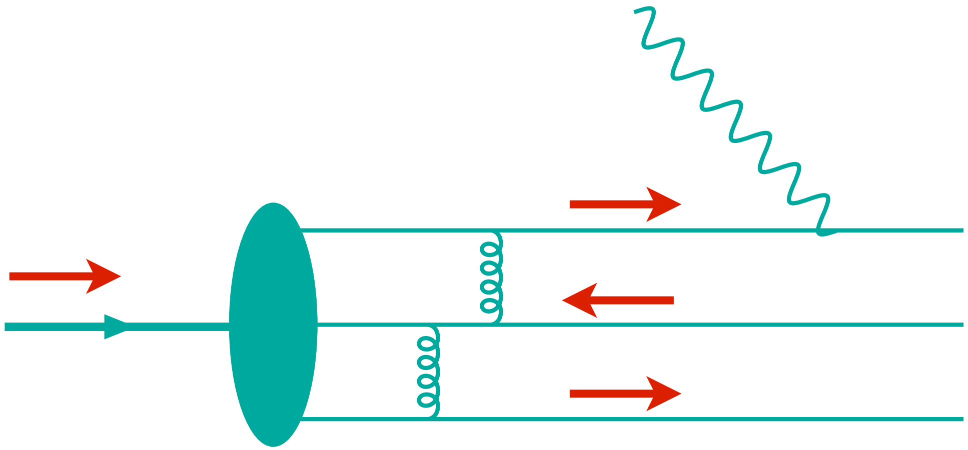


$$q^{\uparrow} \gg q^{\downarrow}$$

$\Longrightarrow$ helicity-zero diquark dominant in $x \to 1$ limit

$\longrightarrow \quad \dfrac{d}{u} \to \dfrac{1}{5}$

$\longrightarrow \quad \dfrac{F_2^n}{F_2^p} \to \dfrac{3}{7}$

Farrar, Jackson 1975

- No **FREE** neutron targets

  (neutron half-life ~ 12 mins)

  → use deuteron as "effective" neutron target

- **BUT** deuteron is a nucleus, and $F_2^d \neq F_2^p + F_2^n$

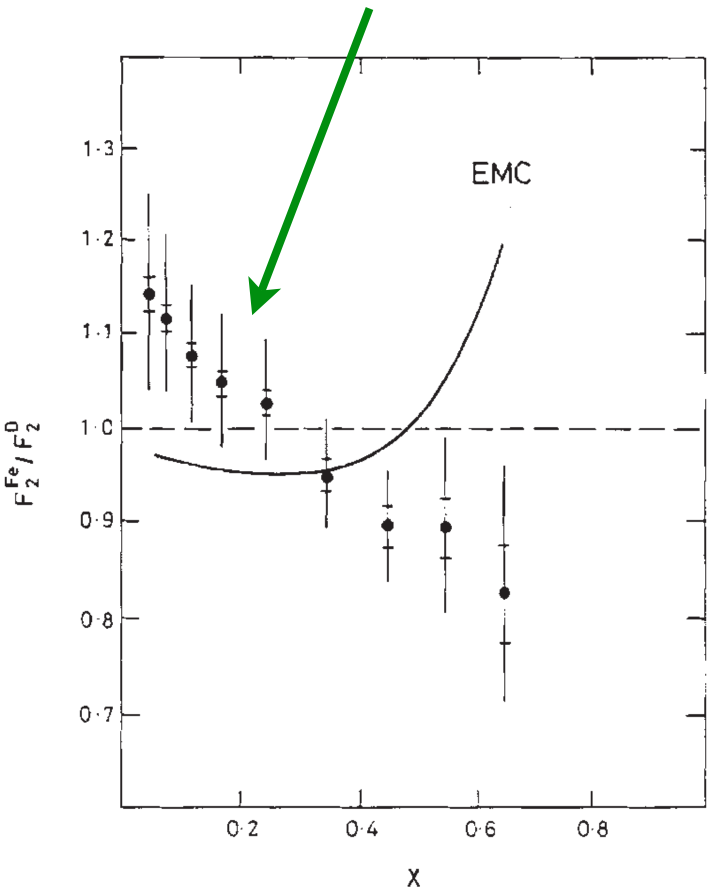
  → nuclear effects (nuclear binding, Fermi motion, shadowing) *obscure neutron structure* information

  → need to correct for "nuclear EMC effect"

Nuclear "EMC effect"

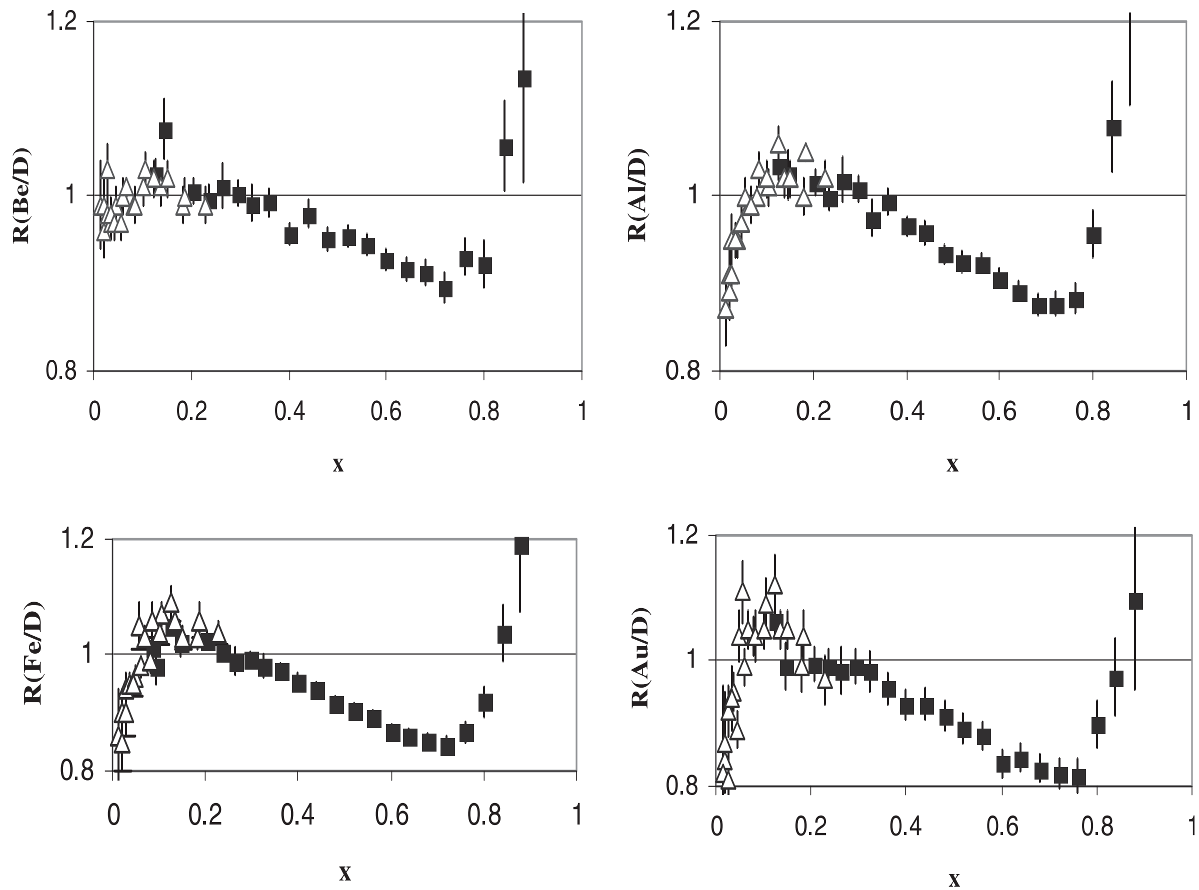
$$F_2^A(x, Q^2) \neq A F_2^N(x, Q^2)$$

Original EMC data



Aubert et al., Phys. Lett. B ***123*** *(1983) 123*

Later SLAC data



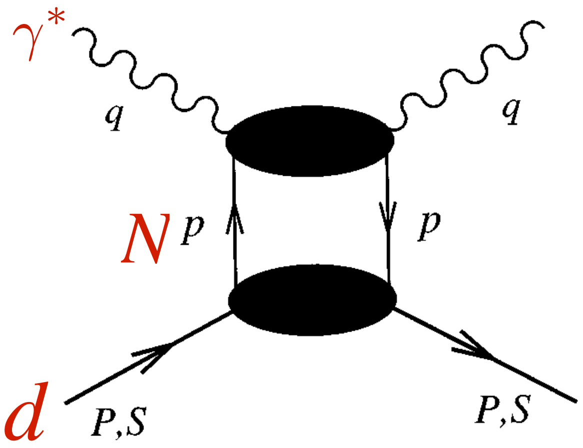
Gomez et al., Phys. Rev. D ***49*** *(1994) 4348*

Large x landscape:
nuclear effects in the deuteron

■ nuclear "impulse approximation"

→ incoherent scattering from individual nucleons in d

(good approx. at $x >> 0$)



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

$N=p+n$

nuclear "impulse approximation"

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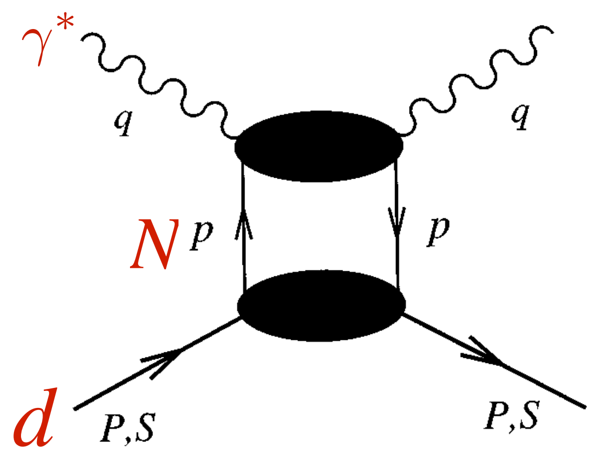


N=p+n

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

nucleon momentum distribution in d ("smearing function")

off-shell correction (~1%)

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

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

*Kulagin, WM, PRC **77**, 015210 (2008)*

N momentum distributions in d

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

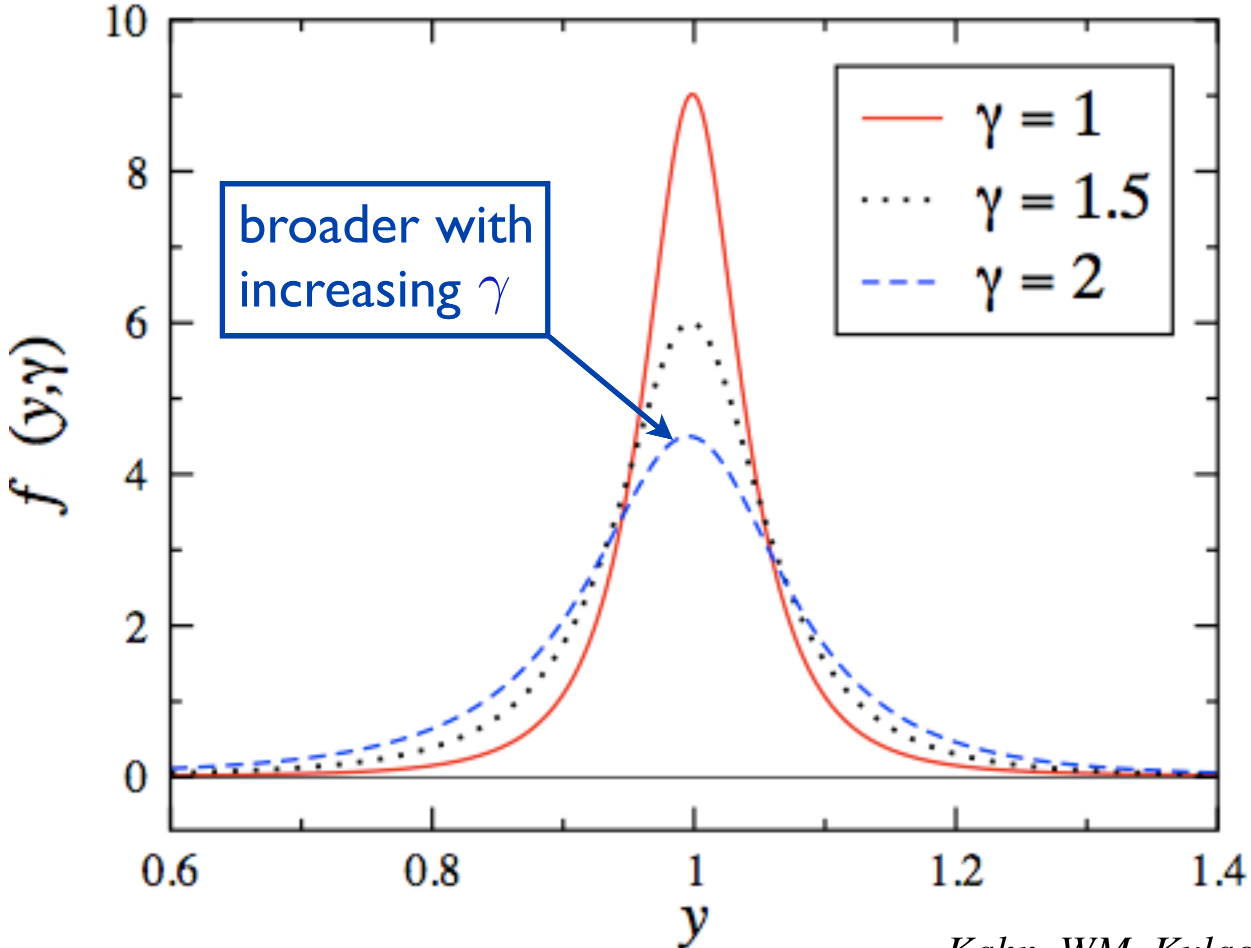
$$f(y,\gamma) = \int \frac{d^3p}{(2\pi)^3}\, |\psi_d(p)|^2\, \delta\Big(y - 1 - \frac{\varepsilon + \gamma p_z}{M}\Big)$$
$$\times \frac{1}{\gamma^2}\Big[1 + \frac{\gamma^2 - 1}{y^2}\Big(1 + \frac{2\varepsilon}{M} + \frac{\vec{p}^{\,2}}{2M^2}(1 - 3\hat{p}_z^2)\Big)\Big]$$

→ deuteron wave function $\psi_d(p)$

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

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

N momentum distributions in d



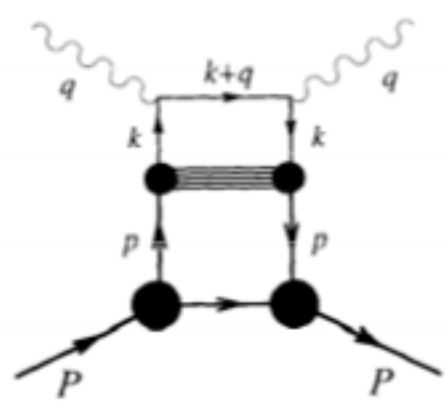
*Kahn, WM, Kulagin, PRC **79**, 035205 (2009)*

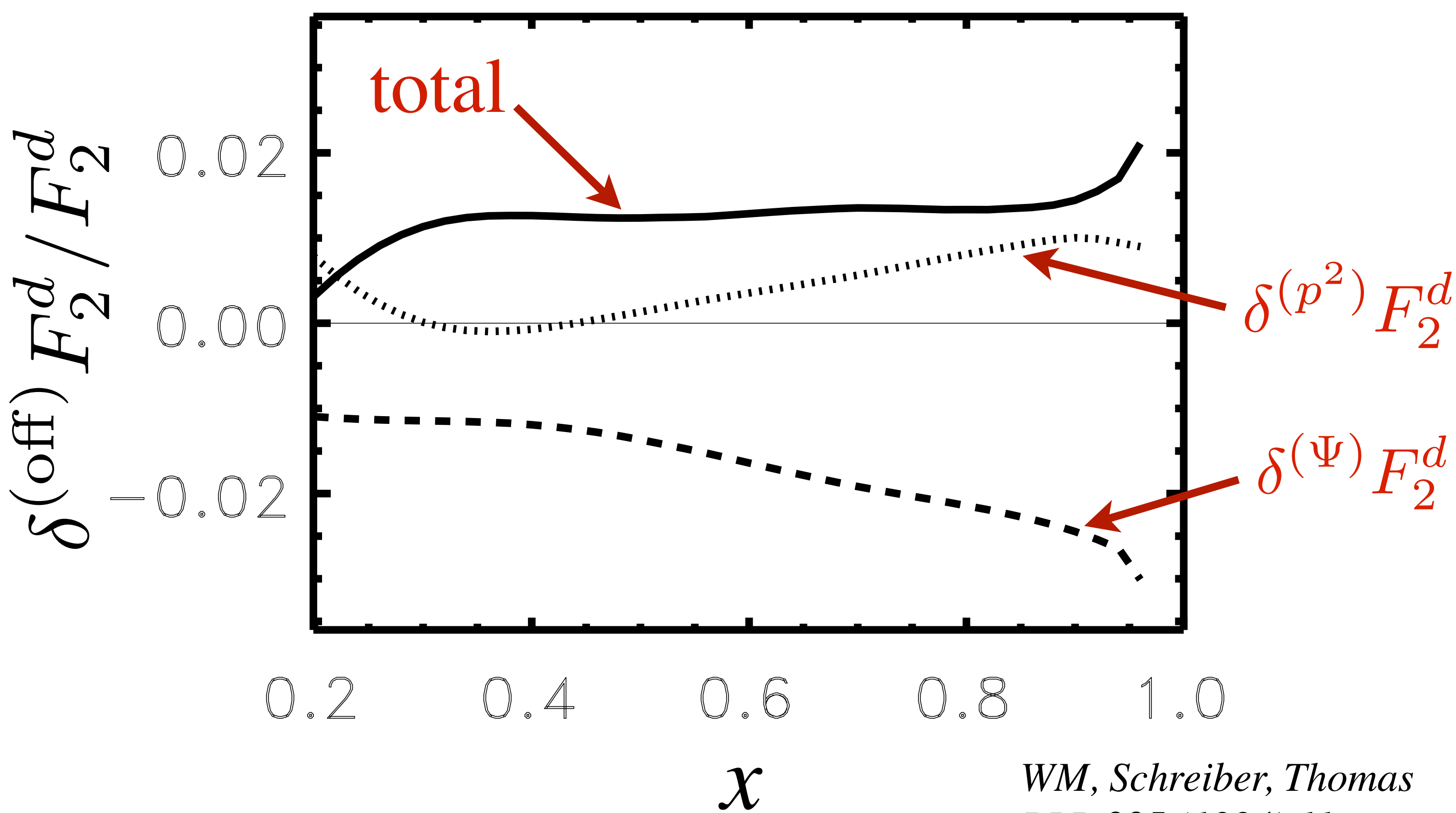
→ for most kinematics $\gamma \lesssim 2$

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

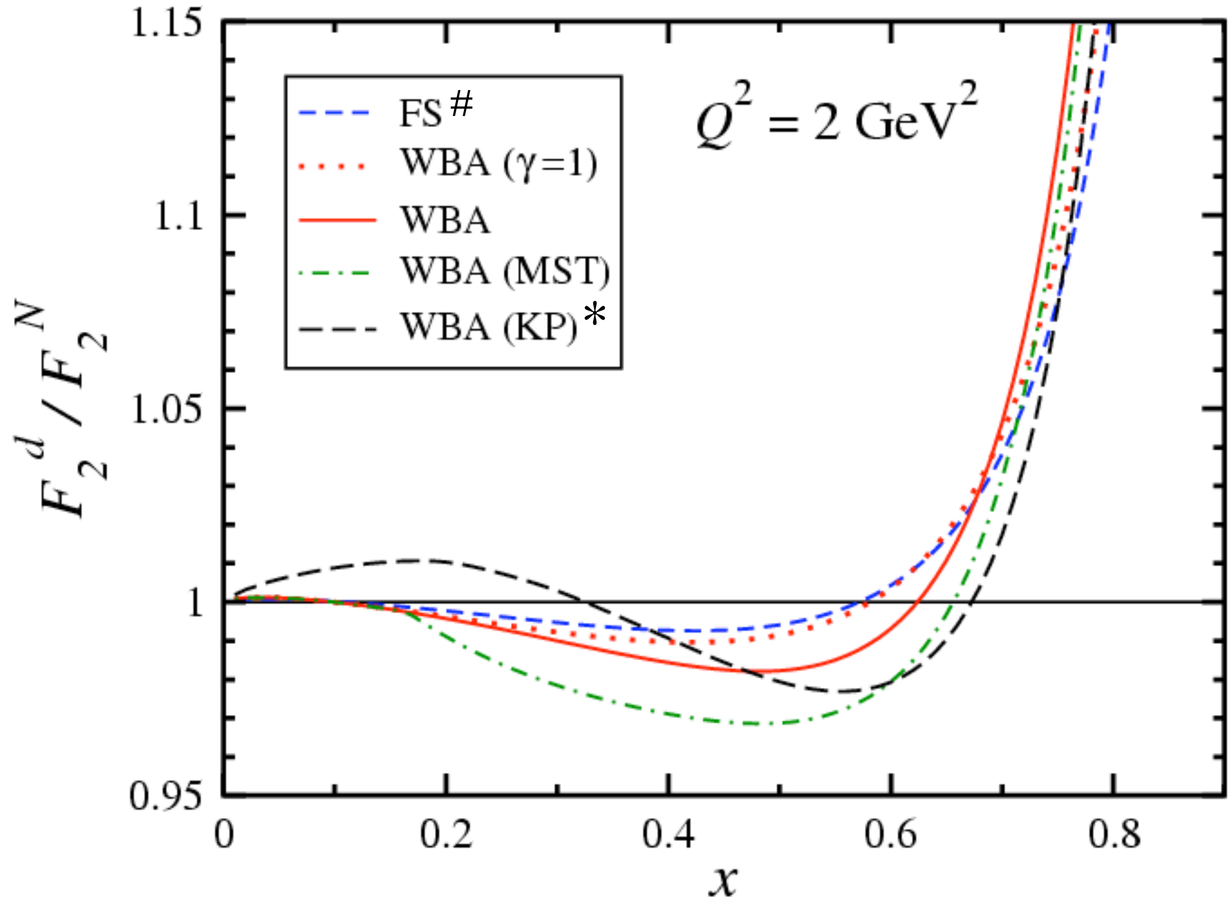




WM, Schreiber, Thomas
PLB ***335*** *(1994) 11*

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

EMC effect in deuteron



Frankfurt, Strikman light-cone model (no binding)

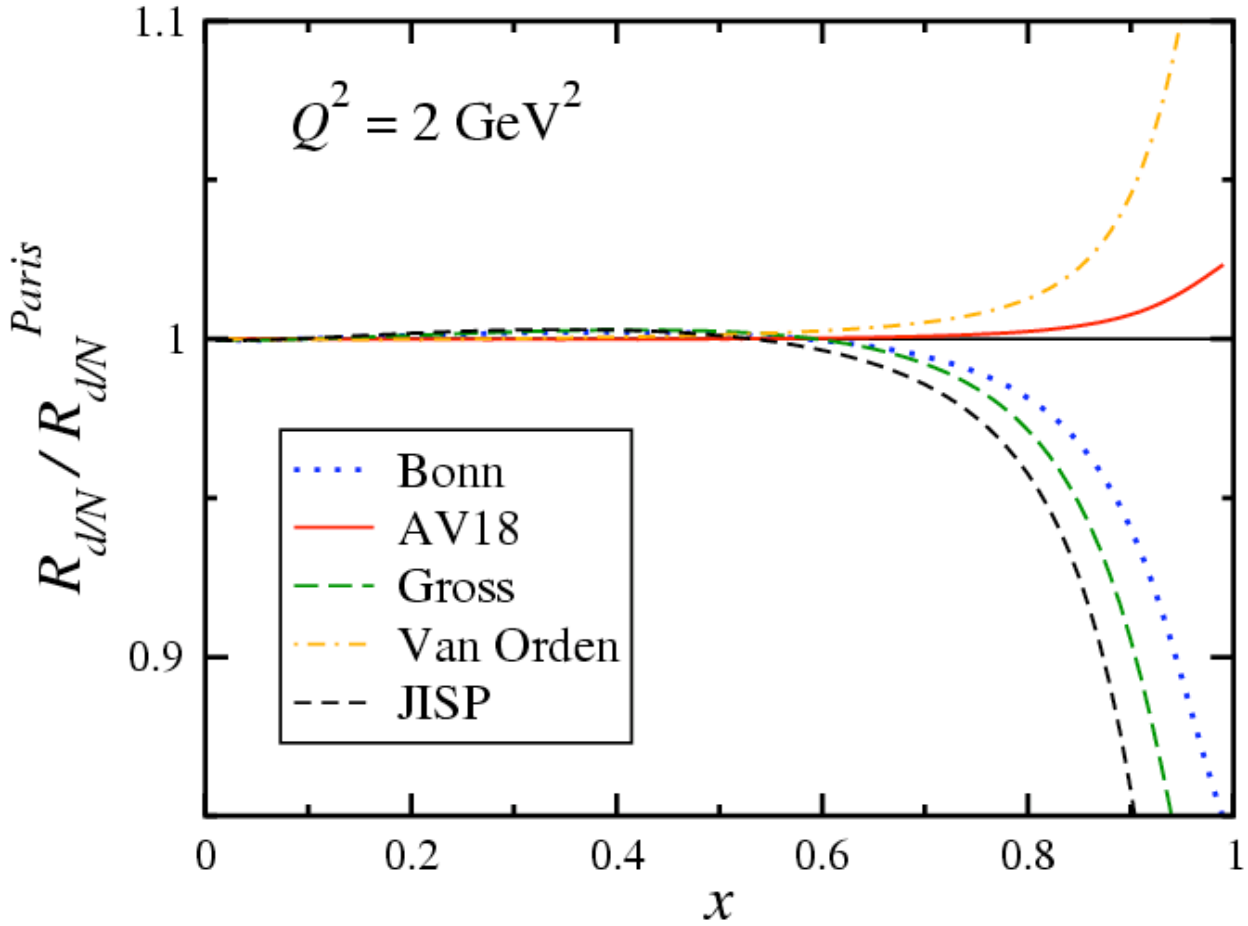
* *Kulagin, Petti NPA765 (2006)126*

→ larger EMC effect (smaller d/N ratio) at $x \sim 0.5–0.6$ with binding + off-shell corrections

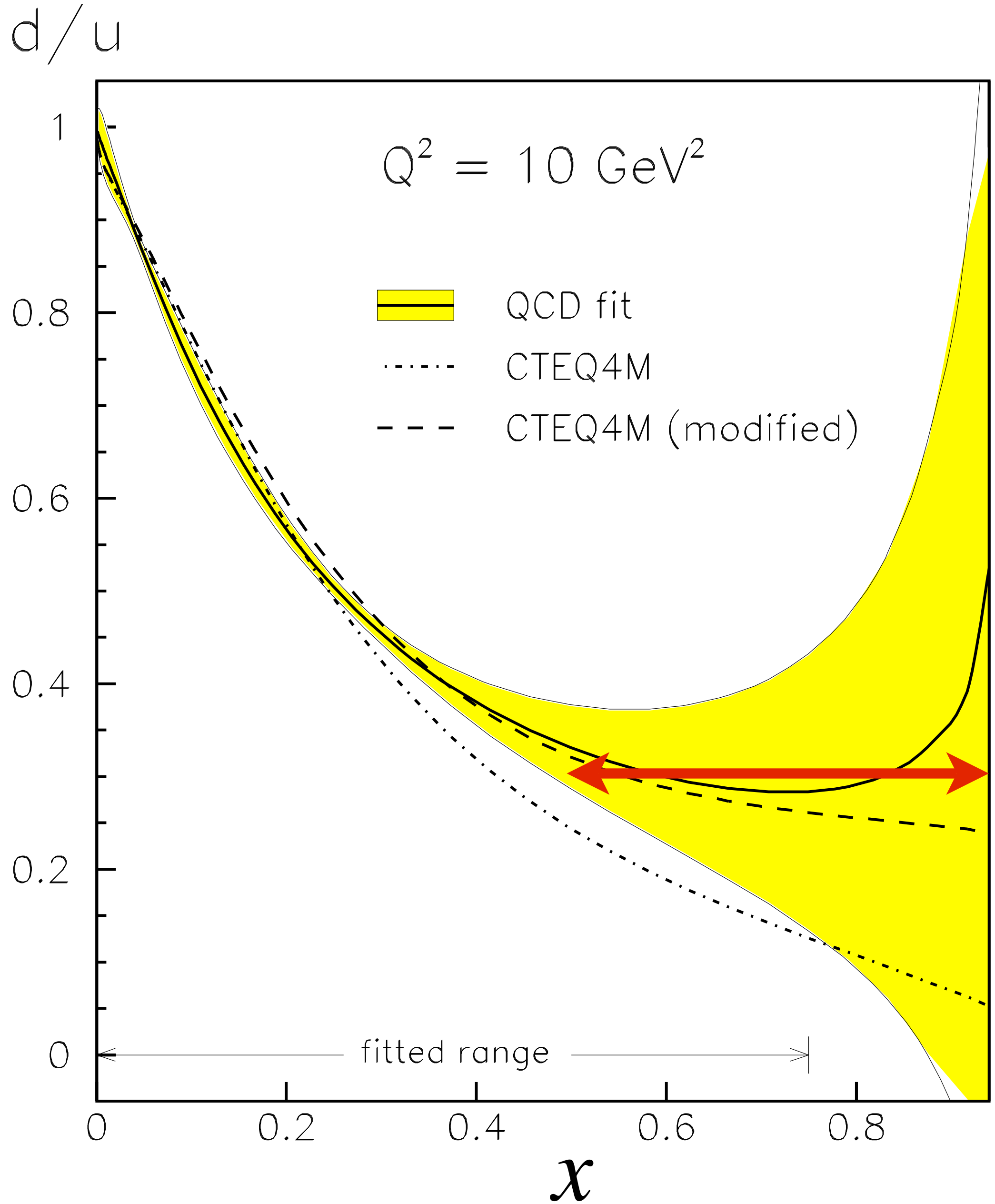
→ can significantly affect neutron extraction

EMC effect in deuteron

deuteron wave function dependence



→ mild dependence for $x < 0.8–0.85$



large uncertainty from nuclear effects in deuteron

(range of nuclear models*)

beyond $x \sim 0.5$

→ symmetry breaking mechanism remains unknown!

* most PDFs assume *no* nuclear corrections

Nuclear corrections

Either

- Extract F_2^n data points from F_2^d, F_2^p data;
  then use data in PDF fits

  → new extraction method developed which can reconstruct functions of arbitrary shape (in DIS and resonance regions)

*Kahn, WM, Kulagin, PRC **79** (2009) 035205*

Or

- Apply nuclear corrections to fitted PDFs;
  then compare with F_2^d data

  → in practice choose this method

Large x landscape:

target mass corrections

Target mass corrections

- Additional corrections from *kinematical* $Q^2/\nu^2 \sim M^2x^2/Q^2$ effects

  $\longrightarrow$ "target mass corrections" (TMC)

- Important at large x and low Q^2

  $\longrightarrow$ new "Nachtmann" scaling variable

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

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

Operator product expansion

→ expand product of currents in series of local operators

$$\int d^4x \; e^{iq\cdot x} \langle N | T(J^\mu(x) J^\nu(0)) | N \rangle$$

$$= \sum_k \left(-g^{\mu\nu} q^{\mu_1} q^{\mu_2} + g^{\mu\mu_1} q^\nu q^{\mu_2} + q^\mu q^{\mu_1} g^{\nu\mu_2} + g^{\mu\mu_1} g^{\nu\mu_2} Q^2 \right)$$

$$\times q^{\mu_3} \cdots q^{\mu_{2k}} \frac{2^{2k}}{Q^{4k}} \underbrace{A_{2k} \Pi_{\mu_1 \cdots \mu_{2k}}}_{\langle N | \mathcal{O}_{\mu_1 \cdots \mu_{2k}} | N \rangle}$$

local operators

$$\Pi_{\mu_1 \cdots \mu_{2k}} = p_{\mu_1} \cdots p_{\mu_{2k}} - (g_{\mu_i \mu_j} \text{ terms})$$

$$= \sum_{j=0}^{k} (-1)^j \frac{(2k-j)!}{2^j (2k)^j} g \cdots g \; p \cdots p$$

traceless, symmetric rank-$2k$ tensor

Georgi, Politzer (1976)

→ 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 (+ tedious manipulations)

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

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

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)

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

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avoids unphysical $x > 1$ region

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avoids unphysical $x > 1$ region

→ at leading order

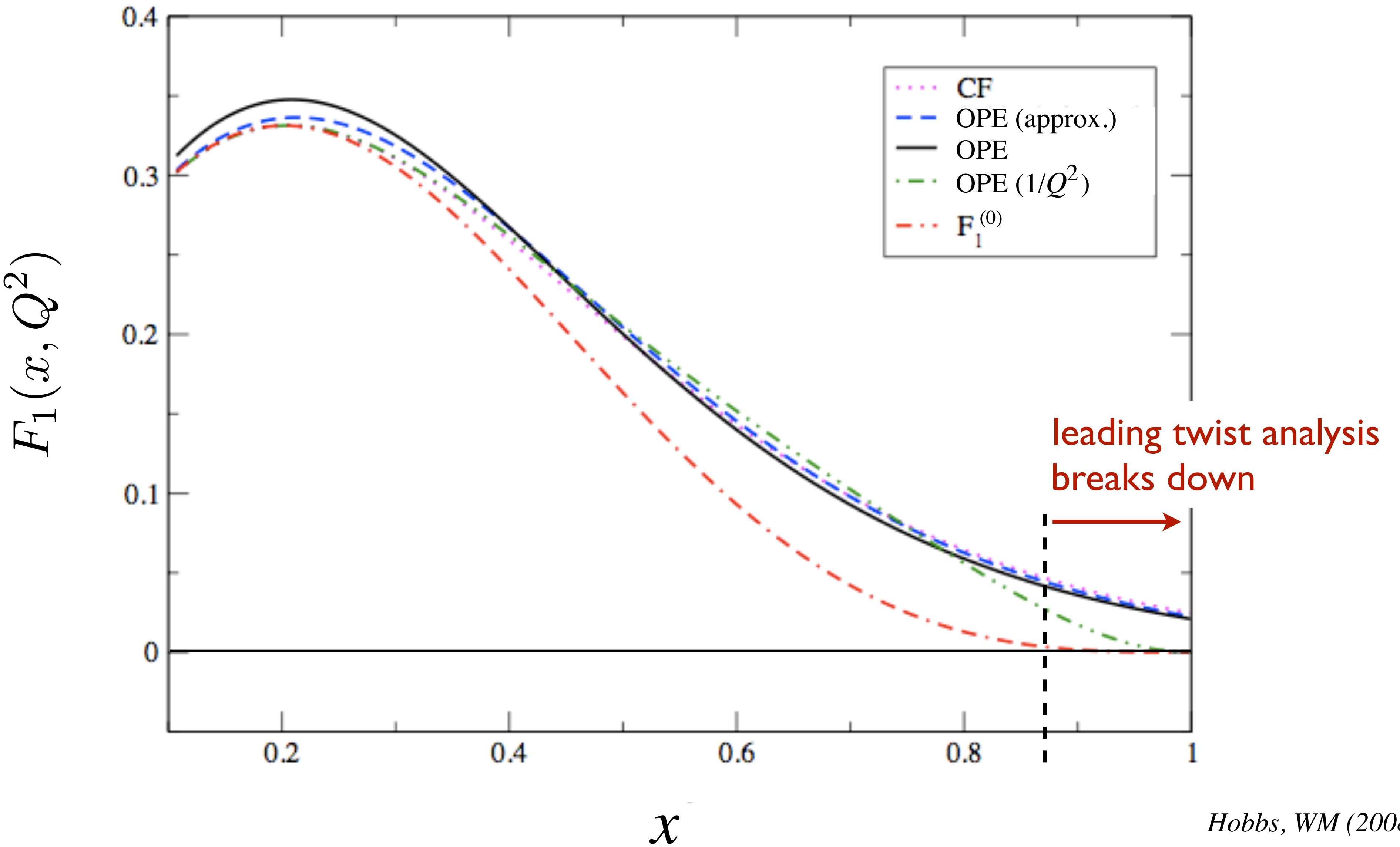
$$F_2^{\rm CF}(x,Q^2) = \frac{x}{\xi\gamma^2}\, F_2^{(0)}(\xi,Q^2)$$

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

Kretzer, Reno (2004)
Accardi, Qiu (2008)

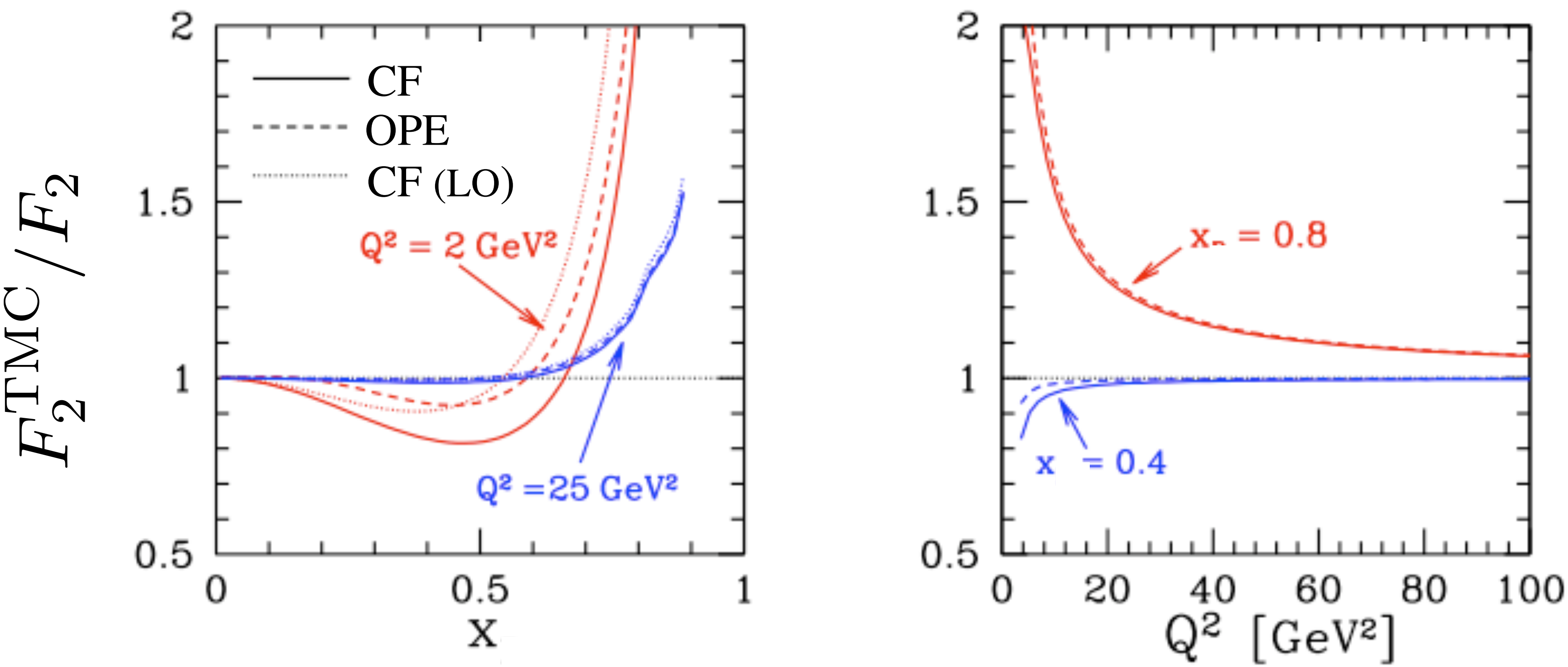
Target mass corrections

prescription dependence



Hobbs, WM (2008)

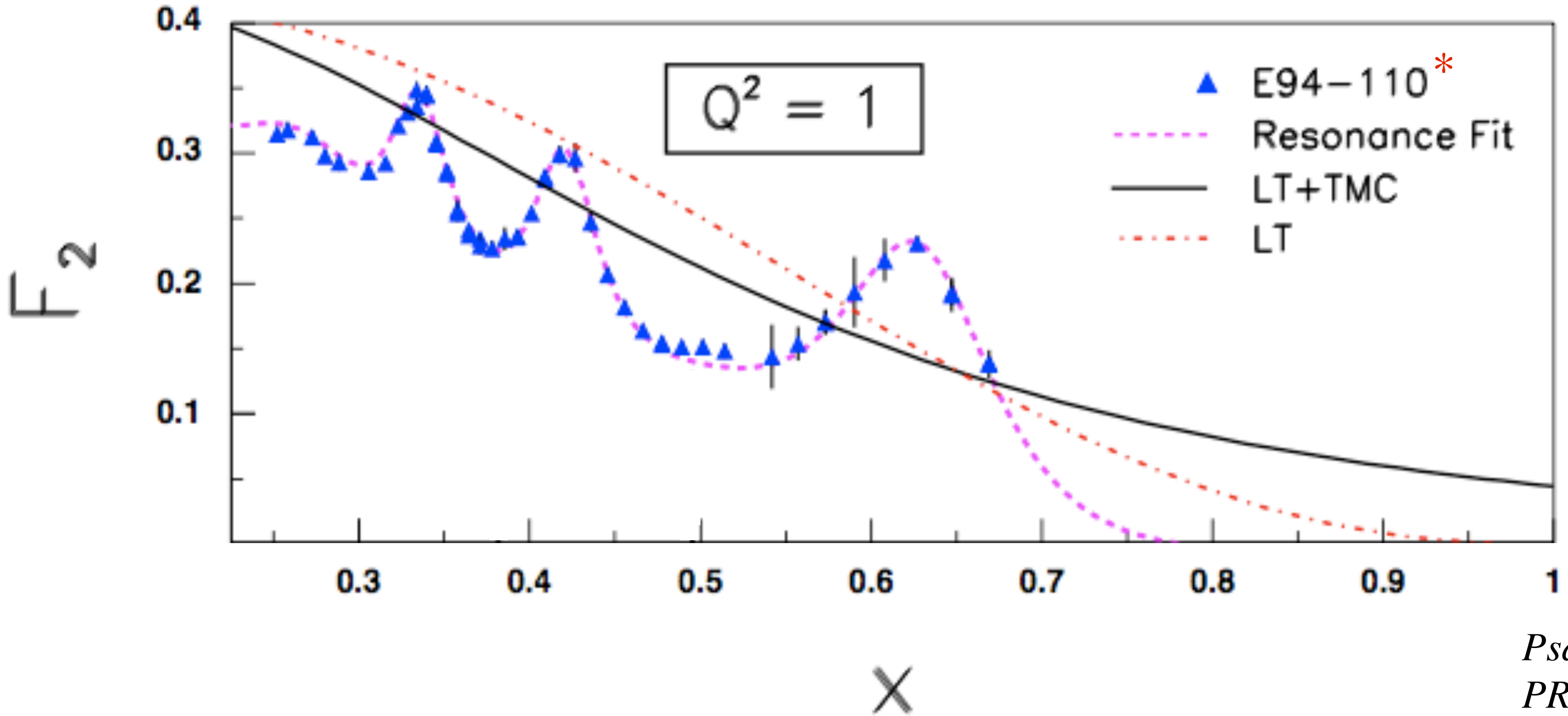
Target mass corrections



Accardi & Qiu,
JHEP ***0807*** *(2008) 090*

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

Target mass corrections



* JLab Hall C

Psaker, WM, et al., PRC 78 (2008) 025206

→ TMC important for verification of quark-hadron duality

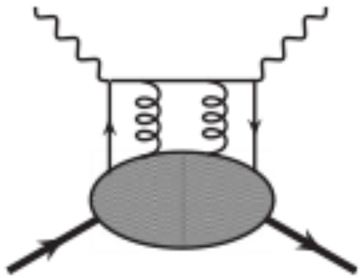
Higher twists

- $1/Q^2$ 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 q-g 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”)

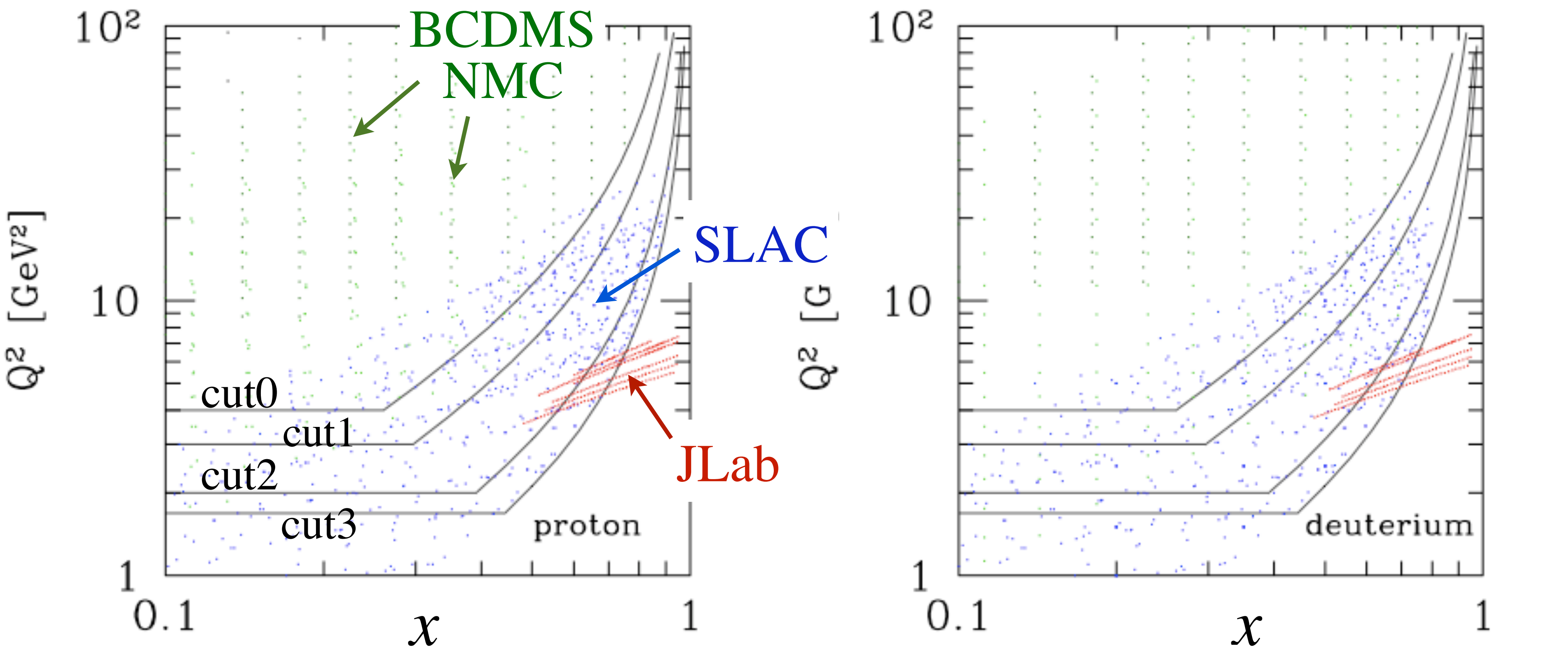
[with Accardi, Christy,*Keppel, Monaghan, Morfin,*Owens]

Global questions

- Can one obtain stable fits including low-Q^2, low-W data?
  - $\longrightarrow$ how do large-x data affect PDFs?
  - $\longrightarrow$ to what extent can uncertainties be reduced?
- Are subleading, $1/Q^2$ corrections under control?
  - $\longrightarrow$ how large are higher twists?
- How do nuclear corrections affect d/u ratio?
  - $\longrightarrow$ what uncertainties do nuclear effects introduce?

➡ New analysis of proton & deuteron data includes effects of Q^2/W *cuts*, *TMCs*, *higher twists*, *nuclear corrections*

Kinematic cuts



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

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

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

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

Data points

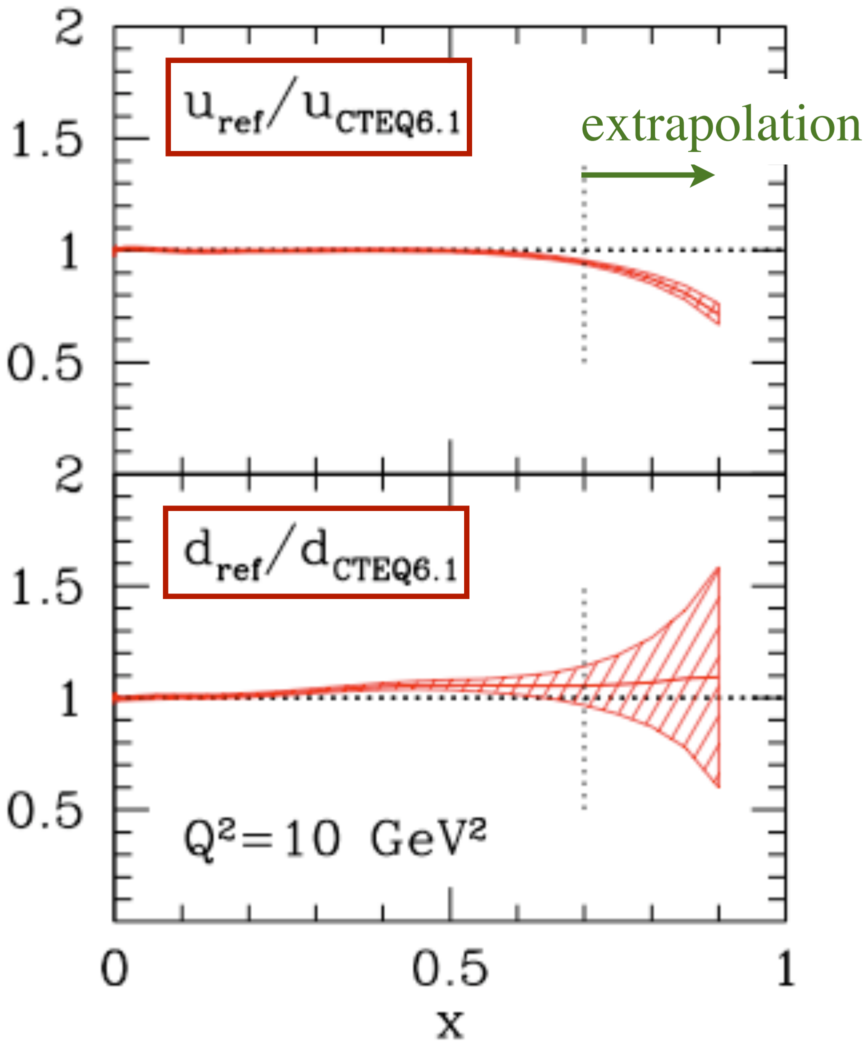
factor 2 increase from cut0 $\longrightarrow$ cut3

		Total		Deuterium		
		cut0	cut3	cut0	cut3	CTEQ6.1
DIS	JLab*#	–	272	–	136	
	SLAC	206	1147	104	582	√
	NMC	324	464	123	189	√
	BCDMS	590	605	251	254	√
	H1	230	351	–	–	√
	ZEUS	229	240			√
DY	E605	119				√
	E866#	375		191		
W asymmetry	CDF '98 (ℓ)	10		–		√
	CDF '05 (ℓ)#	11				
	D0 '08 (ℓ)#	10		–		
	D0 '08 (e)#	12		–		
	CDF '09 (W)#	13				
jet	CDF	33				√
	D0	90		–		√
γ+jet	D0#	56		–		

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

\# new data not included in CTEQ6.1

Effect of new data on “standard” fits



→ “cut0” (as in CTEQ6.1)

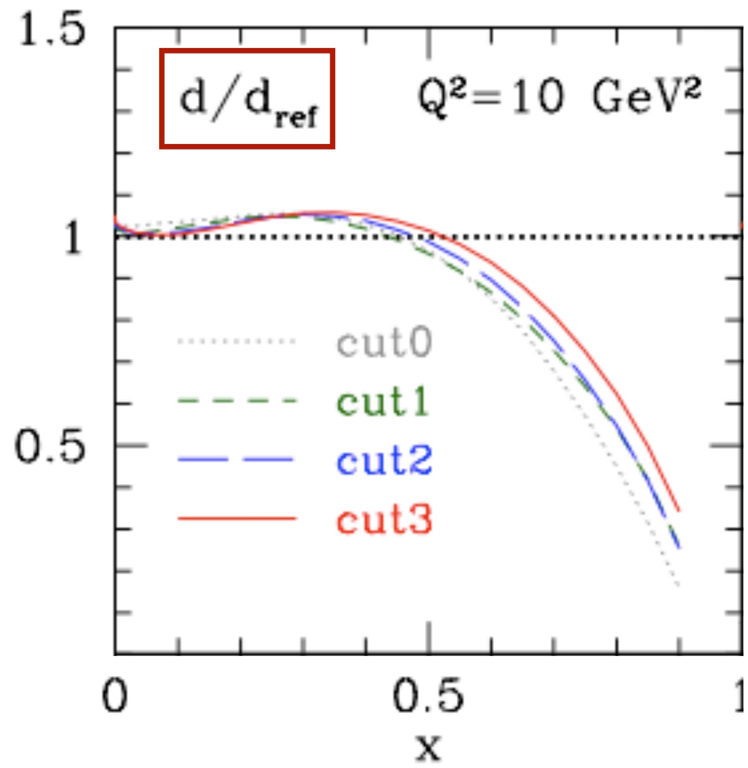
→ no nuclear or $1/Q^2$ corrections

→ no significant effect in measured region

→ u suppression mainly due to E866 DY data

Effect of Q^2 & W cuts

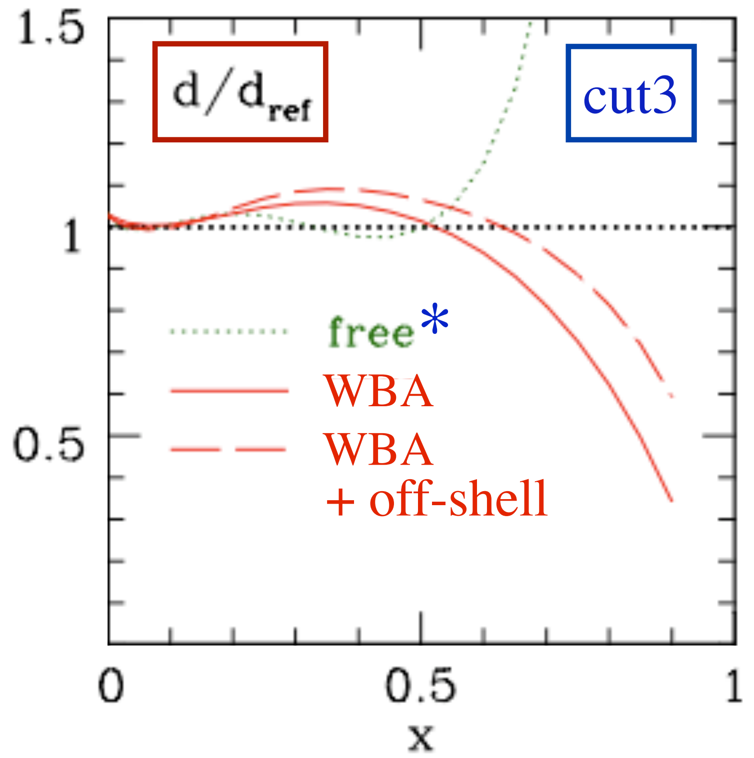
- Systematically reduce Q^2 and W cuts
- Fit includes TMCs (CF), HT term, nuclear corrections (WBA)



→ d suppressed by $\sim 50\%$ for $x > 0.5$

→ driven mostly by nuclear corrections

Effect of nuclear corrections

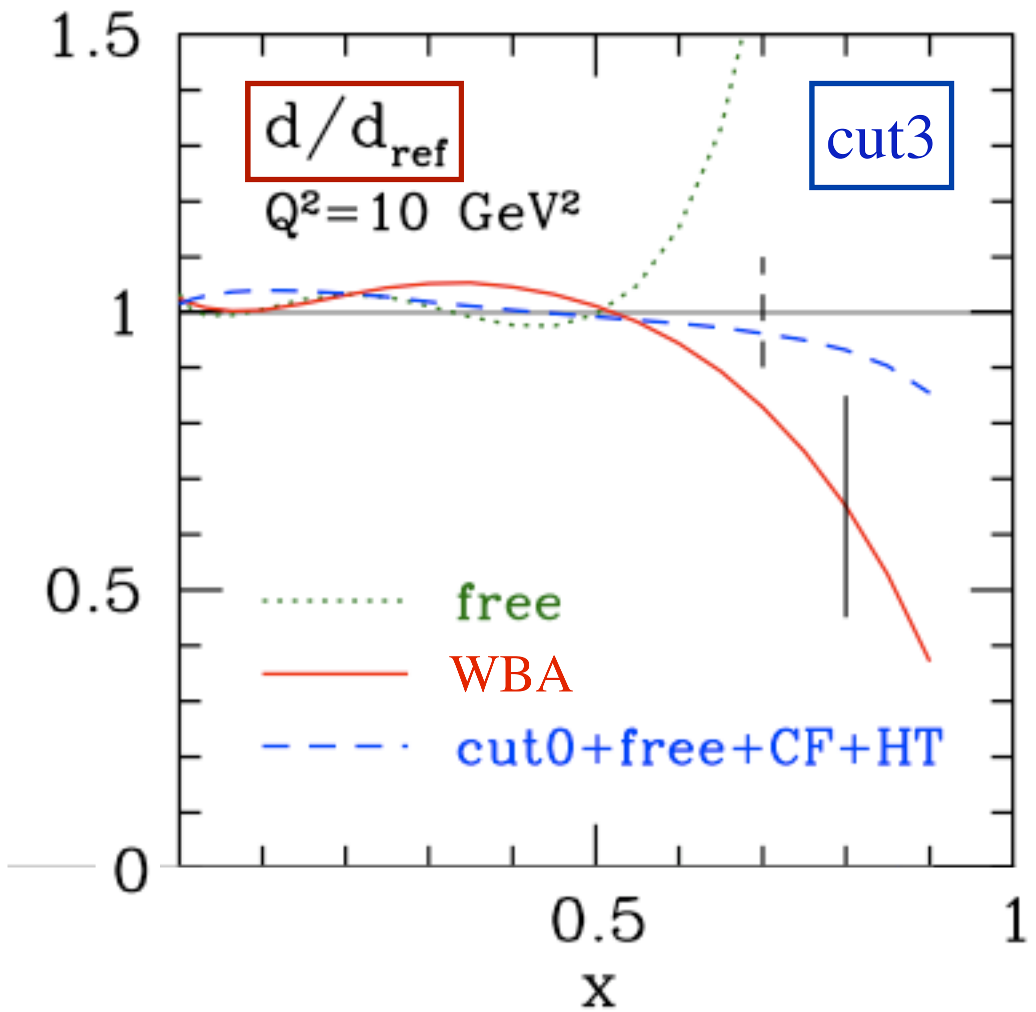


* assumes $F_2^d = F_2^p + F_2^n$ as in CTEQ6.1 and most other global fits

→ dramatic effect of nuclear corrections:
decrease in d distribution for $x > 0.6$

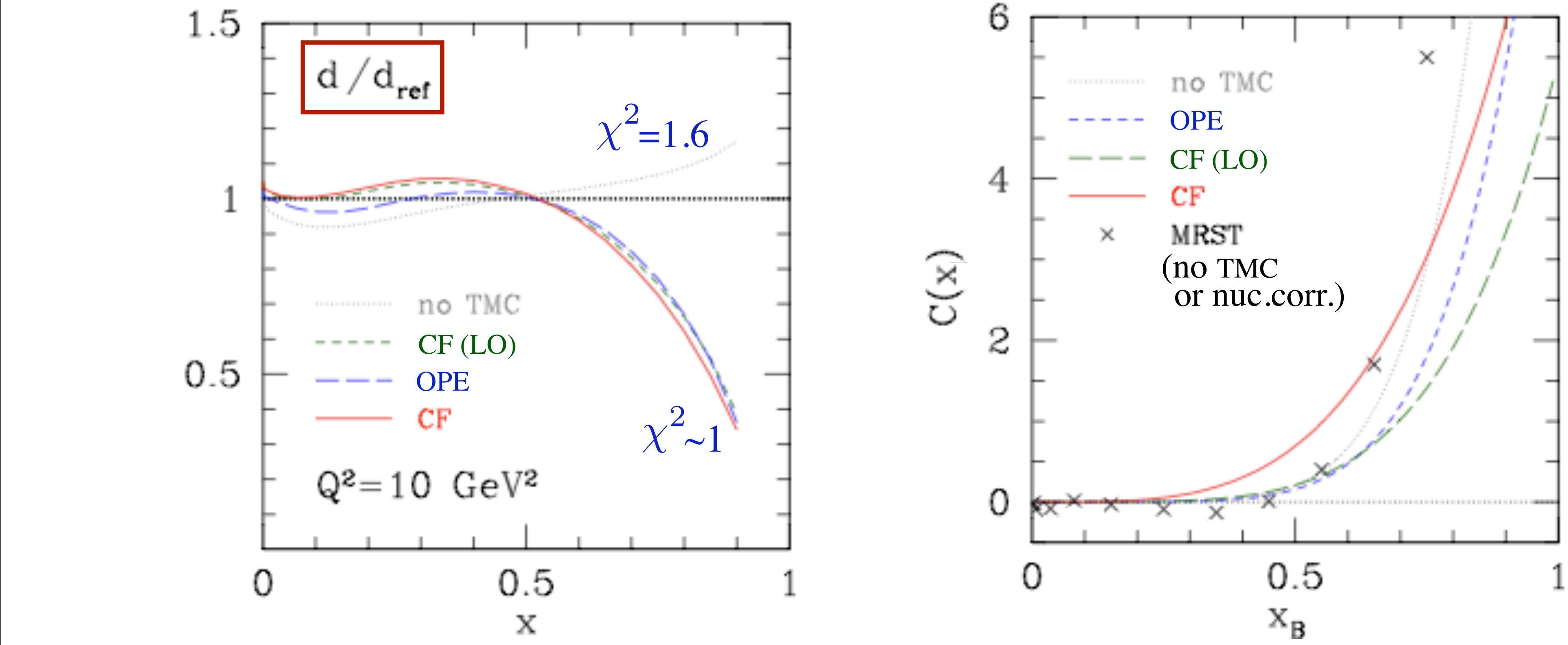
→ modest increase with (additive) off-shell correction
(since EMC ratio has deeper "trough")

Effect of nuclear corrections



→ rise in "free" curve appears to result from enlarged data set

Effect of $1/Q^2$ corrections



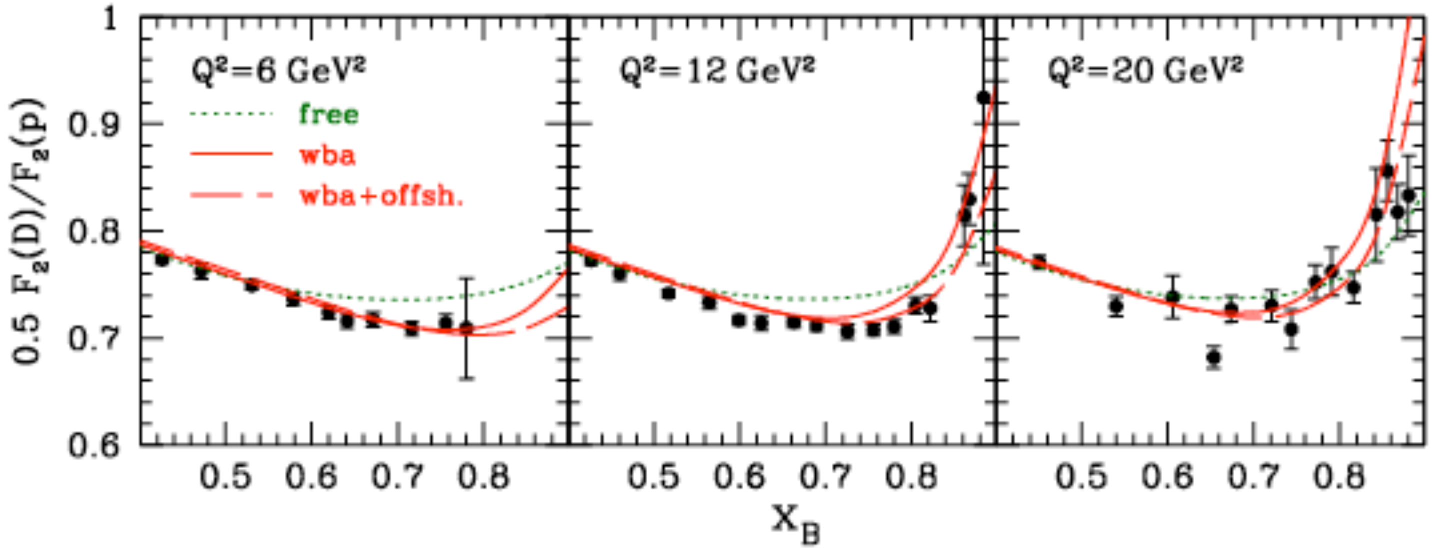
→ $1/Q^2$ HT coefficient parametrized as $C(x) = c_1 x^{c_2}(1 + c_3 x)$

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

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

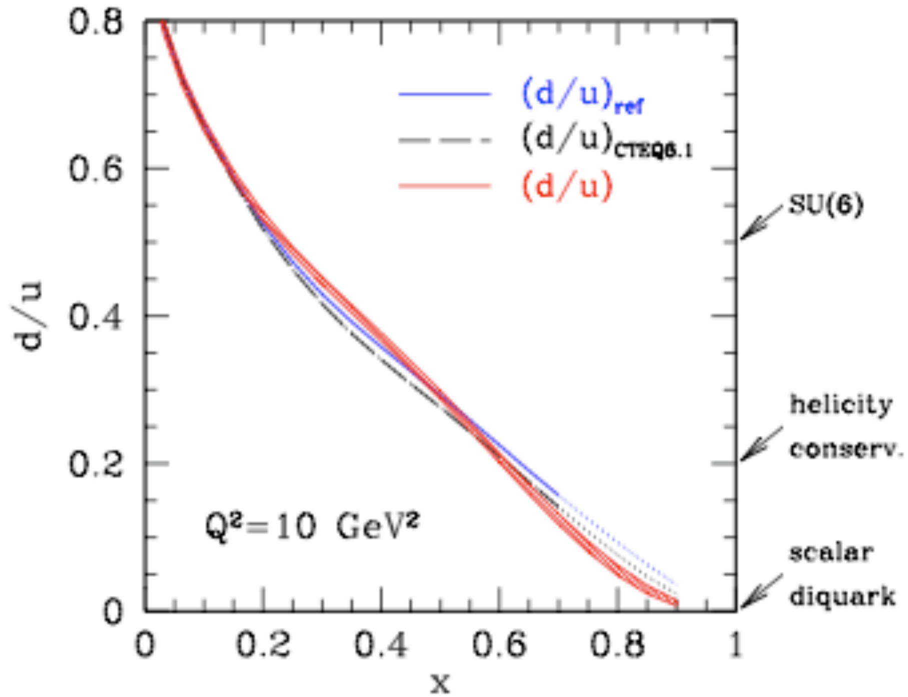
Deuteron / proton ratio

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



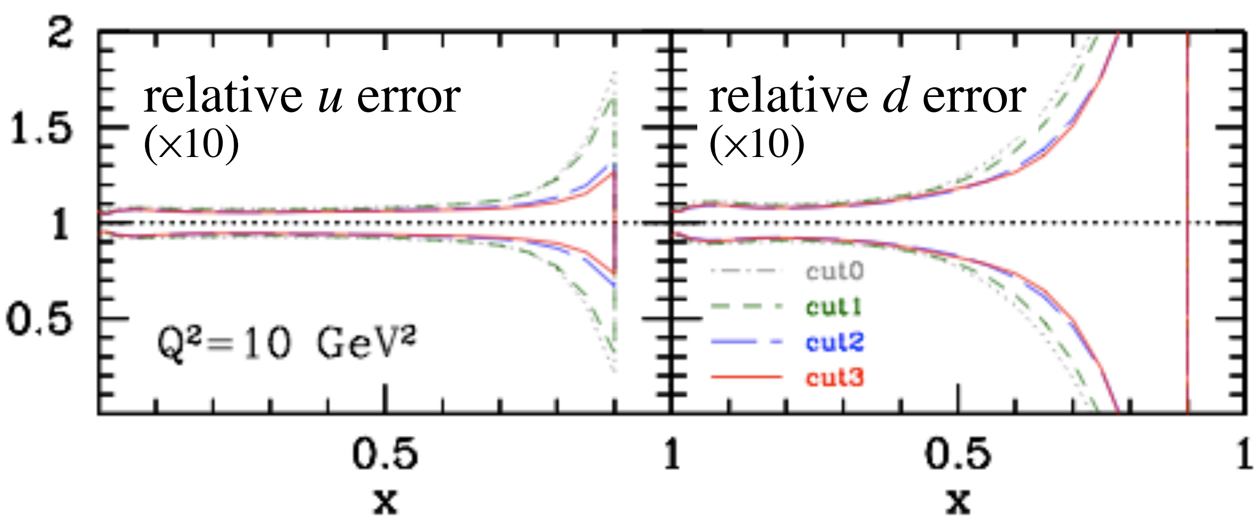
→ fits without nuclear corrections overestimate data at intermediate x, do not reproduce rise at large x

d/u PDF ratio



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

→ dominance of nonperturbative physics?



→ reduced errors with weaker cuts

Future constraints from experiment

"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
  $\longrightarrow$ difficult to get high rates/luminosities

^{3}He–^{3}H mirror nuclei

- EMC ratios for A=3 mirror nuclei

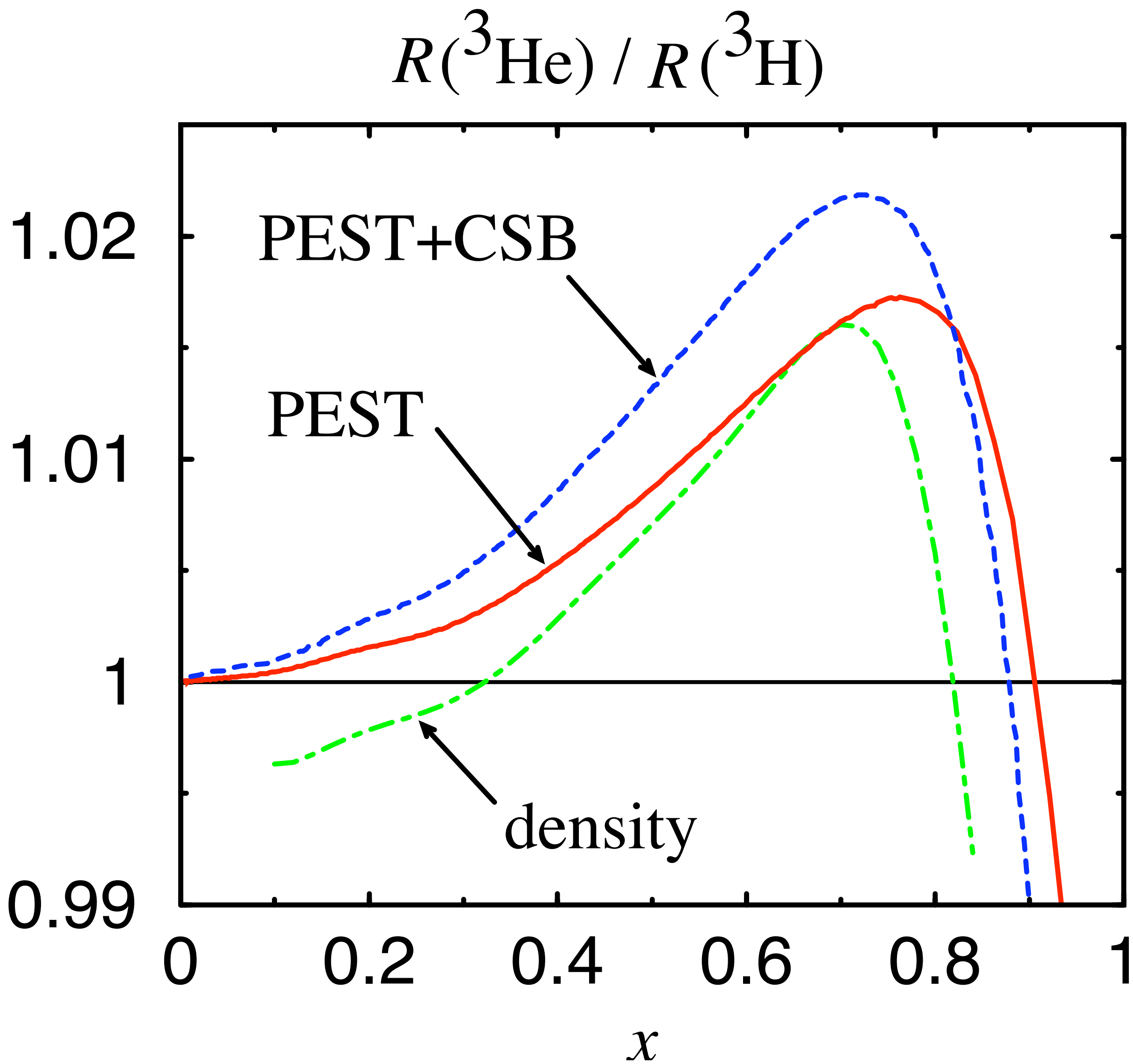
$$R(^3\text{He}) = \frac{F_2^{^3\text{He}}}{2F_2^p + F_2^n}$$

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

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

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

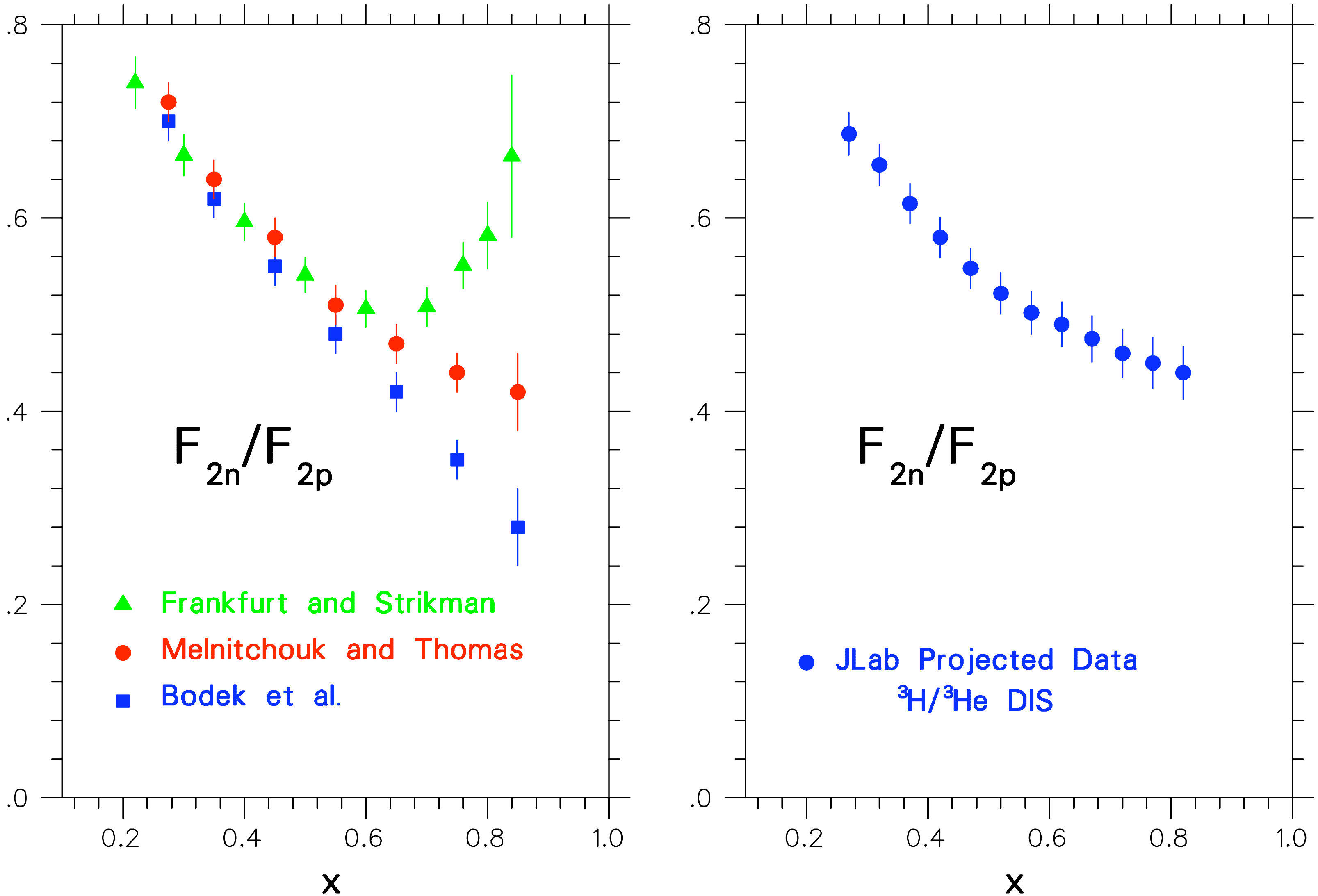
^{3}He–^{3}H mirror nuclei



Afnan et al., *PRC* ***68*** *(2003) 035201*

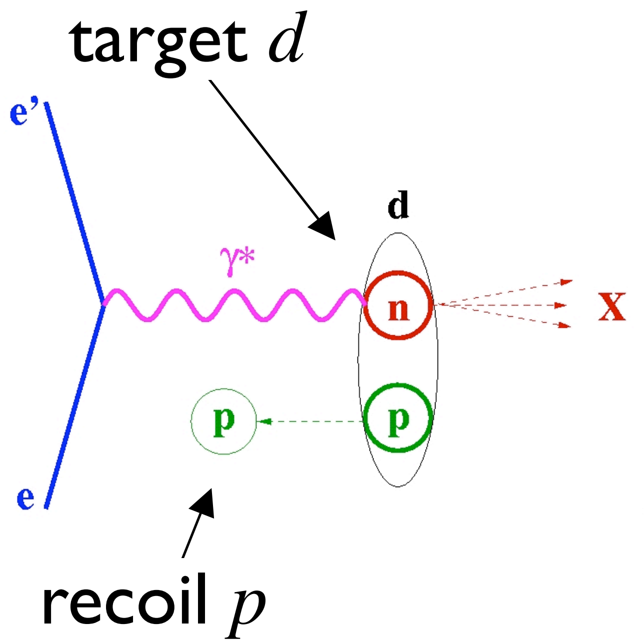
→ nuclear effects cancel to < 1% level

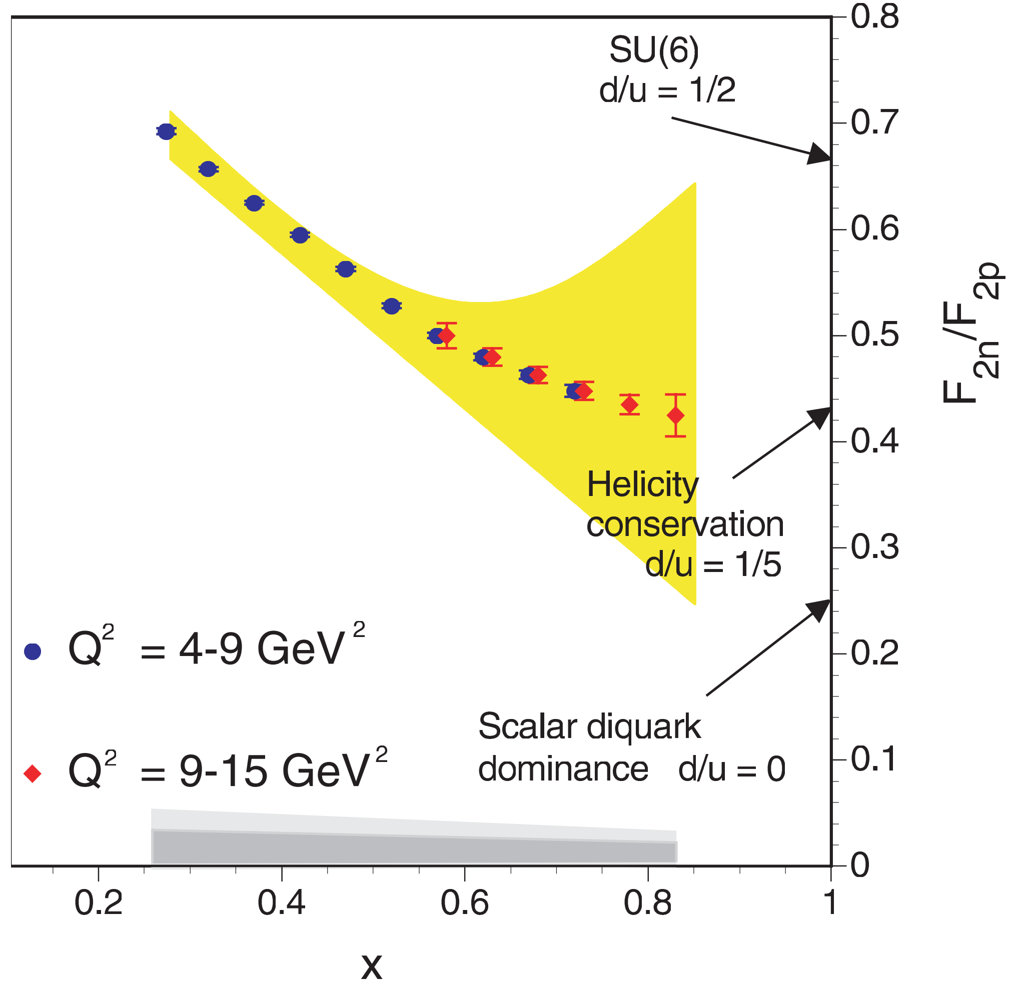
^3He–^3H mirror nuclei



Spectator proton tagging

$$e\ d \rightarrow e\ p\ X$$





slow backward p

→ neutron nearly on-shell

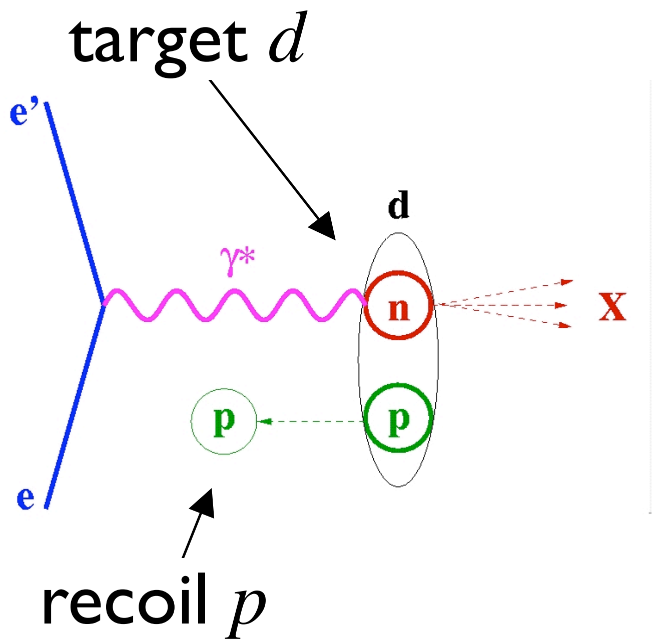
→ minimize rescattering

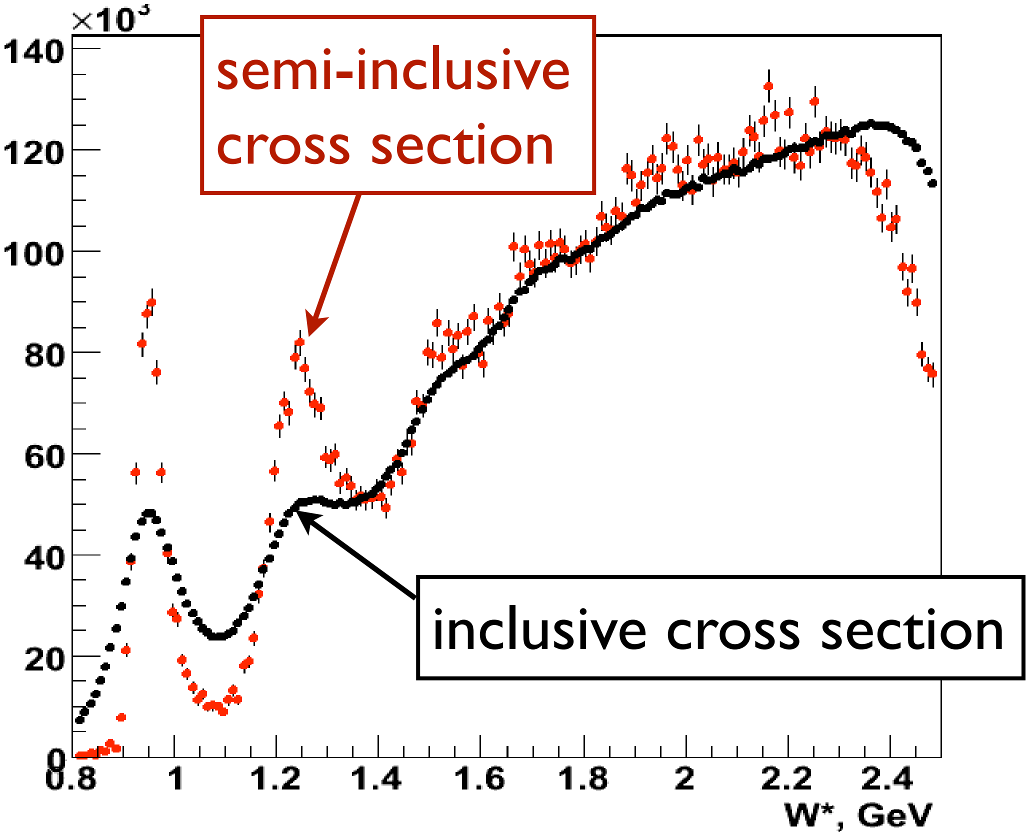
JLab Hall B experiment ("BONUS")

run completed Dec. 2005

Spectator proton tagging

$$e\ d \rightarrow e\ p\ X$$





slow backward p

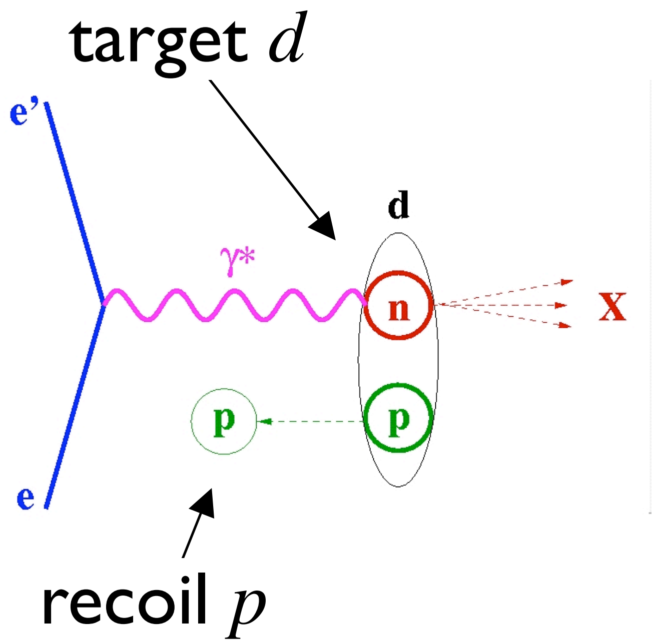
→ neutron nearly on-shell

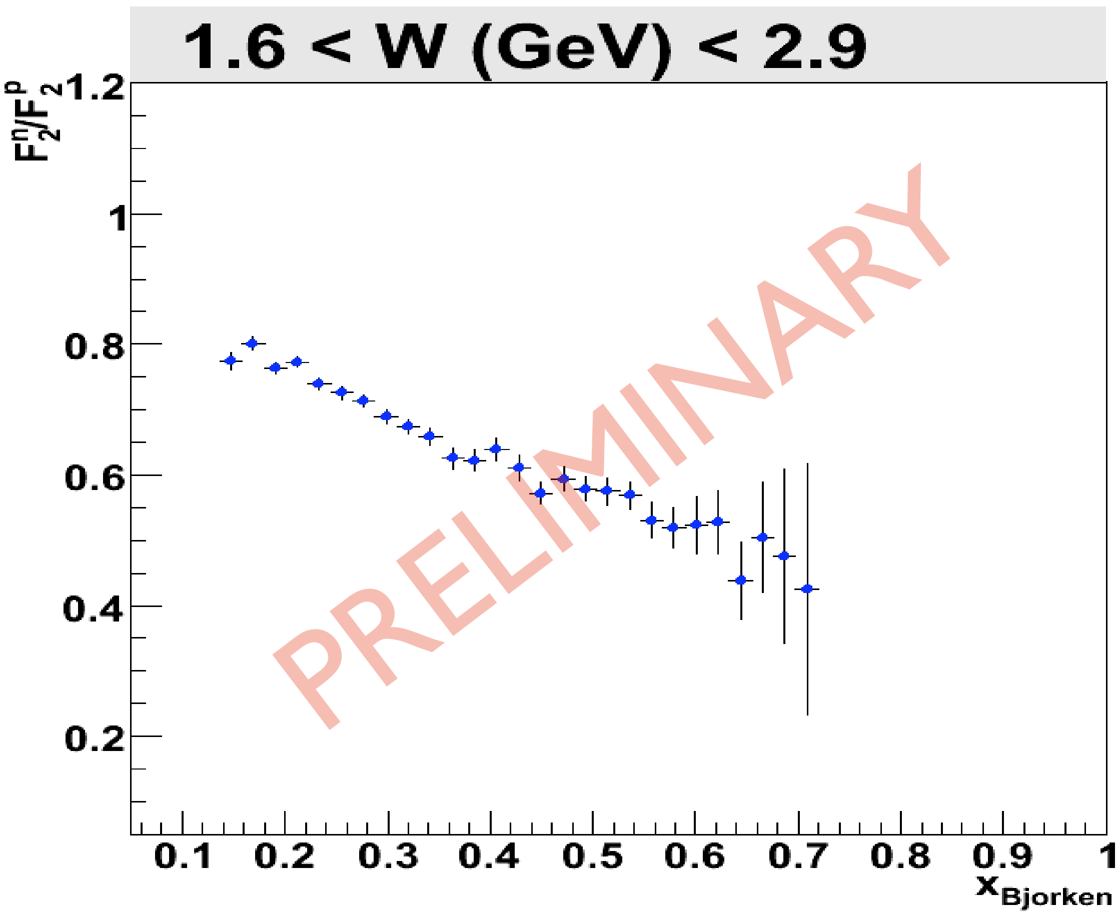
→ minimize rescattering

→ more pronounced neutron resonance structure visible

Spectator proton tagging

$$e\ d \rightarrow e\ p\ X$$





slow backward p

→ neutron nearly on-shell

→ minimize rescattering

→ first "proof of principle" data

→ extend to $x \sim 0.85$ after 12 GeV Upgrade

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

  → opens door to study of quark structure of nucleon over large kinematic domain

  → readily accommodate new data (*e.g.* BONUS)

- Results suggest small d/u ratio up to $x \sim 0.85$

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  - → opens door to study of quark structure of nucleon over large kinematic domain
  - → readily accommodate new data (*e.g.* BONUS)
- Results suggest small d/u ratio up to $x \sim 0.85$
- Additional effects to consider: large-x *resummation* (pQCD), *jet mass* corrections, quark-hadron *duality* (reduce cuts further)
- Extend analysis to *spin-dependent* PDFs

The End