11th CTEQ Summer School on QCD Analysis and Phenomenology
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Models of the Nucleon & Parton Distribution Functions

Wally Melnitchouk

Jefferson Lab

Outline

- Introduction
- Phenomenological PDFs
  - *large x - valence quarks, nuclear EMC effect*
  - *small x - sea quarks, nuclear shadowing*
- Connection with low energy models
- PDFs from lattice QCD
  - *moments*
  - *x dependence*
- Outlook

1.
Introduction

Looking for quarks in the nucleon
is like looking for the Mafia in Sicily -
everybody *knows* they're there,
but it's hard to find the evidence!

Anonymous

"QUARKS. NEUTRINOS. MESONS. ALL THOSE DAMN PARTICLES YOU CAN'T SEE. THAT'S WHAT DROVE ME TO DRINK. BUT NOW I CAN SEE THEM."

Why is (accurate) knowledge of PDFs important?

- PDFs provide basic information on structure of bound states in QCD
  - DIS paved way for development of QCD
- Integrals of PDFs (moments) test fundamental sum rules (Adler, GLS, Bjorken, ...)
- Provide input into nuclear physics (relativistic heavy ion collisions) and astrophysics calculations
- Needed to understand backgrounds in searches for "new physics" in high-energy colliders

Factorization of structure functions

$$F(x,Q^2) \; = \sum_i \int dz \; C_i(x/z, Q^2/\mu^2, \alpha_s(\mu^2)) \; f_i(z, \alpha_s(\mu^2))$$

Wilson coefficient — PDF

- PDFs embody nonperturbative (long-range) structure of nucleon
  - cannot calculate from pQCD
- Calculated from low-energy models
  - evolved to larger Q via DGLAP
- Computed on the lattice
  - moments only, reconstruct PDF

2.
Phenomenological PDFs

Phenomenological PDFs

- PDFs extracted in global pQCD (NLO) analyses of data from e.m. & neutrino DIS, Drell-Yan & W-boson production in hadronic collisions ...
- Parameterized using some functional form, e.g.

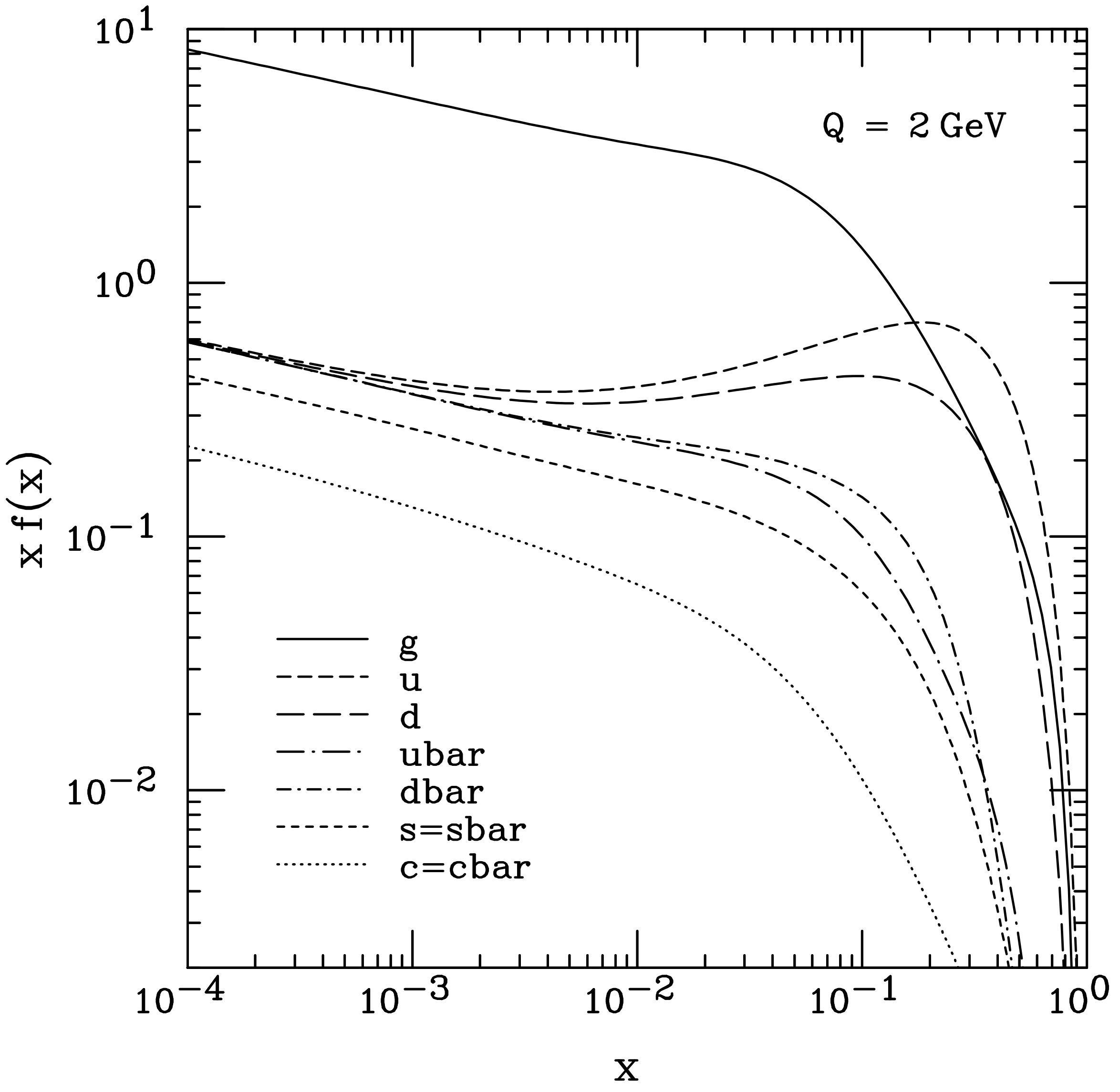
$$xf(x,\mu^2) = A_0 x^{A_1}(1-x)^{A_2} e^{A_3 x}(1+e^{A_4}x)^{A_5}$$

⇨ determined over several orders of magnitude in x and Q^2

$$10^{-6} < x < 1$$

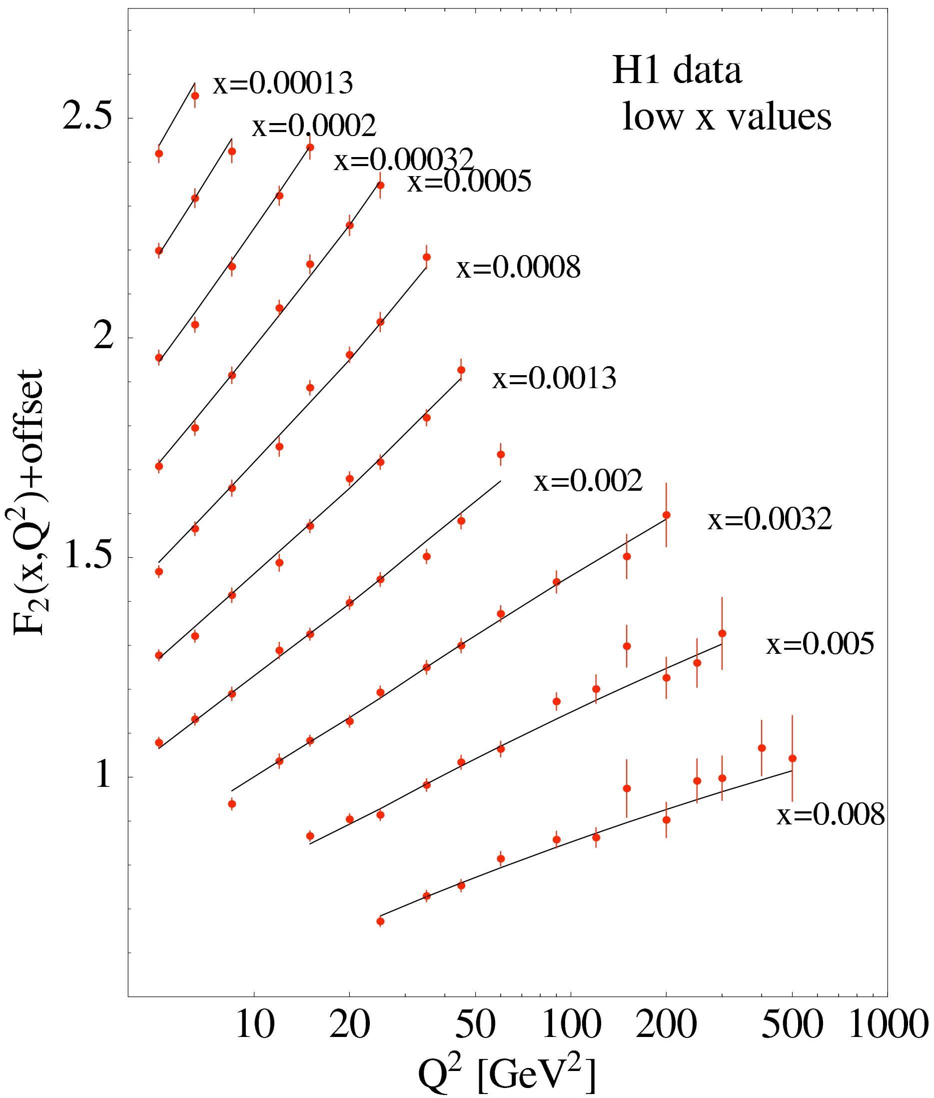
$$1 < Q^2 < 10^8 \text{ GeV}^2$$

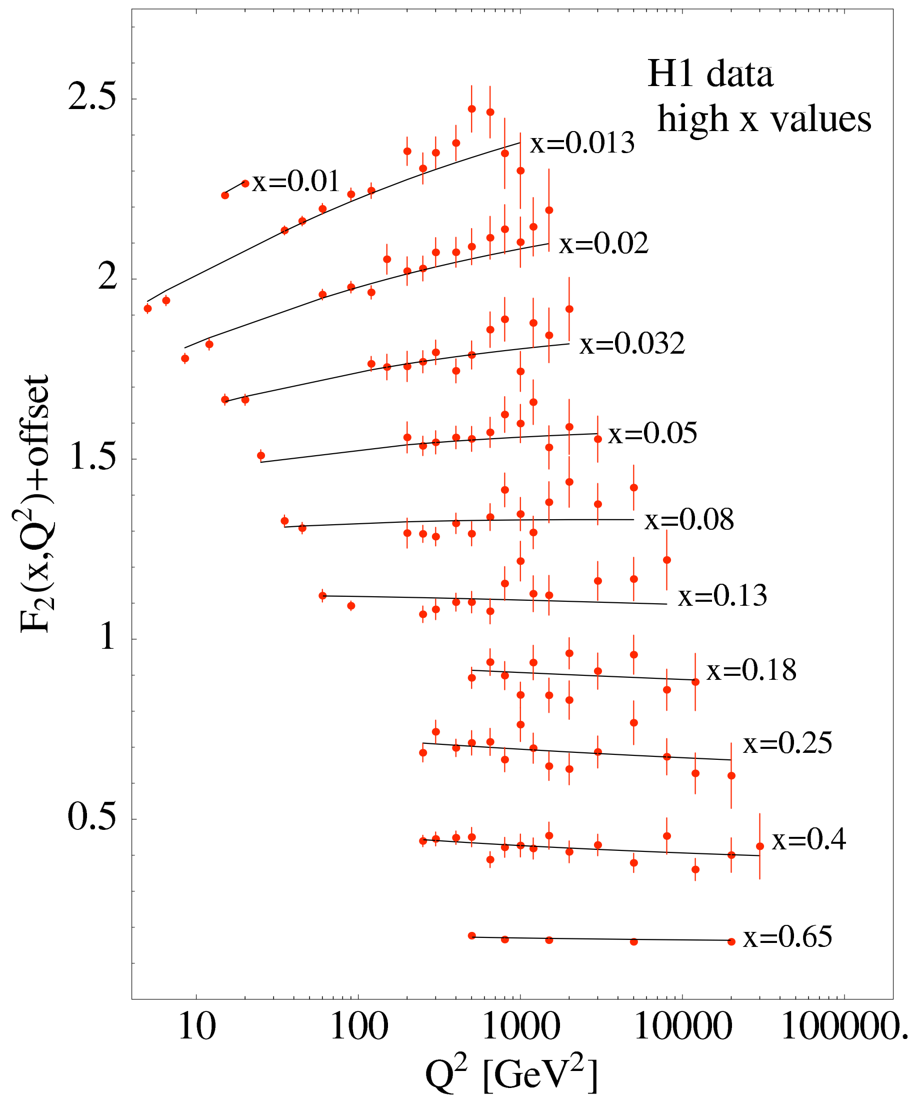
Recent global PDFs (CTEQ6)



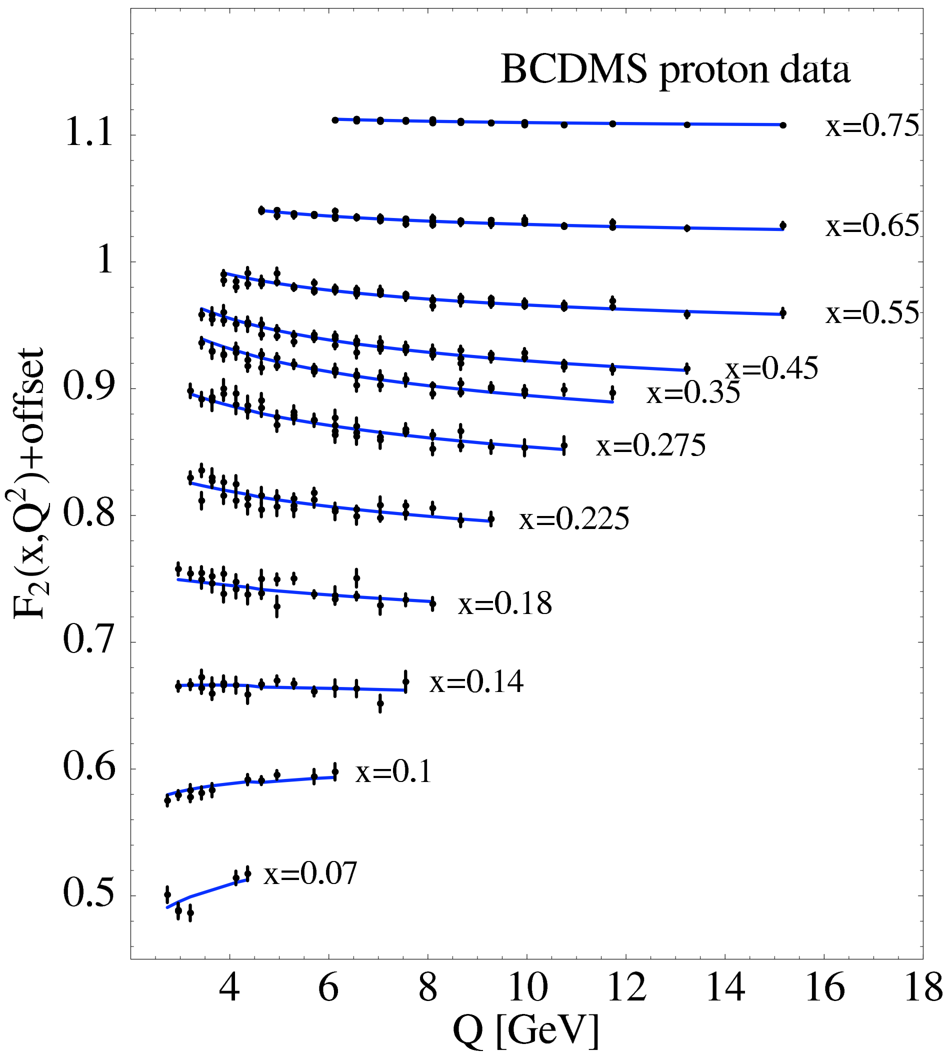
Lai et al., Eur. Phys. J. C12 (2000) 375

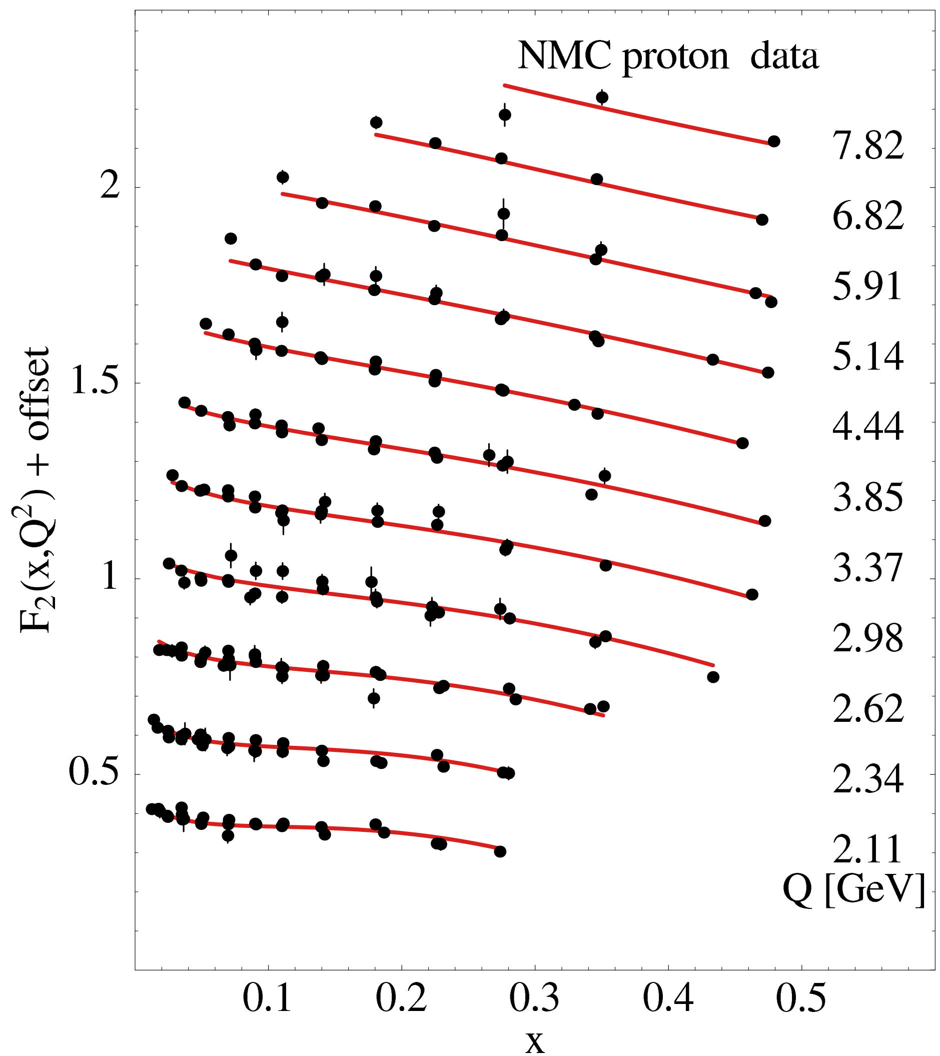
Comparison with data





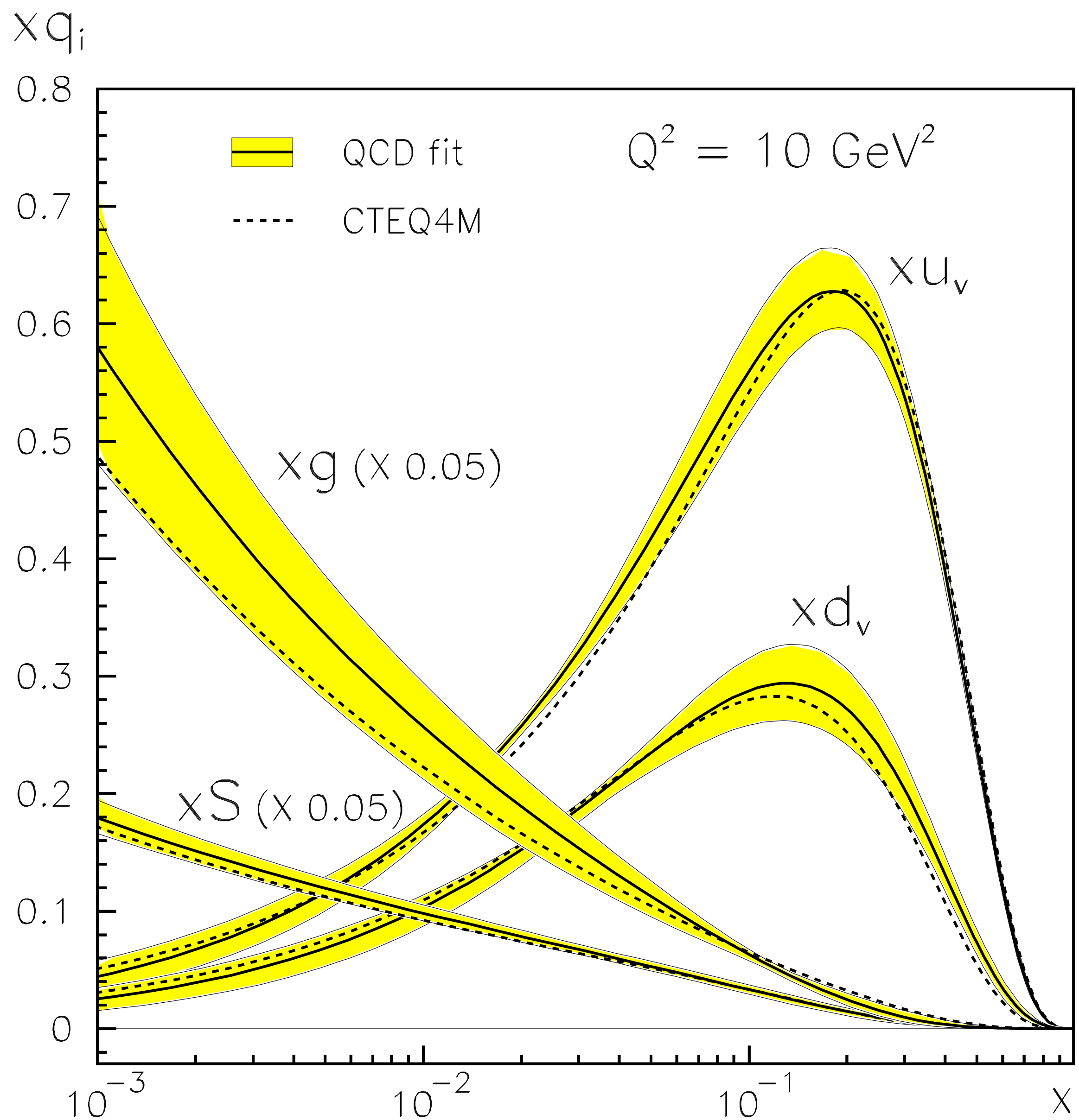
Lai et al., Eur. Phys. J. C12 (2000) 375





Lai et al., Eur. Phys. J. C12 (2000) 375

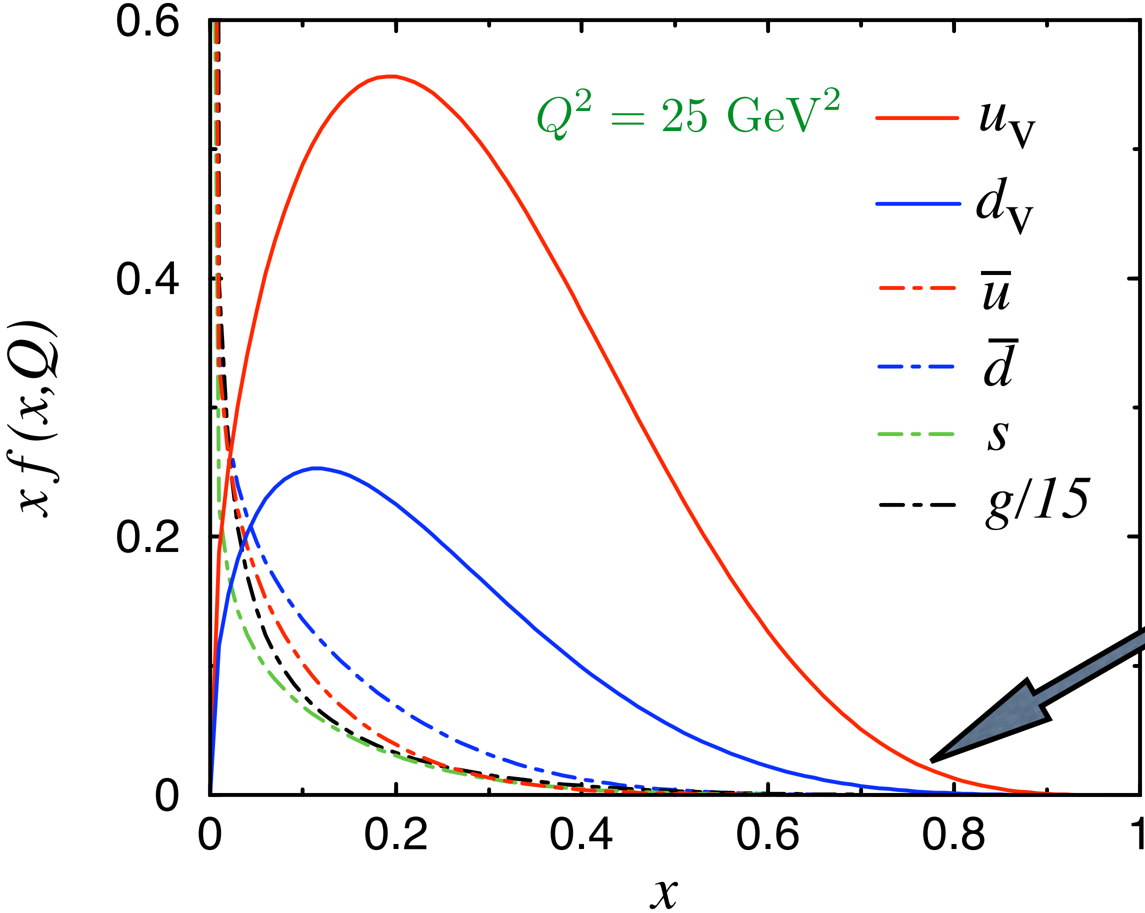
small x -
sea quarks
and gluons
dominate



Botje, Eur. Phys. J. C 14 (2000) 285

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

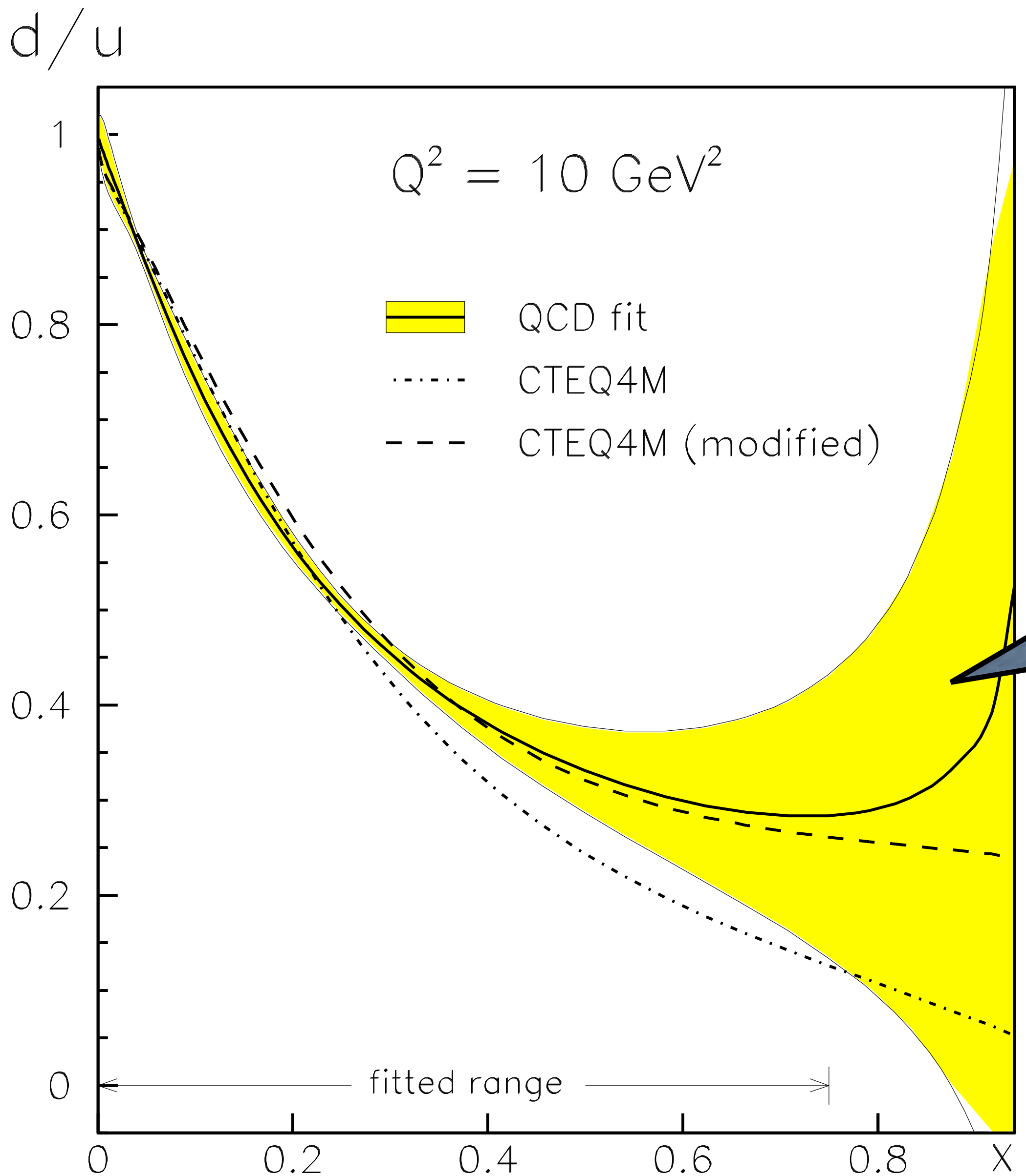
Most direct connection between PDFs and models of the nucleon is through *valence* quarks



large x - valence quarks dominate

PDFs at large x are small

small uncertainties can have large relative effects



Uncertainty due to nuclear effects in neutron

Botje, Eur. Phys. J. C 14 (2000) 285

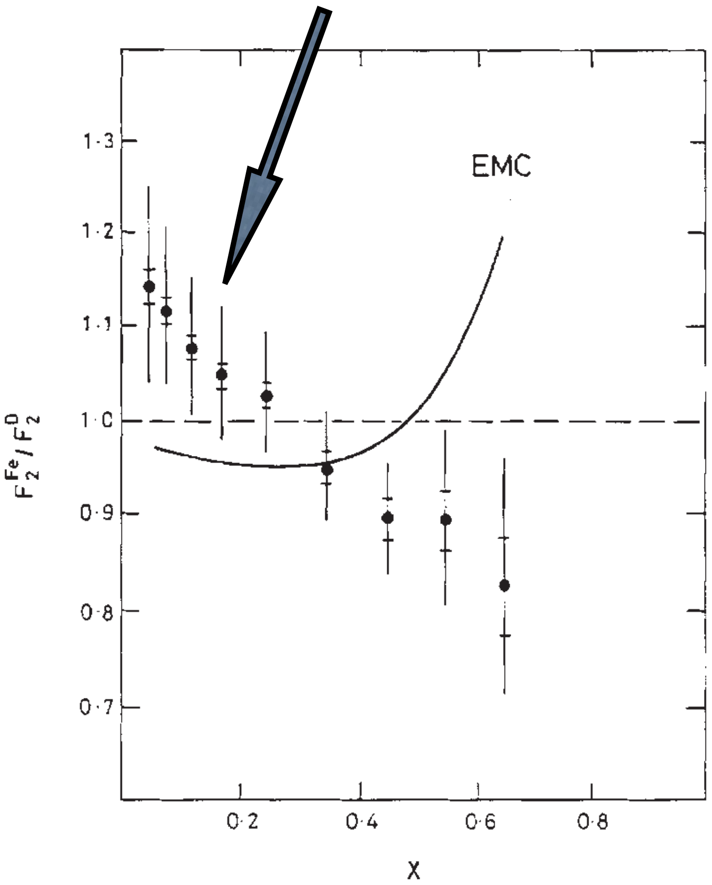
Nuclear effects

- Need proton *and neutron* to resolve u and d flavors
- No free neutron targets (neutron half-life ~ 12 mins)
  - use deuteron as "effective neutron target"
- However $F_2^d \neq F_2^p + F_2^n$!!
- Nuclear effects obscure neutron structure information
  - *nuclear binding + Fermi motion at large* x
  - *nuclear shadowing at small* x
  - *antishadowing? pion cloud? at intermediate* x

Nuclear "EMC effect"

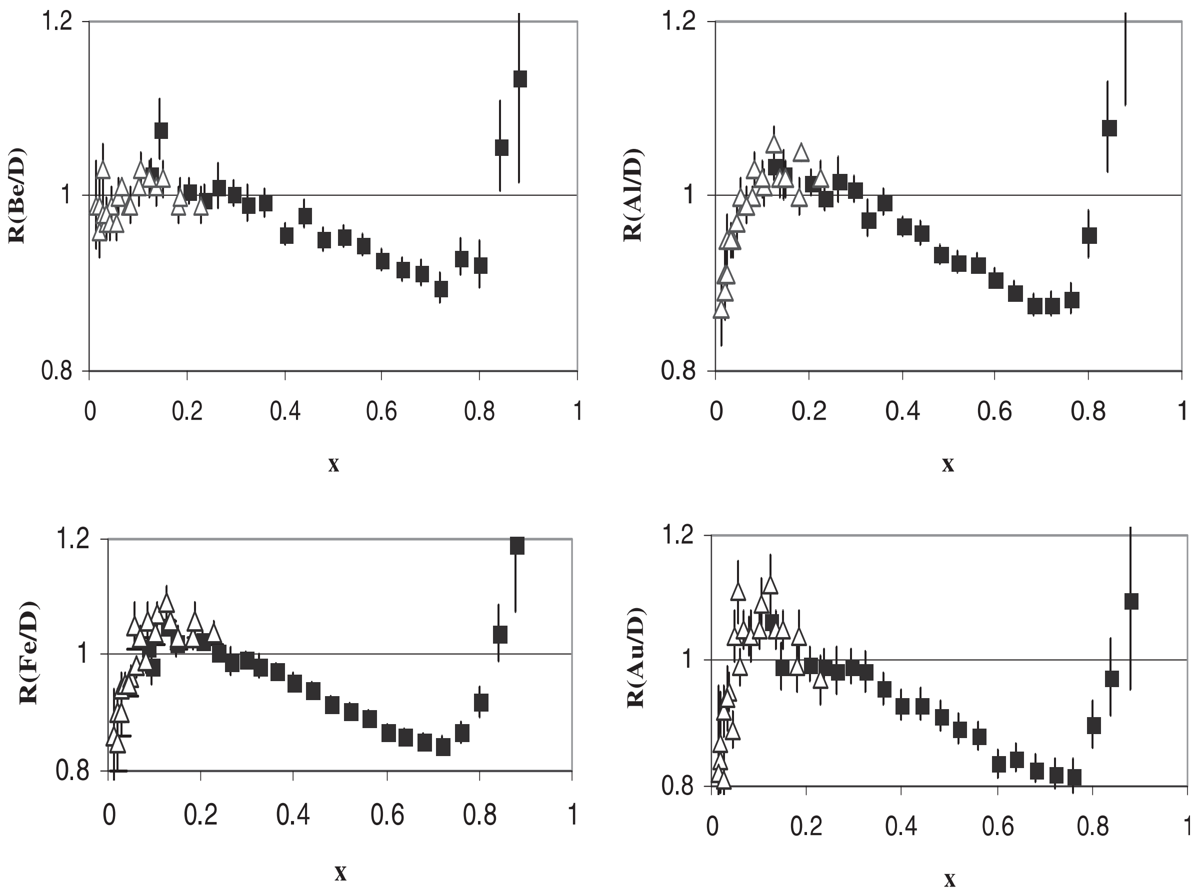
$$F_2^A(x, Q^2) \neq A F_2^N(x, Q^2)$$

Original EMC data



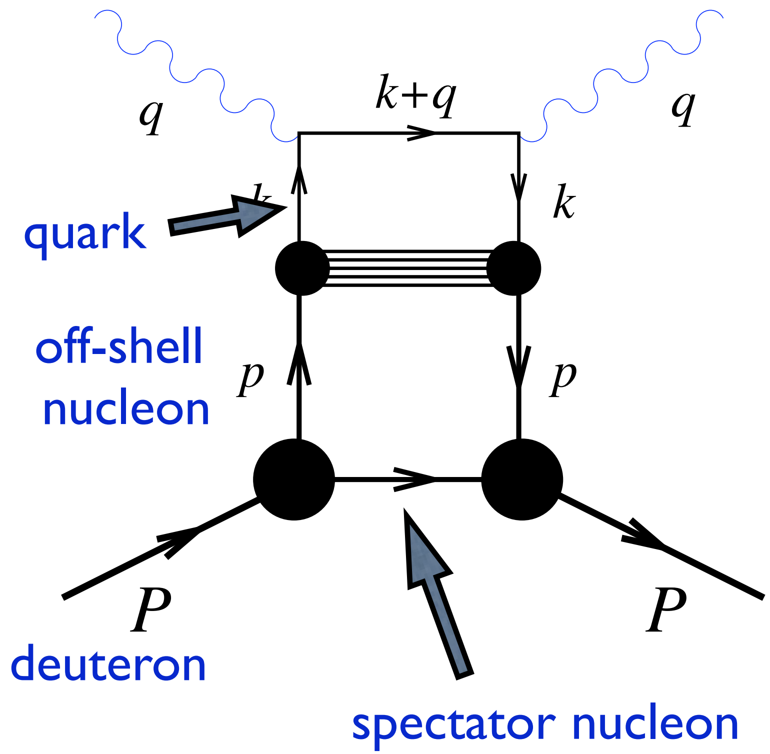
Aubert et al., Phys. Lett. B 123, 123 (1983)

Later SLAC data



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

EMC effect in d at large x



Nuclear "impulse approximation"

⇒ incoherent scattering from individual nucleons in deuteron

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

nucleon momentum distribution

off-shell correction

Nuclear physics in the deuteron

Nucleon momentum distribution in deuteron

→ relativistic dNN vertex function

$$f_{N/d}(y) = \frac{1}{4} M_d \; y \int_{-\infty}^{p^2_{\max}} dp^2 \, \frac{E_p}{p_0} \left| \Psi_d(\vec{p}^{\,2}) \right|^2$$

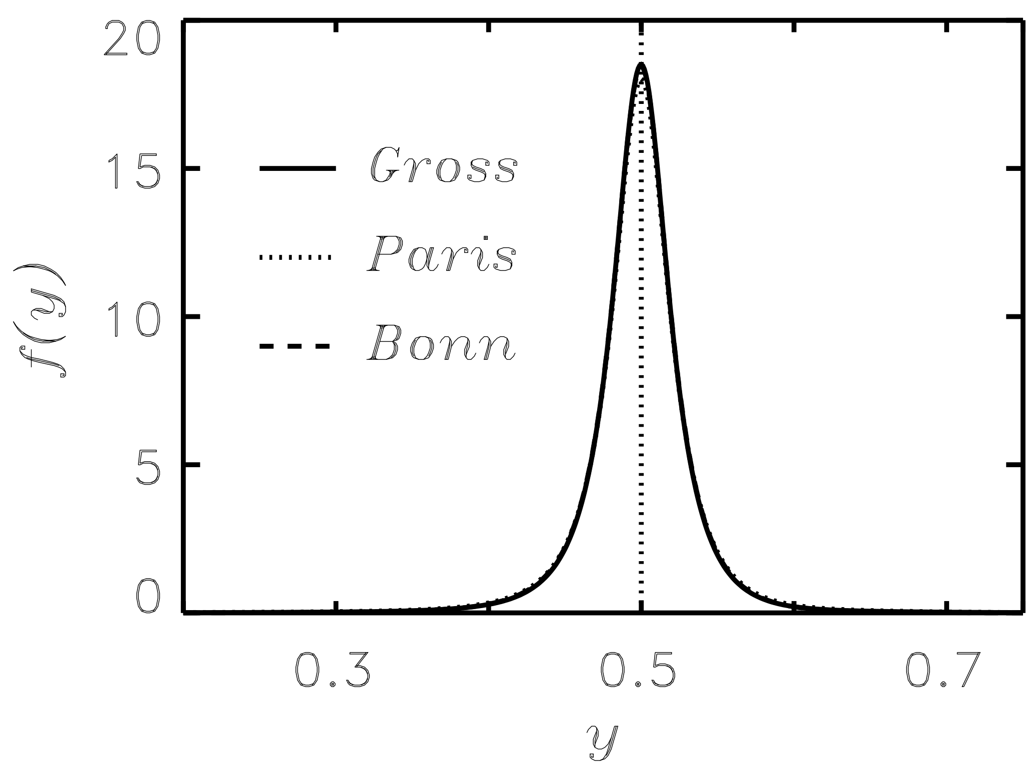
↑ momentum fraction of deuteron carried by nucleon

Nuclear physics in the deuteron

Nucleon momentum distribution in deuteron

→ relativistic dNN vertex function

$$f_{N/d}(y) = \frac{1}{4} M_d \; y \int_{-\infty}^{p^2_{\rm max}} dp^2 \, \frac{E_p}{p_0} \left| \Psi_d(\vec{p}^{\,2}) \right|^2$$

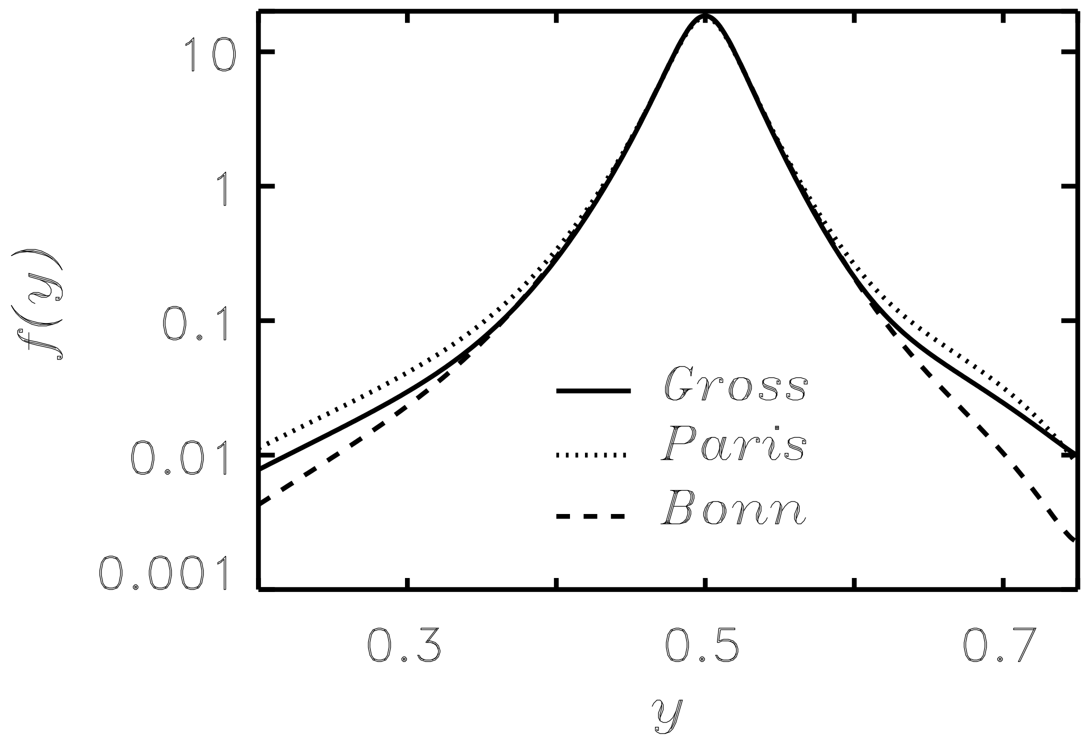


Nuclear physics in the deuteron

Nucleon momentum distribution in deuteron

⟹ relativistic *dNN* vertex function

$$f_{N/d}(y) = \frac{1}{4} M_d \; y \int_{-\infty}^{p^2_{\rm max}} dp^2 \frac{E_p}{p_0} \left|\Psi_d(\vec{p}^{\,2})\right|^2$$



Nuclear physics in the deuteron

Nucleon momentum distribution in deuteron

⟹ relativistic dNN vertex function

$$f_{N/d}(y) = \frac{1}{4} M_d \; y \int_{-\infty}^{p^2_{\max}} dp^2 \, \frac{E_p}{p_0} \left| \Psi_d(\vec{p}^{\,2}) \right|^2$$

Wave function dependence only at large y

⟹ sensitive to large p components of wave function

⟹ not very well known

Nuclear physics in the deuteron

Nucleon momentum distribution in deuteron

⟹ relativistic dNN vertex function

$$f_{N/d}(y) = \frac{1}{4} M_d \; y \int_{-\infty}^{p^2_{\mathrm{max}}} dp^2 \, \frac{E_p}{p_0} \left| \Psi_d(\vec{p}^{\,2}) \right|^2$$

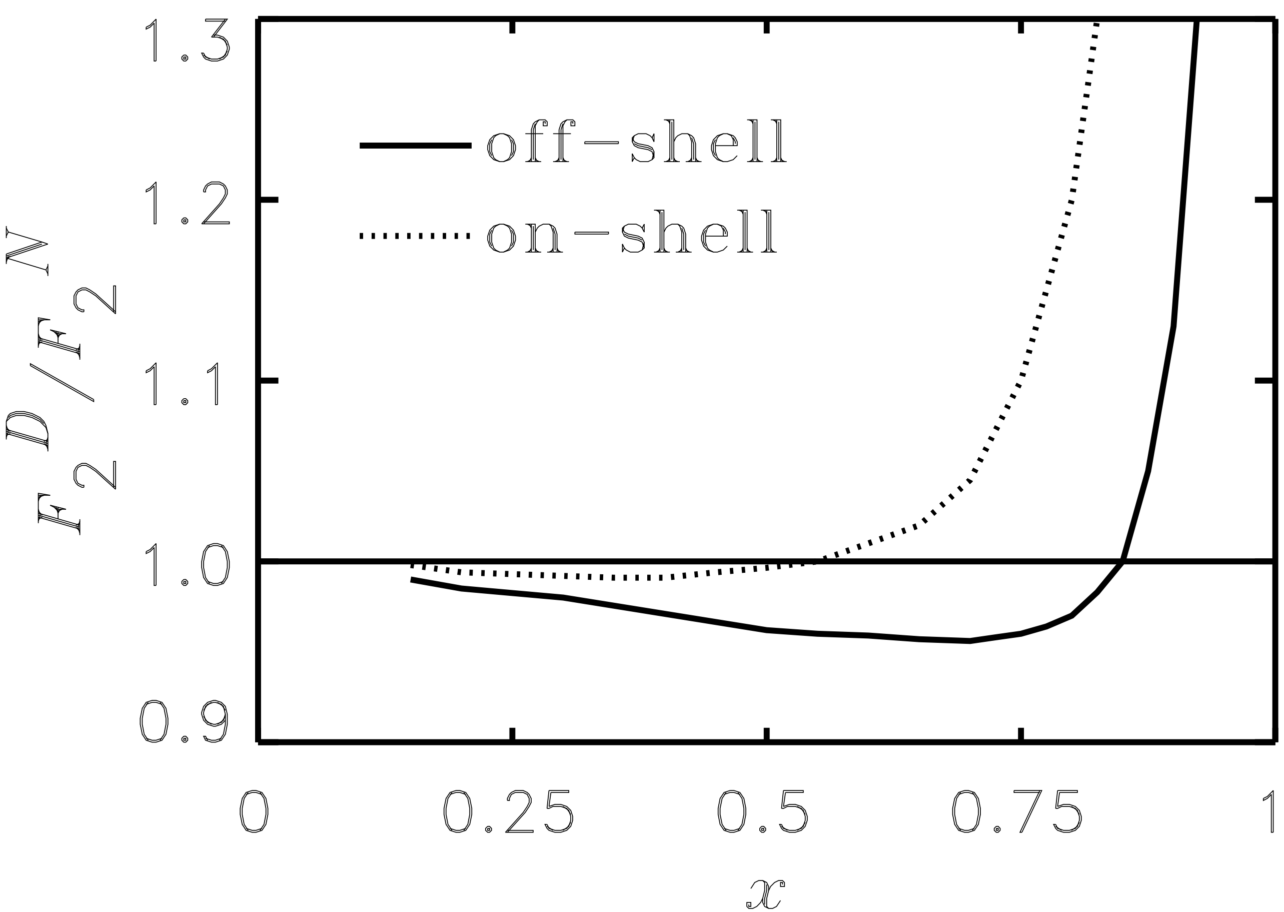
Nucleon off-shell correction

$\delta^{(\mathrm{off})} F_2^d$ ⟹ kinematical: OK

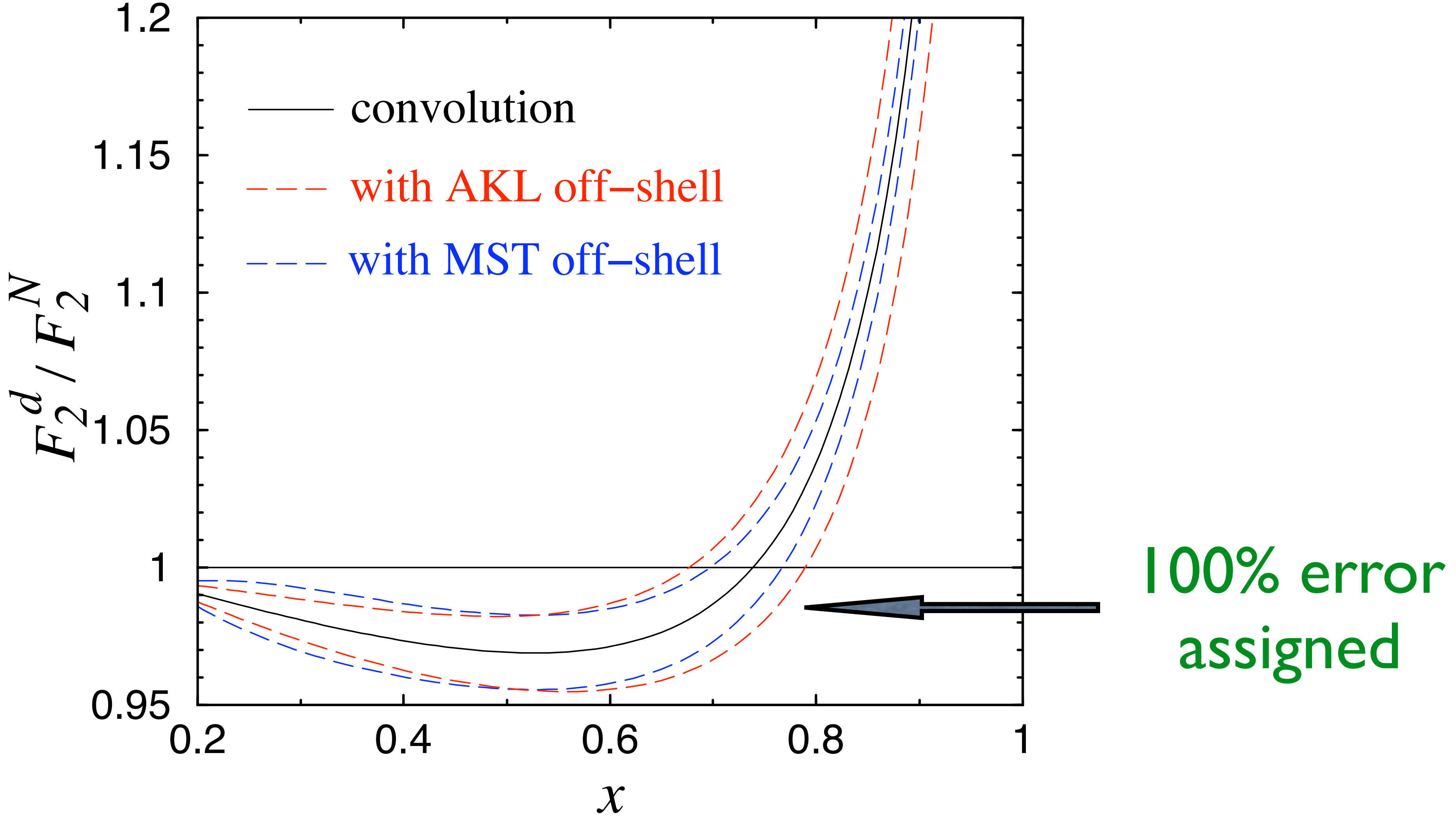
⟹ dynamical: ??

An illustration of possible effects...

WM, Schreiber, Thomas, Phys. Rev. D49 (1994) 1183



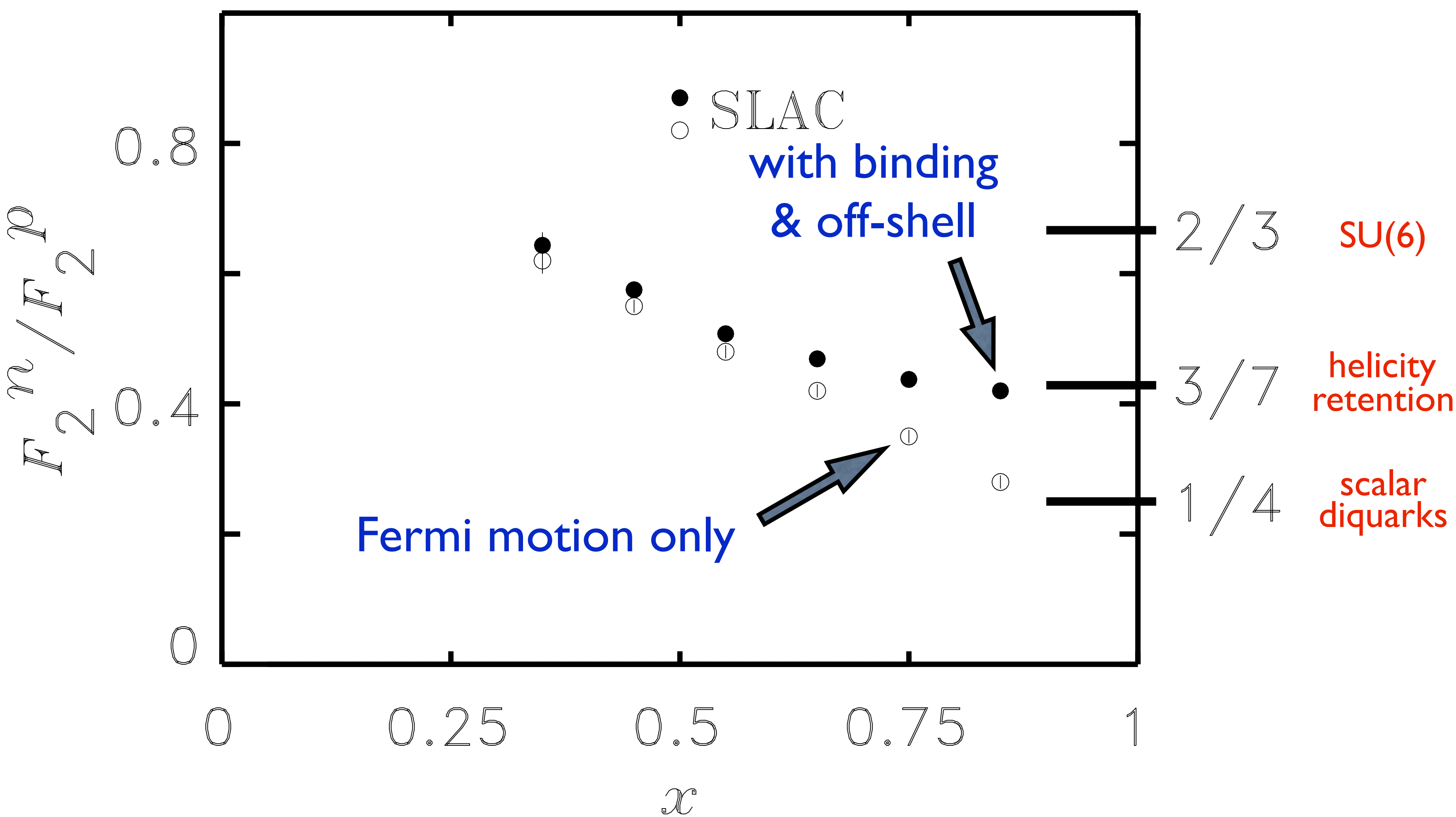
Note: ratio depends on input F_2^n



AKL: *Alekhin, Kulagin, Liuti, Phys. Rev. D 69 (2004) 114009*

MST: *WM, Schreiber, Thomas, Phys. Lett. B 335 (1994) 11*

WM, Thomas, Phys. Lett. B 377 (1996) 11



Without EMC effect in d

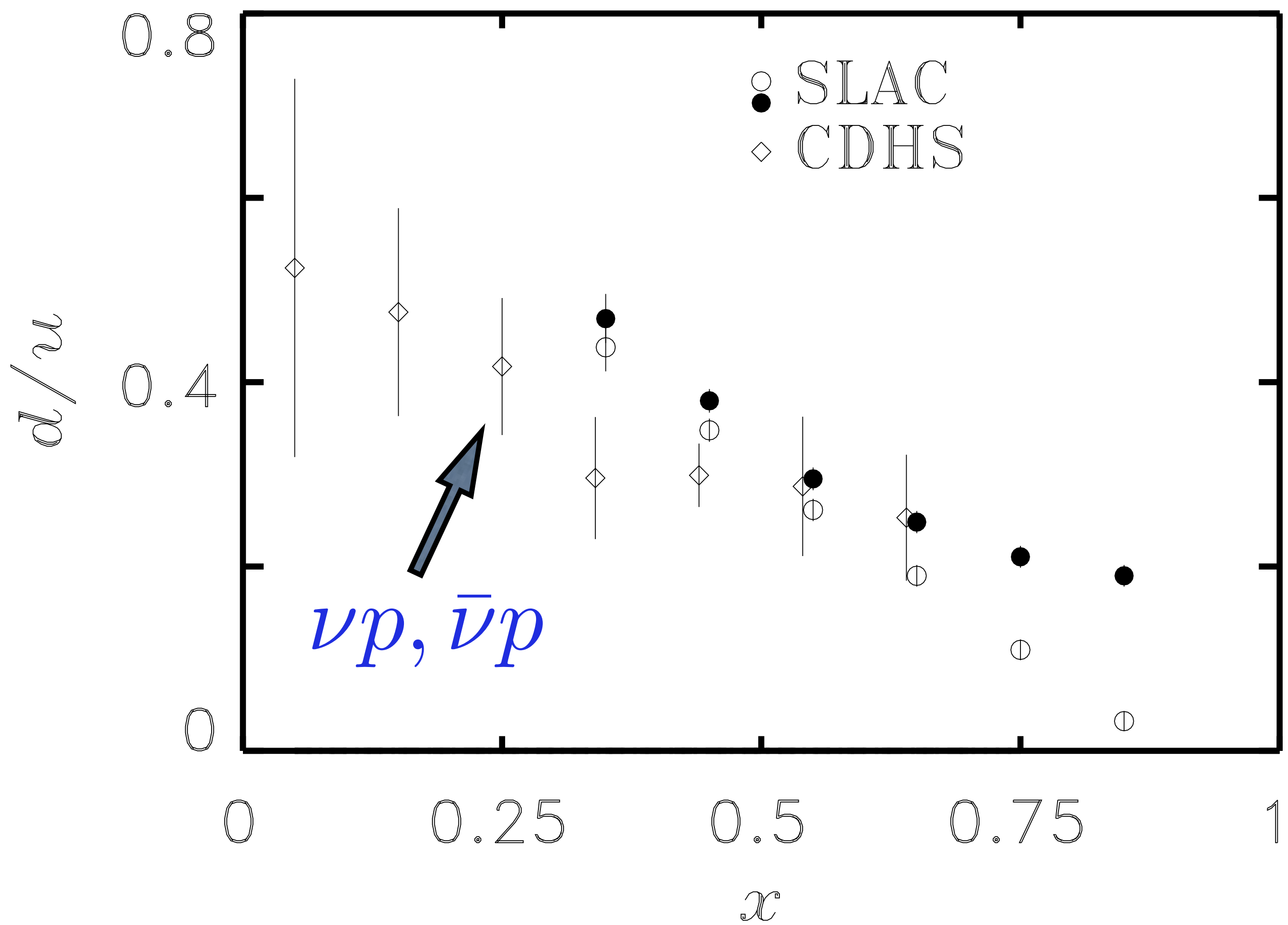
F_2^n underestimated at large x!

At large x (sea quarks, gluons suppressed)

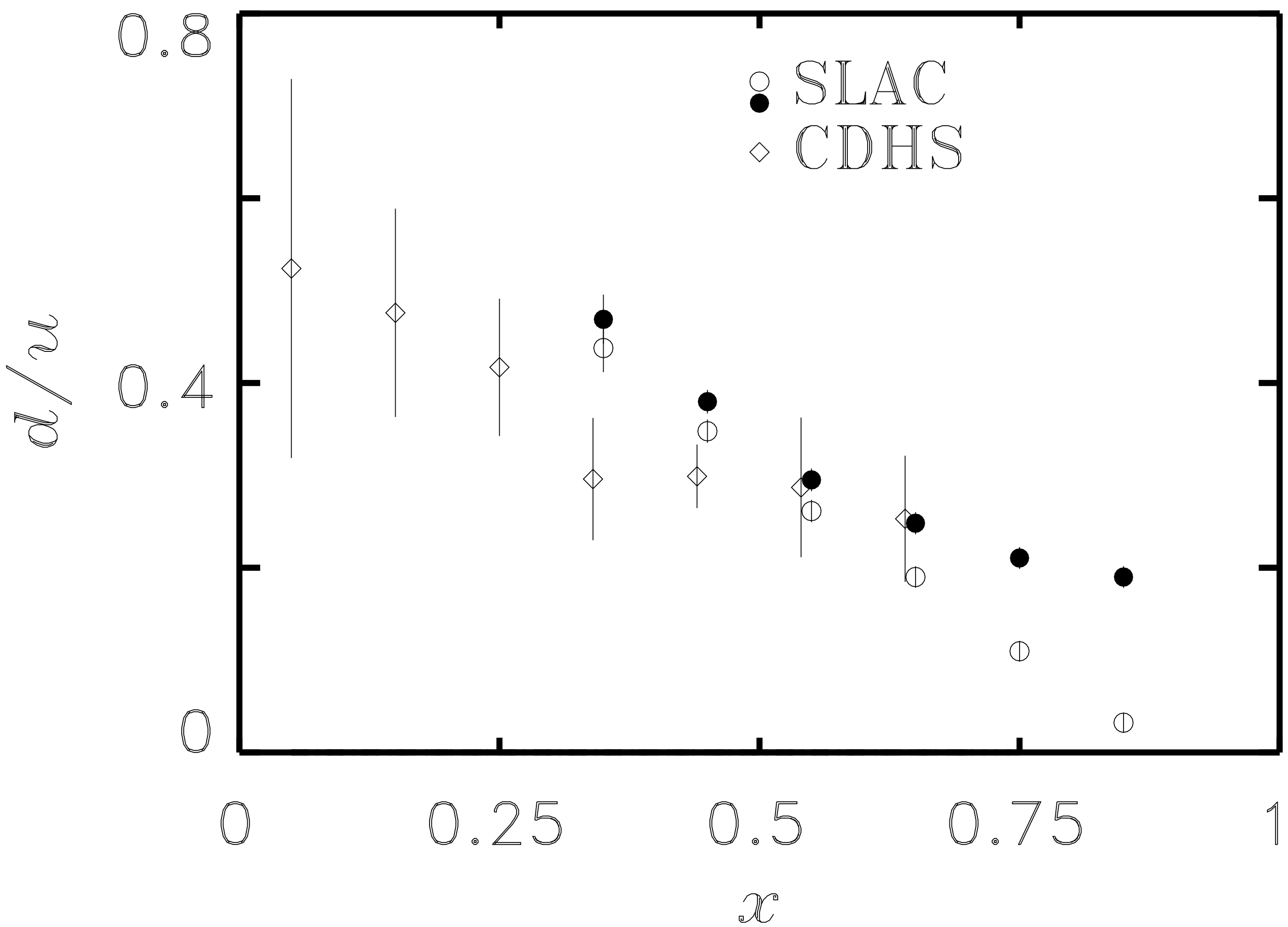
$$F_2^p \sim \frac{4}{9}\, u + \frac{1}{9}\, d$$

$$F_2^n \sim \frac{1}{9}\, u + \frac{4}{9}\, d$$

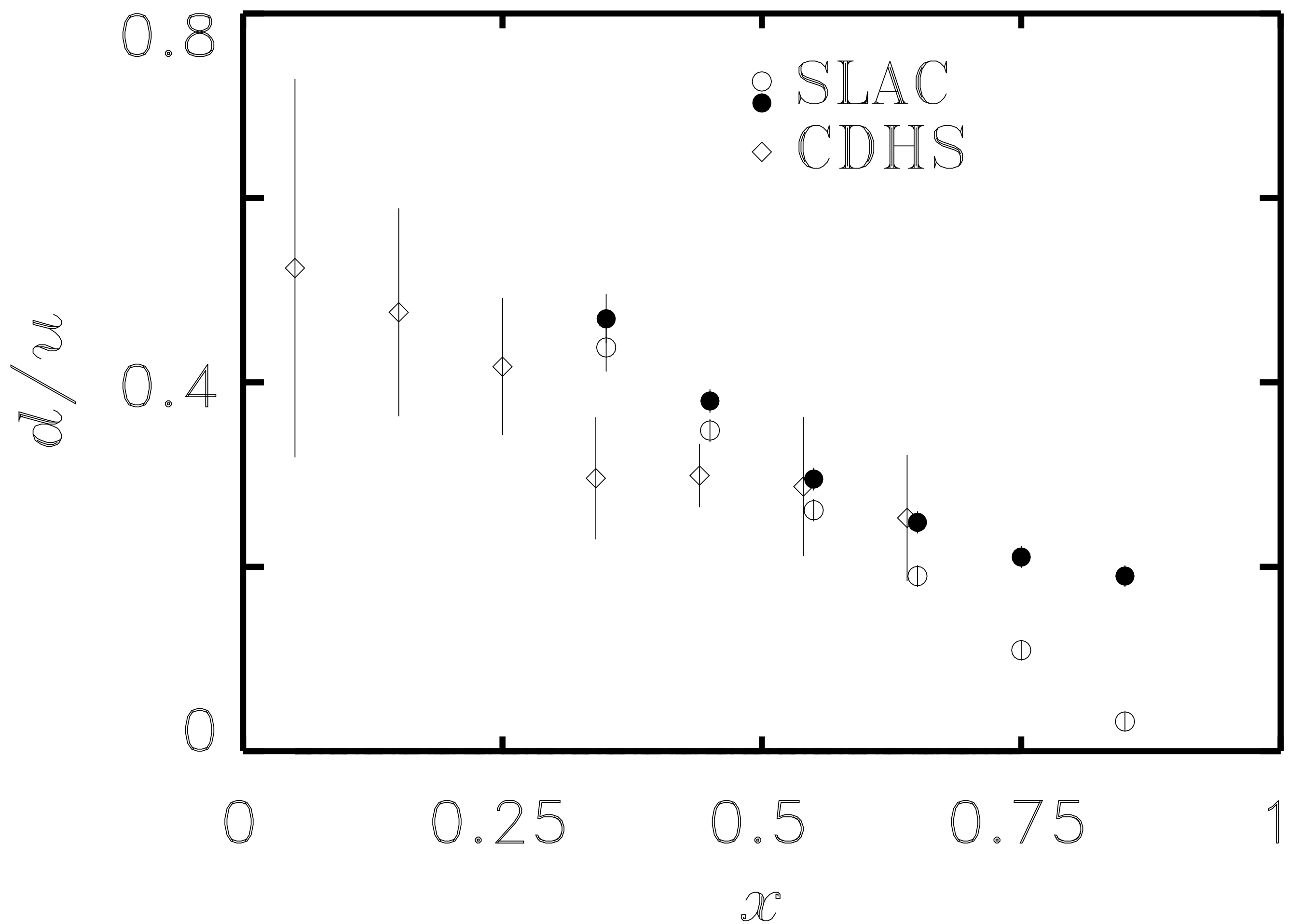
$$\frac{d}{u} \sim \frac{4 - F_2^n / F_2^p}{4F_2^n / F_2^p - 1}$$



Does $d/u \to 0$ as $x \to 1$?



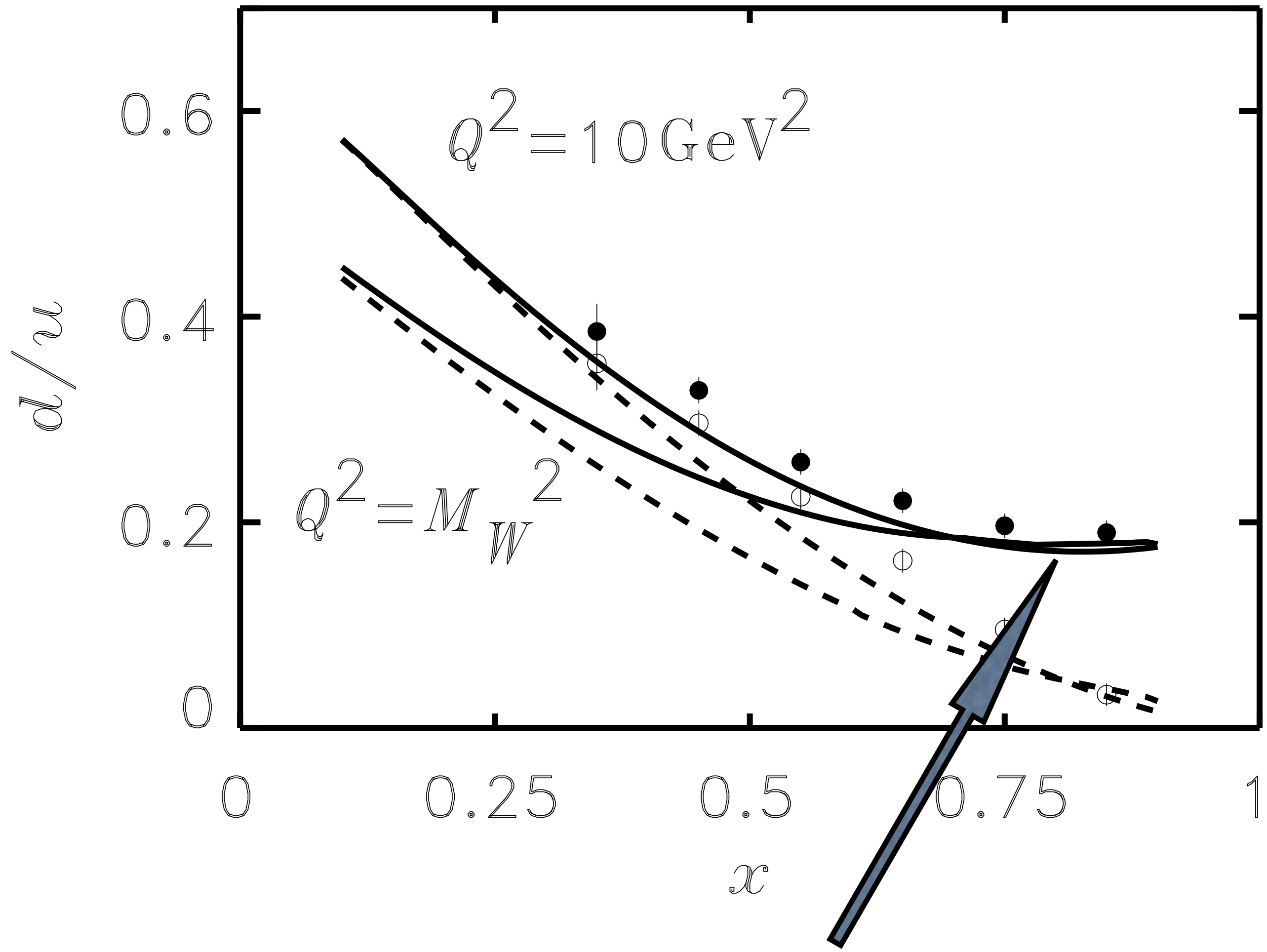
$$\text{pQCD}: \ d/u \to \text{constant as } x \to 1$$



$$\mathrm{pQCD + SU(6)\ wfn:}\ \ d/u \to \frac{1}{5}\ \mathrm{as}\ x \to 1$$

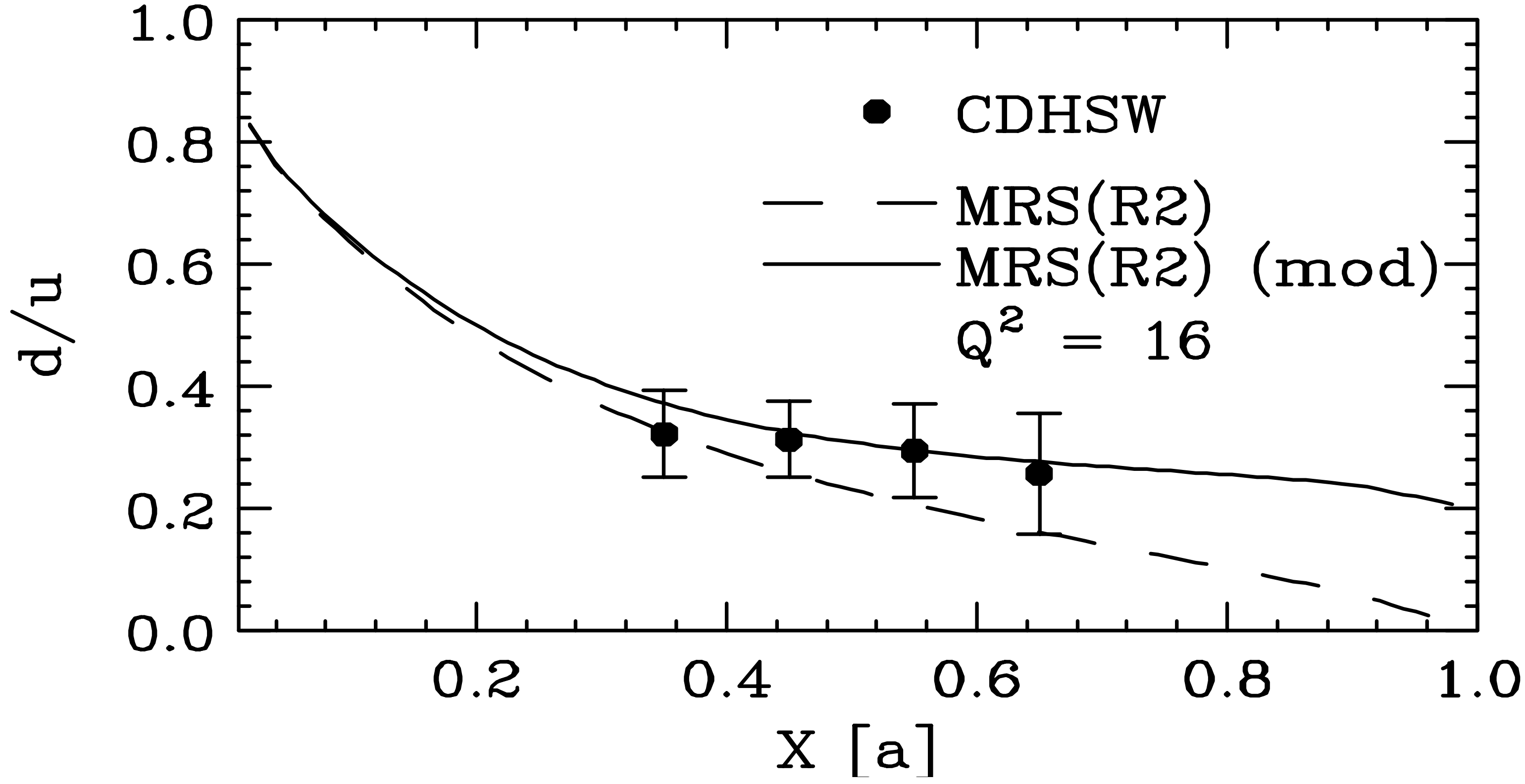
Farrar, Jackson, Phys. Rev. Lett. 35 (1975) 1416

WM, Peng, Phys. Lett. B400 (1997) 220



$$\frac{d}{u} \rightarrow \frac{d}{u} + 0.2\ x^2 \exp(-(1-x)^2)$$

Yang, Bodek, Phys. Rev. Lett. 82 (1999) 2467

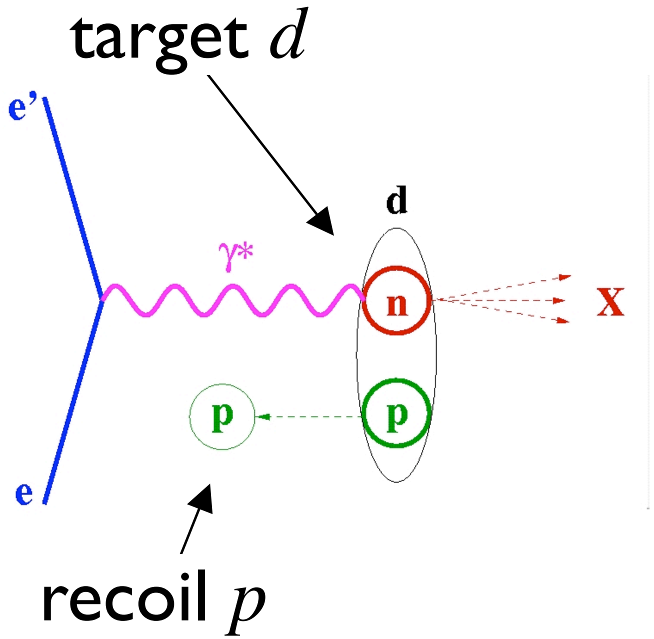


$$\frac{d}{u} \to \frac{d}{u} + 0.1\,x\,(1+x)$$

"Cleaner" methods of determining d/u

$e^{\mp}\ p \to \nu(\bar{\nu})X$	need high luminosity
$\nu(\bar{\nu})\ p \to l^{\mp}\ X$	low statistics
$p\ p(\bar{p}) \to W^{\pm}X$	need large lepton rapidity
$\vec{e}_L(\vec{e}_R)\ p \to e\ X$	low count rate
$e\ p \to e\ \pi^{\pm}\ X$	need $z \sim 1$, factorization
$e\ {}^3\mathrm{He}({}^3\mathrm{H}) \to e\ X$	tritium target

“Cleaner” methods of determining d/u

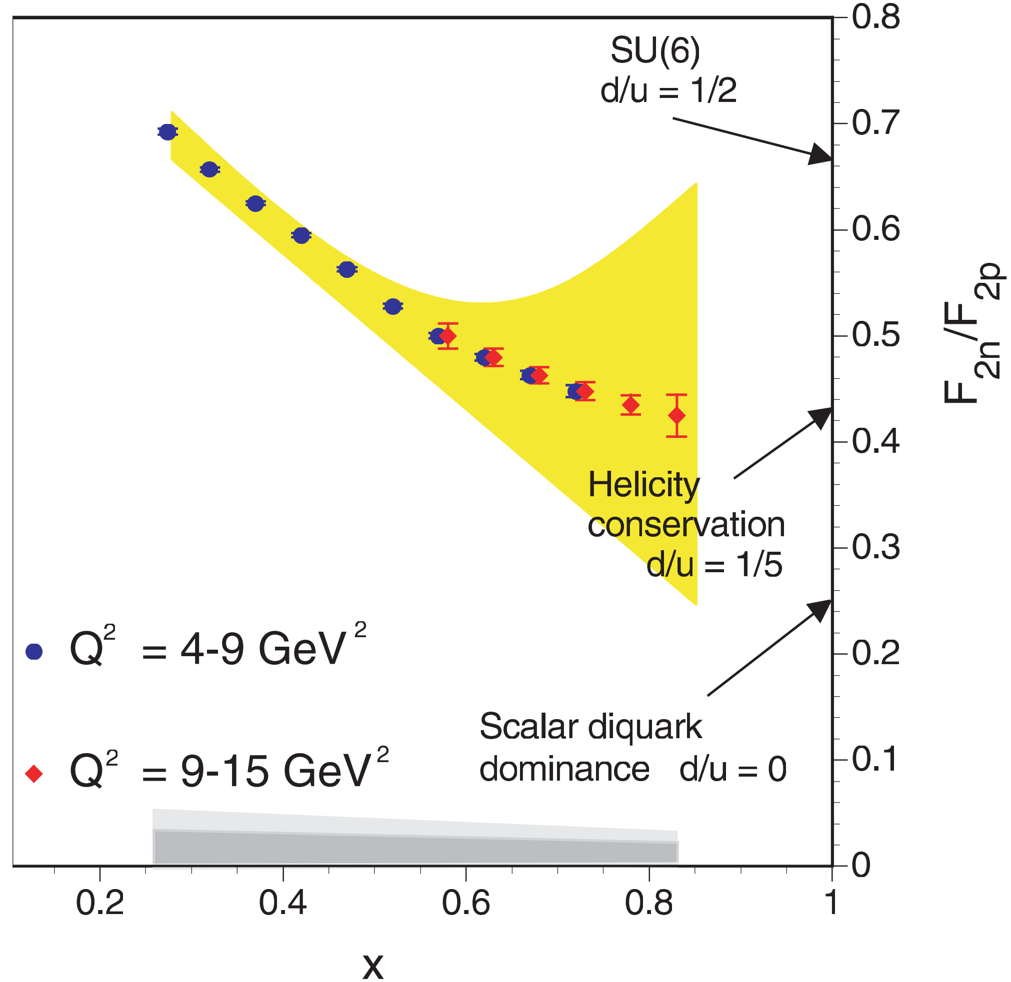


$$e\ d \rightarrow e\ p\ X$$

backward slow p

⟹ neutron nearly on-shell

⟹ minimize rescattering

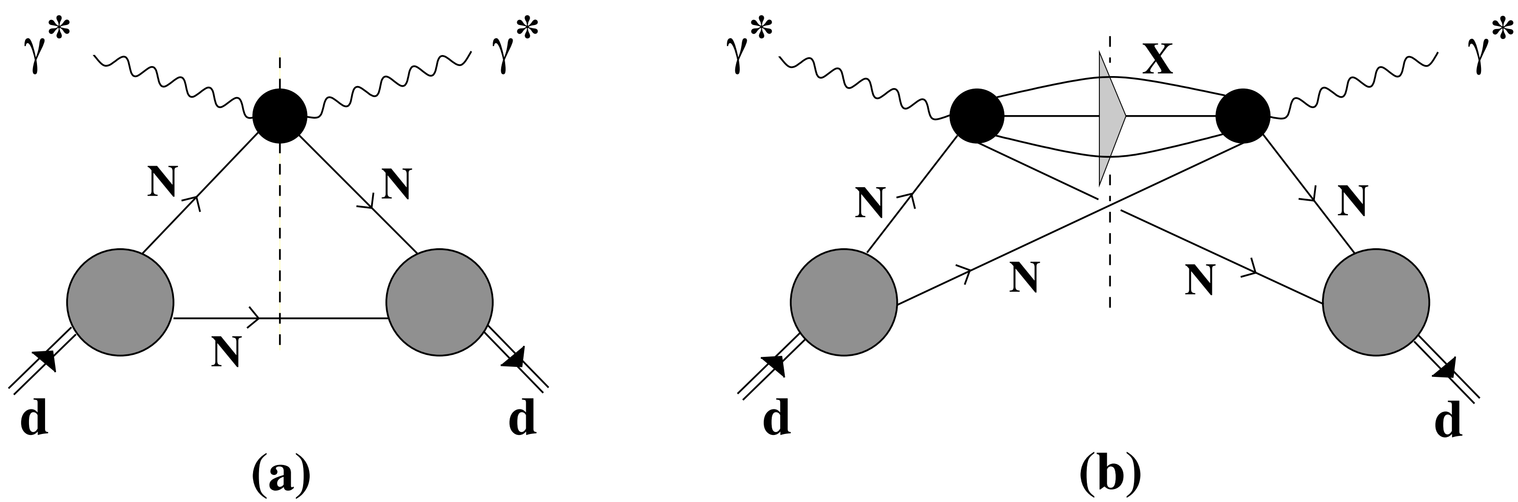


JLab Hall B experiment (“BoNuS”)

Nuclear shadowing

Interference of multiple scattering amplitudes

For deuteron:



Nuclear impulse approximation

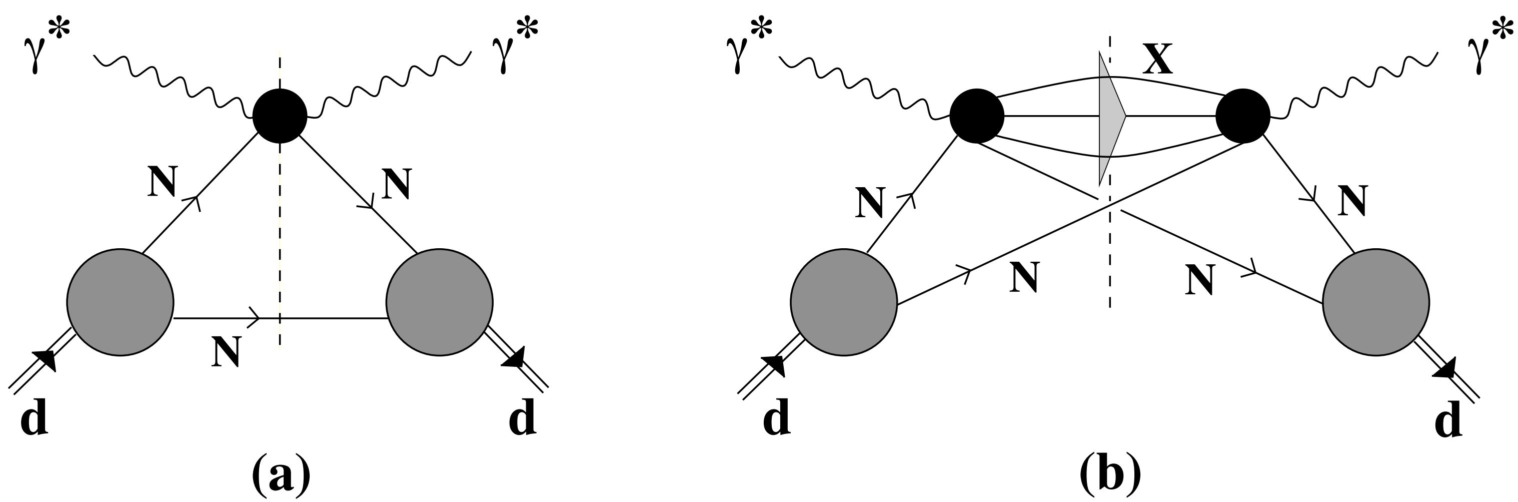
Double scattering

e.g. Piller, Weise, Phys. Rep. 330 (2000) 1

Nuclear shadowing

Interference of multiple scattering amplitudes

For deuteron:

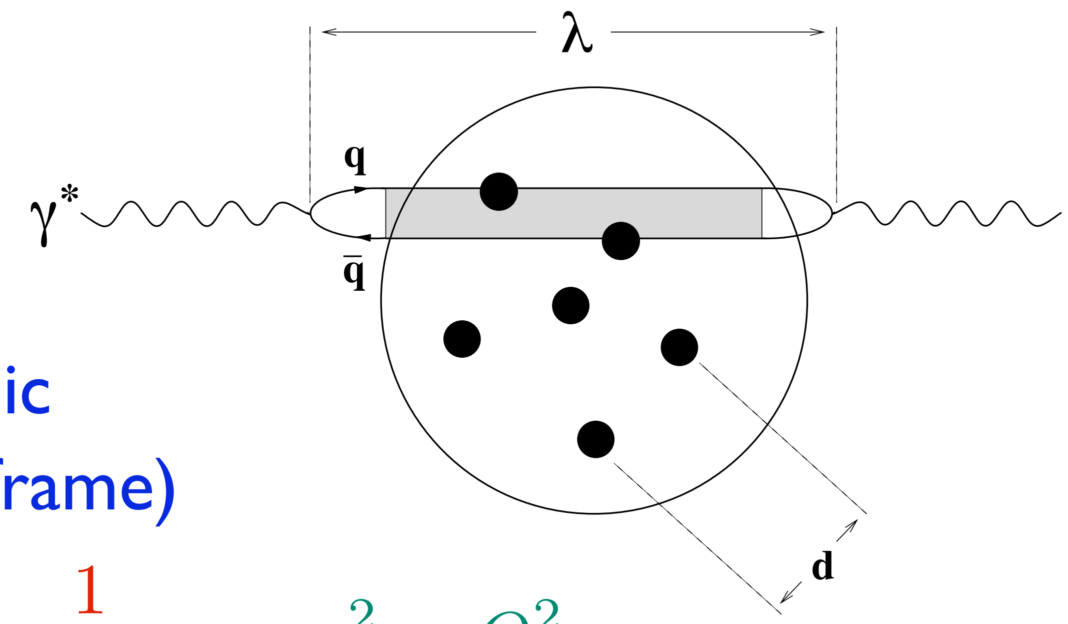


$$F_2^d = F_2^p + F_2^n + \delta^{(\mathrm{shad})} F_2^d$$

e.g. Piller, Weise, Phys. Rep. 330 (2000) 1

Space-time view of shadowing

see e.g. Piller, Weise, Phys. Rep. 330 (2000) 1



propagation length of hadronic fluctuation of mass μ (in lab frame)

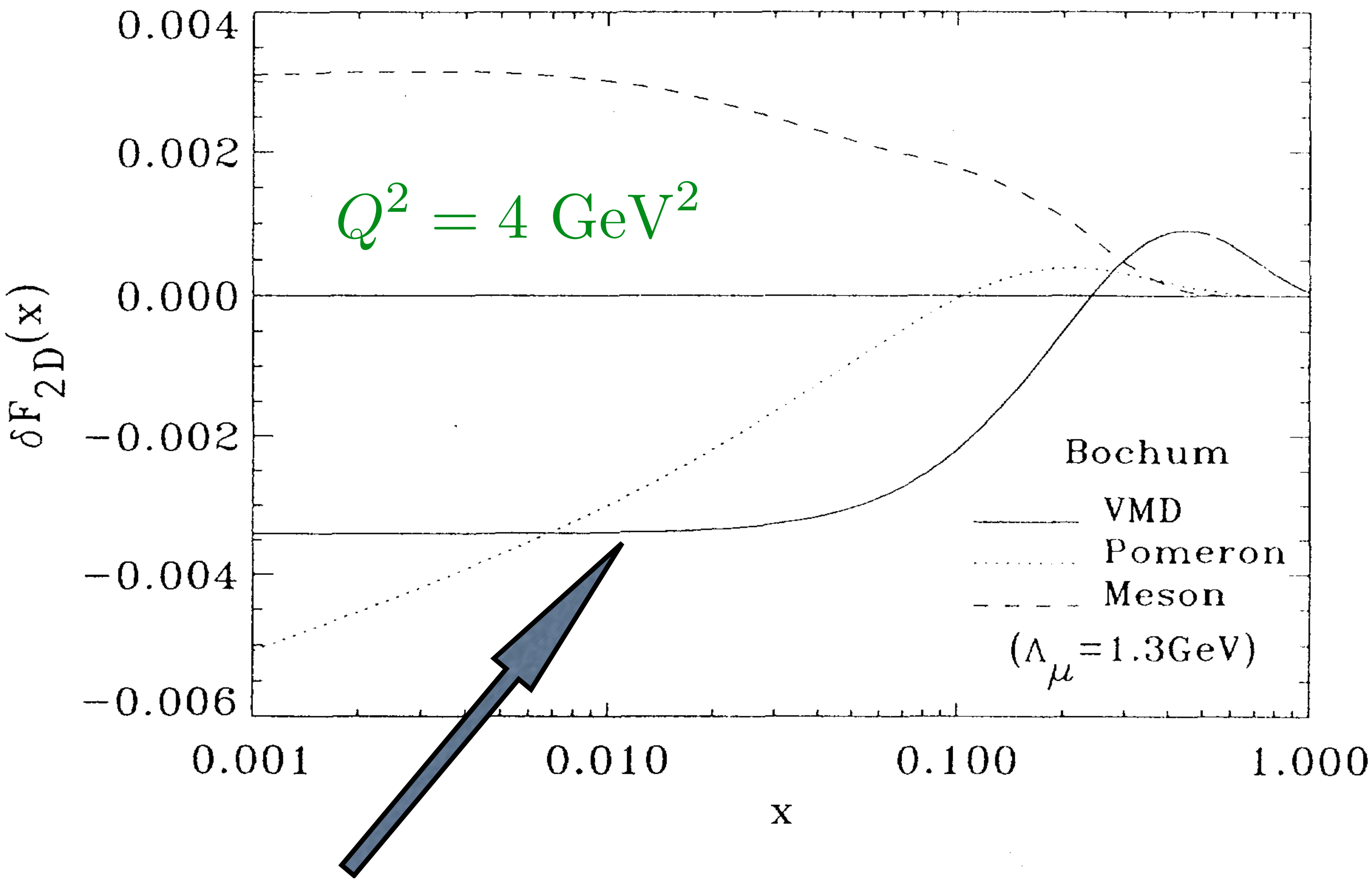
$$\lambda \sim \frac{1}{\Delta E} = \frac{2\nu}{\mu^2 + Q^2} \to \frac{1}{2xM}\ , \quad \mu^2 \sim Q^2$$

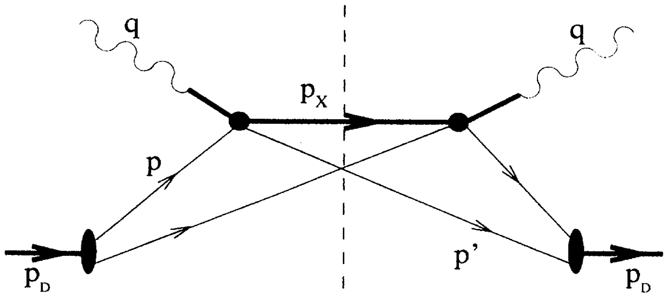
if propagation length exceeds average distance between nucleons $\lambda > d \approx 2\ \mathrm{fm}$

⇒ coherent multiple scattering can occur

$$x < 0.05$$

Shadowing in deuterium

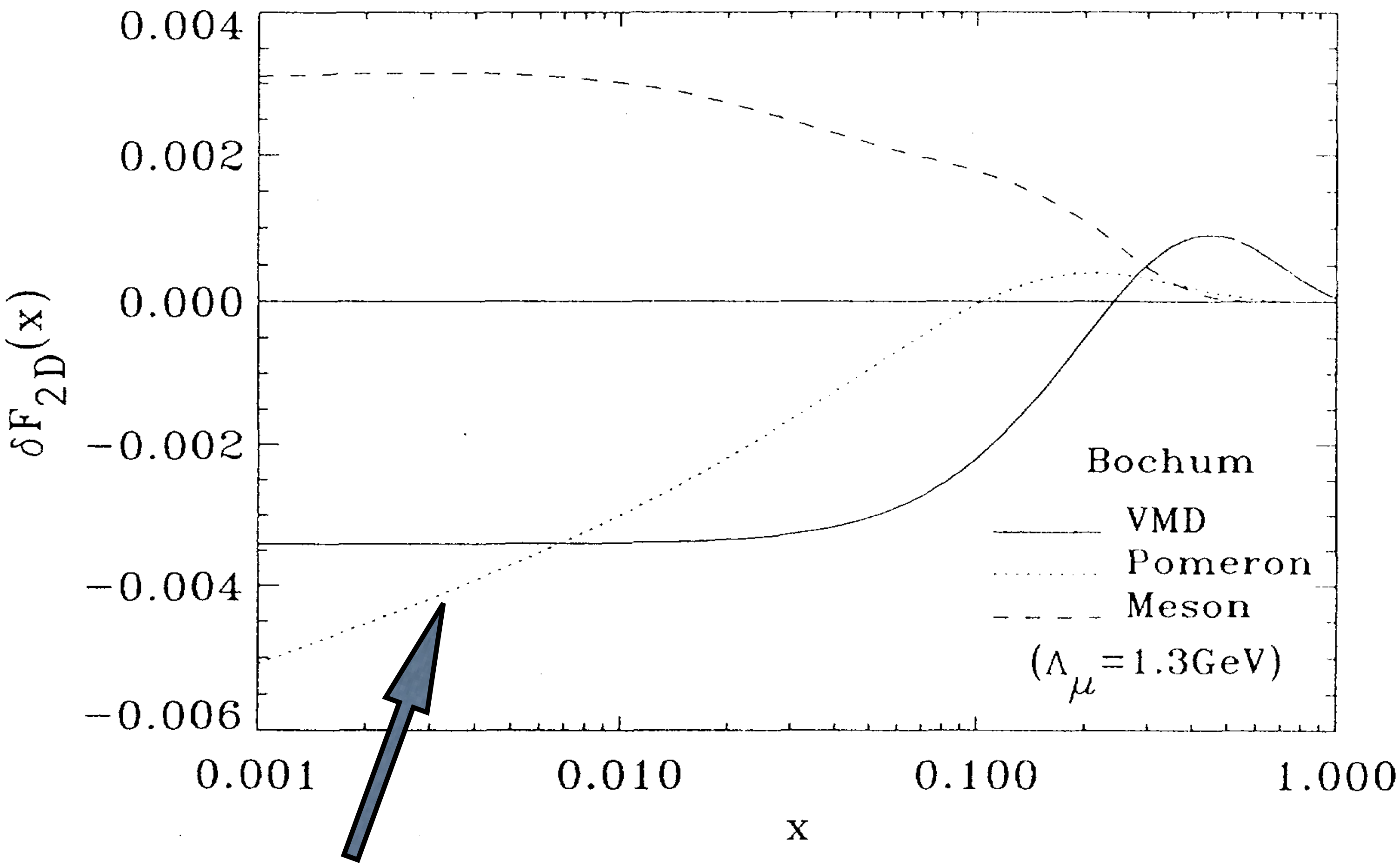


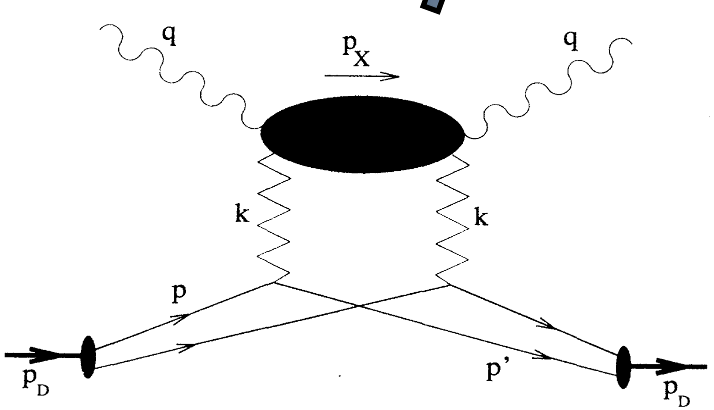


vector meson dominance

(higher twist)

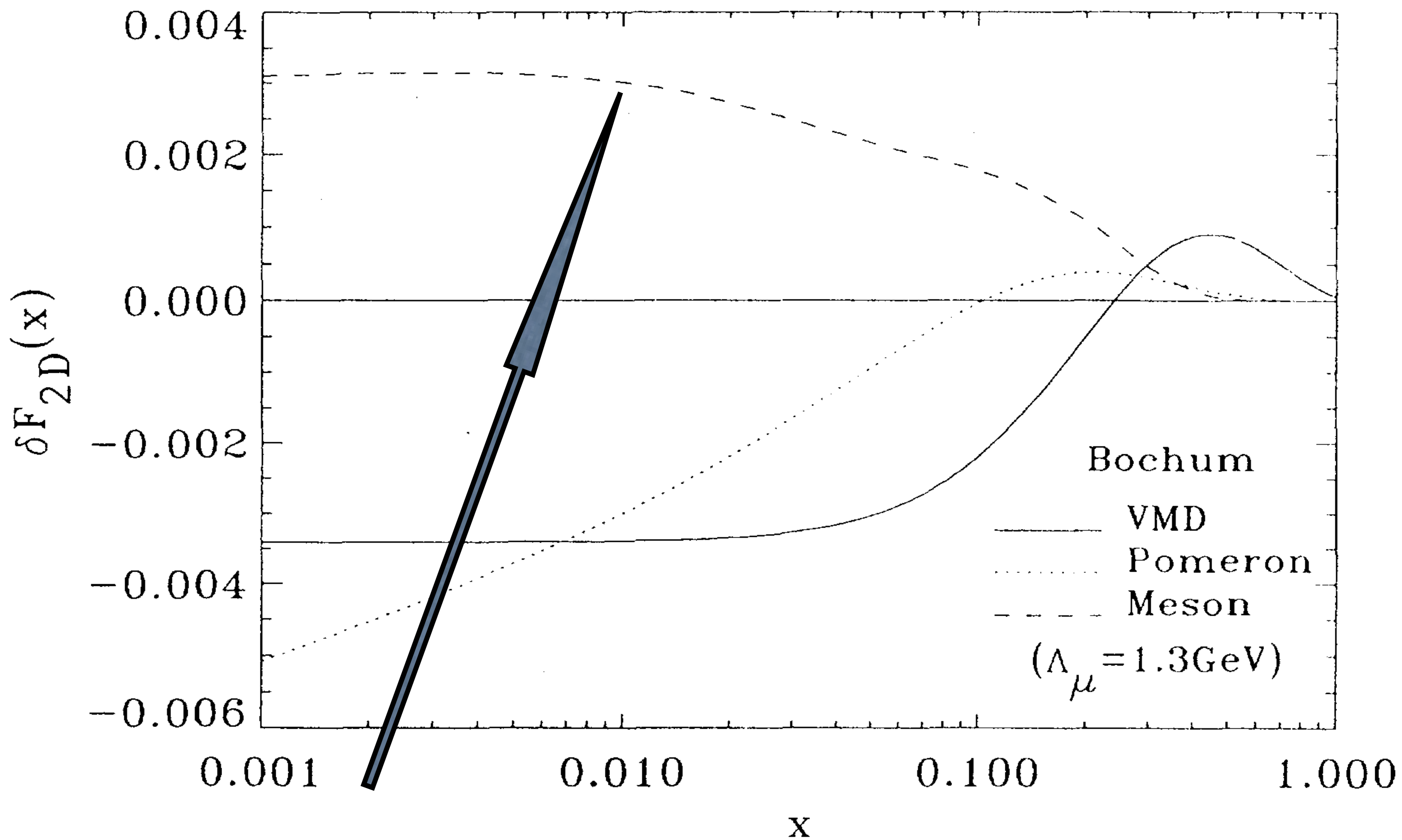
Shadowing in deuterium

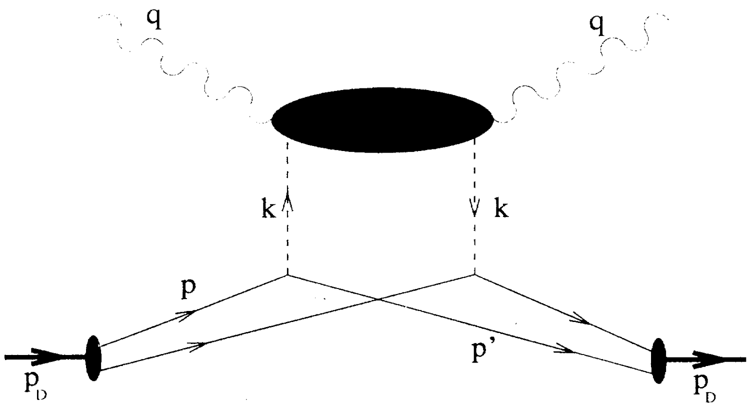




Pomeron exchange

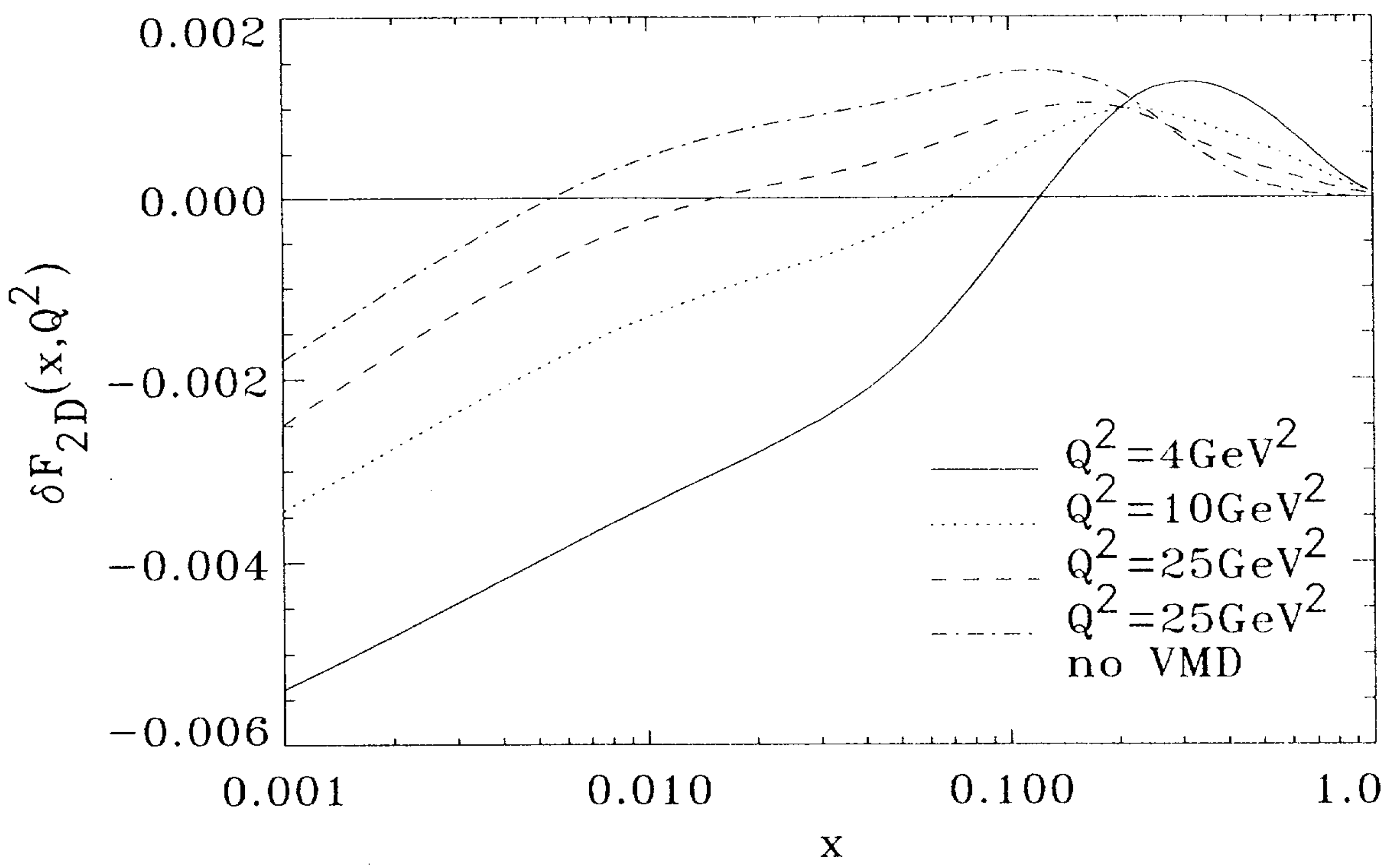
Anti-shadowing in deuterium





meson (pion) exchange

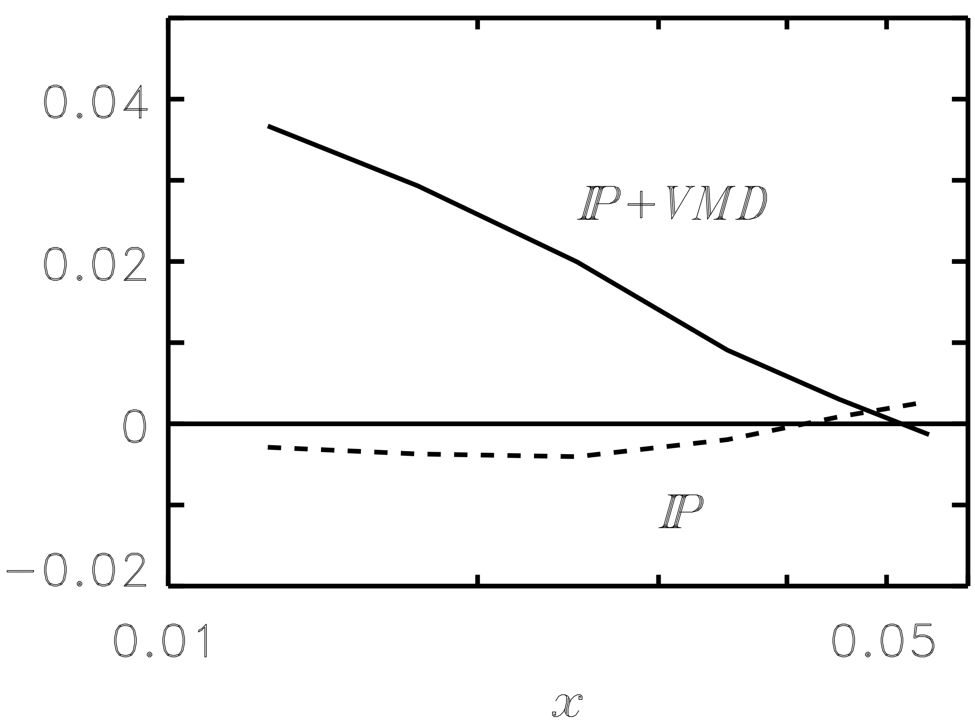
WM, Thomas, Phys. Rev. D47 (1993) 3783



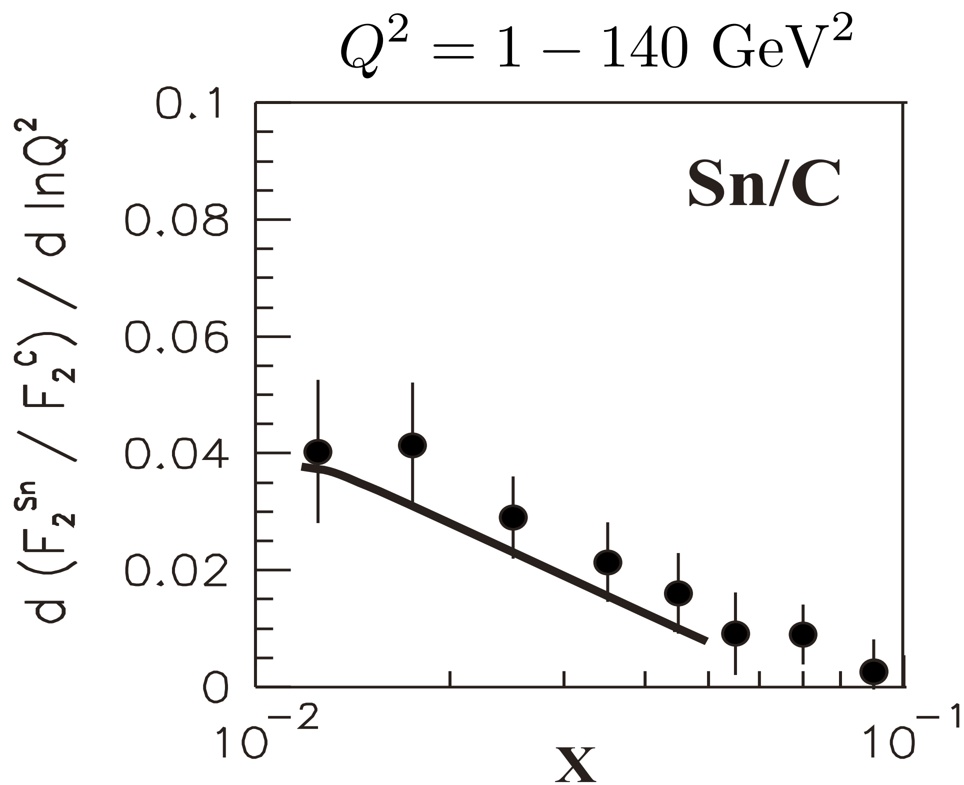
VMD important even at moderate Q^2

Shadowing in nuclei

Perturbative or nonperturbative origin of Q^2 dependence?

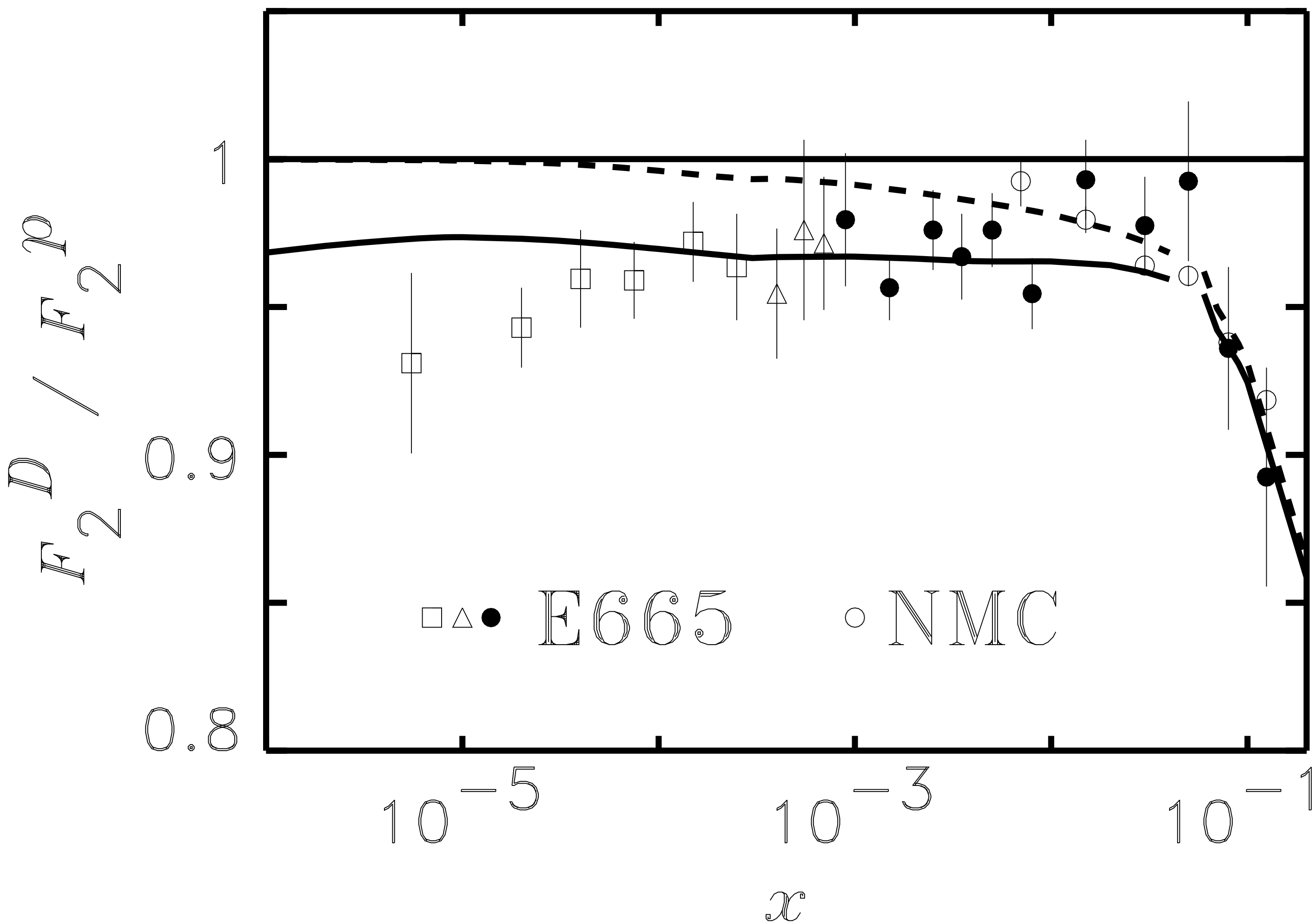


WM, Thomas, Phys. Rev. C52 (1995) 3373



NMC, Nucl. Phys. B481 (1996) 23

Comparison with data



WM, Thomas, Phys. Rev. C 52 (1995) 3373
- see also Badelek, Kwiecinski (1992),
Nikolaev, Zoller (1992)

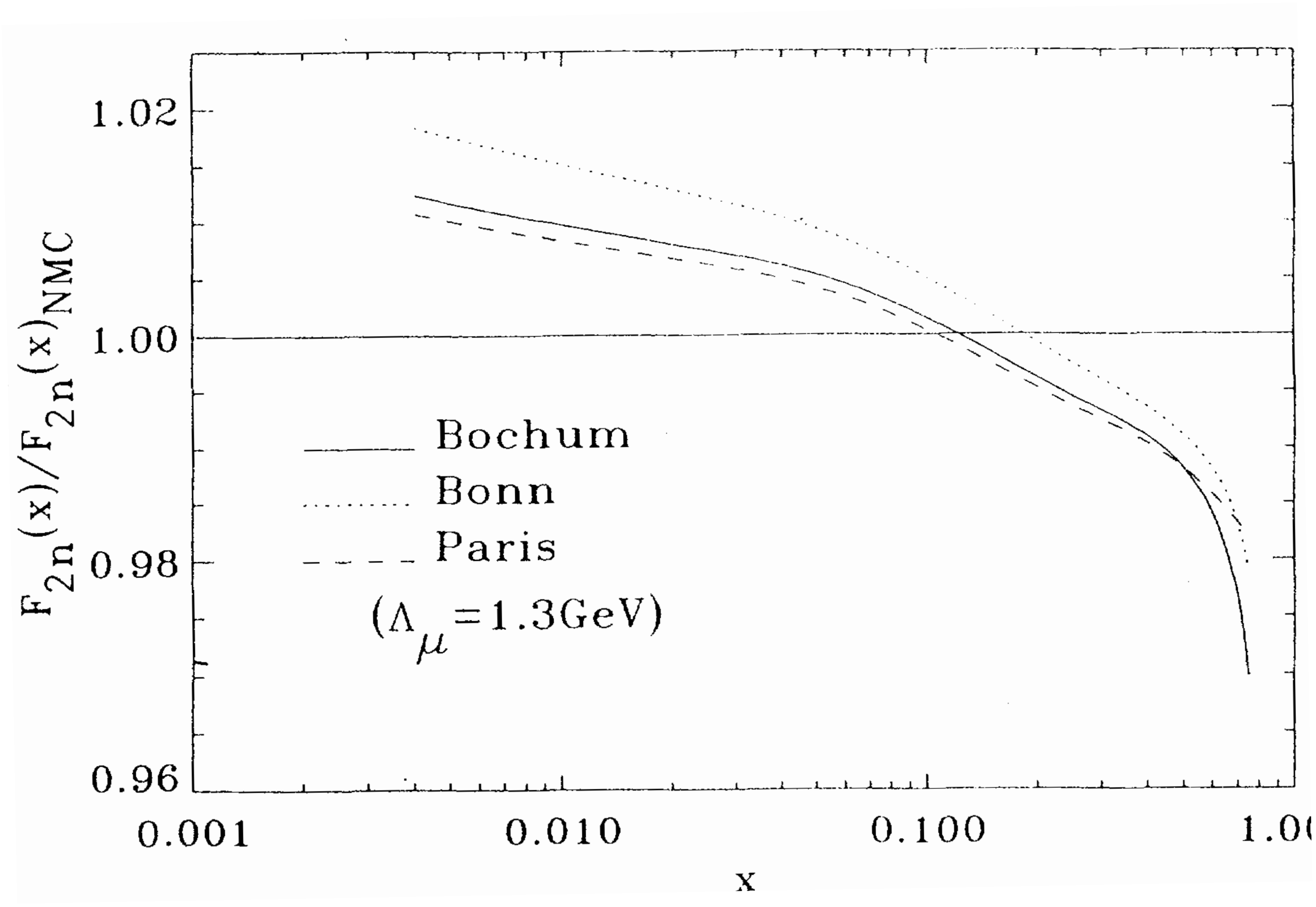
Effect on neutron structure function at small x

$$\frac{F_2^n}{(F_2^n)_{\rm exp}} = 1 - \frac{\delta F_2^d}{F_2^d} \left(\frac{1 + (F_2^n/F_2^p)_{\rm exp}}{(F_2^n/F_2^p)_{\rm exp}} \right)$$

where "experimental" n/p ratio is defined as

$$\left.\frac{F_2^n}{F_2^p}\right|_{\rm exp} \equiv \frac{F_2^d}{F_2^p} - 1$$

Effect on neutron structure function at small x



1-2% enhancement at $x \sim 0.01$

Gottfried sum rule

Integrated difference of p and n structure functions

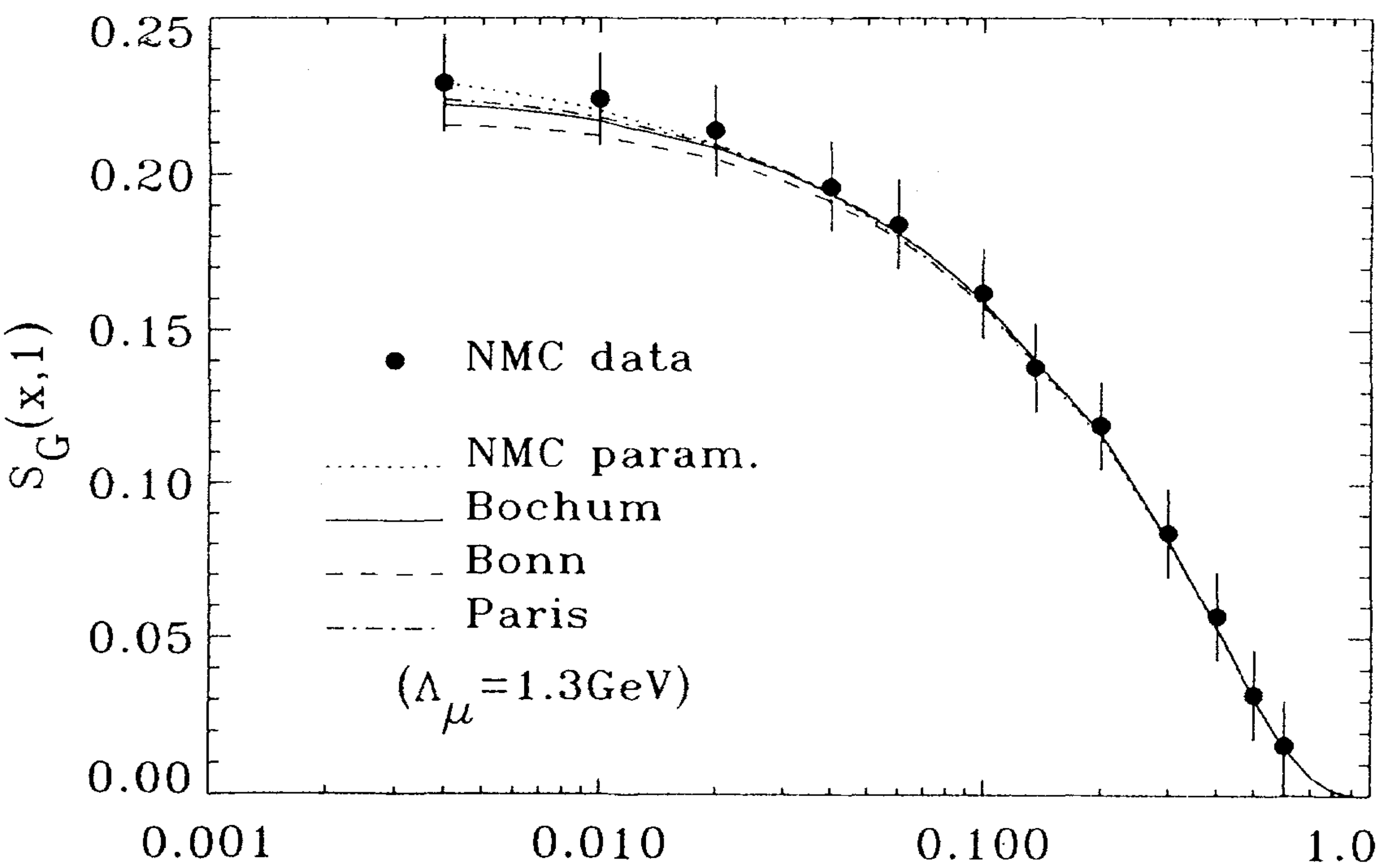
$$S_G = \int_0^1 dx \; \frac{F_2^p(x) - F_2^n(x)}{x}$$
$$= \frac{1}{3} + \frac{2}{3} \int_0^1 dx \; (\bar{u}(x) - \bar{d}(x))$$

Experiment: $S_G = 0.235 \pm 0.026$

NMC, Phys. Rev. D 50 (1994) 1

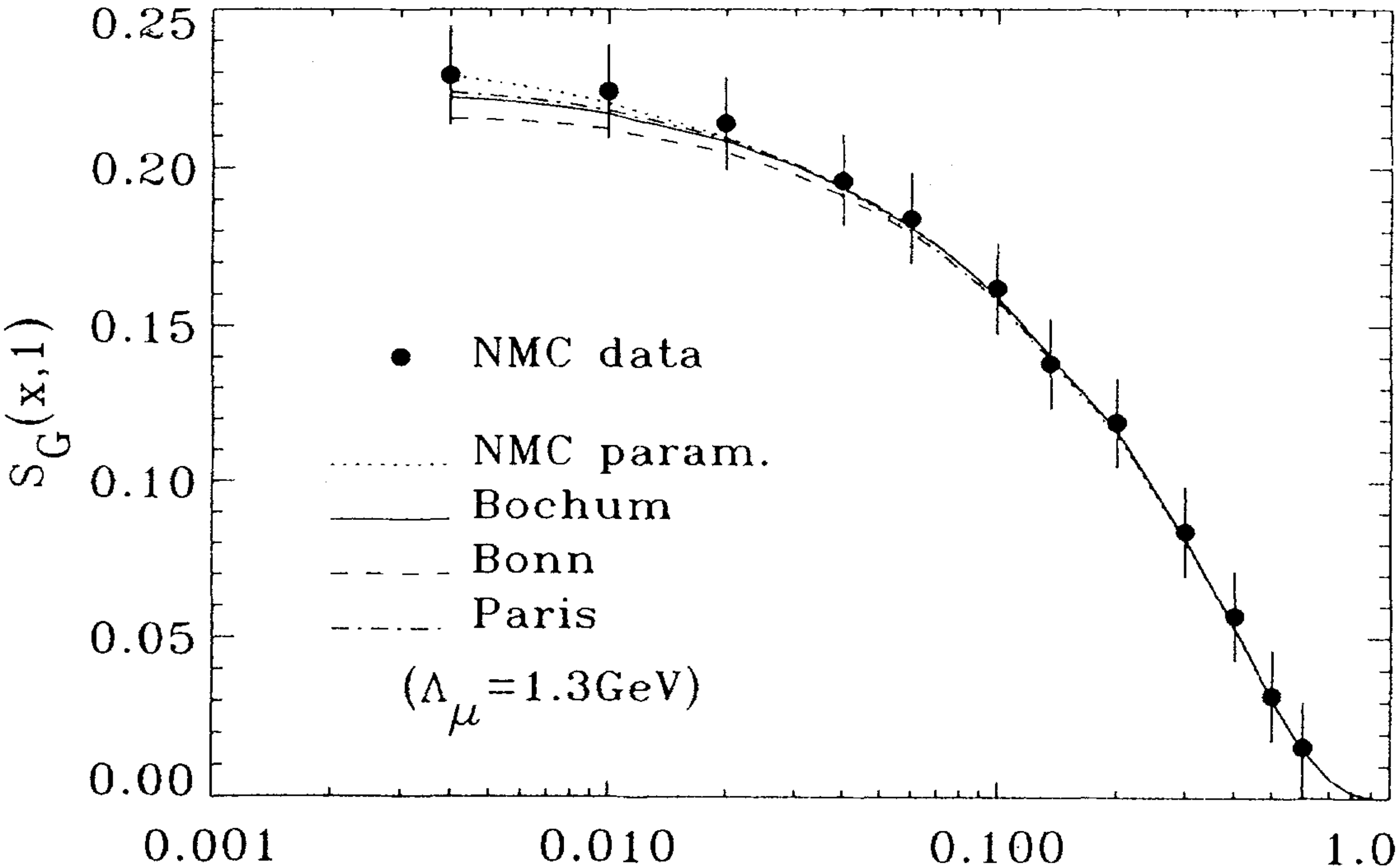
$\Rightarrow$ $\bar{d}(x) \neq \bar{u}(x)$ flavor asymmetric sea!

Saturation of Gottfried sum rule



$$S_G(x,1) = \int_x^1 dx' \; \frac{F_2^p(x') - F_2^n(x')}{x'}$$

Saturation of Gottfried sum rule



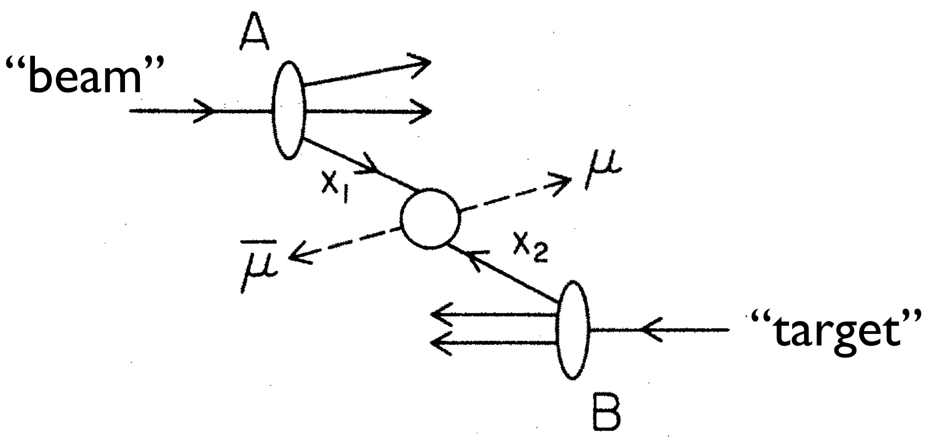
⟹ correction to $S_G(0,1) \approx -0.02$

~ 10% decrease due to shadowing

Fermilab E866 Drell-Yan experiment

$q\bar{q}$ annihilation in hadron-hadron collisions

$$q\bar{q} \rightarrow \gamma^* \rightarrow \mu^+\mu^-$$



Drell, Yan, Phys. Rev. Lett. 25 (1970) 316

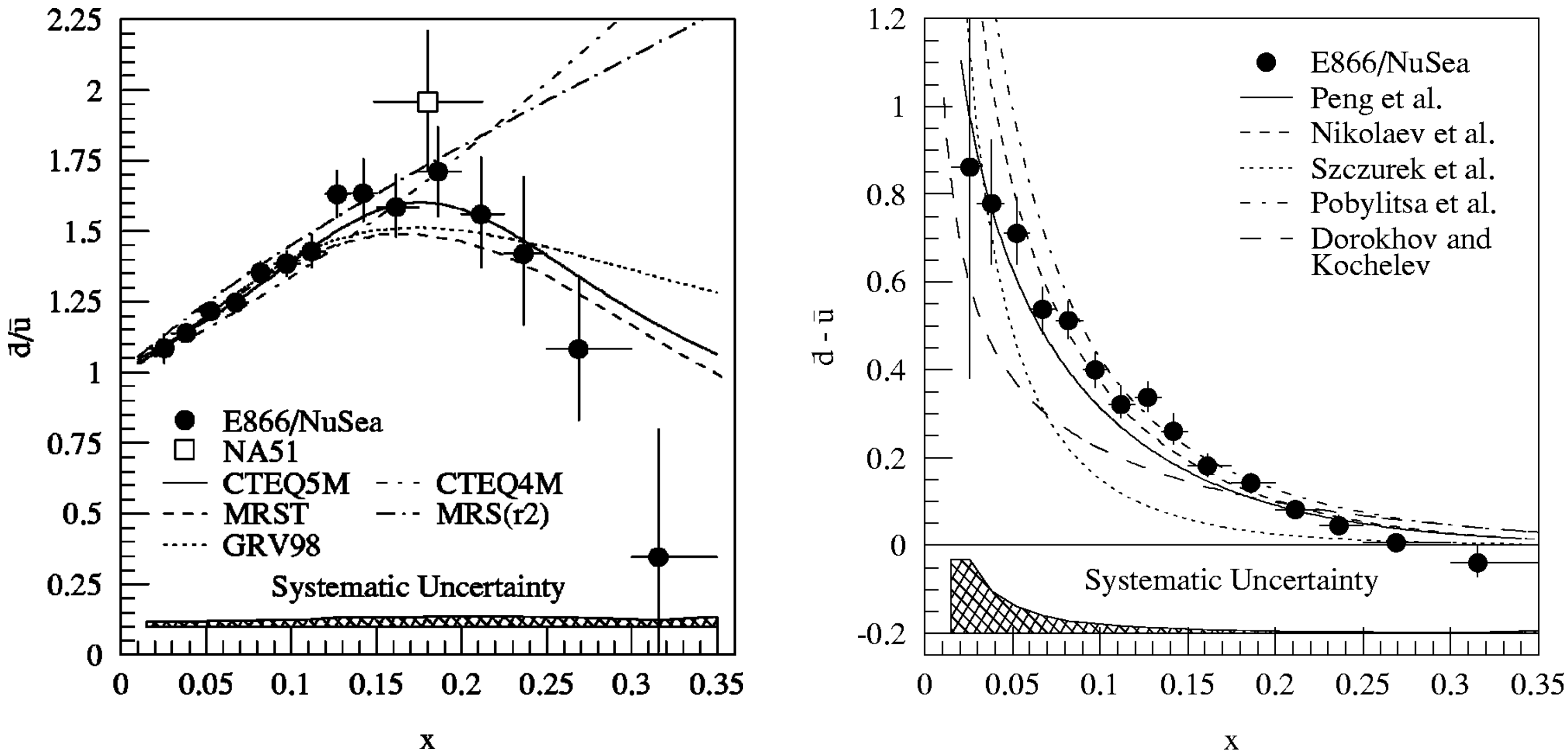
$$\frac{d^2\sigma}{dx_b dx_t} = \frac{4\pi\alpha^2}{9Q^2} \sum_q e_q^2 \left(q(x_b)\bar{q}(x_t) + \bar{q}(x_b)q(x_t)\right)$$

For $x_b \gg x_t$

$$\frac{\sigma^{pd}}{2\sigma^{pp}} \approx \frac{1}{2}\left(1 + \frac{\bar{d}(x_t)}{\bar{u}(x_t)}\right)$$

Ellis, Stirling, Phys. Lett. B256 (1991) 258

Towell et al., Phys. Rev. D 64 (2001) 052002



$$\int_0^1 dx\ (\bar{d}(x) - \bar{u}(x)) = 0.118 \pm 0.012$$

Why is $\bar{d} \neq \bar{u}$?

Pauli blocking

Since proton has more valence u than d

⇨ easier to create $d\bar{d}$ than $u\bar{u}$

Field, Feynman, Phys. Rev. D15 (1977) 2590

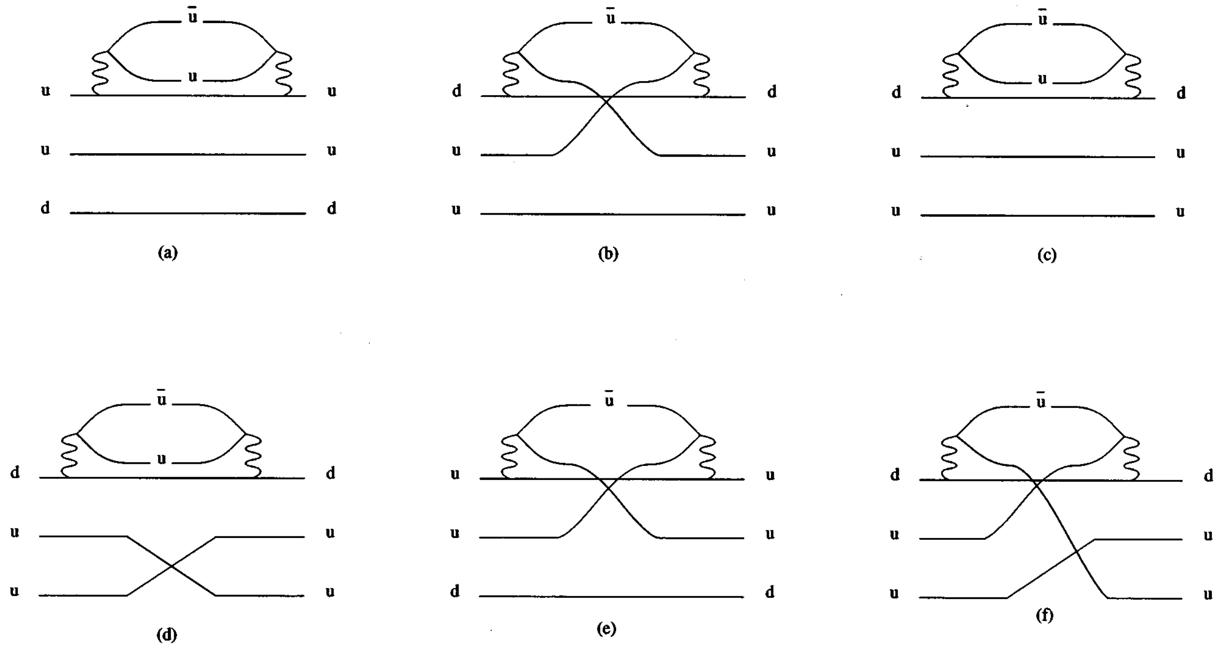
Explicit calculations of antisymmetrization effects in $g \longrightarrow u\bar{u}$ and $g \longrightarrow d\bar{d}$

⇨ $\bar{u} > \bar{d}$

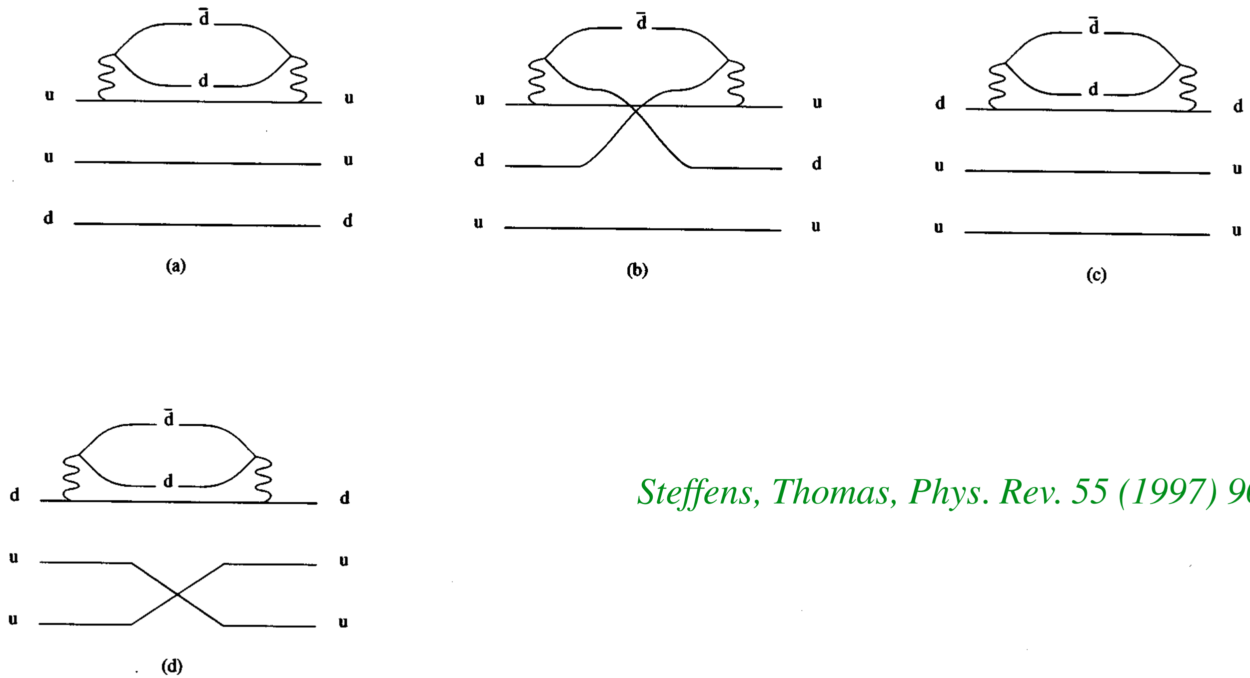
asymmetry tiny

Ross, Sachrajda, Nucl. Phys. B149 (1979) 497
Steffens, Thomas, Phys. Rev. 55 (1997) 900

$u\bar{u}$



$d\bar{d}$



Steffens, Thomas, Phys. Rev. 55 (1997) 900

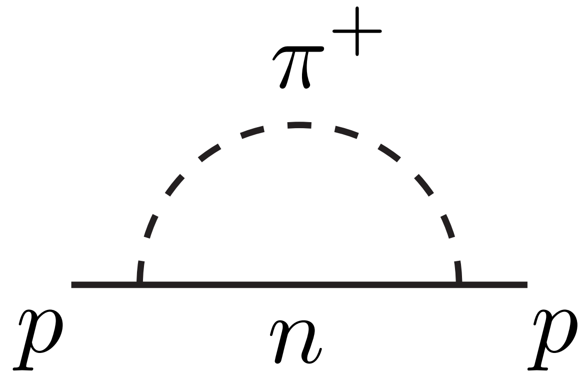
"BUT, HEISENBERG — YOU MUST BE CERTAIN ABOUT SOMETHING!"

Why is $\bar{d} \neq \bar{u}$?

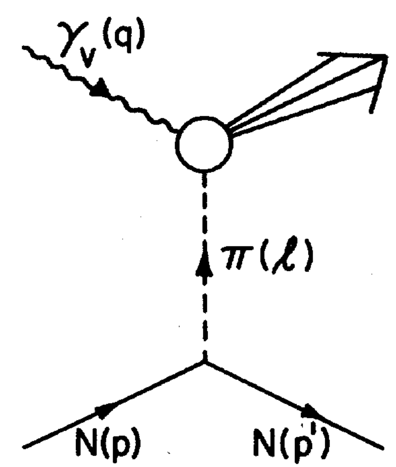
Pion cloud

some of the time the proton looks like a neutron & π^+

(Heisenberg Uncertainty Principle)



$$p \to \pi^+ \, n \to p$$



at the quark level

$$uud \to (udd)(\bar{d}u) \to uud$$

Sullivan, Phys. Rev. D5 (1972) 1732

Thomas, Phys. Lett. 126B (1983) 97

$$\Longrightarrow \quad \bar{d} > \bar{u} \; !$$

see Nucleon Models...

Tomorrow’s lecture:

3. Connection with low energy models
4. PDFs from the lattice