XIV Escola de Veraõ Jorge André Swieca, Fisica Nuclear Teórica *January 25-31, 2009*
Itaipava, Brazil

Quark Structure of the Nucleon

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Jefferson Lab

Outline

Lecture 1

- QCD and the strong nuclear force

- Electron-nucleon scattering

- Quark distributions in the nucleon
  - $\longrightarrow$ valence quarks at large x
  - $\longrightarrow$ nuclear effects on quark structure

Outline

Lecture 2

- Quark-hadron duality
- "Bloom-Gilman" duality in structure functions
- Duality in QCD
- Resonances & local quark-hadron duality
  - → "truncated" moments in QCD
- Duality in the neutron
  - → extraction of neutron resonance structure from nuclear data

Outline

Lecture 3

- Elastic *ep* scattering
- Two-photon exchange
  - $\longrightarrow$ Rosenbluth separation *vs.* polarization transfer
- Global analysis of form factors
- Parity-violating electron scattering
  - $\longrightarrow$ strangeness in the proton
  - $\longrightarrow$ constraints on "new" physics

QCD and the strong nuclear force

Building Blocks of the Universe

FERMIONS matter constituents
spin = 1/2, 3/2, 5/2, ...

Leptons spin = 1/2

Flavor		Mass GeV/c^2	Electric charge
ν_e	electron neutrino	$<1\times10^{-8}$	0
e	electron	0.000511	–1
ν_μ	muon neutrino	<0.0002	0
μ	muon	0.106	–1
ν_τ	tau neutrino	<0.02	0
τ	tau	1.7771	–1

Quarks spin = 1/2

Flavor		Approx. Mass GeV/c^2	Electric charge
u	up	0.003	2/3
d	down	0.006	–1/3
c	charm	1.3	2/3
s	strange	0.1	–1/3
t	top	175	2/3
b	bottom	4.3	–1/3

- **Each quark comes in 3 “colours”: red, green and blue.**
- **Leptons do not carry color charge.**

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most of visible matter made up of these

Force Carriers of the Universe

BOSONS force carriers
spin = 0, 1, 2, ...

Unified Electroweak spin = 1		
Name	Mass GeV/c^2	Electric charge
γ photon	0	0
W^-	80.4	–1
W^+	80.4	+1
Z^0	91.187	0

Strong (color) spin = 1		
Name	Mass GeV/c^2	Electric charge
g gluon	0	0

- **The massless photon mediates the long-range e.m. interactions.**
- **Gluons carry color and mediate the strong interaction.**
- **The very massive W^-, W^+, and Z^0 bosons mediate the weak interaction**

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most of hadron mass due to these

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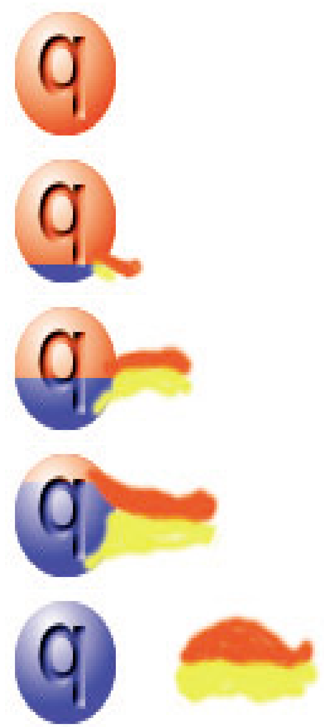
Quantum Chromodynamics (QCD)

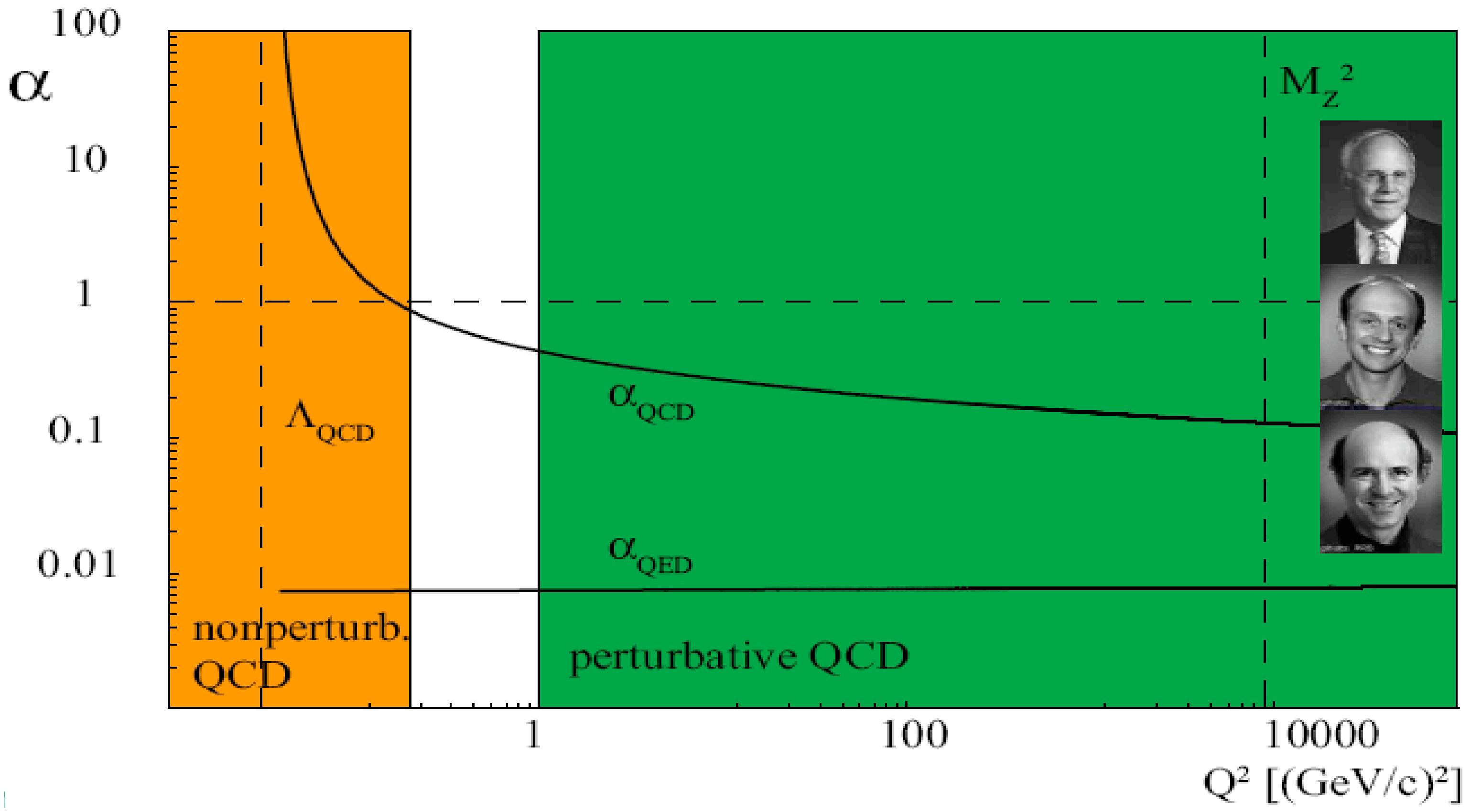
- **Photons do not carry electric charge.**
- **Gluons *do* carry colour charge!**
- **Gluons can directly interact with other gluons!**
- **This is new!**



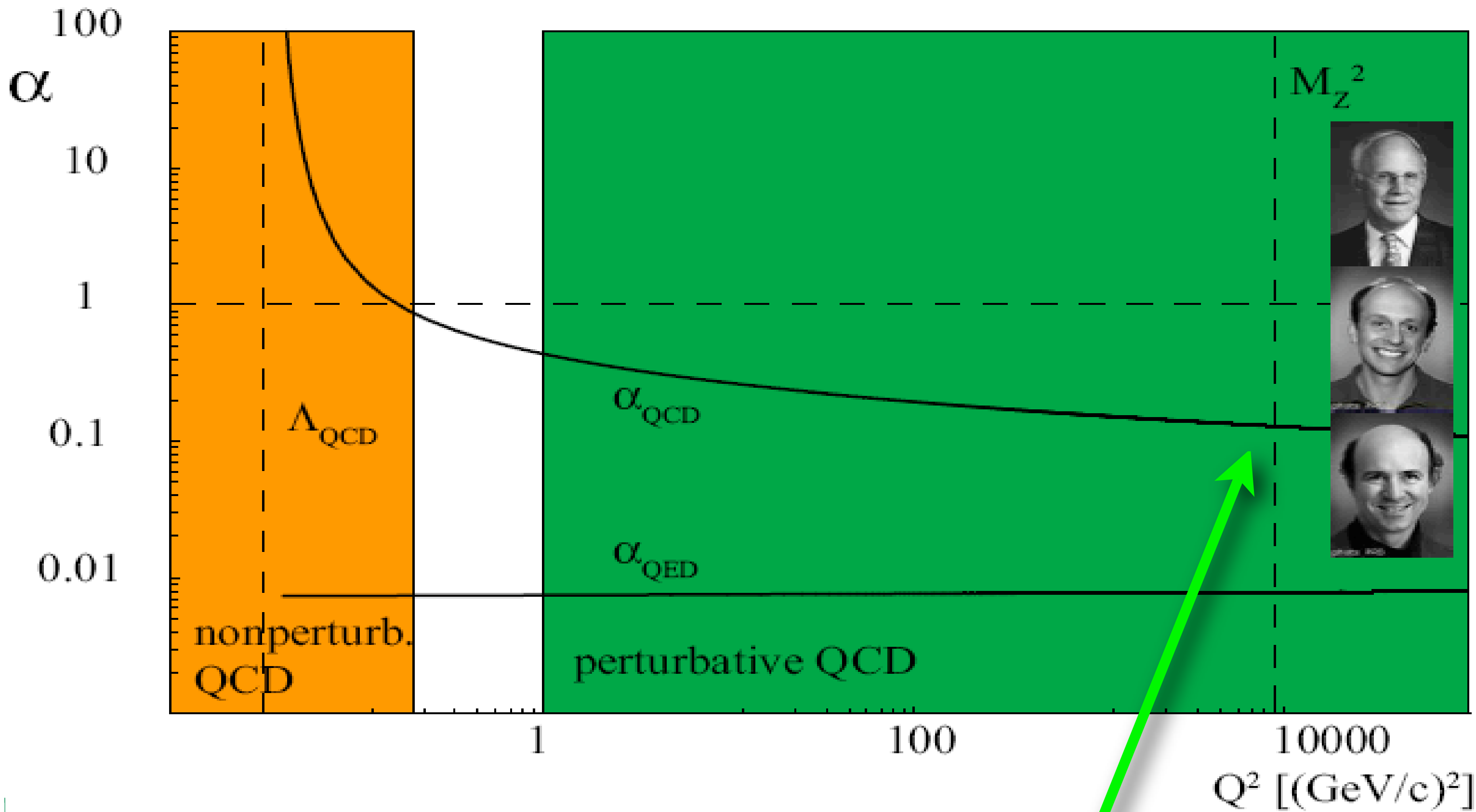
A red quark emitting a red anti-blue gluon to leave a blue quark.

Quark-quark force grows WEAKER as quarks come close

´ “Asymptotic Freedom”

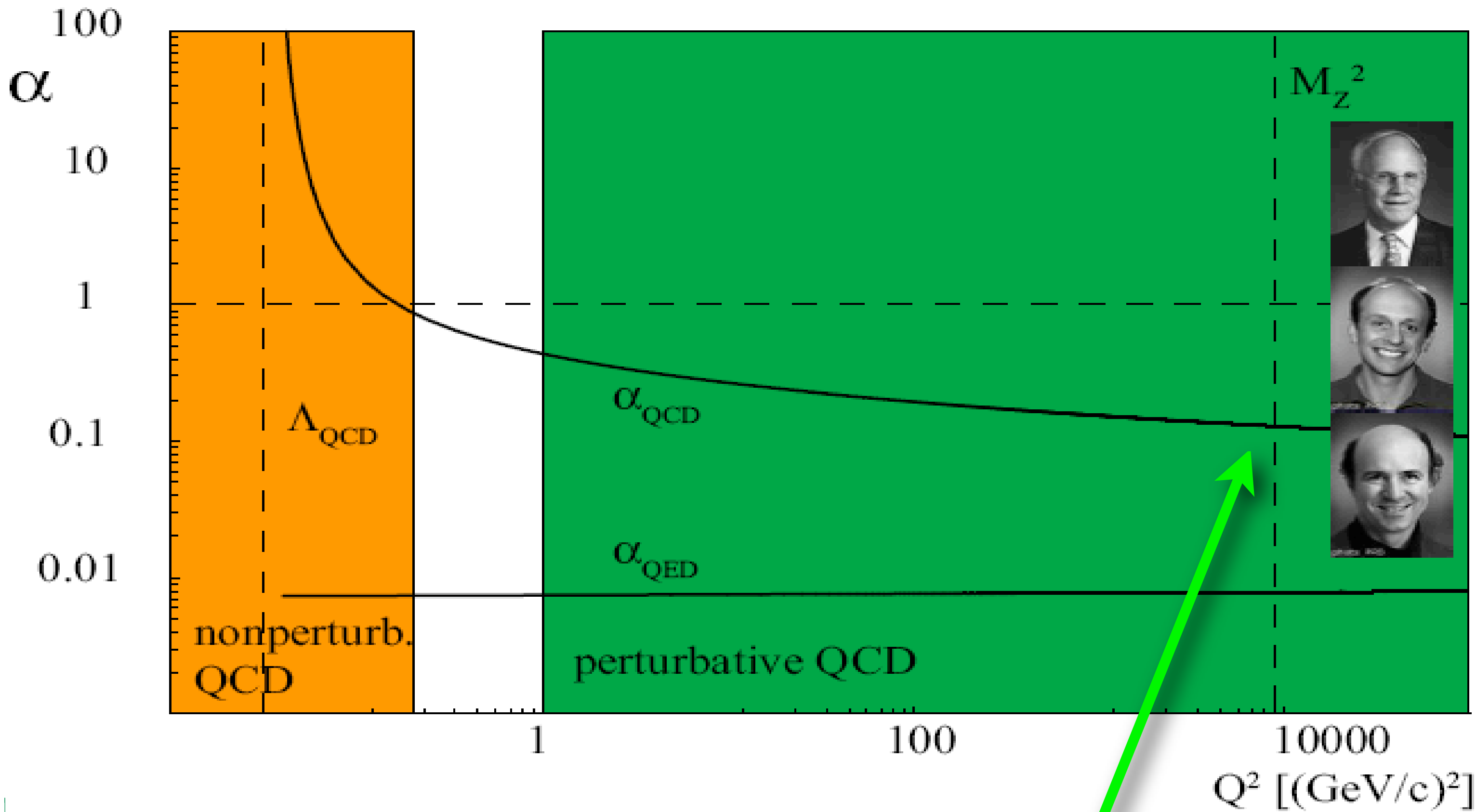


100
α
10
1
0.1
0.01
M_Z^2
Λ_{QCD}
α_{QCD}
α_{QED}
nonperturb.
QCD
perturbative QCD
1
100
10000
Q^2 [(GeV/c)²]



2004 Nobel Prize for discovery of asymptotic freedom (1973)

(Gross, Politzer, Wilczek)



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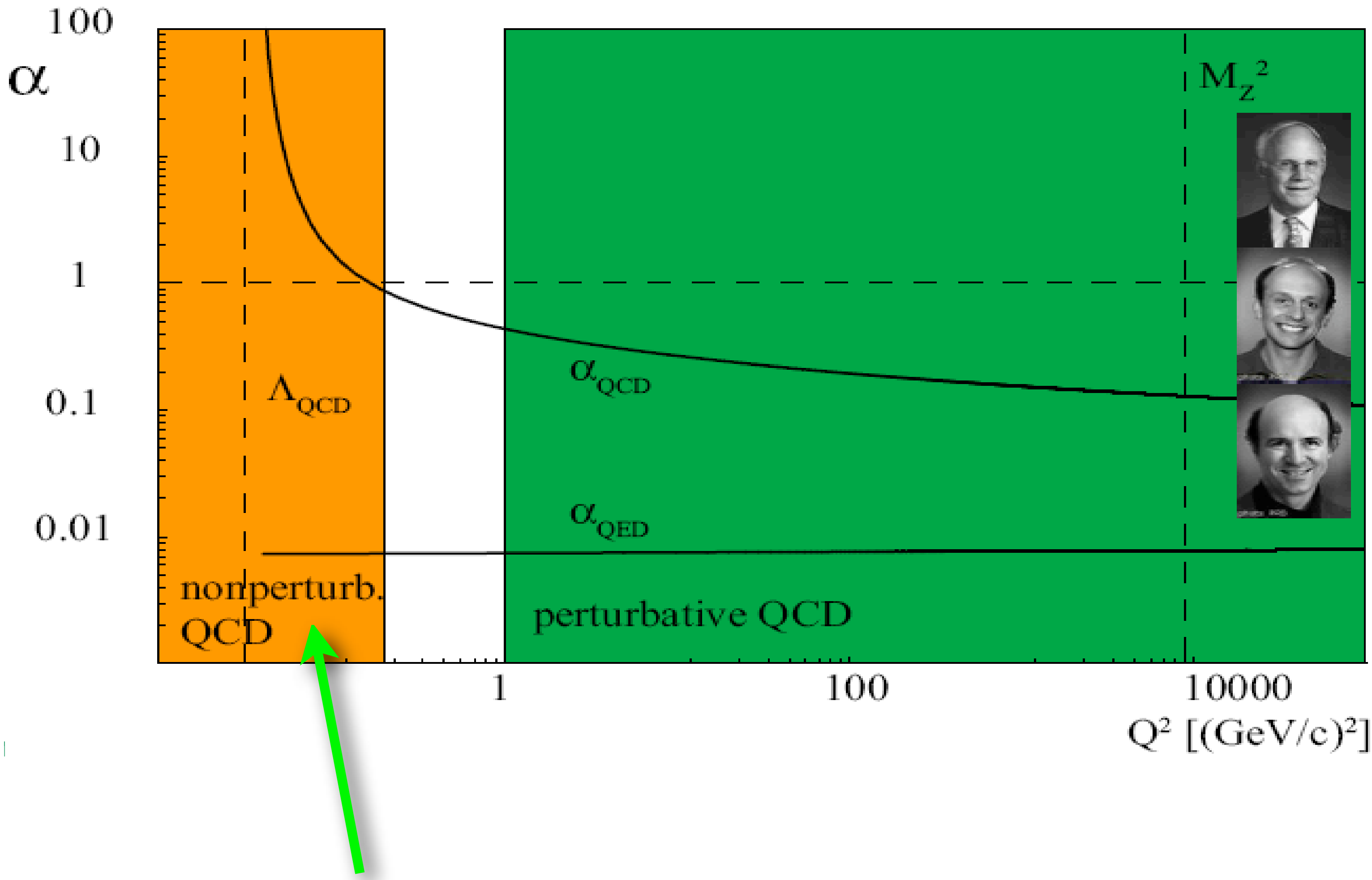
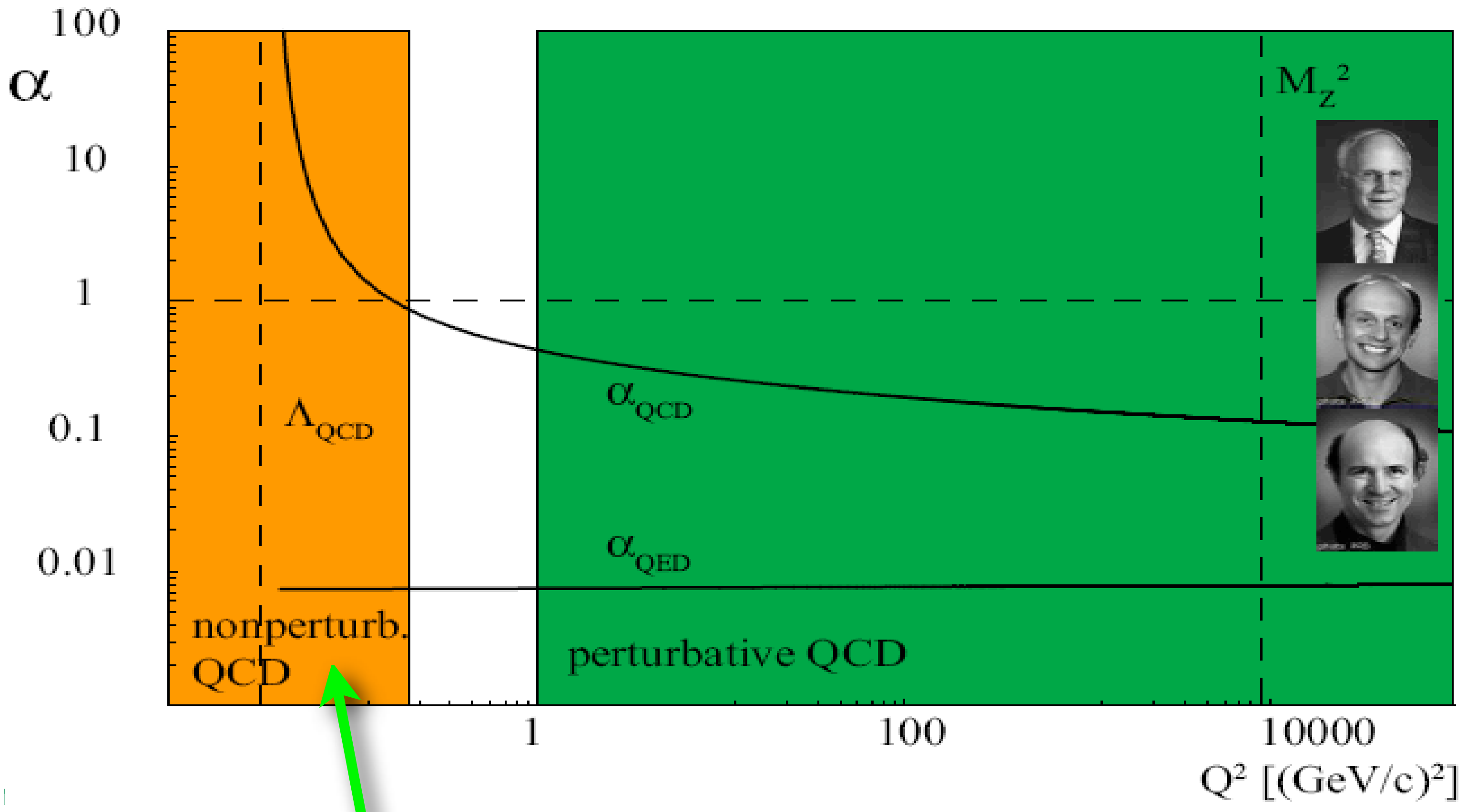
→ calculate observables using perturbation theory as power series in small expansion parameter α_s



BUT - only part of the story...

at low energy ⟶ <u>*confinement*</u> !



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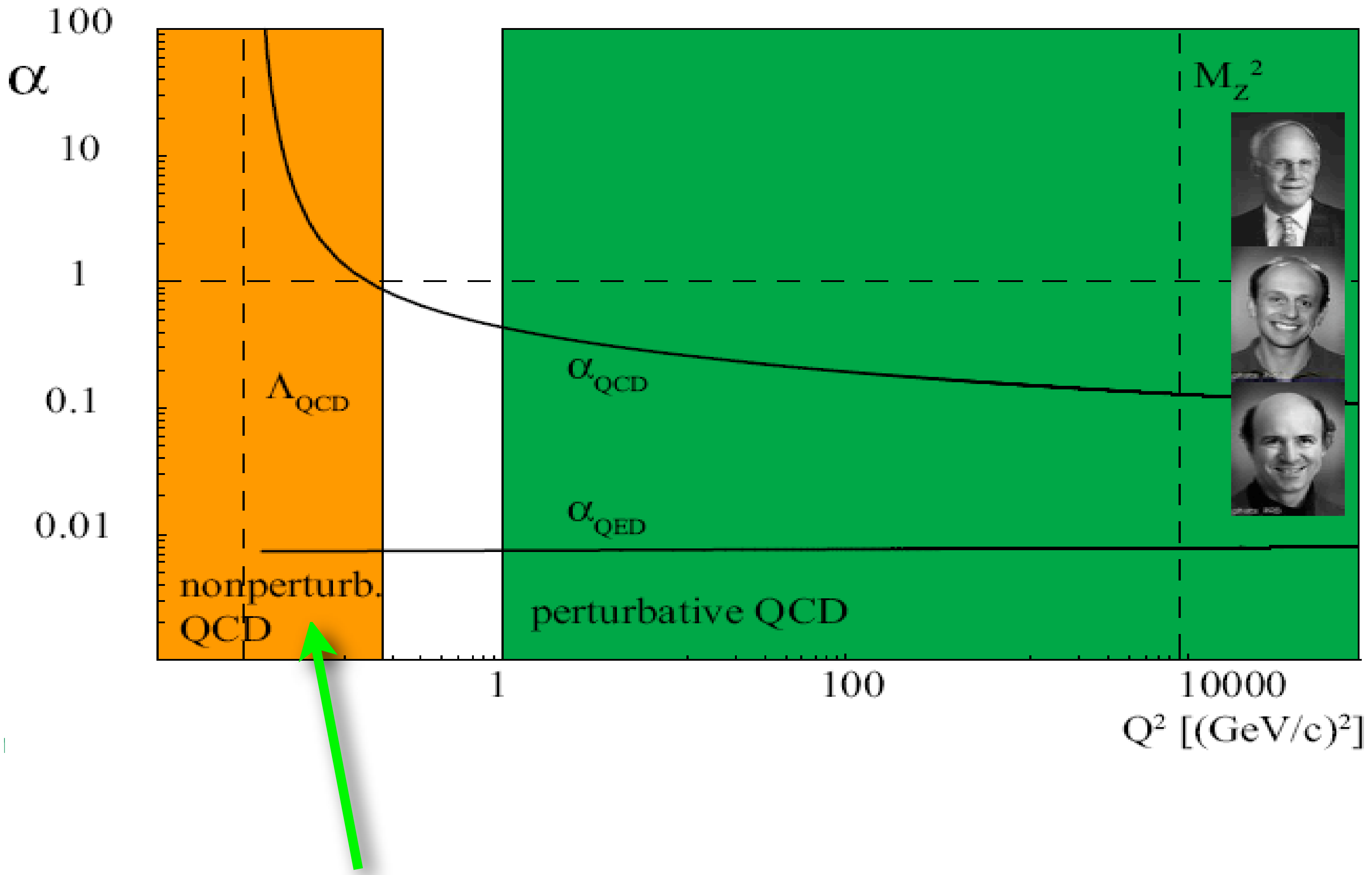
⟹ $\alpha_s \sim 1$ so cannot use perturbative expansion



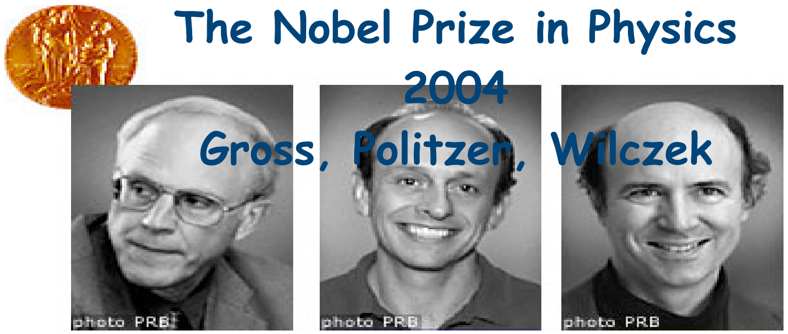
BUT - only part of the story...

at low energy ⟶ *confinement* !

➡ $\alpha_s \sim 1$ so cannot use perturbative expansion

➡ here QCD said to be "nonperturbative"

QCD: Unsolved in Nonperturbative Regime



• **2004 Nobel Prize awarded for "asymptotic freedom"**

• **BUT in nonperturbative regime QCD is still unsolved**

• **One of the top 10 challenges for physics!**

• **Is it right/complete?**

• **Do glueballs, exotics and other apparent predictions of QCD in this regime agree with experiment?**

→ central to answering these questions is the need to understand *how quarks form hadrons*

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."

How to probe the structure of hadrons?

How to probe the structure of hadrons?

collide hadrons

How to probe the structure of hadrons?

collide hadrons

probe with leptons

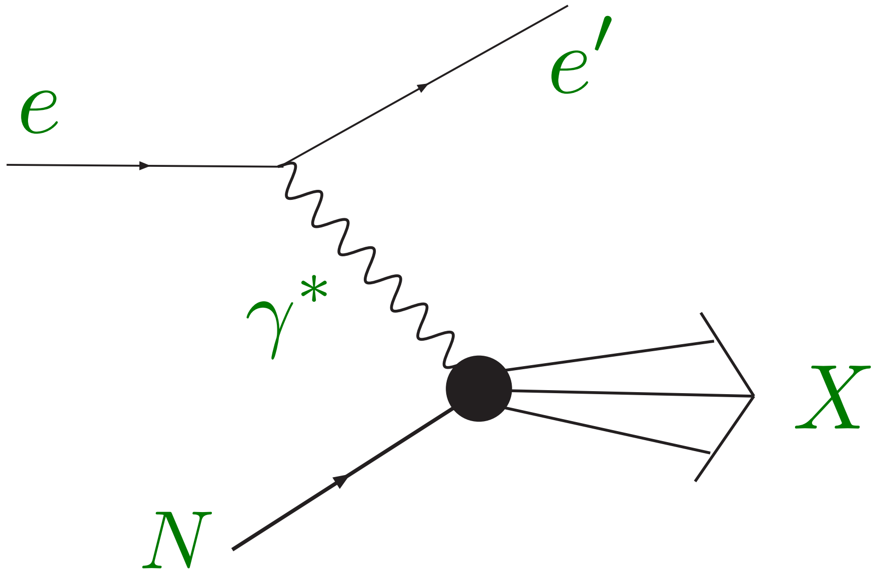
How to probe the structure of hadrons?

collide hadrons

probe with leptons

Electron scattering

Electron Scattering Provides an Ideal Microscope for Nuclear Physics



- Electrons are point-like
- The interaction (QED) is well-known
- The interaction is weak

Electron scattering

(at Jefferson Lab)

Thomas Jefferson National Accelerator Facility (Jefferson Lab)

located in Newport News, Virginia

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"discovery" of America, Jamestown (1607)

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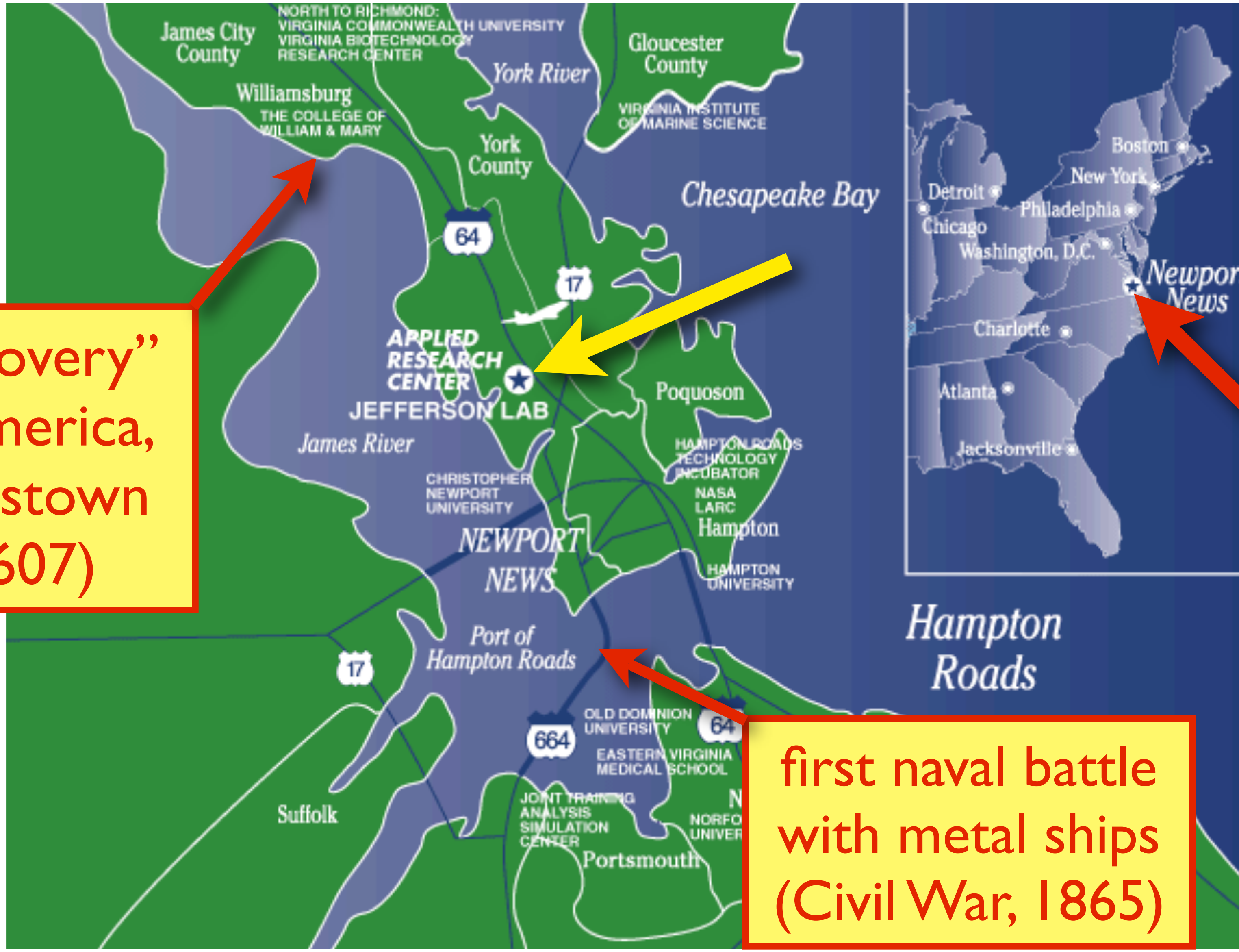


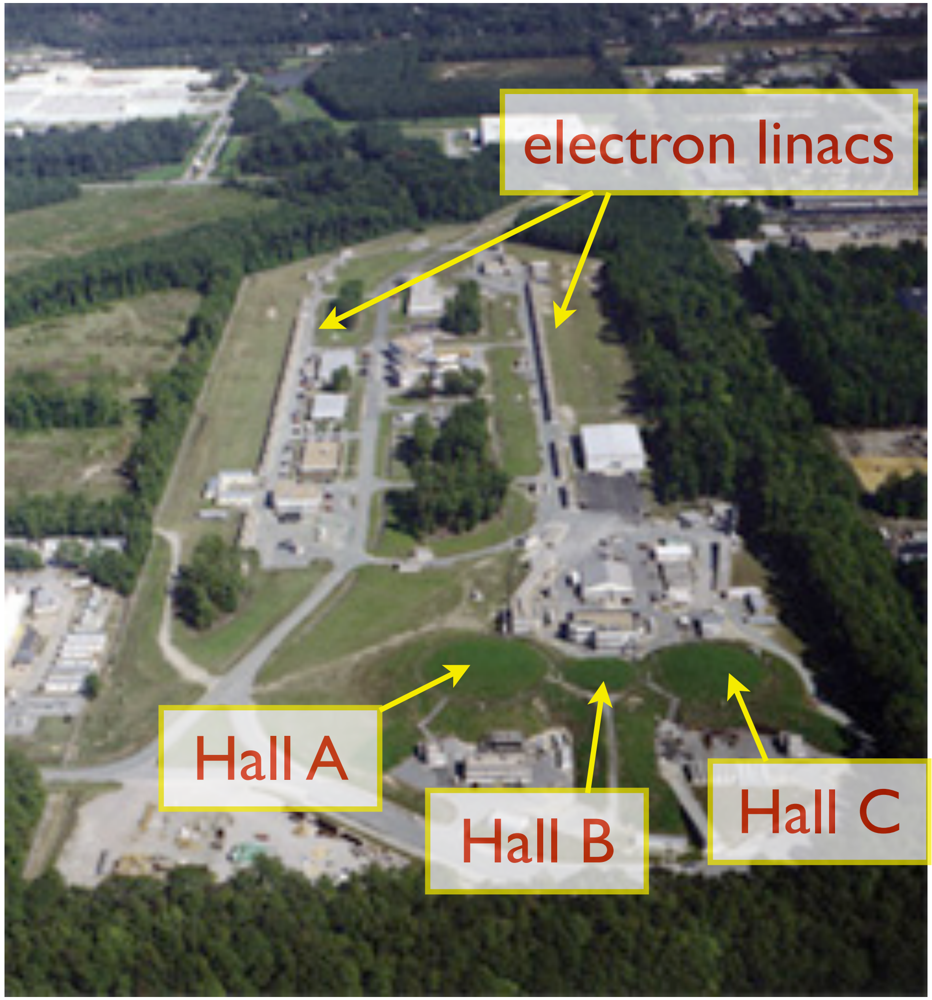
“discovery” of America, Jamestown (1607)

first naval battle with metal ships (Civil War, 1865)

located in Newport News, Virginia

Newport News, Virginia

Thomas Jefferson National Accelerator Facility (Jefferson Lab)



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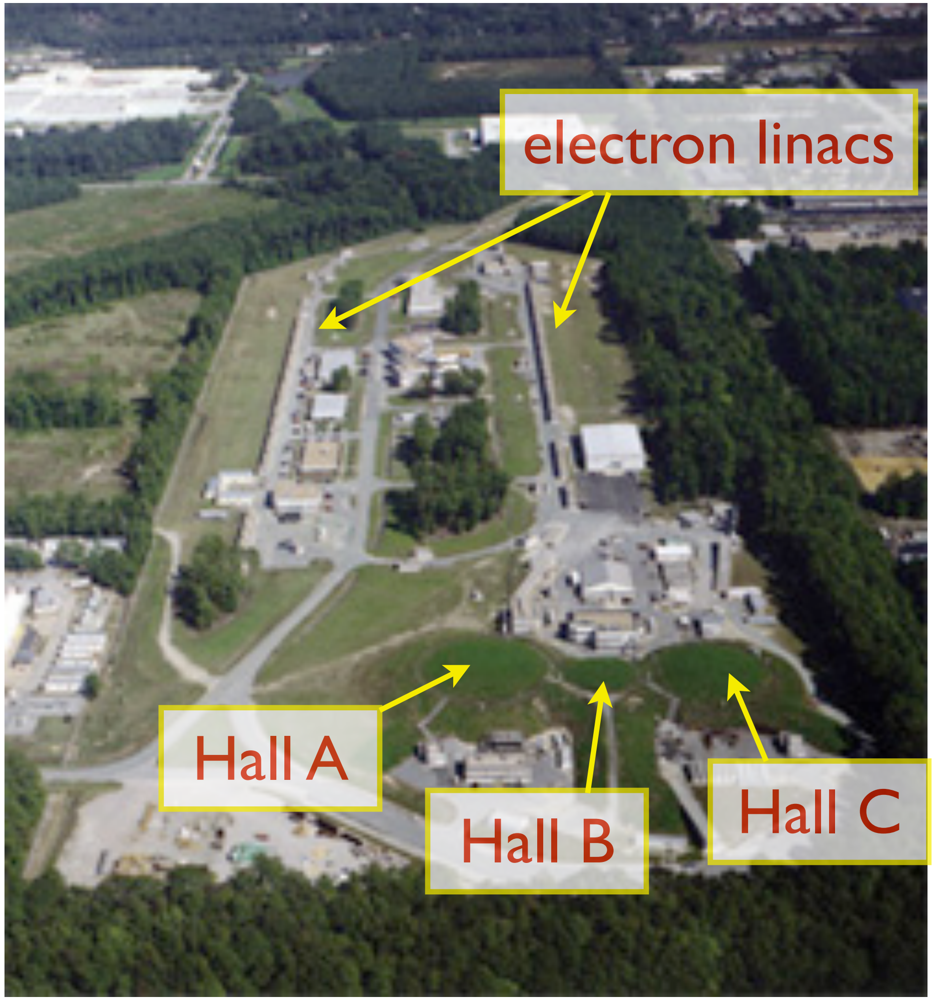
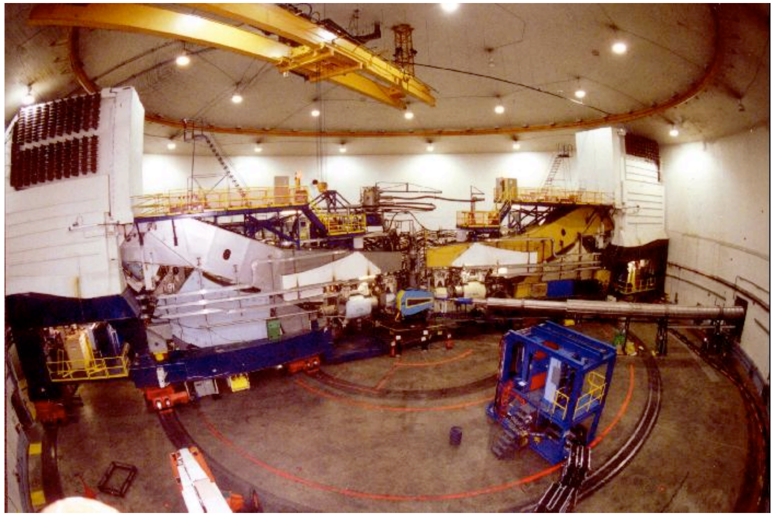


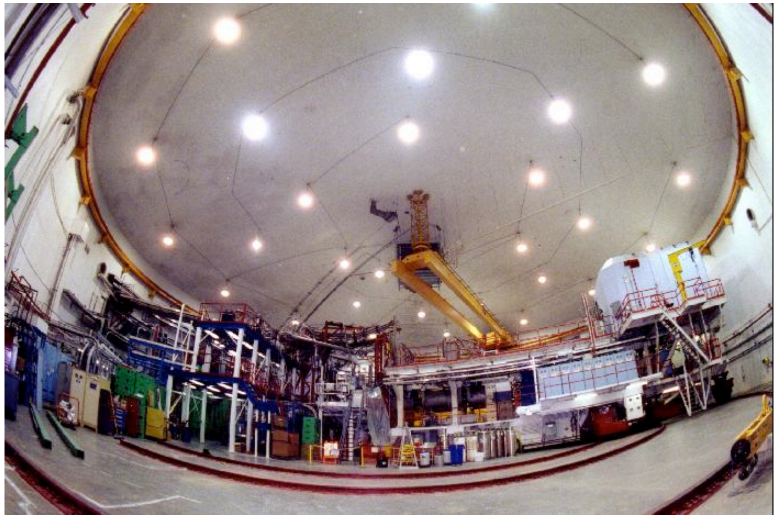
Experimental Halls

Hall A

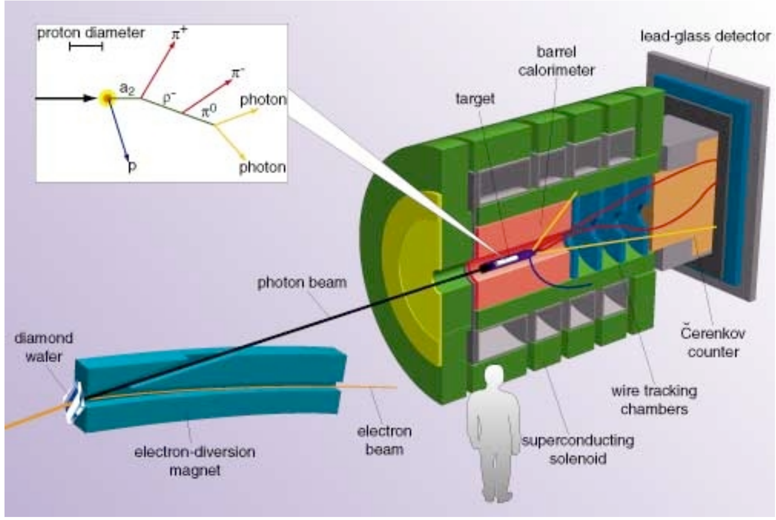


Hall B

Hall C

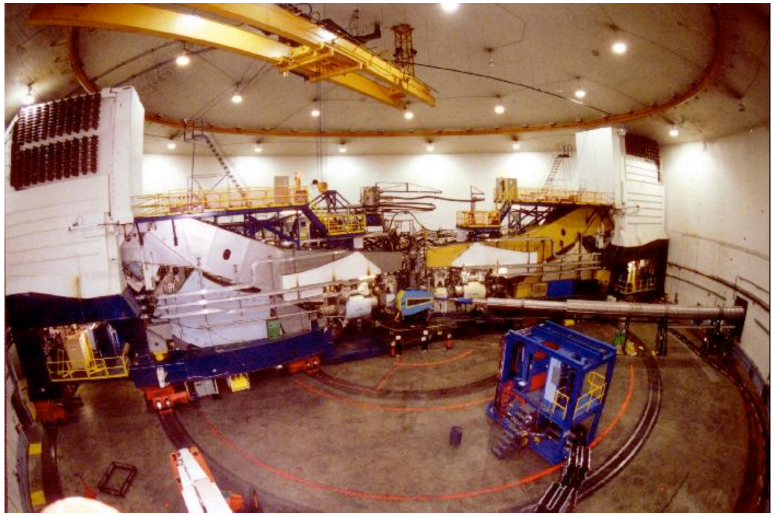


Hall D



Experimental Halls

Hall A



Hall C

- high luminosity
  $> 10^{38}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$
- very high precision measurements
- high Q^2 form factors, parity-violating *e* scattering, precision structure functions

Experimental Halls

Hall B

CLAS

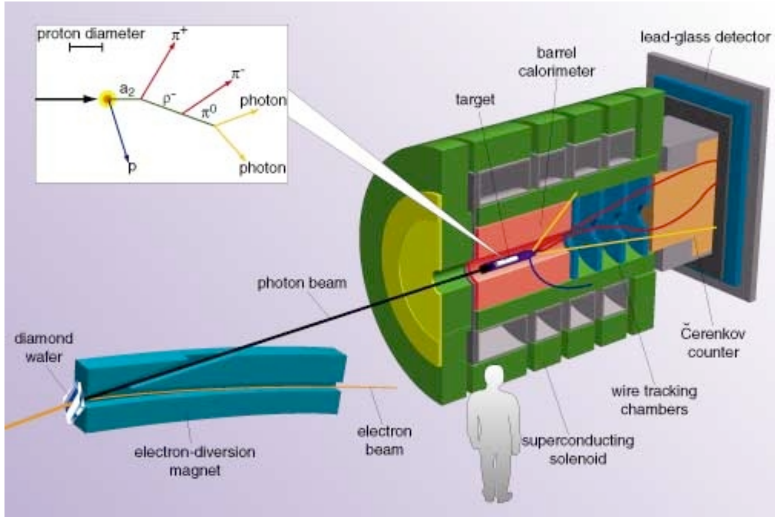
(CEBAF Large Acceptance Spectrometer)

- large acceptance
  lower luminosity
  $\sim 10^{35}\ \mathrm{cm}^{-2}\ \mathrm{s}^{-1}$
- collect all data "at once"
- N^* spectroscopy
  (multi-hadron final states),
  deep exclusive reactions
  (generalized parton distributions)

Experimental Halls

- new Hall to be constructed as part of 12 GeV Upgrade
- 4π acceptance
- photon beam
- exotic meson spectroscopy ($q\bar{q}g$ states)

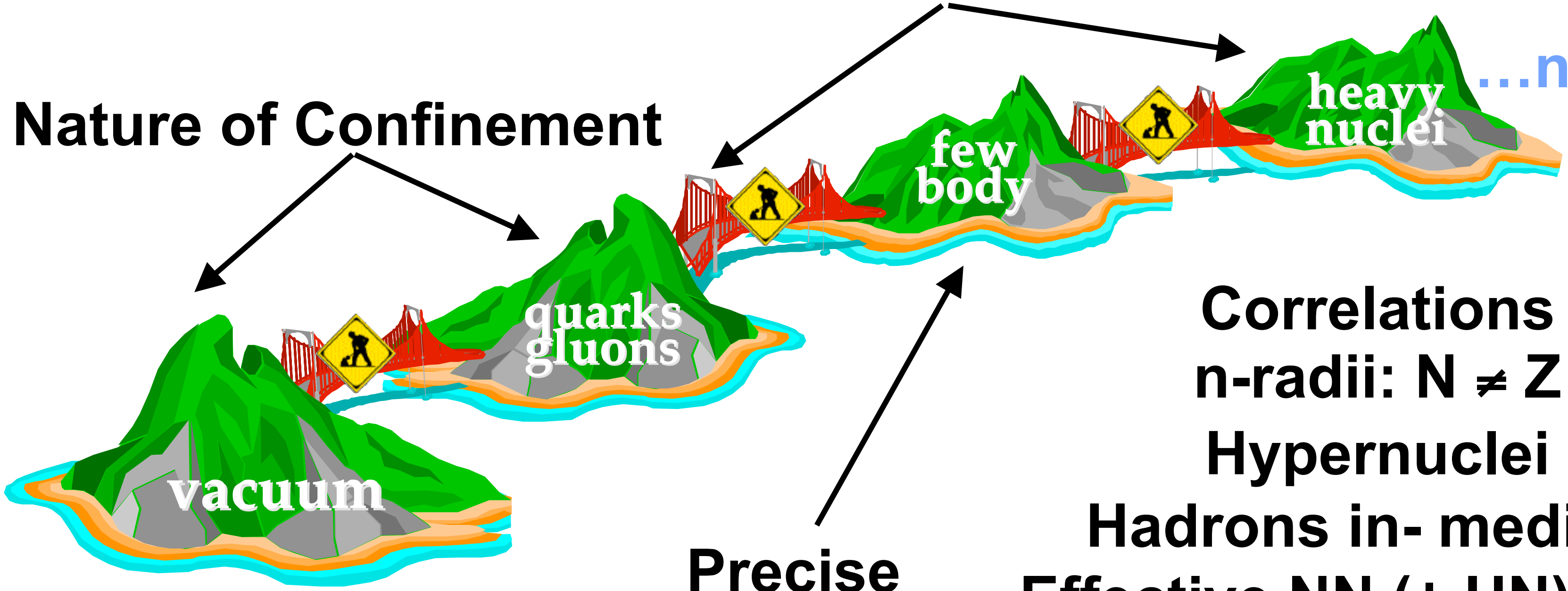
Hall D



JLab Central to *all* of Nuclear Science

Quark-Gluon Structure
Of Nucleons and Nuclei

Nature of Confinement



…n-stars

Correlations
n-radii: N ≠ Z
Hypernuclei
Hadrons in- medium
Effective NN (+ HN) force

Precise
few-nucleon
calculations

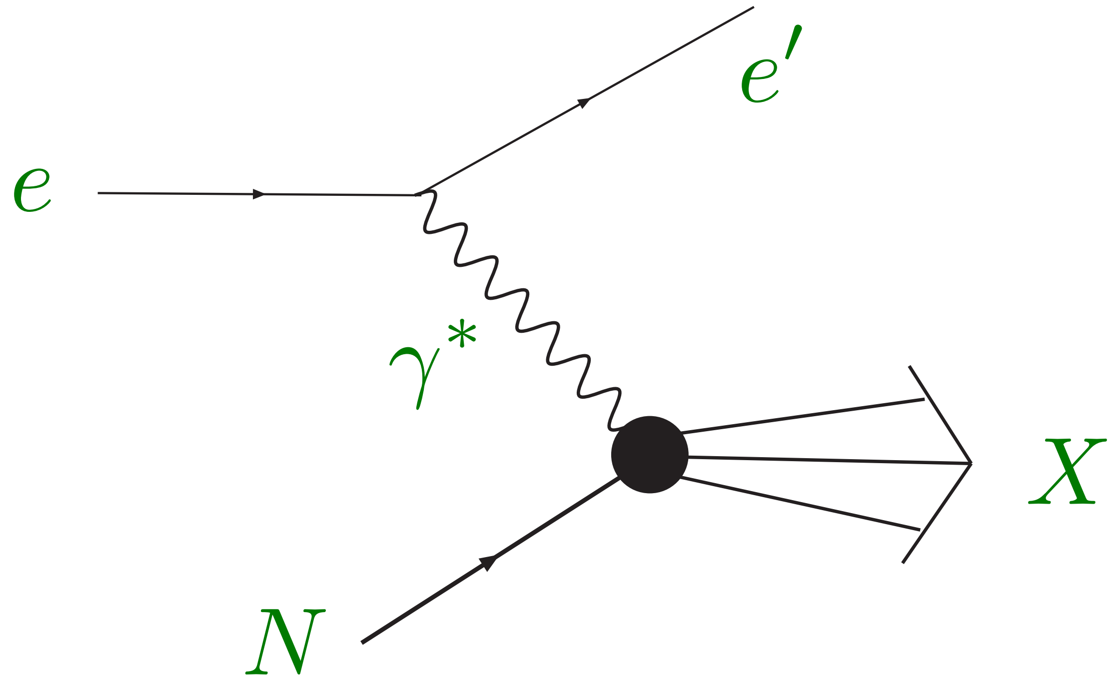
Exotic mesons
and baryons

Electron scattering

(theory)

Electron scattering

Inclusive cross section for $eN \to eX$

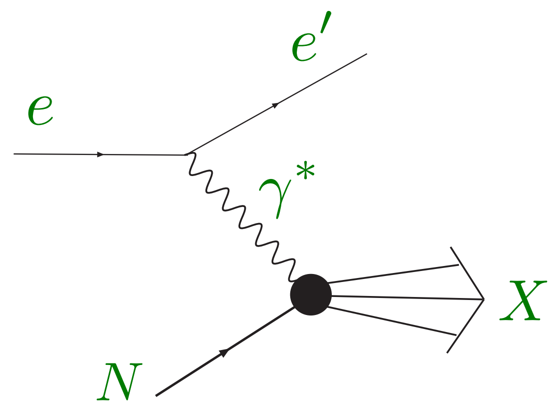


most likely event
at high energy

⟹ one-photon exchange approximation

Electron scattering

Inclusive cross section for $eN \to eX$



$$\frac{d^2\sigma}{d\Omega dE'} = \frac{4\alpha^2 E'^2 \cos^2\frac{\theta}{2}}{Q^4}\left(2\tan^2\frac{\theta}{2}\frac{F_1}{M} + \frac{F_2}{\nu}\right)$$

$$\left.\begin{aligned} \nu &= E - E' \\ Q^2 &= \vec{q}^{\,2} - \nu^2 = 4EE'\sin^2\frac{\theta}{2} \end{aligned}\right\} \quad x = \frac{Q^2}{2M\nu}$$

"Bjorken scaling variable"

F_1 , F_2 "structure functions"

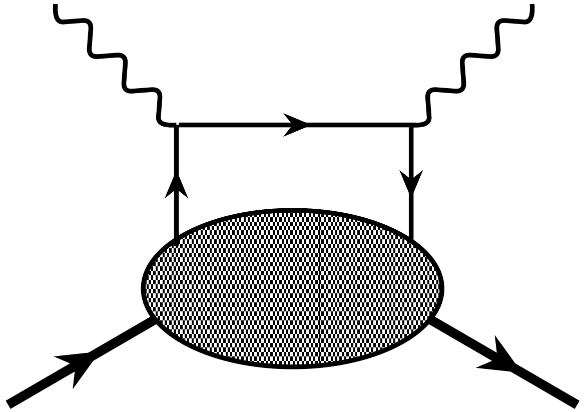
⟶ contain all information about structure of nucleon

⟶ functions of $x,\ Q^2$ in general

Parton model

⟶ scatter from individual quarks ("*partons*") in hadron

$$F_2(x, Q^2) = x \sum_q e_q^2 \, q(x, Q^2) \qquad (q=u,d,s\ldots)$$



Parton model

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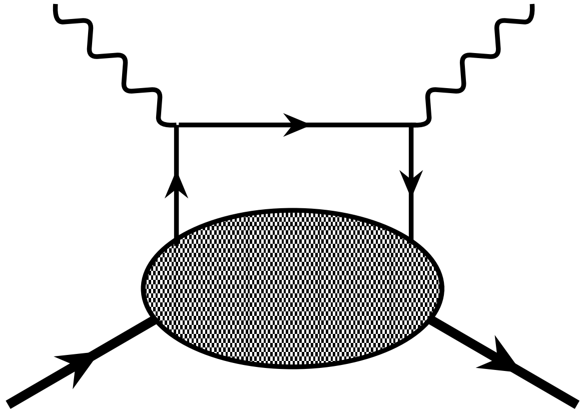

→ $q(x,Q^2)$ = probability to find quark type “q” in nucleon, carrying (light-cone) momentum fraction x

$$x = \frac{p_q^+}{p_N^+} = \frac{p_q^0 + p_q^z}{p_N^0 + p_N^z}$$

Parton model

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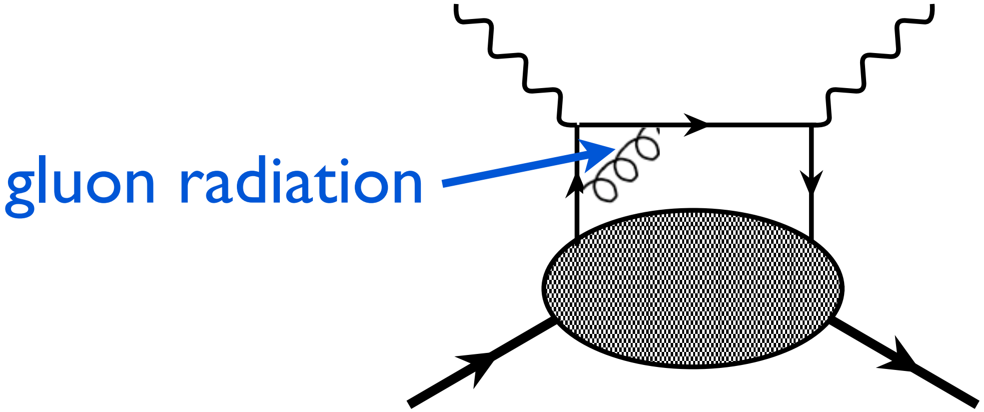
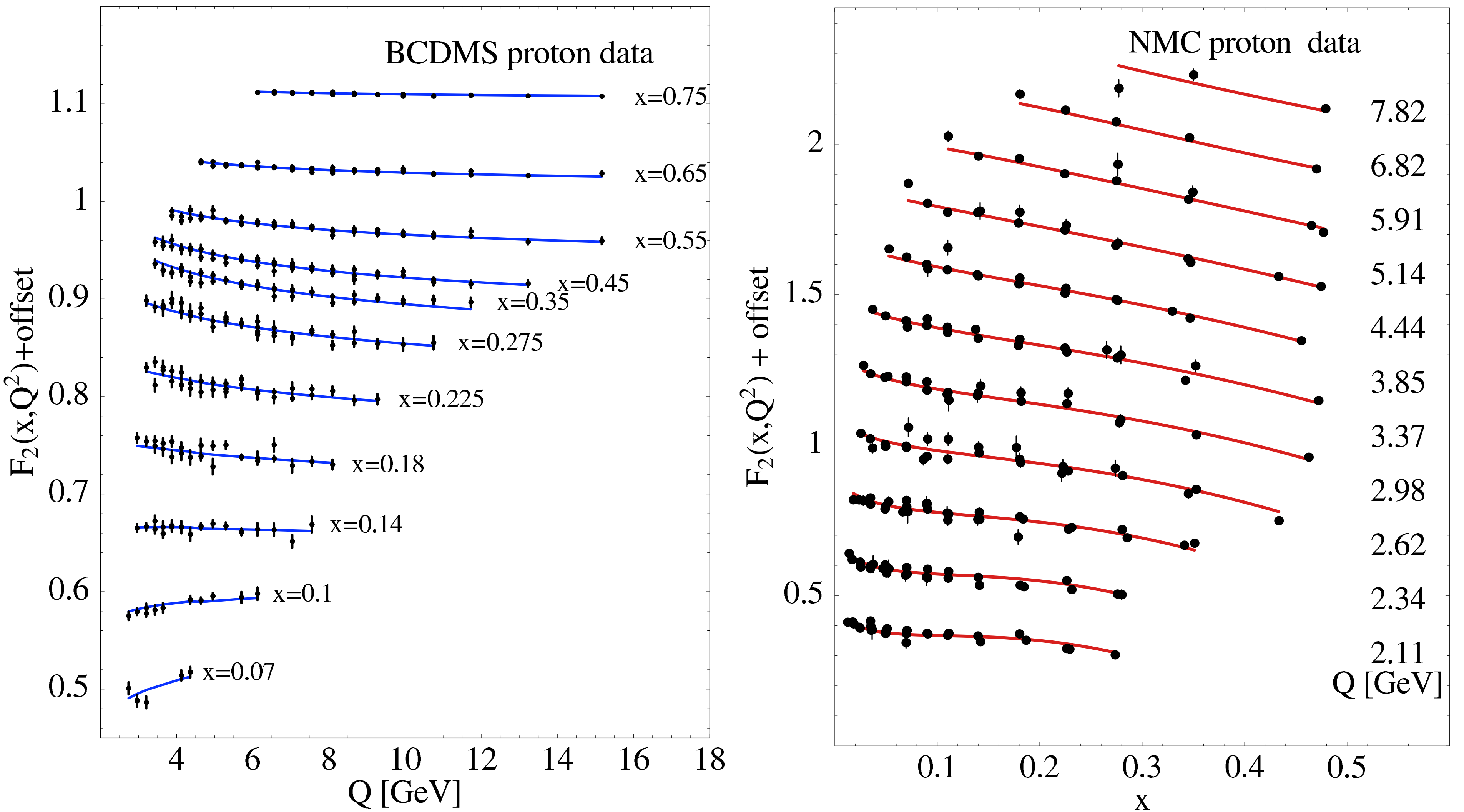


→ Q^2 dependence given by (perturbatively calculable) QCD evolution equations (→ $\log Q^2$ behavior)

→ at large Q^2, "Callan-Gross relation" $F_2 \approx 2x\, F_1$

Structure function data



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

Spin dependent scattering

- Nucleon polarized along z-axis

$$\frac{d^2\sigma}{d\Omega dE'}(\uparrow\Uparrow - \downarrow\Uparrow) = \frac{4\alpha^2 E'}{M\nu E Q^2}\left[(E + E'\cos\theta)\ g_1 \ - \ 2Mx\ g_2\right]$$

$\vec{e}$ $\vec{N}$

spin-dependent structure functions

→ electron spin *parallel* or *anti-parallel* to nucleon spin

- Usually measure polarization asymmetry $A_1 = \dfrac{g_1}{F_1}$

Spin dependent scattering

- Parton model

$$g_1(x, Q^2) \;=\; \frac{1}{2}\sum_q e_q^2\, \Delta q(x, Q^2)$$

$\longrightarrow$ $\Delta q \;=\; q^{\uparrow\Uparrow} \;-\; q^{\downarrow\Uparrow}$

probability to find quark "q" with spin aligned *vs.* antialigned with nucleon spin

$\longrightarrow$ gives total spin of nucleon carried by quarks

$$\Delta\Sigma \;=\; \Delta u + \Delta d + \Delta s$$

Spin dependent scattering

- Spin sum rule

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_q + L_g$$

Spin dependent scattering

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$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_q + L_g$$

spin carried by gluons

q and g orbital angular momentum

Spin dependent scattering

- Spin sum rule

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + L_q + L_g$$

ΔG: spin carried by gluons

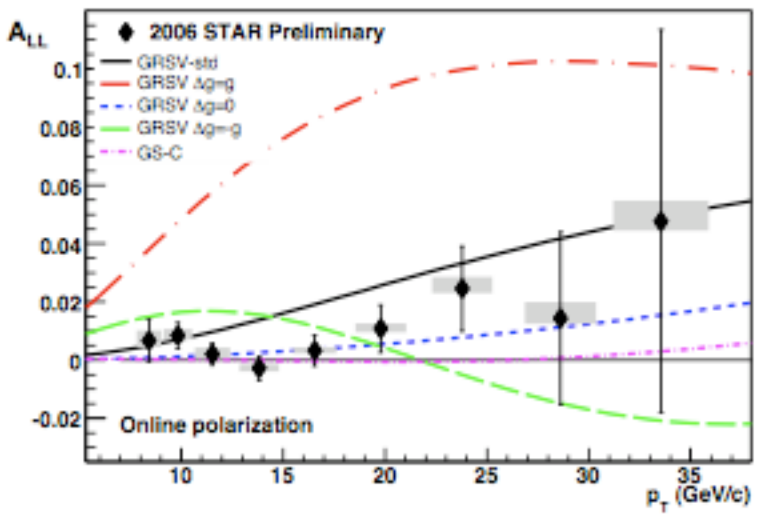
L_q, L_g: q and g orbital angular momentum

$\longrightarrow$ naive (nonrelativistic) expectation: $\Delta\Sigma \sim 1$

$\longrightarrow$ early experiments: $\Delta\Sigma \sim 0$ "proton spin crisis"

$\longrightarrow$ latest data: $\Delta\Sigma \sim 0.3$ (RGI scheme)

$\longrightarrow$ where is the proton spin?

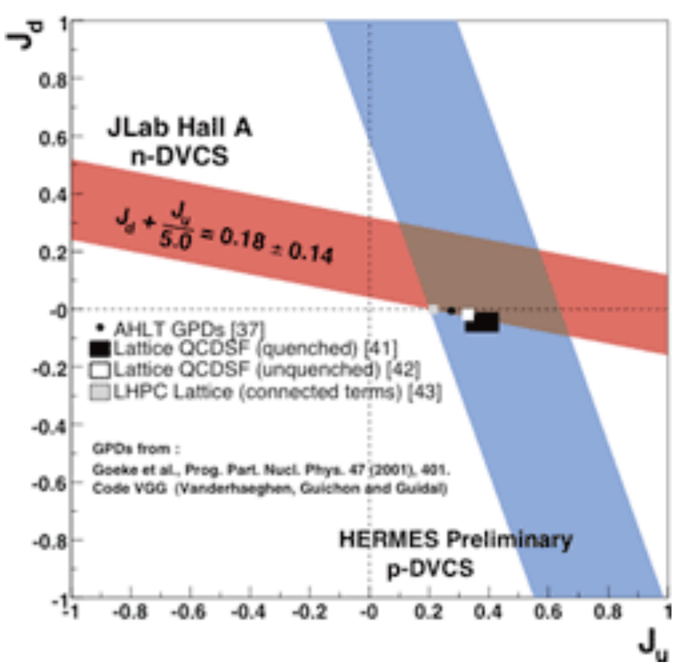


arXiv:0901:4061 [hep-ex]

STAR (RHIC) data on $\vec{p}\,\vec{p} \rightarrow$ jets

$$\Delta g \approx 0$$

"statistically consistent with zero"



HERMES proton + JLab neutron data on deeply virtual Compton scattering

$$J_u \sim 0.4 \pm 0.2$$
$$J_d \sim 0.1 \pm 0.2$$

"model-dependent extraction"

Parton distributions functions

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

  $\longrightarrow$ determined over large range of x and Q^2

- provide basic information on structure of QCD bound states

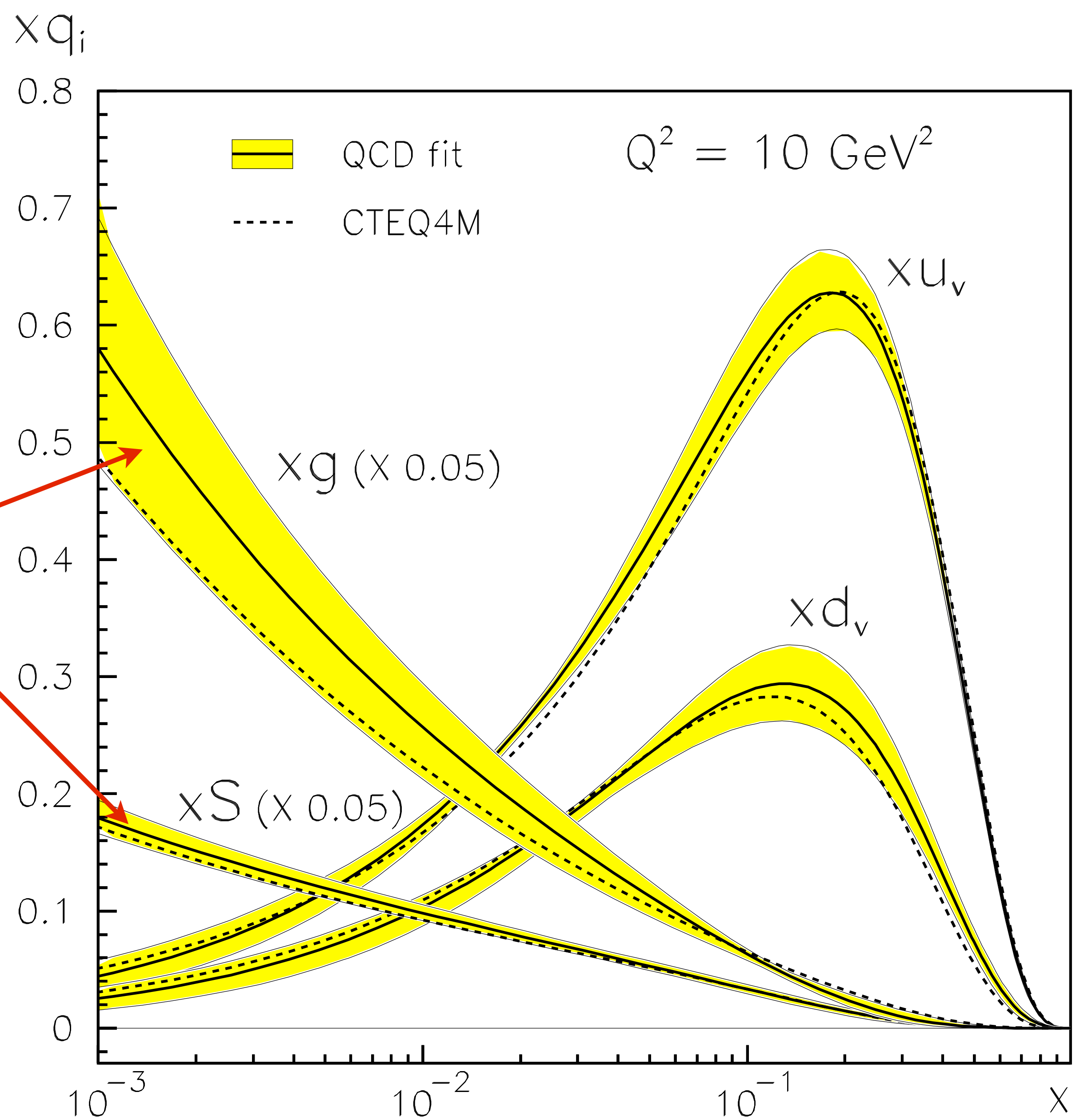
- needed to understand backgrounds in searches for physics beyond the Standard Model in high-energy colliders

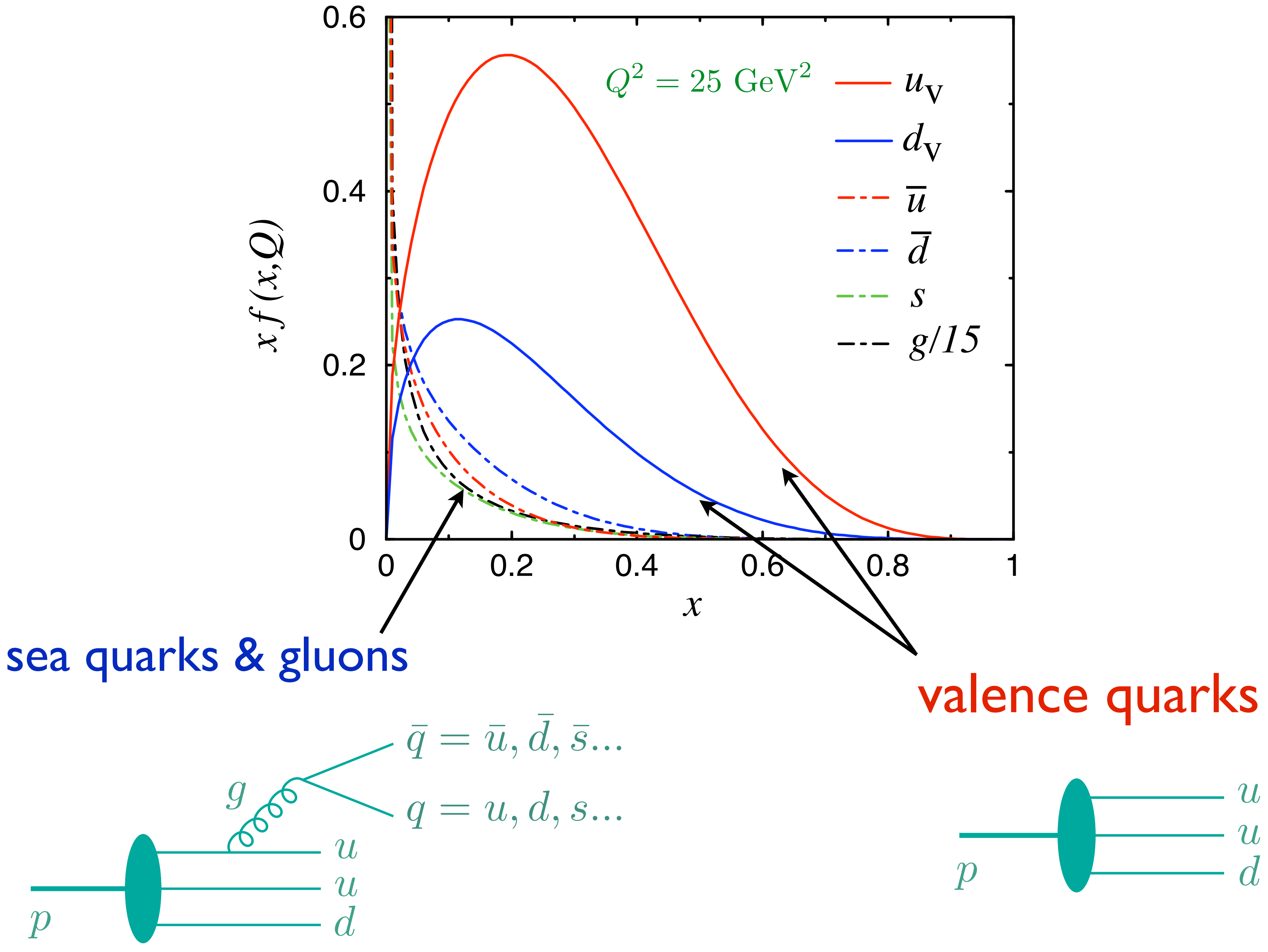
  $\longrightarrow$ $e.g.$ neutrino oscillations

recent parameterization

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

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





0.6
0.4
0.2
0
0
0.2
0.4
0.6
0.8
1
x
$x\,f\,(x,Q)$
$Q^2 = 25\ \mathrm{GeV}^2$
u_V
d_V
$\bar{u}$
$\bar{d}$
s
$g/15$
sea quarks & gluons
valence quarks
$\bar{q} = \bar{u}, \bar{d}, \bar{s}...$
g
$q = u, d, s...$
u
u
d
p
u
u
d
p

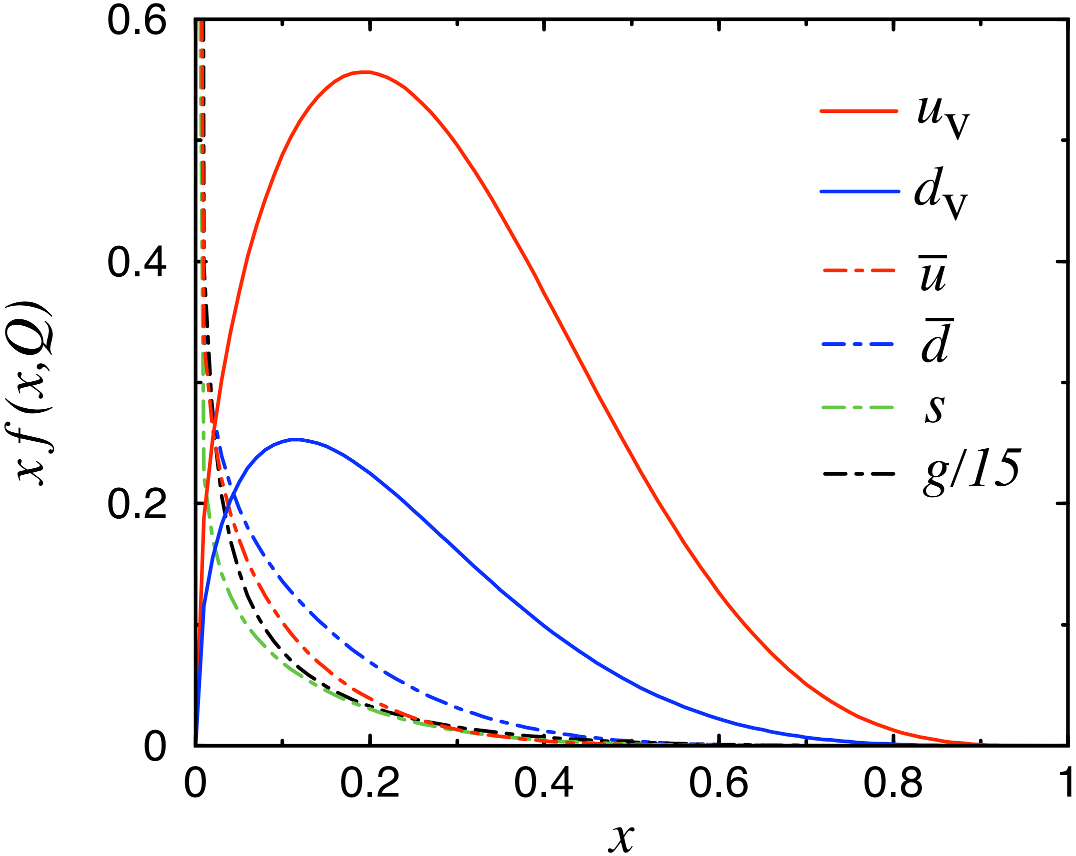
Quark distributions

valence quarks

Valence quarks

- Most direct connection between quark distributions and models of the nucleon is through *valence* quarks

- Nucleon structure at intermediate & large x dominated by valence quarks



valence quarks dominate at large x

Valence quarks

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

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

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

Valence quarks

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

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

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

- u quark distribution well determined from p

- d quark distribution requires n structure function

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

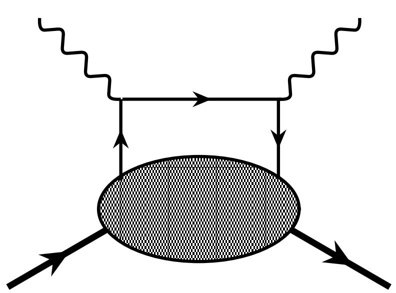
Valence quarks

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

- SU(6) spin-flavor symmetry

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

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

- SU(6) spin-flavor symmetry

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

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

Valence quarks

- scalar diquark dominance

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

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

Valence quarks

- scalar diquark dominance

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

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

since only u quarks couple to scalar diquarks

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

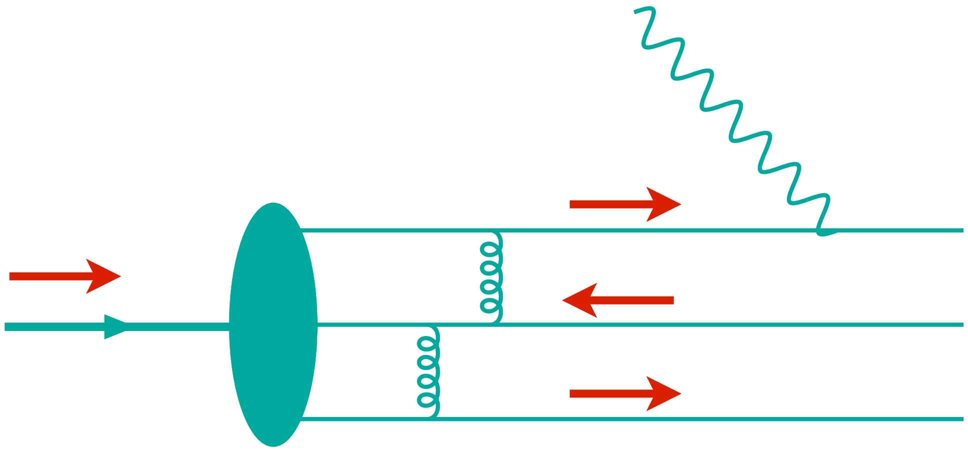
$\longrightarrow \quad \frac{F_2^n}{F_2^p} \to \frac{1}{4}$

Feynman 1972, Close 1973, Close/Thomas 1988

Valence quarks

- <u>hard gluon exchange</u>

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

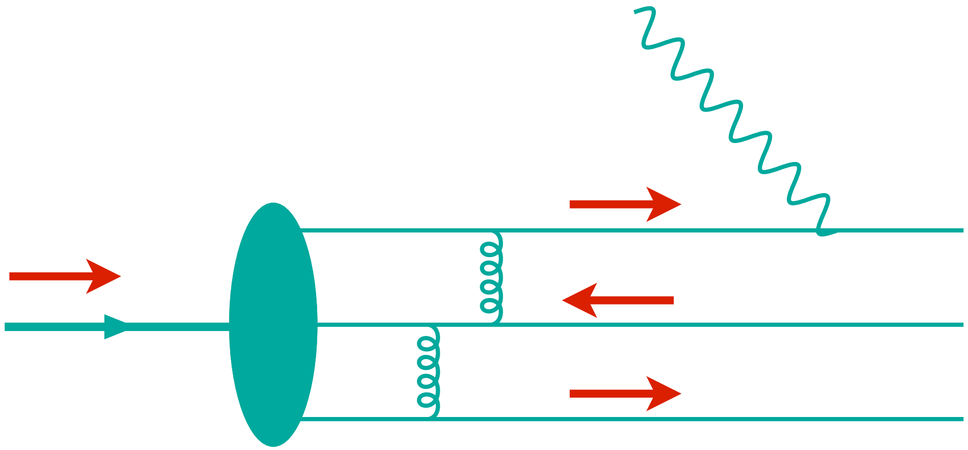


$$q^{\uparrow} \gg q^{\downarrow}$$

Valence quarks

- hard gluon exchange

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



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

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

$\longrightarrow$ $$\frac{d}{u} \to \frac{1}{5}$$

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

Farrar, Jackson 1975

Polarized valence quarks

- SU(6) symmetry

$$A_1^p = \frac{5}{9}\ , \quad A_1^n = 0$$

$$\frac{\Delta u}{u} = \frac{2}{3}\ , \quad \frac{\Delta d}{d} = -\frac{1}{3}$$

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- hard gluon exchange

$$A_1^p \to 1\,, \quad A_1^n \to 1$$

$$\frac{\Delta u}{u} \to 1\,, \quad \frac{\Delta d}{d} \to 1$$

- 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

  → "nuclear EMC effect"

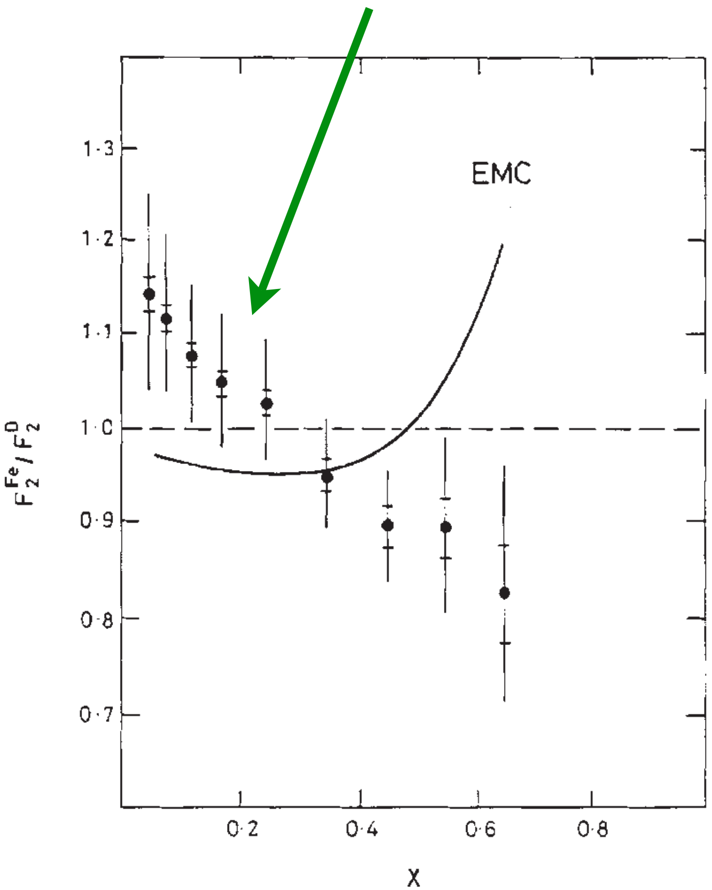
Quark distributions

nuclear effects

Nuclear "EMC effect"

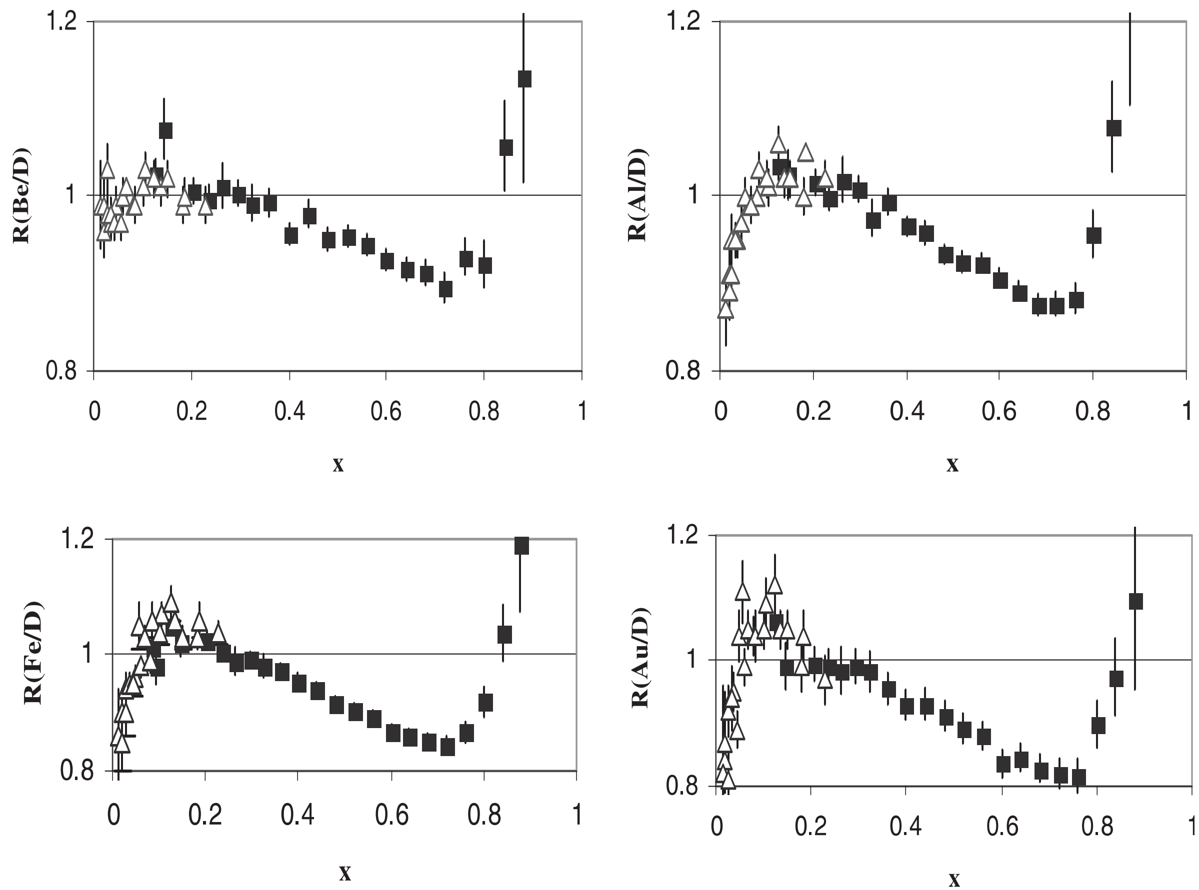
$$F_2^A(x, Q^2) \neq A F_2^N(x, Q^2)$$

Original EMC data



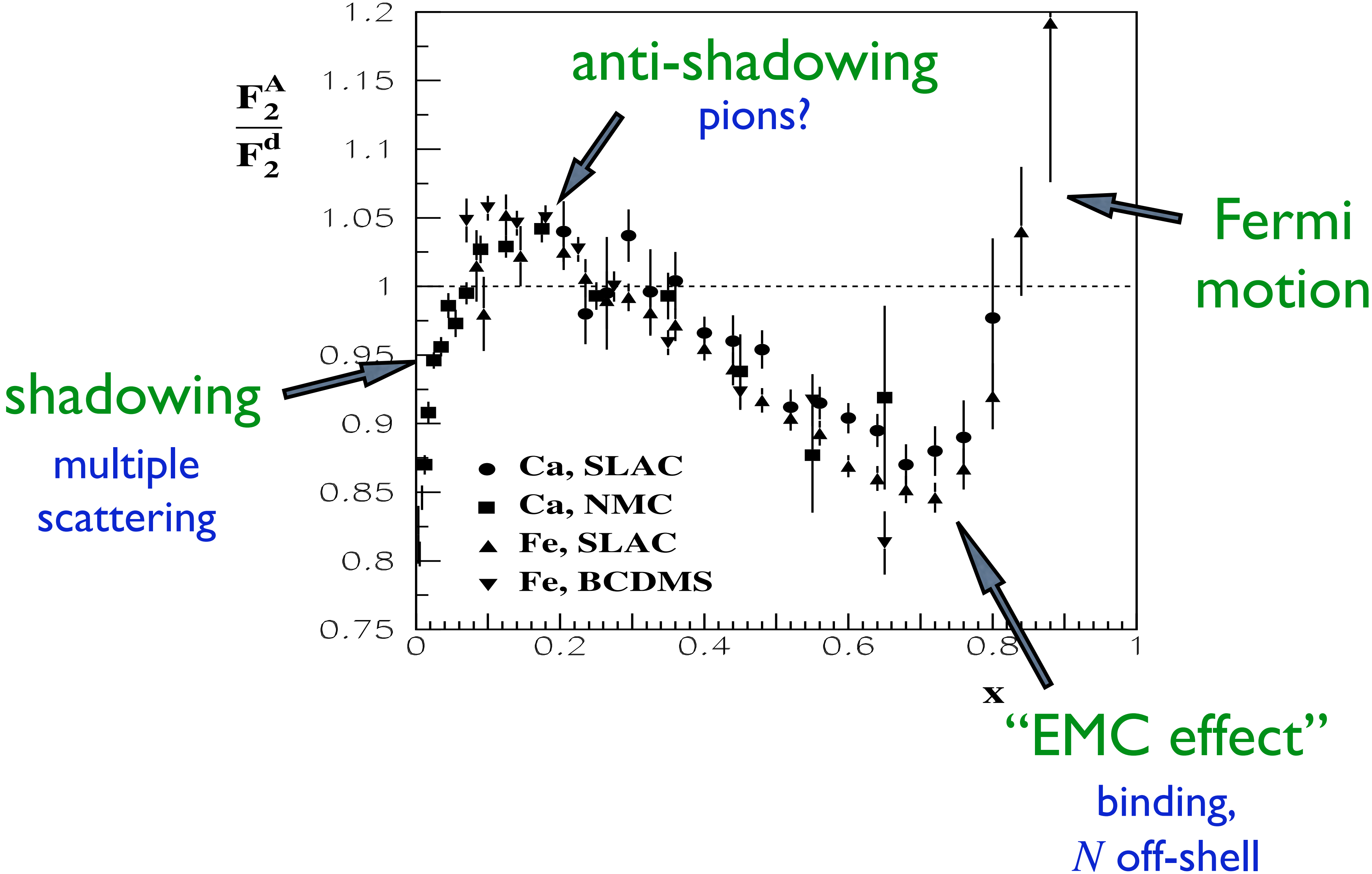
Aubert et al., Phys. Lett. B 123, 123 (1983)

Later SLAC data



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

Nuclear "EMC effect"



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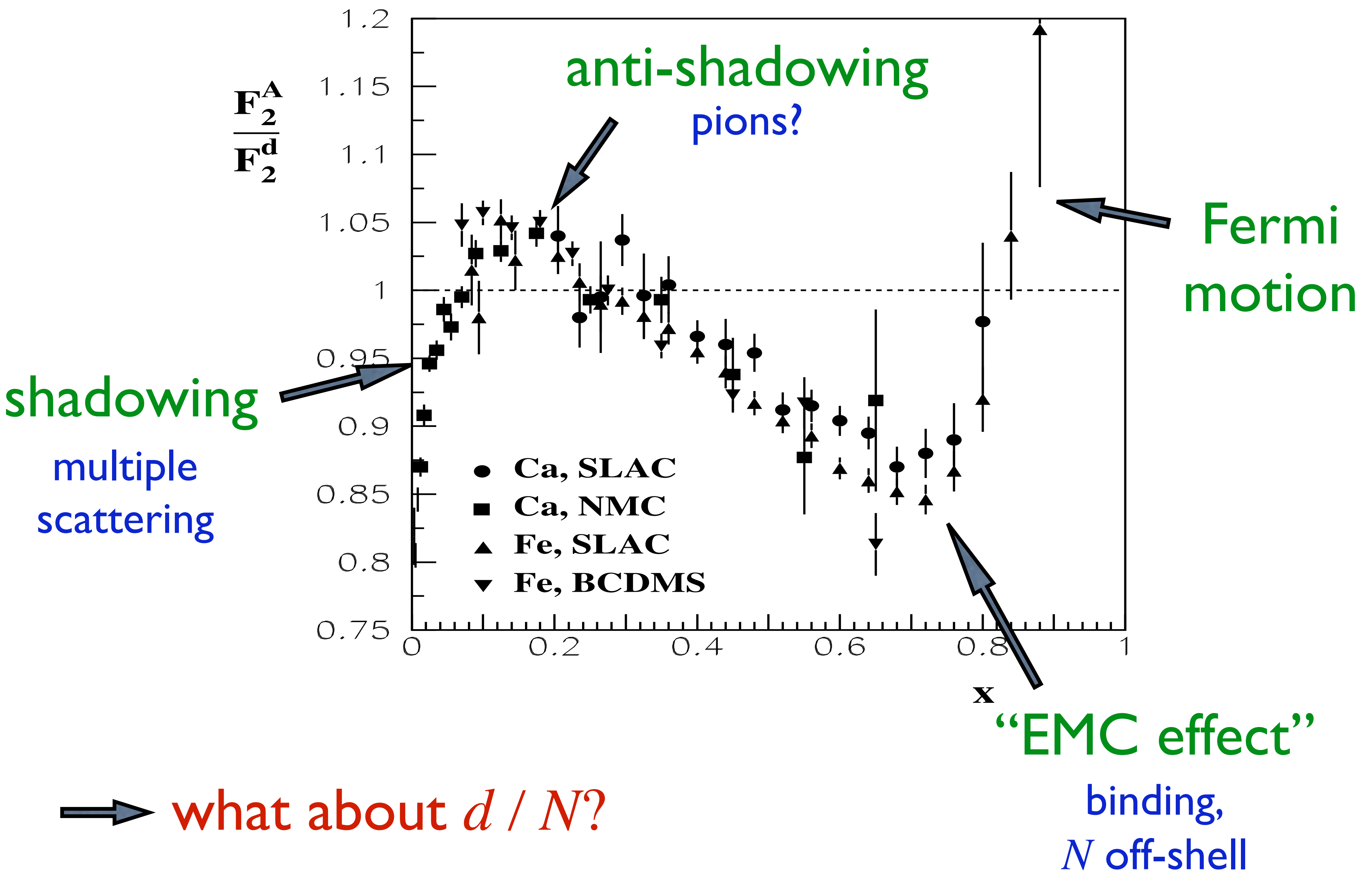
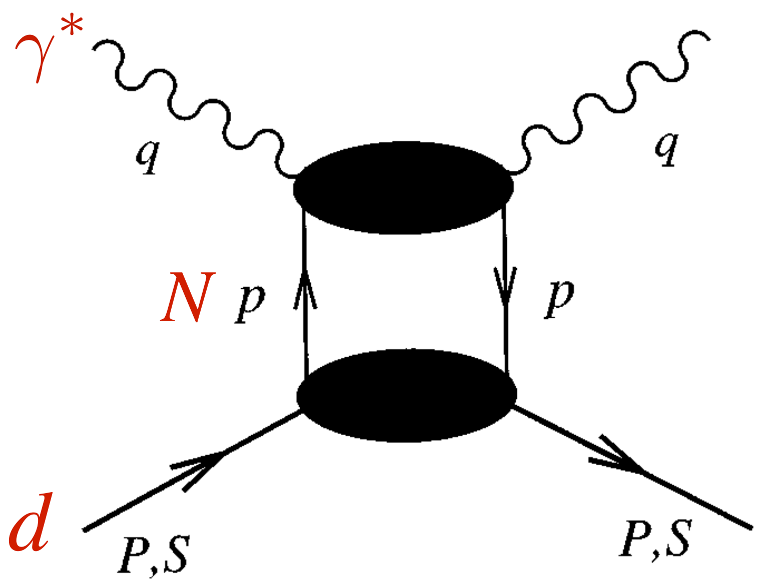


→ what about *d* / *N*?

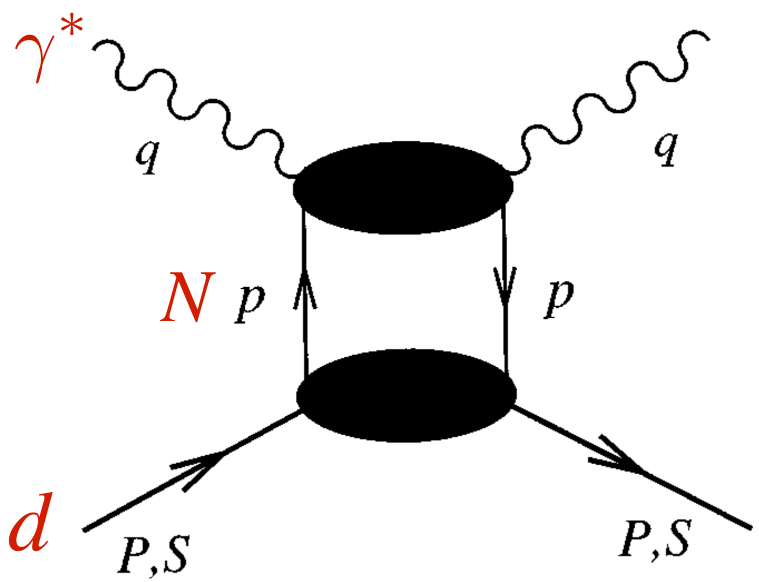
EMC effect in deuteron



Nuclear "impulse approximation"

→ incoherent scattering from individual nucleons in deuteron

EMC effect in deuteron



Nuclear "impulse approximation"

⇨ incoherent scattering from individual nucleons in deuteron

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

nucleon momentum distribution

off-shell correction

EMC effect in deuteron

Nucleon momentum distribution in deuteron

⟹ relativistic dNN vertex function

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

EMC effect in deuteron

Nucleon momentum distribution in deuteron

➡ relativistic dNN vertex function

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

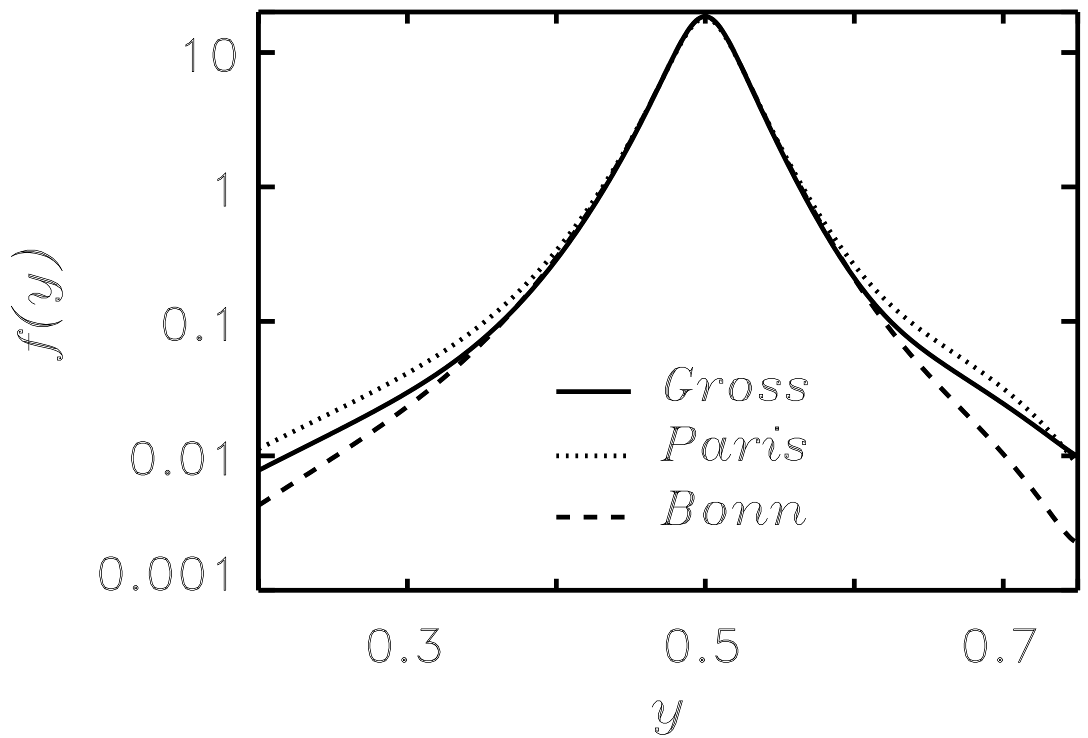
momentum fraction of deuteron carried by nucleon

EMC effect in deuteron

Nucleon momentum distribution in deuteron

➡ relativistic dNN vertex function

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



EMC effect in deuteron

Nucleon momentum distribution in deuteron

➡ relativistic dNN vertex function

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Wave function dependence only at large $|y-1/2|$

➡ sensitive to large-p components of wave function

EMC effect in deuteron

Nucleon momentum distribution in deuteron

→ relativistic dNN vertex function

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

Nucleon off-shell correction

$$\delta^{(\mathrm{off})} F_2^d$$

EMC effect in deuteron

Nucleon momentum distribution in deuteron

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

Nucleon off-shell correction

$$\delta^{(\mathrm{off})} F_2^d \longrightarrow \delta^{(\Psi)} F_2^d$$

negative energy components of d wave function

EMC effect in deuteron

Nucleon momentum distribution in deuteron

→ relativistic dNN vertex function

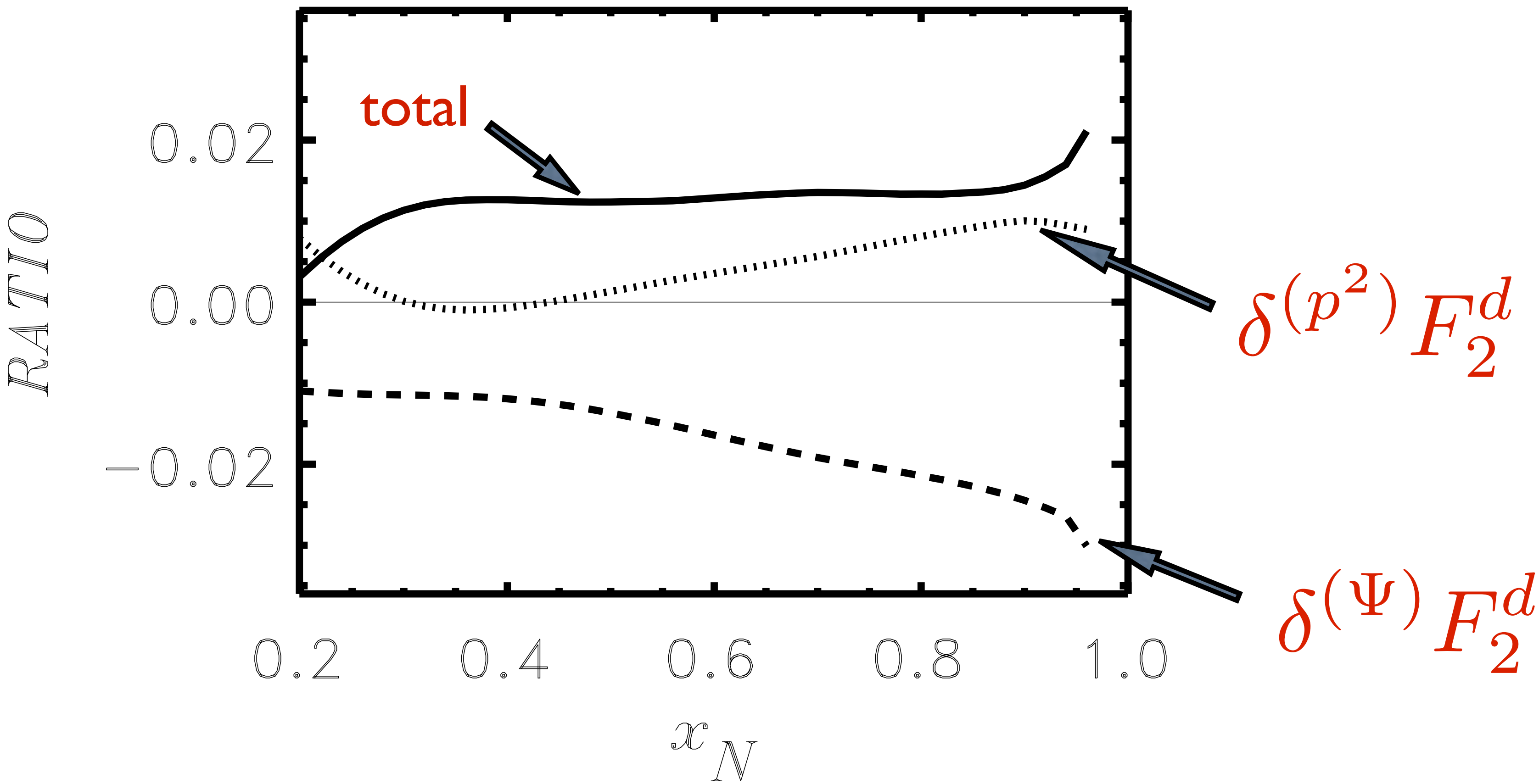
$$f_{N/d}(y) = \frac{1}{4} M_d \; y \int_{-\infty}^{p^2_{\rm max}} dp^2 \, \frac{E_p}{p_0} \left| \Psi_d(\vec{p}^{\,2}) \right|^2$$

Nucleon off-shell correction

$\delta^{(\rm off)} F_2^d$ → $\delta^{(\Psi)} F_2^d$ negative energy components of d wave function

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

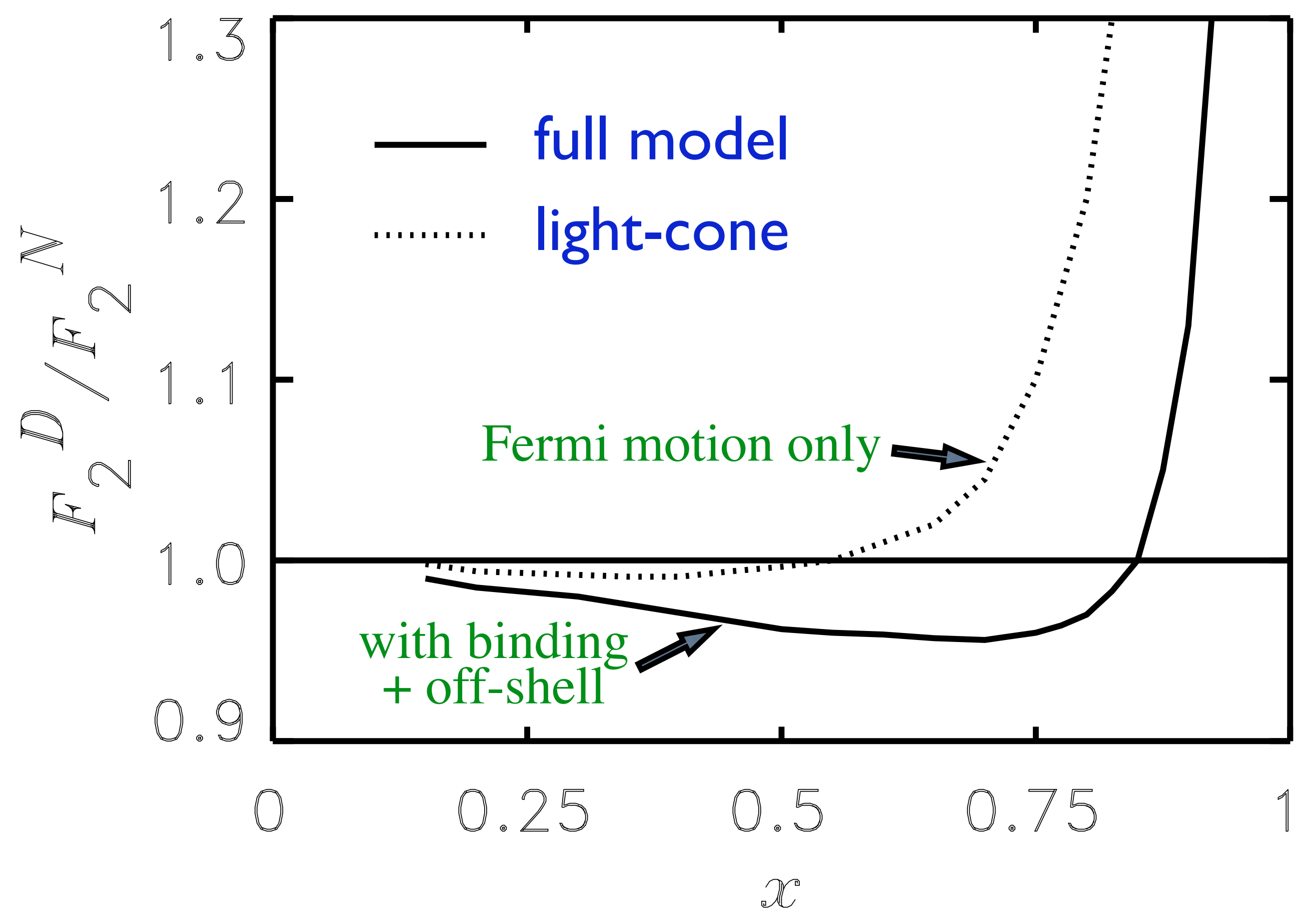
Off-shell correction



→ $\leq 1 - 2$ % effect

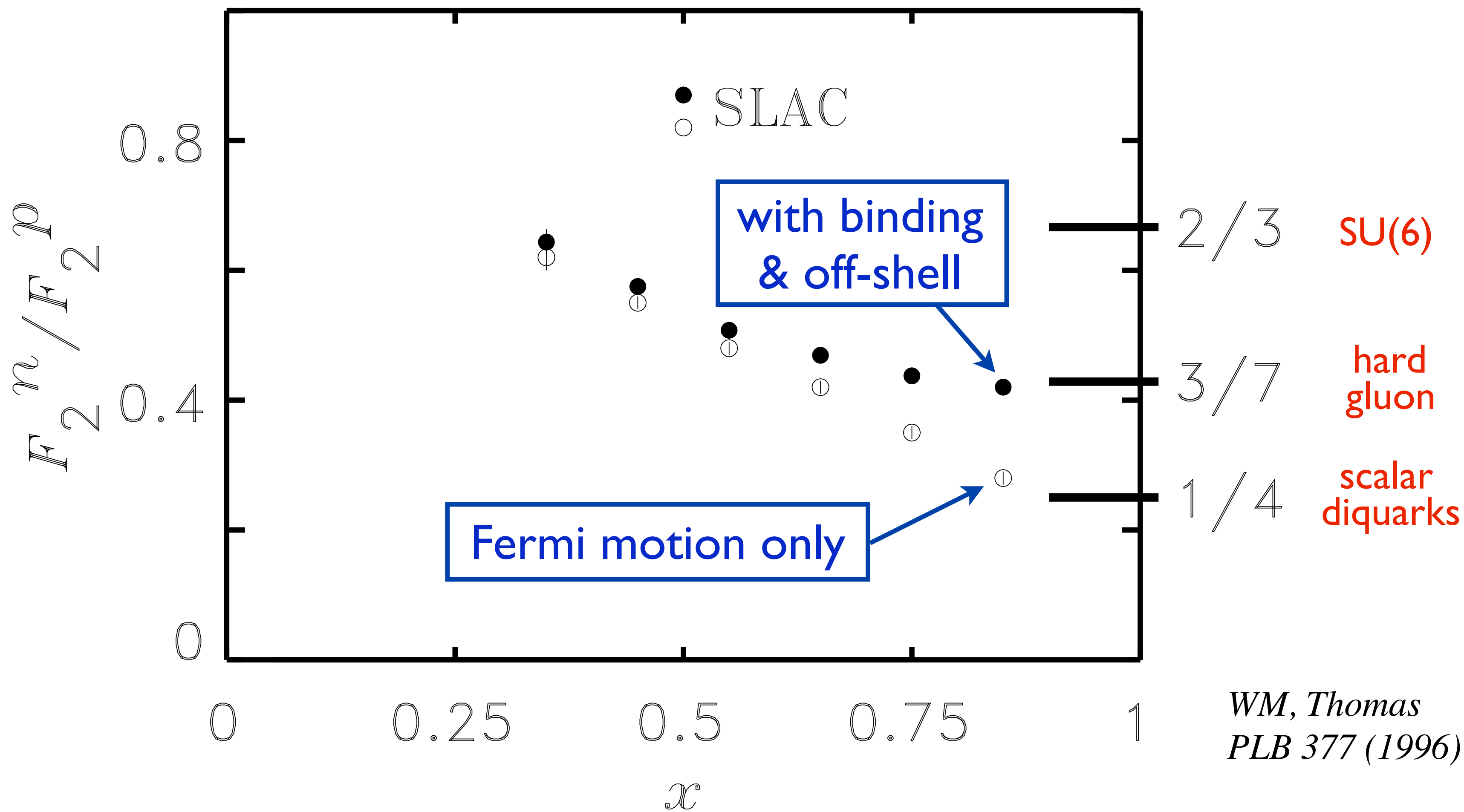
WM, Schreiber, Thomas, Phys. Lett. B 335 (1994) 11

EMC effect in deuteron



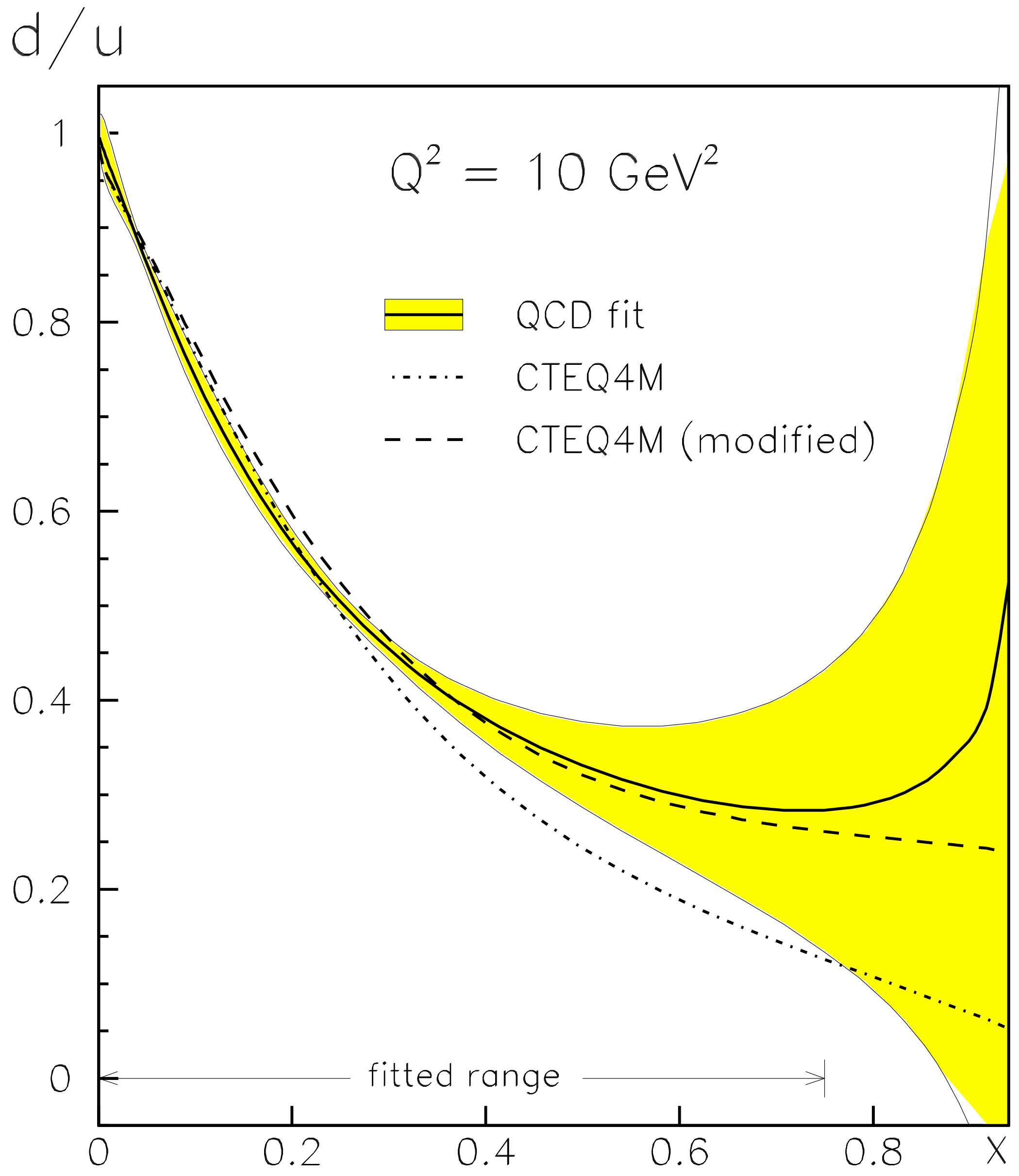
→ larger EMC effect (smaller d/N ratio) with off-shell + binding corrections

Neutron to proton ratio

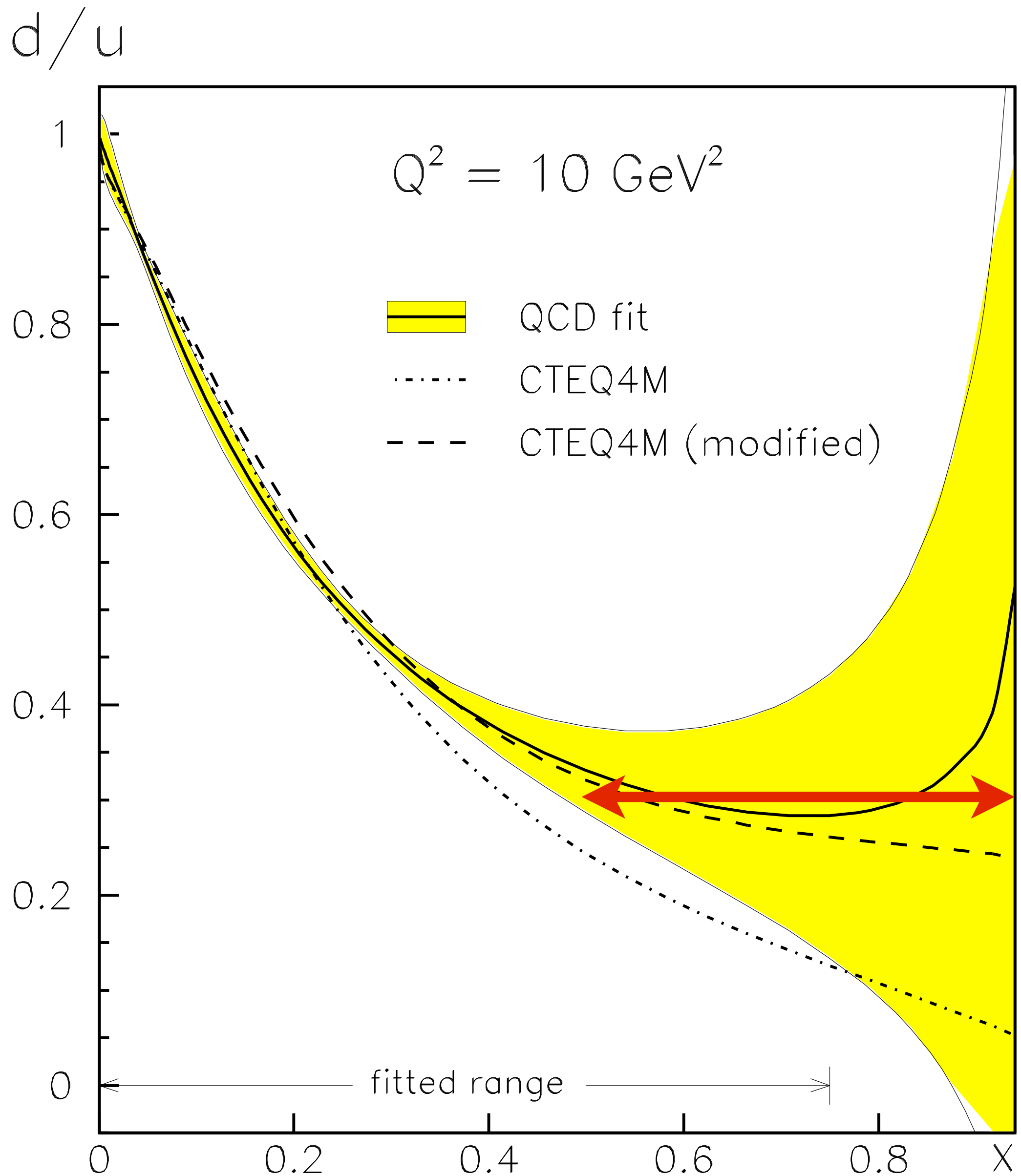


WM, Thomas
PLB 377 (1996) 11

→ F_2^n underestimated at large x !



d/u
$Q^2 = 10\ GeV^2$
QCD fit
CTEQ4M
CTEQ4M (modified)
fitted range
1
0.8
0.6
0.4
0.2
0
0.2
0.4
0.6
0.8
X



large uncertainty from nuclear effects in deuteron

(range of nuclear models)

beyond $x \sim 0.5$

“Cleaner” methods of determining d/u

$$e^{\mp}\ p \to \nu(\bar{\nu}) X$$
$$\nu(\bar{\nu})\ p \to l^{\mp}\ X$$
$$p\ p(\bar{p}) \to W^{\pm} X$$
$$\vec{e}_L(\vec{e}_R)\ p \to e\ X$$

weak current as flavor probe

→ difficult to get high rates/luminosities

$$e\ p \to e\ \pi^{\pm}\ X$$

need $z \sim 1$, factorization

$$e\ {}^3\mathrm{He}({}^3\mathrm{H}) \to e\ X$$

^{3}He-tritium mirror nuclei

$$e\ d \to e\ p_{\mathrm{spec}}\ X$$

semi-inclusive DIS from d

→ tag “spectator” protons

"Cleaner" methods of determining d/u

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^{3}He- ^{3}H mirror

- EMC ratios for A=3 mirror nuclei

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

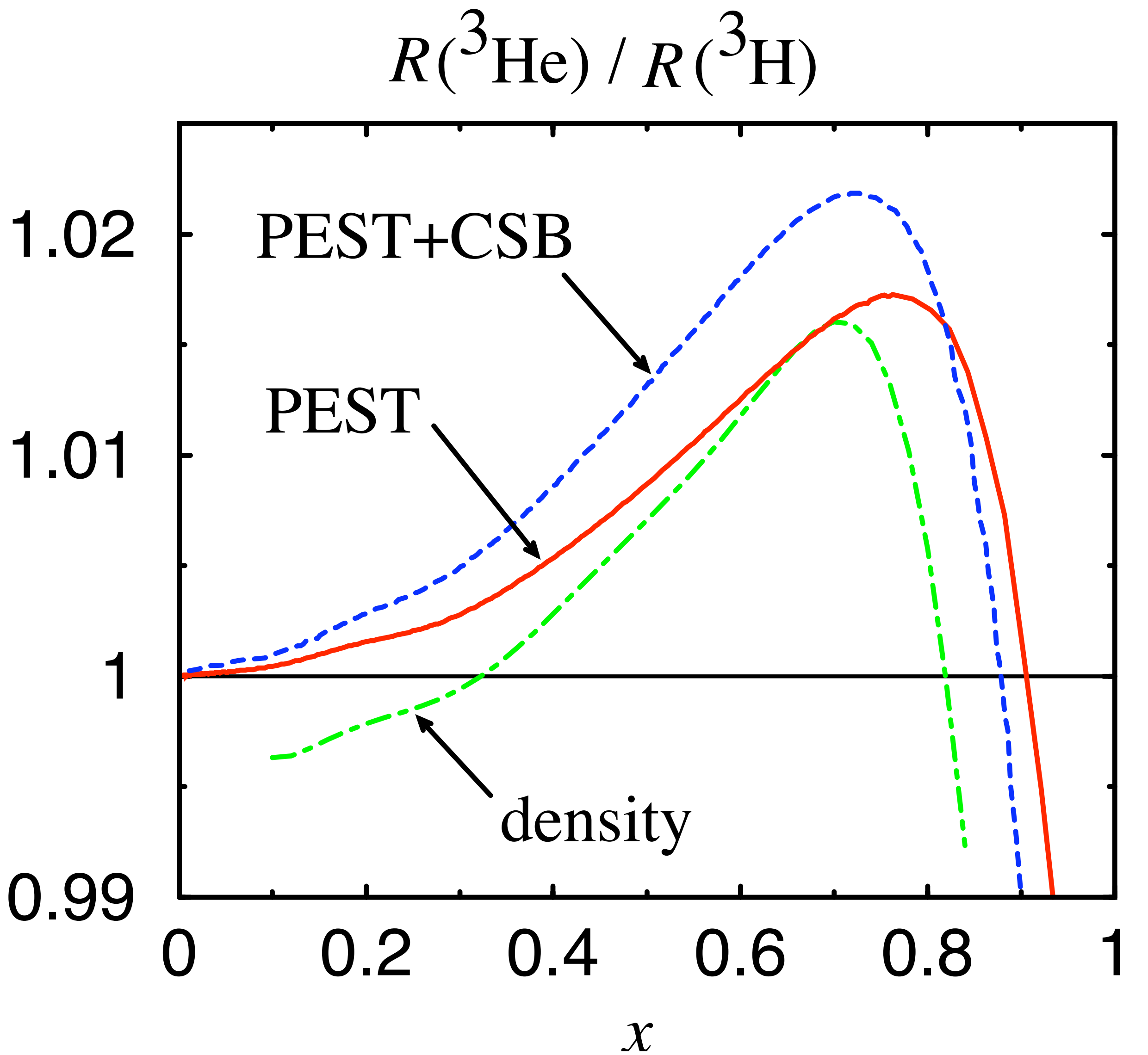
$$R(^3\text{H}) = \frac{F_2^{^3\text{H}}}{F_2^p + 2F_2^n}$$

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

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

$$\mathcal{R} = \frac{R(^3\text{He})}{R(^3\text{H})}$$

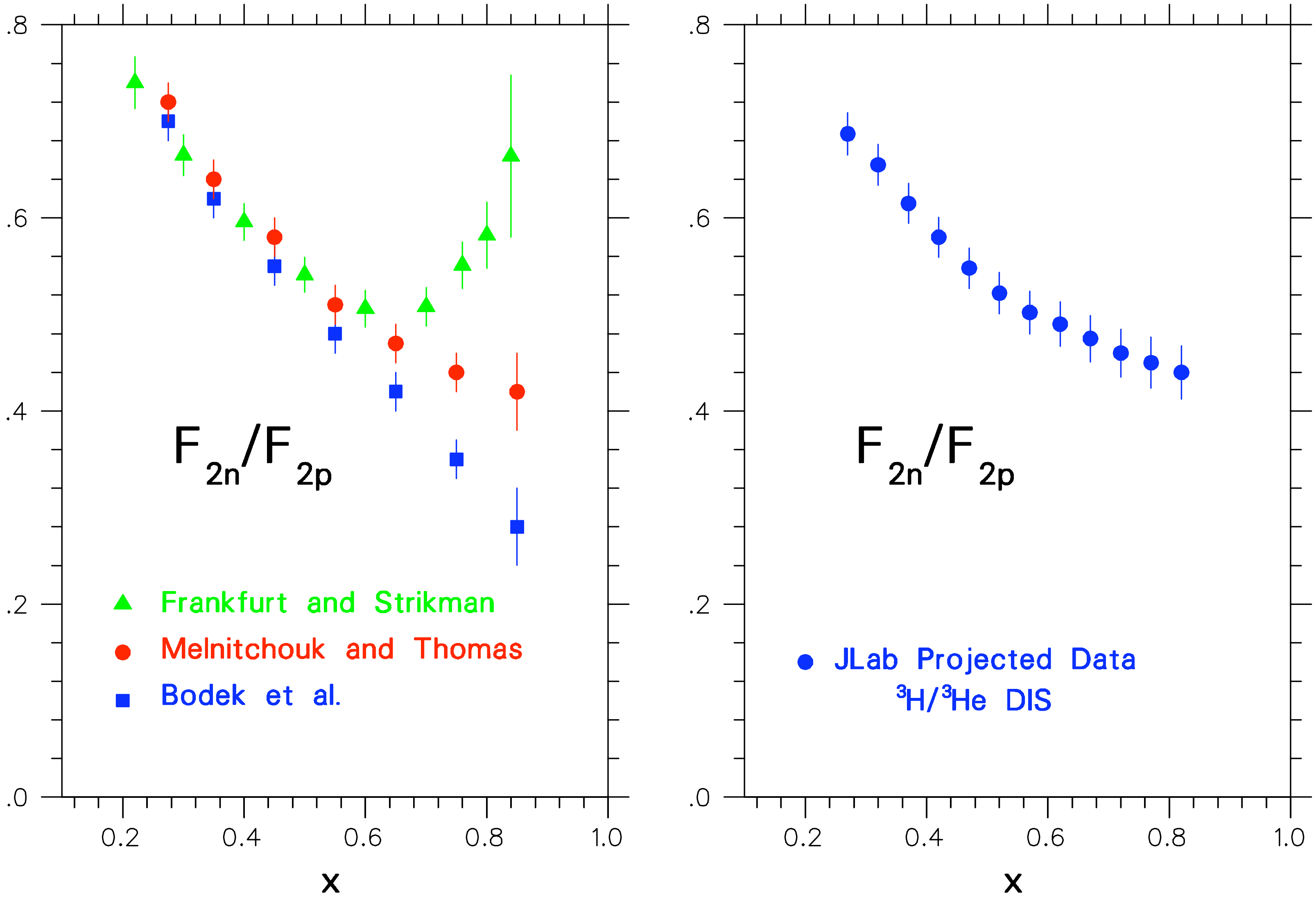
^{3}He- ^{3}H mirror



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

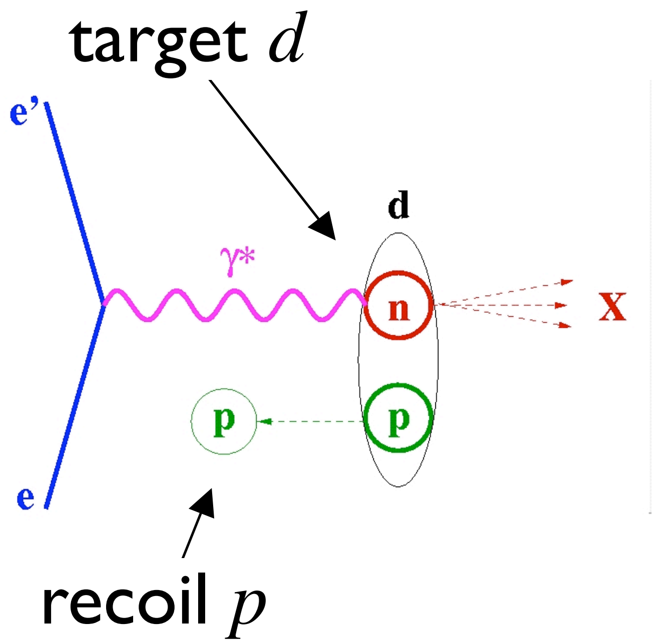
⟶ nuclear effects cancel to < 1% level

^3He- ^3H mirror



Spectator proton tagging

$$e\ d \to e\ p\ X$$



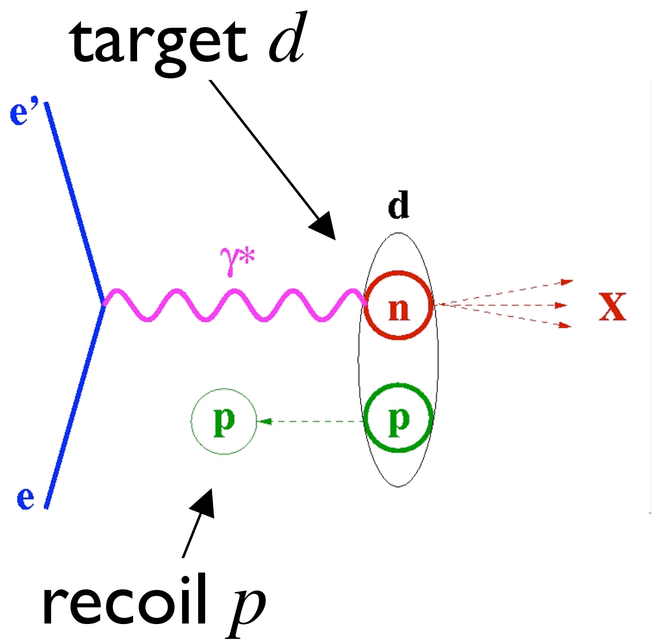
slow backward p

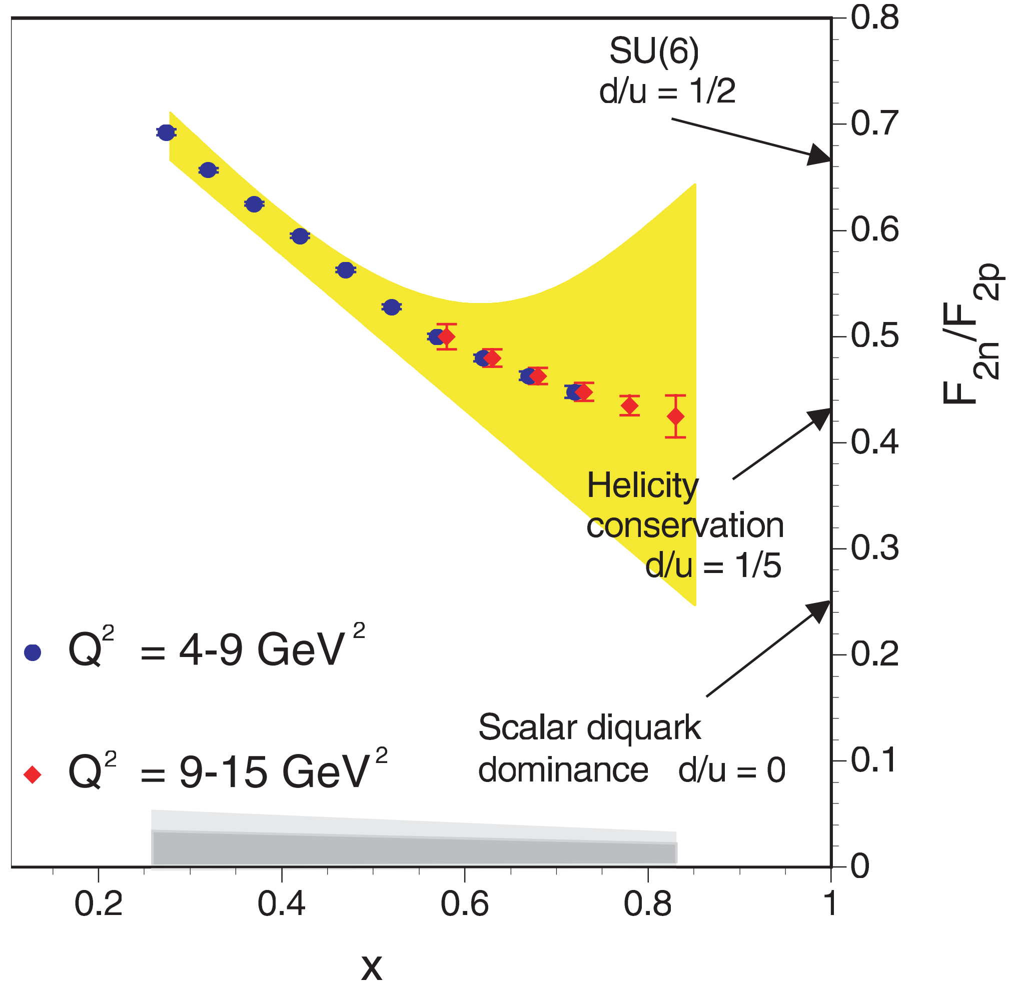
→ neutron nearly on-shell

→ minimize rescattering

Spectator proton tagging

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





slow backward p

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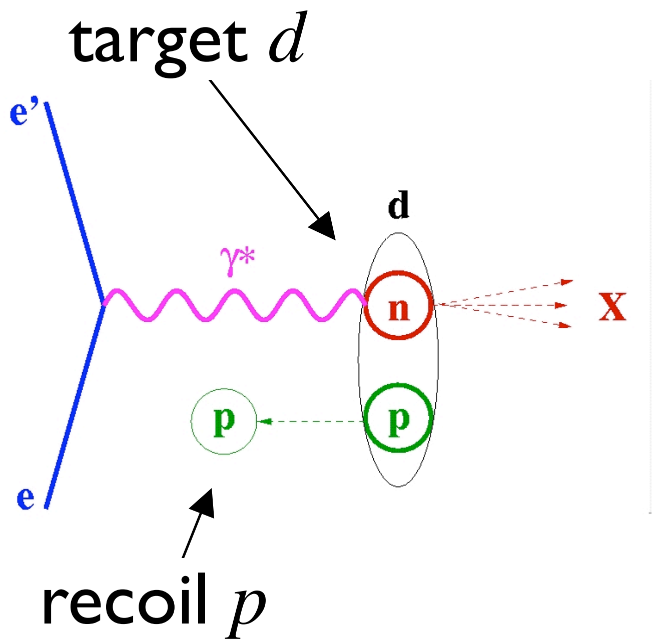
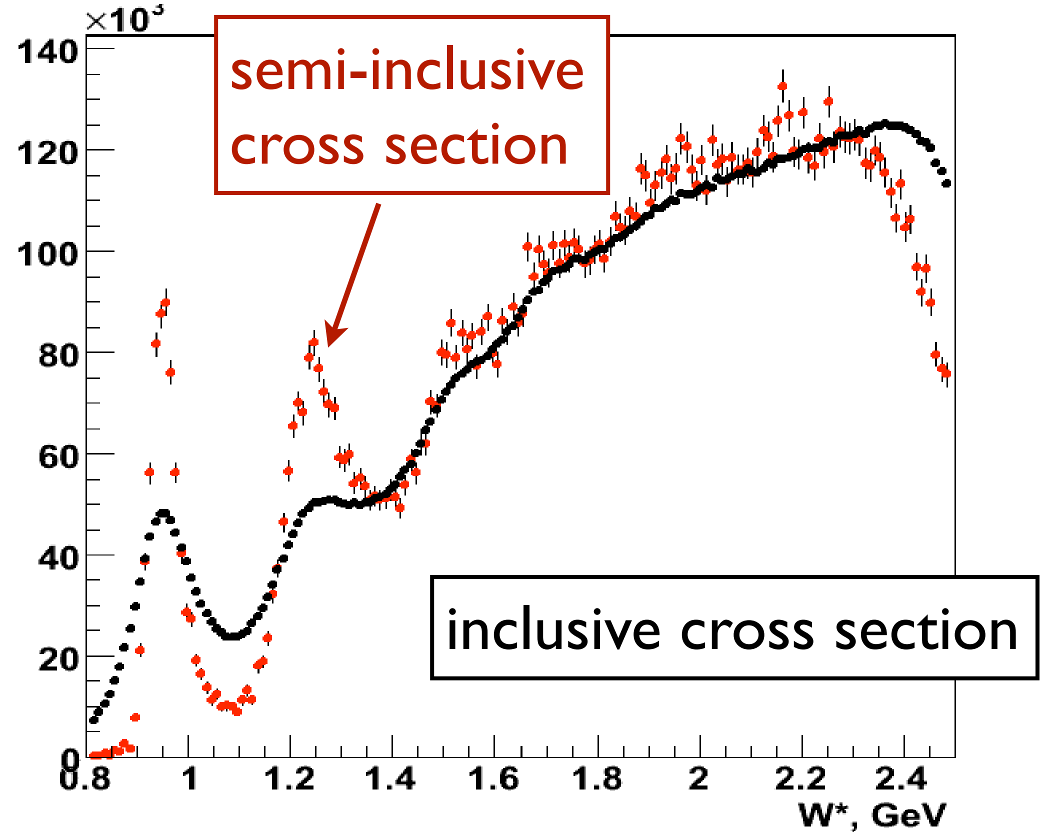
→ minimize rescattering

JLab Hall B experiment ("BoNuS")
run completed Dec. 2005

Spectator proton tagging

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





slow backward p

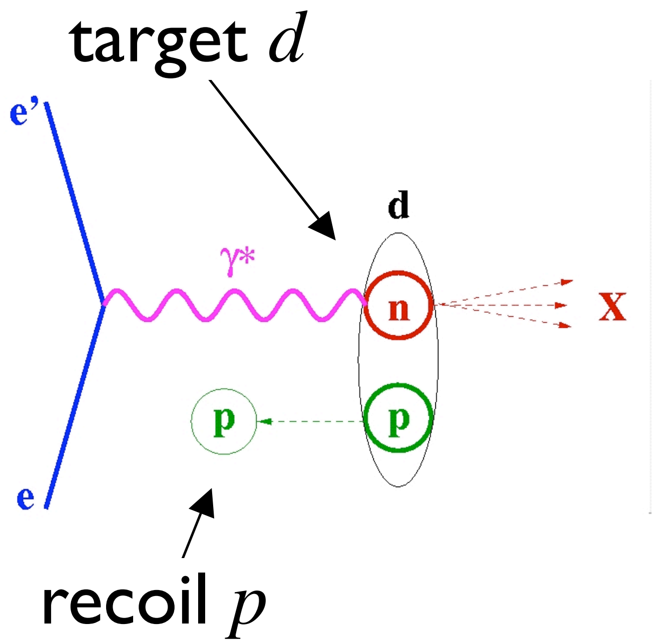
→ neutron nearly on-shell

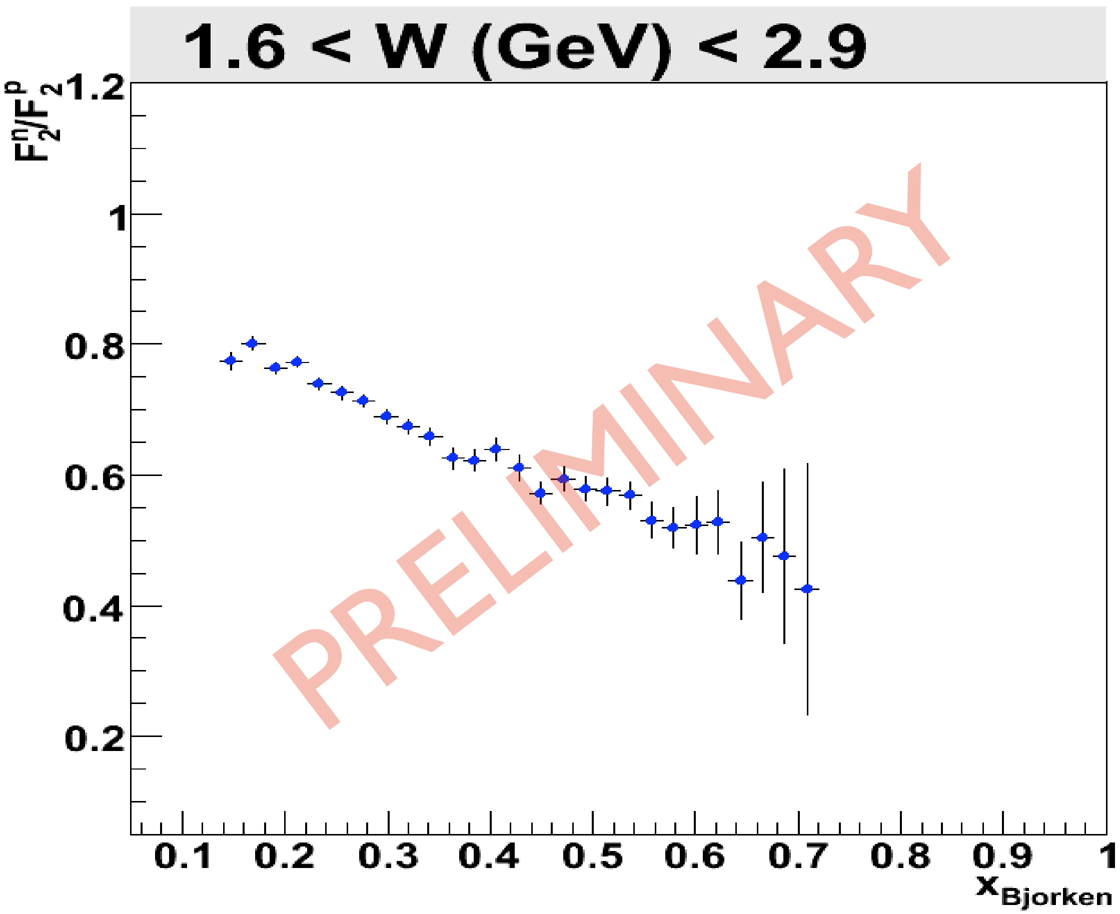
→ minimize rescattering

→ more pronounced neutron resonance structure visible

Spectator proton tagging

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





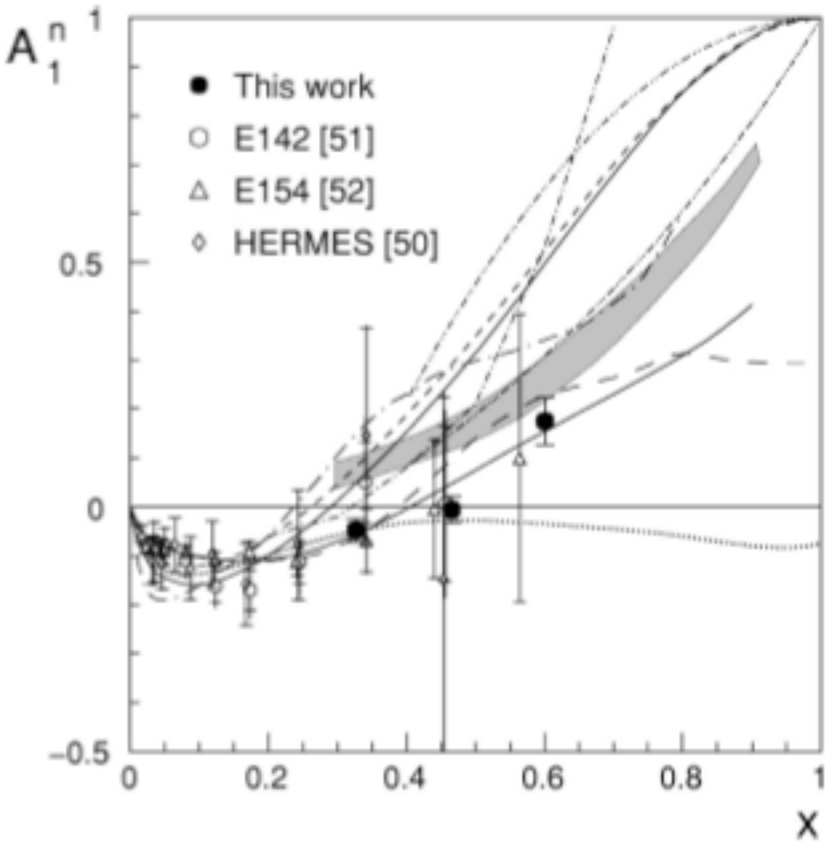
slow backward p

- neutron nearly on-shell
- minimize rescattering

→ first "proof of principle" data

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

Polarization asymmetries



Zheng et al., PRL ***92*** *(2004) 012004*

pQCD (helicity conservation)

$$A_1^n \to 1$$

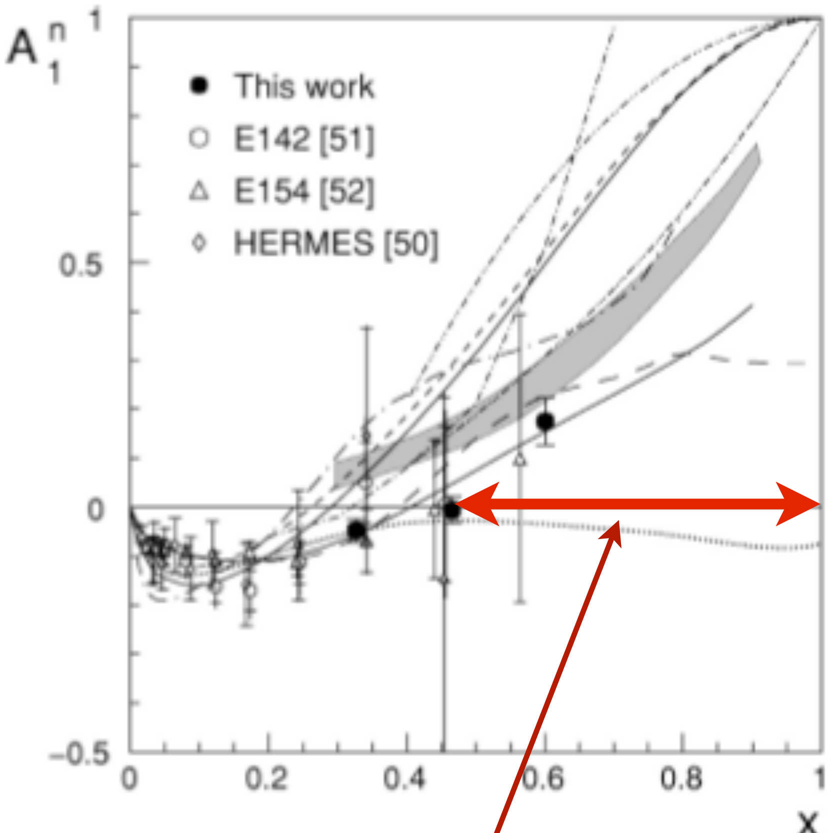
scalar diquark dominance

$$A_1^n \to 1$$

SU(6) symmetry

$$A_1^n = 0$$

Polarization asymmetries



Zheng et al., PRL ***92*** *(2004) 012004*

at large x, A_1^n is essentially unknown!

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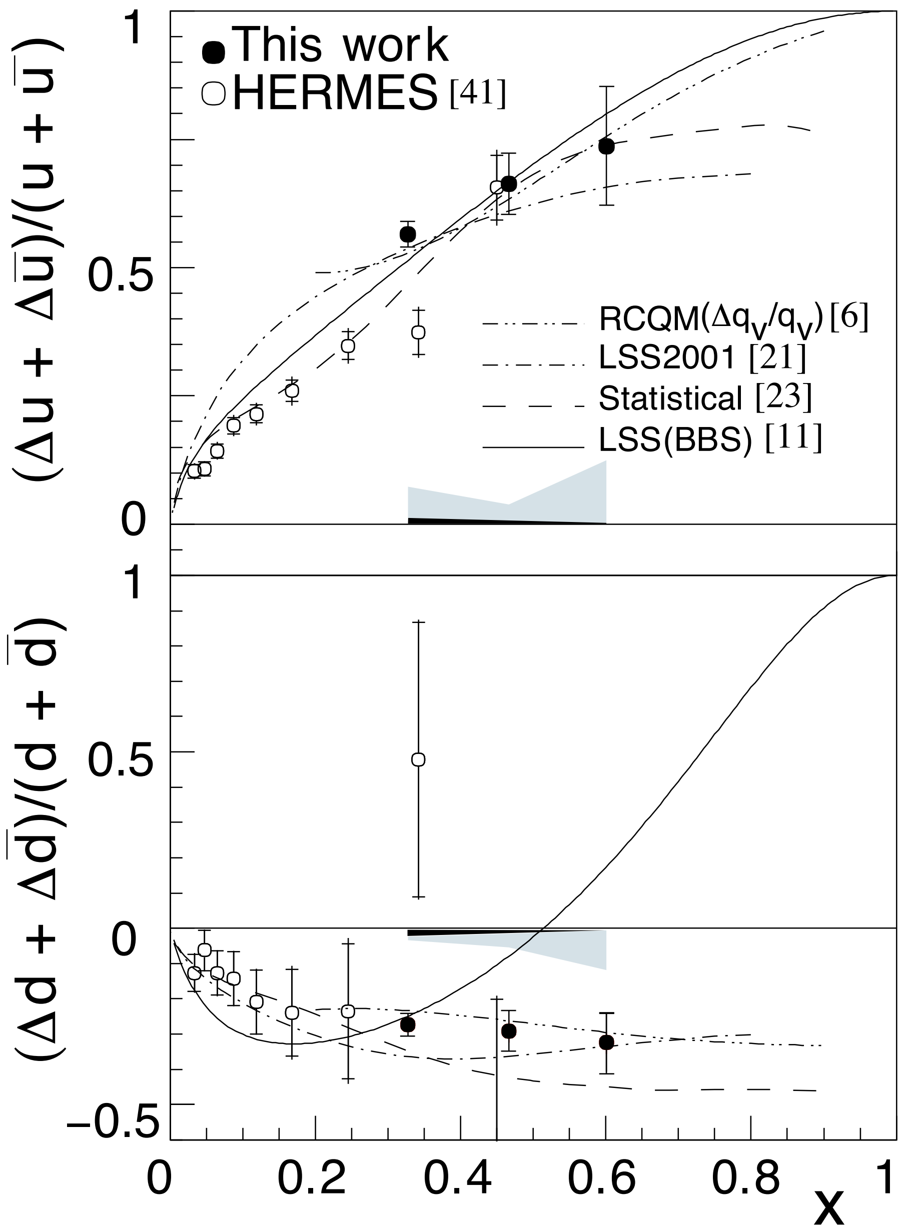

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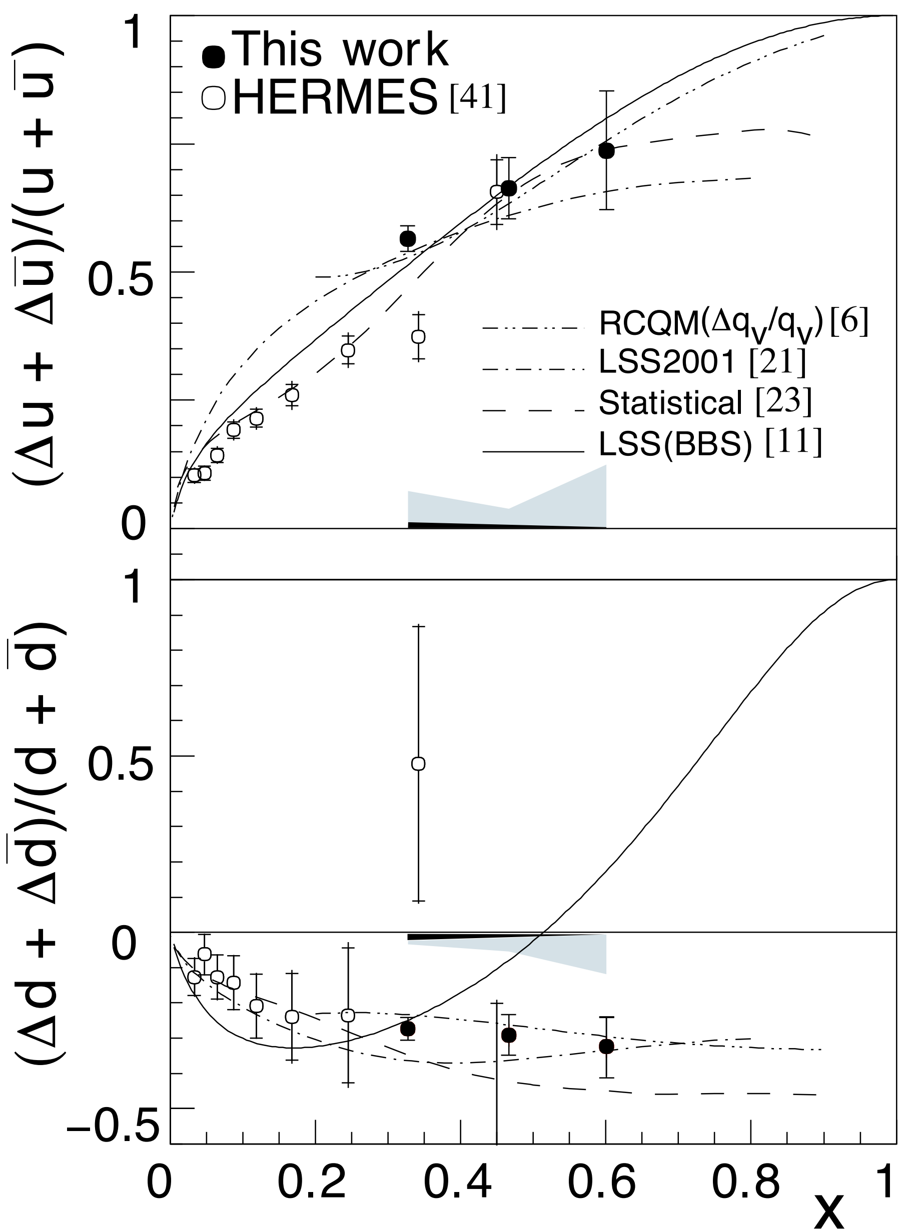
$$\frac{\Delta u}{u} = \frac{2}{3}\,, \quad \frac{\Delta d}{d} = -\frac{1}{3}$$

Polarization asymmetries



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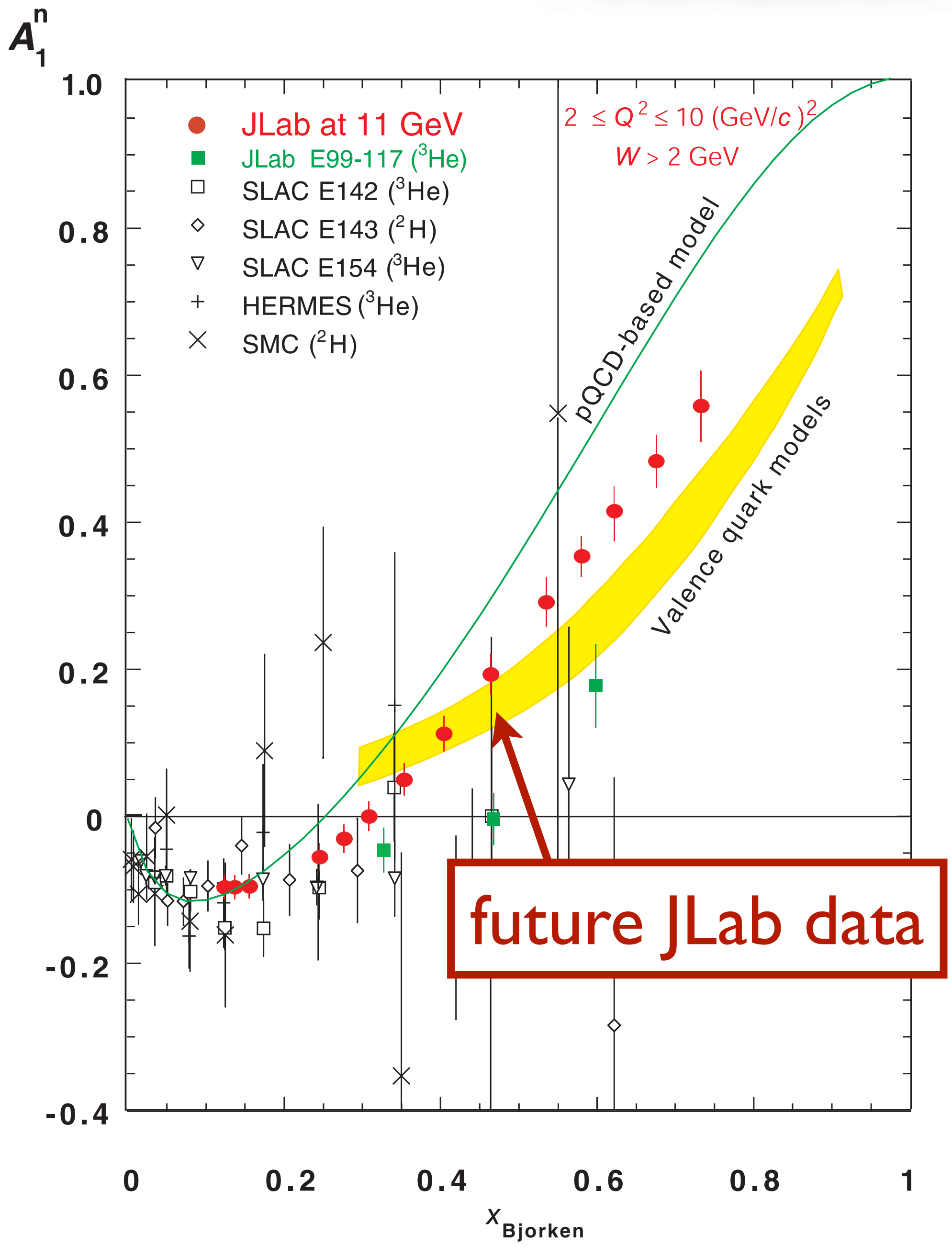
no evidence yet of pQCD behavior!

Polarization asymmetries



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Summary

- Electron scattering
  - → clean probe of quark structure of nucleon
  - → new era of experiments with unprecedented precision

- Valence quarks at large x
  - → d quark properties unknown at large x
  - → nuclear corrections in deuteron important *(deuteron is a nucleus!)*
  - → long-standing puzzles about $x \to 1$ behavior of valence quarks will soon be solved!