April 19, 2002
Testing QCD through Spin Observables in Nuclear Targets

Deep-Inelastic Scattering from Few-Body Nuclei:

overview & recent advances

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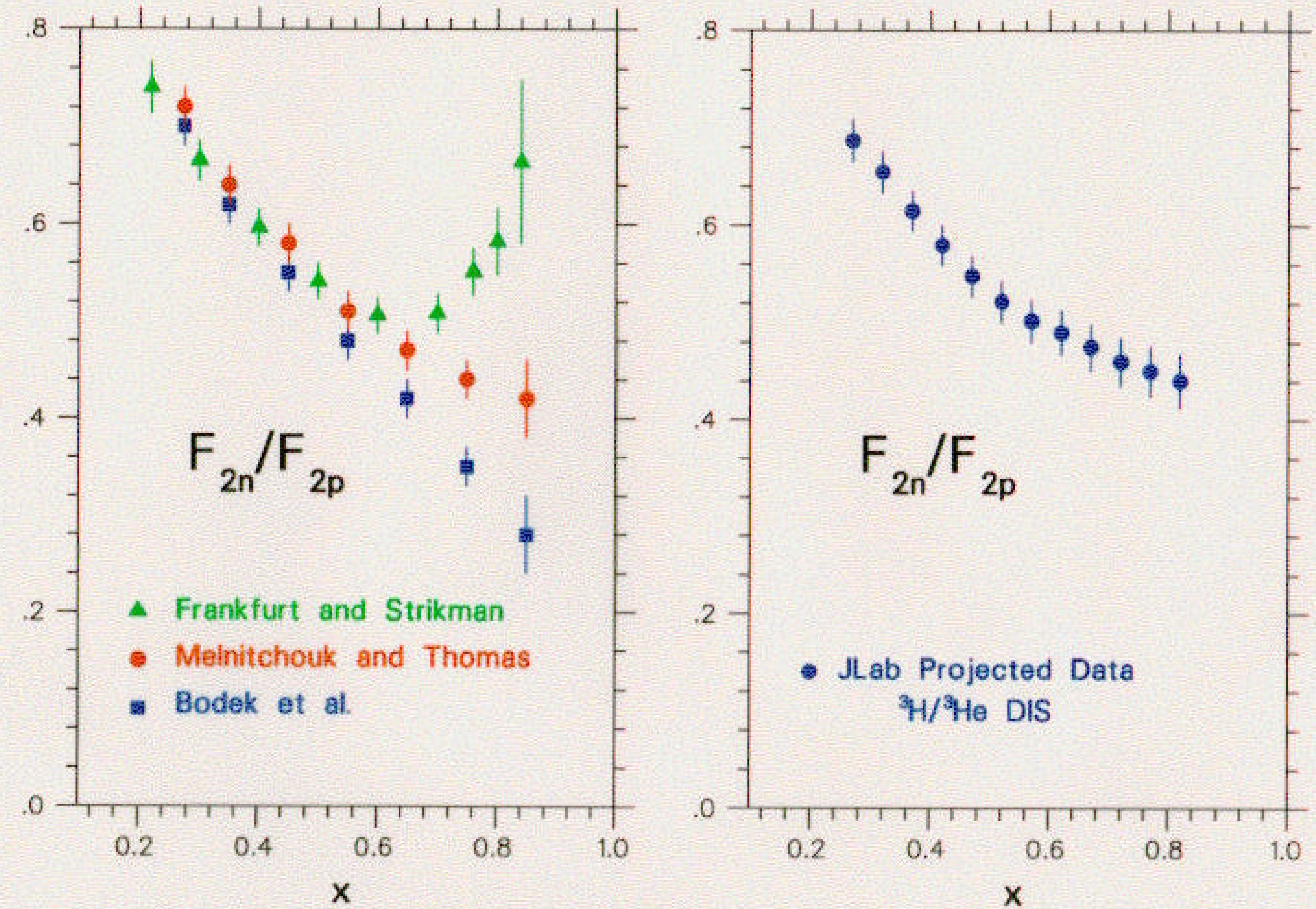
Jefferson Lab


.8
.6
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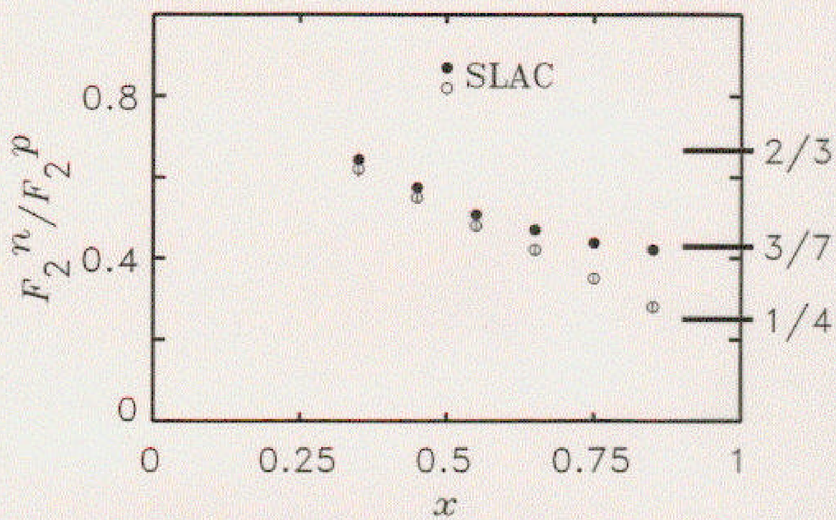
x
F_{2n}/F_{2p}
Frankfurt and Strikman
Melnitchouk and Thomas
Bodek et al.
JLab Projected Data
$^3H/^3He$ DIS

WM, THOMAS PLB377 (96) 11

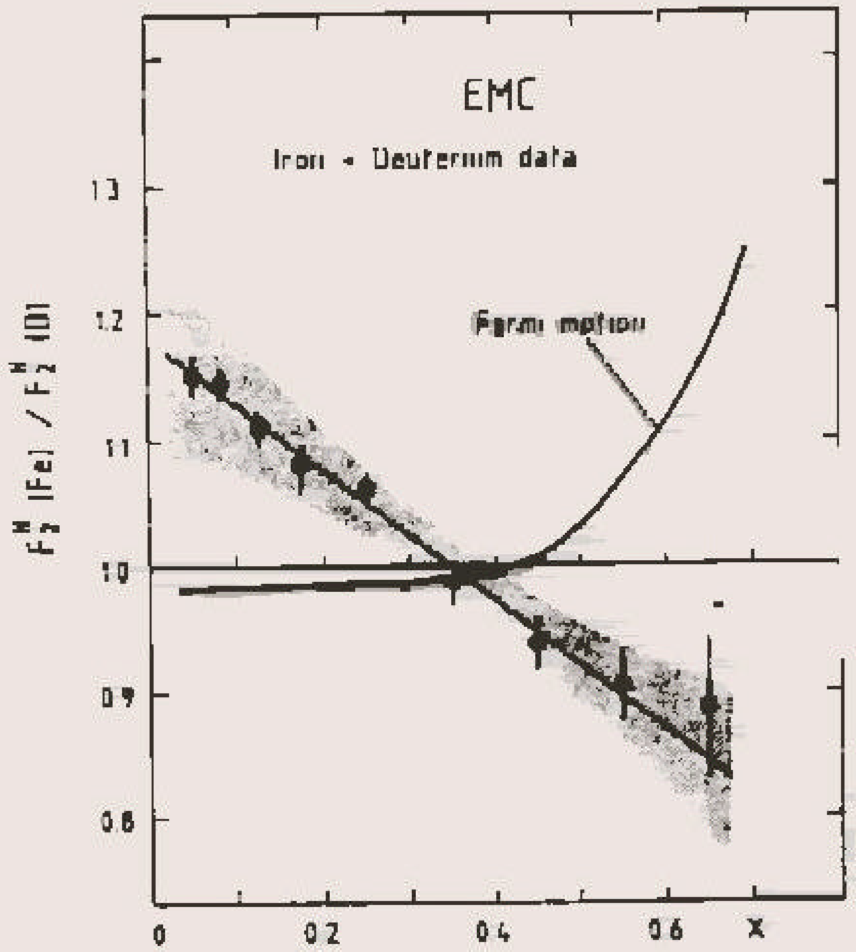


∘ FERMI MOTION

• FERMI MOTION
+ EMC EFFECT

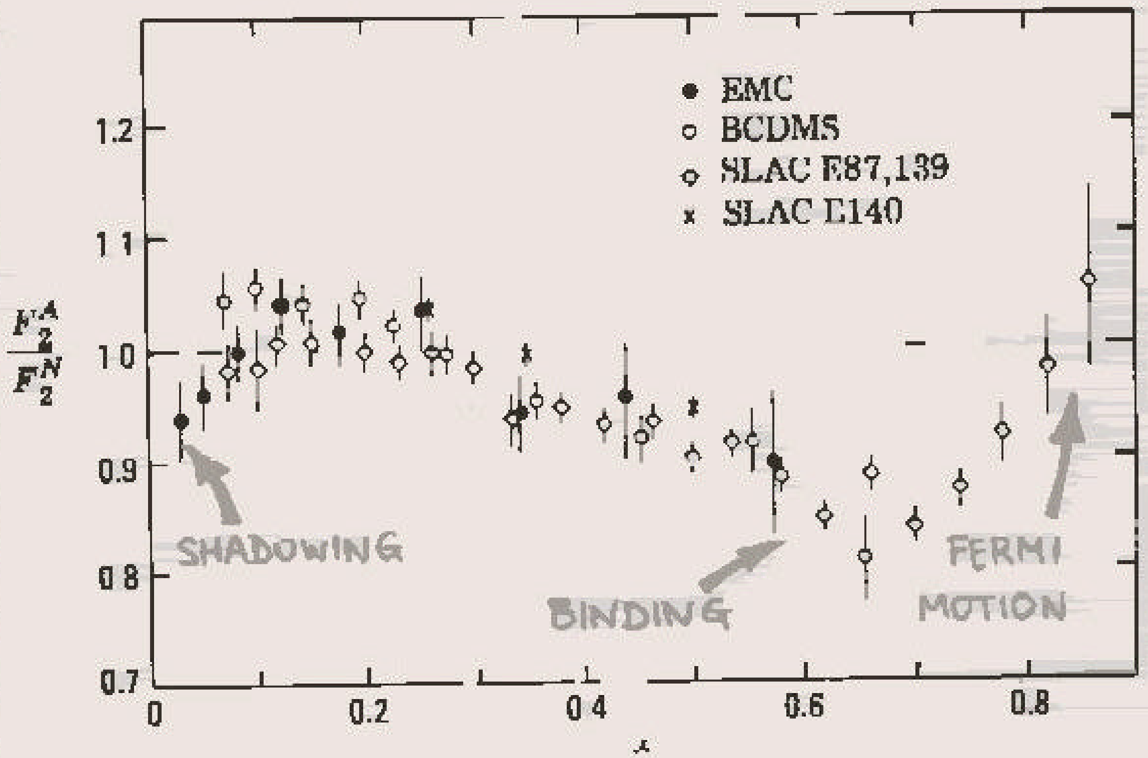
Outline

- Nuclear EMC effect
  - medium modification of nucleon structure functions
- Theoretical foundations
  $\longrightarrow$ conventional description
  $\longrightarrow$ relativistic effects
- Extraction of *neutron* structure functions
  $\longrightarrow$ F_2^n
  $\longrightarrow$ g_1^n, g_2^n
- DIS from *deuterium*
- DIS from *$A=3$ nuclei*
- DIS from *lithium isotopes*
- Medium modification of nucleon electromagnetic *form factors*
- Outlook



CERN NA2 EMC J.J. Aubert et al. Phys. Lett. B 123 (1983) 275

NUCLEAR EMC EFFECT



Models of the Nuclear EMC Effect

There exist many models which describe data (although only partially, and few predictions).

- Q^2-rescaling
- Multi quark clusters
- Deformation of nucleon radius
- Deformation of long range structure
- Nuclear binding
- Point-like configurations
-

→ Current data cannot rule them out

→ Problem is lack of (many) falsifiable predictions!

Words of Wisdom

"Have we really learned anything more than just that bound nucleons are not free?"

(Sir Denys Wilkinson, PANIC'96)

"Looking for quarks in the nucleus is like looking for the Mafia in Sicily: everyone knows they're there, but it's hard to find the evidence"

(Anonymous, 1983)

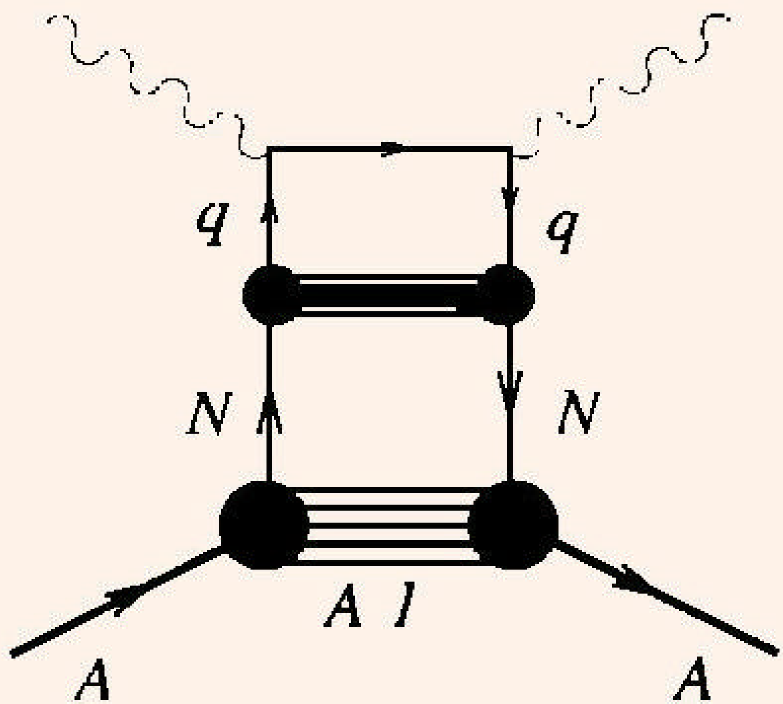
"No smoking gun color remains hidden despite repeated assaults. Know of no single effect attributable to quarks for which there exists no totally hadronic explanation"

(R L Jaffe, 1996)

- Surprisingly, EMC effect in *light nuclei* (where quantitative calculations are more feasible) is less firmly established experimentally, and more controversial theoretically
  $\longrightarrow$ especially for $A = 2$ and $A = 3$ nuclei

- Microscopic few-body calculations with realistic potentials are possible for $A < 6$
  $\rightarrow$ correlate variety of observables (form factors, structure functions, static properties)
  $\longrightarrow$ nuclear structure functions and form factors can be related through generalized parton distributions, and quark-hadron duality

- Ideal testing ground for nuclear models!


q
q
N
N
A 1
A
A

Hadronic tensor for DIS from nucleus A:

$$W^A_{\mu\nu}(P,q) = \int d^4p \; \mathrm{Tr}\left[\hat{A}_{N/A}(P,p)\; \widehat{W}^N_{\mu\nu}(p,q)\right]$$

⟶ truncated (off shell) nucleon tensor

$$\widehat{W}^N_{\mu\nu}(p,q) = g_{\mu\nu}\left(I\,\widehat{W}_0 + \not{p}\,\widehat{W}_1 + \not{q}\,\widehat{W}_2\right)$$

⟶ (off shell) nucleon nucleus amplitude

$$\mathcal{A}_{N/A}(P,p) = (I\,A_S + \gamma_\alpha\,A_V^\alpha)$$

Spin averaged nuclear structure function

$$F_2^A(x) = \int d^4p\,\left(A_S\widehat{W}_0 + p\cdot A_V\,\widehat{W}_1 + q\cdot A_V\,\widehat{W}_2\right)$$

$$= \int dy\; f_{N/A}(y)\; F_2^N(x/y) + \delta^{(\mathrm{off})}F_2^A(x)$$

Factorization of amplitudes *does not imply* factorization of structure functions

Melnitchouk, Schreiber, Thomas

Phys. Rev. D 40 (1994) 1183

RELATIVISTIC DEUTERON STRUCTURE FUNCTION

$$F_2^D(x) = \int_x dy\, f(y)\, F_2^N\left(\frac{x}{y}\right)$$

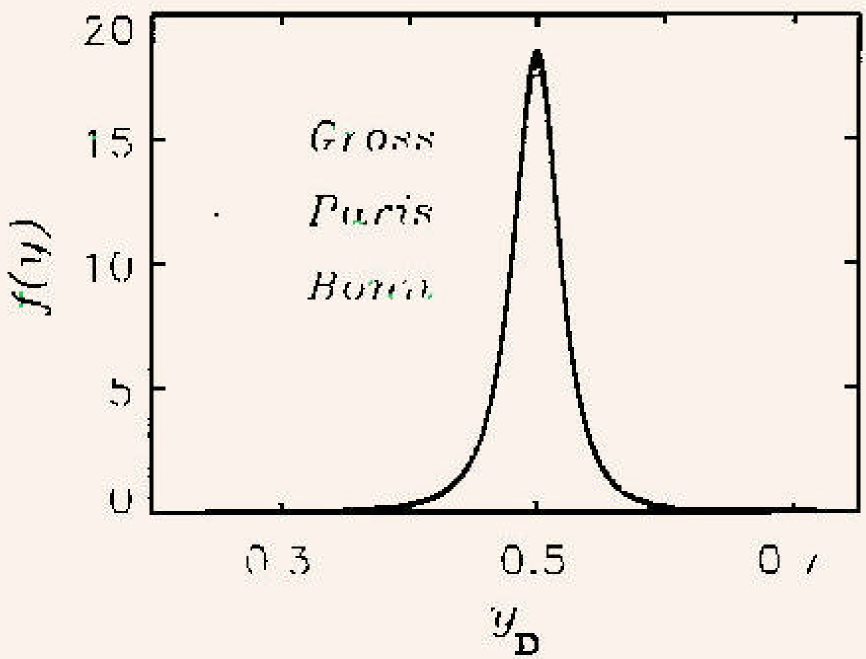
$$+ \underbrace{\delta^{(D)} F_2 + \delta^{(N)} F_2}_{\text{RELATIVISTIC CORRECTIONS}}$$

RELATIVISTIC CORRECTIONS

$\sim 1\%$

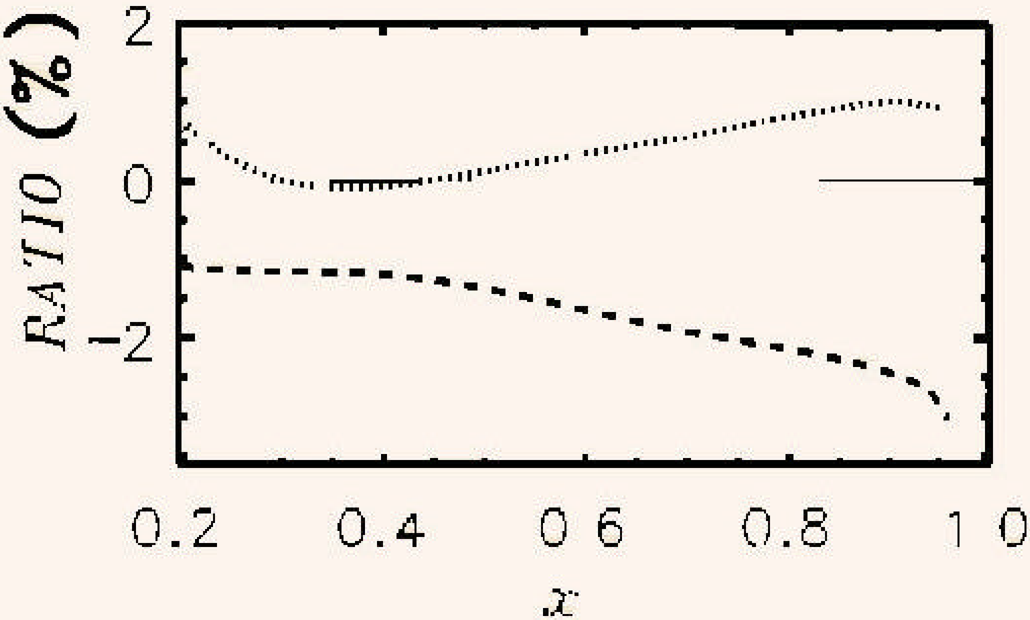
$$f(y) = \frac{M_D}{4}\, y \int_{-\infty}^{p^2_{max}(y)} dp^2\, \frac{E_p}{p_0}\, |\psi_D|^2$$

NUCLEON MOMENTUM DISTRIBUTION IN D



$$f(y) = \frac{M_D}{4} y \int_{-\infty}^{p^2_{max}(y)} dp^2 \, \frac{E_p}{p_0} |\psi_D|^2$$

RELATIVISTIC DEUTERON CORRECTIONS



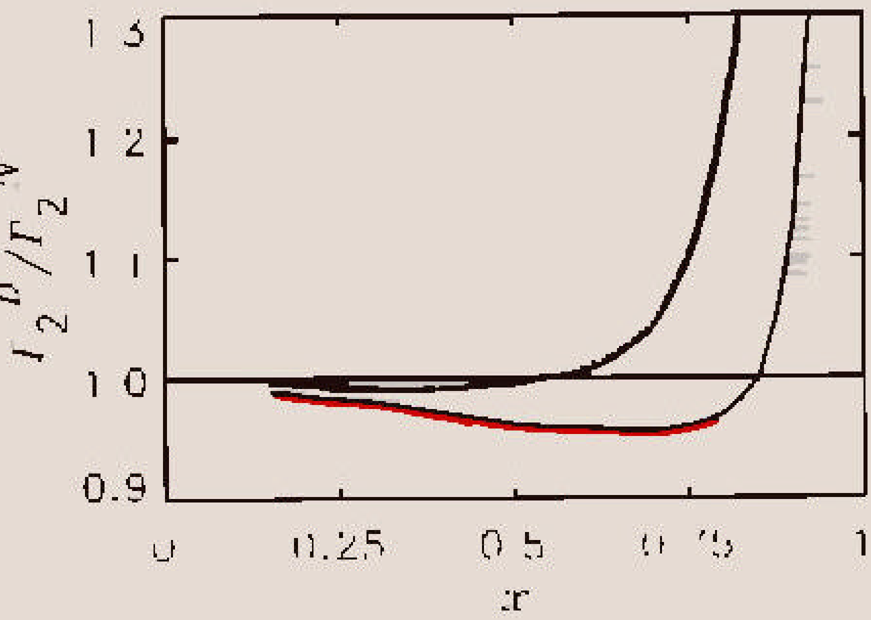
········ $\delta^{(N)} F_2 / F_2^D$

– – – – $\delta^{(D)} F_2 / F_2^D$

Extraction of F_2^n from F_2^D & F_2^p

- Currently all information on F_2^n comes from inclusive DIS on **deuteron**
- How large is EMC effect in the deuteron?
- Answer still controversial!
- Nuclear Fermi motion and binding (off shell) effects are large for $x > 0.6$
- Theoretical uncertainty in F_2^n at large x: whether one corrects for Fermi motion or Fermi motion + binding, F_2^n can differ by $> 50\%$

WM, THOMAS 1996



— FERMI MOTION

— FERMI MOTION

+ EMC EFFECT

Relativistic Polarized Deuterons

In covariant analysis, hadronic tensor for DIS from polarized deuteron

$$W^{D}_{\mu\nu}(P,S,q) = \int d^4p \; \mathrm{Tr}\left[\mathcal{A}_{ND}(P,S,p)\; \hat{G}^{N}_{\mu\nu}(p,q)\right]$$

⟶ truncated polarized nucleon tensor

$$\begin{aligned}\hat{G}^{N}_{\mu\nu}(p,q) = \; & i\epsilon_{\mu\nu\alpha\beta}\, q^{\alpha} \Big(p^{\beta} \not{p}\gamma_5 G_{(p)} + p^{\beta} \not{q}\gamma_5 G_{(q)} \\ & + \gamma^{\beta}\gamma_5 G_{(\gamma)} + i\sigma^{\beta\lambda} p_{\lambda}\gamma_5 G_{(\sigma p)} \\ & + i\sigma^{\beta\lambda} q_{\lambda}\gamma_5 G_{(\sigma q)} + i p^{\beta}\sigma^{\lambda\rho} p_{\lambda} q_{\rho}\gamma_5 G_{(\sigma pq)} \Big)\end{aligned}$$

⟶ spin dependent deuteron nucleon amplitude

$$\hat{\mathcal{A}}_{ND}(p,P,S) = \left(\gamma_5\gamma_{\alpha}\, \mathcal{A}^{\alpha}_{PV} + \sigma_{\alpha\beta}\, \mathcal{A}^{\alpha\beta}_{T}\right)$$

- Relativistic deuteron g_1 structure function

$$g_1^D(x) \quad \int d^4p \left\{ A_{p\gamma} \quad q \left(\quad + \quad \right) + A_{p\gamma} \cdot p \quad \right\}$$

- Off shell structure of bound nucleons
  ⟶ breakdown of convolution

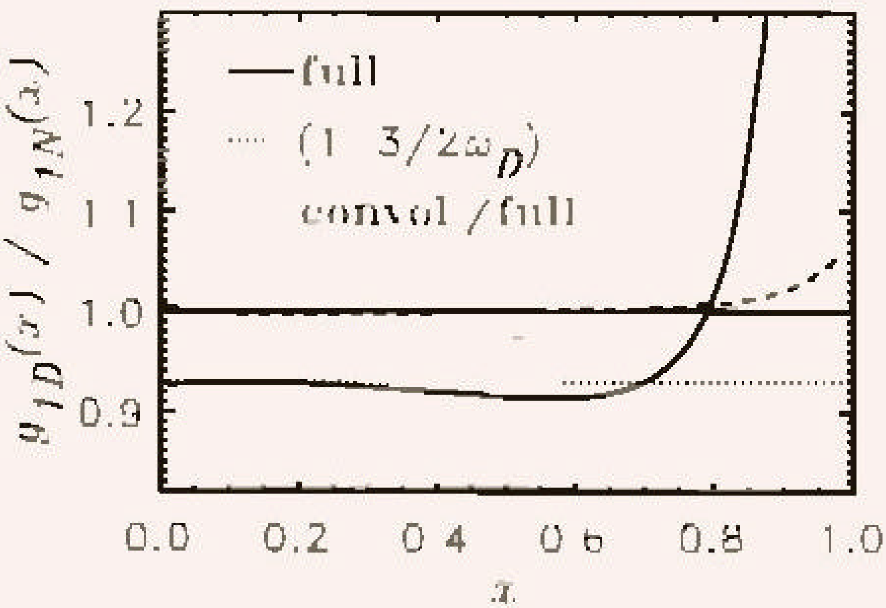
- Taking on shell limits, can nevertheless identify convolution component with relativistic + off shell corrections

⟶ spin dependent nucleon momentum distribution

$$\Delta f(y) - \int d^4p \left(1 + \frac{p_z}{M}\right) \Delta S(p) \, \delta\left(y \quad \frac{p^+}{M_D}\right)$$

→ polarized deuteron spectral function.

$$\Delta S(p) \quad \psi^\dagger_{11}(p) \; S_z \; \psi_{11}(p) \; \delta(p_0 \quad M_D + E_p)$$



EMC effect in the deuteron g_1 structure function

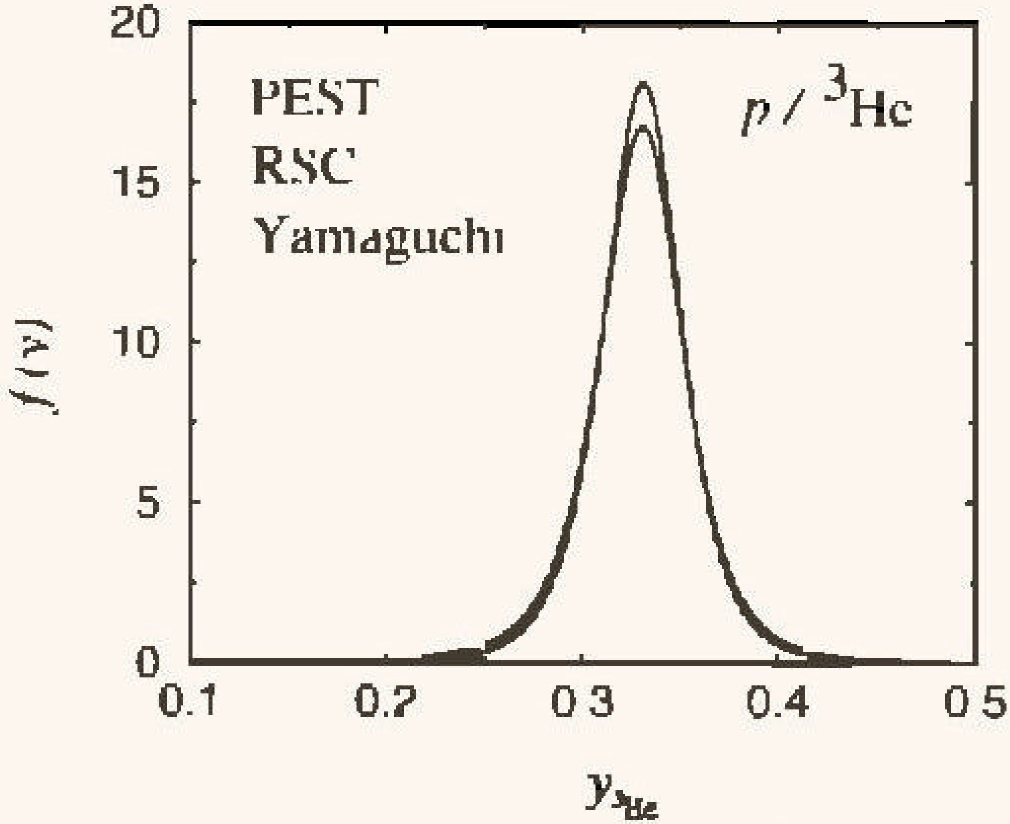
Piller, Melnitchouk, Thomas
Phys. Rev. C 54 (1996) 894

^3He and ^3H Structure Functions

$A = 3$ structure functions at large x

$$F_2^{^3He} \quad 2 \cdot \quad \otimes \; F_2^p + \quad \otimes \; F_2^n$$

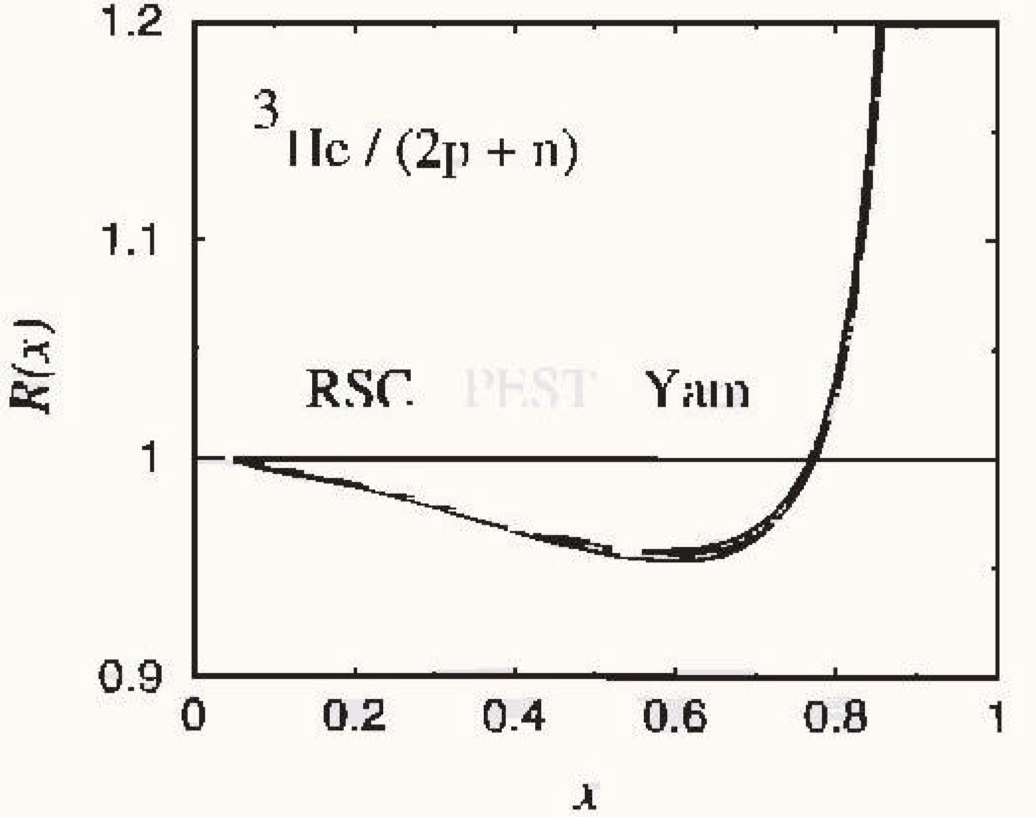
$$F_2^{^3H} \quad \quad \otimes \; F_2^p + 2 \quad \otimes \; F_2^n$$



Proton distribution functions in ^3He

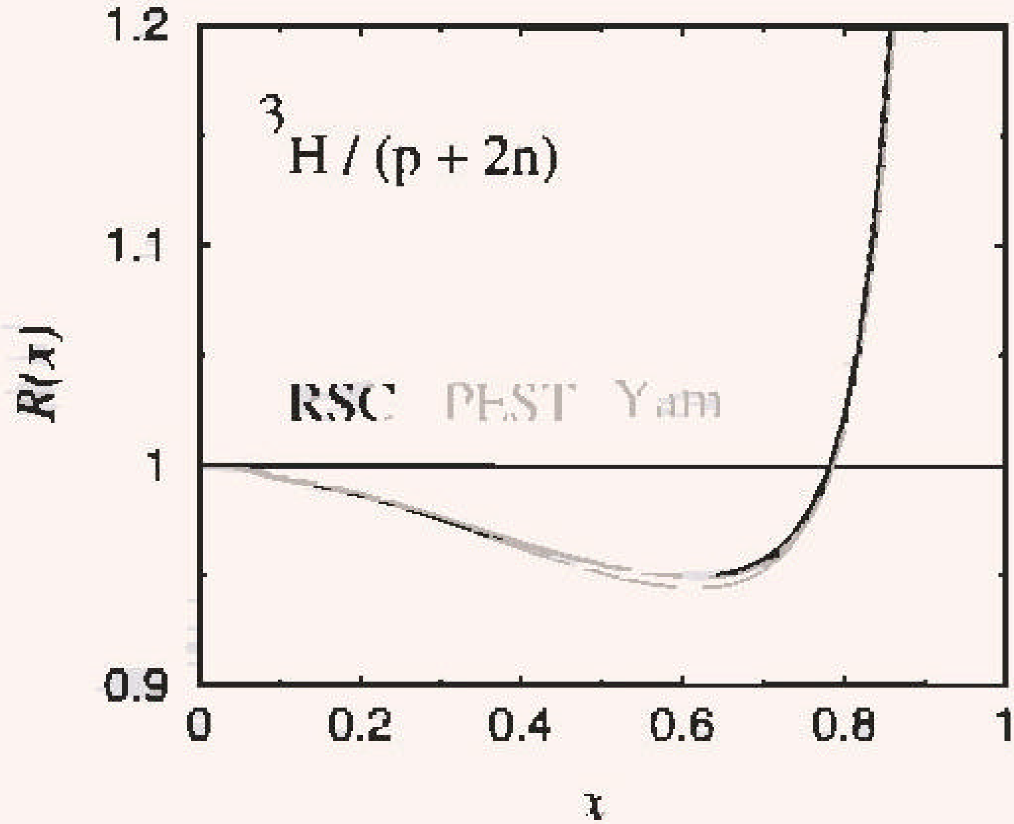
(from Bissey, Thomas, Afnan 2000)

AM, BISSEY, THOMAS, AFNAN 2000

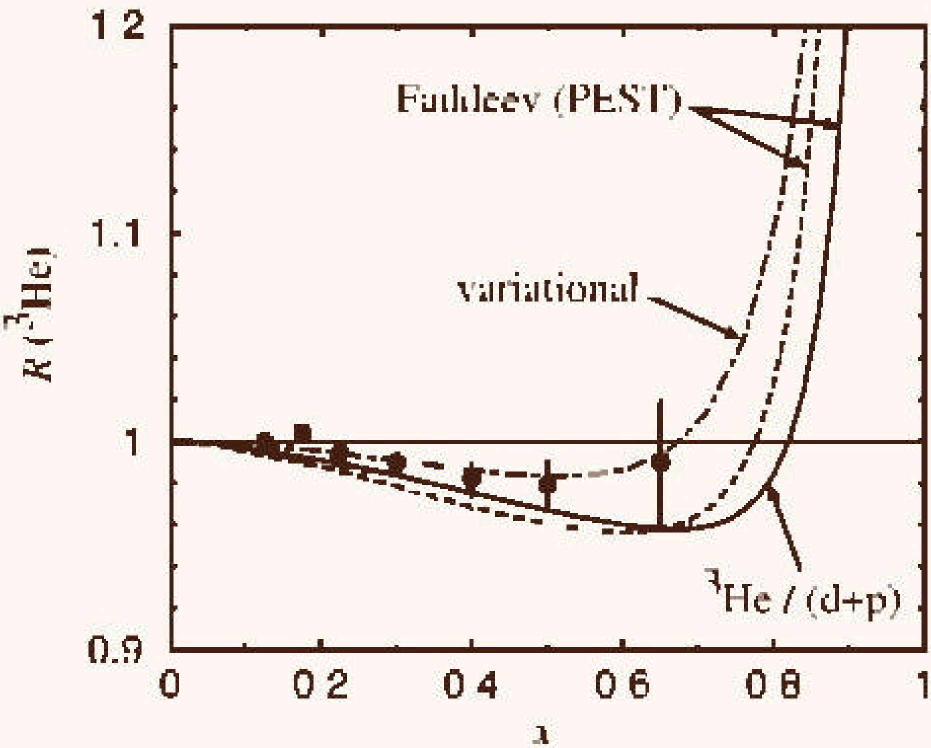


EMC effect in ^{3}He

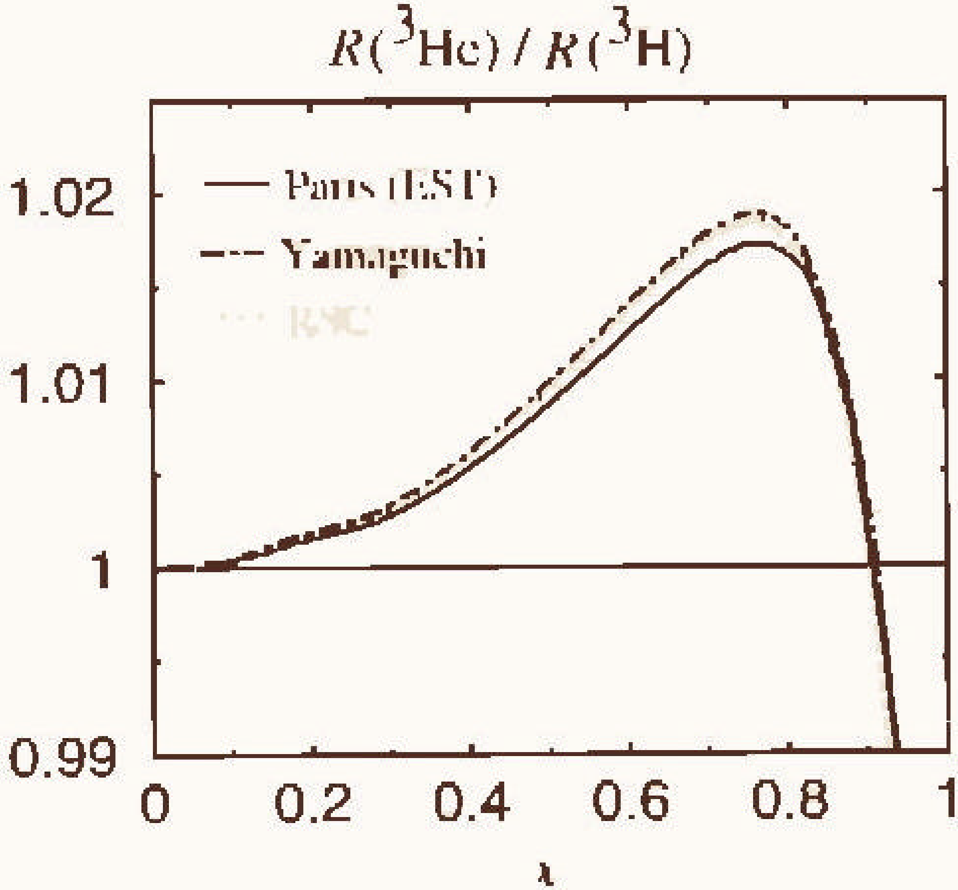
WM, BISSEY, THOMAS, AFNAN 2000



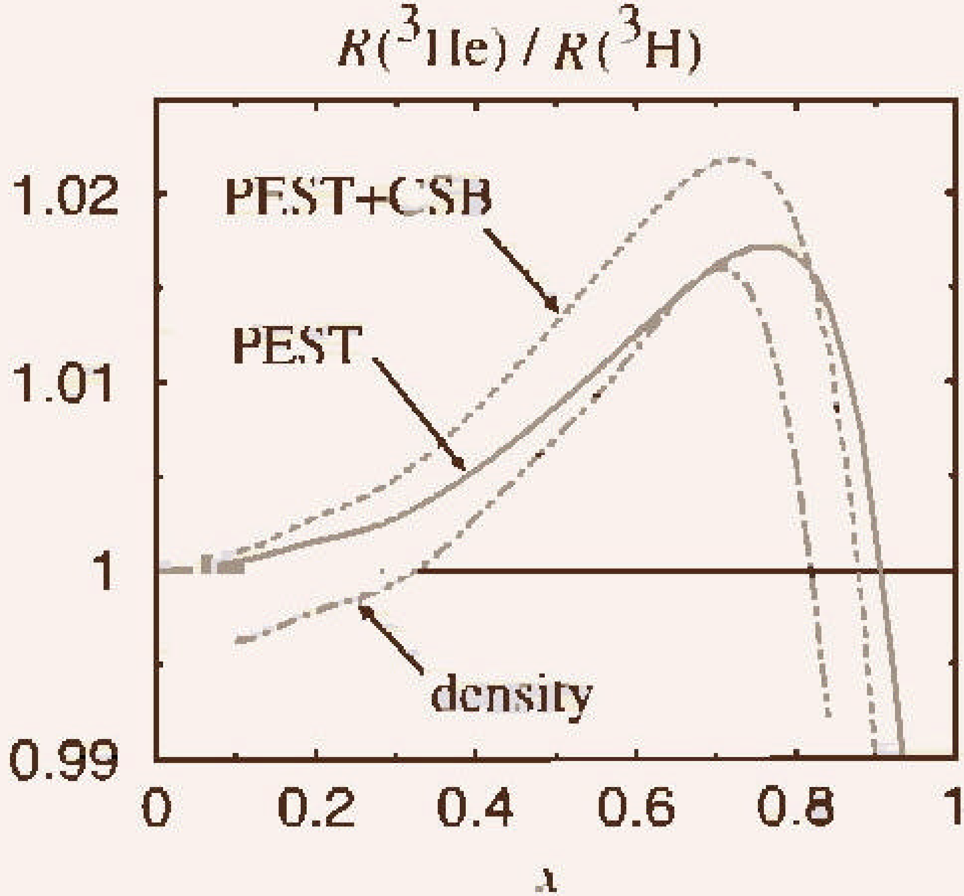
EMC effect in ^{3}H



Nuclear EMC effect in ^{3}He



Ratio of ^3He and ^3H EMC effects for various A = 3 wave functions



Nuclear model dependence of ratio of
^3He and ^3H EMC effects

Extract F_2^n from $F_2^{^3He}/F_2^{^3H}$

EMC ratios for $A = 3$ mirror nuclei:

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

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

Extract n/p ratio from measured $^3He/^3H$ ratio:

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

where the super-ratio $\mathcal{R} = R(^3He)/R(^3H)$