Nuclear structure functions

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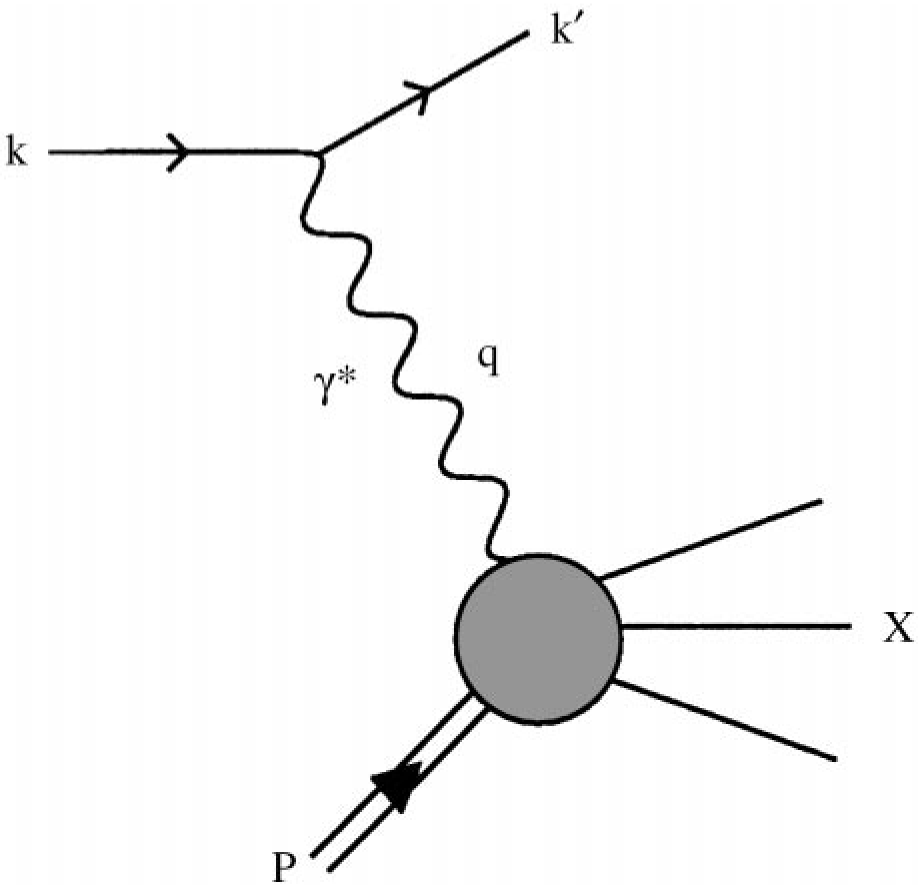
- DIS kinematics — what can we see in DIS ?
- Experiments — what is the nuclear EMC effect ?
- Theoretical approaches — can we understand it ?
- Possible explanations — what do we need ?
- Summary

1. Kinematics of Deep Inelastic Scattering (DIS)



- Initial and final lepton 4-momentum:

$$k^{\mu}, k'^{\mu}, k^2 = k'^2 = m^2 \approx 0$$

- Virtual photon 4-momentum squared:

$$q^2 = (k - k')^2 \equiv -Q^2 < 0$$

- Initial nucleon (nucleus) 4-momentum:

$$P^{\mu} = (E_T, \vec{P}), P^2 = M_T^2$$

- Final hadronic 4-momenyum squared:

$$P_X^2 = (P + q)^2 \equiv W^2$$

- Inelasticity (energy transfer in Lab):

$$\nu = (P \cdot q) / M_T$$

- Bjorken variable:

$$0 < x = Q^2 / 2 M_T \nu \leq 1$$

- The differential cross section (unpolarized):

$$\frac{d^2\sigma}{d\Omega\, dE'} = \frac{\alpha^2 E'}{Q^4 E} L_{\mu\nu} W^{\mu\nu}$$

lepton tensor (symmetric part):

$$L^{\mu\nu} = 2(k^\mu k'^\nu + k'^\mu k^\nu - k \cdot k' g^{\mu\nu})$$

hadronic tensor (symmetric part):

$$W^{\mu\nu} = W_1(x,Q^2) e^{\mu\nu} + [W_2(x,Q^2)/M_T^2] \tilde{P}^\mu \tilde{P}^\nu,$$

$$(e^{\mu\nu} = g^{\mu\nu} - q^\mu q^\nu / q^2, \quad \tilde{P}^\mu = P^\mu - (P \cdot q) q^\mu / q^2)$$

- Structure functions F1 and F2:

$$F_1(x,Q^2) = M_T W_1(x,Q^2), \; F_2(x,Q^2) = (P \cdot q / M_T) W_2(x,Q^2)$$

- Bjorken limit:

$$F_{1,2}(x,Q^2) \xrightarrow{Q^2 \to \infty, \nu \to \infty, x:\ fixed} F_{1,2}(x)$$ Bjorken scaling

●What can we see in DIS ?

The approximate Q^2-independence of the structure functions

→ the virtual photon sees point-like constituents in the target – quarks

→ using distributions of quarks and anti-quarks,

$$F_1(x) = \frac{1}{2}\sum_f e_f^2 [q_f(x) + \overline{q}_f(x)],\ F_2(x) = 2xF_1(x)$$ (Callan-Gross relation)

The small scaling violation is calculated by pQCD.

DIS probes a current-current correlation in the target ground state.

In the Bjorken limit, the probed correlation is light-like:

$$y^{\pm} = (t \pm y_3)/\sqrt{2},\ \ y^- \to 0, \vec{y}_\perp \to 0, y^+ \approx \sqrt{2}/M_T x$$

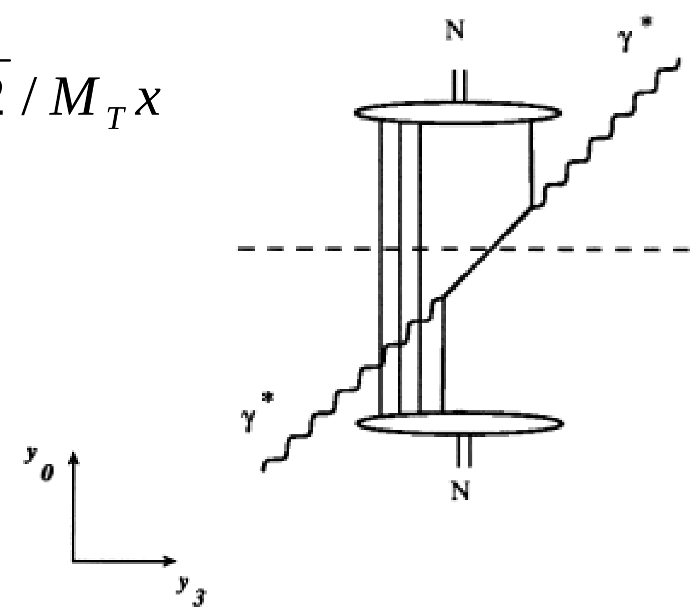
$$|t|,|y^3| \le 0.2(fm)/x \approx \ell_c$$

~ 2.0(fm) for x ~ 0.1

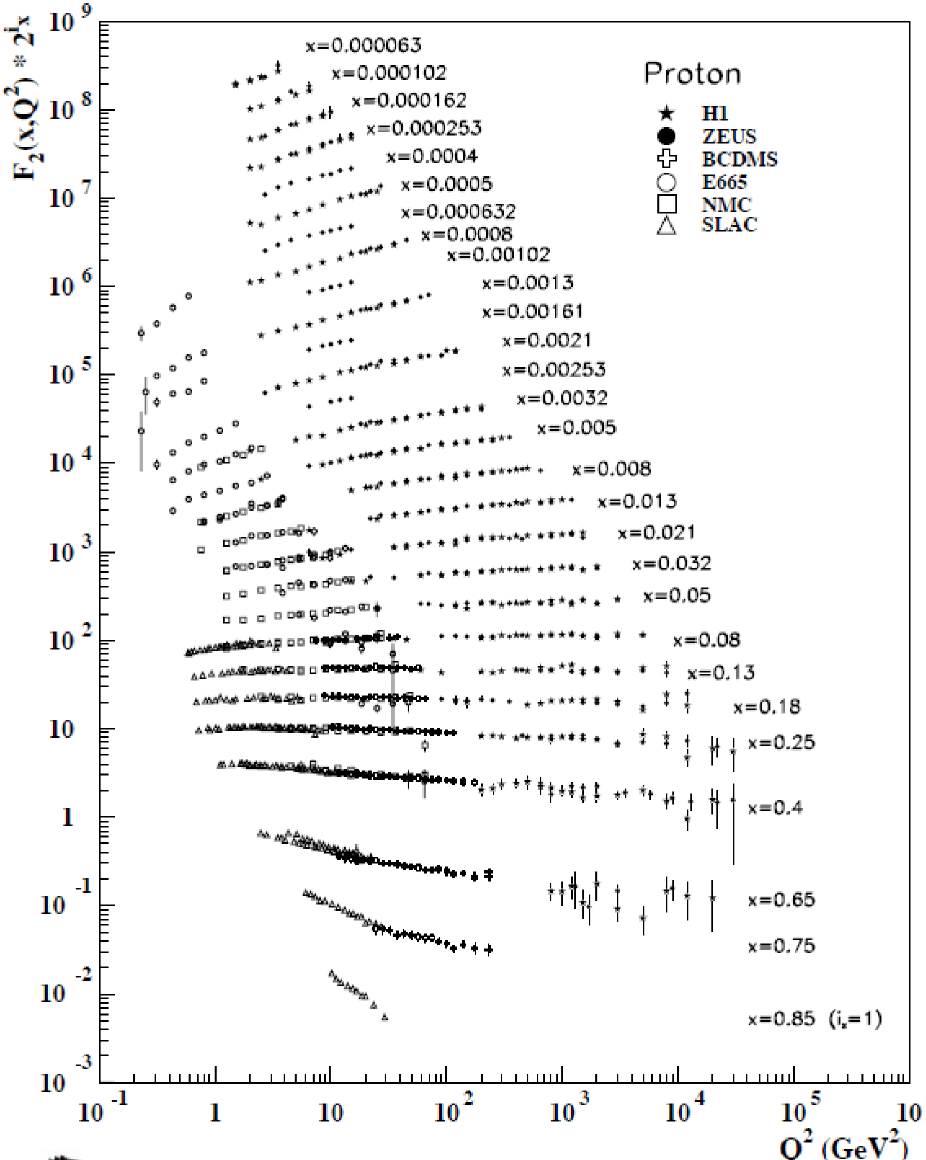
~ 1.0(fm) for x ~ 0.2

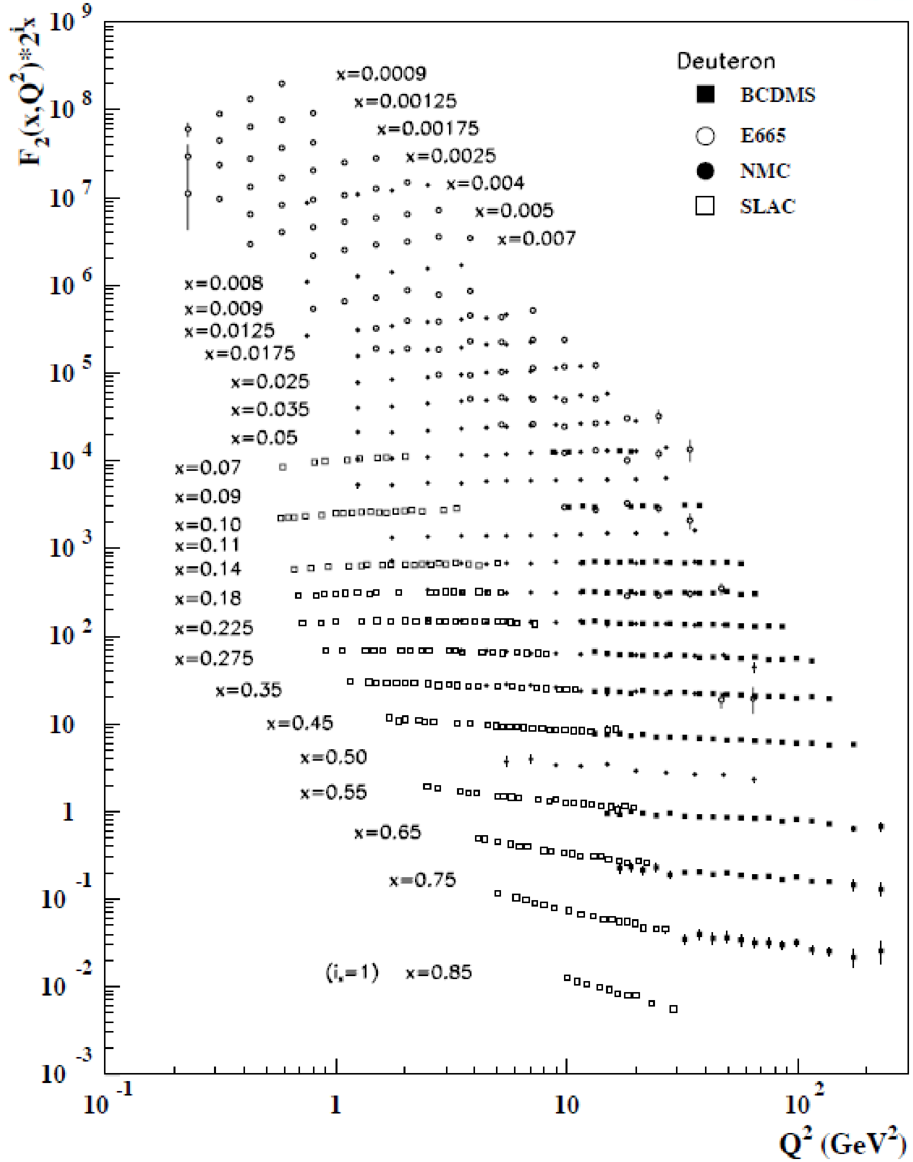
~ 0.4(fm) for x ~ 0.5

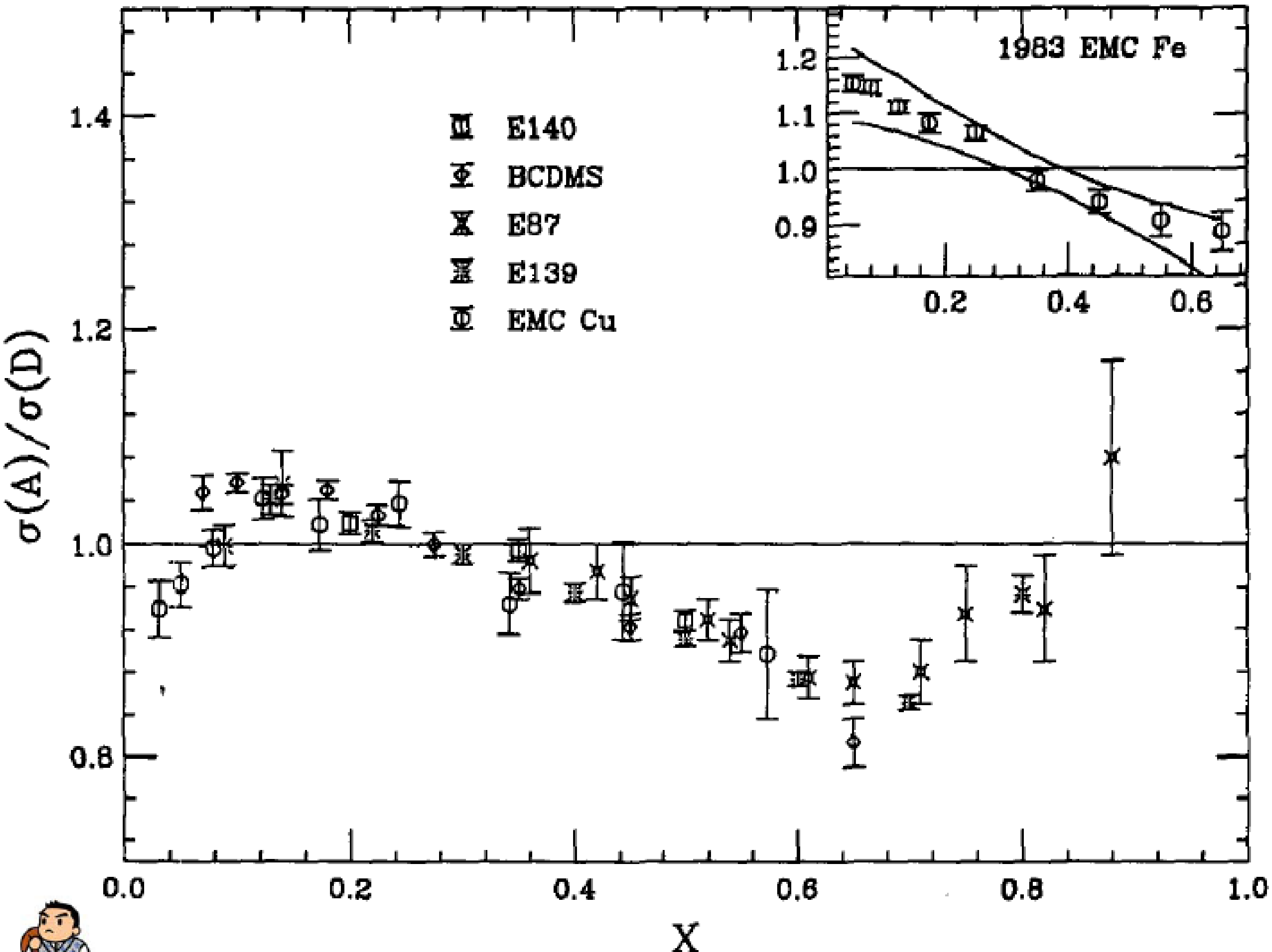
~ 0.2(fm) for x ~ 1.0

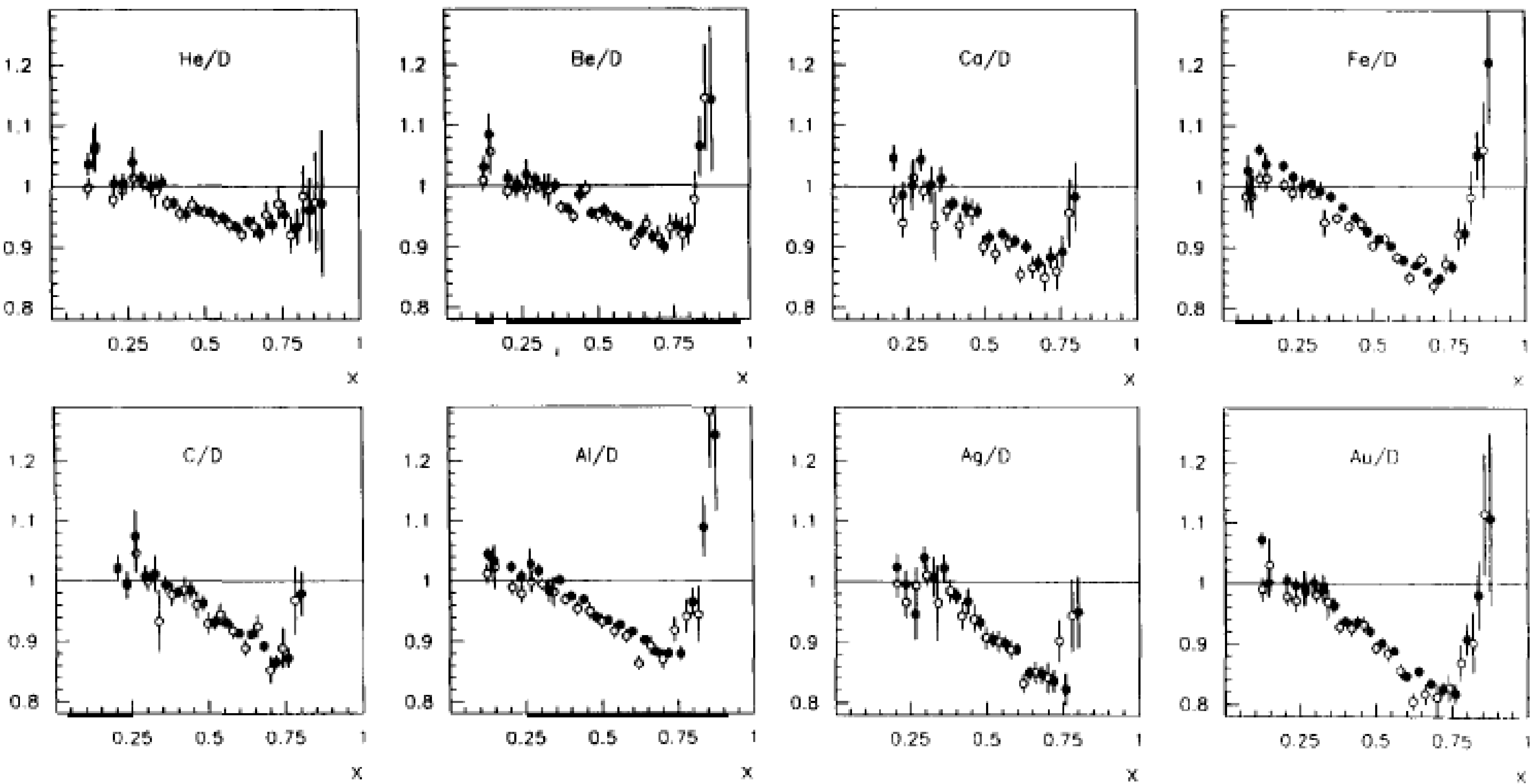


2. Experiments

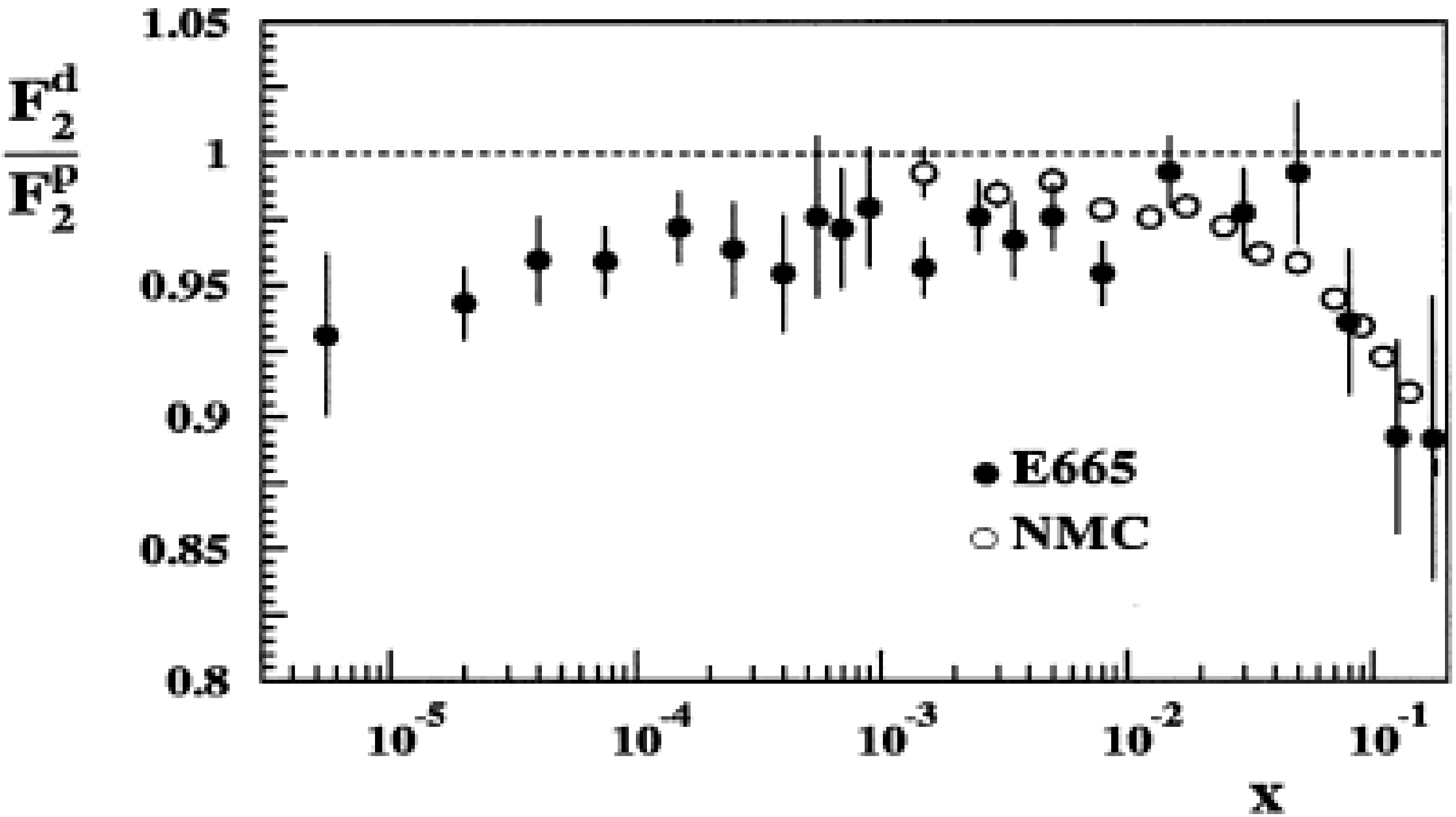





1983 EMC Fe
1.2
1.1
1.0
0.9
0.2
0.4
0.6
E140
BCDMS
E87
E139
EMC Cu
1.4
1.2
1.0
0.8
σ(A)/σ(D)
0.0
0.2
0.4
0.6
0.8
1.0
X



SLAC



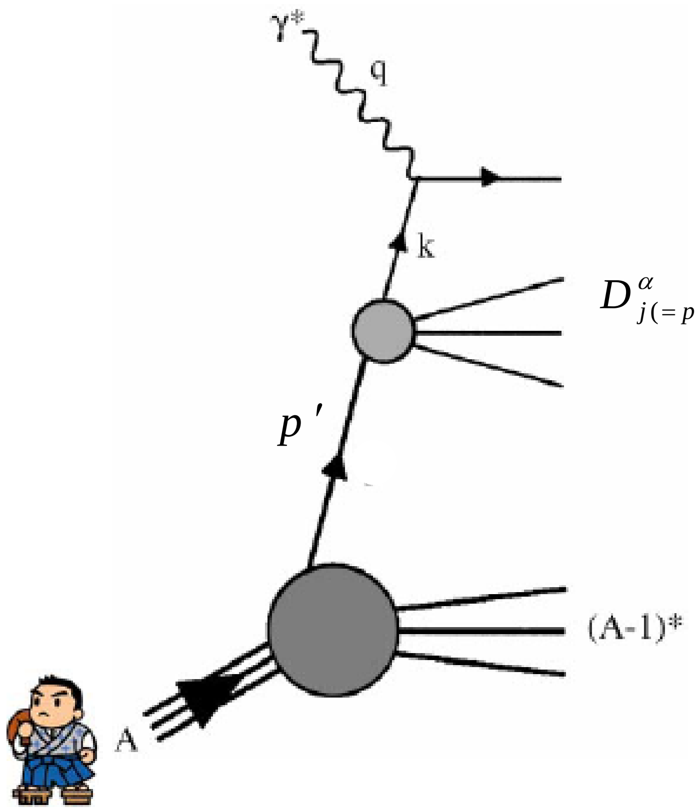
F_2^d / F_2^p
1.05
1
0.95
0.9
0.85
0.8
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
x
E665
NMC

3. Theoretical approaches

3-1. Effect of the conventional nuclear physics — Binding and Fermi motion
3-2. Shadowing effect at small x
3-3. Anti-shadowing ?

3-1. Effect of the conventional nuclear physics — Binding and Fermi motion

How does the conventional nuclear physics affect F2(x) ?



The nucleon is scattered incoherently in case of

$$\ell_c \leq d \approx 2\ fm \rightarrow x \geq 0.1$$

The light-cone momentum distribution of N in A:

$$D^{\alpha}_{j(=p,n)/A}(y,p^2) = y\int \frac{d^4p'}{(2\pi)^4} S^{\alpha}_j(p')\delta\left(y - \frac{p'\cdot q}{P_A\cdot q}\frac{M_A}{M}\right)\delta\left(p^2 - p'^2\right)$$

$$y \approx p'^{+}/P_A^{+}$$

$$S^{\alpha}(p) = \left\langle (A-1)_{\alpha}, -\vec{p}\,|\,\hat{\psi}(0)\,|\,A\right\rangle$$

$$= 2\pi\delta(p_0 - M - \varepsilon_{\alpha} + T_R)\,|\,\psi_{\alpha}(\vec{p})\,|^2$$

Spectral function

Quasi-elastic reaction A(e,e’p)A’ → ε_{α}

Koltun sum rule: E/A = (T-e)/2 (2body force only)

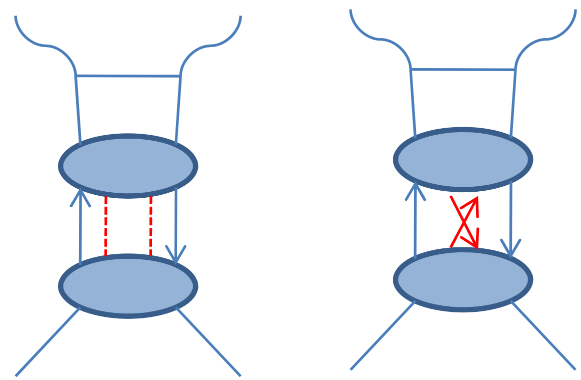
Convolution form:

$$f_{a/A}(x)=\sum_{j,\alpha}\int dydz\delta(x-yz)\int dp^2 D^{\alpha}_{j/A}(y,p^2)\,f_{a/j}(z,p^2)$$

Assumptions in the convolution model:

- on-mass shell approximation → $p^2 = M^2$ → if the binding is weak, OK?
- impulse approximation — final state interactions and interference terms are ignored

If OK, we get $F_2^A(x)=\sum_{j,\alpha}\int_x^A dy D^{\alpha}_{j/A}(y)F_2^j(x/y)$



Ignored diagrams in the convolution

Model-dependent calculations:

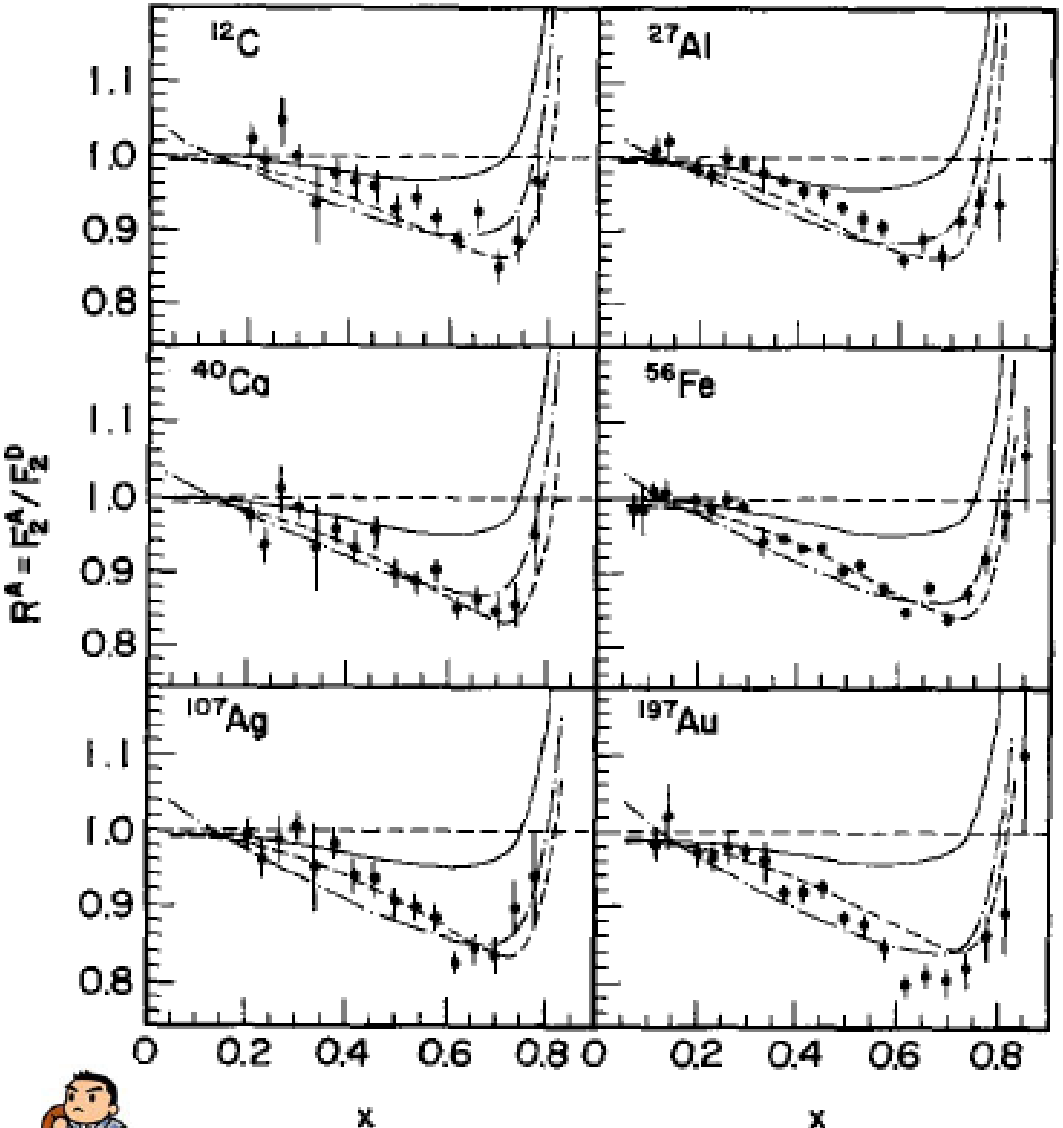
① Off-mass shell effect by Kulagin et al. ↓

② Final state interactions (q-ex.) by Hoodhboy et al. ↓

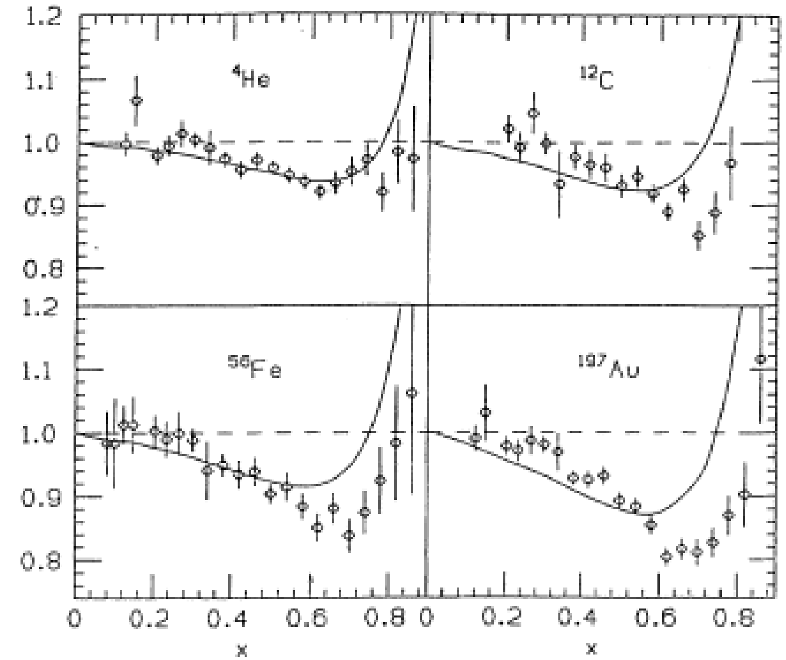
③ "Off-mass" shell (↓) + final state interaction (MFA) by Saito et al. ↑

Note: Deuteron is also different from the average of proton and neutron — small EMC effect.

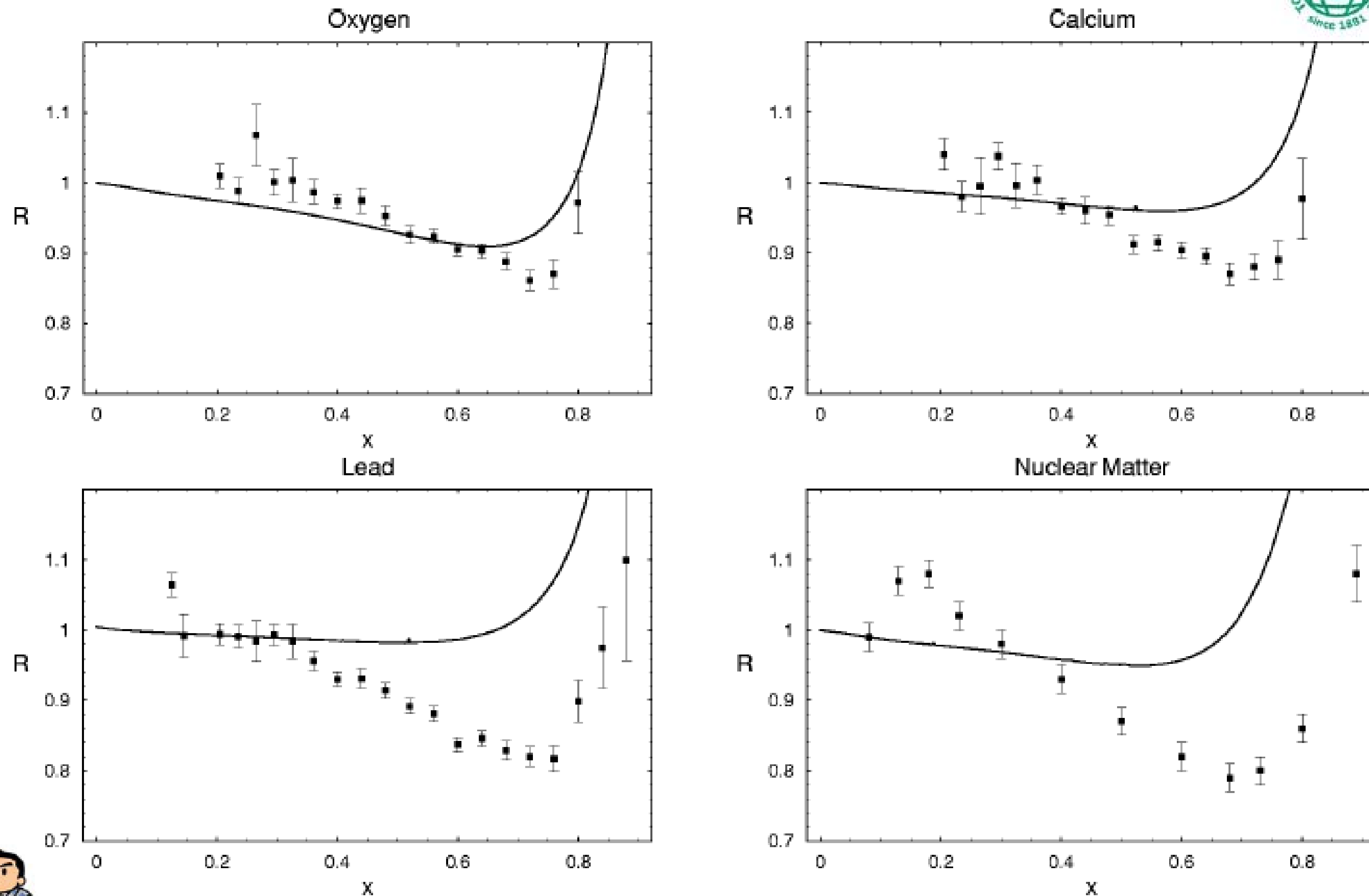
Nonrelativistic calculation (by Li, Liu, Brown)



(by Atti, Liuti)



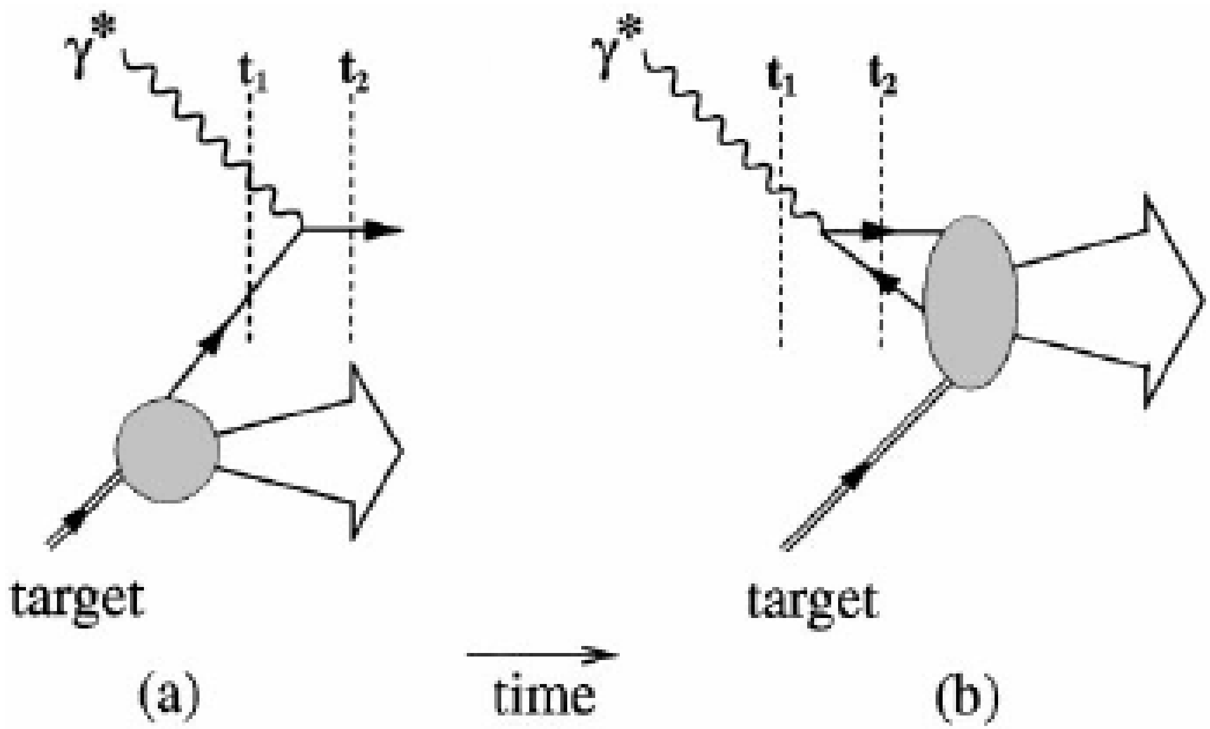
Relativistic calculation (by Smith, Miller)



3-2. Shadowing effect at small x

Shadowing region → $\ell_c \geq d \approx 2\ fm \rightarrow x \leq 0.1$

DIS occurs coherently: $F_2^A(x) \approx \sigma_{\gamma^* A} < A \times \sigma_{\gamma^* N} \ (\sigma_{\gamma^* A} \approx A^{0.8} \times \sigma_{\gamma^* N})$



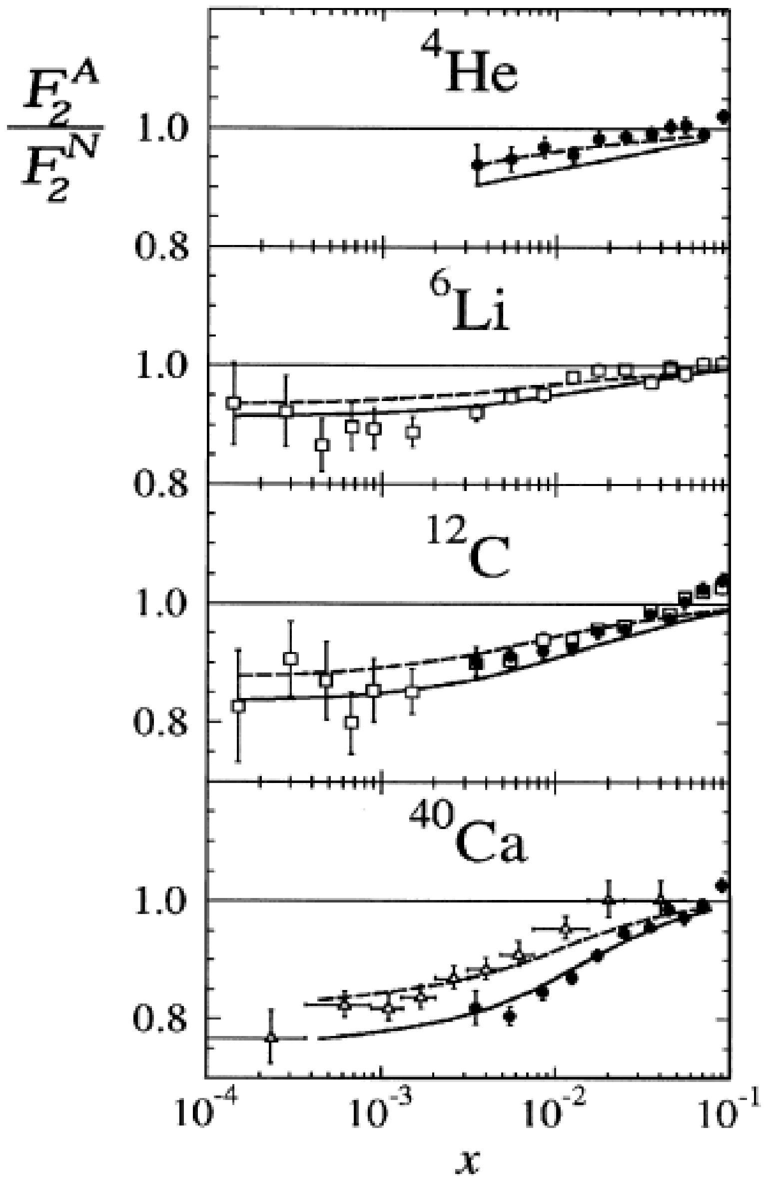
$|A_a / A_b|$ >> 1 for x > 0.1

<< 1 for x < 0.1

for small x, the photon is supposed to be converted into vector mesons

VMD → surface interaction $A^{2/3} \approx A^{0.8}$

Shadowing effect (by Piller et al.)

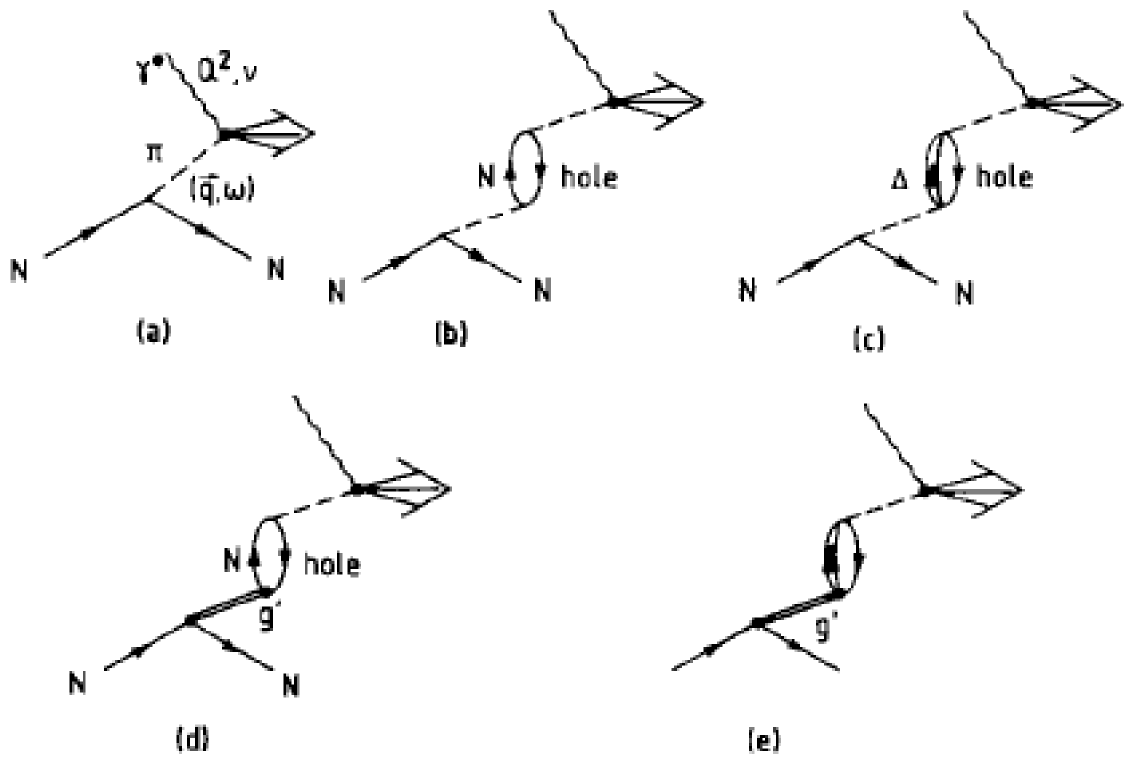


NMC+FNAL（ ρ, ω, ϕ ）

3-3. Anti-shadowing ?

Anti-shadowing region → $0.1 \le x \le 0.2$

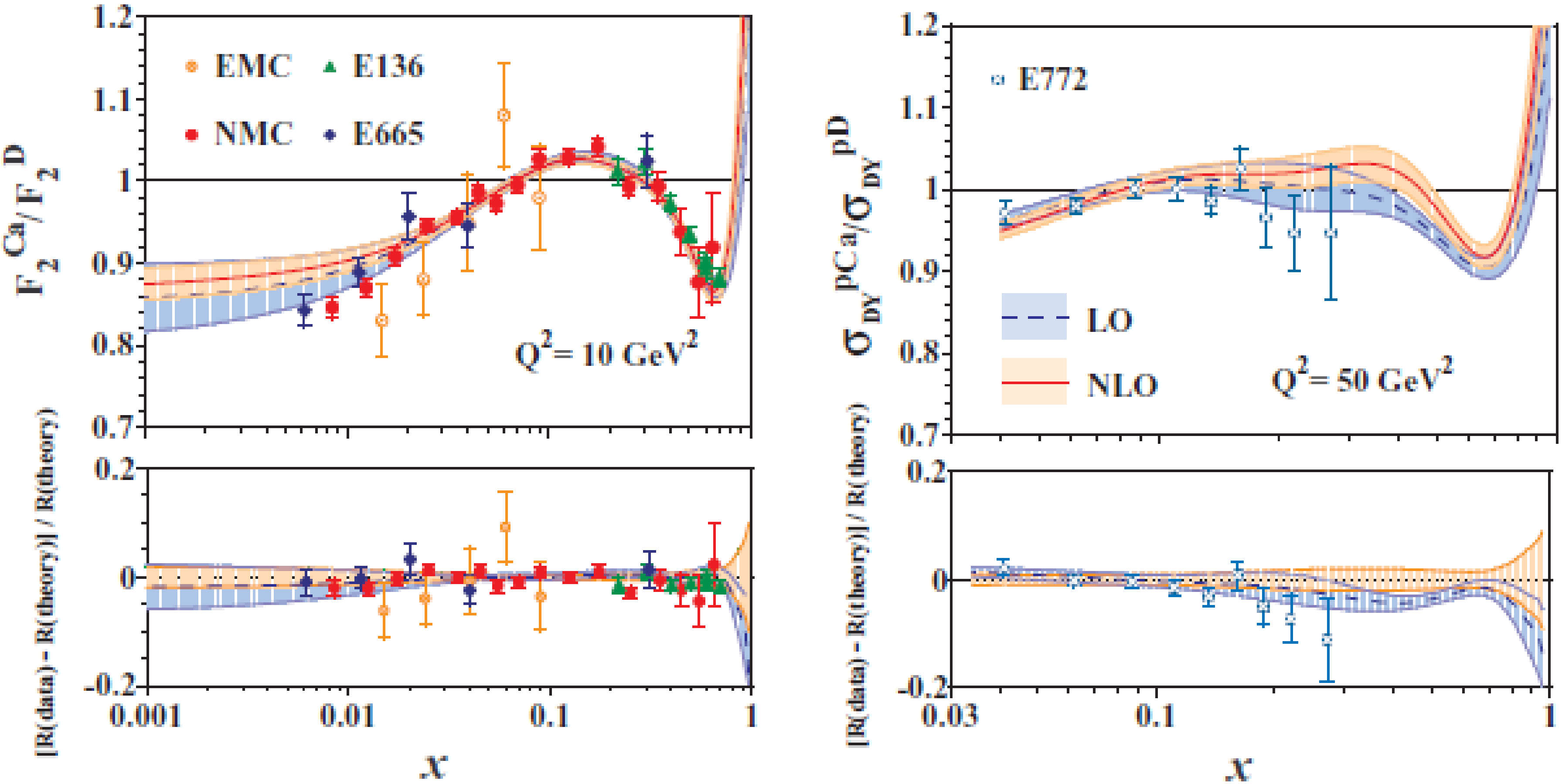
An enhancement at small x region → pion field enhancement ???



Recent data of the giant Gamow-Teller states → the Landau-Migdal parameters

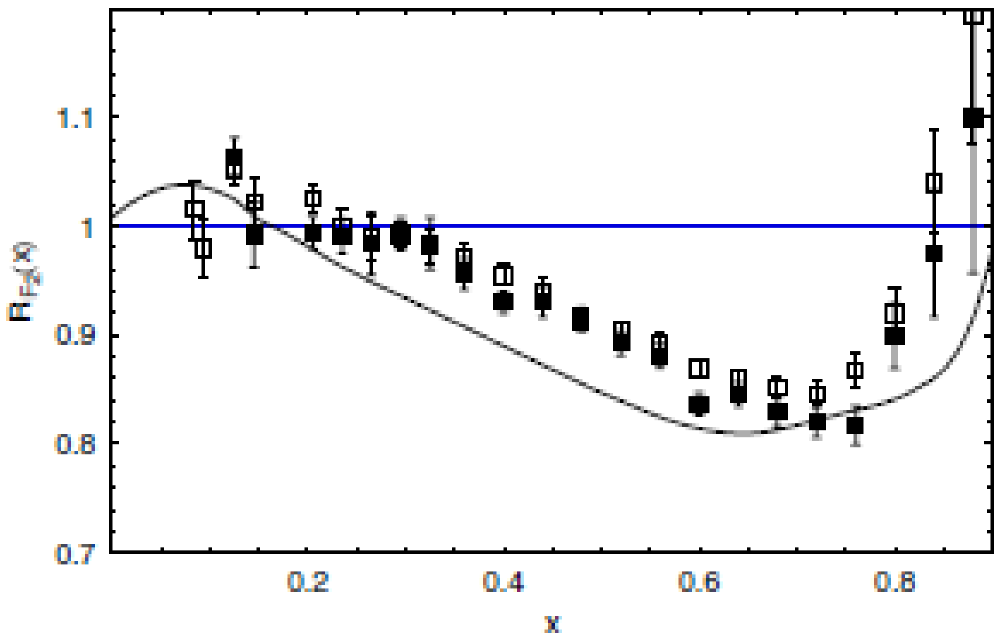
$$g'_{NN} \approx 0.59 \,,\; g'_{N\Delta} \approx 0.18 + 0.05\, g'_{\Delta\Delta}$$

Parameterization of the EMC effect (by M. Hirai et al.)

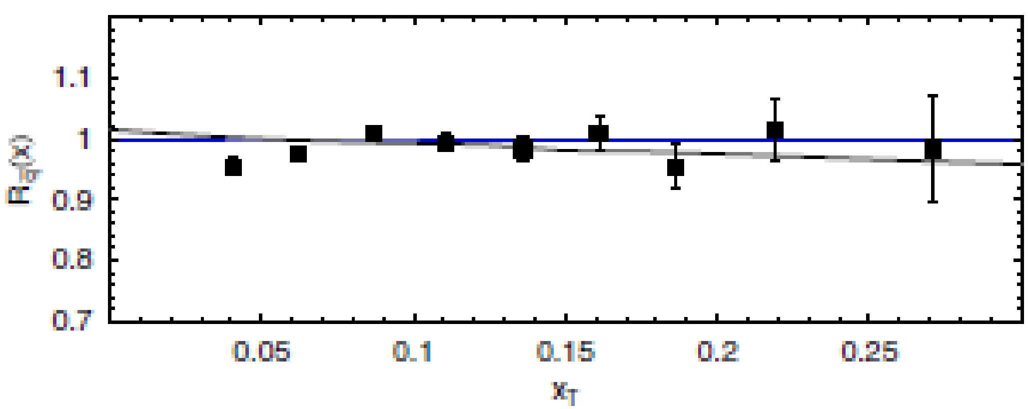


4. Possible explanations — what do we need ?

1. Chiral quark soliton model (by Smith and Miller)



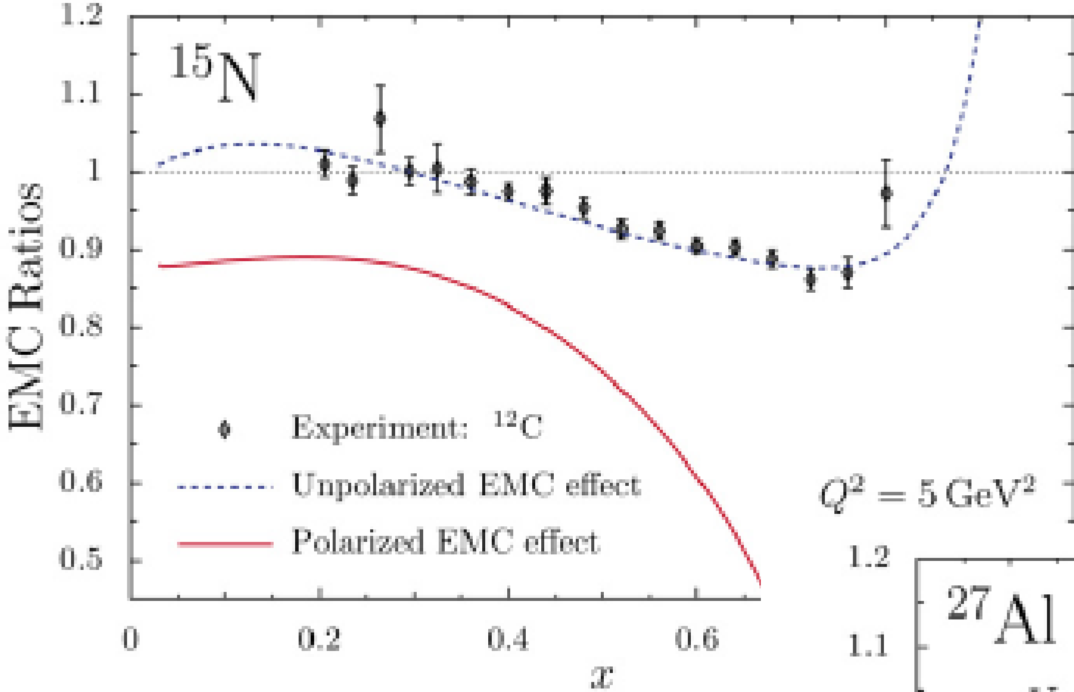
SLAC-E139
Fe & Ag

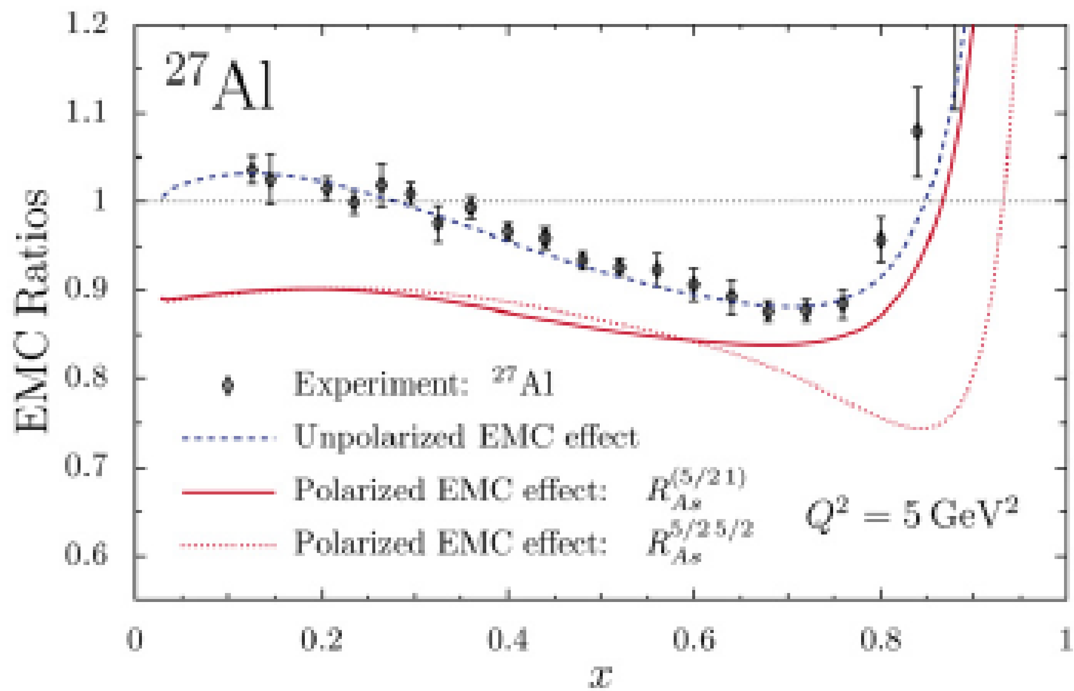


Drell-Yan exp.

FNAL-E772
W

2. NJL model (by Cloet et al.)





5. Summary

1. The quark distribution in a nucleus is different from that in the free nucleon:
   — about 20% reduction at x ~ 0.7-0.8
   — at small x, the structure function is reduced due to shadowing
   — for large x, the EMC ratio is very enhanced because of Fermi motion and short-range correlations

2. The energy-momentum distribution of a nucleon in a nucleus is vital to explain the EMC effect, but its effect is insufficient ?
   — the internal structure of a nucleon is modified in a nucleus ?

3. The sea quark is enhanced in a nucleus around x ~ 0.15 ?
   — cf. the Drell-Yan result

4. At large x (>1), what happens ?