Hadrons in the Nuclear Medium

Structure Functions and EMC Effect

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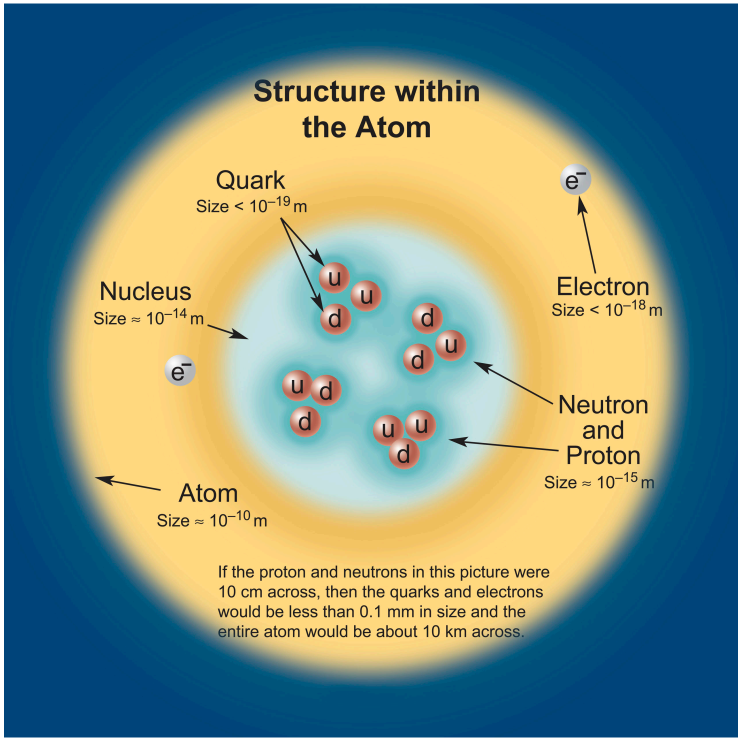
Energy Scales in Molecular and Nucleonic Systems



System	Energy Scale
Molecular	10 eV
Nucleus	10 MeV
Nucleon	100 MeV

- Dynamics of electrons in a molecular system can be completely separated from the dynamics of the nucleons in the nuclear core.

  Ratio of energy scales: 10^{-6}

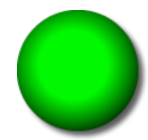
- Can the dynamics of the nucleons in a nucleus also be described independent of the underlying degrees of freedom, namely quark and gluons?

  Ratio of energy scales: 10^{-1}

Nucleons are Modified in the Nuclear Medium

- Conventional Nuclear Physics:
  - Nuclei are effectively and well described as point-like **nucleons** (+ form factor) and interaction through effective forces (**meson** exchange).
  - Medium effects arise through non-nucleonic degrees of freedom.
  - Are **free** nucleons and mesons, under every circumstance, the best quasi-particle to chose?
- Nucleon Medium Modifications:
  - Nucleons and mesons are not the fundamental entities in QCD.
  - Medium effects arise through changes of fundamental properties of the nucleon.
  - Do nucleons change their quark-gluon structure in the nuclear medium? Yes!

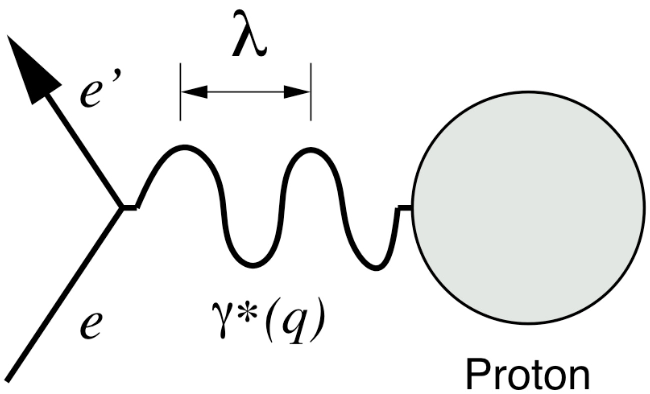
In-Medium Life Time



Free neutron:
τ_n = 15 min

Neutron bound in ^{4}He does not decay, $\tau_n = \infty$

Electron Scattering Experiments

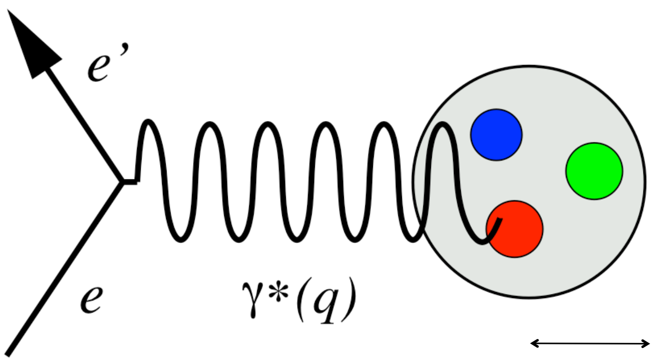


Momentum transfer:

$$k(e) - k(e') = q$$

Resolving power:

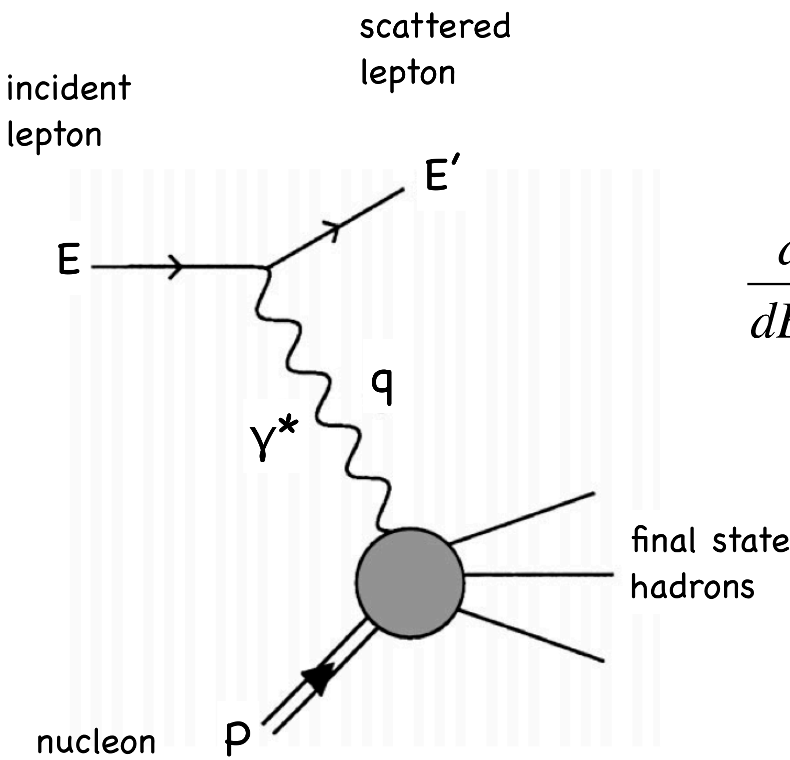
$$\lambda \sim \hbar/\sqrt{Q^2} \quad (Q^2 = -q \cdot q)$$



$r^p_E \approx 0.88$ fm

	Q^2 $(GeV/c)^2$	λ (fm)
MAMI	0.5	0.3
JLab	5	0.1
SLAC	30	0.04

Introduction of Deep Inelastic Scattering



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

structure functions $F_1(Q^2,x)$ and $F_2(Q^2,x)$ contain all information about the structure of the target

$$\nu = E - E'$$

$$Q^2 = -q^2 > 0$$

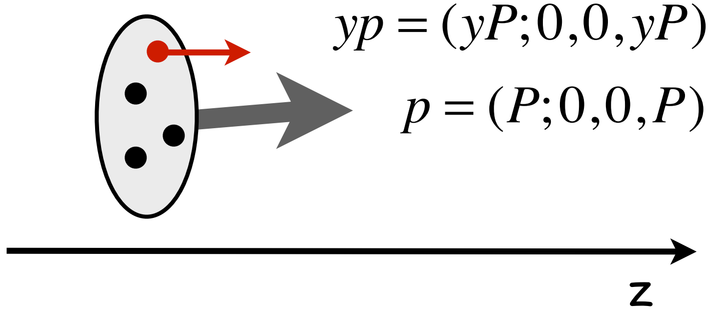
$$x = Q^2 / 2M\nu$$

here: unpolarized cross section and ignoring weak interaction

D.F. Geesaman, K. Saito, A.W. Thomas, Annu. Rev. Nucl. Part. Sci. **45**, 337 (1995).

Parton Model

- Infinite momentum frame



$$yp = (yP;0,0,yP)$$

$$p = (P;0,0,P)$$

$$(yp+q)^2 = (yp)^2 + 2yp \cdot q + q^2$$

$$0 \approx 2yp \cdot q - Q^2$$

$$y \approx \frac{Q^2}{2p \cdot q} = x$$

Bjorken x gives the momentum fraction carried by the constituent

- Quark distribution q(x), number density of quarks in the target; e.g. u(x)xdx gives the fraction of momentum of u quarks in the proton with momentum between xP and (x+dx)P in the IMF

- Structure functions

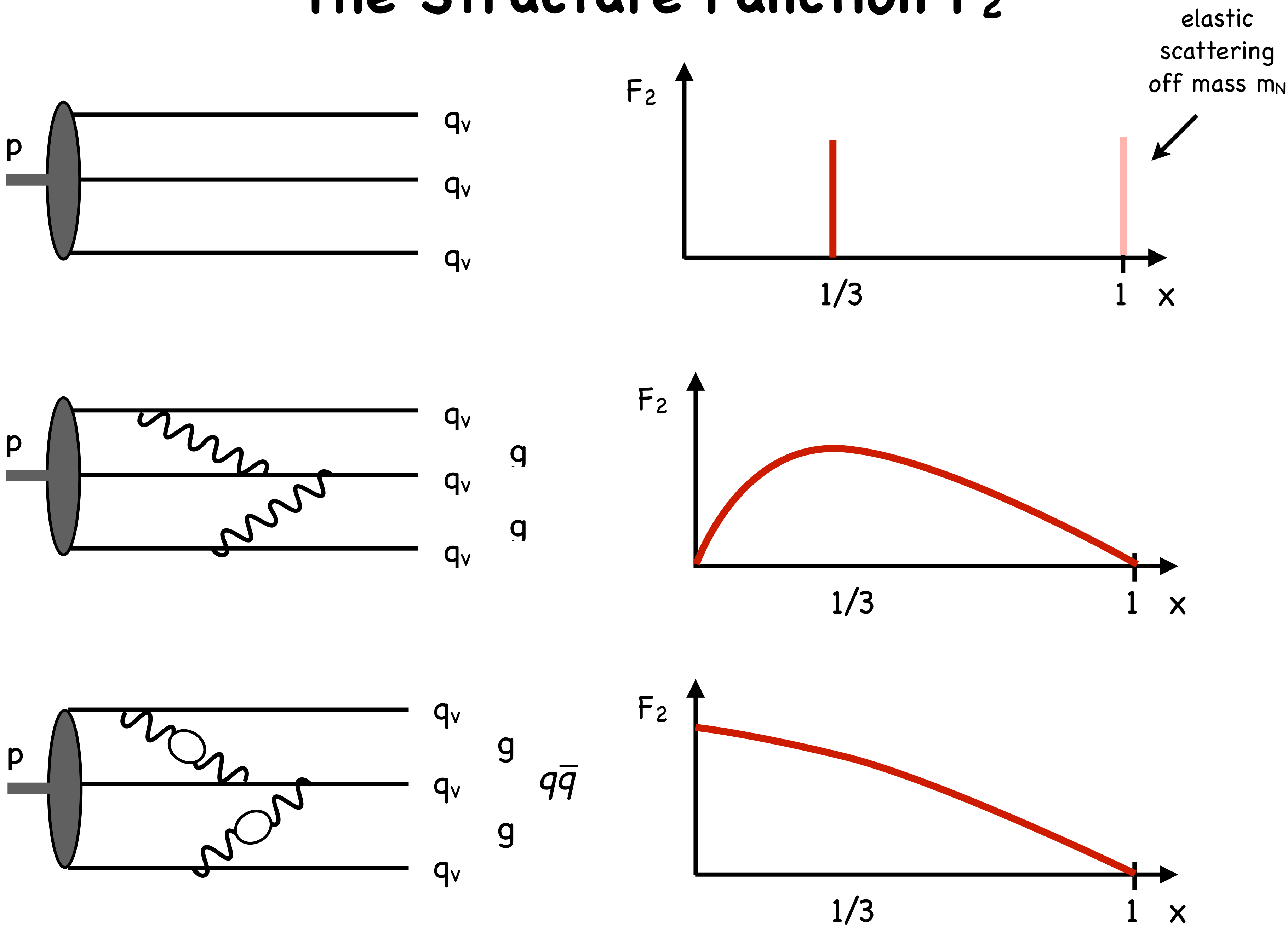
$$F_1(x) = \frac{1}{2} \sum_{i=u,d,s,c,\ldots} e_i^2 (q_i(x) + \bar{q}_i(x))$$

$$F_2(x) = 2xF_1(x)$$

Callan-Gross relation connecting F_1 and F_2 reflects the spin ½ nature of the quarks

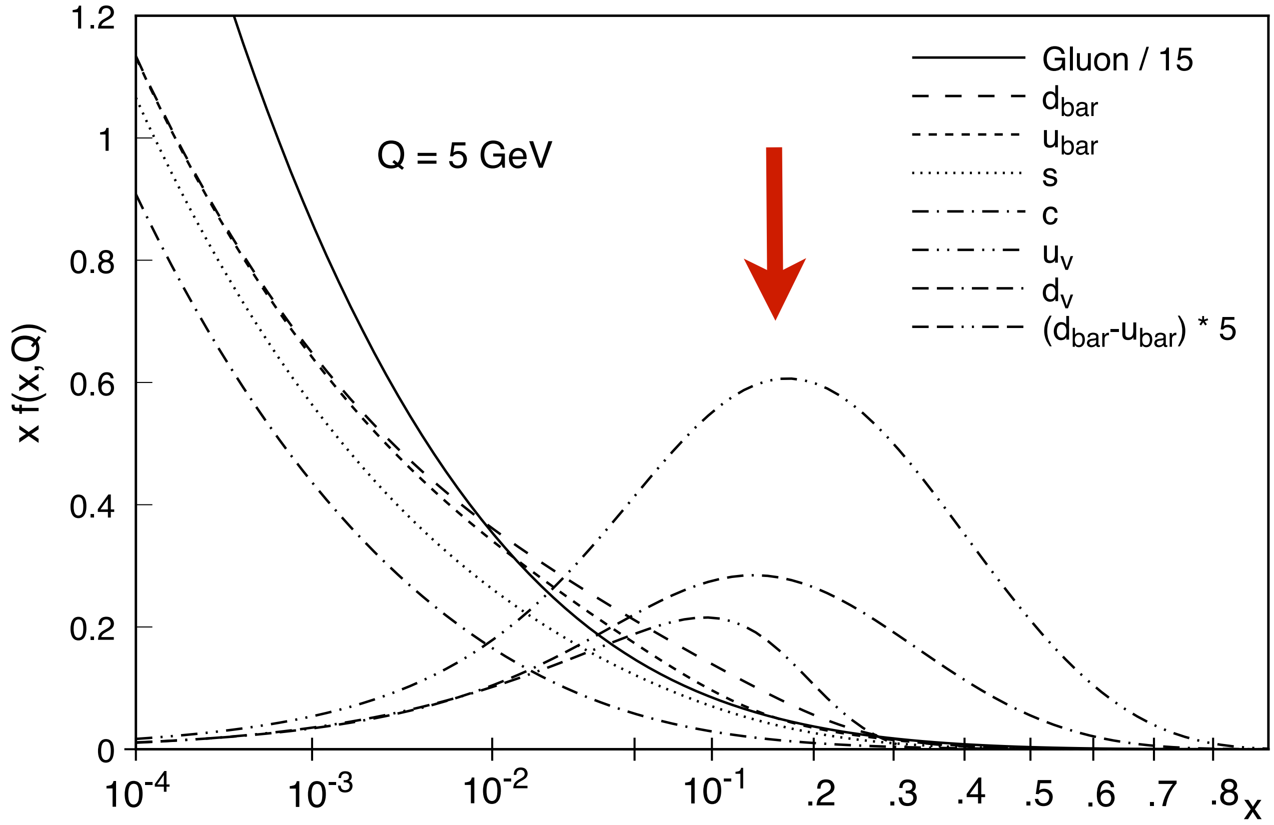
D.F. Geesaman, K. Saito, A.W. Thomas, Annu. Rev. Nucl. Part. Sci. **45**, 337 (1995).

The Structure Function F_2

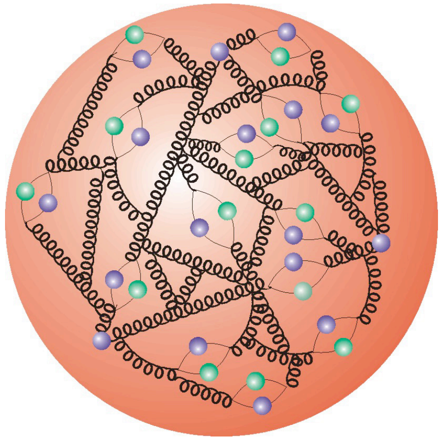


B. Povh, Physik in Unserer Zeit **15**, 131 (1984).

Parton Structure of the Nucleon



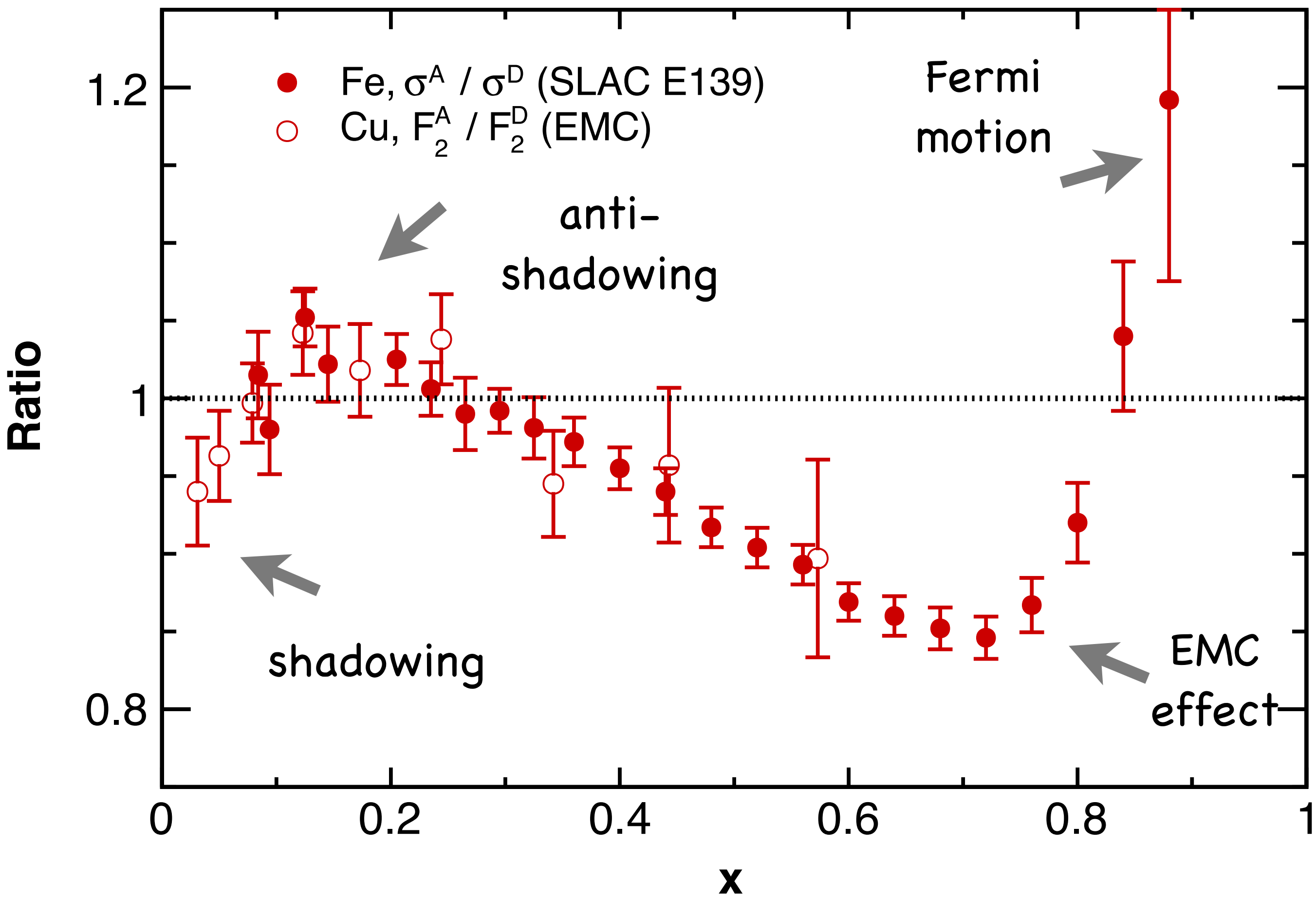
H.L. Lai, Eur. Phys. J. C **12**, 275 (2000).



Proton: uud

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

The Nuclear EMC Effect

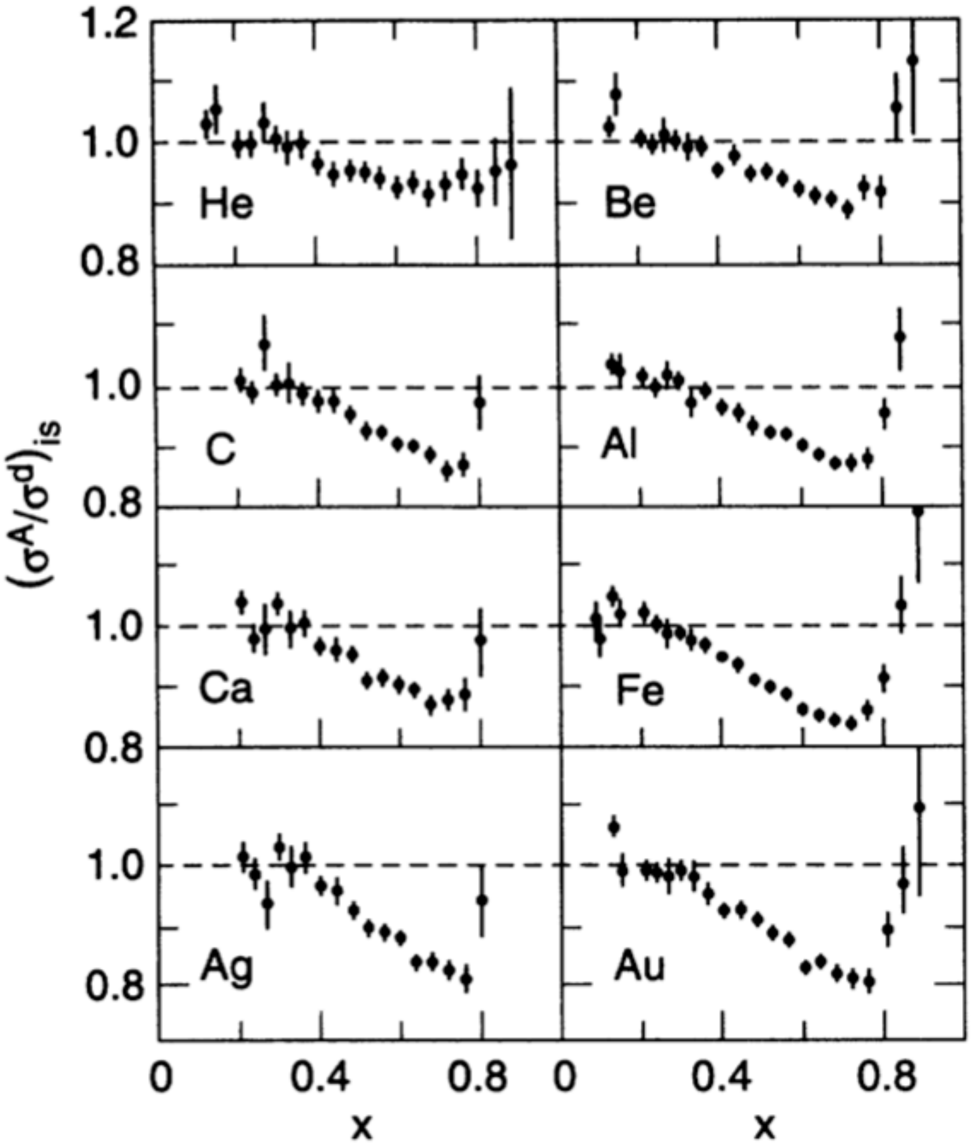


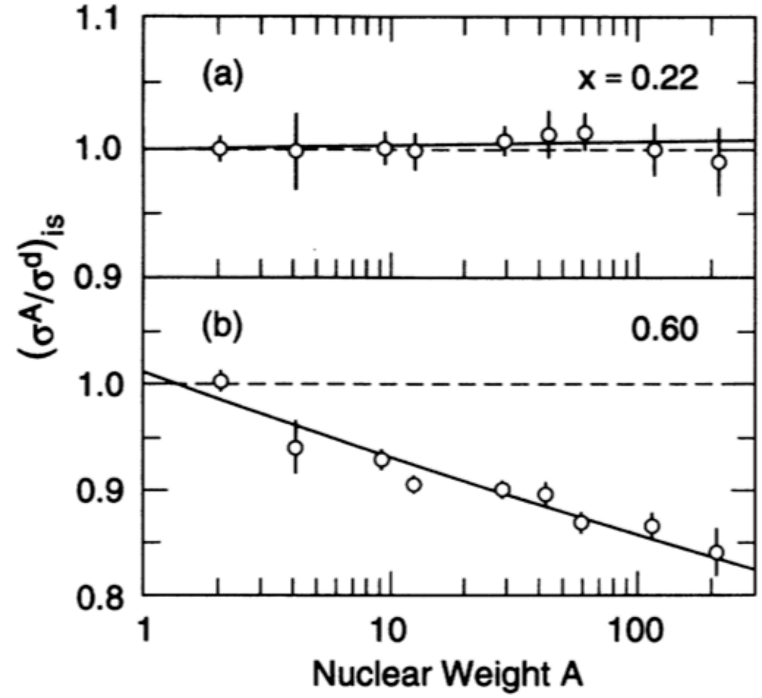
J. Ashman et al., Phys. Lett. B **202**, 603 (1988)
J. Gomez et al., Phys. Rev. D **49**, 4348 (1994)

$x > 1$ forbidden for free nucleons

- The **E**uropean **M**uon **C**ollaboration used muon scattering to measure nuclear structure functions and observed a depletion of the nuclear structure function F_2 in the valence-quark regime $0.3 \le x \le 0.8$.
- Early expectation was that probes at the GeV energy scale would be insensitive to nuclear binding effects, which are typically on the order of several MeV.

A Dependence (SLAC-E139)





- The ratio decreases approximately logarithmically up to the highest values of A.
- Shape of the distribution remains nearly constant.

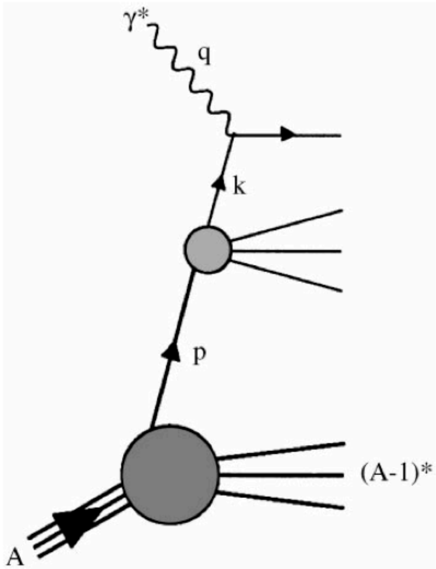
J. Gomez et al., Phys. Rev. D **49**, 4348 (1994)

Models of the EMC Effect

Parton model interpretation: The nucleon bound in a nucleus carries less momentum than in free space.

- Models
  - Models based on single nucleons (no nucleon-nucleon correlations)
  - Models based on a pion enhancement
  - Multiquark clusters
  - Dynamical rescaling
  - ...
- Despite much experimental and theoretical progress, no unique and universally accepted explanation of the depletion has emerged.
- Gerald Miller (1985): "EMC means Everyone's Model is Cool".

Convolution Model

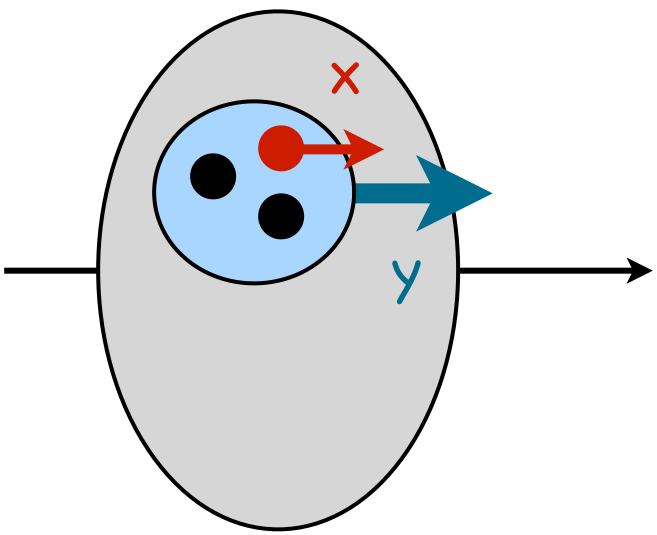


$$F_2^A(x) = \int_x dy\, f^A(y) F_2^N(x/y)$$

structure function of the nucleus

momentum distribution of nucleons

structure function of the nucleon



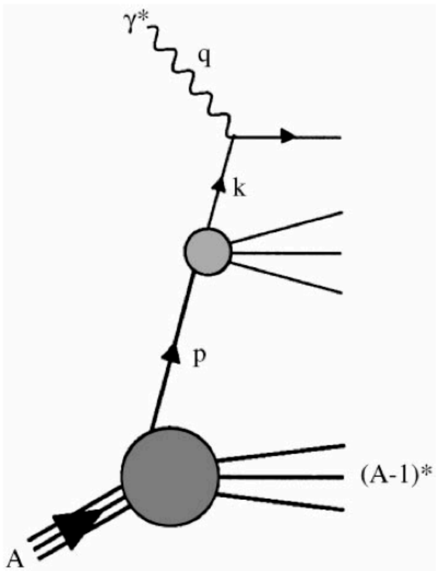
- $F^A(x)$ = Nucleon structure function folded with momentum distribution of nucleons in the nucleus.
- Leading nuclear effects are **binding** and **Fermi motion**.

bound nucleon momentum

$$p = (m_N - |\epsilon_i|,\ \vec{p}_i)$$

Akulinichev et al., Phys. Rev. Lett. **55**, 2239 (1985)

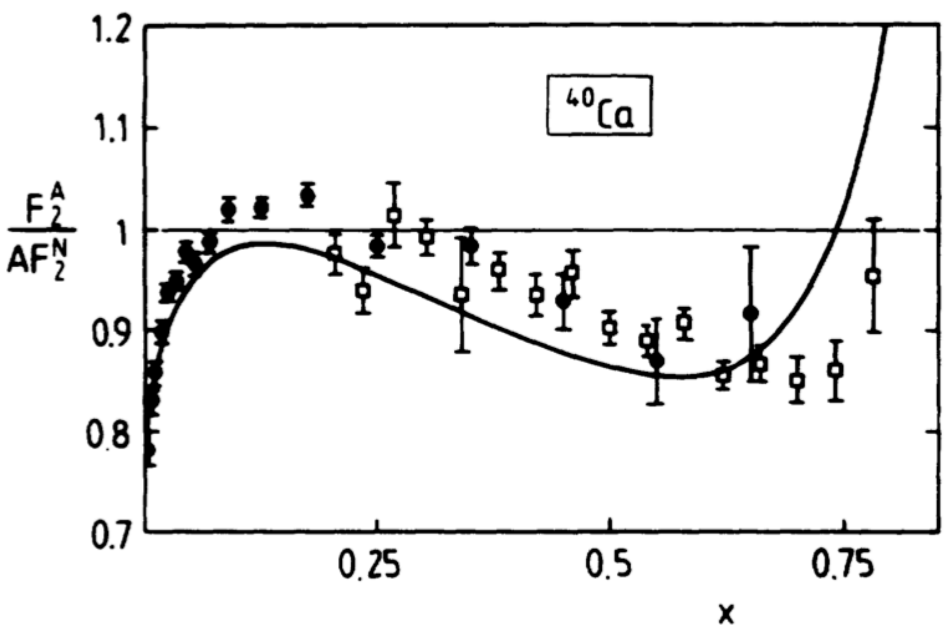
Convolution Model (II)



$$F_2^A(x) = \int_x dy \int dp^2 D_{N/A}(y,p^2) F_2^N(x/y;p^2)$$

distribution function of nucleons

structure function



- Off-shell effects are important (nucleon-only hypothesis fails).
- Assuming unmodified structure function, same on and off the energy shell one gets no EMC effect.*
- "room for a possible small enhancement of F_2^A due to nuclear pion cloud effects"

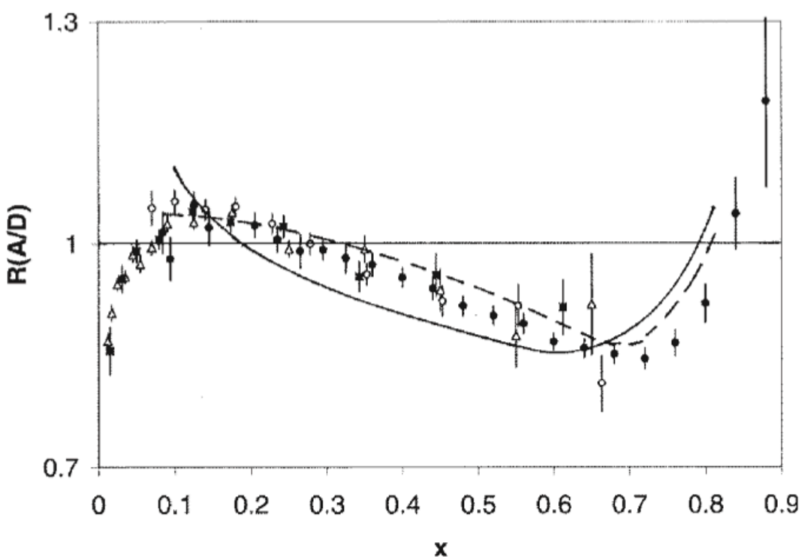
S. A. Kulagin, G. Piller, W. Weise, Phys. Rev. C **50**, 1154 (1994);

*) G.A. Miller, Eur. Phys. J. A **31,** 578 (2007); J.R. Smith and G.A. Miller, Phys. Rev. C **65**, 055206 (2002).

Models Based on a Pion Enhancement

$$F_2^A(x) = \int_x f_N(z) F_2^N\left(\frac{x}{z}\right) dz + \int_x f_\pi(z) F_2^\pi\left(\frac{x}{z}\right) dz$$

momentum distributions



P.R. Norton, Rep. Prog. Phys. **66**, 1253 (2003)

- Because nucleons are bound by mesons, the nucleons do not carry all of the momentum of the nucleus.
- For a stationary pion in the nucleus $0 < x < m_\pi / m_N$ and therefore the contribution of the pion is expected to be concentrated at low values of x.
- The pion model naturally predicts an **increase in the sea in nuclei**.

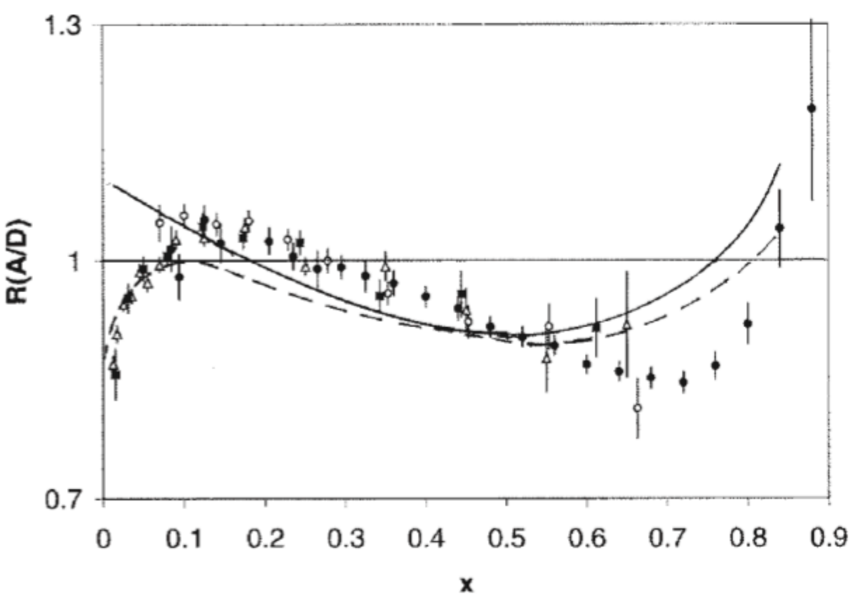
Multiquark Systems

$$F_2^A(x) = \int_z^A f_N(z) F_2^N\left(\frac{x}{z}\right)dz + \int_z^A f_6(z) F_2^6\left(\frac{x}{z}\right)dz$$

six-quark cluster

$$\int f_N(z)dz = 1 - p, \quad \int f_6(z)dz = p$$

$$F_2^6(x) \sim \left(1 - \frac{x}{2}\right)^9; \quad 2n - 1 = 9$$



P.R. Norton, Rep. Prog. Phys. **66**, 1253 (2003)

- A nucleus is dense and the nucleons in it are tightly packed together. It has been conjectured that under these circumstances the confining 'bag' may enlarge to include more than three quarks.
- Colour-singlet states of 6, 9, 12 etc quarks could form with a probability reflecting the fraction of the time that the nucleons are very close together and their wavefunctions overlap.
- The multiquark cluster model makes clear predictions for the behavior of F_2^A at $x_N > 1$

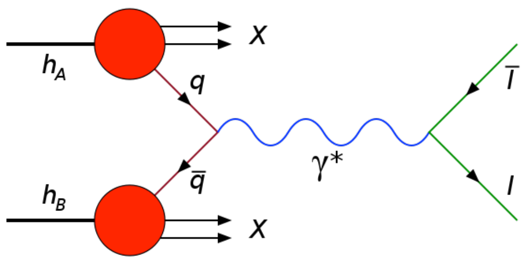
The Drell-Yan Process

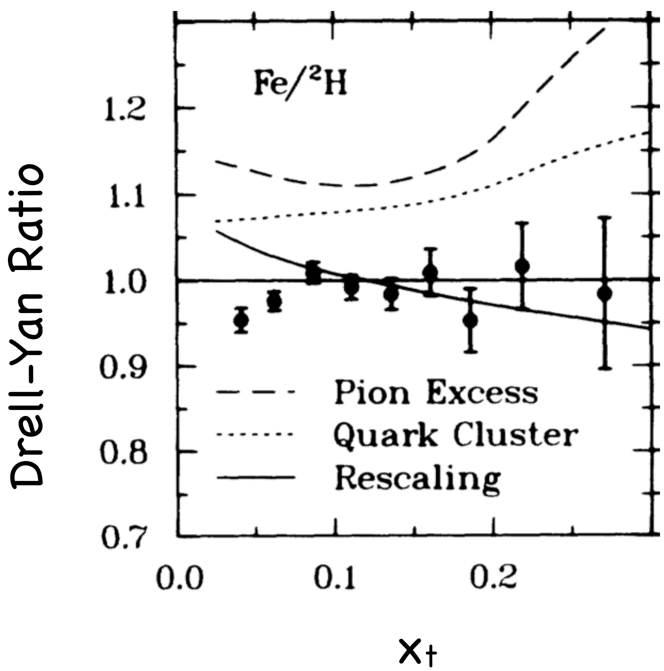
$$\frac{d^2\sigma}{dx_1 dx_2} = K\frac{4\pi\alpha^2}{9s}\sum_i e_i^2 \{q_{iP}(x_1)\bar{q}_{iT}(x_2) + \bar{q}_{iP}(x_1)q_{iT}(x_2)\}$$

P: Projectile
T: Target

dominates for **proton** beams

dominates for **pion** beams





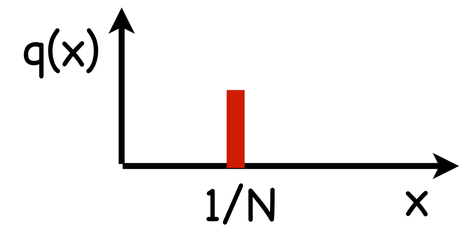
- The Drell-Yan process probes the quark and antiquark content of both the beam and the target hadron.
- The Drell-Yan cross-section ratio fails to rise at small x in contradiction to most of the models.

P.R. Norton, Rep. Prog. Phys. **66**, 1253 (2003);
D.M. Alde et al., Phys. Rev. Lett. **64**, 2479 (1990) - proton beam

A Simple Example (Jaffe/Close)

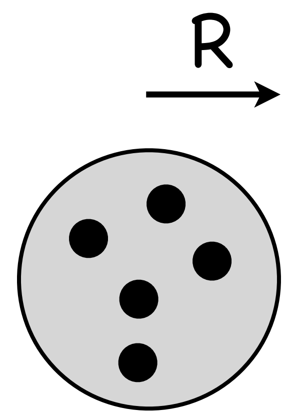
- Consider a system of N non-interacting massless quarks, the momentum being shared equally among them. The normalized distribution is given by

$$q_N(x) = \delta(x - 1/N)$$



- Changing the number of quarks to N' means

$$q_{N'}(x) = \delta(x - 1/N') = (N'/N)q_N((N'/N)x)$$
$$q_{N'}(x) = (M'R'/MR)q_N((M'R'/MR)x)$$



- Allow for the fact that the primed bag carries an enhanced factor M'/M of the momentum of the unprimed bag

$$\boxed{q'(x) = (R'/R)q((R'/R)x)}$$

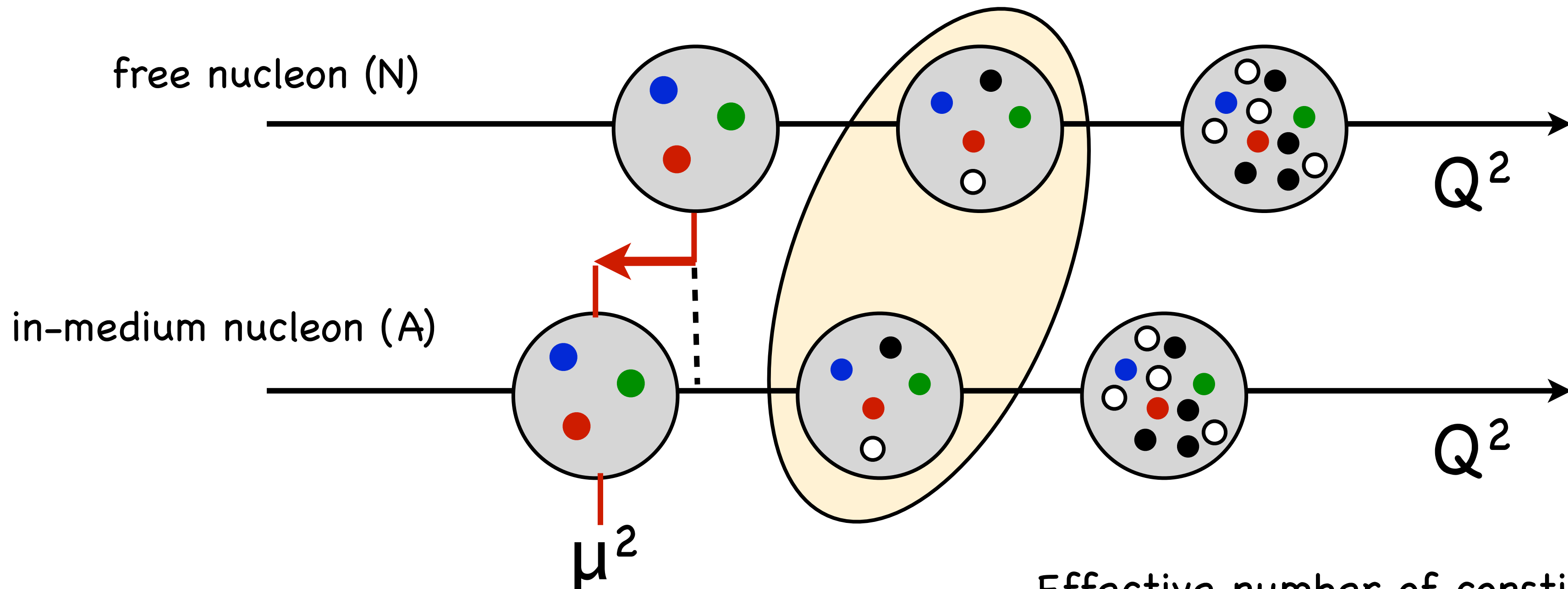
$$M \propto \frac{N}{R}$$

- Thus in the larger primed bag, (R'/R > 1), the quark distribution is degraded to small x, and less momentum is carried by the quarks.

Close et al., Phys. Lett. **129B**, 346 (1983).

Dynamical Rescaling

- Observation: Iron structure function resembles deuterium structure function at a higher value of Q^2



Effective number of constituents grows as the resolution improves with increasing Q^2

- Suggested renormalization point μ^2; starting point for QCD evaluation.
- $\mu^2_N > \mu^2_A$

Close et al., Phys. Lett. 129B, 346 (1983).

Dynamical Rescaling (II)

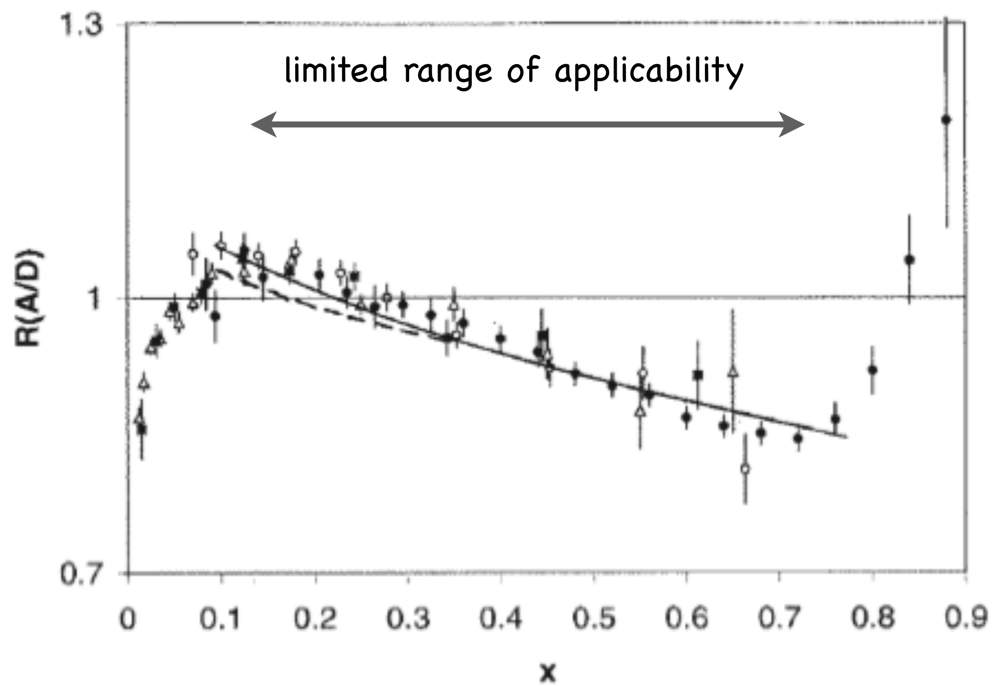
$$\boxed{F_2^A(x,Q^2) = F_2^N(x,\xi_A(Q^2)Q^2)}$$

- Rescaling factor

$$\xi_A(Q^2) = \left[\frac{\mu_N^2}{\mu_A^2}\right]^{\alpha_a(\mu_N^2)/\alpha^2(Q^2)}$$

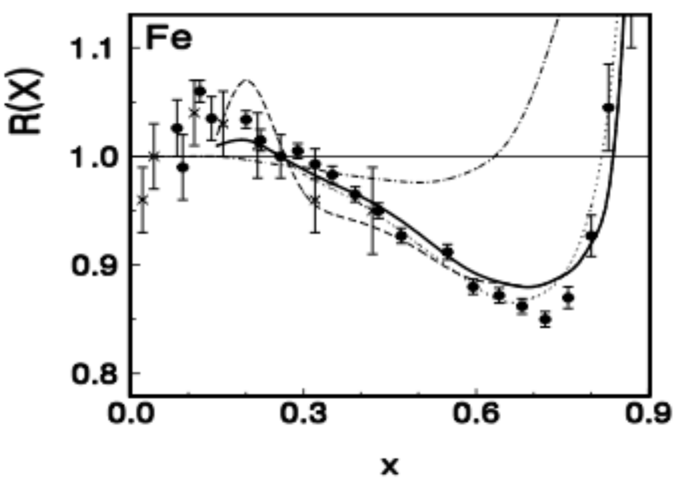
with $\frac{\mu_N^2}{\mu_A^2} = \frac{\lambda_A^2}{\lambda_N^2} > 1$ confinement size λ

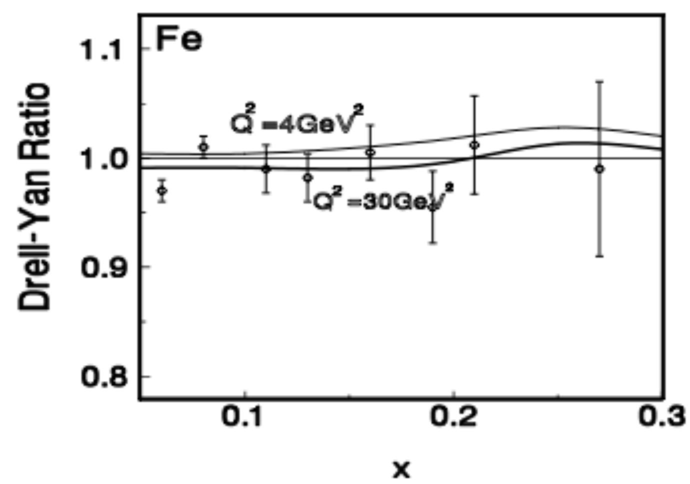
- Confinement size related to nuclear density and the probability for nucleons to overlap.
- The value of ξ = 2 implies an increase in confinement size in iron of about 15%.
- "Swelling" of nucleons.



Close et al., Phys. Lett. 129B, 346 (1983).

Modification of In-Medium Nucleon Rest Mass

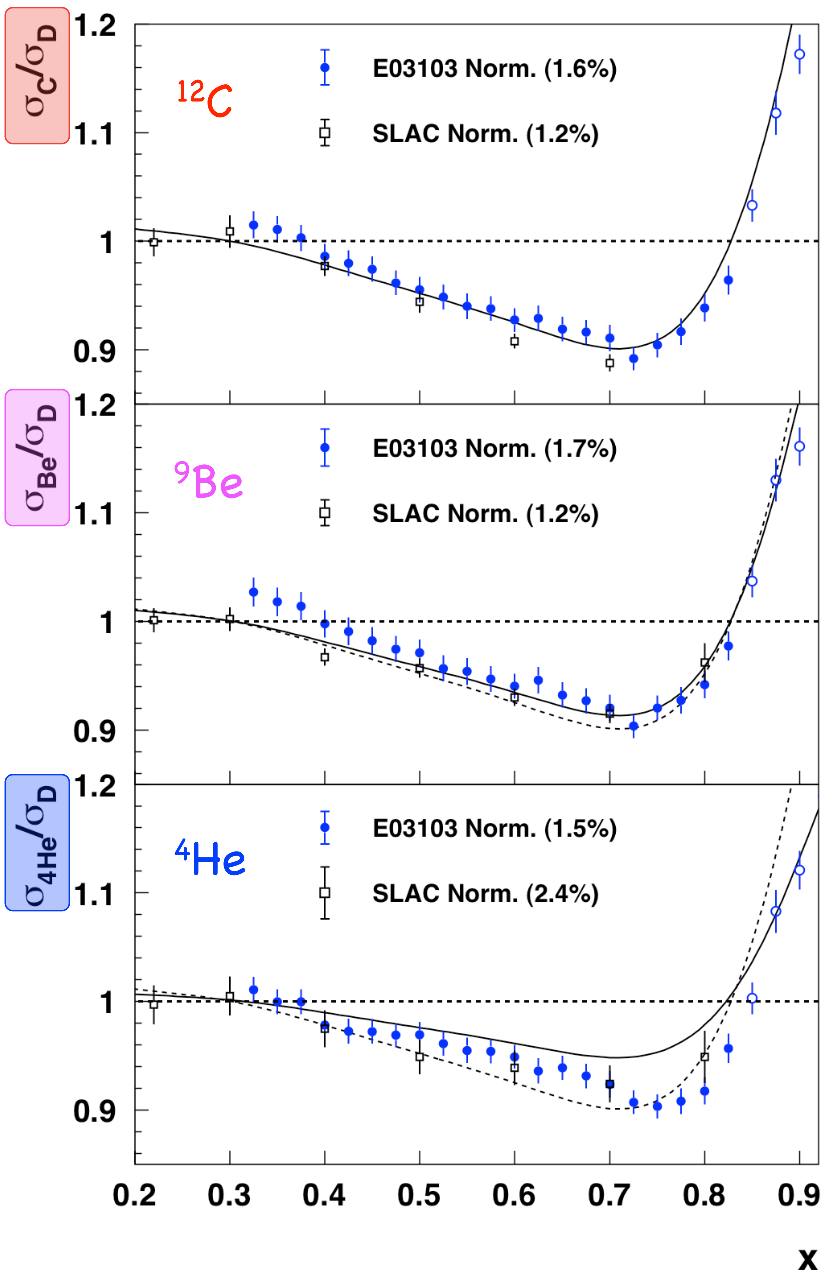




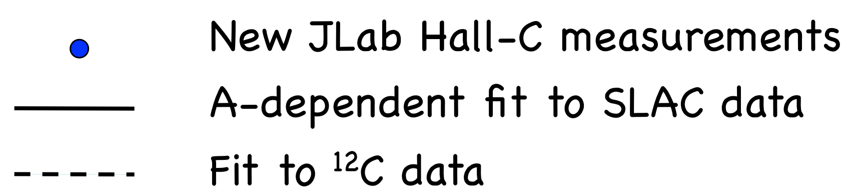
- Account for the EMC effect in DIS on nuclei by using the single particle approach with effective Fermi motion caused by nuclear interactions, which is also responsible for medium changes of the parton distributions inside nucleons.
- The nucleon rest energy is modeled by introducing x-dependent effective nucleon rest energy (nucleon mass) M_x
  - for $x > 0.6$: $M_x = M_N - (20 \div 30)$ MeV
  - for $x < 0.25$: $M_x = M_N$

J. Rozynek and G. Wilk, Phys. Rev. C **71**, 068202 (2005)

EMC Effect in Very Light Nuclei



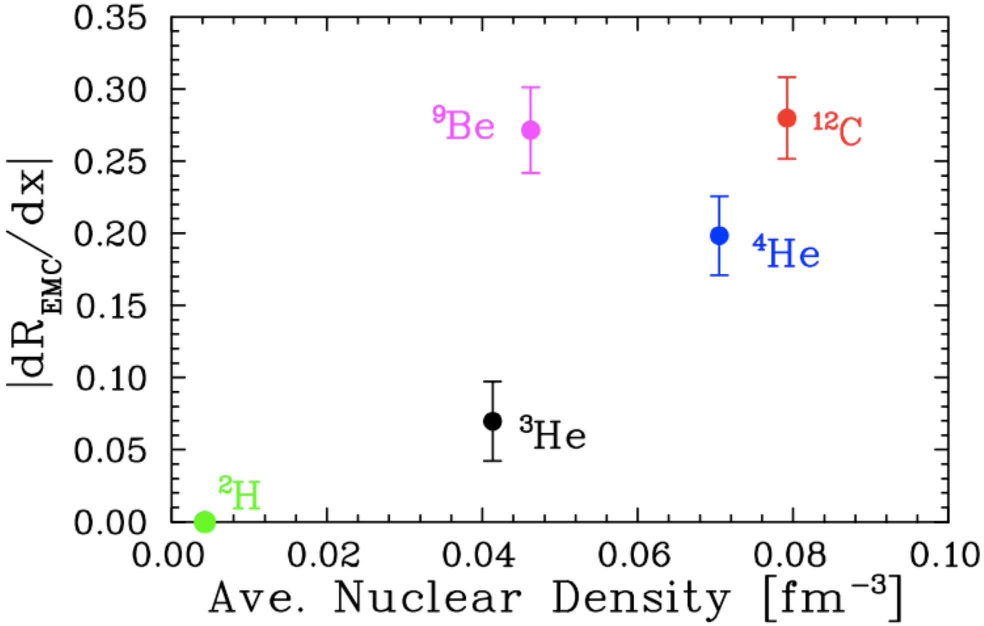
- JLab high-precision measurement of ^{2}H, ^{3}He, ^{4}He, ^{9}Be and ^{12}C for $0.3 < x < 0.9$, $Q^2 \approx 3\text{–}6$ GeV^2
- Few-body nuclei provide the opportunity to test models where the details of the nuclear structure are well understood.
- Test scaling models of the EMC effect:
  - Density-dependent (ρ) effect?
  - Mass-dependent (A) effect?

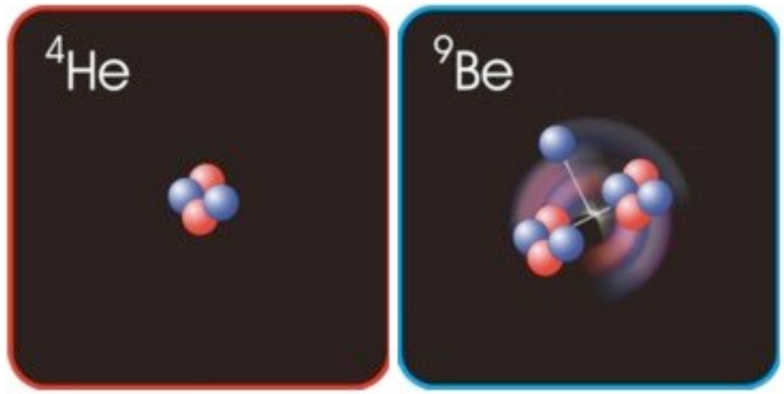


J. Seely et al., Phys. Rev. Lett. **103**, 202301 (2009)

EMC Effect in Very Light Nuclei

Slope dR_{EMC}/dx as measure of the EMC-effect magnitude



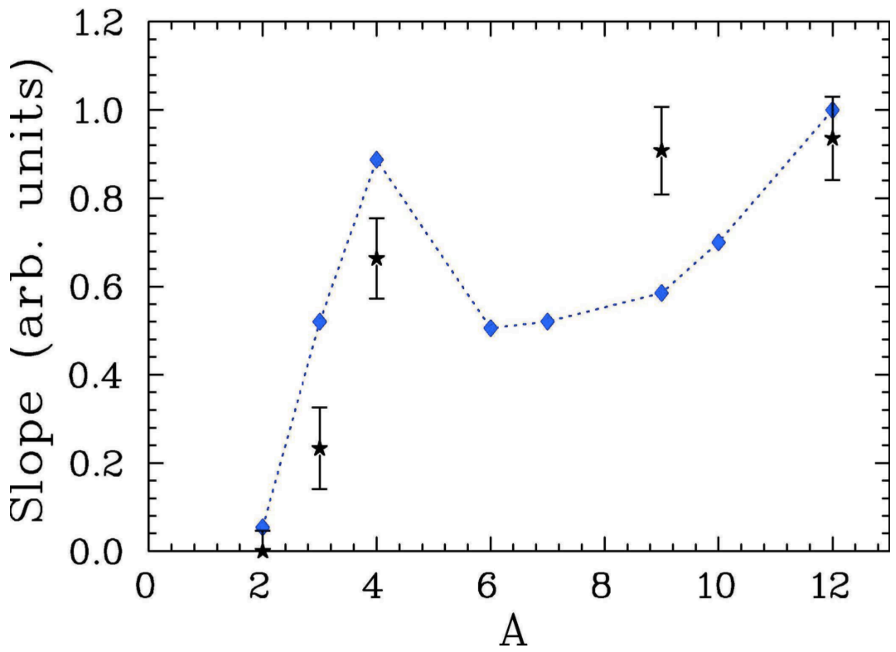


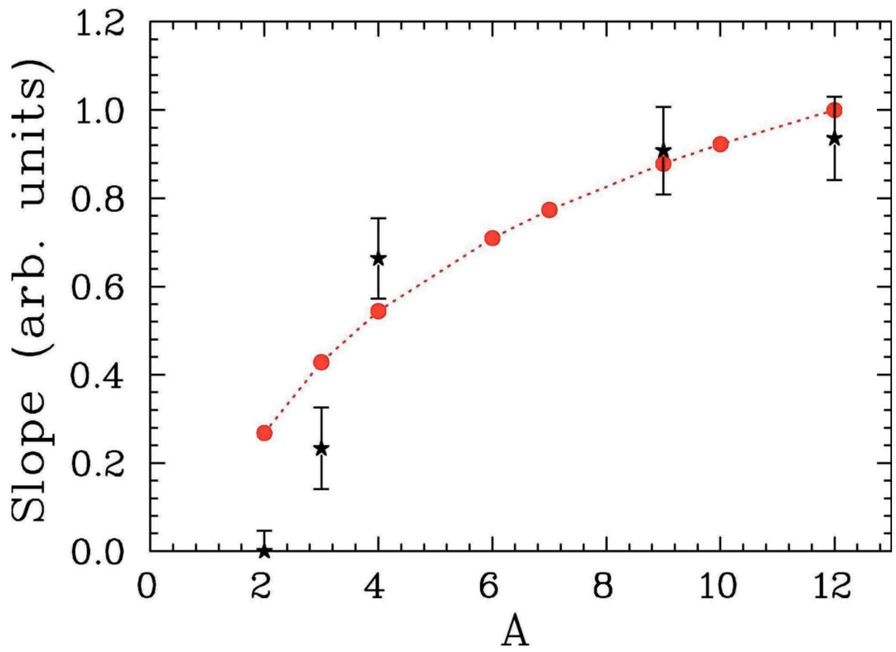
- Nuclear effects in ^{4}He, ^{9}Be (= 2α+n) comparable to effect in ^{12}C
- Data suggest that **local** density drives the modification

J. Seely et al., Phys. Rev. Lett. **103**, 202301 (2009)

E12-10-008: Detailed studies of the nuclear dependence of F_2 in light nuclei

- Map out A-dependence in more detail [E03-103: ^{3}He, ^{4}He, ^{9}Be and ^{12}C]
  - Very hard to explain large ^{3}He – ^{9}Be difference in ρ-dependent fit
  - Hard to explain large ^{3}He – ^{4}He difference in mass-dependent fit



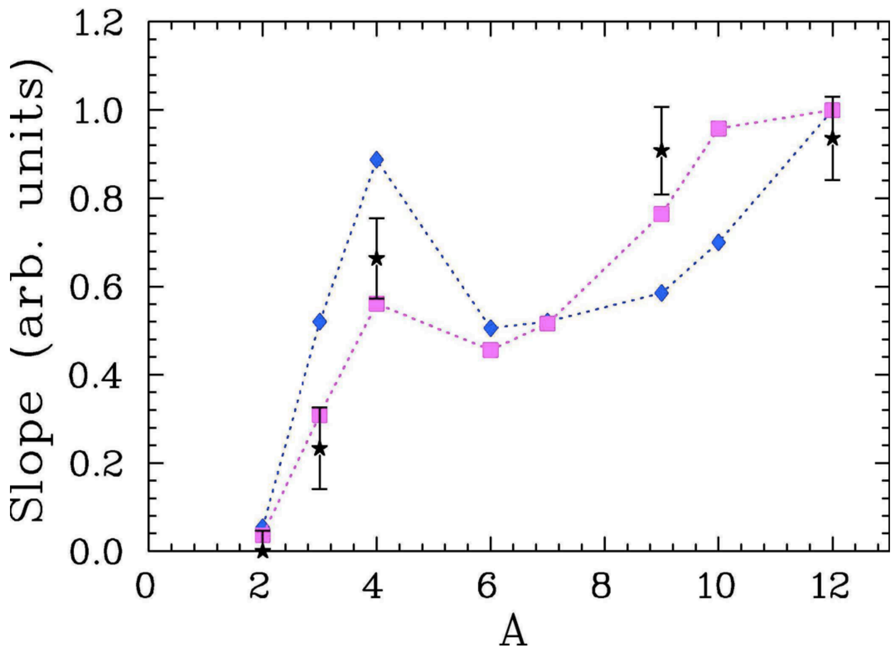


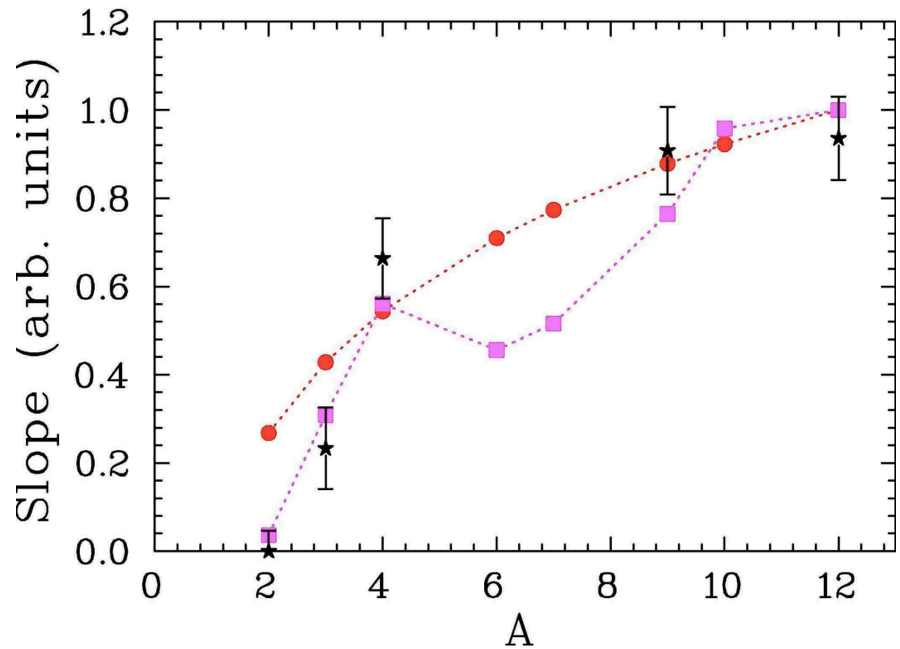
Spokespersons: J.Arrington, A.Daniel, D.Gaskell; figures from PAC presentation

E12-10-008: Detailed studies of the nuclear dependence of F_2 in light nuclei

- Map out A-dependence in more detail [E03-103: ^{3}He, ^{4}He, ^{9}Be and ^{12}C]
  - "Local density" works well, provides different predictions

- E12-10-008 will provide much more detailed data





Spokespersons: J.Arrington, A.Daniel, D.Gaskell; figures from PAC presentation

Polarized EMC

- The unpolarized EMC effect

$$R_A = \frac{F_{2A}}{F_{2A}^{\text{naive}}} = \frac{F_{2A}}{Z F_{2p} + (A-Z) F_{2n}}$$

- The polarized EMC effect

$$R_{As}^{JH} = \frac{g_{1A}^{JH}}{g_{1A,\text{naive}}^{JH}} = \frac{g_{1A}^{JH}}{P_p^{JH}\, g_{1p} + P_n^{JH}\, g_{1n}}$$

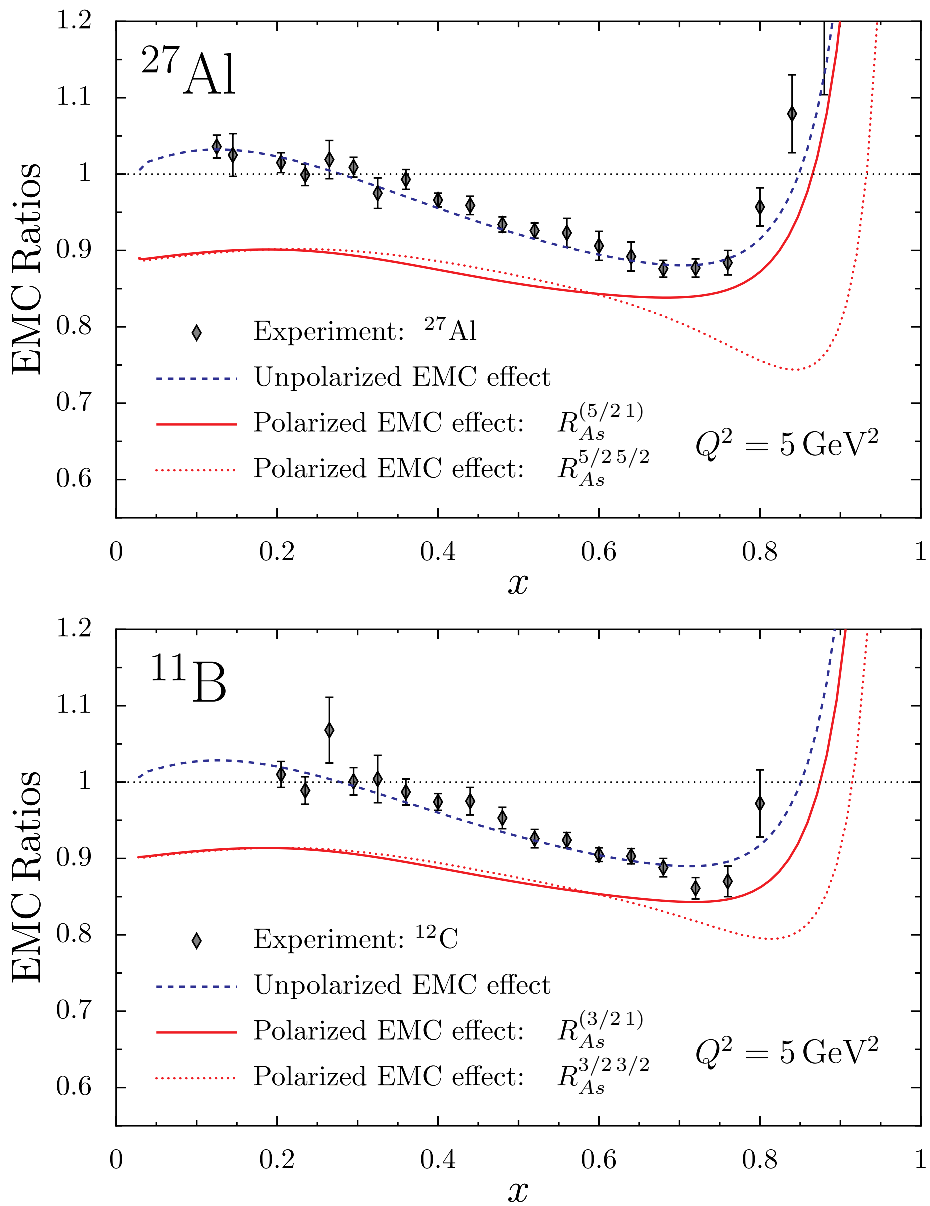
I. Cloet, W. Bentz, A.W. Thomas, Phys. Lett. B **642**, 210 (2006).

g_1: spin-dependent nucleon structure function from measurements of the spin asymmetry in deep inelastic scattering of longitudinally polarized muons by longitudinally polarized protons

$$A = \frac{\sigma^{\uparrow\downarrow} - \sigma^{\uparrow\uparrow}}{\sigma^{\uparrow\downarrow} + \sigma^{\uparrow\uparrow}}$$

P, **J**, and **H**: nucleon polarization, total angular momentum, and helicity along the direction of the incoming electron momentum

Polarized EMC: Nambu–Jona-Lasinio Model



- The nucleon is approximated as a quark-diquark bound state.
- The nucleus is described using a relativistic shell model, including mean scalar and vector fields that couple to the quarks in the nucleon.
- The external scalar field enhances the lower component of the quark's Dirac wave function.
- The polarized EMC effect is larger than the unpolarized case.

I. Cloet, W. Bentz, A.W. Thomas, Phys. Lett. B **642**, 210 (2006).

Summary Part II

- EMC Effect: observation of a depletion of the nuclear structure function F_2 in the valence-quark regime.
- EMC Effect is not (only) due to conventional nuclear physics.
- Relativistic, quark-level models of nuclear structure, predict fundamental changes in the internal structure of bound hadrons due the mean scalar and vector fields in the medium.
- EMC effect and Drell Yan experiments provide tight constraints on models which predict new, independent phenomena (polarized EMC, e.m. form factors, ...)