Nucleon-Nucleon Correlations and the Quarks Within

Gerald A. Miller University of Washington

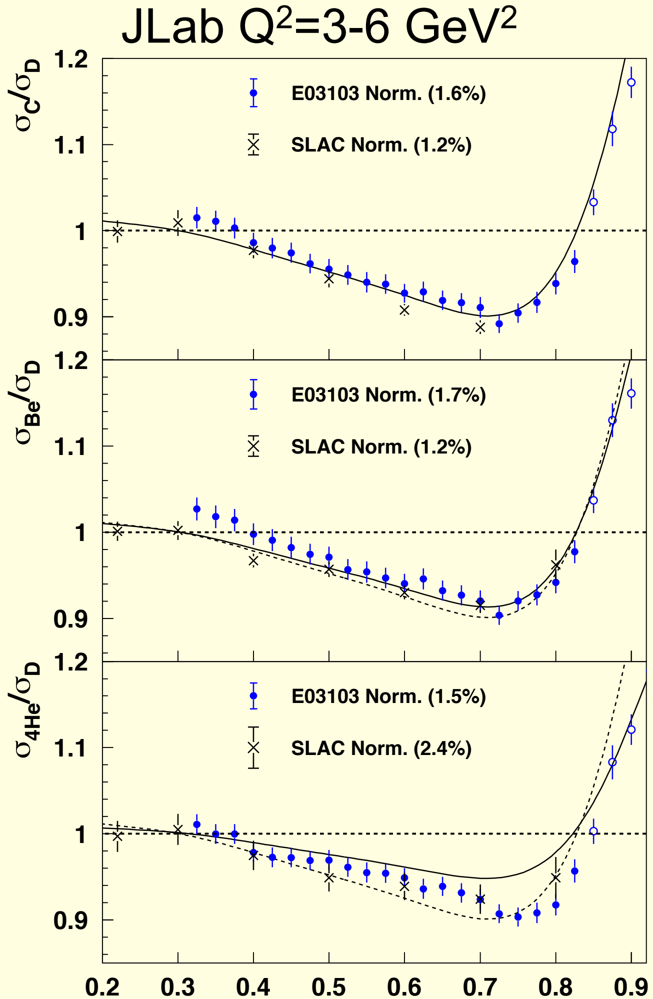
RMP with Or Hen, Eli Piasetzky, Larry Weinstein
arXiv: 1611.09748

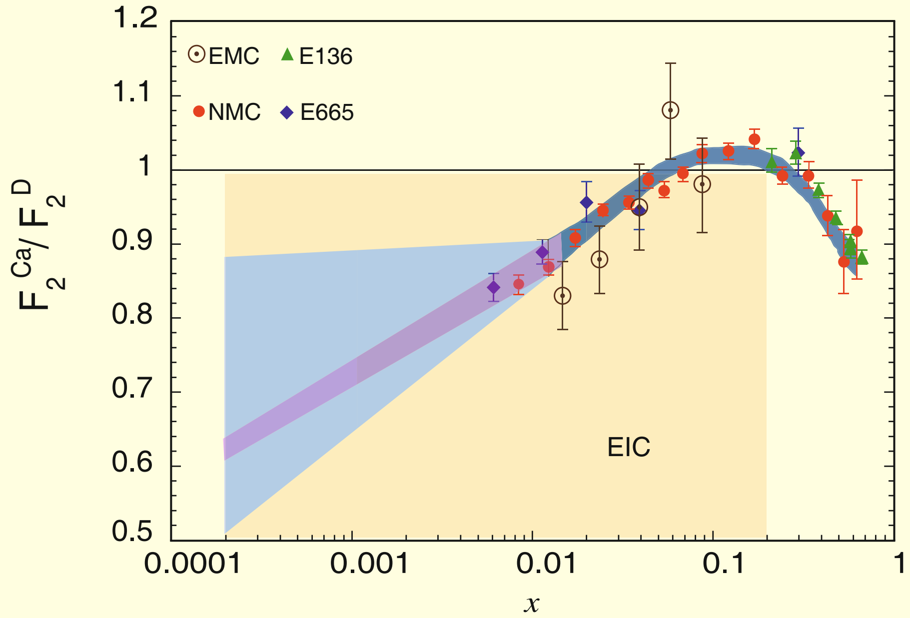
Will focus on 0.3 <x<0.7 Remarkable experimental progress

EMC effect

Higinbotham, Miller, Hen, Rith
CERN Courier 53N4('13)24

The EMC EFFECT





For 0.3<x<0.7 ratio=R^x is approximately linear

Nucleon structure is modified: valence quark momentum depleted.

EFFECTS ARE SMALL ~15%

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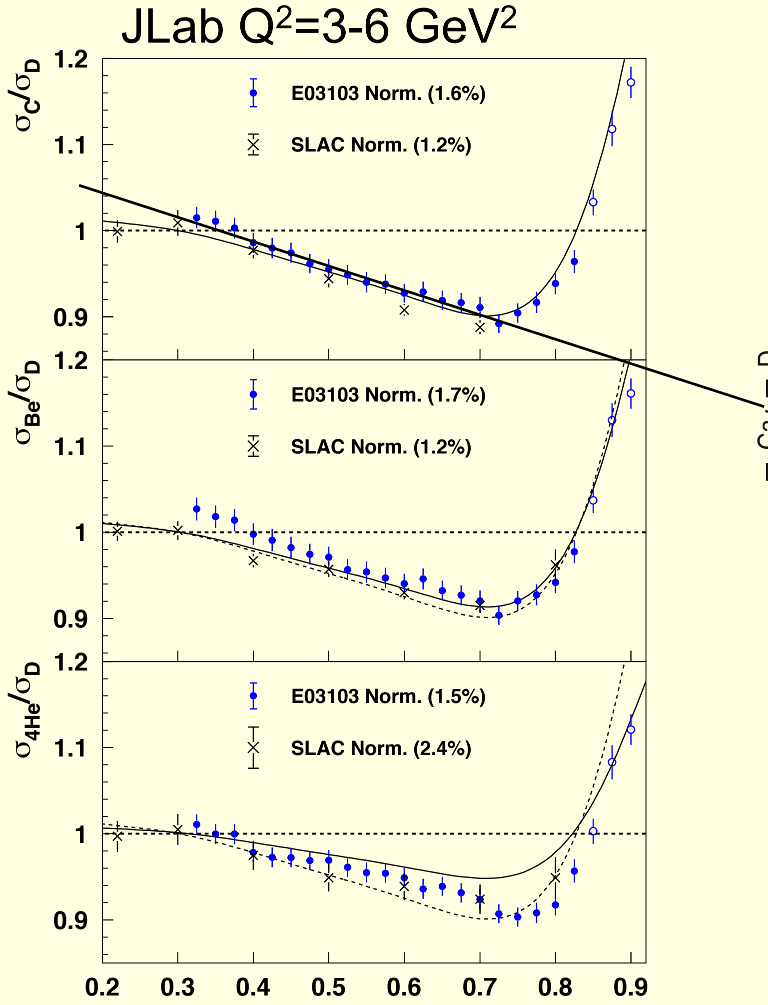

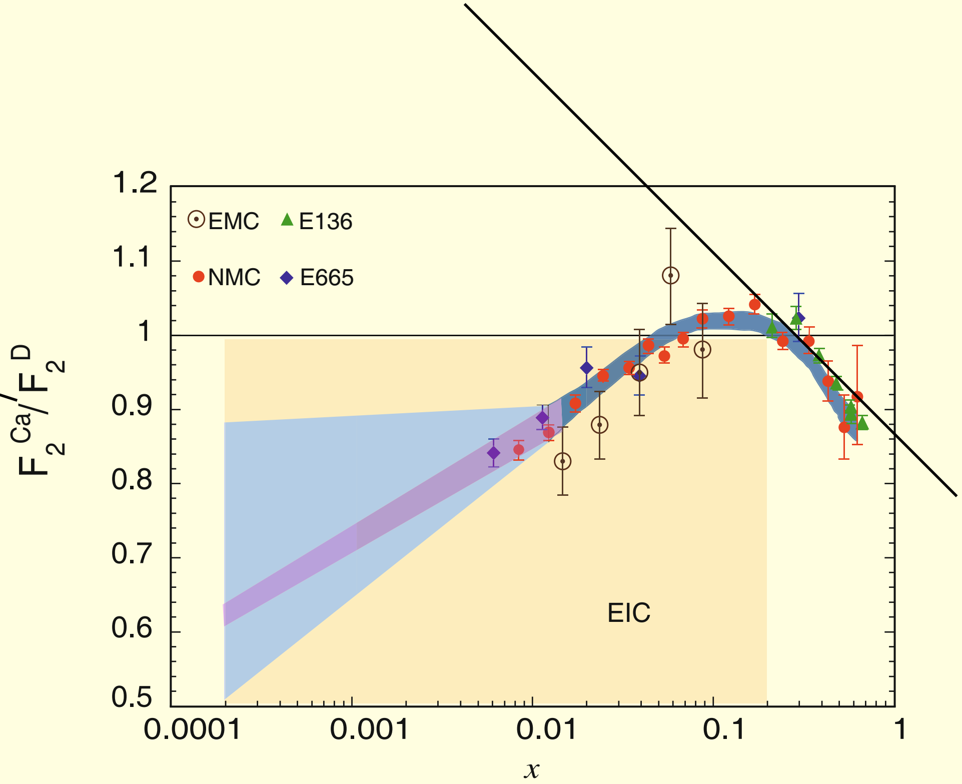

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Ideas: ~1000 papers 3 ideas

- Proper treatment of known effects: binding, Fermi motion, pionic- NO nuclear modification of internal nucleon/pion quark structure
- Quark based- high momentum suppression implies larger confinement volume

a bound nucleon is larger than free one- a mean field effect

b multi-nucleon clusters - beyond the mean field

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EMC – “Everyone’s Model is Cool (1985)”

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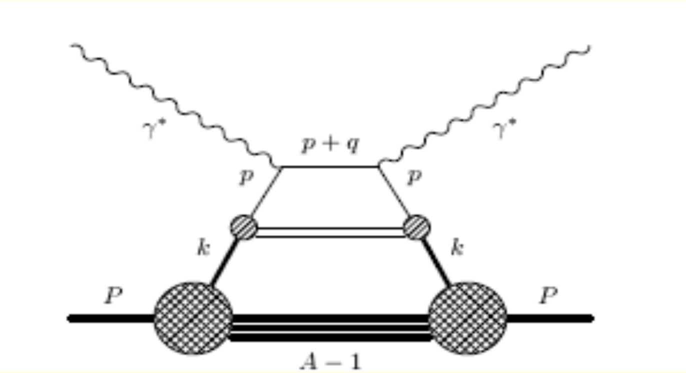
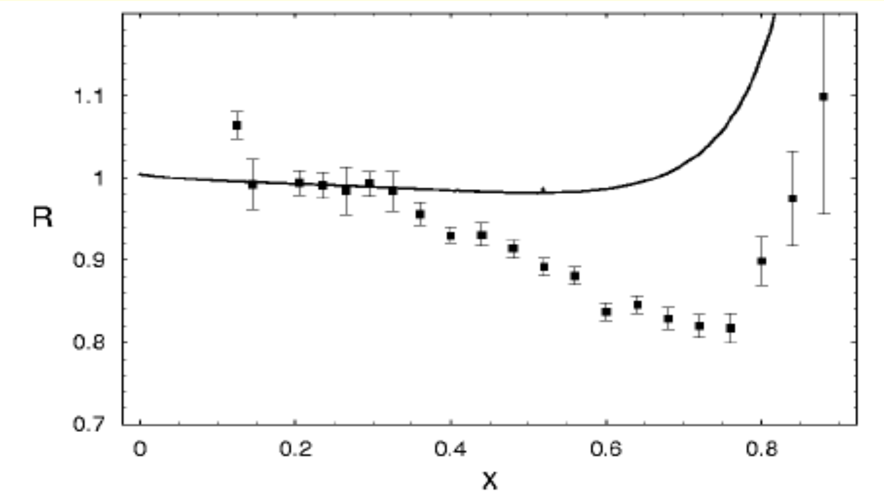
EMC – "Everyone's Model is Cool (1985)"

One thing I learned since ‘85

- Nucleon/pion model is not cool

Deep Inelastic scattering from nuclei-nucleons only free structure function





Binding causes no EMC effect

- **Hugenholz van Hove theorem nuclear stability implies (in rest frame) $P^+ = P^- = M_A$**
- **$P^+ = A(M_N - 8\text{ MeV})$**
- **average nucleon k^+**

  $k^+ = M_N - 8$ MeV, Not much spread

  $F_{2A}/A \sim F_{2N}$ no EMC effect

Momentum sum rule- matrix element of energy momentum tensor

More on sum rules

- Baryon & momentum sum rules originate from matrix elements of conserved currents in the nucleon wave function-Collins book
- Must be respected

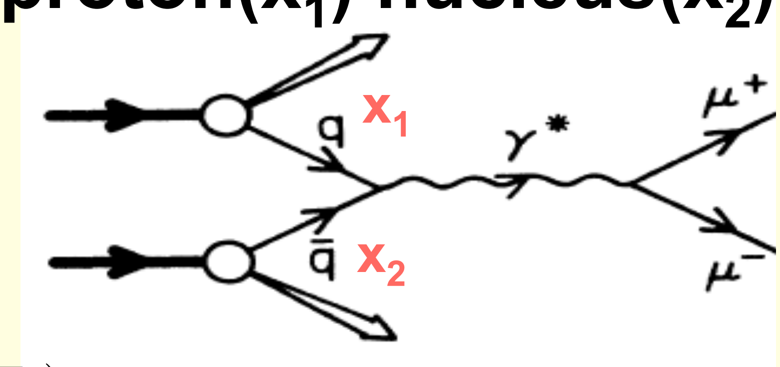
Nucleons and pions

$P_A^+ = P_N^+ + P_\pi^+ = M_A$

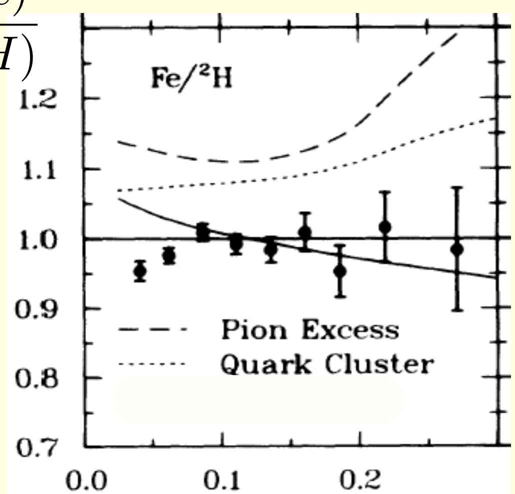
P_π^+/M_A =.04, explain EMC, sea enhanced

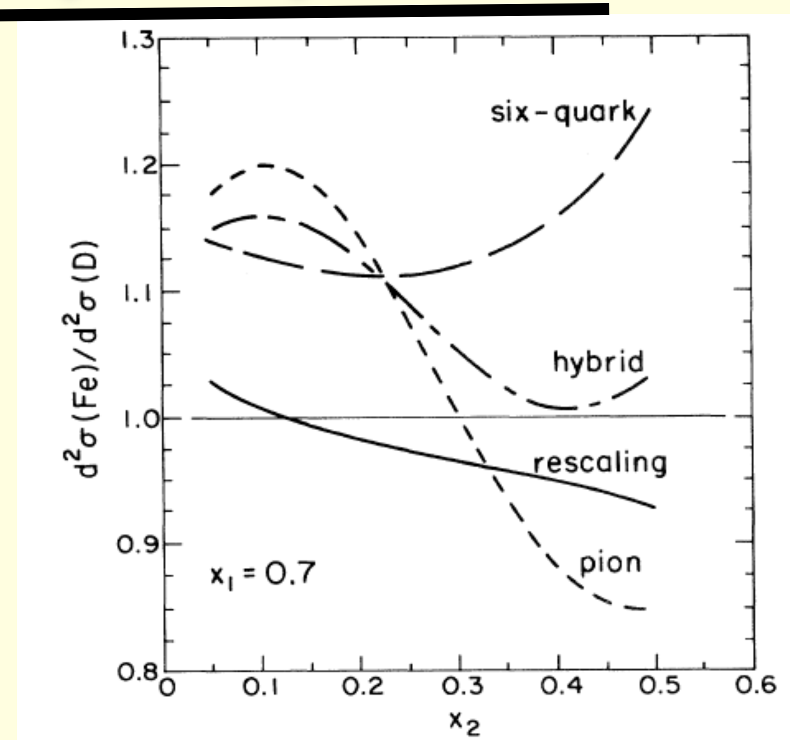
try Drell-Yan, Bickerstaff, Birse, Miller 84

proton(x_1) nucleus(x_2)



$$\frac{\sigma_{DY}(\mathrm{Fe})}{\sigma_{DY}(^2H)}$$





Bertsch, Frankfurt, Strikman "crisis"

E772 PRL 69,1726 (92)

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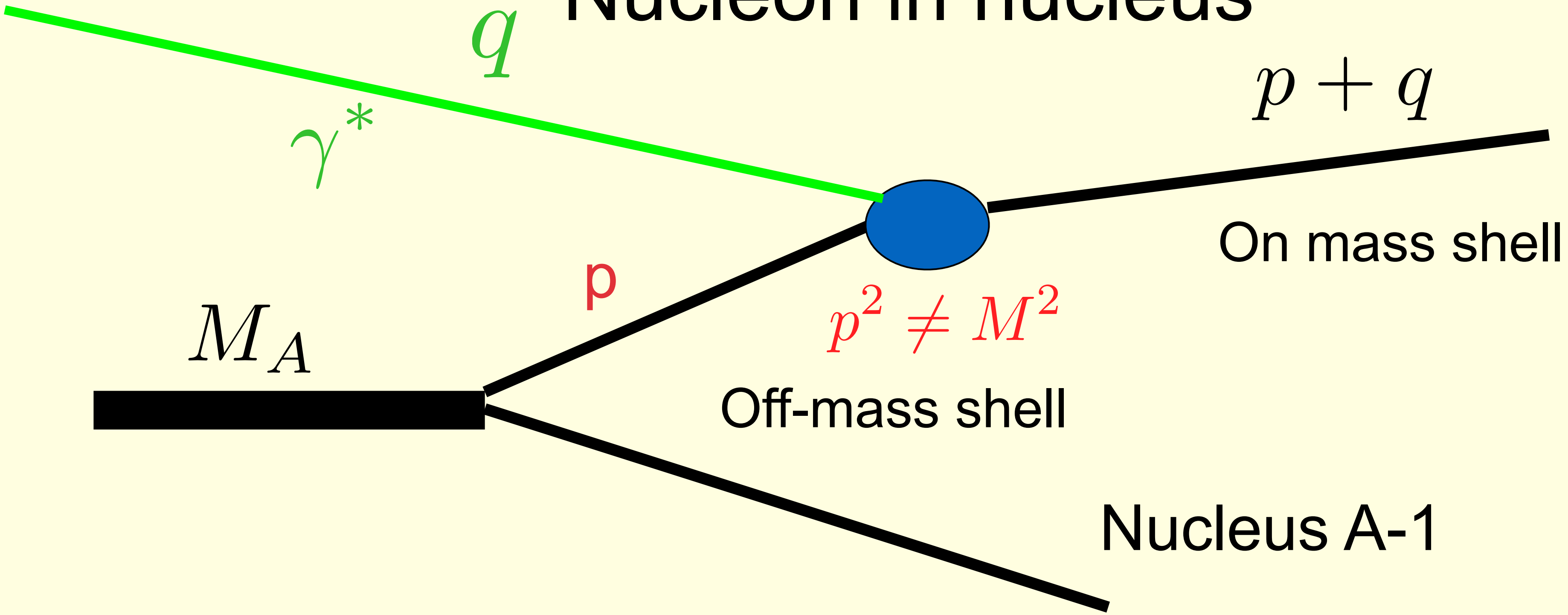
a bound nucleon is larger than free one- a mean field effect

I don't see how you can get plateaus at large x in a mean field model-Fomin

b multi-nucleon clusters - beyond the mean field

Nucleon in nucleus



a A-1 nucleus is low-lying state — is form factor of "large" proton

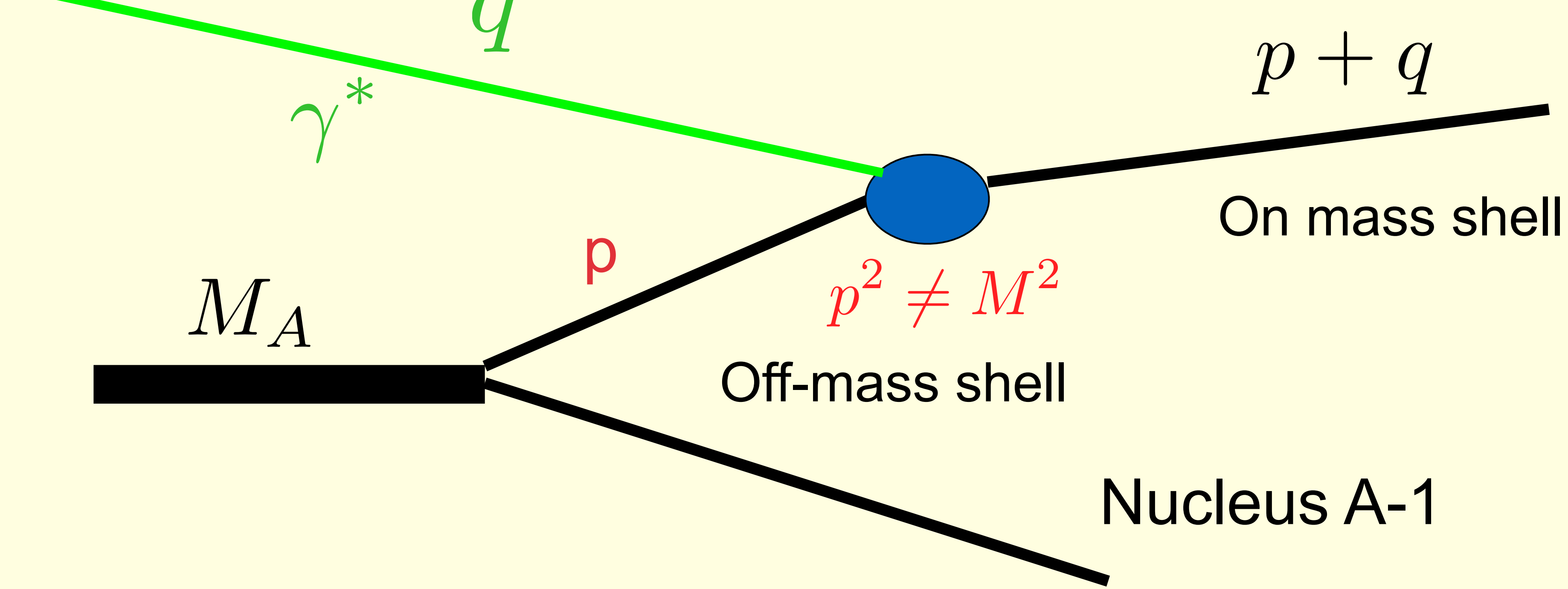
b A- 1 nucleus is 1 fast nucleon +A-2 nucleus
the struck nucleon is part of correlated pair SRC

If Nucleus A-1 is highly excited, then $p^2 - M^2$ is big

Such large virtuality occurs from two nearby correlated nucleons

Highly virtually nucleon is not a nucleon- different quark config.

Nucleon in nucleus



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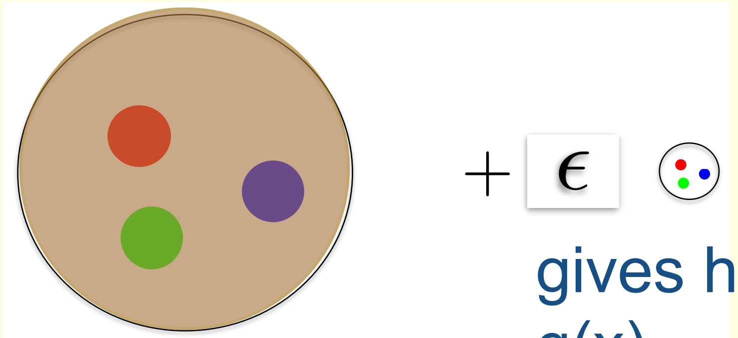
Suppression of Point Like Configurations

Frankfurt Strikman

Free nucleon

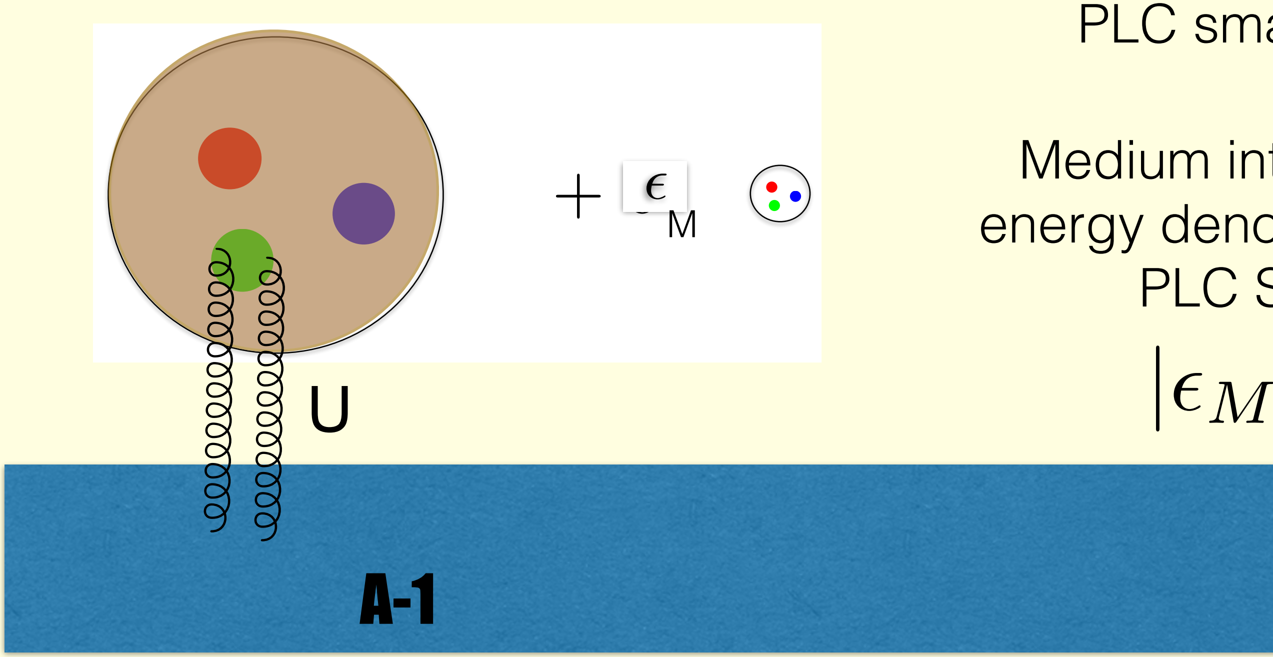


gives high x q(x)

Schematic two-component nucleon model

Blob-like config:BLC
Point-like config: PLC

Bound nucleon



PLC smaller, fewer quarks high x

Medium interacts with BLC energy denominator increases PLC Suppressed

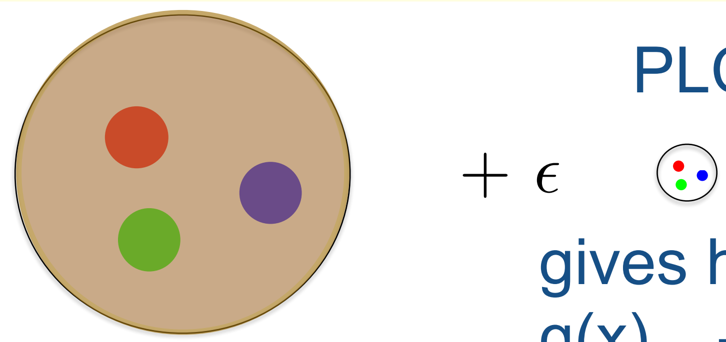
$$|\epsilon_M| < |\epsilon|$$

$$\text{Schroedinger equation} \rightarrow U = (p^2 - M^2)/2M$$ [9]

Quark structure of nucleon

Frankfurt-Strikman

BLC



PLC

gives high x q(x)

PLC does not interact with nucleus

two-component model:
Blob-like config:BLC
Point-like config: PLC

Cioffi degli Atti '07

A	$U = \langle v(\mathbf{p}, E)\rangle/2M$
^{3}H e	-34.59
^{4}He	-69.40
^{12}C	-82.28
^{16}O	-79.68
^{40}Ca	-84.54
^{56}Fe	-82.44
^{208}Pb	-92.20

$$\text{Free nucleon} : H_0 = \begin{bmatrix} E_B & V \\ V & E_P \end{bmatrix}, V > 0$$

$$|N\rangle = |B\rangle + \epsilon|P\rangle,\ \epsilon = \frac{V}{E_B - E_P} < 0$$

$$\text{In nucleus (M)} : H = \begin{bmatrix} E_B - |U| & V \\ V & E_P \end{bmatrix}$$

$$|N\rangle_M = |B\rangle + \epsilon_M|P\rangle,\ |\epsilon_M| < |\epsilon|,\ \text{PLC suppressed},\ \epsilon_M - \epsilon > 0\ \text{amplitude effect!}$$

$|N\rangle_M - |N\rangle \propto (\epsilon_M - \epsilon) \propto$ **U -virtuality**

$q_M(x) = q(x) + (\epsilon_M - \epsilon) f(x)\, q(x),\ \frac{df}{dx} < 0,\ x \geq 0.3$ PLC suppression

$R = \frac{q_M}{q};\ \boldsymbol{\frac{dR}{dx} = (\epsilon_M - \epsilon)\frac{df}{dx} < 0}$ Reproduces EMC effect - like every model

large values from two nucleon correlations Simula

Why this model??? Large effect if **U** is large, it is

EFT: Chen Detmold et al '16

Implications of model

The two state model has a ground state $|N\rangle$ and an excited state $|N^*\rangle$

$|N\rangle_M = |N\rangle + (\epsilon_M - \epsilon)|N^*\rangle$

The nucleus contains excited states of the nucleon

These configurations are the origin of high x EMC ratios

non-nucleon

Previously missing in models of the EMC effect-
same model predicts some other effect

A(e,e') at x>1 shows dominance of 2N SRC

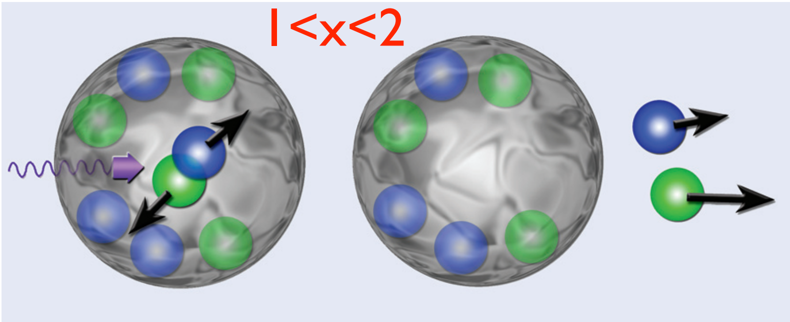
$$x = \frac{Q^2}{2M\nu}$$

x goes from 1 to A

x=1 is **exact** kinematic limit **for all Q²** for the scattering off a free nucleon;
x=2 (x=3) is **exact** kinematic limit **for all Q²** for the scattering off a A=2(A=3) system (up to <1% correction due to nuclear binding)

M Strikman picture

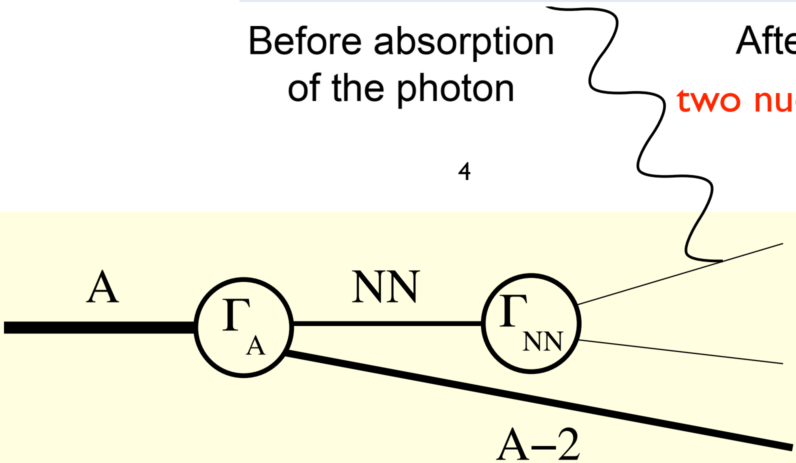
Two nucleons cluster



Before absorption of the photon

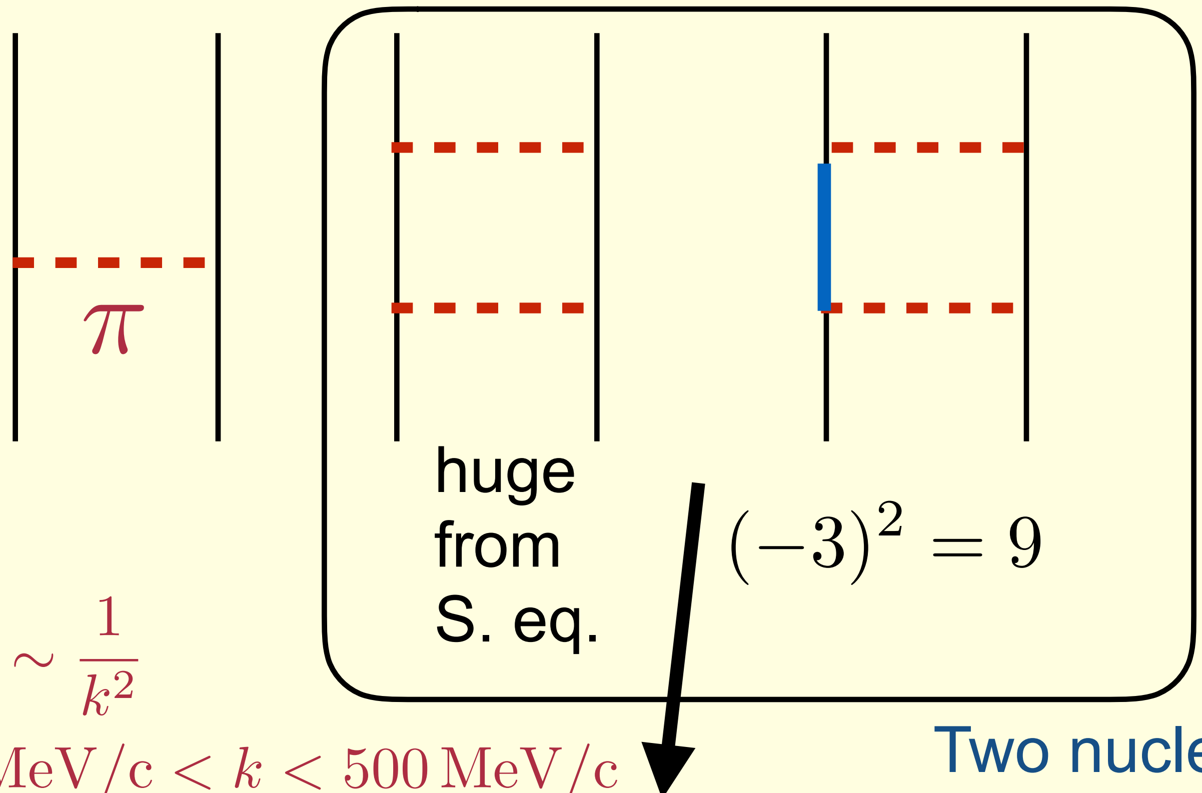
After absorption
two nucleons of SRC are fast

4



How/why nucleons in nuclei cluster

one pion exchange between n and p -tensor force



$$\psi(k) \sim \frac{1}{k^2}$$

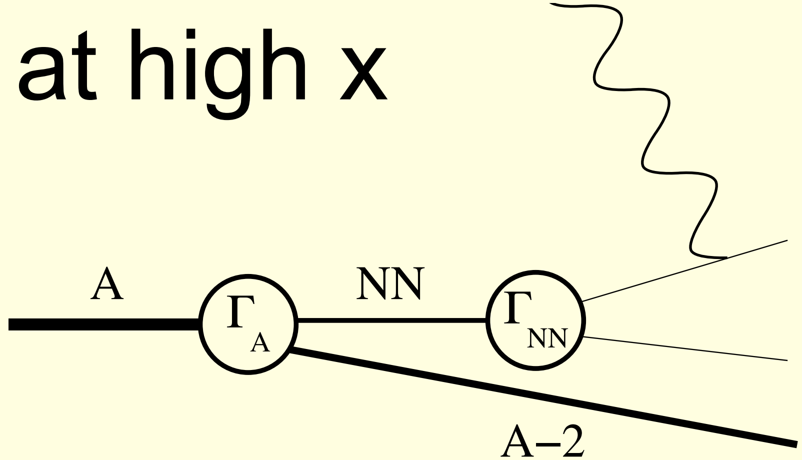
$$300\,\mathrm{MeV/c} < k < 500\,\mathrm{MeV/c}$$

Supports high momentum transfer

Not effective range

Two nucleons are stuck/struck together

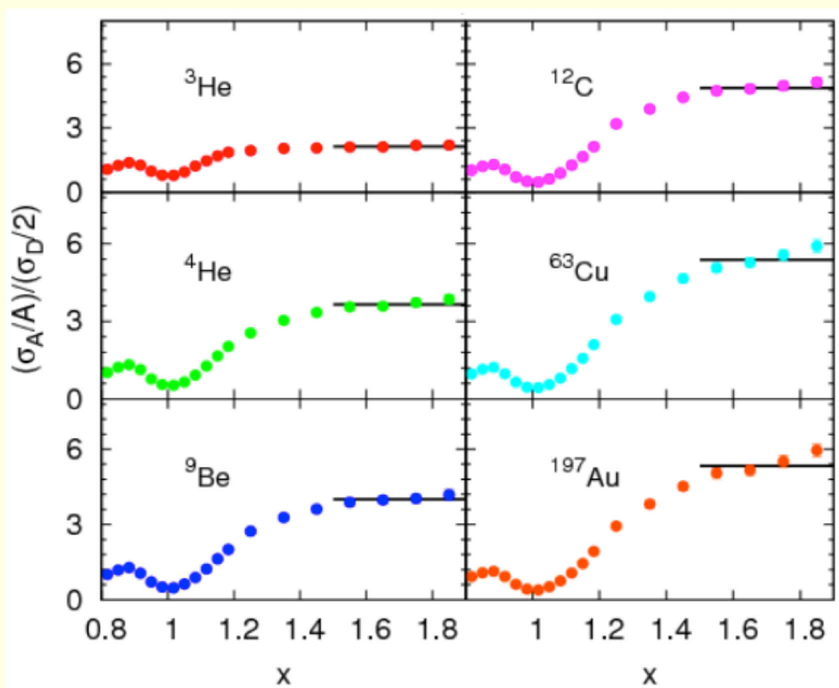
(e,e') at high x



$1 < x < 2$ leading term:

np dominance

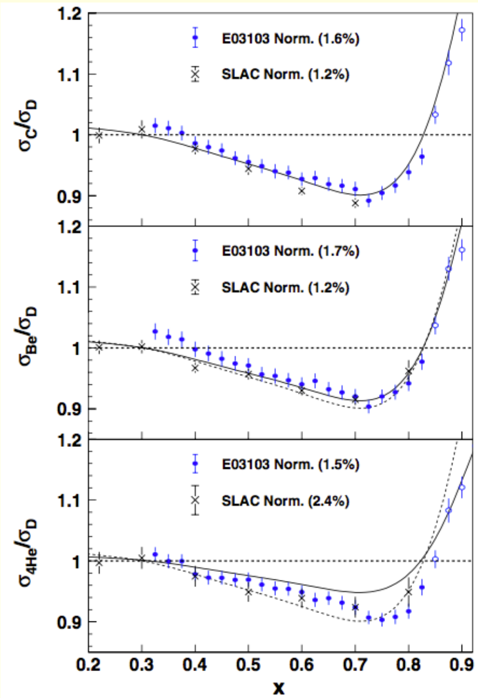
$$\frac{2}{A}\sigma(x,Q^2) \approx a_2(A)\sigma_2(x,Q^2) \approx a_2(A)\sigma_D(x,Q^2)$$



Fomin et al '11

a_2

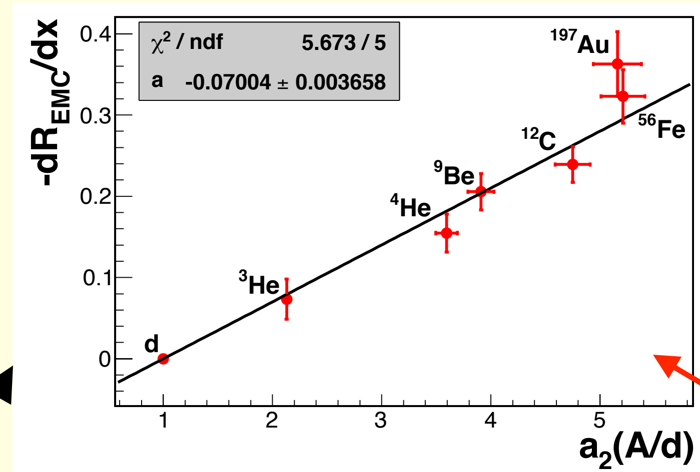
DIS



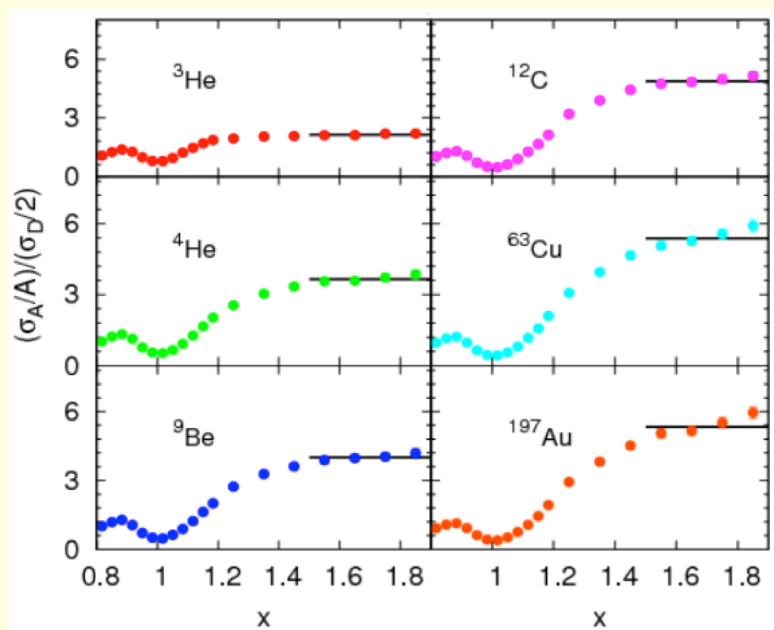
Seely et al 2009

get slope

Hen et al 2013



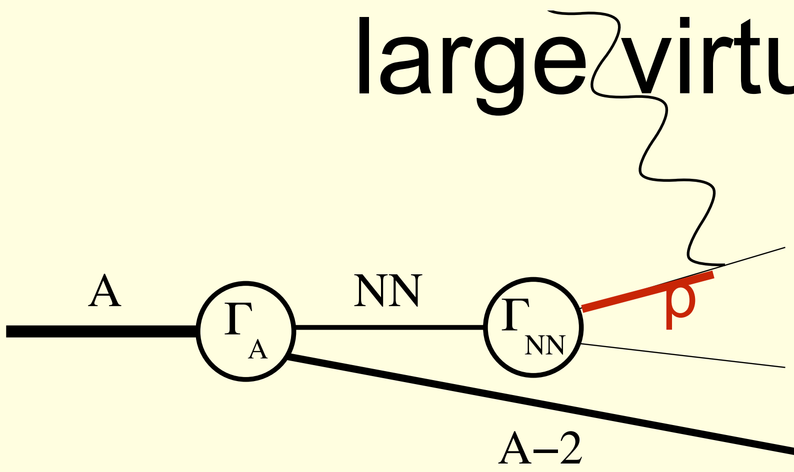
Linear relation accident?



Fomin et al 2012

a_2

Common cause of dR/dx and $a_2(A)$: large virtuality

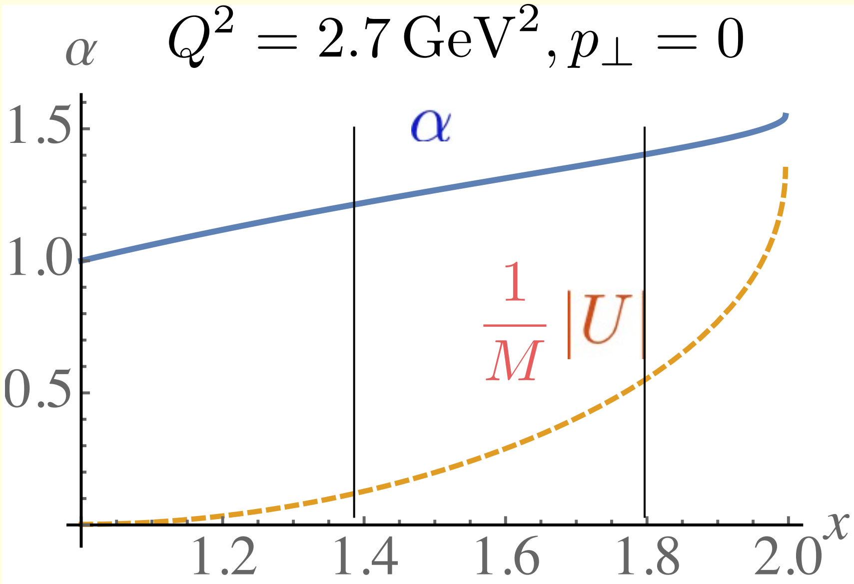


p²-M² large

$$U = v/2M$$

Given Q^2, x, $p_\perp$

4-momentum conservation determines $2\frac{p^+}{P_D^+} \equiv \alpha$ and $v = p^2 - M^2$



Sees wave function at $\alpha \approx 1.2$

|U| is large v is large can only get this from short range correlation

large v is responsible for **both** dR/dx and $a_2(A)$

The word both had been missing from models of EMC effect many models have been ad hoc. The PLC suppression model is not.

Implications for nuclear physics

- Nucleus modifies nucleon electroweak form factors
- Nucleon excited states exist in nuclei
- Medium modifications in deuteron influence extracted neutron F_2
- spectator tagging
- …..

Logic/Summary

Data	DIS-large x	(e,e') Plateau large x	(e,e',NN)
Interpret: kinematics	valence quark momentum decrease in A	2 baryon clusters	
QCD	nucleon wf has BLC,PLC etc PLC -high x PLC suppressed		

Large virtuality

Short-ranged interactions

np dominance

Logic/Summary

EMC effect and large x plateau have same cause

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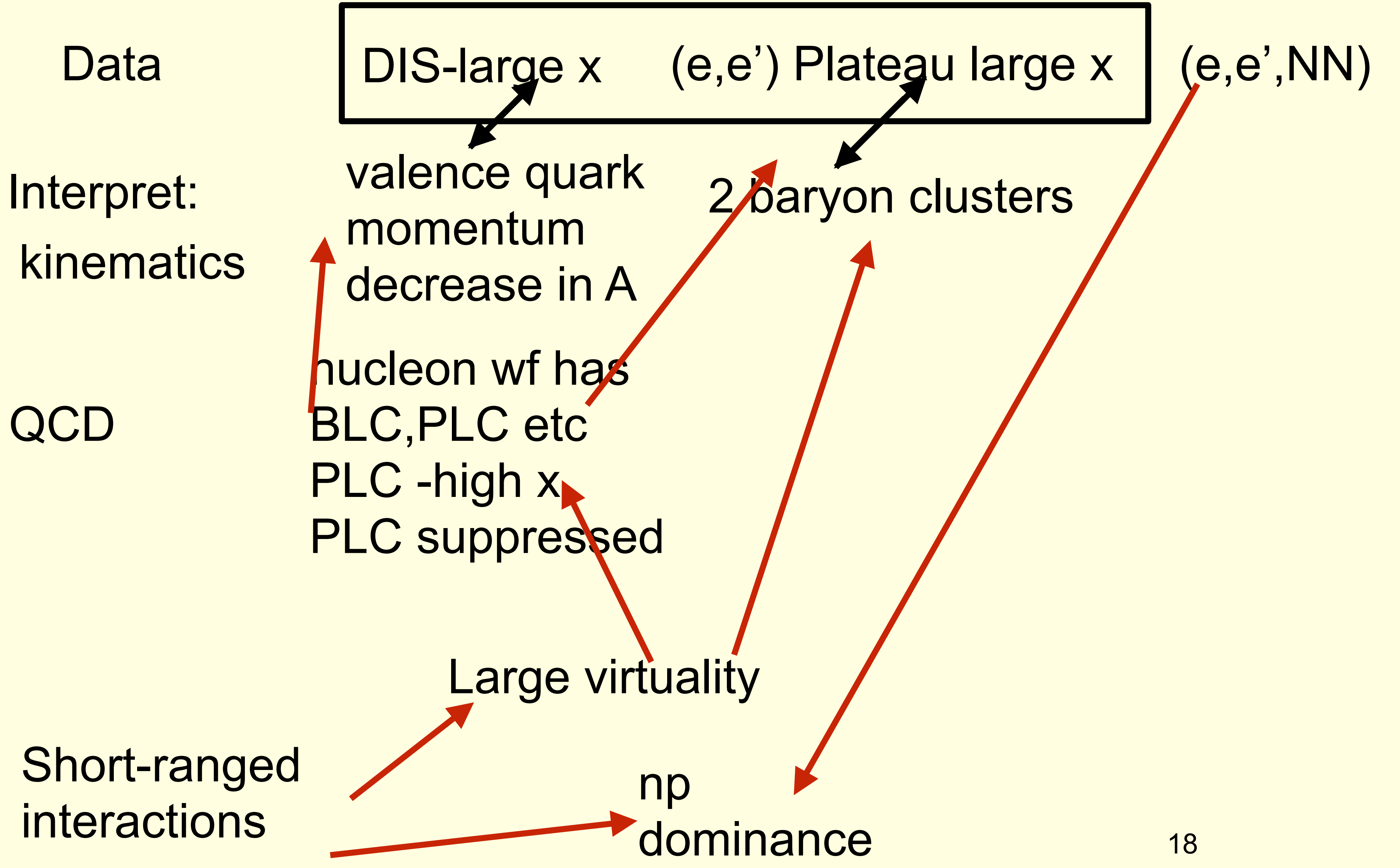

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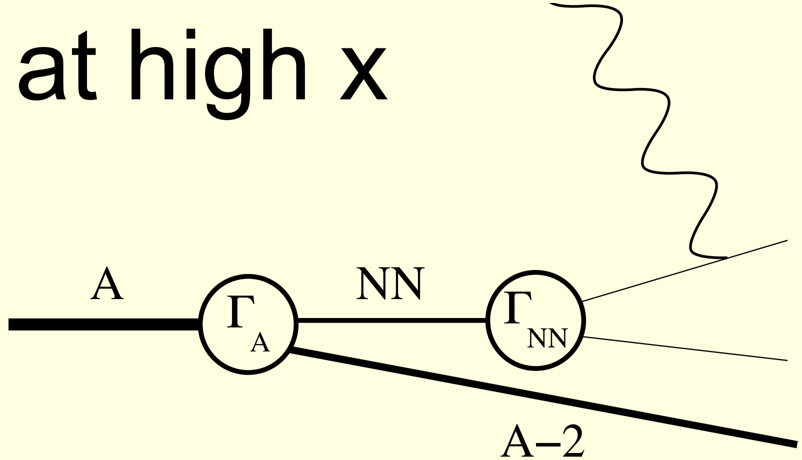
Three phenomena related by common ideas of correlations related to high virtuality

Spares follow

(e,e') at high x



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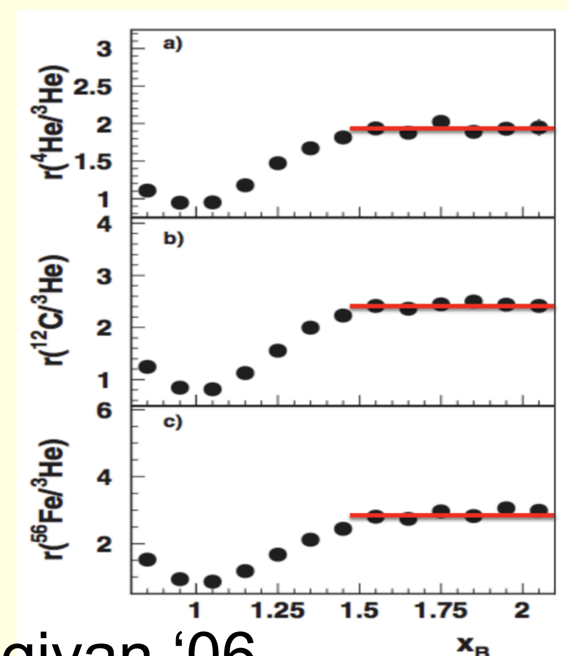
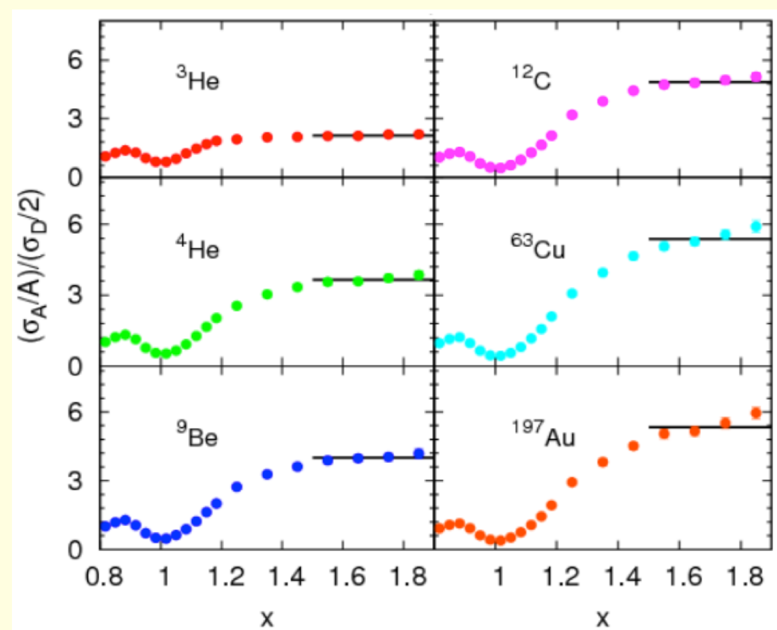


a₂

Egiyan '06



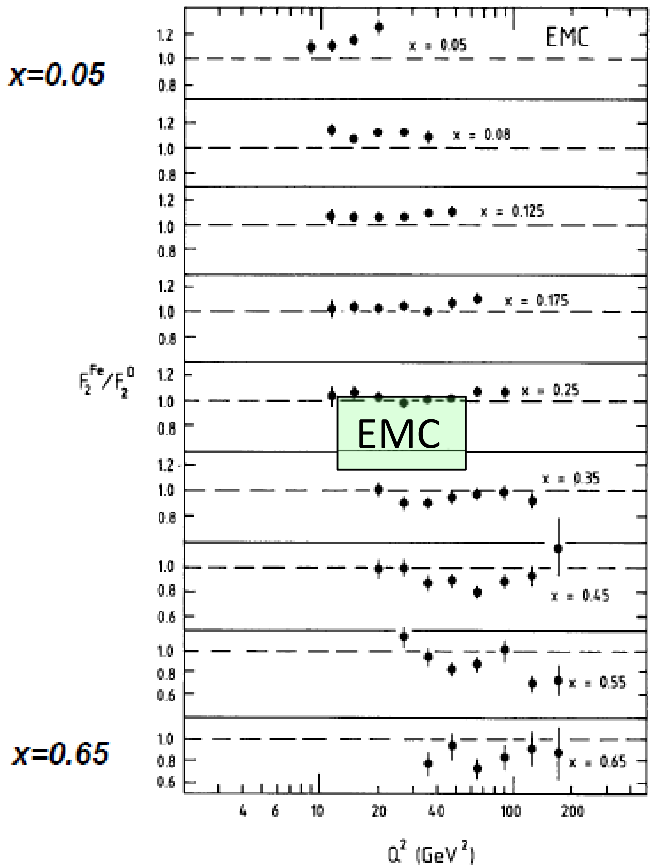
Fomin et al '11

a_2

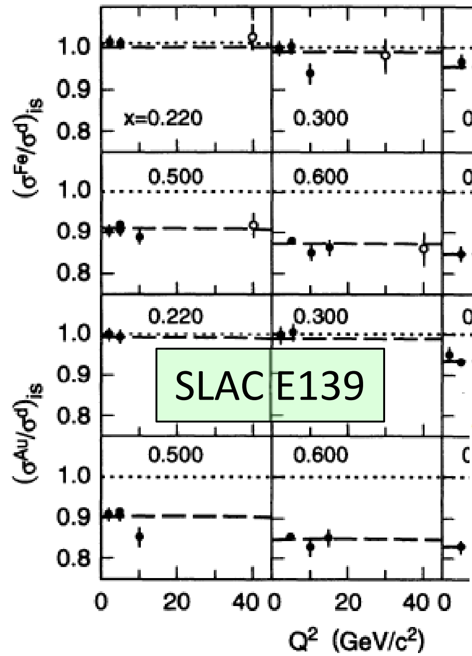
Q^2 dependence of nuclear effects

Klaus Rith

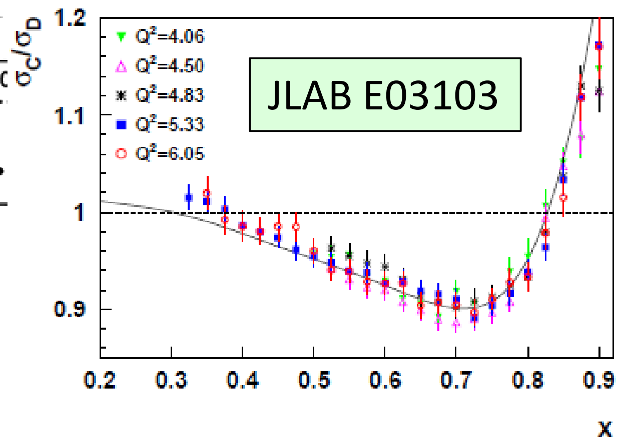
J.J. Aubert et al.,
Nucl. Phys. B 481 (1996) 23



J. Gomez et al.,
PRD 49 (1994) 4348



J. Seely et al.,
PRL 103 (2009) 202301

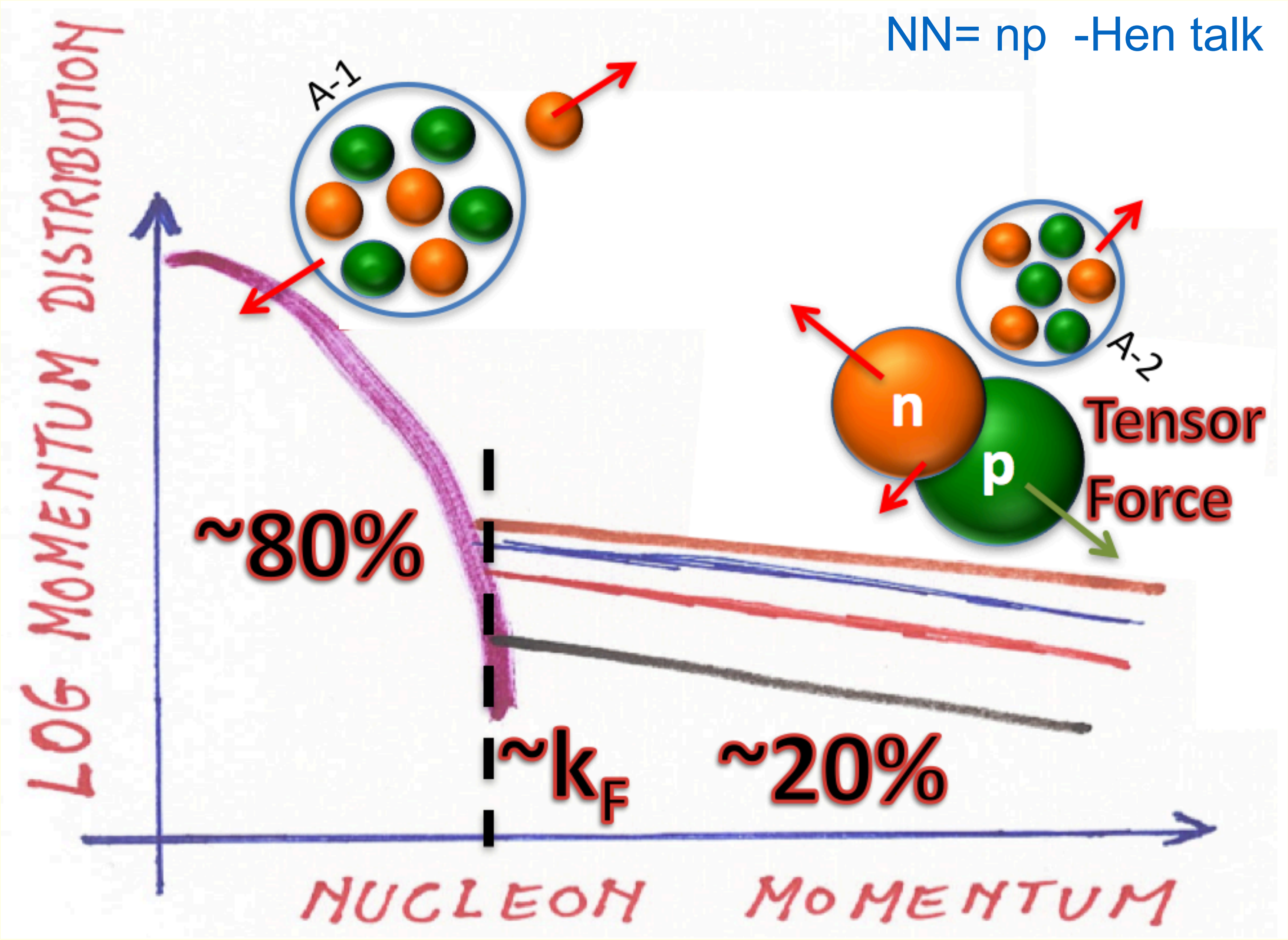


Q^2 dependence of EMC effect is small

Why?

Summary of Correlations

J Ryckebusch pic



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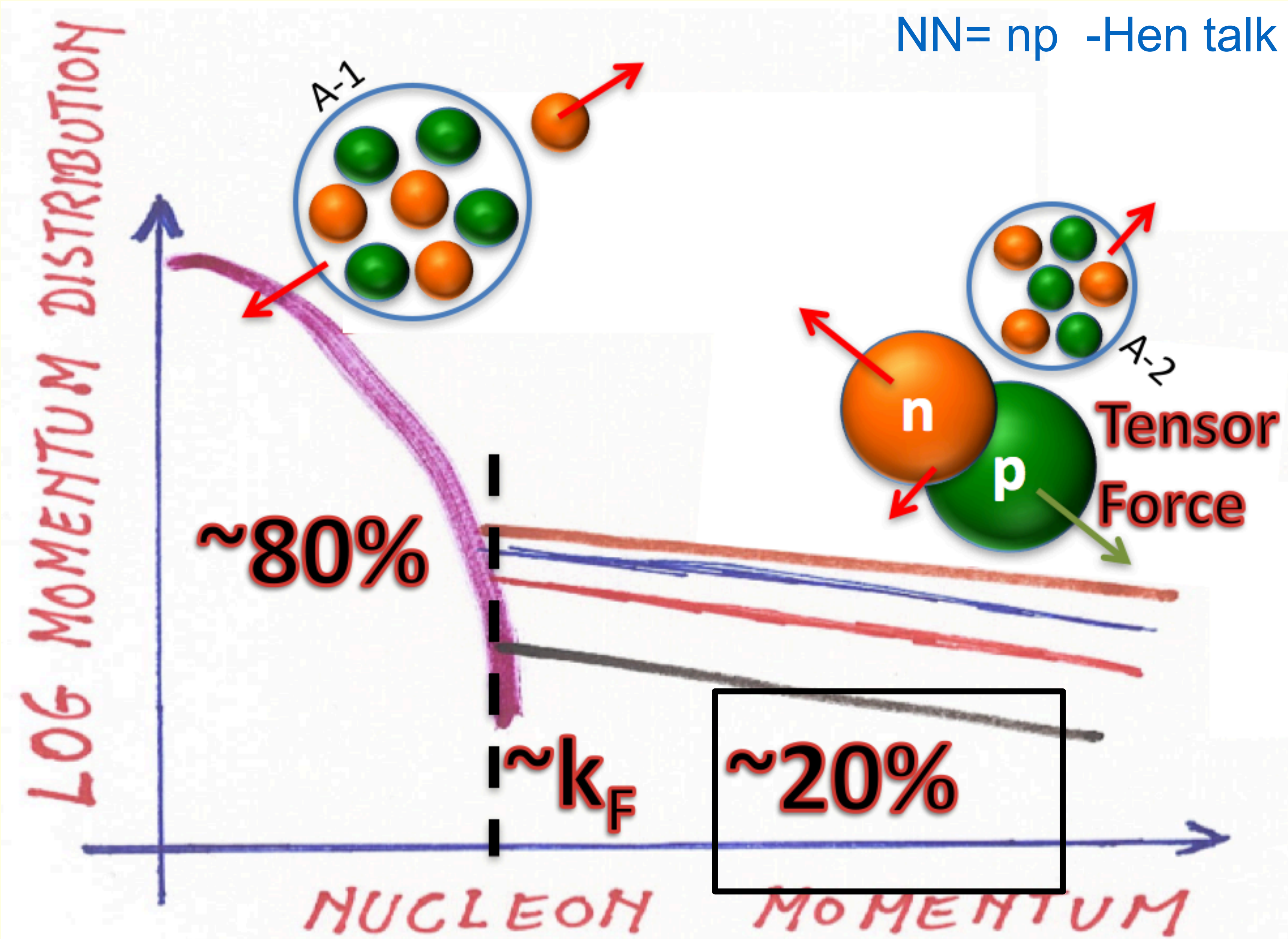


Two nucleon correlations

n(k)

Chen et al '16

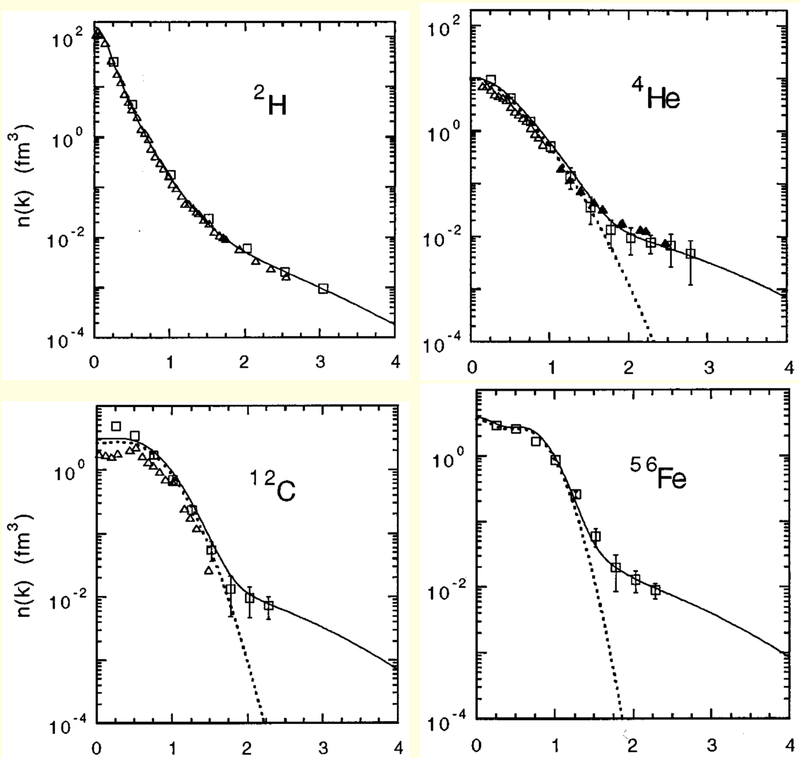
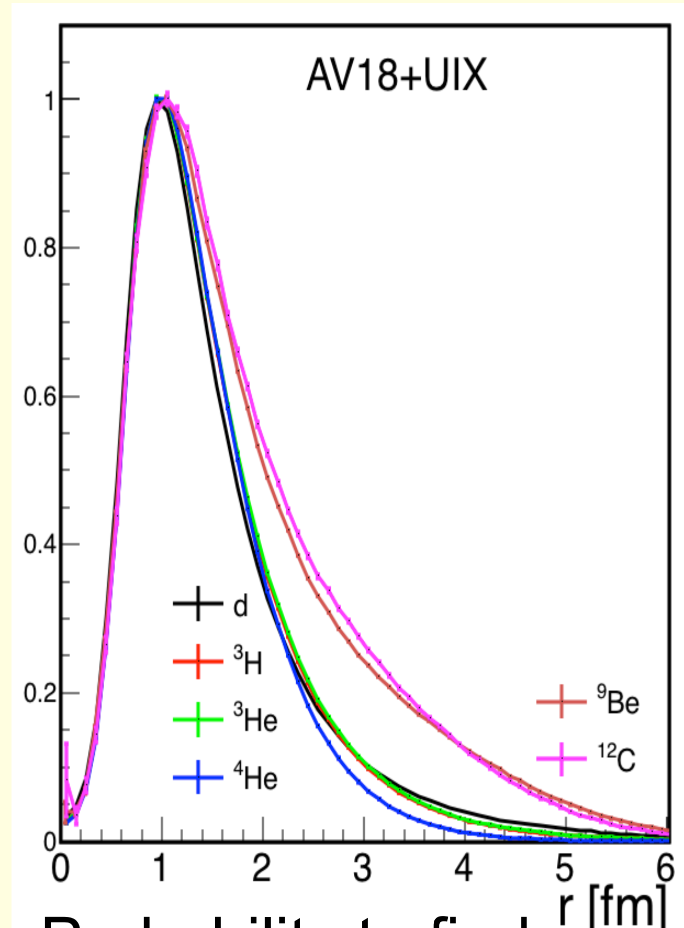


FIG. 4: The nucleon momentum distributions $n_0(k)$ (dashed line) and $n(k)$ (solid line) plotted versus momentum in fm^{-1} for the deuteron, ^{4}He, ^{12}C and ^{56}Fe. Figure adapted from (Ciofi degli Atti and Simula,

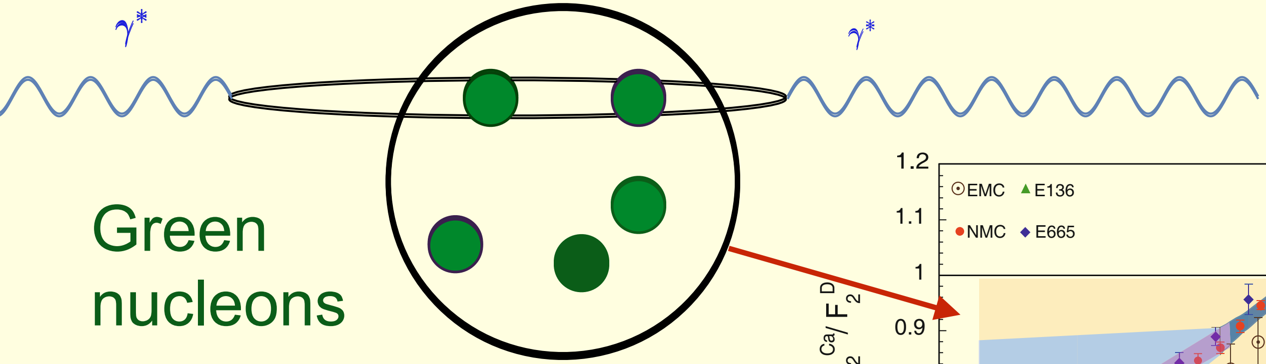


Probability to find nucleons separated by r

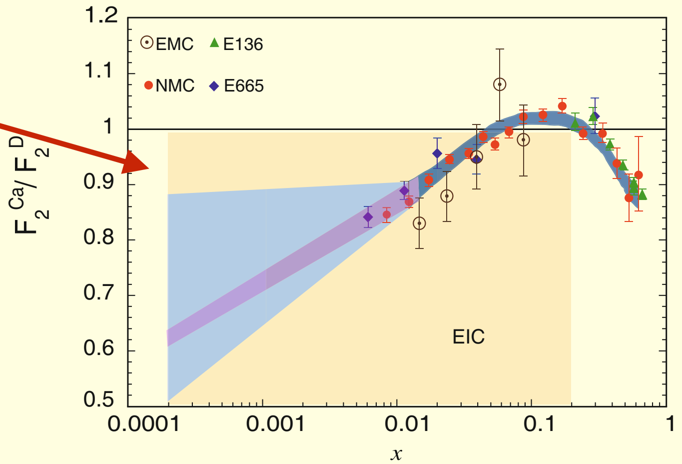
Final summary

- EMC effect is related to NN correlations in two theories. Mechanism: PLC suppression enhanced by correlations
- Correlations account for high x plateau seen in several experiments
- Correlations are important in nuclear shadowing, important for EIC studies of nuclear gluons

Shadowing & Anti-shadowing



Green nucleons

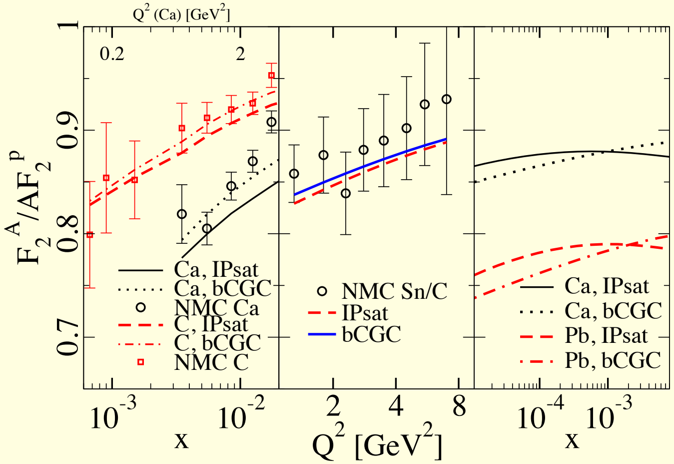


Frankfurt Strikman and Guzey

Physics Reports 512 (2012) 255–393

no parton saturation

Kowalski Lappi Venugopalan PRL 100, 022303 use CGC, gluon saturation; many recent papers & discussion of detailed models



But nuclear wave functions enter in all approaches

All approaches need two-nucleon density: $\rho^{(2)}(\mathbf{r_1},\mathbf{r_2}) \equiv \langle A| \sum_{i\neq j} \delta(\mathbf{r_1}-\mathbf{r_i})\delta(\mathbf{r_2}-\mathbf{r_j})|A\rangle$

Compute thickness function

$$T^{(2)}(b) = \int_{-\infty}^{\infty} dz_1 \int_{-\infty}^{z_1} dz_2\, \rho^{(2)}(b_1=b, z_1; b_2=b, z_2)$$

Usual approximation

$$\rho^{(2)}(b_1=b, z_1; b_2=b, z_2) \approx \rho(b,z_1)\rho(b,z_2)$$

$$T^{(2)}(b) = \frac{1}{2}\left(\int_{-\infty}^{\infty} dz \rho(b,z)\right)^2 = \frac{1}{2}T(b)^2$$

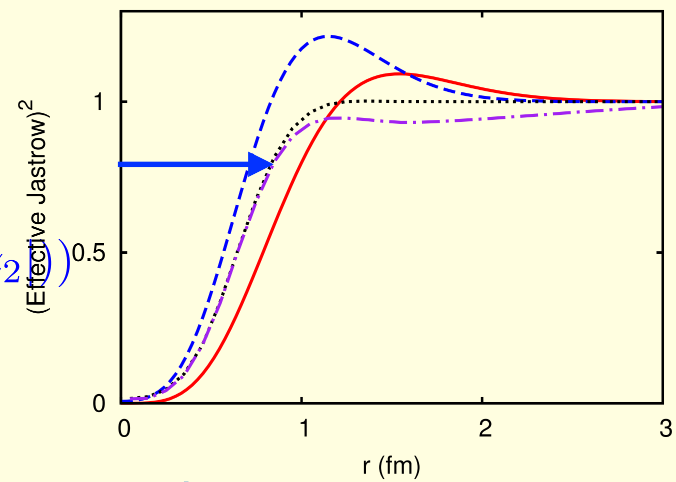
But $\sim 20\%$ of nucleons are in a correlated pair

$$\rho^{(2)}(b_1=b, z_1; b_2=b, z_2) = \rho(b,z_1)\rho(b,z_2)(1+C(|z_1-z_2|))$$

$$T^{(2)}(b) \approx T(b)^2 \frac{l_c}{R_A},\ l_c = 2\int_0^{\infty} dz\, C(z)$$

10-20% reduction depending on nucleus!

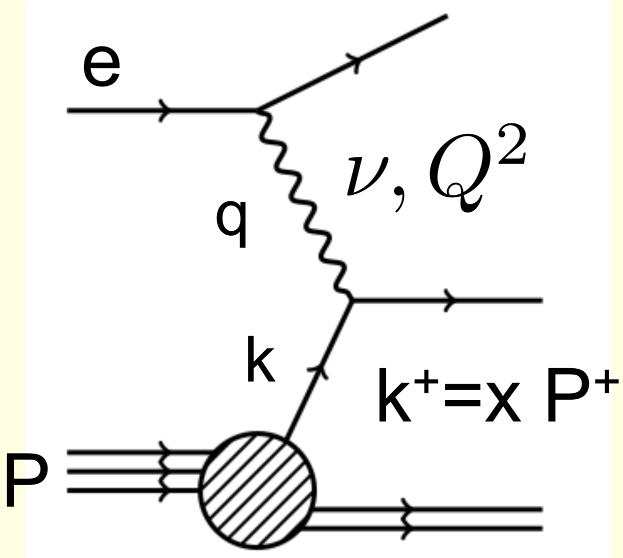
Engel, Carlson, Wiringa '11



$l_c/2$

Shadowing effects are overestimated by significant amounts in all approaches that neglect effects of correlations

Deep Inelastic Scattering

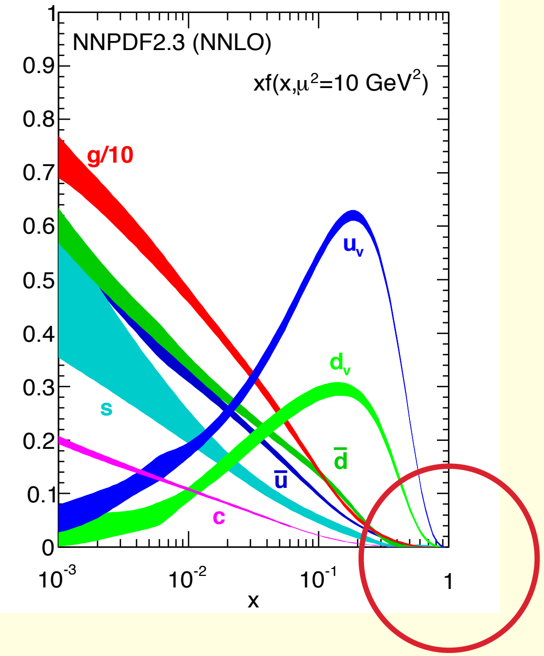


$$x = \frac{Q^2}{2P \cdot q} = \frac{k^0 + k^3}{P^0 + P^3} = \frac{k^+}{P^+}$$

The 1982 EMC effect involves deep inelastic scattering from nuclei

EMC= European Muon Collaboration

Nucleon from PDG



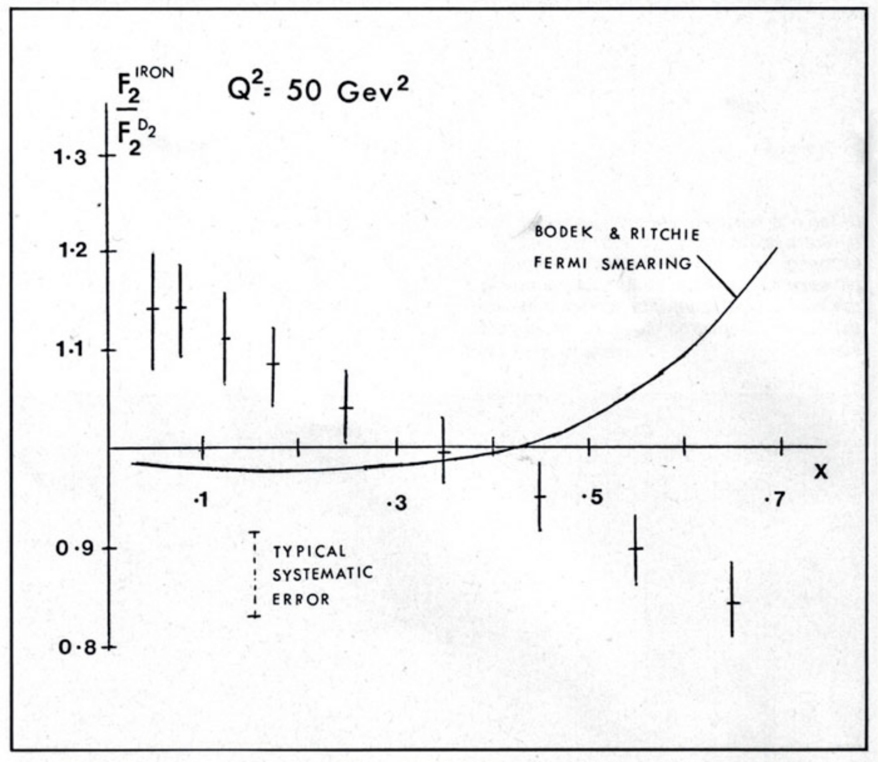
Implication 1 for EIC?

Why are EMC ratios independent of Q^2?

- Is the medium modification for matrix elements yielding higher-twist effects same as for leading twist? M. Strikman
- Can EIC add by examining Q^2 dependence
- Large x is on the kinematic edge, but perhaps can do during a phase in which energy is ramped up

The EMC Effect

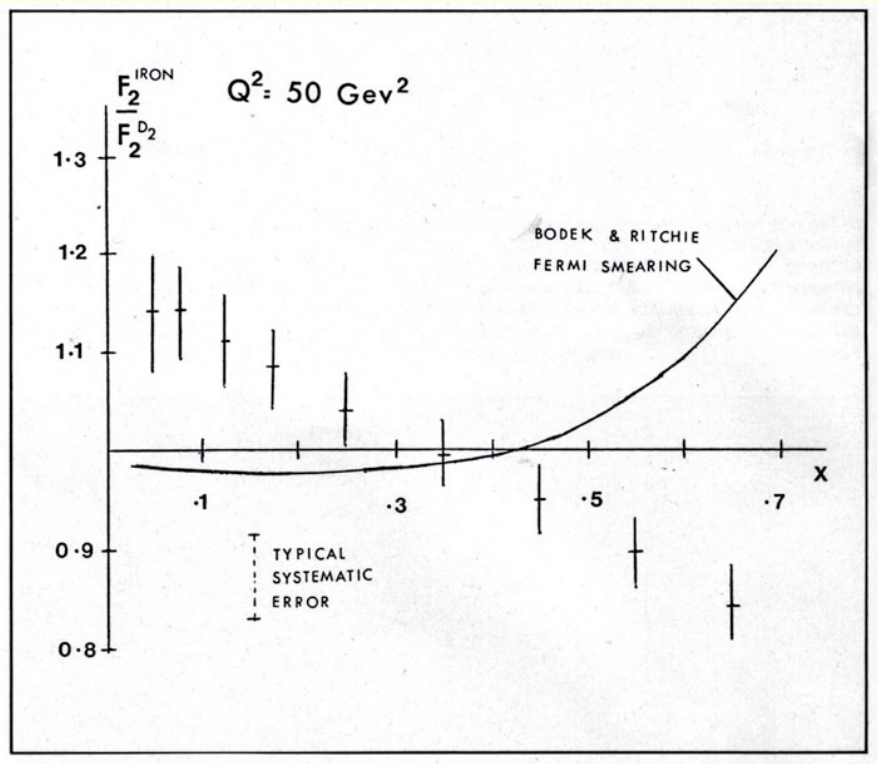
Cern Courier
Nov. 1982



Higinbotham, Miller, Hen, Rith
CERN Courier 53N4('13)24

The EMC Effect

Cern Courier
Nov. 1982



How does the nucleus emerge from QCD, a theory of quarks and gluons?

Higinbotham, Miller, Hen, Rith
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