e A Collective Effects at an EIC:

EMC effect, shadowing and anti-shadowing

V. Guzey talk

Gerald A. Miller

University of Washington

What was known in 2012

What happened since

The future -what can be done with an EIC

RMP with Or Hen, Eli Piasetzky, Larry Weinstein here

Will focus on 0.3 <x<0.7 Remarkable experimental progress

Even though at high x, this work has implications for the EIC

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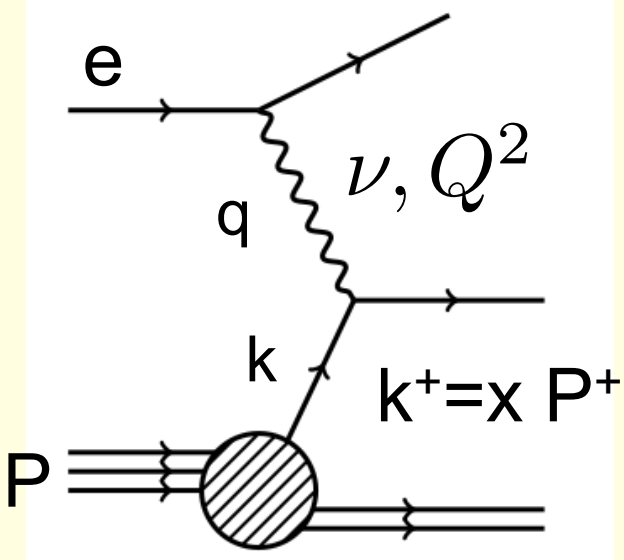
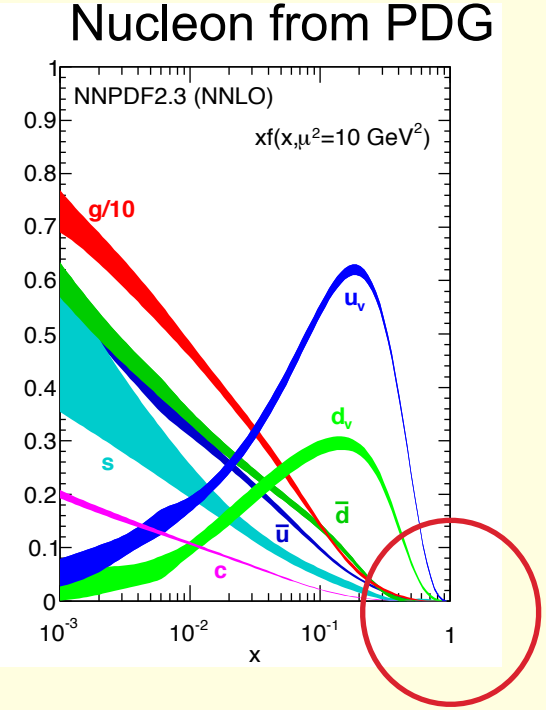
Deep Inelastic Scattering



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

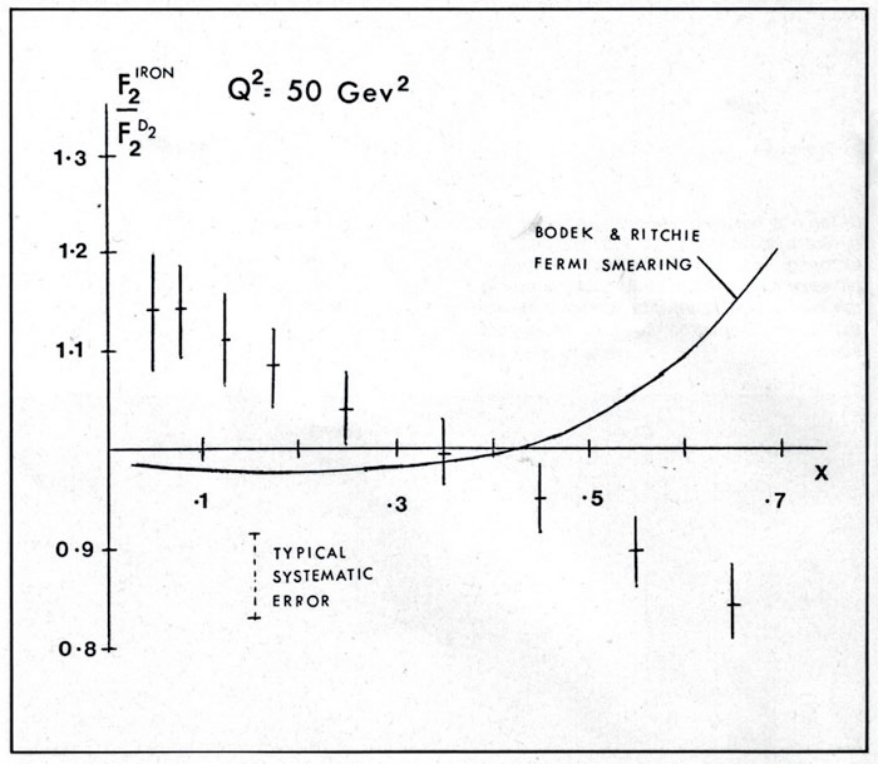


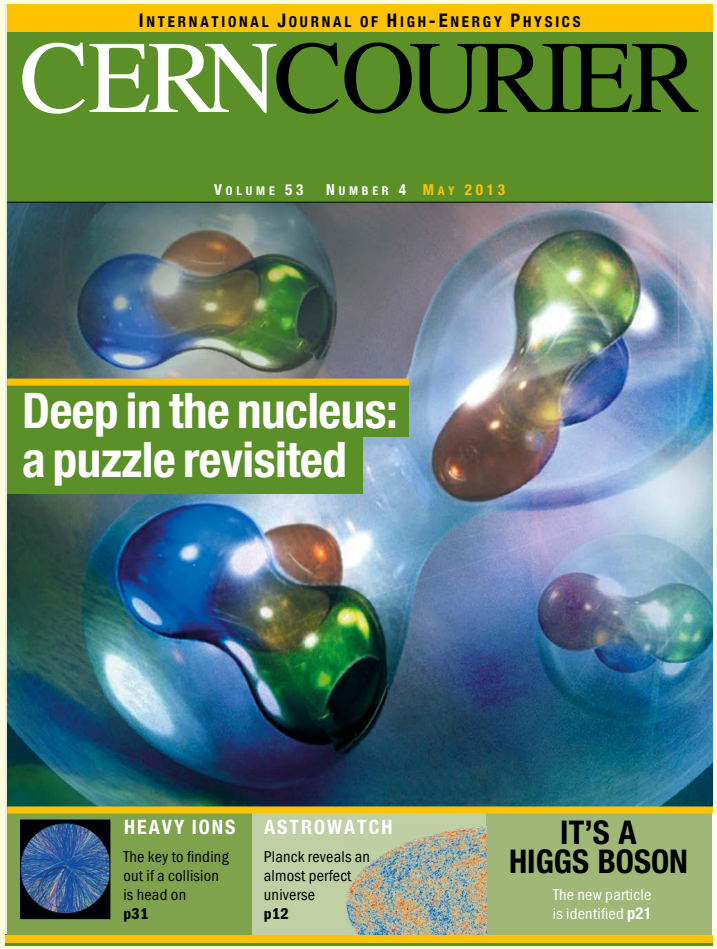
The 1982 EMC effect involves deep inelastic scattering from nuclei

EMC= European Muon Collaboration

The EMC Effect

Cern Courier
Nov. 1982





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

The EMC Effect

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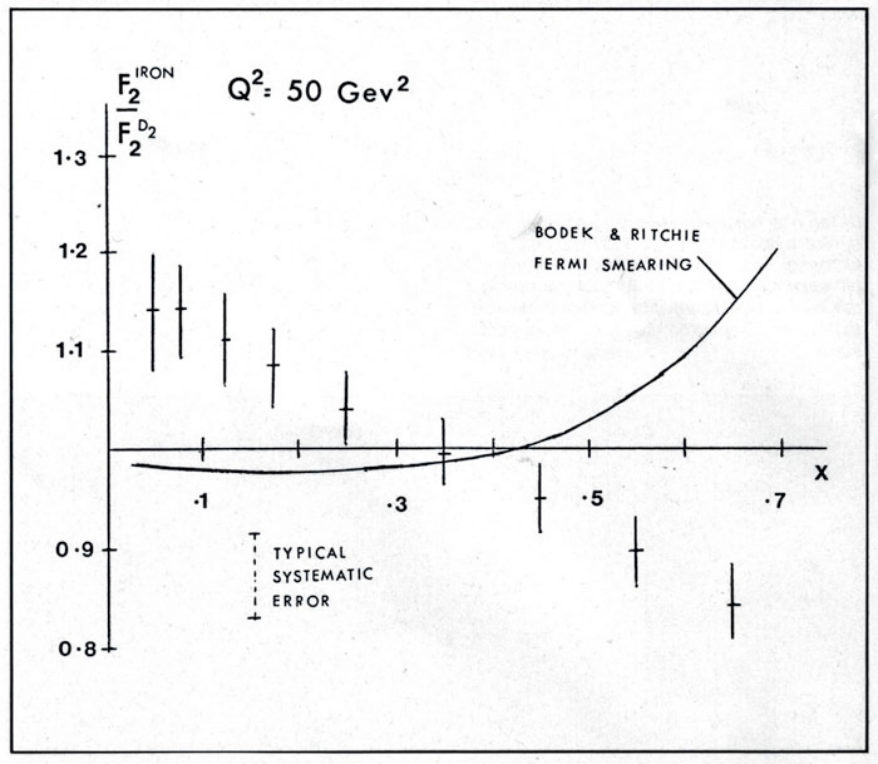

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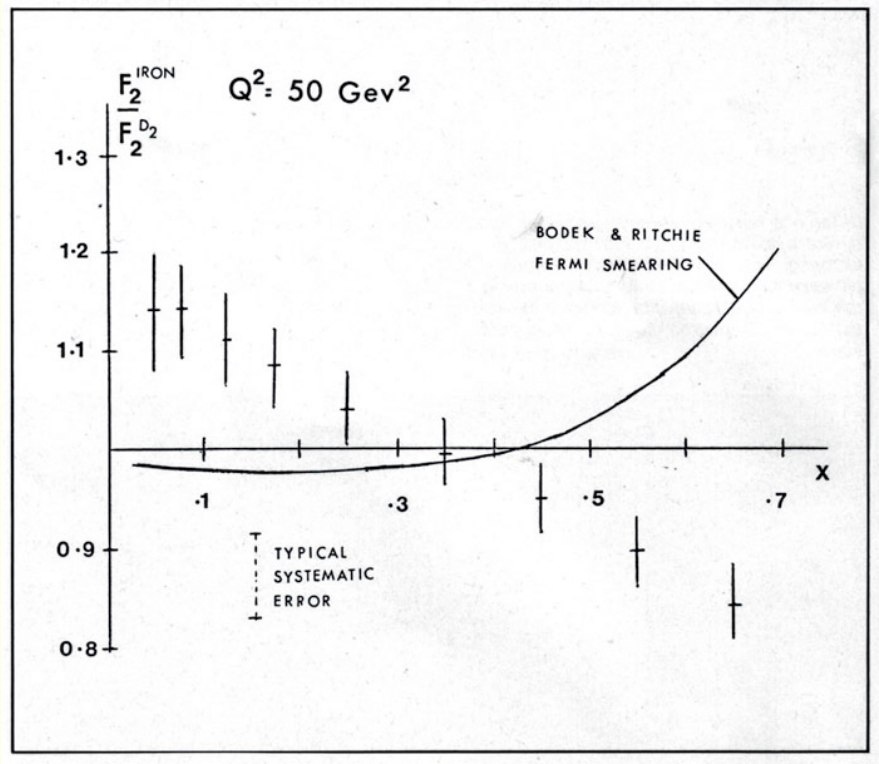
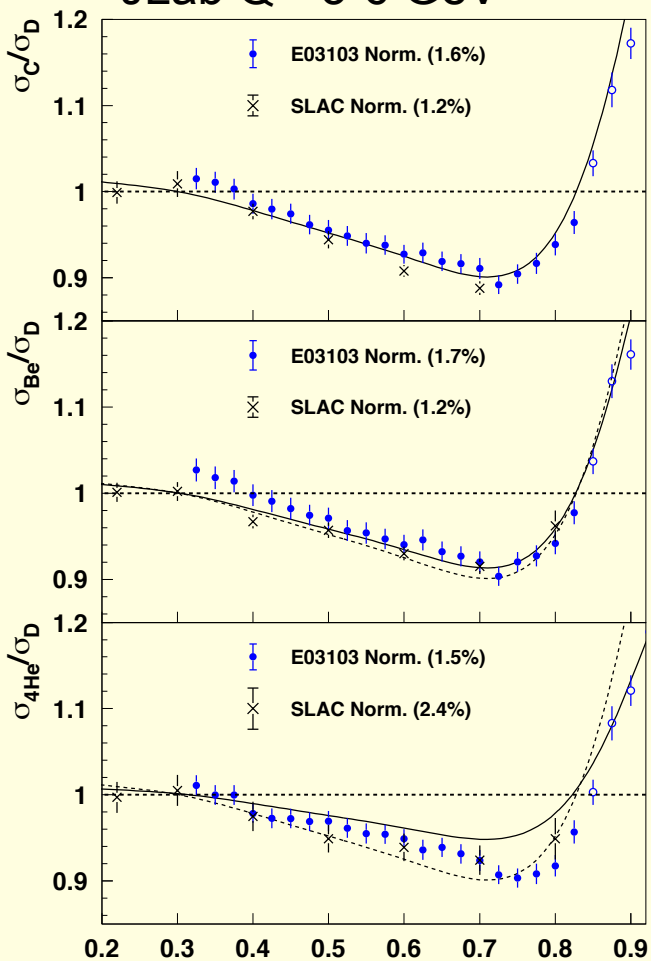


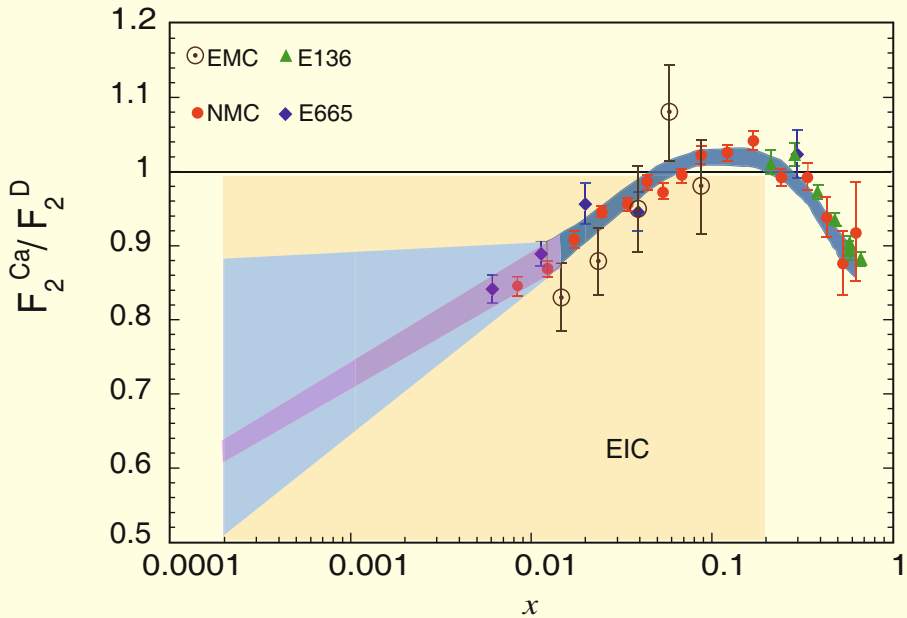
How does the nucleus emerge from QCD, a theory of quarks and gluons?

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

The EMC EFFECT

JLab Q^2=3-6 GeV^2





White Paper

For 0.3<x<0.7 ratio=R is linear

Nucleon structure is modified: valence quark momentum depleted.

EFFECTS ARE SMALL ~15%

Why are ratios independent of Q^2?

The EMC EFFECT

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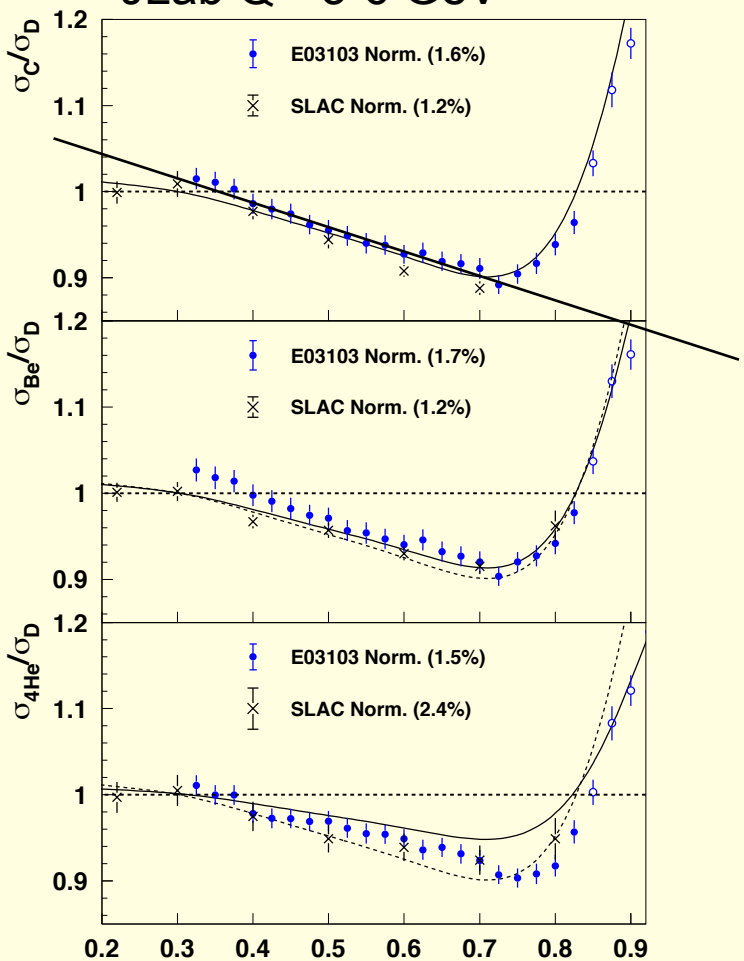

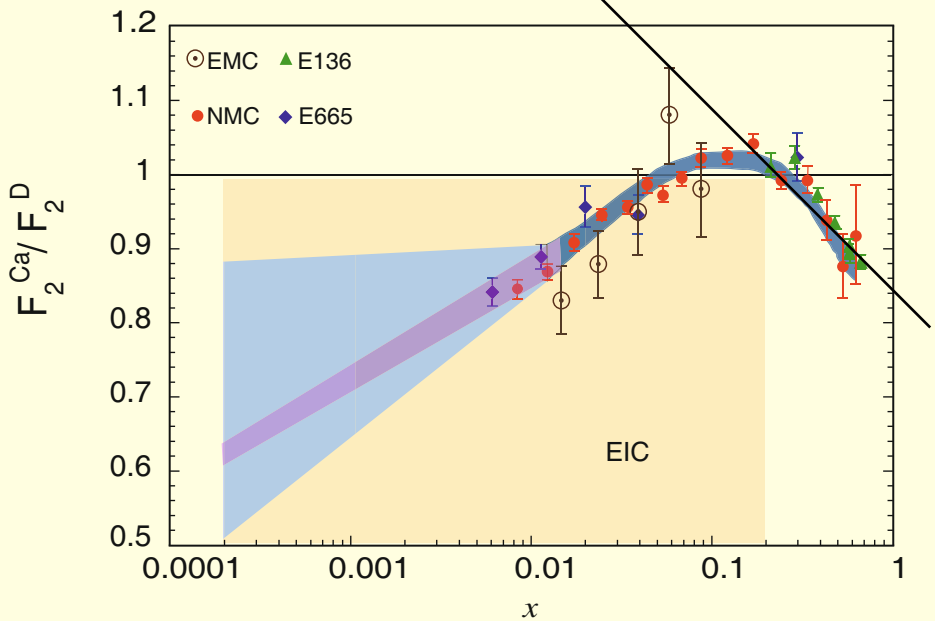

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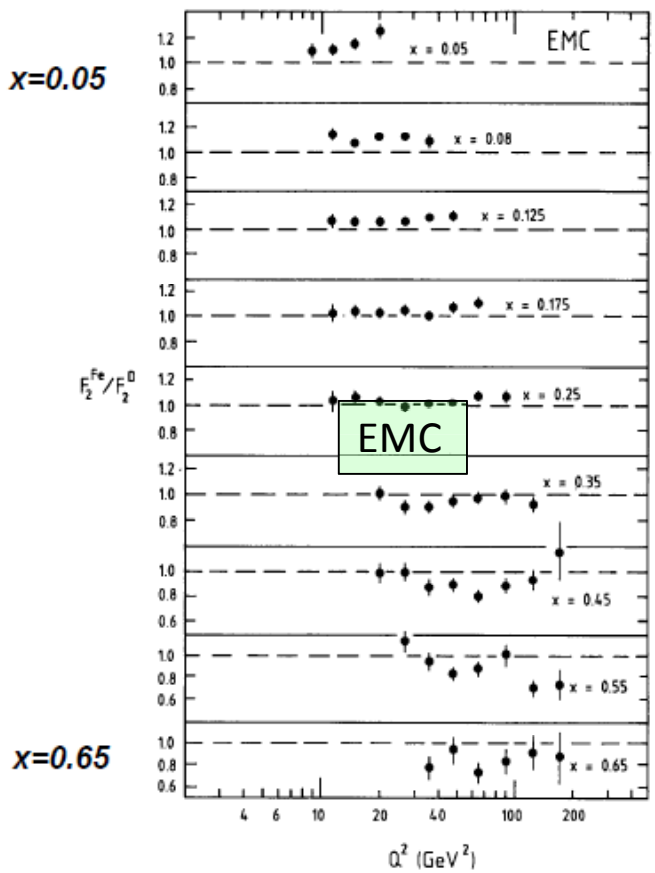
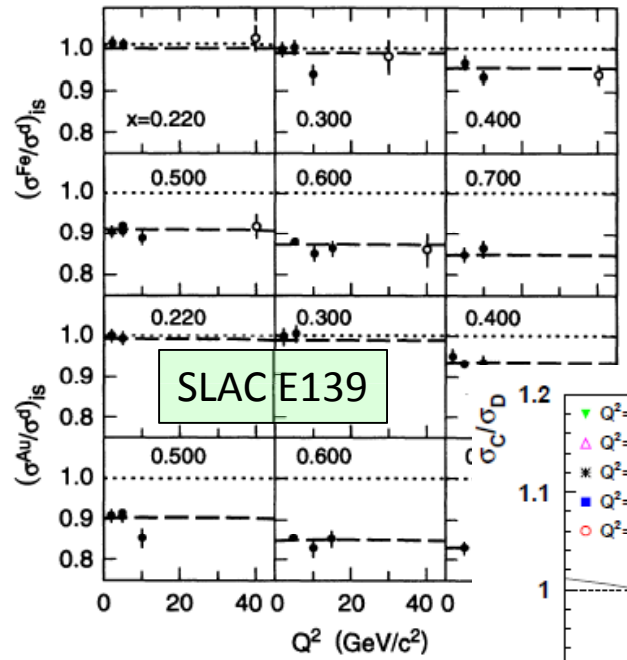
Q^2 dependence of nuclear effects

Klaus Rith

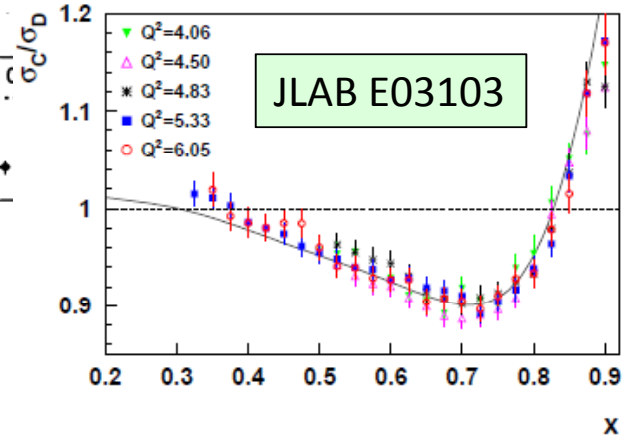
J.J. Aubert et al.,
Nucl. Phys. B 481 (1996) 23



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?

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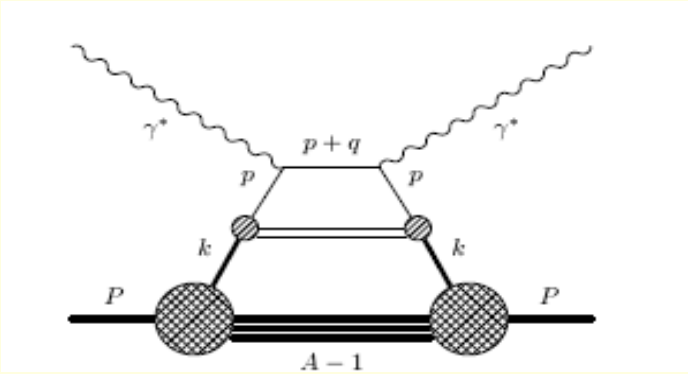
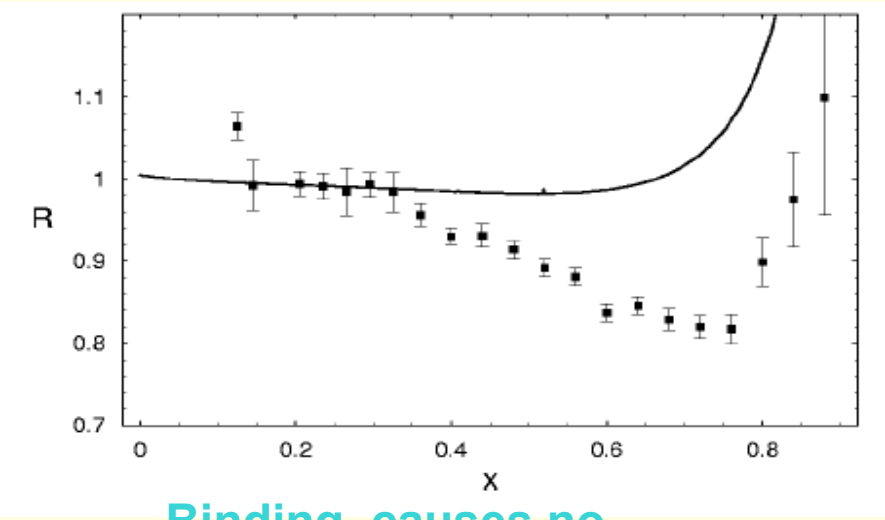
EMC – "Everyone's Model is Cool (1985)"

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

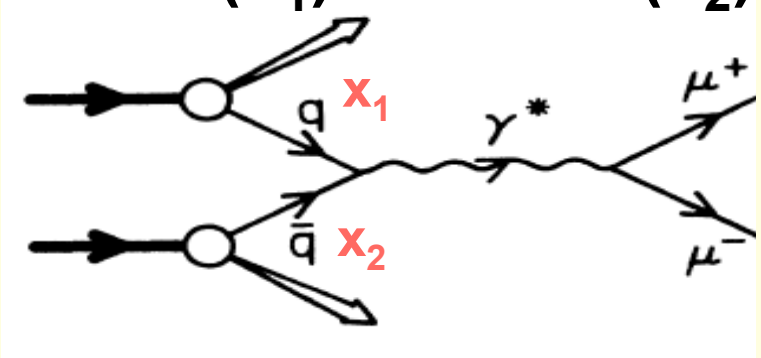
Nucleons and pions

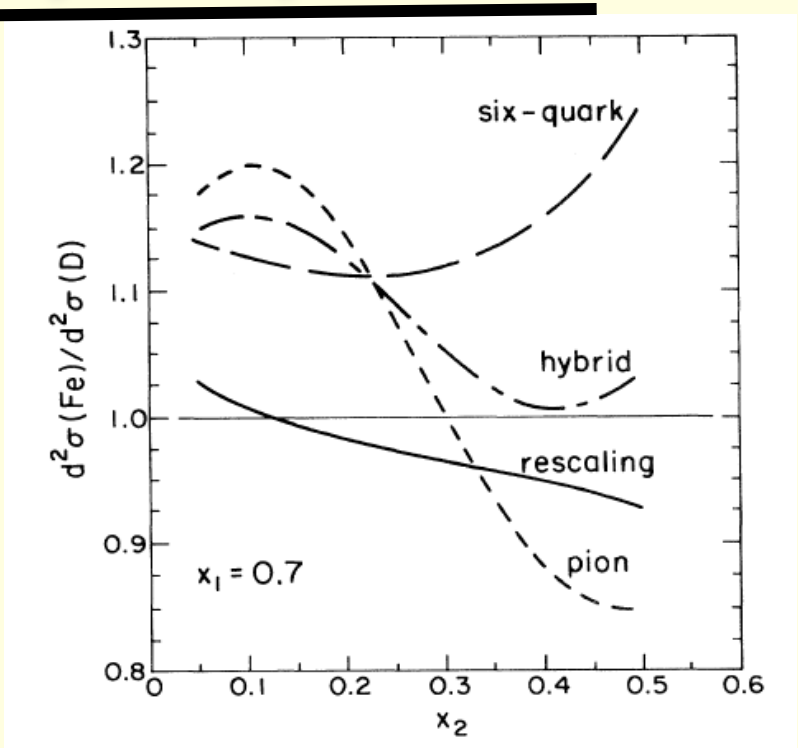
$P_A^+ = P_N^+ + P_\pi^+ = M_A$

$P_\pi^+ / M_A = .04$, explain EMC, sea enhanced

try Drell-Yan, **Bickerstaff, Birse, Miller 84**

proton(x_1) nucleus(x_2)





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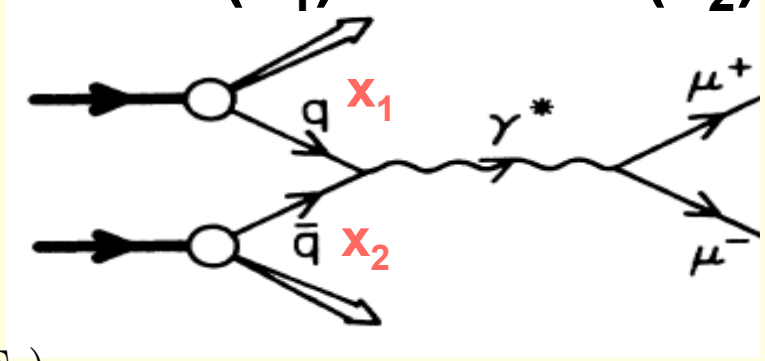
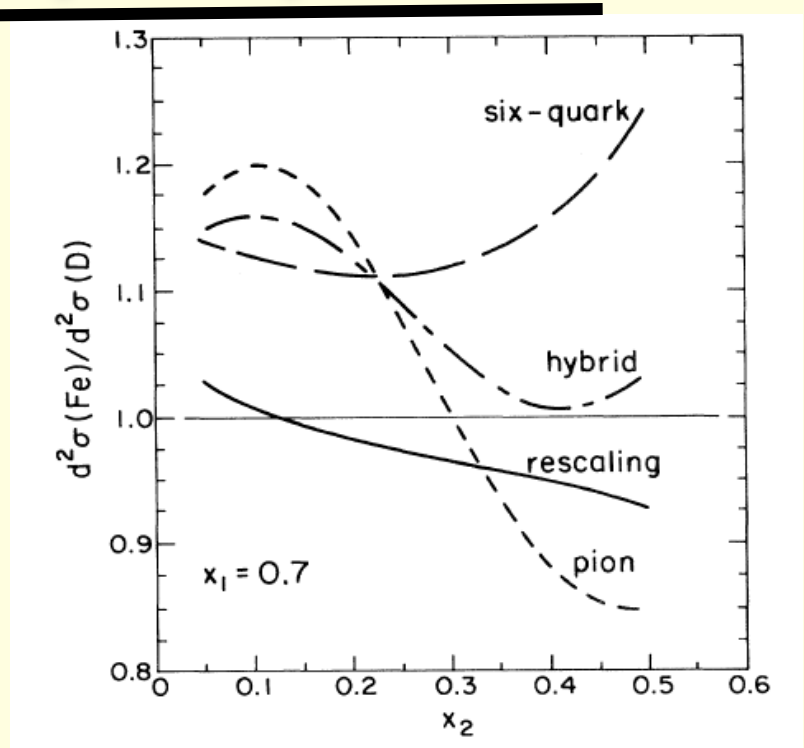
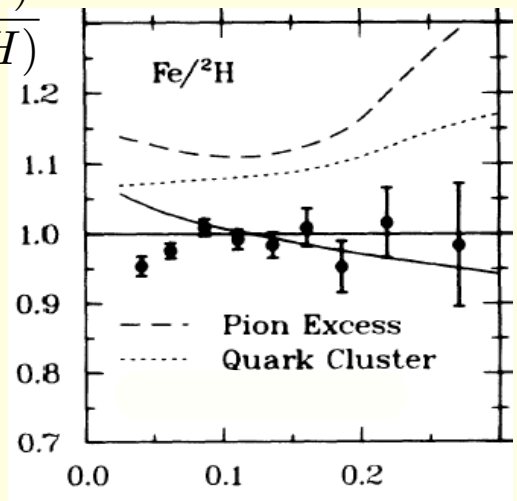




$$\frac{\sigma_{DY}(\mathrm{Fe})}{\sigma_{DY}(^2H)}$$



E772 PRL 69,1726 (92)

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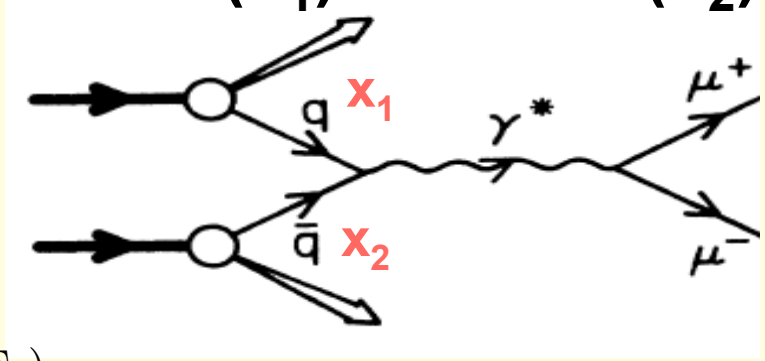

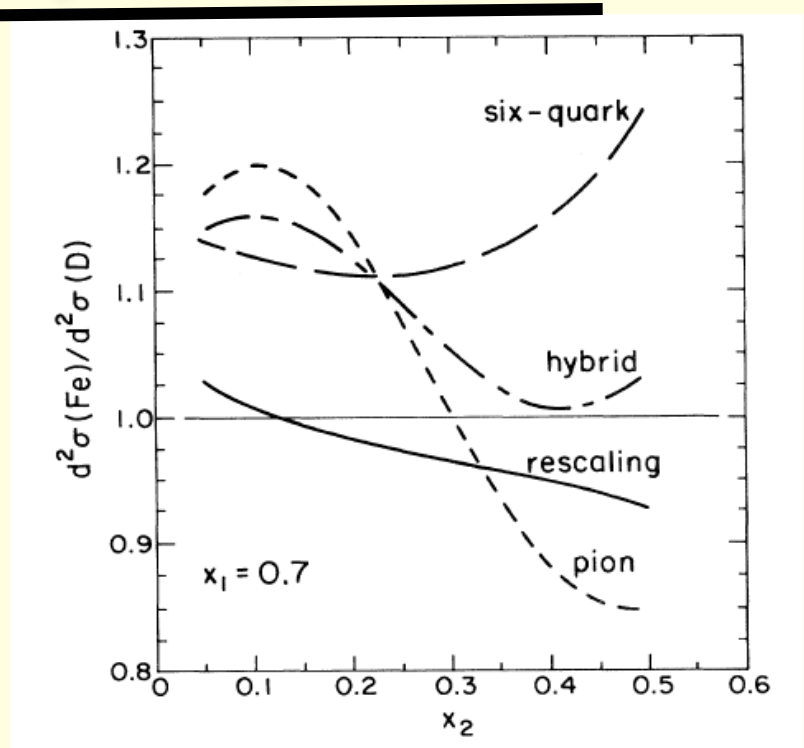

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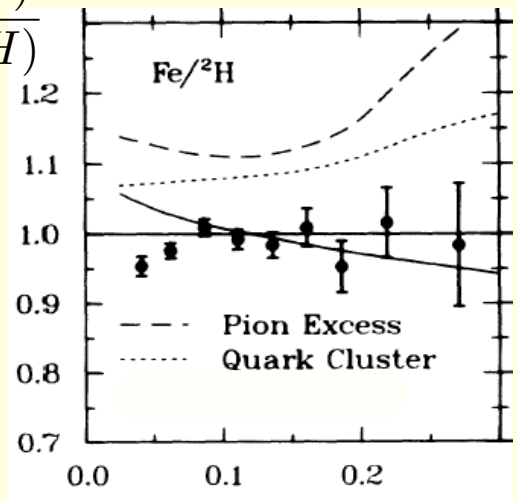

Bertsch, Frankfurt, Strikman "crisis"

E772 PRL 69,1726 (92)

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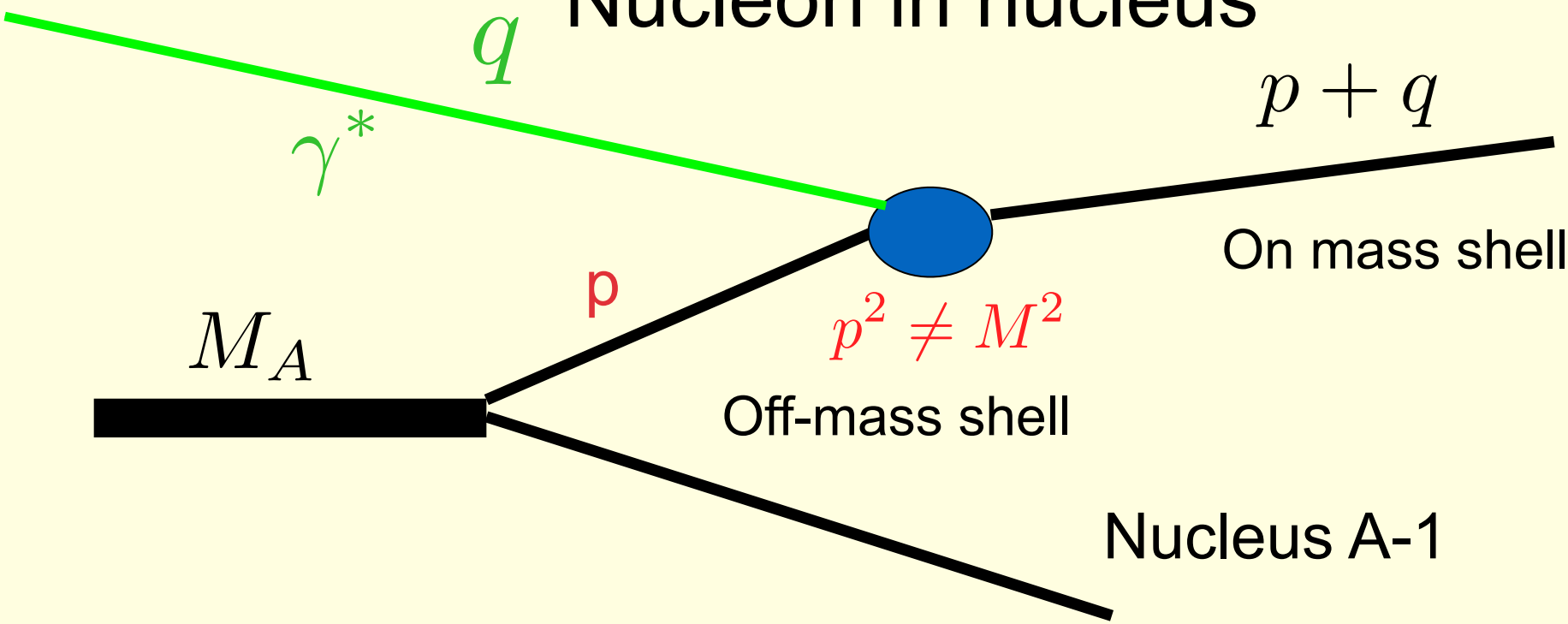
Nucleon in nucleus



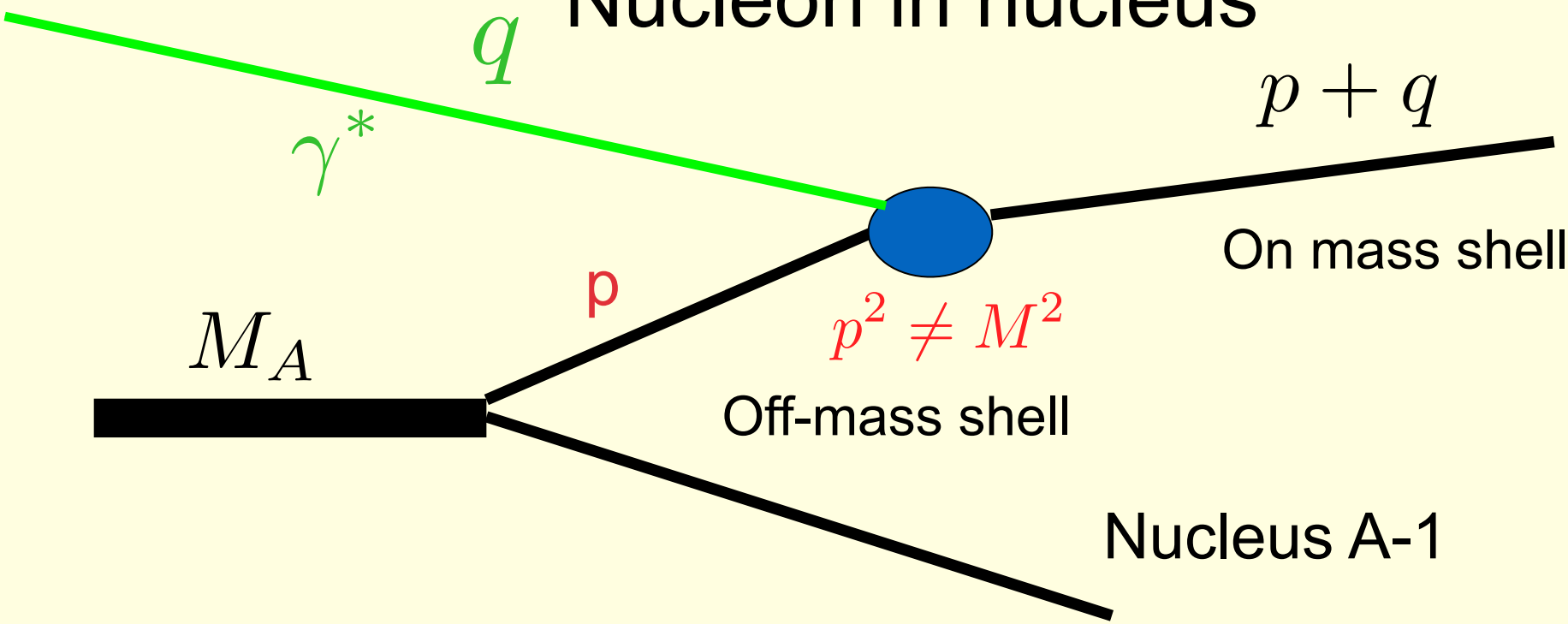
a A-1 nucleus is low-lying state is form factor of "large" proton

b A- 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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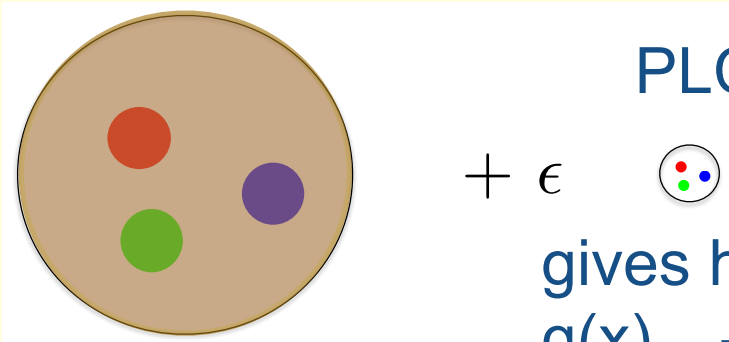
Quark structure of nucleon

Frankfurt-Strikman

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

BLC



PLC

gives high x q(x)

PLC does not interact with nucleus

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

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

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

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

$$|N\rangle_M - |N\rangle \propto (\epsilon_M - \epsilon) \propto U = \frac{p^2 - m^2}{2M}\ \text{Shroedinger eq.}$$

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

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

Why this model??? Large effect if $v = p^2 - m^2$ is large, it is

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

large values from two nucleon correlations Simula

EFT: Chen et al '16

Implication 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

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

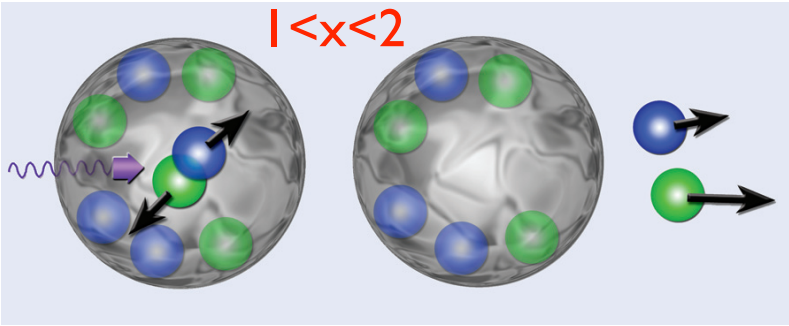
$$x = \frac{Q^2}{2M\nu}$$

x goes from 1 to A

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

M Strikman picture

Two nucleons cluster

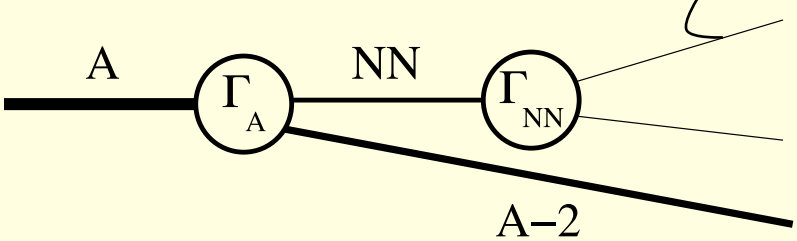


Before absorption of the photon

After absorption

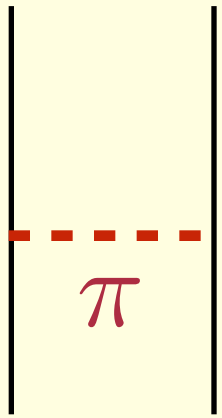
two nucleons of SRC are fast

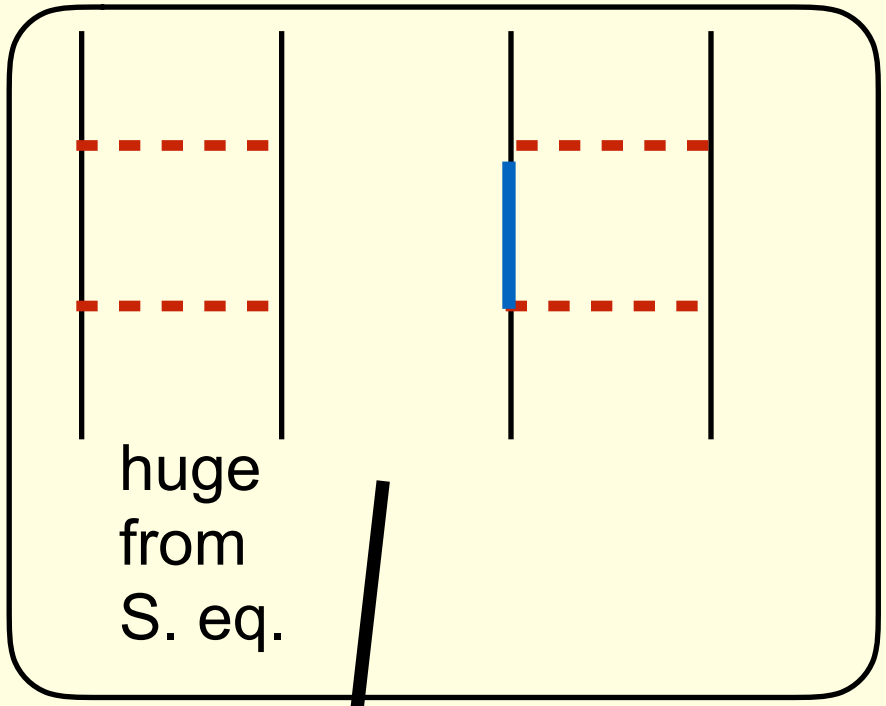
4



How/why nucleons in nuclei cluster

one pion exchange between n and p





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

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

Supports high momentum transfer

Not effective range

Two nucleons are stuck/struck together

Two nucleon correlations

n(k)

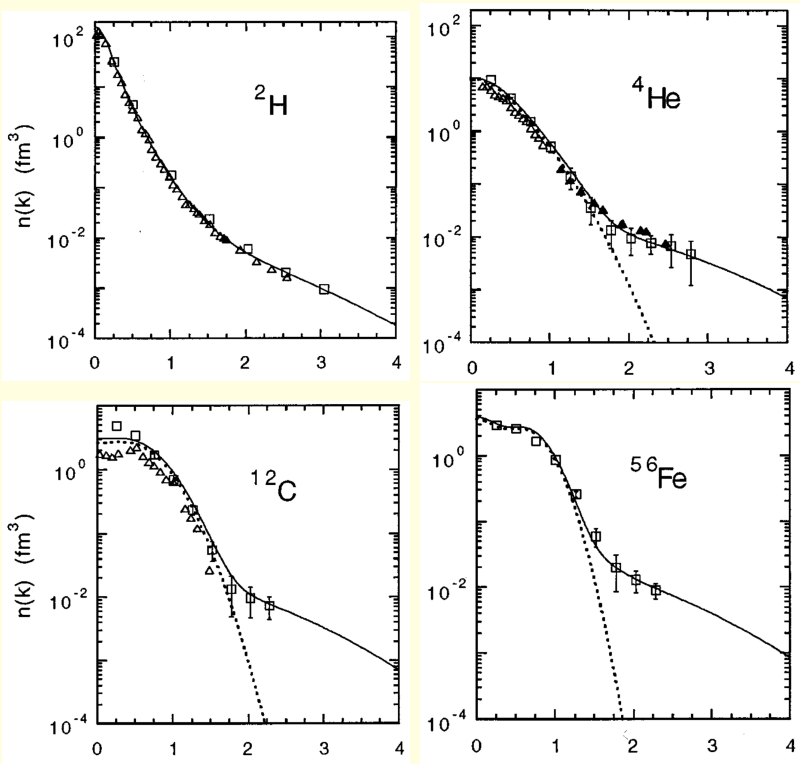
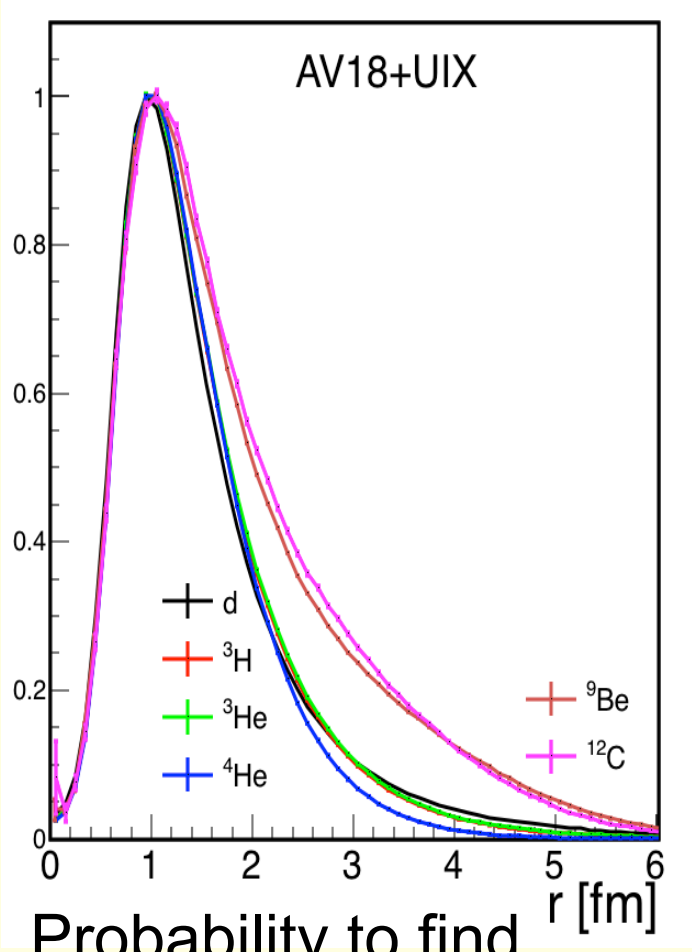


FIG. 4: The nucleon momentum distributions $n_0(k)$ (dashed line) and $n(k)$ (solid line) plotted versus momentum in fm^{-1} for the deuteron, ^{4}He, ^{12}C and ^{56}Fe. Figure adapted from (Ciofi degli Atti and Simula,

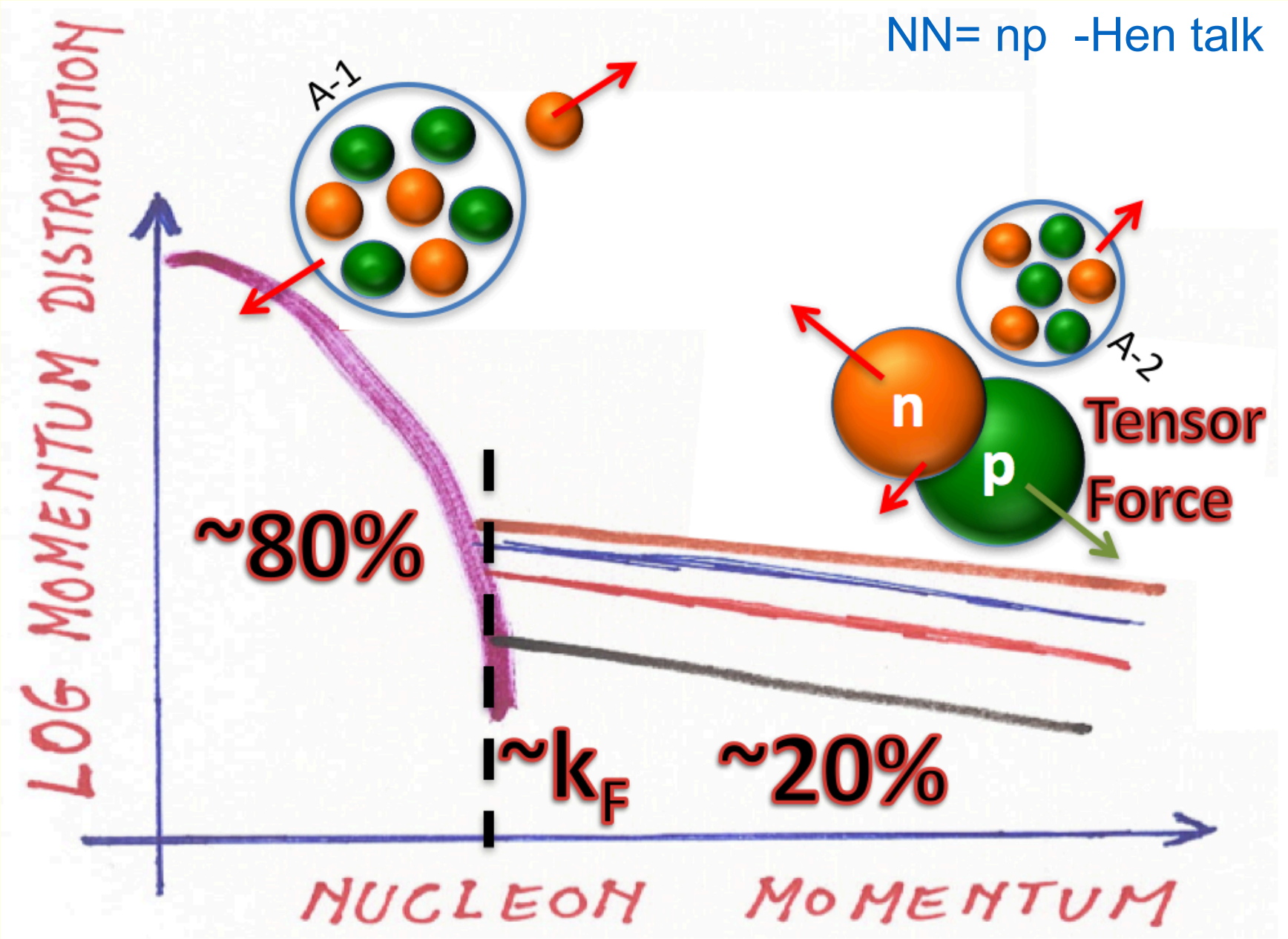
Chen et al '16



Probability to find nucleons separated by r

Summary of Correlations

J Ryckebusch pic



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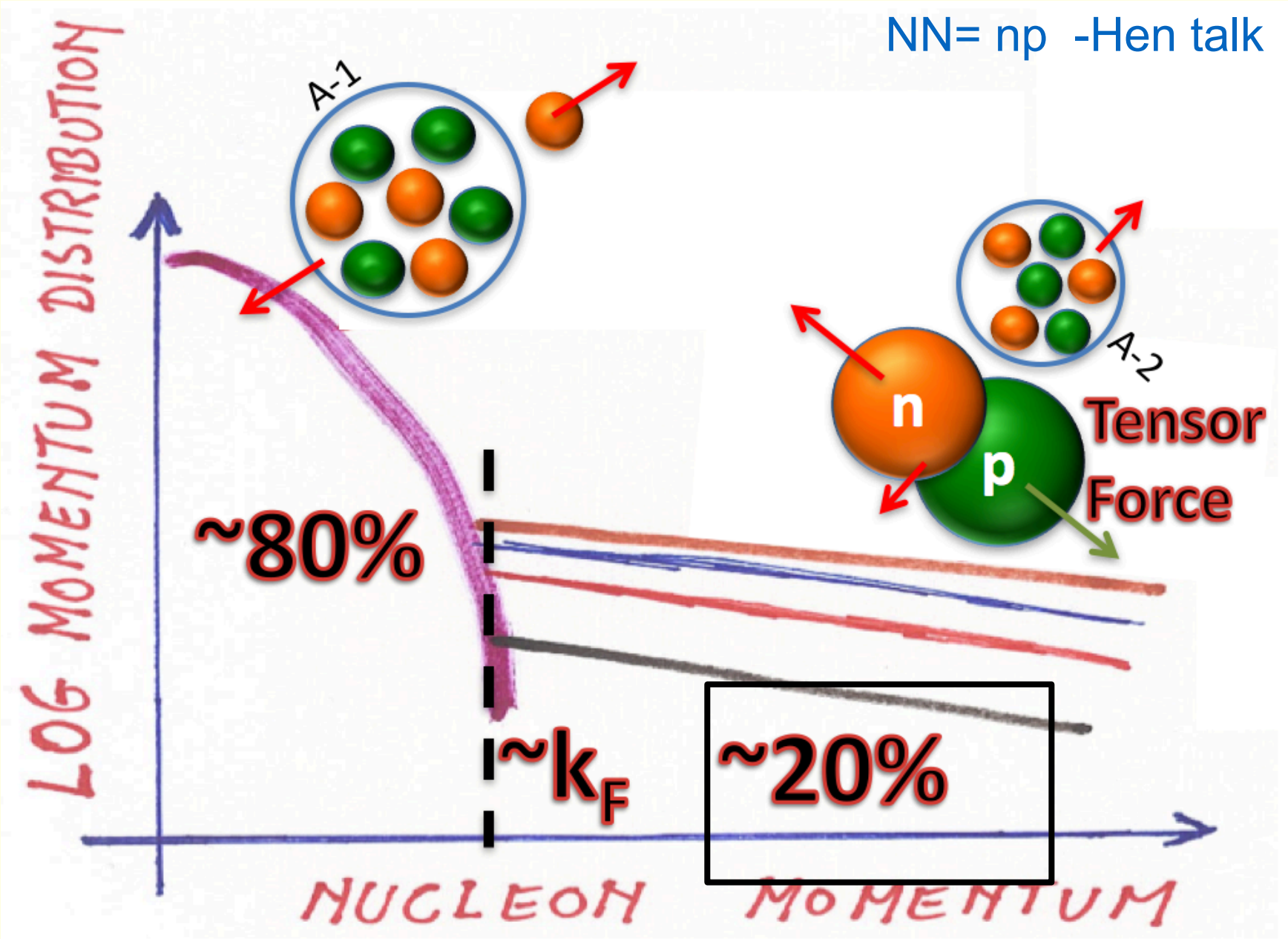
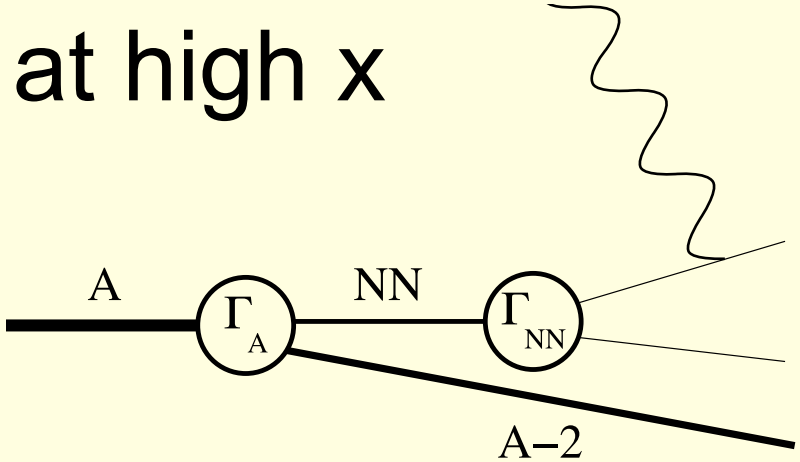


(e,e') at high x

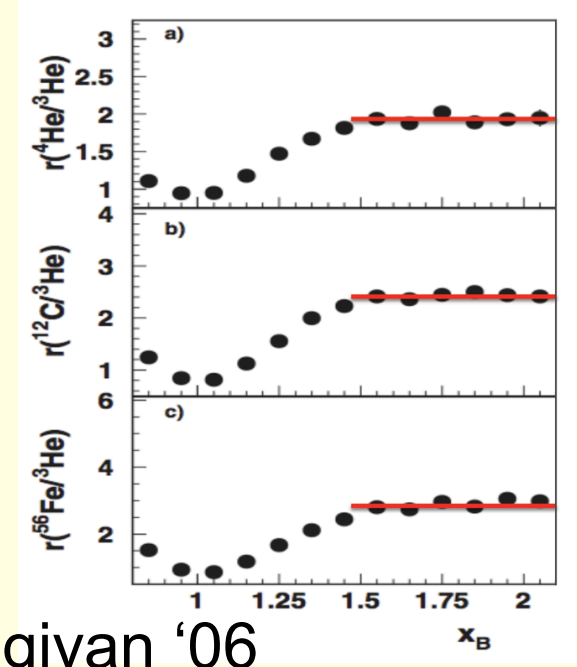


NN= np -Hen talk

$1 < x < 2$ leading term:

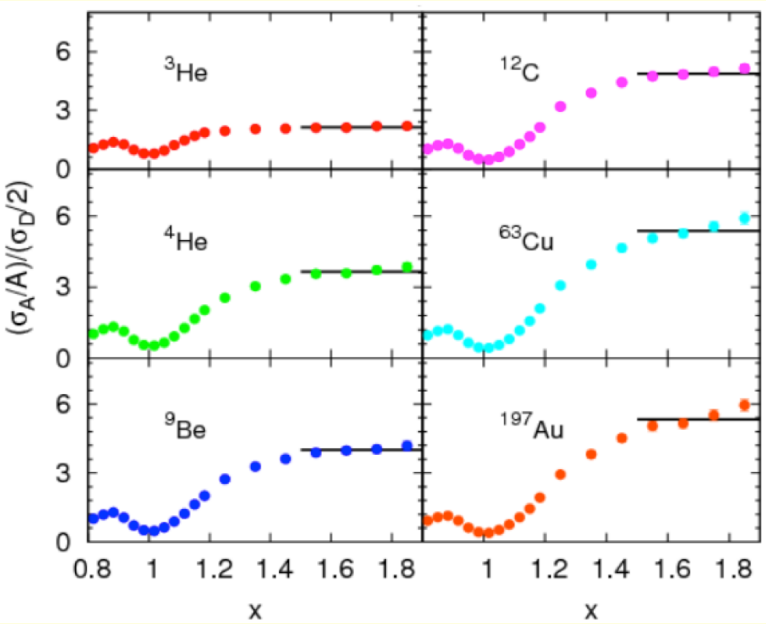
np dominance -Hen talk

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



a_2

Egiyan '06

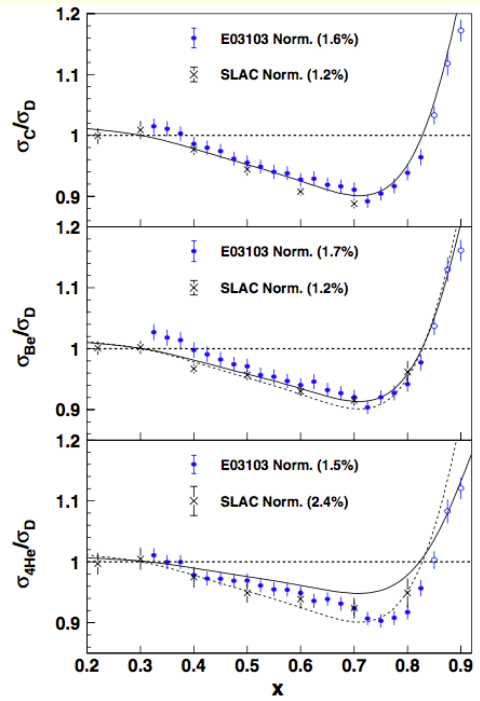


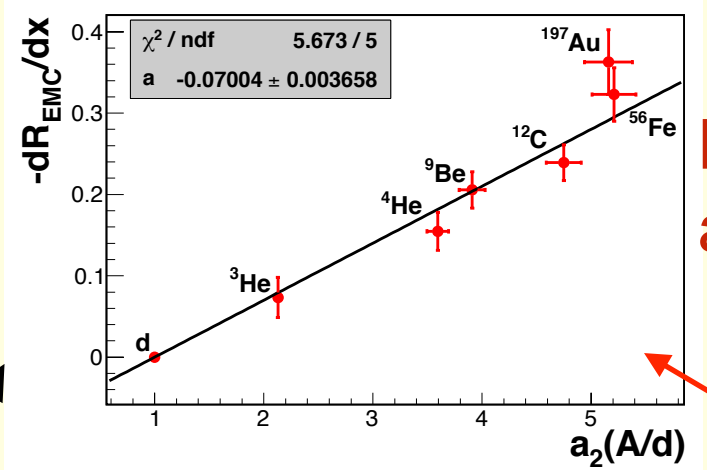
a_2

Fomin et al '11

DIS

Hen et al 2013

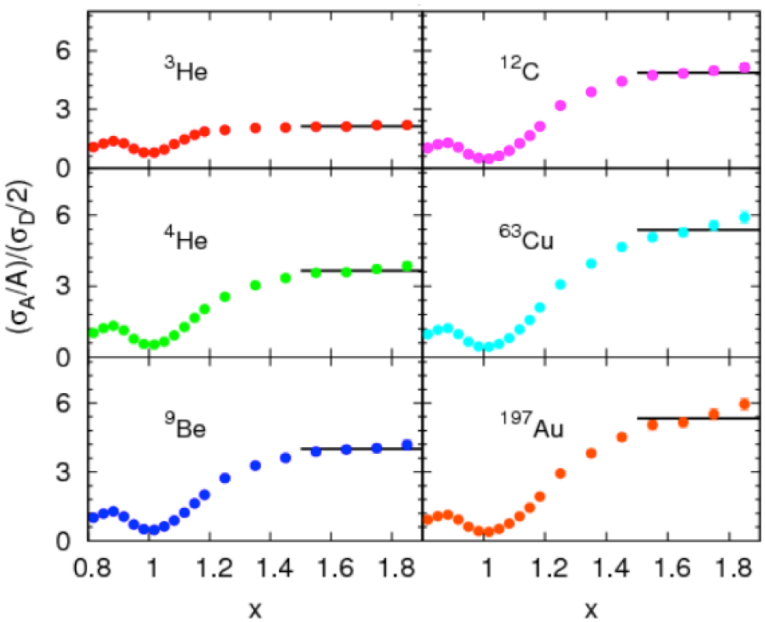




Linear relation accident?

Seely et al 2009

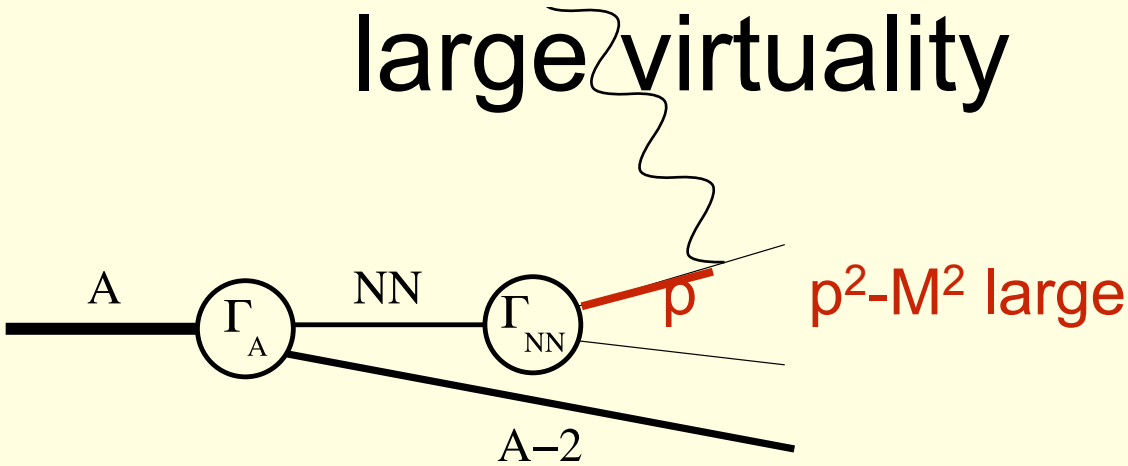
get slope



Fomin et al 2012

a_2

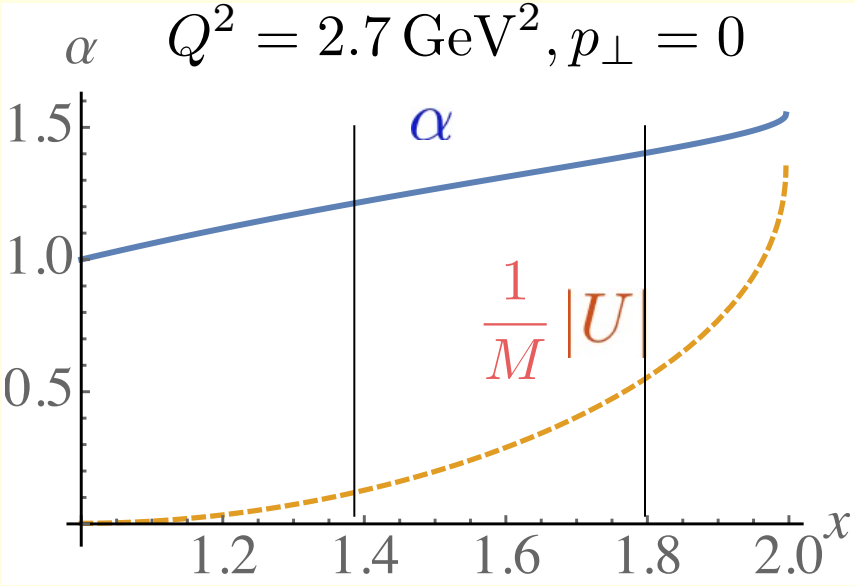
Common cause of dR/dx and $a_2(A)$: large virtuality



p^2-M^2 large

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 $a_2(A)$

Logic/Summary

Data	DIS-large x	(e,e') Plateau large x	(e,e',NN)
Interpret:	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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Implications for nuclear physics

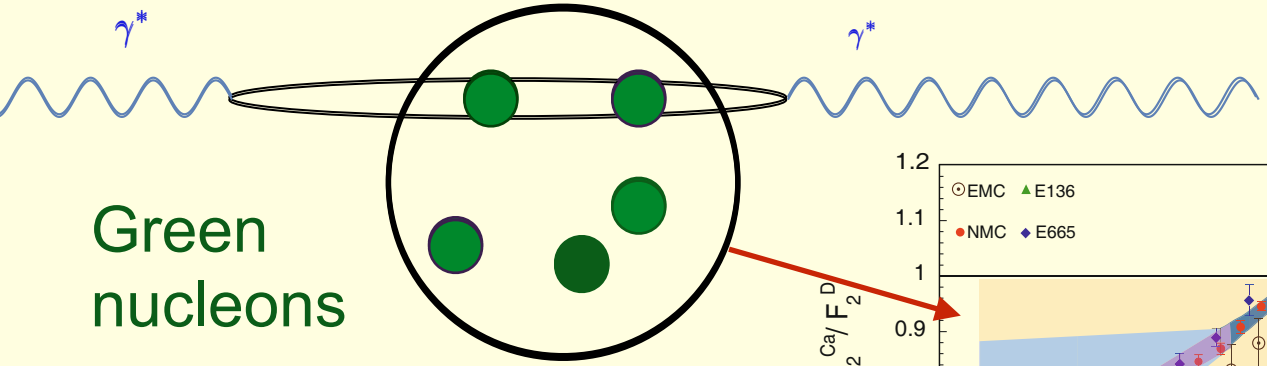
- Nucleus modifies nucleon electroweak form factors
- Nucleon excited states exist in nuclei
- Medium modifications in deuteron influence extracted neutron F_2
- spectator tagging Cosyn talk

Implication 1 for EIC?

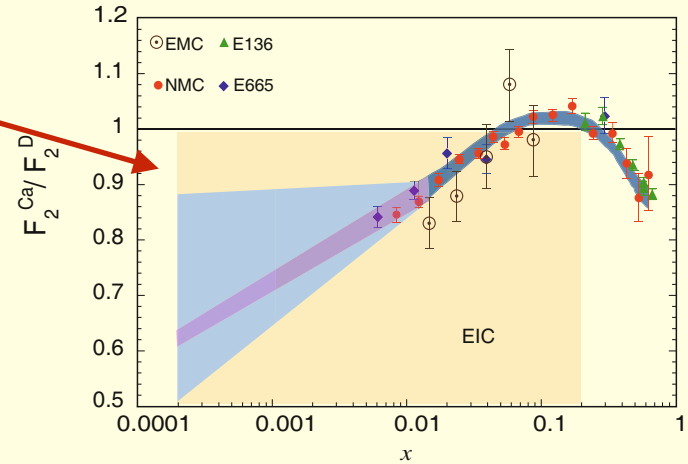
Why are EMC ratios independent of Q^2?

- 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

Shadowing & Anti-shadowing



Green nucleons

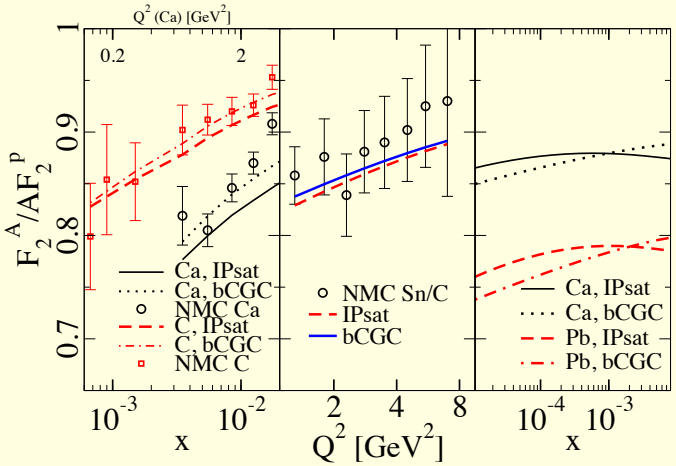


Frankfurt Strikman and Guzey

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

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

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

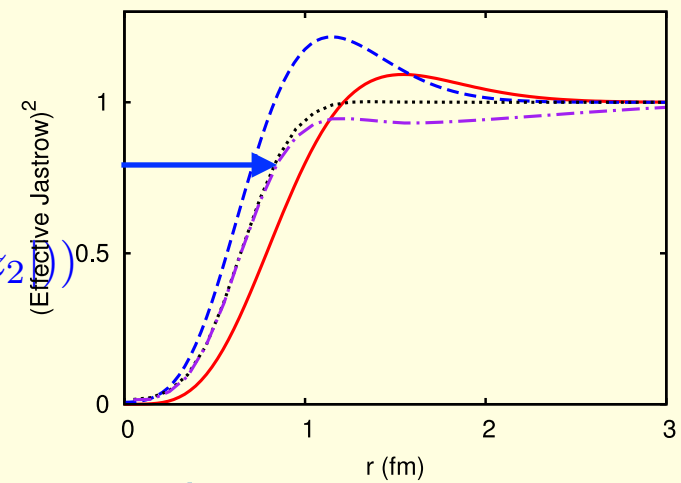
But $\sim 20\%$ of nucleons are in a correlated pair

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

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

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

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