Virtuality Based Models of the EMC Effect

Gerald A. Miller University of Washington

Strikman & Frankfurt several papers

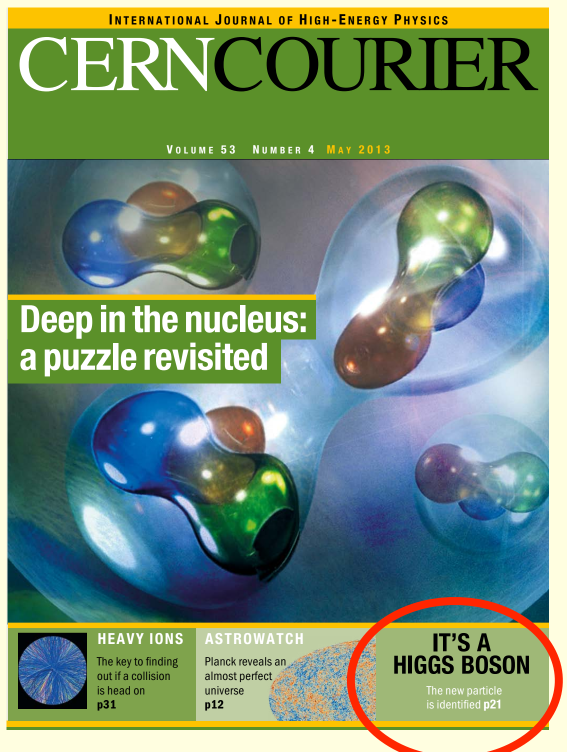
RMP with Or Hen, Eli Piasetzky, Larry Weinstein

RMP 89 (2017) 045002

G A Miller PRC 102, 055206 ; 2008.06524

G A Miller New stuff

Will focus on 0.3 <x<0.7 Remarkable experimental progress



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

Ordinary nuclear physics does not explain EMC Effect

Drell-Yan on nuclei constrains models

1/10

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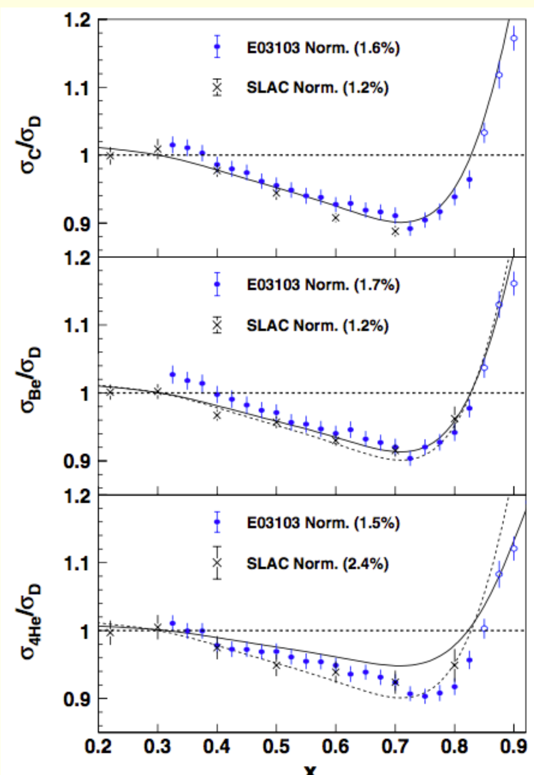

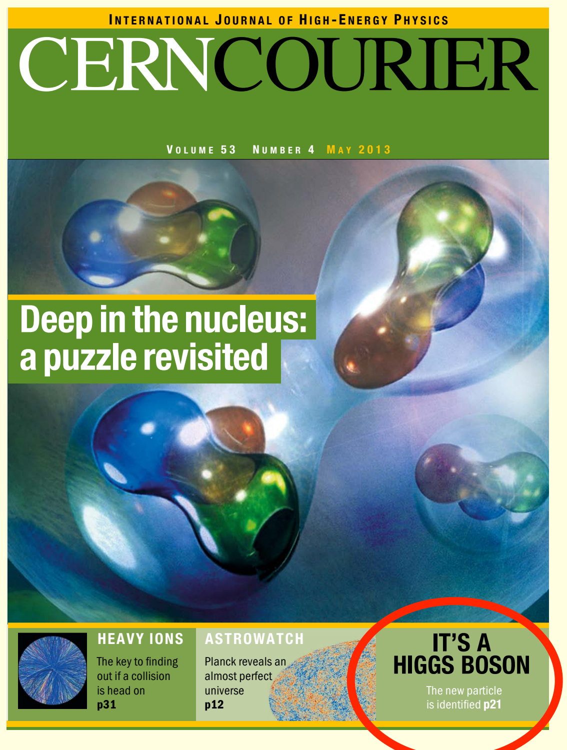

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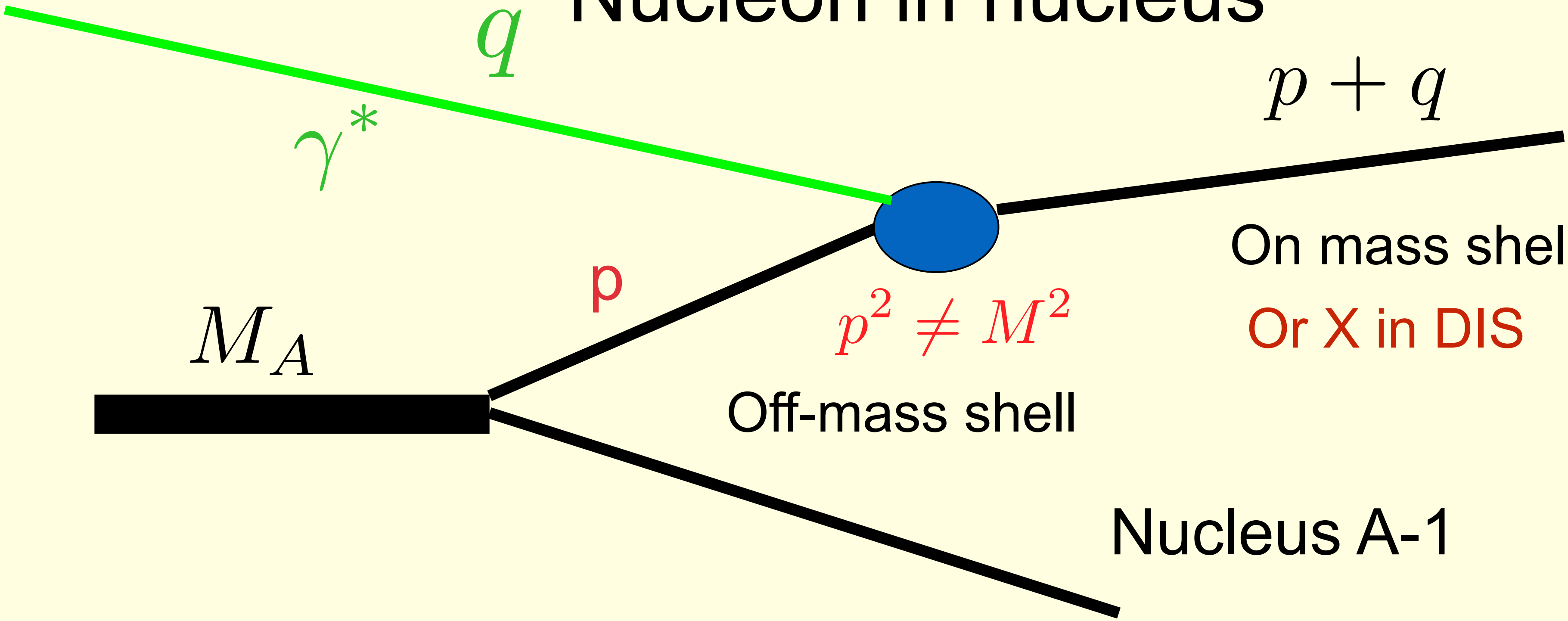
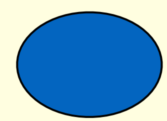
Nucleon in nucleus

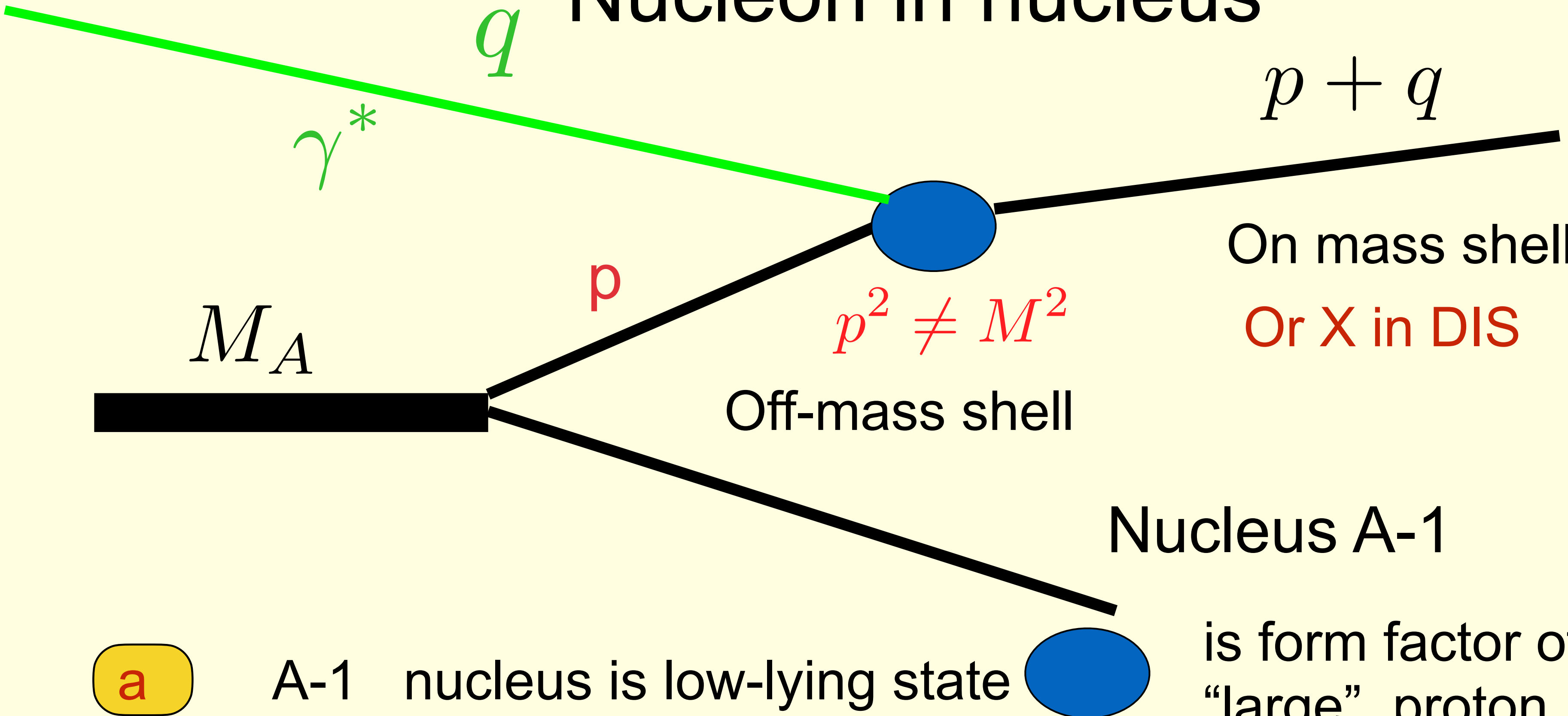


a A-1 nucleus is low-lying state  is form factor of “large” proton

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

In either case $$p^2 - M^2 \neq 0$$

Nucleon in nucleus



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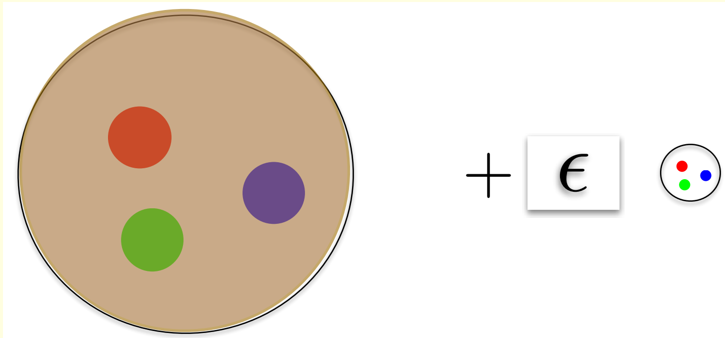
Virtuality is the EMC effect

- No virtuality = no EMC effect
- Average virtuality is small, average binding energy =8 MeV per nucleon,
- EMC effect is in the fluctuations
- Virtuality connects (e,e’) high x to DIS

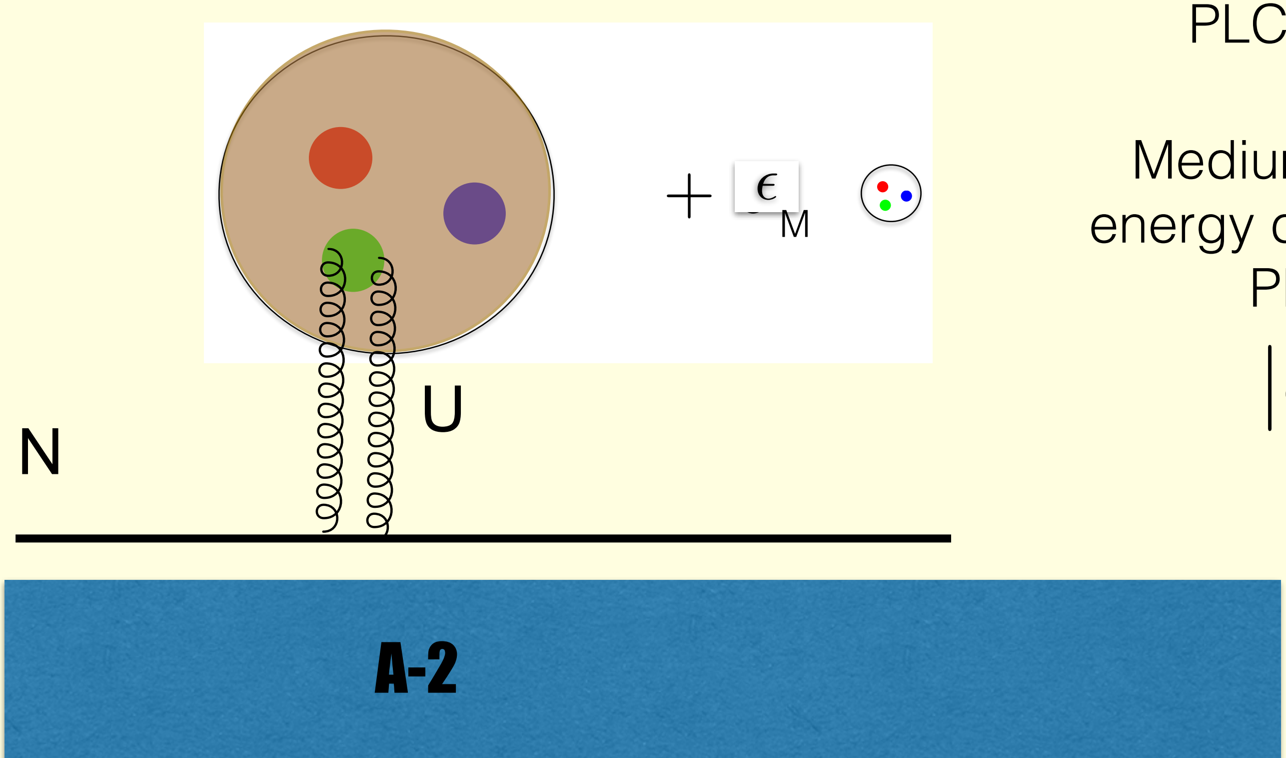
Suppression of Point Like Configurations

Frankfurt Strikman 1985

Free nucleon



Bound nucleon



Schematic two-component nucleon model

Blob-like config:BLC

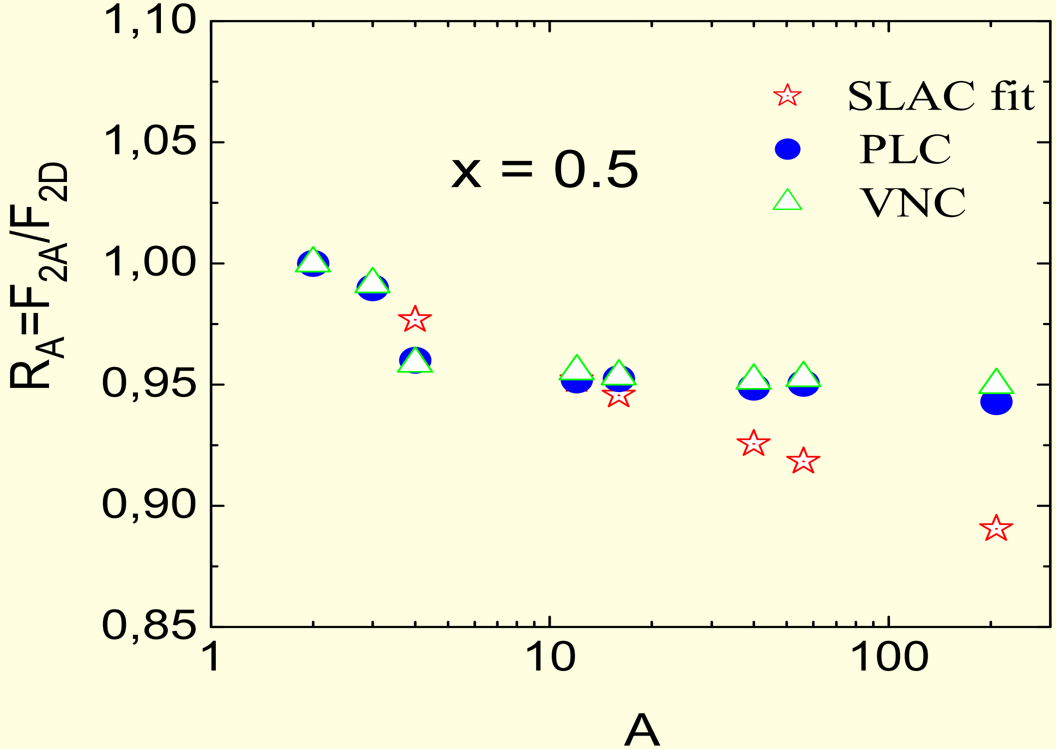
Point-like config: PLC

PLC smaller, fewer quarks high x

Medium interacts with BLC energy denominator increases PLC Suppressed

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

Dependence of the wave function of a bound nucleon on its momentum and the EMC effect
C. Ciofi degli Atti, L. L. Frankfurt, L. P. Kaptari, and M. I. Strikman
Phys. Rev. C 76, 055206



Questions -is there a BLC, PLC, what is x-dependence of BLC, PLC, how do neutrons and protons differ?

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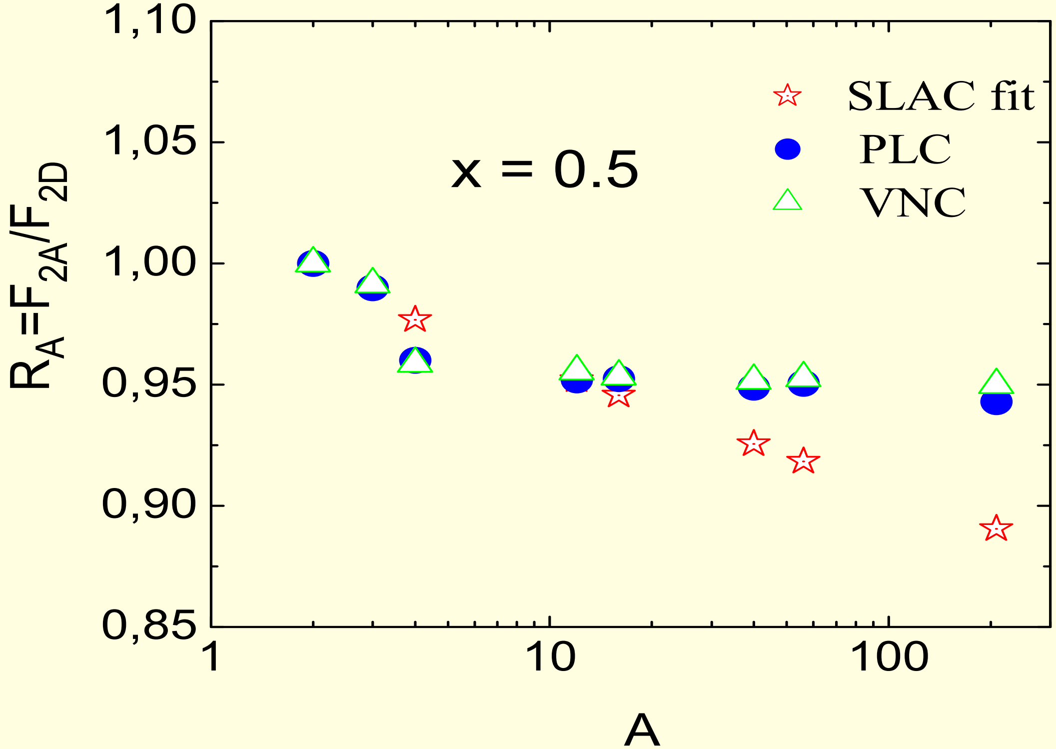


Questions -is there a BLC, PLC, what is x-dependence of BLC, PLC, how do neutrons and protons differ?

Remainder of talk: towards quantitative treatment

Flavor-Independent, Two-State BLC (Blob-like configuration)-PLC Point-like configuration Model

$$\text{Free nucleon}: H_0 = \begin{bmatrix} E_B & V \\ V & E_P \end{bmatrix}, \; B = \text{BLC}, \; P = \text{PLC}, \; E_P > E_B$$

$$\text{Eigenstates}: \; |\text{N}\rangle = \frac{1}{\sqrt{1+\epsilon^2}}(|\text{B}\rangle + \epsilon|\text{P}\rangle), \quad |\text{X}\rangle = \frac{1}{\sqrt{1+\epsilon^2}}(-\epsilon|\text{B}\rangle + |\text{P}\rangle).$$

$$\epsilon = -\tfrac{2V}{\Delta}\tfrac{1}{1+\sqrt{1+\frac{4V^2}{\Delta^2}}}, \; \Delta = E_P - E_B > 0$$

Deep inelastic scattering operator $= \mathcal{O}_{\text{DIS}}$, acts only 1 quark:

$$q(x) = \frac{1}{1+\epsilon^2}\left(\langle B|\mathcal{O}_{\text{DIS}}|B\rangle + \epsilon^2\langle P|\mathcal{O}_{\text{DIS}}|P\rangle\right), \quad \langle P|\mathcal{O}_{\text{DIS}}|P\rangle \equiv f(x)\langle B|\mathcal{O}_{\text{DIS}}|B\rangle,$$

$$q(x) = \frac{1}{1+\epsilon^2}\langle B|\mathcal{O}_{\text{DIS}}|B\rangle(1+\epsilon^2 f(x)).$$

Basic idea: ϵ reduced in nuclei

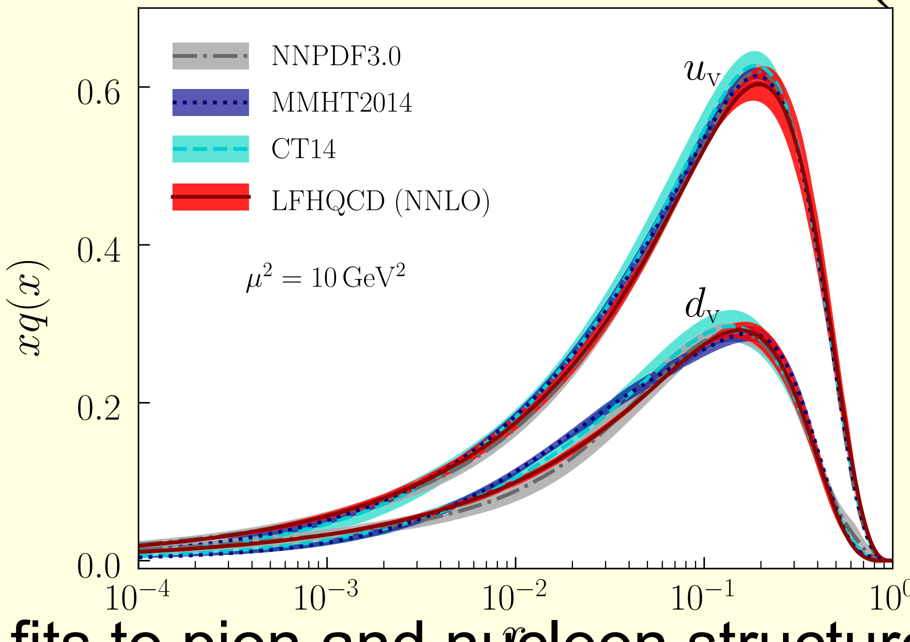
Universality of Generalized Parton Distributions in Light-Front Holographic QCD

Guy F. de Téramond, Tianbo Liu, Raza Sabbir Sufian, Hans Günter Dosch, Stanley J. Brodsky, and Alexandre Deur (HLFHS Collaboration)

Phys. Rev. Lett. **120**, 182001 – Published 4 May 2018

The structure of generalized parton distributions is determined from light-front holographic QCD up to a universal reparametrization function $w(x)$ which incorporates Regge behavior at small x and inclusive counting rules at $x \to 1$. A simple ansatz for $w(x)$ that fulfills these physics constraints with a single-parameter results in precise descriptions of both the nucleon and the pion quark distribution functions in comparison with global fits. The analytic structure of the amplitudes leads to a connection with the Veneziano model and hence to a nontrivial connection with Regge theory and the hadron spectrum.

$w(x)$ is not unique



Good fits to pion and nucleon structure functions
Based on 2-component models

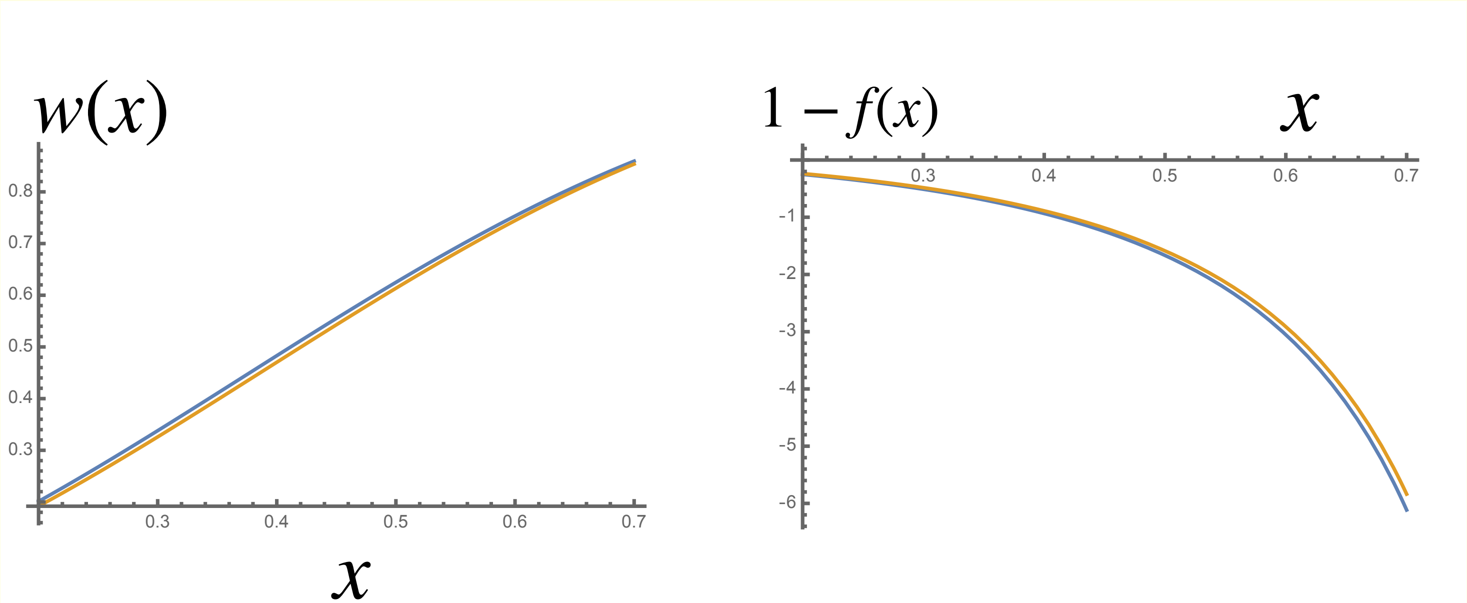
Holographic QCD inputs Free nucleon

q_3 = 3-quark system (PLC) P q_4 = BLC B, $F_3(Q^2) \sim \frac{1}{Q^4}$ $F_4(Q^2) \sim \frac{1}{Q^6}$

$$u(x) = \frac{3}{2}q_3(x) + \frac{1}{2}q_4(x),\ d(x) = q_4(x),$$

excellent reproduction of measured structure functions, elastic form factors obtained!

$$q_3(x)/q_4(x) = 1/(1 - w(x)) = f(x)$$



$$q_p(x) = 0.5q_4(x) + 0.5q_3(x), \quad q_n(x) = 0.75q_4(x) + 0.25q_3(x), \quad \epsilon_p^2 = 1,\ \epsilon_n^2 = 1/3,\ P_B^p = 0.5,\ P^n(B) = 0.25$$

Medium effects- flavor independent intro-Nucleon in Nucleus feels interaction U

$$H_1 = \begin{bmatrix} U & 0 \\ 0 & 0 \end{bmatrix},\ H = \begin{bmatrix} E_B - |U| & V \\ V & E_P \end{bmatrix},$$

Only BLC feels interaction. Energy denominator increased, PLC probability goes down
Medium-modified nucleon & excited state: $|N\rangle_M$ and $|X\rangle_M$, $\Delta \to \Delta + |U|$

$$|N\rangle_M = \frac{1}{\sqrt{1+\epsilon_M^2}}(|B\rangle + \epsilon_M |P\rangle),\ |X\rangle_M = \frac{1}{\sqrt{1+\epsilon_M^2}}(-\epsilon_M |B\rangle + |P\rangle)$$

$$q_M(x) = \frac{1}{1+\epsilon_M^2}\langle B|\mathcal{O}_{\rm DIS}|B\rangle(1+\epsilon_M^2 f(x)),\ \frac{q_M(x)}{q(x)} - 1 = -2|\epsilon|\frac{|U|}{\sqrt{\Delta^2+4V^2}}\frac{f(x)-1}{(1+\epsilon^2)^2}$$

Next: relate U & virtuality $= \mathcal{V}$. Use Schroedinger equation: $\mathcal{V} = \frac{-2|U|}{M}$ $\mathscr{V} \equiv (p^2 - M^2)/M^2$

$$q_M(x) = q(x) + \frac{\mathcal{V}M}{\sqrt{\Delta^2+4V^2}}\frac{|\epsilon|}{(1+\epsilon^2)^2}(f(x)-1)q(x),$$

- $\mathcal{V} < 0$ determined by kinematics
- $q_M(x) < q(x)$ if $f(x) > 1$ expected from idea that BLC important for high x
- x-dependence of modification independent of nuclear A
- 2 parameters Δ, V for neutron and 2 for proton

$$\boxed{q_{Mp}(x) = q_p(x) + 0.686\frac{\mathcal{V}_p}{\Delta_n}(f(x)-1)q_p(x),}$$

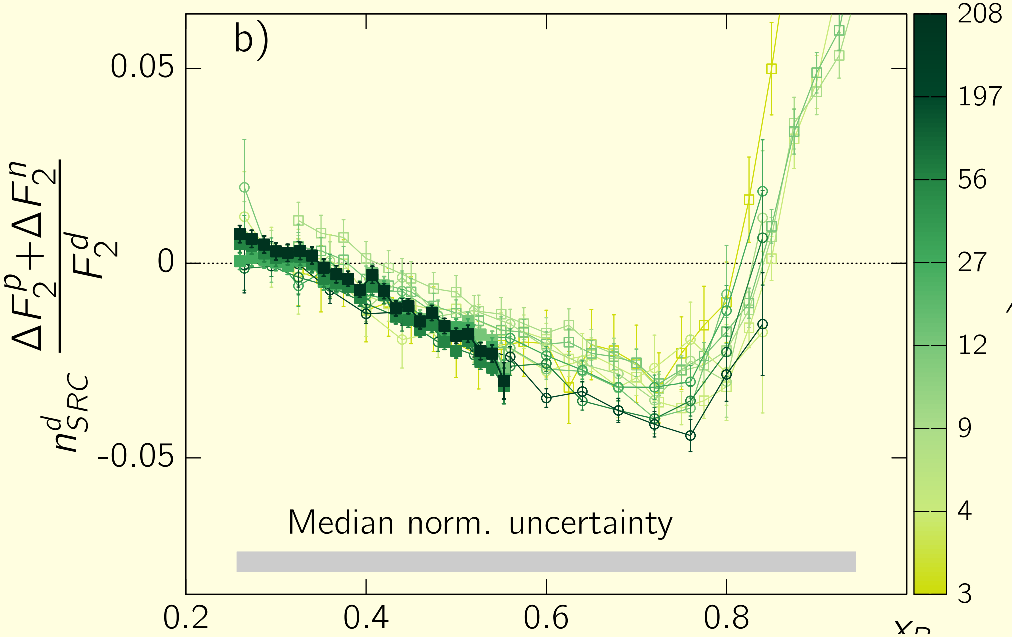
$$\boxed{q_{Mn}(x) = q_n(x) + 0.441\frac{\mathcal{V}_n}{\Delta_n}(f(x)-1)q_n(x),}$$

Neutron mass=proton mass

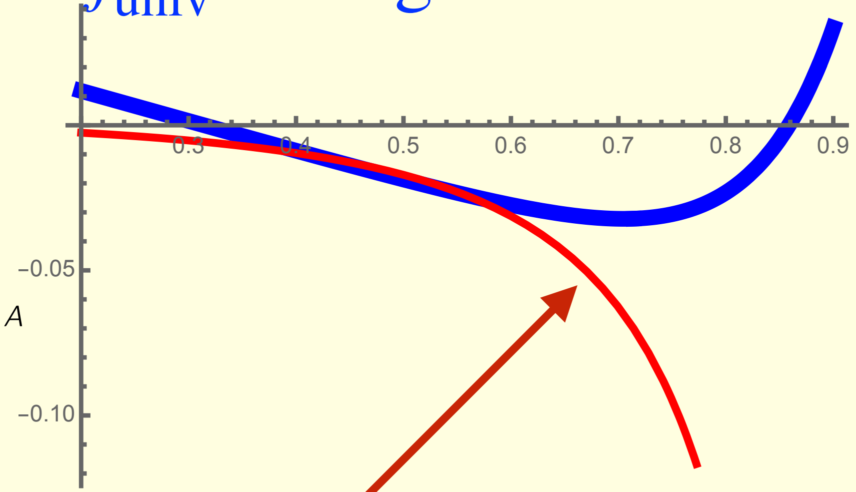
ϵ_p, ϵ_n : 1 parameter

B. Schmookler, M. Duer, A. Schmidt, O. Hen, S. Gilad, E. Piasetzky, M. Strikman, L.B. Weinstein et al.

2004.12065



$f_{\rm univ}$ E . Segarra



Current idea normalized

Does $\mathscr{V}_{\rm p} = \mathscr{V}_{\rm n}$? If so np dominance exists

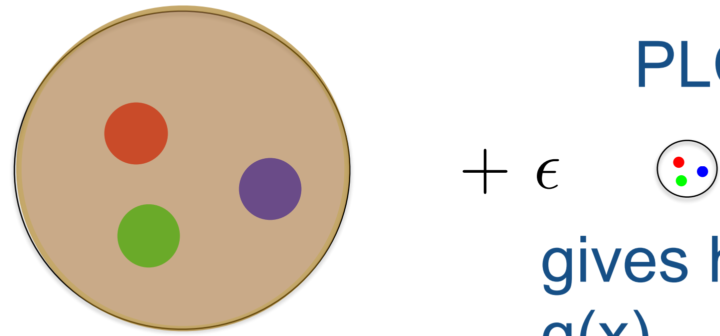
Spares follow

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

Cioffi degli Atti '07

A	$U = \langle v(\mathbf{p}, E)\rangle/2M$
^{3}H	-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

e

large values from two nucleon correlations Simula

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

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

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

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

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

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

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

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

EFT: Chen 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

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

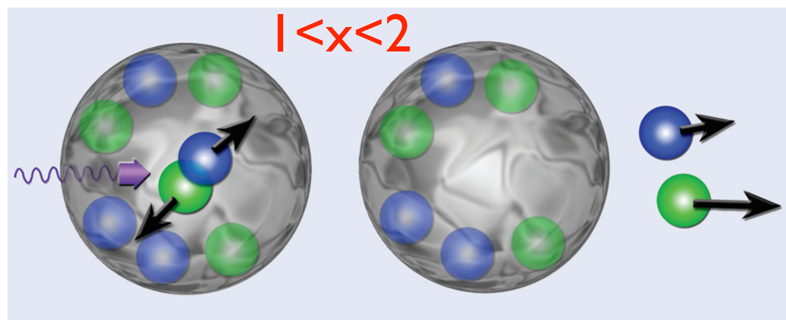
$$x = \frac{Q^2}{2M\nu}$$

x goes from 1 to A

x=1 is **exact** kinematic limit **for all 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

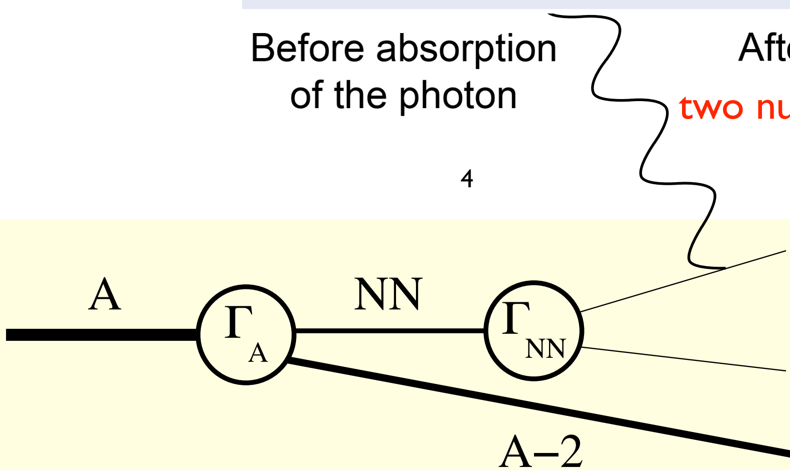
Two nucleons cluster



Before absorption of the photon

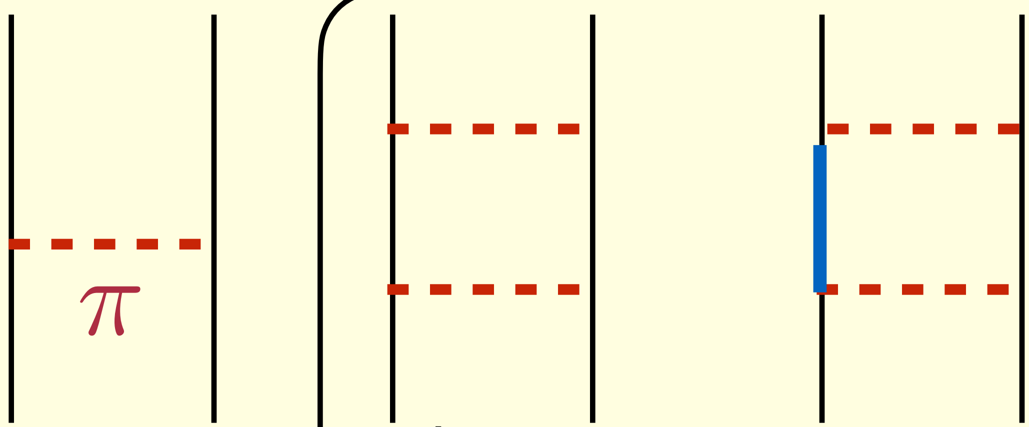
After absorption
two nucleons of SRC are fast

4



How/why nucleons in nuclei cluster

one pion exchange between n and p



huge
from
S. eq.

$$(-3)^2 = 9$$

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

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

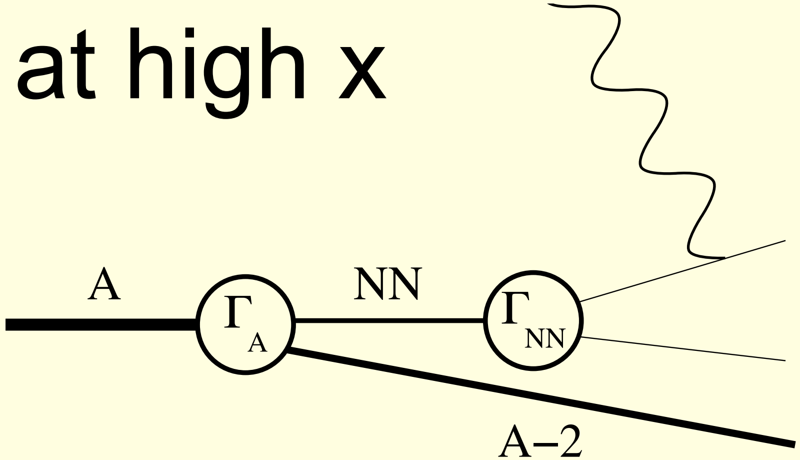
Supports high momentum transfer

Not effective range

Two nucleons are stuck/struck together

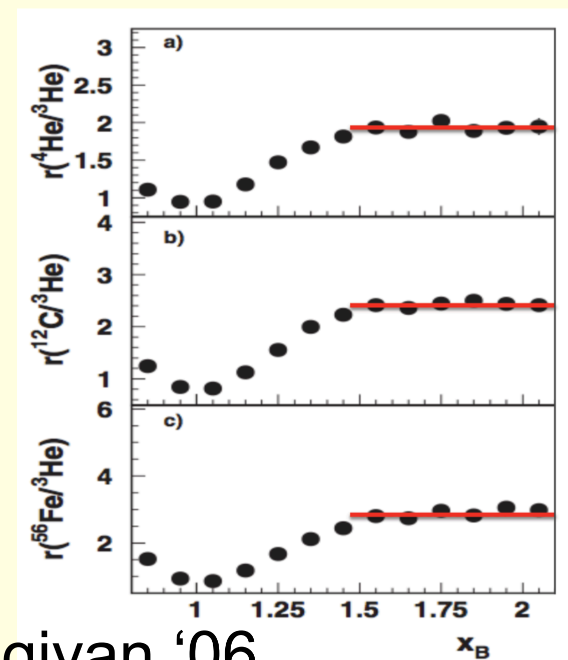
May explain why pionless EFT works so well
van Kolck

(e,e') at high x



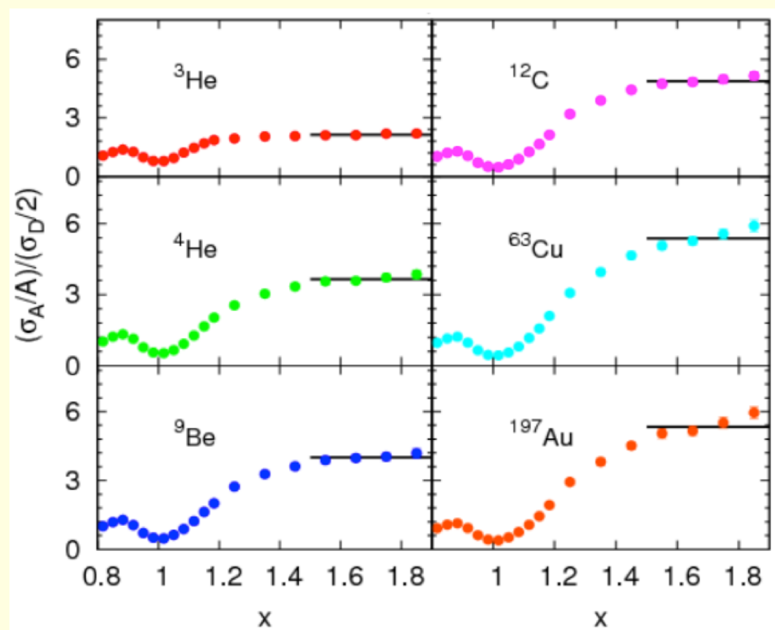
$1 < x < 2$ leading term:

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



Egiyan '06

a_2

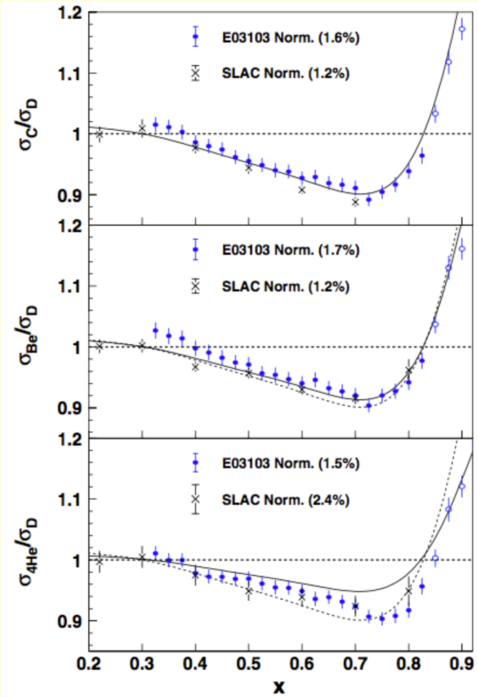


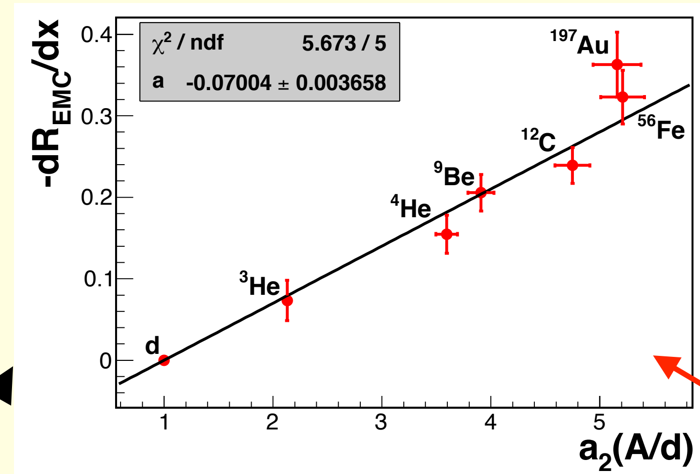
Fomin et al '11

a_2

DIS

Hen et al 2013

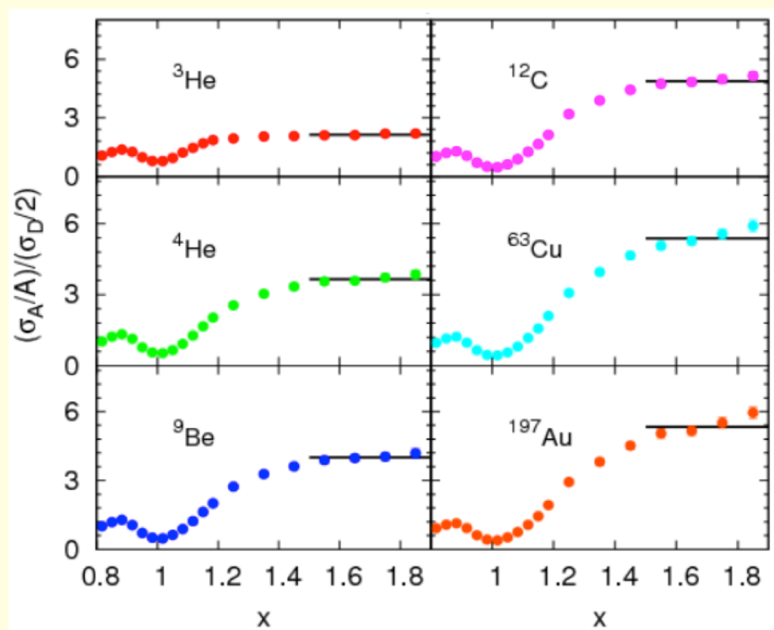




Linear relation accident?

Fomin et al 2012

a_2



Seely et al 2009

get slope

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

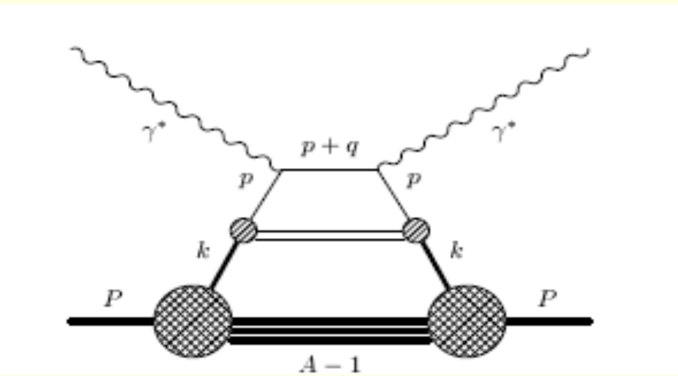
a bound nucleon is larger than free one- a mean field effect Cloet Thomas …..

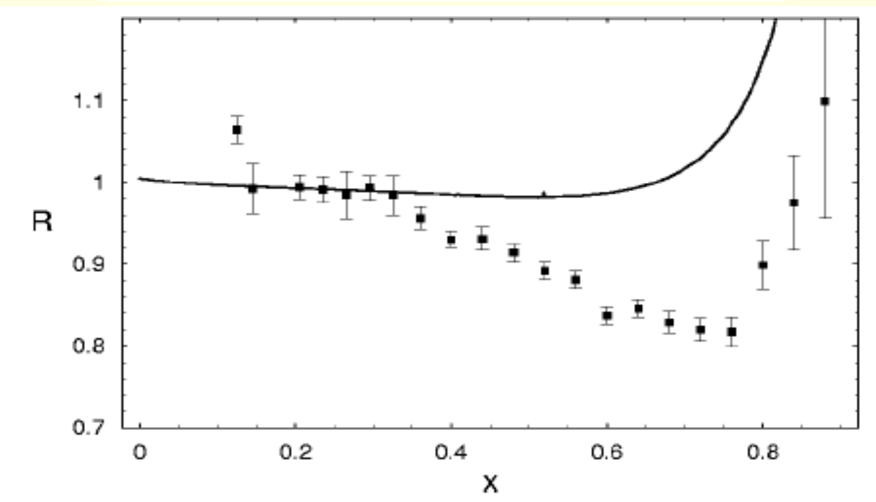
b multi-nucleon clusters - beyond the mean field

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

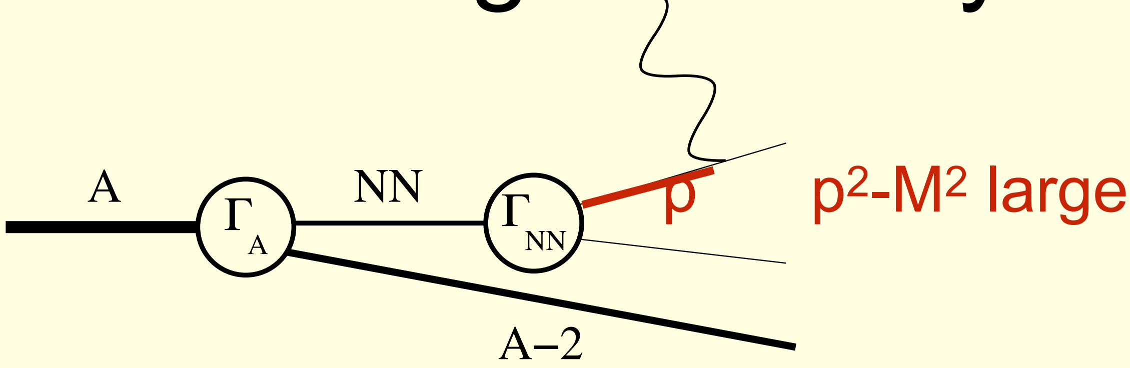
- **Hugenholz van Hove theorem nuclear stability implies (in rest frame) $P^+ = P^- = M_A$**
- **$P^+ = A(M_N - 8\text{ MeV})$**
- **average nucleon k^+**

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

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

Momentum sum rule-matrix element of energy momentum tensor

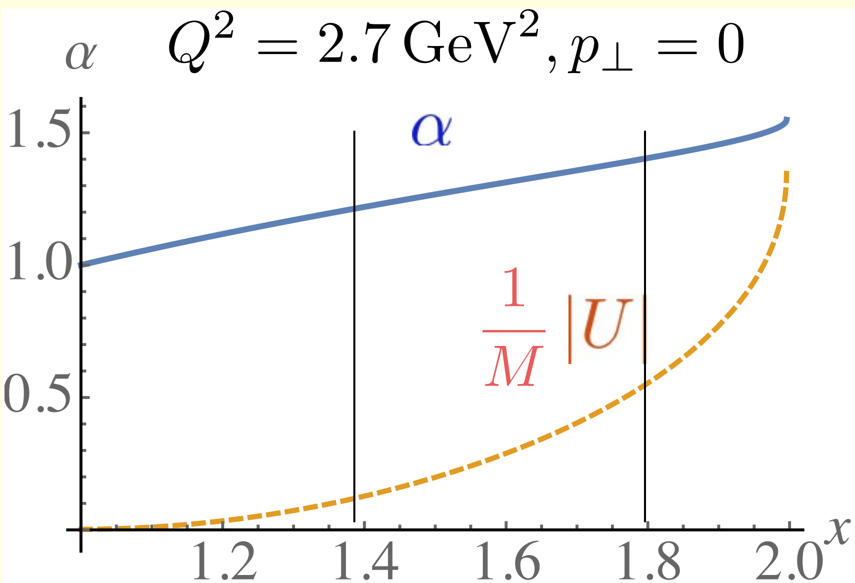
Common cause of dR/dx and $a_2(A)$: large virtuality



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

U=v/(2M)

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 largely 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:	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

Data

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decrease in A

2 baryon clusters

QCD

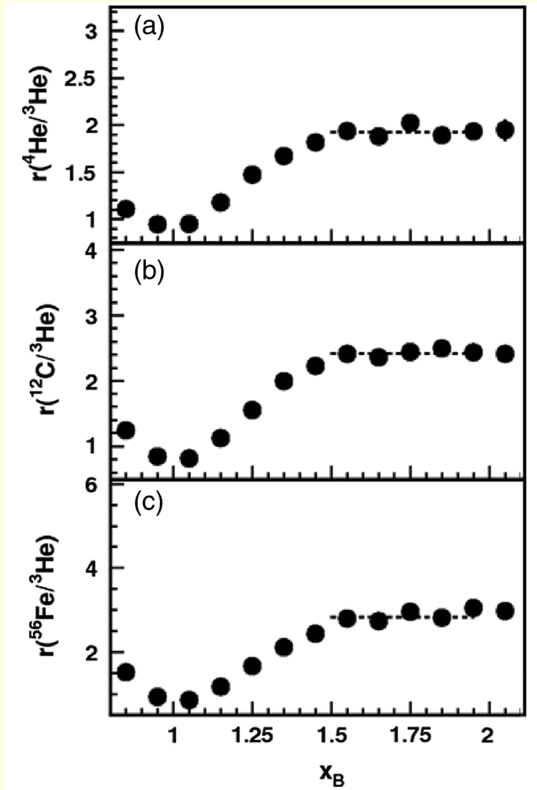
nucleon wf has
BLC,PLC etc
PLC -high x
PLC suppressed

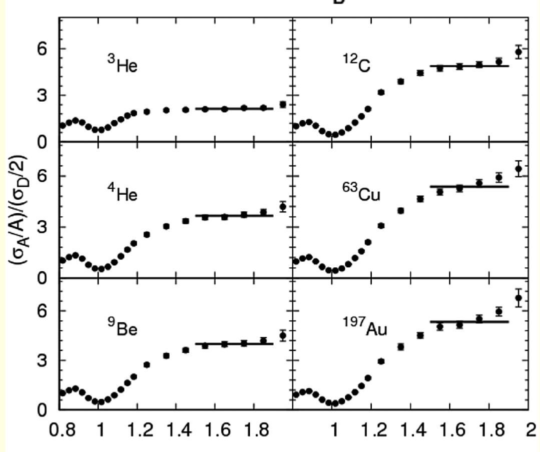
Large virtuality

Short-ranged
interactions

np
dominance

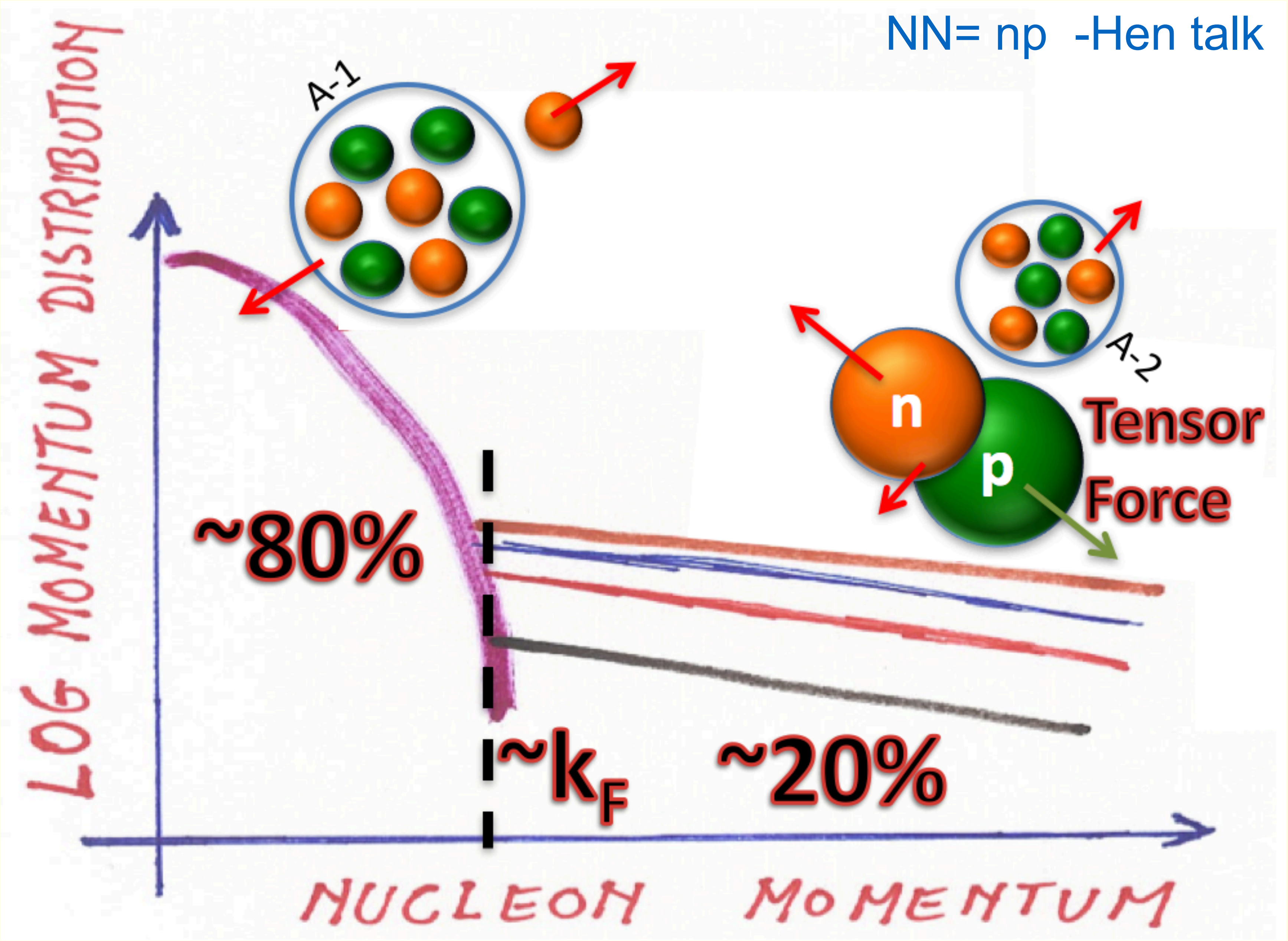
Three phenomena
related by common
ideas of correlations
related to high virtuality


(a)
(b)
(c)
r(4He/3He)
r(12C/3He)
r(56Fe/3He)
xB


3He
12C
4He
63Cu
9Be
197Au
(σA/A)/(σD/2)

Summary of Correlations

J Ryckebusch pic



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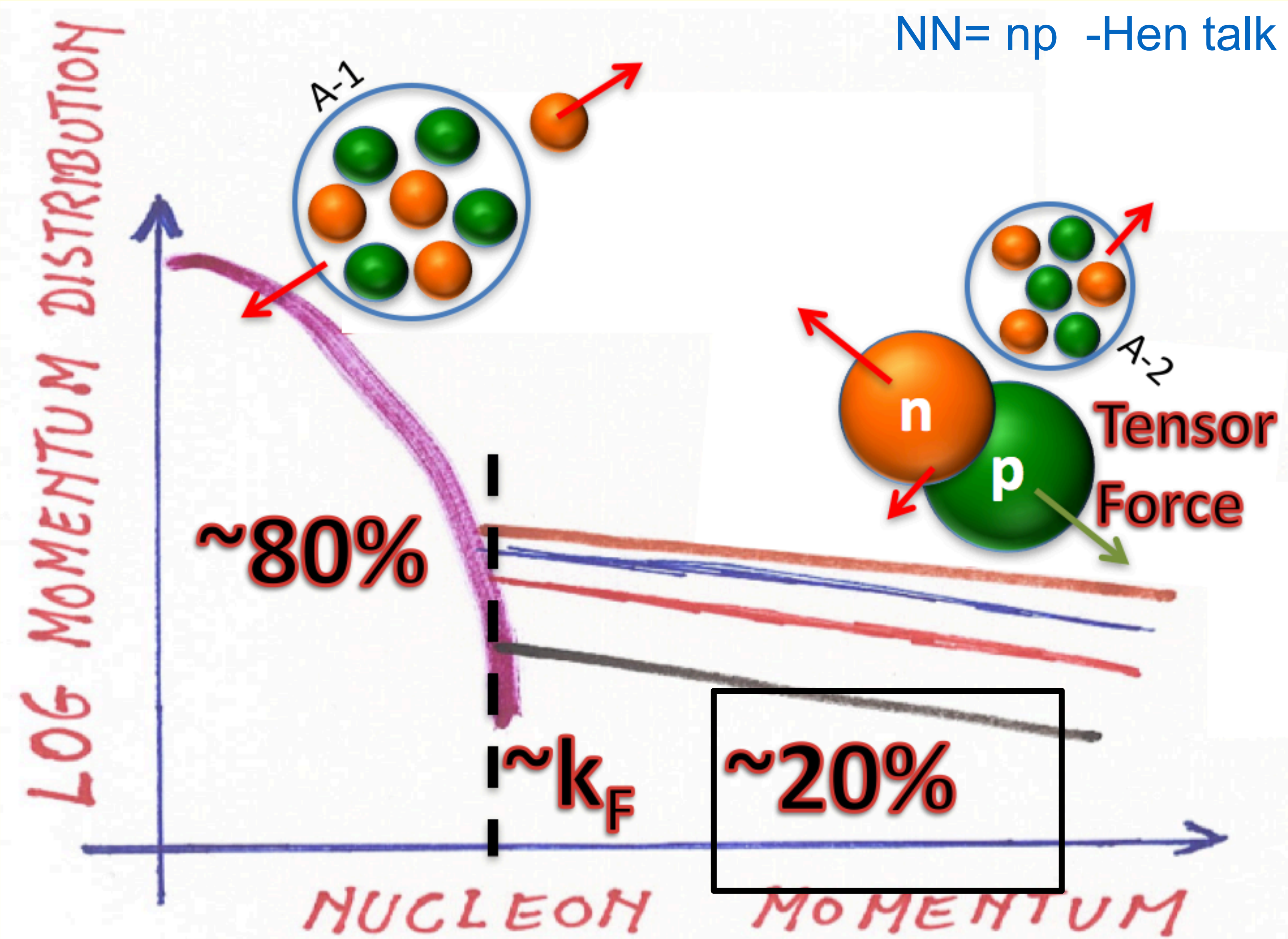


Two nucleon correlations

n(k)

Chen et al '16

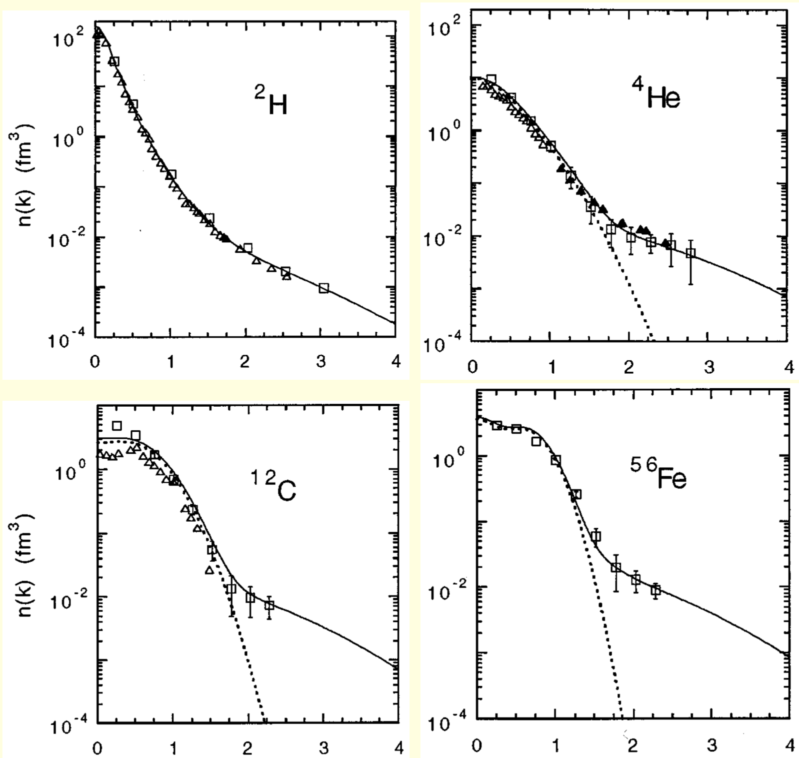
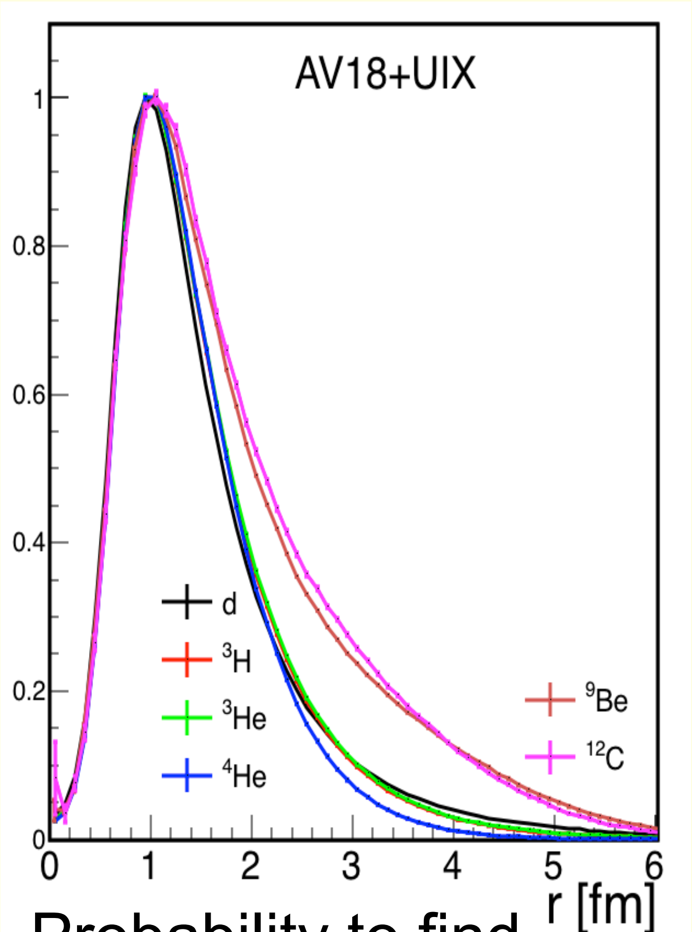


FIG. 4: The nucleon momentum distributions $n_0(k)$ (dashed line) and $n(k)$ (solid line) plotted versus momentum in fm^{-1} for the deuteron, ^{4}He, ^{12}C and ^{56}Fe. Figure adapted from (Ciofi degli Atti and Simula,

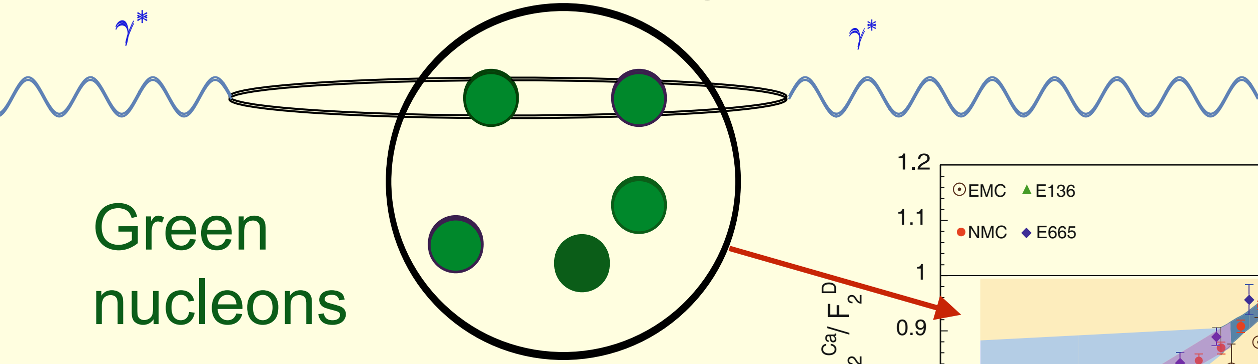


Probability to find nucleons separated by r

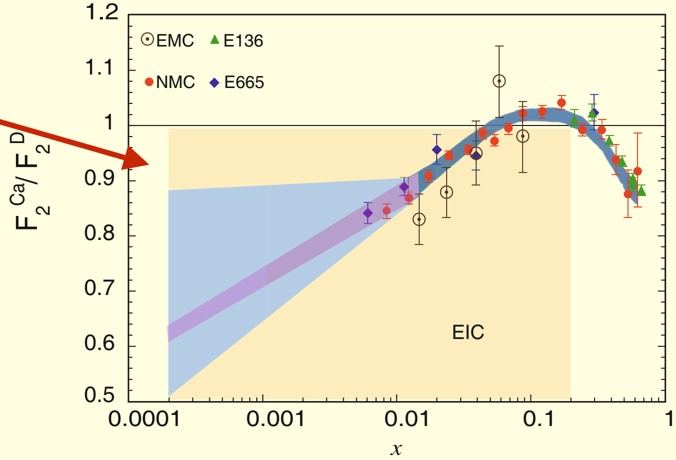
Final summary

- 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

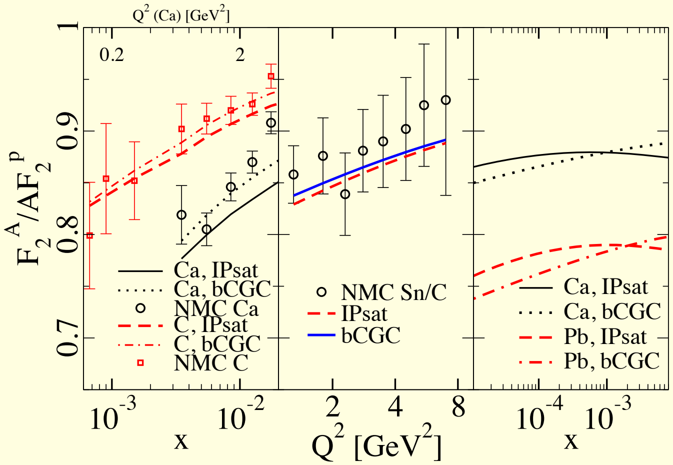


Frankfurt Strikman and Guzey

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

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

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

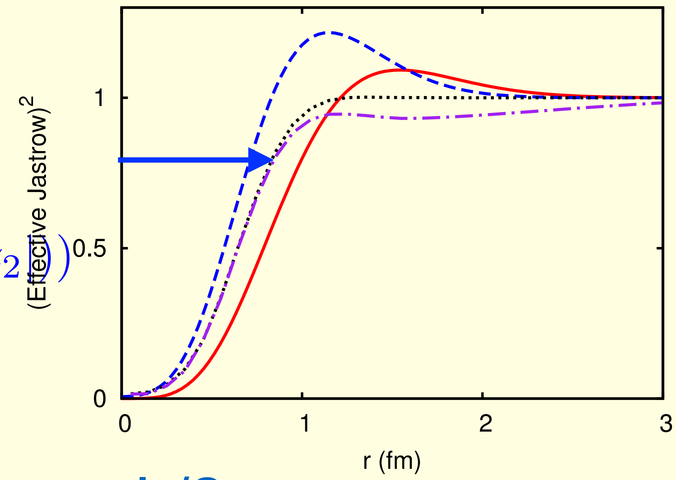
But $\sim$ 20% of nucleons are in a correlated pair

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

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

10-20% reduction depending on nucleus!

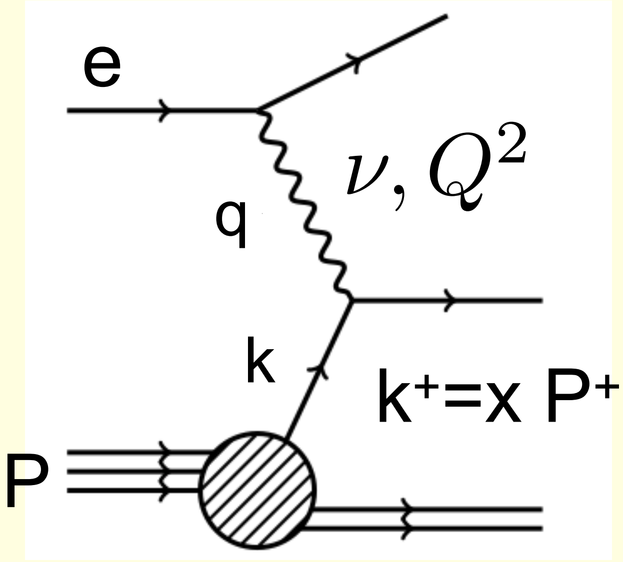
Engel, Carlson, Wiringa '11



$l_c/2$

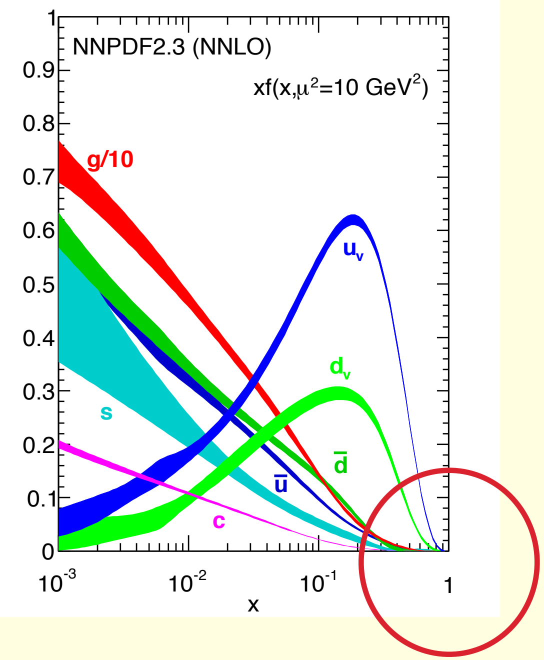
Shadowing effects are overestimated by significant amounts in all approaches that neglect effects of correlations

Deep Inelastic Scattering



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

Nucleon from PDG



The 1982 EMC effect involves deep inelastic scattering from nuclei

EMC= European Muon Collaboration

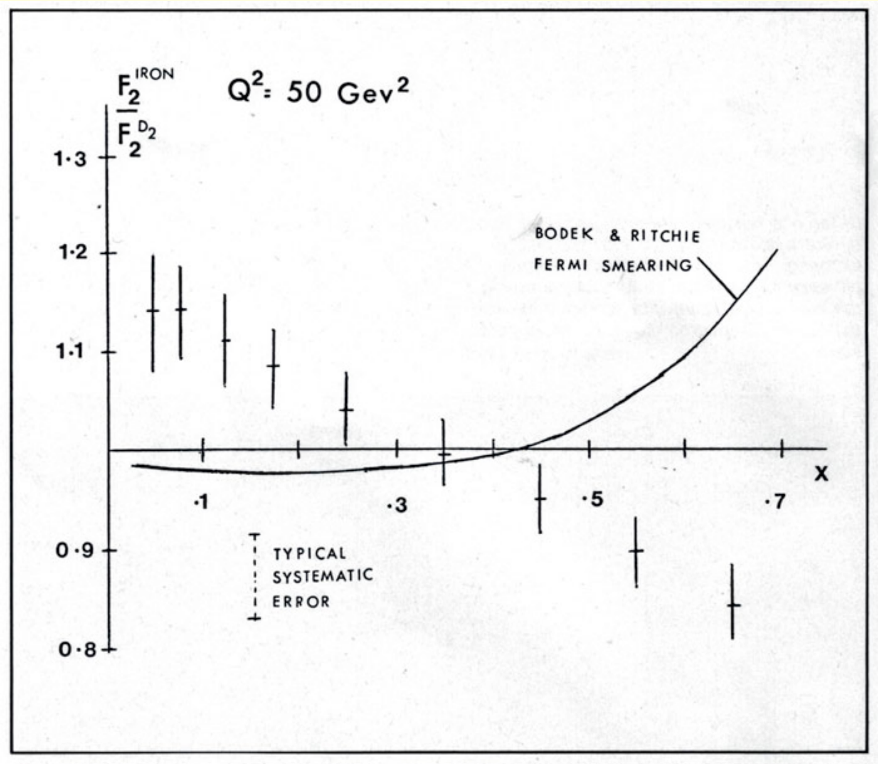
Implication 1 for EIC?

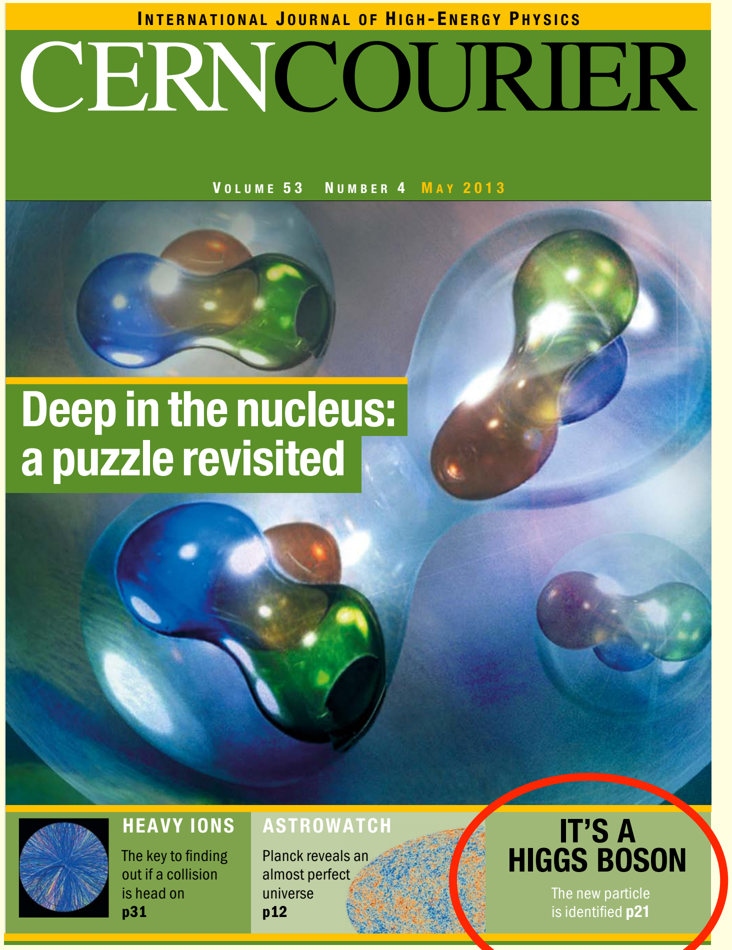
Why are EMC ratios independent of Q^2?

- 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

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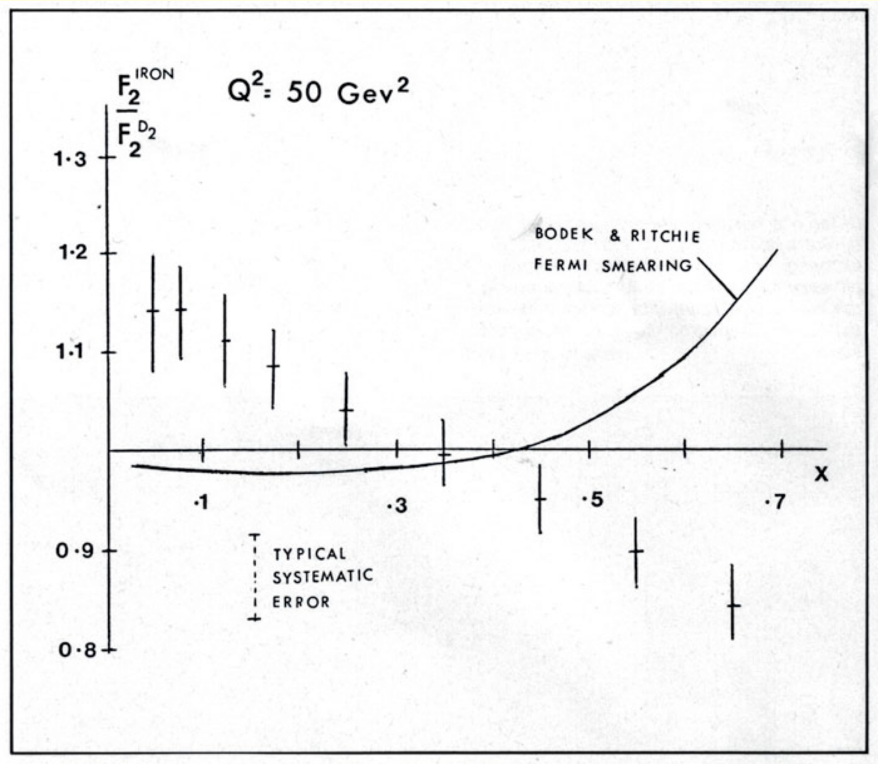
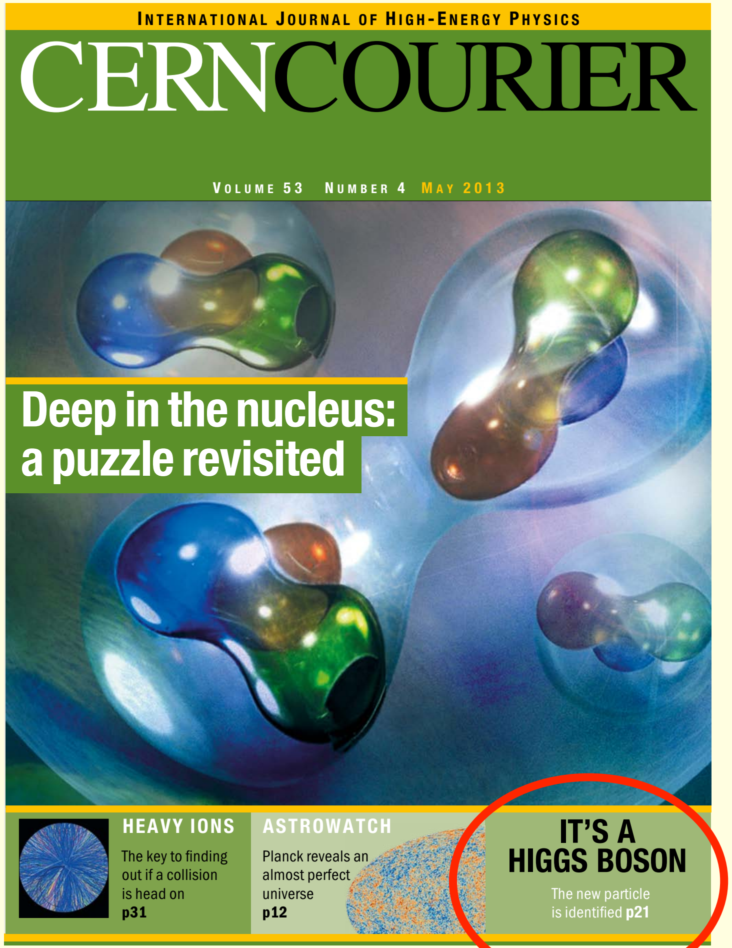
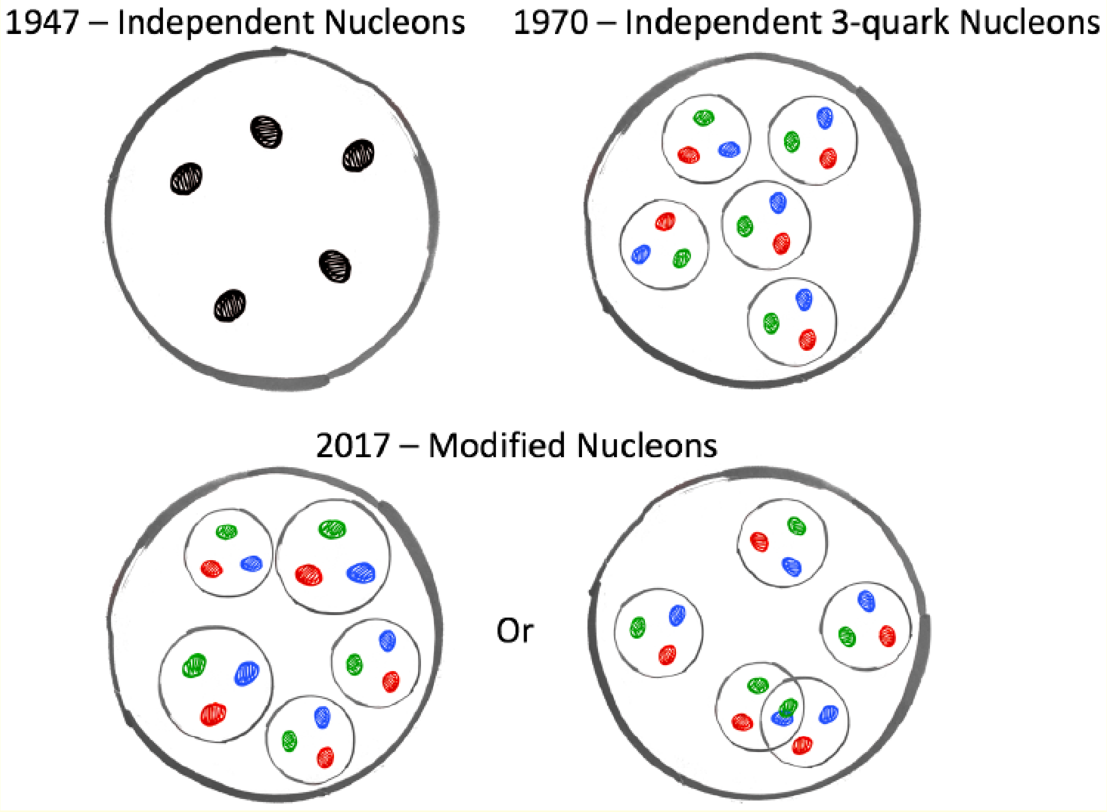




How does the nucleus emerge from QCD, a theory of quarks and gluons?

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

Progress in Quark Nuclear Physics



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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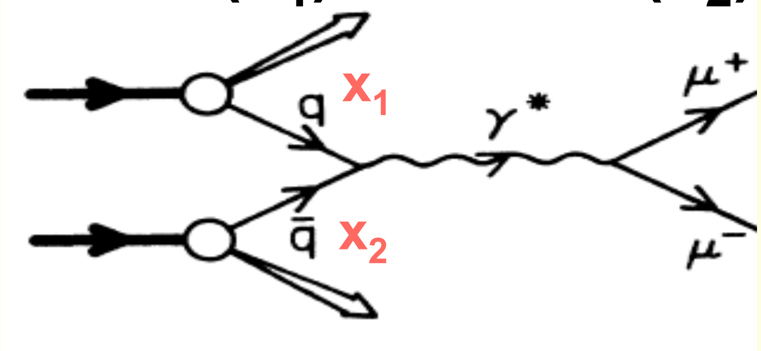
Nucleons and pions

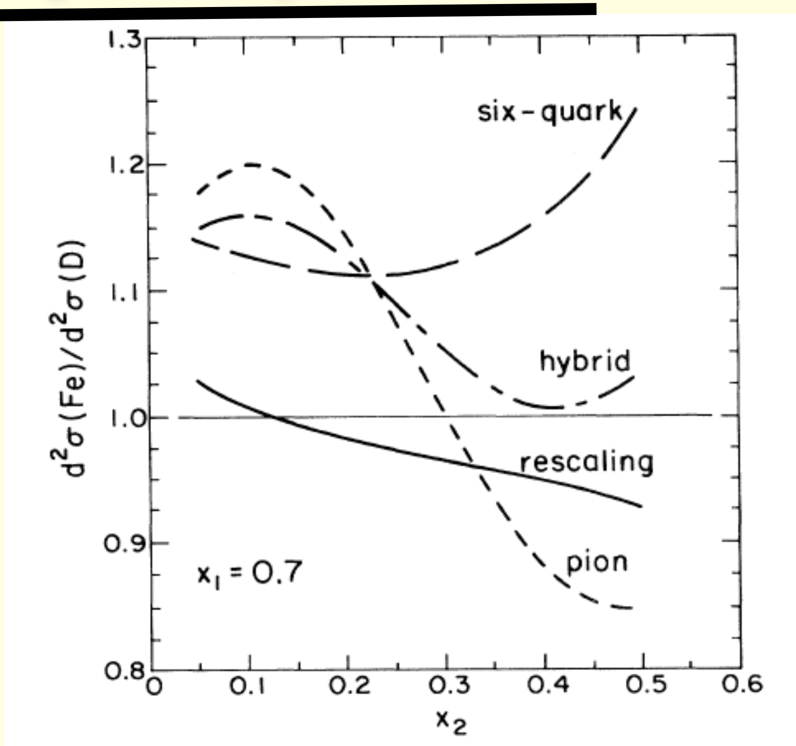
$P_A^+ = P_N^+ + P_\pi^+ = M_A$

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

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

proton(x_1) nucleus(x_2)





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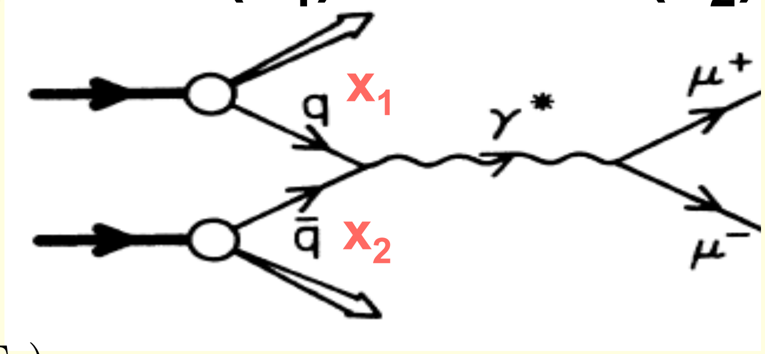
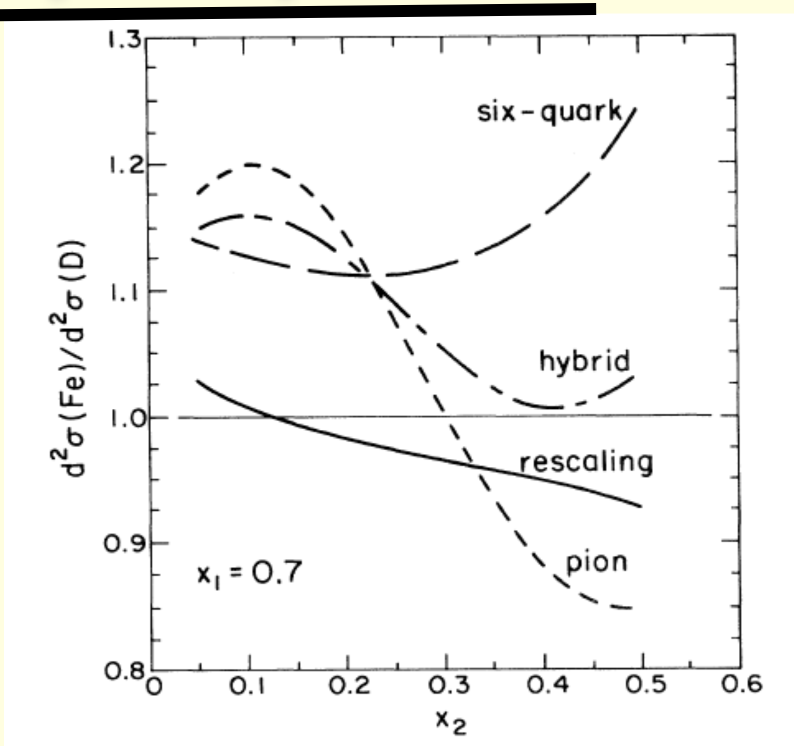
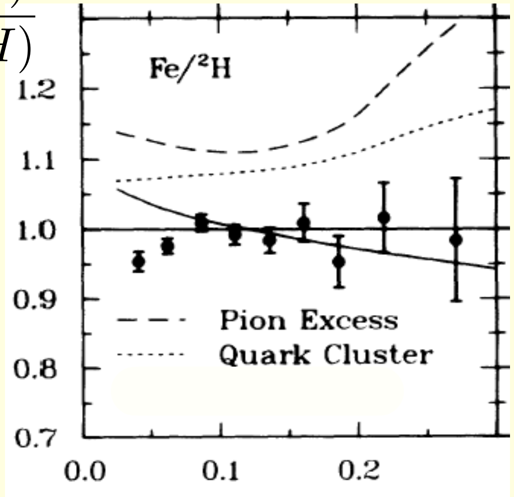




$$\frac{\sigma_{DY}(\mathrm{Fe})}{\sigma_{DY}(^2H)}$$



E772 PRL 69,1726 (92)

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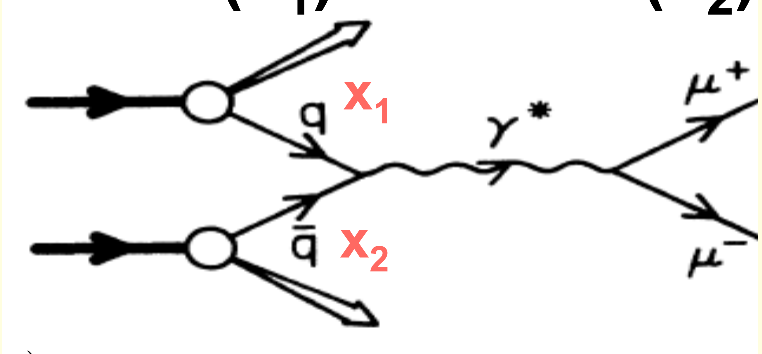

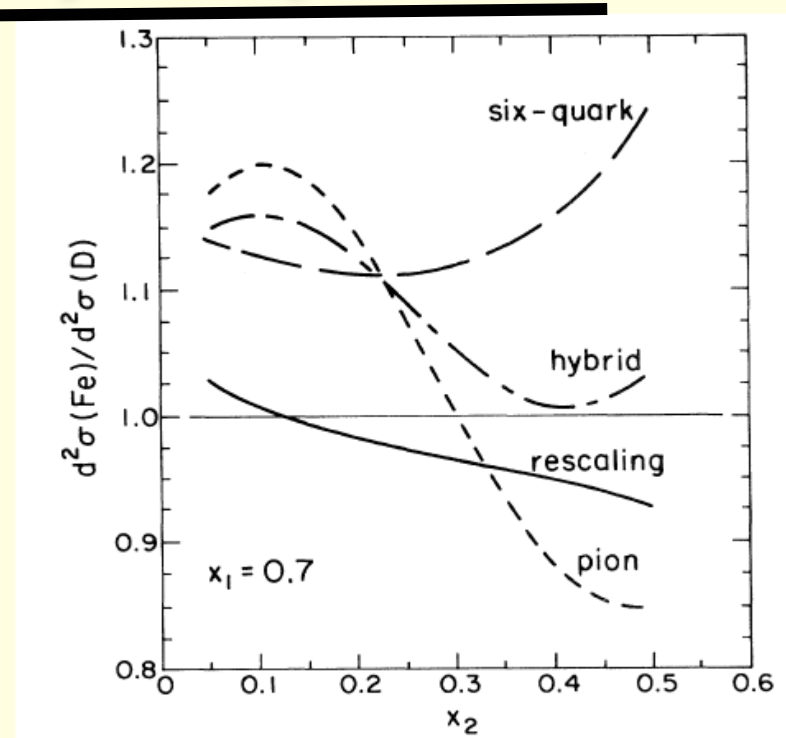

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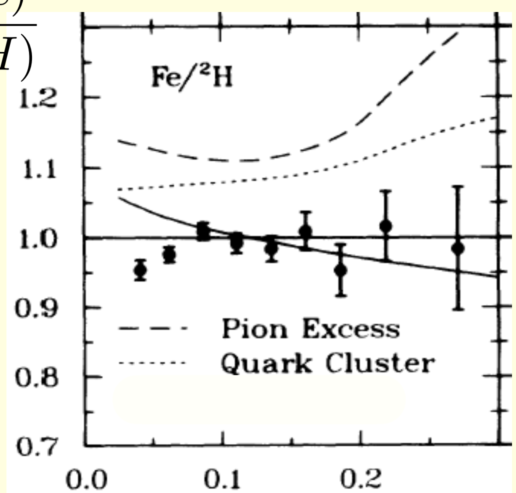

E772 PRL 69,1726 (92)

Bertsch, Frankfurt, Strikman“crisis”