EMC effect in QCD

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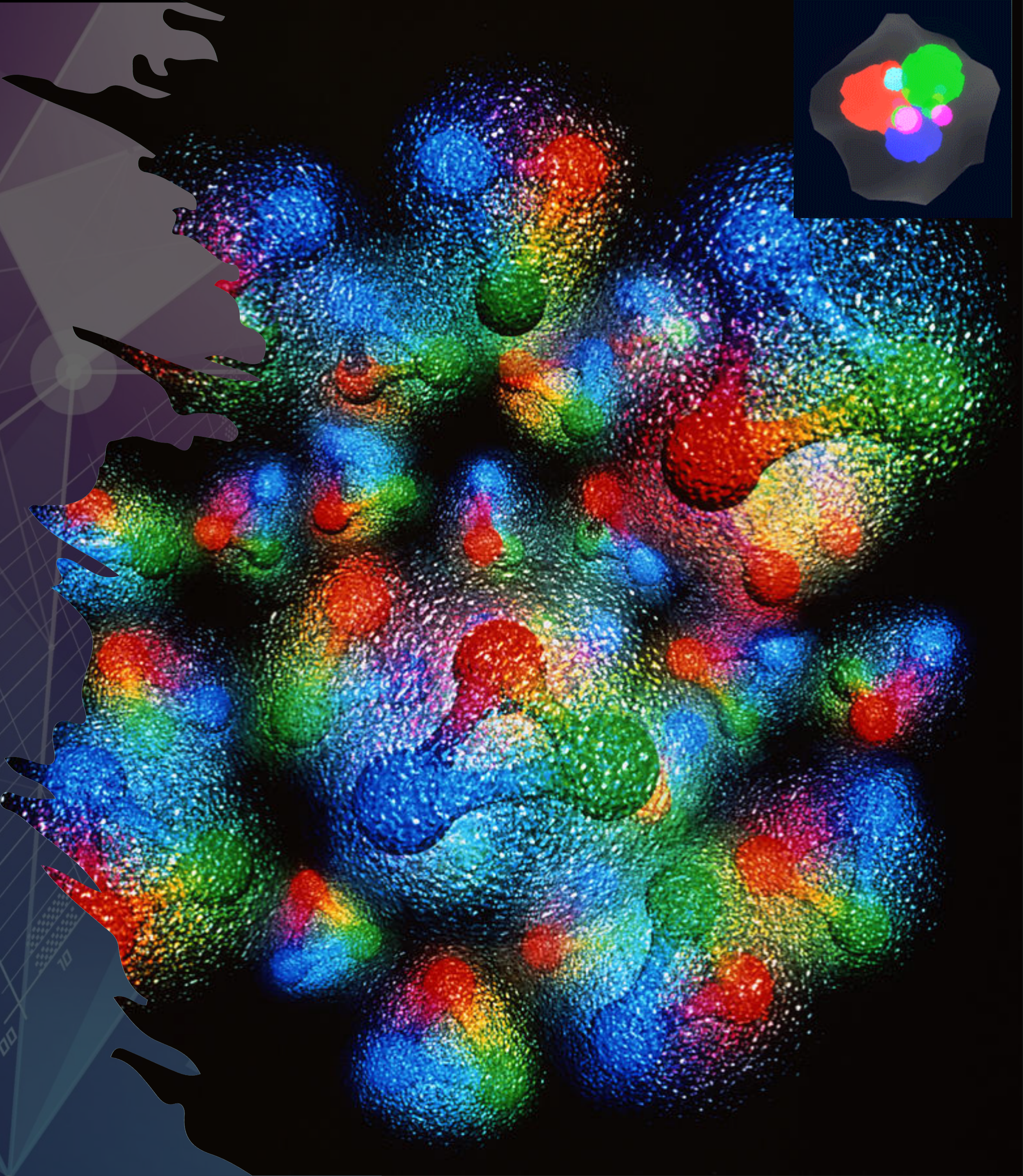
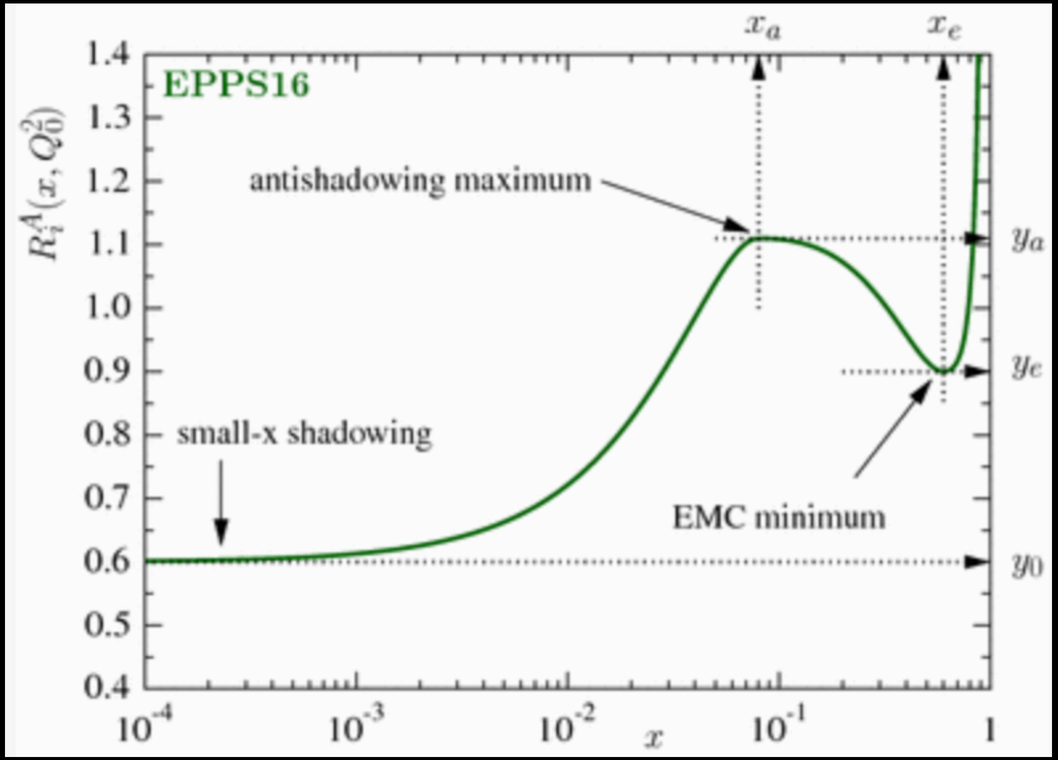
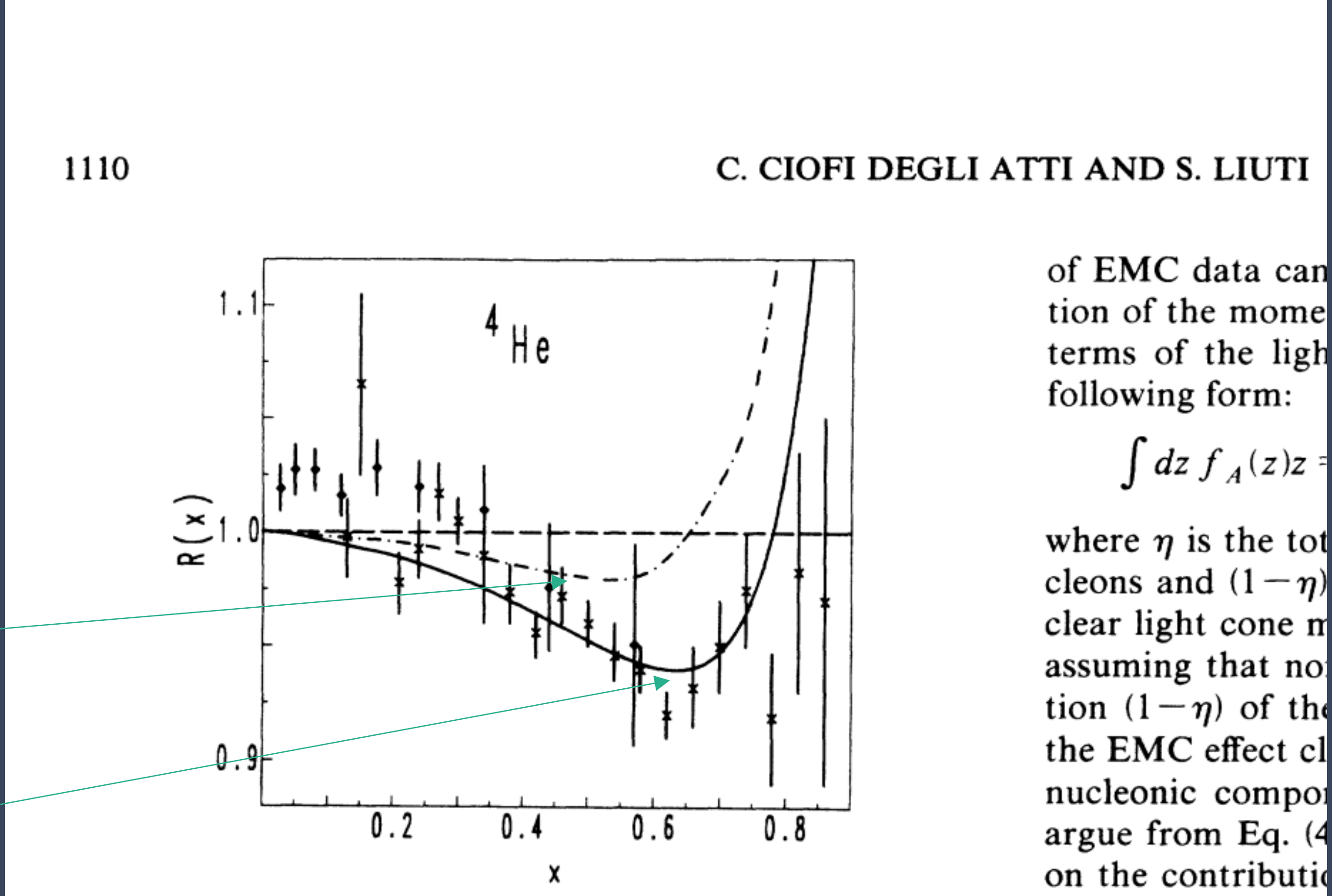
CENTER *for* NUCLEAR FEMTOGRAPHY



EMC Effect


EPPS16
$R_i^A(x, Q_0^2)$
1.4
1.3
1.2
1.1
1.0
0.9
0.8
0.7
0.6
0.5
0.4
10^{-4}
10^{-3}
10^{-2}
x
10^{-1}
1
x_a
x_e
y_a
y_e
y_0
antishadowing maximum
EMC minimum
small-x shadowing

The impact of nucleon nucleon correlations



of EMC data can
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terms of the ligh
following form:

$$\int dz\, f_A(z)z =$$

where η is the tot
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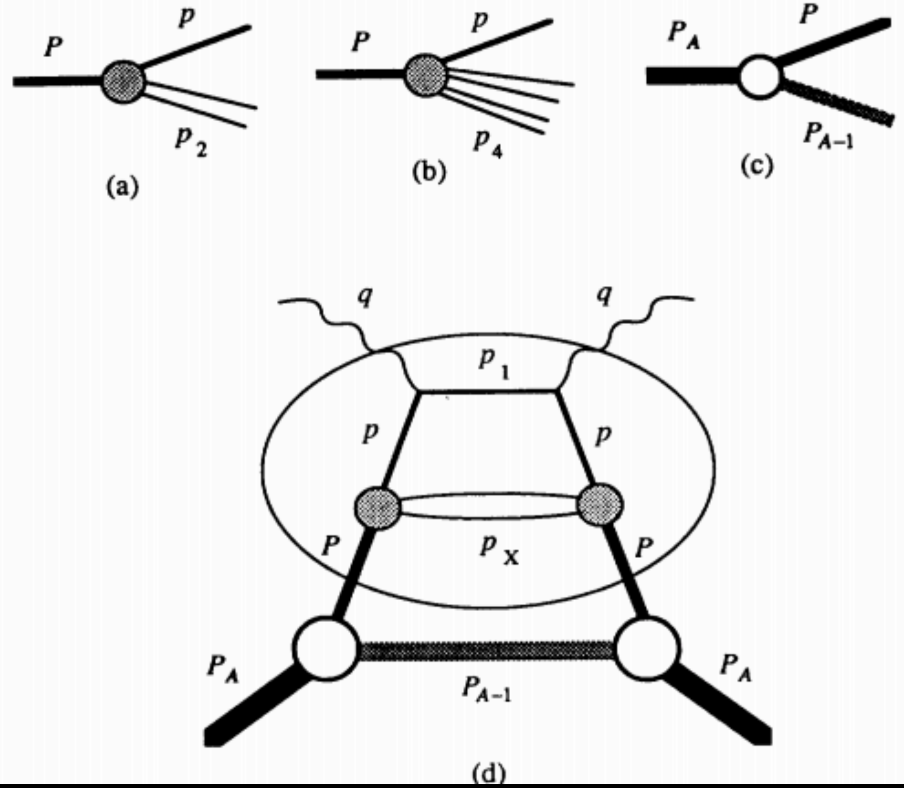
clear light cone m
assuming that no
tion $(1-\eta)$ of the
the EMC effect cl
nucleonic compo
argue from Eq. (4
on the contributi

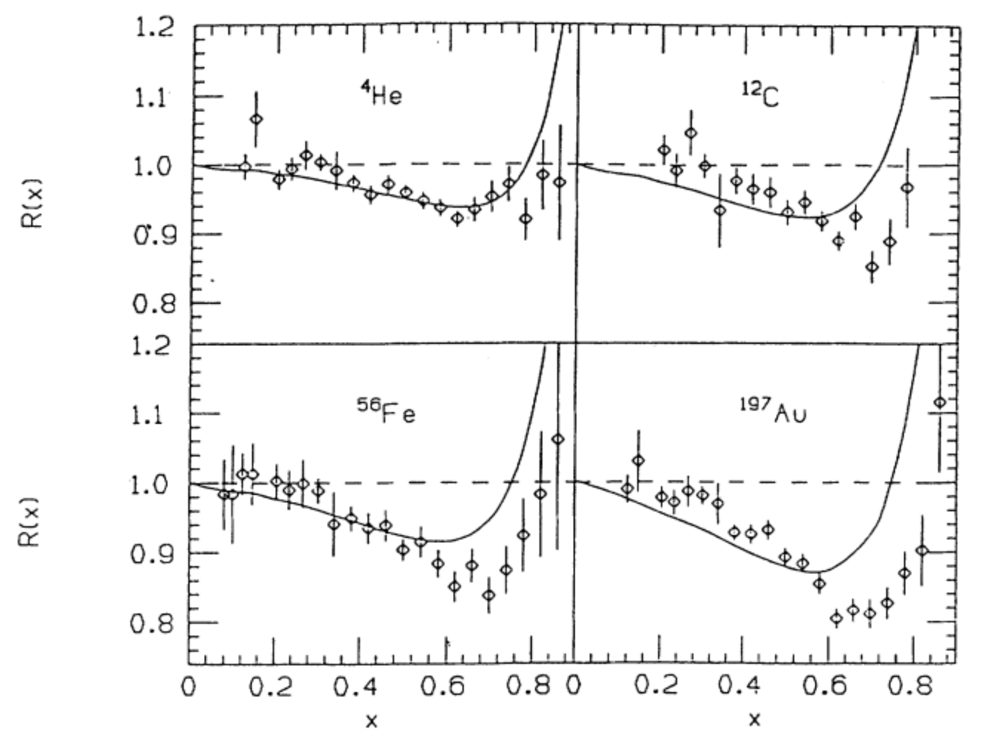
binding, no correlations

NN correlations

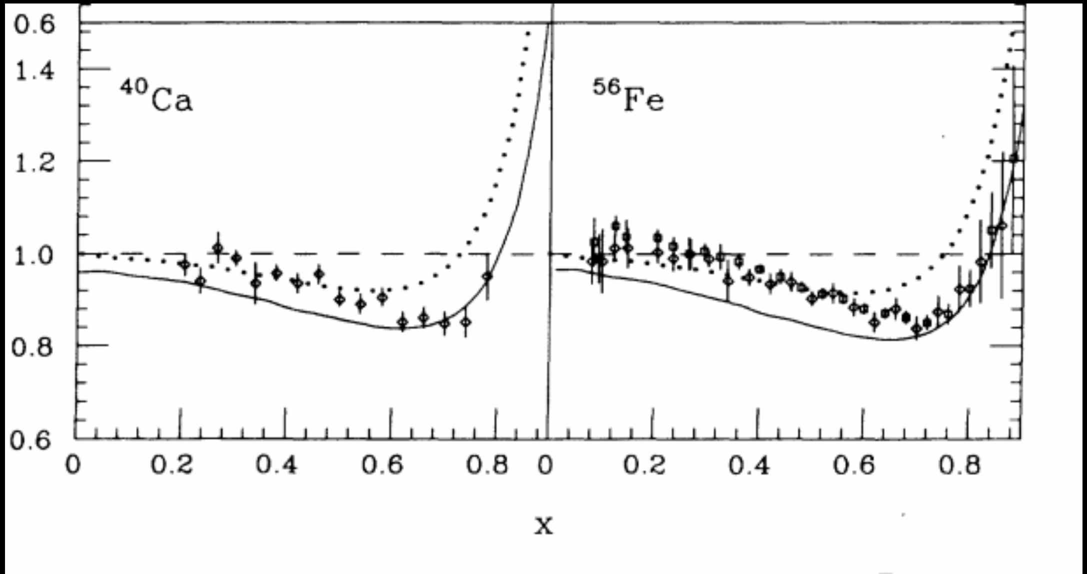
C. Ciofi degli Atti, S. Liuti *Phys.Rev.C* 41 (1990) 1100


P
p
p_2
(a)
P
p
p_4
(b)
P_A
P
P_{A-1}
(c)
q
q
p_1
p
p
P
p_X
P
P_A
P_{A-1}
P_A
(d)

Binding alone cannot explain all of the effect



Role of “relativistic effects” (proper LC treatment)



C. Ciofi degli Atti, S. Liuti *Phys.Rev.C* 44 (1991) R1269

C. Ciofi degli Atti, SL, PLB (1989)

F. Gross, S. Liuti, PRC45 (1992)

Scroll on to the new century…

QCD correlation functions and gauge links give us the key to interpret the EMC effect

Nucleon medium modifications and off-shell effects result from the combination of x-rescaling (binding) and the transverse motion of quarks

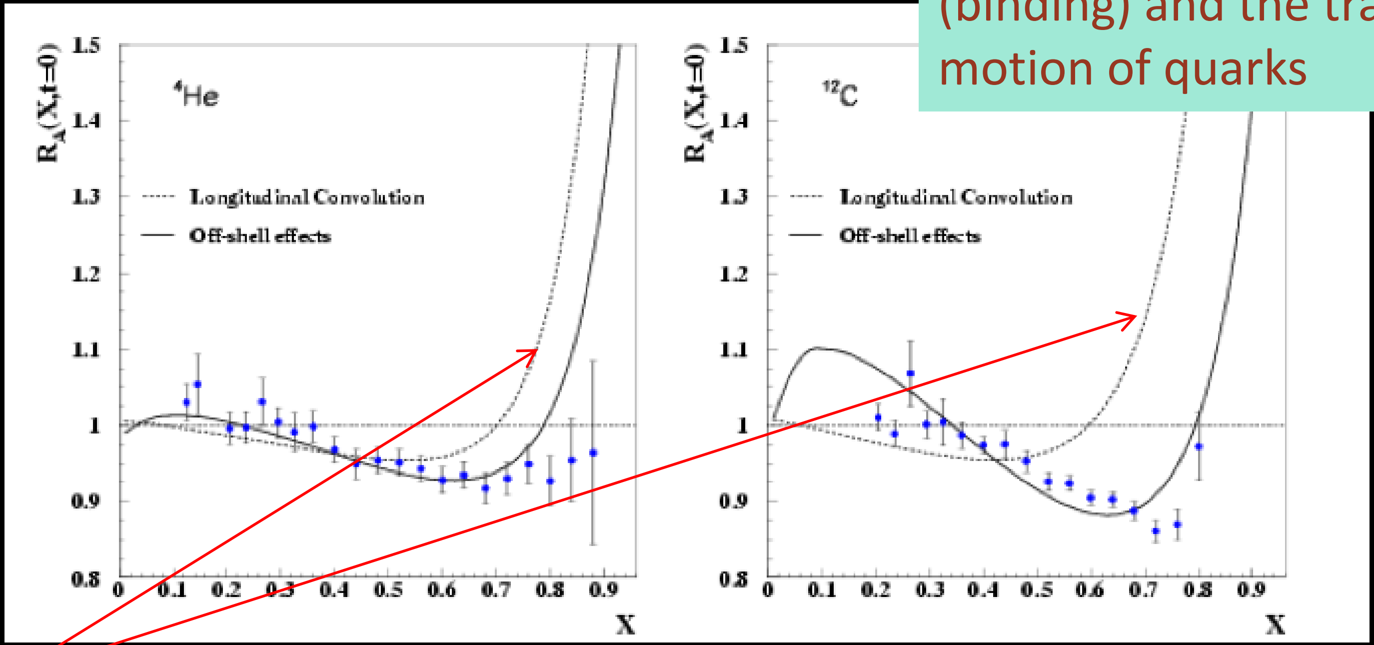
New work in progress

GPDs in nuclei

Liuti and Taneja (2005)

$R_A=F_2^A(x)/F_2^D(x)$

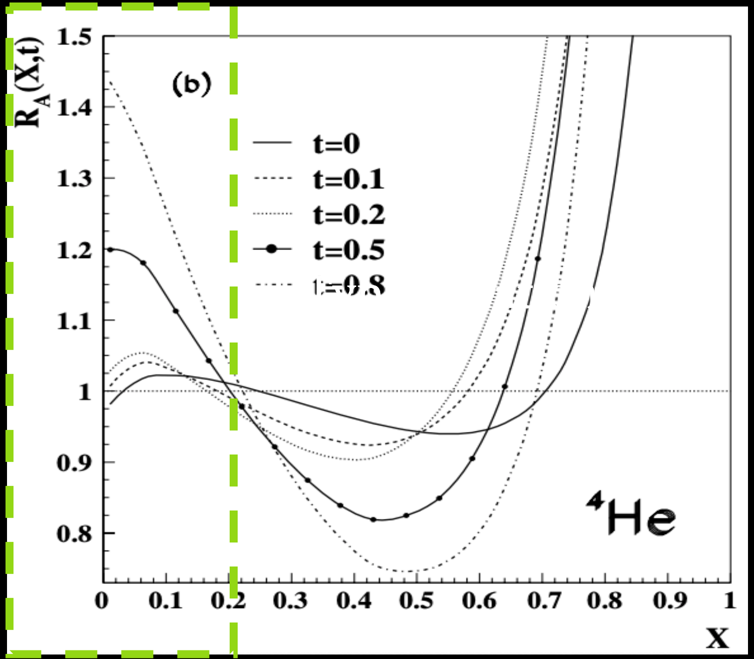
nucleon medium modifications and off-shell effects result from the combination of x-rescaling (binding) and the transverse motion of quarks



- ✓ Calculation including SRC (AV8) with unmodified nucleons
- ➔ Main constraint provided by Koltun sum rule

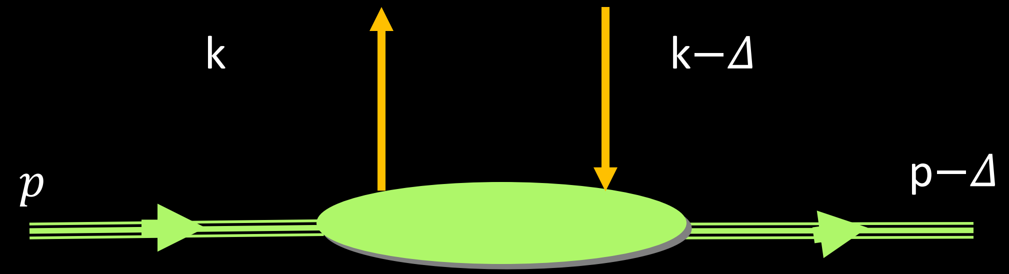
Similarities/Future Measurements: Deeply Virtual Compton Scattering (DVCS) and GPDs/Wigner functions

$$R_A(x,0,t) = \frac{H_A\,(x,0,t)}{H_N(x,o,t)}$$



SL, SK Taneja, PRC72(2005)

… is this trend observable…??



k_T unintegrated free nucleon

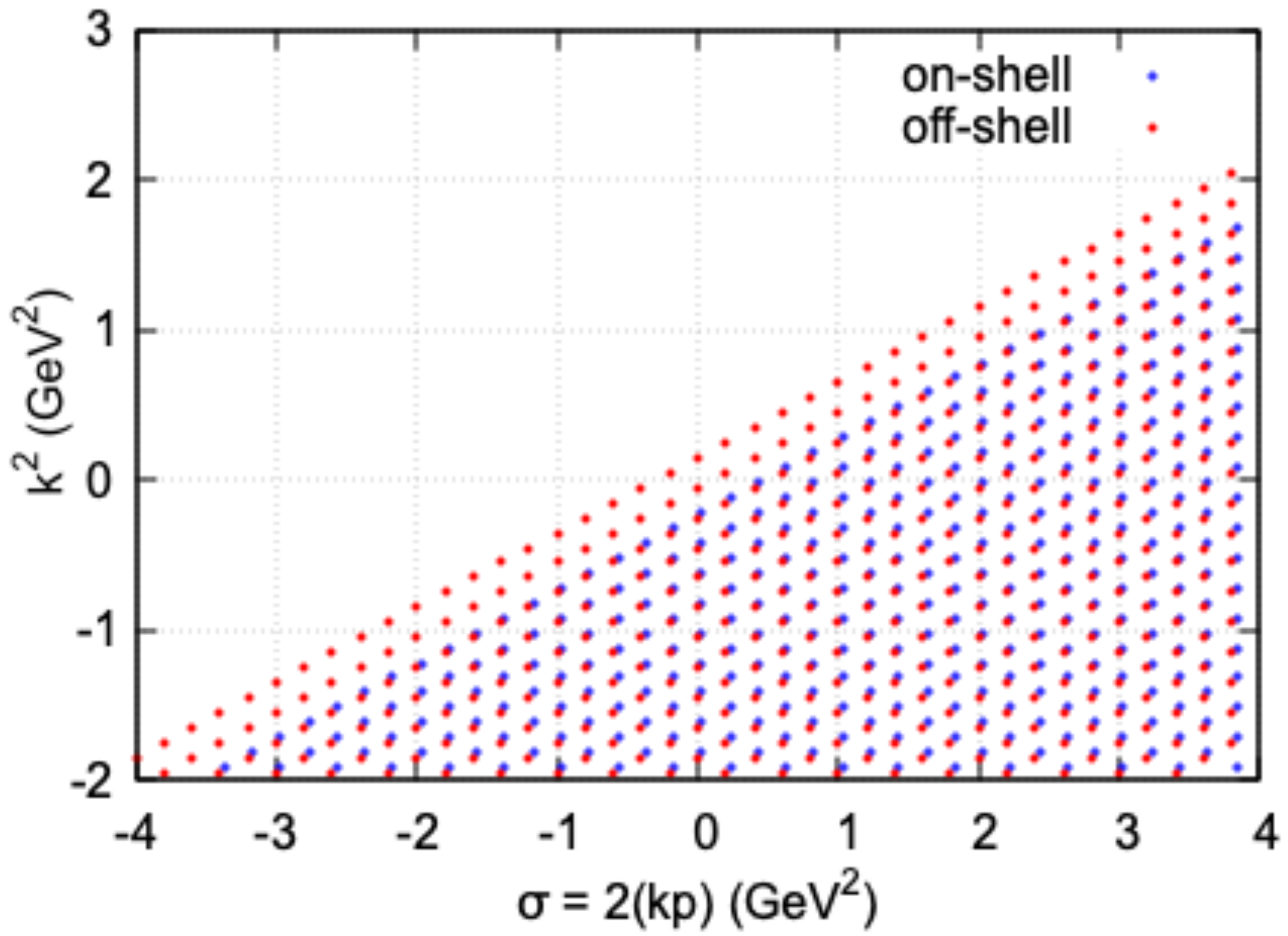
$$f(x,\mathbf{k}_T) = \int dk^- W(x,\mathbf{k}_T,k^-) = \int dy^- d^2\mathbf{y}_T\, e^{i(k^+y^- - \mathbf{k}_T\cdot\mathbf{y}_T)} \langle p \mid \bar{\psi}(0,0,0)\mathcal{U}(0,y)\gamma^+\psi(0,y^-,\mathbf{y}_T) \mid p\rangle_{y^+=0}$$

k_T unintegrated off-shell nucleon

$$f(x',\mathbf{k}'_T) = \int dy^- d^2\mathbf{y}_T\, e^{i(x'p^+y^- - \mathbf{k}'_T\cdot\mathbf{y}_T)} \langle p \mid \bar{\psi}(0,0,0)\mathcal{U}(0,y)\gamma^+\psi(0,y^-,\mathbf{y}_T) \mid p\rangle_{y^+=0}$$

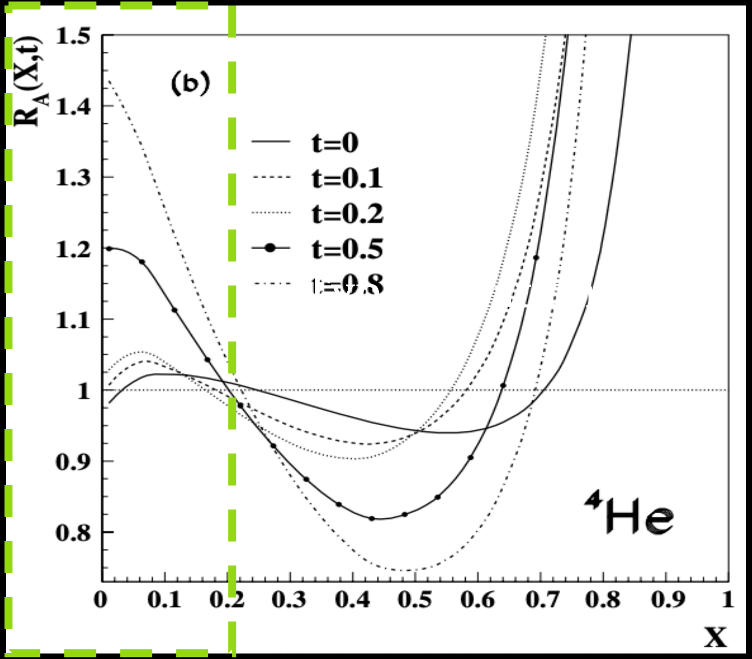
quark off shellness

$$k^2 = 2x(kp) - x^2M^2 - k_T^2 \quad \longrightarrow \quad k^2 = 2\frac{x}{z}(kp) - \left(\frac{x}{z}\right)^2 p^2 - \left(k_T - \frac{x}{z}p_T\right)^2$$


on-shell
off-shell
k^2 (GeV^2)
σ = 2(kp) (GeV^2)
3
2
1
0
-1
-2
-4
-3
-2
-1
0
1
2
3
4

Establishing an inclusive/exclusive connection: Deeply Virtual Compton Scattering (DVCS) and GPDs/Wigner functions

$$R_A(x,0,t) = \frac{H_A\,(x,0,t)}{H_N(x,o,t)}$$



SL, SK Taneja, PRC72(2005)

… is this trend observable…??

QCD at JLab: Diquarks, Hidden Color and Other SU(3) predictions

Jennifer Rittenhouse West
Lawrence Berkeley National Laboratory
Science at the Luminosity Frontier: Jefferson Lab 22 GeV conference
25 January 2023

What are hidden color states?

- Rigorous prediction of $\mathrm{SU}(3)_C$ based QCD
- Color-singlets with quantum numbers that match nuclei
- Nucleus = bag of color singlets
- Hidden-color = 1 color singlet
- Example: Hexadiquark hidden-color state in $^4\mathrm{He}$

QCD states within the nuclear wavefunction:

$$|^4\mathrm{He}\rangle = C_{nnpp}\left|\boxed{(u[ud])_{1_C}}\boxed{(d[ud])_{1_C}}\boxed{(u[ud])_{1_C}}\boxed{(d[ud])_{1_C}}\right\rangle + C_{\mathrm{HdQ}}\left|\boxed{(([ud][ud])_{\bar{\mathbf{6}}_C}([ud][ud])_{\bar{\mathbf{6}}_C}([ud][ud])_{\bar{\mathbf{6}}_C})_{1_C}}\right\rangle + \ldots$$

JRW, S.J.Brodsky, G. de Teramond, I.Schmidt, F.Goldhaber, Nuc. Phys. A 2021

Hidden-color research spans four+ decades:
Brodsky, Ji & Lepage, PRL 1983
Brodsky & Chertok, "The Asymptotic Form-Factors of Hadrons and Nuclei and the Continuity of Particle and Nuclear Dynamics" PRD 1976
M. Harvey, "Effective nuclear forces in the quark model with Delta and hidden color channel coupling" Nuc. Phys. A 1981
G.A.Miller "Pionic and Hidden-Color, Six-Quark Contributions to the Deuteron b1 Structure Function" Phys. Rev. C 2014

Hidden-color states in the nuclear wavefunction

- Hidden-color states in the deuteron: How much do they contribute to ψ_D?
- Probed with superfast quark studies at JLab (*Arrington, Sargsian, et al.*)
- Catching the hidden-color tiger by the tail
- $^4\mathrm{He}$ proposed to have larger hidden-color component than $^2\mathrm{H}$ but same question: $C_{\mathrm{HdQ}} = ?$

$$|\mathrm{D}\rangle = C_{np}\left|(d[ud])_{1_C}(u[ud])_{1_C}\right\rangle + C_{\mathrm{HC}_1}\left|(ud\ ud\ ud)_{1_C}\right\rangle + C_{\mathrm{HC}_2}\left|(uu\ dd\ ud)_{1_C}\right\rangle + \ldots$$

- *Building hidden-color states requires Fermi statistics upon quark exchange, Bose statistics upon diquark exchange.*
- *Spin-statistics constrains the other components of the wavefunction, often requires nonzero L & higher spin states $\Longrightarrow$ higher mass, less contribution to wavefunction (small coefficient C)*

Diquark: Quark-quark bound state, proposed as the cause of Short-range Correlations

JRW, Nuc. Phys. A 2023

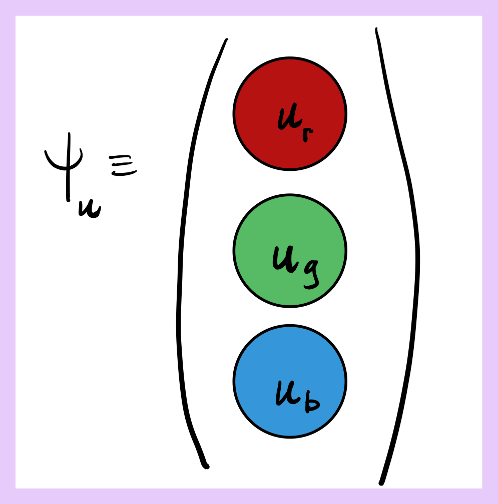
- Diquarks, another rigorous prediction of QCD
- Group theory rules of SU(3) $\Longrightarrow$ 2 quarks combine into anti-color charged object: $3_C \times 3_C \to \bar{3}_C$

If this combination does not occur - something must forbid it!

- Diquarks are bound: ∃ a short-range QCD Coulombic potential between quarks:

$$V(r_{qq}) \propto 1/r$$

Quark in the fundamental rep of $\mathrm{SU}(3)_C$:

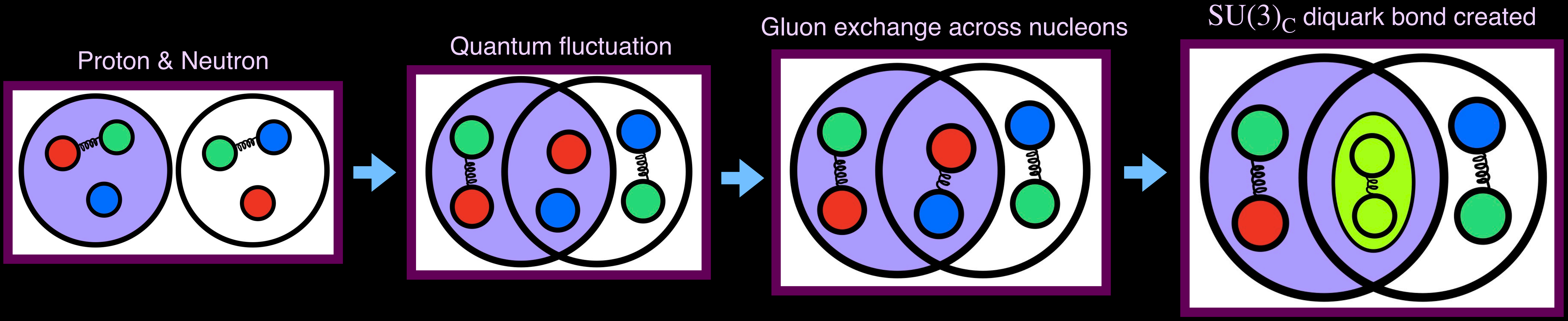


Diquark wavefunction in the antifundamental rep of $\mathrm{SU}(3)_C$:

$$\psi_a^{[ud]} = \frac{1}{\sqrt{2}} \epsilon_{abc} \left(u^b_\uparrow d^c_\downarrow - d^b_\uparrow u^c_\downarrow \right)$$

Diquark formation: Fundamental QCD dynamics causing NN correlations

New model: **Diquark formation** proposed to create short-range correlations (SRC), modifying quark behavior in the NN pair



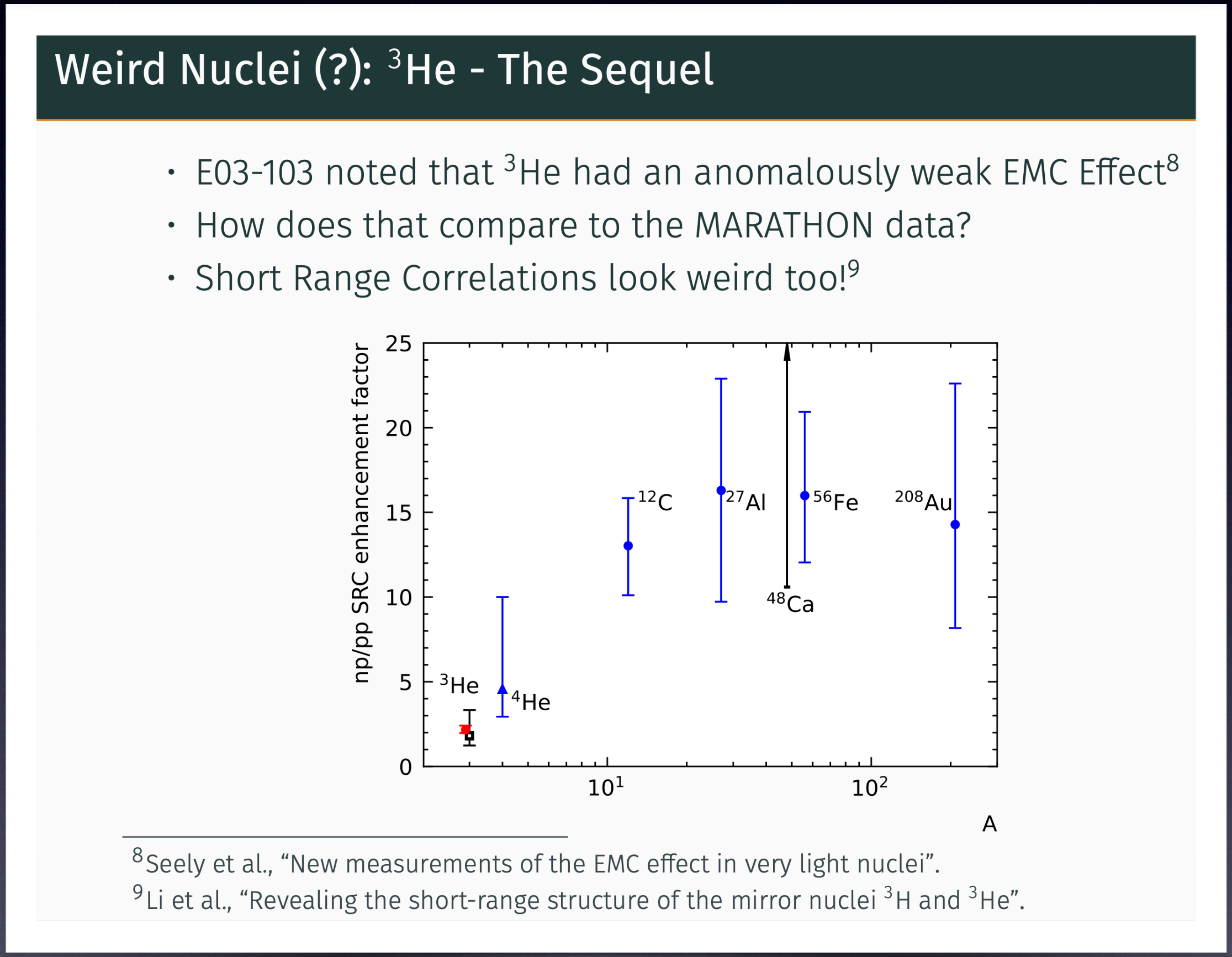
J.Rittenhouse West, Nuc. Phys. A 2023

Short-range QCD potentials act on distance scales < 1 fm. Strong NN overlap can bring valence quarks within range.

Hidden-color, Diquarks & the EMC Effect: Hexadiquark hidden-color state in A≥4 nuclei and Diquarks across nucleons in A=3?

- Hexadiquark in $^4\mathrm{He}$ nuclear wavefunction proposed as cause of EMC effect in A≥4
- Diquark based SRC proposed as cause of EMC effect in A=3
- $\Longrightarrow$ different behavior for A=3 nuclei
- MARATHON A=3 mirror nuclei experiment: “Light nuclei are weird” (*T.Hague*) - do not follow the SRC/EMC behavior - not enough np, not enough EMC
- *HdQ NB: New hadronic excitations predicted due to 6_C bonds between diquarks - X17 solution, to be measured at JLab, PAC50 approved*

V.Kubarovsky, JRW, S.Brodsky, 2206.14441



Weird Nuclei (?): ^{3}He - The Sequel

- E03-103 noted that ^{3}He had an anomalously weak EMC Effect[8]
- How does that compare to the MARATHON data?
- Short Range Correlations look weird too![9]

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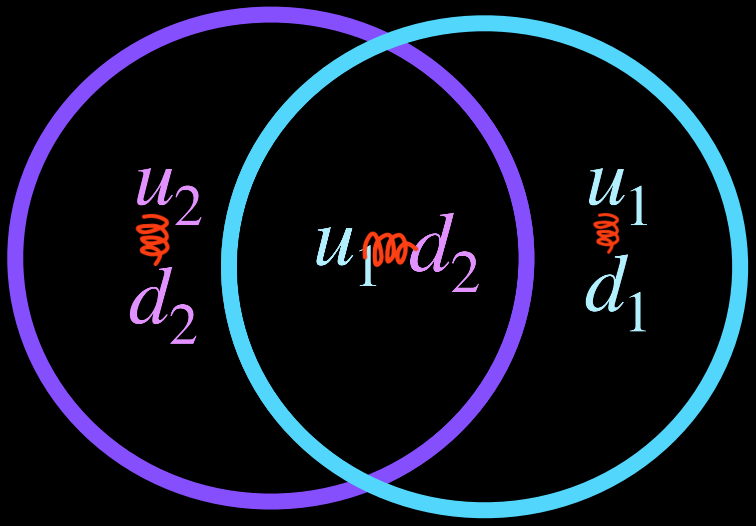
[8] Seely et al., “New measurements of the EMC effect in very light nuclei”.
[9] Li et al., “Revealing the short-range structure of the mirror nuclei ^{3}H and ^{3}He”.

- slide 32 from Tyler Hague, Hadron Ion Tea seminar at Berkeley Lab
https://www.youtube.com/watch?v=nj2mtR3DCzk

Summary: QCD at Jefferson Lab

- Diquark formation proposed to cause short-range correlated nucleon pairs & EMC effect in A=3. Superfast quark experiments probe SRC
- Superfast quarks to catch hidden-color in $^{2}\mathrm{H}$
- Hidden-color state within $^{4}\mathrm{He}$ nucleus proposed as cause of EMC effect in A=4 and larger nuclei.
- Diquarks proposed as cause of SRC and EMC effect in A=3
- Tentative evidence for diquark created SRC from

measured $\frac{\mathcal{N}_{pp \text{ SRC}}}{\mathcal{N}_{np \text{ SRC}}}$ from MARATHON @JLab



np SRC pair

Fin

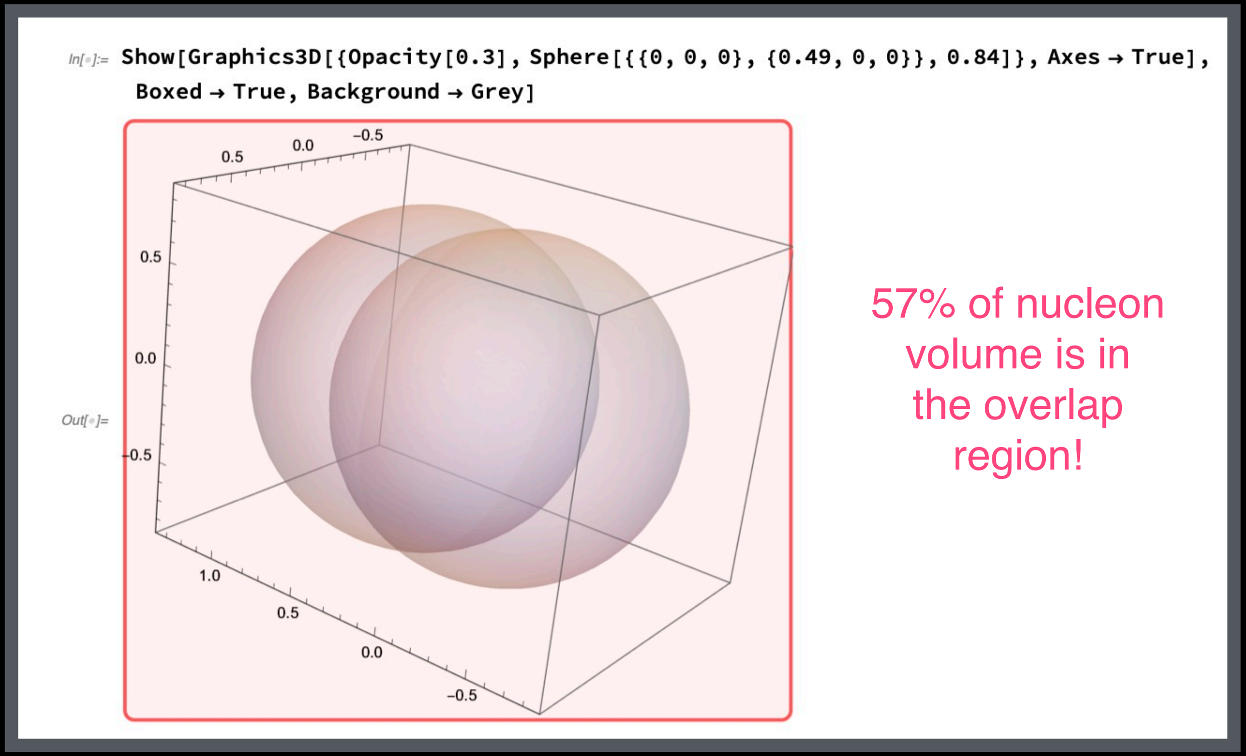
Jennifer Rittenhouse West
Berkeley Lab & EIC Center @JLab
Science at the Luminosity Frontier: Jefferson Lab at 22 GeV
23-25 January 2023

EIC^2
EIC Center at Jefferson Lab

BERKELEY
LAB

SRC 3D-overlap for relative momenta 400 MeV/c & 800 MeV/c

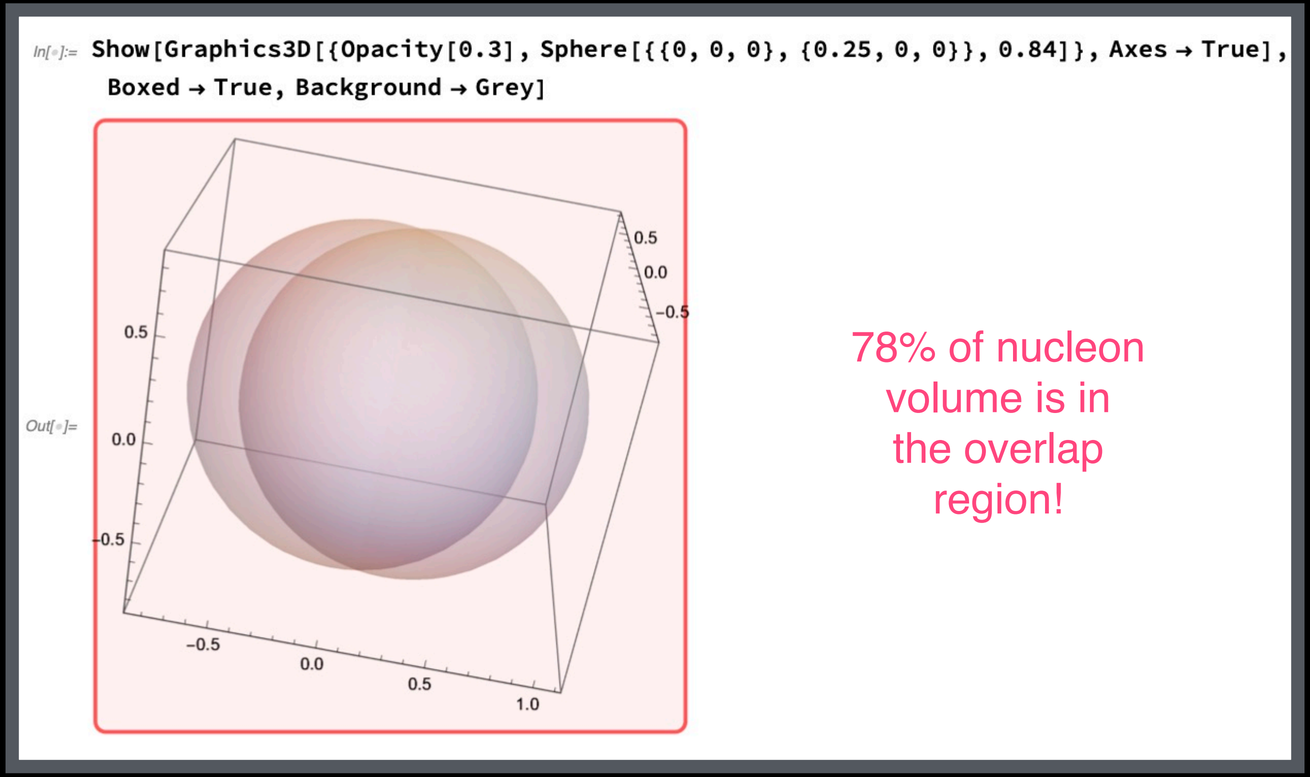
- *SRC Plot 1*: According to the $^{12}\mathrm{C}$ measurements from 2021 CLAS, NN tensor force dominates at 400 MeV/c relative momenta. Natural unit conversion gives 0.49 fm = 400 MeV/c.



```
In[▫]:= Show[Graphics3D[{Opacity[0.3], Sphere[{{0, 0, 0}, {0.49, 0, 0}}, 0.84]}, Axes → True],
         Boxed → True, Background → Grey]
```

57% of nucleon volume is in the overlap region!

- *SRC Plot 2*: Tensor-scalar transition momenta - according to the $^{12}\mathrm{C}$ measurements from 2021 CLAS, NN scalar force is in effect at 800 MeV/c relative momenta . Natural unit conversion gives 0.25 fm = 800 MeV/c .



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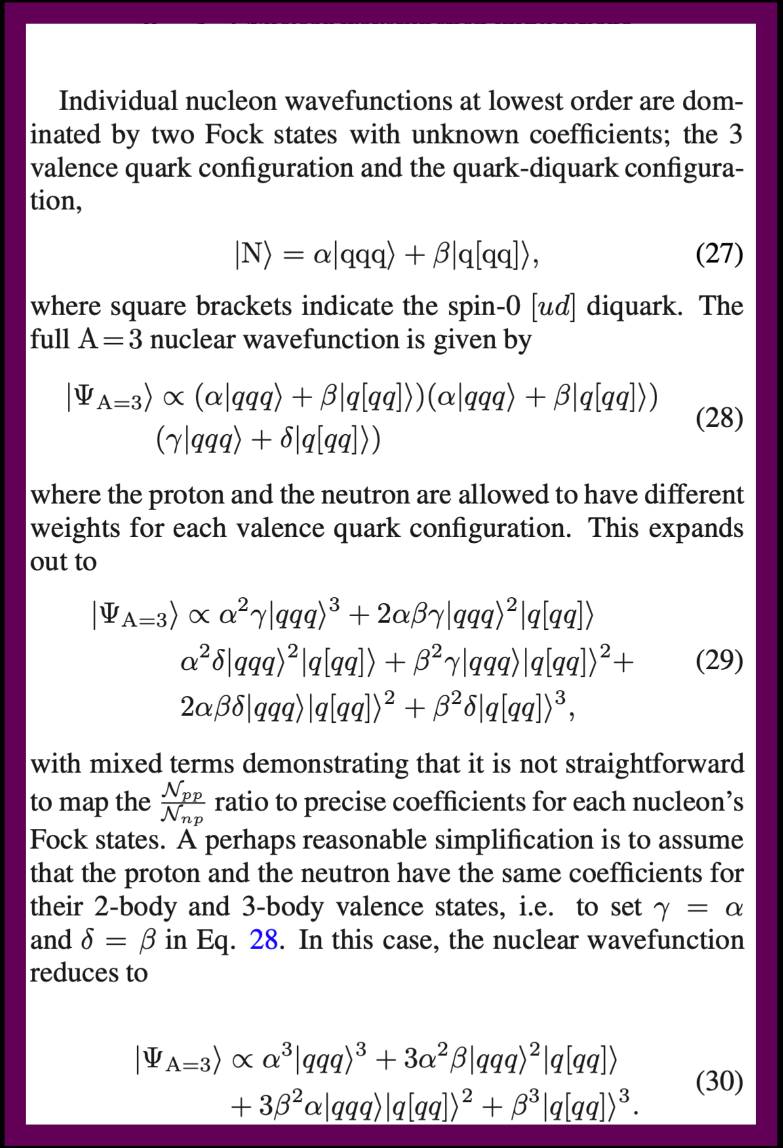
In[▫]:= Show[Graphics3D[{Opacity[0.3], Sphere[{{0, 0, 0}, {0.25, 0, 0}}, 0.84]}, Axes → True],
         Boxed → True, Background → Grey]
```

78% of nucleon volume is in the overlap region!

Diquark formation induced SRC inequality comparison to data: JLab experiment E12-11-112 A=3 mirror nuclei results

Nature paper from JLab/LBNL: $\dfrac{\mathcal{N}_{\rm pp}}{\mathcal{N}_{\rm np}} = \dfrac{1}{4.23} \sim 0.24$

Shujie Li, John Arrington & collaborators, September 2022



Individual nucleon wavefunctions at lowest order are dominated by two Fock states with unknown coefficients; the 3 valence quark configuration and the quark-diquark configuration,

$$|\mathrm{N}\rangle = \alpha|\mathrm{qqq}\rangle + \beta|\mathrm{q[qq]}\rangle, \qquad (27)$$

where square brackets indicate the spin-0 $[ud]$ diquark. The full A = 3 nuclear wavefunction is given by

$$|\Psi_{\mathrm{A}=3}\rangle \propto (\alpha|qqq\rangle + \beta|q[qq]\rangle)(\alpha|qqq\rangle + \beta|q[qq]\rangle) \\ (\gamma|qqq\rangle + \delta|q[qq]\rangle) \qquad (28)$$

where the proton and the neutron are allowed to have different weights for each valence quark configuration. This expands out to

$$|\Psi_{\mathrm{A}=3}\rangle \propto \alpha^2\gamma|qqq\rangle^3 + 2\alpha\beta\gamma|qqq\rangle^2|q[qq]\rangle \\ \alpha^2\delta|qqq\rangle^2|q[qq]\rangle + \beta^2\gamma|qqq\rangle|q[qq]\rangle^2 + \\ 2\alpha\beta\delta|qqq\rangle|q[qq]\rangle^2 + \beta^2\delta|q[qq]\rangle^3, \qquad (29)$$

with mixed terms demonstrating that it is not straightforward to map the $\frac{\mathcal{N}_{pp}}{\mathcal{N}_{np}}$ ratio to precise coefficients for each nucleon's Fock states. A perhaps reasonable simplification is to assume that the proton and the neutron have the same coefficients for their 2-body and 3-body valence states, i.e. to set $\gamma = \alpha$ and $\delta = \beta$ in Eq. 28. In this case, the nuclear wavefunction reduces to

$$|\Psi_{\mathrm{A}=3}\rangle \propto \alpha^3|qqq\rangle^3 + 3\alpha^2\beta|qqq\rangle^2|q[qq]\rangle \\ + 3\beta^2\alpha|qqq\rangle|q[qq]\rangle^2 + \beta^3|q[qq]\rangle^3. \qquad (30)$$

JRW, Nuc.Phys.A 2023

Isospin dependent SRC ratio inequalities from diquark induced SRC :

$$^3He: \quad 0 \leq \frac{\mathcal{N}_{pp\ \rm SRC}}{\mathcal{N}_{np\ \rm SRC}} \leq 0.4$$

$$^3H: \quad 0 \leq \frac{\mathcal{N}_{nn\ \rm SRC}}{\mathcal{N}_{np\ \rm SRC}} \leq 0.4$$

$\Longrightarrow$ Nucleon wavefunction : $\alpha|\mathrm{qqq}\rangle + \beta|\mathrm{q[ud]}\rangle$ combination

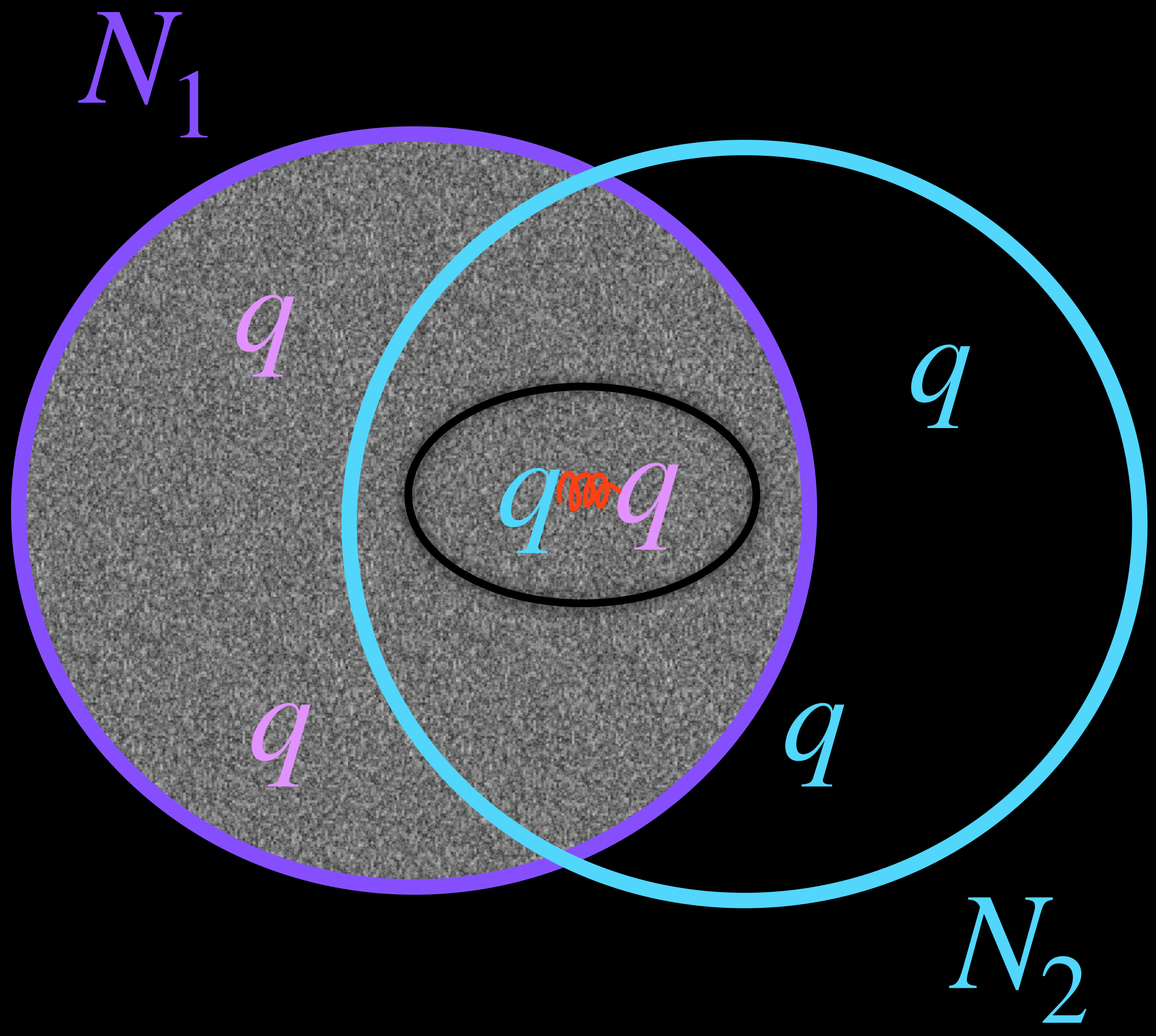
may have approximately equal coefficients, $\alpha \approx \beta$

2 Caveats: Non-zero probability that existing diquarks may be broken up if overlap sufficient -
Nucleon wavefunction written to lowest order - corrections in the form of spin-1 diquarks will exist

Diquark formation across N-N pairs

Requirements for diquark induced SRC:

1. Nucleon-Nucleon wavefunctions must strongly overlap
2. Attractive short-range QCD potential between valence quarks
3. Significant binding energy for diquark to form (much stronger than nuclear binding energies - comparable to confinement scale)



J.Rittenhouse West, Nuc. Phys. A 2023

Tetraquarks

Hidden-color in plain sight

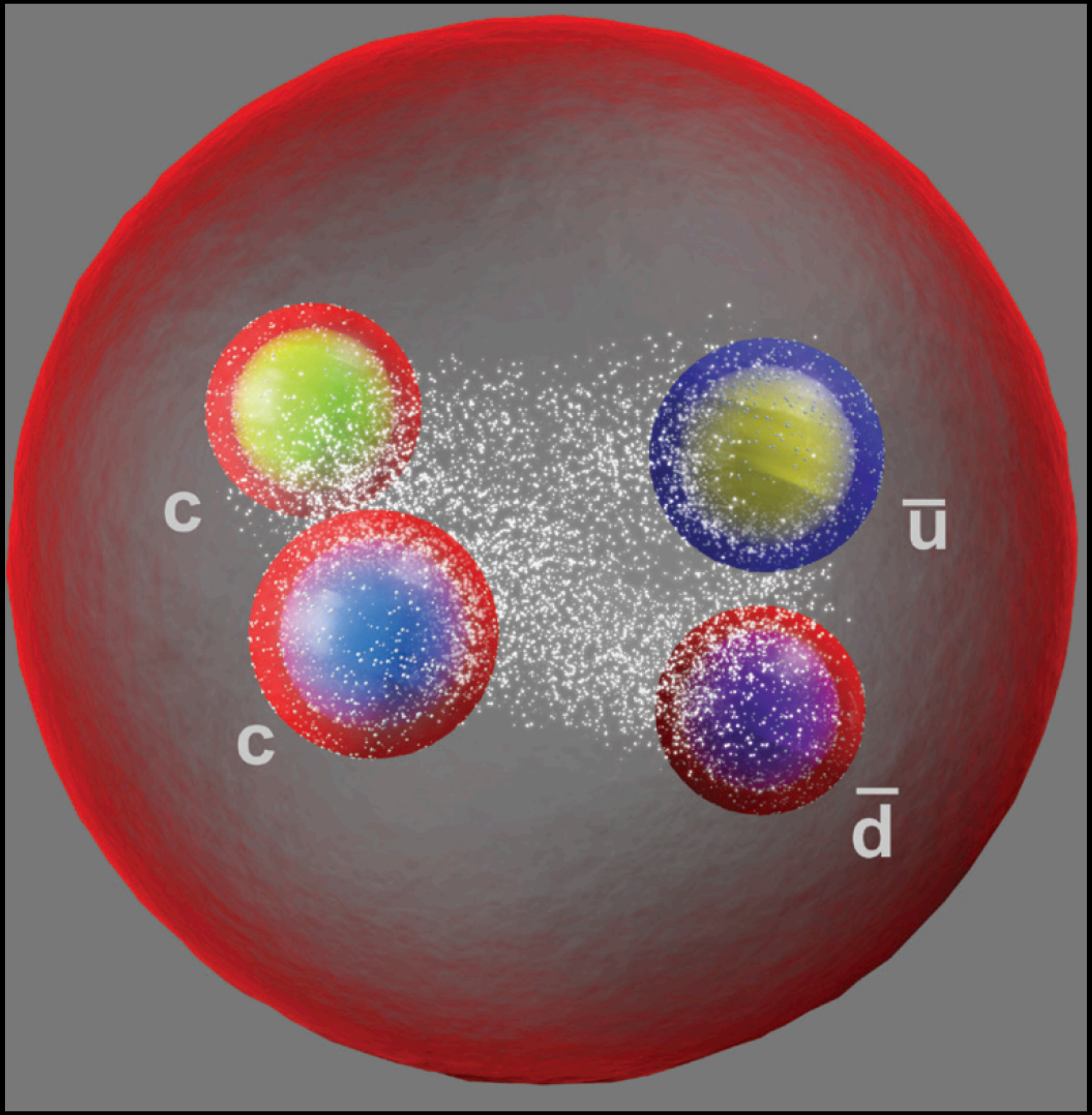
Combination of multiple color singlets vs. one color singlet - open question in QCD

Compact configuration of diquarks?

$$cc + \bar{u}\bar{d}$$

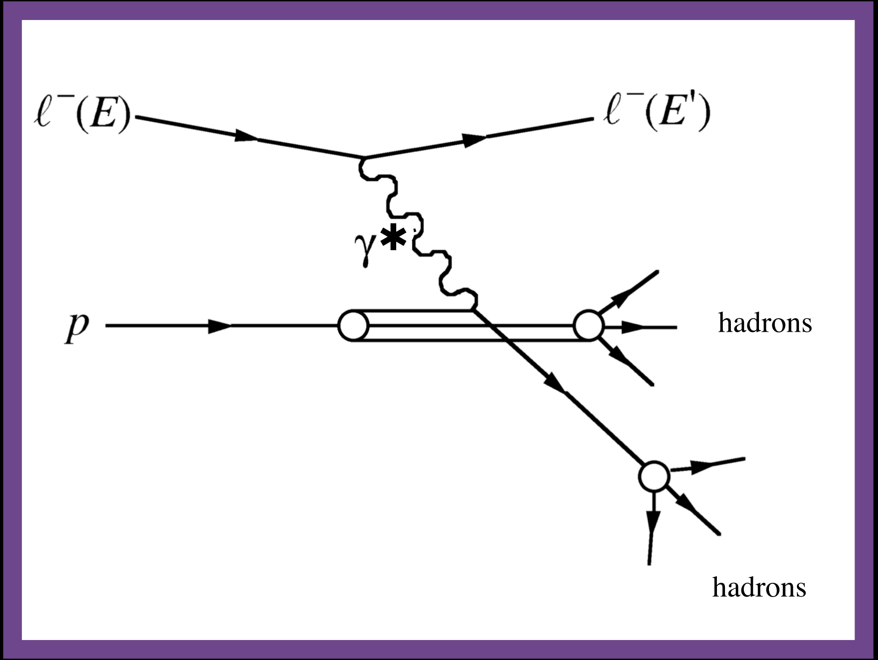
Or molecular mesonic state?

$$c\bar{u} + c\bar{d}$$



Bridge from fQCD to nuclear: EMC effect

- Lepton scatters from target, exchanging virtual photon with 4-momentum q^2 given by: $Q^2 \equiv -q^2 = 2EE'(1-\cos\theta)$
- γ^* strikes quark: We know the fraction of nucleon momentum carried by the struck quark via Bjorken scaling variable $x_B = \frac{Q^2}{2M_p\nu}$ where $\nu = E - E'$, M_p= proton mass, lepton masses neglected
- EMC plots: Ratios of structure functions vs. momentum fraction carried by struck quark x_B



Adapted from Nuclear & Particle Physics by B.R. Martin, 2003

Differential cross section for DIS:

$$\boxed{\frac{d\sigma}{dxdy}\left(e^-p \to e^-X\right) = \sum_f x\, e_f^2 \left[\, q_f(x) + \bar{q}_{\bar{f}}(x)\right] \cdot \frac{2\pi\alpha^2 s}{Q^4}\left(1 + (1-y)^2\right)}$$

where $y = \frac{\nu}{E}$ is the fraction of ℓ^- energy transferred to the target. $F_2(x)$ is the **nuclear structure function**, defined as:

$$\boxed{F_2(x_B) \equiv \sum_f x_B\, e_f^2 \left(\, q_f(x_B) + \ \bar{q}_{\bar{f}}(x_B)\right)}$$

in terms of quark distribution functions $q_f(x)$: probability to find a quark with momentum $x_i \in [x, x+dx]$.

EMC effect: Distortion of nuclear structure functions

$$\text{Plotting ratios of } F_2(x_B) \equiv \sum_f x_B\, e_f^2 \left(q_f(x_B) + \bar{q}_{\bar{f}}(x_B)\right) \text{ vs. } x_B$$

- Predicted $F_2(x_B)$ ratio in complete disagreement with theory

- Why should quark behavior - confined in nucleons at QCD energy scales ~200 MeV - be so affected when nucleons embedded in nuclei, BE $\geq$ 2.2 MeV?

- Mystery has not been solved to this day.

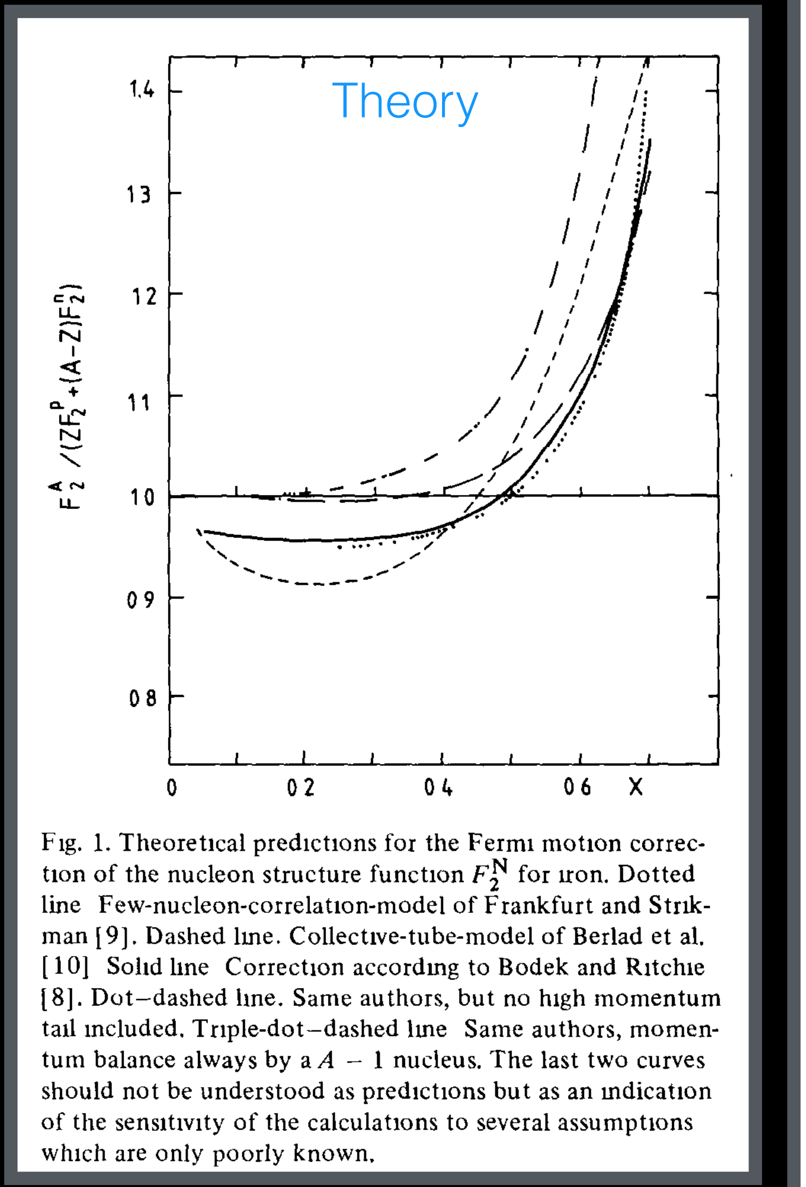


Fig. 1. Theoretical predictions for the Fermi motion correction of the nucleon structure function F_2^N for iron. Dotted line Few-nucleon-correlation-model of Frankfurt and Strikman [9]. Dashed line. Collective-tube-model of Berlad et al. [10] Solid line Correction according to Bodek and Ritchie [8]. Dot–dashed line. Same authors, but no high momentum tail included. Triple-dot–dashed line Same authors, momentum balance always by a $A - 1$ nucleus. The last two curves should not be understood as predictions but as an indication of the sensitivity of the calculations to several assumptions which are only poorly known.

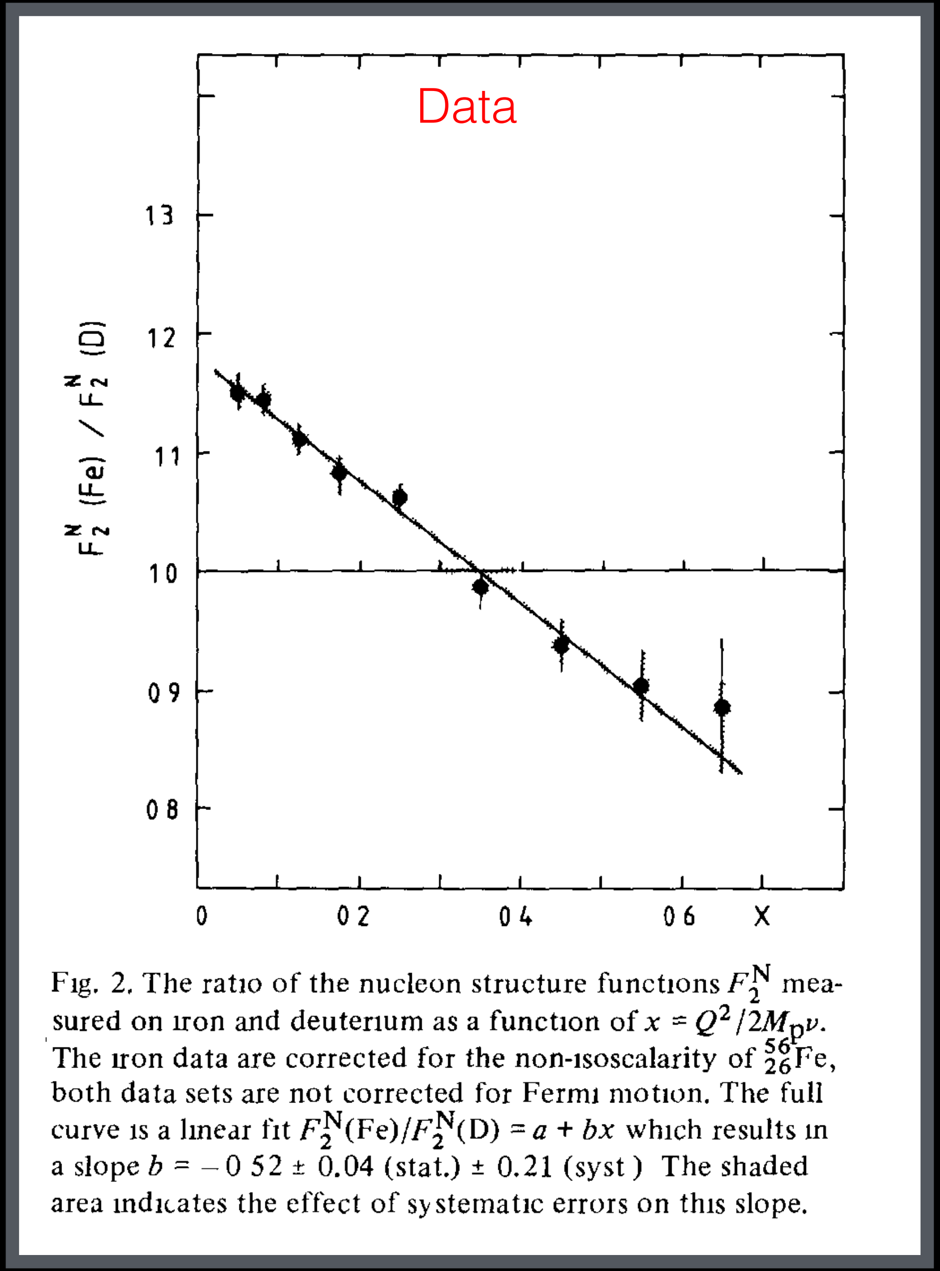


Fig. 2. The ratio of the nucleon structure functions F_2^N measured on iron and deuterium as a function of $x = Q^2/2M_p\nu$. The iron data are corrected for the non-isoscalarity of $^{56}_{26}$Fe, both data sets are not corrected for Fermi motion. The full curve is a linear fit $F_2^N(\mathrm{Fe})/F_2^N(\mathrm{D}) = a + bx$ which results in a slope $b = -0\ 52 \pm 0.04$ (stat.) ± 0.21 (syst) The shaded area indicates the effect of systematic errors on this slope.

“THE RATIO OF THE NUCLEON STRUCTURE FUNCTIONS F_2^N FOR IRON AND DEUTERIUM “
The European Muon Collaboration, J.J. AUBERT et al. 1983

EMC effect experiments & explanations

POSSIBLE EXPLANATIONS

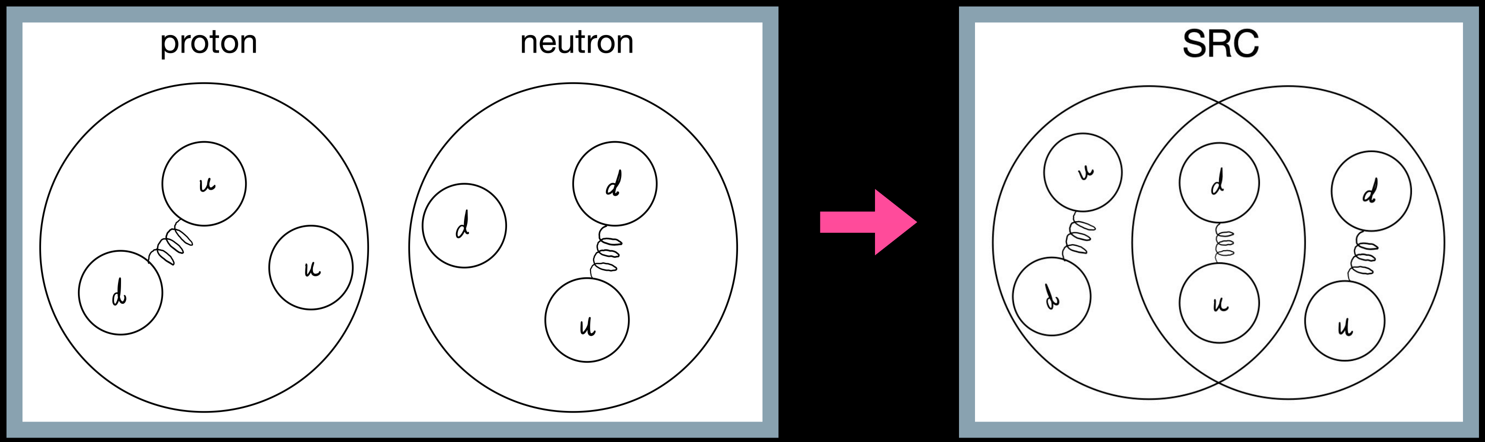
- Mean field effects involving the whole nucleus
- Local effects, *e.g.*, 2-nucleon correlations

Advance in field: Simple mean field effects inconsistent with the EMC effect in ^{9}Be, Seely *et al.*, 2009.

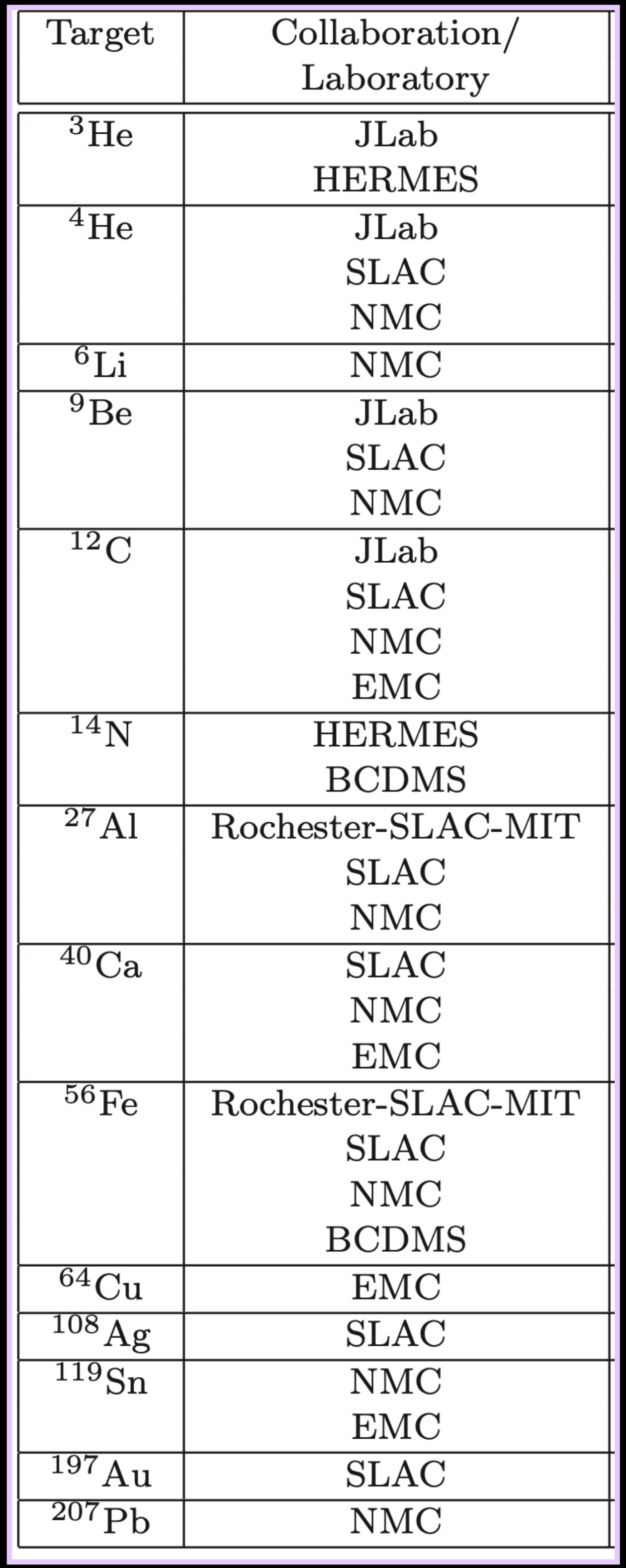
“This one new bit of information has reinvigorated the experimental and theoretical efforts to pin down the underlying cause of the EMC effect.” *Malace et al., 2014*

Short-range N-N correlated pairs (SRC) may cause EMC effect (first suggested in *Ciofi & Liuti 1990, 1991*).
Neutron-proton pairs found to dominate SRC (CLAS collaboration & others)

New model: **Diquark formation** proposed to create short-range correlations (SRC), modifying quark behavior in the NN pair



DOZENS OF EXPERIMENTS CONFIRM EMC EFFECT



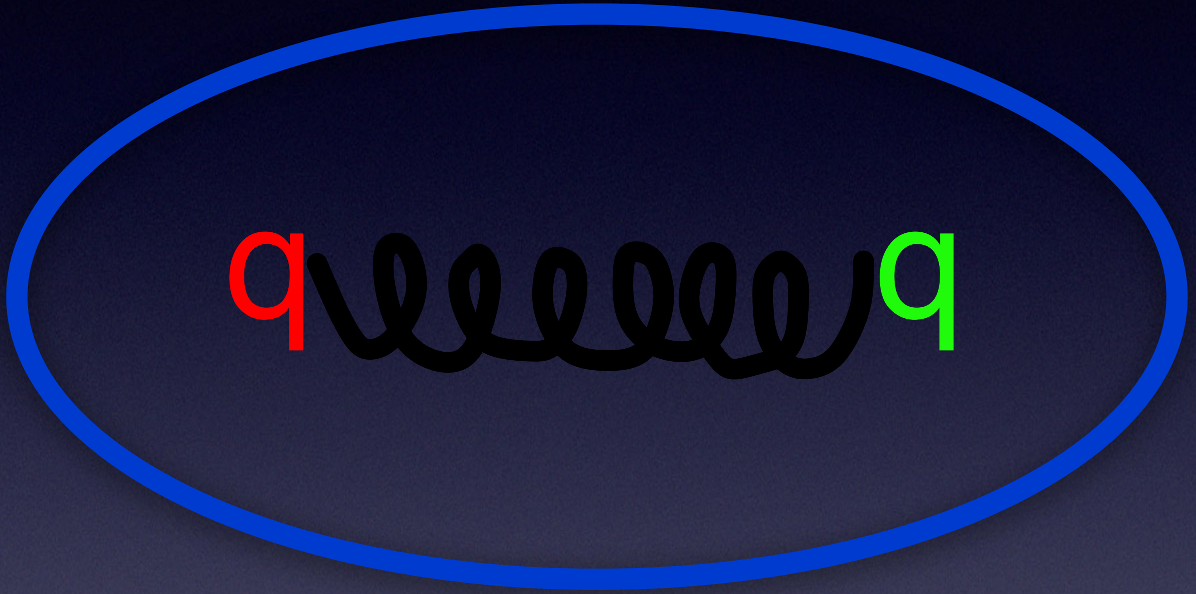
Target	Collaboration/ Laboratory
^{3}He	JLab HERMES
^{4}He	JLab SLAC NMC
^{6}Li	NMC
^{9}Be	JLab SLAC NMC
^{12}C	JLab SLAC NMC EMC
^{14}N	HERMES BCDMS
^{27}Al	Rochester-SLAC-MIT SLAC NMC
^{40}Ca	SLAC NMC EMC
^{56}Fe	Rochester-SLAC-MIT SLAC NMC BCDMS
^{64}Cu	EMC
^{108}Ag	SLAC
^{119}Sn	NMC EMC
^{197}Au	SLAC
^{207}Pb	NMC

Malace, Gaskell, Higinbotham & Cloet, Int.J.Mod.Phys.E 23 (2014)

What is a diquark?

- Strong force described by special unitary group $\mathrm{SU(3)}_C$, local symmetry of the strong interaction $\equiv$ QCD
- QCD $\Longrightarrow$ Diquark creation: Quark-quark bond with single gluon exchange **&** group theory transformation into a fundamentally different object:

$$3_C \otimes 3_C \rightarrow \overline{3}_C$$



Like quarks and gluons, diquarks carry color charge. They cannot be seen directly due to color confinement. Only 1_C (red+green+blue or red-antired etc.) directly detected.

Therefore there is no direct evidence for diquarks. Work in progress for diquark detection experimental proposals (*e.g.*, diquark jets from DIS increase Λ production)

Strong indirect evidence exists (baryon mass splittings, Regge slopes).

Why spin-0 $[ud]$ diquark formation?

There are 4 options for diquarks created out of valence quarks in the proton and neutron:

- Spin-0, Isospin-0 $[ud]$
- Spin-1, Isospin-1 (ud)
- Spin-1, Isospin-1 (uu)
- Spin-1, Isospin-1 (dd)

The scalar $[ud]$ is lower in mass by nearly 200 MeV.

What about a spin-0, isospin-1 $[ud]'$? Doesn't work due to spin-statistics constraints on the diquark wave function:

$$\Psi_{[ud]'} \propto \underset{\substack{\uparrow \\ \text{Antisymmetric}}}{\psi_{\text{color}}}\ \psi_{\text{spin}}\ \psi_{\text{iso}}\ \underset{\substack{\uparrow \\ \text{Symmetric, L=0}}}{\psi_{\text{space}}}$$

Diquark formation prediction for A=3 SRC

$$\text{Nucleon wavefunction}: \quad |\mathrm{N}\rangle = \alpha|\mathrm{qqq}\rangle + \beta|\mathrm{q[qq]}\rangle$$

Scalar [ud] diquark formation for nucleons
with 3-valence quark internal structure
$|\mathrm{N}\rangle \propto |\mathrm{qqq}\rangle$:

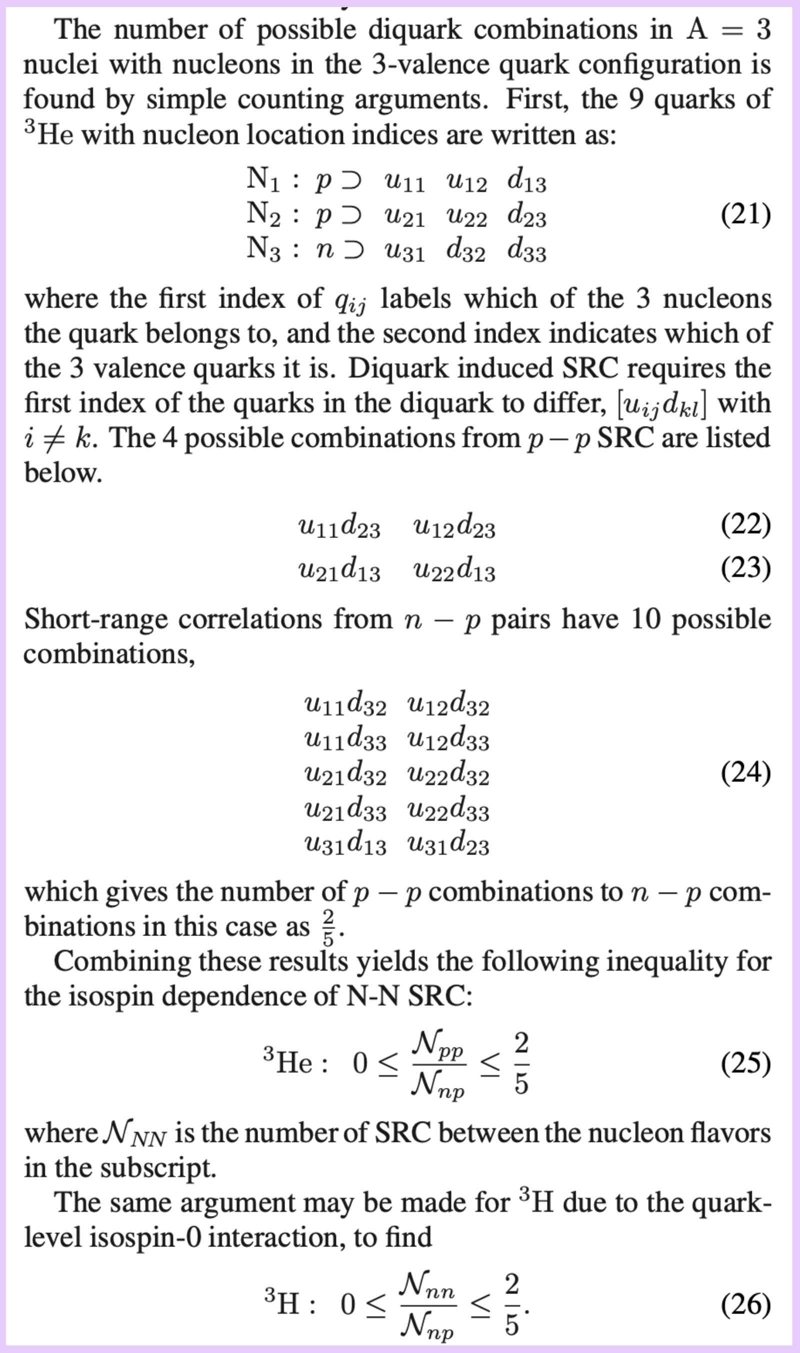
$$^3H: \quad 2n + p \to 4u,\, 5d \implies np \supset [ud] \text{ x}10$$
$$\implies nn \supset [ud] \text{ x}4 \quad \implies 60\,\%\ \mathrm{np},\ 40\,\%\ \mathrm{nn}$$

$$^3He: \quad 2p + n \to 5u,\, 4d \implies np \supset [ud] \text{ x}10$$
$$\implies pp \supset [ud] \text{ x}4 \quad \implies 60\,\%\ \mathrm{np},\ 40\,\%\ \mathrm{pp}$$

Scalar diquark formation for nucleons in quark-diquark
internal configuration $|\mathrm{N}\rangle \propto |\mathrm{q[qq]}\rangle$:

$$^3H: \quad u\ [ud] \ + \ d\ [ud] \ + \ d\ [ud] \implies 100\,\%\ \mathrm{np}$$

$$^3He: \quad u\ [ud] \ + \ u\ [ud] \ + \ d\ [ud] \implies 100\,\%\ \mathrm{np}$$



The number of possible diquark combinations in A $= 3$ nuclei with nucleons in the 3-valence quark configuration is found by simple counting arguments. First, the 9 quarks of ^{3}He with nucleon location indices are written as:

$$\begin{aligned} \mathrm{N}_1 &: p \supset \ u_{11}\ \ u_{12}\ \ d_{13} \\ \mathrm{N}_2 &: p \supset \ u_{21}\ \ u_{22}\ \ d_{23} \\ \mathrm{N}_3 &: n \supset \ u_{31}\ \ d_{32}\ \ d_{33} \end{aligned} \qquad (21)$$

where the first index of q_{ij} labels which of the 3 nucleons the quark belongs to, and the second index indicates which of the 3 valence quarks it is. Diquark induced SRC requires the first index of the quarks in the diquark to differ, $[u_{ij}d_{kl}]$ with $i \neq k$. The 4 possible combinations from $p-p$ SRC are listed below.

$$u_{11}d_{23} \quad u_{12}d_{23} \qquad (22)$$
$$u_{21}d_{13} \quad u_{22}d_{13} \qquad (23)$$

Short-range correlations from $n-p$ pairs have 10 possible combinations,

$$\begin{array}{cc} u_{11}d_{32} & u_{12}d_{32} \\ u_{11}d_{33} & u_{12}d_{33} \\ u_{21}d_{32} & u_{22}d_{32} \\ u_{21}d_{33} & u_{22}d_{33} \\ u_{31}d_{13} & u_{31}d_{23} \end{array} \qquad (24)$$

which gives the number of $p-p$ combinations to $n-p$ combinations in this case as $\frac{2}{5}$.

Combining these results yields the following inequality for the isospin dependence of N-N SRC:

$$^3\mathrm{He}: \quad 0 \leq \frac{\mathcal{N}_{pp}}{\mathcal{N}_{np}} \leq \frac{2}{5} \qquad (25)$$

where $\mathcal{N}_{NN}$ is the number of SRC between the nucleon flavors in the subscript.

The same argument may be made for ^{3}H due to the quark-level isospin-0 interaction, to find

$$^3\mathrm{H}: \quad 0 \leq \frac{\mathcal{N}_{nn}}{\mathcal{N}_{np}} \leq \frac{2}{5}. \qquad (26)$$

JRW, Nuc.Phys.A 2023

Combine into isospin dependent SRC ratio predictions :

$$^3He: \quad 0 \leq \frac{\mathcal{N}_{pp\ \mathrm{SRC}}}{\mathcal{N}_{np\ \mathrm{SRC}}} \leq \frac{2}{5}, \quad {}^3H: \quad 0 \leq \frac{\mathcal{N}_{nn\ \mathrm{SRC}}}{\mathcal{N}_{np\ \mathrm{SRC}}} \leq \frac{2}{5}, \quad \mathit{Maximum}\ 40\%!$$