Fundamental QCD in Nuclei: *Hidden Color States and Diquark Phenomenology*

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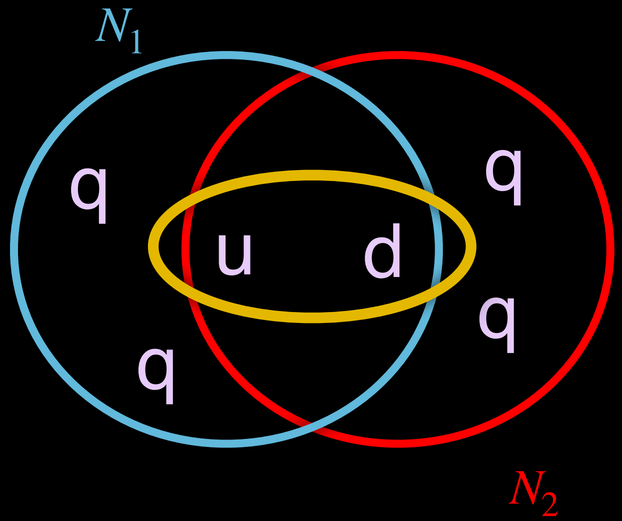
Electron-Ion Collider: QCD Testing Ground

Rigorous predictions of the $\mathrm{SU}(3)_C$ basis of QCD - 6 examples:

1. Diquarks (quark-quark bound state)
2. Tetraquarks (diquark-diquark bound state)
3. Hidden-color states in nuclear wavefunctions
4. Glueballs (color-singlet combinations of gluons)
5. “Hidden-glue” states in mesonic wavefunctions
6. Color transparency (collisions that cause hadrons to become point-like and therefore color neutral, exiting the nucleus as if it was transparent)



“Diquark induced short-range nucleon-nucleon correlations & the EMC effect”
JRW, Nuc.Phys.A 2023

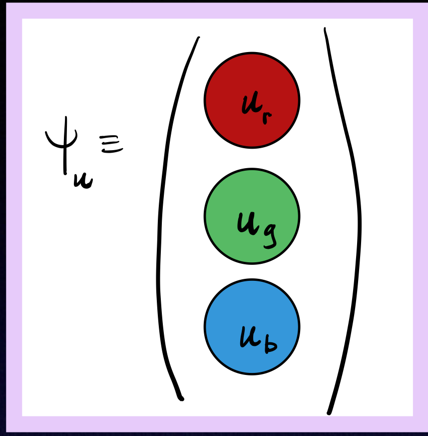
Quantum Chromodynamics predicts **Diquarks** (*& all viable* $\mathrm{SU}(3)_C$ *combinations*)

- Strong force described by special unitary group $\mathrm{SU}(3)_C$, local symmetry of the strong interaction $\equiv \mathrm{QCD}$

- QCD $\Longrightarrow$ Diquark creation: Quark-quark bond with single gluon exchange **&** group theory transformation into a fundamentally different object:

$$3_C \otimes 3_C \to \bar{3}_C$$

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



Diquark wavefunction in the antifundamental rep of $\mathrm{SU(3)_C}$, the antitriplet aka $\bar{3}_\mathrm{C}$:

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

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).

Hidden color overview with example in $^4\mathrm{He}$

- 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:

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

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

$$C_{\mathrm{HdQ}}\left|\Big(([ud][ud])_{\bar{\mathbf{6}}_C}([ud][ud])_{\bar{\mathbf{6}}_C}([ud][ud])_{\bar{\mathbf{6}}_C}\Big)_{1_C}\right\rangle + .$$

- *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)*

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 as a rigorous prediction of QCD

Building blocks: Quantum chromodynamics, spin-statistics

- Begin with group theory mathematics of the strong interaction: $\mathrm{SU}(3)_\mathrm{C}$
- Next, degrees of freedom (particles carrying strong force charge) - indices run over 3 color charges:

$$q_a \text{ (triplet, } 3_\mathrm{C}\text{)}, \quad q^a \text{ (antitriplet, } \overline{3}_\mathrm{C}\text{)}, \quad g^b_c \text{ (octet, } 8_\mathrm{C}\text{)}$$

- All combinations of D.o.F. allowable, color charged & color singlet. Examples (use δ^a_b, ϵ^{abc}, ϵ_{abc} to combine):

$$(\bar{q}^a q_a)_{1_\mathrm{C}} \quad (\epsilon^{abc}\ q_a q_b q_c)_{1_\mathrm{C}} \quad (\epsilon_{abc}\ \bar{q}^a \bar{q}^b \bar{q}^c)_{1_\mathrm{C}}, \quad (q_a q_b \epsilon^{abc})_{\bar{3}_C} \quad (qq)^c$$

- Higher Fock states (hadrons with 2 or 3 valence quarks are lowest order Fock states), e.g., the 5-quark Fock state for baryons:

$$(\epsilon^{abc} q_a q_b q_c\ \bar{q}^e q_e)_{1_\mathrm{C}} \subset \mathrm{N}$$

- To get to hidden color, first build nuclei beginning with heavy hydrogen aka the deuteron, $^2\mathrm{H}$:

$$(\epsilon^{abc} q_a q_b q_c)_{1_\mathrm{C}}\ (\epsilon^{def} q_d q_e q_f)_{1_\mathrm{C}}$$

- Hidden color singlets carry same quantum numbers as a hadron or nucleus - subdominant components of the total wavefunction. The HC octet in the deuterium nucleus:

$$q_a\ q_b\ q_c\ q_d\ q_e\ q_f \implies \Big((\epsilon^{abf} q_a q_b q_c)_{8_\mathrm{C}}\ (\epsilon^{dec} q_d q_e q_f)_{8_\mathrm{C}} \Big)_{1_\mathrm{C}} = (p^f_c\ n^c_f)_{1_\mathrm{C}} \subset\ ^2\mathrm{H}$$

Hidden color in $^2\mathrm{H}$

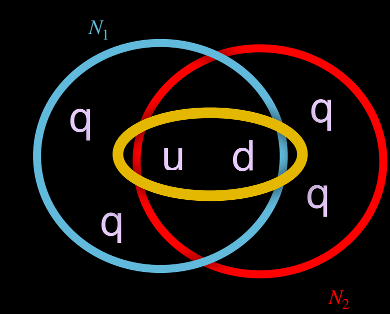
Work in progress:

- Brodsky & Ji state ∃ 5 QCD states in the deuteron - one of which is the nuclear state:

$$|np\rangle = |(\epsilon^{abc}u_a d_b d_c)_{1_C}\ (\epsilon^{lmn}u_l u_m d_n)_{1_C}\rangle$$

- Typically the literature has color octets as the hidden-color state:

$$\Big((\epsilon^{abn}u_a d_b d_c)_{8_C}\ (\epsilon^{lmc}u_l u_m d_n)_{8_C}\Big)_{1_C}$$



"Diquark induced short-range nucleon-nucleon correlations & the EMC effect"
JRW, Nuc.Phys.A 2023

A proposal for 3 others:

1. 3 antitriplet diquarks: $\Big(\epsilon_{prs}\ (qq)^p\ (qq)^r (qq)^s\Big)_{1_C}$, where $(qq)^s = \epsilon^{abs} q_a q_b$
2. 3 sextet (symmetric - also slightly repulsive!) diquarks: $6_C \otimes 6_C \otimes 6_C \rightarrow 1_C$
3. 2 Triplet-1 sextet combo: $\bar{3}_C \otimes \bar{3}_C \otimes 6_C \rightarrow 1_C$

- However, lowest order $^2\mathrm{H}$ wavefunction is very likely the following (with $\alpha \gg \beta$):

$$|np\rangle = \alpha|(\epsilon^{abc}u_a d_b d_c)_{1_C}\ (\epsilon^{lmn}u_l u_m d_n)_{1_C}\rangle\ +\ \beta|(\epsilon^{abn}u_a d_b d_c)_{8_C}\ (\epsilon^{lmc}u_l u_m d_n)_{8_C}\rangle$$

Hexadiquark (HdQ) hidden color state in A≥4 nuclei

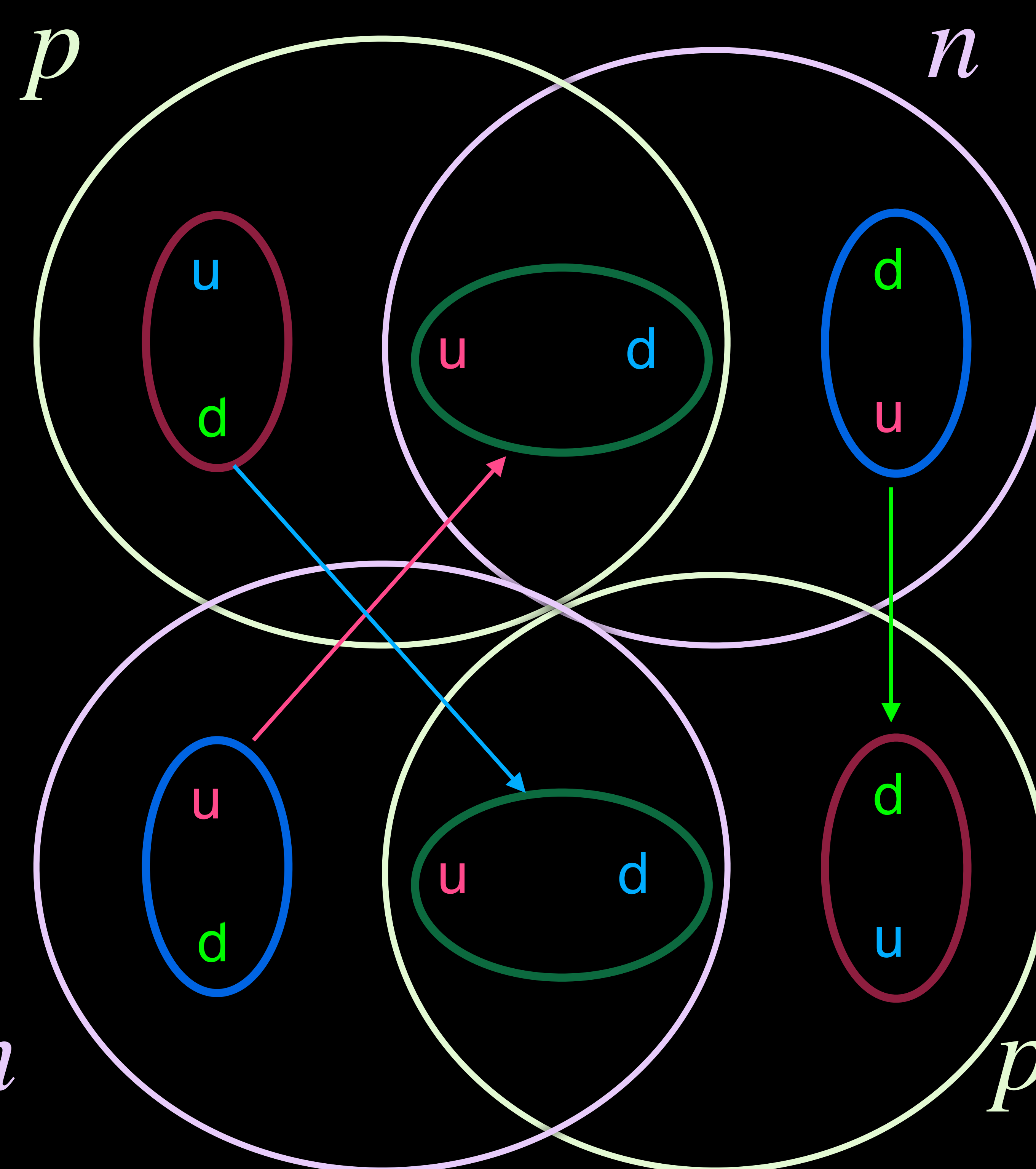
- $^{4}\mathrm{He}$ nuclear wavefunction a linear combination of nnpp and HdQ with unknown coefficients

$$|\alpha\rangle = C_{pnpn}\left|(u[ud])_{1_C}(d[ud])_{1_C}(u[ud])_{1_C}(d[ud])_{1_C}\right\rangle$$
$$+\ C_{\mathrm{HdQ}}\left|(([ud][ud])_{\bar{6}_C}([ud][ud])_{\bar{6}_C}([ud][ud])_{\bar{6}_C})_{1_C}\right\rangle$$

- n-p dominance of SRC required by the HdQ model - PDF calculation work in progress

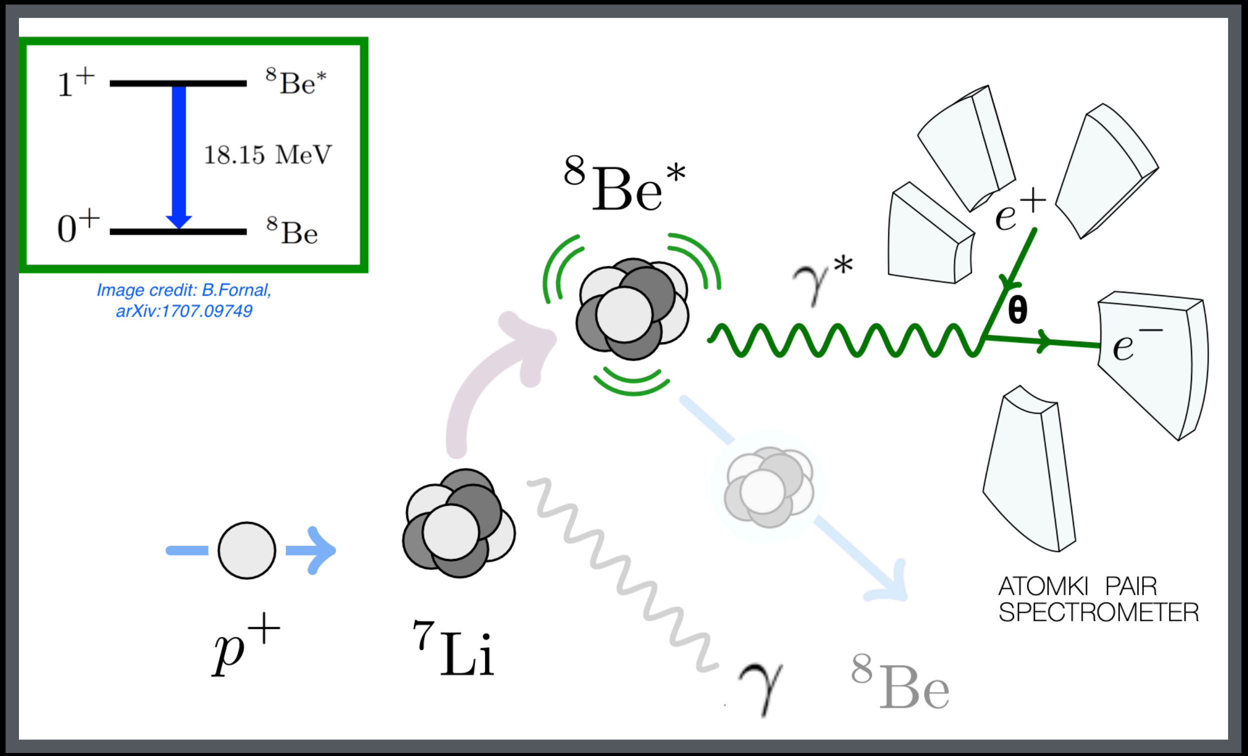
- New hadronic excitations predicted due to 6_C bonds between diquarks

- X17 solution proposed



X17 anomaly from ATOMKI experiments: Possible Hidden Color basis - JLab to search for 3-60 MeV dark sector bosons

- *First signal in* ^{8}Be: proton capture on ^{7}Li creates excited state of ^{8}Be. Decays to virtual photon which decays to $e^{+}e^{-}$ pair. ∃ an anomaly in the angular correlation which may be translated to the creation and decay of an intermediate ~16.9 MeV particle, dubbed the X17.



- *Also seen in* ^{4}He: proton capture on ^{3}H, same process.
- We can fit their data with a decay from a new subdominant excited state of ^{4}He:

$$E^{*} = 17.9 \pm 1\text{MeV}$$

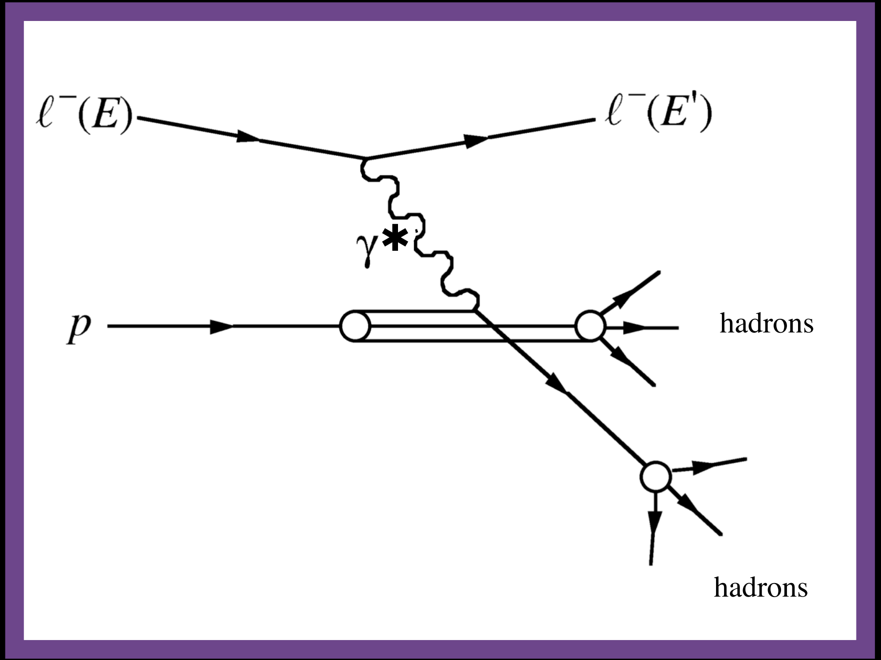
achieved with a hidden color excitation - radial or orbital - between 2 diquarks in the hexadiquark.

$$\Gamma_{^4\text{He}} = \int_{2m_e}^{m-m_0} dm_{e^+e^-} \left|\mathscr{M}_q\left(q^2\right)\right|^2 \left|p_e^*\right| \left|p_{He}\right|$$

"Quantum Chromodynamics Resolution of the ATOMKI Anomaly in 4He Nuclear Transitions"
V.Kubarovsky, JRW, S.J.Brodsky, 2206.14441

Bridge from QCD to nuclear: EMC effect

- Deep inelastic scattering (DIS) experiments
- 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: The fraction of nucleon momentum carried by the struck quark is known via the Bjorken scaling variable $x_B = \dfrac{Q^2}{2M_p \nu}$ where $\nu = E - E'$, M_p=mass of proton, lepton mass neglected



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

Differential cross section for DIS:

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

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

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

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

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

- 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.

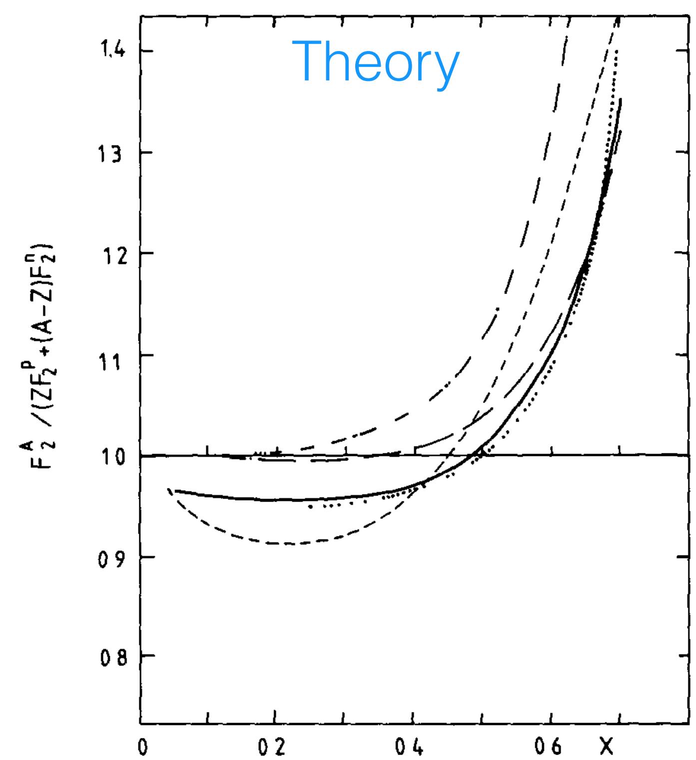


Fig. 1. Theoretical predictions for the Fermi motion correction of the nucleon structure function F_2^N for iron. Dotted line Few-nucleon-correlation-model of Frankfurt and Strikman [9]. Dashed line. Collective-tube-model of Berlad et al. [10] Solid line Correction according to Bodek and Ritchie [8]. 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.

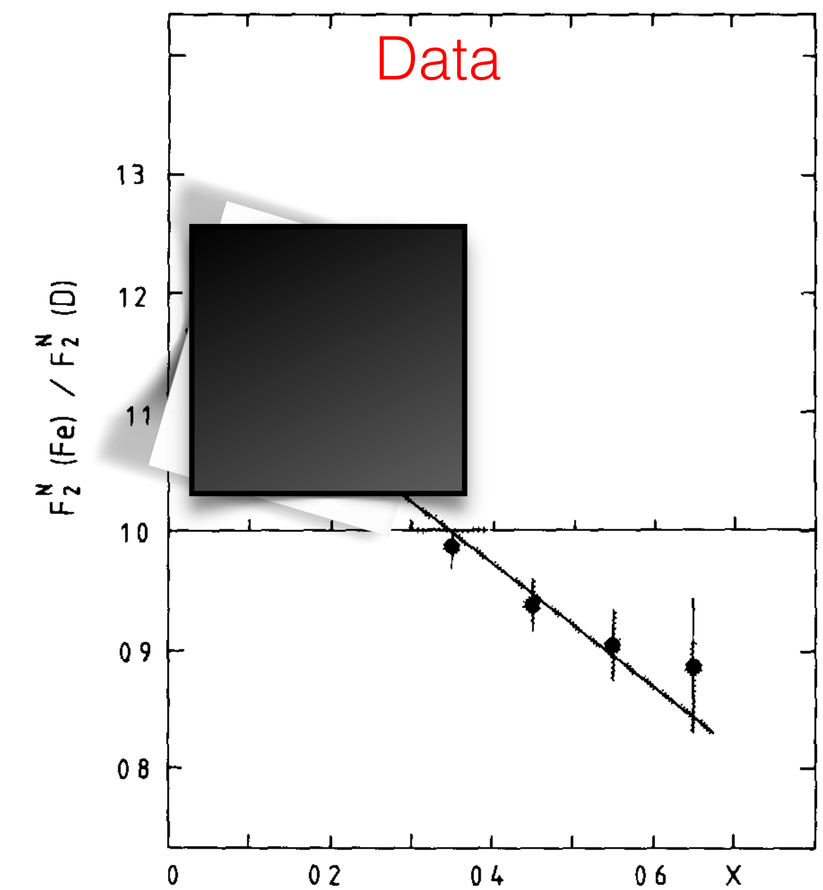
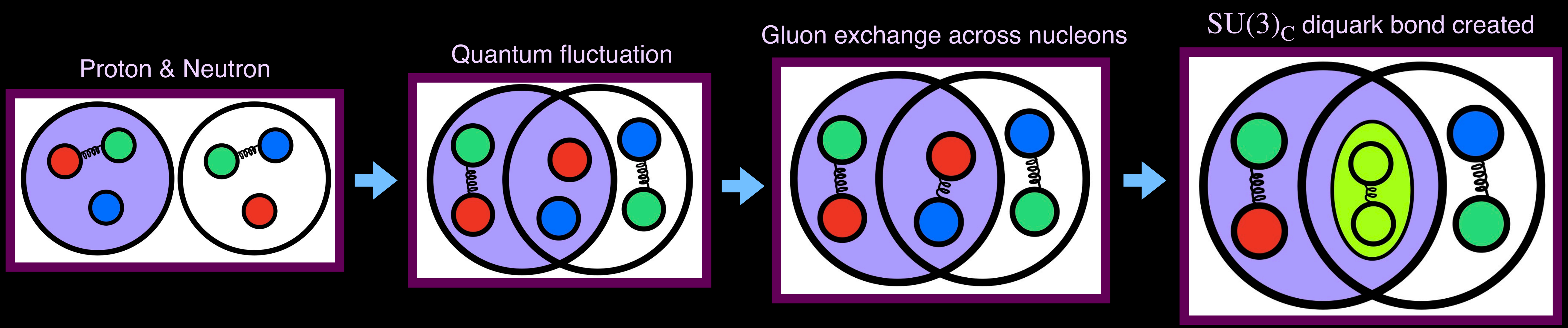


Fig. 2. The ratio of the nucleon structure functions F_2^N measured on iron and deuterium as a function of $x = Q^2/2M_p\nu$. The iron data are corrected for the non-isoscalarity of $^{56}_{26}$Fe, both data sets are not corrected for Fermi motion. The full curve is a linear fit $F_2^N(\mathrm{Fe})/F_2^N(\mathrm{D})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

Overview: Fundamental QCD dynamics in NN pairs

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



Color scheme: The 3 SU(3) color charges are the usual red, green, blue - anticolor charge of antigreen represented by lime green

Diquark-induced SRC

What causes the "short-range" part of short-range NN correlations?

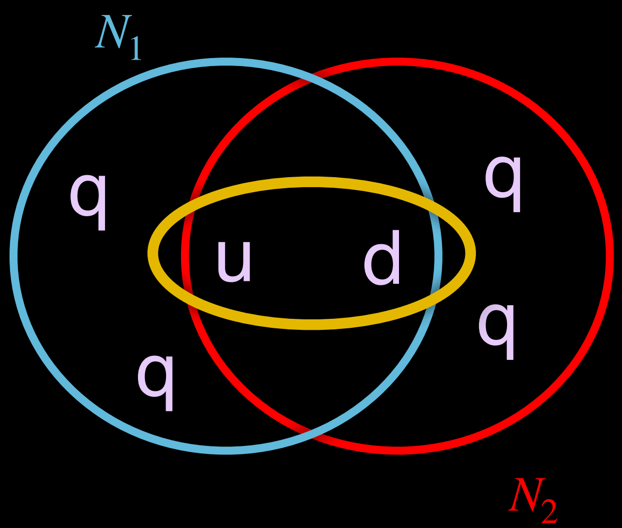
- Quantum fluctuations in separation distance between 2 nucleons
- Quantum fluctuations in relative momentum between 2 nucleons

How short is the range between the NN pair?

- SRC have relative momenta greater than the Fermi momentum, $k_F \sim 250\ \mathrm{MeV/c}$
- Translates to a center-to-center separation distance of $d_{\mathrm{NN}} \sim 0.79\ \mathrm{fm}$
- Radius of proton $r_p \sim 0.84\ \mathrm{fm}$
- Very large wavefunction overlap between SRC nucleons!

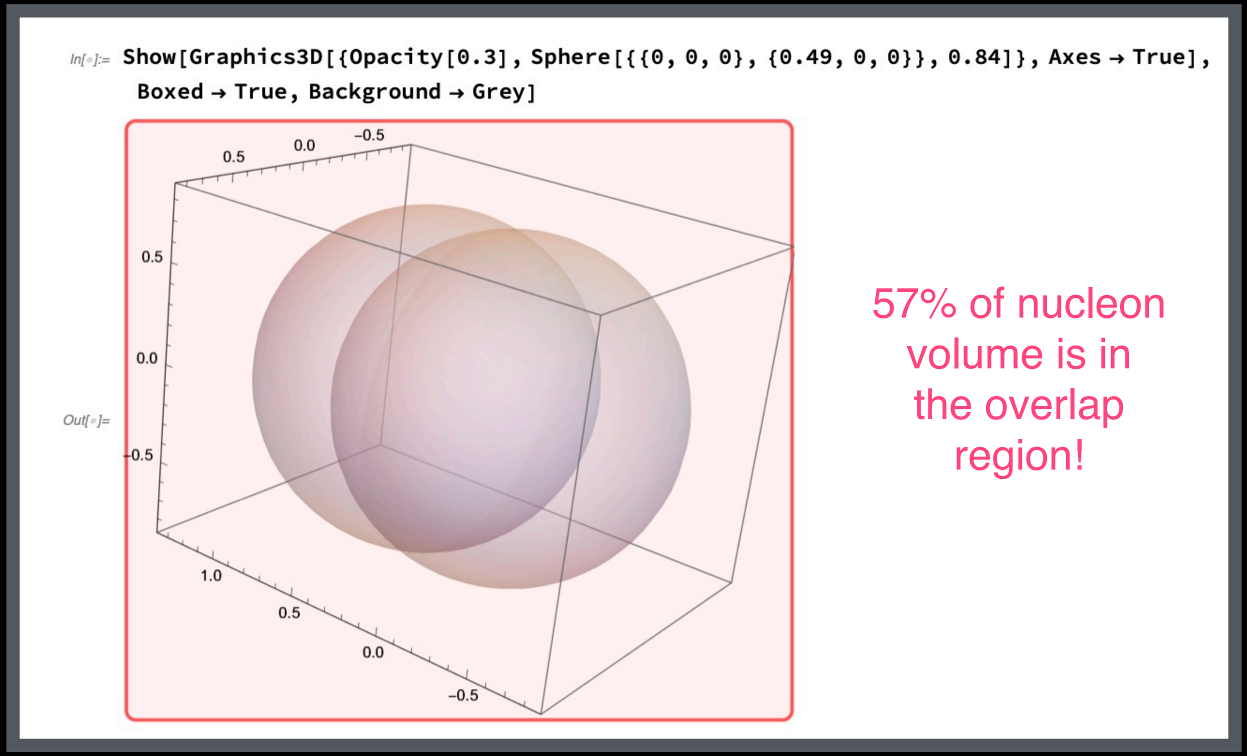
What causes the "correlation" in SRC?

- Diquark forms across nucleons
- Valence quarks from different nucleons "fall into" short-range quark-quark potential
- Highly energetically favorable $[ud]$ diquark created

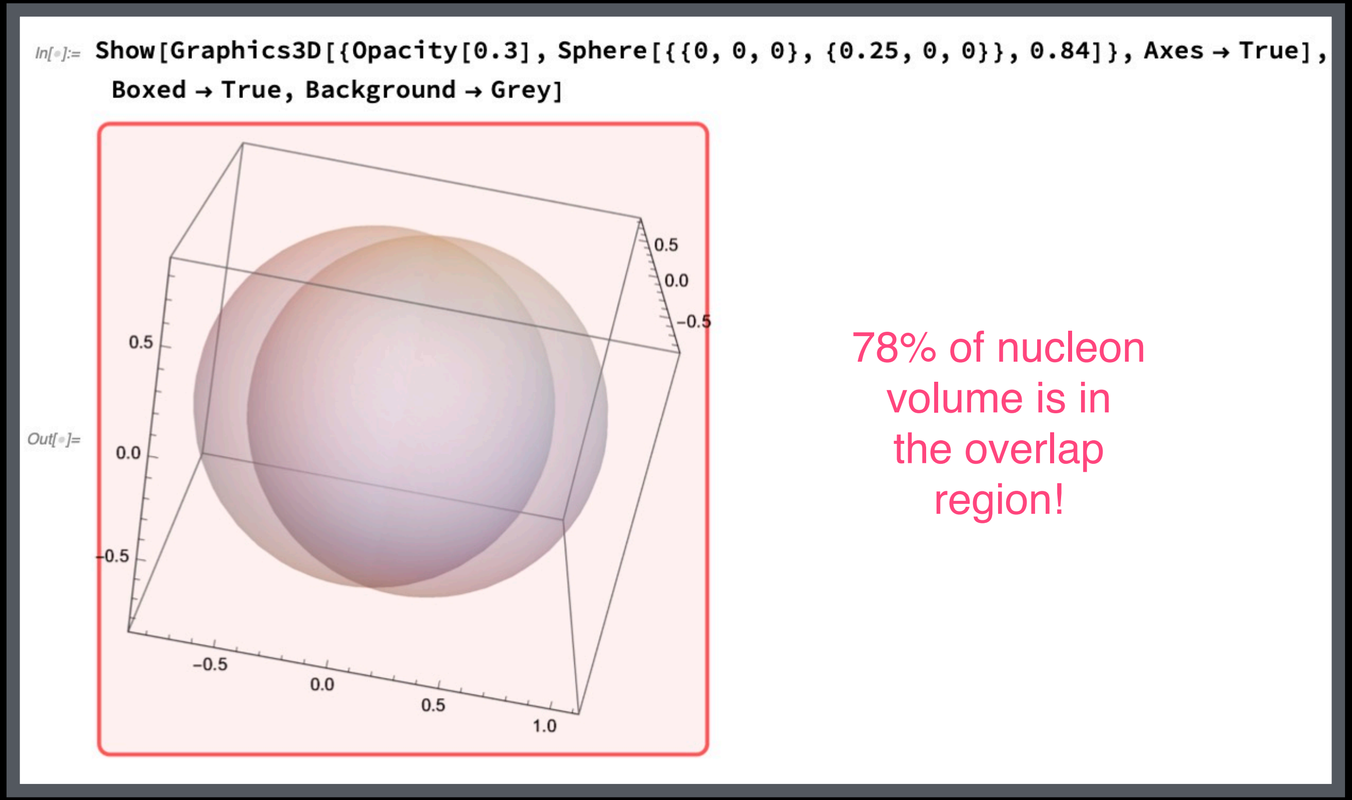


1. SRC 3D-overlap for relative momenta 400 MeV/c & 800 MeV/c

- *SRC Plot 1*: According to the ^{12}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.



- *SRC Plot 2*: Tensor-scalar transition momenta - according to the ^{12}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 .



Diquark formation across N-N pairs

<u>Requirements for diquark induced SRC:</u>

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) for spin-0 up-down diquark

Fin

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