# Diquarks as a QCD Breakthrough into Nuclear Physics
# (via Short-Range NN Correlations)

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# Overview: Fundamental QCD effects in nuclei

- Fundamental QCD degrees of freedom: color-charged quarks, gluons
- fQCD underlies all of nuclear physics but often unnecessary to descend to that level - Effective field theory sufficient
- Experimental puzzle: 1983 EMC effect, mysterious quark behavior in nuclei $\Longrightarrow$ possible fQCD effects on nuclear scales
- Diquark & Hexadiquark solutions proposed to affect structure functions $F_2$ - short-range QCD physics appears in nuclei

*Electron-Ion Collider*

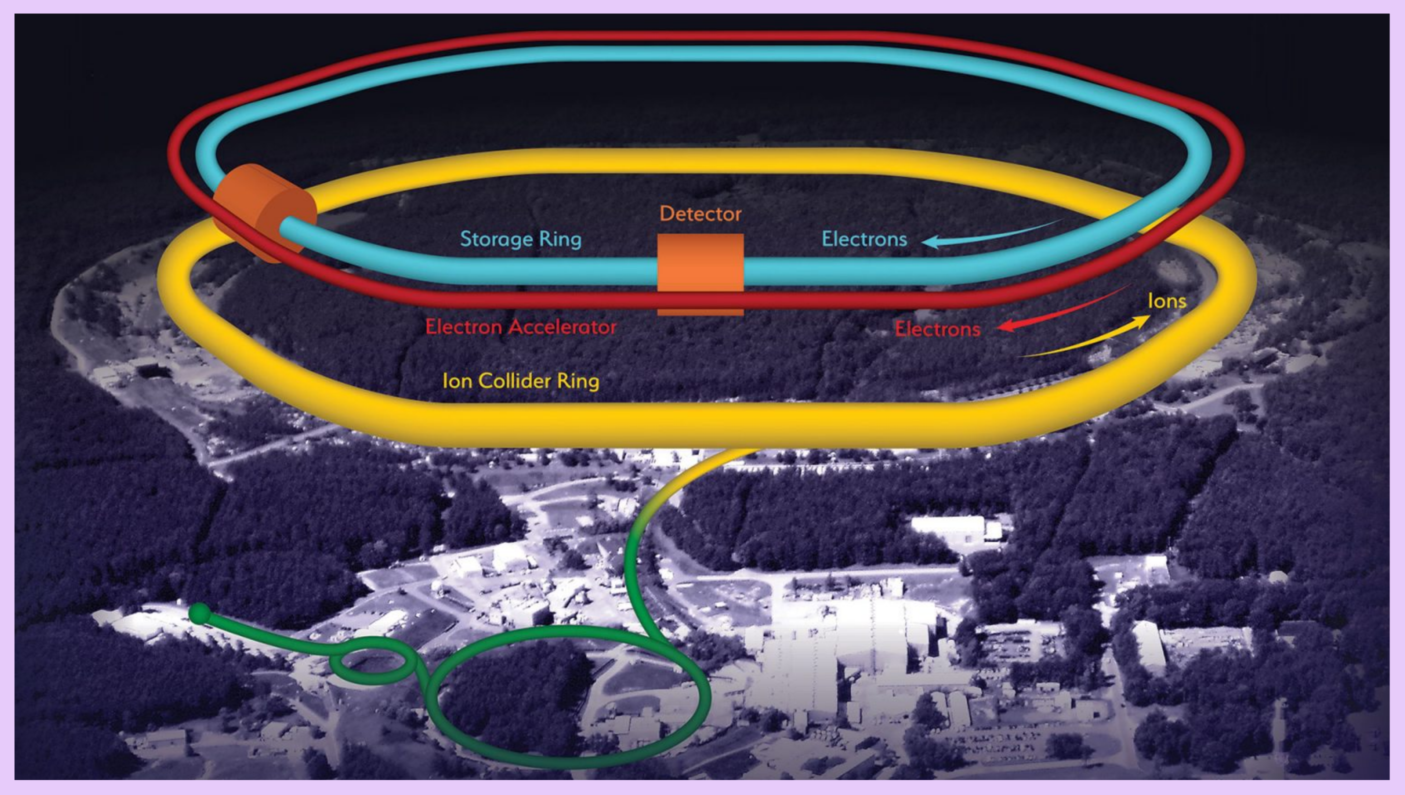


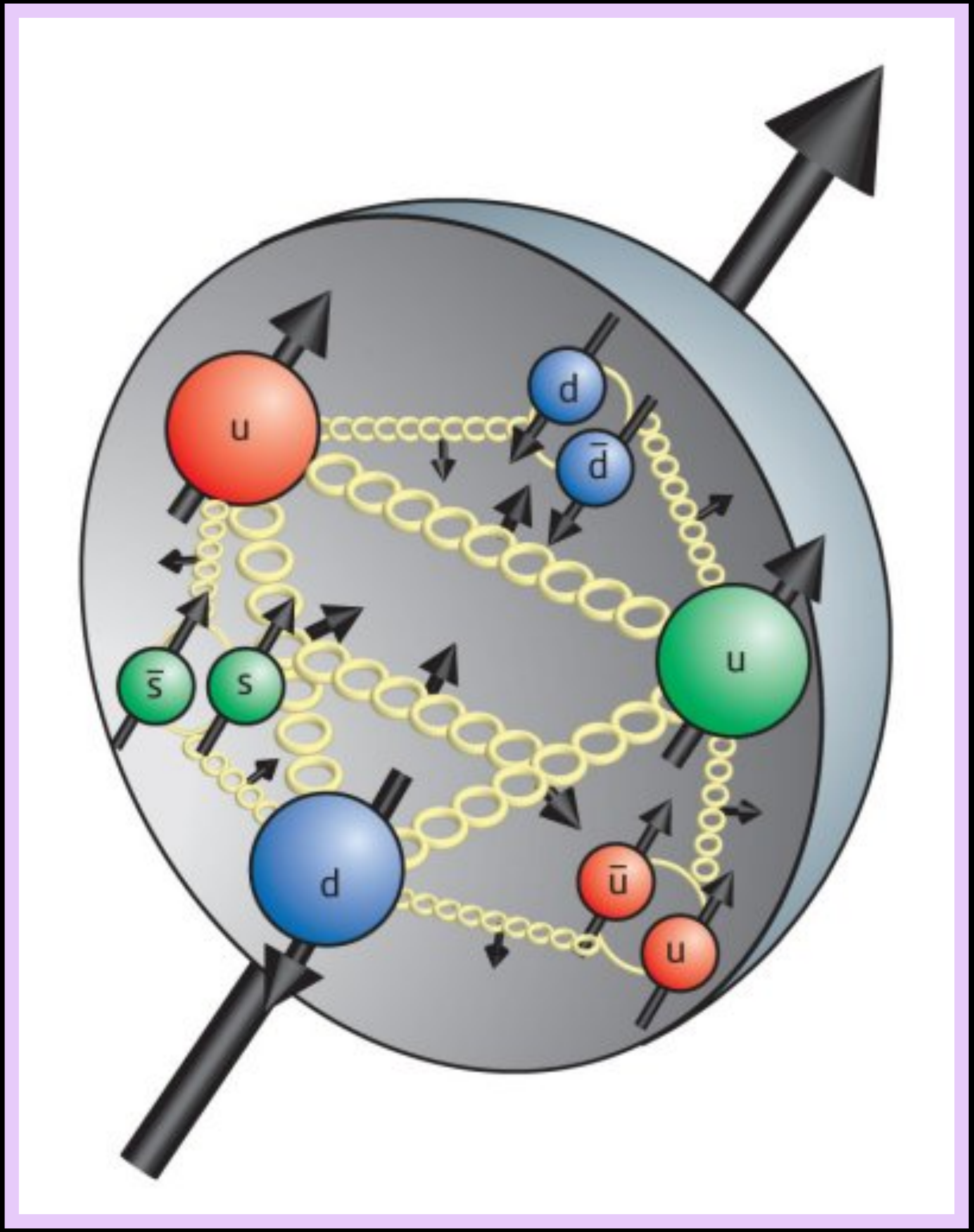
*Image credit: Brookhaven National Lab*

# Motivations for focusing on mysterious quark behavior in nuclei:

- QCD gives rise to mass, spin and dynamics of protons and neutrons - hadronic physics

- If short-range QCD is causing the distorted quark behavior in nuclei - this is the boundary between hadronic and nuclear physics - arguably, at the hadronic frontier as well

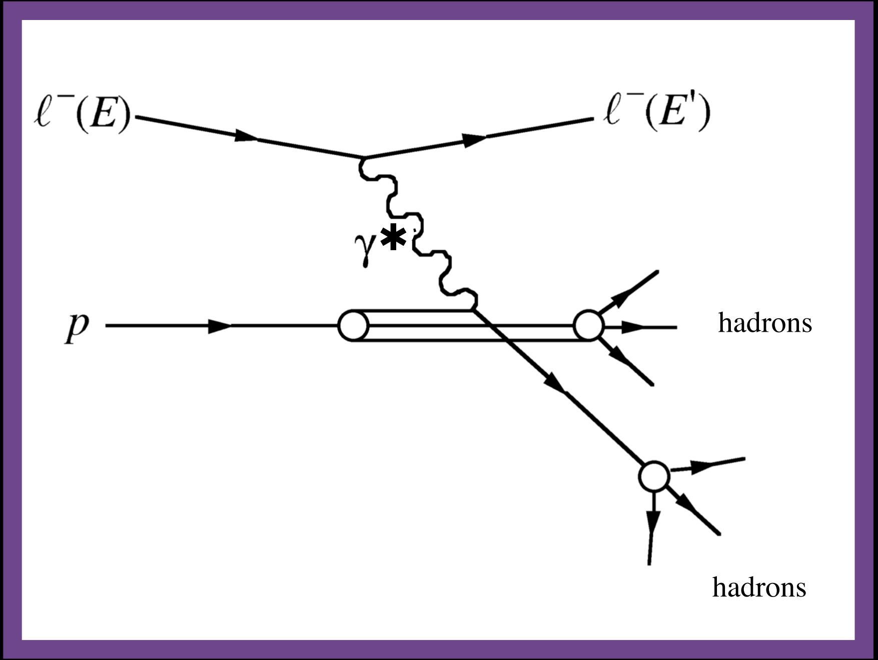
- *Other important hadronic frontier physics: Sea quark asymmetries, d/u measurements, neutron spin structure, deep dive into SRC & more*



*proton image: Quantum Diaries, Anna Phan 2012*

# EMC effect: Deep Inelastic Scattering

- Lepton scatters from target, exchanging virtual photon with 4-momentum $q^2$ given by: $Q^2 \equiv -q^2 = 2EE'(1-\cos\theta)$
- $\gamma^*$ strikes quark: We know the fraction of nucleon momentum carried by the struck quark via the Bjorken scaling variable $x_B = \dfrac{Q^2}{2M_p \nu}$ where $\nu = E - E'$, $M_p$=mass of proton, lepton masses neglected
- EMC plots: Ratio 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 $y = \dfrac{\nu}{E}$ is the fraction of $\ell^-$ energy transferred to the target. $F_2(x)$ is the **nucleon 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

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

- 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 $\gtrsim$ 2.2 MeV?
- Mystery has not been solved to this day.

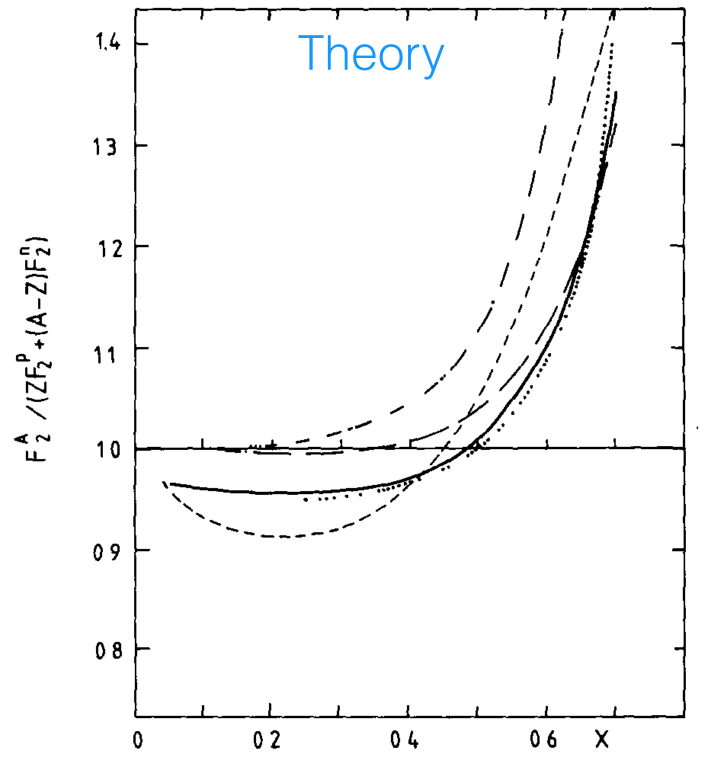


Fig. 1. Theoretical predictions for the Fermi motion correction of the nucleon structure function $F_2^N$ for iron. Dotted line Few-nucleon-correlation-model of Frankfurt and Strikman [9]. Dashed line. Collective-tube-model of Berlad et al. [10] Solid line Correction according to Bodek and Ritchie [8].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

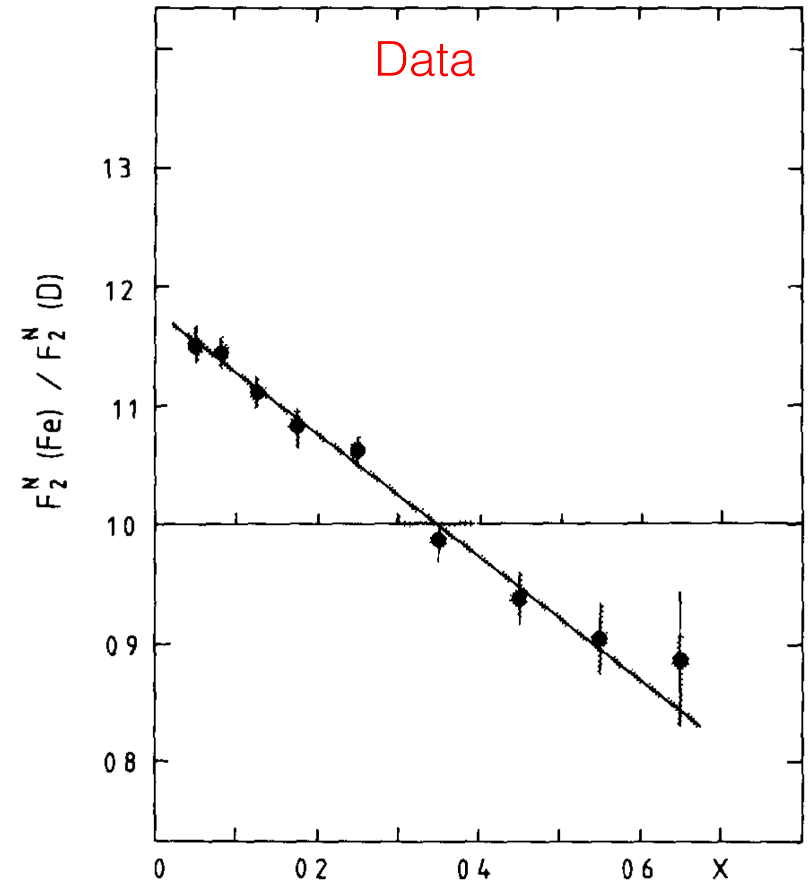


Fig. 2. The ratio of the nucleon structure functions $F_2^N$ measured on iron and deuterium as a function of $x = Q^2/2M_p\nu$. The iron data are corrected for the non-isoscalarity of $^{56}_{26}$Fe, both data sets are not corrected for Fermi motion. The full curve is a linear fit $F_2^N(\mathrm{Fe})/F_2^N(\mathrm{D})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

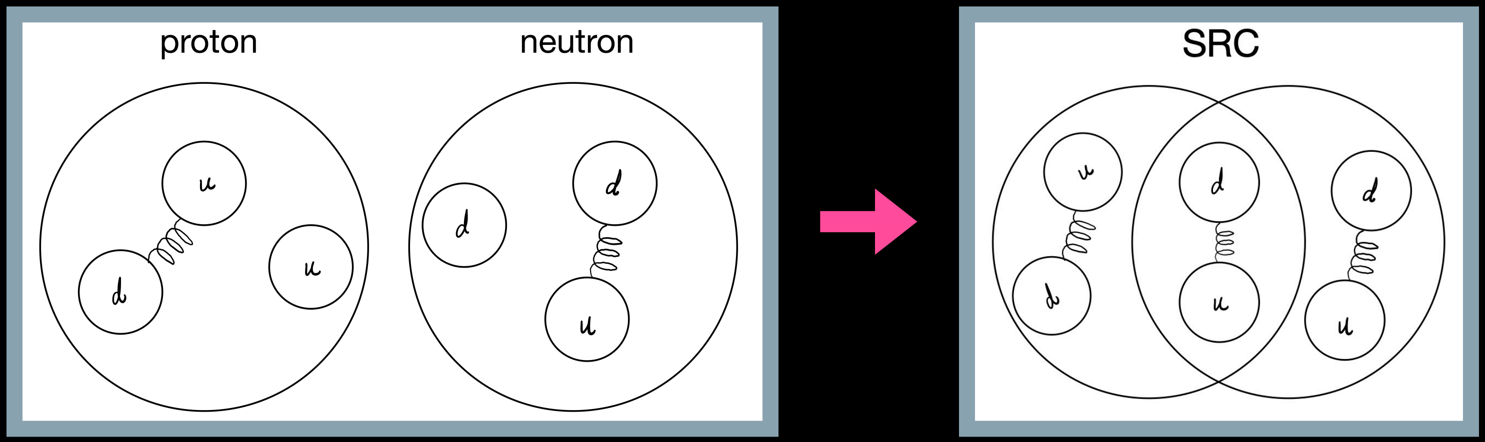
- Mean field effects involving the whole nucleus
- Local effects, *e.g.*, 2-nucleon correlations

Simple mean field effects inconsistent with the EMC effect in light nuclei - MC of $^{9}\text{Be} \Longrightarrow$clustering
Seely *et al.*, 2009.

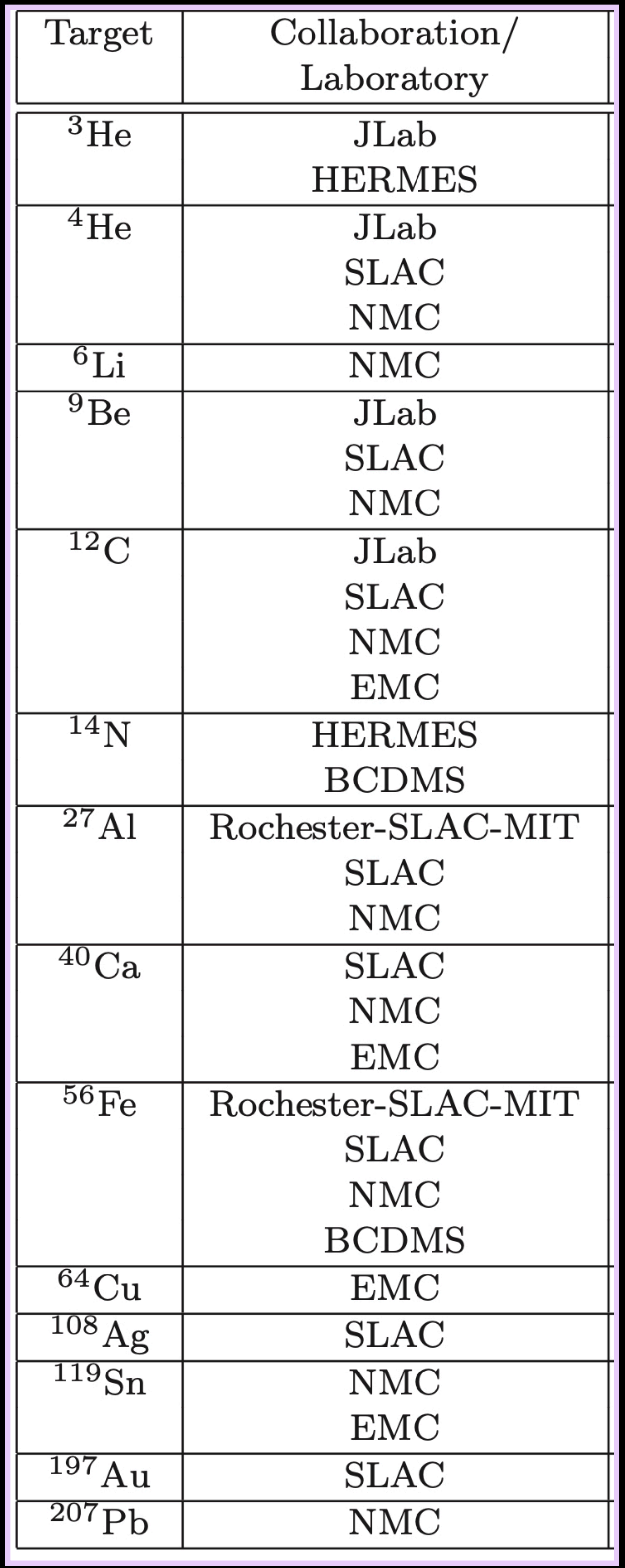
“This one new bit of information has reinvigorated the experimental and theoretical efforts to pin down the underlying cause of the EMC effect.” *Malace et al., 2014*

Short-range N-N correlated pairs (SRC) may cause EMC effect (first suggested in *Ciofi & Liuti 1990, 1991*).
*Neutron-proton pairs later 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

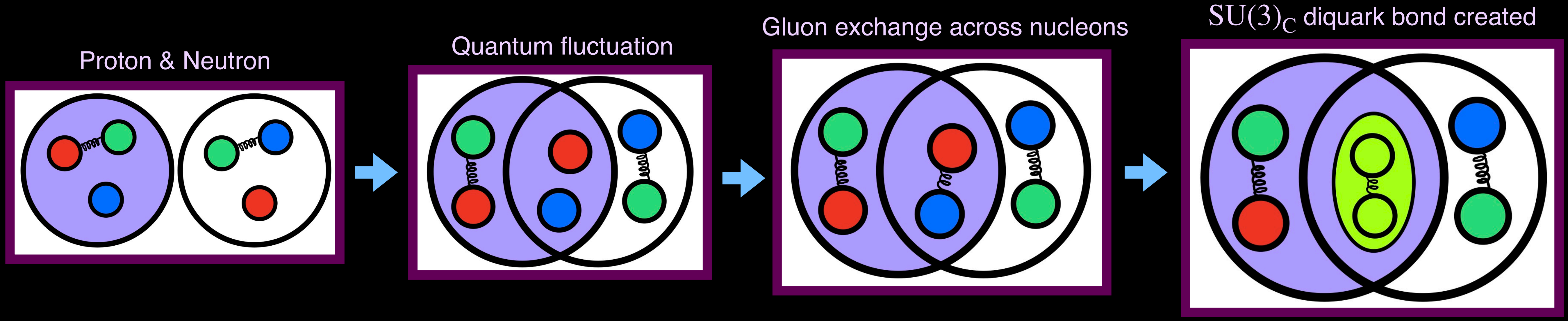


| Target | Collaboration/ Laboratory |
|---|---|
| $^{3}$He | JLab<br>HERMES |
| $^{4}$He | JLab<br>SLAC<br>NMC |
| $^{6}$Li | NMC |
| $^{9}$Be | JLab<br>SLAC<br>NMC |
| $^{12}$C | JLab<br>SLAC<br>NMC<br>EMC |
| $^{14}$N | HERMES<br>BCDMS |
| $^{27}$Al | Rochester-SLAC-MIT<br>SLAC<br>NMC |
| $^{40}$Ca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

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

# 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



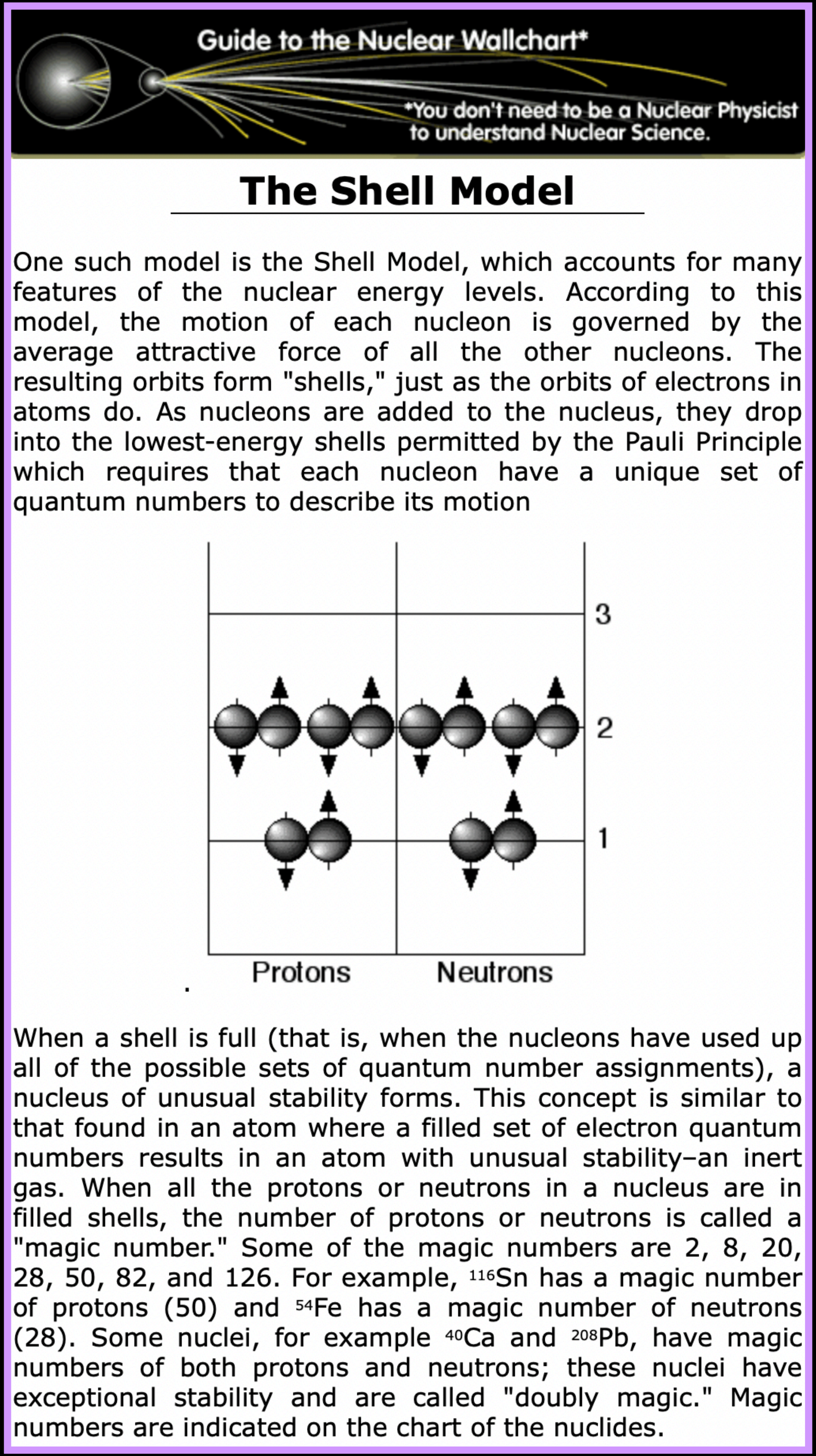
Short-range QCD potentials act on distance scales < 1 fm. Strong NN overlap can bring valence quarks within range.

# What are SRC?
# Short-range correlated nucleon-nucleon pairs

- Nuclei consist of protons and neutrons ~80% of which are organized into shells/ LRC
- Nuclear shell model is a "description of nuclei of atoms by analogy with the Bohr atomic model of electron energy levels.
- It was developed independently in the late 1940s by the American physicist Maria Goeppert Mayer and the German physicist J. Hans D. Jensen, who shared the Nobel Prize for Physics in 1963 for their work."
  *- William L. Hosch, www.britannica.com*

*~20% of nucleons are in short-range correlated pairs - not shells/LRC*

- SRC have very high relative momentum - nearly all nucleons above the Fermi momentum of the nucleus, $k_F \sim 250\ \mathrm{MeV/c}$, are in SRC



Guide to the Nuclear Wallchart*

*You don't need to be a Nuclear Physicist to understand Nuclear Science.

**The Shell Model**

One such model is the Shell Model, which accounts for many features of the nuclear energy levels. According to this model, the motion of each nucleon is governed by the average attractive force of all the other nucleons. The resulting orbits form "shells," just as the orbits of electrons in atoms do. As nucleons are added to the nucleus, they drop into the lowest-energy shells permitted by the Pauli Principle which requires that each nucleon have a unique set of quantum numbers to describe its motion

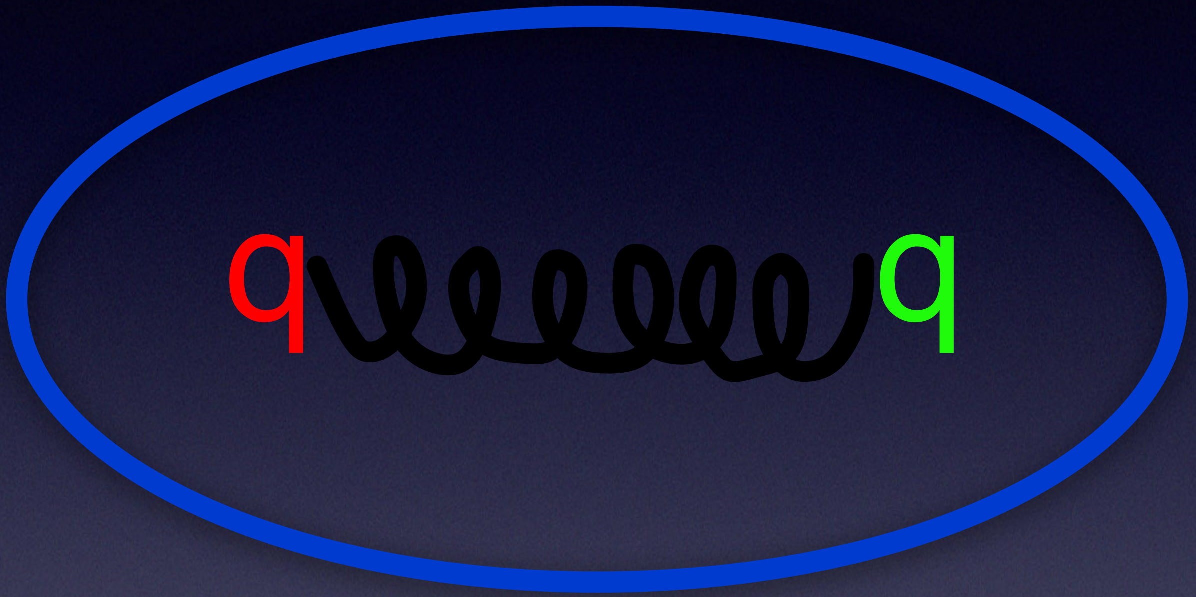
When a shell is full (that is, when the nucleons have used up all of the possible sets of quantum number assignments), a nucleus of unusual stability forms. This concept is similar to that found in an atom where a filled set of electron quantum numbers results in an atom with unusual stability–an inert gas. When all the protons or neutrons in a nucleus are in filled shells, the number of protons or neutrons is called a "magic number." Some of the magic numbers are 2, 8, 20, 28, 50, 82, and 126. For example, $^{116}$Sn has a magic number of protons (50) and $^{54}$Fe has a magic number of neutrons (28). Some nuclei, for example $^{40}$Ca and $^{208}$Pb, have magic numbers of both protons and neutrons; these nuclei have exceptional stability and are called "doubly magic." Magic numbers are indicated on the chart of the nuclides.

*www2.lbl.gov/abc/wallchart/chapters/06/1.html*

# What is a diquark?

- 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:

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



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 $\Lambda$ production)

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

What are diquark-induced short-range correlations (SRC)?

# Diquark-induced SRC

## What causes the “short-range” part of short-range NN correlations?

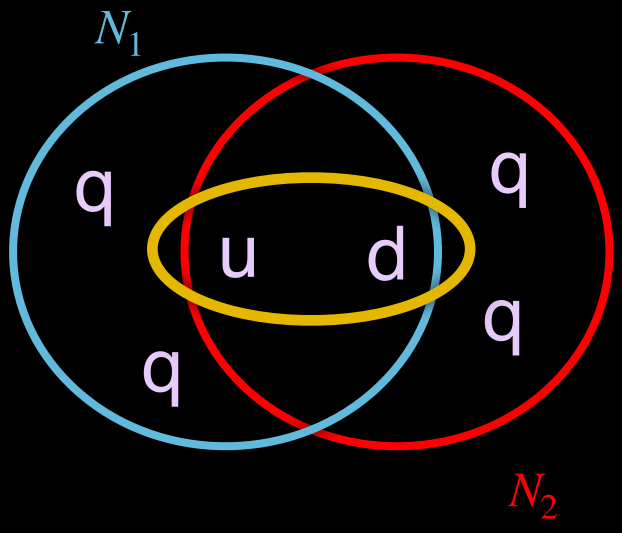
- Quantum fluctuations in separation distance between 2 nucleons

*or*

- Quantum fluctuations in relative momentum between 2 nucleons

## What causes the “correlation” in SRC?

- Diquark forms across nucleons
- Valence quarks from different nucleons “fall into” short-range QCD potential V(r)
- Highly energetically favorable $[ud]$ diquark created, a spin-0, isospin-0 qq combination



# 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:

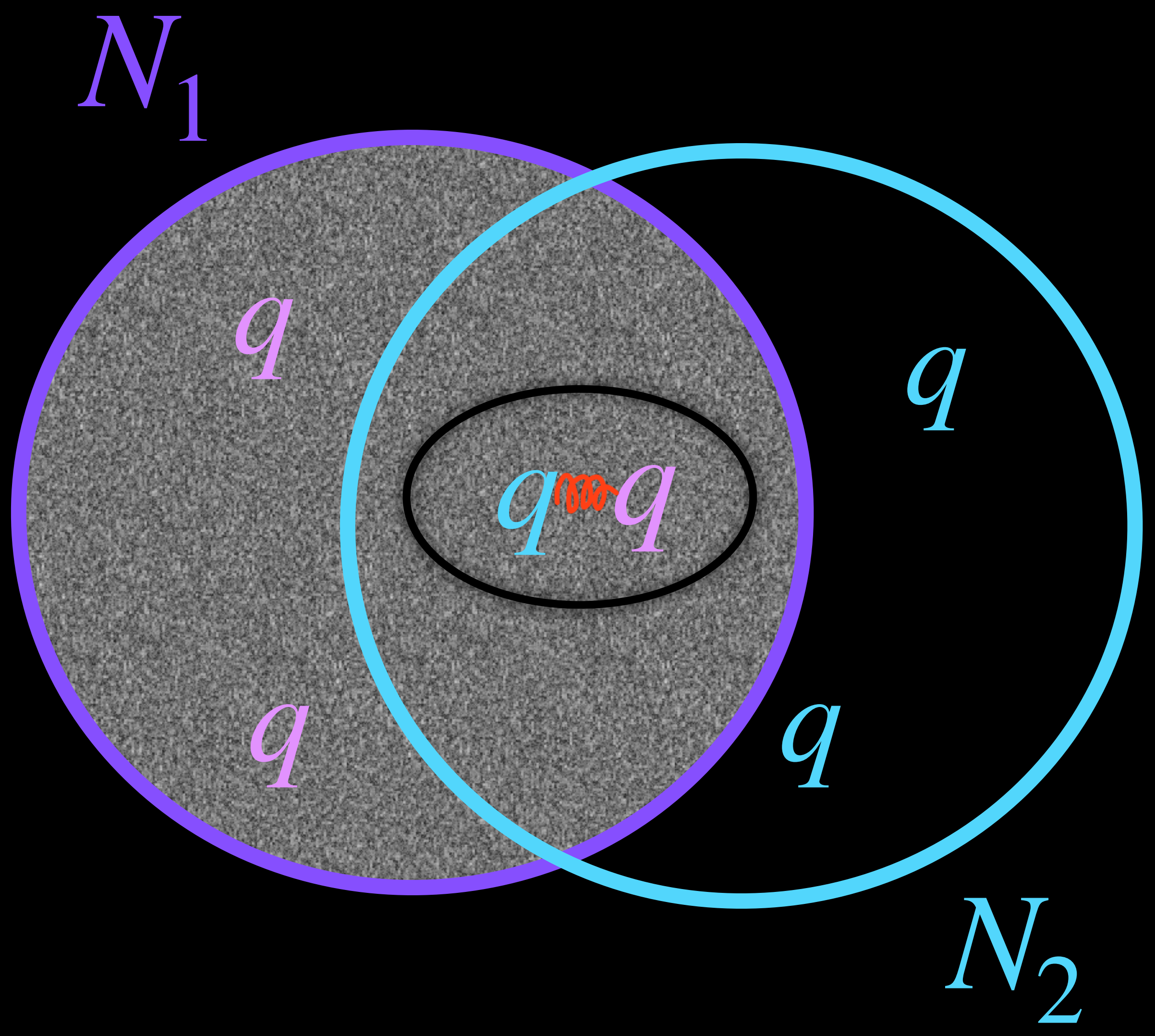
$$\Psi_{[ud]'} \propto \underset{\substack{\uparrow \\ \text{Antisymmetric}}}{\psi_{\text{color}}} \; \psi_{\text{spin}} \; \psi_{\text{iso}} \; \underset{\substack{\uparrow \\ \text{Symmetric, L=0}}}{\psi_{\text{space}}}$$

What are the requirements for a diquark to form in the nuclear environment?
(not inside of a single baryon)

# Diquark formation across N-N pairs

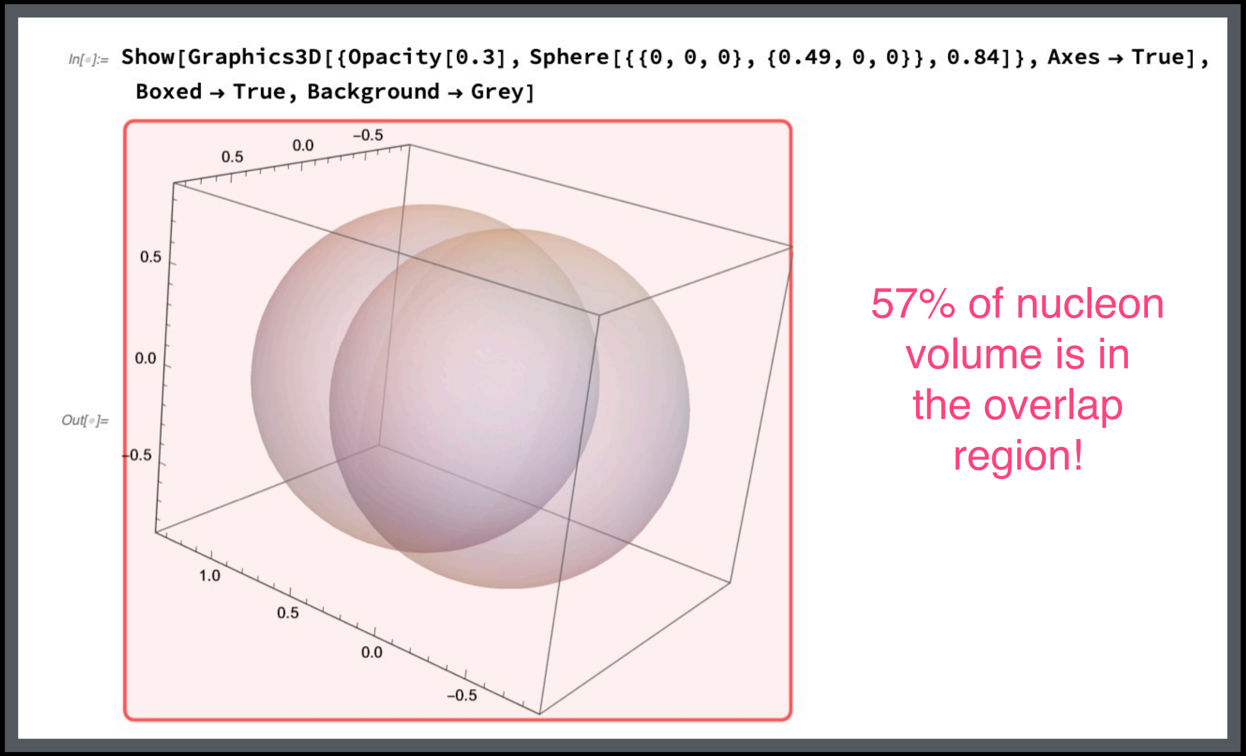
Requirements for diquark induced SRC:

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)



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

- *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.



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         Boxed → True, Background → Grey]
Out[•]=
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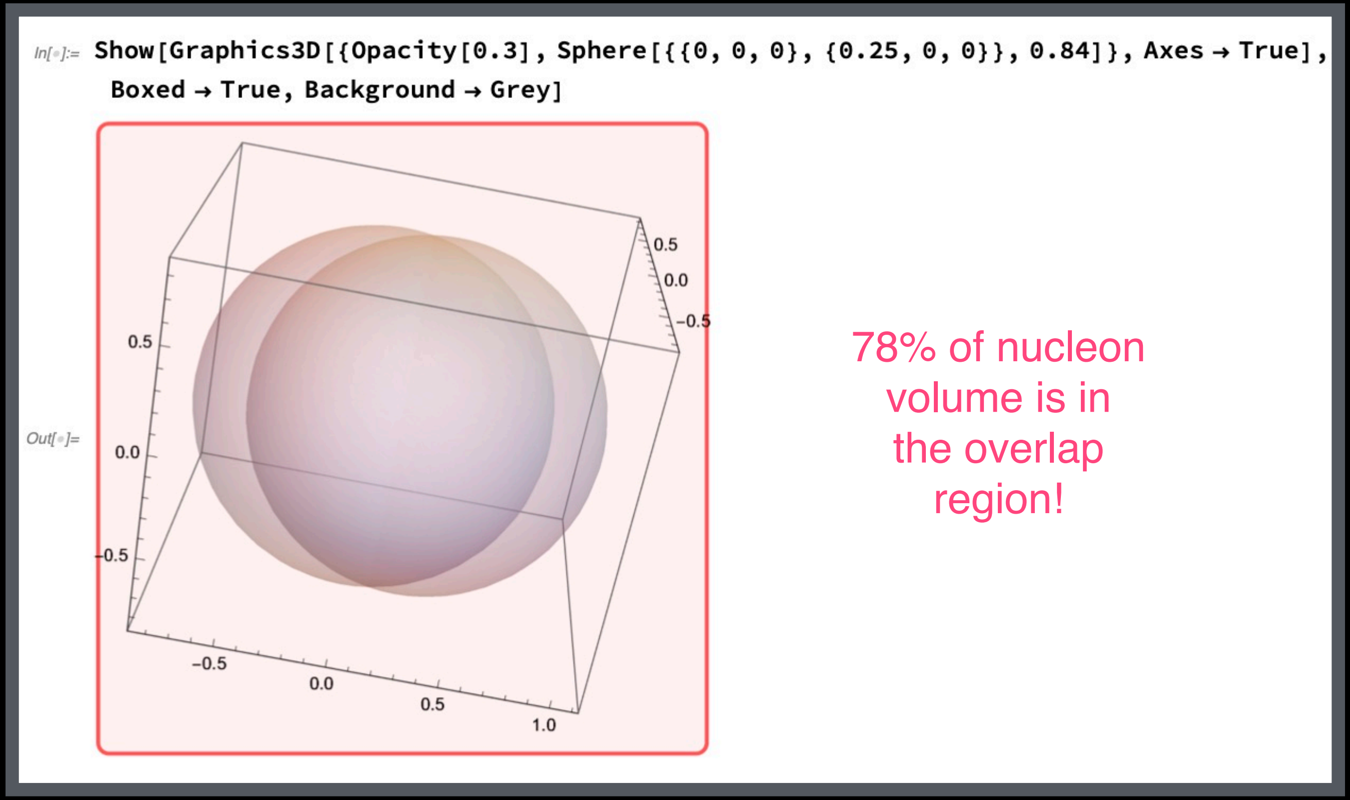
57% of nucleon volume is in the overlap region!

- *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]
Out[•]=
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78% of nucleon volume is in the overlap region!

# 2. Quark-quark potential in QCD: $V(r)$ calculation

- The $\mathrm{SU}(3)_C$ invariant QCD Lagragian:

$$\mathscr{L}_{\mathrm{QCD}} = -\frac{1}{4}F^{\mu\nu a}F^{a}_{\mu\nu} + \bar{\Psi}_f\left(i\gamma^\mu D_\mu - m\right)\Psi_f$$

where covariant derivative $D_\mu = \partial_\mu - ig_s A^a_\mu t^a$ acts on quark fields, $t^a$ are the 3x3 traceless Hermitian matrices (e.g. the 8 Gell-Mann matrices), $g_s$ the strong interaction coupling, $\alpha_s \equiv \frac{g_s^2}{4\pi}$.

- QCD potential for states in representations $R$ and $R'$ is given by:

$$V(r) = \frac{g_s^2}{4\pi r} t^a_R \otimes t^a_{R'}$$

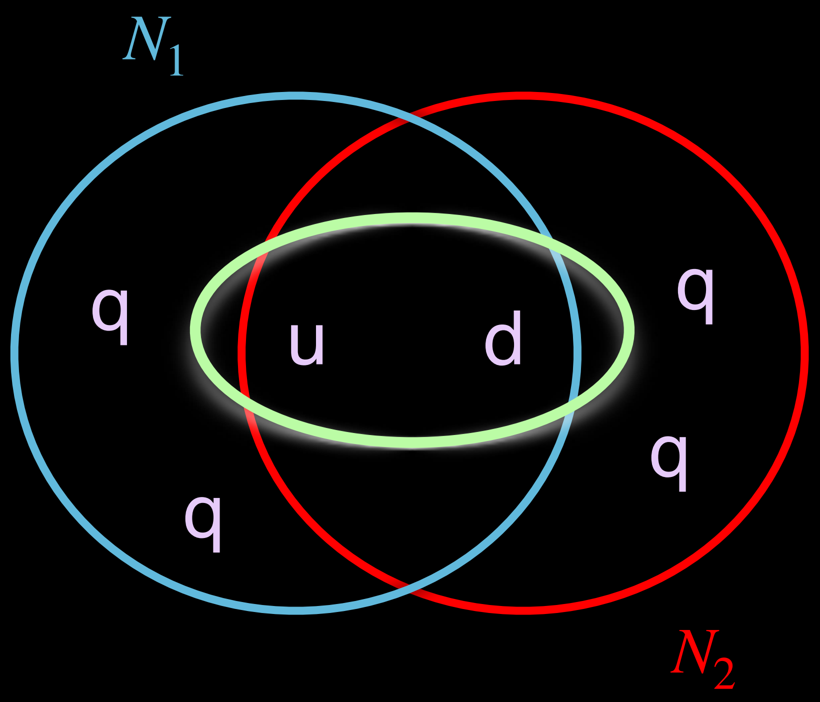
- To compute $V(r)$ for a $3_c \otimes 3_c \rightarrow \bar{3}_{c'}$, we use the definition of the scalar $C_2(R)$, $t^a_R\ t^a_R \equiv C_2(R)\ \mathbf{1}$, the *quadratic Casimir operator* (NB: $R_f$ is the final state representation):

$$V(r) = \frac{g_s^2}{4\pi r}\cdot\frac{1}{2}\cdot\left(C_2\left(R_f\right) - C_2(R) - C_2(R')\right)$$

- Diquarks combine 2 fundamental representation quarks into an anti-fundamental, $3_C \otimes 3_c \rightarrow \bar{3}_C$:

$$\boxed{V(r) = -\frac{2}{3}\frac{g_s^2}{4\pi r} \Longrightarrow \text{Diquark is bound!}}$$

Diquark induced N-N correlation:



Compare to color singlet attractive potential:

$$\boxed{q\bar{q}:\quad V(r) = -\frac{4}{3}\frac{g_s^2}{4\pi r}}$$

# 3. Diquark binding energy: Color hyperfine structure

Use $\Lambda^0$ baryon to find binding energy of $[ud]$ :

$$\text{B.E.}_{[ud]} = m_u^b + m_d^b + m_s^b - M_{\Lambda^0}$$

Spin-spin interaction contribute to hadron mass; QCD hyperfine interactions:

1. $M_{(\text{baryon})} = \sum_{i=1}^{3} m_i + a' \sum_{i<j} \left(\sigma_i \cdot \sigma_j\right) / m_i m_j$
2. $M_{(\text{meson})} = m_1 + m_2 + a \left(\sigma_1 \cdot \sigma_2\right) / m_1 m_2$

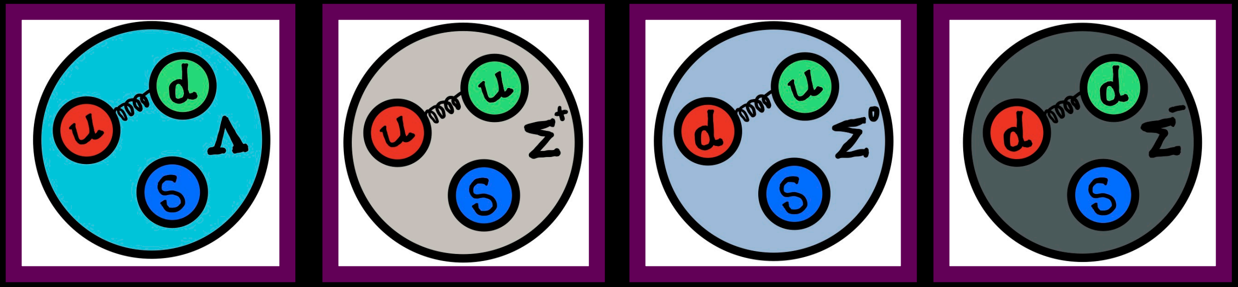
*(de Rujula, Georgi & Glashow 1975, Gasiorowicz & Rosner 1981, Karliner & Rosner 2014)*

Effective masses of light quarks are found using Eq.1 and fitting to measured baryon masses:

$$m_u^b = m_d^b \equiv m_q^b = 363 \text{ MeV}, \;\; \text{m}_\text{s}^\text{b} = 538 \text{ MeV}$$

$$\text{B.E.}_{[ud]} = m_u^b + m_d^b + m_s^b - M_\Lambda = 148 \;\pm\; 9 \text{ MeV}$$

Relevant diquark-carrying baryons: $\Lambda$, $\Sigma^+$, $\Sigma^0$, $\Sigma^-$



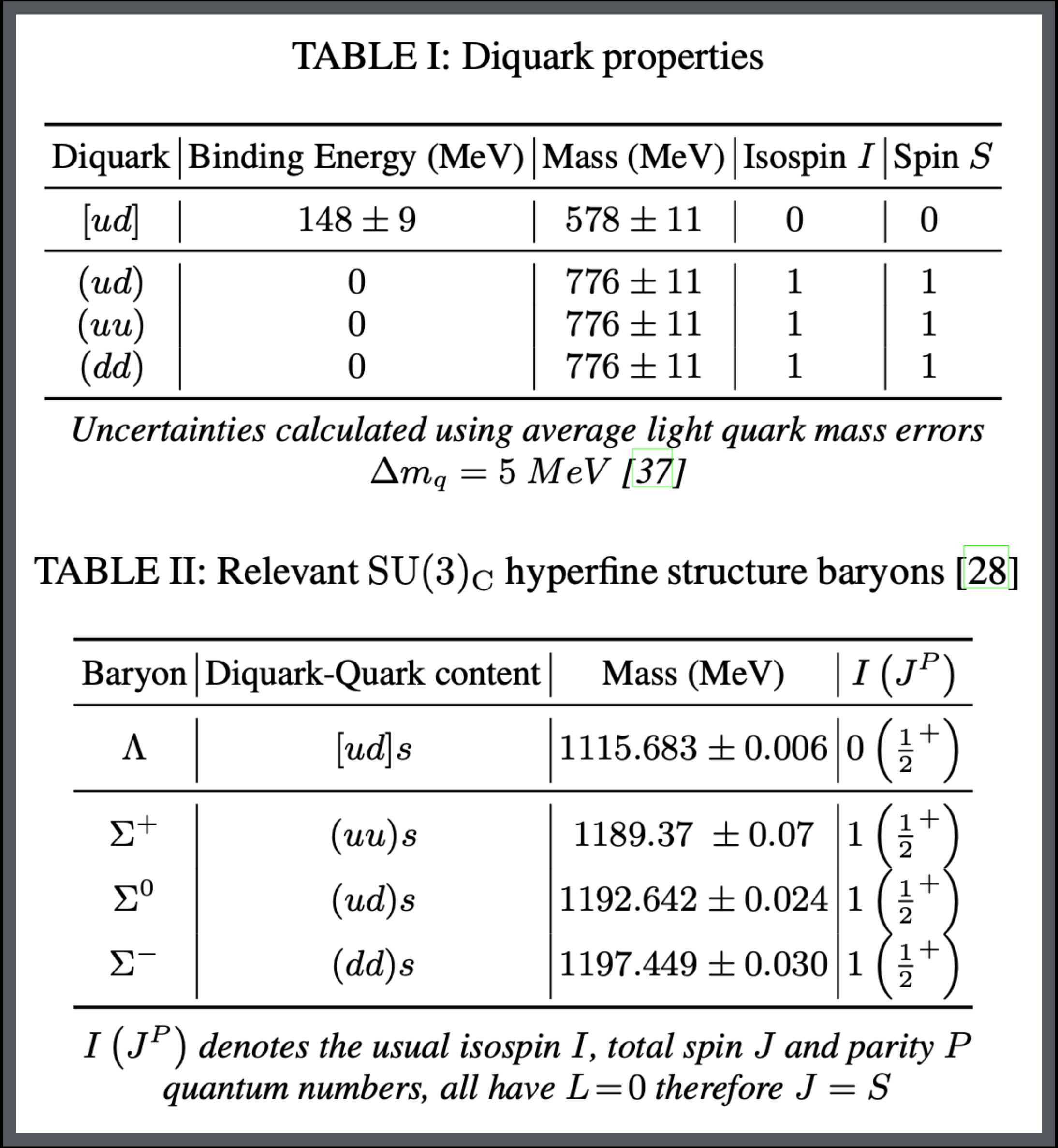


TABLE I: Diquark properties

| Diquark | Binding Energy (MeV) | Mass (MeV) | Isospin $I$ | Spin $S$ |
|---|---|---|---|---|
| $[ud]$ | $148 \pm 9$ | $578 \pm 11$ | 0 | 0 |
| $(ud)$ | 0 | $776 \pm 11$ | 1 | 1 |
| $(uu)$ | 0 | $776 \pm 11$ | 1 | 1 |
| $(dd)$ | 0 | $776 \pm 11$ | 1 | 1 |

*Uncertainties calculated using average light quark mass errors* $\Delta m_q = 5 \; MeV$ *[37]*

TABLE II: Relevant $\text{SU}(3)_\text{C}$ hyperfine structure baryons [28]

| Baryon | Diquark-Quark content | Mass (MeV) | $I\left(J^P\right)$ |
|---|---|---|---|
| $\Lambda$ | $[ud]s$ | $1115.683 \pm 0.006$ | $0\left(\frac{1}{2}^+\right)$ |
| $\Sigma^+$ | $(uu)s$ | $1189.37 \pm 0.07$ | $1\left(\frac{1}{2}^+\right)$ |
| $\Sigma^0$ | $(ud)s$ | $1192.642 \pm 0.024$ | $1\left(\frac{1}{2}^+\right)$ |
| $\Sigma^-$ | $(dd)s$ | $1197.449 \pm 0.030$ | $1\left(\frac{1}{2}^+\right)$ |

*$I\left(J^P\right)$ denotes the usual isospin $I$, total spin $J$ and parity $P$ quantum numbers, all have $L=0$ therefore $J = S$*

*"Diquark Induced Nucleon-Nucleon Correlations and the EMC Effect," JRW, arXiv:2009.06968*

# 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)

✓

What are the implications of NN diquark formation?
Quark flavor dependence of low mass $[ud]$ will affect the np vs. pp SRC!

# Diquark formation prediction for A=3 SRC: Isospin

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

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

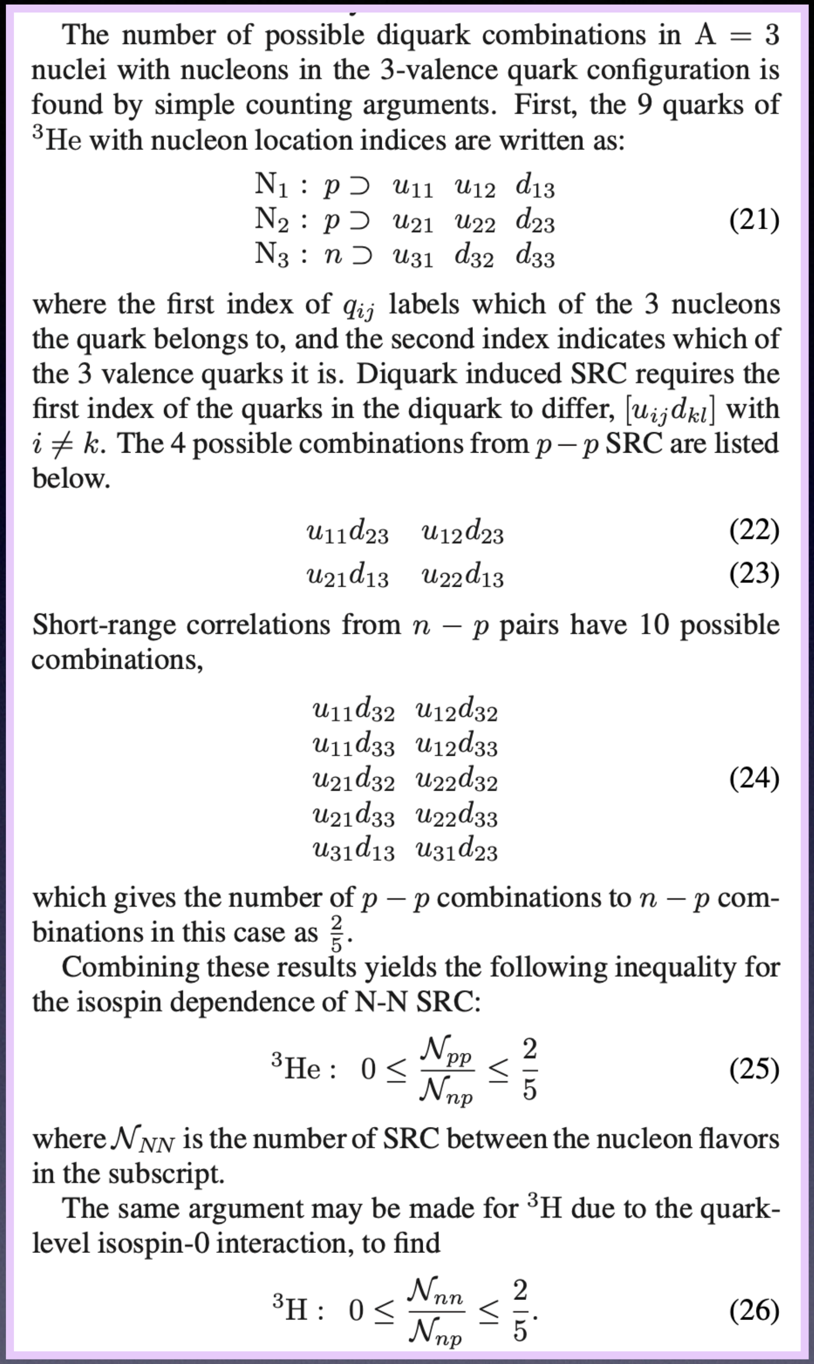
$$^3H: \quad 2n + p \rightarrow 4u,\, 5d \implies np \supset [ud]\ \mathrm{x}10 \implies nn \supset [ud]\ \mathrm{x}4 \implies 60\,\%\ n-p,\ 40\,\%\ n-n$$

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

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

$$^3H: \quad u\ [ud]\ +\ u\ [ud]\ +\ d\ [ud] \implies 100\,\%\ n-p$$

$$^3He: \quad d\ [ud]\ +\ d\ [ud]\ +\ u\ [ud] \implies 100\,\%\ n-p$$



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:

$$\begin{array}{l} \mathrm{N}_1 : p \supset \; u_{11} \;\; u_{12} \;\; d_{13} \\ \mathrm{N}_2 : p \supset \; u_{21} \;\; u_{22} \;\; d_{23} \\ \mathrm{N}_3 : n \supset \; u_{31} \;\; d_{32} \;\; d_{33} \end{array} \tag{21}$$

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.

$$u_{11}d_{23} \quad u_{12}d_{23} \tag{22}$$

$$u_{21}d_{13} \quad u_{22}d_{13} \tag{23}$$

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

$$\begin{array}{ll} u_{11}d_{32} & u_{12}d_{32} \\ u_{11}d_{33} & u_{12}d_{33} \\ u_{21}d_{32} & u_{22}d_{32} \\ u_{21}d_{33} & u_{22}d_{33} \\ u_{31}d_{13} & u_{31}d_{23} \end{array} \tag{24}$$

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:

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

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

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

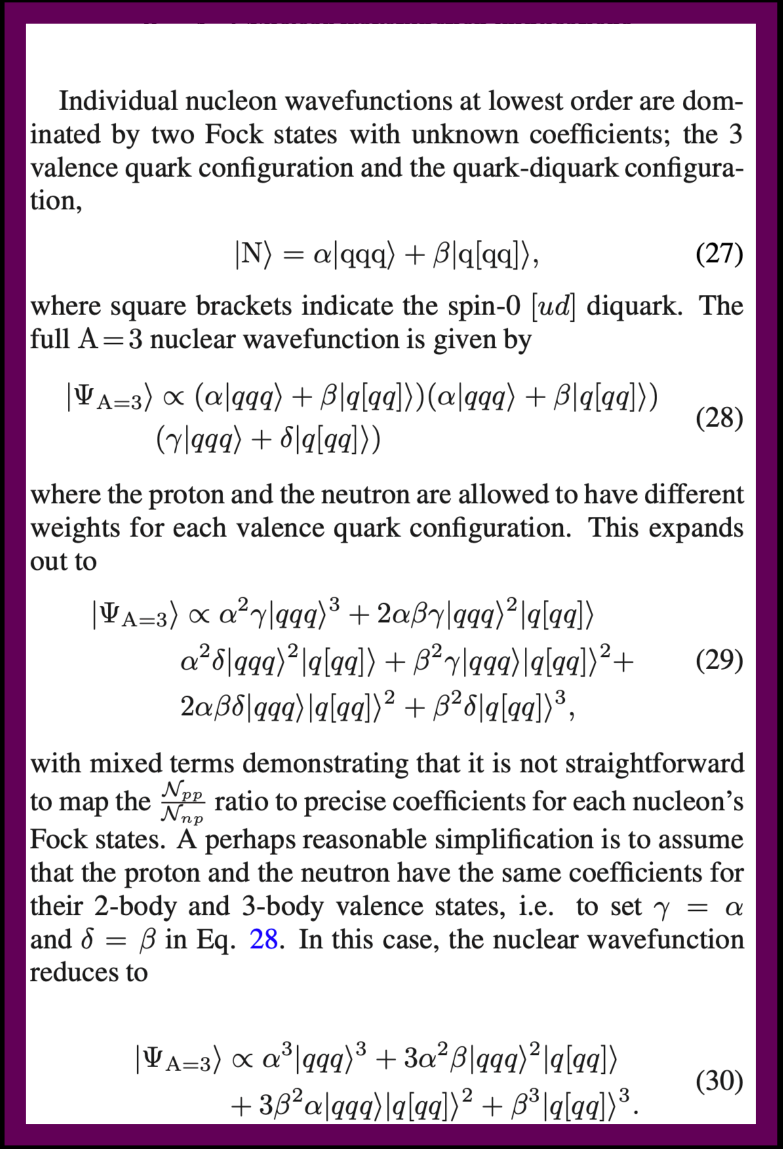
*JRW, arXiv:2009.06968*

## Combine into isospin dependent SRC ratio predictions :

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

# Diquark formation induced SRC inequality tentatively confirmed: JLab experiment E12-11-112 A=3 mirror nuclei results

$$\text{Preliminary results from JLab:}\ \frac{\mathcal{N}_{\text{nn}}}{\mathcal{N}_{\text{np}}} = \frac{1}{4.23} \sim 0.24$$



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,

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

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

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

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

$$\begin{aligned}|\Psi_{\mathrm{A=3}}\rangle \propto\ & \alpha^2\gamma|qqq\rangle^3 + 2\alpha\beta\gamma|qqq\rangle^2|q[qq]\rangle \\ & \alpha^2\delta|qqq\rangle^2|q[qq]\rangle + \beta^2\gamma|qqq\rangle|q[qq]\rangle^2 + \\ & 2\alpha\beta\delta|qqq\rangle|q[qq]\rangle^2 + \beta^2\delta|q[qq]\rangle^3,\end{aligned} \tag{29}$$

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

$$\begin{aligned}|\Psi_{\mathrm{A=3}}\rangle \propto\ & \alpha^3|qqq\rangle^3 + 3\alpha^2\beta|qqq\rangle^2|q[qq]\rangle \\ & + 3\beta^2\alpha|qqq\rangle|q[qq]\rangle^2 + \beta^3|q[qq]\rangle^3.\end{aligned} \tag{30}$$

*JRW, arXiv:2009.06968*

Isospin dependent SRC ratio inequalities from diquark induced SRC :

$$^3He: \quad 0 \leq \frac{N_{pp\ \mathrm{SRC}}}{N_{np\ \mathrm{SRC}}} \leq 0.4$$

$$^3H: \quad 0 \leq \frac{N_{nn\ \mathrm{SRC}}}{N_{np\ \mathrm{SRC}}} \leq 0.4$$

$\Longrightarrow$ Nucleon wavefunction MAY contain both $|\mathrm{qqq}\rangle$ and $|\mathrm{q[ud]}\rangle$ with approximately equal coefficients

$\Longrightarrow$ Diquark formation – single gluon exchange & $\mathrm{SU(3)_C}$ transformation – favored over quark and diquark exchange.

# Nuclear structure functions $F_2(x_B)$ from the diquark model?

# Likely wrong: Diquark formation modification of $F_2$ from Fermi motion of quarks in 2-nucleon SRC

Recall quark momentum distribution functions $q(x_B)$ : $\boxed{F_2(x_B) \equiv \sum_f x_B\, e_f^2 \left( q_f(x_B) + \bar{q}_{\bar{f}}(x_B) \right)}$

$$\text{Fermi energy :} \quad E_F = \frac{p_F^2}{2m}$$

$$\text{Fermi momentum :} \quad p_F = \sqrt{2mE_F} \propto m^{\frac{1}{2}}$$

- Diquarks lower the mass of the system
- Effective masses of quarks in nucleons: $m_u = m_d = 363\ \text{MeV}$
- $[ud]$ diquark mass: $m_{[ud]} = 578\ \text{MeV}$
- Therefore each quark loses $75\ \text{MeV}$ and its Fermi momentum is depleted: $m_{\text{final}} = \sqrt{m_q - \frac{BE}{2}}$

Momentum ratio of quark in diquark to free quark :

$$\frac{p_{\text{final}}}{p_{\text{initial}}} = \sqrt{\frac{m_f}{m_i}} \approx 0.89$$

# Diquark structures in nuclei: X17 anomaly

New work on arXiv →

Effects of Hexadiquark Fock state in $^4$He nuclear wavefunction

Based on “QCD hidden-color hexadiquark in the core of nuclei,” *jrw, Brodsky, de Teramond, Goldhaber & Schmidt, 2021*

*HdQ predicts a bump in EMC effect for each $\alpha$ particle*

*jennifer@lbl.gov*

### Quantum Chromodynamics Resolution of the ATOMKI Anomaly in $^4$He Nuclear Transitions

Valery Kubarovsky,[1] Jennifer Rittenhouse West,[2,3] and Stanley J. Brodsky[4]

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(Dated: Wednesday 29th June, 2022)

Recent observations of the angular correlation spectra in the decays $^4\mathrm{He}^* \to {}^4\mathrm{He} + e^+e^-$ and $^8\mathrm{Be}^* \to {}^8\mathrm{Be}+e^+e^-$ have been suggested as due to the creation and subsequent decay to an electron-positron pair of a new light particle with a mass of $\sim 17$ MeV. In this work, we present a calculation of the invariant mass $m_{e^+e^-}$ spectrum of the electromagnetic transition of an excited state of helium and estimate the differential and total width of the decay. We investigate the possibility that the source of the signal is an $e^+e^-$ pair created by a new electromagnetic decay of $^4$He caused by a proposed 12-quark hidden-color Fock state in the $^4$He nuclear wavefunction, the “hexadiquark.” We find that we can fit the shape of the signal with the QCD Fock state at excitation energy $\mathrm{E}^* \simeq 17.9$ MeV and a Gaussian form factor for the electromagnetic decay. We address the physical issues with the fit parameters using properties of the hexadiquark state. In light of this work, we emphasize the need for independent experimental confirmation or refutation of the ATOMKI results as well as further experiments to detect the proposed new excitation of $^4$He.

#### Introduction

Observations by the ATOMKI collaboration of anomalous angular correlations in electron-positron pairs produced in the nuclear decays $^4\mathrm{He}^* \to {}^4\mathrm{He} + e^+e^-$ [1, 2] and $^8\mathrm{Be}^* \to {}^8\mathrm{Be} + e^+e^-$ [3] have been attributed to the creation and subsequent decay of a new light particle to an $e^+e^-$ pair of a new light particle with mass of $\sim 17$ MeV, dubbed the X17 or simply X. Recently, the same group reported observations of the lepton pair in the off-resonance region of $^7\mathrm{Li}(\mathrm{p}, \mathrm{e}^+\mathrm{e}^-)^8\mathrm{Be}$ direct proton-capture reactions [4]. Our work in this article will focus on the $^4$He experiment in which the observed invariant mass $m_{e^+e^-}$ of the lepton pair was found to be $m_\mathrm{X} = 16.94 \pm 0.12(\mathrm{stat.}) \pm 0.21$ (syst.) MeV. The Feynman diagram for this transition is shown in Fig. 1. The signal has generated a great deal of theoretical interest in both the particle and nuclear physics communities [5–25].

The light-front Fock state expansion of QCD has led to new perspectives for the nonperturbative eigenstructure of hadrons, including the quark-antiquark structure of mesons, the quark-diquark structure of baryons (such as the $|u[ud]\rangle$ composition of the proton) and the diquark-antidiquark structure of tetraquarks. In the case of nuclear physics, the color-singlet $|[ud][ud][ud][ud][ud][ud]\rangle$ “hexadiquark” Fock state has the same quantum numbers as the $^4$He nucleus. The existence of the hexadiquark Fock state in the eigensolution of the $^4$He nuclear eigenstate [27] can explain the anomalously large binding energy of the $\alpha$ particle. QCD also predicts orbital and radial excitations of the hexadiquark and thus novel excitations of $^4$He beyond the standard excitations predicted by nucleonic degrees of freedom. The excitation energy of the hexadiquark can be below the energy required to produce hadronic decays such as $p+{}^3$ H and thus have evaded detection.

# Hexadiquark (HdQ) color singlet in A≥4 nuclei

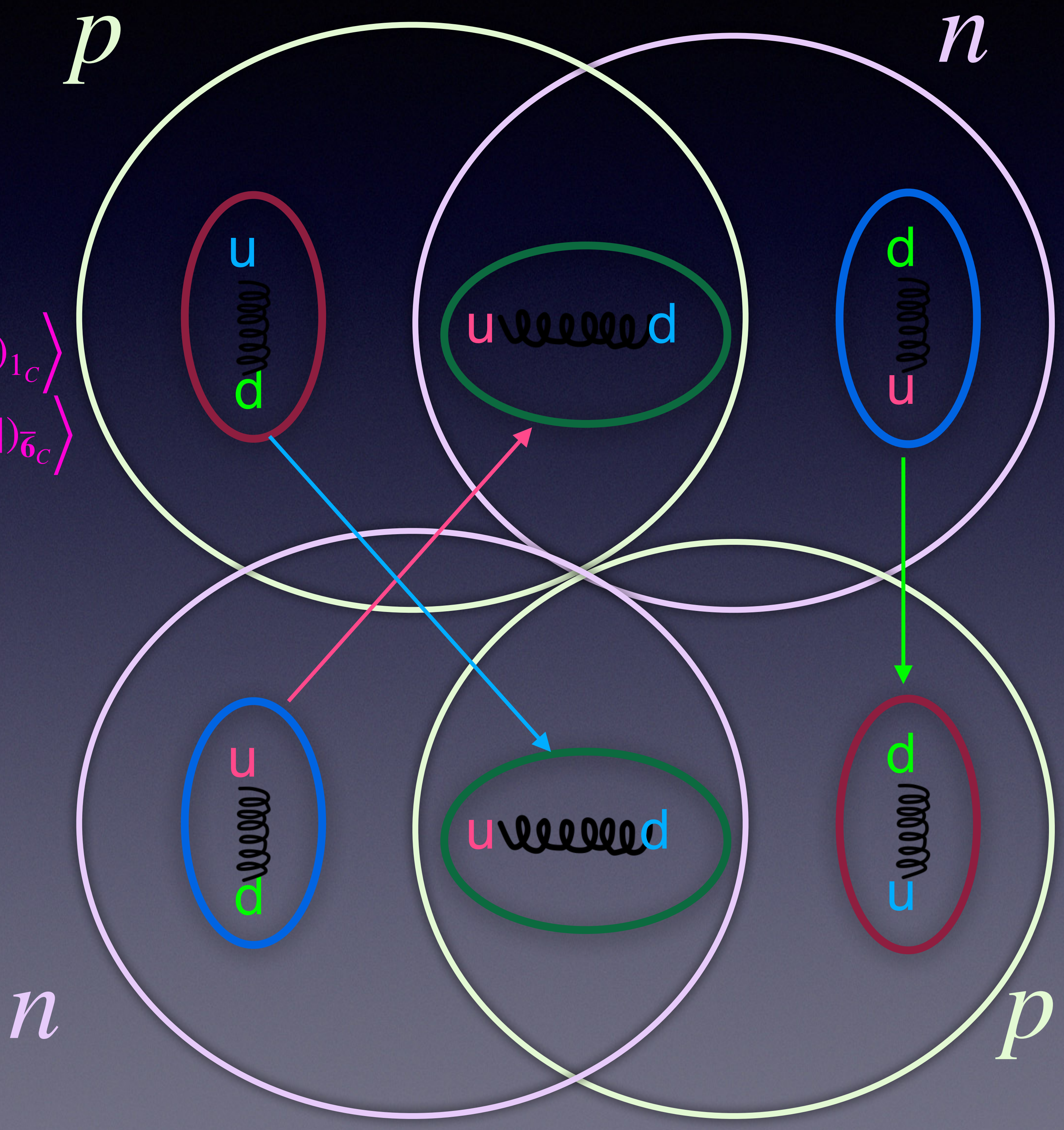
*jrw, S.J.Brodsky, G. de Teramond, I.Schmidt, F.Goldhaber, 2004.14659, Nuc. Phys A 2021*

- $^4$He nuclear wavefunction a linear combination of nnpp and 6-diquark state, the hexadiquark

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

- n-p dominance of SRC required by the HdQ model

- EIC and JLab experiments to determine if the HdQ exists - isospin dependence of SRC

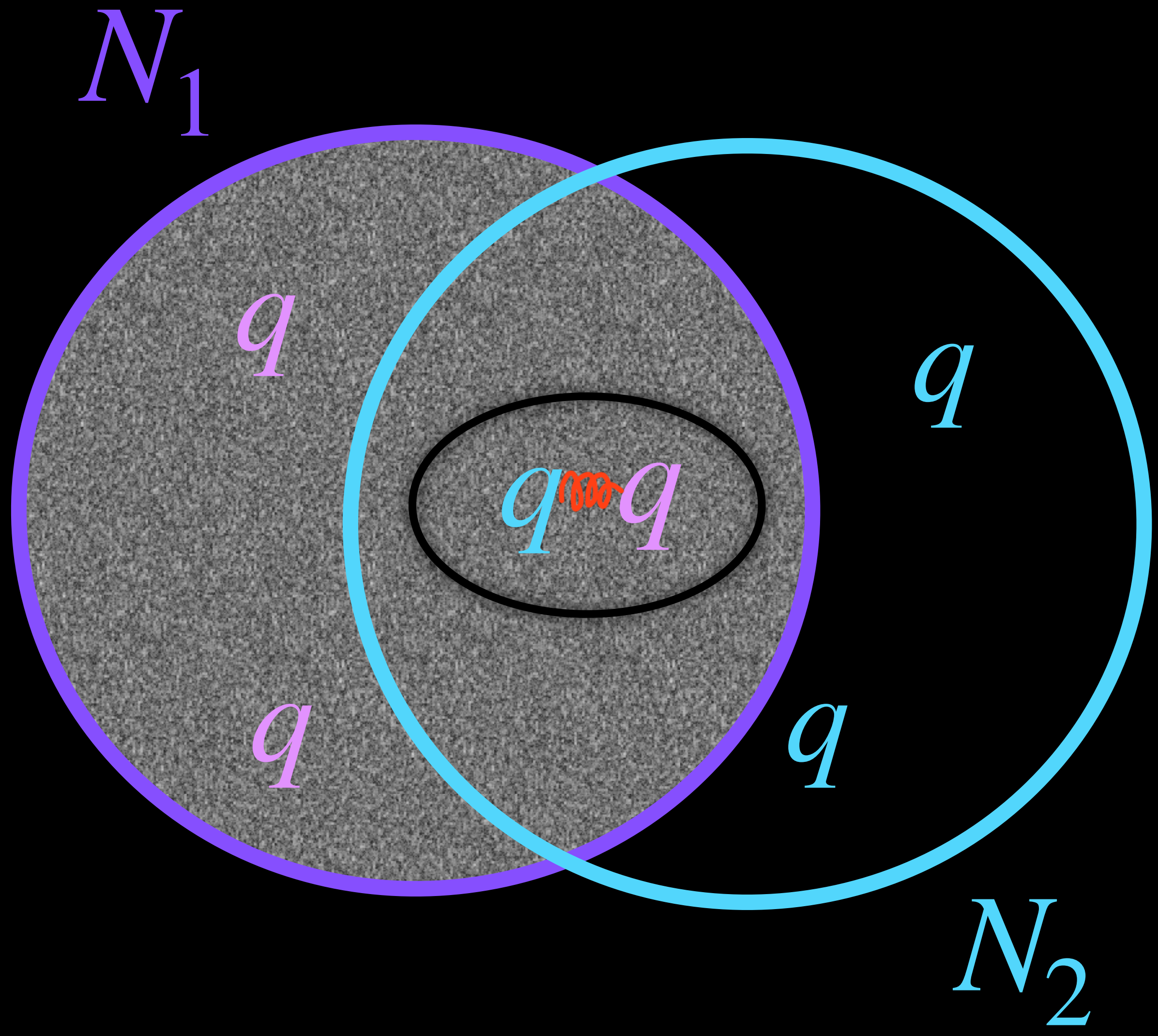


# Summary

- Diquark formation proposed to cause short-range correlated nucleon pairs
- Diquark-induced SRC may be a viable explanation for the EMC effect
- Direct calculations of $F_2$ ideal; Complete $F_2$ ∀ nuclear targets missing for 39 years:

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

- Approach the problem obliquely & look for indirect evidence of NN diquarks like the SRC flavor inequality
- Aim: Calculate the ~20% SRC from QCD - this needs both imaging and dynamics of nucleons



# Fin

Jennifer Rittenhouse West
Berkeley Lab & EIC Center @JLab
*Frontiers & Careers in Hadronic Physics @MIT*
*6 August 2022*

EIC$^2$
EIC Center at Jefferson Lab

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# backup slides

Diquarks can give a fQCD basis for SRC with isospin implications - but do they?
What about quark exchange or diquark exchange between nucleons instead?

# *Preliminary:* Diquark exchange prediction for A=3 SRC flavors

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

$$^{3}H: \quad 2n + p \rightarrow each\ nucleon \ \supset 1\ [ud] \quad \Longrightarrow \quad 66\,\%\ np,\ 33\,\%\, nn$$

$$^{3}He: \quad 2p + n \rightarrow each\ nucleon \ \supset 1\ [ud] \quad \Longrightarrow \quad 66\,\%\ np,\ 33\,\%\, pp$$

Same values for scalar diquark exchange for nucleons in quark-diquark internal configuration, $|\mathrm{N}\rangle \propto |\mathrm{q[qq]}\rangle$:

$$^{3}H: \quad u\ [ud] \ + \ d\ [ud] \ + \ d\ [ud] \ \Longrightarrow \ 66\,\%\ np$$

$$^{3}He: \quad u\ [ud] \ + \ u\ [ud] \ + \ d\ [ud] \ \Longrightarrow \ 66\,\%\ np$$

$$\mathrm{Preference\ for\ np\ SRC:} \quad \mathrm{A} = 3\ \mathrm{nuclei} \ \Longrightarrow \ \frac{\mathcal{N}_{\mathrm{nn/pp}}}{\mathcal{N}_{\mathrm{np}}} = \frac{1}{2}$$

*jennifer@lbl.gov, EIC Early Career 2022*

# *Preliminary:* Quark exchange prediction for A=3 SRC flavors

Quark exchange for nucleons with 3-valence quark internal structure $|\mathrm{N}\rangle \propto |\mathrm{qqq}\rangle$:

$$^3H: \quad 2n + p \to 9 \ exchangeable \ quarks \quad \Longrightarrow \quad 66\,\% \ np, \ 33\,\% \ nn$$

$$^3He: \quad 2p + n \to 9 \ exchangeable \ quarks \quad \Longrightarrow \quad 66\,\% \ np, \ 33\,\% \ pp$$

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

$$^3H: \quad u\ [ud] \ + \ u\ [ud] \ + \ d\ [ud] \ \Longrightarrow \ 66\,\% \ n-p$$

$$^3He: \quad d\ [ud] \ + \ d\ [ud] \ + \ u\ [ud] \ \Longrightarrow \ 66\,\% \ n-p$$

$$\text{Preference for np SRC}: \quad \mathrm{A} = 3 \text{ nuclei} \Longrightarrow \frac{\mathcal{N}_{\mathrm{nn}}}{\mathcal{N}_{\mathrm{np}}} = \frac{\mathcal{N}_{\mathrm{pp}}}{\mathcal{N}_{\mathrm{np}}} \lesssim \frac{1}{2}$$

Quark exchange depends upon quark flavor. Identical quark exchange is favored over $u$ exchanged for $d$, *e.g.*, under $u \longleftrightarrow d$ interchange:
$p + p \to n + \Delta^{++}$, where $m_{\Delta^{++}} = 1232 \text{ MeV} > m_p = 938 \text{ MeV}$

*jennifer@lbl.gov, EIC Early Career 2022*

# *Further into:* Quark exchange prediction for A=3 SRC flavors

Quark exchange for nucleons with 3-valence quark internal structure $|\mathrm{N}\rangle \propto |\mathrm{qqq}\rangle$:

$$^3H: \quad 2n + p \to 9 \; exchangeable \; quarks \quad \Longrightarrow \quad 66\,\% \; np, \, 33\,\% \, nn$$

$$^3He: \quad 2p + n \to 9 \; exchangeable \; quarks \quad \Longrightarrow \quad 66\,\% \; np, \, 33\,\% \, pp$$

Same values for quark exchange for nucleons in quark-diquark internal configuration $|\mathrm{N}\rangle \propto |\mathrm{q[qq]}\rangle$.

$$\text{Preference for np SRC via identical quark exchange}: \quad \mathrm{A} = 3 \text{ nuclei} \Longrightarrow \frac{\mathcal{N}_{\mathrm{nn}}}{\mathcal{N}_{\mathrm{np}}} = \frac{\mathcal{N}_{\mathrm{pp}}}{\mathcal{N}_{\mathrm{np}}} = \frac{1}{2}$$

$u \leftrightarrow d$ ***quark exchange: Higher mass states created in pp and nn SRC, np SRC favored.***

Under $u \longleftrightarrow d$ interchange:

pp SRC: With multiplicity 4, $p + p \to n + \Delta^{++}$, where $m_{\Delta^{++}} = 1232 \text{ MeV } (m_p = 938 \text{ MeV})$.

np SRC: With multiplicity 4, under $u \longleftrightarrow d$ interchange, $n + p \to n + p$. However, with multiplicity 1,

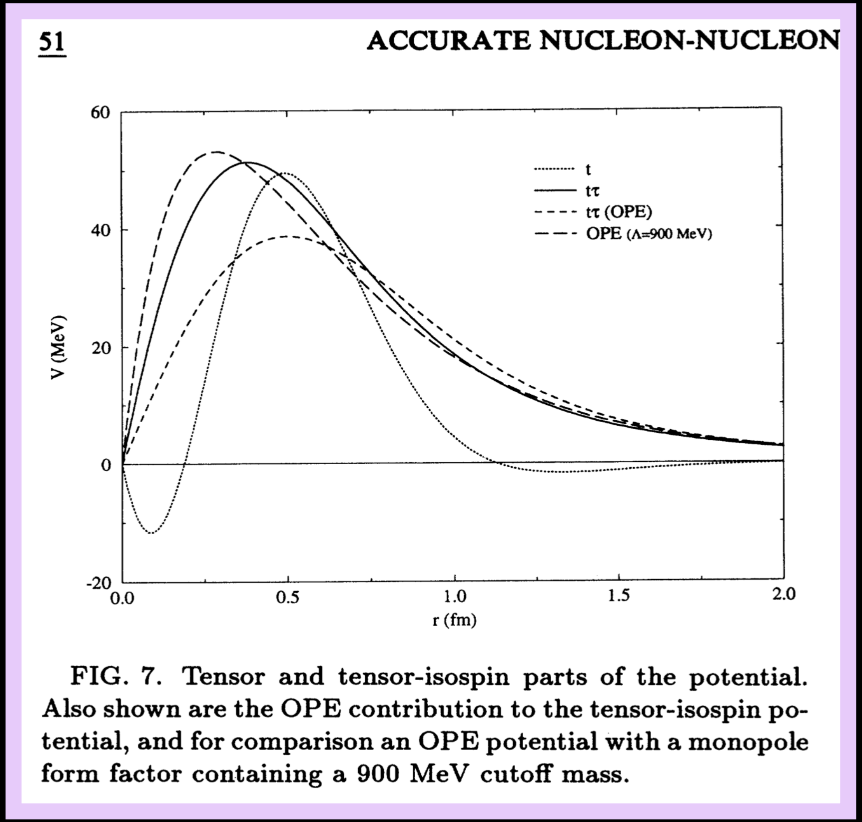
$$n + p \to \Delta^- + \Delta^{++}.$$

Favors np SRC (5 np states, 1 with 588 MeV higher mass than np) over pp (4 states each with 294 MeV higher mass than pp).

$$\therefore \text{ Quark exchange for } \mathrm{A} = 3 \text{ nuclei} \Longrightarrow \frac{\mathcal{N}_{\mathrm{nn}}}{\mathcal{N}_{\mathrm{np}}} = \frac{\mathcal{N}_{\mathrm{pp}}}{\mathcal{N}_{\mathrm{np}}} \leq \frac{1}{2}$$

Nuclear physics:  Diquark formation should account for *pieces* of the known NN potential

# Argonne $v_{18}$ nucleon-nucleon potential: $V = \sum_{n=1}^{18} V_n(r)\; O_n$



<u>51</u> **ACCURATE NUCLEON-NUCLEON**

FIG. 7. Tensor and tensor-isospin parts of the potential. Also shown are the OPE contribution to the tensor-isospin potential, and for comparison an OPE potential with a monopole form factor containing a 900 MeV cutoff mass.

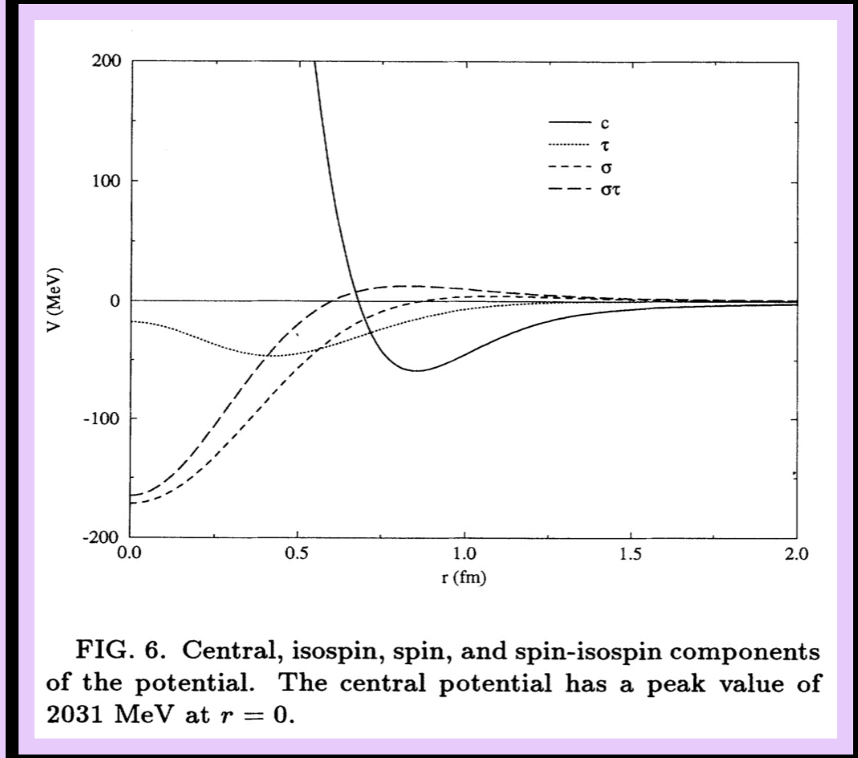
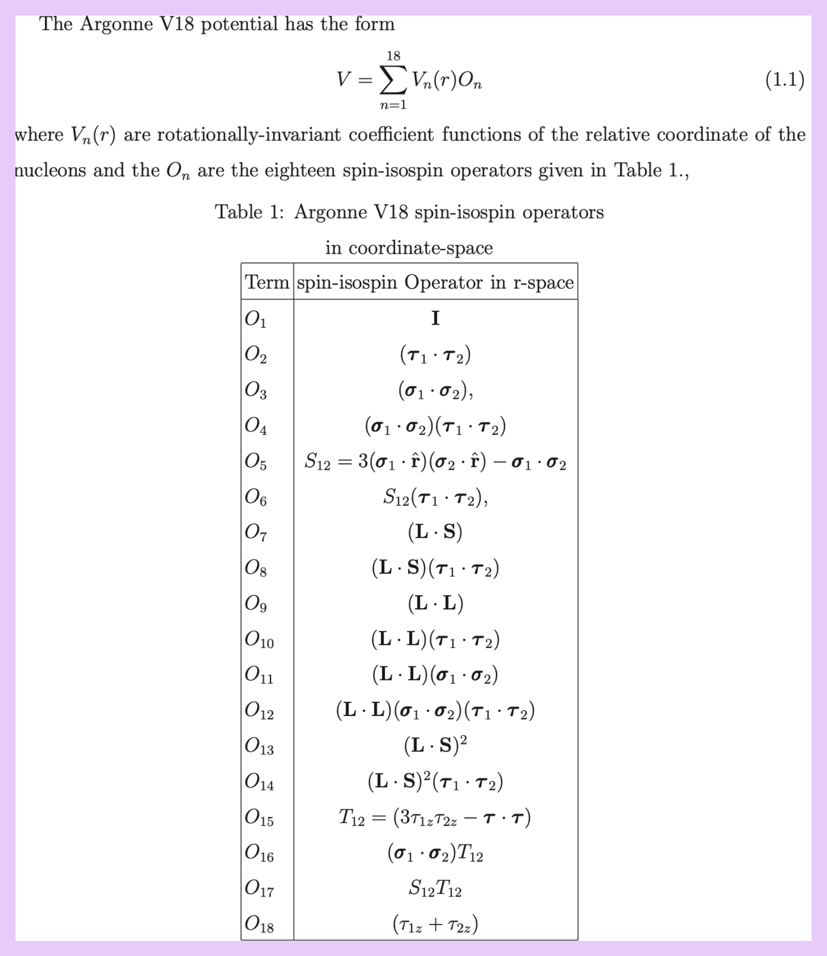


FIG. 6. Central, isospin, spin, and spin-isospin components of the potential. The central potential has a peak value of 2031 MeV at $r = 0$.

*Wiringa, Stoks, Schiavilla 1995*



The Argonne V18 potential has the form

$$V = \sum_{n=1}^{18} V_n(r) O_n \tag{1.1}$$

where $V_n(r)$ are rotationally-invariant coefficient functions of the relative coordinate of the nucleons and the $O_n$ are the eighteen spin-isospin operators given in Table 1.,

Table 1: Argonne V18 spin-isospin operators in coordinate-space

| Term | spin-isospin Operator in r-space |
|---|---|
| $O_1$ | $\mathbf{I}$ |
| $O_2$ | $(\boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_2)$ |
| $O_3$ | $(\boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2)$, |
| $O_4$ | $(\boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2)(\boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_2)$ |
| $O_5$ | $S_{12} = 3(\boldsymbol{\sigma}_1 \cdot \hat{\mathbf{r}})(\boldsymbol{\sigma}_2 \cdot \hat{\mathbf{r}}) - \boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2$ |
| $O_6$ | $S_{12}(\boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_2)$, |
| $O_7$ | $(\mathbf{L} \cdot \mathbf{S})$ |
| $O_8$ | $(\mathbf{L} \cdot \mathbf{S})(\boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_2)$ |
| $O_9$ | $(\mathbf{L} \cdot \mathbf{L})$ |
| $O_{10}$ | $(\mathbf{L} \cdot \mathbf{L})(\boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_2)$ |
| $O_{11}$ | $(\mathbf{L} \cdot \mathbf{L})(\boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2)$ |
| $O_{12}$ | $(\mathbf{L} \cdot \mathbf{L})(\boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2)(\boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_2)$ |
| $O_{13}$ | $(\mathbf{L} \cdot \mathbf{S})^2$ |
| $O_{14}$ | $(\mathbf{L} \cdot \mathbf{S})^2(\boldsymbol{\tau}_1 \cdot \boldsymbol{\tau}_2)$ |
| $O_{15}$ | $T_{12} = (3\tau_{1z}\tau_{2z} - \boldsymbol{\tau} \cdot \boldsymbol{\tau})$ |
| $O_{16}$ | $(\boldsymbol{\sigma}_1 \cdot \boldsymbol{\sigma}_2)T_{12}$ |
| $O_{17}$ | $S_{12}T_{12}$ |
| $O_{18}$ | $(\tau_{1z} + \tau_{2z})$ |

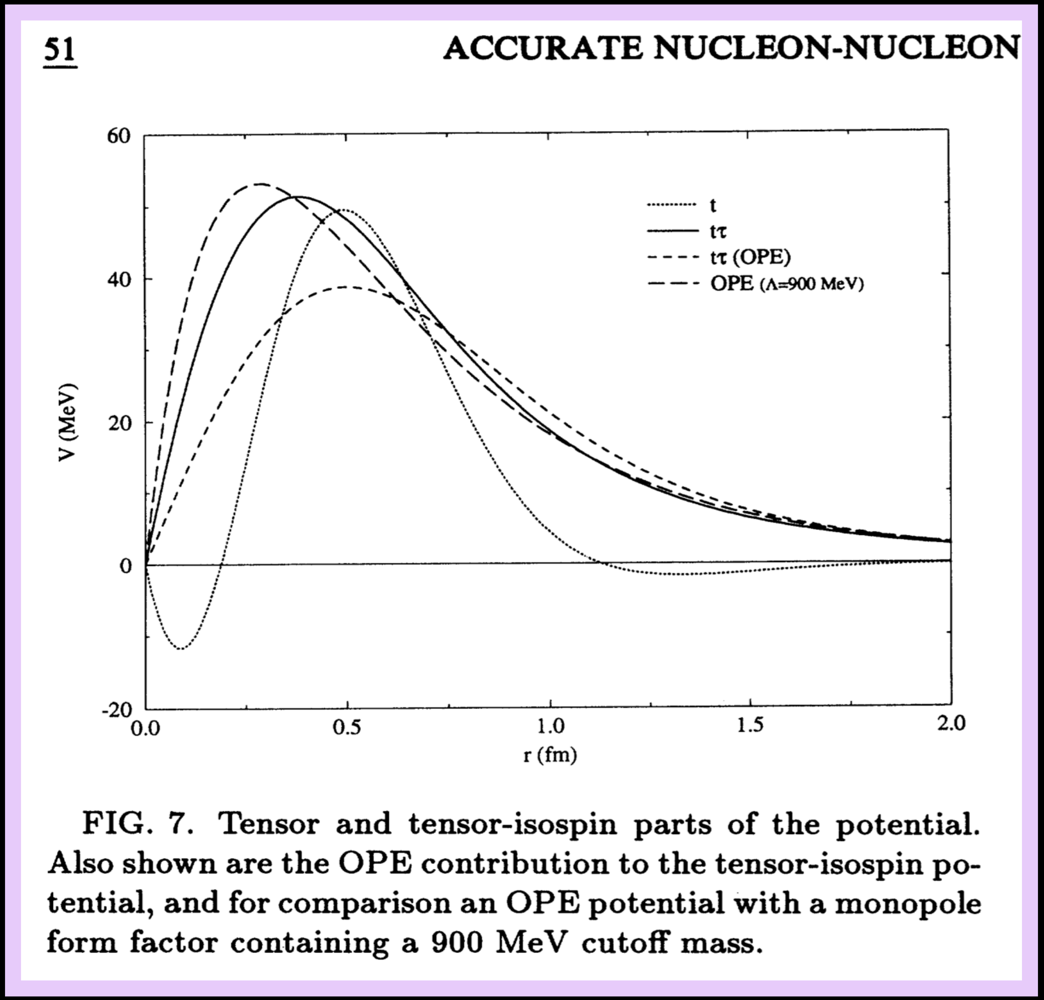
*S. Veerasamv and W. N. Polvzou 2011*

"The NN potential is written as a sum of an electromagnetic (EM) part, a one-pion-exchange (OPE) part, and an intermediate- and short-range phenomenological part:"

$$v(NN) = v^{\mathrm{EM}}(NN) + v^{\pi}(NN) + v^{R}(NN)$$

The short and intermediate range pieces are a sum of central + tensor + (others, $L^2$, spin-orbit, quadratic spin-orbit) $\Longrightarrow$ diquark potentials within tensor piece

# Argonne $v_{18}$ nucleon-nucleon potential: $V = \sum_{n=1}^{18} V_n(r)\ O_n$



51 **ACCURATE NUCLEON-NUCLEON**

FIG. 7. Tensor and tensor-isospin parts of the potential. Also shown are the OPE contribution to the tensor-isospin potential, and for comparison an OPE potential with a monopole form factor containing a 900 MeV cutoff mass.

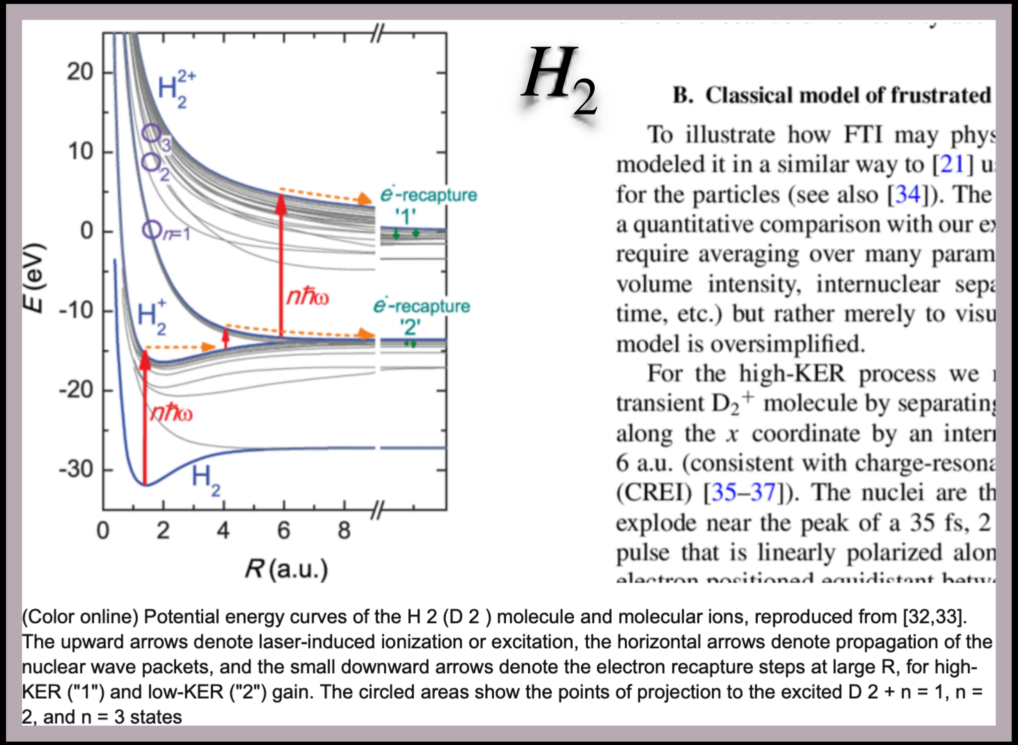
*Wiringa, Stoks, Schiavilla 1995*

**$\exists$ a dip in tensor V(r) at $r = 0.1$ fm**

- V(0.1) $\approx -10$ MeV
- QCD short-range potentials ~200 MeV
- The scale problem is here too!
- Solution: In a strongly overlapping N-N pair, the diquark V(r) is not the only potential acting in the system - linear combination of QCD potentials just like the nuclear $V_{\text{total}}$
- Valence quark $q_1$ from $N_1$, fluctuating into a short distance from valence quark $q_2$ from $N_2$, senses the diquark potential as well as its "home" color singlet potential:

$$V(r_{q_1-q_2}) = -\frac{2}{3}\frac{g_s^2}{4\pi r_{12}} \text{ vs. } V(r_{q_1-dq_1}) = -\frac{4}{3}\frac{g_s^2}{4\pi r_{11}}$$

# AV18: Argonne $v_{18}$ nucleon-nucleon potential



**B. Classical model of frustrated**

To illustrate how FTI may phys
modeled it in a similar way to [21] u
for the particles (see also [34]). The
a quantitative comparison with our ex
require averaging over many param
volume intensity, internuclear sepa
time, etc.) but rather merely to visu
model is oversimplified.

For the high-KER process we i
transient $D_2{}^+$ molecule by separatin
along the $x$ coordinate by an inter
6 a.u. (consistent with charge-resona
(CREI) [35–37]). The nuclei are th
explode near the peak of a 35 fs, 2
pulse that is linearly polarized alon

(Color online) Potential energy curves of the H 2 (D 2 ) molecule and molecular ions, reproduced from [32,33]. The upward arrows denote laser-induced ionization or excitation, the horizontal arrows denote propagation of the nuclear wave packets, and the small downward arrows denote the electron recapture steps at large R, for high-KER ("1") and low-KER ("2") gain. The circled areas show the points of projection to the excited D 2 + n = 1, n = 2, and n = 3 states

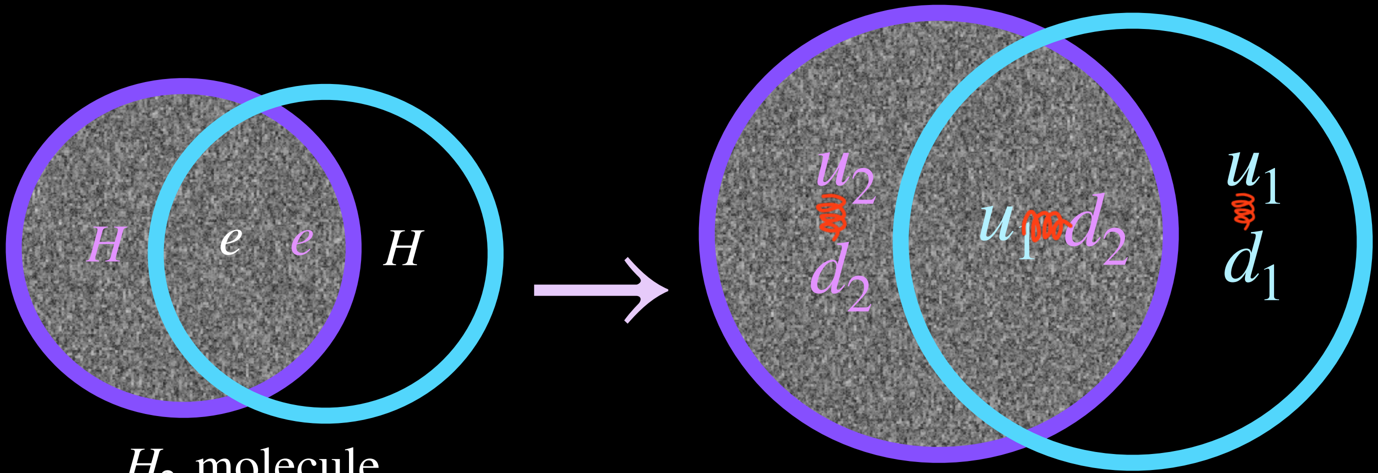
*McKenna et al. 2011*

- N-N system - nucleons in quark-diquark configuration - analogous to the hydrogen molecule

- Complicated problem. Proof of principle only.

2D 2-body approximation. Set V to 10 MeV, solve for separation distances:

$$V_{\text{total}} = -\frac{2}{3}\frac{g_s^2}{4\pi r_{12}} - \frac{4}{3}\frac{g_s^2}{4\pi r_{11}} = -10\ \text{MeV}$$



$H_2$ molecule

$n-p$ SRC pair

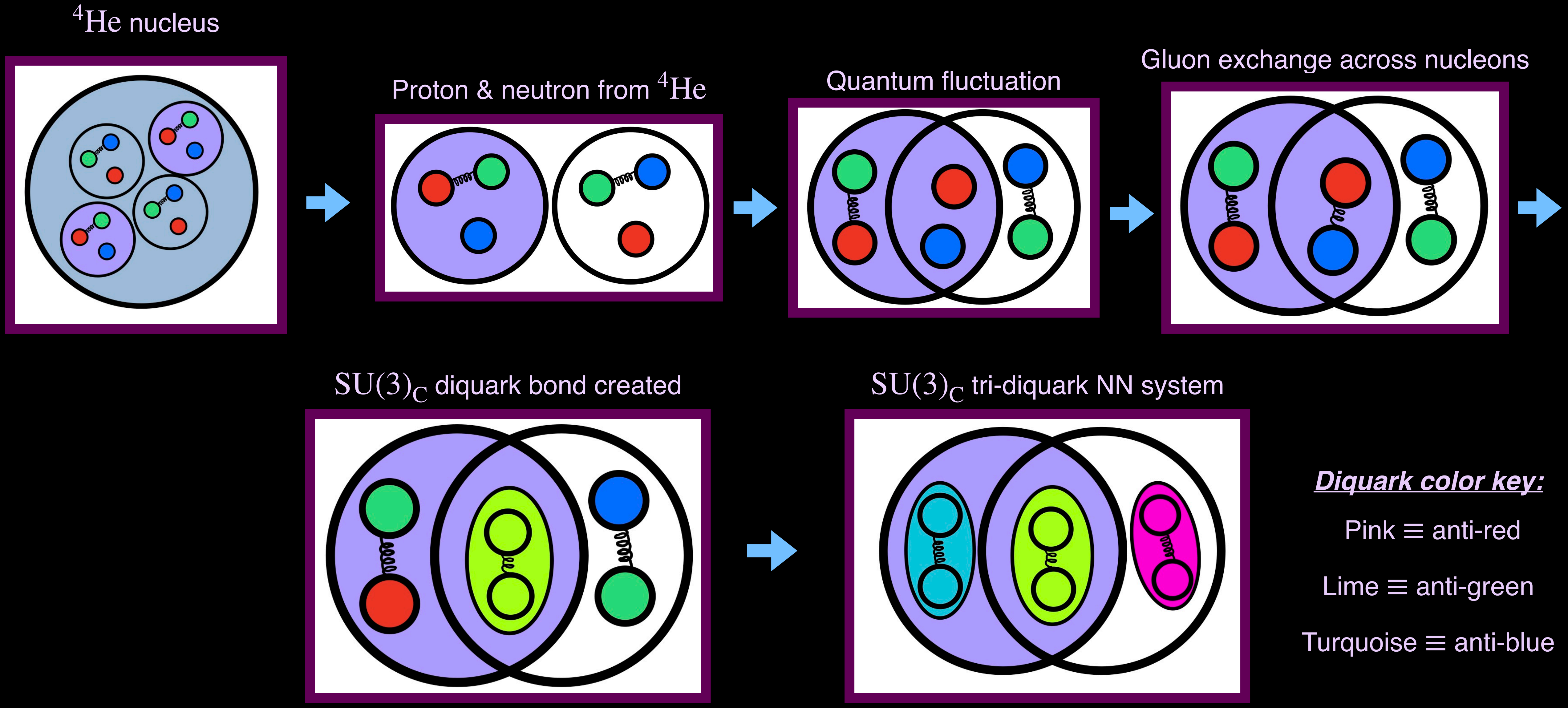
- For separation distance between quarks in the newly formed diquark: $r_{q_1-q_2} = 0.1$ fm

- Solving for separation distance between $q_1$ and $[u_1 d_1]$: $r_{q_1-dq_1} \approx 0.65$ fm

*Reasonable. Work in progress.*

# Diquark formation across NN pairs with color charge schematic:

Evolution of NN pair: **Diquark formation** creates correlations between overlapping nucleons, modifying quark behavior in the NN pair



***Diquark color key:***

Pink ≡ anti-red

Lime ≡ anti-green

Turquoise ≡ anti-blue

Triple diquark in the NN system viable color singlet ($\bar{r} + \bar{g} + \bar{b} \rightarrow 1_C$) - but L=0, S=0 wavefunction does not obey spin-statistics theorem. Must use either S=1 or L=1 to form viable state.

EMC effect in $^{4}\mathrm{He}$: 12-quark color-singlet HEXADIQUARK proposed in the core of all A>3 nuclei

# Hexadiquark (HdQ) color singlet in A≥4 nuclei

*JRW, S.J.Brodsky, G. de Teramond, I.Schmidt, F.Goldhaber, arXiv:2004*

- $^4\mathrm{He}$ nucleus proposed to contain a new 12 quark color singlet state
- 6 scalar diquarks strongly bound together to form a color singlet
- May be the reason $^4\mathrm{He}$ is strongly bound, 28 MeV B.E.

$$\left|\psi_{\mathrm{HdQ}}\right\rangle \propto |[ud][ud][ud][ud][ud][ud]\rangle$$

$$[ud] \equiv \frac{1}{\sqrt{2}}\epsilon_{abc}\left(u^b \uparrow d^c \downarrow - d^b \uparrow u^c \downarrow\right)$$

*Quark indices a, b, c = 1, 2, 3 are color indices in the fundamental* $\mathrm{SU}(3)_\mathrm{C}$ *representation.*

*Diquarks are in the anti-fundamental representation:* $3_\mathrm{C} \otimes 3_\mathrm{c} \to \overline{3}_\mathrm{C}$

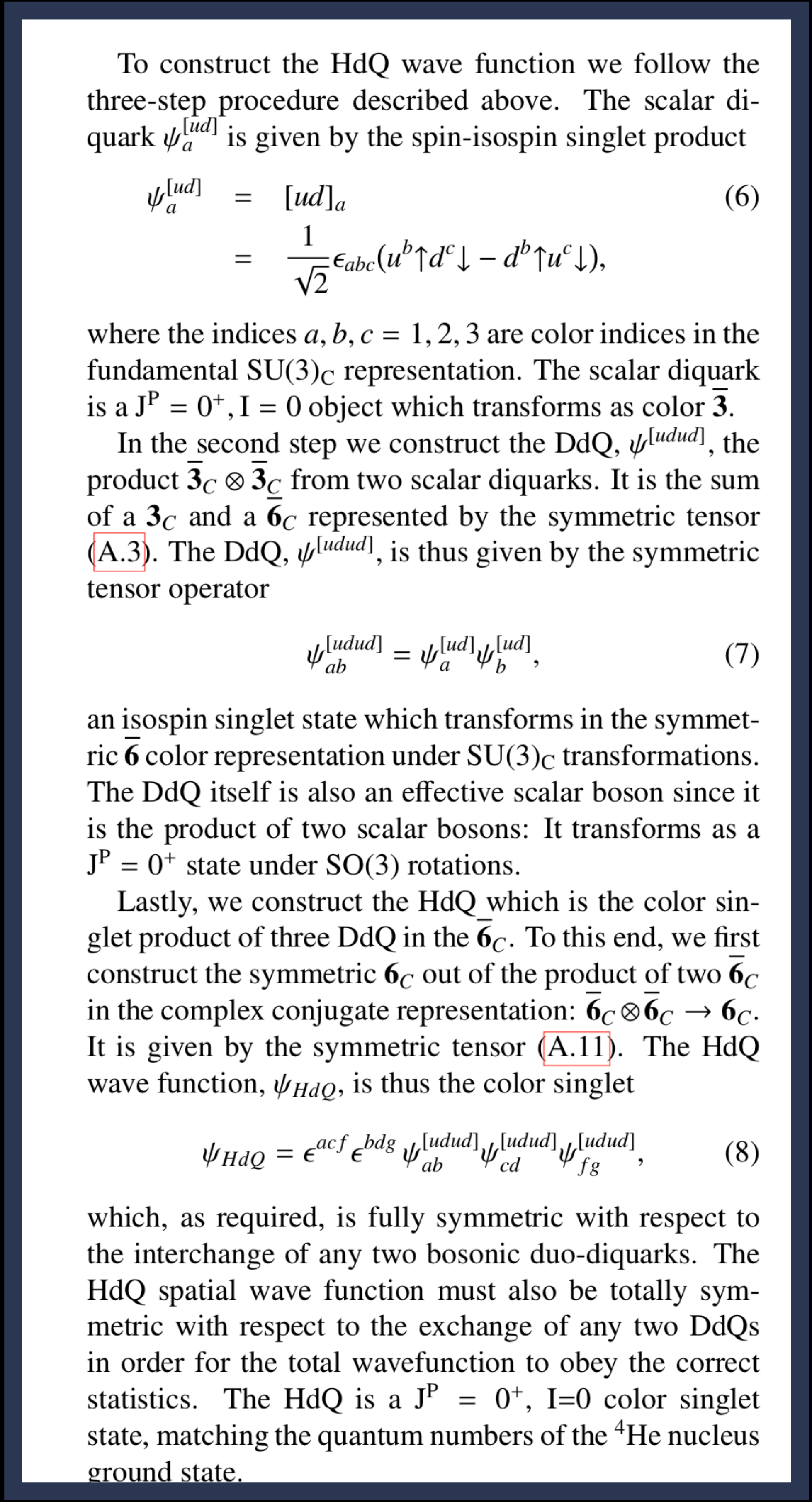
# Hexadiquark wavefunction:

The HdQ is a $\mathrm{J^P = 0^+, \ \ I = 0}$ state which is a component of the $^4\mathrm{He}$ nuclear wavefunction:

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

All quantum numbers of the HdQ and the $^4\mathrm{He}$ ground state are identical: Q=2, B=4, I=0, J=0

Important: HdQ requires 2 neutron-proton pairs. The effect of the HdQ is "isophobic" because $[ud]$ diquarks form only across n-p pairs in the quark-diquark nucleon configuration. EMC effect must be n-p dominated.



To construct the HdQ wave function we follow the three-step procedure described above. The scalar diquark $\psi_a^{[ud]}$ is given by the spin-isospin singlet product

$$\begin{aligned} \psi_a^{[ud]} &= [ud]_a \\ &= \frac{1}{\sqrt{2}}\epsilon_{abc}(u^b\uparrow d^c\downarrow - d^b\uparrow u^c\downarrow), \end{aligned} \tag{6}$$

where the indices $a, b, c = 1, 2, 3$ are color indices in the fundamental $\mathrm{SU(3)_C}$ representation. The scalar diquark is a $\mathrm{J^P = 0^+, I = 0}$ object which transforms as color $\bar{\mathbf{3}}$.

In the second step we construct the DdQ, $\psi^{[udud]}$, the product $\bar{\mathbf{3}}_C \otimes \bar{\mathbf{3}}_C$ from two scalar diquarks. It is the sum of a $\mathbf{3}_C$ and a $\bar{\mathbf{6}}_C$ represented by the symmetric tensor (A.3). The DdQ, $\psi^{[udud]}$, is thus given by the symmetric tensor operator

$$\psi_{ab}^{[udud]} = \psi_a^{[ud]}\psi_b^{[ud]}, \tag{7}$$

an isospin singlet state which transforms in the symmetric $\bar{\mathbf{6}}$ color representation under $\mathrm{SU(3)_C}$ transformations. The DdQ itself is also an effective scalar boson since it is the product of two scalar bosons: It transforms as a $\mathrm{J^P = 0^+}$ state under SO(3) rotations.

Lastly, we construct the HdQ which is the color singlet product of three DdQ in the $\bar{\mathbf{6}}_C$. To this end, we first construct the symmetric $\mathbf{6}_C$ out of the product of two $\bar{\mathbf{6}}_C$ in the complex conjugate representation: $\bar{\mathbf{6}}_C \otimes \bar{\mathbf{6}}_C \rightarrow \mathbf{6}_C$. It is given by the symmetric tensor (A.11). The HdQ wave function, $\psi_{HdQ}$, is thus the color singlet

$$\psi_{HdQ} = \epsilon^{acf}\epsilon^{bdg}\psi_{ab}^{[udud]}\psi_{cd}^{[udud]}\psi_{fg}^{[udud]}, \tag{8}$$

which, as required, is fully symmetric with respect to the interchange of any two bosonic duo-diquarks. The HdQ spatial wave function must also be totally symmetric with respect to the exchange of any two DdQs in order for the total wavefunction to obey the correct statistics. The HdQ is a $\mathrm{J^P = 0^+}$, I=0 color singlet state, matching the quantum numbers of the $^4$He nucleus ground state.

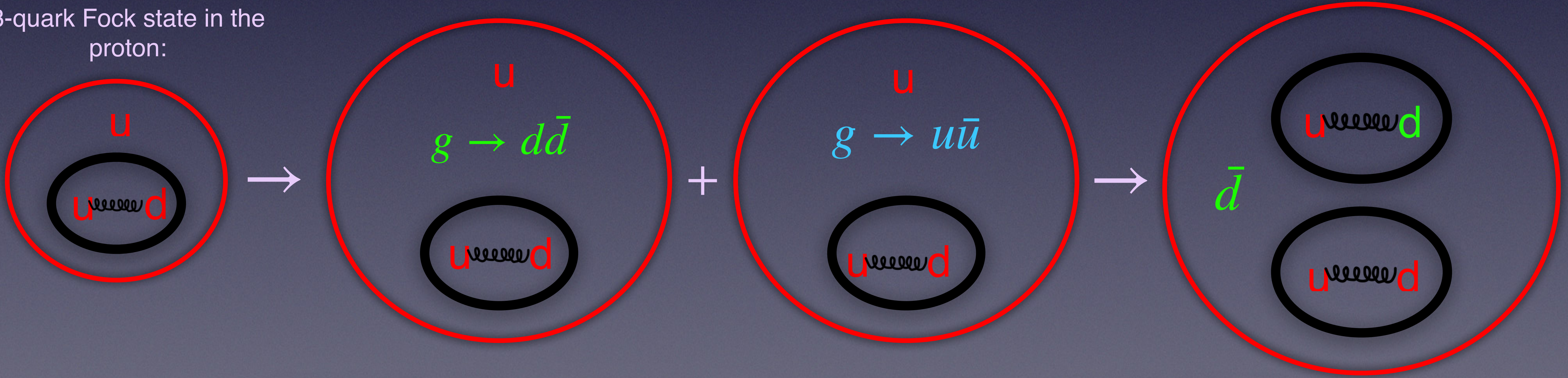
"QCD hidden-color hexadiquark in the core of nuclei," JRW, Brodsky, de Teramond, Goldhaber, Schmidt, *Nucl.Phys.A* 1007 (2021), arXiv:2004.14659

## Diquark dynamics in the nucleon sea:

## Diquark capture from gluon → $q\overline{q}$ processes

# Antiquark spin in proton: Diquark induced $\bar{d} > \bar{u}$ spin

- Gluons in nucleon pair produce $q\bar{q}$ in addition to the 3-valence quarks
- This is the 5-quark Fock state in the nucleon wavefunction
- $g \rightarrow u\bar{u}$, $g \rightarrow d\bar{d}$ produced equally
- Diquark formation $[ud]$ has ~150 MeV binding energy - valence $u$ may capture the $d$ quark from $d\bar{d}$ pair
- Creates residual $\bar{d}$ in the quark sea - in the quark-diquark configuration of the proton, $\bar{d}$ *must* carry more of the proton's spin than $\bar{u}$ - STAR experiment may contradict this



3-quark Fock state in the proton:

5-quark Fock state creation:

5-quark Fock state w

**L=1 duo-diquark, S=1/2 $\bar{d}$, anti-aligned $\Longrightarrow$ S=1/2 proton**

# Diquark formation implications: SeaQuest Antimatter Asymmetry

## Antimatter asymmetry in the quark sea of protons

## Excess of $\bar{d}$ quarks over $\bar{u}$

- Gluons produce quark-antiquark pairs in nucleons.
- $u\bar{u}$ and $d\bar{d}$ pairs form in equal amounts
- Binding energy of spin-0 $[ud]$ diquarks is ~148 MeV
- Proton's valence $u$ (when proton in quark-diquark structure) binds with $d$ from gluon-to-$d\bar{d}$ - it is captured into a $[ud]$ diquark
- Leaves a $\bar{d}$ quark behind - excess $\bar{d}$ in proton
- Predicts excess of $\bar{u}$ in the neutron sea
- SpinQuest prediction: $\bar{d}$ carries more of the spin of the proton for the 5-quark Fock state than $\bar{u}$:

$$[ud][ud]\ \bar{d}$$

$$\int_0^1 \frac{dx}{x}\left[F_2^p(x) - F_2^n(x)\right] = \frac{1}{3} + \frac{2}{3}\int_0^1 dx[\bar{u}(x) - \bar{d}(x)]$$

$$\int_0^1 dx[\bar{d}(x) - \bar{u}(x)] = 0.147 \pm 0.039, \ \text{New Muon Collaboration}$$

$$= 0.118 \pm 0.012, \ \text{NuSea}$$

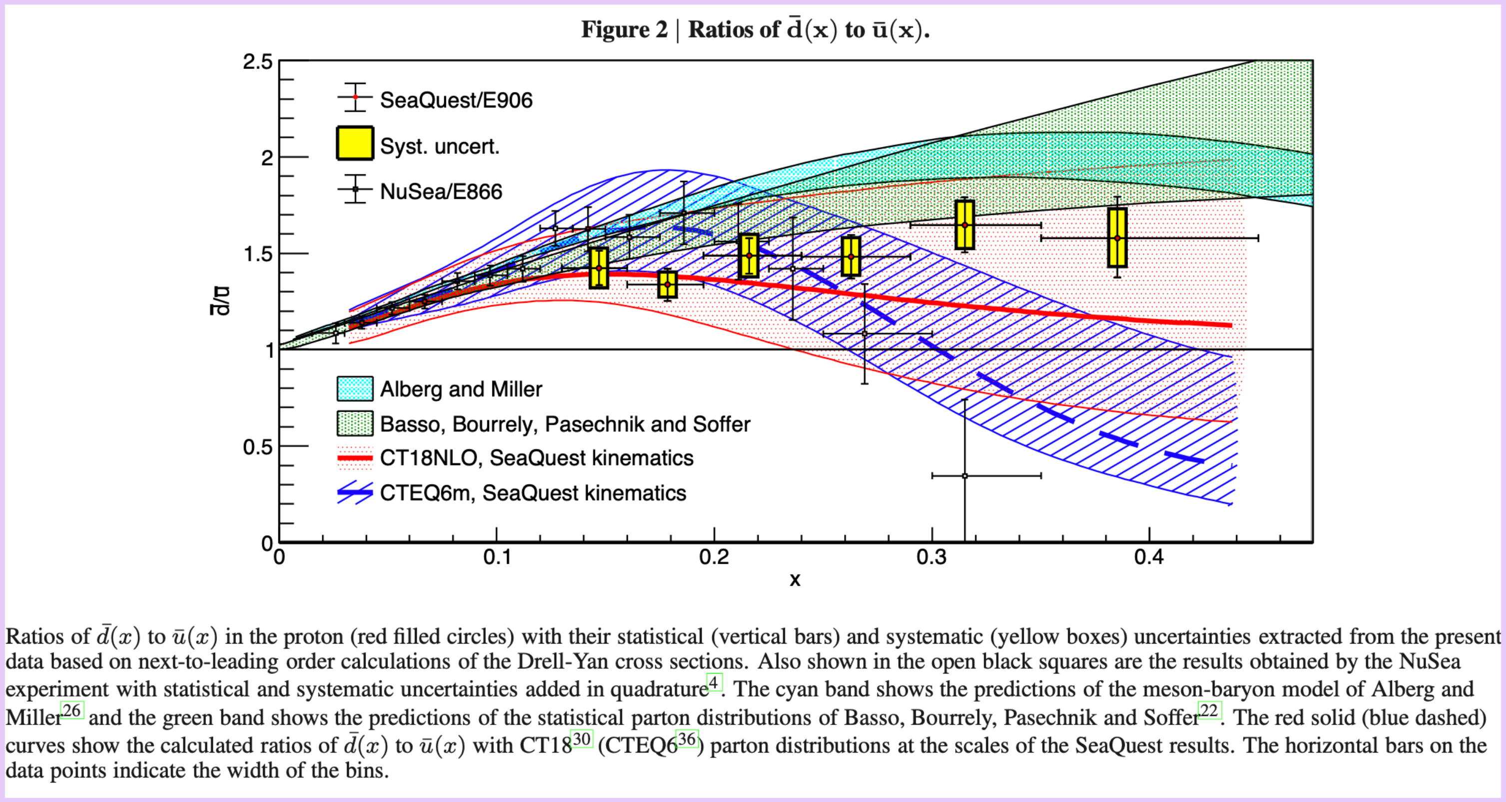


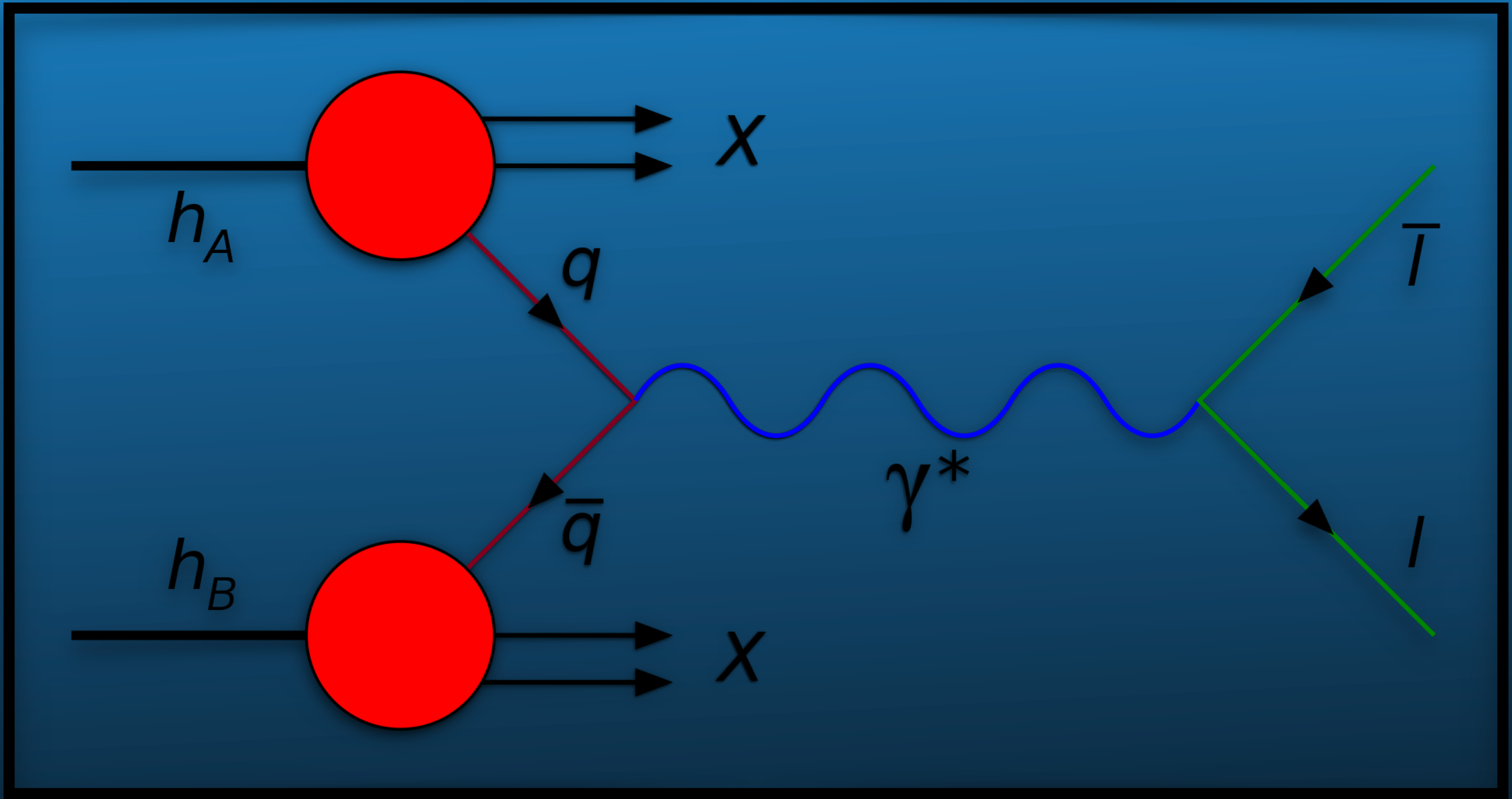
**Figure 2** | **Ratios of $\bar{d}(x)$ to $\bar{u}(x)$.**

Ratios of $\bar{d}(x)$ to $\bar{u}(x)$ in the proton (red filled circles) with their statistical (vertical bars) and systematic (yellow boxes) uncertainties extracted from the present data based on next-to-leading order calculations of the Drell-Yan cross sections. Also shown in the open black squares are the results obtained by the NuSea experiment with statistical and systematic uncertainties added in quadrature[4]. The cyan band shows the predictions of the meson-baryon model of Alberg and Miller[26] and the green band shows the predictions of the statistical parton distributions of Basso, Bourrely, Pasechnik and Soffer[22]. The red solid (blue dashed) curves show the calculated ratios of $\bar{d}(x)$ to $\bar{u}(x)$ with CT18[30] (CTEQ6[36]) parton distributions at the scales of the SeaQuest results. The horizontal bars on the data points indicate the width of the bins.

*Dove et al. 2021*

# Drell-Yan process for sea quark studies

$$\frac{\sigma^{pd}}{2\sigma^{pp}} = \frac{1}{2}\left[1 + \frac{\bar{d}(x)}{\bar{u}(x)}\right], \qquad \frac{\sigma_{W^+}}{\sigma_{W^-}} \approx \frac{u\left(x_1\right)\bar{d}\left(x_2\right) + u\left(x_2\right)\bar{d}\left(x_1\right)}{d\left(x_1\right)\bar{u}\left(x_2\right) + d\left(x_2\right)\bar{u}\left(x_1\right)}$$



“The Drell–Yan process occurs in high energy **hadron**–hadron scattering. It takes place when a **quark** of one hadron and an **antiquark** of another hadron annihilate, creating a **virtual photon** or **Z boson** which then decays into a pair of oppositely-charged **leptons**. Importantly, the energy of the colliding quark-antiquark pair can be almost entirely transformed into the mass of new particles. This process was first suggested by **Sidney Drell** and **Tung-Mow Yan** in 1970 to describe the production of **lepton–antilepton** pairs in high-energy hadron collisions. Experimentally, this process was first observed by J.H. Christenson *et al.*[2] in proton–uranium collisions at the **Alternating Gradient Synchrotron**."

*- Image & text from wikipedia*