Electron-Ion Collider Physics

"From RHIC to the EIC: Taking Our Exploration of Matter to the Next Frontier"
- *Doon Gibbs, BNL Director*

EIC^2
EIC Center at Jefferson Lab

Jennifer Rittenhouse West
Lawrence Berkeley National Lab
EIC theory talk for the RHIC/AGS Users' Group
October 2022 DNP, New Orleans

BERKELEY LAB

Electron-Ion Collider Foundation: Quantum Chromodynamics

"The electron beams at the EIC, and the knowledge the collisions of electrons with ions will reveal about the arrangement and interactions of quarks and gluons, ***will help us understand the force that holds these fundamental building blocks – and nearly all visible matter – together.***"

- *Doon Gibbs, ibid.*

Electron-Ion Collider

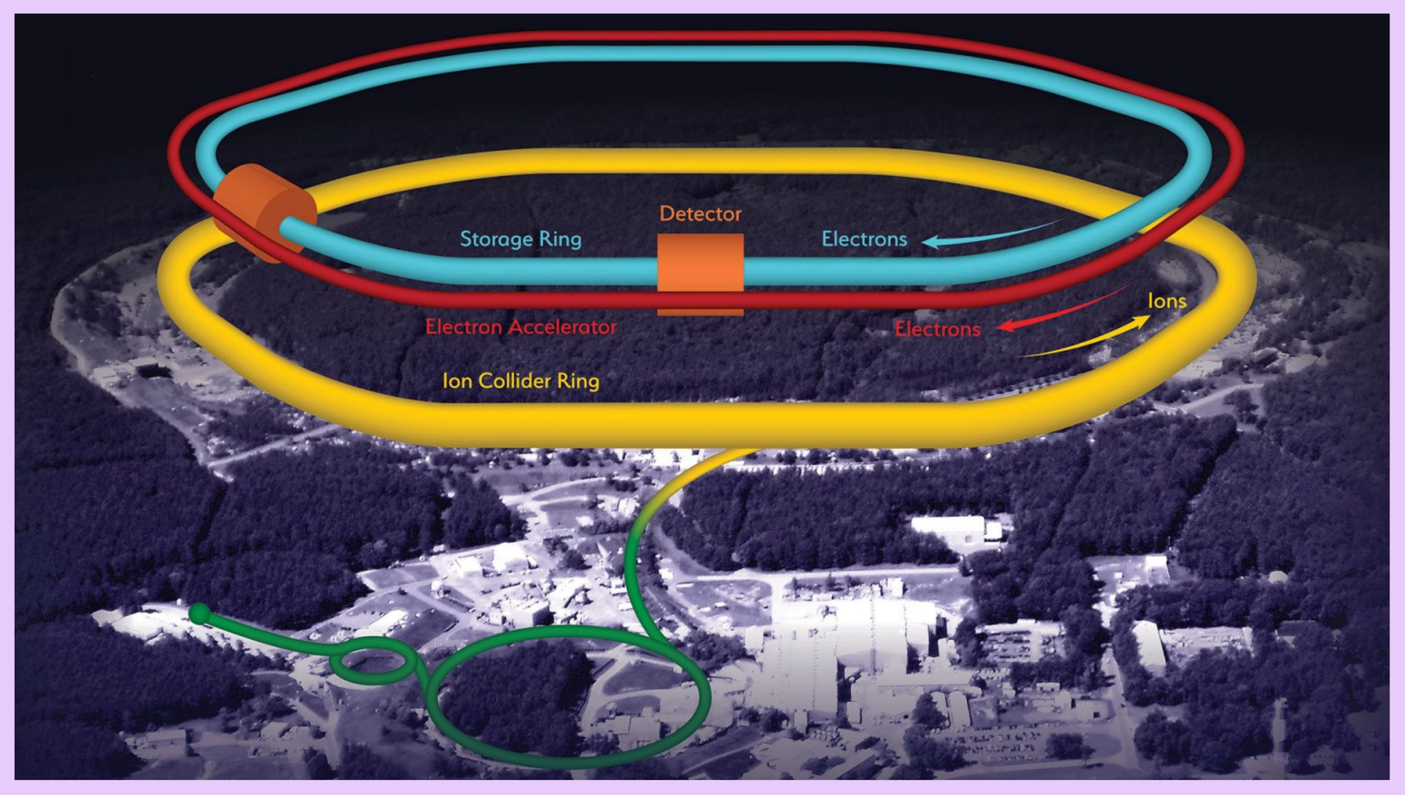
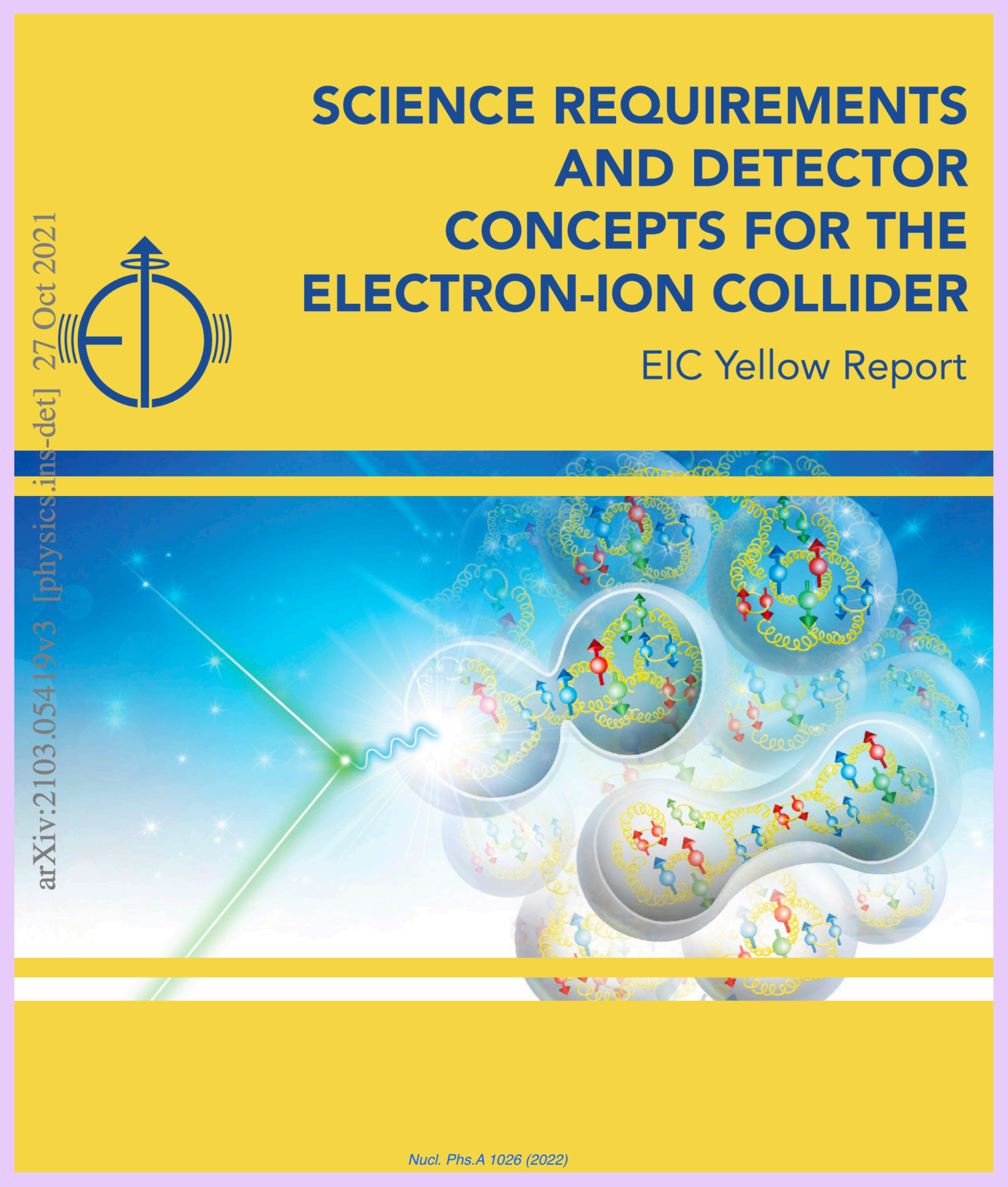


Image credit: Brookhaven National Lab

Electron-Ion Collider Physics Aims

- Origin of Nucleon Spin
- Origin of Nucleon Mass
- Multi-dimensional Imaging of the Nucleon
- Imaging the Transverse Spatial Distributions of Partons *(partons = quarks, antiquarks, gluons, everything that is part of the nucleon)*
- Physics with High Energy Nuclear Beams at the EIC
- Nuclear Modifications of Parton Distribution Functions *(aka the EMC effect!)*
- Passage of Color Charge through Cold QCD Matter *(hadronization! jets! **color transparency**…)*
- Connections to Other Fields



SCIENCE REQUIREMENTS AND DETECTOR CONCEPTS FOR THE ELECTRON-ION COLLIDER

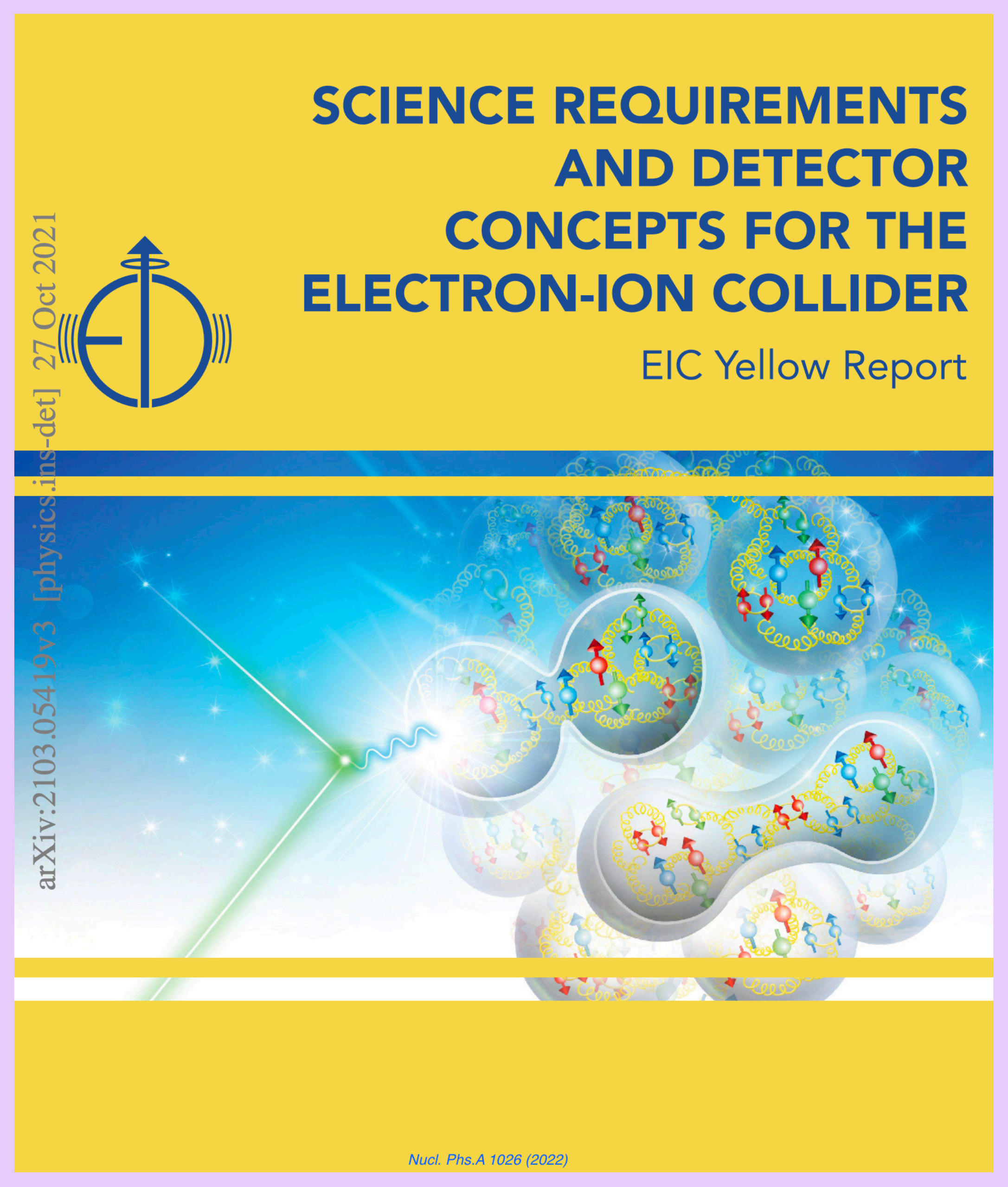
EIC Yellow Report

arXiv:2103.05419v3 [physics.ins-det] 27 Oct 2021

Nucl. Phs.A 1026 (2022)

Electron-Ion Collider Physics Aims

- Origin of Nucleon Spin
- Origin of Nucleon Mass
- Multi-dimensional Imaging of the Nucleon
- Imaging the Transverse Spatial Distributions of Partons *(partons = quarks, antiquarks, gluons, everything that is part of the nucleon)*
- Physics with High Energy Nuclear Beams at the EIC
- Nuclear Modifications of Parton Distribution Functions *(aka the EMC effect!)*
- Passage of Color Charge through Cold QCD Matter *(hadronization! jets! **color transparency**…)*
- Connections to Other Fields



arXiv:2103.05419v3 [physics.ins-det] 27 Oct 2021

SCIENCE REQUIREMENTS AND DETECTOR CONCEPTS FOR THE ELECTRON-ION COLLIDER

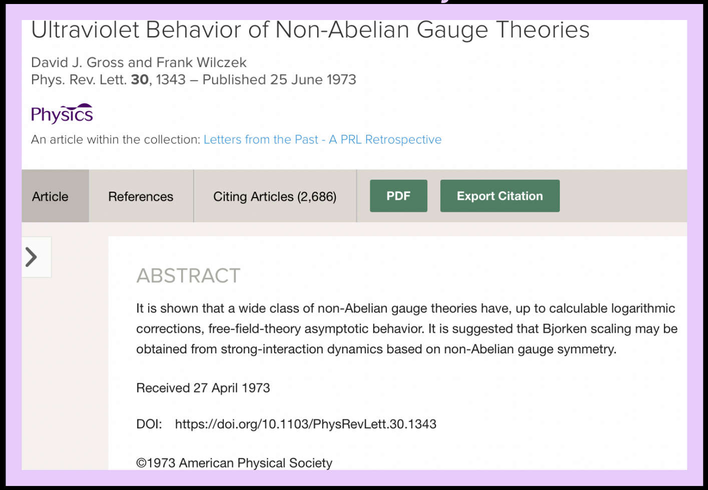
EIC Yellow Report

Nucl. Phs.A 1026 (2022)

Nuclear physics & the strong force, a history

- 1911: Rutherford et al.'s discovery of the nucleus
- 1948: Maria Goeppert Mayer publishes evidence for the nuclear shell model, analogous to electron shell structure in atoms (Nobel prize 1963)
- 1968: Prediction of quarks by Bjorken, point-like spin-half constituents of the proton found soon after in DIS
- 1973: Strong force described by a $\mathrm{SU}(3)_C$ group theory called QCD
- *1983: Quark behavior in nuclei is not as expected (EMC effect)*
- *1993: Quasi-elastic electron scattering off nuclei* $\Longrightarrow$ *~20% of nucleons in short-range correlations, not in shells*

Quantum chromodynamics



Ultraviolet Behavior of Non-Abelian Gauge Theories

David J. Gross and Frank Wilczek
Phys. Rev. Lett. **30**, 1343 – Published 25 June 1973

An article within the collection: Letters from the Past - A PRL Retrospective

ABSTRACT

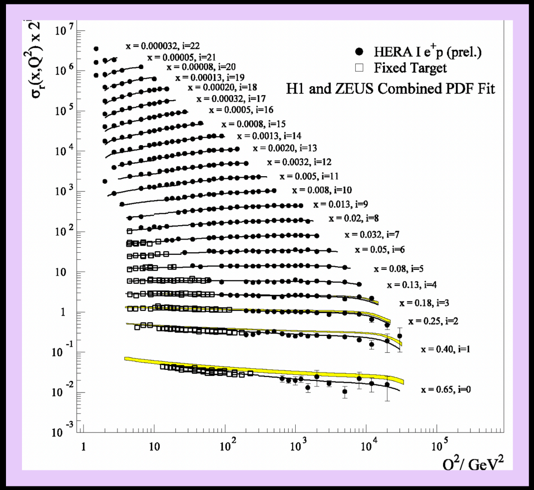
It is shown that a wide class of non-Abelian gauge theories have, up to calculable logarithmic corrections, free-field-theory asymptotic behavior. It is suggested that Bjorken scaling may be obtained from strong-interaction dynamics based on non-Abelian gauge symmetry.

Received 27 April 1973

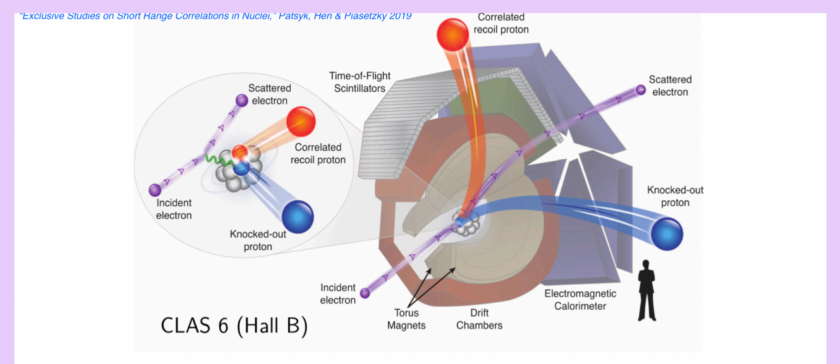
DOI: https://doi.org/10.1103/PhysRevLett.30.1343

©1973 American Physical Society

Bjorken scaling: DIS cross sections indpendent of Q^2



Beyond the Shell Model: Long Range and Short Range Correlations between Nucleons



"Exclusive Studies on Short Range Correlations in Nuclei," Patsyk, Hen & Piasetzky 2019

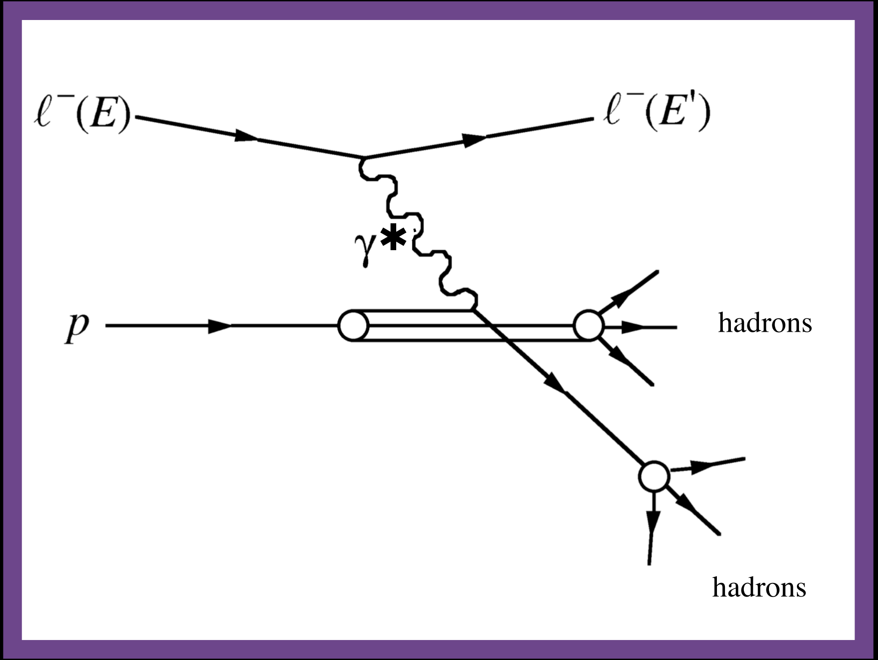
Figure 1. The CLAS spectrometer. The reaction of hard knockout of two nucleons from the target nucleus by an electron probe is shown. All three final state particles are detected by the spectrometer which ensures the exclusiveness of the measurement

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:

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

where $y = \dfrac{\nu}{E}$ is the fraction of ℓ^- 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

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

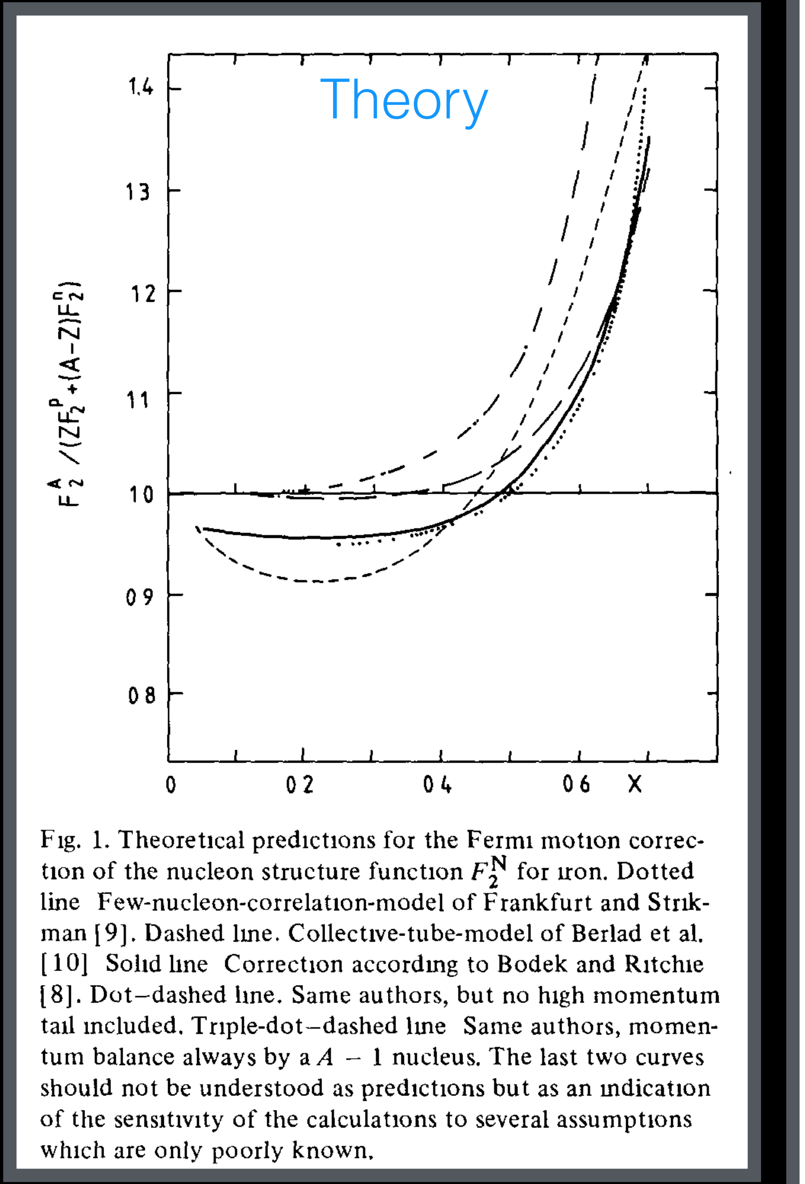


Fig. 1. Theoretical predictions for the Fermi motion correction of the nucleon structure function F_2^N for iron. Dotted line Few-nucleon-correlation-model of Frankfurt and Strikman [9]. Dashed line. Collective-tube-model of Berlad et al. [10] Solid line Correction according to Bodek and Ritchie [8].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

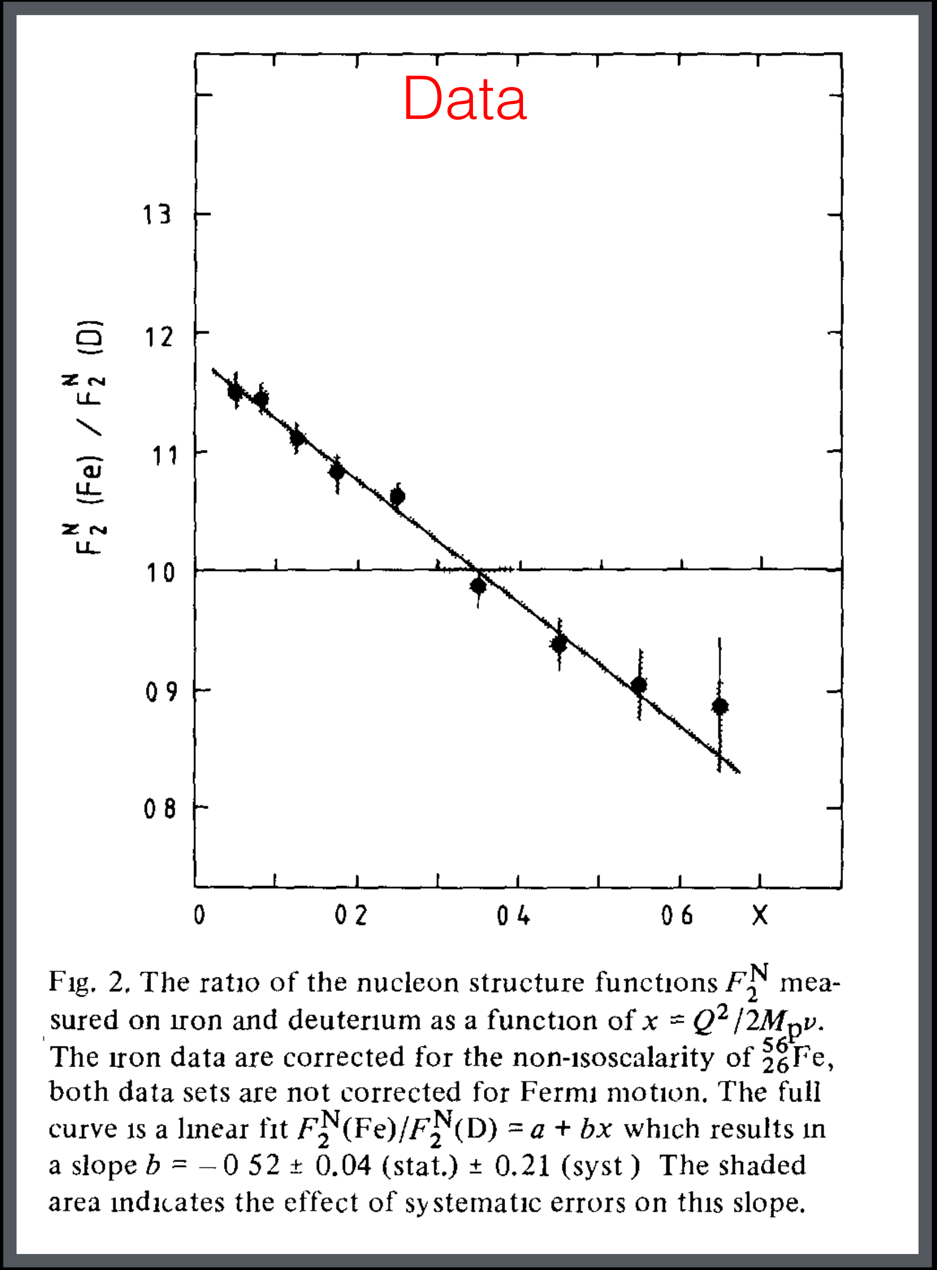


Fig. 2. The ratio of the nucleon structure functions F_2^N measured on iron and deuterium as a function of $x = Q^2/2M_p\nu$. The iron data are corrected for the non-isoscalarity of $^{56}_{26}$Fe, both data sets are not corrected for Fermi motion. The full curve is a linear fit $F_2^N(\mathrm{Fe})/F_2^N(\mathrm{D})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

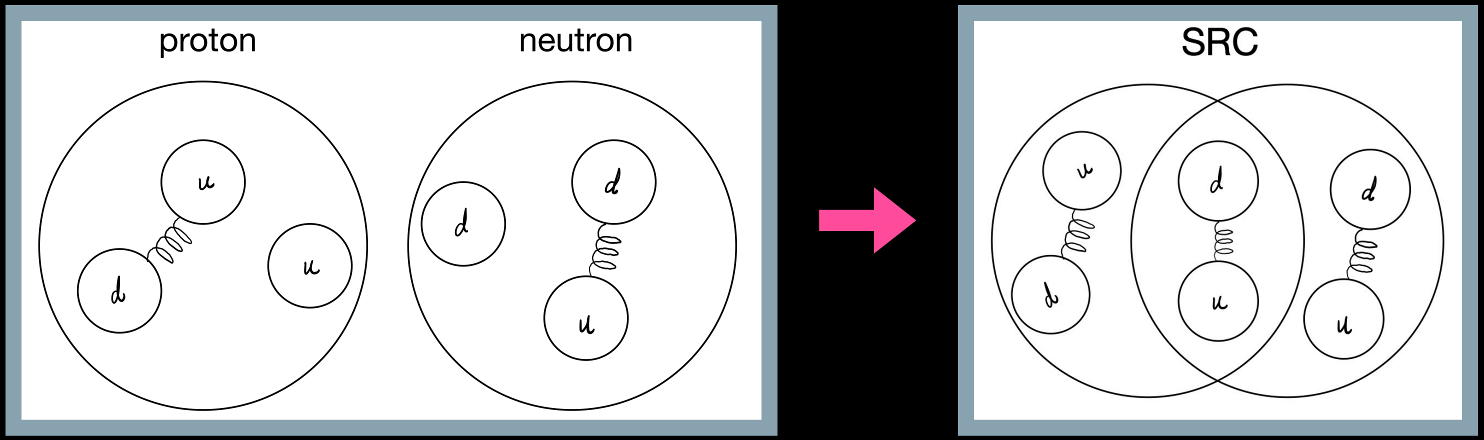
- Mean field effects involving the whole nucleus
- Local effects, *e.g.*, 2-nucleon correlations

Simple mean field effects inconsistent with the EMC effect in light nuclei - MC of $^{9}\mathrm{Be} \Longrightarrow$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



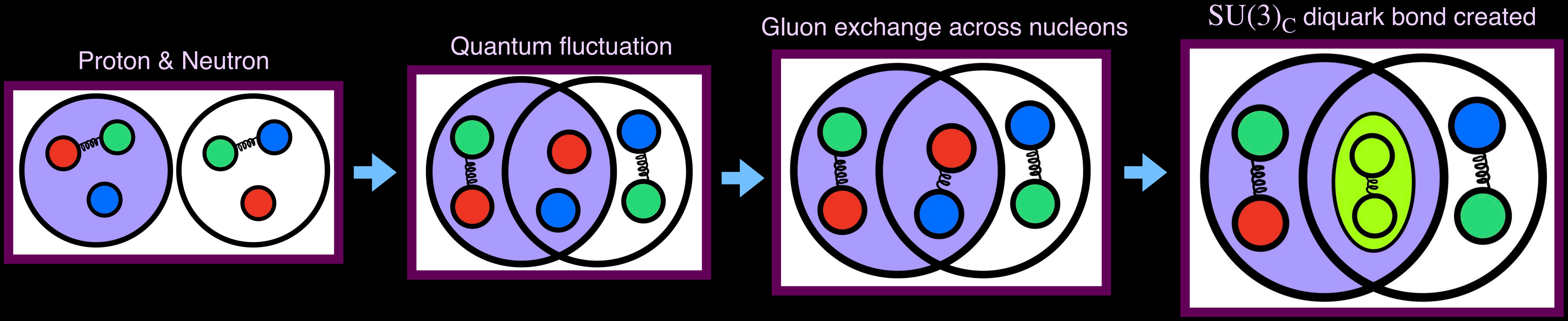
DOZENS OF EXPERIMENTS CONFIRM EMC EFFECT

Target	Collaboration/ Laboratory
^{3}He	JLab 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)

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.

Diquarks

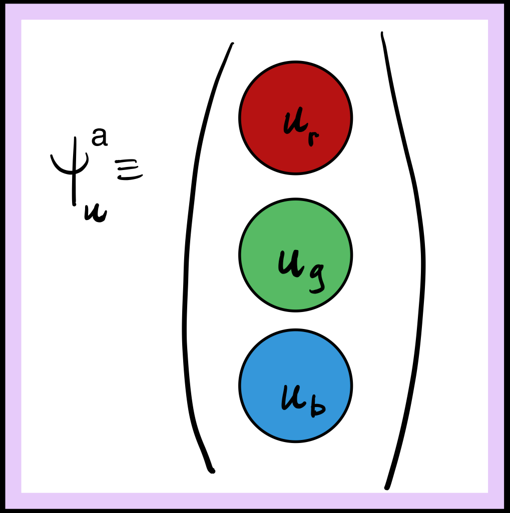
- Group theory rules of SU(3) $\implies$ 2 quarks combine into anti-color charged object: $3_C \times 3_C \rightarrow \bar{3}_C$

(If this combination does not occur - something must forbid it)

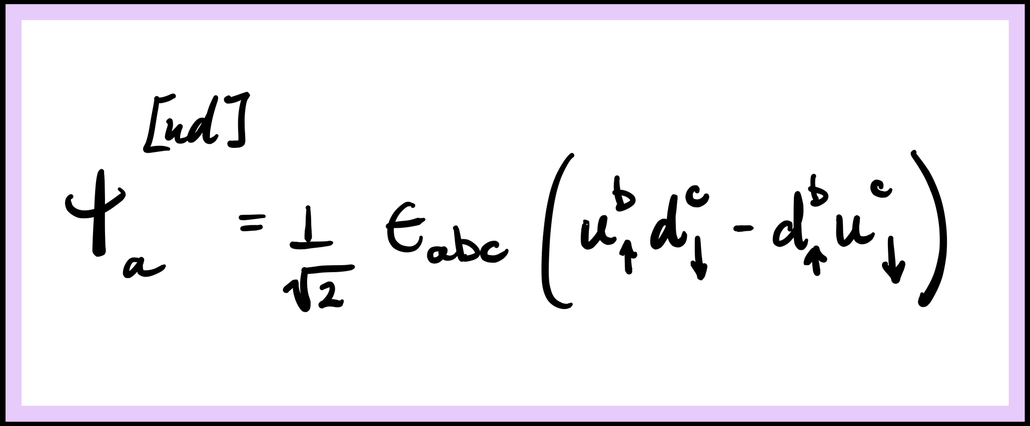
- $\exists$ a short-range QCD Coulomb potential between quarks:

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

Quark in the fundamental rep of $SU(3)_C$:



Diquark wavefunction in the antifundamental rep of $SU(3)_C$:



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

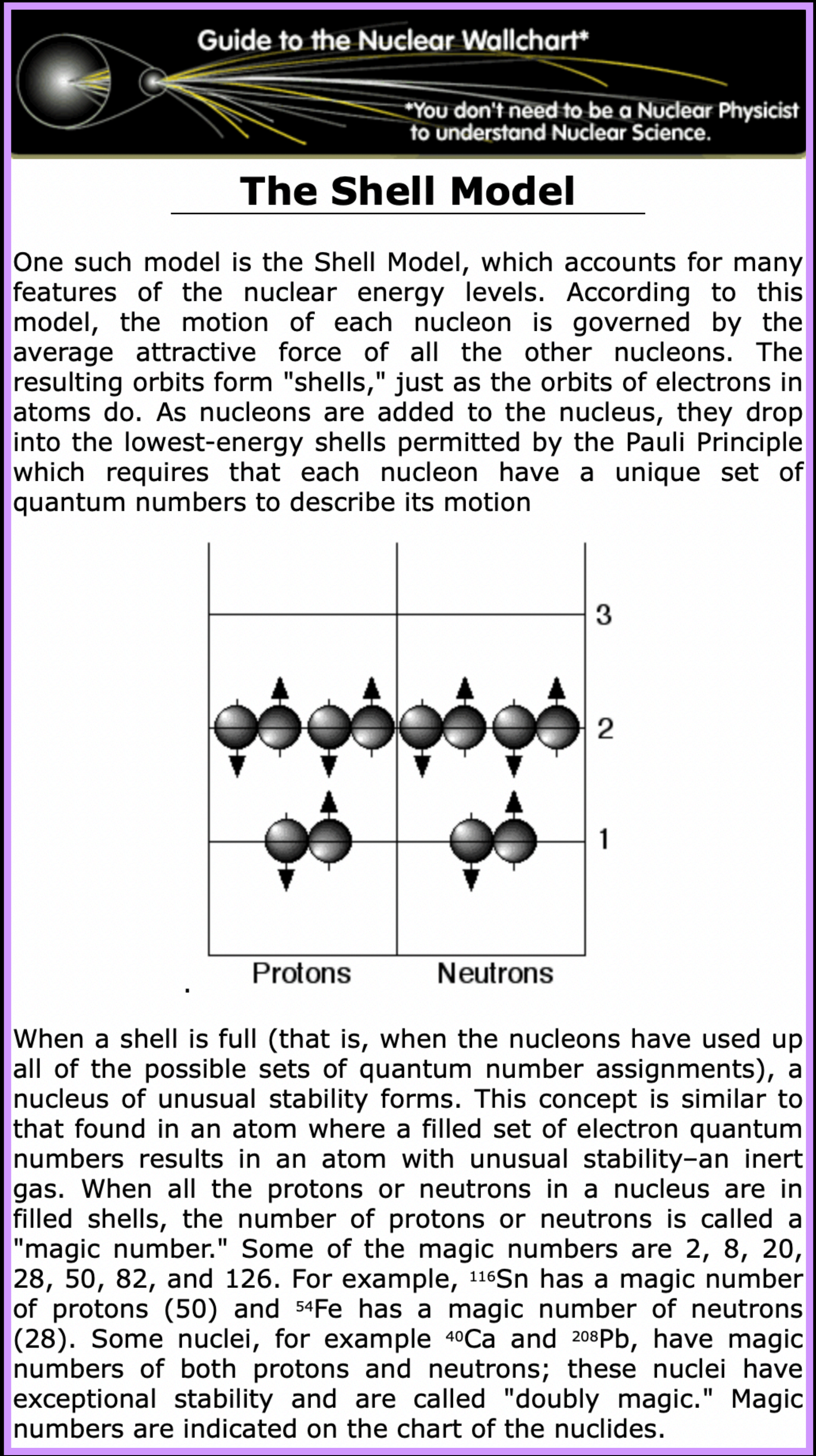
What are diquark-induced short-range correlations (SRC)?

First define SRC: Short-range correlated nucleon-nucleon pairs

- Nuclei consist of protons and neutrons ~80% of which are organized into shells
- Nuclear shell model organizes neutrons and protons into shells obeying the Pauli principle, just like electron shells in atoms

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

- 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

Diquark-induced SRC

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

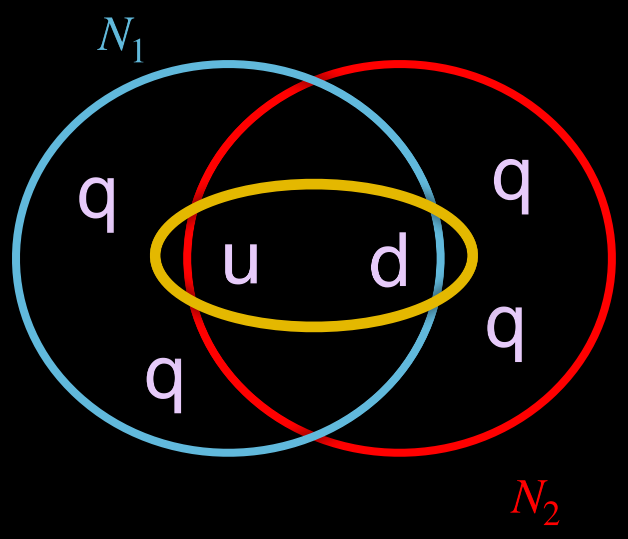
- Quantum fluctuations in separation distance between 2 nucleons
- Quantum fluctuations in relative momentum between 2 nucleons

How short is the range between the NN pair?

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



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:

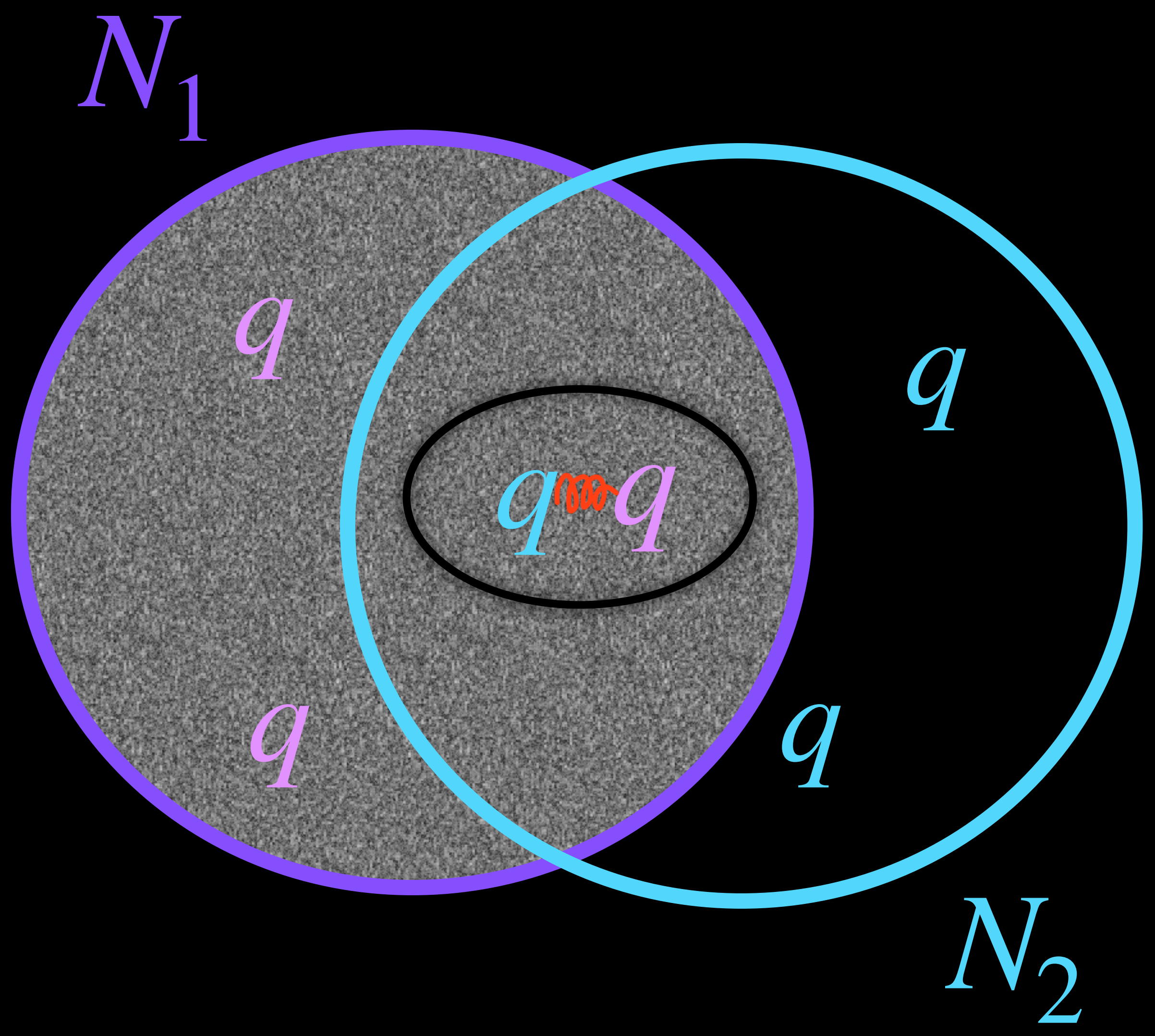
$$\Psi_{[ud]'} \propto \underset{\substack{\uparrow \\ \text{Antisymmetric}}}{\psi_{\text{color}}} \, \psi_{\text{spin}} \, \psi_{\text{iso}} \, \underset{\substack{\uparrow \\ \text{Symmetric, L=0}}}{\psi_{\text{space}}}$$

What are the requirements for a diquark to form in the nuclear environment?

Diquark formation across N-N pairs

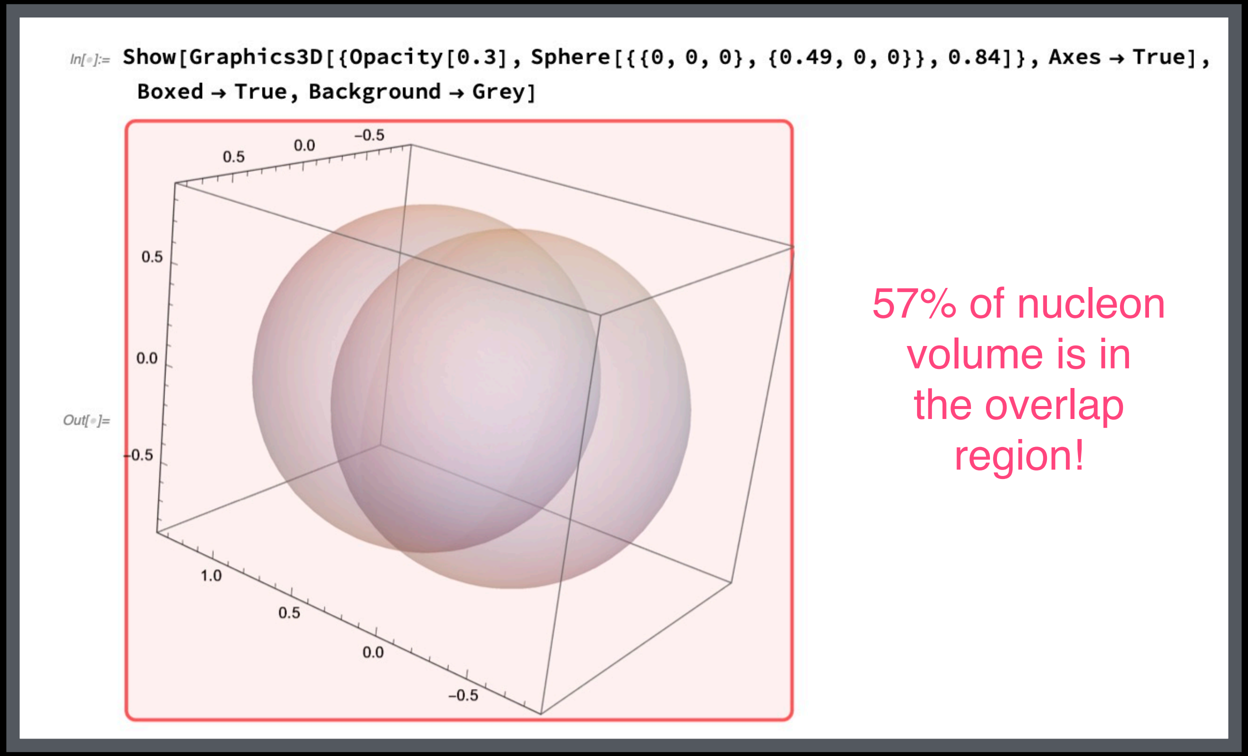
Requirements for diquark induced SRC:

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 $400\ \mathrm{MeV/c}$ & $800\ \mathrm{MeV/c}$

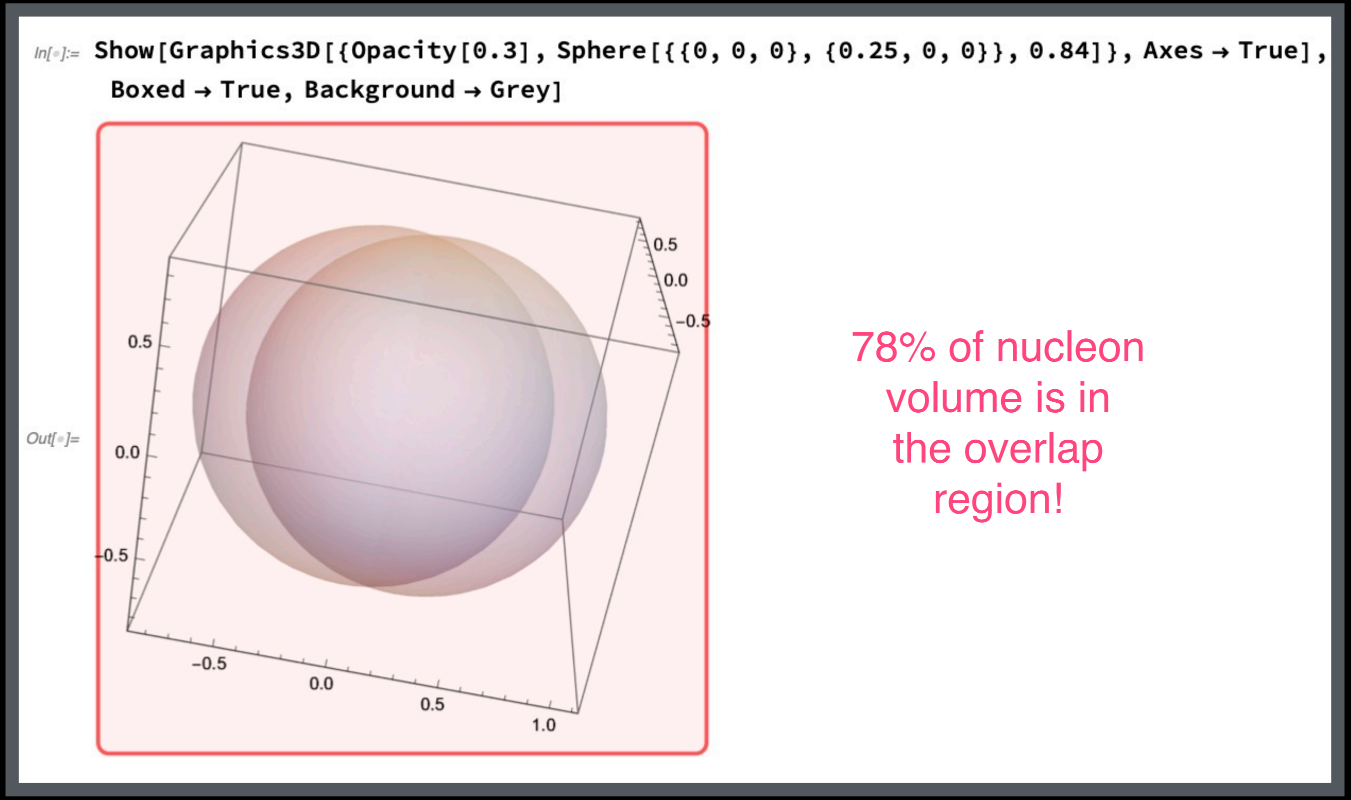
- *Plot 1*: According to the $^{12}\mathrm{C}$ measurements from 2021 CLAS, NN tensor force dominates at 400 MeV/c relative momenta. Natural unit conversion gives 0.49 fm = 400 MeV/c.



```
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!

- *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 .



```
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!

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

- The $\mathrm{SU}(3)_\mathrm{C}$ 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:

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

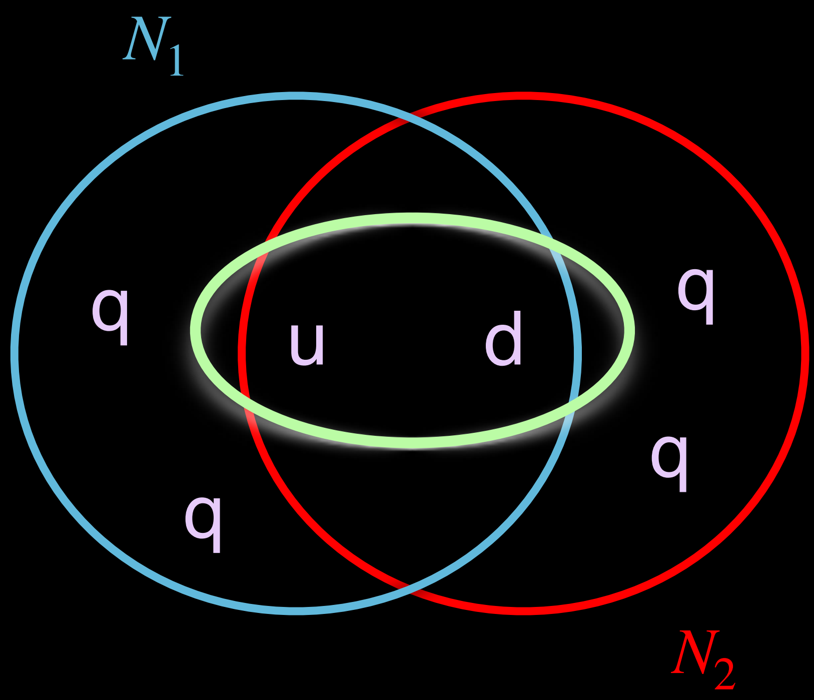
- To compute $V(r)$ for a $3_c \otimes 3_c \to \overline{3}_{c'}$, we use the definition of the scalar $C_2(R)$, $t^a_R\ t^a_R \equiv C_2(R)\ \mathbf{1}$, the *quadratic Casimir operator* (NB: R_f is the final state representation):

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

- Diquarks combine 2 fundamental representation quarks into an anti-fundamental, $3_\mathrm{C} \otimes 3_\mathrm{c} \to \overline{3}_\mathrm{C}$:

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

Diquark induced N-N correlation:



Compare to color singlet attractive potential:

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

Jennifer Rittenhouse West, EIC theory for RHIC/AGS @DNP in New Orleans 2022

3. Diquark binding energy: Color hyperfine structure

Use Λ^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. $M_{\text{(meson)}} = m_1 + m_2 + a \left(\sigma_1 \cdot \sigma_2\right) / m_1 m_2$

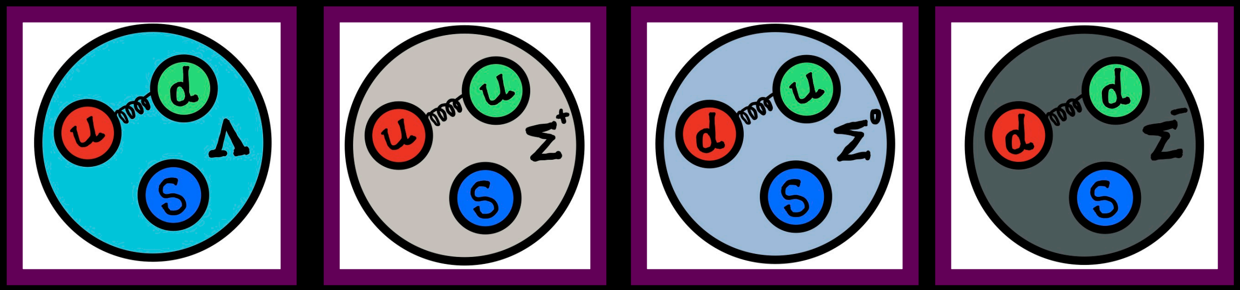
(de Rujula, Georgi & Glashow 1975, Gasiorowicz & Rosner 1981, Karliner & Rosner 2014)

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

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

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

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



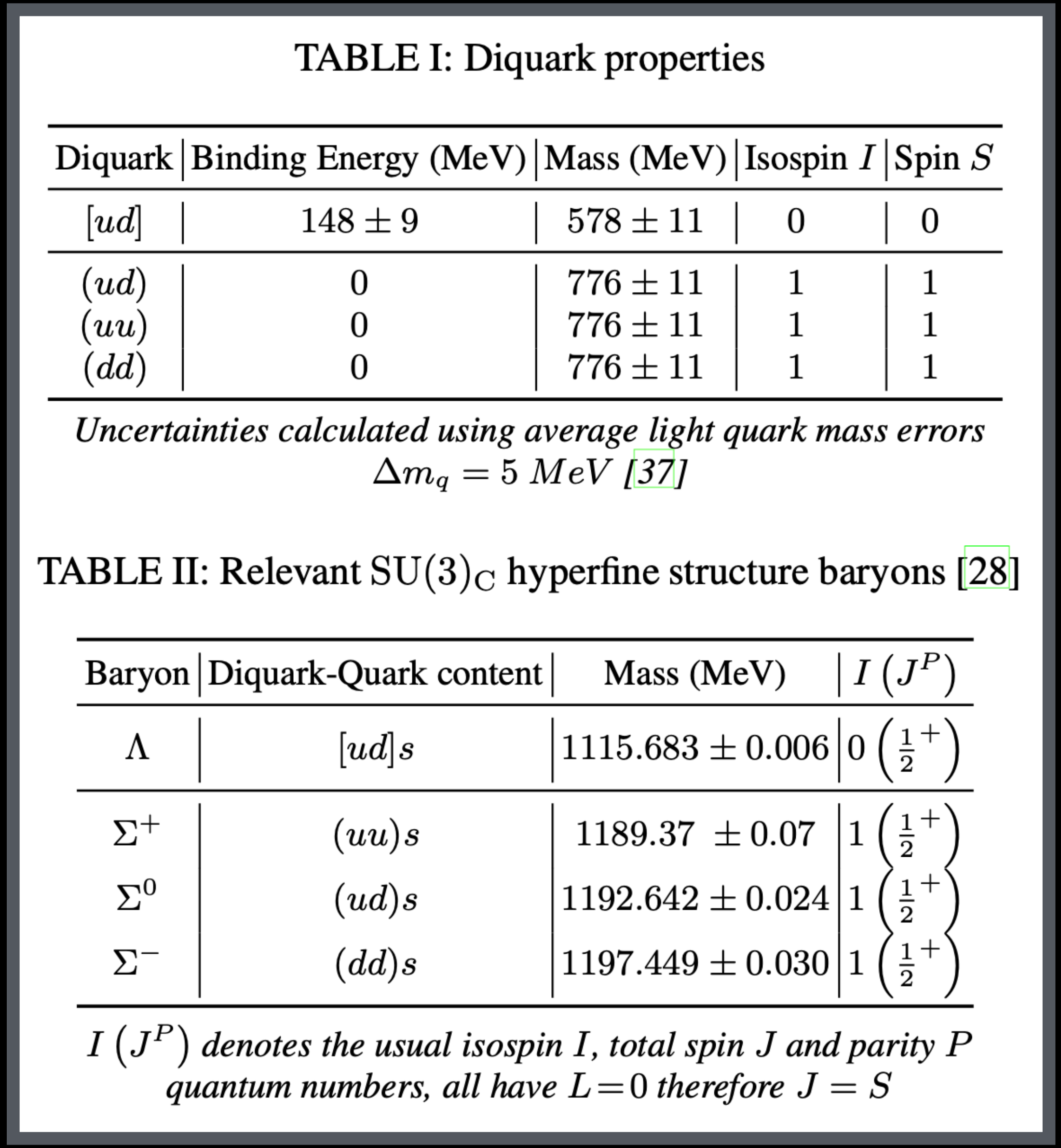


TABLE I: Diquark properties

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

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

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

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

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

"Diquark Induced Short-Range Correlations & the EMC Effect," JRW, Nucl.Phys.A 2023

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

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

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

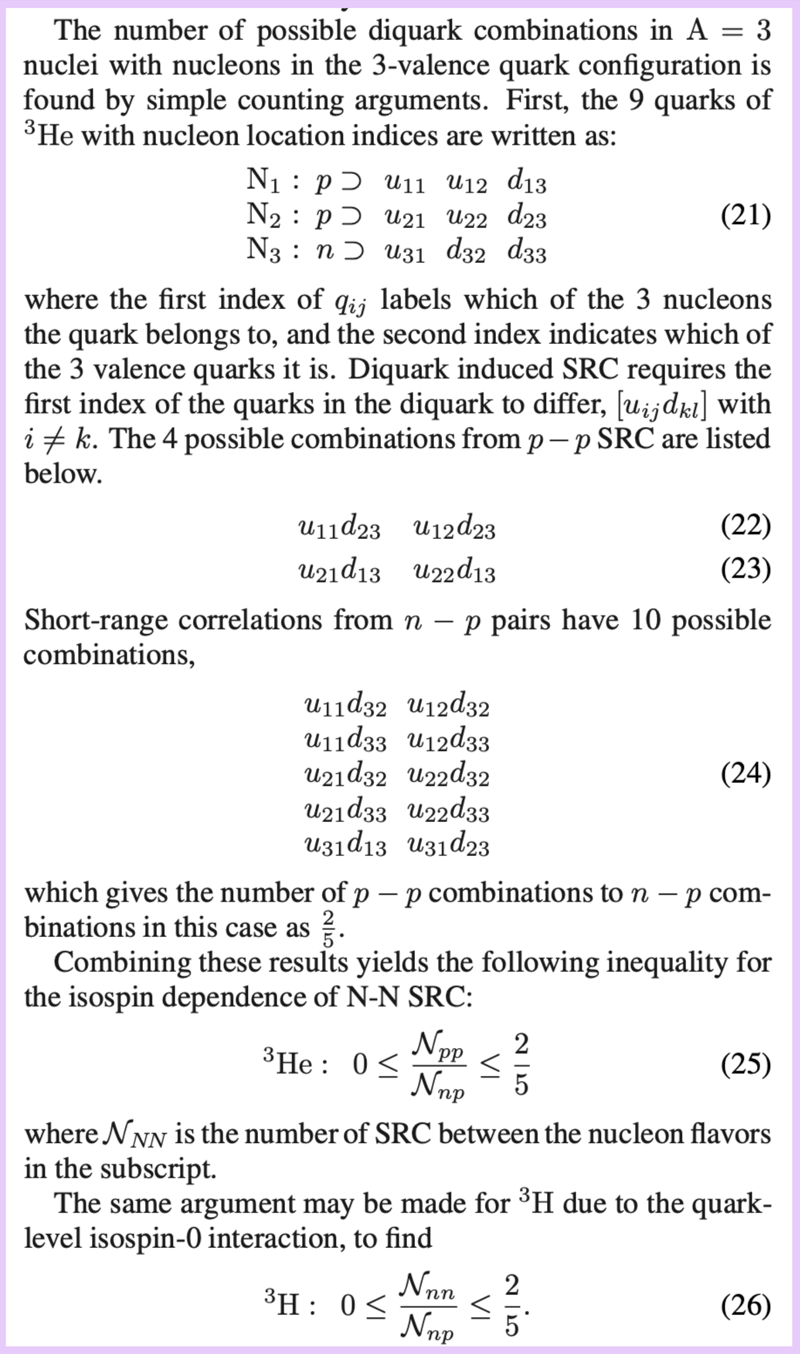
$$^3H: \quad 2n+p \rightarrow 4u,\, 5d \implies np \supset [ud]\ \mathrm{x}10$$
$$\implies nn \supset [ud]\ \mathrm{x}4 \implies 60\,\%\ n-p,\ 40\,\%\ n-n$$

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

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

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

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



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:

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

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,

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

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

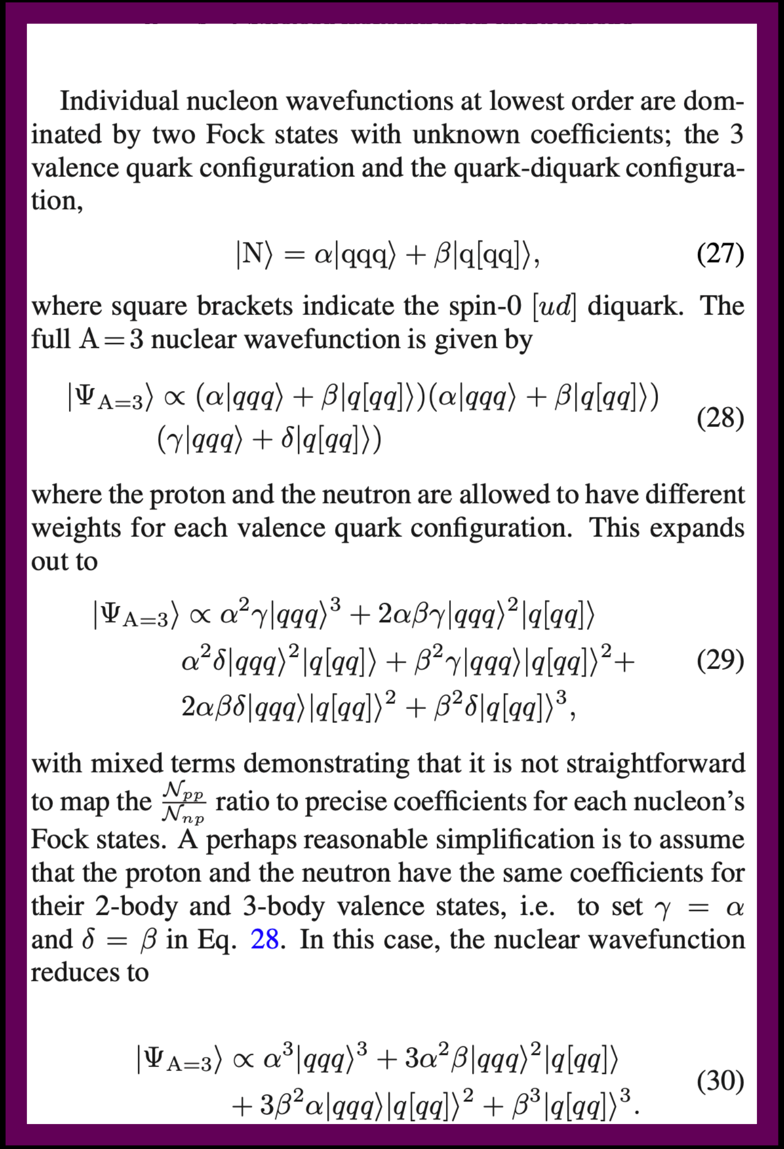
Combine into isospin dependent SRC ratio predictions :

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

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

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

By 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,

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

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

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

Nuclear structure functions $F_2(x_B)$ and PDFs from the diquark model

Non-relativistic check: Diquark formation modification of F_2 from Fermi motion of quarks in SRC

Recall quark (parton) 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 MeV and its Fermi momentum is depleted:

$$m_{\text{final}} = \sqrt{m_q - \frac{BE}{2}} \implies p_{\text{final}} < p_i$$

$$\text{Momentum ratio of quark in diquark to free quark :}$$

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

Electron-Ion Collider Physics Aims Revisited

- Test all rigorous predictions of QCD
- *(is it at all possible to break QCD? Find limits & boundaries - aim at confinement!)*
- Color transparency of baryons - QCD calculations show hard exclusive processes will isolate an extremely small component of the hadron wavefunction - mesons and baryons become pointlike & exit collision debris without interacting
- All that we do not know to ask for. There will be another EMC effect, the mysterious quark behavior in nuclei from 1983 until today
- Intrinsic charm! Charm and anti-charm quarks in the nucleon have different momentum distributions
- Hidden-color states - QCD predicts color singlets in nuclear wavefunctions, $^4\mathrm{He}$ contains a low mass hidden color state - EIC signatures?

Electron-Ion Collider

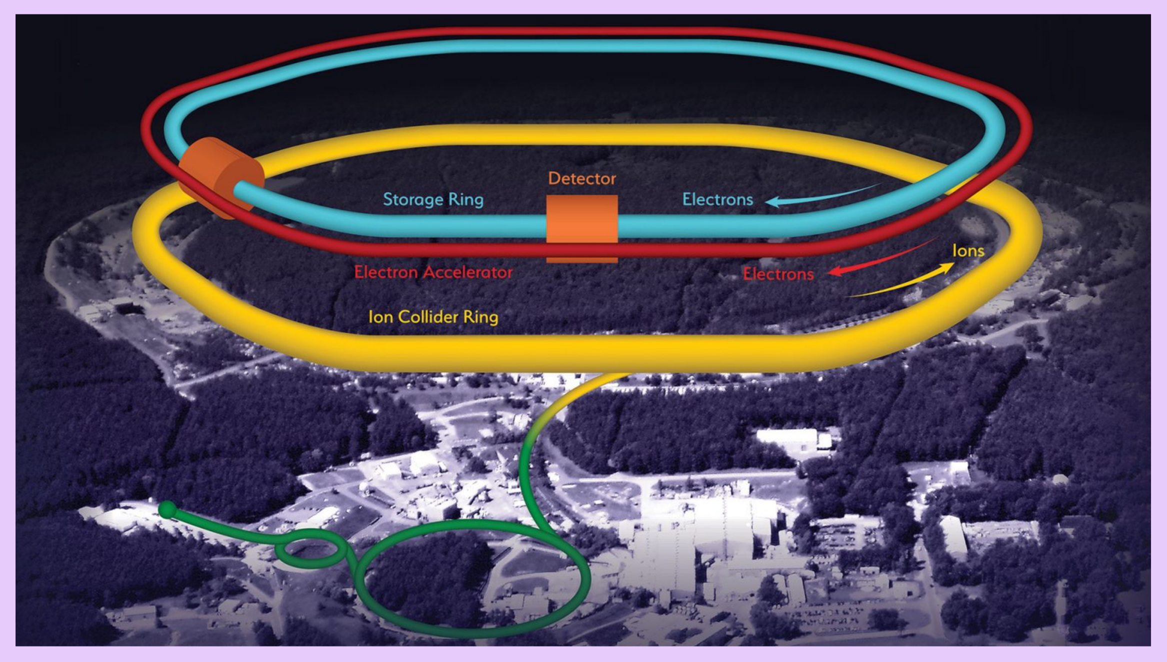


Image credit: Brookhaven National Lab

Fin

Jennifer Rittenhouse West
Lawrence Berkeley National Laboratory
EIC Theory for RHIC/AGS Users' Group @DNP Fall Meeting
28 October 2022

EIC^2
EIC Center at Jefferson Lab

BERKELEY
LAB