Diquark-based SRC & Hidden-Color with EIC Detector II

EIC^2
EIC Center at Jefferson Lab

Jennifer Rittenhouse West
Lawrence Berkeley National Lab
EIC Detector II Workshop @CFNS
7 December 2022

BERKELEY LAB

EIC Detector II Physics: Diquarks & Hidden-Color

- 8 physics goals outlined in EIC Yellow Report
- Second detector at Interaction-Region 8 and its far forward region OPTIMIZED for tagging struck ions (nuclear fragments & particles in the ion direction)
- After collision, A-N or A-2N ions may be more precisely tagged
- Extremely useful for Short-Range Correlation studies and Hidden-Color studies
- Diquarks feature heavily in both cases: as the proposed fundamental QCD basis for SRC & as building blocks for hidden-color states

Double-diquark bound state: Tetraquarks

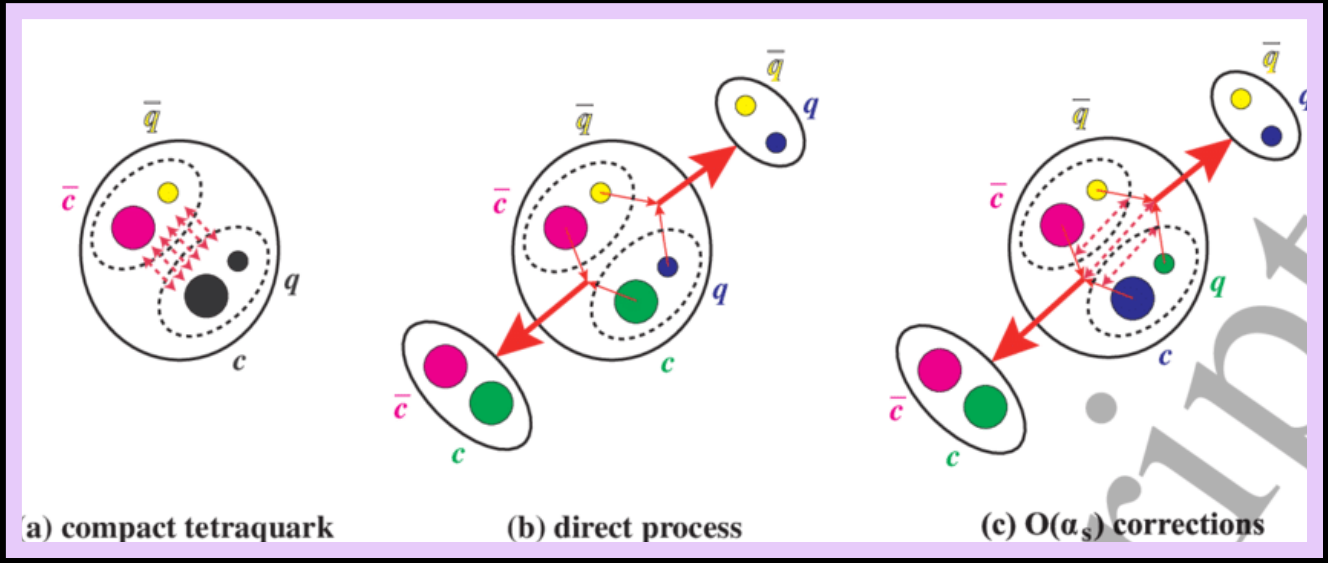


Image credit: Hua-Xing Chen (陈华星) 2020, "Decay Properties of the Zc(3900) through the Fierz rearrangement"

Electron-Ion Collider Physics Aims

1. Origin of Nucleon Spin

2. Origin of Nucleon Mass

3. Multi-dimensional Imaging of the Nucleon

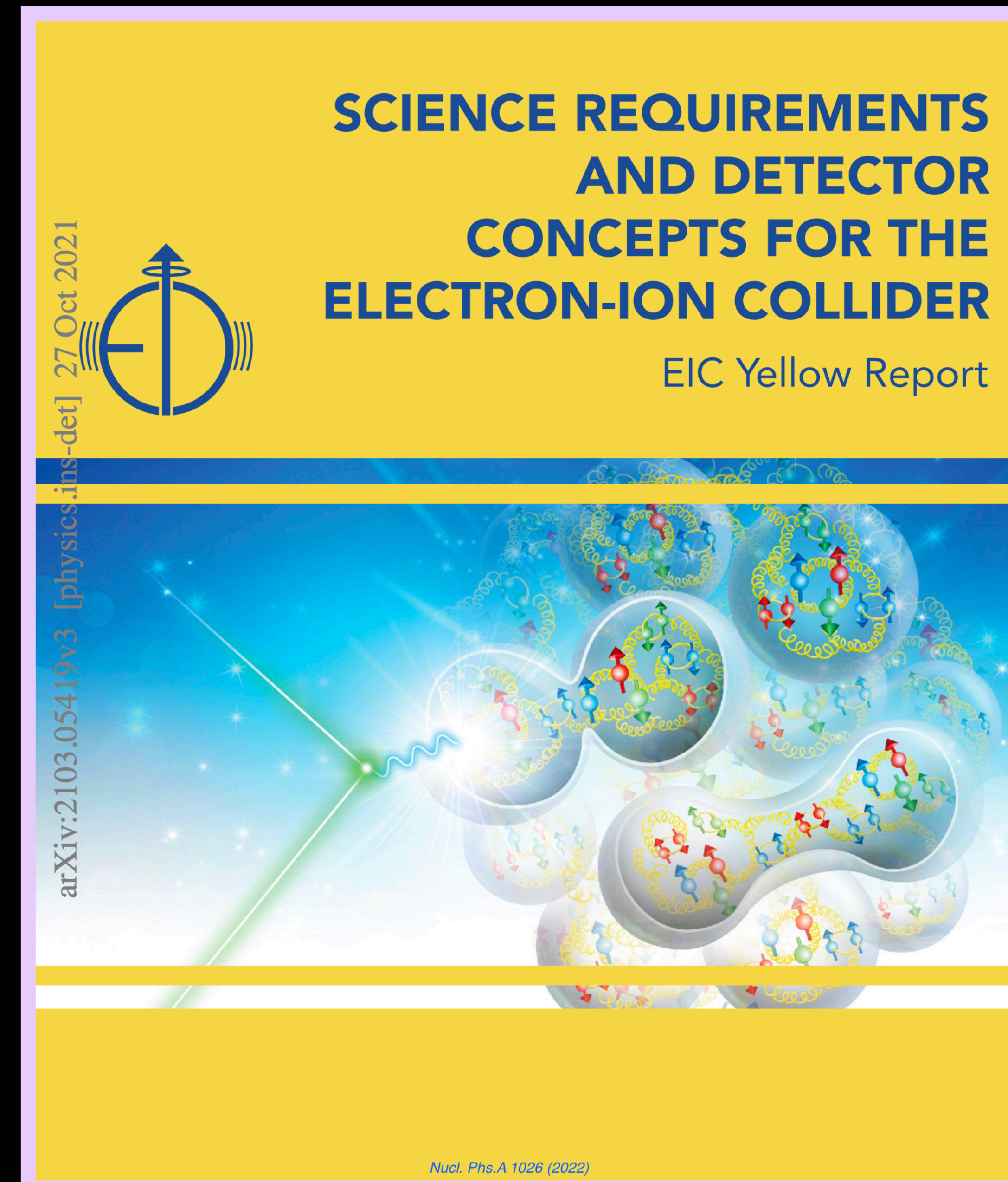
4. Imaging the Transverse Spatial Distributions of Partons *(partons = quarks, antiquarks, gluons)*

5. Physics with High Energy Nuclear Beams at the EIC (the nucleus as a QCD molecule - "quark-gluon origin of short-range nucleon-nucleon forces," SRC studies, low-x studies)

6. Nuclear Modifications of Parton Distribution Functions *(relates to the EMC effect)*

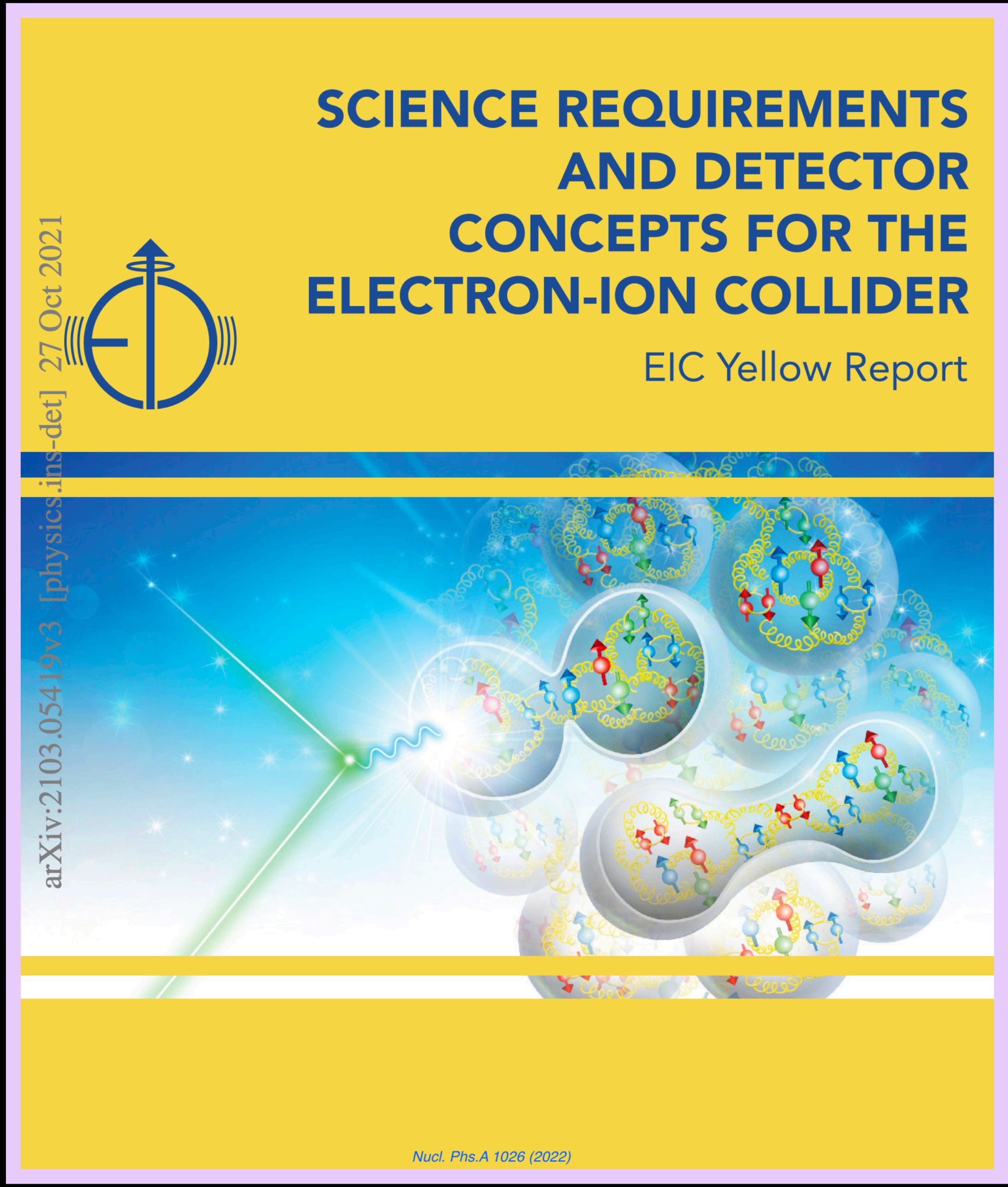
7. Passage of Color Charge through Cold QCD Matter *(hadronization! jets! **color transparency**…)*

8. Connections to Other Fields



Electron-Ion Collider Physics: Focus on SRC/EMC

1. Origin of Nucleon Spin
2. Origin of Nucleon Mass
3. Multi-dimensional Imaging of the Nucleon
4. Imaging the Transverse Spatial Distributions of Partons *(partons = quarks, antiquarks, gluons)*
5. Physics with High Energy Nuclear Beams at the EIC (the nucleus as a QCD molecule - "quark-gluon origin of short-range nucleon-nucleon forces" aka SRC studies - low-x studies)
6. Nuclear Modifications of Parton Distribution Functions *(EMC effect numerator)*
7. Passage of Color Charge through Cold QCD Matter *(hadronization! jets! **color transparency**…)*
8. Connections to Other Fields



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, Director of BNL*

"From RHIC to the EIC: Taking Our Exploration of Matter to the Next Frontier"

August 2022

Electron-Ion Collider

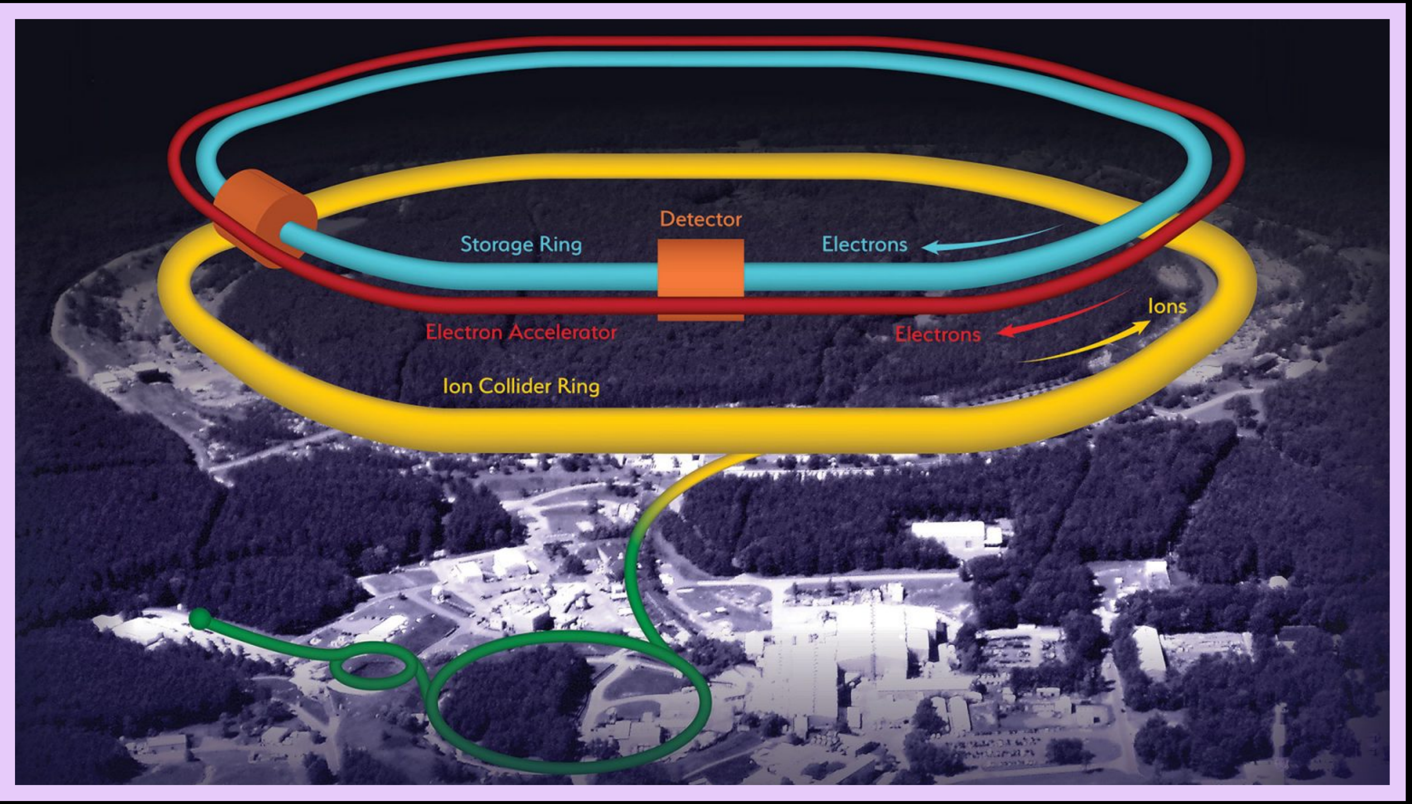


Image credit: Brookhaven National Lab

EIC Detector II Physics: Test Rigorous Predictions of QCD

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)

Double-diquark bound state: Tetraquarks

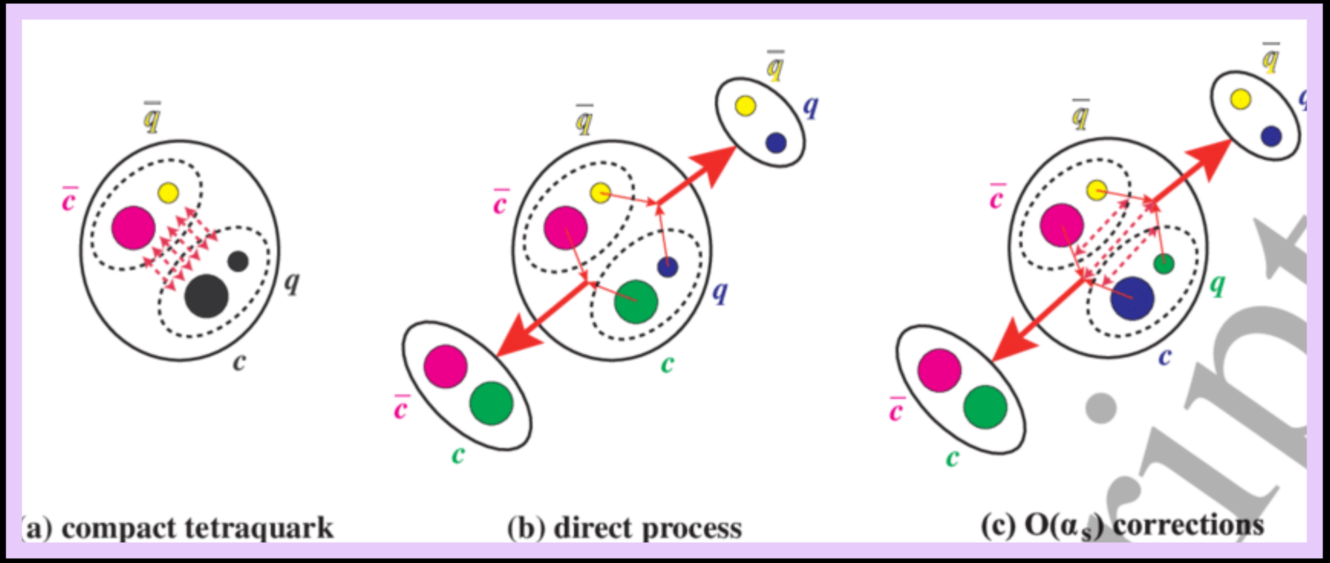


Image credit: Hua-Xing Chen (陈华星) 2020, “Decay Properties of the Zc(3900) through the Fierz rearrangement”

EIC Detectors I & II Physics: 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 and NN SRC isospin values - short-range QCD physics proposed to appear in nuclei

Electron-Ion Collider

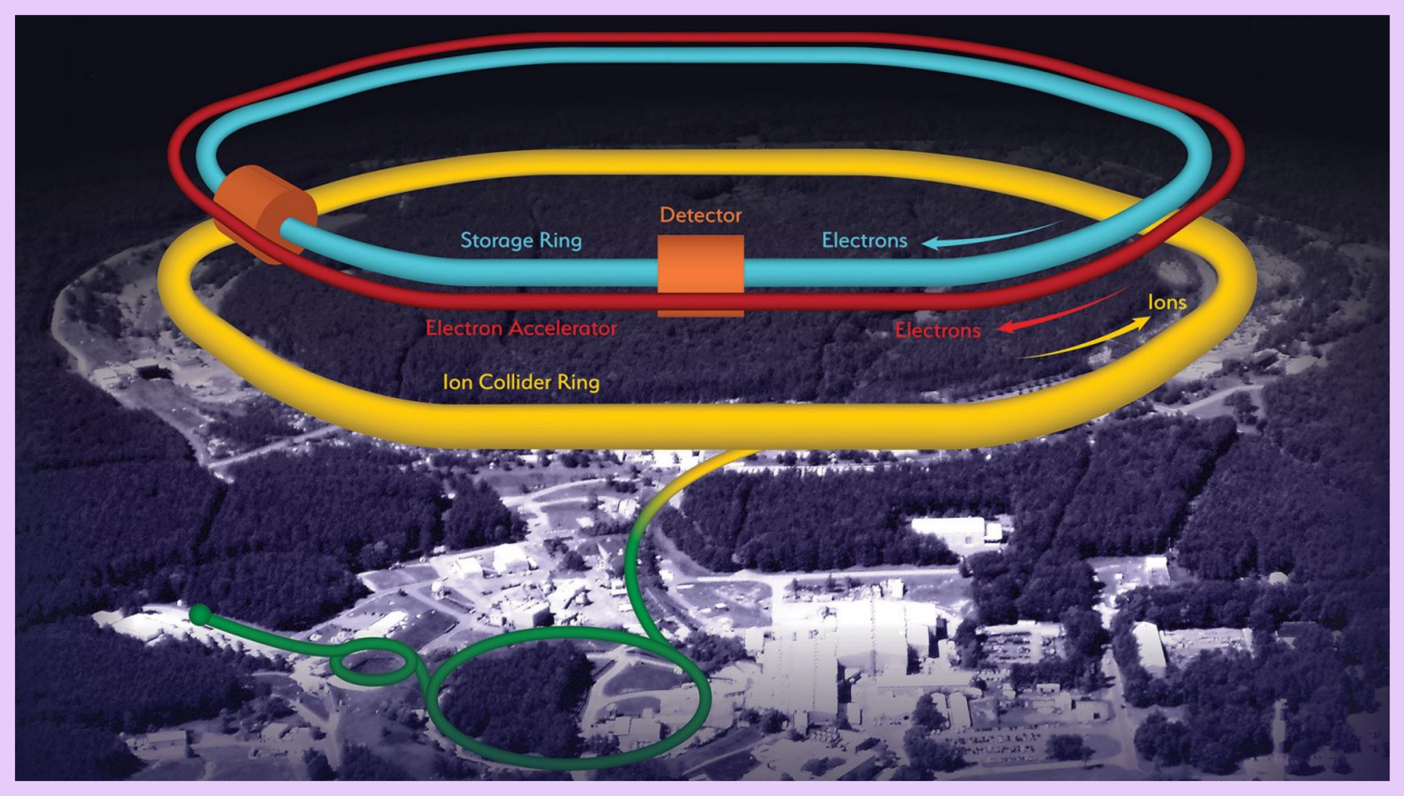


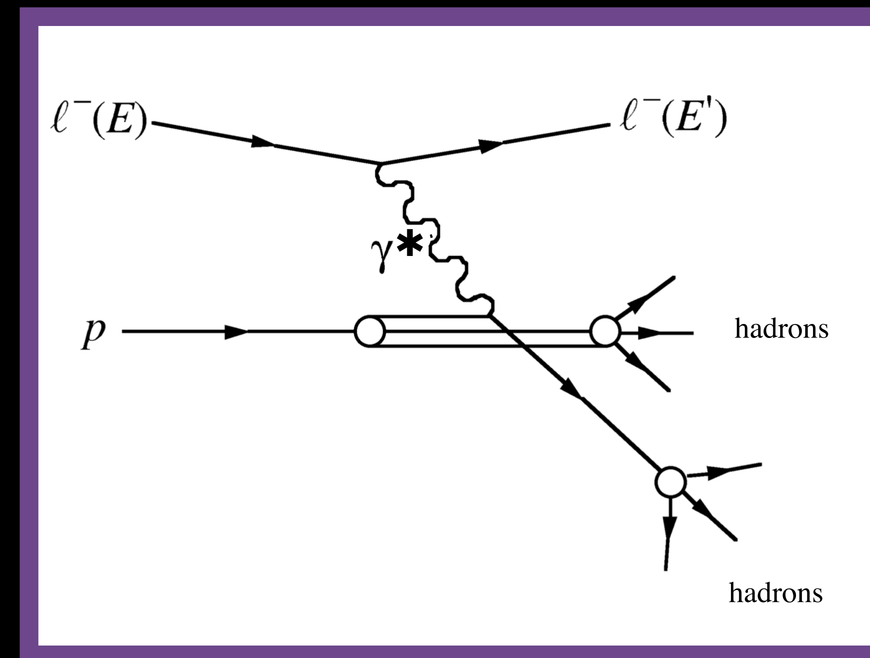
Image credit: Brookhaven National Lab

Bridge from fQCD to nuclear: EMC effect

- Lepton scatters from target, exchanging virtual photon with 4-momentum q^2 given by: $Q^2 \equiv -q^2 = 2EE'(1-\cos\theta)$

- γ^* strikes quark: We know the fraction of nucleon momentum carried by the struck quark via Bjorken scaling variable $x_B = \dfrac{Q^2}{2M_p\nu}$ where $\nu = E - E'$, M_p= proton mass, lepton masses neglected

- EMC plots: Ratios of structure functions vs. momentum fraction carried by struck quark x_B



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

Differential cross section for DIS:

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

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

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

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

EMC effect: Distortion of nuclear structure functions

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

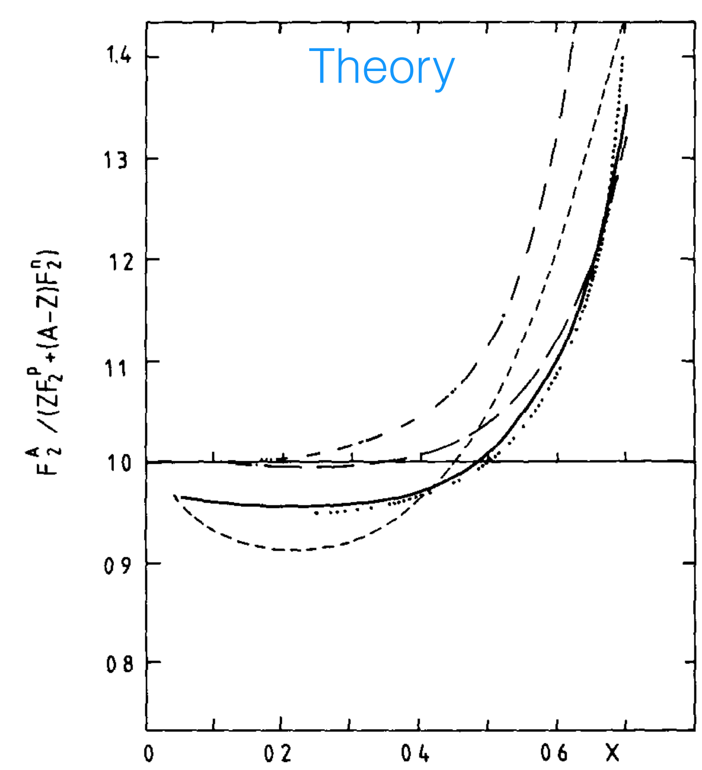


Fig. 1. Theoretical predictions for the Fermi motion correction of the nucleon structure function F_2^N for iron. Dotted line Few-nucleon-correlation-model of Frankfurt and Strikman [9]. Dashed line. Collective-tube-model of Berlad et al. [10] Solid line Correction according to Bodek and Ritchie [8].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

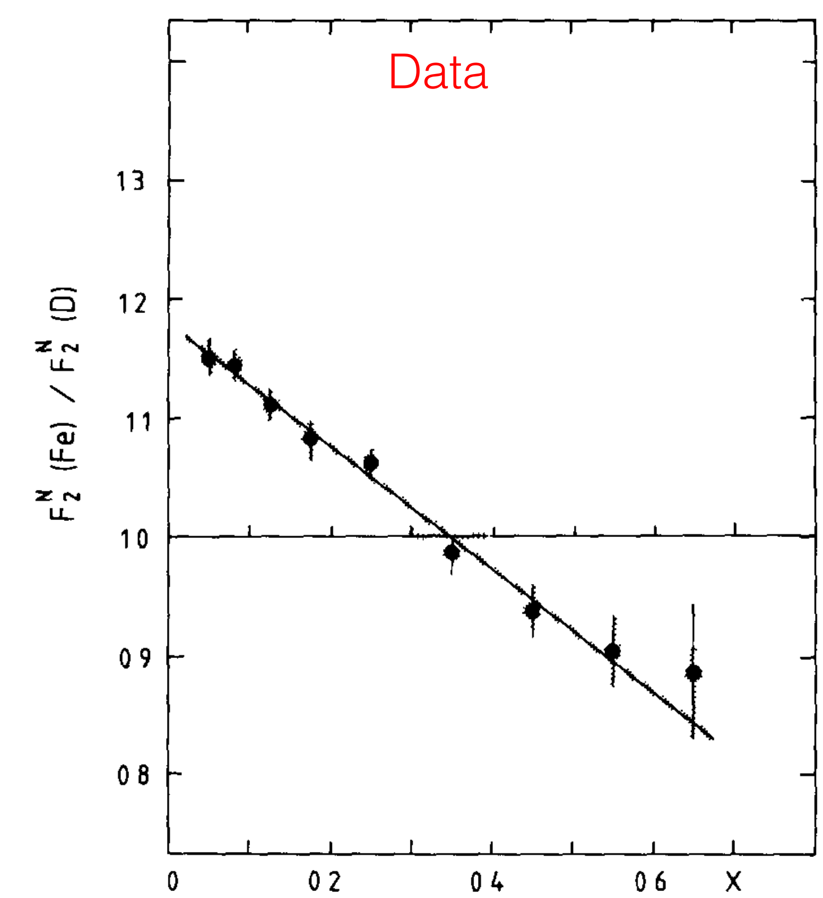


Fig. 2. The ratio of the nucleon structure functions F_2^N measured on iron and deuterium as a function of $x = Q^2/2M_p\nu$. The iron data are corrected for the non-isoscalarity of $^{56}_{26}$Fe, both data sets are not corrected for Fermi motion. The full curve is a linear fit $F_2^N(\mathrm{Fe})/F_2^N(\mathrm{D})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

EMC effect experiments & explanations

Possible explanations

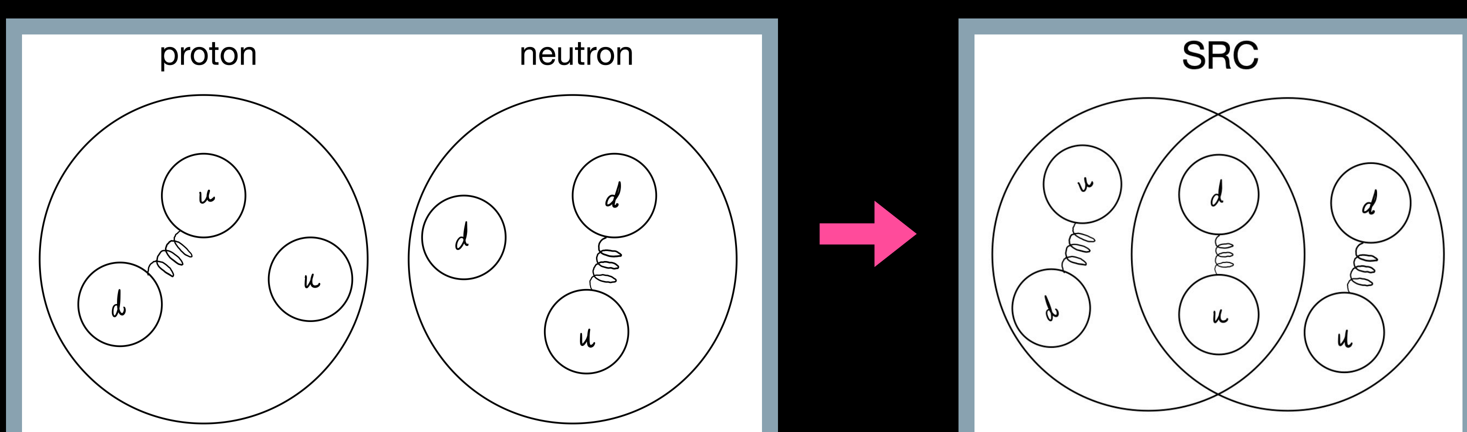
- Mean field effects involving the whole nucleus
- Local effects, *e.g.*, 2-nucleon correlations

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

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

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

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



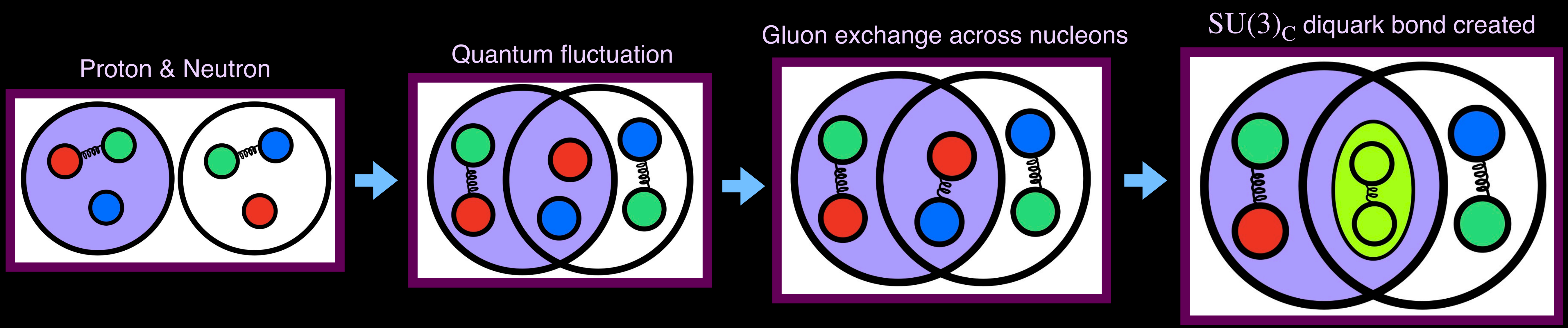
Dozens of experiments confirm EMC effect

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

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

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



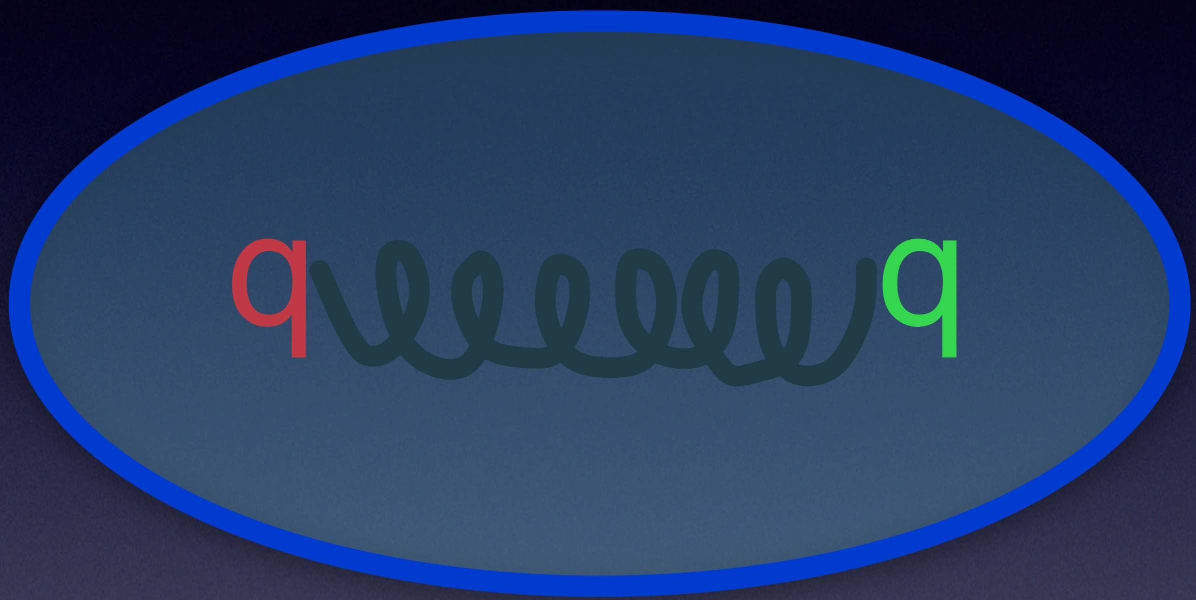
Short-range QCD potentials act on distance scales < 1 fm. Strong NN overlap can bring valence quarks within range.

What 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 Λ production)

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

Diquarks

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

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

- $\exists$ a short-range QCD Coulombic potential between quarks (gluon exchange):

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

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

$$\psi_a^{[ud]} = \frac{1}{\sqrt{2}} \epsilon_{abc} \left(u_\uparrow^b d_\downarrow^c - d_\uparrow^b u_\downarrow^c \right)$$

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

$$\psi_u \equiv \begin{pmatrix} u_r \\ u_g \\ u_b \end{pmatrix}$$

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 and long range correlations
- Nuclear shell model organizes neutrons and protons into shells obeying the Pauli principle, in analogy to electron shells in atoms

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

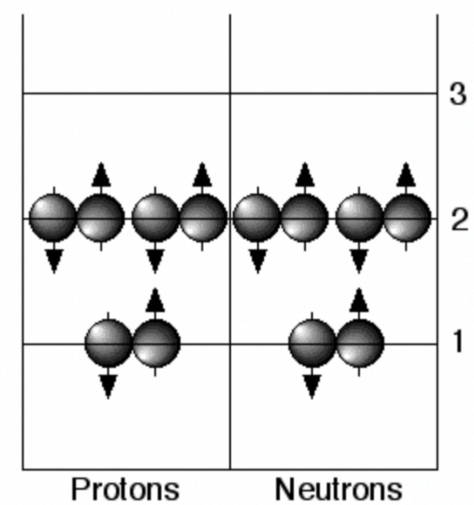
- SRC have very high relative momentum - nearly all nucleons above the Fermi momentum of the nucleus, $k_F \sim 250 \text{ MeV/c}$, are in SRC

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?

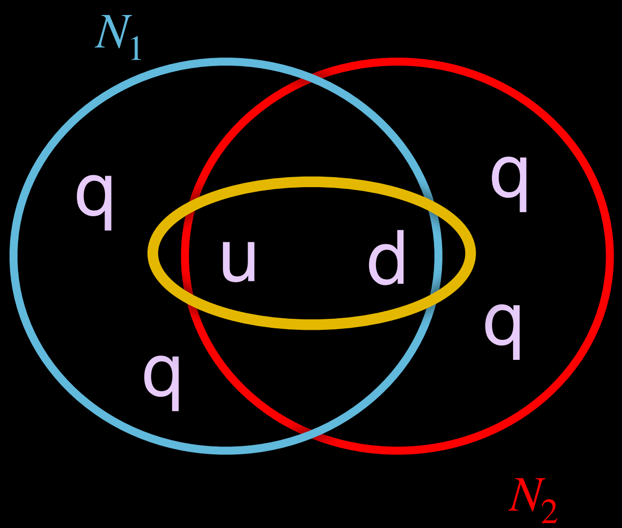
- Quantum fluctuations in separation distance between 2 nucleons
- Quantum fluctuations in relative momentum between 2 nucleons

How short is the range between the NN pair?

- SRC have relative momenta greater than the Fermi momentum, $k_F \sim 250\ \mathrm{MeV/c}$
- 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



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:

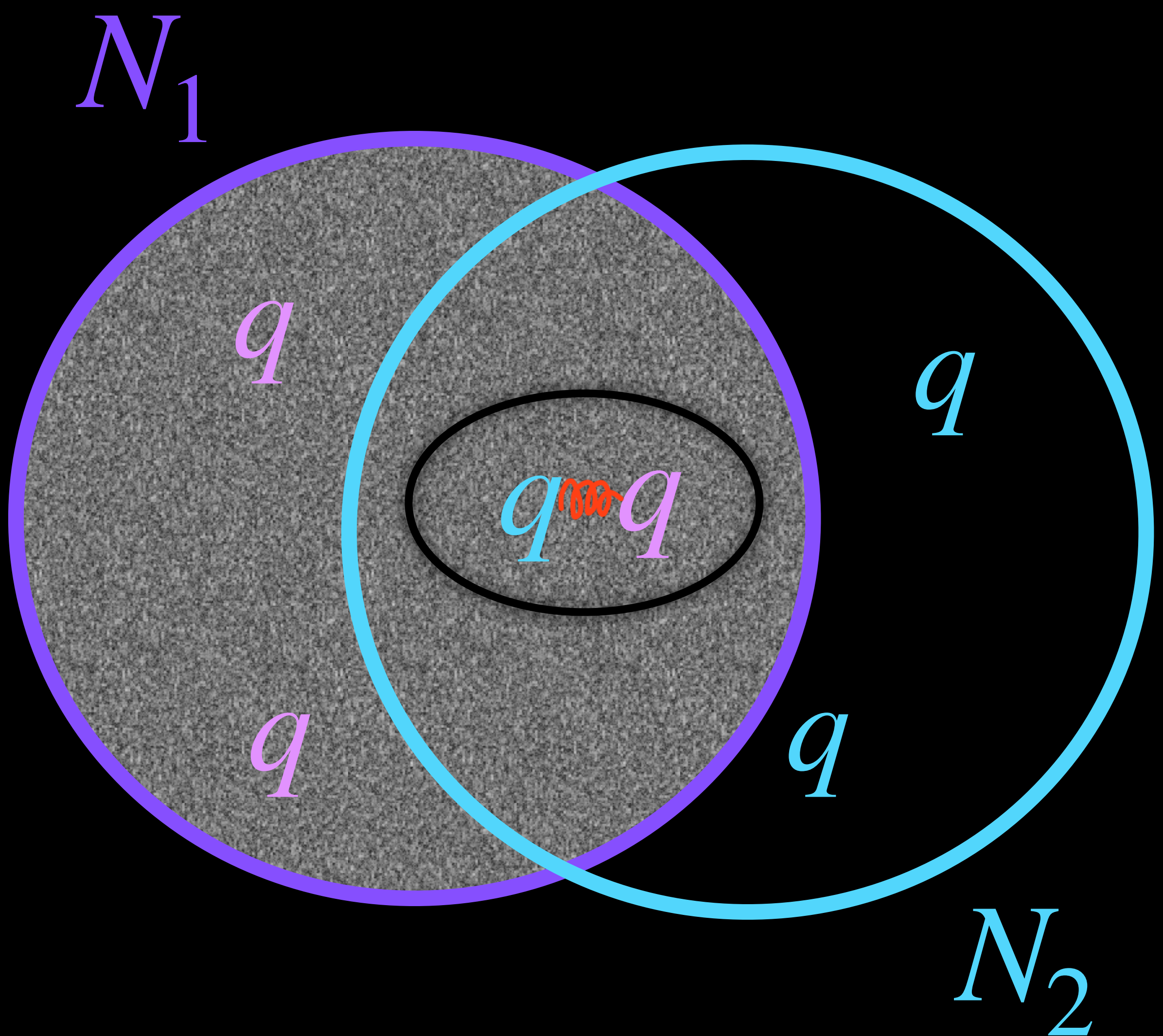
$$\Psi_{[ud]'} \propto \underbrace{\psi_{\text{color}}}_{\text{Antisymmetric}} \psi_{\text{spin}} \psi_{\text{iso}} \underbrace{\psi_{\text{space}}}_{\text{Symmetric, L=0}}$$

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

Diquark formation across N-N pairs

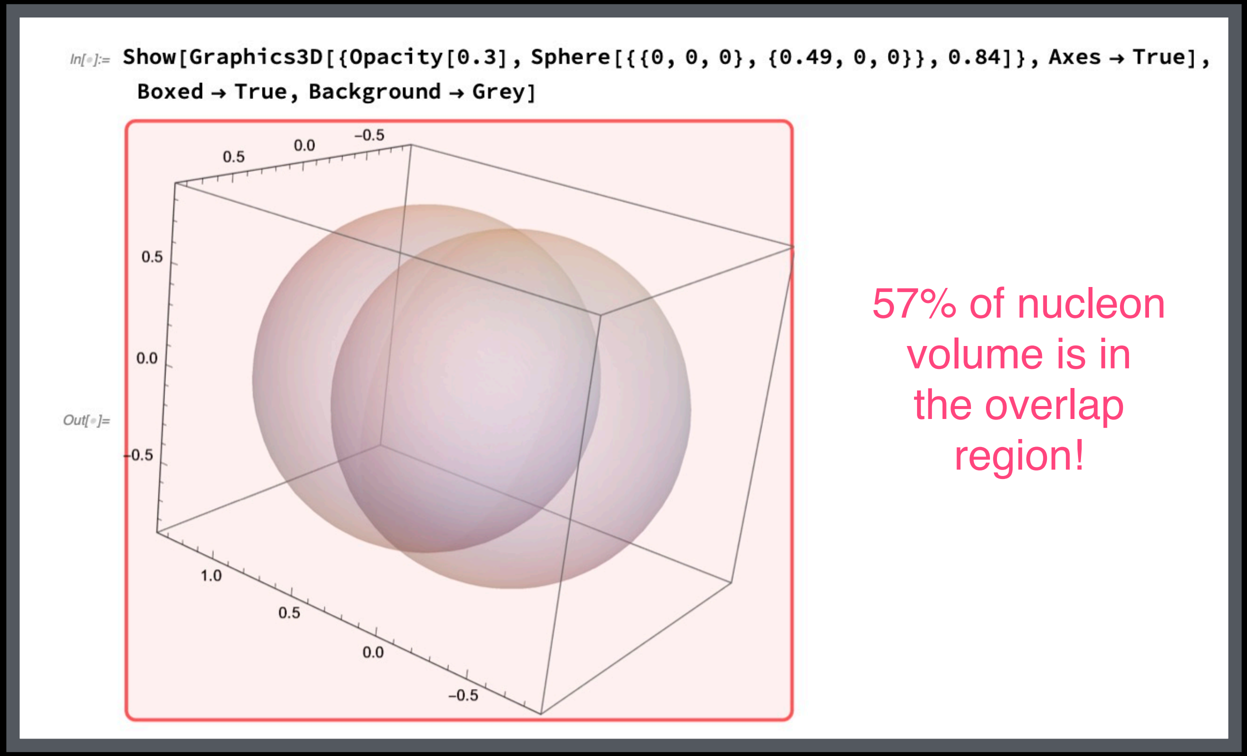
Requirements for diquark induced SRC:

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)

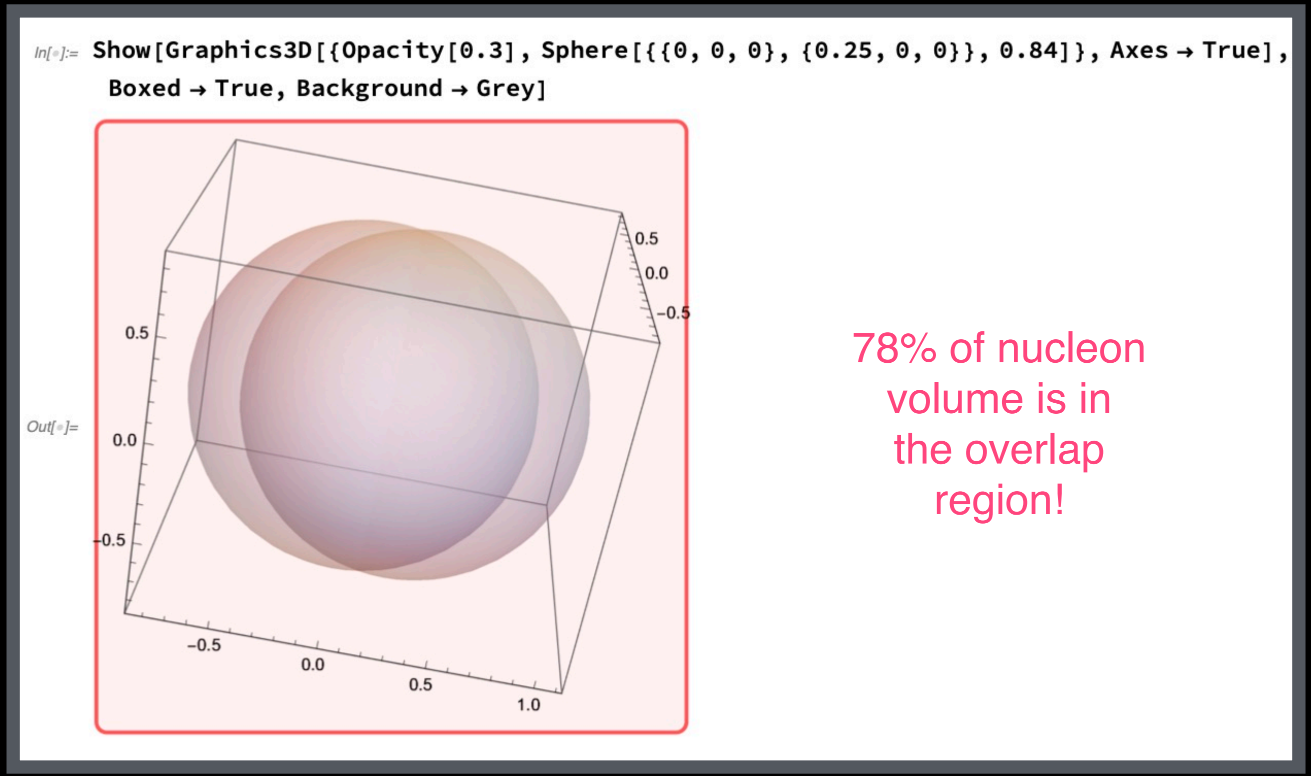


1: SRC 3D-overlap for relative momenta $400\ \mathrm{MeV/c}$ & $800\ \mathrm{MeV/c}$

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



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



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:

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

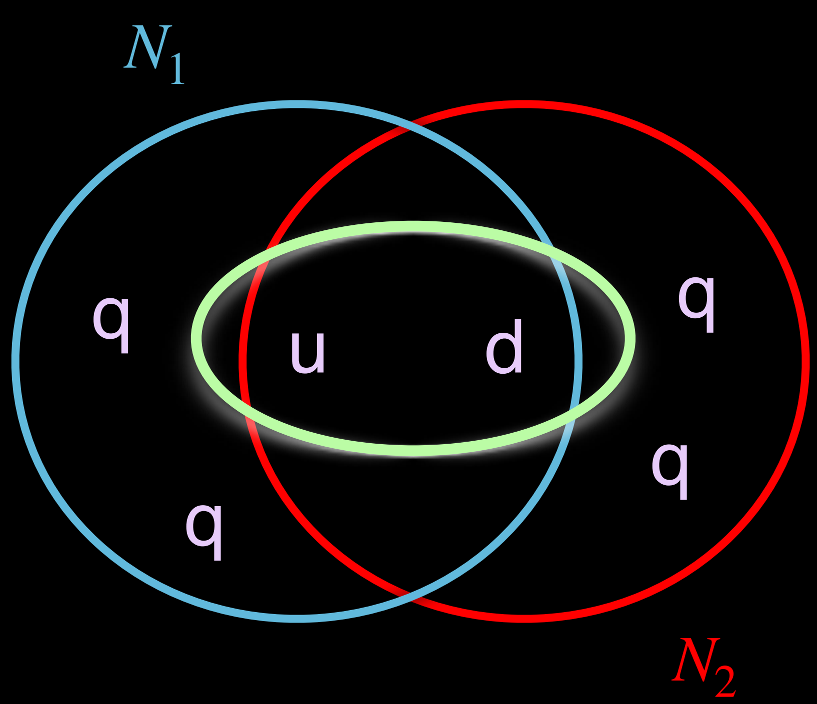
- To compute $V(r)$ for a $3_c \otimes 3_c \to \overline{3}_c$, use the definition of the scalar $C_2(R)$, $t^a_R\, t^a_R \equiv C_2(R)\,\mathbf{1}$, the *quadratic Casimir operator* (NB: R_f is the final state representation):

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

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

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

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 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 contributes 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:

$$m_u^b = m_d^b \equiv m_q^b = 363 \text{ MeV}, \quad \mathrm{m_s^b} = 538 \text{ MeV}$$

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

Relevant diquark-carrying baryons: Λ, Σ^+, Σ^0, Σ^-

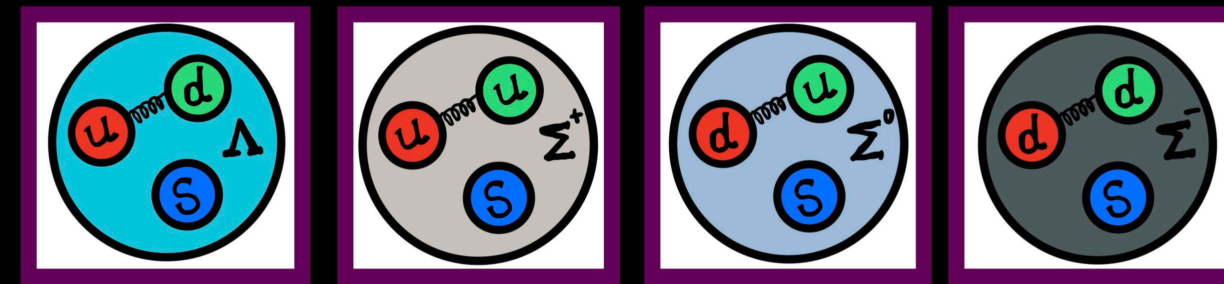


TABLE I: Diquark properties

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 $\mathrm{SU(3)_C}$ hyperfine structure baryons [28]

Baryon	Diquark-Quark content	Mass (MeV)	$I\left(J^P\right)$
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	$1\left(\frac{1}{2}^+\right)$

$I\left(J^P\right)$ 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 $[ud]$ affects # of np, pp, nn SRC.

Diquark formation prediction for A=3 SRC

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 $|\mathrm{N}\rangle \propto |\mathrm{qqq}\rangle$:

$$^3H: \quad 2n + p \to 4u,\, 5d \implies np \supset [ud] \text{ x10} \quad \implies nn \supset [ud] \text{ x4} \implies 60\,\%\ \mathrm{np},\ 40\,\%\ \mathrm{nn}$$

$$^3He: \quad 2p + n \to 5u,\, 4d \implies np \supset [ud] \text{ x10} \quad \implies pp \supset [ud] \text{ x4} \implies 60\,\%\ \mathrm{np},\ 40\,\%\ \mathrm{pp}$$

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

JRW, Nuc.Phys.A 2023

Combine into isospin dependent SRC ratio predictions :

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

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

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

Shujie Li, John Arrington & collaborators, September 2022

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

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

where square brackets indicate the spin-0 $[ud]$ diquark. The full $\mathrm{A}=3$ 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, Nuc.Phys.A 2023

Isospin dependent SRC ratio inequalities from diquark induced SRC :

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

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

$\Longrightarrow$ Nucleon wavefunction : $\alpha|\mathrm{qqq}\rangle + \beta|\mathrm{q[ud]}\rangle$ combination may have approximately equal coefficients, $\alpha \approx \beta$

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

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

What is hidden-color? A QCD Study

- Rigorous prediction of $\mathrm{SU}(3)_C$
- Color-singlets with quantum numbers that match nuclei
- Nuclei = bag of color singlets
- Hidden-color = 1 color singlet
- Gluons also participate, e.g., standalone glueballs & hidden-glue in hadronic wavefunctions

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

The hexadiquark $|[ud][ud][ud][ud][ud][ud]\rangle$ is a 6-diquark, 12-quark hidden-color state, a novel color-singlet of QCD. Such hidden-color states are rigorous predictions of the $\mathrm{SU}(3)_\mathrm{C}$ group theory basis of QCD. In general, a hadronic or nuclear eigenstate of the QCD Hamiltonian is a sum over all color-singlet Fock states which match its quantum numbers. This has special impact for the ^{4}He nucleus, since the hexadiquark Fock state has the same quantum numbers as the usual nuclear Fock state $|nnpp\rangle$ [14].

Nuclear wavefunctions are typically dominated by the neutron and proton Fock state, i.e., the multiple 3-quark color singlet Fock state. In the ^{4}He nuclear wavefunction, the dominant state is the $|nnpp\rangle$ containing 4 color singlets (2 protons and 2 neutrons). In addition to this state, every 12-quark combination that has the same quantum numbers of ^{4}He is also in the wavefunction - including the single color-singlet hexadiquark. The hexadiquark is a special hidden-color state because it is an unusually low mass combination of quarks - all spin-0, isospin-0 and S-wave combinations - that obeys the spin-statistics theorem at every stage of the build. This means it has the opportunity to have a larger effect on nuclear physics than is typical. But hidden-color states are not ad hoc in the least - they arise in QCD by the rules of SU(3).

"Quantum Chromodynamics Resolution of the ATOMKI Anomaly in 4He Nuclear Transitions" Kubarovsky, Rittenhouse West & Brodsky 2206.14441

$$|{}^4\mathrm{He}\rangle = C_{pnpn}\left|u[ud])_{1_c}\, d[ud])_{1_c}\, u[ud])_{1_c}\, d[ud])_{1_c}\right\rangle + C_{\mathrm{HdQ}}\left|([ud][ud])_{\bar{6}_c}([ud][ud])_{\bar{6}_c}([ud][ud])_{\bar{6}_c}\right\rangle$$

"One of the most important distinctions between traditional nuclear physics and QCD descriptions of nuclei are the hidden color degrees of freedom of the nuclear wavefunction."

- S.J. Brodsky, Structure Function Working Group, Wisconsin 2005, "Novel Nuclear Effects in QCD"

Hexadiquark (HdQ) color singlet in A≥4 nuclei

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

- $^4\mathrm{He}$ nucleus to contain a new 12 quark color singlet state
- 6 scalar diquarks strongly bound together to form a color singlet - low mass! S-wave, isosinglet spin singlet states only!
- Proposed as cause of $^4\mathrm{He}$ anomalously large binding energy, ~28 MeV

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

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

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: $3_\mathrm{C} \otimes 3_\mathrm{c} \rightarrow \bar{3}_\mathrm{C}$

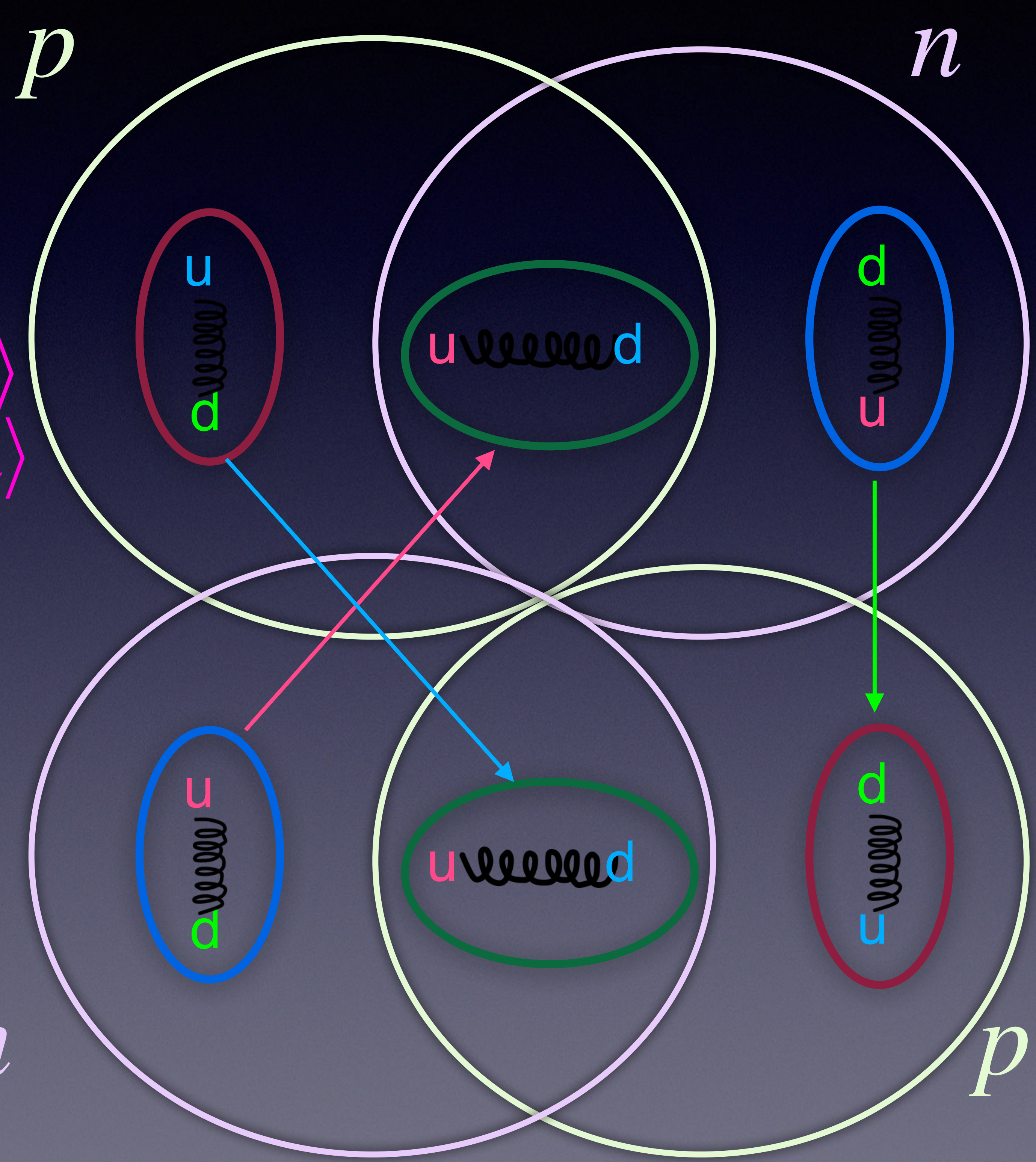
Hexadiquark (HdQ) color singlet in A≥4 nuclei

JRW, S.J.Brodsky, G. de Teramond, I.Schmidt, F.Goldhaber, arXiv:2004.14659, Nuc. Phys A 2020

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

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

- n-p dominance of SRC required by the HdQ model
- New hadronic excitations predicted due to 6_C bonds between diquarks



Hexadiquark state effects:

SRC knockout downstream products, e.g., $^{12}\mathrm{C} \to {}^{10}\mathrm{B}$ vs. $^{12}\mathrm{C} \to {}^{4}\mathrm{He} + {}^{4}\mathrm{He} + np$

HdQ state: $\mathrm{J^P} = 0^+, \;\; \mathrm{I} = 0$ component of $^4\mathrm{He}$ 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 created from 2 SRC pairs. Effect of HdQ is "isophobic" because $[ud]$ diquarks form only across np pairs in the quark-diquark nucleon configuration. EMC effect must be np 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

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

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 $\mathrm{J^P} = 0^+, \mathrm{I} = 0$ 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

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

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: $\bar{\mathbf{6}}_C \otimes \bar{\mathbf{6}}_C \to \mathbf{6}_C$. It is given by the symmetric tensor (A.11). The HdQ wave function, ψ_{HdQ}, is thus the color singlet

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

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

EIC Detector II: Funding Incubation

Looking to other fields of physics in order to fund the only foreseeable new collider's second detector, 2 examples:

- **Astrophysics**: Vera Rubin Observatory in Chile - Primarily NSF and private funding (also DOE and international contributors). Goal to "address some of the most pressing questions about the structure and evolution of the universe and the objects in it."

  8.4-meter Simonyi Survey Telescope is housed in the Rubin Observatory - named after private funding by Charles Simonyi

- **Theoretical physics, general**: Kavli Institute for Theoretical Physics (formerly the Institute for Theoretical Physics) at UC Santa Barbara - NSF and private funding

  KITP expanded and named after private funding by Fred Kavli

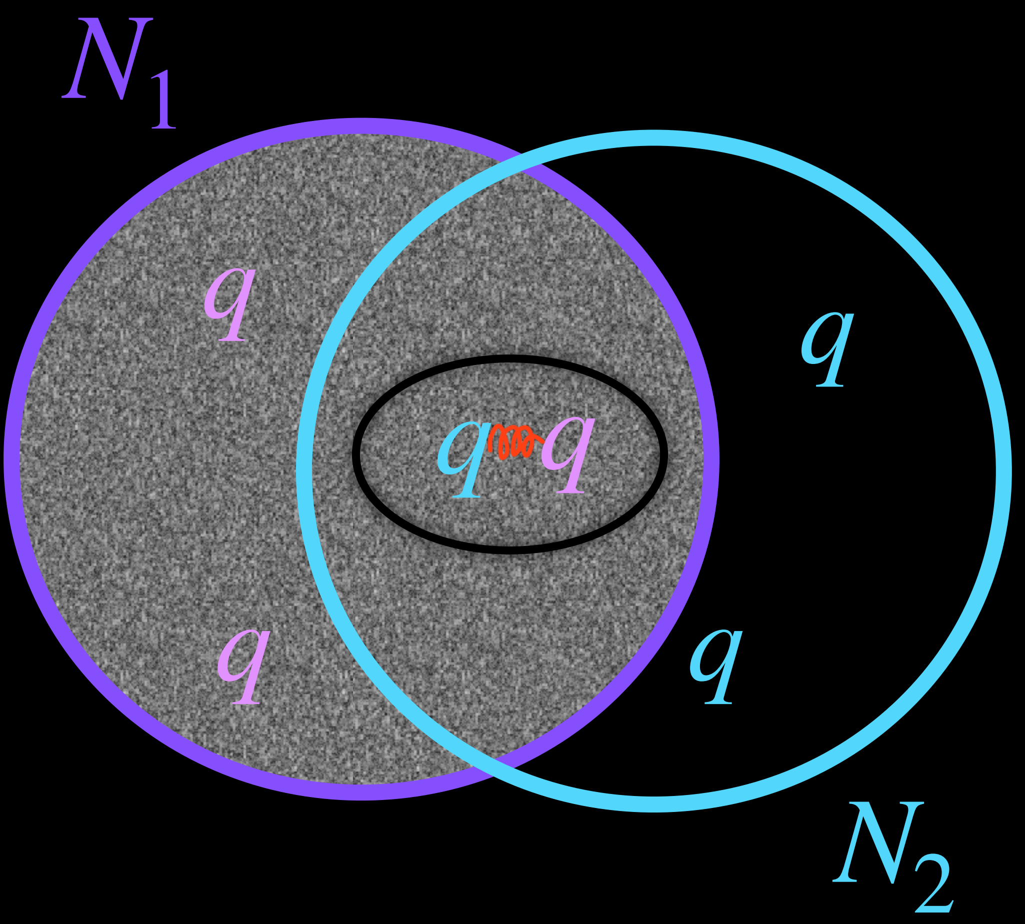
- Detector II could be given a name and privately funded. Goal to address the most pressing questions about the structure and dynamics of matter, from the nucleus to the nucleon to the quarks and gluons within.

Summary: EIC Detector II (& I) Physics

- Diquark formation proposed to cause short-range correlated nucleon pairs & EMC effect - EIC Detector II a great boost to physics
- Hexadiquark hidden-color state within $^4\mathrm{He}$ nucleus, further physical implications e.g., B.E. & ATOMKI calculations
- Direct calculations of F_2 needed; Complete F_2 $\forall$ nuclear targets missing for 39 years:

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

- Search for indirect evidence of diquark created NN such as the $\dfrac{\mathcal{N}_{pp\ \mathrm{SRC}}}{\mathcal{N}_{np\ \mathrm{SRC}}}$ inequality
- Future: F_2 calculation, NN repulsion, strength of 3N & 4N correlations
- Future Aim: Calculate ~20% SRC from QCD - requires 3D imaging of nucleons - EIC Detectors I & II



Fin

Jennifer Rittenhouse West
Berkeley Lab & EIC Center @JLab
EIC Detector II Incubation Workshop, CFNS Stony Brook
6-8 December 2022

EIC²
EIC Center at Jefferson Lab

BERKELEY LAB