

The Nature of Hadron Mass and Quark-Gluon Confinement from JLab Experiments in the 12-GeV Era



The Electron-Ion Collider: – Exploring the science of Nuclear Femtography

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Theory Center, Jefferson Lab

July 1-4, 2018

Asia Pacific Center for Theoretical Physics, Pohang, Korea



U.S. DEPARTMENT OF
ENERGY

Office of
Science



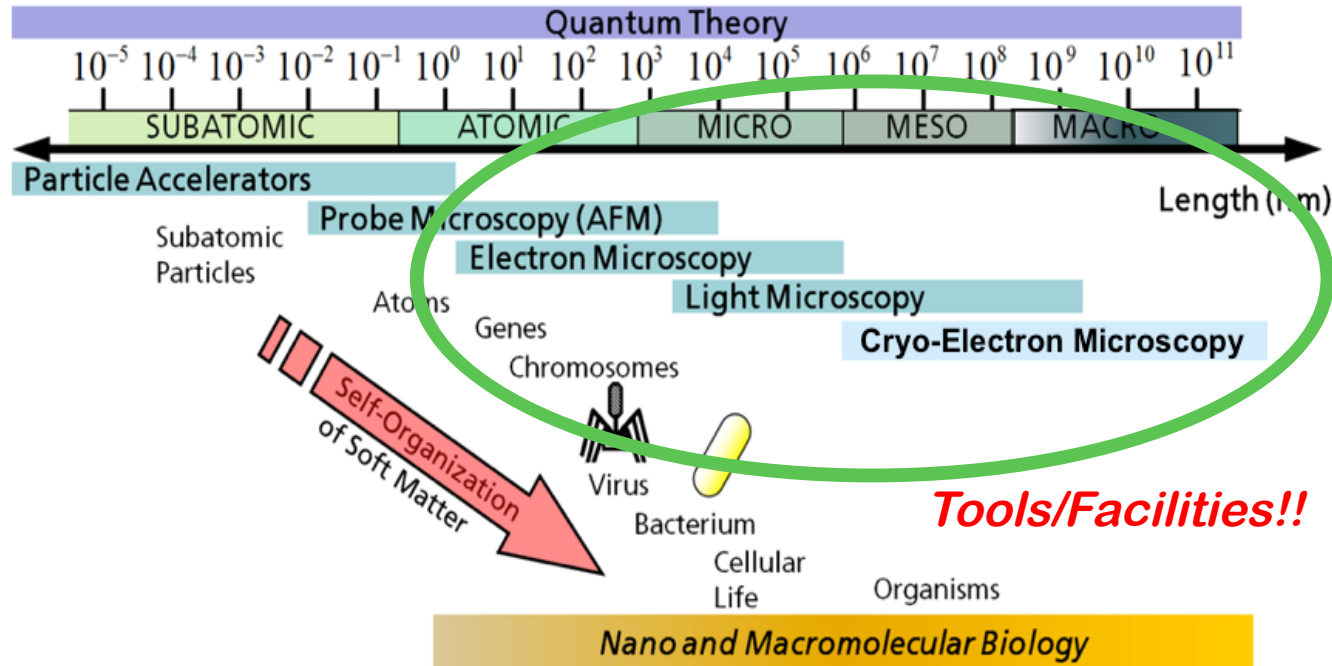
Nano-Science and Technology

□ Nano-Science – *the Idea*:

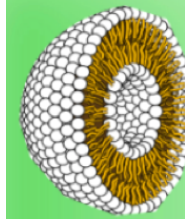
“There’s plenty of room at the bottom”

Feynman, APS meeting at Caltech, December 29, 1959

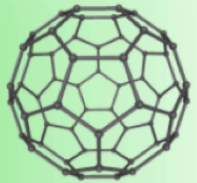
□ Need tools/facilities to advance:



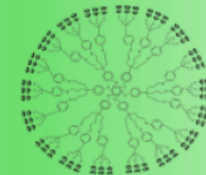
Applications!!!



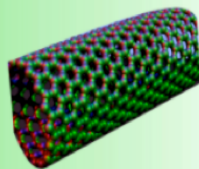
Liposome



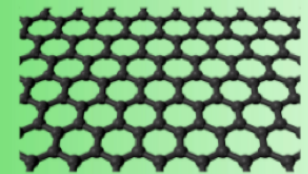
Fullerene



Dendrimer



Carbon nanotube



Graphene

□ The Support:

National Nanotechnology Initiative

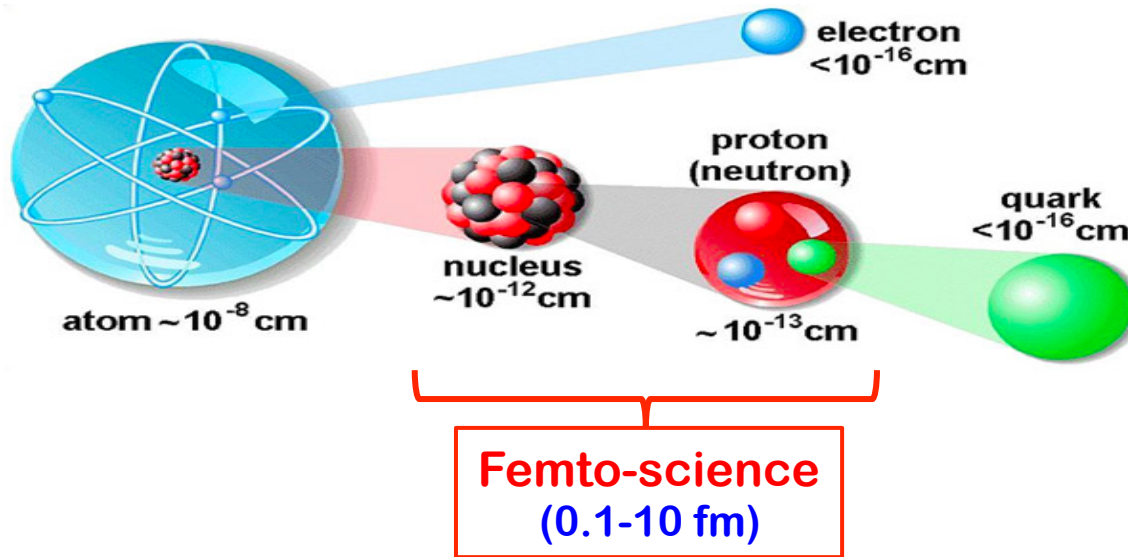
Nano-science
(1-100 nm)

*Ensure the role
of quantum physics*

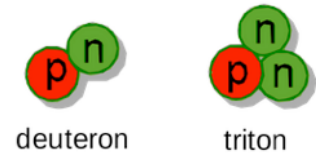
NSF proposed to White House in 1999, signed into law in 2003

Femto-Science and Technology

□ Femto-Science:



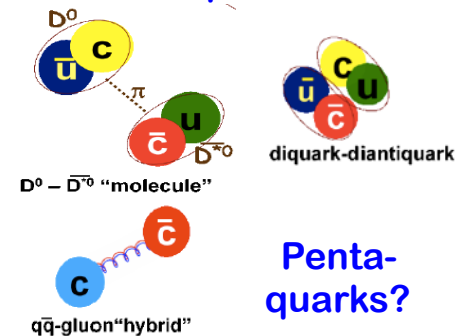
2-body force



3-body force

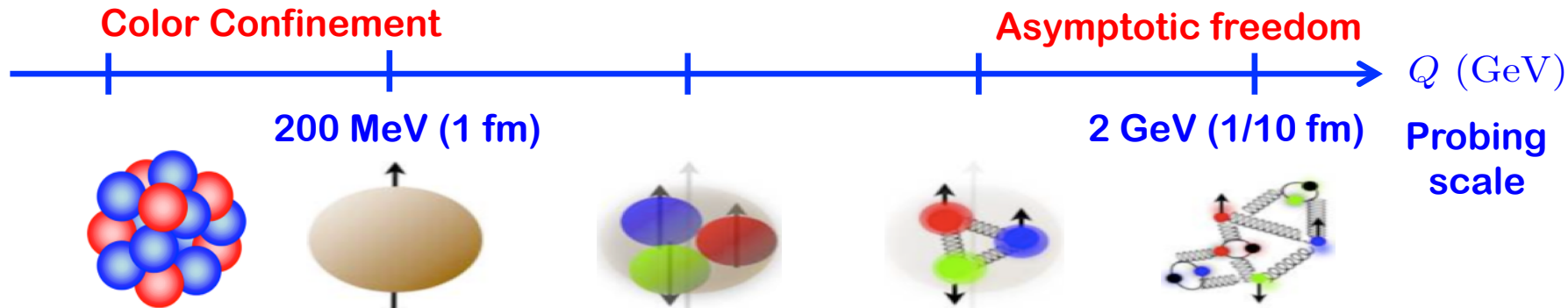


XYZ-particles



Penta-quarks?

□ QCD landscape of nucleon and nuclei?



Need a facility to explore/see the structure and dynamics ! Jefferson Lab

Unprecedented intellectual challenge!

❑ The challenge: **Gluons are dark!**

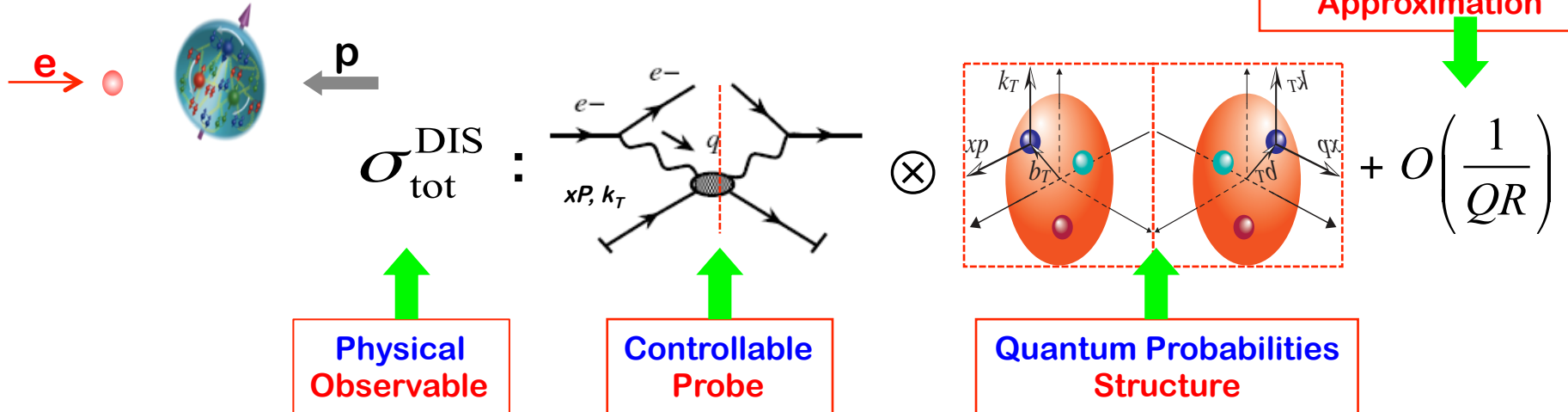
No modern detector has been able to see quarks and gluons in isolation!

❑ Answer to the challenge:

Theory advances:

QCD factorization

**Color entanglement
Approximation**

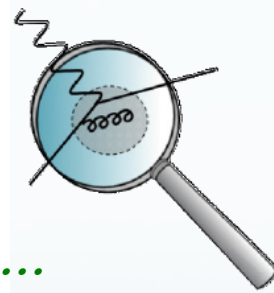


Experimental breakthroughs:

Jets – *Footprints of energetic quarks and gluons*

Quarks – *Need an EM probe to “see” their existence, ...*

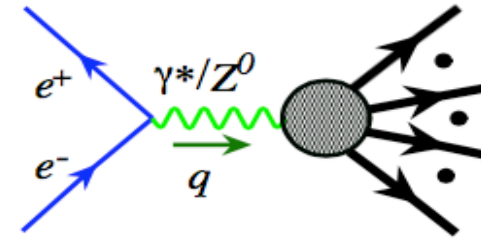
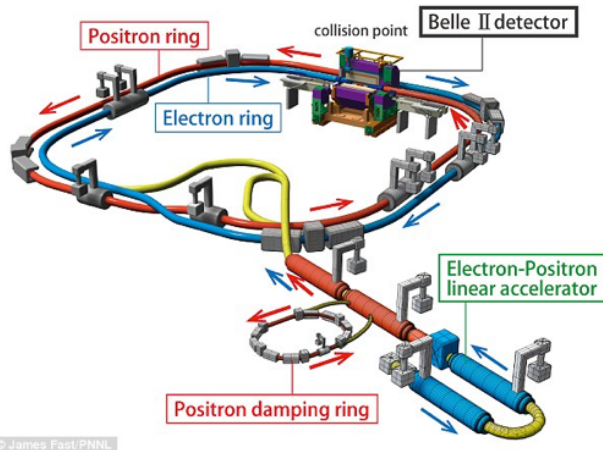
Gluons – *Varying the probe’s resolution to “see” their effect, ...*



Need probes with sub-femtometer resolution – particle nature!

Advantage of Lepton-Hadron Facility

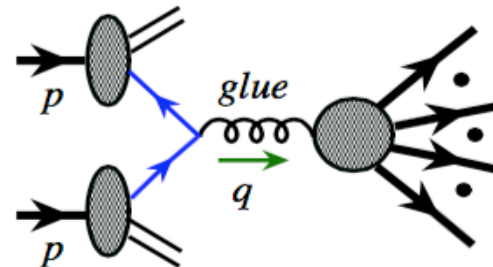
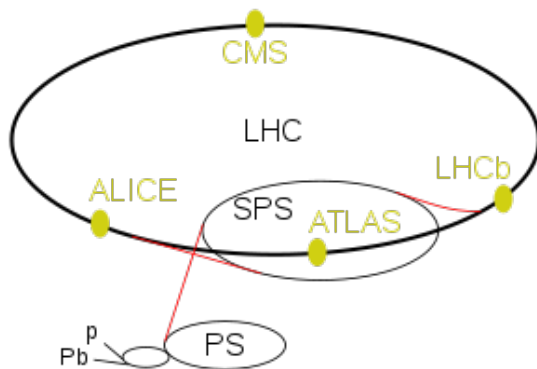
□ Lepton-lepton collisions:



Hadrons

- ✧ No hadron in the initial-state
- ✧ **Hadrons are emerged from energy**
- ✧ Not ideal for studying hadron structure

□ Hadron-hadron collisions:



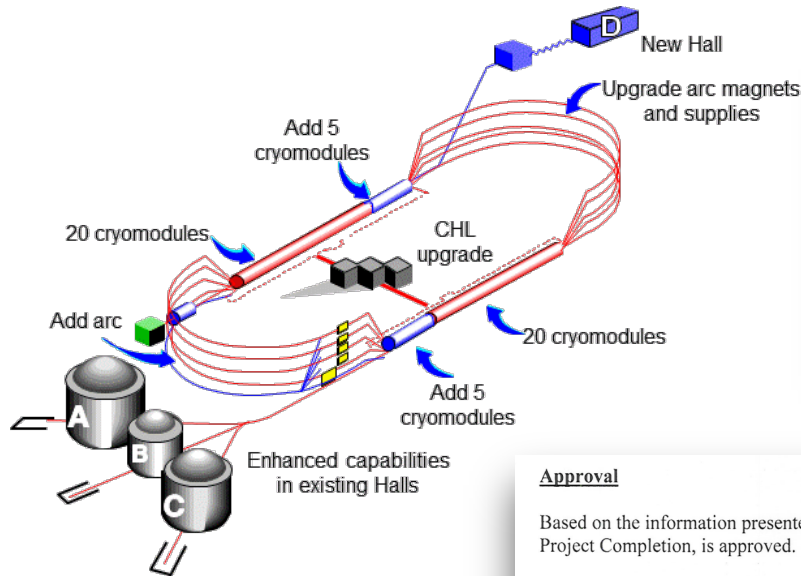
Hadrons

- ✧ Hadron structure – motion of quarks, ...
- ✧ Emergence of hadrons, ...
- ✧ Initial hadrons **broken** – collision effect, ..

□ Lepton-hadron collisions:

Hard collision without breaking the initial-state hadron!

Jefferson Lab @ 12 GeV



Approval

Based on the information presented above and at this review, Critical Decision 4, Approve Project Completion, is approved.



Dr. J. Stephen Binkley
Deputy Director for Science Programs
Office of Science



Date



Project Completion Approved September 27, 2017

All four Halls are in physics operations

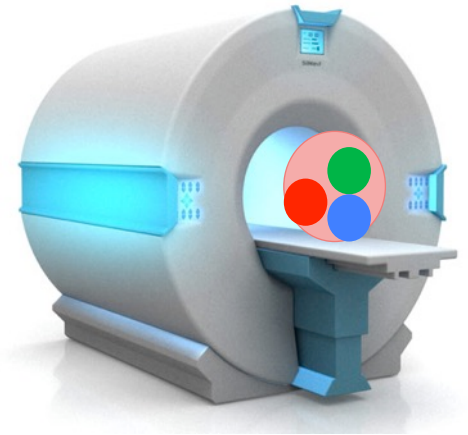
JLab 12 GeV science era is here!

A critical step toward EIC!

The Electron-Ion Collider (EIC) – the Future!

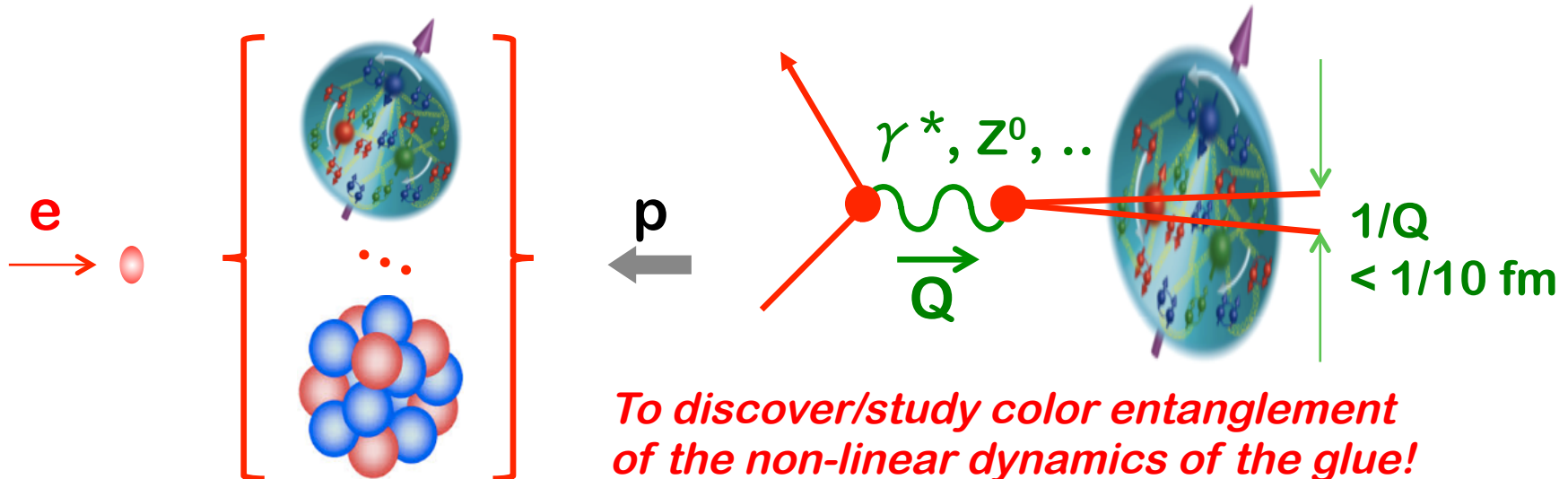
□ A sharpest “CT” – “**imagine**” quark/gluon structure **without breaking the hadron**

- “cat-scan” the nucleon and nuclei with a better than $1/10$ fm resolution
- “see” proton “radius” of quark/gluon density comparing with the radius of EM charge density



To discover color confining radius, hints on confining mechanism!

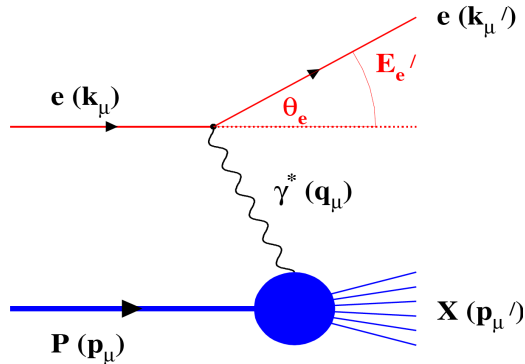
□ A giant “Microscope” – “**see**” quarks and gluons by **breaking the hadron**



To discover/study color entanglement of the non-linear dynamics of the glue!

Many complementary probes at one facility

□ A new generation of “Rutherford” experiment:



$Q^2 \rightarrow$ Measure of resolution

$y \rightarrow$ Measure of inelasticity

$x \rightarrow$ Measure of momentum fraction of the struck quark in a proton

$$Q^2 = S \times y$$

Inclusive events: $e+p/A \rightarrow e'+X$

Detect only the scattered lepton in the detector

(Modern Rutherford experiment!)

Semi-Inclusive events: $e+p/A \rightarrow e'+h(p,K,p,jet)+X$

Detect the scattered lepton in coincidence with identified hadrons/jets

(Initial hadron is broken – confined motion! – cleaner than h-h collisions)

Exclusive events: $e+p/A \rightarrow e'+p'/A'+h(p,K,p,jet)$

Detect every things including scattered proton/nucleus (or its fragments)

(Initial hadron is NOT broken – tomography! – almost impossible for h-h collisions)

EIC: the World Wide Interest

	HERA@DESY	LHeC@CERN	eRHIC@BNL	JLEIC@JLab	HIAF@CAS	ENC@GSI
E_{CM} (GeV)	320	800-1300	45-175	12-140	12 $\rightarrow$ 65	14
proton x_{min}	1×10^{-5}	5×10^{-7}	3×10^{-5}	5×10^{-5}	$7 \times 10^{-3} \rightarrow 3 \times 10^{-4}$	5×10^{-3}
ion	p	p to Pb	p to U	p to Pb	p to U	p to $\sim {}^{40}\text{Ca}$
polarization	-	-	p, ${}^3\text{He}$	p, d, ${}^3\text{He}$ (${}^6\text{Li}$)	p, d, ${}^3\text{He}$	p,d
L [$\text{cm}^{-2} \text{s}^{-1}$]	2×10^{31}	10^{33}	10^{33-34}	10^{33-34}	$10^{32-33} \rightarrow 10^{35}$	10^{32}
IP	2	1	2+	2+	1	1
Year	1992-2007	2022 (?)	2022	Post-12 GeV	2019 $\rightarrow$ 2030	upgrade to FAIR



The past



Possible future

US EIC – Two Options of Realization

The White Paper
A. Accardi et al
Eur. Phys. J.
A52 (2016) 268

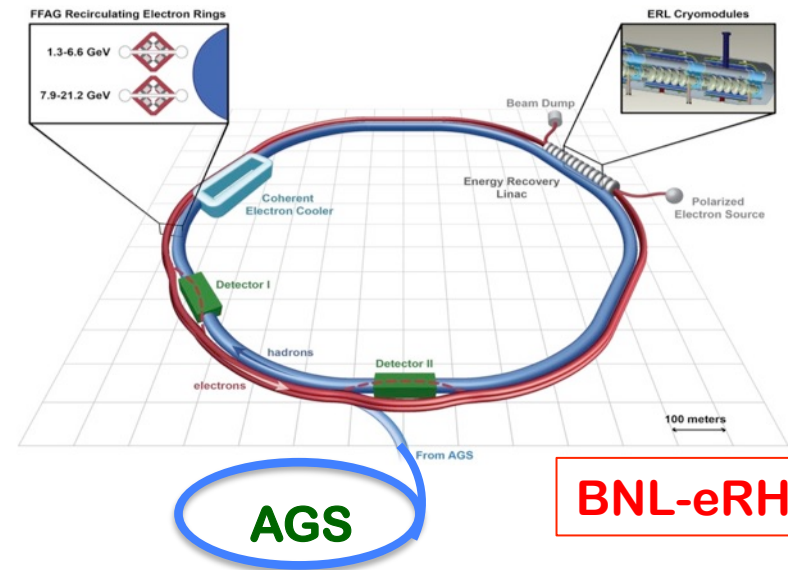


Electron Ion Collider: The Next QCD Frontier

Understanding the glue
that binds us all

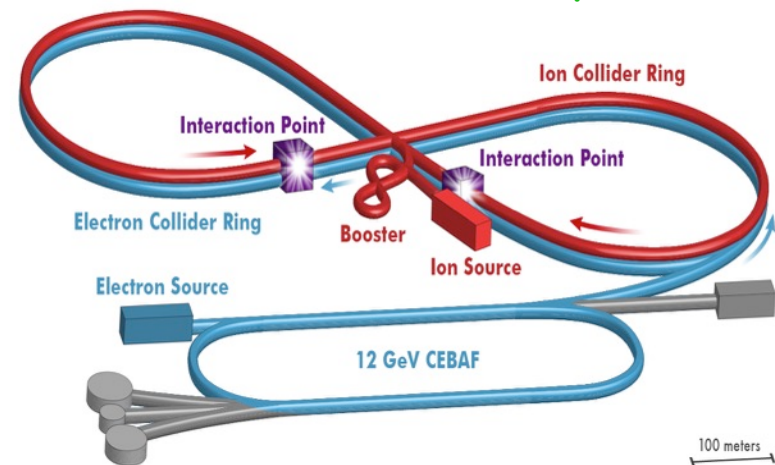
Edited by A. Deshpande
Z.-E. Meziani
J.-W. Qiu

SECOND EDITION



BNL-eRHIC

See A. Deshpande's talk



JLab-JLEIC

Jefferson Lab

US-EIC – can do what HERA could not do

- Quantum imaging:

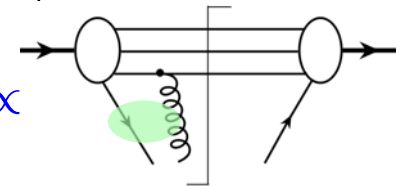
- ✧ HERA discovered: 15% of e-p events is diffractive – Proton not broken!
- ✧ US-EIC: 100-1000 times **luminosity** – *Critical for 3D tomography!*

❑ Quantum interference & entanglement:

- ✧ **US-EIC: Highly polarized beams – Origin of hadron property: Spin, ...**
Direct access to chromo-quantum interference!

$$\sigma(Q, \vec{s}) \propto \left| \begin{array}{c} \text{Diagram 1} + \text{Diagram 2} + \text{Diagram 3} + \dots \\ \text{Diagram 1: } p, \vec{s} \text{ and } k \text{ are incoming, } t \sim 1/Q \text{ is outgoing} \\ \text{Diagram 2: } p, \vec{s} \text{ and } k \text{ are incoming, } t \sim 1/Q \text{ is outgoing} \\ \text{Diagram 3: } p, \vec{s} \text{ and } k \text{ are incoming, } t \sim 1/Q \text{ is outgoing} \end{array} \right|^2$$

$$\sigma(s) - \sigma(-s) \Rightarrow \text{Quantum interference} \Rightarrow T^{(3)}(x, x) \propto$$



❑ Nonlinear quantum dynamics:

- ✧ US-EIC: Light-to-heavy **nuclear** beams – *Origin of nuclear force, ...*
Catch the transition from chromo-quantum fluctuation
to chromo-condensate of gluons, ...
Emergence of hadrons (femtometer size detector!),
 – “a new **controllable knob**” – Size of nuclei
- Jefferson Lab

EIC Science & Overarching Questions

- How did hadrons, the building blocks of visible world, emerge from quarks and gluons?

Necessary knowledge for understanding
where and how did we come from?

- What is the internal structure of hadrons, and the dynamics behind the structure?

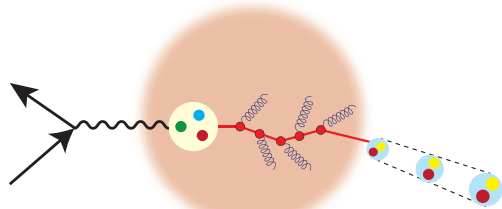
Necessary knowledge for understanding
what are we made of, and
what hold us together, as well as
how do we improve and move forward?

- What is the key for understanding color confinement?

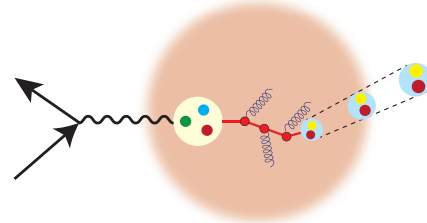
Necessary knowledge for understanding
What is the mother nature of the nonlinear,
strongly interacting dynamics of color force?

Emergence of Hadrons from quarks & gluons

□ Femtometer sized detector:



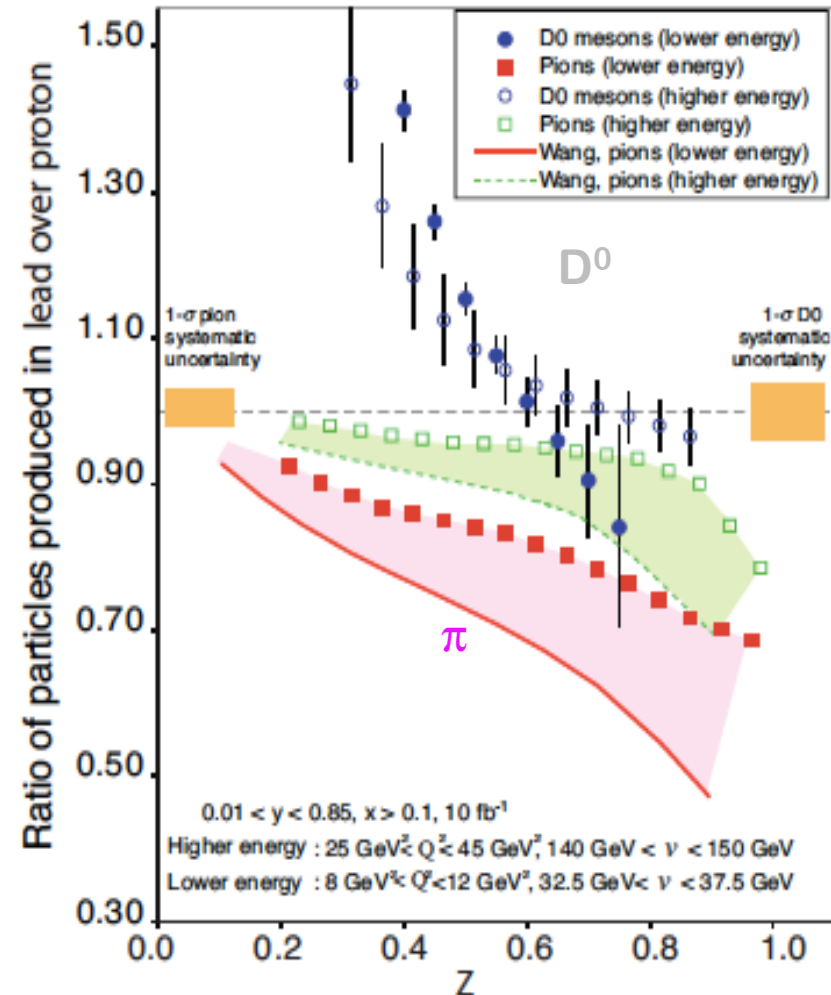
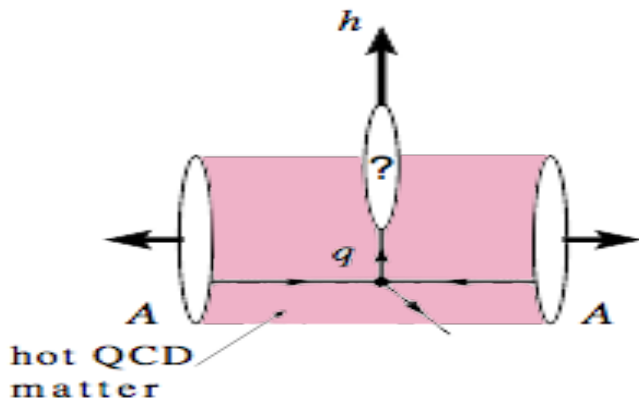
$$\nu = \frac{Q^2}{2mx}$$



Control of ν and medium length!

Mass dependence of hadronization

□ Apply to heavy-ion collisions:



Need the collider energy of EIC and its control on parton kinematics

Hadron Properties: Mass & Spin, ...

□ Mass – intrinsic to a particle:

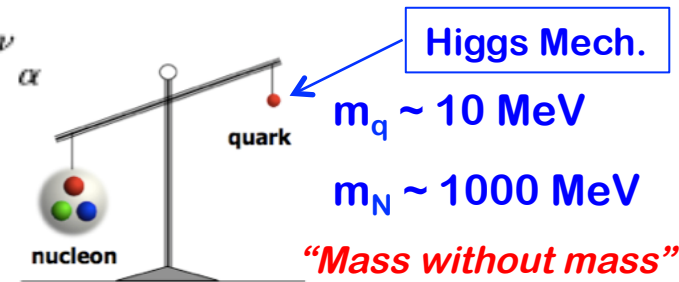
= Energy of the particle when it is at the rest

✧ QCD energy-momentum tensor in terms of quarks and gluons

$$T^{\mu\nu} = \frac{1}{2} \bar{\psi} i \overleftrightarrow{D}^{(\mu} \gamma^{\nu)} \psi + \frac{1}{4} g^{\mu\nu} F^2 - F^{\mu\alpha} F^{\nu}_{\alpha}$$

✧ Proton mass:

$$m = \frac{\langle p | \int d^3x T^{00} | p \rangle}{\langle p | p \rangle} \sim \text{GeV}$$



□ Spin – intrinsic to a particle:

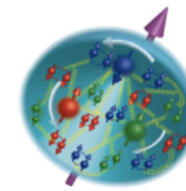
= Angular momentum of the particle when it is at the rest

✧ QCD angular momentum density in terms of energy-momentum tensor

$$M^{\alpha\mu\nu} = T^{\alpha\nu} x^{\mu} - T^{\alpha\mu} x^{\nu} \quad J^i = \frac{1}{2} \epsilon^{ijk} \int d^3x M^{0jk}$$

✧ Proton spin:

$$S(\mu) = \sum \langle P, S | \hat{J}_f^z(\mu) | P, S \rangle = \frac{1}{2}$$



EMC found:

$$\sum_q (\Delta q + \Delta \bar{q}) \sim 0.12 \pm 0.17$$

"Proton spin puzzle"

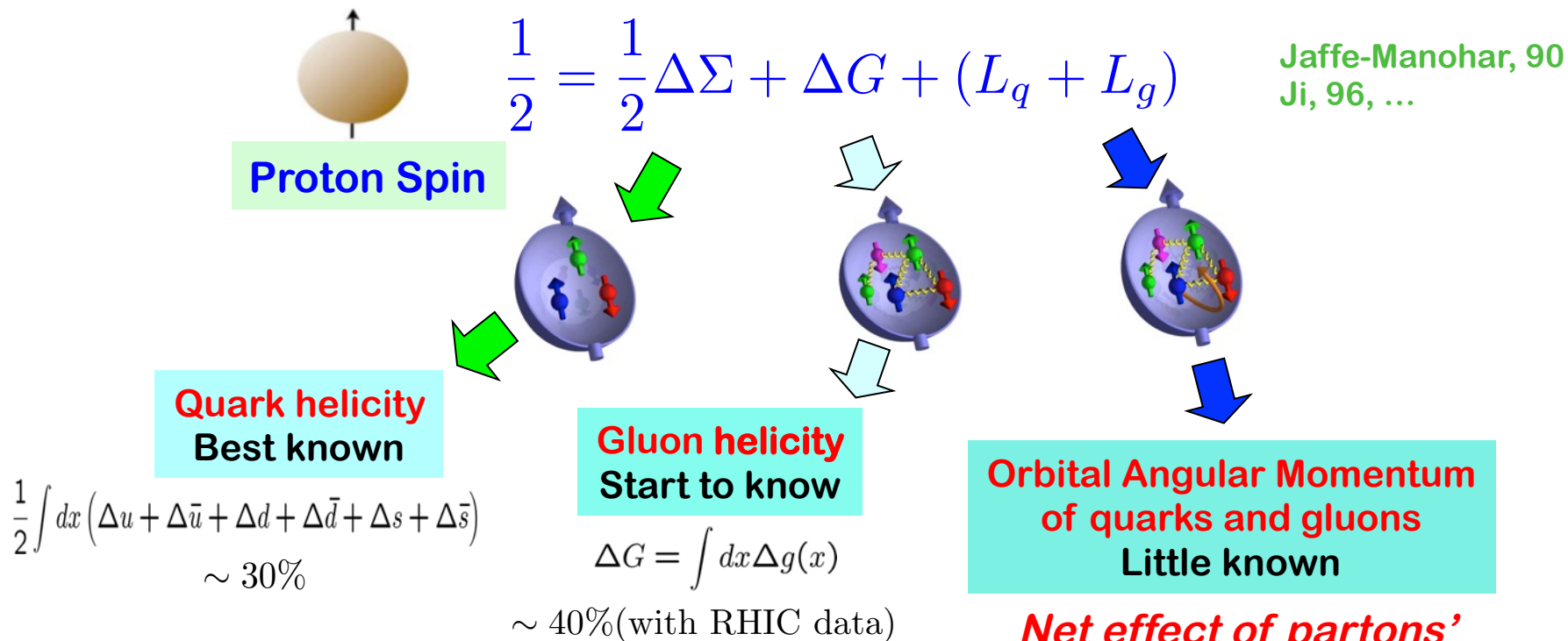
*If we do not understand proton mass & spin,
 we do not understand QCD!*

The Proton Spin

□ **The sum rule:**
$$S(\mu) = \sum_f \langle P, S | \hat{J}_f^z(\mu) | P, S \rangle = \frac{1}{2} \equiv J_q(\mu) + J_g(\mu)$$

- Infinite possibilities of decompositions – connection to observables?
- Intrinsic properties + dynamical motion and interactions

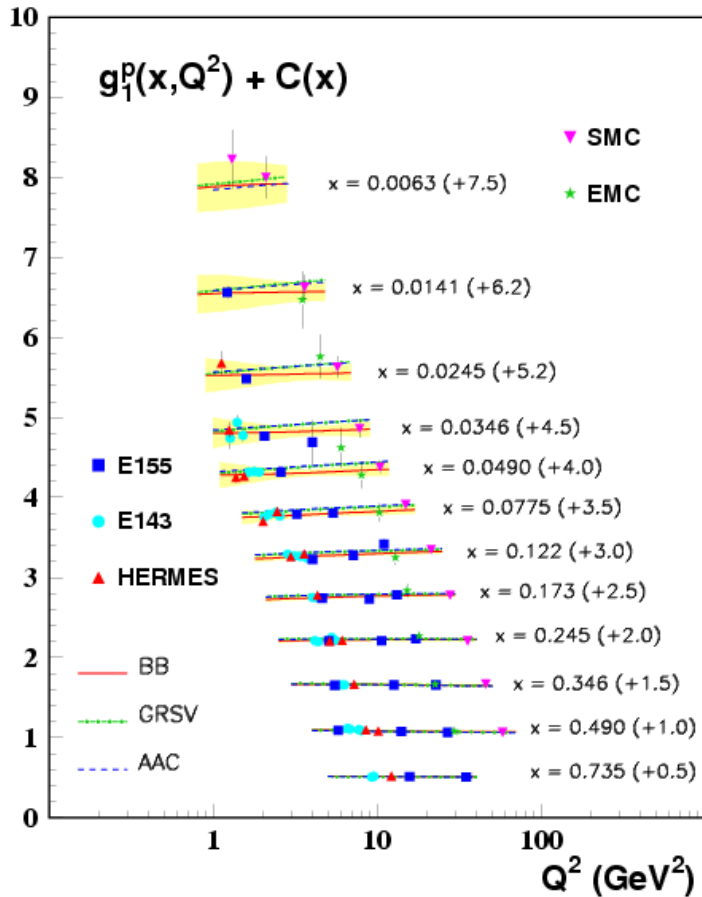
□ **An incomplete story:**



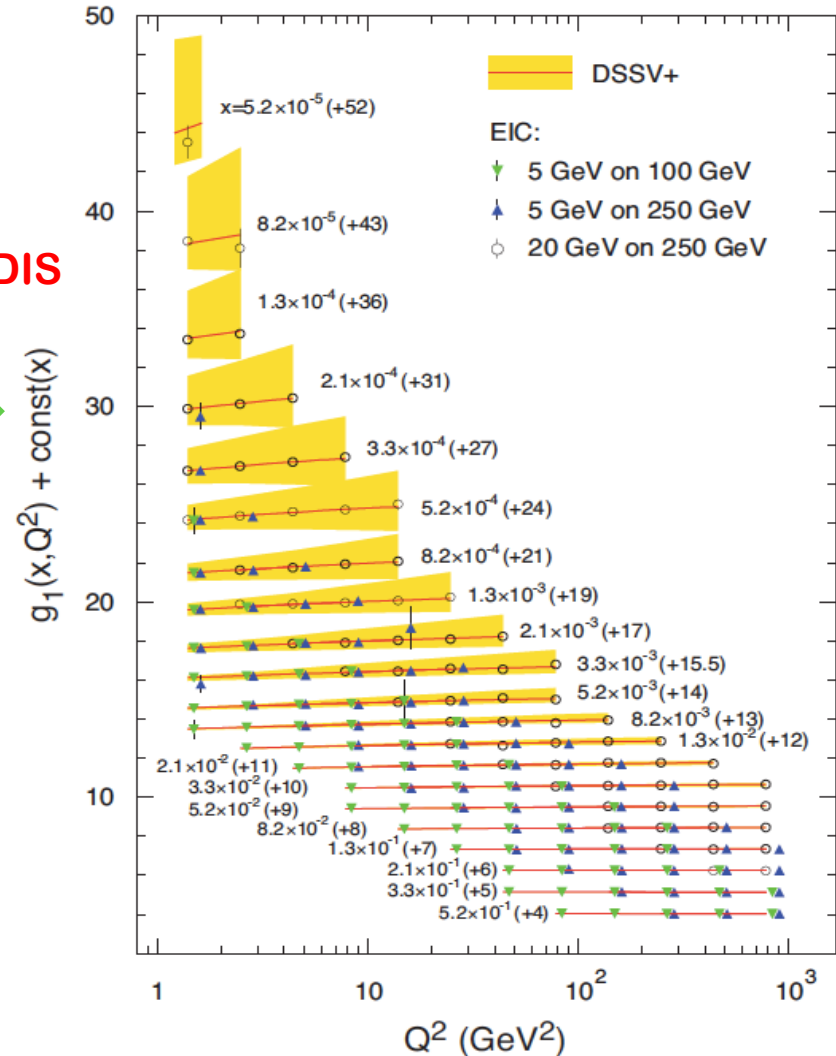
Jaffe-Manohar, 90
Ji, 96, ...

The Proton Spin

□ The power & precision of EIC:



Polarized DIS
at EIC



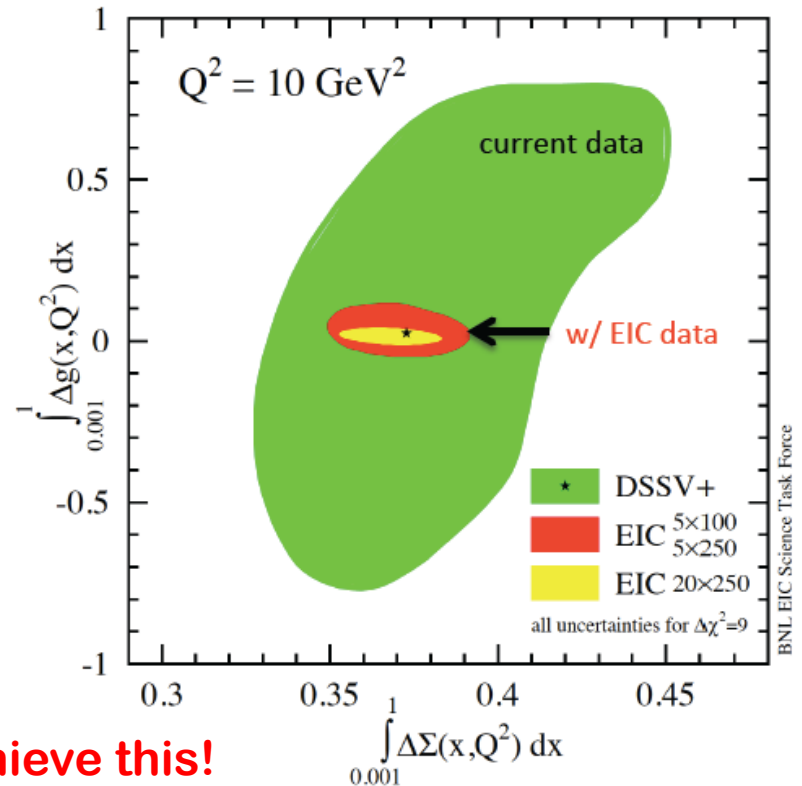
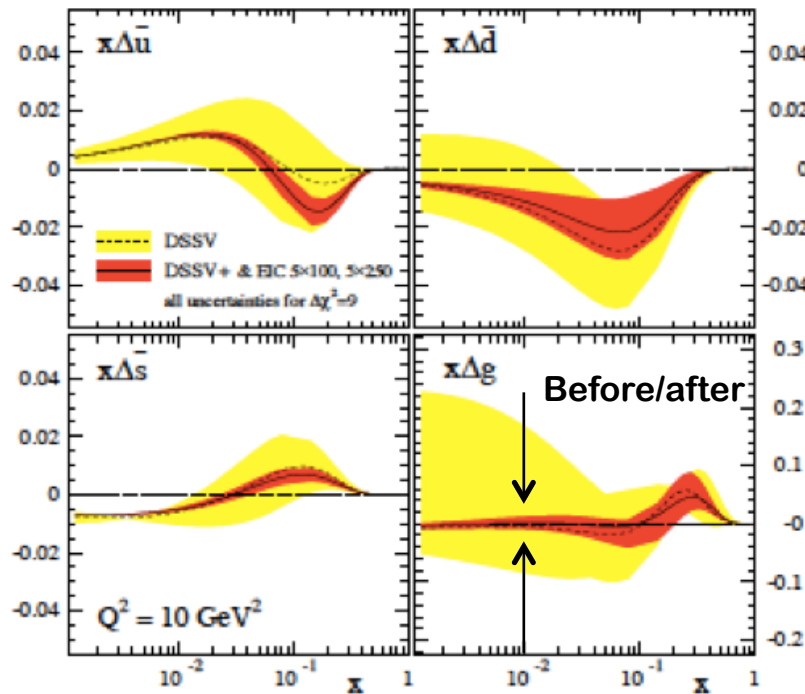
□ Reach out the glue:

$$\frac{dg_1(x, Q^2)}{d \ln Q^2} = \frac{\alpha_s}{2\pi} P_{qg} \otimes \Delta g(x, Q^2) + \dots$$

The Proton Spin

□ One-year of running at EIC:

Wider Q^2 and x range including low x at EIC!



No other machine in the world can achieve this!

□ Ultimate solution to the proton spin puzzle:

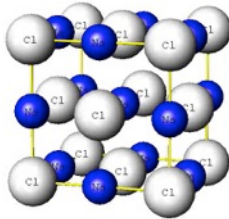
- ✧ Precision measurement of $\Delta g(x)$ – extend to smaller x regime
- ✧ Orbital angular momentum contribution?

– internal motion & structure – encoded in TMDs & GPDs!

Hadron's partonic structure in QCD

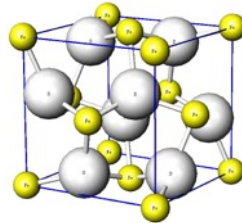
❑ Structure – “a still picture”

Crystal
Structure:



NaCl,

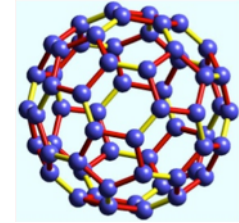
B1 type structure



FeS2,

C2, pyrite type structure

Nano-
material:



Fullerene, C60

Motion of nuclei is much slower than the speed of light!

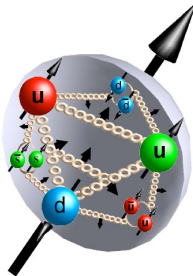
❑ No “still picture” for hadron's partonic structure!

Motion of quarks/gluons is relativistic!

Partonic
Structure:

Quantum “probabilities” $\langle P, S | \mathcal{O}(\bar{\psi}, \psi, A^\mu) | P, S \rangle$

None of these matrix elements is a direct physical observable in QCD – color confinement!



❑ Accessible hadron's partonic structure?

= Universal quantum matrix elements of quarks and/or gluons

1) can be related to **good** physical cross sections of hadron(s)

with controllable approximation,

2) can be calculated in lattice QCD, ...

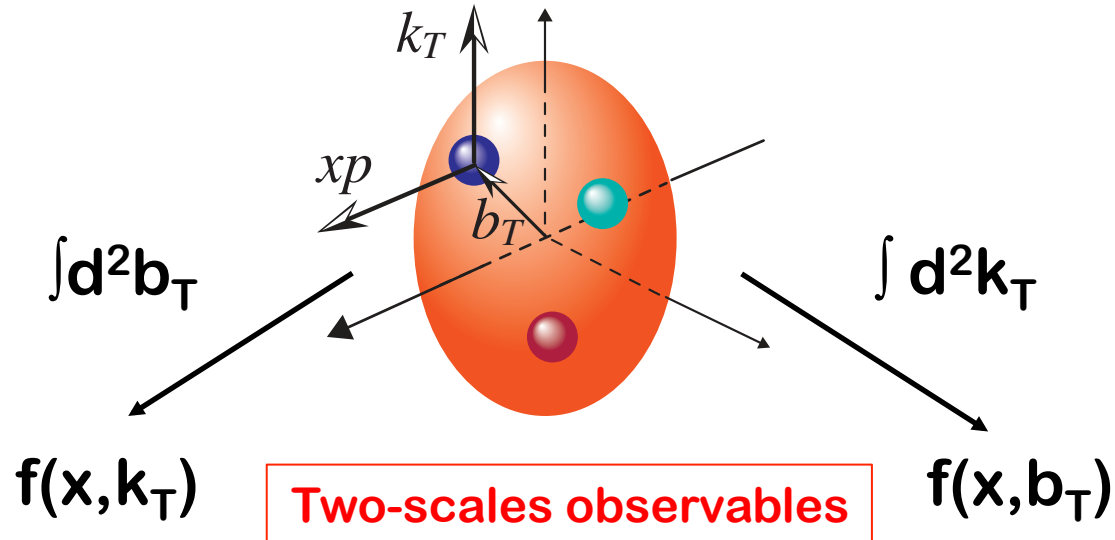
3D confined motion and spatial distribution

□ 3D boosted partonic structure:

*Momentum
Space*

TMDs

*Confined
motion*



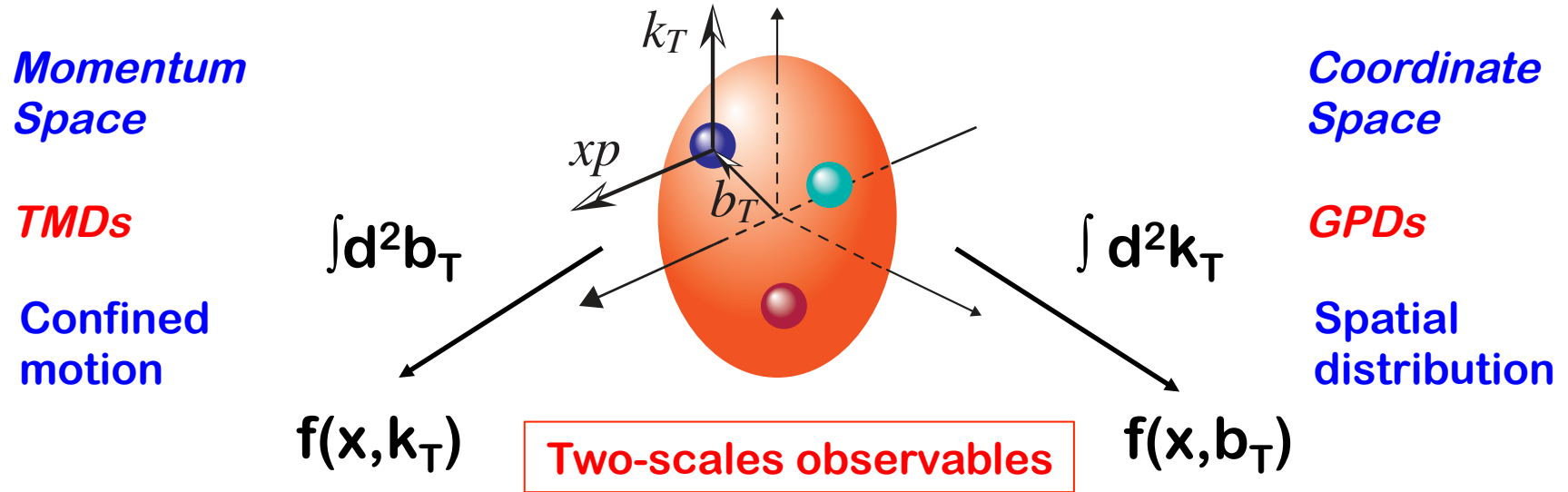
*Coordinate
Space*

GPDs

*Spatial
distribution*

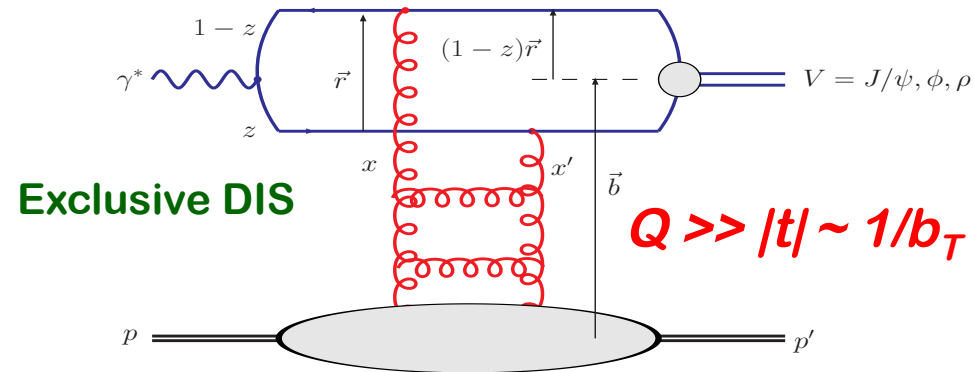
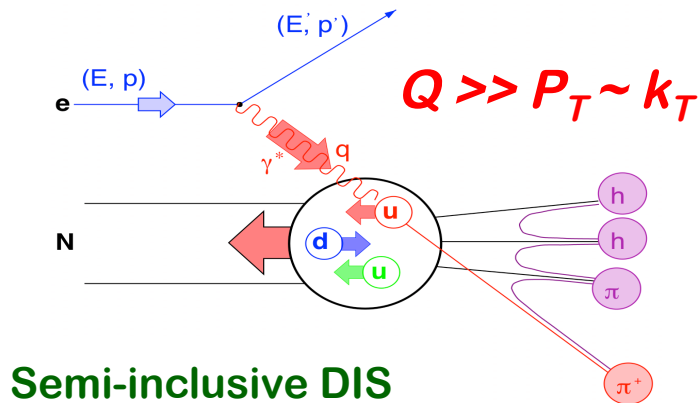
3D confined motion and spatial distribution

3D boosted partonic structure:



3D momentum space images

2+1D coordinate space images



JLab12 – valence quarks, EIC – sea quarks and gluons

3D confined motion and spatial distribution

3D boosted partonic structure:

Momentum
Space

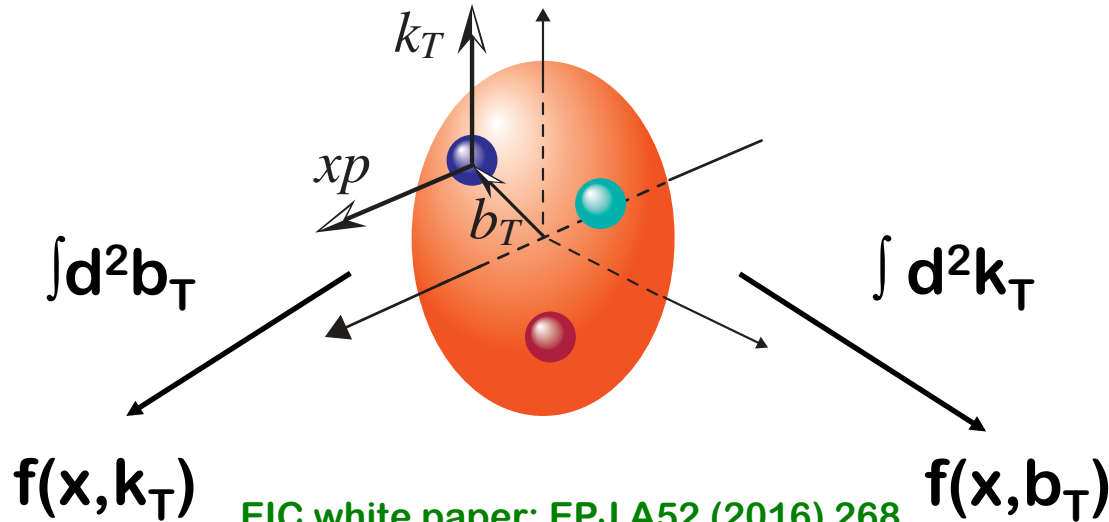
Coordinate
Space

TMDs

GPDs

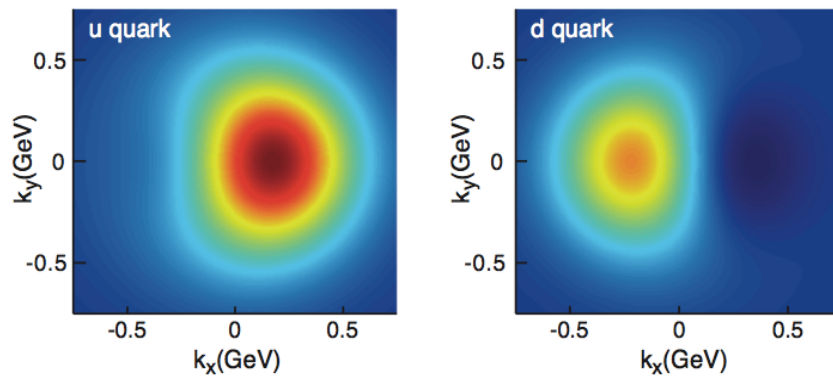
Confined
motion

Spatial
distribution

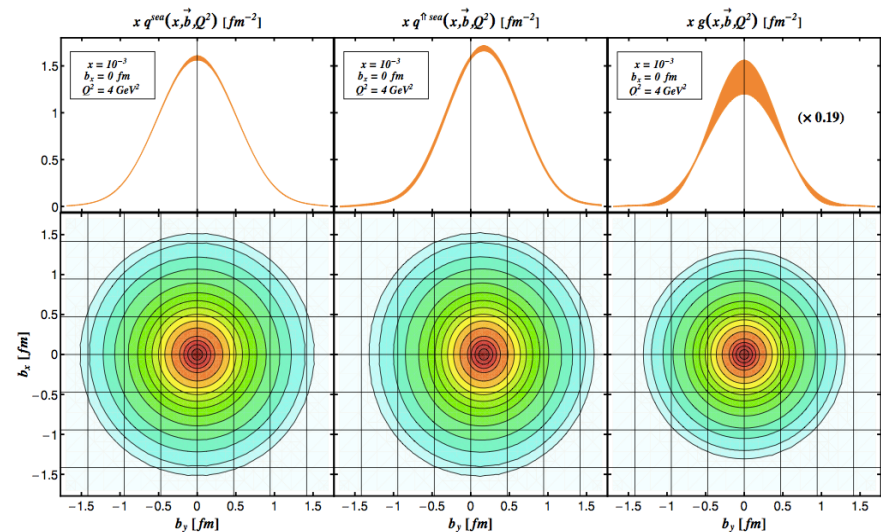


Sivers Function

Imaging



Density distribution of an unpolarized quark in a proton moving in z direction and polarized in y-direction



Spatial density distributions — radius

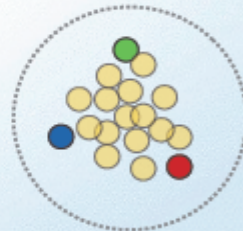
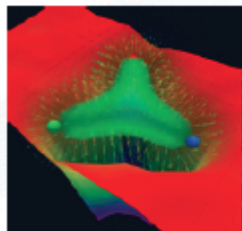
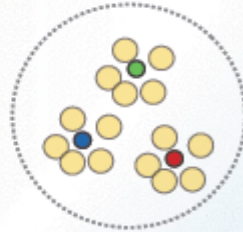
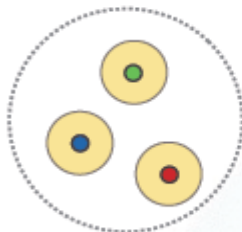
Why 3D nucleon structure?

□ Spatial distributions of quarks and gluons:

Static



Boosted



Bag Model:

Gluon field distribution is wider than the fast moving quarks.

Gluon radius $>$ Charge Radius

Constituent Quark Model:

Gluons and sea quarks hide inside massive quarks.

Gluon radius $\sim$ Charge Radius

Lattice Gauge theory (with slow moving quarks):

Gluons more concentrated inside the quarks

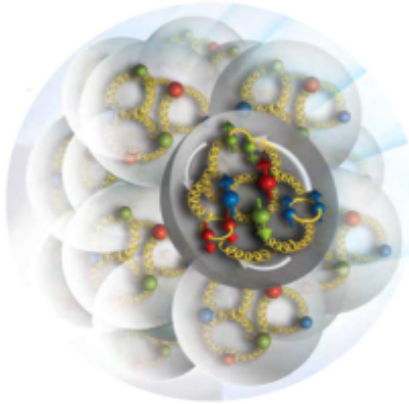
Gluon radius $<$ Charge Radius

*3D confined motion (TMDs) + spatial distribution (GPDs)
Hints on the color confining mechanism*

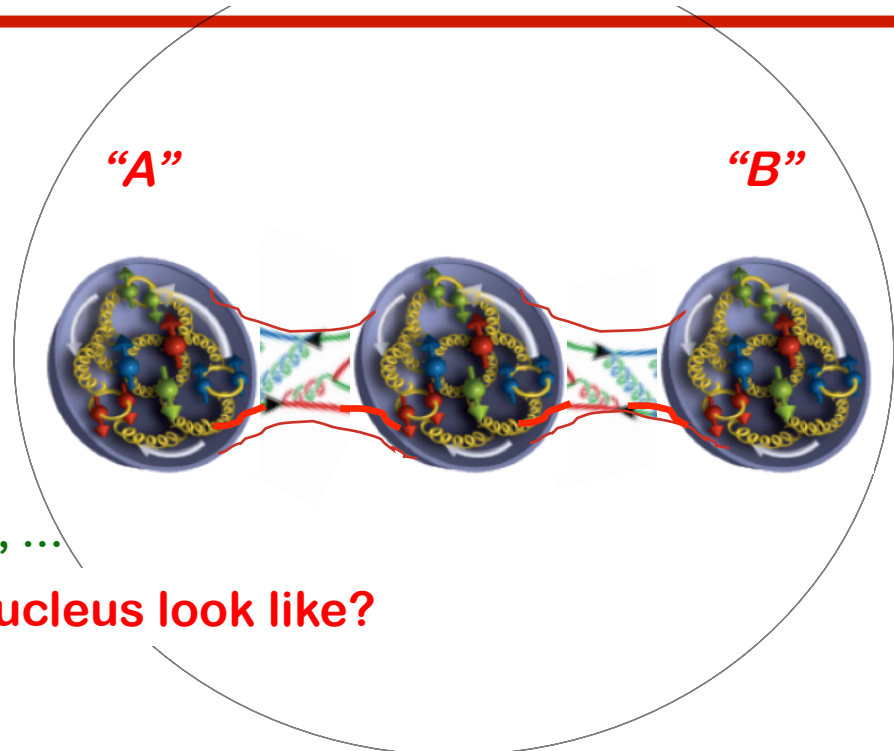
Radius of Charge, Radius (x) of quark/gluon distribution?

Emergence of nuclear force?

□ Nature of nuclear force:



If we only see
quarks and gluons, ...



What does the nucleus look like?

□ Range of color force:

*Does glue color of nucleon "A" correlated
or entangled with glue color of nucleon "B"?*

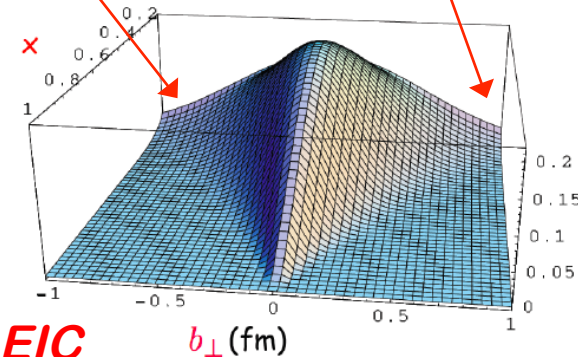
If it does, what is the strength of
such correlation?

*Can a large nucleus look like a big
proton at small-x? the range &
strength of color correlation?*

How far does glue
density spread?

How fast does
glue density fall?

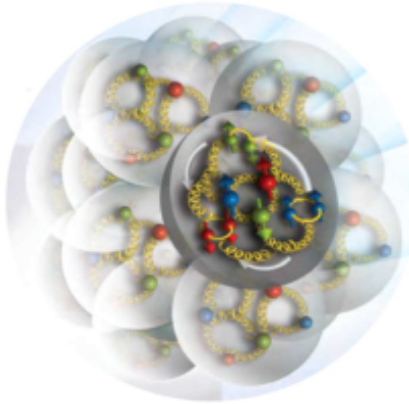
Imaging
3D gluon
density



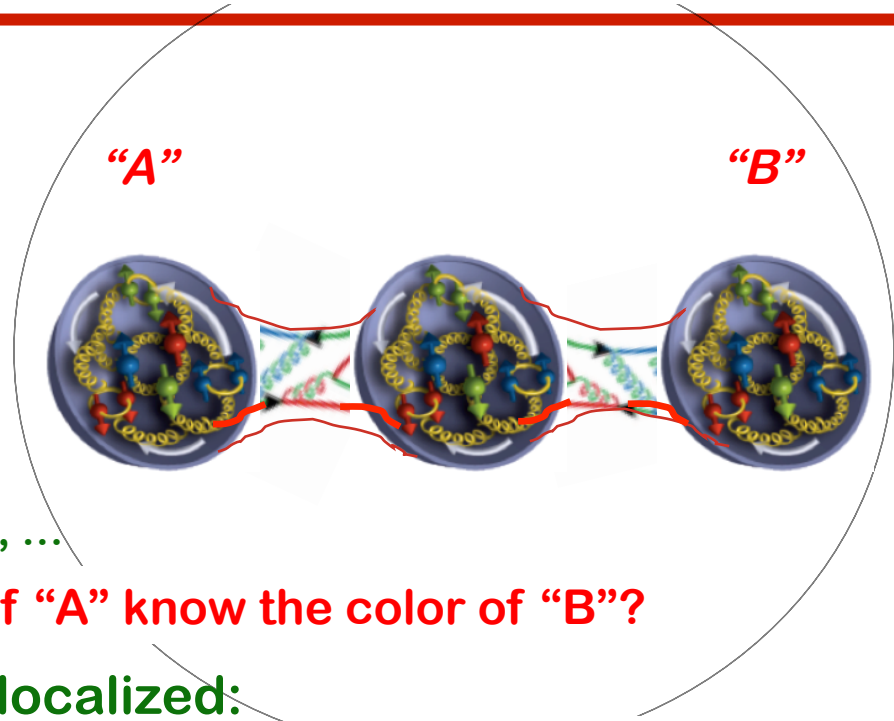
Only possible at EIC

Emergence of nuclear force?

□ Nature of nuclear force:

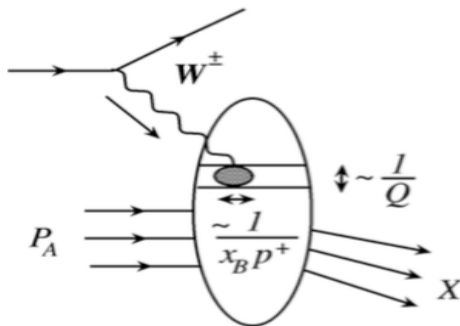


If we only see
quarks and gluons, ...



Does the color of “A” know the color of “B”?

□ The hard probe at small-x is NOT localized:



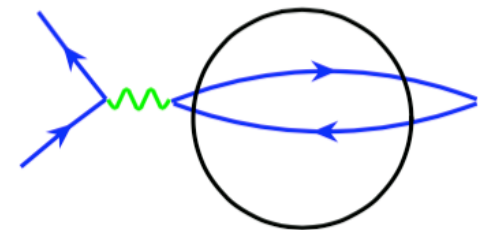
c.m. frame

Longitudinal probing size

> Lorentz contracted nucleon, if

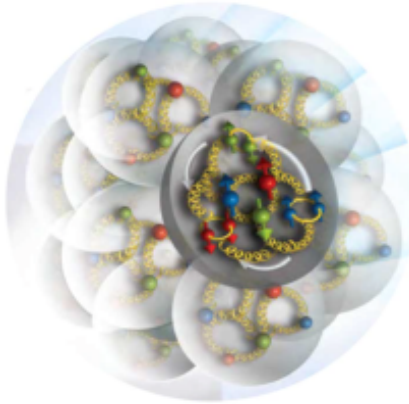
$$\frac{1}{xp} > 2R_A \frac{m}{p} \quad \text{or} \quad x \lesssim 0.01$$

Hadron rest frame

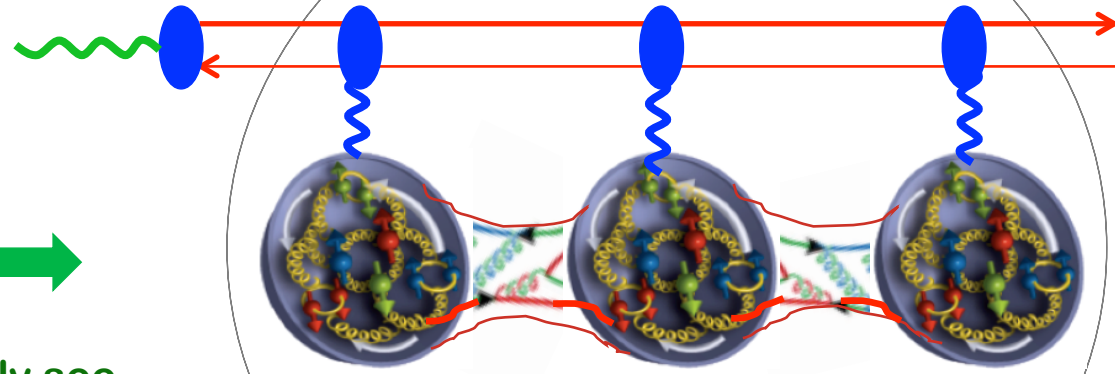


Emergence of nuclear force?

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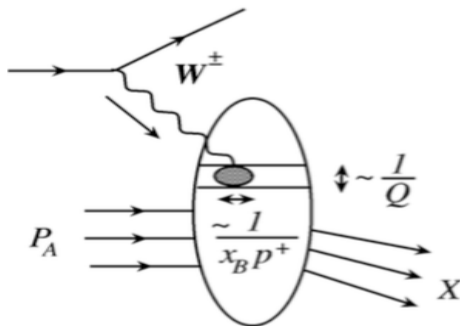


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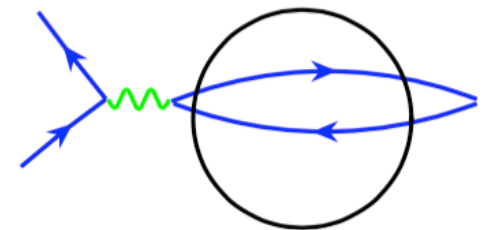
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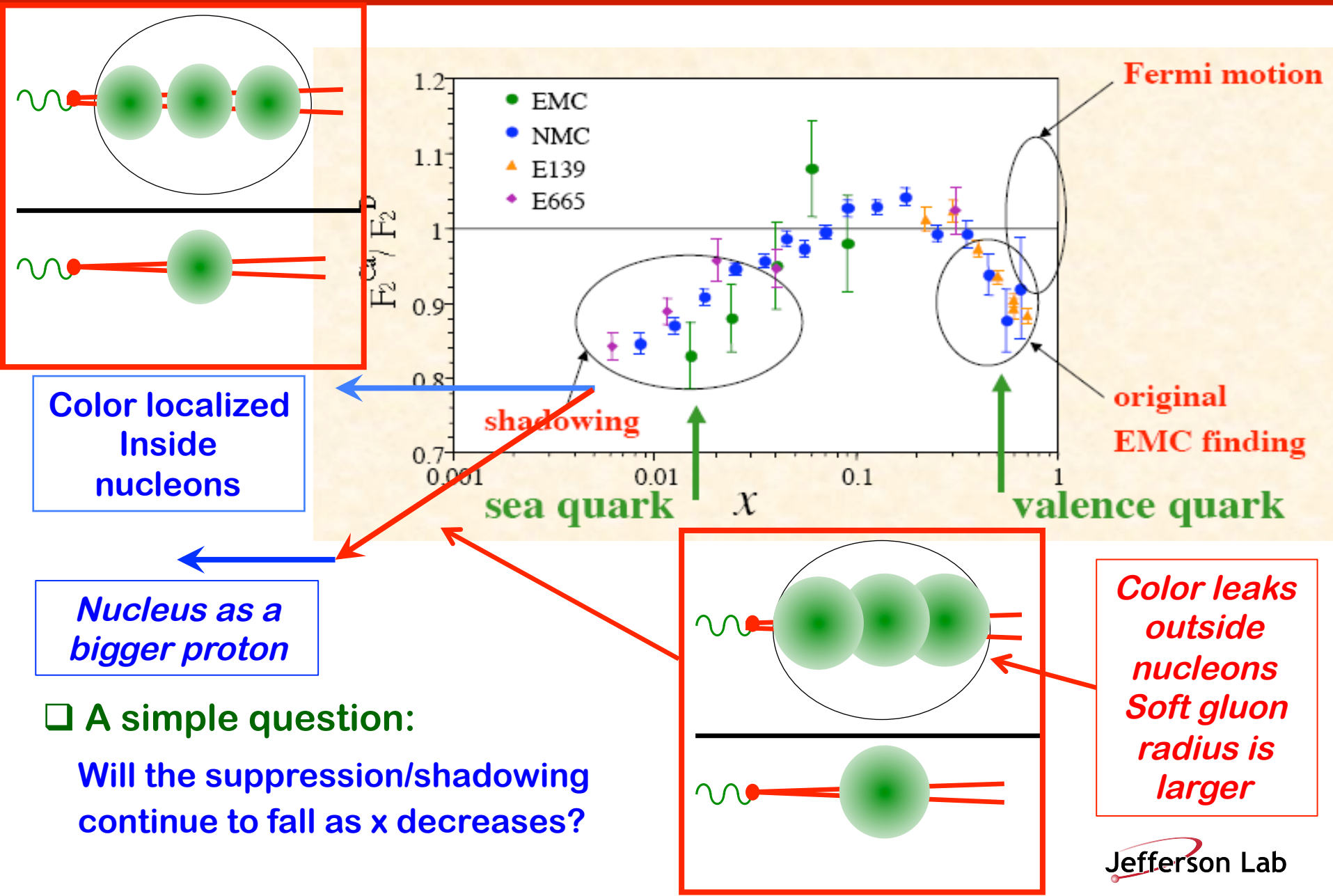
Hadron rest frame



✧ **N:** *Observed nuclear effect due to coherent collisions*

✧ **Y:** *Different medium + coherent collisions*
Nucleus could act like a bigger proton
at small- x !

Role of color for nuclear force?



Summary and outlook

- ❑ EIC is a ultimate QCD machine:
 - 1) **to discover and explore** the quark/gluon structure and properties of hadrons and nuclei,
 - 2) **to search for** hints and clues of color confinement, and
 - 3) **to measure** the color fluctuation and color neutralization
- ❑ EIC is a tomographic machine for nucleons/nuclei (1/10 fm resolution)
– **necessarily for exploring nuclear femtography**
- ❑ EIC could study major Nuclear Science issues that other existing facilities, even with upgrades, cannot do
- ❑ US-EIC is sitting at a sweet spot for rich QCD dynamics
– **capable of exploring the science of nuclear femtography!**

More on US-EIC and its path forward
See Abhay Deshpande's talk

Thanks!