APCTP Asia Pacific Center for Theoretical Physics

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

Jianwei Qiu
Theory Center, Jefferson Lab

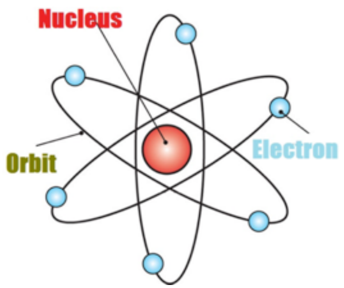
July 1-4, 2018
Asia Pacific Center for Theoretical Physics, Pohang, Korea

Nano-Science and Technology

- **Nano-Science – *the Idea*:**

  "There's plenty of room at the bottom"

  Feynman, APS meeting at Caltech, December 29, 1959



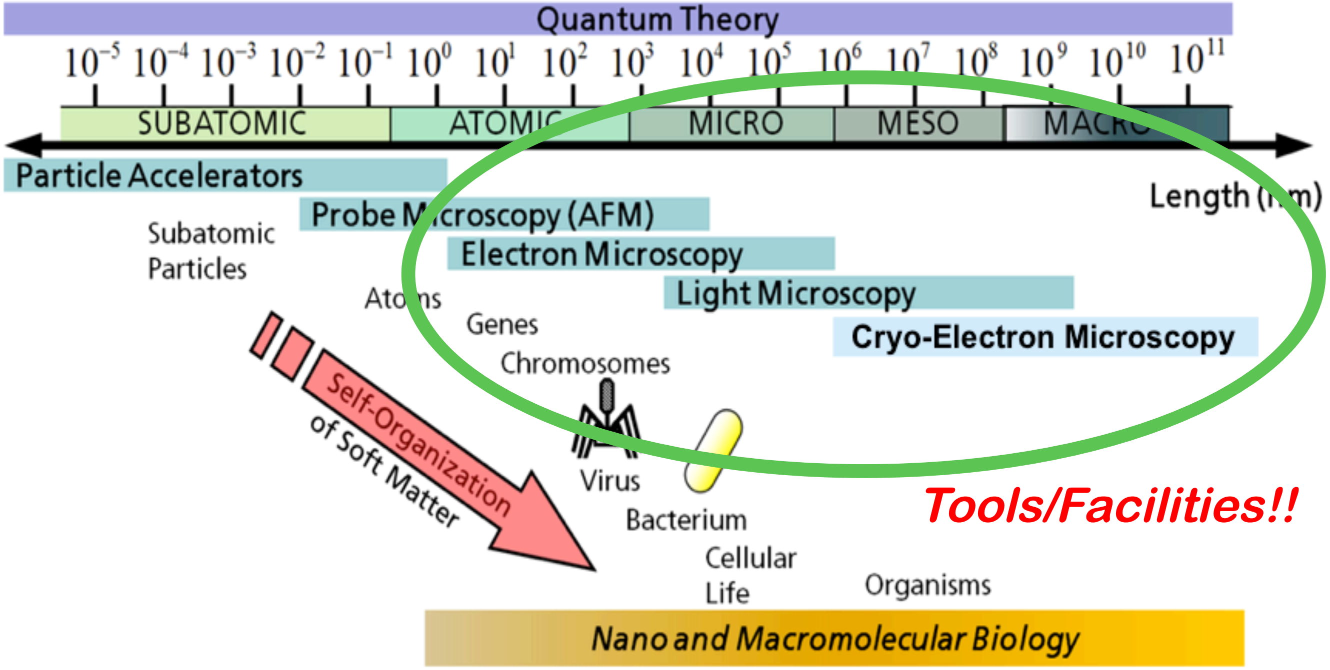
Nano-Science and Technology

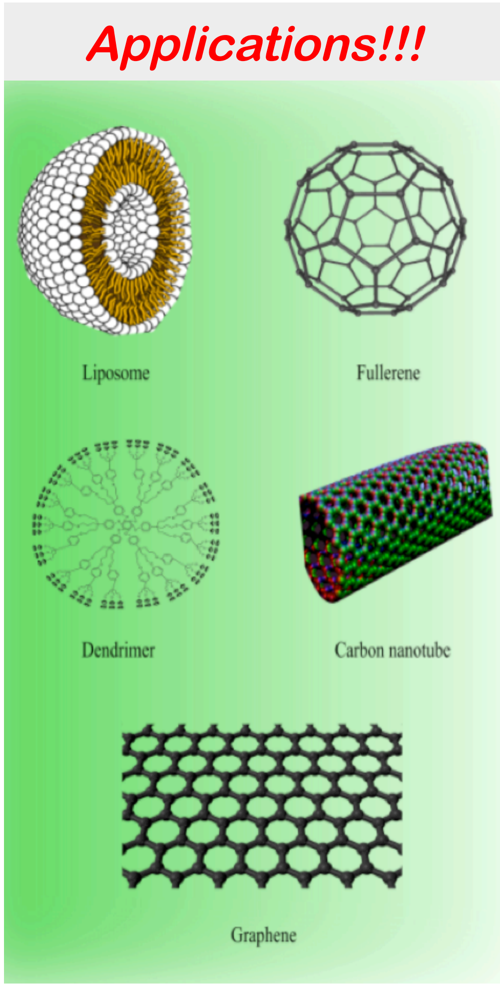
- Nano-Science – *the Idea*:

  "There's plenty of room at the bottom"

  Feynman, APS meeting at Caltech, December 29, 1959

- Need tools/facilities to advance:





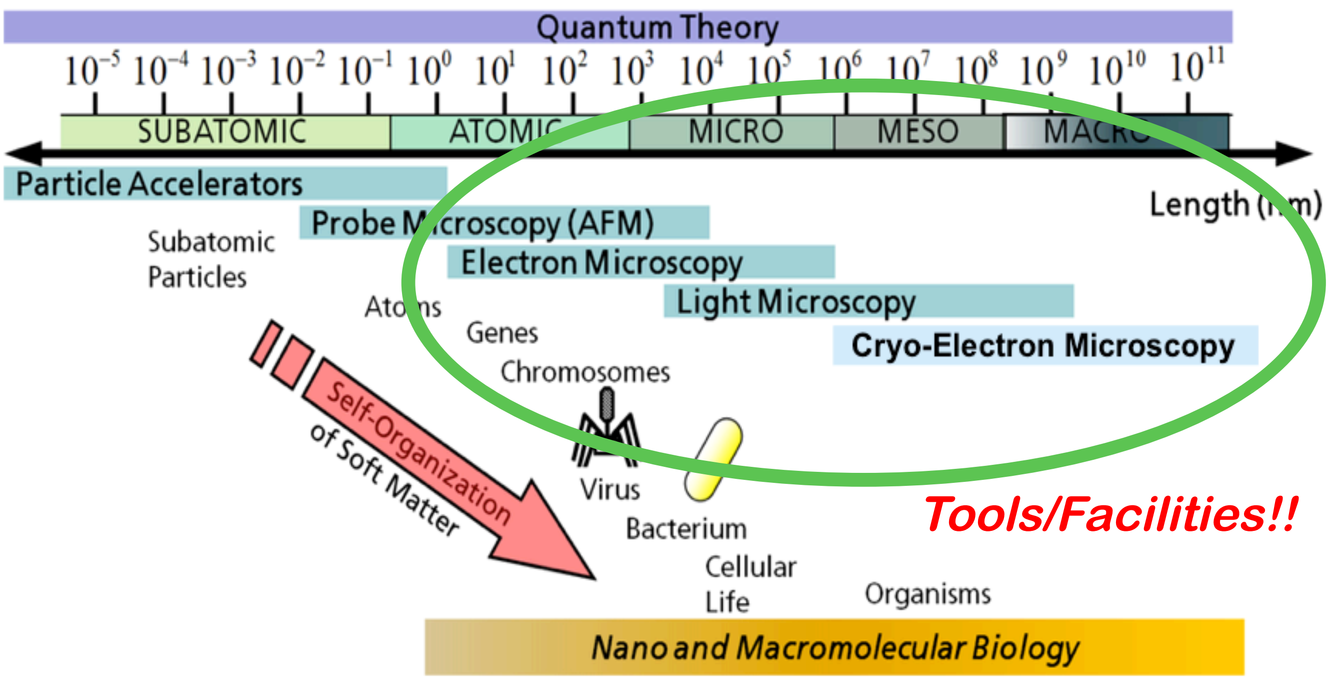
Nano-Science and Technology

- **Nano-Science – *the Idea*:**

  “There’s plenty of room at the bottom”

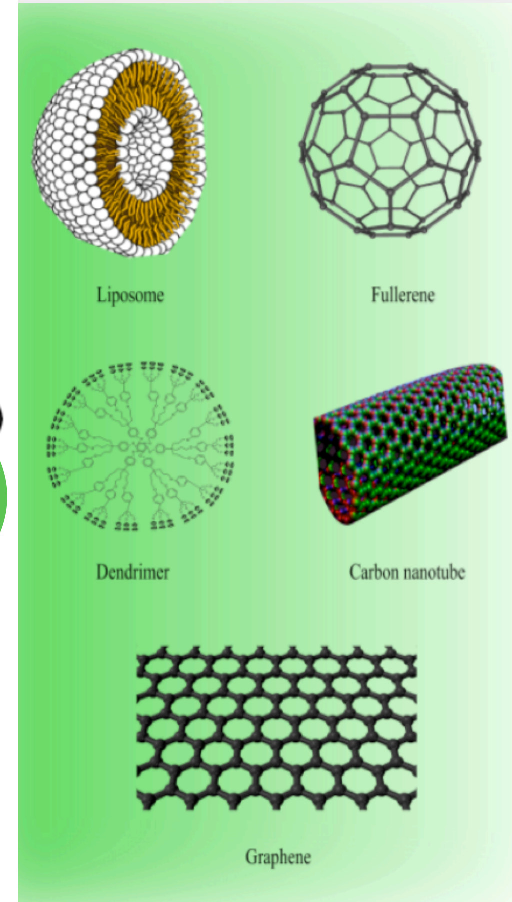
  Feynman, APS meeting at Caltech, December 29, 1959

- **Need tools/facilities to advance:**



Tools/Facilities!!

Applications!!!



- **The Support:**

  National Nanotechnology Initiative

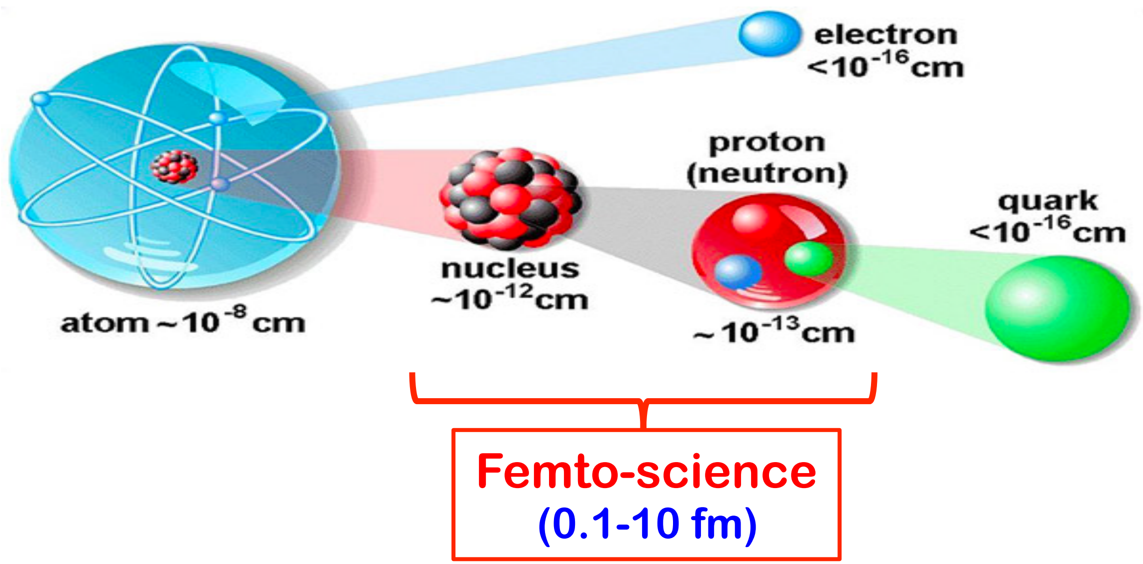
  NSF proposed to White House in 1999, signed into law in 2003

Nano-science (1-100 nm)

Ensure the role of quantum physics

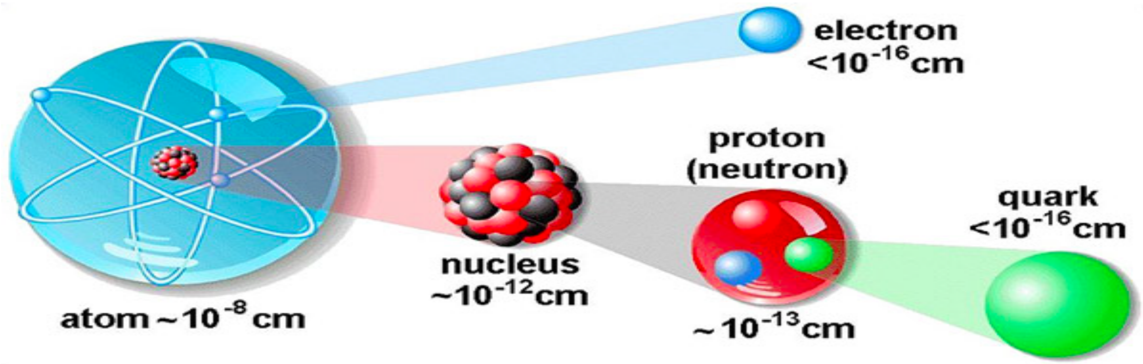
Femto-Science and Technology

❑ **Femto-Science:**



Femto-Science and Technology

❑ Femto-Science:

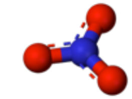


Femto-science
(0.1-10 fm)

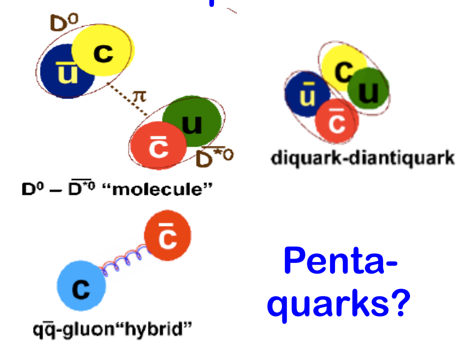
2-body force

deuteron triton

3-body force



XYZ-particles



Penta-quarks?

❑ QCD landscape of nucleon and nuclei?

Color Confinement **Asymptotic freedom**

Q (GeV)

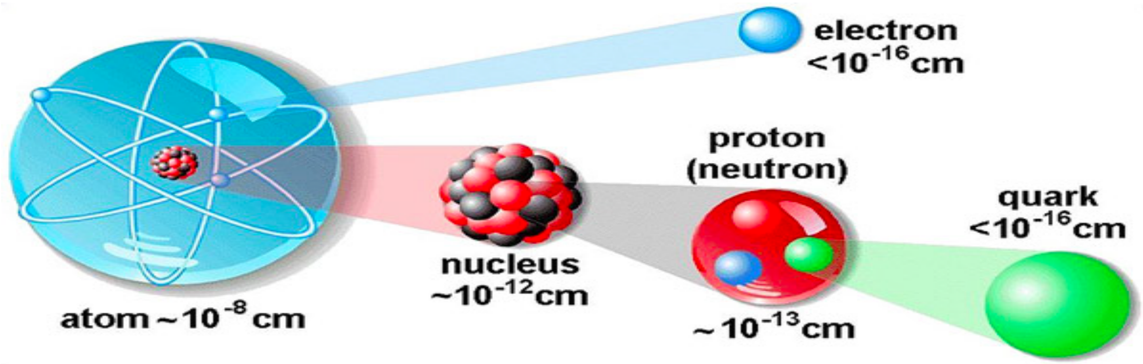
200 MeV (1 fm) **2 GeV (1/10 fm)**

Probing scale

Jefferson Lab

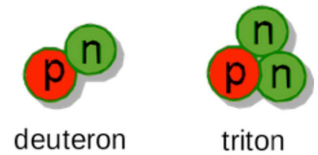
Femto-Science and Technology

❑ Femto-Science:



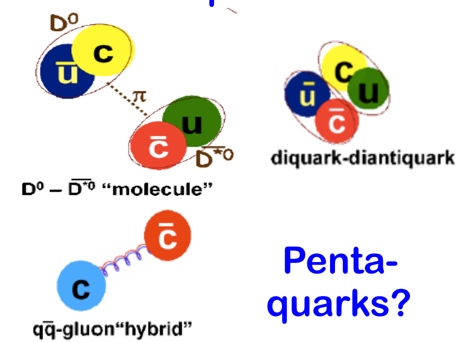
Femto-science
(0.1-10 fm)

2-body force



3-body force

XYZ-particles



Penta-quarks?

❑ QCD landscape of nucleon and nuclei?

Color Confinement

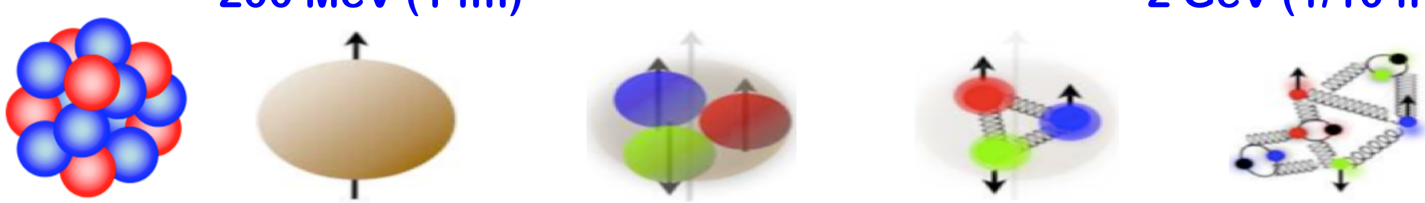
Asymptotic freedom

Q (GeV)

200 MeV (1 fm)

2 GeV (1/10 fm)

Probing scale



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!

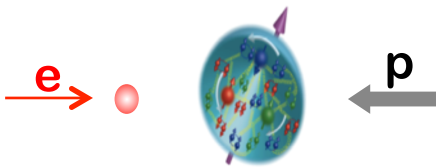
Unprecedented intellectual challenge!

- **The challenge:** **Gluons are dark!**

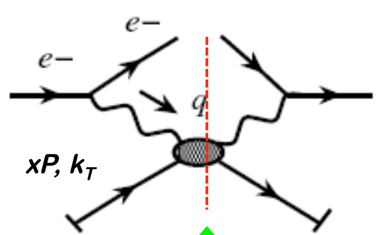
  No modern detector has been able to see quarks and gluons in isolation!

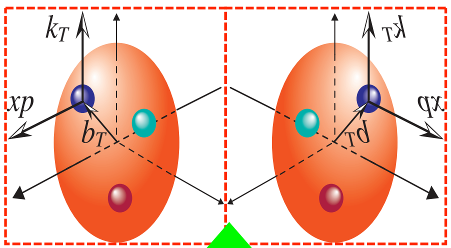
- **Answer to the challenge:**

  Theory advances: **QCD factorization**



$$\sigma_{\rm tot}^{\rm DIS} : \quad [\text{diagram}] \otimes [\text{diagram}] + O\left(\frac{1}{QR}\right)$$





Color entanglement Approximation

Physical Observable

Controllable Probe

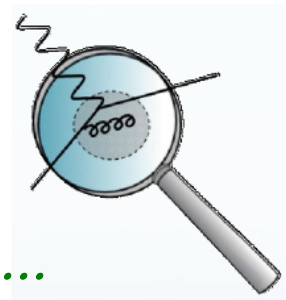
Quantum Probabilities Structure

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, …*



Unprecedented intellectual challenge!

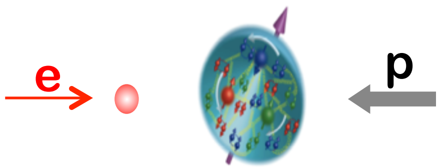
- **The challenge:** Gluons are dark!

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

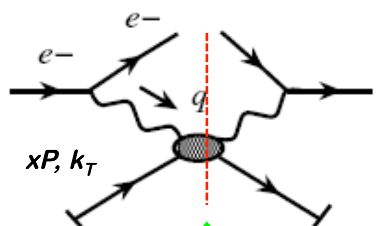
- **Answer to the challenge:**

  Theory advances: QCD factorization

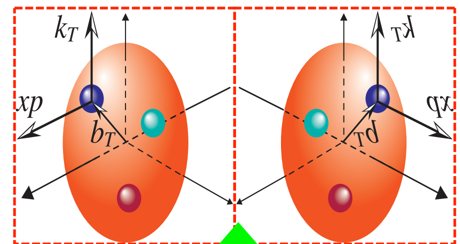
Color entanglement
Approximation



$$\sigma_{\rm tot}^{\rm DIS} :$$



$$\otimes$$



$$+\, O\left(\frac{1}{QR}\right)$$

Physical
Observable

Controllable
Probe

Quantum Probabilities
Structure

Experimental breakthroughs:

Jets – *Footprints of energetic quarks and gluons*

Quarks – *Need an EM probe to "see" their existence, …*

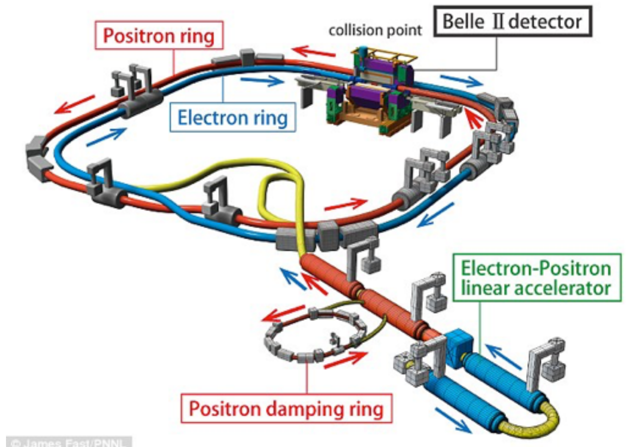
Gluons – *Varying the probe's resolution to "see" their effect, …*

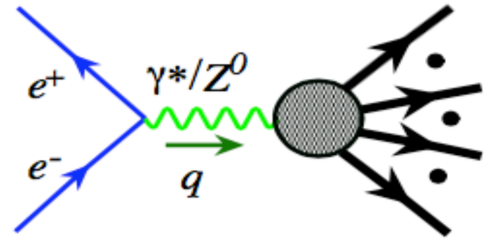
Need probes with sub-femtometer resolution – particle nature!

Jefferson Lab

Advantage of Lepton-Hadron Facility

- Lepton-lepton collisions:

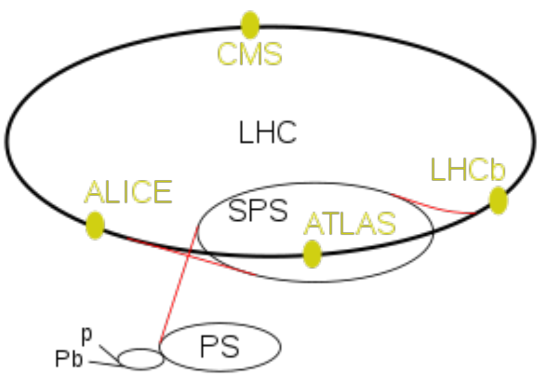


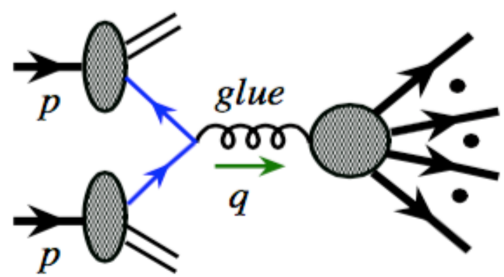


Hadrons

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

- Hadron-hadron collisions:





Hadrons

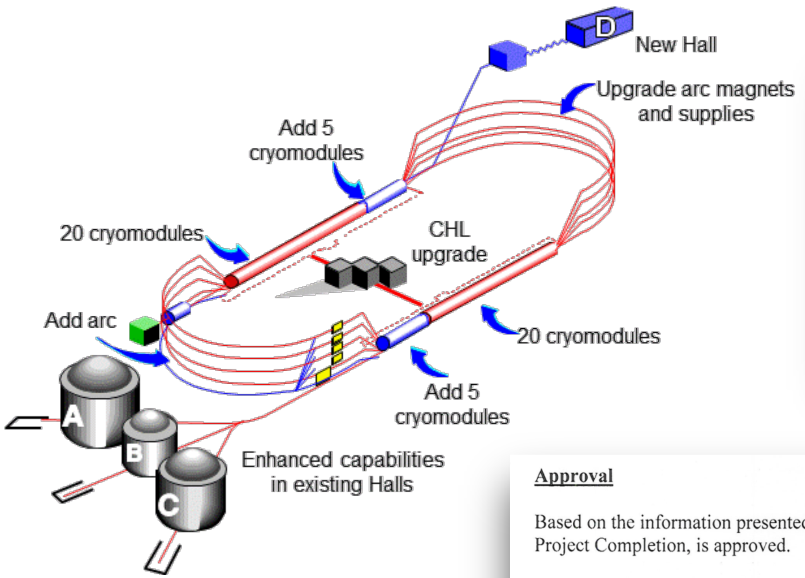
✧ Hadron structure – motion of quarks, …
✧ Emergence of hadrons, …
✧ Initial hadrons broken – collision effect, …

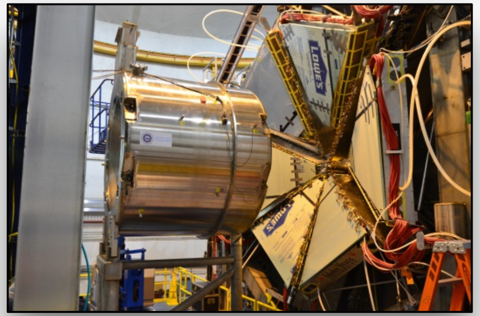
- Lepton-hadron collisions:

Hard collision without breaking the initial-state hadron!

Jefferson Lab

Jefferson Lab @ 12 GeV





Approval

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

J Binkley — 9/27/17

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

12 GeV CEBAF Upgrade CD-4B (CD-4) ESAAB Approval — Page 8

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!

Jefferson Lab

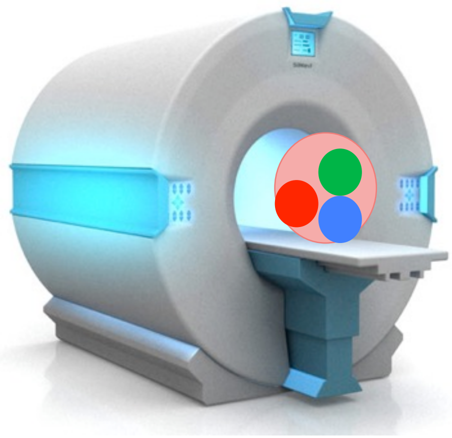
The Electron-Ion Collider (EIC) – the Future!

- ❑ 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!

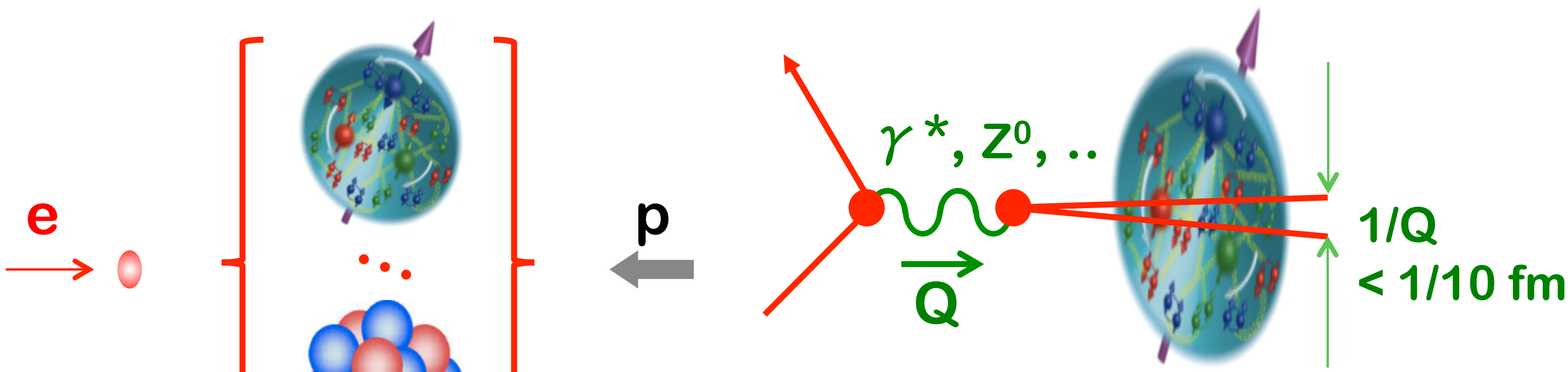
The Electron-Ion Collider (EIC) – the Future!

- **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!

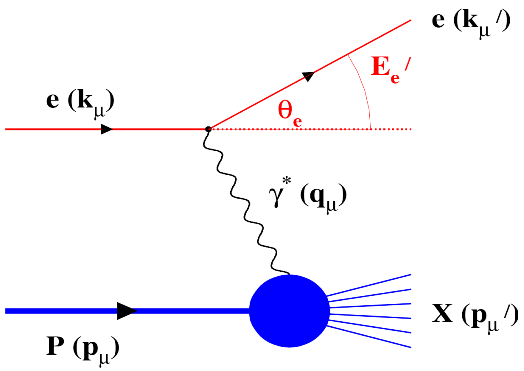
- **A giant "Microscope" – "see" quarks and gluons by breaking the hadron**



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 → Measure of resolution

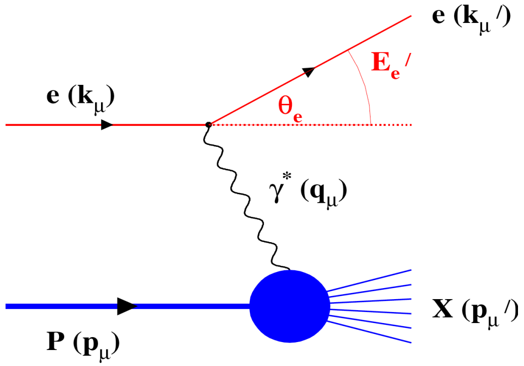
y → Measure of inelasticity

x → Measure of momentum fraction of the struck quark in a proton

$$Q^2 = S\, x\, y$$

Many complementary probes at one facility

- A new generation of "Rutherford" experiment:



Q^2 → Measure of resolution

y → Measure of inelasticity

x → Measure of momentum fraction of the struck quark in a proton

$Q^2 = S\ x\ y$

Inclusive events: e+p/A → e'+X

Detect only the scattered lepton in the detector

(Modern Rutherford experiment!)

Semi-Inclusive events: e+p/A → 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 → 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)

Jefferson Lab

EIC: the World Wide Interest

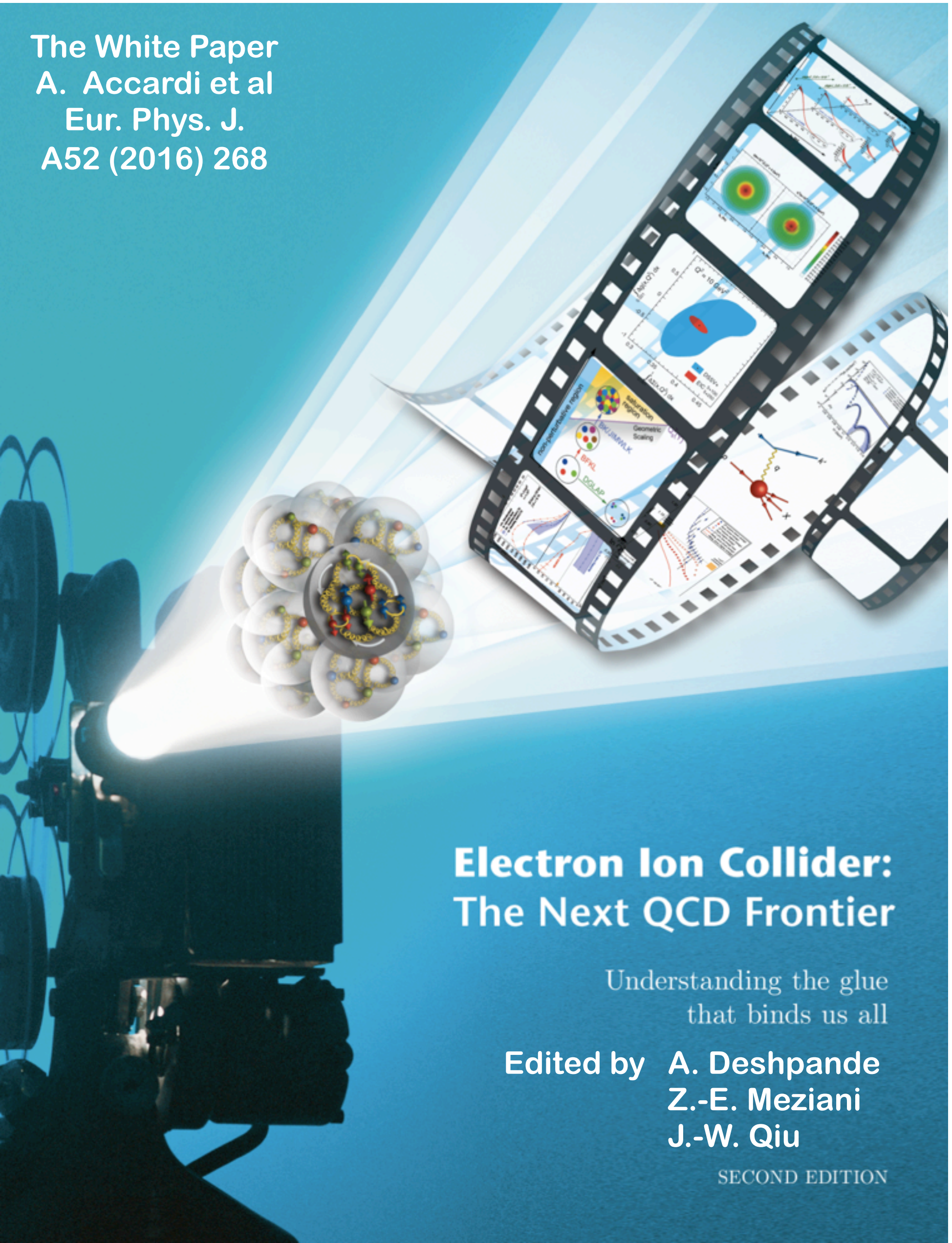
	HERA@DESY	LHeC@CERN	eRHIC@BNL	JLEIC@JLab	HIAF@CAS	ENC@GSI
E_{CM} (GeV)	320	800-1300	45-175	12-140	12 → 65	14
proton x_{min}	1×10^{-5}	5×10^{-7}	3×10^{-5}	5×10^{-5}	$7 \times 10^{-3} \rightarrow 3 \times 10^{-4}$	5×10^{-3}
ion	p	p to Pb	p to U	p to Pb	p to U	p to ~ ^{40}Ca
polarization	-	-	p, ^{3}He	p, d, ^{3}He (^{6}Li)	p, d, ^{3}He	p,d
L [cm^{-2} 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 → 2030	upgrade to FAIR

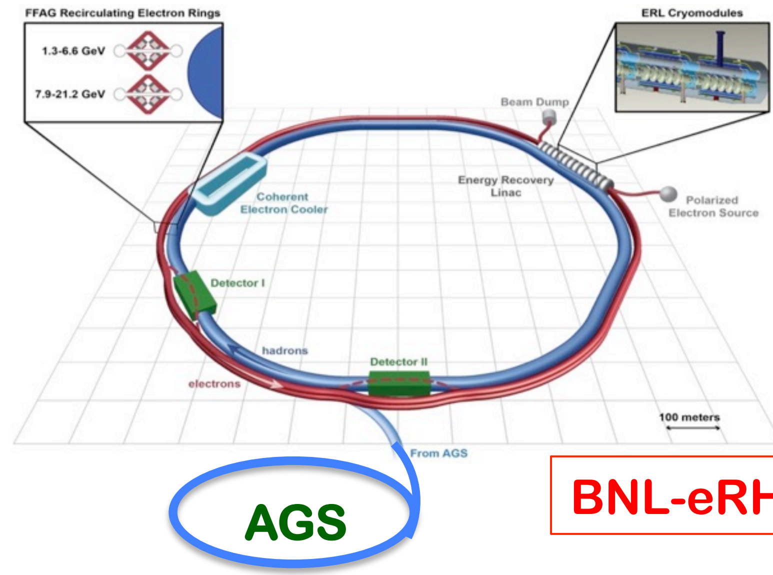
The past

Possible future

Jefferson Lab

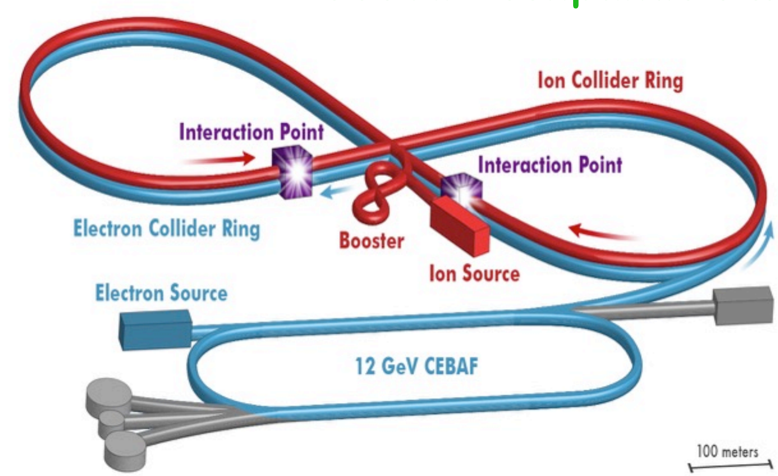
US EIC – Two Options of Realization





BNL-eRHIC

See A. Deshpande's talk



JLab-JLEIC

Jefferson Lab

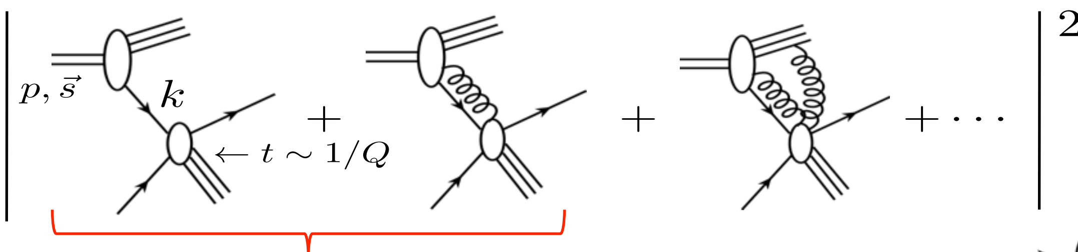
US-EIC – can do what HERA could not do

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

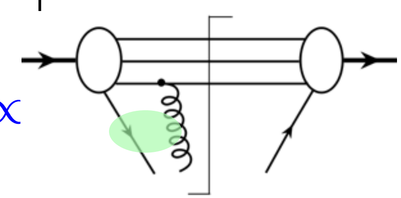
US-EIC – can do what HERA could not do

- **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!

$\sigma(Q, \vec{s}) \propto$



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

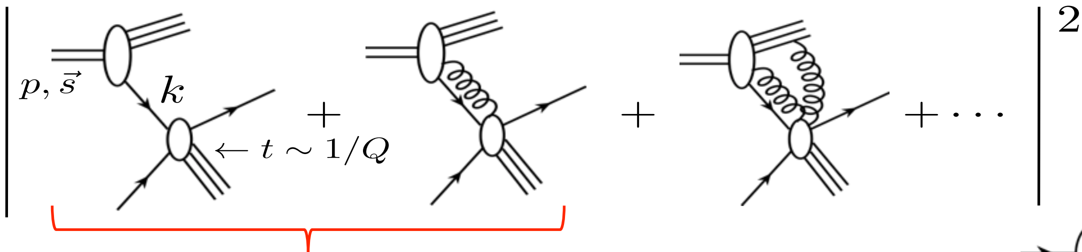


US-EIC – can do what HERA could not do

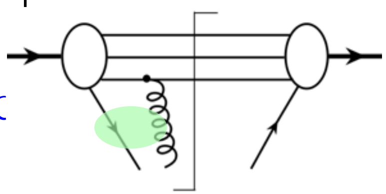
- **Quantum imaging:**
  - ✧ **HERA discovered: 15% of e-p events is diffractive – Proton not broken!**
  - ✧ **US-EIC: 100-1000 times luminosity – *Critical for 3D tomography!***

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

$\sigma(Q,\vec{s}) \propto$



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



- **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?

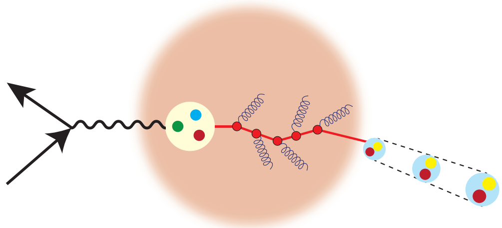
  Necessary knowledge for understanding
  what are we made of, and
  what hold us together, as well as
  how do we improve and move forward?

- What is the key for understanding color confinement?

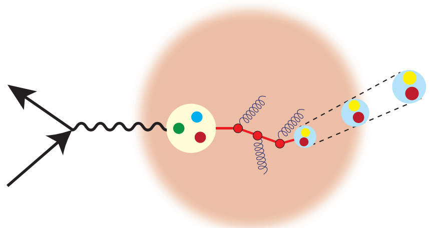
  Necessary knowledge for understanding
  What is the mother nature of the nonlinear, strongly interacting dynamics of color force?

Emergence of Hadrons from quarks & gluons

❑ **Femtometer sized detector:**



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

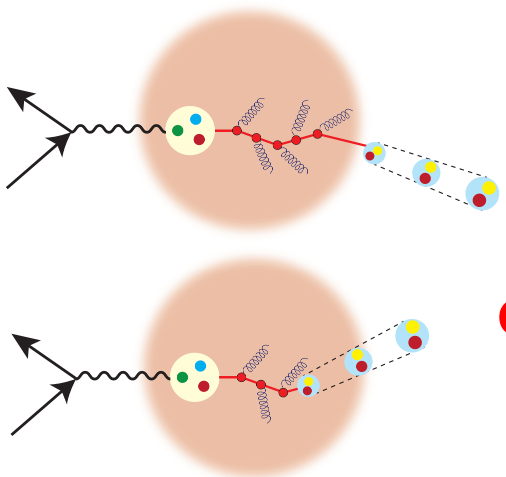


Control of ν and medium length!

Mass dependence of hadronization

Emergence of Hadrons from quarks & gluons

- **Femtometer sized detector:**

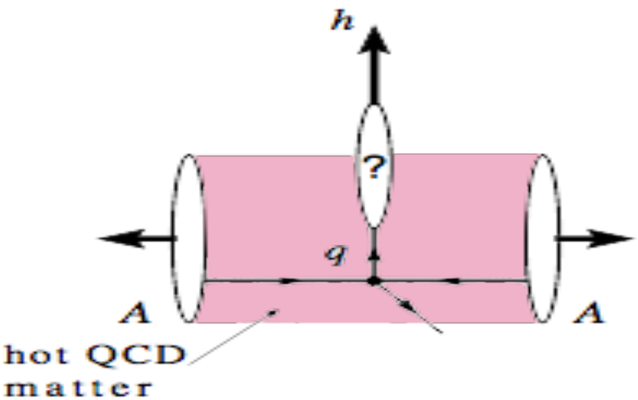


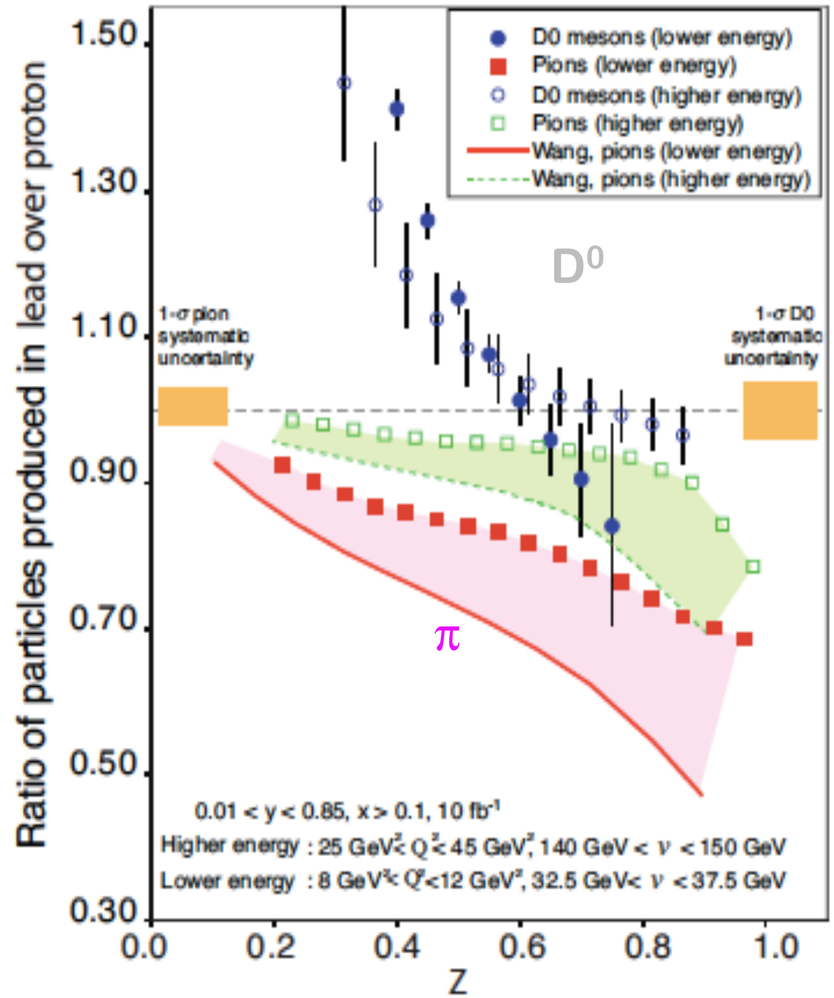
$$\nu = \frac{Q^2}{2mx}$$

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

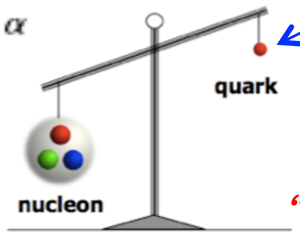
✧ QCD energy-momentum tensor in terms of quarks and gluons

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

✧ Proton mass:

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

Higgs Mech.



$m_q \sim 10$ MeV

$m_N \sim 1000$ MeV

"Mass without mass"

Hadron Properties: Mass & Spin, …

❑ Mass – intrinsic to a particle:

= Energy of the particle when it is at the rest

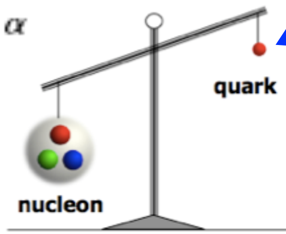
✧ QCD energy-momentum tensor in terms of quarks and gluons

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

✧ Proton mass:

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

Higgs Mech.



m_q ~ 10 MeV

m_N ~ 1000 MeV

"Mass without mass"

❑ Spin – intrinsic to a particle:

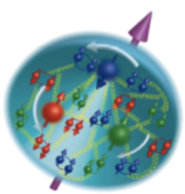
= Angular momentum of the particle when it is at the rest

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

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

✧ Proton spin:

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



EMC found:

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

"Proton spin puzzle"

Hadron Properties: Mass & Spin, …

❑ Mass – intrinsic to a particle:

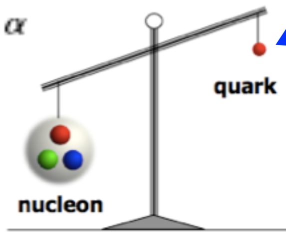
= Energy of the particle when it is at the rest

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

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

✧ Proton mass:

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



Higgs Mech.

$m_q \sim 10$ MeV

$m_N \sim 1000$ MeV

"Mass without mass"

❑ Spin – intrinsic to a particle:

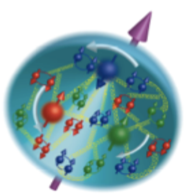
= Angular momentum of the particle when it is at the rest

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

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

✧ Proton spin:

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



EMC found:

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

"Proton spin puzzle"

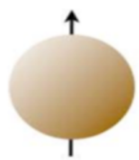
If we do not understand proton mass & spin,
we do not understand QCD!

Jefferson Lab

The Proton Spin

- **The sum rule:** $$S(\mu) = \sum_f \langle P, S | \hat{J}^z_f(\mu) | P, S \rangle = \frac{1}{2} \equiv J_q(\mu) + J_g(\mu)$$
  - **Infinite possibilities of decompositions – connection to observables?**
  - **Intrinsic properties + dynamical motion and interactions**

- **An incomplete story:**



Proton Spin

$$\frac{1}{2} = \frac{1}{2}\Delta\Sigma + \Delta G + (L_q + L_g)$$

Jaffe-Manohar, 90
Ji, 96, …

Quark helicity
Best known

$$\frac{1}{2}\int dx \left(\Delta u + \Delta\bar{u} + \Delta d + \Delta\bar{d} + \Delta s + \Delta\bar{s}\right)$$

$$\sim 30\%$$

Gluon helicity
Start to know

$$\Delta G = \int dx \Delta g(x)$$

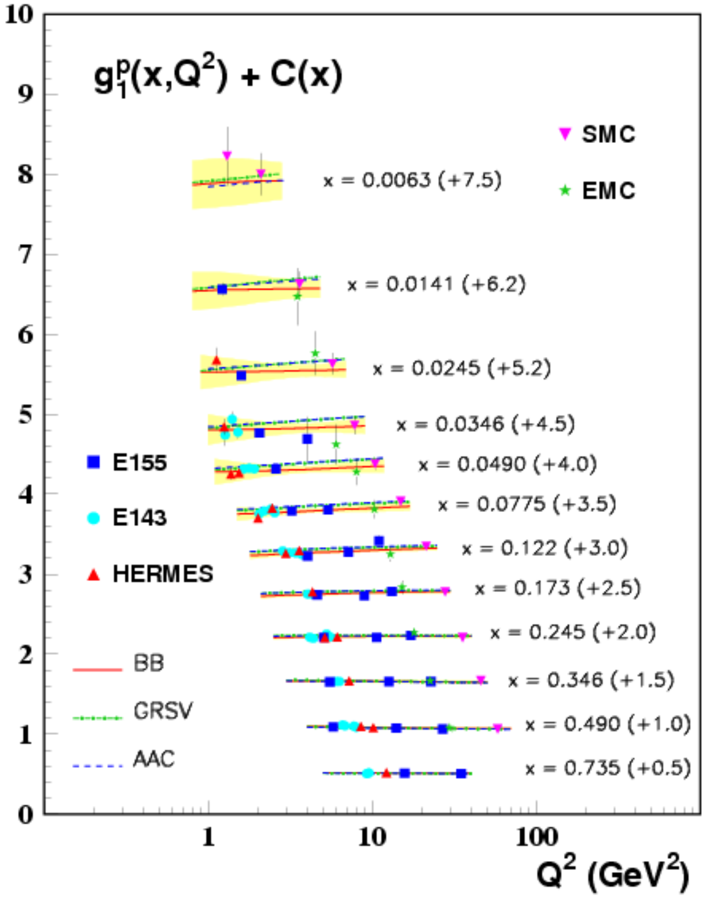
$$\sim 40\% (\text{with RHIC data})$$

Orbital Angular Momentum of quarks and gluons
Little known

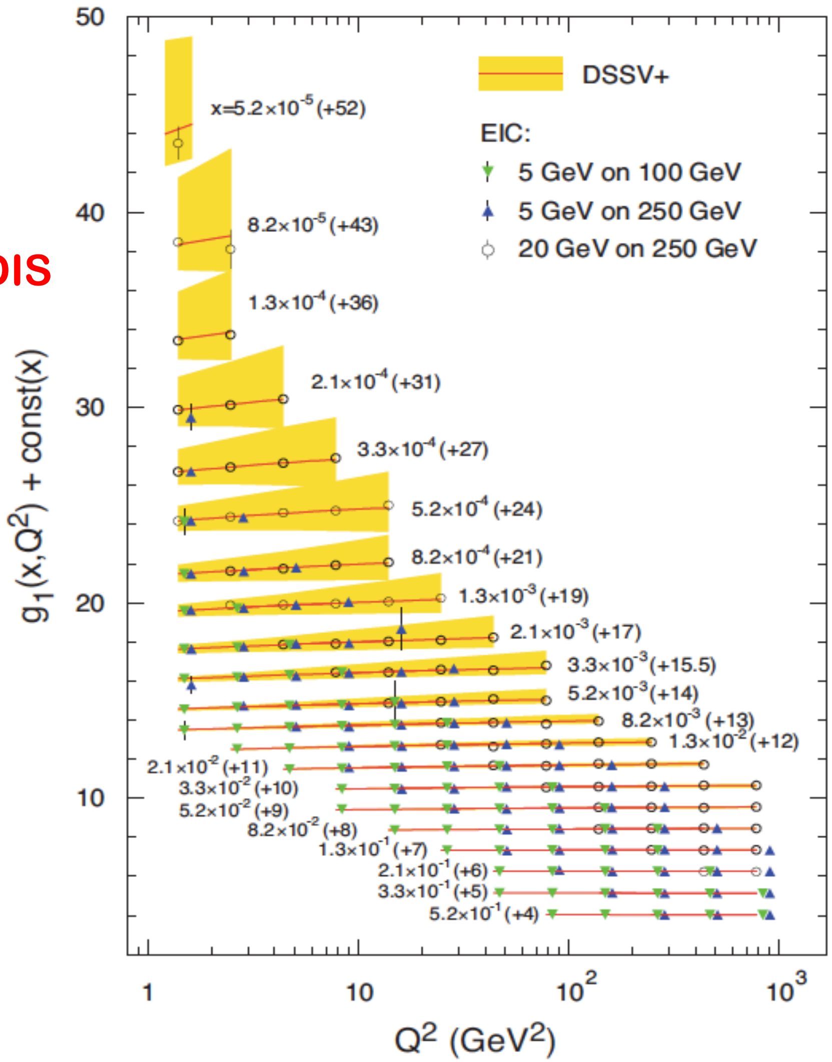
Net effect of partons' transverse motion?

The Proton Spin

- ❑ **The power & precision of EIC:**



Polarized DIS at EIC



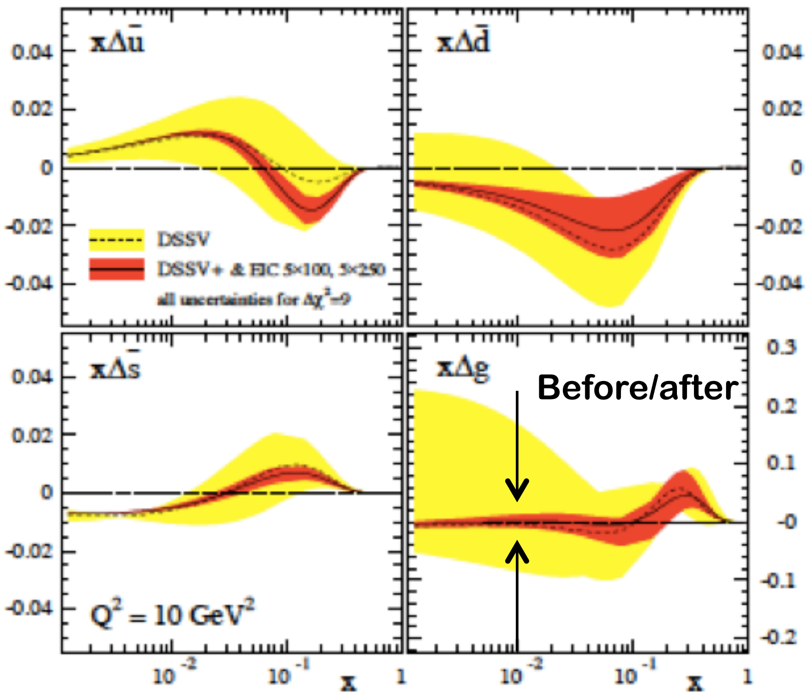
- ❑ **Reach out the glue:**

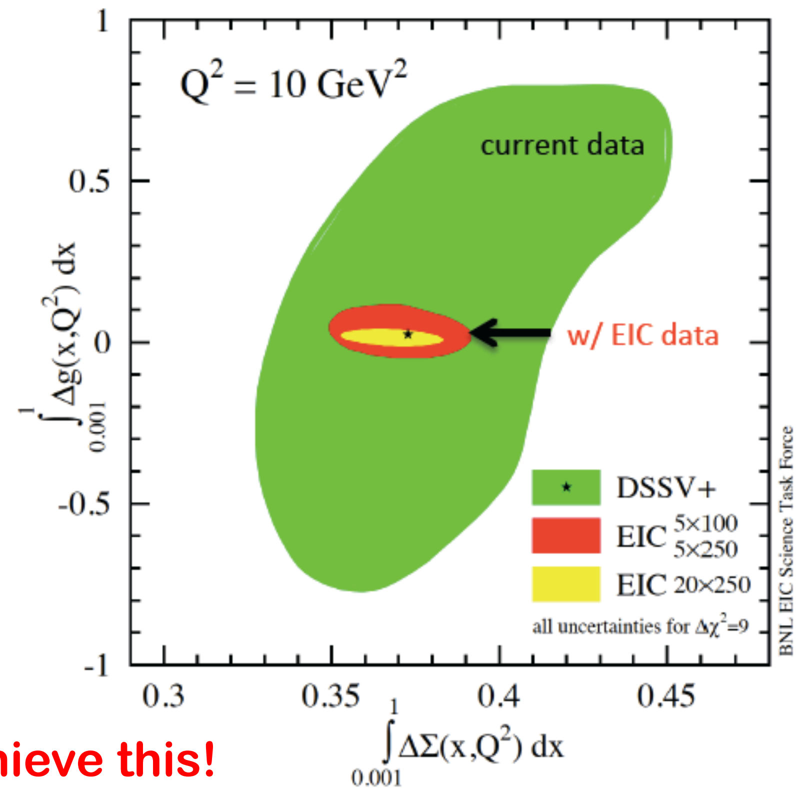
$$\frac{dg_1(x,Q^2)}{d\ln Q^2} = \frac{\alpha_s}{2\pi} P_{qg} \otimes \Delta g(x,Q^2) + \cdots$$

The Proton Spin

- ❑ **One-year of running at EIC:**

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



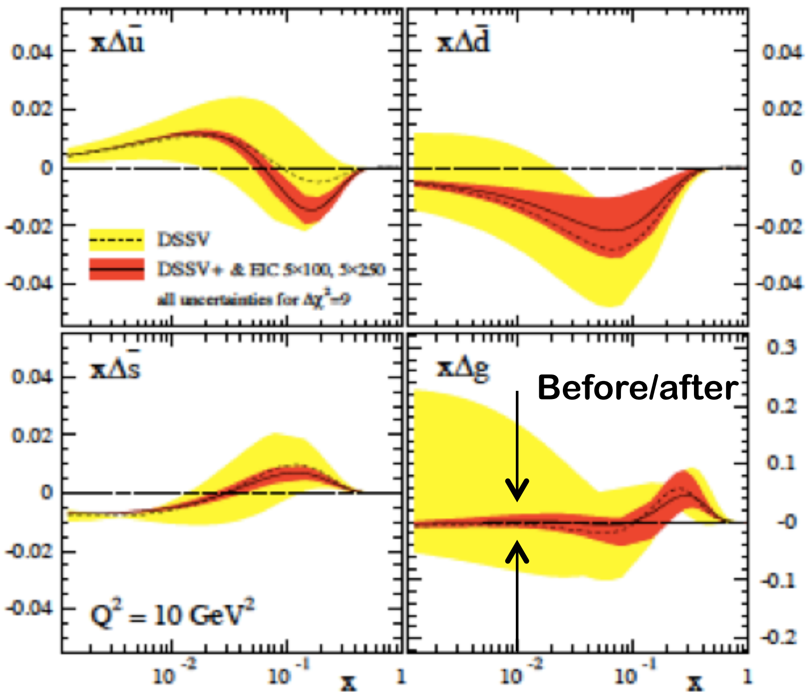


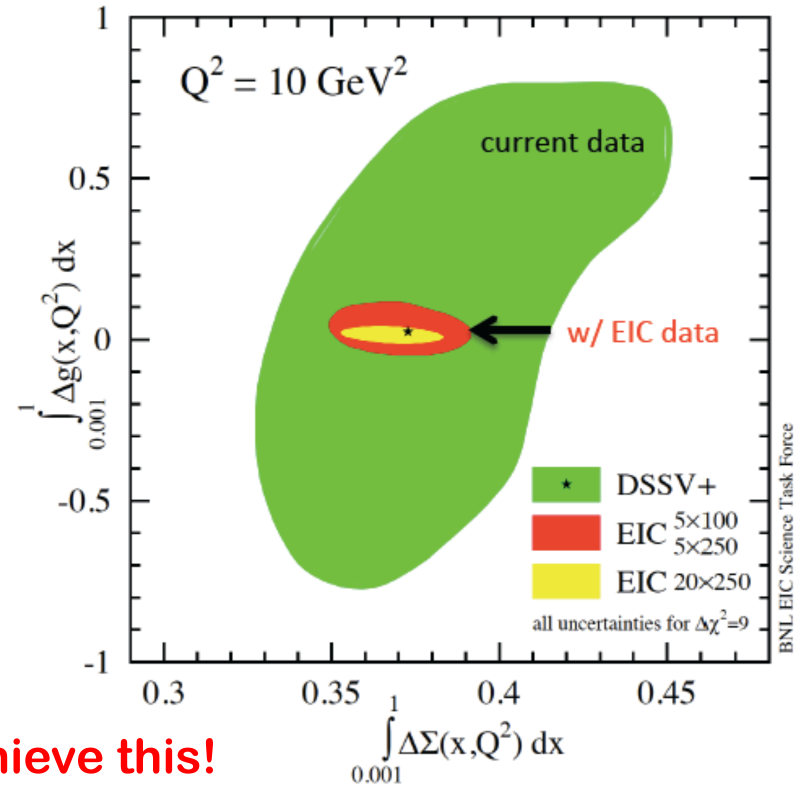
No other machine in the world can achieve this!

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:

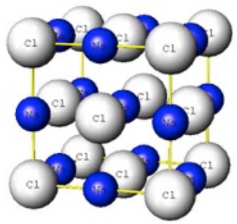
- ✧ ***Precision measurement of $\Delta g(x)$ – extend to smaller x regime***
- ✧ ***Orbital angular momentum contribution?***
  - ***– internal motion & structure – encoded in TMDs & GPDs!***

Jefferson Lab

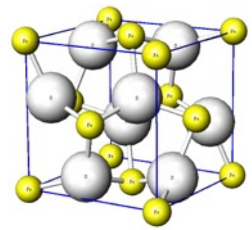
Hadron's partonic structure in QCD

- ❑ **Structure – "a still picture"**

Crystal Structure:

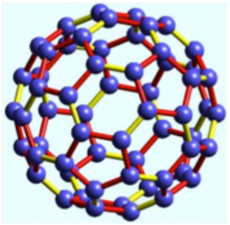


NaCl,
B1 type structure



FeS2,
C2, pyrite type structure

Nano-material:



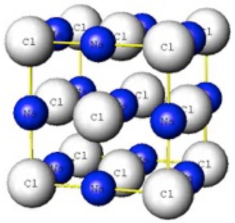
Fullerene, C60

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

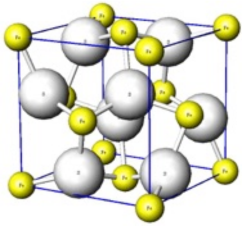
Hadron’s partonic structure in QCD

- **Structure – “a still picture”**

Crystal Structure:

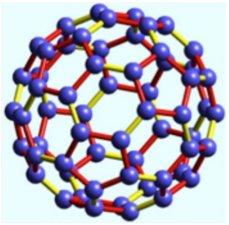


NaCl,
B1 type structure



FeS2,
C2, pyrite type structure

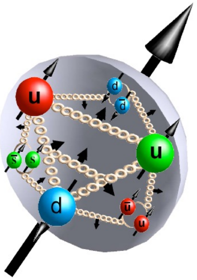
Nano-material:



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:

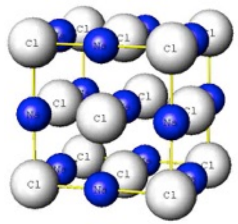
Quantum “probabilities” $\langle P, S | \mathcal{O}(\overline{\psi}, \psi, A^{\mu}) | P, S \rangle$

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

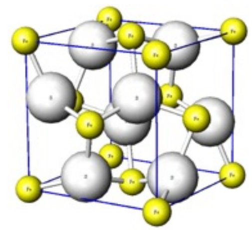
Hadron's partonic structure in QCD

- **Structure – "a still picture"**

Crystal Structure:

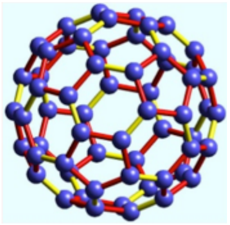


NaCl,
B1 type structure



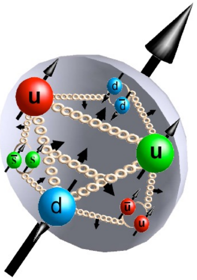
FeS2,
C2, pyrite type structure

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" $\langle P, S | \mathcal{O}(\overline{\psi}, \psi, A^{\mu}) | P, S \rangle$

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, …

Jefferson Lab

3D confined motion and spatial distribution

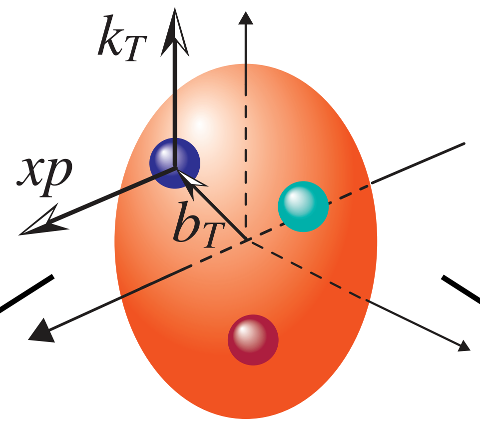
- 3D boosted partonic structure:

Momentum Space

TMDs

Confined motion

$\int d^2 b_T$



$\int d^2 k_T$

Coordinate Space

GPDs

Spatial distribution

$f(x, k_T)$

Two-scales observables

$f(x, b_T)$

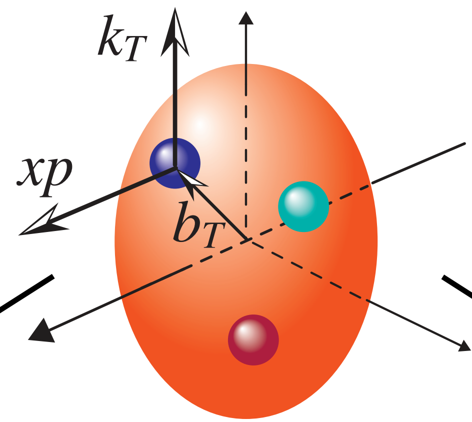
3D confined motion and spatial distribution

- 3D boosted partonic structure:

Momentum Space

TMDs

Confined motion



Coordinate Space

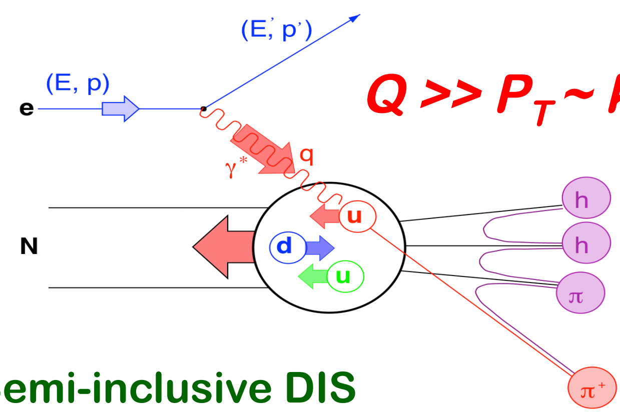
GPDs

Spatial distribution

$\int d^2 b_T$ $\int d^2 k_T$

$f(x,k_T)$ **Two-scales observables** $f(x,b_T)$

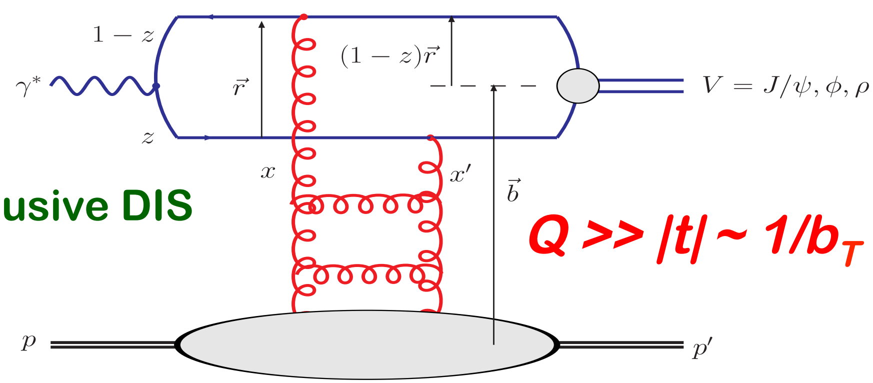
3D momentum space images



$Q >> P_T \sim k_T$

Semi-inclusive DIS

2+1D coordinate space images



Exclusive DIS

$Q >> |t| \sim 1/b_T$

JLab12 – valence quarks, EIC – sea quarks and gluons

Jefferson Lab

3D confined motion and spatial distribution

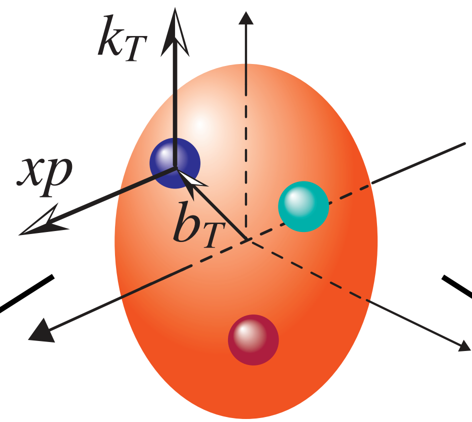
❑ 3D boosted partonic structure:

Momentum Space

TMDs

Confined motion

$\int d^2b_T$



$\int d^2k_T$

Coordinate Space

GPDs

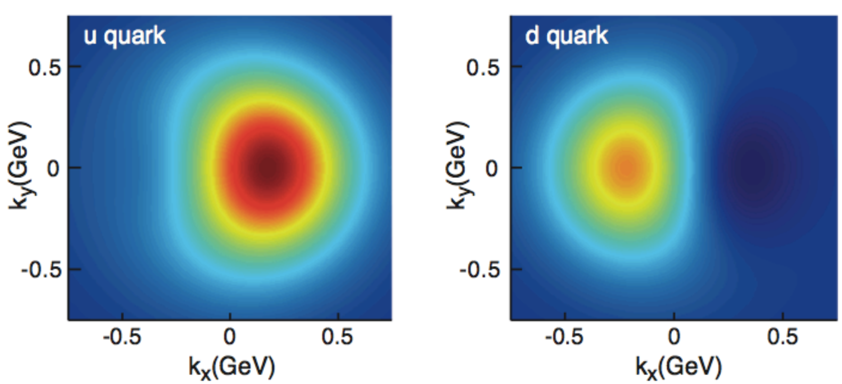
Spatial distribution

$f(x,k_T)$

EIC white paper: EPJ A52 (2016) 268

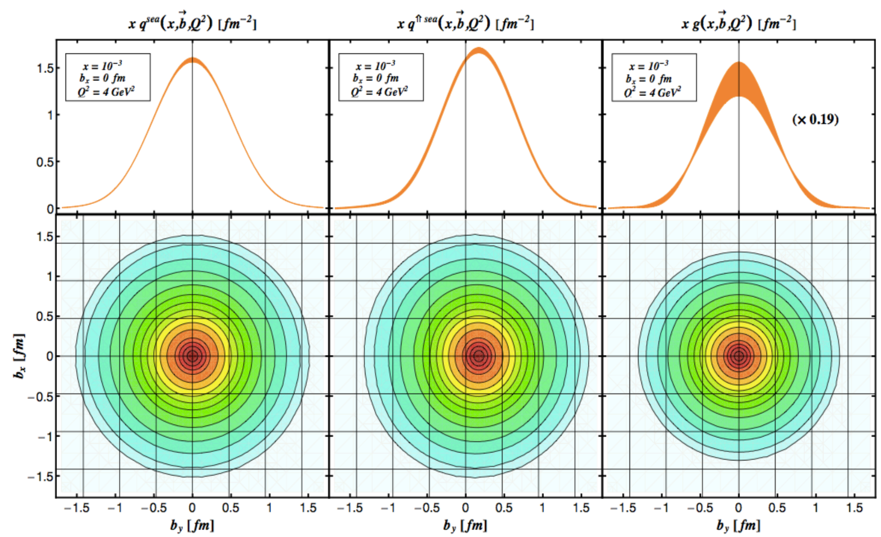
$f(x,b_T)$

Sivers Function



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

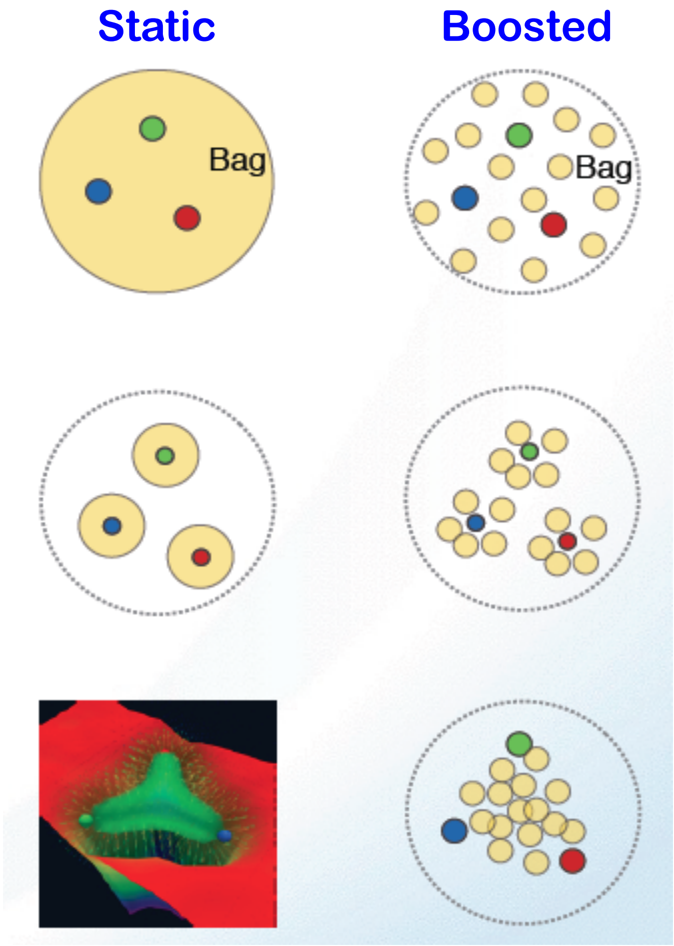
Imaging



Spatial density distributions – "radius"

Why 3D nucleon structure?

❑ **Spatial distributions of quarks and gluons:**



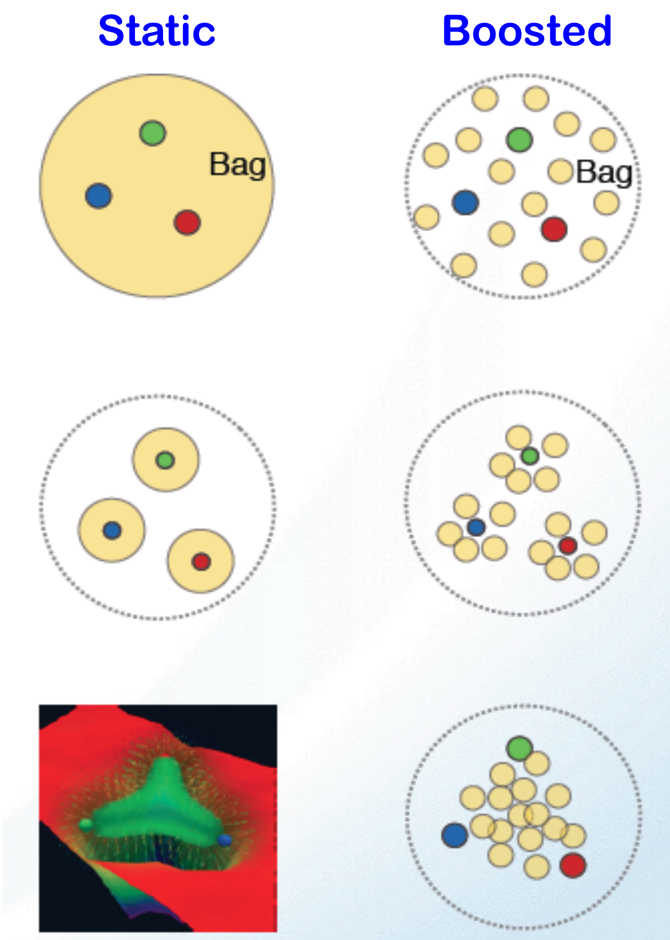
Bag Model:
Gluon field distribution is wider than the fast moving quarks.
Gluon radius > Charge Radius

Constituent Quark Model:
Gluons and sea quarks hide inside massive quarks.
Gluon radius ~ Charge Radius

Lattice Gauge theory (with slow moving quarks):
Gluons more concentrated inside the quarks
Gluon radius < Charge Radius

Why 3D nucleon structure?

- ❑ **Spatial distributions of quarks and gluons:**



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 ~ Charge Radius

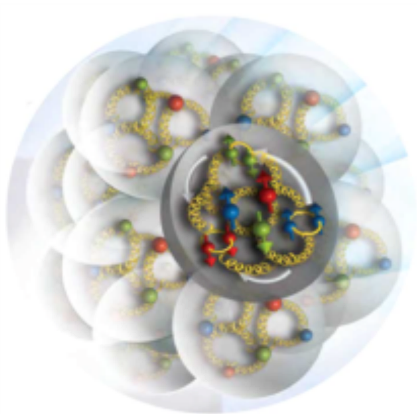
Lattice Gauge theory (with slow moving quarks):
Gluons more concentrated inside the quarks
Gluon radius < Charge Radius

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

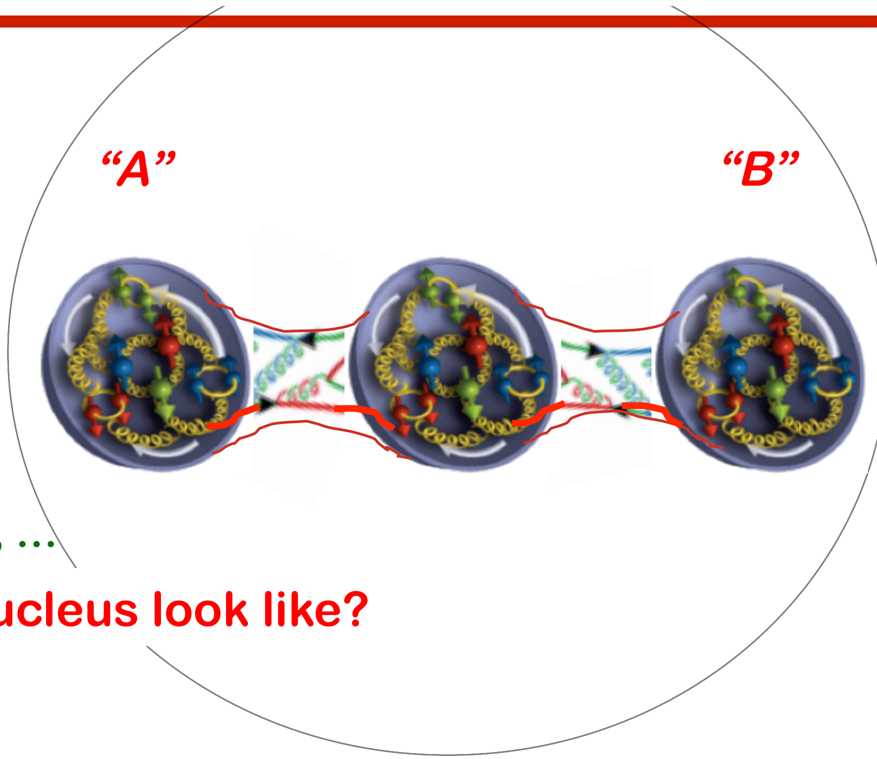
Radius of Charge, Radius (x) of quark/gluon distribution?

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"?

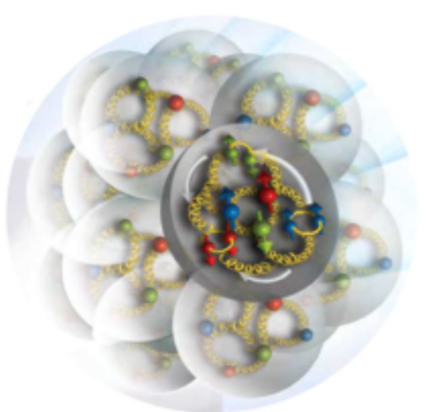
If it does, what is the strength of such correlation?

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

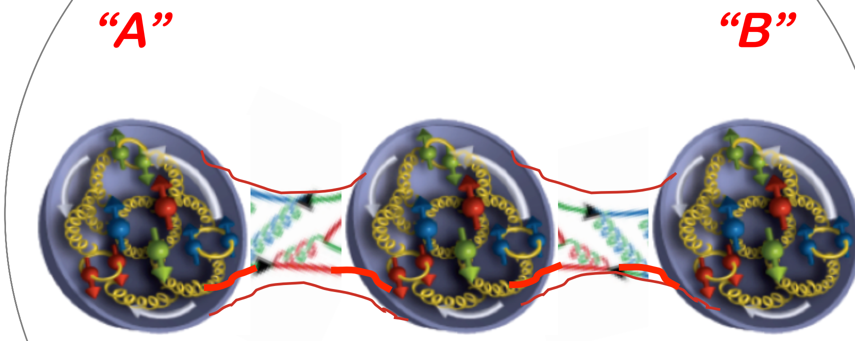
Jefferson Lab

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"?

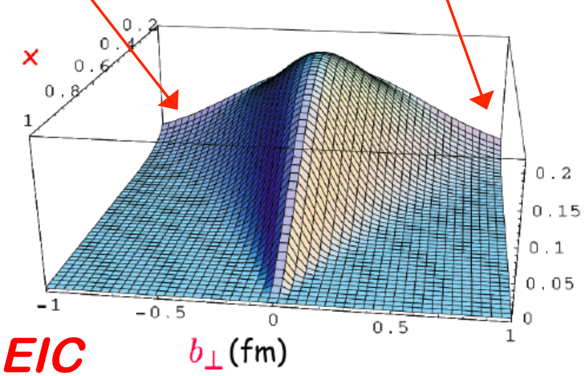
If it does, what is the strength of such correlation?

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?

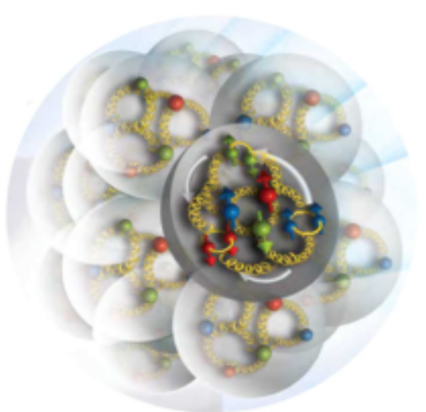
Imaging 3D gluon density

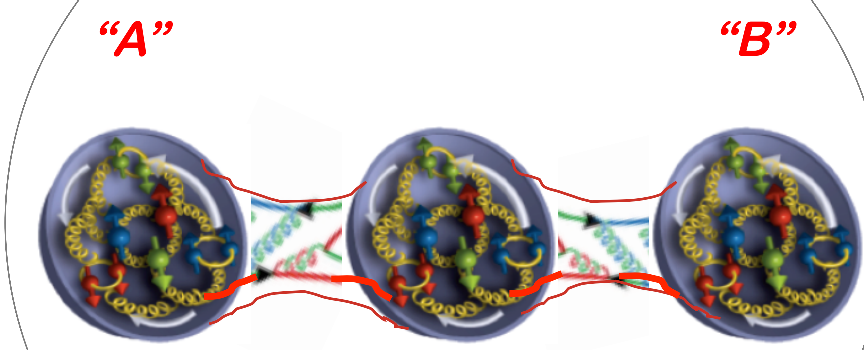


Only possible at EIC

Emergence of nuclear force?

❑ Nature of nuclear force:

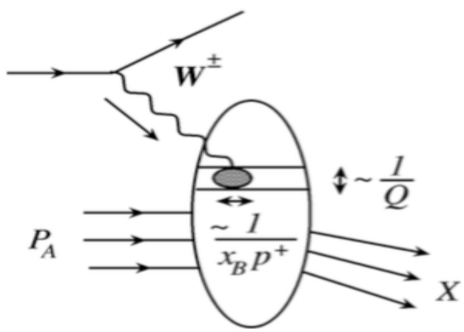




If we only see quarks and gluons, …

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

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



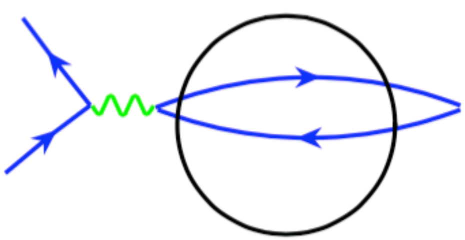
c.m. frame

Longitudinal probing size

> Lorentz contracted nucleon, if

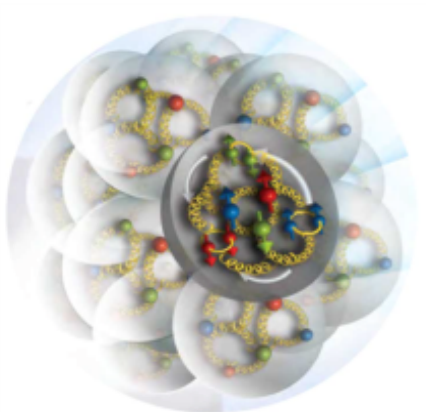
$$\frac{1}{xp} > 2R_A \frac{m}{p} \quad \text{or} \quad x \lesssim 0.01$$

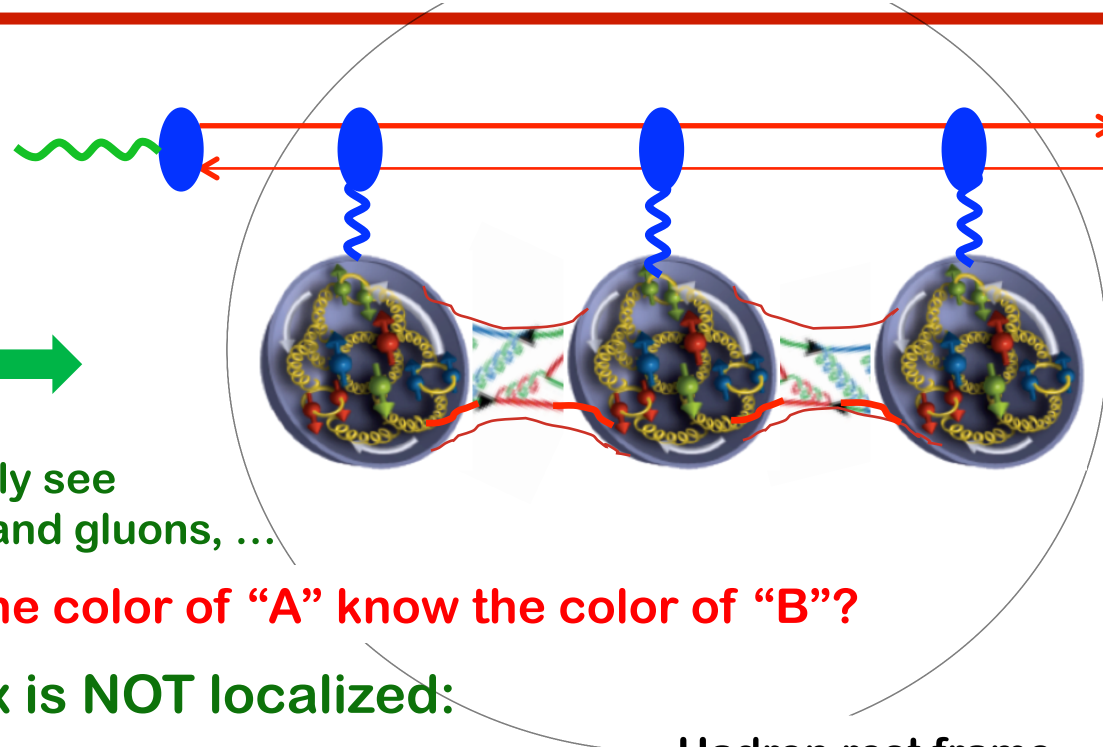
Hadron rest frame



Emergence of nuclear force?

- ❑ **Nature of nuclear force:**

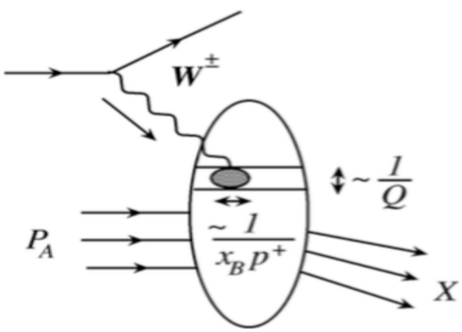




If we only see
quarks and gluons, …

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

- ❑ **The hard probe at small-x is NOT localized:**

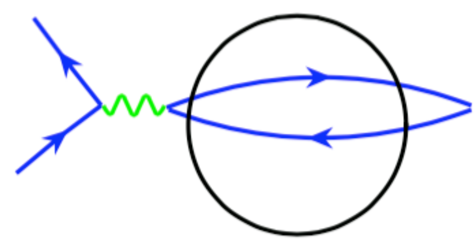


c.m. frame

Longitudinal probing size
\> Lorentz contracted nucleon, if

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

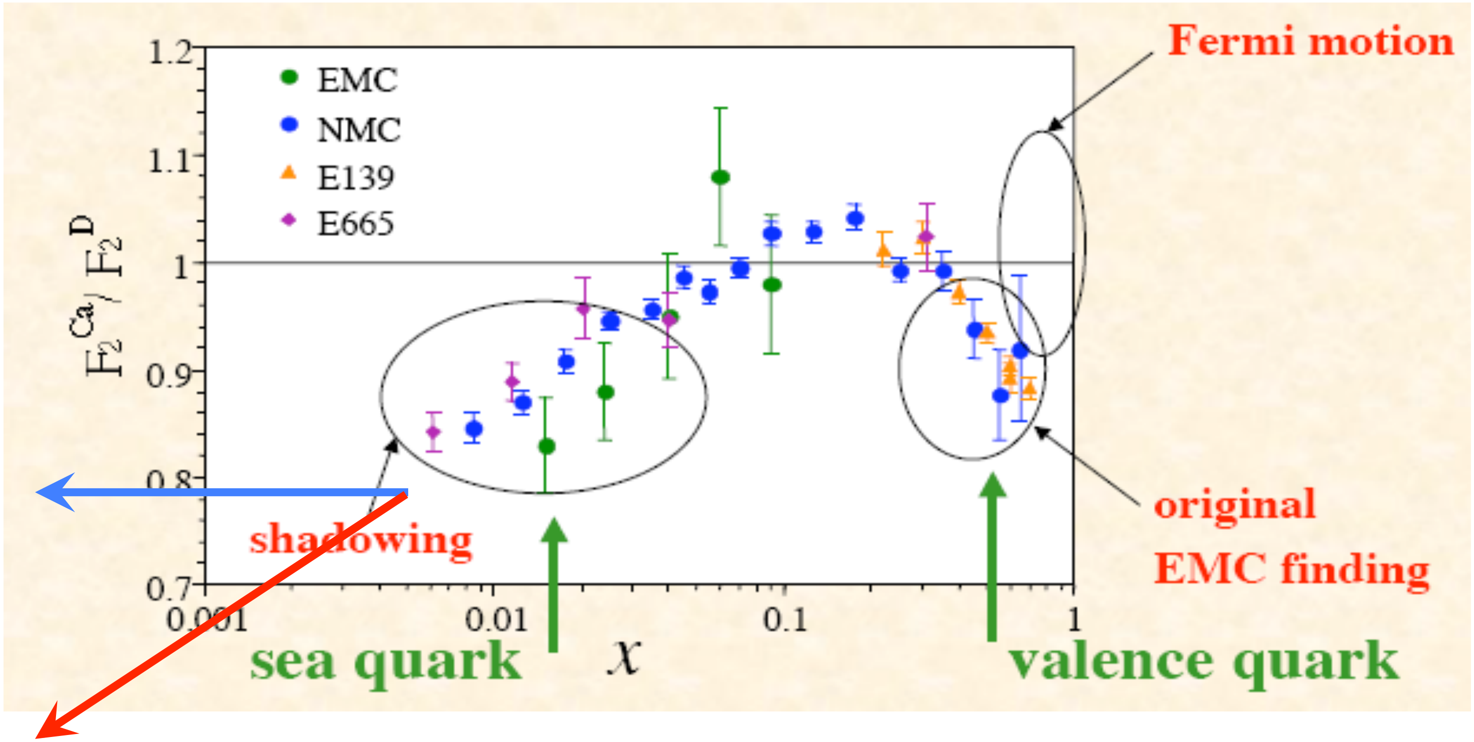
Hadron rest frame



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

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

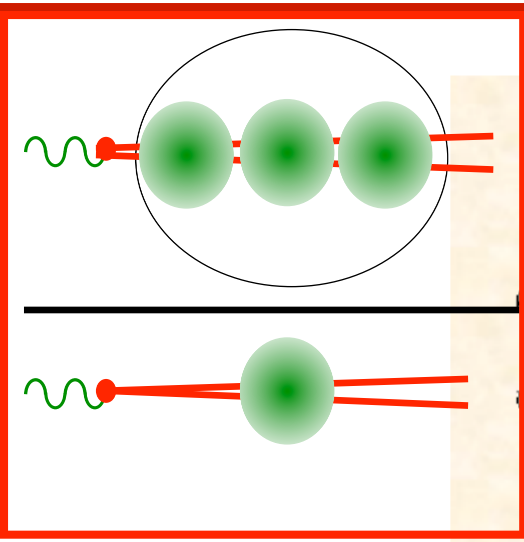
Role of color for nuclear force?



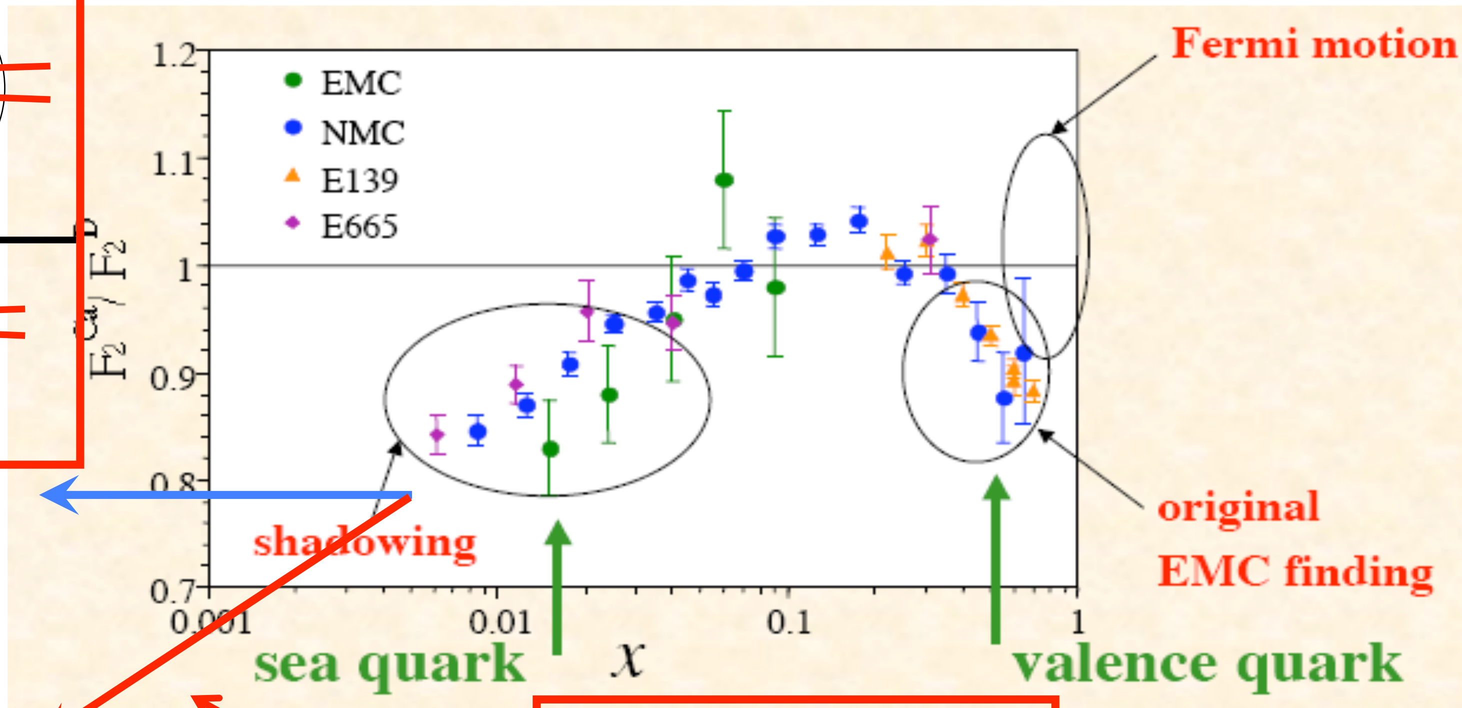
- ❑ **A simple question:**

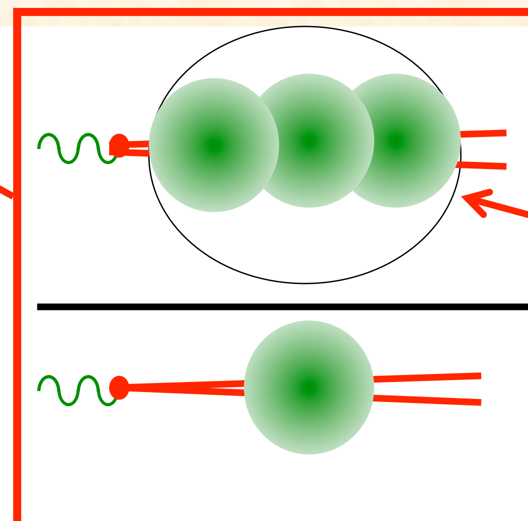
  Will the suppression/shadowing continue to fall as x decreases?

Role of color for nuclear force?



Color localized Inside nucleons





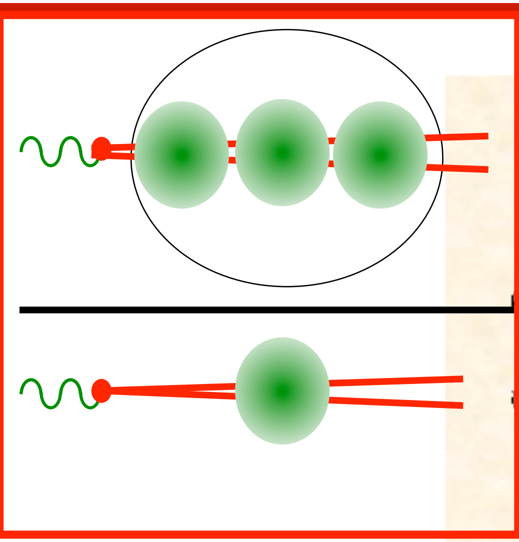
Color leaks outside nucleons Soft gluon radius is larger

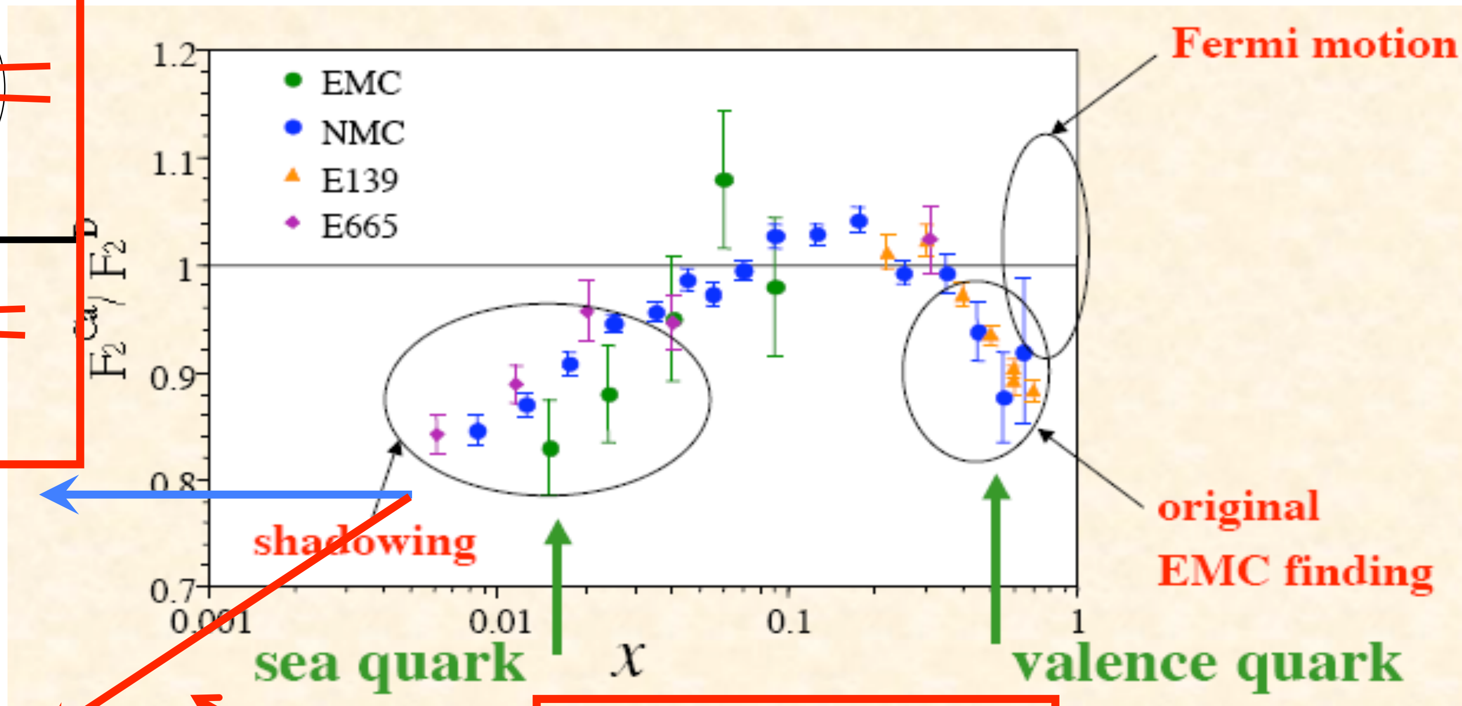
❑ A simple question:

Will the suppression/shadowing continue to fall as x decreases?

Jefferson Lab

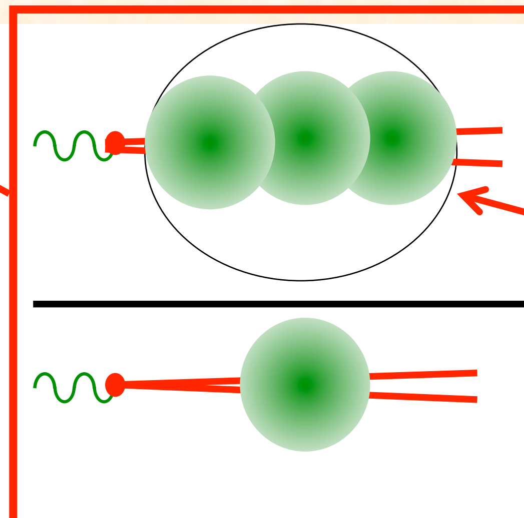
Role of color for nuclear force?





Color localized Inside nucleons

Nucleus as a bigger proton



Color leaks outside nucleons Soft gluon radius is larger

❑ A simple question:

Will the suppression/shadowing continue to fall as x decreases?

Jefferson Lab

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!

Jefferson Lab