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

Jianwei Qiu  
Theory Center, Jefferson Lab  
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Eternal Questions

People have long asked

Where did we come from?
The Big Bang theory?

What is the world made of?
Basic building blocks?

What holds it together?
Fundamental forces?

Where are we going to?
The future?

The Role of 21st Century Nuclear Science in addressing all these questions?
Eternal Questions

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The future?

2015 Long-Range Plan: Probing nuclear matter in all its forms, and Exploring their potential for applications
Where did we come from?

History of the Universe

Can we go back in time or recreate the condition of early universe?
Going back in time?

Expansion of the universe

Little Bang in the Laboratory
Create a matter (QGP) with similar temperature and energy density

BNL - RHIC
CERN - LHC
Gold - Gold
Lead - Lead
Relativistic heavy-ion collisions – the little bang

A Virtual Journey of Visible Matter:

- Lorentz contraction
- Near collision
- Quark-gluon plasma
- Hadronization
- Freeze-out

“Seeing” the unseen

Visible!

Visible!
Relativistic heavy-ion collisions – the little bang

A Virtual Journey of Visible Matter:

- Lorentz contraction
- Near collision
- Quark-gluon plasma
- Hadronization
- Freeze-out

Where we are now

Discovery:
A nearly perfect quantum fluid (NOT a gas!) at 4 trillion degrees Celsius, Not, at $10^{-5}$ K like $^6$Li

Visible!

Visible!
Relativistic heavy-ion collisions – the little bang

A Virtual Journey of Visible Matter:

- Lorentz contraction
- Near collision
- Quark-gluon plasma
- Hadronization
- Freeze-out
- Seen in the detector

Visible!

Emergence of hadronic particles?

Where we are now

Structure of hadrons? = initial conditions of RHIC?

Visible!

QCD phase Diagram!
What the world is made of?

Human is only a tiny part of the universe.

Visible world

But, human is exploring the whole universe!
From atomic structure to quantum world, ...

- Atomic structure: dating back to Rutherford’s experiment:
  \[ \alpha + Au \rightarrow \alpha + X \]
  Over 100 years ago

  J.J. Thomson’s plum-pudding model

  Rutherford’s Experiment - Data

  Discovery: ✨ Tiny nucleus - less than 1 trillionth in volume of an atom
  ✨ Quantum probability - the Quantum World!

- Localized mass and charge centers – vast “open” space:

  Molecule:
  Crystal:
  Nanomaterial:

  Infinite opportunities to create & improve … !
From nuclear structure to QCD, ...

- A modern “Rutherford” experiment (about 50 years ago):
  - **Nucleon:** The building unit of all atomic nuclei
  - **Reaction:** $e + p \rightarrow e + X$
  - **Discovery:** 1968

- **Discovery of quarks!**

- **Discovery of Quantum Chromodynamics (QCD):**
  - **Nanometer:** atom $\sim 10^{-8}$ cm
  - **Femtometer:** nucleu $\sim 10^{-12}$ cm, proton (neutron) $\sim 10^{-13}$ cm, quark $< 10^{-16}$ cm
  - **Gluons**
  - **Fluctuation**
From nano-science to femto-science

- Force, distance, complexity, & application:

![Diagram showing the transition from nano-science to femto-science with a focus on cryo-electron microscopy.](image)

- Ensure the role of quantum physics.
From nano-science to femto-science

- Force, distance, complexity, & application:
  - Force, distance, complexity, & application:
    - From nano-science to femto-science
    - Force, distance, complexity, & application:
    - Femto-science (0.1-10 fm)

- QCD landscape of nucleon and nuclei?
  - QCD landscape of nucleon and nuclei?
  - Need a facility to be able to explore/see the structure and dynamics!
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?
What hold us together?

- Understanding the glue that binds us all – Next frontier of SM!

- Gluons are weird particles!
  - Massless, yet, responsible for nearly all visible mass
  - Carry color charge, unlike photon, responsible for color confinement
  - but, also for asymptotic freedom, as well as the abundance of glue!

Without gluons, there would be NO nucleons, NO atomic nuclei… NO visible world!
Unprecedented intellectual challenge!

- **Facts:**
  - Gluons are dark!
  - No modern detector has been able to see quarks and gluons in isolation!

- **The challenge:**
  - *How to probe the quark-gluon dynamics, quantify the hadron structure, study the emergence of hadrons, …, if we cannot see quarks and gluons?*

- **Answer to the challenge:**
  - **Theory advances:**
    - QCD factorization – matching the quarks/gluons to hadrons with controllable approximations!
  - **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, …*
    - Hadron “structure” – dynamical!
      - *No still picture of 3D structure!*
      - *Need hard probes with the sub-femtometer resolution!*
Hard probes from high energy collisions

- **Lepton-lepton collisions:**
  - No hadron in the initial-state
  - Hadrons are emerged from energy
  - Not ideal for studying hadron structure

- **Hadron-hadron collisions:**
  - Initial hadrons broken – collision effect, …
  - Hadron structure – motion of quarks, …
  - Emergence of hadrons, …

- **Lepton-hadron collisions:**
  - Hard collision without breaking the initial-state hadron – spatial imaging, …
Many complementary probes at one facility

The future “Rutherford” experiment:

\[ Q^2 \rightarrow \text{Measure of resolution} \]
\[ y \rightarrow \text{Measure of inelasticity} \]
\[ x \rightarrow \text{Measure of momentum fraction of the struck quark in a proton} \]

\[ Q^2 = S \times y \]

Inclusive events:  \( e+p/A \rightarrow e'+X \)
Detect only the scattered lepton in the detector
(Modern Rutherford experiment!)

Semi-Inclusive events:  \( e+p/A \rightarrow e'+h(\pi,K,p,jet)+X \)
Detect the scattered lepton in coincidence with identified hadrons/jets
(Initial hadron is broken – confined motion! – cleaner than h-h collisions)

Exclusive events:  \( e+p/A \rightarrow e' + p'/A' + h(\pi,K,p,jet) \)
Detect every things including scattered proton/nucleus (or its fragments)
(Initial hadron is NOT broken – tomography! – almost impossible for h-h collisions)
The Electron-Ion Collider (EIC)

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

\[ e + p \rightarrow \gamma^*, Z^0, \ldots \]

\[ 1/Q < 1/10 \text{ fm} \]

To see the non-linear dynamics of the glue!

- 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!
# EIC: the World Wide Interest

<table>
<thead>
<tr>
<th></th>
<th>HERA@DESY</th>
<th>LHeC@CERN</th>
<th>eRHIC@BNL</th>
<th>JLEIC@JLab</th>
<th>HIAF@CAS</th>
<th>ENC@GSI</th>
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<tbody>
<tr>
<td><strong>$E_{CM}$ (GeV)</strong></td>
<td>320</td>
<td>800-1300</td>
<td>45-175</td>
<td>12-140</td>
<td>12 → 65</td>
<td>14</td>
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<td>proton $x_{\text{min}}$</td>
<td>1 x 10$^{-5}$</td>
<td>5 x 10$^{-7}$</td>
<td>3 x 10$^{-5}$</td>
<td>5 x 10$^{-5}$</td>
<td>7 x 10$^{-3}$ → 3 x 10$^{-4}$</td>
<td>5 x 10$^{-3}$</td>
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<tr>
<td>ion</td>
<td>p</td>
<td>p to Pb</td>
<td>p to U</td>
<td>p to Pb</td>
<td>p to U</td>
<td>p to ~ 40Ca</td>
</tr>
<tr>
<td>polarization</td>
<td>-</td>
<td>-</td>
<td>p, $^3$He</td>
<td>p, d, $^3$He ($^6$Li)</td>
<td>p, d, $^3$He</td>
<td>p,d</td>
</tr>
<tr>
<td><strong>$L$ [cm$^2$ s$^{-1}$]</strong></td>
<td>2 x 10$^{31}$</td>
<td>10$^{33}$</td>
<td>10$^{33-34}$</td>
<td>10$^{33-34}$</td>
<td>10$^{32-33}$ → 10$^{35}$</td>
<td>10$^{32}$</td>
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<tr>
<td>IP</td>
<td>2</td>
<td>1</td>
<td>2+</td>
<td>2+</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Year</td>
<td>1992-2007</td>
<td>2022 (?)</td>
<td>2022</td>
<td>Post-12 GeV</td>
<td>2019 → 2030</td>
<td>upgrade to FAIR</td>
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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
U.S.-based Electron-Ion Collider

- **NSAC 2007 Long-Range Plan:**
  
  “An Electron-Ion Collider (EIC) with polarized beams has been embraced by the U.S. nuclear science community as embodying the vision for reaching the next QCD frontier.”

- **NSAC Facilities Subcommittee (2013):**
  
  “The Subcommittee ranks an EIC as Absolutely Central in its ability to contribute to world-leading science in the next decade.”

- **NSAC 2015 Long-Range Plan:**
  
  “We recommend a high-energy high-luminosity polarized EIC as the highest priority for new facility construction following the completion of FRIB.”

- **Under review of National Academy of Science:**
  
  Expect to have the committee report early next year!
Why US-EIC can do what HERA can’t 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!*

\[
\sigma(Q, \vec{s}) \propto \langle p, \vec{s} \rangle \langle k \rangle \quad t \sim 1/Q
\]

\[
\sigma(s) - \sigma(-s) \quad \text{Quantum interference} \quad T^{(3)}(x, x) \propto
\]

- **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” – Atomic weight of nuclei*
What can a US EIC do?

Major Nuclear Science issues to be studied at an EIC or “Big” questions/puzzles about QCD, …

The key Deliverables & Opportunities

Why existing facilities, even with upgrades, cannot do the same?

Due to the time, only a few examples to be presented in this talk!
Emergence of hadrons from quarks & gluons

- Femtometer sized detector:
  - Control of $\nu$ and medium length!

- Heavy quark energy loss:
  - Mass dependence of fragmentation

Need the collider energy of EIC and its control on parton kinematics
Hadron properties: mass, spin, ...

- **Mass – intrinsic to a particle:**
  - Definition: Energy of the particle when it is at the rest
  - Quantum Chromodynamics (QCD) energy-momentum tensor in terms of quarks and gluons:
    \[ T^{\mu\nu} = \frac{1}{2} \bar{\psi} i \gamma^{(\mu} \gamma^{\nu)} \psi + \frac{1}{4} g^{\mu\nu} F^2 - F^{\mu\alpha} F^{\nu}_{\alpha} \]
  - Proton mass:
    \[ m = \frac{\langle p \rangle \int d^3x \, T^{00} \, |p\rangle}{\langle p | p \rangle} \sim \text{GeV} \]

- **Spin – intrinsic to a particle:**
  - Definition: Angular momentum of the particle when it is at the rest
  - QCD angular momentum density in terms of energy-momentum tensor:
    \[ M^{\alpha\mu\nu} = T^{\alpha\mu} x^{\nu} - T^{\alpha\mu} x^{\nu} \]
    \[ J^i = \frac{1}{2} \epsilon^{ijk} \int d^3x M^{0jk} \]
  - Proton spin:
    \[ S(\mu) = \sum \langle P, S | \hat{J}^{\hat{i}}(\mu) | P, S \rangle = \frac{1}{2} \]

*If we do not understand proton mass & spin, we do not understand QCD!*
The Proton Mass?

How does QCD generate the nucleon mass?

“… The vast majority of the nucleon’s mass is due to quantum fluctuations of quark-antiquark pairs, the gluons, and the energy associated with quarks moving around at close to the speed of light. …” — The 2015 Long Range Plan for Nuclear Science

Higgs mechanism is not relevant to hadron mass!

“Mass without mass!”

Higgs mechanism

Dynamics of gluons

Quarks

Mass \( \approx 1.78 \times 10^{-26} \text{ g} \)

\(~ 1\% \) of proton mass

Proton

Mass \( \approx 168 \times 10^{-26} \text{ g} \)

\(~ 99\% \) of proton mass
The Proton Mass?

- Hadron mass from Lattice QCD calculation:

How does QCD generate this? The role of quarks vs that of gluons?
The Proton Mass?

- **Role of quarks and gluons?**
  - Trace of the QCD energy-momentum tensor: \[ T^\alpha_\alpha = \frac{\beta(g)}{2g} F^{\mu\nu,a} F^a_{\mu\nu} + \sum_{q=u,d,s} m_q (1 + \gamma_m) \bar{\psi}_q \psi_q \]
    - QCD trace anomaly
    - Chiral symmetry breaking
  - Mass, trace anomaly, chiral symmetry break, and …
    \[ m^2 \propto \langle p | T^\alpha_\alpha | p \rangle \quad \Rightarrow \quad \frac{\beta(g)}{2g} \langle p | F^2 | p \rangle \quad \text{at chiral limit!} \]
  - Heavy quarkonium production near the threshold, from JLab12 to EIC

- **Decomposition or sum rules – could be frame dependent!**
  \[ M_p = \frac{\langle P | \int d^3 x T^{00} | P \rangle}{\langle P | P \rangle} \bigg|_{\text{at rest}} = E_q + E_g + \chi m_q + T_g \]
  - This is useful if only if individual terms can be measured independently
The Proton Mass?

- Three-pronged approach to explore the origin of hadron mass
  - Lattice QCD
  - Mass decomposition – roles of the constituents
  - Model calculation – approximated analytical approach

The Proton Mass
At the heart of most visible matter.
Temple University, March 28-29, 2016

http://www.ectstar.eu/node/2218

https://phys.cst.temple.edu/meziani/proton-mass-workshop-2016/
How does QCD generate the nucleon’s spin?

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

- **Proton Spin**
- **Quark helicity**
  - Best known
  - \[ \frac{1}{2} \int dx (\Delta u + \Delta \bar{u} + \Delta d + \Delta \bar{d} + \Delta s + \Delta \bar{s}) \]
  - \( \sim 30\% \)
- **Spin “puzzle”**
- **Gluon helicity**
  - Start to know
  - \[ \Delta G = \int dx \Delta g(x) \]
  - \( \sim 20\% \) (with RHIC data)
- **Orbital Angular Momentum of quarks and gluons**
  - Little known
The Proton Spin?

How does QCD generate the nucleon’s spin?

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

What can JLab12 and EIC do?

Plus many more JLab12 experiments – flavor
How does QCD generate the nucleon’s spin?

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

To understand the proton spin, fully, we need to understand the distribution and confined motion of quarks and gluons inside the proton in QCD, encoded in GPDs, TMDs, GTMDs, …

Need new “probes” with two distinctive momentum scales!

Hard scale – to “see” the particle nature of quarks and gluons
Soft scale – to “be” sensitive to the QCD confinement ~ 1/fm ~ 200 MeV
3D confined motion and spatial distribution

- **3D boosted partonic structure:**
  - **Momentum Space**
  - **TMDs**
  - **Confined motion**
  - \( \int d^2 b_T \)
  - \( f(x, k_T) \) Two-scales observables
  - \( \int d^2 k_T \)
  - \( f(x, b_T) \)

**3D momentum space images**

\( Q >> P_T \sim k_T \)

**2+1D coordinate space images**

- **Exclusive DIS**
- \( Q >> |t| \sim 1/b_T \)

**JLab12 – valence quarks, EIC – sea quarks and gluons**
3D confined motion and spatial distribution

- **3D boosted partonic structure:**
  - **Momentum Space**
  - **Coordinate Space**
  - **TMDs**
  - **GPDs**

\[ f(x, k_T) \]

\[ \int d^2 b_T \]

\[ \int d^2 k_T \]

**Sivers Function**

**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:

- **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

Relation between charge radius, quark radius (x), and gluon radius (x)?
The origin 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 the color of nucleon “A” correlated with the 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 of color correlation?*
  
  How far does glue density spread?
  
  How fast does glue density fall?
  
  Imaging gluon density
  
  Only possible at EIC
A simple question:

Will the suppression/shadowing continue to fall as $x$ decreases?
Another HERA discovery

- Run away gluon density at small $x$?
  - What causes the low-$x$ rise?
    - gluon radiation
    - non-linear gluon interaction
  - What could tame the low-$x$ rise?
    - gluon recombination
    - non-linear gluon interaction

- QCD vs. QED:
  - **QCD – gluon in a proton:**
    $$ Q^2 \frac{d}{dQ^2} xG(x, Q^2) \approx \frac{\alpha_s N_c}{\pi} \int_x^1 \frac{dx'}{x'} x'G(x', Q^2) $$
    - At very small-$x$, proton is “black”, positronium is still transparent!
  - **QED – photon in a positronium:**
    $$ Q^2 \frac{d}{dQ^2} x\phi_\gamma(x, Q^2) \approx \frac{\alpha_{em}}{\pi} \left[ -\frac{2}{3} x\phi_\gamma(x, Q^2) + \int_x^1 \frac{dx'}{x'} x'[\phi_{e+}(x', Q^2) + \phi_{e-}(x', Q^2)] \right] $$
    - Recombination of large numbers of glue could lead to saturation phenomena
How to answer the “Big” questions?

- Run away gluon density at small x?
  - What causes the low-x rise?
    - gluon radiation
    - non-linear gluon interaction
  - What could tame the low-x rise?
    - gluon recombination
    - non-linear gluon interaction

- Particle vs. wave feature:
  - Gluon saturation – Color Glass Condensate
    - Radiation = Recombination

Leading to a collective gluonic system?
- with a universal property of QCD?
- new effective theory QCD – CGC?

Expectation: $x=10^{-5}$ in a proton at $Q^2=5$ GeV$^2$
Best signature for gluon saturation

**Diffractive cross section:**

\[ \sigma_{\text{diff}} \propto \left[ g(x, Q^2) \right]^2 \]

- *off a single hard, local interaction*

At HERA

ep: 10-15\% diffractive

At EIC eA, if Saturation/CGC

eA: 25-30\% diffractive

**Early work – E665 @ FNAL:**

Nuclear shadowing, diffractive scattering and low momentum protons in \( \mu \) Xe interactions at 490 GeV

\[ Z. \text{ Phys.} \ C 65, \ 225–244 \ (1995) \]
EIC – An International Effort

EIC Users Group – EICUG.ORG:

715 collaborators, 29 countries, 169 institutions... (September, 2017)

Map of institution’s locations
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 and nuclei with a resolution better than 1/10 fm

- **EIC** could study major Nuclear Science issues that other existing facilities, even with upgrades, cannot do

- **US-EIC** designs explore the polarization and intensity frontier, as well as the frontier of new accelerator/detector technology

- **US-EIC** is sitting at a sweet spot for rich QCD dynamics – capable of taking us to the next frontier of Nuclear Science!

Thanks!
Electroweak physics at EIC

Running of weak interaction – high luminosity:

- Fills in the region that has never been measured
- Have a real impact on testing the running of weak interaction
Emergence of Hadrons/Jets – A puzzle?

- **Emergence of hadrons:**
  - How do hadrons emerge from a created quark or gluon?
  - How is the color of quark or gluon neutralized?

- **Need a femtometer detector or “scope”:**
  - Nucleus, a laboratory for QCD
  - A “vertex” detector: Evolution of hadronization

- **Strong suppression of heavy flavors in AA collisions:**

![Graphs showing suppression of D^0 and D^+ mesons in Au+Au and Pb+Pb collisions](image_url)