Exploring the fundamental properties of matter with an Electron-Ion Collider

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Acknowledgement: Much of the physics presented here are based on the work of EIC White Paper Writing Committee put together by BNL and JLab managements, …
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?
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
- Seen in the detector

Discoveries – Properties of QGP:

- A nearly perfect quantum fluid – NOT a gas!
  at 4 trillion degrees Celsius, Not, at $10^{-5}$ K like $^{6}\text{Li}$

Questions:

- How the observed particles were emerged (after collision)?
- Does the initial condition matter (before collision)?
What the world is made of?

Human is only a tiny part of the universe!

But, human is exploring the whole universe!
What hold it together?

Science and technology:

Particle & Nuclear Physics

Nucleon:
Proton, or Neutron
Nucleon – building block of all atomic matter

- Our understanding of the nucleon evolves

- Nucleon is a strongly interacting, relativistic bound state of quarks and gluons

- Quantum Chromodynamics (QCD) bound states:
  - Neither quarks nor gluons appear in isolation!
  - Understanding such systems completely is still beyond the capability of the best minds in the world

- The great intellectual challenge:
  Probe nucleon structure without “seeing” quarks and gluons?
Why the EIC?

To understand the role of gluons in binding Quarks and Gluons into Nucleons and Nuclei

Outline of the rest of my talk

- 21st Century Nuclear Science
- “Big” questions/puzzles about QCD, …
- The Electron-Ion Collider
- Key deliverables & opportunities, …
- Summary
21st Century Nuclear Science

- What is the role of QCD in the evolution of the universe?
- How hadrons are emerged from quarks and gluons?
- How does QCD make up the properties of hadrons?
  Their mass, spin, magnetic moment, ...
- What is the QCD landscape of nucleon and nuclei?
  Color Confinement
  200 MeV (1 fm)
  Asymptotic freedom
  2 GeV (1/10 fm)
  Probing momentum
- How do the nuclear force arise from QCD?
- ...
The next QCD frontier

Understanding the glue that binds us all – the Next QCD Frontier!

Gluons are weird particles!

- Massless, yet, responsible for nearly all visible mass

“Mass without mass!”

Higgs mechanism

Quarks
Mass ≈ 1.78x10^{-26} g

Proton
Mass ≈ 1.68x10^{-26} g

~ 1% of proton mass

Dynamics of gluons

~ 99% of proton mass

Bhagwat & Tandy/Roberts et al
Gluons are weird particles!

- Massless, yet, responsible for nearly all visible mass
- Carry color charge, responsible for color confinement and strong force

Force between a heavy quark pair:

Heavy quarks experience a force of ~16 tons at ~1 Fermi ($10^{-15}$ m) distance
Gluons are weird particles!

- Massless, yet, responsible for nearly all visible mass
- Carry color charge, responsible for color confinement and strong force
- but, also for asymptotic freedom

QCD perturbation theory

Nobel Prize, 2004
The next QCD frontier

- Understanding the glue that binds us all – the Next QCD Frontier!

- Gluons are weird particles!
  - Massless, yet, responsible for nearly all visible mass
  - Carry color charge, responsible for color confinement and strong force
  - but, also for asymptotic freedom, as well as the abundance of glue
The next QCD frontier

- Understanding the glue that binds us all – the Next QCD Frontier!

- Gluons are wired particles!
  - Massless, yet, responsible for nearly all visible mass
  - Carry color charge, responsible for color confinement and strong force
  - 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!
How quarks and gluons are confined inside the hadrons – 3D structure?

- Can we develop analytical tools to connect hadron structure and properties at low energy to their parton descriptions at high energy?!

  Hadron mass, spin, confined parton motion, ...
  Proton radius: EM charge, quarks, gluons, ...
  Nuclear force from QCD, ...

- Can lattice QCD and EFT help?
“Big” questions/puzzles about QCD, ...

- How quarks and gluons are confined inside the hadrons – 3D structure?
  - Can we develop analytical tools to connect hadron structure and properties at low energy to their parton descriptions at high energy?!

  Hadron mass, spin, confined parton motion, ...
  Proton radius: EM charge, quarks, gluons, ...
  Nuclear force from QCD, ...

- Can lattice QCD and EFT help?

- How does the glue fill out hadron’s inner space – 3D glue distribution?
  - Can we develop better probes to go beyond the current accuracy?!

  Glue distribution in proton, and in ions,
  Color confinement radius, ...
  Initial condition for HI collision,
  The physics and role of the momentum “x”, ...

Glue tomography toward small-x

How far does glue density spread?
How fast does glue density fall?

Only possible at EIC
“Big” questions/puzzles about QCD, ...

- How hadrons are emerged from the color charge(s)?
  - Can we develop analytical tools to “see” the evolution of the color/jet and to predict the jet structure and the emergence of hadrons?!
  - Control of the partonic kinematics?
  - Hadronization mechanism?

- How to understand the family of hadrons?
  - Can we see gluonic excitations in hadron spectrum?
  - Can we understand the newly observed hadronic particles, XYZ, ...?
  - XYZ particles at future ep + eA, ...
  - Not covered here!
Electron-Ion Collider (EIC)

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

- A sharpest “CT” – “imagine” quark/gluon without breaking the hadron
  - “cat-scan” the nucleon and nuclei with better than 1/10 fm resolution
  - “see” the proton “radius” of gluon density

- Why now?
  Exp: advances in luminosity, energy reach, detection capability, ...
  Thy: breakthrough in factorization – “see” confined quarks and gluons, ...

“see” the non-linear dynamics of the glue!
Many complementary probes at one facility

- **Lepton-hadron facility:**

  - **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

  - **Semi-Inclusive events:** \( e + p/A \rightarrow e^' + h(\pi, K, p, \text{jet}) + X \)
    - Detect the scattered lepton in coincidence with identified hadrons/jets

  - **Exclusive events:** \( e + p/A \rightarrow e^' + p'/A' + h(\pi, K, p, \text{jet}) \)
    - Detect every things including scattered proton/nucleus (or its fragments)
# 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>$E_{\text{CM}}$ (GeV)</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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<tr>
<td>proton $x_{\text{min}}$</td>
<td>$1 \times 10^{-5}$</td>
<td>$5 \times 10^{-7}$</td>
<td>$3 \times 10^{-5}$</td>
<td>$5 \times 10^{-5}$</td>
<td>$7 \times 10^{-3} \rightarrow 3 \times 10^{-4}$</td>
<td>$5 \times 10^{-3}$</td>
</tr>
<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 $^{40}$Ca</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>$L$ [cm$^{2}$ s$^{-1}$]</td>
<td>$2 \times 10^{31}$</td>
<td>$10^{33}$</td>
<td>$10^{33-34}$</td>
<td>$10^{33-34}$</td>
<td>$10^{32-33} \rightarrow 10^{35}$</td>
<td>$10^{32}$</td>
</tr>
<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 – Kinematic reach & properties

For e-N collisions at the EIC:
✓ Polarized beams: e, p, d/\(^3\)He
✓ Variable center of mass energy
✓ Wide Q\(^2\) range → evolution
✓ Wide x range → spanning from valence to low-x physics
✓ 100-1K times of HERA Luminosity

For e-A collisions at the EIC:
✓ Wide range in nuclei
✓ Variable center of mass energy
✓ Wide Q\(^2\) range (evolution)
✓ Wide x region (high gluon densities)
US EIC – Kinematic reach & properties

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✓ Wide x region (high gluon densities)

EIC explores the “sea” and the “glue”, the “valence” with a huge level arm
The key deliverables & opportunities

Why existing facilities, even with upgrades, cannot do the same?
“Big” questions to be answered, …

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. …”

REACHING FOR THE HORIZON
The 2015 Long Range Plan for Nuclear Science

Hadron mass from Lattice QCD calculation:
“Big” questions to be answered, …

- **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. …”

**REACHING FOR THE HORIZON**

*The 2015 Long Range Plan for Nuclear Science*

- **Role of quarks and gluons?**

  ✧ **QCD energy-momentum tensor:**
  
  \[ T_{\mu\nu} = \frac{1}{2} \overline{\psi} i \mathcal{D}^{(\mu} \gamma^{\nu)} \psi + \frac{1}{4} g^{\mu\nu} F^2 - F^{\mu\alpha} F^{\nu}_\alpha \]

  ✧ **Trace of the QCD energy-momentum tensor:**
  
  \[ T^\alpha = \frac{\beta(g)}{2g} F^{\mu\nu,a} F_{\mu\nu}^a + \sum_{q=u,d,s} m_q (1 + \gamma_m) \overline{\psi}_q \psi_q \]

  **QCD trace anomaly**
  
  \[ \beta(g) = -(11 - 2n_f/3) g^3/(4\pi)^2 + \ldots \]

  ✧ **Mass, trace anomaly, chiral symmetry break, and …**

  \[ m^2 \propto \langle p \mid T^\alpha \mid p \rangle \quad \rightarrow \quad \frac{\beta(g)}{2g} \langle p \mid F^2 \mid p \rangle \]

  **quarkonium production near the threshold, from JLab12 to EIC**
“Big” questions to be answered, ...

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

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
Nov. 27 – Dec. 1, 2017
Z.-E. Meziani, B. Pasquini, J.-W. Qiu, M. Vanderhaeghen
“Big” questions to be answered, …

How does QCD generate the nucleon’s spin?

\[
\frac{1}{2} = \frac{1}{2} \Delta \Sigma + \Delta G + (L_q + L_g) = \sum \langle P, S | \hat{J}_z (\mu) | P, S \rangle
\]

Proton Spin

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\%

Spin “puzzle”

Gluon helicity
Start to know

\[
\Delta G = \int dx \Delta g(x)
\]

\sim 20\%(\text{with RHIC data})

Orbital Angular Momentum of quarks and gluons
Little known
“Big” questions to be answered, …

- How does QCD generate the nucleon’s spin?

\[
\frac{1}{2} = \frac{1}{2} \Delta \Sigma + \Delta G + (L_q + L_g) = \sum \langle P, S | \hat{J}_f^z (\mu) | P, S \rangle
\]

Proton Spin

- What can EIC do?

To understand the proton spin, fully, we need to understand the confined motion of quarks and gluons in QCD

Need “probes” for two-scale observables!

TMDs, GTMDs, …
“Big” questions to be answered, ...

- **3D boosted partonic structure:**

  - **Momentum Space**
  - **TMDs**
  - **Confined motion**

  \[ \int d^2b_T \quad f(x,k_T) \]

  \[ \int d^2k_T \quad f(x,b_T) \]

  - **Coordinate Space**
  - **GPDs**
  - **Spatial distribution**

  **Two-scales observables**

- **3D momentum space images**

  \( Q >> P_T \sim k_T \)

- **2+1D coordinate space images**

  \( Q >> |t| \sim 1/b_T \)

  - **Exclusive DIS**
  - **Semi-inclusive DIS**

  **JLab12 – valence quarks, EIC – sea quarks and gluons**
“Big” questions to be answered, ...

- 3D boosted partonic structure:

  - Momentum Space
  - Coordinate Space
  - TMDs
  - GPDs

\[
\int d^2b_T f(x,b_T) \quad \text{EIC white paper: arXiv:1212.1701} \quad \int d^2k_T f(x,k_T)
\]

Sivers Function

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

Spatial density distributions – “radius”
“Big” questions to be answered, …

- **3D boosted partonic structure:**

  \[
  \int d^2 b_T \quad \text{Momentum Space} \quad \text{TMDs}
  \]

  \[
  \int d^2 k_T \quad \text{Coordinate Space} \quad \text{GPDs}
  \]

  \[
  f(x, k_T) \quad \text{EIC white paper: arXiv:1212.1701} \quad f(x, b_T) \quad \text{Imaging}
  \]

  **Sivers Function**

  **Position** $r \times$ **Momentum** $p \rightarrow$ **Orbital Motion of Partons**
“Big” questions to be answered, …

- **3D boosted partonic structure:**
  
  ![Diagram of partonic structure with Momentum Space and Coordinate Space](image)

  - **TMDs**: $\int d^2b_T f(x,k_T)$
  - **GPDs**: $\int d^2k_T f(x,b_T)$

  - **Quarks**: Distribution of quarks
  - **Gluons**: From EIC white paper: arXiv:1212.1701

  **Transverse momentum, $k_T$ (GeV)**
  **Transverse distance from center, $b_T$ (fm)**

  **Role of momentum fraction - “x”, and nature of pion cloud?**
Nuclear landscape, ...

History:

Electromagnetic
Elastic electron-nucleus scattering $\rightarrow$ charge distribution of nuclei

Present/Near-future:

Electroweak
Parity-violating elastic electron-nucleus scattering (or hadronic reactions e.g. at FRIB) $\rightarrow$

Future: at the EIC:

Color dipole
$\phi$ Production in coherent electron-nucleus scattering $\rightarrow$ gluon spatial distribution in nuclei
Nuclear landscape, ... 

**History:**
Electromagnetic
Elastic electron-nucleus scattering → charge distribution of nuclei

**Present/Near-future:**
Electroweak
Parity-violating elastic electron-nucleus scattering (or hadronic reactions *e.g.* at FRIB) → neutron skin

**Future: at the EIC:**
Color dipole
ψ Production in coherent electron-nucleus scattering → gluon spatial distribution in nuclei

Fourier transform gives unprecedented info on gluon spatial distribution, including impact of gluon saturation

Provide important information for the initial conditions in Nucleus-Nucleus Collisions
Color fluctuation – azimuthal asymmetry at EIC

Preliminary low energy data:

Any distribution seen in Carbon should be washed out in heavier nuclei

Surprise:

Azimuthal asymmetry in transverse momentum broadening

Fluctuation and $v_n$ at EIC!
Color fluctuation – azimuthal asymmetry at EIC

- Preliminary low energy data:

- Classical expectation:
  Any distribution seen in Carbon should be washed out in heavier nuclei

- Surprise:
  Azimuthal asymmetry in transverse momentum broadening

\[ \langle p_T^2(\phi) \rangle_A = \int dp_T^2 dp_T^2 \frac{d\sigma_{eA}}{dx_B dQ^2 dp_T d\phi} \]

\[ \langle \Delta p_T^2(\phi) \rangle_{AN} = \langle p_T^2(\phi) \rangle_A - \langle p_T^2(\phi) \rangle_N \]

- Fluctuation and \( v_n \) at EIC!
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:**
“Big” questions to be answered, …

- Emergence of a hadron?

- Heavy quark energy loss:
  - Mass dependence of fragmentation

\[
\nu = \frac{Q^2}{2mx}
\]

Need the collider energy of EIC and its control on parton kinematics
“Big” questions to be answered, …

- Run away gluon density at small $x$?

  What causes the low-$x$ rise?
  - gluon radiation
    - non-linear gluon interaction

  What tames the low-$x$ rise?
  - gluon recombination
    - non-linear gluon interaction

- QCD vs. QED:

  **QCD – gluon in a proton:**
  \[ Q^2 \frac{d}{dQ^2} x G(x, Q^2) \approx \frac{\alpha_s N_c}{\pi} \int_x^1 \frac{dx'}{x'} x' G(x', Q^2) \]

  At very small-$x$, proton is “black”, positronium is still transparent!

  **QED – photon in a positronium:**
  \[ Q^2 \frac{d}{dQ^2} x \phi_\gamma(x, Q^2) \approx \frac{\alpha_{em}}{\pi} \left[ -\frac{2}{3} x \phi_\gamma(x, Q^2) \right. \]

  \[ + \left. \int_x^{-1} \frac{dx'}{x'} x' \left[ \phi_{e^+}(x', Q^2) + \phi_{e^-}(x', Q^2) \right] \right] \]

  Recombination of large numbers of glue could lead to saturation phenomena
“Big” questions to be answered, ...

- Run away gluon density at small $x$?
  - What causes the low-$x$ rise?
    - gluon radiation
    - non-linear gluon interaction
  - What tames 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?
An “easiest” measurement at EIC

Ratio of $F_2$: EMC effect, Shadowing and Saturation:

Color localized inside nucleons
An “easiest” measurement at EIC

- **Ratio of $F_2$: EMC effect, Shadowing and Saturation:**

  - Will the suppression/shadowing continue fall as $x$ decreases?
  - Could nucleus behaves as a large proton at small-$x$?

  - Range of color correlation – could impact the center of neutron stars!

- **Questions:**

**Color localized inside nucleons**

**Color leaks outside nucleons**

**Fermi motion**

**original EMC finding**

**sea quark**

**valence quark**
An “easiest” measurement at EIC

- **Ratio of $F_2$:** EMC effect, Shadowing and Saturation:
  
  - **Color localized inside nucleons**
  
  - Saturation in $RF_2^A$  
    - No saturation in $F_2^A$
  
  - **Color leaks outside nucleons**

- **Questions:**
  
  Will the suppression/shadowing continue fall as $x$ decreases?  
  Could nucleus behaves as a large proton at small-$x$?  
  *Range of color correlation – could impact the center of neutron stars!*
An “easiest” measurement at EIC

- Ratio of $F_2$: EMC effect, Shadowing and Saturation:

- Questions:
  - Will the suppression/shadowing continue fall as $x$ decreases?
  - Could nucleus behaves as a large proton at small-$x$?
  - Range of color correlation – could impact the center of neutron stars!
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 designs explore the polarization and intensity frontier, as well as the frontier of new accelerator/detector technology

EIC@US is sitting at a sweet spot for rich QCD dynamics – capable of taking us to the next QCD frontier

Thanks!
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.

The Subcommittee ranks an EIC as Absolutely Central in its ability to contribute to world-leading science in the next decade.

We recommend a high-energy high-luminosity polarized EIC as the highest priority for new facility construction following the completion of FRIB.

EIC User Group Meetings:
Stony Brook University, NY – June 24-27, 2014
UC at Berkeley, CA – January 6-9, 2016
Argonne National Lab, IL – July 7-10, 2016
US EIC – Physics vs. Luminosity & Energies

- Tomography (p/A) Transverse Momentum Distribution and Spatial Imaging
- Spin and Flavor Structure of the Nucleon and Nuclei
- Parton Distributions in Nuclei
- QCD at Extreme Parton Densities - Saturation

Luminosity (cm$^{-2}$ sec$^{-1}$)

$\sqrt{S}$ (GeV)
An immediate consequence

- Quark GPDs and its orbital contribution to proton’s spin:

\[ J_q = \frac{1}{2} \lim_{t \to 0} \int dx \, x \left[ H_q(x, \xi, t) + E_q(x, \xi, t) \right] = \frac{1}{2} \Delta q + L_q \]

The first meaningful constraint on quark orbital contribution to proton spin by combining the sea from the EIC and valence region from JLab 12

This could be checked by Lattice QCD

\[ L_u + L_d \sim 0? \]
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
Why 3D nucleon structure?

- Rutherford’s experiment – atomic structure (100 years ago):
  - Atom:
  - J.J. Thomson’s plum-pudding model
  - Rutherford’s planetary model
  - Modern model Quantum orbitals

- Completely changed our “view” of the visible world:
  - Mass by “tiny” nuclei – less than 1 trillionth in volume of an atom
  - Motion by quantum probability – the quantum world!

- Provided infinite opportunities to improve things around us:
  - Gas, Liquid, Solid, Nano materials, Quantum computing, ...