Overview of EIC Physics Goals

Jianwei Qiu
Theory Center, Jefferson Lab

WG7: Future of DIS at DIS 2018, April 17, 2018

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 we have been asking ...

- Where did we come from?

  How did hadrons are emerged from the energy, the quarks and gluons?

- What are we made of?

  What is the internal structure and dynamics of hadrons?

- What holds us together?

  How does the glue bind us all?

Goals of EIC: to help search for answers of these questions in various stages!
Going back in time?

- Relativistic heavy-ion collisions - RHIC:
  - Lorentz contraction
  - Near collision
  - Quark-gluon plasma
  - Hadronization
  - Freeze-out
  - Seen in the detector

Visible!

“Seeing” the unseen

A virtual journey of the visible matter!
A virtual journey of the visible matter

- Relativistic heavy-ion collisions - RHIC:

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

Visible! Visible!

Emergence of hadronic particles?

Where we are now

Structure of hadrons? = initial conditions of RHIC?
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!**

  - **Partonic Structure:**
    - Quantum “probabilities” \( \langle P, S | O(\bar{\psi}, \psi, A^\mu) | P, S \rangle \)

  *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, …
The challenge:

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

Answer to the challenge:

Theory advances:

QCD factorization

Experimental tools:

- 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, and “see” the gluons!
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:**
  - Hadron structure – motion of quarks, …
  - Emergence of hadrons, …
  - Initial hadrons broken – collision effect, …

- **Lepton-hadron collisions:**
  - Hard collision without breaking the initial-state hadron – spatial imaging, …
Why a lepton-hadron facility is special?

- Many complementary probes at one facility:
  
  **Inclusive events:** $e+p/A \rightarrow e'+X$
  
  Detect only the scattered lepton in the detector
  
  (Modern Rutherford experiment!)

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

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

**Measurements:**

- $Q^2 \rightarrow $ Measure of resolution
- $y \rightarrow $ Measure of inelasticity
- $x \rightarrow $ Measure of momentum fraction of the struck quark in a proton

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

\( e \rightarrow e^* \), \( \gamma^*, Z^0, \ldots \)
\( p \rightarrow p^* \)

To discover/study color entanglement of the non-linear dynamics of the glue!
# 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>$E_{CM}$ (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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<td>proton $x_{\min}$</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>
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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 $^{40}$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>
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<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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</table>

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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

BNL-eRHIC
JLab-JLEIC
US EIC – Luminosity & kinematics coverage

[Diagram showing luminosity and kinematics coverage with various experiments and measurements.]
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:
    Direct access to chromo-quantum interference!

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

- Emergence of hadrons
- Hadron properties:
  - mass, spin, ...
- Hadron’s 3D partonic structure:
  - confined motion, spatial distribution, color correlation, fluctuation, saturation, ...
- Quantum correlation between hadron properties and parton dynamics, ...

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

- Femtometer sized detector:

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

- Control of \( \nu \) and medium length!

- Mass dependence of hadronization

- Apply to heavy-ion collisions:

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

\[ T^{\mu\nu} = \frac{1}{2} \overline{\psi} i \mathcal{D}^{(\mu} \gamma^{\nu)} \psi + \frac{1}{4} g^{\mu\nu} F_{\alpha\beta}^{\alpha} F^{\nu\beta} \]

Proton mass:

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

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

\[ M^{\alpha\mu\nu} = T^{\alpha\nu} x^\mu - T^{\alpha\mu} x^\nu \]

Proton spin:

\[ S(\mu) = \sum_{q} \langle P, S \mid \hat{J}_z^q(\mu) \mid P, S \rangle = \frac{1}{2} \]

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:**

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

- Quark helicity
  - Best known
  - $\frac{1}{2} \int dx (\Delta u + \Delta \bar{u} + \Delta d + \Delta \bar{d} + \Delta s + \Delta \bar{s}) \sim 30\%$

- Gluon helicity
  - Start to know
  - $\Delta G = \int dx \Delta g(x) \sim 40\%$(with RHIC data)

- Orbital Angular Momentum of quarks and gluons
  - Little known

Net effect of partons’ transverse motion?

See H. Gao’s Plenary Talk

Jaffe-Manohar, 90
Ji, 96, …
The Proton Spin

- The power & precision of EIC:

$$g_1^p(x, Q^2) + C(x)$$

Reach out the glue:

$$\frac{dg_1(x, Q^2)}{d \ln Q^2} = \frac{\alpha_s}{2\pi} P_{qq} \otimes \Delta g(x, Q^2) + \cdots$$
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 – measurement of TMDs & GPDs!
Hadron’s 3D partonic structure

- Cross sections with two-momentum scales observed:
  \[ Q_1 \gg Q_2 \sim 1/R \sim \Lambda_{QCD} \]
  - **Hard scale:** \( Q_1 \) localizes the probe particle nature of quarks/gluons
  - **“Soft” scale:** \( Q_2 \) could be more sensitive to the structure, e.g., confined motion

- Two-scale observables at the EIC:
  - **Semi-inclusive DIS:** Parton’s confined motion encoded into TMDs
    - SIDIS: \( Q \gg P_T \)
  - **Exclusive DIS:** Parton’s spatial imaging from Fourier transform of GPDs’ t-dependence
    - DVCS: \( Q^2 \gg |t| \)
Theory is solid – unified description

- Wigner distributions in 5D (or GTMDs):

  \[ \int d^2b_T \quad \int d^2k_T \]

  \[ f(x,k_T) \quad f(x,b_T) \]

  Two-scales observables

- TMDs & SIDIS as an example:

  ⊳ **Low** \( P_{hT} (P_{hT} \ll Q) – TMD factorization:**

  \[
  \sigma_{SIDIS}(Q, P_{h\perp}, x_B, z_h) = \hat{H}(Q) \otimes \Phi_f(x, k_{\perp}) \otimes D_{f\rightarrow h}(z, p_{\perp}) \otimes S(k_{\perp}) + \mathcal{O}\left(\frac{P_{h\perp}}{Q}\right)
  \]

  ⊳ **High** \( P_{hT} (P_{hT} \sim Q) – Collinear factorization:**

  \[
  \sigma_{SIDIS}(Q, P_{h\perp}, x_B, z_h) = \hat{H}(Q, P_{h\perp}, \alpha_s) \otimes \phi_f \otimes D_{f\rightarrow h} + \mathcal{O}\left(\frac{1}{P_{h\perp}}, \frac{1}{Q}\right)
  \]

  ⊳ **\( P_{hT} \) Integrated - Collinear factorization:**

  \[
  \sigma_{SIDIS}(Q, x_B, z_h) = \hat{H}(Q, \alpha_s) \otimes \phi_f \otimes D_{f\rightarrow h} + \mathcal{O}\left(\frac{1}{Q}\right)
  \]

  ⊳ **Very high** \( P_{hT} \gg Q – Collinear factorization:**

  \[
  \sigma_{SIDIS}(Q, P_{h\perp}, x_B, z_h) = \sum_{abc} \hat{H}_{ab\rightarrow c} \otimes \phi_{\gamma\rightarrow a} \otimes \phi_b \otimes D_{c\rightarrow h} + \mathcal{O}\left(\frac{1}{Q}, \frac{Q}{P_{h\perp}}\right)
  \]
Confined motion of quarks & gluons

- Quantum correlation between hadron spin and parton motion:
  - Polarized hadron
  - Transversity
  - Sivers effect – Sivers function
  - Hadron spin influences parton’s transverse motion

- Quantum correlation between parton’s spin and its hadronization:
  - Collins effect – Collins function
  - Parton’s transverse polarization influences its hadronization

- TMDs and their separation at EIC:
Spatial imaging of quarks & gluons

- No color elastic nucleon form factor!
  - Spatial distribution of quark/gluon densities – GPDs

- DVCS at EIC:
  - Proton radius of quarks (x)!
    - Only possible at the EIC

- “Seeing” the glue at EIC:
  - Proton radius of gluons (x)!
    - Only possible at EIC!

Diagram:
- Graphs showing DVCS and GPDs with factorization and Proton 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 \((x)\)?
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

Color entanglement enhanced at small-x:

\[ \sigma_{\text{DIS tot}} = \sum_f \hat{C}_f \otimes \Phi_f + \mathcal{O} \left( \frac{Q_s^2}{Q^2} \right) + \mathcal{O} \left( \frac{Q_s^4}{Q^4} \right) + \ldots \]

Saturation:
Counting single parton is meaningless if every term is equally important!

Color Glass Condensate (CGC)
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

- **Color entanglement enhanced at small-x:**

- **Saturation:**
  - is a part of QCD!
  - Where to find it?
    - Expectation: $x=10^{-5}$ in a proton at $Q^2=5\text{ GeV}^2$
Can a large nucleus help!

- The hard probe at small-x is NOT localized:
  - Longitudinal probing size
  - > Lorentz contracted nucleon, if
  - \( \frac{1}{xp} > 2R_A \frac{m}{p} \) or \( x \lesssim 0.01 \)
  - Hard probe can “see” gluons from all nucleons at the same impact parameter, coherently!

- Help explore the nature of nuclear force!
  - If we only see quarks and gluons, ...
  - What does a nucleus look like? Does the color of “A” know the color of “B”?
    - ✧ NO → Observed nuclear effect is a coherent collision effect
    - ✧ YES → Nucleus could act like a bigger proton at small-x, and could reaching the saturation sooner!

EIC can tell!
A simple question:

Will the suppression/shadowing continue to fall as $x$ decreases?
US EIC – An International Effort

- **EIC Users Group – EICUG.ORG:**
  - 732 collaborators, 29 countries, (no students included yet!)
  - 169 institutions... (growing, ...)

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/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 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!
Backup slides
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 this year soon!
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

A true international effort!
The Proton Spin

- JLab 12GeV – upgrade project just completed:

12 GeV CEBAF Upgrade Project is just complete, and all 4-Halls are taking data

Plus many more JLab experiments, COMPASS, Fermilab-fixed target expts
Best signature for gluon saturation

- **Diffractive cross section:**

  \[
  \frac{1}{\sigma_{\text{tot}}^e A} \frac{d\sigma_{\text{diff}}^{eA}}{dM_x^2} \Bigg/ \frac{1}{\sigma_{\text{tot}}^{e p}} \frac{d\sigma_{\text{diff}}^{e p}}{dM_x^2} \sim \frac{25 - 30\%}{10 - 15\%} > 1
  \]

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

  - off a single hard, local interaction

  \[
  \frac{1}{\sigma_{\text{tot}}^e A} \frac{d\sigma_{\text{diff}}^{eA}}{dM_x^2} \Bigg/ \frac{1}{\sigma_{\text{tot}}^{e p}} \frac{d\sigma_{\text{diff}}^{e p}}{dM_x^2} \sim \left[ \frac{g^p(x)}{g^A(x)} \right]_{\text{tot}} \left[ \frac{g^A(x)}{g^p(x)} \right]_{\text{diff}}^2 < 1
  \]

  \[
  fLdt = 1 \text{ fb}^{-1}/A
  \]

  With Saturation

  Without Saturation

  Fraction of diffractive events in eAu over that in ep

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 \( \mu \text{ Xe} \) interactions at 490 GeV

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

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