Glimpse into the Vast EIC Science: “Exploring the glue that binds us all”

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on behalf of many ...

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Nuclei are responsible for almost all visible matter in the Universe.

We still strive to fully understand how quarks and gluons are arranged inside the nucleon and nuclei.

EIC will be like a powerful microscope to help us understand this further via nucleon “femtography”!
We never observe free quarks and gluons.
- Confined in nuclear matter by the strong force.
- Strong force acts on "colour" charge.
- Gluons are the carrier of the strong force.
- Extremely complex.
- Many aspects still not understood.
- EIC will transform our understanding of the force keeping our visible world together!

6 quark flavours
Each with different mass
and electrical charge.
Microcosm of the Nucleon

3 valence quarks
Proton = uud

• Everyday properties emerge from the nature of the strong interaction
  • mass (mass spectrometry in pharmaceutics)
  • spin (magnetic moment in MRI machines)

• We exploit these properties, but don’t fully understand them!

• We want to understand the nucleon structure and observed properties in terms of
  the quark/gluon dynamics
  • For this, we need the EIC

Sea of transient quark/antiquark pairs and gluons
Proton = uud + uū + d̅d + s̅s +…
A Deep Dive into Nuclear Matter

EIC will be a revolutionary tool for nuclear physics, to push the frontier in our knowledge of nuclear matter

Understand better the building blocks of our visible Universe

Unlock discoveries and technologies which may benefit other sciences/society

• Extensive scientific program which has been shaped by a wide international community, which is still growing!

• Example critical questions from the 2018 NAS Report (NAS Report (DOI 10.17226/25171):
  
  How does the mass of the nucleon arise?
  
  How does the spin of the nucleon arise?
  
  What are the emergent properties of dense system of gluons?
  
  How are quarks and gluons distributed inside nucleons and nuclei
World’s first polarised electron-proton/light ion and electron-nucleus collider

- Ranging from protons, light nuclei, up to uranium

- High-luminosities: $10^{33} - 10^{34}$ cm$^{-2}$s$^{-1}$; 10 - 100 fb$^{-1}$/year

- High spin polarised beams: 70%

- Large and variable centre of mass energy:
  - $20 < \sqrt{s} < 140$ GeV

- ePIC and beam line detectors to reconstruct all particles with high precision

☑️ State-of-the-art, multi-purpose facility
Deep Inelastic Scattering (DIS) - the Golden Process

- Electrons → electromagnetic interaction → unmatched precision
- World first opportunity for a dedicated e+A DIS program

\[ Q^2 = s \cdot x \cdot y \]

Q^2 = Resolution power
s = Centre-of-mass energy squared
x = Fraction of nucleon’s momentum that the struck quark carries (0 < x < 1)
y = Inelasticity

Vastly expanded landscape over resolution (Q^2) and quark/gluon density (1/x)

The only facility in the world which is uniquely designed to probe the ocean of gluons and sea quarks!
How do hadrons emerge? What’s the nature of confinement?

How do colour charged quarks, gluons and colourless jets interact with nuclear medium?

EIC \rightarrow \text{ideal place to compare jets of particles created in e+p vs e+A} 
- Range of nuclei to study how different nuclear mediums affect different quarks types

How does this influence nuclear binding?

Measuring nucleons knocked out from light nuclei will shed light on how protons and neutrons interact with each other inside nuclei

Access to heavy charm quarks will help pin down gluon contributions to nuclear modifications
Deep Dive into Unchartered Gluon Territory

- Previous 1D studies show an explosion of gluon density
- Does it saturate? When?
- Does this give rise to a new phase of matter in nucleons/nuclei?

- EIC will provide a large suite of measurements to study the onset of saturation - multi-faceted approach
- e.g. angular correlations in the production of di-jets in e+p vs e+A
- EIC ideal for this:
  - high energies, low reach in x, range of nuclei
  - $Q_S$ can be reached at lower energies with heavier nuclei

Gluons are self-interacting!

Splitting $\rightarrow$ Re-combining

$Q_S^2 \propto A^{1/3}$

Coverage of Saturation Region for $Q^2 > 1\text{ GeV}^2$

- $\sqrt{s_{\text{max}}}=90\text{ GeV}$, $y \leq 0.95$
- $\sqrt{s_{\text{max}}}=40\text{ GeV}$, $y \leq 0.95$

Coverage of Saturation Region for $Q^2 > 1\text{ GeV}^2$

- $Q_S^2(Ca)$
- $Q_S^2(Fe)$
- $Q_S^2(U)$
- $Q_S^2(Au)$
- $Q_S^2(Xe)$

EIC (eAu) $\sqrt{s_{\text{max}}}=90\text{ GeV}$
EIC (eAu) $\sqrt{s_{\text{max}}}=40\text{ GeV}$

$\Phi(x, k_T^2)$

$\sim 1/k_T$

Infinite Momentum Frame:
- BFKL (linear QCD): splitting functions $\rightarrow$ gluon density grows
- BK (non-linear): recombination of gluons $\rightarrow$ gluon density tamed

$\alpha_s \ll 1$

$\alpha_s \sim 1/\Lambda_{\text{QCD}}$

know how to do physics here?

Max. density $\sim 1/k_T$
How are the quarks/gluons distributed in space and momentum inside the nucleon?

- EIC will go beyond historical 1D picture to deliver a 3D imaging program:
  - collect “images” of position and momentum distributions for several x-slices (like in a CT)
  - build up multi-dimensional pictures

- Offers insights into properties like angular momentum, mass, and pressure inside the nucleon

- EIC will provide unrivalled precision in tomography, extending beyond the valence quark regime into sea quarks and gluons
Production of certain mesons in e+p at the EIC might give hints about confinement.

Gluons in the nucleon → only possible at the EIC.

A meson is a particle made from a qq pair.

Tomography of Gluons

Gluon spatial densities in proton for the first time!

- Production of certain mesons in e+p at the EIC e.g. J/Ψ (cc), will provide tomography of gluons in the nucleon.
- In e+A scattering, ions scatter
  - coherently (ion stays in tact)
  - incoherently (ion breaks apart)
- Mesons produced in coherent scattering of ions can probe the gluon spatial distribution of a nucleus
  - → might give hints about confinement
Nucleon Mass Enigma

• Mass - intrinsic property of a particle

• Gluons are massless

• Quark masses generated by Higgs ~1% nucleon mass!

• Nucleon is unexpectedly heavy

• Large coupling between u/d valence quarks and gluons
  • valence quarks in nucleon are surrounded by sea quarks (q̅q) and gluons

• ~99% of nucleon’s mass is due to quantum fluctuations of q̅q pairs, gluons, and energy associated with quarks moving close to speed of light within it
• Pion ($u\bar{d}$) and kaon ($u\bar{s}$) mesons appear unexpectedly light
• Gluon contents are expected to be different within pions, kaons and nucleon
• What can this tell us? We need more data!

• EIC will compare inner compositions of pions and kaons with the nucleon to shed light on mass enigma

• Heavier mesons will also be measured
  • e.g. $J/\Psi$ ($c\bar{c}$), $\Upsilon$ ($b\bar{b}$)
  • These mesons interact primarily with gluons in the nucleon

• Tomography of $J/\Psi$ and $\Upsilon$ can be related to distribution of mass inside nucleon

EIC will get comparable data for pions/kaons compared to the proton
Nucleon Spin Puzzle

- Inherent property of a particle (like mass or electrical charge)
- Allows a particle to behave like a tiny magnet (e.g., hydrogen nuclei in MRI)

- Either integer or half integer, and aligned ↑ or anti-aligned ↓
- Proton spin appears as 1/2 - spins of its components should sum to this

- Only a small fraction is carried by valence quarks

- How does the nucleon’s spin originate from quarks and gluons, and their interactions?

For proton with 3 valence quarks, is it

\[ \uparrow = \uparrow + \uparrow + \downarrow? \]

What about the sea?

\[ \frac{1}{2} = \frac{1}{2} \Delta \Sigma + \Delta G + \left( \sum L^z_q + L^z_g \right) \]

We need to pin down:
- Gluon spin
- Orbital angular momentum
- Improve existing quark spin measurements
EIC:
- Unprecedented DIS program with spin polarised beams
- High precision mapping of different spin contributions across vast landscape
- Unchartered territory of high gluon densities
- Pioneering measurements of gluon contributions

EIC can align the spins of the beams to enable measurements like this for protons and light nuclei (i.e. neutrons)!

- Measurements of cross-section differences according to spin alignment
- Tomography will also offer new insights on:
  - Quark flavour contributions
  - Angular momentum
Summary

• Nuclear matter (what we are made of!) is governed by gluons and the **dynamics** of the strong interaction

• EIC will delve deep into the building blocks of our visible Universe to revolutionise our understanding of the nucleon, nuclei and the strong interaction

• The EIC will be one of the world’s most sophisticated particle accelerators and use the cutting edge ePIC detector
• Its instrumentation is designed to realise this exciting science

• Specific physics topics include
  - Origins of mass and spin
  - Nucleon and nuclei tomography
  - Dense systems of gluons in the nucleon/nuclei
  - More…

• EIC will push the frontiers of nuclear science unlike anything before!
Thank you for your attention
The physics case has been developed for >20 years and is still growing - these slides drew from a breadth of resources generated by numerous colleagues of EIC community

This includes: previous slides from M. Żurek (ANL), R. Ent (JLab), E.C. Aschenauer (BNL)

Images and studies showcasing the science have been taken from the reports below

EIC-related images are from BNL

White Paper
arXiv:1212.1701 [nucl-ex]

NAS Report
DOI 10.17226/25171

Yellow Report
arXiv:2103.05419v2 [physics.ins-det]

NSAC LRP
EIC - Reaching the next QCD Frontier
Back Up Slides Follow
Fundamental Questions at the EIC

How are partons distributed inside the nucleon?

How do the nucleon’s mass and spin emerge from quarks and gluons and their dynamics?

How do colour charged quarks, gluons and colourless jets interact with the nuclear medium?

How do colourless hadrons emerge and what’s the nature of confinement?

How do quark-gluon interactions create nuclear binding?

How does a dense nuclear environment affect the dynamics of quarks and gluons and their interactions?

What happens to gluon density in nuclei? Does it saturate? When? Does this yield a new phase of matter with universal properties in nuclei and the nucleon?

And more (e.g. electroweak and beyond standard model)

EIC physics case has evolved over the last 20 years and still growing
Tools to Unlock a Vast Scope of Physics

**Neutral Current Inclusive**

\[ e + X \rightarrow e' + X \]

**Charged current inclusive**

\[ e + X \rightarrow e' + W \]

**Semi-inclusive**

\[ p + X \rightarrow h, \ldots \]

**Exclusive**

\[ p + X \rightarrow h', \gamma \]

**Jets**

\[ j + j' \]

Many complimentary probes ...

**Neutral Current**

- Inclusive

**Charged current**

- Inclusive

**Transverse Momentum**

- Distribution and Spatial Imaging

**Spin and Flavor Structure of the Nucleons and Nuclei**

**QCD at Extreme Parton Densities - Saturation**

**Internal Landscape of Nuclei**

**Tomography (p/A)**

\[ \text{Luminosity (cm}^{-2} \text{s}^{-1}) \]

\[ \text{Annual Integrated Luminosity (fb}^{-1}) \]

\[ \text{Center-of-Mass Energy [GeV]} \]

\[ x: \text{longitudinal momentum fraction carried by struck parton} \]

\[ b_T: \text{transverse position, a.k.a. impact parameter} \]
Different Facilities

Long range plan

$CJ15\text{nlo}$

$Q^2 = 10 \text{ GeV}^2$

Proton PDF

$\text{g}$

$\text{u}$

$\bar{d} - \bar{u}$

$d$

$(\bar{d} + \bar{u})/2$

$(s + c + b)/2$

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

$\text{EIC} (2030s-2040s)$

$\text{JLab12 (SolID)} (2020s-2030s)$

$\text{JLab12} (2010s-2020s)$

$\text{HERA}$

$\text{EMC}$

$\text{COMPASS} (2000s-2010s)$

$\text{Hermes} (1980s-2000s)$
Previous 1D studies show an explosion of gluons. What happens to them?

Does gluon density start to saturate? When?

Does this give rise to a new phase of matter with universal properties in the nucleon and nuclei?
• EIC will provide a large suite of measurements to study the onset of saturation - multi-faceted approach

• EIC is ideal place for this due to its high energies, low reach in x, and its range of nuclei

• Saturation scale $Q_S$ can be reached at lower energies with heavier nuclei

• e.g. angular correlations in the production of di-jets in $e+p$ vs $e+A$
Different combinations of quark flavours define hadron properties
E.g. mass, charge, spin
# The Universe’s Lego Bricks

<table>
<thead>
<tr>
<th>QUARKS</th>
<th>LEPTONS</th>
<th>SCALAR BOSONS</th>
<th>GAUGE BOSONS</th>
</tr>
</thead>
<tbody>
<tr>
<td>up (u)</td>
<td>electron (e)</td>
<td>Z</td>
<td>W boson</td>
</tr>
<tr>
<td>charm (c)</td>
<td>muon (\mu)</td>
<td>Z</td>
<td></td>
</tr>
</tbody>
</table>
Nucleon 1D Picture

Gluons

Sea quarks

White Paper

HERA
$Q^2 = 10 \, \text{GeV}^2$

Valence quarks $x_u$, $x_d$

Experimental uncertainty

Model uncertainty

Parametrization uncertainty

$X_f$

$10^3$  $10^2$  $10^1$  $10^{-1}$  $10^{-2}$  $10^{-3}$

$X$

$10^{-4}$  $10^{-3}$  $10^{-2}$  $10^{-1}$  $1$