Physics at the EIC:
How could nuclear physics at the energy frontier profit from electron-Nucleon/Ion collider measurements

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QCD is expected to describe building blocks of visible matter (nucleons) and their binding in nuclei

Strongly interacting non-abelian gauge theory which has implications far from being fully understood
QCD studies lead to discovery

40 years of continuous discovery
40 years of powerful R&D to help us elucidate it.

Heavy Ion Collisions and the discovery of the formation of a Quark Gluon Plasma:

- Jet production and quenching
- Viscosity
- Transport properties
- Collectivity
- Heavy flavor and photon production
- QGP onset
- How do we transition from point like to non-point like physics. How do we arrive at a perfect liquid?

- How do color charged-quarks gluons and colorless jets interact with a nuclear medium?

- How do the confined hadronic states emerge from these quarks and gluons.

Many open questions we need to address

The EIC Electron Ion Collider
The case for an EIC

NSAC Long Range Plan (2015) - Recommendation III
We recommend a high-energy, high-luminosity polarized Electron Ion Collider as the highest priority for new facility construction following the completion of FRIB.

National Academy of Sciences Report (June 2018):

-A unique facility in the world. The science that can be addressed by an EIC is compelling, fundamental, and timely.

-The project is strongly supported by the nuclear physics community. The technological benefits of meeting the accelerator challenges are enormous, both for basic science and for applied areas that use accelerators, including material science and medicine.

https://vimeo.com/282001733
EIC Requirements

- Large luminosity \( (10^{33} - 10^{34} \text{ cm}^{-2}\text{s}^{-1}) \)
- Center of mass energy range (30–140) GeV
- Hadron and electron beams highly longitudinally spin polarized (~70%)
- Ion beams from D to heaviest stable nuclei
- Large detector acceptance, in particular for small-angle scattered hadrons (optimized high luminosity & high acceptance running modes)
EIC Designs

**eRHIC (NY):**
Upgrade to RHIC hadron beam
- New electron injector
- 5-18 GeV electron energy,
- Heavy Ions up to 100 GeV/u
- $\sqrt{s}$: 20-140 GeV
- peak $L \sim 0.4 \times 10^{34}$ cm$^{-2}$s$^{-1}$/A base design,
  $1.0 \times 10^{34}$ cm$^{-2}$s$^{-1}$/A with strong cooling

**JLEIC (VA):**
- Upgrade to CEBAF 12 GeV electron beam facility
- New hadron injector,
- New figure-8 collider configuration,
- 3-12 GeV electron energy,
- Heavy ions up to 80 GeV/u (upgradable to 160 GeV/u),
  $-\sqrt{s}$ 20-100 GeV upgradable to 140 GeV
- average $L$/run $\sim 10^{34}$ cm$^{-2}$s$^{-1}$/A
Physics at the energy frontier

A selection of recent QGP (and nucleon spin physics) results that will need the EIC

1. Hadronization, particle spectra and abundances
2. Collective Expansion
3. Hard Processes
4. Nucleon’s spin
1. Hadronization, particle spectra and abundances
QGP Onset: Strangeness enhancement

Among the first proposed signatures of the QGP PRL48(1982)1066 Observed in A-A at SPS, RHIC, LHC
QGP Onset: Strangeness enhancement

Enhancement of strange particles with respect to non-strange yield is also observed for high multiplicity pp and p-Pb collisions.

- Smooth transition connecting small and larger systems.
- These measurements may give us insights about the underlying dynamics.
- eA can provide a more robust reference.
- More experimental insight is needed to interpret the final state strangeness we are observing in large and small systems.

Heavy flavor vs multiplicity: quarkonia

The contribution of the QCD vacuum condensates to the masses for the three light quark flavours u, d, s considerably exceed the mass believed to be generated by the Higgs field.

Blue: masses generated by electroweak symmetry breaking (current quark mass)

Yellow: additional masses of the light quark flavors generated by spontaneous chiral symmetry breaking in QCD (constituent quark masses)

• Charm and beauty quark masses are not affected by QCD vacuum (ideal probes to study QGP)

• Charm and beauty quarks provide hard scale for QCD calculations

• Charmonium production proceeds from hard initial processes and no strong correlations with event activity are expected
Heavy flavor vs multiplicity: quarkonia

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Heavy flavor vs multiplicity: quarkonia

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Increase is not linear: highlights importance of other physical processes.
Heavy flavor vs multiplicity

**pp collisions**

- Similar effects observed for D’s
- Hadronization doesn’t seem to play a role


- Mid-and backward rapidity (Pb-going):
  - Qualitatively similar behavior as in pp collisions

**Forward rapidity (p-going):** Saturation at high multiplicities?
Bjorken-x range in the domain of shadowing / saturation?
A novel regime of QCD?

Large parton densities
What happens to the gluon density in nuclei? Does it saturate at high energy? Are we observing a hint of universal properties in all nuclei? (small and large).

https://arxiv.org/abs/1803.11093

- With the EIC we have enhanced color density with nuclear targets: access the non-linear evolution in the high gluon density region via nuclear diffraction.
2. Collective Expansion
Hydrodynamical flow

**Radial Flow:**
Affects shape of low $p_T$ particle spectra

**Elliptic Flow:**
Sensitive to initial geometry
Requires early thermalization of the medium
- Pb-Pb no significant energy dependence

- Radial flow pushes protons to intermediate $p_T$ and depletes low $p_T$

- Stronger radial flow in central Pb–Pb collisions

- Low to mid-$p_T$ described by hydrodynamic models

- Similar effects observed in high-multiplicity pp and p–Pb collisions
Anisotropic flow

Initial overlap asymmetric $\rightarrow$ pressure gradients

Momentum anisotropy $\rightarrow$ Fourier decomposition:

$$\frac{d^2 N}{dp_T d\phi} \approx 1 + 2v_1 \cos(d\phi) + 2v_2 \cos(2d\phi) + 2v_3 \cos(3d\phi) + 2v_4 \cos(4d\phi) + 2v_5 \cos(5d\phi) + \ldots$$

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-Low $p_T$: Mass ordering expected in a collective expansion scenario.

-Low-$p_T$: $v_2$ sensitive to hydrodynamic expansion and initial conditions (geometry).

-Similar results observed in a high multiplicity p-Pb environment.

-Effect in these systems may be due to initial state (saturation?) or final state effects (expansion and/or thermal equilibrium ?)
Flow in small systems?

- $\sqrt{s} = 200$ GeV PHENIX
- $\sqrt{s} = 5.02$ TeV ALICE
- $\sqrt{s} = 8.16$ TeV CMS:
  - arXiv:1804.09767

QGP? Saturation? Quantum entanglement?
3. Hard Processes
Nuclear modification factor

Measure spectra of probe and compare to those in pp collisions or A-A collisions

\[ R_{AA} = \frac{A\text{A}}{\text{scaled pp}} = \frac{d^2N_{AA}/dp_Tdy}{\langle N_{coll}\rangle d^2N_{pp}/dp_Tdy} \]

Enhancement

Suppression

Transverse Momentum (GeV/c)
Energy loss in the medium

- High momentum partons lose energy while propagating through the QGP
- Energy loss depends on parton type properties of the medium.
- It can modify color flow

\[ R_{AA} = \frac{\text{AA}}{\text{scaled pp}} = \frac{\frac{d^2N_{AA}}{dp_Tdy}}{\langle N_{\text{coll}} \rangle \frac{d^2N_{pp}}{dp_Tdy}} \]

\[ R_{AA}^{D/_{\text{ch}}/\text{ch}} = \frac{R_{D/_{\text{ch}}/\text{ch}}}{R_{AA}} \]

\[ R_{AA} \]

Pb-Pb suppression
- Similar to that of pions (at high enough \( p_T \))

-ALICE-PUBLIC-2017-003
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Pb-Pb suppression:
- Increases with centrality
- Not initial state
- Final state effect; due to hot and dense QCD matter

“Unintuitive observation that RAA is below unity in peripheral Pb-Pb, but equal to unity in minimum-bias p-Pb collisions despite similar charged-particle multiplicities”.

ALICE-PUBLIC-2017-003

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Energy loss in the medium

PHENIX reports an enhancement observed at backward rapidity in p-Al (and p-Au) collisions.

CMS dijet results support the observation of the gluon’s EMC effect as well as quark modification. **Data is more precise than current nPDF’ uncertainties**

PHENIX: QM2018 J. Bryslawskyj
CMS: https://arxiv.org/abs/1805.04736
Impact on nPDF’s

- Electron- Ion collisions will significantly reduced sea/gluon nPDF uncertainties at lower x values ($x \sim 10^{-4}$)

- HF in e+A collision constraints at large-x gluon

DOI: 10.1140/epja/i2016-16268-9

arXiv:1708.01527

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Energy loss in the medium

**eA** provides a stable nuclear medium (CNM):
- Controlled kinematics of hard scattering
- Final state particle with known properties.
- Varying nuclei size and initial parton energy control fragmentation' length.
- Independent and complementary information essential for the understanding the response of the nuclear medium to a fast moving quark.

![Energy loss by light vs. heavy quarks](https://arxiv.org/abs/1212.1701)

**Ratio of particles produced in lead over proton**

- Pions (model-I)
- Pions (model-II)
- D0 mesons

- $x > 0.1$
- $25 \text{ GeV}^2 < Q^2 < 45 \text{ GeV}^2$
- $140 \text{ GeV} < v < 150 \text{ GeV}$
- $\int L dt = 10 \text{ fb}^{-1}$

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4. Proton’s spin: How does nucleon spin emerge from quarks and gluons
Spin

How do quarks/gluons + their dynamics make up the proton spin?

\[ S(\mu) = \frac{1}{2} \]

Quark helicities
Best known

Gluon helicities
Starting to know

Orbital angular momentum
Largely unknown

How is proton’s spin correlated with the motion of quarks/gluons?

TMD’s
Transverse Momentum Distributions

How does proton’s spin influence the spatial distribution of partons?

GPD’s
Generalized Parton Distribution Functions

How much spin is at small-x?
The EIC can help complete the story

“Unveil the role of the intrinsic spin of quarks and gluons in the proton’s spin budget”
Phys. Rev. D 92, 094030

Anti-quark helicity

Gluon helicity

Orbital momenta

Two orders in $x$ and $Q^2$ compared to existing/planned SIDIS data

Two orders in $x$ and $Q^2$ compared to existing/planned polarized data. Two to three orders of magnitude in luminosity for unpolarized data.
EIC Users group

EIC User Group and R&D activities

EIC User Group:

- EICUG organization established in summer 2016
- In numbers....: 817 members (470: Experimentalists / 163: Theorists / Accelerator Scientists: 142 / Support: 3 / Other: 39), 173 institutions, 30 countries, 7 world regions
- World map:

R&D activities:

- EIC Detector R&D program operated by BNL with ~$1M / year
- EIC Accelerator R&D with ~$7M / year

WWW-page: [www.eicug.org](http://www.eicug.org)
QCD studies have given us decades of discoveries. Many open questions remain on how the transition from a small system to a dense system occurs: this information is needed to fully understand the properties of the QGP. To this date we have yet not unraveled how partons and their dynamic interactions make up the proton spin.

Essential experimental bibliography from this presentation:

-The Electron-Ion Collider: Assessing the Energy Dependence of Key Measurements:

-QGP:
  -Strangeness enhancement in pp collisions:
    Nature Physics 13 (2017) 535-539
  -Particle production vs multiplicity
  -Flow in large and small systems:
    pp: PRL116, 172301 (2016)
  -Nuclear PDFs with dijets:

-Spin: -Unveiling the Proton Spin Decomposition at a Future Electron-Ion Collider:
  Phys. Rev. D 92, 094030
Backups
Enhancement of strange particles with respect to non-strange yield is also observed for high multiplicity pp and p-Pb collisions.

- Smooth transition connecting small and larger systems.
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Charm flows

Non zero $v_2$ for D-meson
Non zero $v_2$ for J/$\psi$’s

Strong coupling of c-quark with the medium
Participation of low $p_T$ charm to collective motion in the QGP
Additionally for the J/$\psi$ this is interpreted as proof of recombination.

Kinematic reach

- LTFC
- Jlab 6+12
- SLAC
- HERA and CERN
- Fixed Target
- EIC Projects

LHeC

EIC

Luminosity ($10^{30}$ cm$^{-2}$s$^{-1}$)

Center-of-Mass Energy (GeV)

Measurements with $A \geq 56$ (Fe):
- $eA\mu A$ DIS (E-139, E-665, EMC, NMC)
- $\nu A$ DIS (CCFR, CDHSW, CHORUS, NuTeV)
- DY (E772, E866)
Beyond the longitudinal view

Representative charged pion measurements; positive PID essential
10 inv. fb, points at indicated x and Q2, uncertainties as indicated
Multiple (central) detector concepts are being pursued within the EIC community.

Detector Concepts EIC: requirements

- **Acceptance**: Close to $4\pi$ coverage with a $\eta$-coverage ($\eta = -\ln(\tan(\theta/2))$) of approximately $\eta < |3.5|$ combined calorimetry (EM CAL and hadron CAL at least in forward direction) and tracking coverage.

- **Low dead material** budget in particular in rear direction (~5% $X/X_0$).

- **Good momentum resolution** $\Delta p/p \sim$ few %.

- **Electron ID** for $e/h$ separation varies with $\theta / \eta$ at the level of $1:10^4 / \sim 2-3%/\sqrt{E}$ for $\eta<-2$ and $\sim 7%/\sqrt{E}$ for $-2<\eta<1$.

- **Particle ID** for $\pi/K/p$ separation over wide momentum range (Forward $\eta$ up to ~50 GeV/c / Barrel $\eta$ up to ~4 GeV/c / Rear $\eta$ up to ~6 GeV/c).

- **High spatial vertex resolution** ~ 10-20 $\mu$m for vertex reconstruction.

- **Low-angle taggers**:
  - Recoil proton
  - Low $Q^2$ electron
  - Neutrons on hadron direction

- **Luminosity** (Absolute and relative) and local polarization direction measurement.

- **Scattered electron**

- **Fragmented particles** (e.g. $\pi$, $K$, $p$) of struck quark.

- **Nuclear and nucleonic fragments / scattered proton**
Detector Concepts EIC: requirements

Generic Detector R&D program for an EIC

-In January 2011, BNL, in association with JLab and the DOE Office of NP, announced a -
generic detector R&D program to address the scientific requirements for measurements at
a future EIC facility.

Goals:
-Enable successful design and timely implementation of an EIC experimental program
-Develop instrumentation solutions that meet realistic cost expectations
-Stimulate the formation of user collaborations to design and build experiments
-Peer-reviewed program funded by DOE and managed by BNL with $1M/year to
$1.5M/year Initiated and coordinated by Tom Ludlam (BNL) until 2014 / Since 2014
coordinated by Thomas Ullrich (BNL)
Detector Concepts EIC: BEAST

Detector design: BEAST (1) - BNL

- hadronic calorimeters
- e/m calorimeters
- RICH detectors
- Silicon trackers
- TPC
- GEM tracker
- MicroMegas Tracker
- 3T solenoid cryostat
- magnet yoke

hadrons

up to 9.0m

electron
Detector Concepts EIC: BEAST

Highly redundant tracker (TPC / endcap GEM disks and MAPS vertex detector)

2 barrel layers of MAPS sensors (20X20μm2) with ~0.3% X0 per layer / Similar technology for forward and rear disks

Rear and Forward GEM disks

TPC

MicroMegas tracker
Detector Concepts EIC: sPHENIX

- Solenoid
- EM Calorimeter
- Hadron Calorimeter
- Flux return
- Central Tracker
- Forward Tracker
- Particle ID
Detector Concepts EIC: sPHENIX

<table>
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<tr>
<th>η Range</th>
<th>Material</th>
<th>Size</th>
<th>Resolution</th>
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</thead>
<tbody>
<tr>
<td>-4 &lt; η &lt; -1.55</td>
<td>PbWO₄</td>
<td>2 cm x 2 cm</td>
<td>2.5% / √E ⊕ 1%</td>
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<tr>
<td>-1.55 &lt; η &lt; 1.24</td>
<td>W-SciFi</td>
<td>0.025 x 0.025</td>
<td>16% / √E ⊕ 5%</td>
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<td>1.24 &lt; η &lt; 3.3</td>
<td>PbScint</td>
<td>5.5 cm x 5.5 cm</td>
<td>8% / √E ⊕ 2%</td>
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<tr>
<td>3.3 &lt; η &lt; 4</td>
<td>PbWO₄</td>
<td>2.2 cm x 2.2 cm</td>
<td>12% / √E</td>
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<tr>
<td>-1.1 &lt; η &lt; 1.1</td>
<td>Fe Scint + Steel</td>
<td>0.1 x 0.1</td>
<td>81% / √E ⊕ 12%</td>
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<tr>
<td>-1.24 &lt; η &lt; 5</td>
<td>Fe Scint</td>
<td>10 cm x 10 cm</td>
<td>70% / √E</td>
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Detector Concepts EIC:TOPSiDE

- **TOPSiDE**: Timing Optimized PID Silicon Detector for the EIC

- **Features**:
  - **Ultra-fast Si detectors** (UFSD TOF) (PID π/K/p separation)
  - **Highly granular imaging calorimeters** and particle flow algorithms (PID of hadrons/neutrals and background rejection)
  - **Full particle-ID over entire central and rear regions** (-5 < η < 3)
  - **Forward detectors (3 < η < 5)**: UFSD TOF and RICH PID (π/K/p separation for SIDIS) / Dipole or Toroid for p measurement
  - **Rear detectors (-5 < η < -3)**: UFSD TOF for full PID (No RICH needed!) / Crystal calorimeter for optimal energy resolution
Detector Concepts EIC:JLEIC

Extended detector: 80m
30m for multi-purpose chicane, 10m for central detector, 40m for the forward hadron spectrometer
fully integrated with accelerator lattice
Auxiliary detector systems: Luminosity (Abs. / Rel.) and Polarimetry

**Luminosity (Absolute / Relative)**

**Bethe-Heitler process** \((e+p \rightarrow e+\gamma+p)\) successfully used at HERA I/II (QED theory precision \(\sim 0.2\%\)) / \(\rightarrow e+\gamma+p)\) successfully used at HERA I/II (QED theory precision \(\sim 0.2\%\))

Systematic uncertainty achieved \(\sim 1\%-2\%\). For polarized beam-mode, **polarization dependence**.

Systematic uncertainty of e/p polarization and theory uncertainty will limit abs./rel. luminosity -
Critical for asymmetry measurements in particular at low \(x\).

**Polarimetry: Lepton**

**Compton back-scattering** / HERA used two setups of measuring trans. (TPOL) and long. (LPOL) polarization and achieved for sys. uncertainties 3.5% (TPOL) and 1.6% (LPOL) at HERA I / 1.9% (TPOL) and 2.0% (LPOL) at HERA II. Prospect to improve precision to \(\sim 1\%\).

**Polarimetry: Hadron**

**Extensive experience at RHIC from polarized \(p\) program.** Two aspects are relevant: Absolute and relative polarization measurement.

Absolute: Elastic scattering of polarized \(p\) on polarized hydrogen jet target
Relative: High statistics bunch-by-bunch polarized proton on carbon fiber target

Achieved precision: 3.3% (Run 13 - 255GeV polarized \(p\) beam) for single-spin asymmetry
Further improvements from stability control of hydrogen jet target / carbon-fiber target and energy calibration of recoil silicon detectors.