Thanks to E.C. Aschenauer (BNL), R. Ent (JLab) and EIC UG community
Outline

- Introduction
- EIC accelerator
- EIC physics
- EIC UG activity
- Summary

“EIC HF Overview” Ivan Vitev
“EIC Cold QCD Future Physics Program” Andreas Metz
“Jet Measurements at the EIC” Felix Ringer
Introduction

2019 Two accelerator proposals

- eRHIC (BNL)
- JLEIC (JLAB)

January 9, 2020

DOE CD-0 and Site selection

Work towards CD-1

U.S. Department of Energy Selects Brookhaven National Laboratory to Host Major New Nuclear Physics Facility

January 9, 2020

The Relativistic Heavy Ion Collider (RHIC) at Brookhaven National Laboratory will provide crucial infrastructure for the new Electron-Ion Collider.

WASHINGTON, D.C. - Today, the U.S. Department of Energy (DOE) announced the selection of Brookhaven National Laboratory in Upton, NY, as the site for a planned major new nuclear physics research facility.
Our Mission

- 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?

Jianwei Qiu (DIS2018)
EIC physics

How are the sea quarks and gluons, and their spins, distributed in space and momentum inside the nucleon?
How do the nucleon properties emerge from them and their interactions?

How do color-charged quarks and gluons, and colorless jets, interact with a nuclear medium?
How do the confined hadronic states emerge from these quarks and gluons?
How do the quark-gluon interactions create nuclear binding?

How does a dense nuclear environment affect the quarks and gluons, their correlations, and their interactions?
What happens to the gluon density in nuclei? Does it saturate at high energy, giving rise to a gluonic matter with universal properties in all nuclei, even the proton?
Deep inelastic scattering

\[ Q^2 = -q^2 : \text{4-momentum transfer squared} \]

\[ x (0 < x < 1) - \text{fraction of proton momentum carried by the struck quark} \]

\[ y (0 < y < 1) = \frac{(E_e - E_e')}{E_e} - \text{fractional energy transfer} \]

Ability to change \( Q^2 \) changes the resolution scale

\[ Q^2 = 400 \text{ GeV}^2 \]

\[ \Rightarrow \frac{1}{Q} = 0.01 \text{ fm} \]

Ability to change \( x \) projects out different configurations where different dynamics dominate

\[ (0 < x < 1) \]

perturbative radiation

non-pert. fields

x < 0.01

x \sim 0.1

x \sim 0.3

gluons dominant

sea quarks gluons

valence quarks
From RHIC to EIC

Design based on existing RHIC, RHIC is well maintained, operating at its peak

**Hadron storage ring 40-275 GeV** (existing)
- Many bunches
- Bright beam emittance
- Need strong cooling or frequent injections

**Electron storage ring (2.5–18 GeV)** (new)
- Many bunches,
- Large beam current (2.5 A) ➔ 10 MW S.R. power

**Electron rapid cycling synchrotron** (new)
- 1-2 Hz
- Spin transparent due to high periodicity

**High luminosity interaction region(s)** (new)
- \( L = 10^{34} \text{cm}^{-2}\text{s}^{-1} \)
- Superconducting magnets
- 25 mrad Crossing angle with crab cavities
- Spin Rotators (longitudinal spin)
- Forward hadron instrumentation
- Up to 2 interaction regions
EIC capabilities

✓ DIS facility
✓ Nuclear beams $A = 2-208$
✓ $CM$ energy $\sqrt{s} (eN)$
  $\sim 20-140$ GeV
✓ Luminosity $L \sim 10^{34}$ cm$^{-2}$ s$^{-1}$
✓ polarized lepton & hadron beams (up to 70%)
✓ Next generation of detectors

➢ control of the kinematic
➢ first eA collider in the world!
➢ wide coverage for $Q^2, x_B$;
  Include non-perturbative, perturbative
  and transition regimes.
  overlap with existing measurements
➢ high precision physics;
  rare processes;
  various measurements/ configurations:
  (different ions, different center of mass
  energies, different polarizations)
➢ Spin properties and spin dependences
➢ final states
Mass of the Proton, Pion, Kaon

Visible world: mainly made of light quarks – its mass emerges from quark-gluon interactions.

Proton
Quark structure: uud
Mass ~ 940 MeV (~1 GeV)
Most of mass generated by dynamics.

Gluon rise discovered by HERA e-p

Pion
Quark structure: ud
Mass ~ 140 MeV
Exists only if mass is dynamically generated.

Empty or full of gluons?

Kaon
Quark structure: us
Mass ~ 490 MeV
Boundary between emergent- and Higgs-mass mechanisms.
More or less gluons than in pion?

For the proton the EIC will allow determination of an important term contributing to the proton mass, the so-called “QCD trace anomaly”

For the pion and the kaon the EIC will allow determination of the quark and gluon contributions to mass with the Sullivan process.
The Spin of the Proton

SPIN is one of the fundamental properties of matter all elementary particles, but the Higgs carry spin
Spin cannot be explained by a static picture of the proton
It is more than the number $\frac{1}{2}$! It is the interplay between the intrinsic properties and interactions of quarks and gluons

What do we know:

$$\frac{1}{2} \hbar = \left\langle P, \frac{1}{2} | J^{z}_{\text{QCD}} | P, \frac{1}{2} \right\rangle = \frac{1}{2} \int_{0}^{1} dx \Delta \Sigma(x, Q^{2}) + \int_{0}^{1} dx \Delta G(x, Q^{2}) + \int_{0}^{1} dx \sum_{q} L_{q}^{z} + L_{g}^{z}$$

~ 30%  ~ 40%  ~ ?

EMC found: 
$\Delta \Sigma = 0.12 \pm 0.17$  ~ 30%
The Spin of the Proton

The current knowledge about $g_1$ as function of $x$ at $Q^2=10$ GeV$^2$

$g_1 \sim$

quark contribution:
The integral of $g_1$ over $x$ from 0 to 1

gluon contribution:
$dg_1(x,Q^2)/d\ln Q^2 \rightarrow \Delta g(x,Q^2)$
3-Dimensional imaging

Wigner functions $W(x, b_T, k_T)$ offer unprecedented insight into confinement and chiral symmetry breaking.

Spin-dependent 3D momentum space images from semi-inclusive scattering

Spin-dependent 2+1D coordinate space images from exclusive scattering

RHIC & AGS Annual Users' Meeting 2020

Yulia Furletova
Extreme Parton Densities

**Low-\(x\)**

At very low \(x\), cross-section will saturate.could be investigated in transition region.

\[
\text{gluon emission} = \text{gluon recombination} \quad \text{At } Q_s
\]

- CTEQ 6.5 parton distribution functions
  - \(Q^2 = 10 \text{ GeV}^2\)

\[
\ln Q^2
\]

\[
\ln x
\]

\[
\text{Momentum Fraction Times Parton Density}
\]

\[
\text{Fraction of Overall Proton Momentum Carried by Parton}
\]
**Extreme Parton Densities**

**Low-\(x\)**

Saturation regime reached at significantly lower energy in nuclei

EIC will allow to unambiguously map the transition from a non-saturated to saturated regime.
Gluon density and nucleon interactions

**High-\(x\)**

Nucleon interactions

Boson (photon or Z) Gluon Fusion (BGF)

Heavy quark production probes large-\(x\) gluons “almost locally” at 
\(x'_{\text{glue}} \geq x_{\text{BJ}} (1+4m^2h/Q^2)\)

- \(x > 0.3\) “EMC effect”
  Modified single-nucleon structure? Non-nucleonic degrees of freedom?

- \(x \sim 0.1\) “Antishadowing”
  QCD structure of pairwise NN interaction, exchange mechanisms

- \(x < 0.01\) “Shadowing”
  QM interference, collective gluon fields

N.Sato, C. Weiss

Nuclear gluon ratio \(g_{1A}(x)/[A g_0(x)]\)

- \(A = 56\)
- \(A = 2\) GeV
- \(\mu^2 = 2\) GeV

Antishadowing?

Shadowing?

EMC effect?
Emergence of hadrons

(colored) quark passing through cold QCD matter emerges as color-neutral hadron.

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

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

➢ What does a nucleus look like?
Does the color of “A” know the color of “B”

Understand energy loss of light vs. heavy quarks traversing the cold nuclear matter: Connect to energy loss in Hot QCD

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

Ivan Vitev
Electroweak physics at EIC

Charm jets in the Charged Current reactions as a probe for strangeness complementary to neutrino facilities ($\nu N$).

$e^+/e^-$ beams $\Rightarrow s/s$-bar
Charged Lepton Flavor Violation

- Current limits set by HERA sitting at sensitivities of a few fb. The high luminosity of the EIC will gain us 2 orders of magnitude
- Polarization, electron/positron beam, proton vs deuteron

via Leptoquark or parity-violation,...
Far-forward physics at EIC

- e+p DVCS events with proton tagging

- **Diffraction**

  - Meson structure: 
    - with neutron tagging \((ep \to (\pi^\pm) \to e' n X)\).
    - Lambda decays \((\Lambda \to p\pi^- \text{ and } \Lambda \to n\pi^0)\)

- Saturation (coherent/incoherent \(J/\psi\) production)

- e+d exclusive \(J/\psi\) events with proton or neutron tagging

- e+He3 with spectator proton tagging.

- e+He4 coherent He4 tagging.

- e+Au events with neutron tagging to veto breakup and photon acceptance.

- e+Au events with neutron tagging to veto breakup and photon acceptance.

- e+Au events with neutron tagging to veto breakup and photon acceptance.
Far-forward hadron going instrumentation

\[ x_L = \frac{p_{z,nucleon}}{p_{z,beam}} \]

ZDC

Roman pots (inside pipe)

Off-Momentum Detectors

B2pf dipole

B1pf dipole

Q2pf quadrupole

Q1bpf quadrupole

B0afp dipole

B0 pf dipole

5x41 [GeV] DVCS

<table>
<thead>
<tr>
<th>Detector</th>
<th>Detector Position (x,z)</th>
<th>Angular Acceptance</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>ZDC</td>
<td>(0.96m, 37.5m)</td>
<td>( \theta &lt; 5.5 ) mrad</td>
<td>About 4.0 mrad at ( \phi \sim \pi )</td>
</tr>
<tr>
<td>Roman Pots (2 stations)</td>
<td>(0.845m, 26m) &amp; (0.936m, 28m)</td>
<td>( 0.0^\circ &lt; \theta &lt; 5.0 ) mrad</td>
<td>Need 10( \circ ) cut. Depending on optics/beam energy, lower ( \theta ) bound changes.</td>
</tr>
<tr>
<td>Off-Momentum Detectors</td>
<td>(0.8, 22.5m) &amp; (0.85m, 24.5m)</td>
<td>( 0.0 &lt; \theta &lt; 5.0 ) mrad</td>
<td>Roughly 0.4 &lt; ( x_L ) &lt; 0.6</td>
</tr>
<tr>
<td>B0 Sensors (4 layers, evenly spaced)</td>
<td>( x = 0.19m, 5.4m &lt; z &lt; 6.4m )</td>
<td>( 5.5 &lt; \theta &lt; 20.0 ) mrad</td>
<td>Could change a bit depending on pipe and electron quad.</td>
</tr>
</tbody>
</table>

Needs an integration with accelerator at the early stage of the IR design

A. Jentsch

Entries: 20000
Mean: 0.3768
RMS: 0.1799

Hadron beam coming from IP

B0 Silicon Detector
Photoproduction

- Most events ep event at EIC are photoproduction (cross section $\sim 1/Q^4$)
- Exchange photon is almost real at $Q^2 \sim 0$ (DIS $Q^2 > 1 \text{GeV}$)

- This area is designed to provide coverage for the low-$Q^2$ events (photoproduction)
- Need space for the luminosity detector (ep -> epg bremsstrahlung photons)
EICUG organization established in 2016

EICUG now: 1073 members
  - 645 Exp. scientists
  - 147 Accel. scientists
  - 273 Th. scientists
  - 3 Support
  - 5 Other

EICUG now: 221 institutions from 31 countries in 6 world regions

EICUG now: world map

EICUG Yellow Book (physics/detector)

www.eicug.org
General purpose EIC Detector

- p/A beam
- electron beam

- high $Q^2$
- medium $x$
- low $Q^2$
- low $x$
- high $x$

- scattered lepton
- hadrons
- scattered leptons

- $\Theta = 90^\circ$
- $\Theta = 135^\circ$
- $\Theta = 45^\circ$
- $\Theta = 2^\circ$
- $\Theta = 178^\circ$

asymmetric beam momenta
boosted kinematics
Endcaps important

- Bethe-Heitler photons for luminosity
- particles from nuclear breakup
- scattered protons and ions from diffractive reactions

Yulia Furletova
Any general purpose EIC Detector is complex

Overall detector requirements:

- Large rapidity (-4 < $\eta$ < 4) coverage; and far beyond in especially far-forward detector regions
- High precision low mass tracking
  - small (µ-vertex) and large radius (gaseous-based) tracking
- Electromagnetic and Hadronic Calorimetry
  - equal coverage of tracking and EM-calorimetry
- High performance PID to separate $\pi$, $K$, $p$ on track level
  - also need good $e/\pi$ separation
- Large acceptance for diffraction, tagging, neutrons from nuclear breakup: critical for physics program
  - Many ancillary detector integrated in the beam line: low-$Q^2$ tagger, Roman Pots, Zero-Degree Calorimeter, ....
- High control of systematics
  - luminosity monitor, electron & hadron Polarimetry

Integration into the Interaction Region is critical
Integration with accelerator at the early stage of the design

Total size detector: ~75m
Central detector: ~10m
Backward electron detection: ~35m
Forward hadron spectrometer: ~40m
## Schedule

<table>
<thead>
<tr>
<th>FY19</th>
<th>FY20</th>
<th>FY21</th>
<th>FY22</th>
<th>FY23</th>
<th>FY24</th>
<th>FY25</th>
<th>FY26</th>
<th>FY27</th>
<th>FY28</th>
<th>FY29</th>
<th>FY30</th>
<th>FY31</th>
<th>FY32</th>
<th>FY33</th>
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<tbody>
<tr>
<td><strong>Critical Decisions</strong></td>
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<tr>
<td>CD-1 (A)</td>
<td>CD-1</td>
<td>CD-2</td>
<td>CD-3</td>
<td>CD-4a</td>
<td>CD-4</td>
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<tr>
<td>Dec 2019</td>
<td>Mar 2021</td>
<td>Sep 2022</td>
<td>Sep 2023</td>
<td>Approve start of operations Sep 2030</td>
<td>Approve proj. completion Jun 2031</td>
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</table>

| **Research & Development** |      |      |      |      |      |      |      |      |      |      |      |      |      |      |
| Detector Research & Development |      |      |      |      |      |      |      |      |      |      |      |      |      |      |
| Jan 2021 | Mar 2021 |      |      |      |      |      |      |      |      |      |      |      |      |      |

| **Design** |      |      |      |      |      |      |      |      |      |      |      |      |      |      |
| Infrastructure | Concept & Design |      |      |      |      |      |      |      |      |      |      |      |      |      |
| Accelerator Systems | May 2021 | Apr 2022 | Sep 2023 |      |      |      |      |      |      |      |      |      |      |      |
| Detector |      |      |      |      | May 2021 | Apr 2022 | Sep 2023 |      |      |      |      |      |      |      |

| **Construction & Installation** |      |      |      |      |      |      |      |      |      |      |      |      |      |      |
| Infrastructure | Conventional Construction |      |      |      |      |      |      |      |      |      |      |      |      |      |
| Accelerator Systems | Procurement, Fabrication, Installation & Test |      |      |      |      |      |      |      |      |      |      |      |      |      |
| Detector | Procurement, Fabrication, Installation & Test |      |      |      |      |      |      |      |      |      |      |      |      |      |

| **Commissioning & Pre-Ops** |      |      |      |      |      |      |      |      |      |      |      |      |      |      |
| Accelerator Systems | Commission & Pre-Ops |      |      |      |      |      |      |      |      |      |      |      |      |      |
| Detector | Commission & Pre-Ops |      |      |      |      |      |      |      |      |      |      |      |      |      |

**Key**
- **(A) Actual**
- **Completed**
- **Planned**
- **Data**
- **Date**
- **Level 0 Milestones**
- **Critical Path**
- **Schedule Contingency**

26
Conclusion

• Physics of nucleon and nuclear structure must drive the accelerator and detector design.

• Theory developments will allow to obtain the answers to the big questions discussed

• Detector technologies will allow for a high resolution EIC detector with a wide acceptance, particle identification and machine integration for far-forward areas.

• Machine parameters, interaction region and detector design must go hand in hand, paying close attention to the emerging physics program of the EIC (a good collaboration among Accelerator Physicists, Experimentalists, and Theoreticians)
Thank you!

EIC

Thank you!

EIC
Backup
Past, existing and proposed DIS facilities

Luminosity - vs Energy and EIC Physics:

<table>
<thead>
<tr>
<th>Facility</th>
<th>Energy (GeV)</th>
<th>Luminosity (cm² sec⁻¹)</th>
<th>Integrated Luminosity [fb⁻¹/yr]</th>
</tr>
</thead>
<tbody>
<tr>
<td>JLAB/CEBAF</td>
<td>6, 12</td>
<td>10^38</td>
<td></td>
</tr>
<tr>
<td>SLAC</td>
<td></td>
<td>10^37</td>
<td></td>
</tr>
<tr>
<td>LHeC/HE-LHC</td>
<td></td>
<td>10^35</td>
<td></td>
</tr>
<tr>
<td>LHeC/HL-LHC</td>
<td></td>
<td>10^33</td>
<td></td>
</tr>
<tr>
<td>LHeC/CDR</td>
<td></td>
<td>10^32</td>
<td></td>
</tr>
<tr>
<td>HERA (ZEUS/H1)</td>
<td></td>
<td>10^31</td>
<td></td>
</tr>
<tr>
<td>HERMES NMC</td>
<td></td>
<td>10^30</td>
<td></td>
</tr>
<tr>
<td>BCDMS</td>
<td></td>
<td>10^29</td>
<td></td>
</tr>
<tr>
<td>COMPASS</td>
<td></td>
<td>10^28</td>
<td></td>
</tr>
<tr>
<td>HIAF-EIC</td>
<td></td>
<td>10^27</td>
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</tr>
</tbody>
</table>

EIC:
- Ep Facilities & Experiments:
  - Past Colliders
  - Collider Concepts
  - Past Fixed Target
  - Ongoing Fixed Target
  - EIC Project

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
## IR-related physics requirements

Table 8.1: Summary of the requirements from the physics program on the overall IR design.

<table>
<thead>
<tr>
<th></th>
<th>Hadron</th>
<th>Lepton</th>
</tr>
</thead>
<tbody>
<tr>
<td>Machine element free region</td>
<td>$\pm 4.5\text{ m main detector}$</td>
<td>$\text{beam elements &lt; 1.5}^\circ$ in main detector volume</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Beam Pipe</td>
<td></td>
<td>Low mass material, i.e. Beryllium</td>
</tr>
<tr>
<td>Integration of detectors</td>
<td></td>
<td>Local Polarimeter</td>
</tr>
<tr>
<td>Zero Degree Calorimeter</td>
<td>$40\text{ cm }\times 40\text{ cm }\times 1\text{ m } @s = 30\text{ m}$</td>
<td></td>
</tr>
<tr>
<td>scattered proton/neutron acc.</td>
<td>$0.18\text{ GeV/c } &lt; p_T &lt; 1.3\text{ GeV/c}$</td>
<td>$0.5 &lt; x_L &lt; 1 (x_L = E_p' / E_{Beam})$</td>
</tr>
<tr>
<td>all energies for $e+p$</td>
<td>$\text{Proton:}$</td>
<td>Neutron: $p_T &lt; 1.3\text{ GeV/c}$</td>
</tr>
<tr>
<td></td>
<td>$0.5 &lt; x_L &lt; 1 (x_L = E_p' / E_{Beam})$</td>
<td></td>
</tr>
<tr>
<td>scattered proton/neutron acc.</td>
<td>Proton and Neutron:</td>
<td></td>
</tr>
<tr>
<td>all energies for $e+A$</td>
<td>$\theta &lt; 6\text{ mrad } (\text{for } \sqrt{s} = 50\text{ GeV})$</td>
<td>$\theta &lt; 4\text{ mrad } (\text{for } \sqrt{s} = 100\text{ GeV})$</td>
</tr>
<tr>
<td></td>
<td>Relative Luminosity: $R = L^{++/-}/L^{++/-} &lt; 10^{-4}$</td>
<td></td>
</tr>
<tr>
<td>Luminosity</td>
<td></td>
<td>$\gamma$ acceptance: $\pm 1\text{ mrad}$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$\rightarrow \delta L / L &lt; 1%$</td>
</tr>
<tr>
<td>Low $Q^2$-Tagger</td>
<td>Acceptance: $Q^2 &lt; 0.1\text{ GeV}^2$</td>
<td></td>
</tr>
</tbody>
</table>
~4π hermetic coverage in tracking, particle ID and calorimetry with the polar angle acceptance only limited by the beam pipe

Low material budget in the acceptance (at the level of 3-5% X/X₀):
- To minimize multiple Coulomb scattering for the low-momenta particles
- To minimize bremsstrahlung in front of the e/m calorimeters

Need to integrate the support structures, services and cabling
Start thinking about the assembly, installation and maintenance
Central detector installation in IP6

- Limited space along the beam line (the final focusing quads are placed as close to the IP as possible in order to maximize the luminosity)
- Barrel part of the main detector is designed to fit through the door
- Use large assembly hall for the long detector maintenance

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
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</thead>
<tbody>
<tr>
<td>Hall length</td>
<td>~3200 cm</td>
</tr>
<tr>
<td>Hall width</td>
<td>~1615 cm</td>
</tr>
<tr>
<td>Door width</td>
<td>823 cm</td>
</tr>
<tr>
<td>Door height</td>
<td>823 cm</td>
</tr>
</tbody>
</table>
Central detector installation in IP8

- Very small exp. hall
- Large doorway

<p>| | |</p>
<table>
<thead>
<tr>
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</thead>
<tbody>
<tr>
<td>Hall length</td>
<td>~1740 cm</td>
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<tr>
<td>Hall width</td>
<td>~1860 cm</td>
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<tr>
<td>Door width</td>
<td>927 cm</td>
</tr>
<tr>
<td>Door height</td>
<td>1017 cm</td>
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</table>