Electron Ion Collider
The Next QCD Frontier

2015
Physics of EIC

2016

2018
Evaluation

2019
Realization

2019-present

Abhay Deshpande

12/3/21
EIC Status at Light Cone 2021
EIC moving forward….

- DOE announced: January 9, 2020
  - CD0 December 19, 2019
  - Site of EIC: Brookhaven National Laboratory
- BNL and JLab realize EIC as partners
  - A formal EIC project is now setup at BNL
  - BNL+Jlab management & scientists
- CD1 June 28, 2021
- Detector Proposals in December 1, 2021
- CD2 Approval 3rd Quarter FY2023
- CD3 1st Quarter FY2024 (start construction)
- EIC CD4A Early Finish 4thQ FY (2030→2031)
  - Start of collisions
- EIC CD4 ~ 4thQ FY(2031→2033)
  - Start of Physics
EIC Science: a very short overview

- Experiment: EIC high luminosity measurements; systematic uncertainties limited
- Theory: is theory ready for EIC? (N^XLO, summation, underlying assumptions of factorizability and such issues), and reliable lattice/continuation QCD methods
EIC Physics at-a-Glance

How are the sea quarks and gluons, and their spins, distributed in space and momentum inside the nucleon?
How do the nucleon properties (mass & spin) emerge from 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?
Nucleon Spin: Precision with EIC

\[ \frac{1}{2} = \left[ \frac{1}{2} \Delta \Sigma + L_Q \right] + [\Delta g + L_G] \]

\( \Delta \Sigma/2 \) = Quark contribution to Proton Spin
\( \Delta g \) = Gluon contribution to Proton Spin
\( L_Q \) = Quark Orbital Ang. Mom
\( L_G \) = Gluon Orbital Ang. Mom

Spin structure function \( g_1 \) needs to be measured over a large range in \( x-Q^2 \)

Precision in \( \Delta \Sigma \) and \( \Delta g \) ➔ A clear idea
Of the magnitude of \( L_Q+L_G = L \)

SIDIS: strange and charm quark spin contributions
2+1D Imaging of hadrons: beyond precision PDFs

- Wigner distributions: $W(x,b_T,k_T)$
- Transverse momentum distributions (TMDs) and semi-inclusive processes: $f(x,k_T)$ and $f(x,b_T)$
- Fourier transform: $f(x,b_T) \leftrightarrow H(x,0,t) = -\Delta^2$
- Generalized parton distributions (GPDs) and exclusive processes: $H(x,\xi,t)$ and $A_n(t) + 4\xi^2 A_{n+2}(t) + ...$

Precision PDFs and TMDs valuable for LHC(?)

Near future promise of direct comparison with lattice QCD
Low x physics with nuclei

\[ (Q_s^A)^2 \approx c Q_0^2 \left( \frac{A}{x} \right)^{1/3} \]

\[ L \sim (2m_S x)^{-1} > 2 R_A \sim A^{1/3} \]

Accessible range of saturation scale \( Q_s^2 \) at the EIC with e+Au collisions.

arXiv:1708.01527

\[ x \leq 0.01 \]

EIC \( \sqrt{s}_{\text{max}} = 40 \text{ GeV} \) (eAu)

EIC \( \sqrt{s}_{\text{max}} = 90 \text{ GeV} \) (eAu)

HERA (ep)

300 GeV

perturbative regime

\[ Q_s^2 (\text{GeV}^2) \]
EIC science highlights

Mass
Tomography (p/A)
Transverse Momentum Distribution and Spatial Imaging

Spin and Flavor Structure of the Nucleons and Nuclei
Internal Landscape of Nuclei
QCD at Extreme Parton Densities - Saturation

Infinite Momentum Frame:
• BFKL (linear QCD): splitting functions
  $\alpha_s \ll 1$
  $\alpha_s \sim 1$ $\Lambda_{\text{QCD}}$
  know how to do physics here?
  $Q_s \sim 1/k_T$
  $k_T \phi(x, k_T^2)$
  • At $Q_s$:
    gluon emission balanced by recombination
Unintegrated gluon distribution depends on $k_T$ and $x$:
the majority of gluons have transverse momentum $k_T \sim Q_S$ (common definition)

CTEQ 6.5 parton distribution functions $Q^2 = 10 \, \text{GeV}^2$

Momentum Fraction Times Parton Density

Fraction of Overall Proton Momentum Carried by Parton
Physics of EIC
- Emergence of Spin
- Emergence of Mass
- Physics of high-density gluon fields

Machine Design Parameters:
- High luminosity: up to $10^{33}$-$10^{34} \text{ cm}^{-2}\text{sec}^{-1}$
  - a factor ~100-1000 times HERA
- Broad range in center-of-mass energy: ~20-100 GeV upgradable to 140 GeV
- Polarized beams $e^-, p$, and light ion beams with flexible spin patterns/orientation
- Broad range in hadron species: protons…. Uranium
- Up to two detectors well-integrated detector(s) into the machine lattice
Physics @ the US EIC beyond the EIC’s core science

Of HEP/LHC-HI interest to Snowmass 2021 (EF 05, 06, and 07 and possibly also EF 04)

New Studies with proton or neutron target:
• Heavy quark and quarkonia (c, b quarks) studies with 100-1000 times lumi of HERA
• Feasibility to study kaon and pion structure
• Impact of precision measurements of unpolarized PDFs at high x/Q^2, on LHC
• What role would TMDs in e-p play in W-Production at LHC? Gluon TMDs?
• Does polarization of play a role (in all or many of these?)

Physics with nucleons and nuclear targets:
• Quark Exotica: 4,5,6 quark systems…? Much interest after recent LHCb led results.
• Physic of and with jets with EIC as a precision QCD machine:
  • Internal structure of jets : novel new observables, energy variability, polarization,
  • Entanglement, entropy, connections to fragmentation, hadronization and confinement
  • Studies with jets: Jet propagation in nuclei… energy loss in cold QCD media
• Connection to p-A, d-A, A-A at RHIC and LHC
• Polarized light nuclei in the EIC

Precision electroweak and BSM physics:
• Electroweak physics & searches beyond the SM: Parity, charge symmetry, lepton flavor violation
The EIC Users Group: EICUG.ORG

Formally established in 2016, now we have:
~1300 Ph.D. Members from 34 countries, 254 institutions
New members welcome

EICUG Structures in place and active:
EIC UG Steering Committee, Institutional Board, Speaker’s Committee, Election & Nominations Committee

Year long workshops: Yellow Reports for detector design


New:
Center for Frontiers in Nuclear Science (at Stony Brook/BNL)
EIC² at Jefferson Laboratory
EIC Project & Path Towards Realization
EIC Project Organization

BROOKHAVEN NATIONAL LABORATORY
D. Gibbs
Laboratory Director

R. Tribble
Deputy Director for Science & Technology

J. Anderson
Deputy Director for Operations

ELECTRON-ION COLLIDER PROJECT
J. Yeck (BNL), Project Director
E. Willeke (BNL), Deputy Project Director and Technical Director

R. Ent (TJ), Co-Associate Director for the Experimental Program
E. Aschenauer (BNL), Co-Associate Director for the Experimental Program

A. Lung (TJ), Deputy Project Director for TJNAF Partnership
A. Sery (TJ), Associate Director for Accelerator Systems & International Partnership

D. Hatton (BNL), Project Manager

EIC User Group Steering Committee
R. Fatemi, Chair
M. Radici, Co-Chair
A. Deshpande (BNL), EIC Science Director

Electron-Ion Collider Council
D. Gibbs, Chair

Project Advisory Committee
T. Glasmacher, Chair

Detector Advisory Committee
E. Kinney, Chair

Machine Advisory Committee
T. Raubenheimer, Chair

Infrastructure Construction Advisory Committee
M. Faller, Chair

[Diagram showing various roles and committees related to the EIC Project Organization]
**EIC Accelerator Design**

**Center of Mass Energies:** 20GeV - 140GeV

**Luminosity:** $10^{33} - 10^{34}$ cm$^{-2}$s$^{-1}$ / 10-100 fb$^{-1}$ / year

**Highly Polarized Beams:** 70%

**Large Ion Species Range:** p to U

**Number of Interaction Regions:** Up to 2!

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![Diagram of the EIC Accelerator Design](image)
December 2019 – March 2021
EICUG Yellow Report

• Led by EICUG Steering Committee, a UG-wide effort towards a detailed detector design

• Meetings from December 2019 Boston followed by 4 more meetings in 2020 all remote: Philadelphia, Pavia, Miami, Washington DC, Berkeley
This detector concept was included in the EIC CDR prepared for the CD1 Review.
Reference Detector – Backward/Forward Detectors

Highly Integrated detector system: ~75m
1. Central detector: ~10m
2. Backward electron detection: ~35m
3. Forward hadron spectrometer: ~40m

Lesson learned from HERA – ensure low-$Q^2$ coverage

Various stage detector to capture forward-going protons and neutrons, and also decay products ($\Delta, \Lambda$).
Summary of the call for detector proposals

• Detector 1 (D1): within the scope of the EIC project
  • Will cover most but not all acquisitions
  • Must satisfy EIC “mission need” ➔ Physics of EIC White Paper “blessed” by the NAS
  • Design should be compatible with accelerator & interaction region layout in CDR
  • Completion mandatory by **CD4A** — @ beginning accelerator operation

• Detector 2 (D2): not within the scope of the EIC project
  • How to realize it are being explored
  • Focus on **specific topic within EIC WP** or (and) **science beyond** the EICWP & NAS
  • IR should be consistent with machine design in CDR, but modified IR design possible
  • Detector should be ready by **CD4** — about 2-5(?) years later

Siting location of D1 and D2 between IP6 and IP8 is left open, with the caveat that the EIC project has so far assumed D1 will go to IP6
The three proposals
ATHENA
https://athena-eic.org

ATHENA - A global pursuit for a new EIC experiment at IP6 at BNL
A Totally Hermetic Electron-Nucleus Apparatus

90+ institutions
CORE
https://eic.joab.org/core

- CORE is a hermetic general-purpose detector for EIC physics outlined in the Yellow Report & EIC White Paper
- COMPACT size has advantages including reduced cost, accommodates closer strong focusing IR magnets to allow high luminosity
  - New 3T magnet, 2.5m long, 1.1m inner radius
  - Central all Si tracker, (+ MPGD/GEM in h-endcap)
  - Particle ID: AC-LGAD (e-endcap), DIRC Barrel, dRHIC, (h-endcap)
  - EMCalorimetry: PbWO₄ (barrel and endcap) W-shashlyk (barrel and h-endcap)
  - HCal: some new and some from STAR + KLM

25+ institutions
ECCE
https://www.ecce-eic.org

Magnet: 1.5T existing solenoid s-conducting magnet BaBar/sPHENIX

Tracking:
- Barrel mRWell, end-caps: Si tracker
- Particle ID: barrel hpDIRC, h- dRICH, e-mRICH, AC-LGAD ToF

EMCalorimetry:

HCAlorimetry:
- forward Steel-scintillator, Central barrel: Steel

ECCE Institutions

90+ institutions
A White Paper on: Physics with Low CM & High Luminosity
A dedicated detector at IP8?

- Aim: to produce a White Paper to highlight the science at the EIC with a high-luminosity at low-CM energy Interaction Region.
- DES, SIDIS, Jets, HF, Spectroscopy, various researches with light nuclei
- Contact: Volker Burkert, Latifa Elouadrhiri, AD, X. Ji
- Conditions from the Call for proposal for the 2\textsuperscript{nd} detector:
  - D2/IR2 complementary to D1/IR1, physics focus beyond EIC WP, and possibly modified IR2 design (compatible with IR1 and machine operations)
- Series of Center for Frontiers In Nuclear Science Workshops: 1\textsuperscript{st} @ CFNS, 2\textsuperscript{nd} @ ANL-CFNS, 3\textsuperscript{rd} APCTP-CFNS, 4\textsuperscript{th} CNF-CFNS (DC) in Spring 2022.

Recent machine development and studies
Possible to get high luminosity by only adjusting magnetic polarities of near-IR magnets
Timeline for Proposal Evaluation

**December 1, 2021**  Proposals submitted: ATHENA, ECCE, CORE expected
Proposals distributed to Advisory Panel and DAC members

**December 13-15, 2021**  First public Advisory Panel meeting (3 days, Virtual)
- Presentations from proto-collaborations
- Panel discussion of DAC input (written report)
- Panel develops homework questions for collaborations to address at January meeting

**January 19-21, 2022**  Second 3-day public Advisory Panel meeting
- Responses to homework and further input from DAC
- Panel begins Report writing

**March 1, 2022**  Panel Report & Recommendations submitted
## Reference Schedule

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<th>Fiscal Year</th>
<th>Critical Decisions</th>
<th>Research &amp; Development</th>
<th>Design</th>
<th>Construction &amp; Installation</th>
<th>Commissioning &amp; Pre-Ops</th>
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<td>FY19</td>
<td>CD-0(A) Dec 2019</td>
<td>Accelerator Systems</td>
<td>Concept. Des.</td>
<td>Infrastructure</td>
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<td>Detector</td>
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<td>FY20</td>
<td>CD-1(A) June 2021</td>
<td>Research &amp; Development</td>
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<td>Procurement, Fabrication, Installation &amp; Test</td>
<td>Commission. &amp; Pre-Ops</td>
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<td>CD-4a Approve start of operations Jul 2031</td>
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<td>Early CD-4a Completion Jul 2030</td>
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**Key**
- (A) Actual
- Green: Completed
- Yellow: Planned
- Red: Critical Path
- Red/Black: Schedule Contingency
- Data Date: Level 0 Milestones

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J. Yeck, EICUG Meeting
Summary: Challenging but EXCITING times ahead

EIC Science: enthusiastically supported by NAS & 1300+ (growing) users, 254 institutions and 34 countries from 6 continents

EIC Project is moving forward with great speed within the DOE at BNL working closely with JLab

• International partners are significant component of the success:

EIC Detector: unique in its demanding: IR integration: Designs being developed and finalized

• Three detector proposals submitted in response to the Call for Proposals – Decision by March 2022

Precision anticipated from the EIC will push theory on multiple fronts: LO, NLO, NNLO and resummation, lattice/continuum QCD methods, aspects of universality, explicit proofs of factorization will become essential components for physics in 2030’s. (no long room for “hand-waving” arguments)

An exciting symbiotic program between experiment and theory could emerge on many fronts: Mass, spin of hadrons, mesons… nuclei…
Thank you.