Electron Ion Collider: Science, Status and Opportunities for Collaboration

Physics of EIC

Evaluation

Realization

2015

2016

2018

2019

2019 - future
On the menu today:

- The science of Electron Ion Collider: an overview & highlights
- The EIC project (machine & detector design) status and plans
- EIC Users Group (science program, detector design and collaboration) aspirations
- Realization & opportunities for collaboration
QCD: The Holy Grail of Quantum Field Theories

- QCD: “nearly perfect”, fundamental quantum field theory of quarks and gluons that explains nature’s strong interactions
- QCD is rich with symmetries:

\[ SU(3)_C \times SU(3)_L \times SU(3)_R \times U(1)_A \times U(1)_B \]

1. (1) Gauge “color” symmetry: unbroken but confined
2. (2) Global “chiral” flavor symmetry: exact for massless quarks
3. (3) Baryon number and axial charge (massless quarks) conservation
4. (4) Scale invariance for massless quarks and gluon fields
5. (5) Discrete C, P & T symmetries

- Chiral, Axial, Scale & P&T symmetries broken by quantum effects: Most of the visible matter in the Universe emerges as a result
- Inherent in QCD are the deepest aspects of relativistic quantum field theories: (confinement, asymptotic freedom, anomalies, spontaneous breaking of chiral symmetry)

⇒ ALL DEPEND ON NON-LINEAR DYNAMICS IN QCD
Non-linear Dynamics of QCD has Fundamental Consequences

- Quark (Color) confinement:
  - Unique property of the strong interaction
  - Consequence of nonlinear gluon self-interactions

- Strong Quark-Gluon Interactions:
  - Confined motion of quarks and gluons – Transverse Momentum Dependent Parton Distributions (TMDs)
  - Confined spatial correlations of quark and gluon distributions -- Generalized Parton Distributions (GPDs)

Deeply connected to emergence of mass and spin of observed building blocks of nature

- Ultra-dense color (gluon) fields in all nucleons and nuclei?
  - Runaway growth in gluon number: Is it tamed by existing mechanisms in QCD?
  - Is there a universal many-body structure due to ultra-dense color fields?
  - Happens in all hadrons and nuclei? ⇒ Universal?

A-A, p-A, e-A, p-p, e/μ-p/A and e-e collisions are all essential for fully understanding of QCD
Emergent Dynamics in QCD

*Without gluons, there would be no nucleons, no atomic nuclei... no visible world!*

- Massless gluons & almost massless quarks, *through their interactions*, generate most of the mass of the nucleons
- Gluons carry ~50% of the proton’s momentum, a significant fraction of the nucleon’s spin, and are essential for the dynamics of confined partons
- Properties of hadrons are emergent phenomena resulting not only from the equation of motion but are also inextricably tied to the properties of the QCD vacuum. (Striking examples besides confinement are spontaneous symmetry breaking and anomalies).
- How do the nucleon-nucleon forces emerge from quark-gluon interactions? -- A mystery....

*Experimental insight and guidance crucial for complete understanding of how hadrons & nuclei emerge from quarks and gluons*
Deep Inelastic Scattering: Precision and control

Kinematics:

\[ Q^2 = -q^2 = -(k_\mu - k'_\mu)^2 \]
\[ Q^2 = 2E_eE'_e(1 - \cos \Theta_{e'}) \]
\[ y = \frac{pq}{pk} = 1 - \frac{E'_e}{E_e} \cos^2 \left( \frac{\Theta_{e'}}{2} \right) \]
\[ s = 4E_tE_e \]
\[ x = \frac{Q^2}{2pq} = \frac{Q^2}{sy} \]

Measure of resolution power
Measure of inelasticity
Measure of momentum fraction of struck quark

Exclusive DIS
detect & identify everything \( e+p/A \rightarrow e'+h(\pi,K,p,\text{jet})+\ldots \)

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

Inclusive events:
\( e+p/A \rightarrow e'+X \)
detect only the scattered lepton in the detector

Hadron:
\[ z = \frac{E_h}{\sqrt{p_t}} \] with respect to \( \gamma \)
QCD Landscape to be explored by a future facility

QCD at high resolution ($Q^2$) — weakly correlated quarks and gluons are well-described

Strong QCD dynamics creates many-body correlations between quarks and gluons → hadron structure emerges

Systematically explore correlations in this region.

An exciting opportunity: Observation of a new regime in QCD of weakly coupled high-density matter

Need Precision and Control
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?
EIC science highlights

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
EIC science: compelling, fundamental and timely

Machine Design Parameters:

- **High luminosity**: up to $10^{33-10^{34}}$ cm$^{-2}$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**
EIC: Kinematic reach & properties

For e-N collisions at the EIC:
- Polarized beams: e, p, d/3He
- Variable center of mass energy
- Wide $Q^2$ range $\rightarrow$ evolution
- Wide x range $\rightarrow$ spanning valence to low-x physics

For e-A collisions at the EIC:
- Wide range in nuclei
- Luminosity per nucleon same as e-p
- Variable center of mass energy
- Wide x range (evolution)
- Wide x region (reach high gluon densities)
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) ➔ Interesting to High Energy Physicists at LHC

New Studies with proton or neutron target:
- Impact of precision measurements of unpolarized PDFs at high $x/Q^2$, on LHC-Upgrade results(?)
- What role would TMDs in e-p play in W-Production at LHC? Gluon TMDs at low-x!
- Heavy quark and quarkonia (c, b quarks) studies with 100-1000 times lumi of HERA
- 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
  - Studies with jets: Jet propagation in nuclei… energy loss in cold QCD medium
- Entanglement entropy & connection to fragmentation, hadronization, confinement
- 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
EIC Status and Realization

- CD0 : December 19, 2019
- Site BNL : January 9, 2020
- BNL and JLab realize EIC as partners

- A formal EIC project is now setup at BNL
- BNL+Jlab management & scientists are working together to realize it on a fast timeline.

- CD1 anticipated March 2021
- CD2 September 2022 (final design)
- CD3 4th Quarter FY2023 (start construction)

- EIC CD4A Early Finish 4th Q FY2029
- EIC CD4B 3rd Q FY 2032
The EIC Project captures project delivery experience from BNL and TJNAF.


EIC Project Executive Management Team (EMT) Established: Elke Aschenauer, Rolf Ent, Diane Hatton, Allison Lung, Andrei Seryi, Ferdinand Willeke, and Jim Yeck.

Abhay Deshpande, EIC Science Director, participates in the EMT meeting as an ex-officio member providing an additional connection to the User community.

J. Yech, EIC project Director
The US Electron Ion Collider

Hadrons up to 275 GeV
- Existing RHIC complex: Storage (Yellow), injectors (source, booster, AGS)
- Need few modifications
- RHIC beam parameters fairly close to those required for EIC@BNL

Electrons up to 18 GeV
- Storage ring, provides the range $\sqrt{s} = 20-140$ GeV. Beam current limited by RF power of 10 MW
- Electron beam with variable spin pattern $s$ accelerated in on-energy, spin transparent injector (Rapid-Cycling-Synchrotron) with 1-2 Hz cycle frequency
- Polarized e-source and a 400 MeV s-band injector LINAC in the existing tunnel

Electron storage ring with frequent injection of fresh polarized electron bunches
- Hadron storage ring with strong cooling or frequent injection of hadron bunches

Design optimized to reach $10^{34}$ cm$^{-2}$ sec$^{-1}$
The EIC Users Group: [EICUG.ORG](#)

Formally established in 2016, now we have:
~1200 Ph.D. Members from 33 countries, 230 institutions
New members welcome

EICUG Structures in place and active:
EIC UG Steering Committee, Institutional Board, Speaker’s Committee, Election & Nominations Committee
Task forces on:
-- Beam polarimetry, Luminosity measurement
-- Background studies, IR Design

Year long workshops: Yellow Reports for detector design

Experimental Program Preparations:
Yellow Reports, Expressions of Interests & Proposals

• EIC Community’s Yellow Report Initiative (Kickoff in December 2019, site)
  • Four workshops planned to advance the state and detail of the documented physics studies and detector concepts in preparation for the realization of the EIC.
  • Report ready February 2021
• BNL and TJNAF Jointly Leading Process for Defining Detector(s) strategy
  • Project contains machine, IR and 1 detector; Users aspire for two detectors: Carefully considered by Project
  • Call for “Potential Cooperation on the EIC Experimental Program” published in May
  • Includes two questionnaires, FAQ, and input received
  • Expressions of Interest (EOIs) due November 1, 2020:
    • Following the EOI Response Deadline
      • Status report at 4th Yellow Report meeting in November 18-20, LBNL: Summary – see later
      • Responses evaluated and Call for Proposal(s) finalized
        • Assessment by an external committee including: members of the Users Group and Project Management with advice from Detector Advisory Committee (DAC)
        • Call for Detector Proposal(s) in March 2021

EIC EOI Site: https://www.bnl.gov/eic/EOI.php
Yellow Reports Conveners

- **Physics Conveners:**
  - Adrian Dumitru (Baruch)
  - Olga Evdokimov (University of Illinois at Chicago)
  - Andreas Metz (Temple)
  - Carlos Muñoz Camacho (Orsay)

- **Detector Conveners:**
  - Ken Barish (UC Riverside)
  - Tanja Horn (CUA)
  - Peter Jones (Birmingham)
  - Silvia Dalla Torre (Trieste)
  - Markus Diefenthaler, ex-officio (JLab)

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Other YR meetings:

- March 2020 (Temple U)
- May 2020 (Pavia)
- July/August 2020 (FIU)
- September 2020 (CUA)
- November 2020 (LBNL)

YR Final: by February 23, 2021
Physics Working Group Sub-conveners

Inclusive
  Theory: Nobuo Sato (JLab)
  Experiment: Renee Fatemi (Kentucky), Barak Schmookler (Stony Brook)

Semi-Inclusive DIS
  Theory: Bowen Xiao (CCNU, China), Alexey Vladimirov (Regensburg)
  Experiment: Anselm Vossen (Duke), Ralf Seidl (RIKEN), Justin Stevens (W&M)

Jets, heavy quarks
  Theory: Ivan Vitev (LANL), Frank Petriello (Argonne & Northwestern U.)
  Experiment: Ernst Sichtermann (LBL), Brian Page (BNL), Leticia Mendez (ORNL)

Exclusive
  Theory: Tuomas Lappi (Jyvaskyla), Barbara Pasquini (Pavia)
  Experiment: Raphaël Dupré (Orsay), Salvatore Fazio (BNL), Daria Sokhan (Glasgow)

Diffractive & Tagging
  Theory: Wim Cosyn (Florida), Anna Stasto (PSU)
  Experiment: Or Hen (MIT), Douglas Higinbotham (JLab), Spencer Klein (LBNL)
EXPERIMENTAL REQUIREMENTS

More and more demanding moving from inclusive to fully exclusive scattering

- **Inclusive measurements (DIS), required:**
  - Precise scattered electron identification (e.m. calorimetry, e/h PID) and extremely fine resolution in the measurement of its angle (tracking) and energy (calorimetry)

- **Semi-inclusive measurements (SI-DIS), also required:**
  - excellent hadron identification over a wide momentum and rapidity range (h-PID)
  - full $2\pi$ acceptance for tracking (tracking) and momentum analysis (central magnet)
  - excellent vertex resolution (low-mass vertex detector)

- **Exclusive measurements also required:**
  - Tracker with excellent space-point resolution (high resolution vertex) and momentum measurement (tracking),
  - Jet energy measurements (h calorimetry)
  - very forward detectors also to detect n and neutral decay products (Roman pots, large acceptance zero-degree calorimetry)

- **And luminosity control, e and A polarimeters, r-o electronics, DAQ, data handing**
REFERENCE DETECTOR IN A CARTOON
Extensive integration of forward and backward detector elements into the accelerator lattice
Overview of EIC Project and Layout

- Hadron Storage Ring
- Electron Storage Ring
- Electron Injector Synchrotron
- Possible on-energy Hadron injector ring
- Hadron injector complex

EIC Project: 1 Machine, 1 IR, 1 Detector cost
Possibility of the 2nd IR and a 2nd Detectors to be preserved

Two possible locations – IP6 and IP8 – for detectors/IR

Current Assumption: IP6 is “default” EIC detector location (as IP8 has sPHENIX).

Details of one or two detectors (designs, complementarity) to be finalized in the coming years.
Expressions of Interest: analysis by EIC Project

- 46 Expressions of Interest received
- There is clearly large interest in EIC science and experimental equipment
  - Both domestically among universities and national labs
  - And international, with many countries represented (Canada, China, Czech, France, India, Italy, Japan, Korea, Poland, UK and institutional EoIs of Chile, Hungary, Mexico, Rumania, and group EoIs with Armenia, Israel, Saudi Arabia and Taiwan as members)
- With EIC science still a decade away, impressively many are committed to work on EIC.
- In-kind contributions suffice to maintain low-risk for a general-purpose EIC detector.
- It is clear we need to remain vigilant and follow up to secure in-kind contributions and even argue, based on our strong EIC science, for further contributions, if we want to be able to secure a second detector, with crisp arguments on why.
- Remain unified and make the case for collaboration internationally
## EIC Bilateral & Other Collaborative Initiatives

### Machine and Detector

#### September 2020
- SLAC – EIC: 9/30
- ORNL – EIC: 9/18
- TRIUMF – EIC: 9/17
- CERN – EIC: 9/14
- DESY – EIC: 9/14
- ANL – EIC: 9/8
- LBNL – EIC: 9/2

#### June – August 2020
- CERN FCC – EIC: 7/6
- INF Krakow – EIC: 7/2
- ANL – EIC: 7/1
- CEA-Saclay – EIC: 6/16

#### October 7-10, 2020
- **EIC Accelerator Collaboration Meeting**
- **Cockcroft Institute in UK**
- [https://www.cockcroft.ac.uk/events/eic20/](https://www.cockcroft.ac.uk/events/eic20/)

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**Electron Ion Collider Project Launch, September 18, 2020**

**Movie Clip: CERN Director General Fabiola Gianotti (starts at 1:01:50)**
Summary & Outlook

• Electron Ion Collider, a high-energy **high-luminosity polarized e-p, e-A collider**, funded by the DOE will be built in this decade and operate in 2030’s.
  - Up to two hermetic full acceptance detectors under consideration, currently **EIC project has funds for 1 detector**, cost of a second detector from non-DOE sources
  - Community led detector design being developed through a Yellow Report Writing effort
  - **Experimental collaboration(s) to be formed by late 2021**

• EIC project assumes **an aggressive timeline** with support from both Labs and the DOE to have first collisions around 2030 (CD4A) & routine operation with high lumi, and polarization after 2032 (CD4B)

• **There is high interest in having international partners both on detector and accelerator**
  - Easiest & direct way to participate in the EIC Physics is through the EIC Users Group
  - Contact the EIC Project Management for contributions to the project (machine & detector)
R. Ent, T. Ullrich, R. Venugopalan
Scientific American (2015)
*Translated into multiple languages*

E. Aschenauer
R. Ent
October 2018

A. Deshpande
& R. Yoshida
June 2019
*Translated in to multiple languages*