The Electron Ion Collider: Science and Status

Abhay Deshpande
Stony Brook University & Brookhaven National Laboratory
Epiphany 2019, Krakow, Poland
January 11th, 2019
Deep Inelastic Scattering: Precision & Control

**Kinematics:**

- \( Q^2 = -q^2 = -(k_{\mu} - k'_{\mu})^2 \)
- \( Q^2 = 2E_e E'_{e}(1 - \cos \Theta_e) \)
- \( y = \frac{pq}{pk} = 1 - \frac{E'_{e}}{E_e} \cos^2 \left( \frac{\Theta_e'}{2} \right) \)
- \( x = \frac{Q^2}{2pq} = \frac{Q^2}{sy} \)

**Hadron:**

- \( z = \frac{E_h}{\gamma}; p_t \)

**Inclusive events:** \( e+p/A \rightarrow e'+X \)

**Semi-Inclusive events:** \( e+p/A \rightarrow e'+h(\pi,K,p,\text{jet})+X \)

**Exclusive events:** \( e+p/A \rightarrow e'+p'/A'+h(\pi,K,p,\text{jet}) \)
QCD at high resolution ($Q^2$) — weakly correlated quarks and gluons are well-described

Strong QCD dynamics creates quarks and gluons many-body correlations between quarks and gluons $\rightarrow$ hadron structure emerges

EIC will systematically explore correlations in this region.

An exciting opportunity: Observation by EIC of a new regime in QCD of weakly coupled high density matter
A new facility is needed to investigate, with precision, the dynamics of gluons & sea quarks and their role in the structure of visible matter.

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?
RECOMMENDATION:
We recommend a high-energy high-luminosity polarized EIC as the highest priority for new facility construction following the completion of FRIB.

Initiatives:
Theory
Detector & Accelerator R&D

Detector R&D money ~1.3M/yr since 2011; significant increase anticipated soon.

Anticipated Now:
NEW Money for EIC Accelerator R&D already assigned $7m/yr
The committee will assess the scientific justification for a U.S. domestic electron ion collider facility, taking into account current international plans and existing domestic facility infrastructure. In preparing its report, the committee will address the role that such a facility could play in the future of nuclear physics, considering the field broadly, but placing emphasis on its potential scientific impact on quantum chromodynamics.
The committee will assess the scientific justification for a U.S. domestic electron ion collider facility, taking into account current international plans and existing domestic facility infrastructure. In preparing its report, the committee will address the role that such a facility could play in the future of nuclear physics, considering the field broadly, but placing emphasis on its potential scientific impact on quantum chromodynamics.

In particular, the committee will address the following questions:

- What is the merit and significance of the science that could be addressed by an electron ion collider facility and what is its importance in the overall context of research in nuclear physics and the physical sciences in general?
- What are the capabilities of other facilities, existing and planned, domestic and abroad, to address the science opportunities afforded by an electron-ion collider?
- What unique scientific role could be played by a domestic electron ion collider facility that is complementary to existing and planned facilities at home and elsewhere?
- What are the benefits to U.S. leadership in nuclear physics if a domestic electron ion collider were constructed?
- What are the benefits to other fields of science and to society of establishing such a facility in the United States?
EIC Science Endorsed Unanimously by the NAS

Developed by US QCD community over two decades

Developed by NAS with broad science perspective

A consensus report
July 26, 2018
EIC science and required luminosity
In order to definitively answer the compelling scientific questions elaborated in Chapter 2, including the origin of the mass and spin of the nucleon and probing the role of gluons in nuclei, a new accelerator facility is required, an electron-ion collider (EIC) with unprecedented capabilities beyond previous electron scattering programs. An EIC must enable the following:

- Extensive center-of-mass energy range, from ~20–~100 GeV, upgradable to ~140 GeV, to map the transition in nuclear properties from a dilute gas of quarks and gluons to saturated gluonic matter.
- Ion beams from deuterons to the heaviest stable nuclei.
- Luminosity on the order of 100 to 1,000 times higher than the earlier electron-proton collider Hadron-Electron Ring Accelerator (HERA) at Deutsches Elektronen-Synchrotron (DESY), to allow unprecedented three-dimensional (3D) imaging of the gluon and sea quark distributions in nucleons and nuclei.
- Spin-polarized (~70 percent at a minimum) electron and proton/light-ion beams to explore the correlations of gluon and sea quark distributions with the overall nucleon spin. Polarized colliding beams have been achieved before only at HERA (with electrons and positrons only) and Relativistic Heavy Ion Collider (RHIC; with protons only).

NAS Study endorses machine parameters suggested by the 2012 White Paper and 2015 NSAC Long Range Plan
Uniqueness of EIC among all DIS Facilities

All DIS facilities in the world.

However, if we ask for:

EIC stands out as unique facility …
Uniqueness of EIC among all DIS Facilities

All DIS facilities in the world.

However, if we ask for:

- high luminosity &
  wide reach in $\sqrt{s}$

EIC stands out as unique facility ...
Uniqueness of EIC among all DIS Facilities

All DIS facilities in the world.

However, if we ask for:

• high luminosity & wide reach in $\sqrt{s}$
• polarized lepton & hadron beams
• nuclear beams

EIC stands out as unique facility ...
The science questions that an EIC will answer are central to completing an understanding of atoms as well as being integral to the agenda of nuclear physics today. In addition, the development of an EIC would advance accelerator science and technology in nuclear science; it would as well benefit other fields of accelerator based science and society, from medicine through materials science to elementary particle physics.
### Critical Decision Process DOE

#### PROJECT ACQUISITION PROCESS AND CRITICAL DECISIONS

<table>
<thead>
<tr>
<th>Mission</th>
<th>Preconceptual Planning</th>
<th>Conceptual Design</th>
<th>Preliminary Design</th>
<th>Final Design</th>
<th>Construction</th>
<th>Operations</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mission Need</td>
<td>i CD-0</td>
<td>i CD-1</td>
<td>i CD-2</td>
<td>i CD-3</td>
<td>i CD-4</td>
<td></td>
</tr>
<tr>
<td>Preconceptual Planning</td>
<td>i CD-0</td>
<td>Approve Preliminary Design Baseline Range</td>
<td>Approve Performance Baseline</td>
<td>Approve Start of Construction</td>
<td>Approve Start of Operations or Project Closeout</td>
<td></td>
</tr>
<tr>
<td>Conceptual Design</td>
<td>i CD-1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Preliminary Design</td>
<td>i CD-2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Final Design</td>
<td>i CD-3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Construction</td>
<td>i CD-4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Operations</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

#### Actions Authorized by Critical Decision Approval

<table>
<thead>
<tr>
<th>CD-0</th>
<th>CD-1</th>
<th>CD-2</th>
<th>CD-3</th>
<th>CD-4</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Actions Authorized by Critical Decision Approval</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>• Proceed with conceptual design using program funds</td>
<td>• Allow expenditure of PED funds for design</td>
<td>• Establish baseline budget for construction</td>
<td>• Approve expenditure of funds for construction</td>
<td>• Allow start of operations or project closeout</td>
</tr>
<tr>
<td>• Request PED funding</td>
<td>• Continue design</td>
<td>• Request construction funding</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
The EIC Machines: eRHIC and JLEIC

Two designs
Hadron Beam
- entirely re-uses injection chain and one of RHIC rings (Yellow ring)
- partially re-uses components of other ion RHIC ring
- A $2.5B investment in RHIC is reused

Electron Accelerator added inside the existing RHIC tunnel:
- 5-18 GeV Storage Ring
- On-energy injector: 18 GeV Rapid Cycling Synchrotron
- Polarized electron source & 400 MeV injector LINAC: 10nC, 1 Hz

Hadron cooling system required for $L = 10^{34} cm^{-2}s^{-1}$
*Without cooling the peak luminosity reaches $4.4 \times 10^{33} cm^{-2}s^{-1}$*

Wide Center of mass energy: 29-140 GeV
- Large acceptance detectors integrated in the accelerator IR for forward particle detectors
- Polarized e, p, D and $^3$He beams planned for the physics program
eRHIC – IR layout

IR design requirements:

- Small $\beta^*$ for high luminosity
- Limited IR chromaticity contributions
- Large final focus quadrupole aperture
- Large detector acceptance
- Design meets all requirements
- Very constrained systems, requires novel types of magnets in the IR

- Large quadrupole aperture, limited beam divergence
- Accommodate spectrometer in the low-$\beta$ optics
- No accelerator magnets +/-4.5 m
- 25 mrad crossing angle, crab crossing, crab cavities 90° from IP
- Accommodate synchrotron radiation:
  - no electron bends on the forward side
  - absorb SR far from IP
  - need mask against backscattered SR photons
- Accommodate spin rotators, spin matching
- Space for luminosity monitor, neutron detector, “Roman Pots”
- Multi-stage separation:
  - Electrons from protons
  - Protons from neutrons
  - Electrons from Bethe-Heitler photons (luminosity monitor)

January 11th, 2019
eRHIC Design Luminosity

Path to the high luminosity:
- High beam currents
- Many bunches (up to 1320)
- Large beam-beam tune-shift
- Flat beams
- Short hadron bunches (5-7 cm)
- 25 mrad crossing angle with crab cavities
- Strong hadron cooling for highest luminosity ($10^{34}$)

Luminosity limiting factors are based on experience from previous and present colliders (HERA, RHIC, B-factories, LHC)
eRHIC pCDR has been completed in July 2018
(Submitted to DOE as requested by them)

The eRHIC Pre-Conceptual Design Report has been finalized in the end of July 2018.

The detailed document (~770 pages)
• Presents accelerator design which fully satisfies physics requirements
• Summarizes results of accelerator physics studies which validates reaching goal luminosity and high polarization
• Includes sufficiently deep description of accelerator systems, providing good basis for ongoing cost estimate work
• Evaluates required improvements in BNL/RHIC infrastructure

Presently available for eRHIC designers and collaborators. The public release is being coordinated with the Lab Management and DOE.

January 11th, 2019
JLEIC electron-ion collider design – built up on CEBAF

- CEBAF extensive fixed-target science program
  - Fixed-target program compatible with concurrent JLEIC operations
- CEBAF 12 GeV : JLEIC injector
  - Fast fill of collider ring
  - Full energy
  - ~90% polarization
  - Enables top-off
- New operation mode but no hardware modifications

Electron complex: CEBAF as a full energy injector, Electron collider ring

Ion complex: Ion source, SRF linac, Booster, Ion collider ring

January 11th, 2019
• Integrated detector region design developed satisfying requirements of detection, beam dynamics and geometric match

• GEANT4 detector model developed, simulations in progress
JLEIC luminosity curves

JLEIC e-p average luminosity for the 65 GeV CM optimized design

Current EIC General Purpose Detector Concepts

Brookhaven concept: BEAST

Jefferson lab concept: JLEIC

sPHENIX → EIC

Argonne concept: TOPSiDE
The EIC Users Group: EICUG.ORG

Formally established in 2016
837 Ph.D. Members from 30 countries, 177 institutions
(Significant International interest ~32% Europe. ~17% Asia)

EICUG Structures in place and active.
EIC UG Steering Committee (w/ European Representative)
EIC UG Institutional Board
EIC UG Speaker’s Committee (w/European Rep.)

Task forces on:
- Beam polarimetry
- Luminosity measurement
- Background studies
- IR Design

EIC support, outreach and other news

European High Energy Physics Strategic Planning:
Rolf Ent (Jlab), Rik Yoshida (Jlab) and Abhay Deshpande (SBU/BNL) went to CERN in October 2018 to meet with Eckhard Elsen (CERN’s Research and Technology Director)

• Very well informed about the US EIC status, very supportive, suggested strong involvement and input on EIC in the European High Energy Strategy Planning activity (ongoing now)
• EICUG presenting a science paper (led by its European contingent), and an accelerator design paper led by BNL and Jlab together
• EIC at the Plenary session of ECFA meeting November 2018

Recent success in funding of EIC as part of the Hadron studies (Hadron2020) in European Nuclear Physics $Eu 12M (Saclay, INFN, Warsaw-group and others) over 3 years

A Consortium of 5 California Universities and 3 national labs supported by UC Chancellor’s office for EIC in addition to direct monies forwarded by the States of New York and Virginia.
Summary: US EIC has momentum…

• The US EIC project has significant momentum on all fronts right now:
  • National Academy’s positive evaluation → EIC science compelling, fundamental and timely
  • EICUG is energized, active and enthusiast: organized
    • EICUG led working groups on polarimetry, luminosity measurement, IR design evolving
  • Funding agencies taking note of the momentum: not just in the US but also internationally

• The science of EIC, technical designs (eRHIC and JLEIC) moving forward
  • Pre-CDRs prepared by BNL (eRHIC) and Jlab (under preparation) for the machine designs
  • CFNS, EIC² Centers established in the US to help EIC Users

• CD0 for the EIC project very near. – We are waiting…
Thank you
2+1 Dimensional Structure of the Proton

The theoretical framework we have sketched is valid over a wide range of momentum fractions $x$, connecting in particular the region of valence quarks with the one of gluons and the quark sea. While the present chapter is focused on the nucleon, the concept of parton distributions is well adapted to study the dynamics of partons in nuclei, as we will see in Sec. 3.3. For the regime of small $x$, which is probed in collisions at the highest energies, a different theoretical description is at our disposal. Rather than parton distributions, a basic quantity in this approach is the amplitude for the scattering of a color dipole on a proton or a nucleus. The joint distribution of gluons in $x$ and in $k_T$ or $b_T$ can be derived from this dipole amplitude. This high-energy approach is essential for addressing the physics of high parton densities and of parton saturation, as discussed in Sec. 3.2.

On the other hand, in a regime of moderate $x$, around $10^{-3}$ for the proton and higher for heavy nuclei, the theoretical descriptions based on either parton distributions or color dipoles are both applicable and can be related to each other. This will provide us with valuable flexibility for interpreting data in a wide kinematic regime.

The following sections highlight the physics opportunities in measuring PDFs, TMDs and GPDs to map out the quark-gluon structure of the proton at the EIC. An essential feature throughout will be the broad reach of the EIC in the kinematic plane of the Bjorken variable $x$ (see the Sidebar on page 18) and the invariant momentum transfer $Q^2$ to the electron. While $x$ determines the momentum fraction of the partons probed, $Q^2$ specifies the scale at which the partons are resolved. Wide coverage in $x$ is hence essential for going from the valence quark regime deep into the region of gluons and sea quarks, whereas a large lever arm in $Q^2$ is the key for unraveling the information contained in the scale evolution of parton distributions.

$A_n^\delta(t) + 4\xi^2 A_n^2(t) + \ldots$ generalized form factors

lattice calculations

$F_i(t)$ form factors

elastic scattering

$H(x,0,t)$

$t = -\Delta^2$

$\xi = 0$

$H(x,\xi,t)$

generalized parton distributions (GPDs)

exclusive processes

$W(x,b_T,k_T)$

Wigner distributions

$\int d^2b_T$

transverse momentum distributions (TMDs)

semi-inclusive processes

$\int d^2k_T$

impact parameter distributions

$\int dx$

parton densities

inclusive and semi-inclusive processes

$\int d^2k_T$

$\int d^2b_T$

$\int dx x^{n-1}$
2+1 D partonic image of the proton with the EIC

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

Transverse Momentum Distributions

Spin-dependent 2D coordinate space (transverse) + 1D (longitudinal momentum) images from exclusive scattering

Transverse Position Distributions

sea-quarks
unpolarized
polarized

Gluons
EIC physics with nuclei

Valence Sea Gluon

\[ Q^2 = 1.69 \text{ GeV}^2 \]

\[ Q^2 = 10 \text{ GeV}^2 \]

\[ \alpha_s \ll 1 \]

\[ \alpha_s \sim 1 \]

\[ k_T \phi(x, k_T^2) \]

At \( Q_s \)

\[ \text{gluon emission} \quad \Rightarrow \quad \text{gluon recombination} \]

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

In Q^2

ln x

pQCD evolution equation

saturation

non-perturbative region

Infinite Momentum Frame:

• BFKL (linear QCD): splitting functions \( \alpha_s \ll 1 \)

• BK (non-linear): recombination of gluons \( \alpha_s \sim 1 \)

Unintegrated gluon distribution depends on \( k_T \) and \( x \): the majority of gluons have transverse momentum \( k_T \sim Q_s \) (common definition)

Know how to do physics here? max. density \( Q_s \approx \frac{1}{k_T} \)

\[ \phi(x, k_T^2) \]

At \( Q_s \): gluon emission balanced by recombination

αs ≪ 1

αs ~ 1

\[ k_T \phi(x, k_T^2) \]

• At \( Q_s \): gluon emission balanced by recombination

New Approach: Non-Linear Evolution

• New evolution equations at low-x & low to moderate \( Q^2 \)

• Saturation of gluon densities characterized by scale \( Q_s(x) \)

• Wave function is Color Glass Condensate

In QCD, the proton is made up of quanta that fluctuate in and out of existence

- Boosted proton:
  - Fluctuations time dilated on strong interaction time scales
  - Long lived gluons can radiate further small x gluons
  - Explosion of gluon density violates unitarity

"##" "$#" "$ 

&'

\( \alpha_s \ll 1 \)

\( \alpha_s \sim 1 \)

\( \Lambda_{\text{QCD}} \)
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
✓ Lum. per nucleon same as e-p
✓ Variable center of mass energy
✓ Wide $x$ range (evolution)
✓ Wide $x$ region (reach high gluon densities)
Assumptions on integrated luminosity: Accelerator is 75% of the time in colliding beam mode; 25% of the time is needed for injection, acceleration, run preparation as well as maintenance, machine development, and failures. The average luminosity within a luminosity run is very close to the peak luminosity (>95%) due to strong hadron cooling.