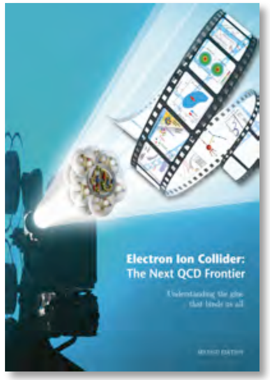
Center for Frontiers in Nuclear Science

"Science: Compelling & fundamental, Realization: Timely"

The US Electron Ion Collider

Status and Realization Plans

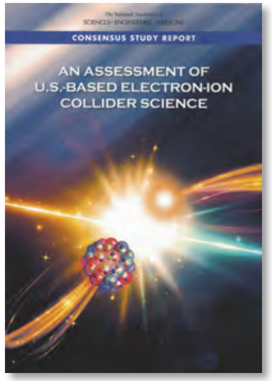
2015



2016

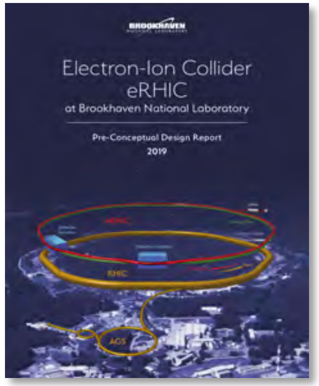
Physics of EIC

2018

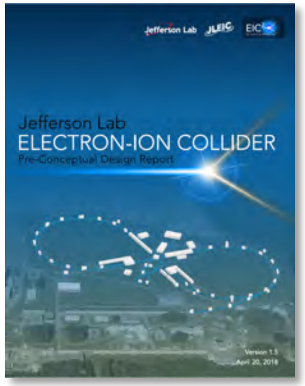


Evaluation

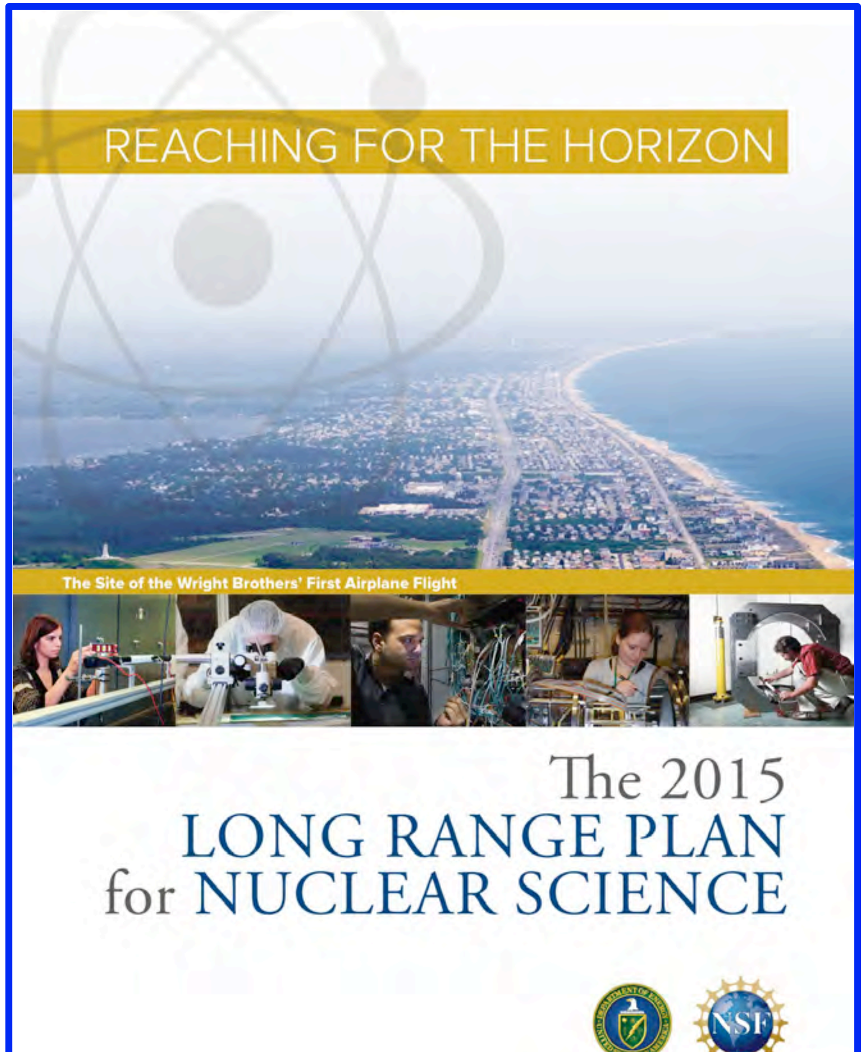
2019



2019



Realization



http://science.energy.gov/np/reports

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

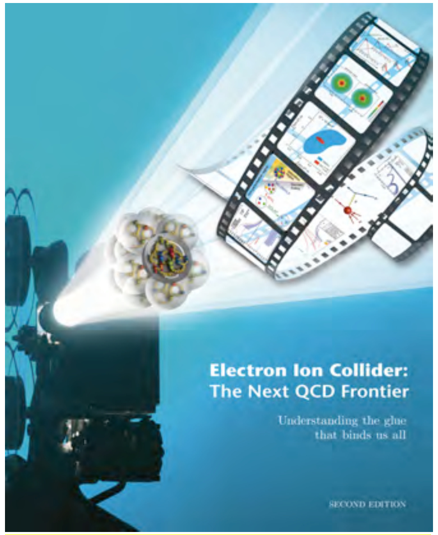
Detector R&D money ~1.3M/yr since 2011

Increase anticipated soon after project officially begins

Since FY 2017

EIC Accelerator R&D already assigned $7M/yr

The Electron Ion Collider



1212.1701.v3
A. Accardi et al
Eur. Phy. J. A, 52 9(2016)

For e-N collisions at the EIC:

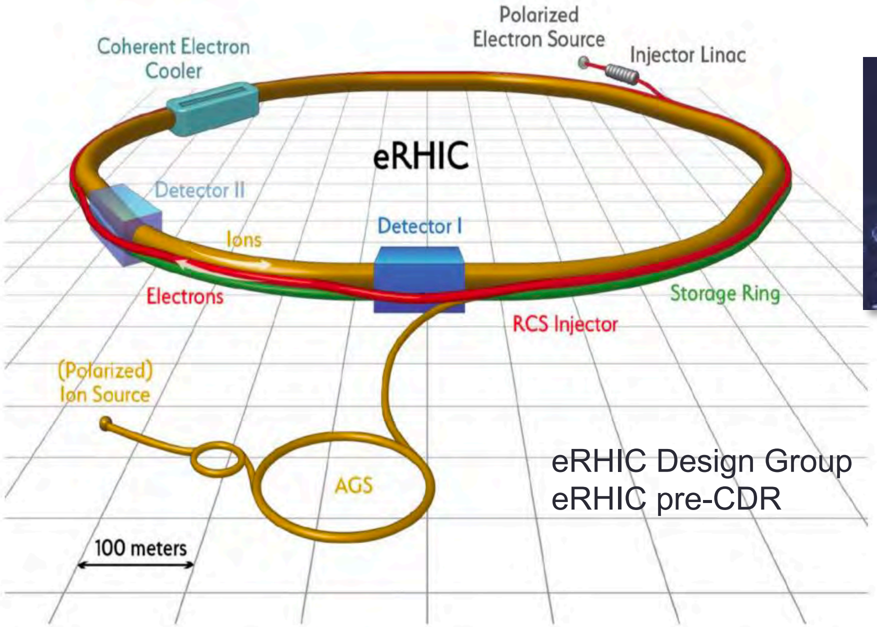
- ✓ Polarized beams: e, p, d/^{3}He
- ✓ e beam 5-10(20) GeV
- ✓ Luminosity L_{ep} ~ 10^{33-34} cm^{-2}sec^{-1}
  100-1000 times HERA
- ✓ 20-100 (140) GeV Variable CoM

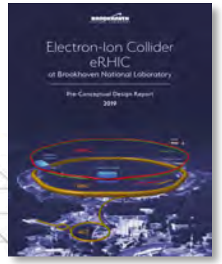
For e-A collisions at the EIC:

- ✓ **Wide range in nuclei**
- ✓ Luminosity per nucleon same as e-p
- ✓ Variable center of mass energy

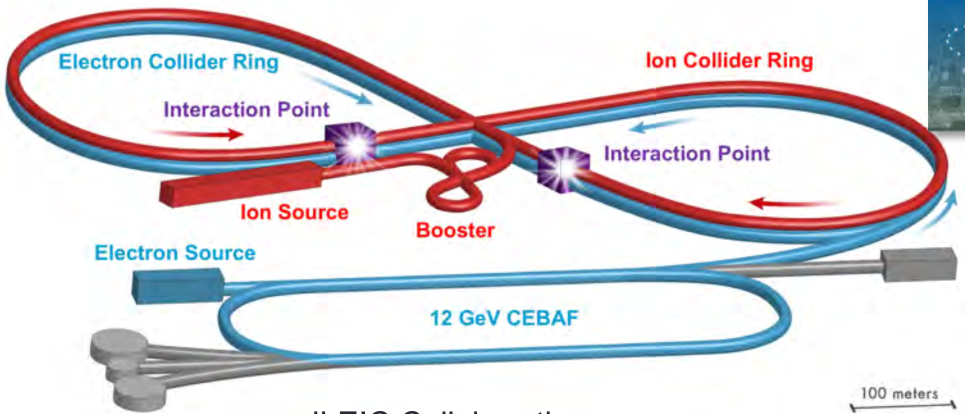
World's first
Polarized electron-proton/light ion
and electron-Nucleus collider

Both designs use DOE's significant investments in infrastructure



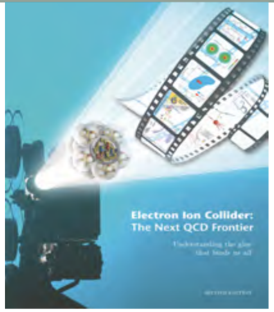


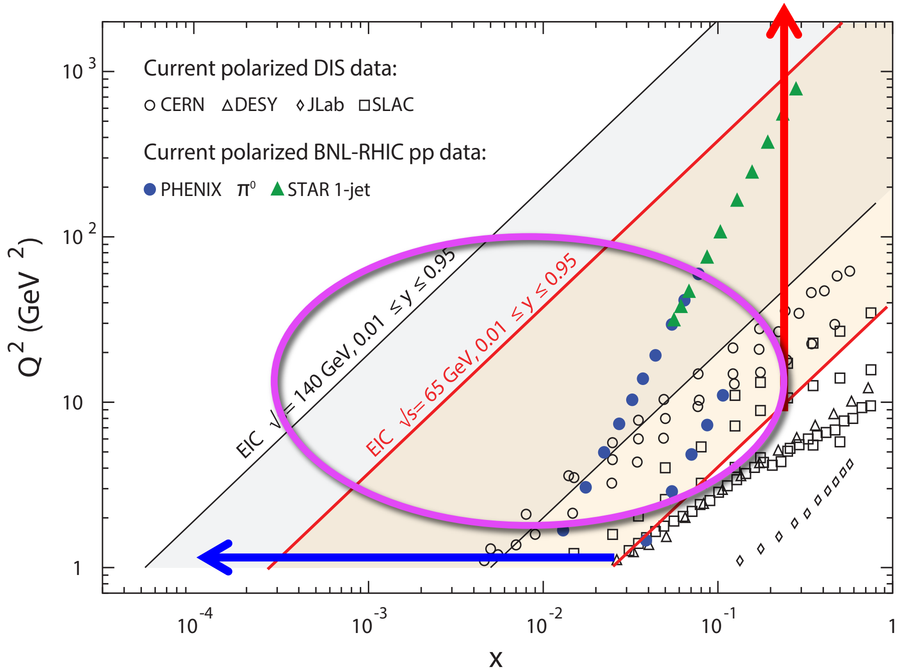
eRHIC Design Group
eRHIC pre-CDR



JLEIC Collaboration
JLEIC Pre-CDR

EIC: Kinematic reach & properties



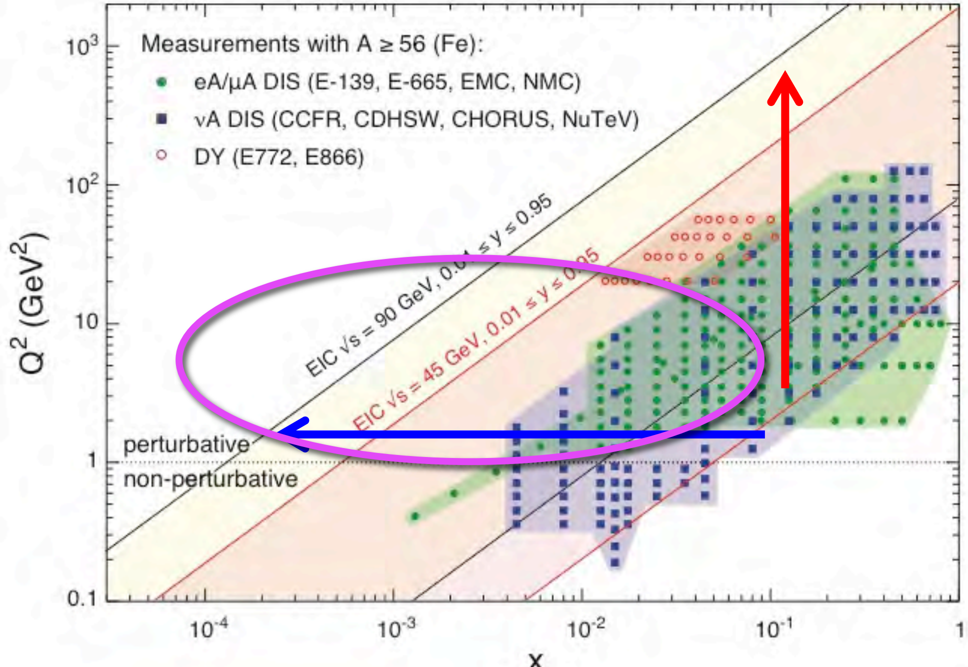


For e-N collisions at the EIC:

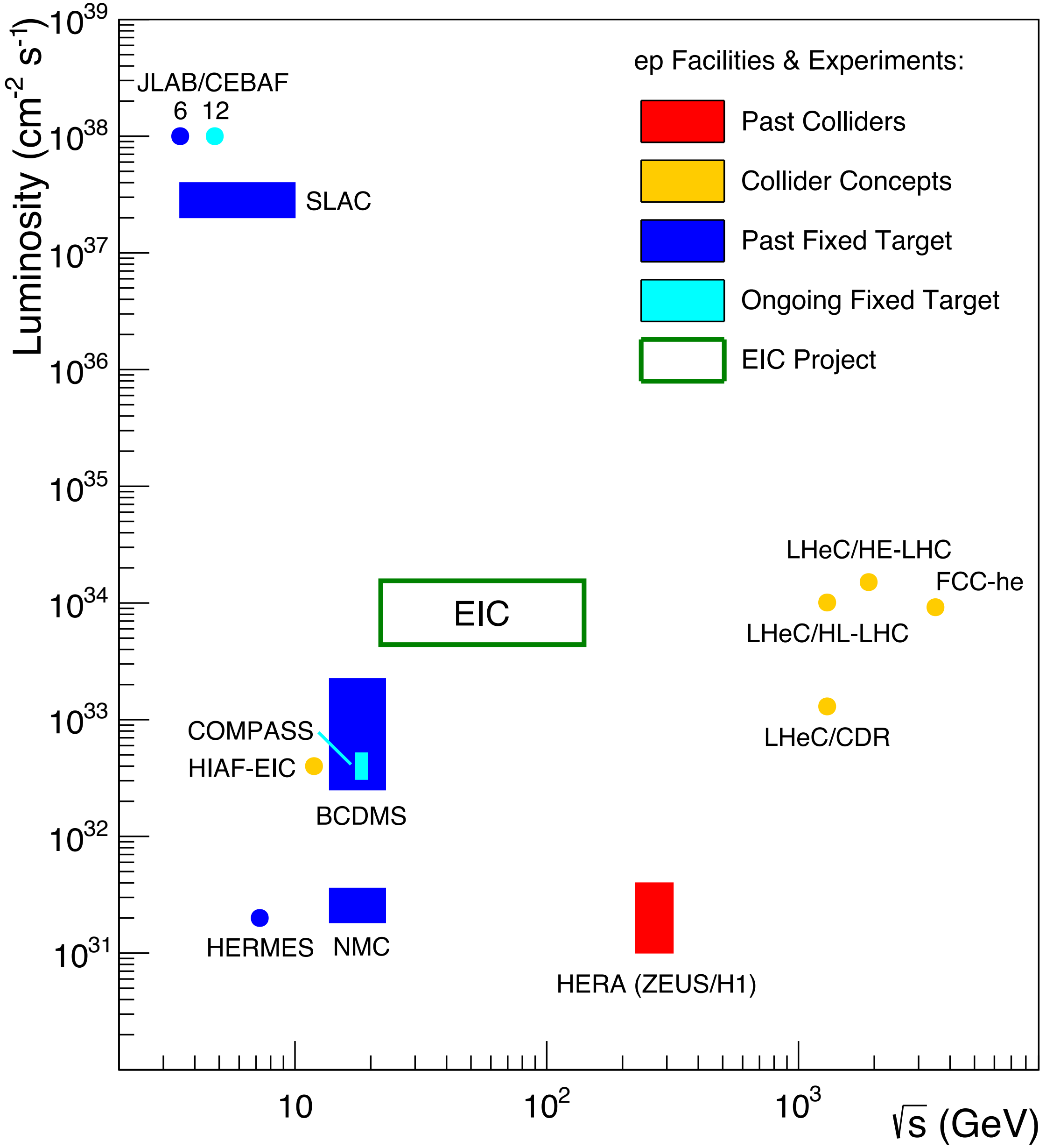
- ✓ **Polarized** beams: e, p, d/^{3}He
- ✓ Variable center of mass energy
- ✓ Wide Q^2 range → evolution
- ✓ Wide x range → spanning valence to low-x physics

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)



Uniqueness of the US EIC among all DIS Facilities



All DIS facilities in the world.

However, if we ask for:

- high luminosity & **wide reach in √s**

No other facility has or plans for

- **polarized lepton & hadron beams**
- **nuclear beams**

EIC a truly unique facility

The National Academy Review of the EIC Science

2017-2018

Statement of Task from the Office of Science (DOE/NSF) to the National Academy of Science, Engineering & Medicine (NAS)

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.

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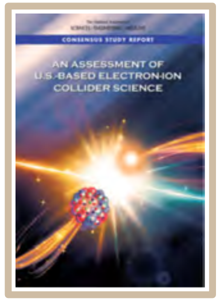
In particular, the committee will address the following questions:

- 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?

NAS Consensus: EIC science compelling, fundamental, and timely

July 26, 2018



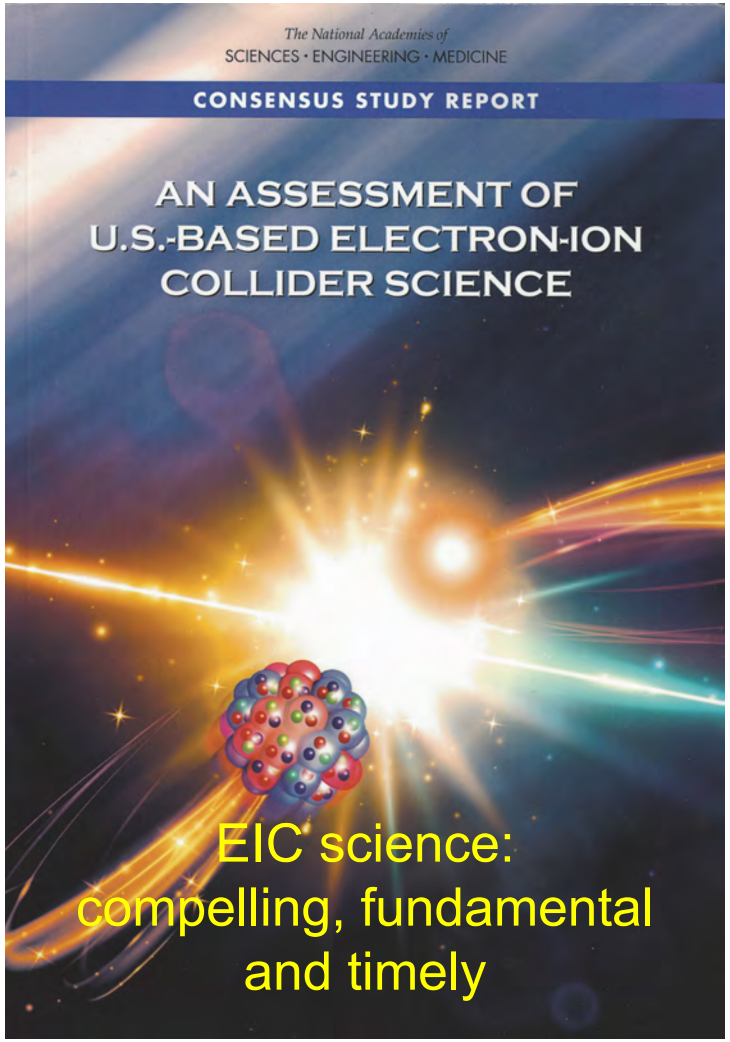
- **Finding 1**: An EIC can uniquely address three profound questions about nucleons—neutrons and protons—and how they are assembled to form the nuclei of atoms:
  - How does the mass of the nucleon arise?
  - How does the spin of the nucleon arise?
  - What are the emergent properties of dense systems of gluons?
- **Finding 2:** These three high-priority science questions can be answered by an EIC with highly polarized beams of electrons and ions, with sufficiently high luminosity and sufficient, and variable, center-of-mass energy.

Other findings:

An EIC would be a unique facility in the world

Leadership in the accelerator science and technology of colliders

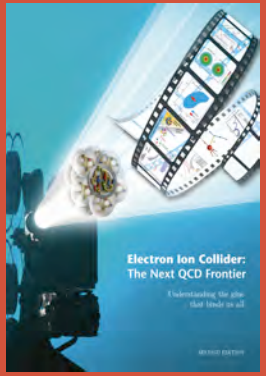
US EIC Cost effective: takes advantage of existing accelerator infrastructure and expertise ➔ reduced risk

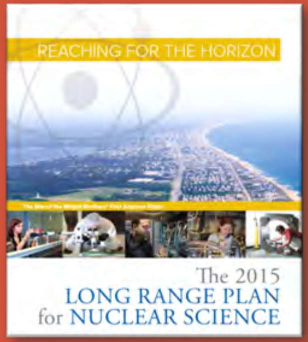


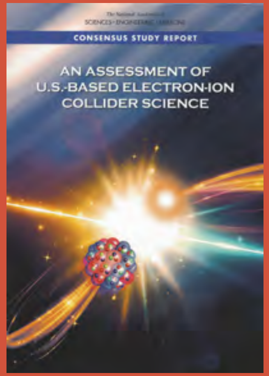
Consensus Study Report on the US based Electron Ion Collider

Summary:

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







The Compelling And Fundamental Science Of EIC

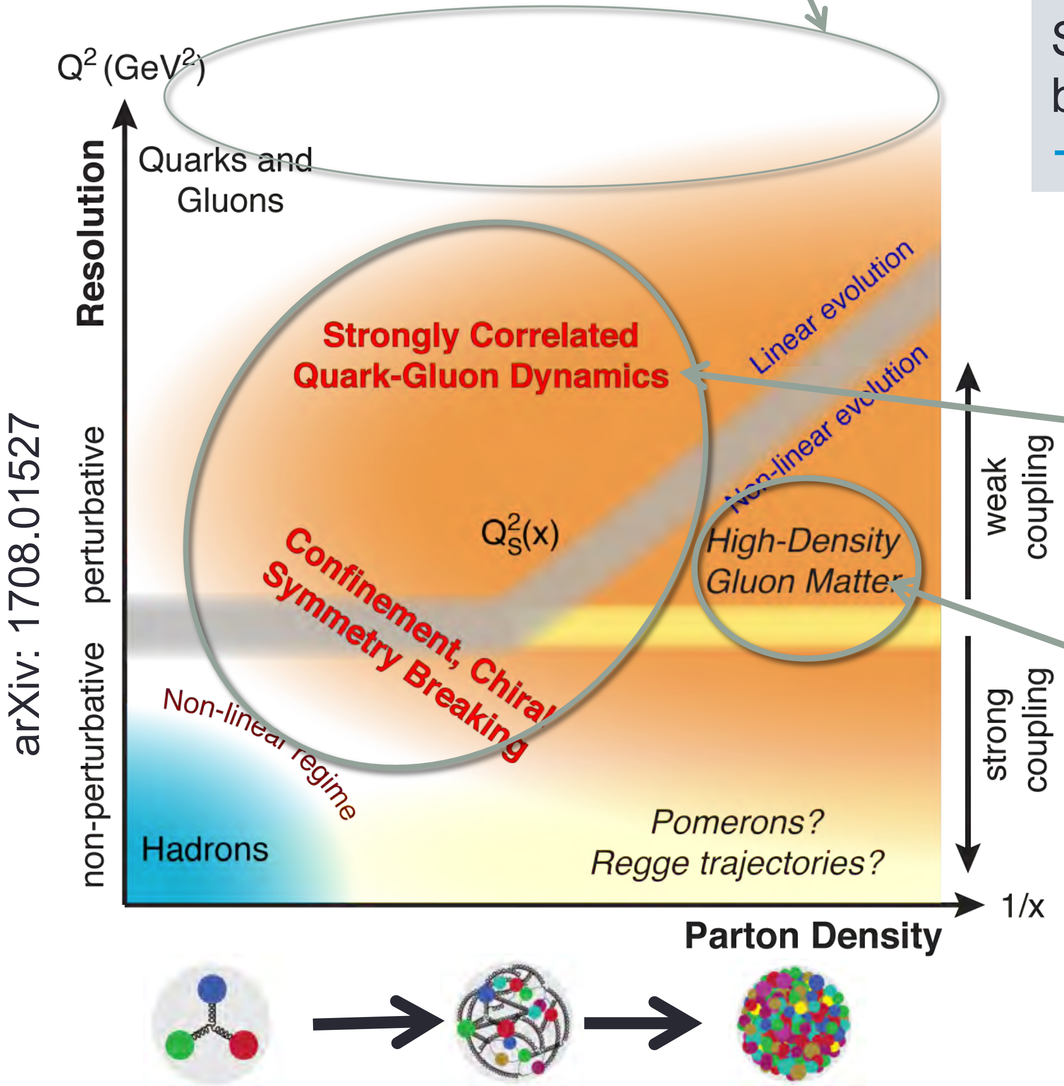
The science of EIC @ BNL and at Jefferson Lab not fundamentally different.

Just the realization may depend on the details of project realization

QCD Landscape to be explored by EIC

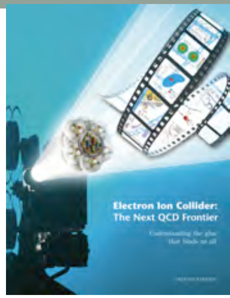
QCD at high resolution (Q^2) —weakly correlated quarks and gluons are well-described

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



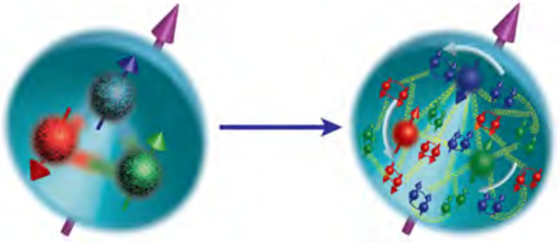
EIC will systematically explore correlations in this region.

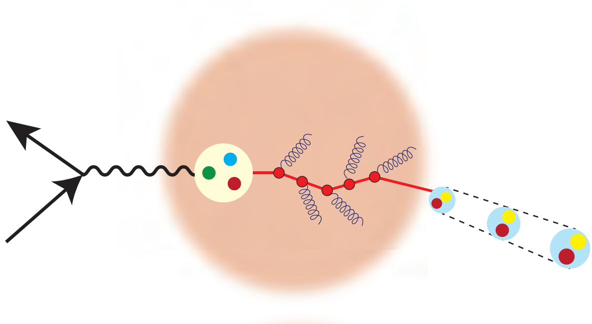
An exciting opportunity: Observation by EIC of a new regime in QCD of weakly coupled high density matter



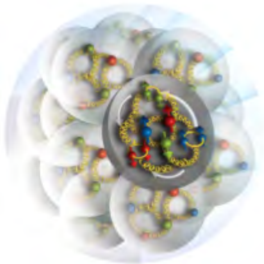
A new facility is needed to investigate, with precision, the dynamics of gluons & sea quarks and their role in the structure of visible matter

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?

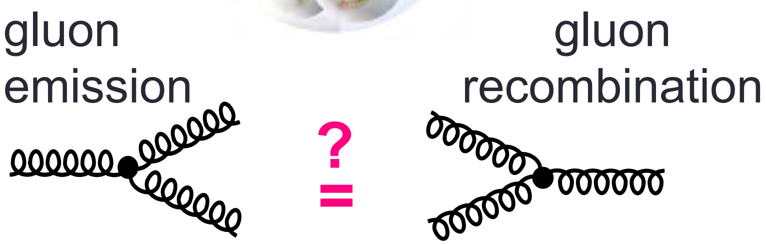




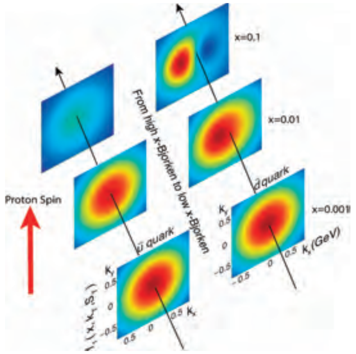
How do color-charged quarks and gluons, and colorless jets, interact with a nuclear medium?
How do the confined hadronic states emerge from these quarks and gluons?
How do the quark-gluon interactions create nuclear binding?



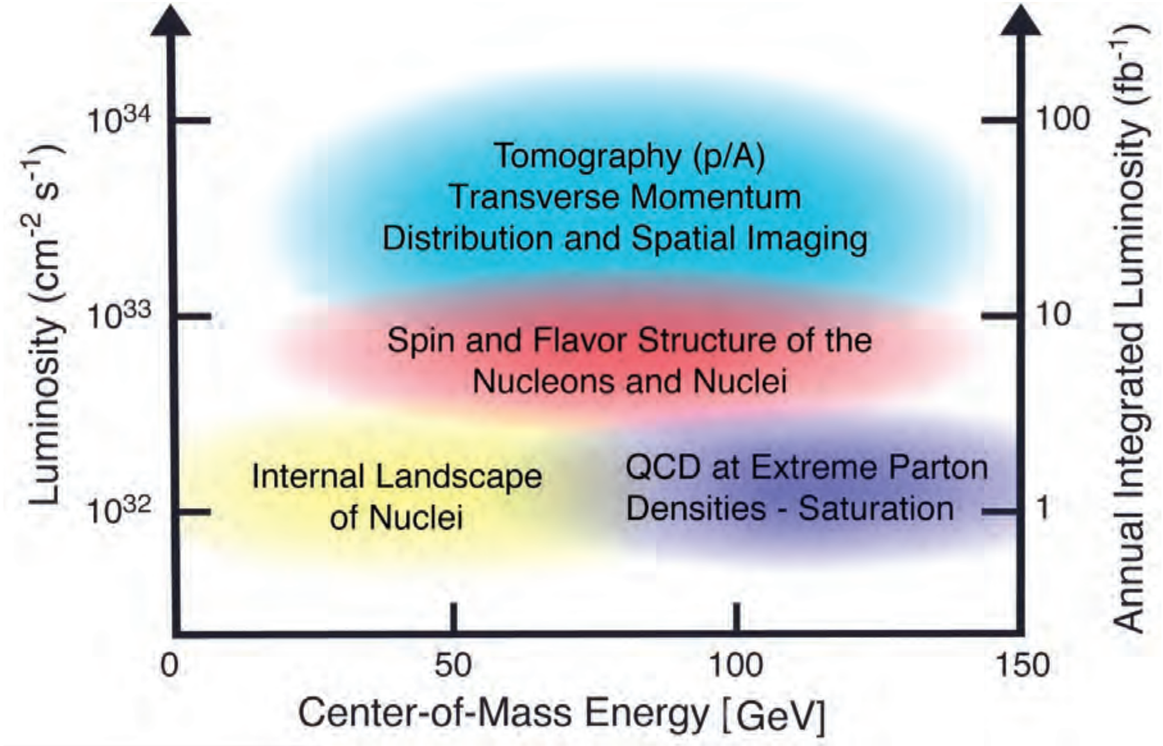
How does a dense nuclear environment affect the quarks and gluons, their correlations, and their interactions?
What happens to the gluon density in nuclei? Does it saturate at high energy, giving rise to a gluonic matter with universal properties in all nuclei, even the proton?

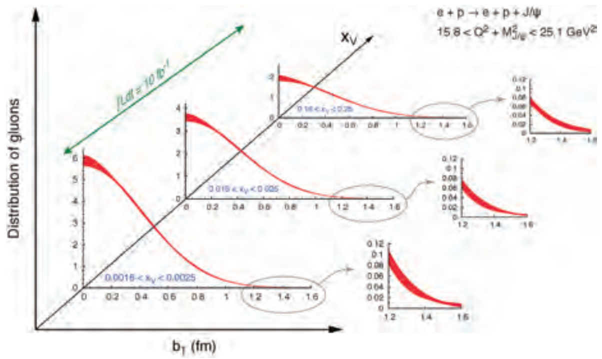


EIC science and required luminosity

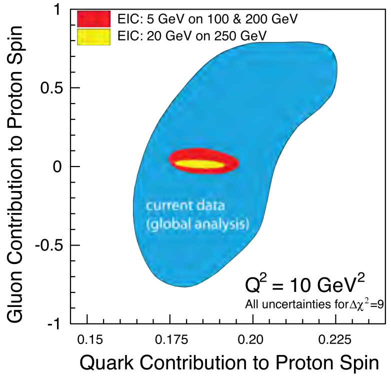


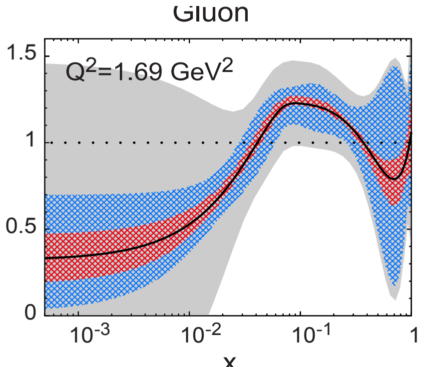
2+1D imaging of quarks and gluons, dynamics, and emergence of spin & mass

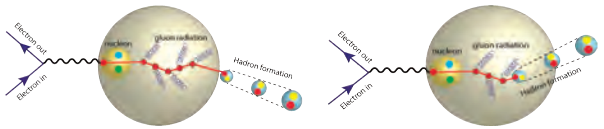




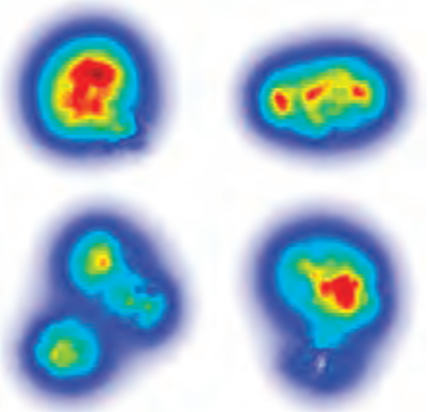
Gluon imaging in nucleons







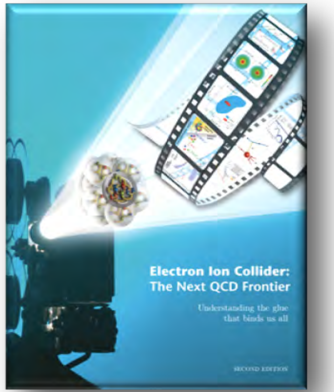
Color propagation, neutralization in nuclei & hadronization

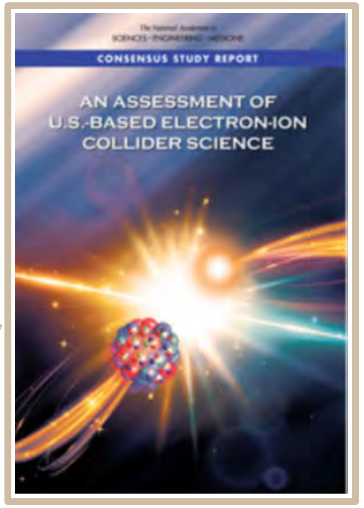


Gluons at high energy in nuclei:
(Gluon imaging in nuclei)

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

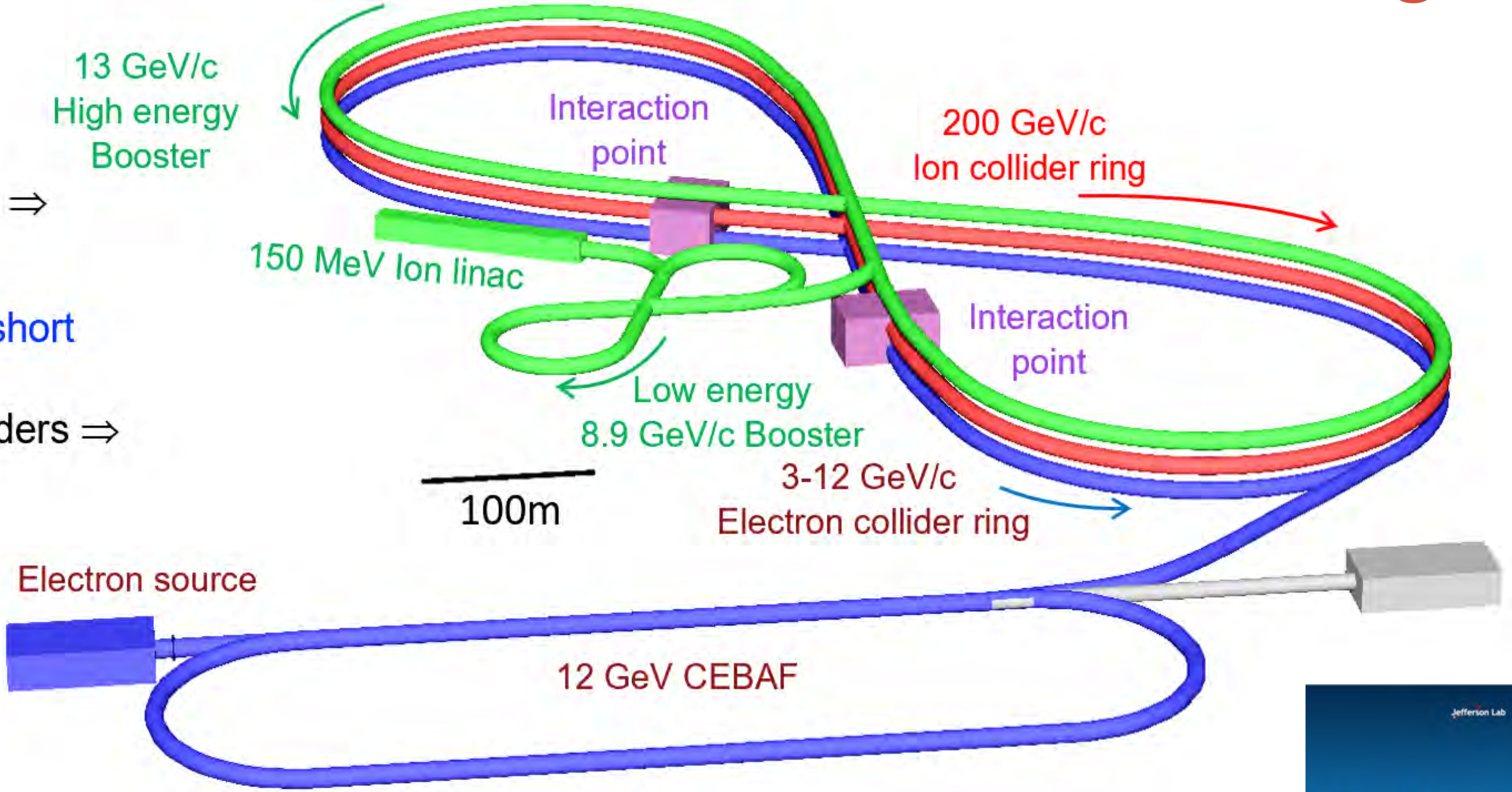
US EIC's Path to realization

The machine design parameters of the EIC (BNL and Jlab) are chosen to address all science that the community led EIC White Paper defined and the NAS supported

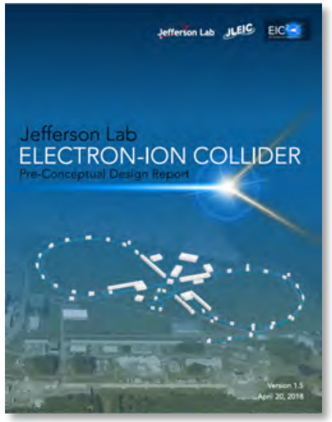
Seryi & Willeke EICUG 2019

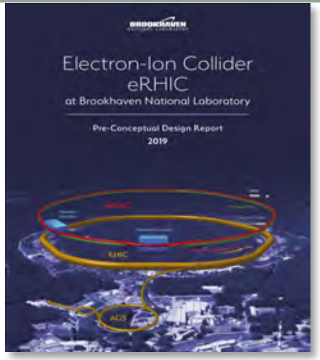
JLEIC Design

- Full-energy top-up injection of highly polarized electrons from CEBAF ⇒ High electron current and polarization
- Full-size high-energy booster ⇒ Quick replacement of colliding ion beam ⇒ High average luminosity
- High-rate collisions of strongly-focused short low-charge low-emittance bunches similarly to record-luminosity lepton colliders ⇒ High luminosity
- Multi-stage electron cooling using demonstrated magnetized cooling mechanism ⇒ Small ion emittance ⇒ High luminosity

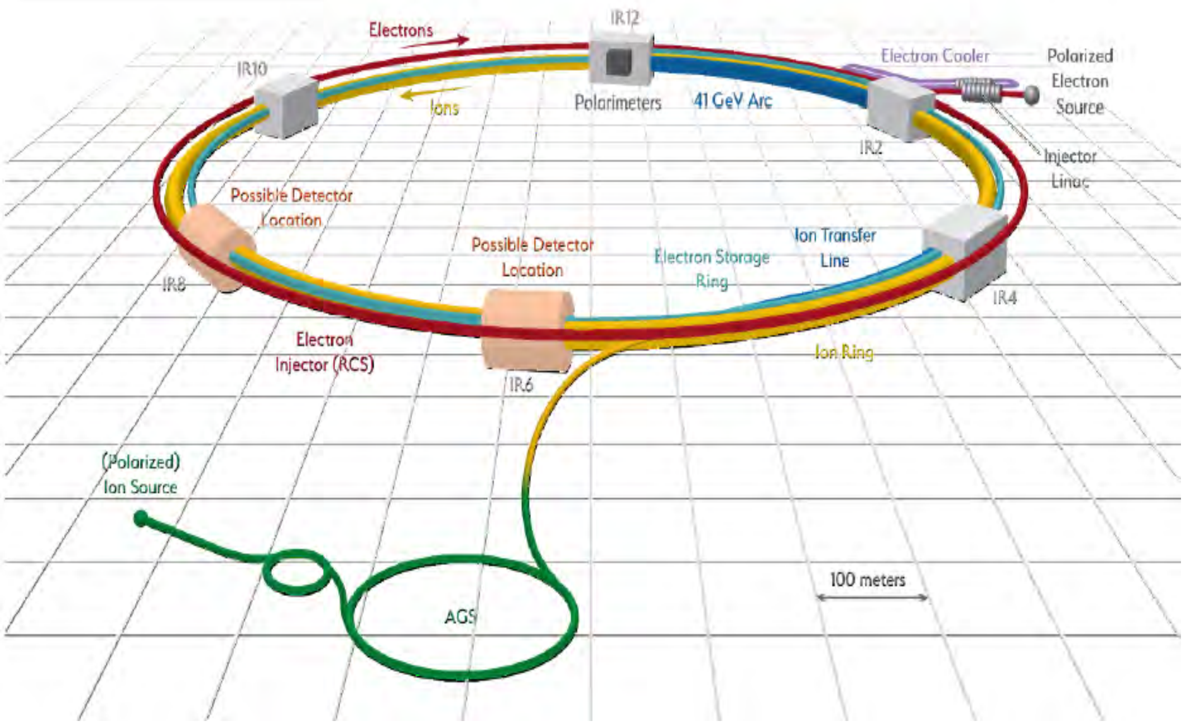


- Figure-8 ring design ⇒ High electron and ion polarizations, polarization manipulation and spin flip
- Integrated full acceptance detector with far-forward detection sections being parts of both machine and detector
- Upgradable to 140 GeV CM by replacing the ion collider bending dipoles only with 12 T magnets





The Electron Ion Collider at BNL



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

Protons 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

Polarized He, Deuterons possible with minimal well understood modifications

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

Design optimized to reach 10^{34} $cm^{-2}sec^{-1}$

Strategy for maximizing luminosity at any CoM

Storage ring design of e-p/A for the Electron Ion Collider require the following for luminosity maximization:

- ✓ **Large bunch charge** ➔ large number of protons in a bunch (source dependent)

- ✓ **Many bunches**
  - ❖ large total bunch current
  - ❖ crossing angle in collision geometry

- ✓ **Small beam size** (cross section) at the collision point
  - ❖ small emittance ➔ requires strong hadron cooling or frequent injection fresh bunches
  - ❖ strong focusing at the IR (small $\beta*$) ➔ requires short bunches need strong cooling

- ✓ **Beam-beam limit** negotiation: Transverse beam density at collision point limited by the detrimental effect of the corresponding nonlinear effects

Key EIC Machine Parameters

as required by the NSAC LRP & NAS

Seryi and Willeke, EICUG2019

Parameter	Unit	JLEIC	eRHIC
Center of Mass Energies	[GeV]	20-100 a)	20-140
Ion Species		p to U	p to U
Number of Interaction Regions		2	2
Hadron Beam Polarization		80%-85%	80%
Electron Beam Polarization		80%	80%
Maximum Luminosity	$[10^{34} cm^{-2} s^{-1}]$	1.55	1.3

a) upgradable to 140 GeV

EIC Luminosity

IR Designs can be adjusted to obtain peak luminosity at different center of mass energies. The EIC@BNL Luminosity curves below show luminosity vs E_{cm} with IRs optimized for **high** or **low** center of mass energy. With two IRs, both optimization could coexist. JLEIC curves shows scenarios **without** and **with the upgrade of** ion magnets in the arcs.

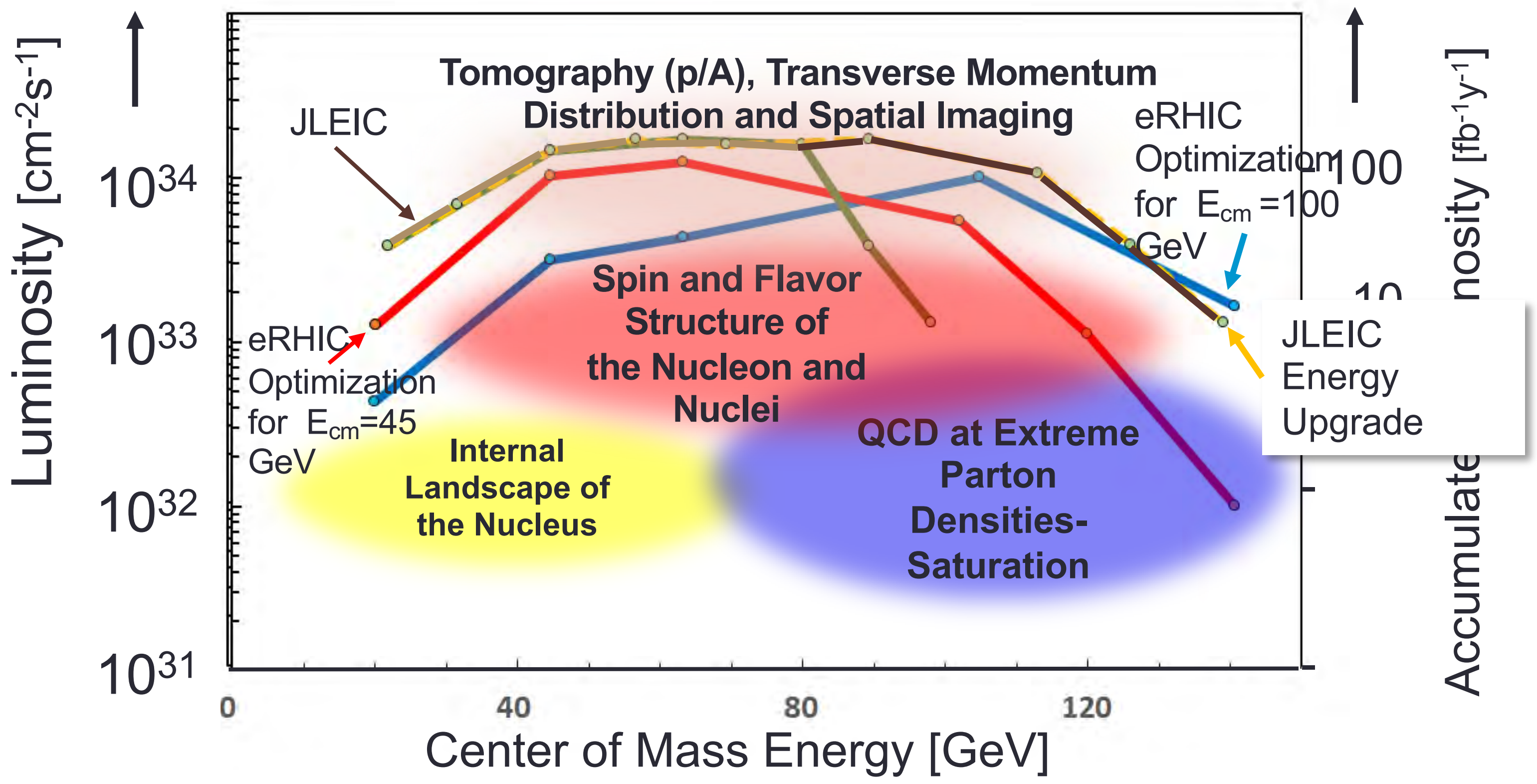
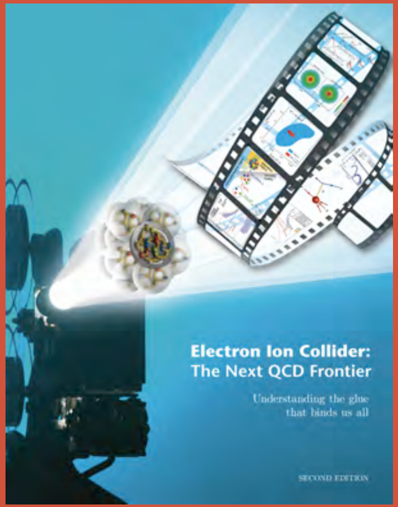


Figure from Seryi & Willeke EICUG 20119

Luminosity differences depend on comfort level with various parameters assumed in two designs

For electron ion collisions, the E_{cm} scale needs to be reduced by a factor $(Z/A)^{1/2}$



1212.1701.v3 Ed. A. Deshpande, J.-W. Chiu, Z.E. Meziani
A. Accardi et al Eur. Phy. J. A, 52 9(2016)

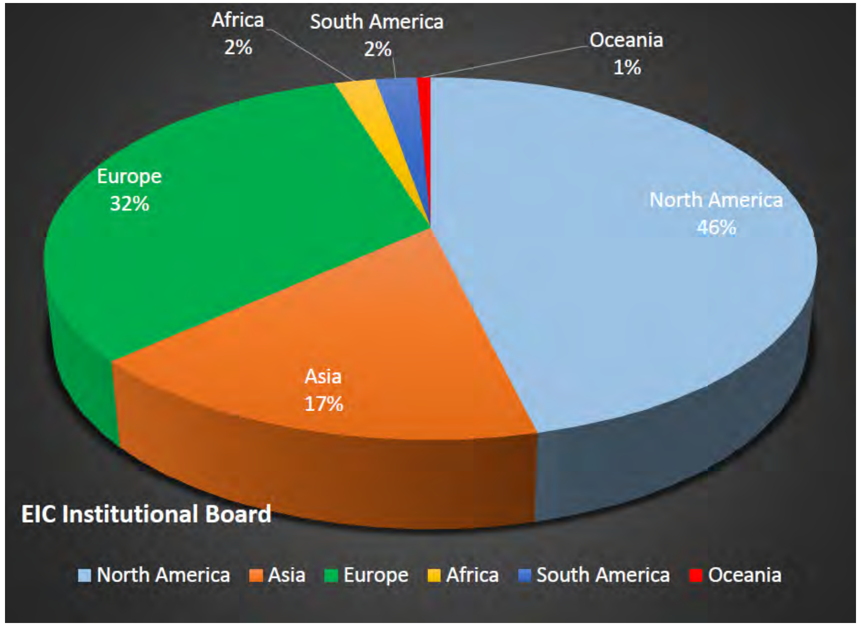
The International EUC Users

Organizing to maximize the Science Potential of the EIC most optimally

The EIC Users Group: EICUG.ORG

Formally established in 2016
890+ Ph.D. Members from 30 countries, 189 institutions

New:
[Center for Frontiers in Nuclear Science](#) (at Stony Brook/BNL)
[EIC²](#) at Jefferson Laboratory



EICUG Structures in place and active.

EIC UG Steering Committee
EIC UG Institutional Board
EIC UG Speaker's Committee

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

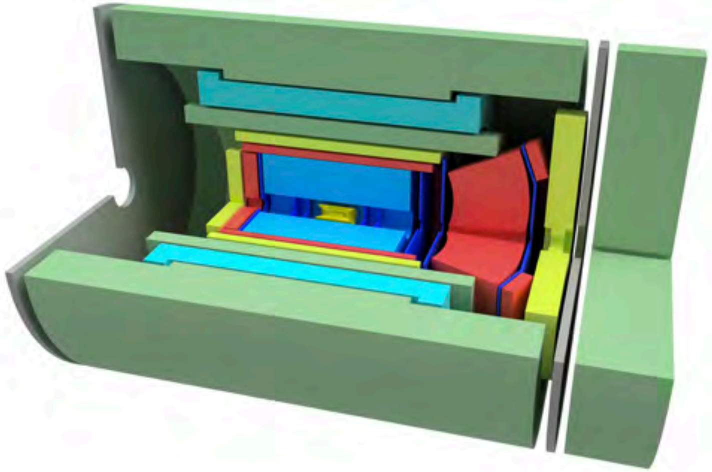
Annual meetings: Stony Brook (2014), Berkeley (2015), **ANL (2016)**, **Trieste (2017)**, **CAU (2018)**, **Paris (2019)**, **[FIU (2020)](#)**, **Warsaw (2021)**

Opportunities for YOU: Physics @ the US EIC beyond the EIC White Paper:

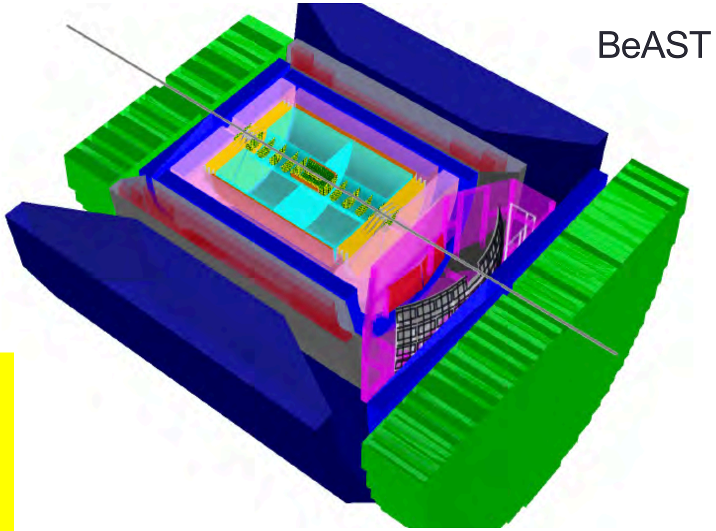
- Nucleon Mass? Upsilon on the threshold. *(Joosten's talk)*
- Heavy quark and quarkonia (c, b quarks) studies beyond HERA, with 100-1000 times luminosities (??) Does polarization of hadron play any role?
- *Quark Exotica: 4,5,6 quark systems…?* *(Joosten's talk)*
- Impact of precision measurements of unpolarized PDFs, especially at high x, for LHC
- *What role would TMDs in e-p play in W-Production at LHC?*
- Study of jets: Internal structure of jets
- *Jet propagation in nuclei… energy loss in cold QCD medium: a topic interest*
- Initial state affects QGP formation!….. p-A, d-A, A-A at RHIC and LHC: many puzzles
- *Gluon TMDs at low-x!*
- Polarized light nuclei in the EIC *(Weiss, Deshpande et al. Workshop Series)*
- *Entanglement entropy in nuclear medium and its connections to fragmentation, hadronization and confinement*
- Electroweak physics and searches beyond the Standard Model

EIC Detector Concepts: integration of detectors in to machine lattice

EIC Day 1 detector, with BaBar Solenoid

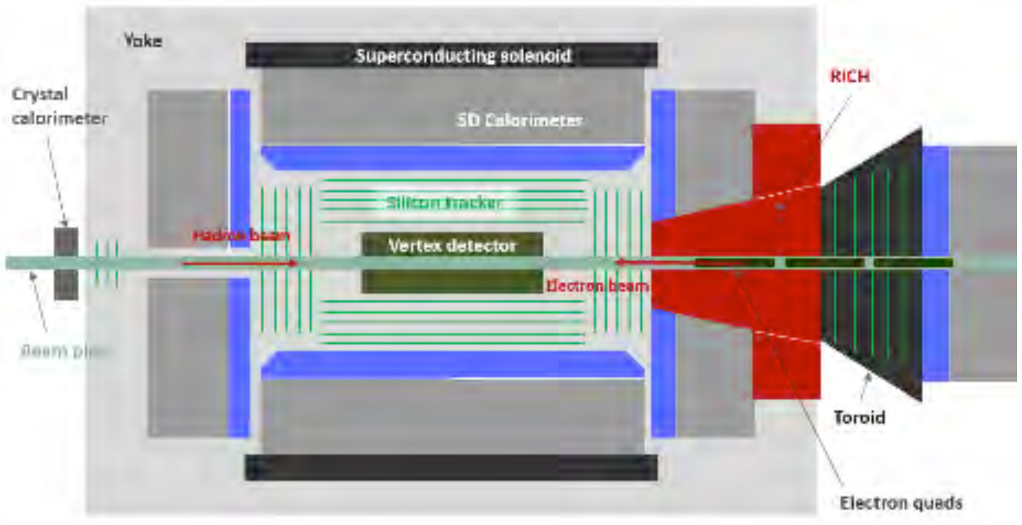


BeAST at BNL

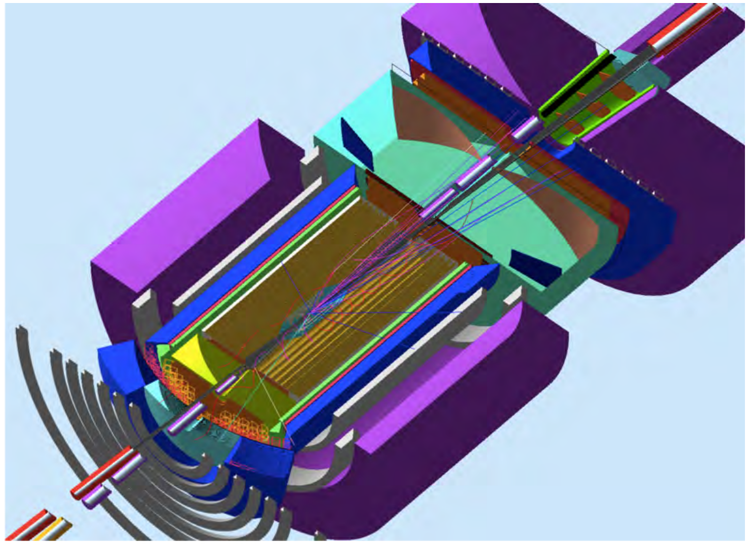


Ample opportunity and need for additional contributors and collaborators

TOPSiDE: Time Optimized PID Silicon Detector for EIC



JLEIC Detector Concept, with CLEO Solenoid



Dir. Of office of NP
Tim Hallman's presentation

EICUG
Paris,
July
2019

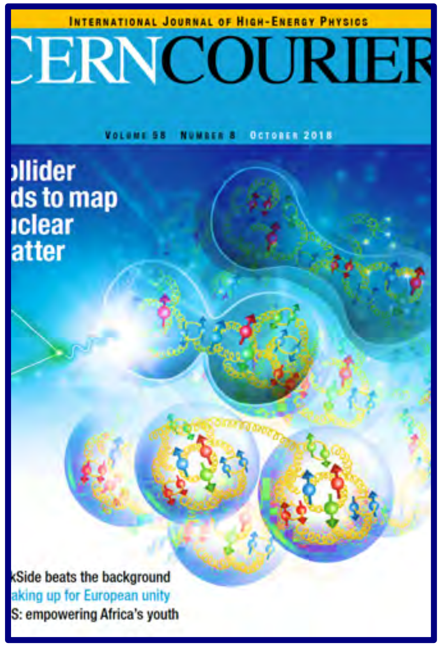
Current Status and Path forward of EIC

The "wickets" are substantially aligned for a major step forward on the EIC

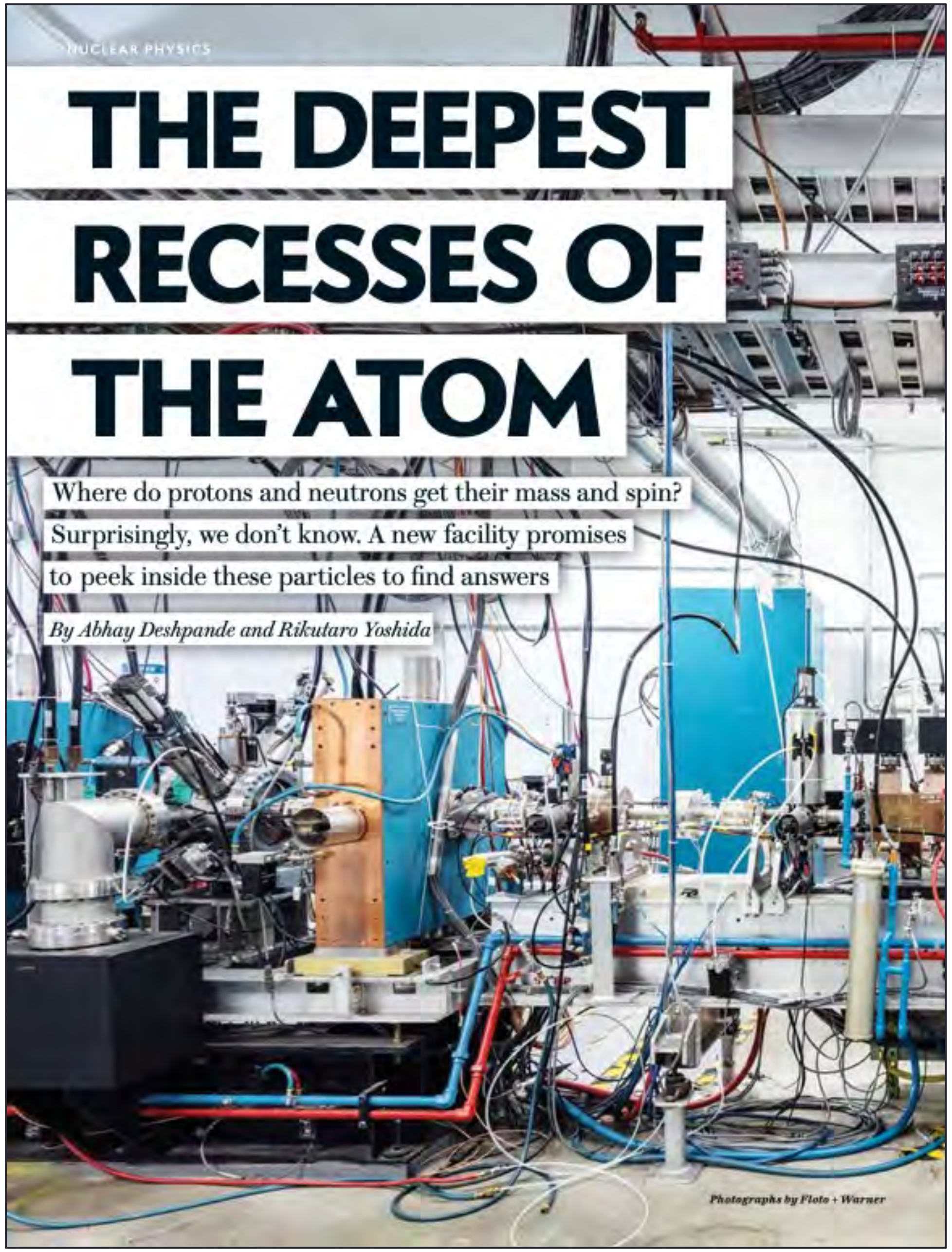
- A Mission Need Statement for an EIC has been approved by DOE
- An Independent Cost Review (ICR) Exercise mandated by DOE rules for projects of the projected scope of the EIC is very far along
- DOE is moving forward with a request for CD-0 (approve Mission Need)
- DOE has organized a panel to assess options for siting and consideration of "best value" between the two proposed concepts
- The Deputy Secretary is the Acquisition Executive for this level of DOE Investment
- **The FY 2020 President's Request includes $ 1.5 million OPC. The FY 2020 House Mark includes $ 10 million OPC and $ 1 million TEC.**

R. Ent, T. Ullrich, R. Venugopalan
Scientific American (2015)

E. Aschenauer
R. Ent
October 2018



A. Deshpande
& R. Yoshida
June 2019



Summary:

- Science of EIC: Gluons that bind us all… understanding their role in QCD
- EIC's precision, control and versatility will revolutionize our understanding QCD
  - ➢ 3D nucleon/nuclear structure, cold nuclear matter & physics high gluon density

- The US EIC project has significant momentum on all fronts right now:
  - National Academy's positive evaluation → Science compelling, fundamental and timely
  - Funding agencies taking note of the momentum: not just in the US but also internationally

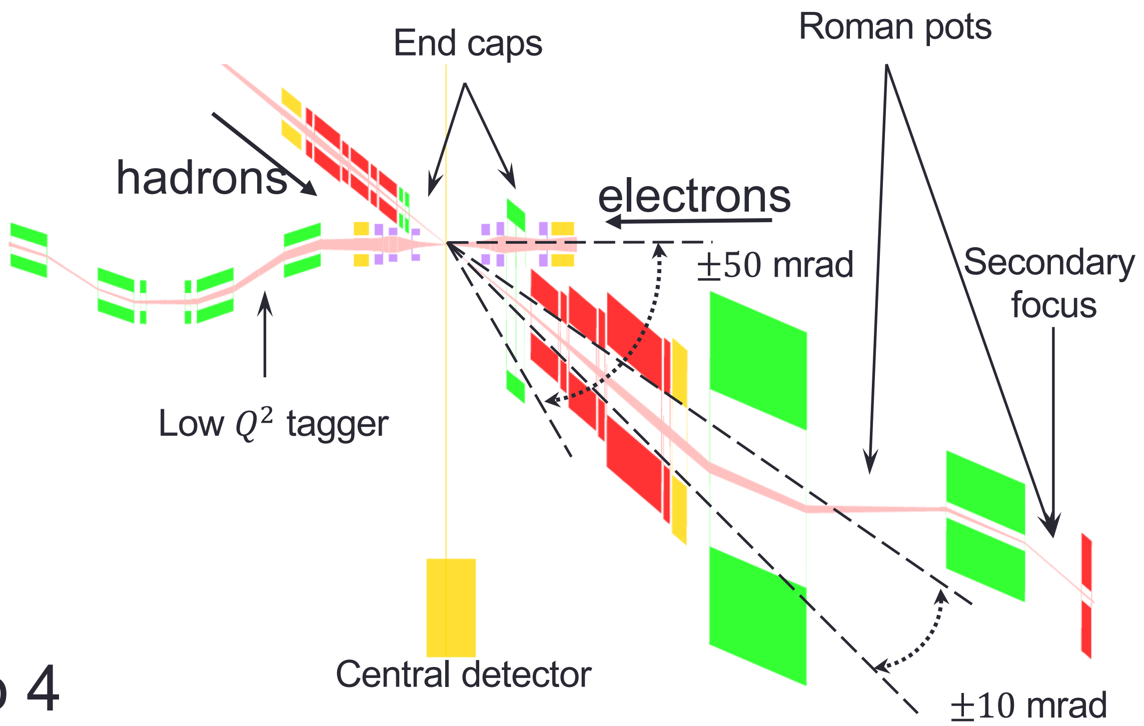
- The science of EIC, technical designs (eRHIC and JLEIC) moving forward
  - Pre-CDRs prepared by BNL (eRHIC) and JLab: machine & IR designs
  - Independent Cost Review underway ➔ CD0 anticipated soon. Siting decision process also underway.

Both Lab managements are committed to working with the DOE, the EICUG and the international partners to realize the US EIC no matter its site (BNL or JLab)

Thank you.

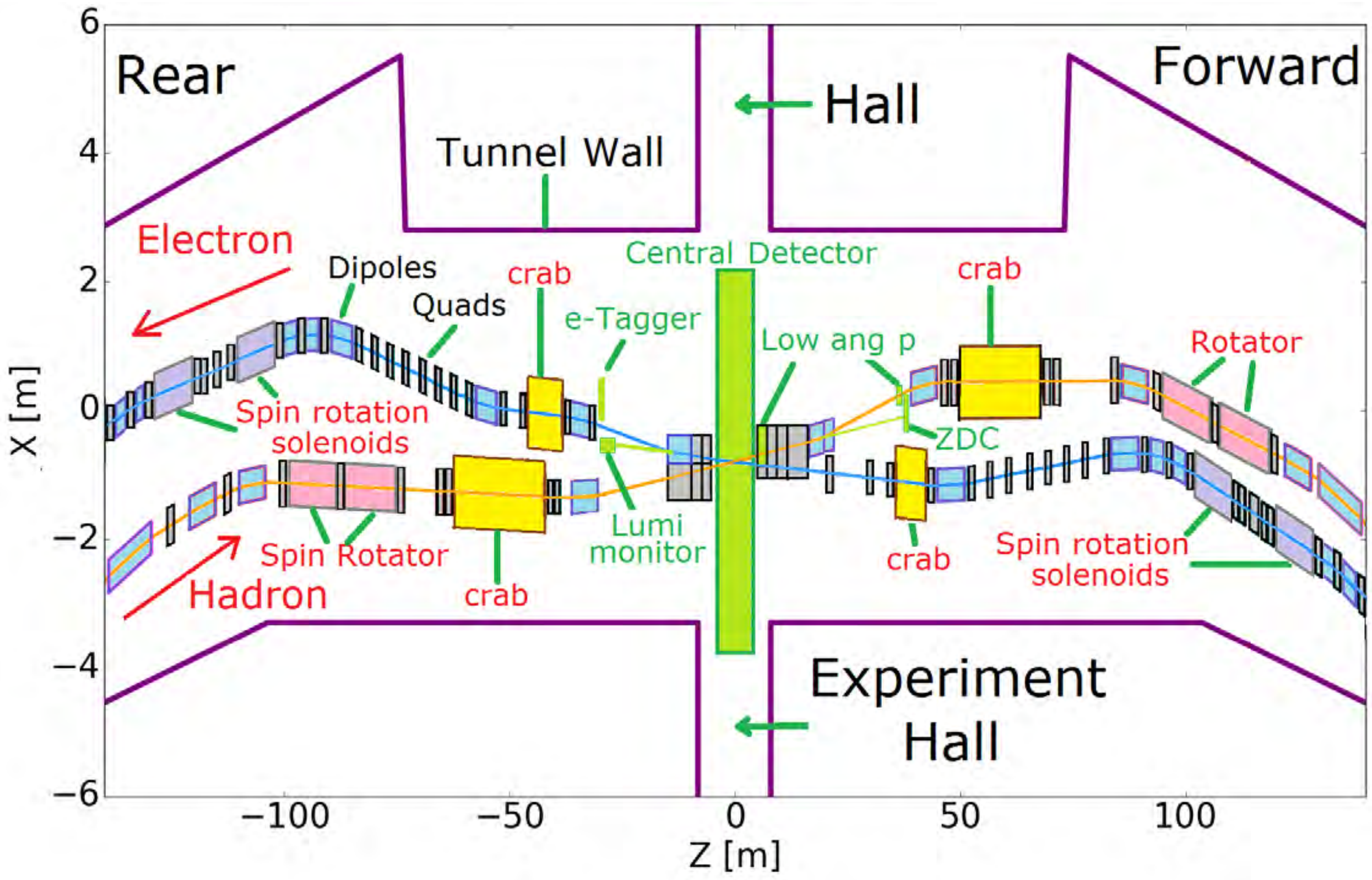
JLEIC Full Acceptance IR Layout

- 50 mrad crossing angle
- Forward hadron detection in three stages
  - Endcap
  - Small dipole covering angles up to ~3°
  - Far forward, ~10 mrad, for particles passing through accelerator quads
- Low-Q2 tagger
  - Small-angle electron detection
- Large beta functions in the IR up to 4 km but manageable chromatics and dynamic aperture



Courtesy V., Morozov, A. Seryi

Full Acceptance eRHIC IR Layout



Design

- All superconducting magnets
- ➢ Only 5 magnets need collared Nb-Ti coils
- ➢ All other magnets can be built with **direct wind** of Nb-Ti wire

- Full acceptance e.g. P_t =200 MeV/c-1.3 GeV/c
- ➢ Neutrons 4 mrad

- Large Aperture Dipole w/ instrumented gap

- Modest IR chromaticity

- Hadrons up to β<200m
- ➔ Manageable dynamic aperture optimization