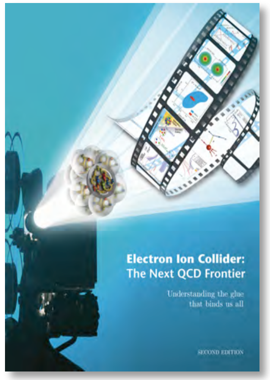
Center for Frontiers in Nuclear Science

The US Electron Ion Collider

An introduction

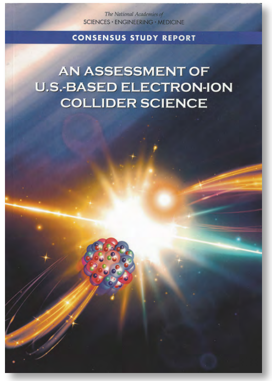
2015



2016

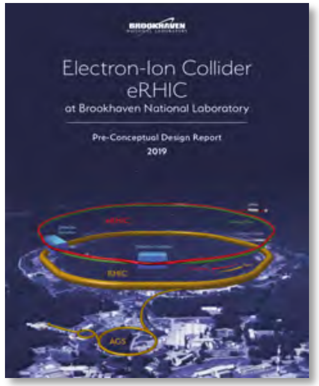
Physics of EIC

2018

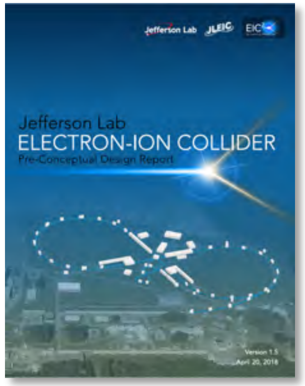


Evaluation

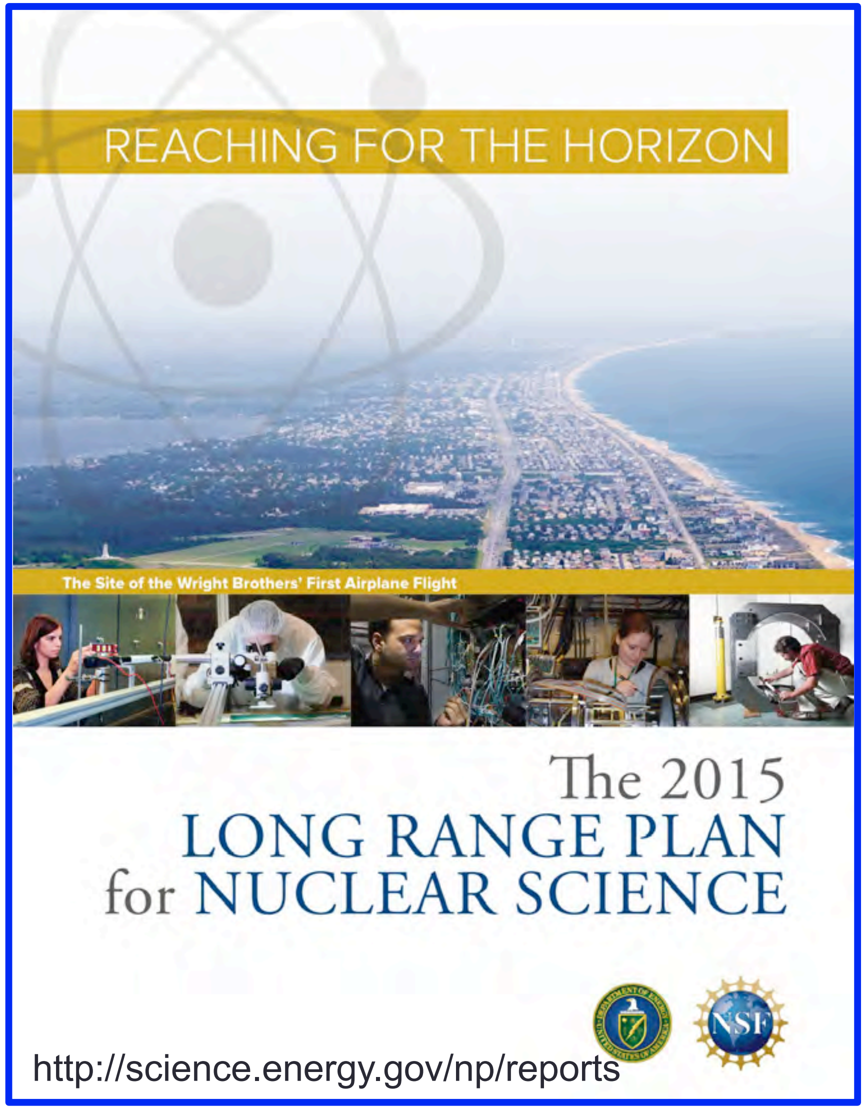
2019



2019



Realization



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

Gluons, the carriers of the strong force, bind the quarks together inside nucleons and nuclei and generate nearly all of the visible mass in the universe. Despite their importance, fundamental questions remain about the role of gluons in nucleons and nuclei. These questions can only be answered with a powerful new electron ion collider (EIC), providing unprecedented precision and versatility. The realization of this instrument is enabled by recent advances in accelerator technology.

RECOMMENDATION:

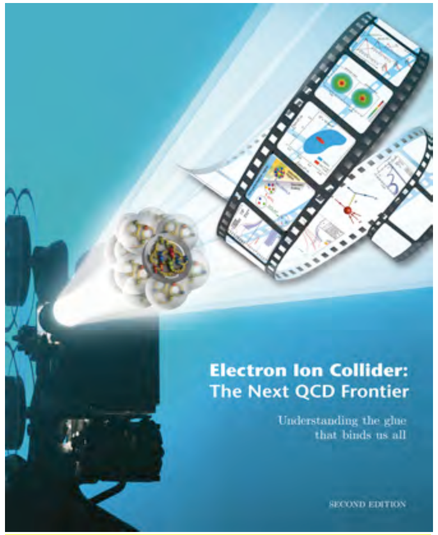
We recommend a high-energy high-luminosity polarized EIC as the highest priority for new facility construction following the completion of FRIB.

Initiatives:

Theory

Detector & Accelerator R&D

The Electron Ion Collider



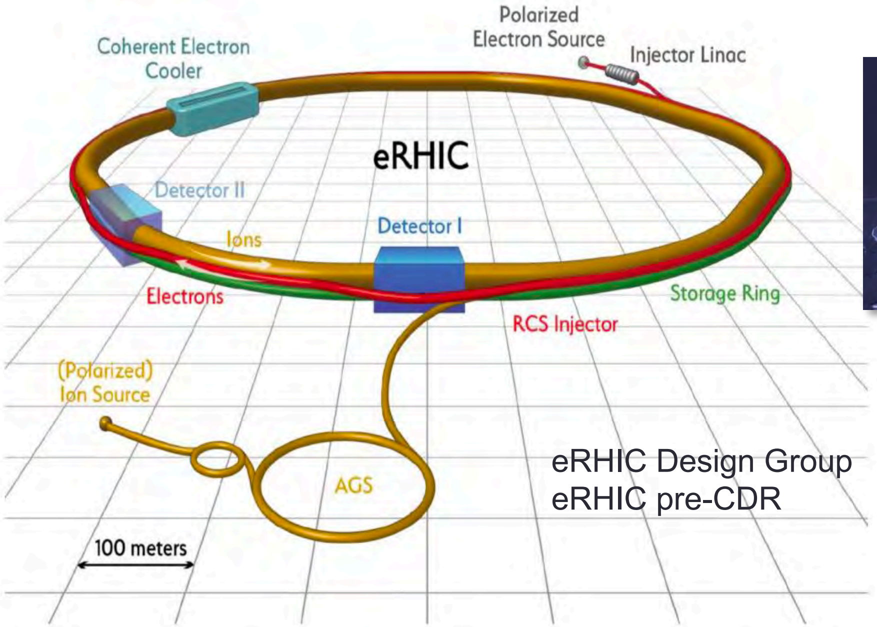
1212.1701.v3
A. Accardi et al
Eur. Phy. J. A, 52 9(2016)

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

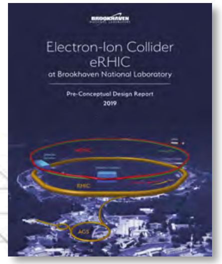
For e-A collisions at the EIC:
- ✓ **Wide range in nuclei**
- ✓ Luminosity per nucleon same as e-p
- ✓ Variable center of mass energy

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

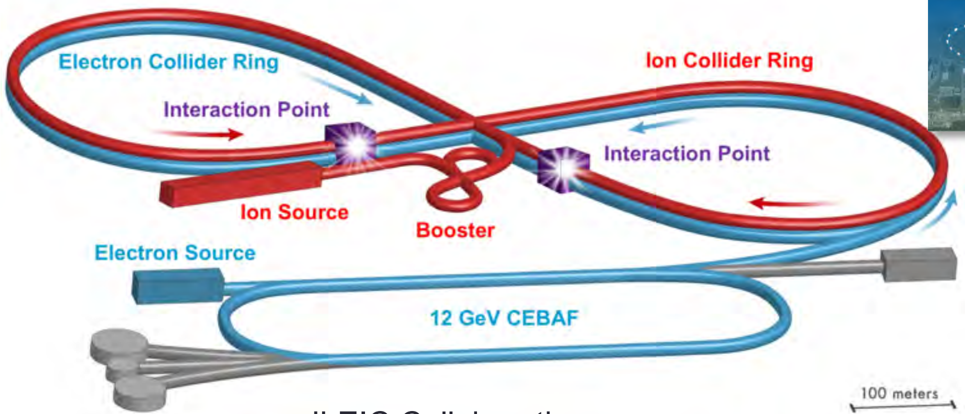
Both designs use DOE's significant investments in infrastructure



eRHIC Design Group
eRHIC pre-CDR

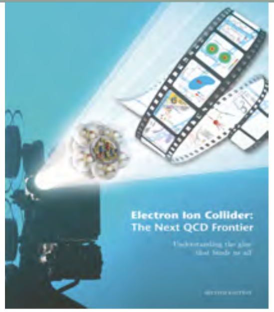


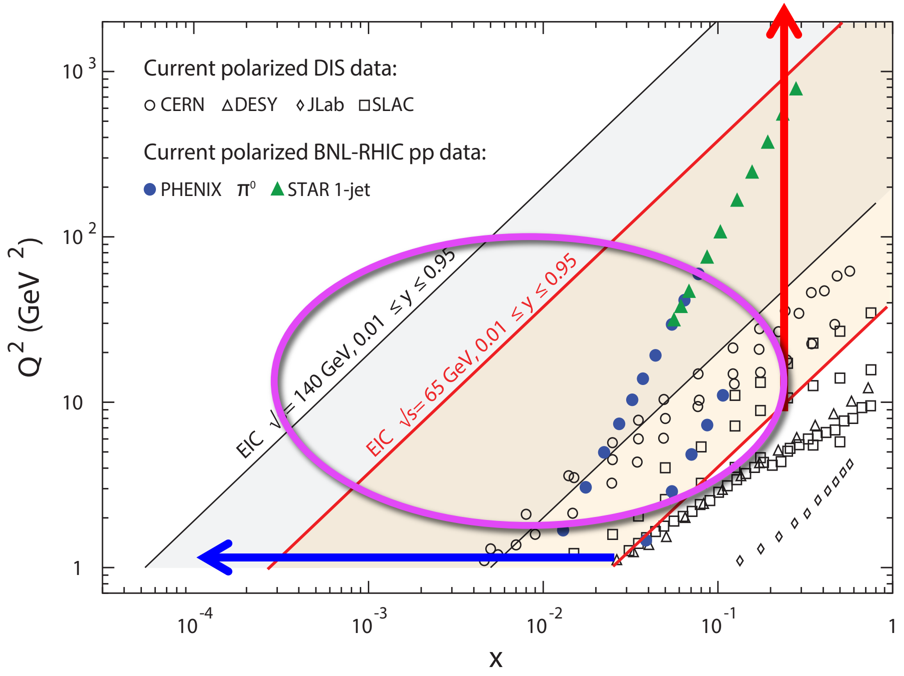
Details in Morozov's talk



JLEIC Collaboration
JLEIC Pre-CDR

EIC: Kinematic reach & properties



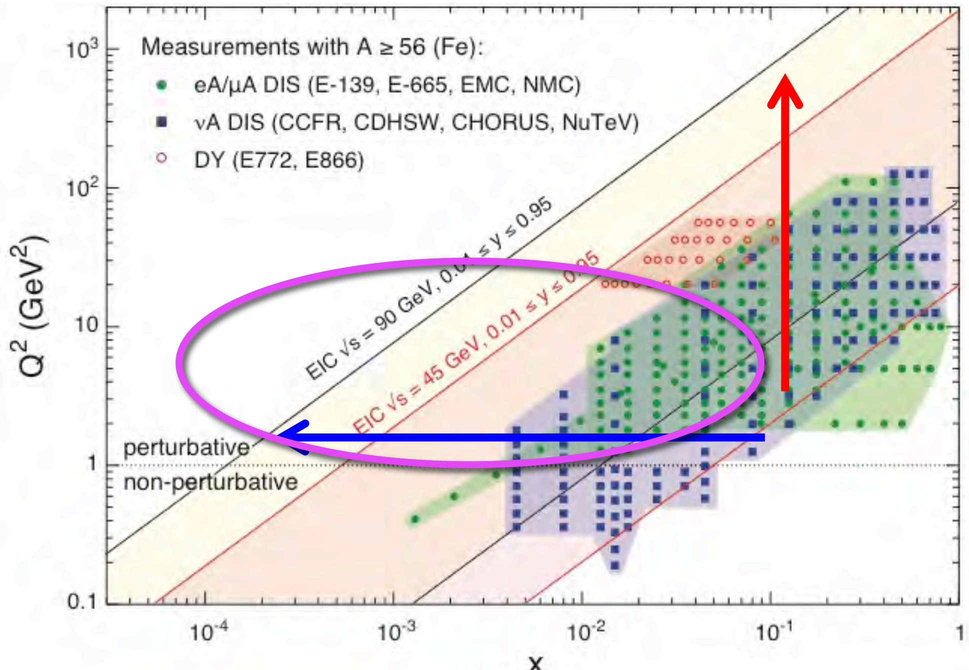


For e-N collisions at the EIC:

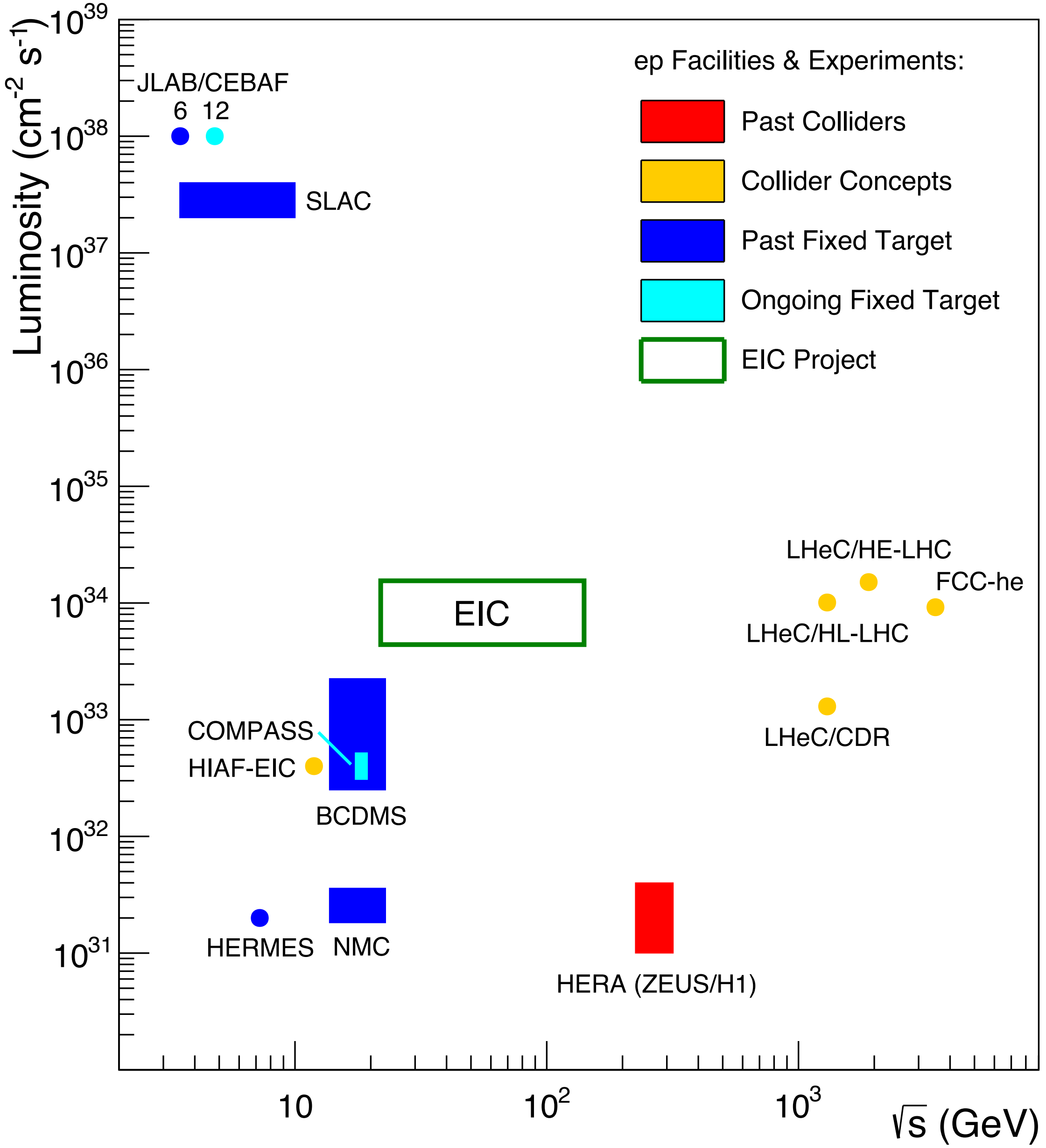
- ✓ **Polarized** beams: e, p, d/^{3}He
- ✓ Variable center of mass energy
- ✓ Wide Q^2 range → evolution
- ✓ Wide x range → spanning valence to low-x physics

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.

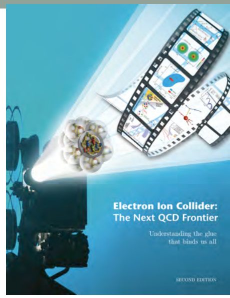
However, if we ask for:

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

No other facility has or plans for

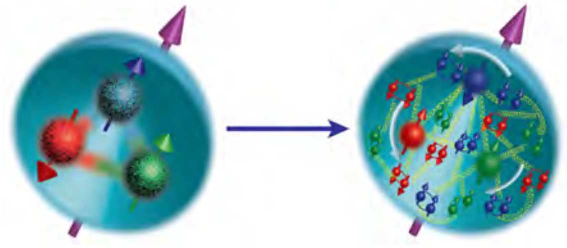
- **polarized lepton & hadron beams**
- **nuclear beams**

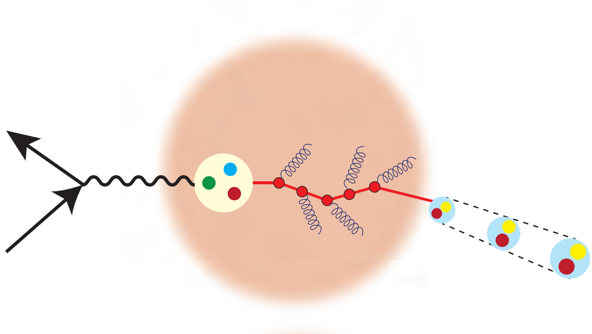
EIC stands out as a truly unique facility …



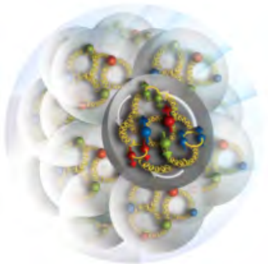
A new facility is needed to investigate, with precision, the dynamics of gluons & sea quarks and their role in the structure of visible matter

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?





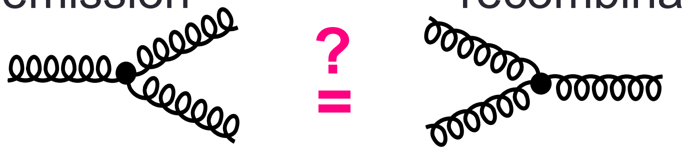
How do color-charged quarks and gluons, and colorless jets, interact with a nuclear medium?
How do the confined hadronic states emerge from these quarks and gluons?
How do the quark-gluon interactions create nuclear binding?



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?

gluon emission

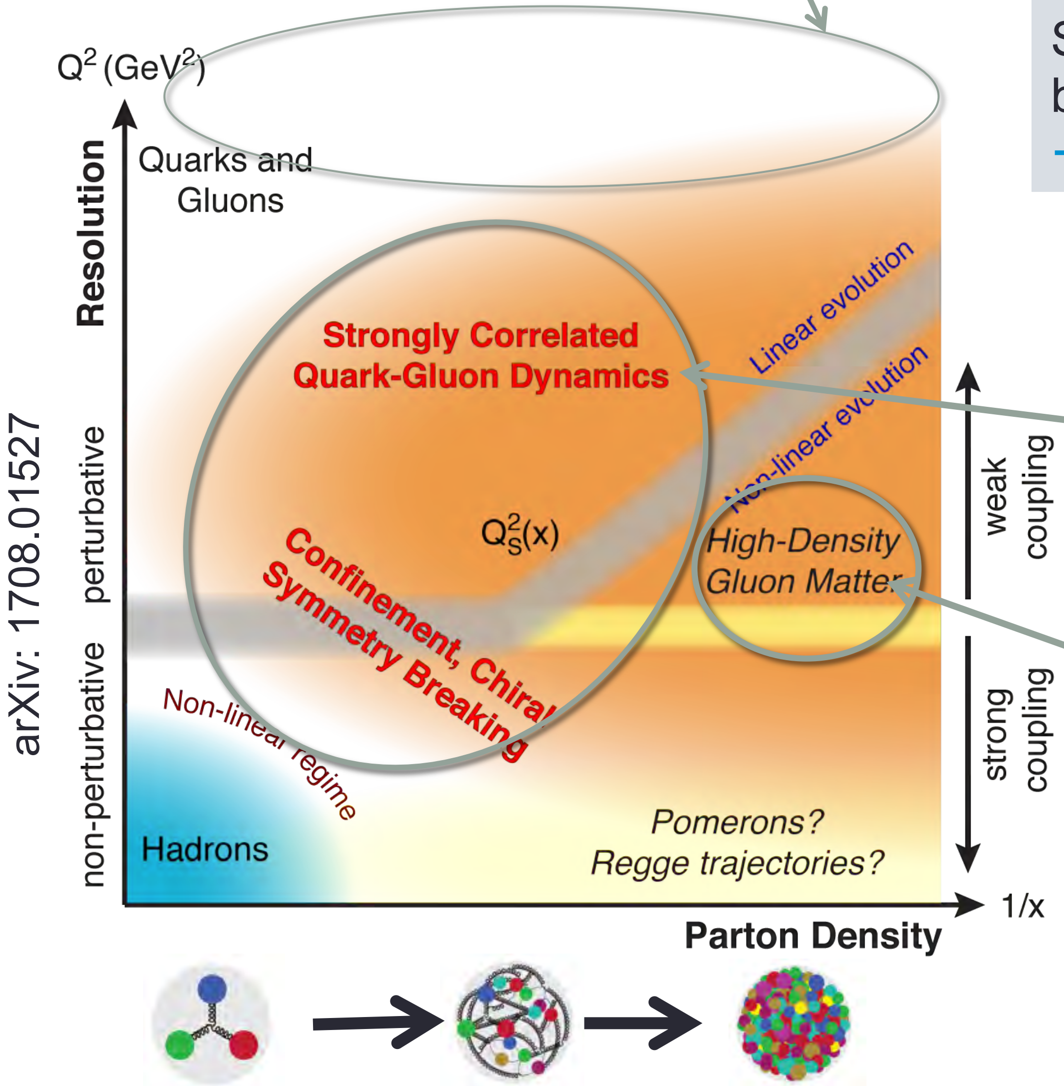
gluon recombination



QCD Landscape to be explored by a future facility

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

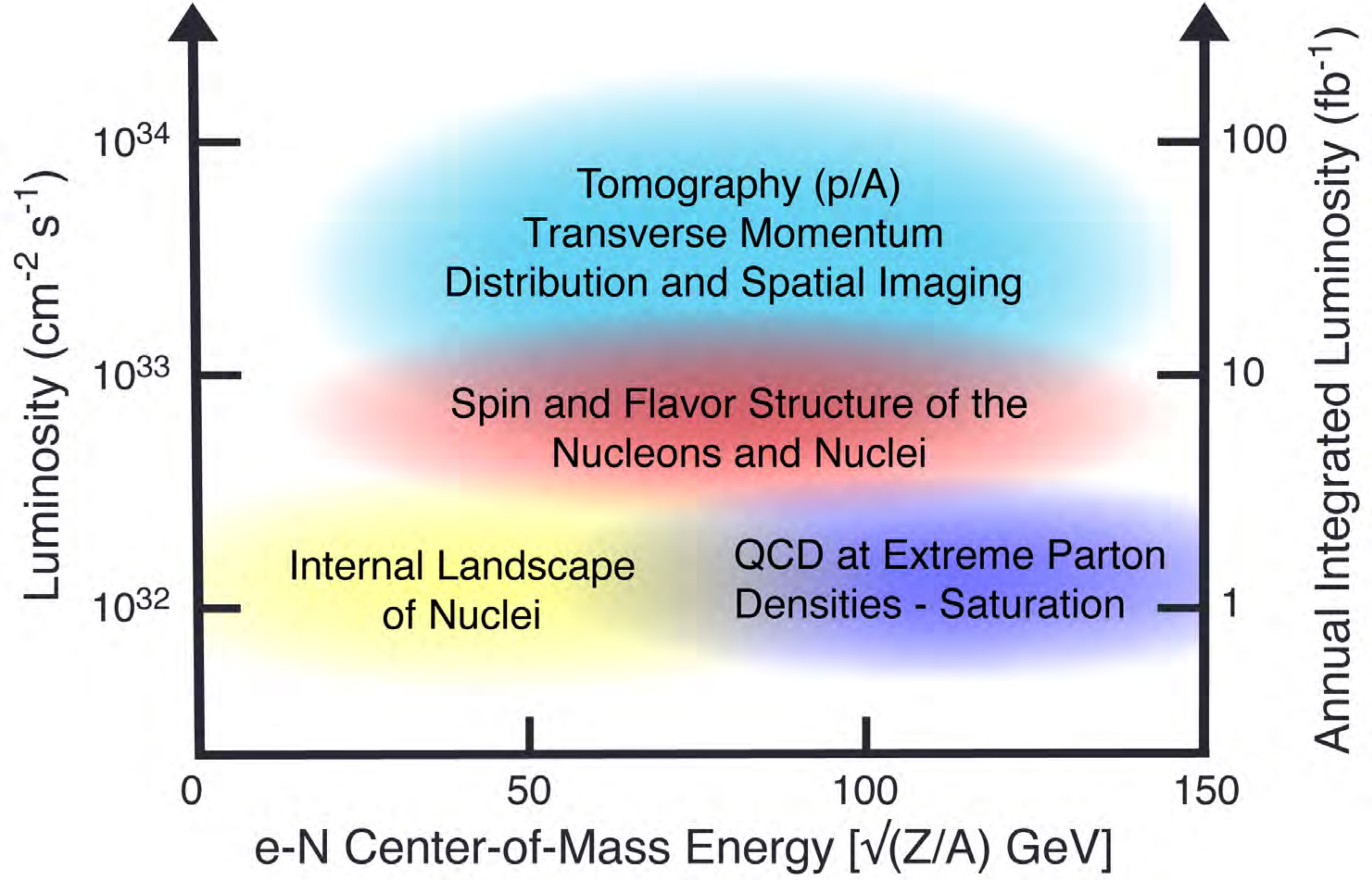
Strong QCD dynamics creates many-body correlations between quarks and gluons
→ hadron structure emerges



Systematically explore correlations in this region.

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

Summary: EIC Physics: CM vs. Luminosity vs. Integrated luminosity

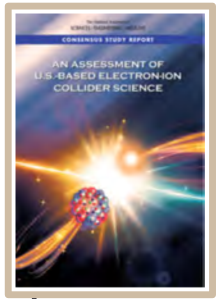


Statement of Task from the Office of Science (DOE/NSF) to the
National Academy of Science, Engineering & Medicine (NAS)

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.

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

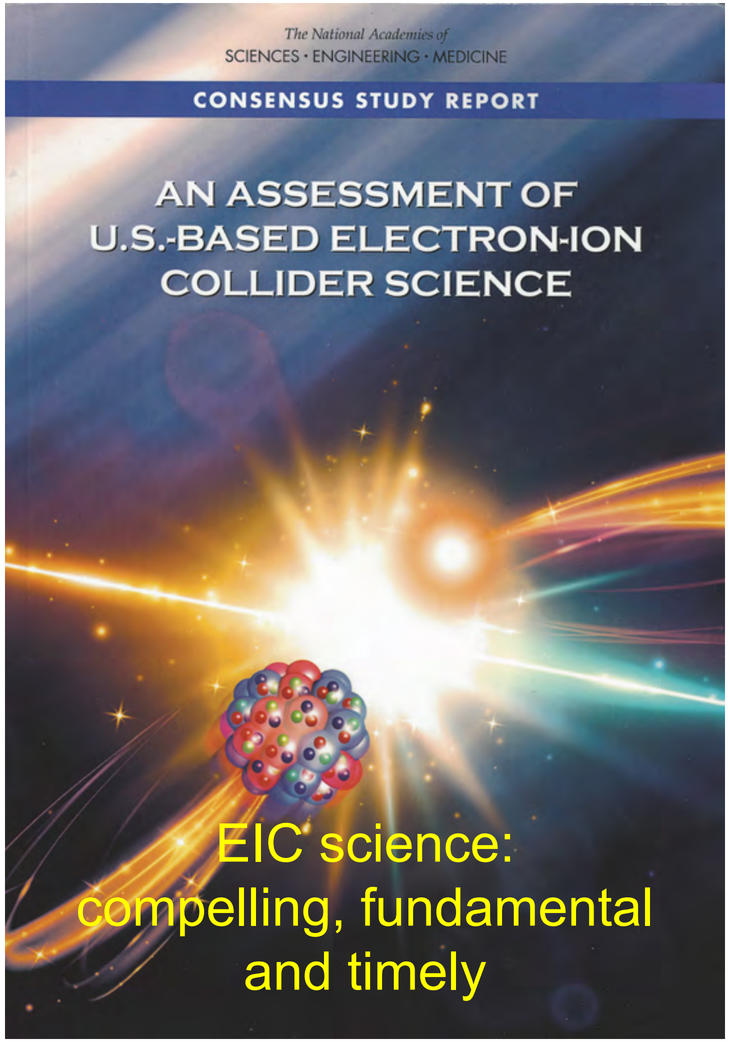
- **Finding 1**: An EIC can uniquely address three profound questions about nucleons—neutrons and protons—and how they are assembled to form the nuclei of atoms:
  - How does the mass of the nucleon arise?
  - How does the spin of the nucleon arise?
  - What are the emergent properties of dense systems 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 <u>sufficiently high luminosity and sufficient, and variable, center-of-mass energy.</u>

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 ➔ significantly reduced risk

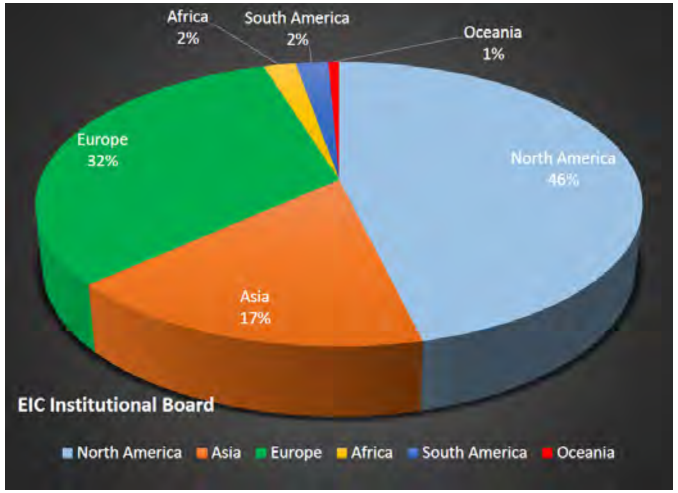


Consensus Study Report on the US based Electron Ion Collider

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 EIC Users Group: EICUG.ORG



Formally established in 2016
~950 Ph.D. Members from 30 countries, 189 institutions

New:
Center for Frontiers in Nuclear Science (at Stony Brook/BNL)
EIC[2] at Jefferson Laboratory

EICUG Structures in place and active.
EIC UG Steering Committee, Institutional Board, Speaker's Committee

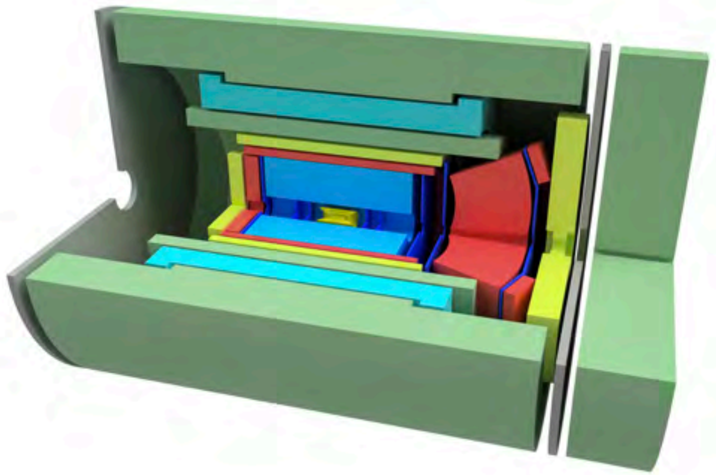
Task forces on:
-- Beam polarimetry, Luminosity measurement
-- Background studies, IR Design

Year long workshops: Yellow Reports for detector design

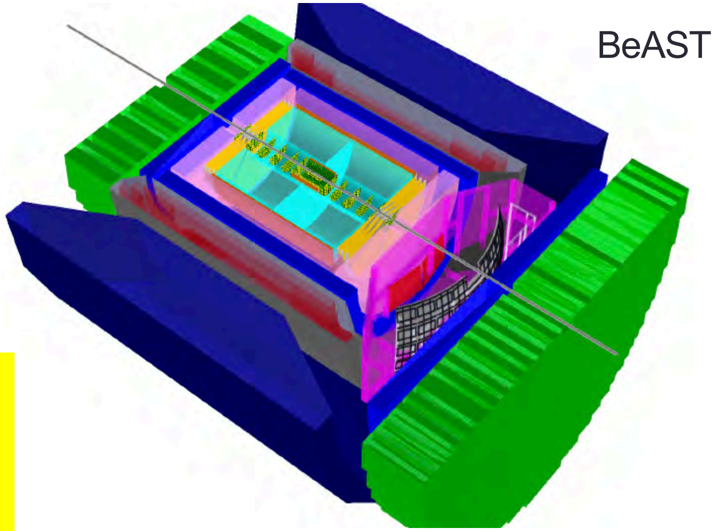
Annual meetings: Stony Brook (2014), Berkeley (2015), **ANL (2016)**, **Trieste (2017)**, **CAU (2018)**, **Paris (2019)**, **FIU (2020)**, **Warsaw (2021)**

EIC Detector Concepts: integration of detectors in to machine lattice

EIC Day 1 detector, with BaBar Solenoid

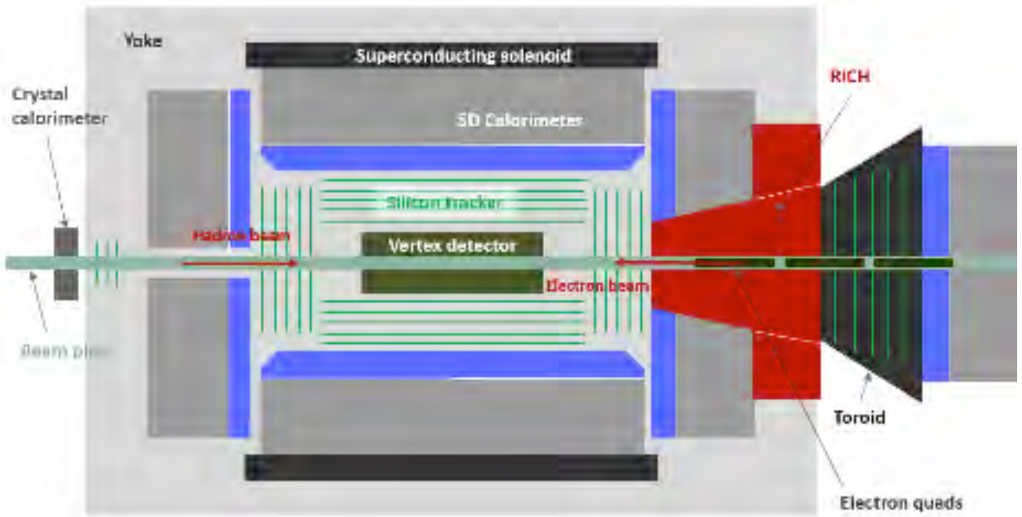


BeAST at BNL

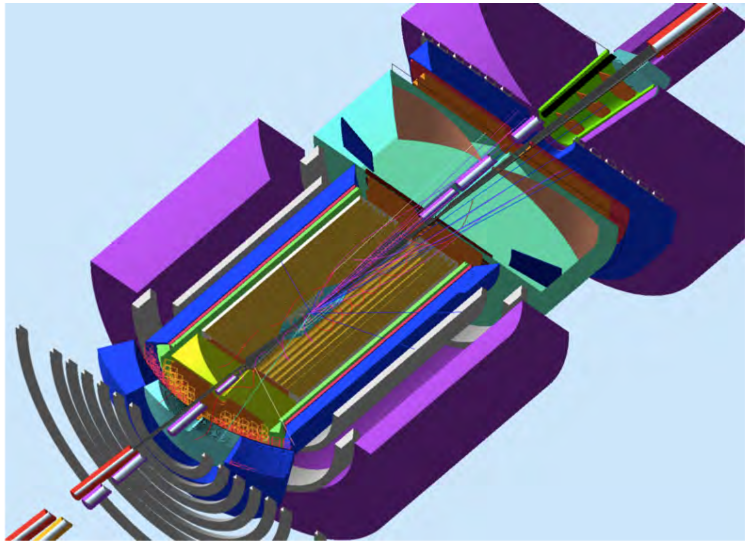


Ample opportunity and need for additional contributors and collaborators

TOPSiDE: Time Optimized PID Silicon Detector for EIC



JLEIC Detector Concept, with CLEO Solenoid



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

New Studies with proton or neutron target:

- 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?*
- *Gluon TMDs at low-x!*
- Heavy quark and quarkonia (c, b quarks) studies beyond HERA, with 100-1000 times luminosities (??) Does polarization of hadron play any role?

Physics with nucleons and nuclear targets:

- *Quark Exotica: 4,5,6 quark systems…?*
- Study of jets: Internal structure of jets
- *Studies with 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
- Polarized light nuclei in the EIC
- *Entanglement entropy in nuclear medium and its connections to fragmentation, hadronization and confinement*

Precision electroweak and BSM physics:

- Electroweak physics and searches beyond the Standard Model

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.**

Summary:

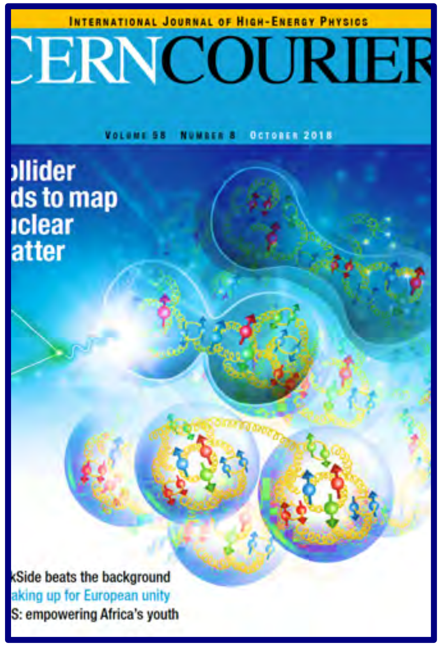
- Science of EIC: Gluons that bind us all… understanding their role in QCD
- EIC's precision, control and versatility will revolutionize our understanding QCD
  - 3D nucleon/nuclear structure, cold nuclear matter & physics high gluon density

- 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.

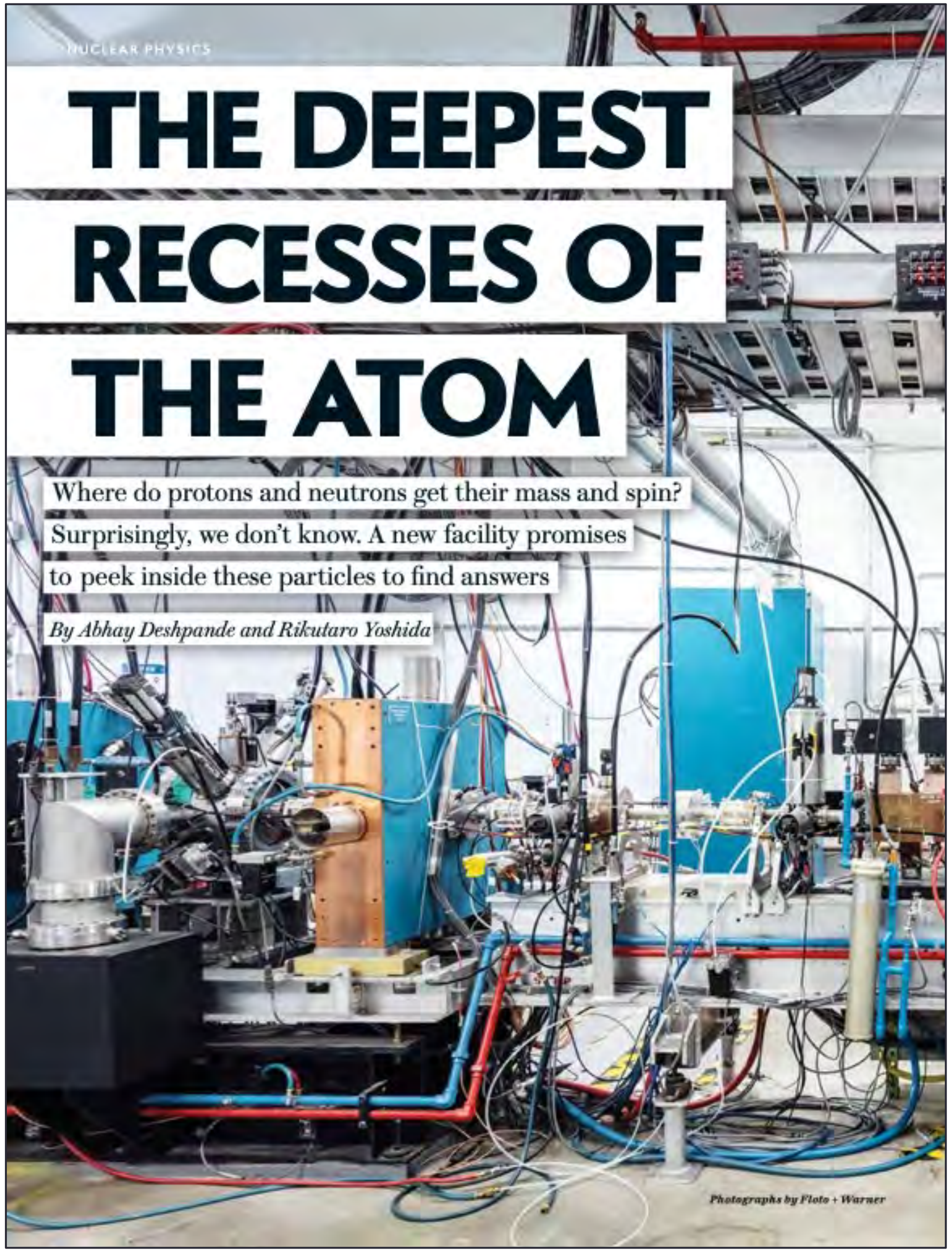
Both Lab managements are committed to working with the DOE, the EICUG and the international partners to realize the US EIC no matter its site (BNL or JLab)

R. Ent, T. Ullrich, R. Venugopalan
Scientific American (2015)
Translated in to multiple languages

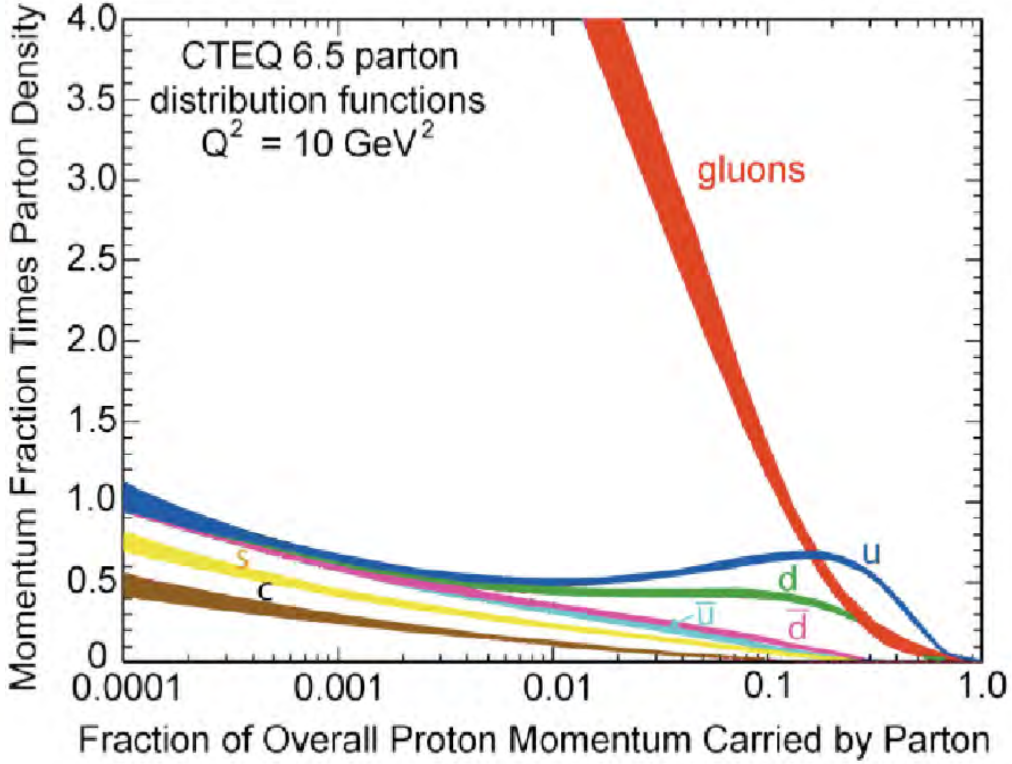


E. Aschenauer
R. Ent
October 2018

A. Deshpande
& R. Yoshida
June 2019
Translated in to Chinese (Taiwan), Italian and other languages



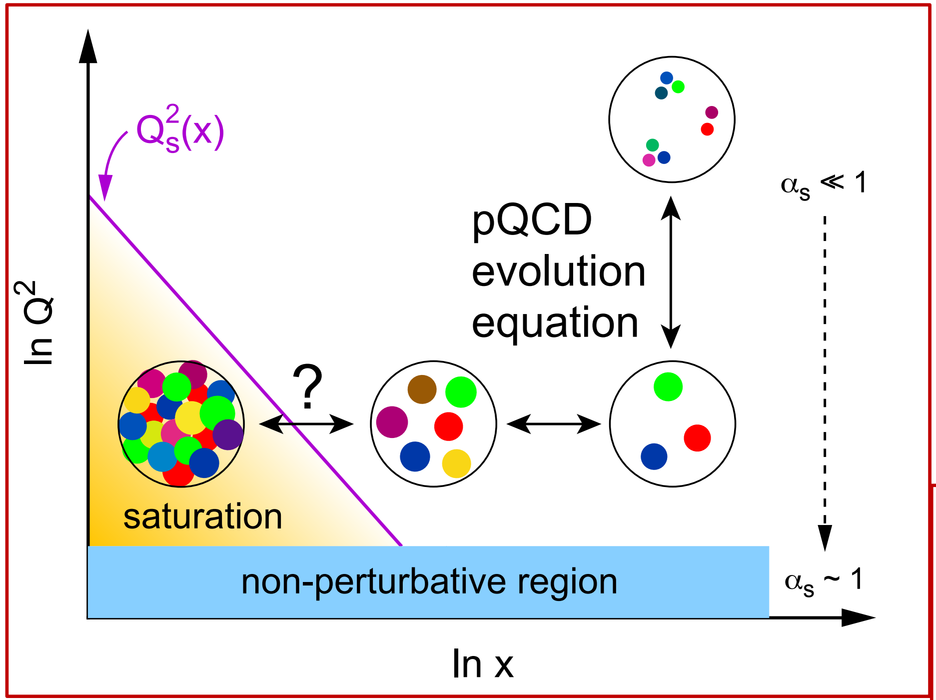
HERA collider at DESY

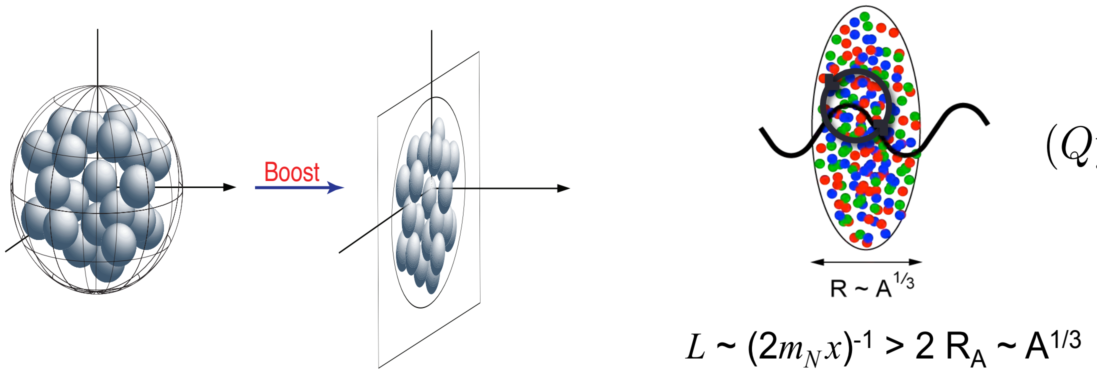


30 GeV electrons x 900 GeV protons ➔ 300 GeV in CoM

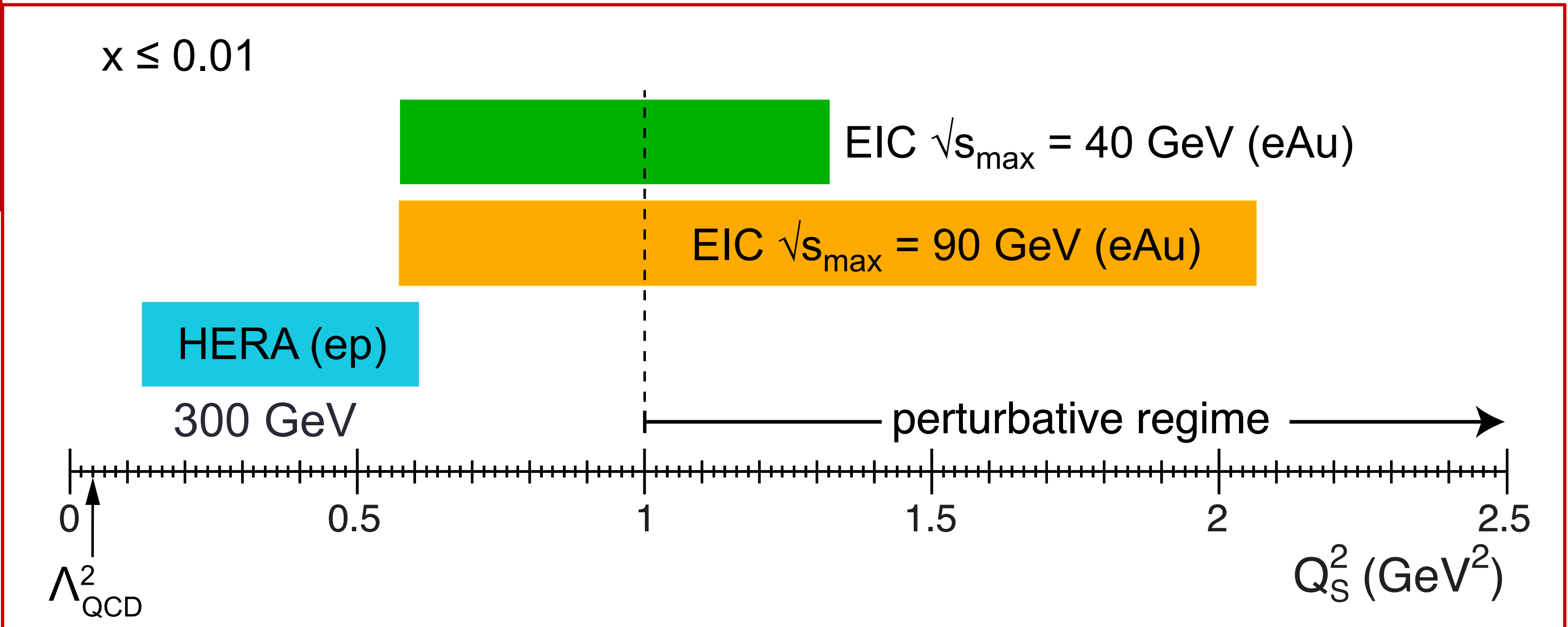
EIC ➔
18 GeV electrons x 250 GeV protons ➔ 140 CoM
How would we reach the saturation region?

Advantage of the nucleus over proton





$$(Q_s^A)^2 \approx cQ_0^2 \left[\frac{A}{x}\right]^{1/3}$$

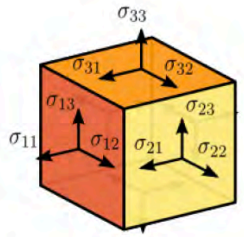


Accessible range of saturation scale $Q_s{}^2$ at the EIC with e+A collisions.
arXiv:1708.01527

Energy Momentum Tensor (EMT)

C. Lorcé

Mass, **spin** and **pressure** all encoded in



Energy density — Momentum density

$$T^{\mu\nu} = \begin{bmatrix} T^{00} & T^{01} & T^{02} & T^{03} \\ T^{10} & T^{11} & T^{12} & T^{13} \\ T^{20} & T^{21} & T^{22} & T^{23} \\ T^{30} & T^{31} & T^{32} & T^{33} \end{bmatrix}$$

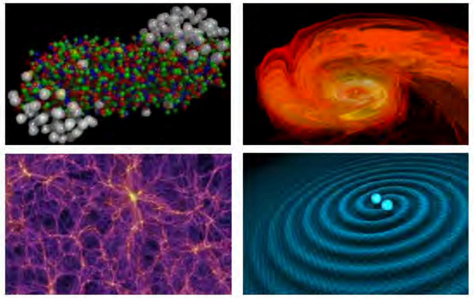
Shear stress

Normal stress (pressure)

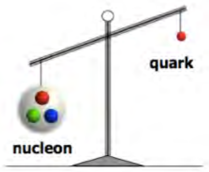
Energy flux — Momentum flux

Key concept for

- Nucleon mechanical properties
- Quark-gluon plasma
- Relativistic hydrodynamics
- Stellar structure and dynamics
- Cosmology
- Gravitational waves
- Modified theories of gravitation
- ...



Mass of the Nucleon



"The mass is the result of the equilibrium reached through dynamical processes." **X. Ji**

"… The vast majority of the nucleon's mass is due to quantum fluctuations of quark-antiquark pairs, the gluons, and the energy associated with quarks moving around at close to the speed of light. …"
-- The 2015 Long Range Plan for Nuclear Science

Relativistic Motion ***Chiral Symmetry Breaking*** ***Quantum Fluctuations***

$$M = E_q + E_g + \chi_{m_q} + T_g$$

X. Ji, PRL 74 1071 (1995)

Quark Energy **Gluon Energy** **Quark Mass** **Trace Anomaly**

- Criticisms: not scale-invariant, decompositions: Lorentz invariant vs. rest frame
- Recent interest (workshops): Temple U., March 2016; ECT, April 2017
- Community wide consensus on how to determine the different contributions not yet reached
- Lattice QCD providing estimates

E_q ~30% E_g ~40% χ_{m_q} ~10% T_g ~ 25%

arXiv: 1710.09011

Trace anomaly:
Upsilon production near threshold