The Electron Ion Collider (EIC) moving forward….

Workshop on Present and Future Perspectives in Hadron Physics

Strong-2020, INFN Frascati

June 18, 2024

Abhay Deshpande

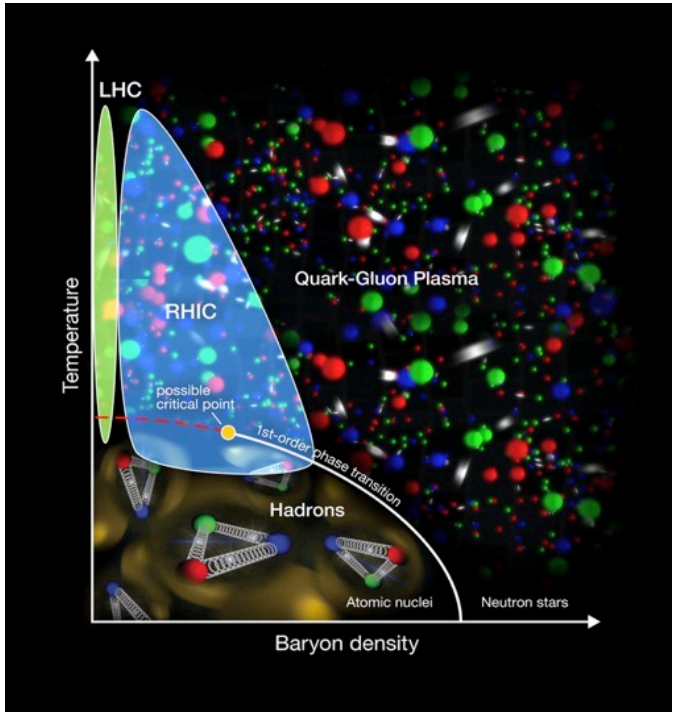
EIC Science Director

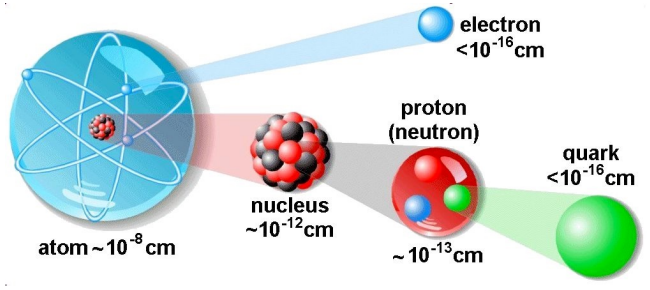
And

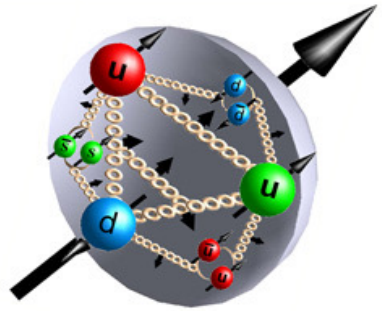
Incoming Interim Associate Laboratory Director for Nuclear and Particle Physics at BNL

RHIC – a Unique Research Tool

- Heavy ion collisions
  - Explore new state of matter: Quark Gluon Plasma
  - Highest collision rates and collide many different ion species
- Polarized proton collisions
  - Only collider of spin polarized protons to explore the internal spin structure of protons.
  - Gluons carry part of proton spin



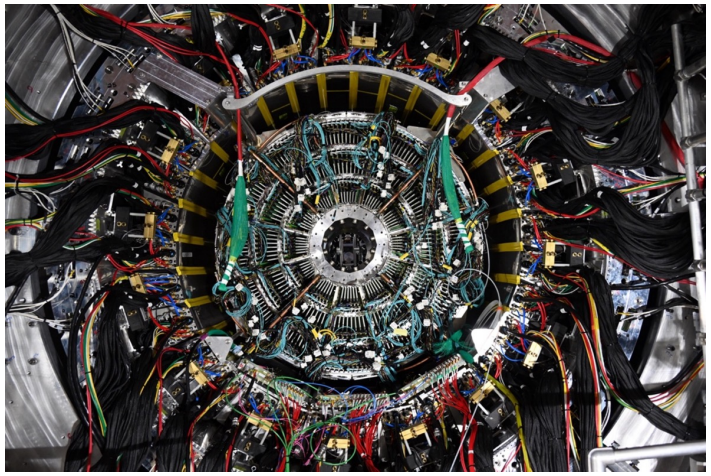


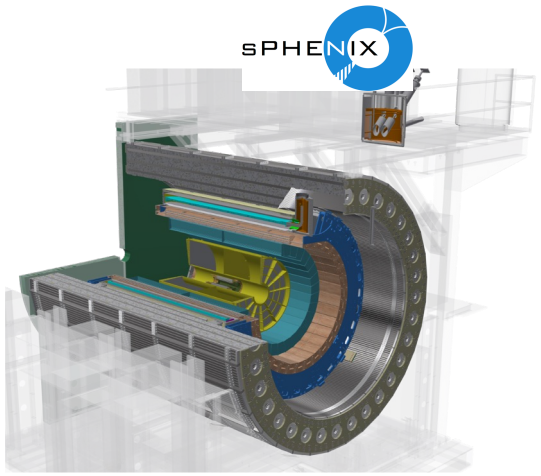


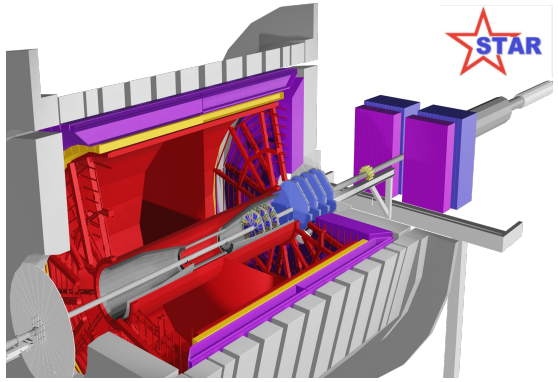
Completing the RHIC Mission with sPHENIX and STAR

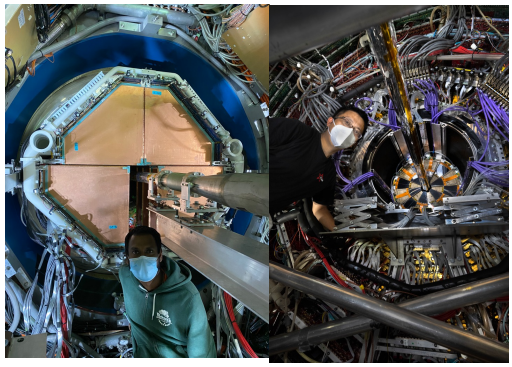
- sPHENIX will use energetic probes (jets, heavy quarks) to study quark-gluon plasma with unprecedented precision
  - How the structureless "perfect" fluid emerges from the underlying interactions of quarks and gluons at high temperature
- sPHENIX outer hadron calorimeter will be part of the EIC project detector

- STAR with forward upgraded detectors will understand the initial state of nucleon and nuclei from high to low x and the inner workings of QGP
- How are gluons and sea quarks distributed in space and momentum inside the nucleon?
- How does a dense nuclear environment affect quarks and gluons, their correlations, and their interactions and giving rise to non-linear effects?



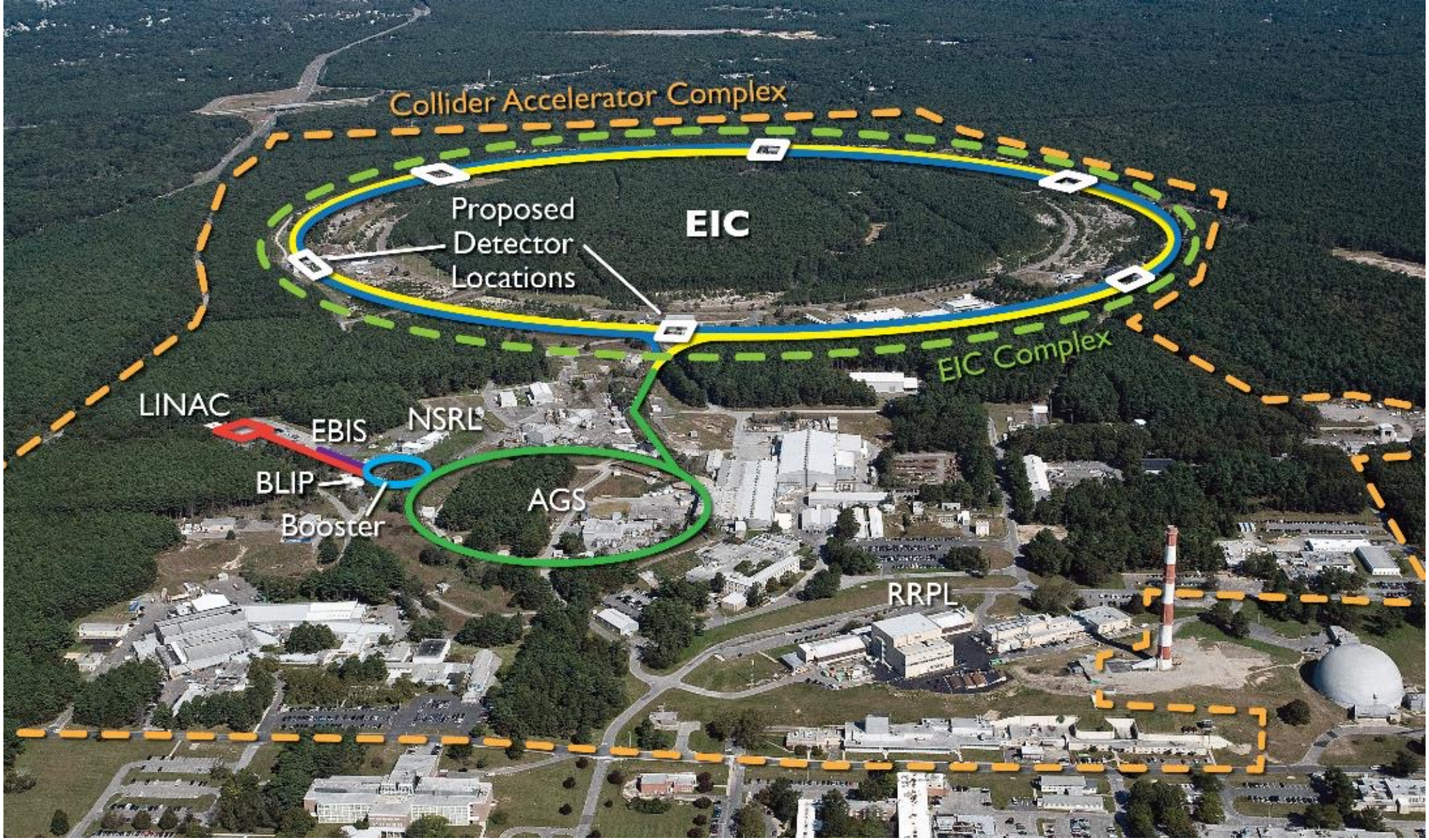




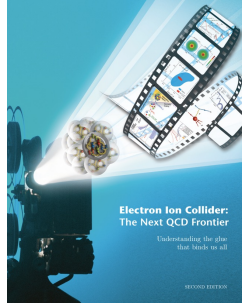


Synergies with the EIC science and contribute to EIC workforce development

RHIC data taking scheduled for 2024–2025
sPHENIX and STAR with forward upgrade will fully utilize the enhanced (~50 times Au+Au design) luminosity of RHIC

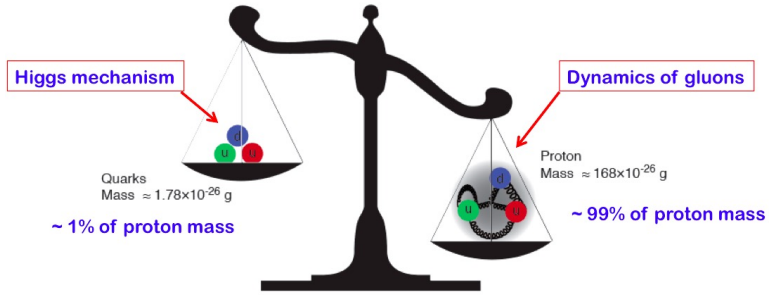


- EIC benefits from $2.4B class investments at BNL (RHIC and Injectors) & a highly successful RHIC program.
- RHIC will conclude operations in 2025. Electron Ion Collider installation will begin after RHIC ops concludes.

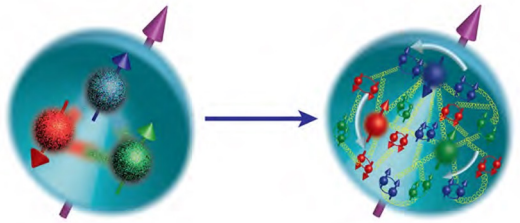


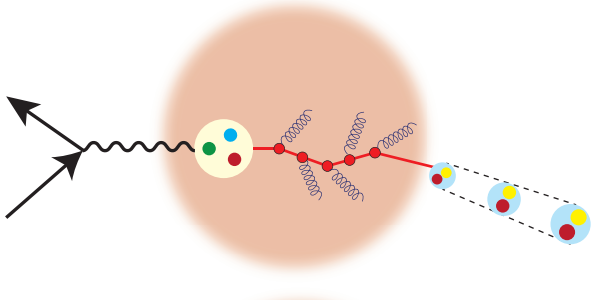
EIC Physics at-a-Glance

Eur. Phys. J. A 52 (2016) 9, 268 arXiv:1212.1701 (nucl-ex)



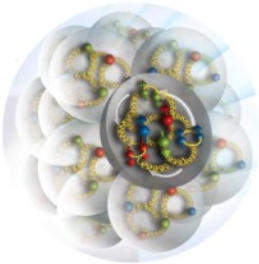
How are the sea quarks and gluons, and their spins, distributed in space and momentum inside the nucleon? How do the nucleon properties (mass & spin) emerge from their interactions?



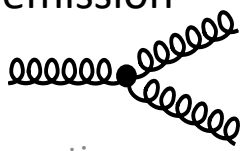


How do color-charged quarks and gluons, and colorless jets, interact with a nuclear medium? How do the confined hadronic states emerge from these quarks and gluons? How do the quark-gluon interactions create nuclear binding?

How does a dense nuclear environment affect the quark- and gluon- distributions? 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?

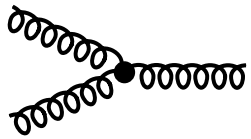


gluon emission

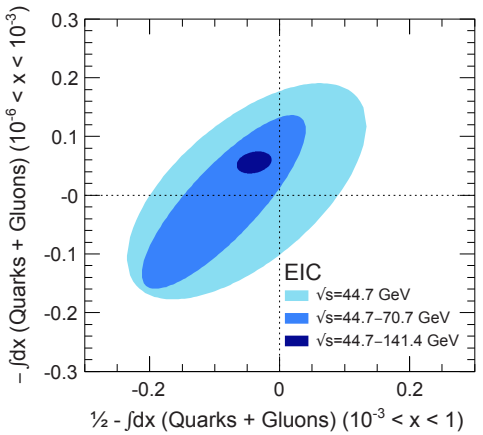


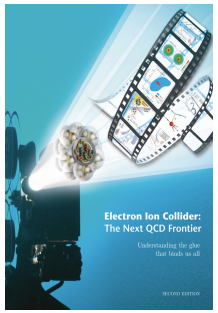
?
=

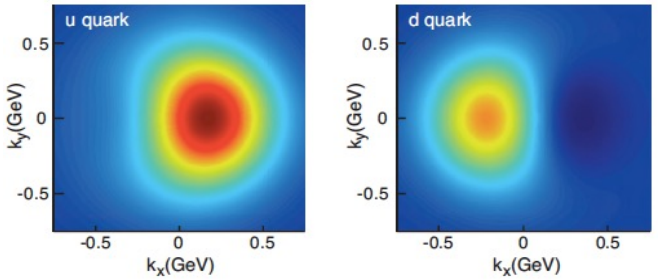
gluon recombination

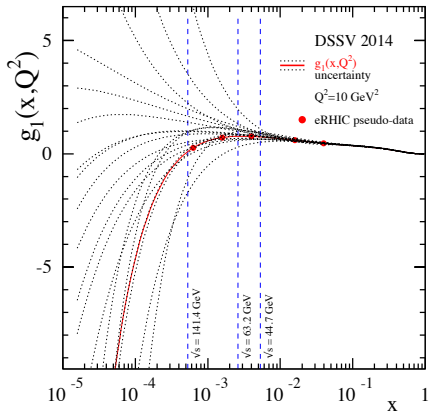


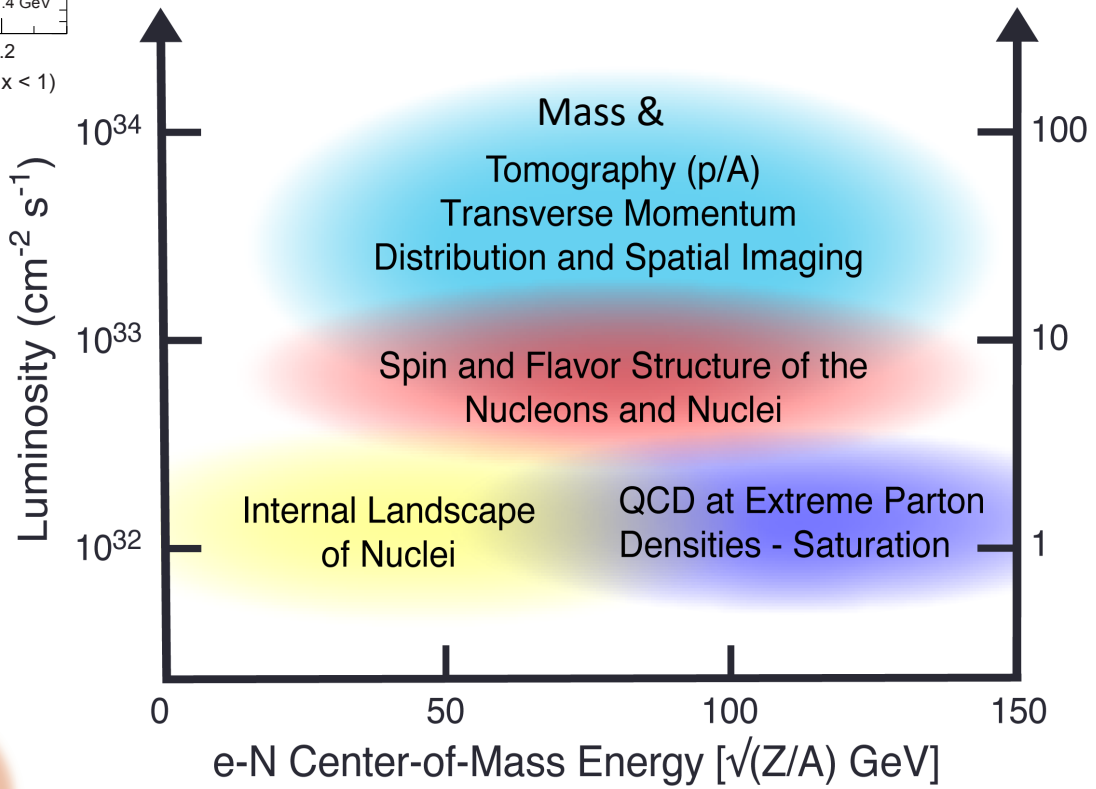
EIC science selected highlights

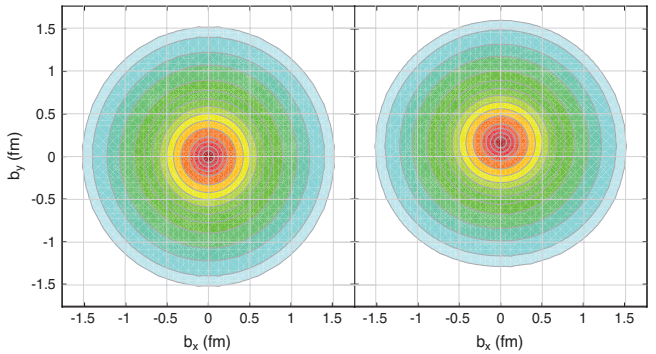


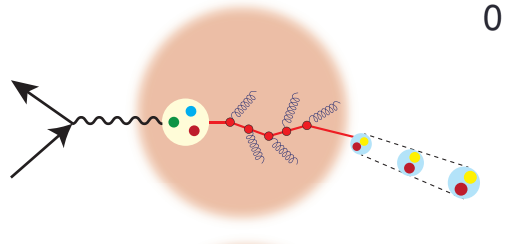


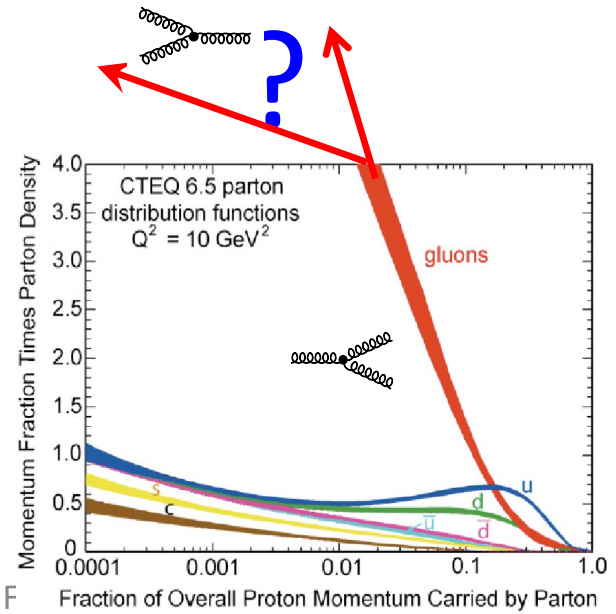




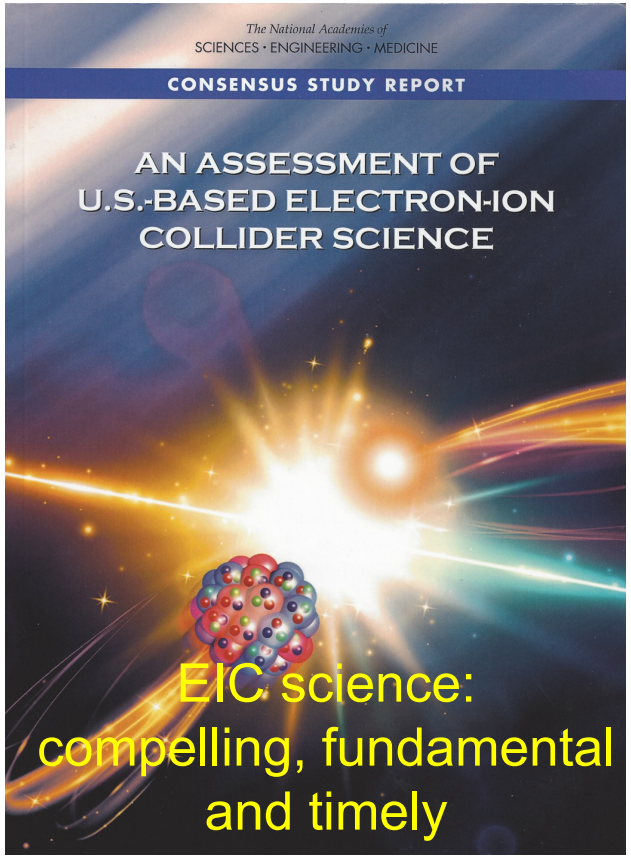






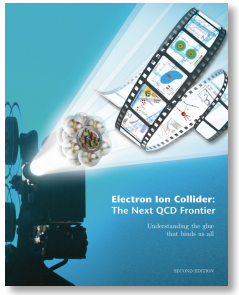


National Academy's Assessment, July 2018
Electron Ion Collider



Electron Ion Collider Science:

- Origin of nucleon spin & 3D imaging of partons
- Understanding the origin of mass of the visible universe
- Intense gluon fields ➔ novel gluonic matter?

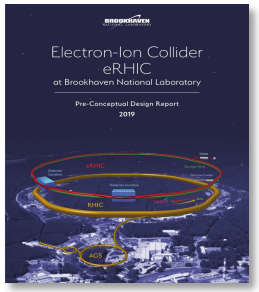


Machine Design Parameters:

- 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

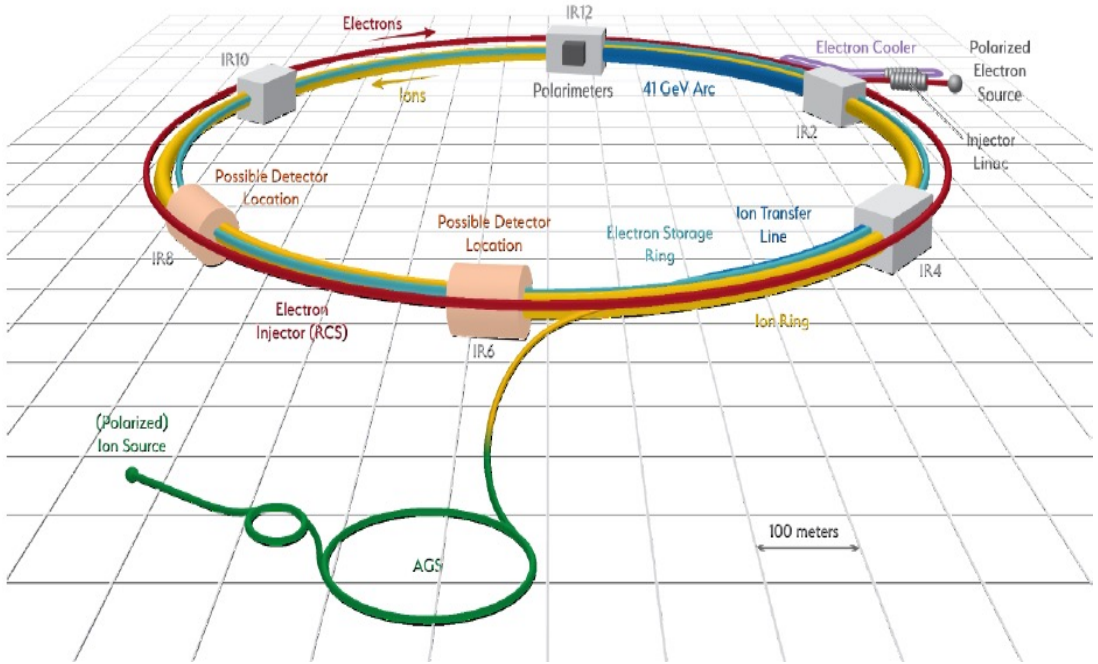
Since then: first operational facility & detector using AI and ML

- Optimization of machine operations &
- Detector design & data acquisition (triggerless data collections)



The Electron Ion Collider

DOE Milestones: D0: Dec. 2019, CD1 July 2021, CD3-A March 2024



- ❖ Electron storage ring with frequent injection of fresh polarized electron bunches
- ❖ Hadron storage ring with strong cooling or frequent injection of hadron bunches
- ❖ AI and ML surely will play a major role in optimizing this complex accelerator operation

Hadrons up to 275 GeV

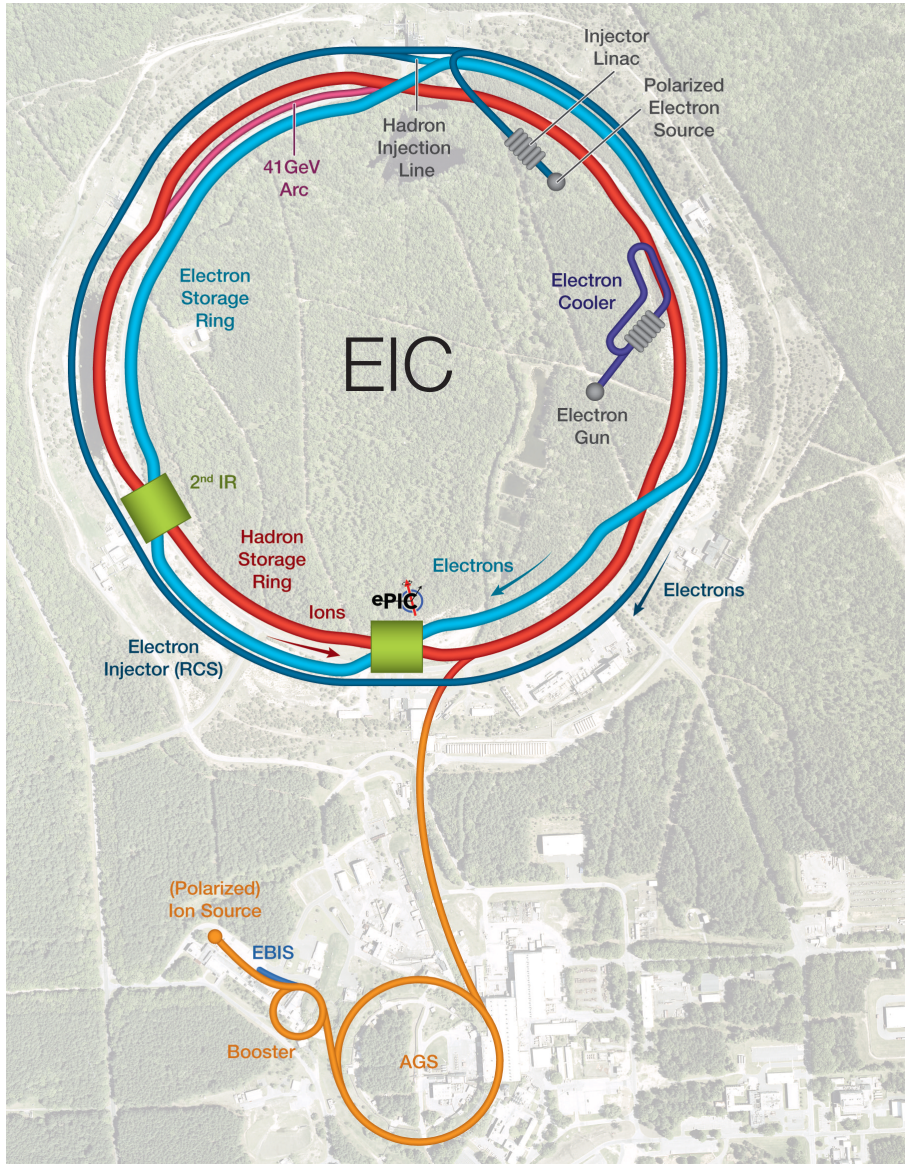
- ➢ Existing RHIC complex: Storage (Yellow), injectors (source, booster, AGS)
- ➢ Need few modifications
- ➢ RHIC beam parameters fairly close to those required for EIC@BNL

Electrons up to 18 GeV

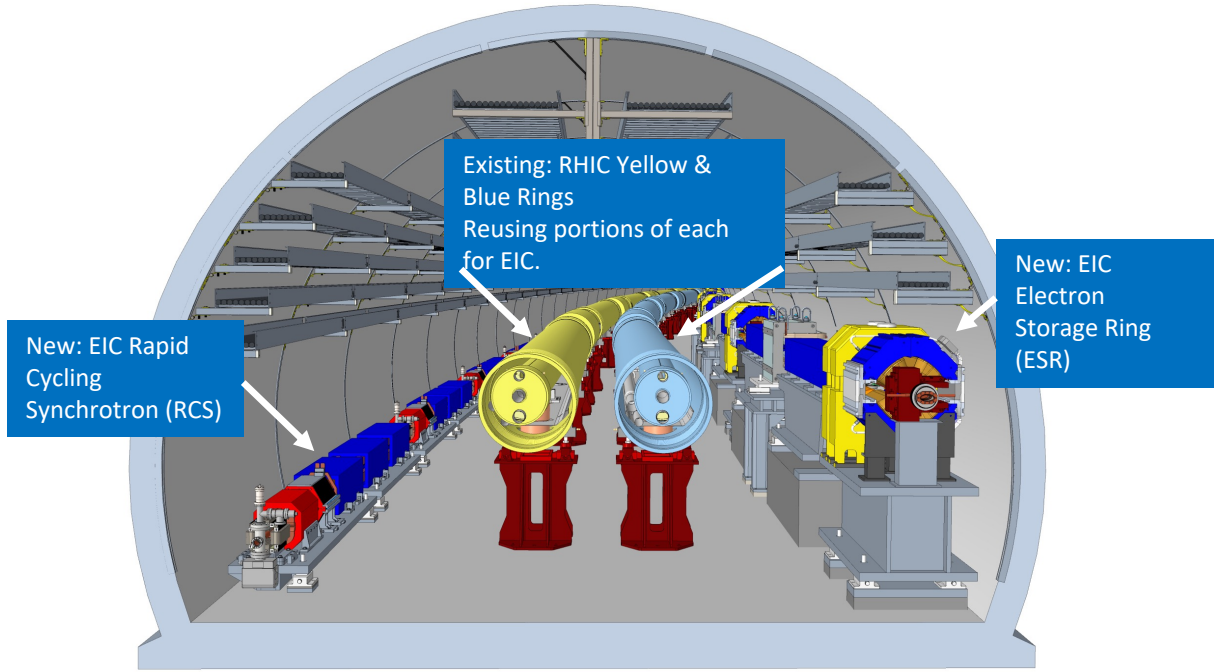
- ➢ Storage ring, provides the range sqrt(s) = 20-140 GeV. Beam current limited by RF power of 10 MW
- ➢ Electron beam with variable spin pattern (s) accelerated in on-energy, spin transparent injector (Rapid-Cycling-Synchrotron) with 1-2 Hz cycle frequency
- ➢ Polarized e-source and a 400 MeV s-band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

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

EIC Accelerator Design & Layout



Center of Mass Energies:	20GeV - 140GeV
Luminosity:	10^{33} - 10^{34} $cm^{-2}s^{-1}$ / 10-100fb^{-1} / year
Highly Polarized Beams:	70%
Large Ion Species Range:	p to U
Number of Interaction Regions:	Up to 2!



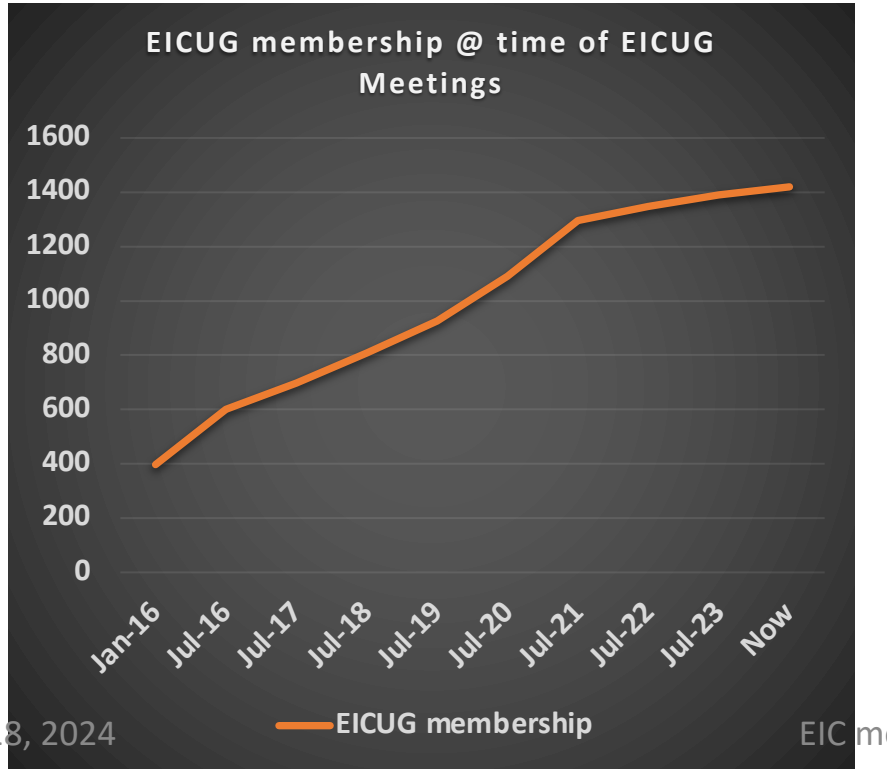
Worldwide Interest in EIC

The EIC User Group:
https://eicug.github.io/

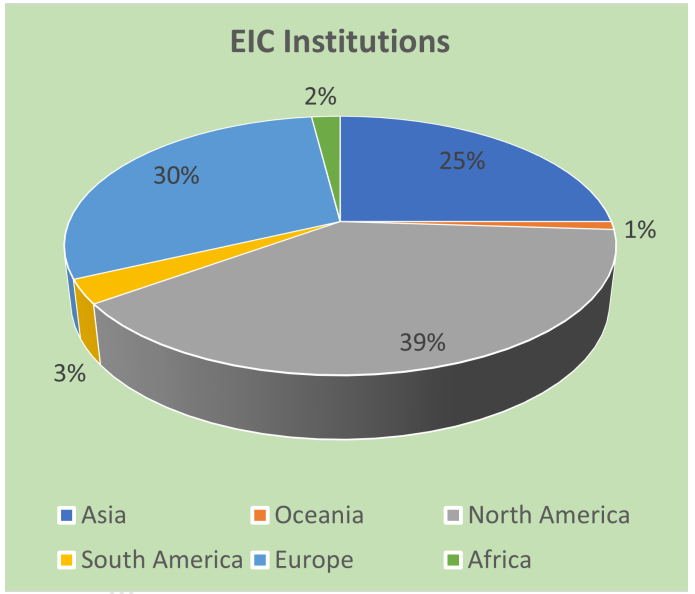
Formed 2016 – (with 700 enthusiasts)
- **1450+ collaborators,**
- **~40 countries,**
- **290+ institutions**

as of May, 2024.

Strong International Participation.



Annual EICUG meeting
2016 UC Berkeley, CA
2016 Argonne, IL
2017 Trieste, Italy
2018 CUA, Washington, DC
2019 Paris, France
2020 FIU, Miami, FL
2021 VUU, VA & UCR, CA
2022 Stony Brook U, NY
2023 Warsaw, Poland
2024 Lehigh U, PA



Physics @ the EIC: Connections to High Energy Physics

Of HEP/LHC-HI interest to Snowmass 2021 (EF 05, 06, and 07 and possibly also EF 04)
LHC – EIC Synergies workshops in Europe

Novel precision QCD Studies with proton & (light & heavy) nuclear targets:

- Impact of precision measurements of unpolarized PDFs at high x/Q^2, on LHC-Up
- Precision calculation of α_S : higher order pQCD calculations, twist 3
- Heavy quark and quarkonia (c, b quarks) studies with **100-1000 times lumi of H**
- Polarized light nuclei in the EIC
- Quark Exotica: 4,5,6 quark systems…? Much interest after recent **Belle**, **LHCb** le
- Physic of and with jets with EIC as a precision QCD machine:
  - Jets as probe of nuclear matter
  - Internal structure of jets in e-p collisions, momentum, energy correlators ➔ mass energy variability ➔ adds additional control to the studies: Entanglem fragmentation, hadronization and their relation to confinement

Could be topics for thrusts for 2nd detector (beyond ePIC)?

Precision electroweak and BSM physics:

- Electroweak physics & searches beyond the SM: Parity, charge symmetry, lepton flavor violation
- LHC-EIC Synergies & complementarity

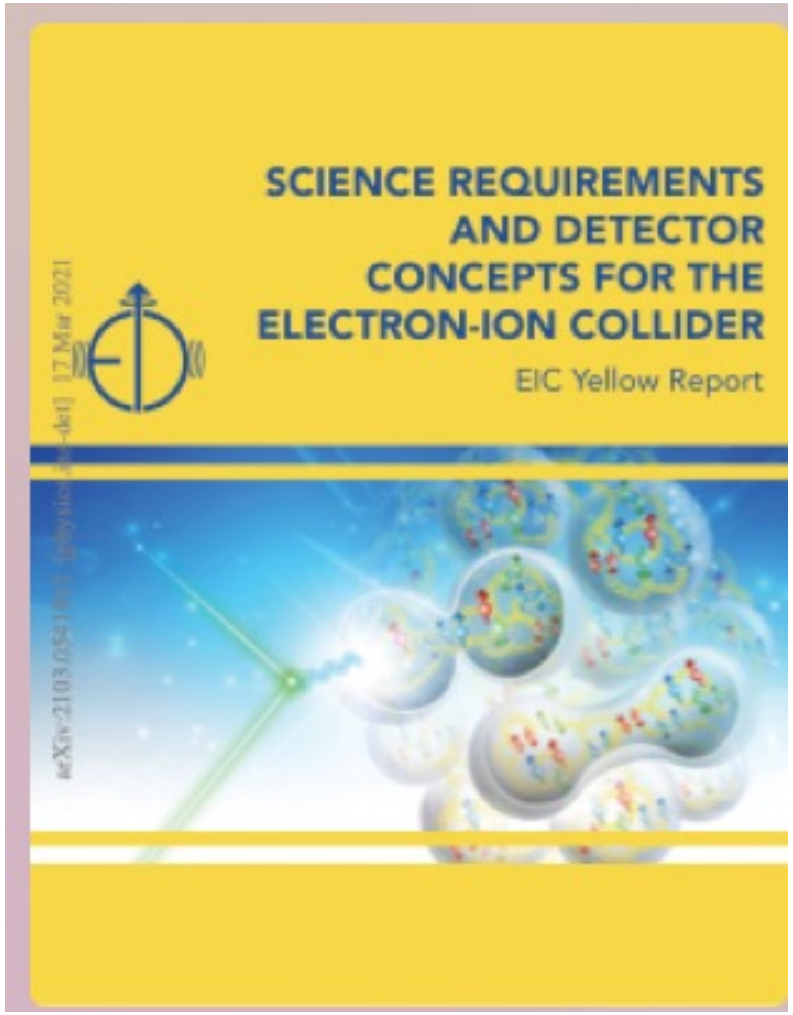
Study of universality: e-p/A vs. p-A, d-A, A-A at RHIC and LHC

Detector design and new physics ideas….

The EIC Users Group members utilized the COVID related forced homestay very effectively

December 2019 – March 2021 EICUG Yellow Report

- Led by EICUG Steering Committee, UG-wide effort towards a detailed detector design effort with a detailed document.
- Kick off meeting at MIT in December 2019 followed by 4 more meetings in 2020 all remote: Philadelphia, Pavia, Miami, Washington DC, Berkeley

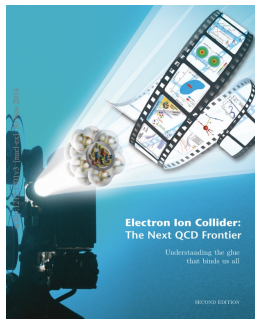


902 pages
415 authors
151 institutions

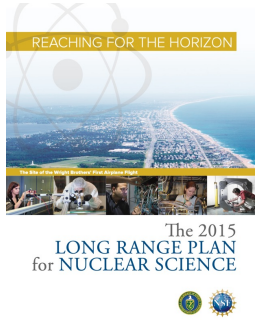
120 MB

arXiv:2103.05419
Nucl. Phys. A 1026 (2022)

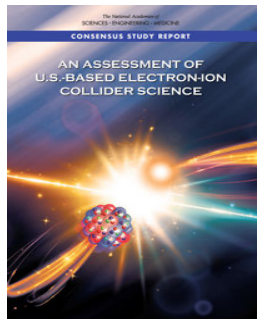
Detector Design Process Timeline



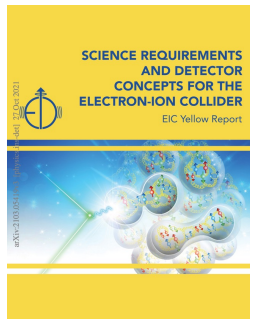
2012



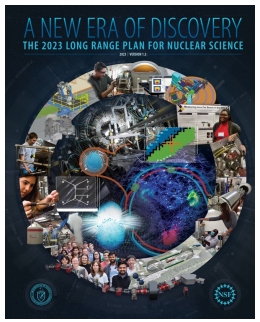
2015



2018



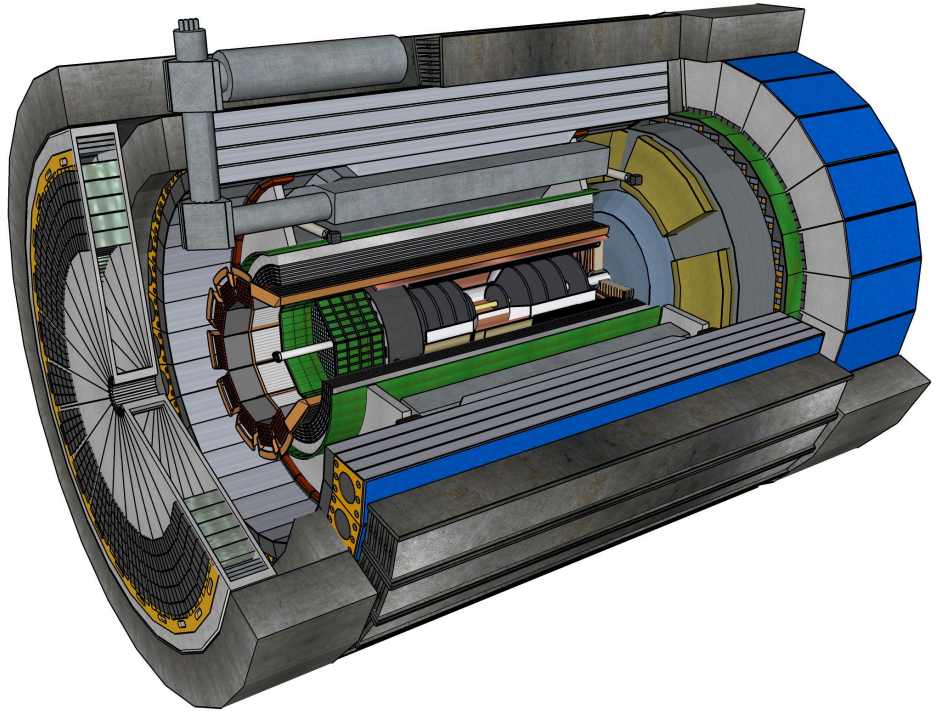
2020



2023

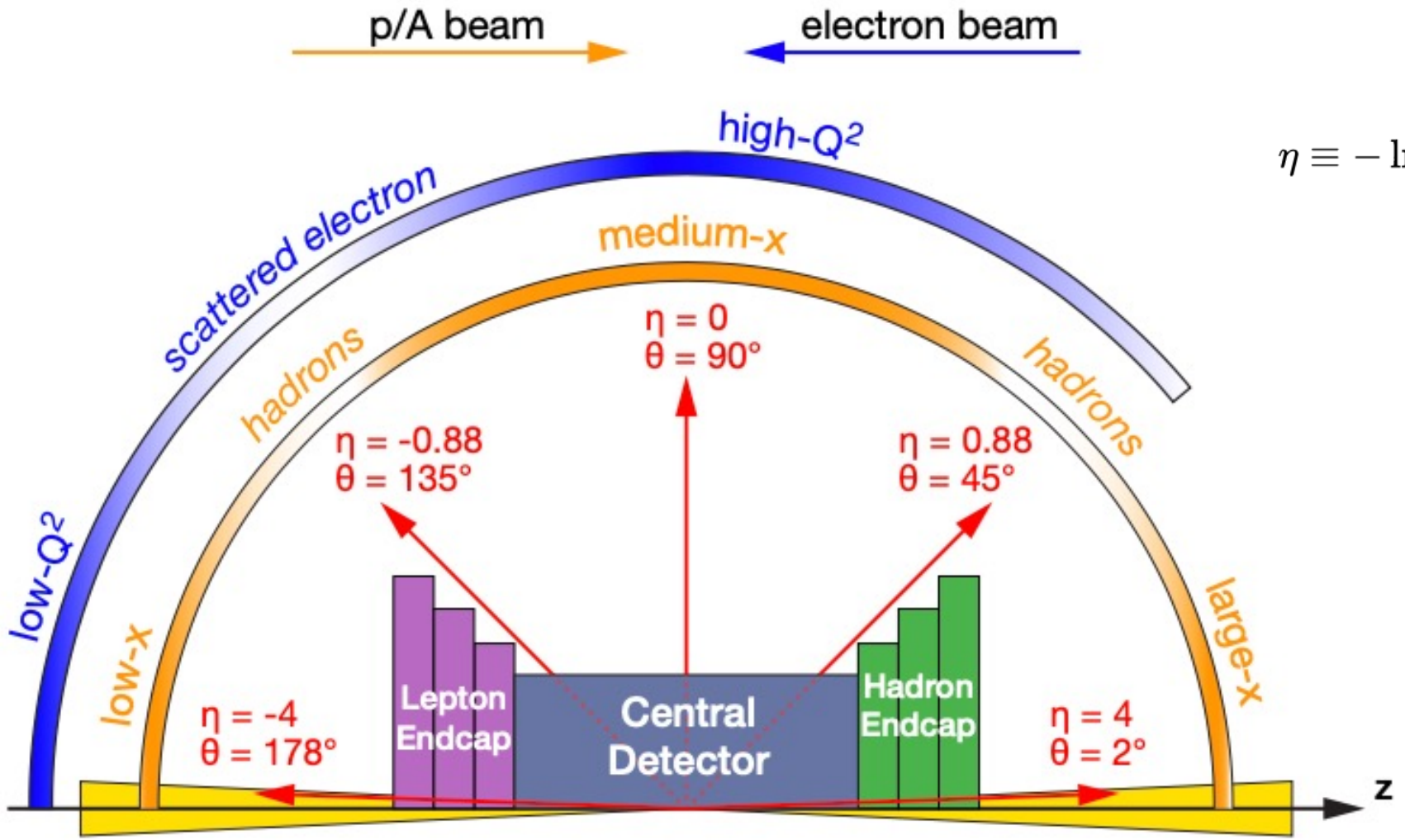
Detector and machine design parameters driven by physics objectives

- Call for proposals issued jointly by BNL and JLab in **March 2021** (Due Dec 2021)
  - ATHENA, CORE and ECCE proposals submitted
- DPAP review **Dec 2021 – Jan 2022**, closeout **March 2022**
  - ECCE proposal chosen as basis for first EIC detector reference design
- **Spring/Summer 2022** – ATHENA and ECCE form joint leadership team
  - Joint WG's formed and consolidation process undertaken
  - Coordination with EIC project on development of technical design
- Collaboration formation process started **July 2022**
- Charter ratified & elected ePIC Leadership Team **February 2023**
- **EIC/ePIC endorsed as highest priority for new facility construction in 2023 LRP.**
- **Working towards TDR and CD-2/3 (2025)**



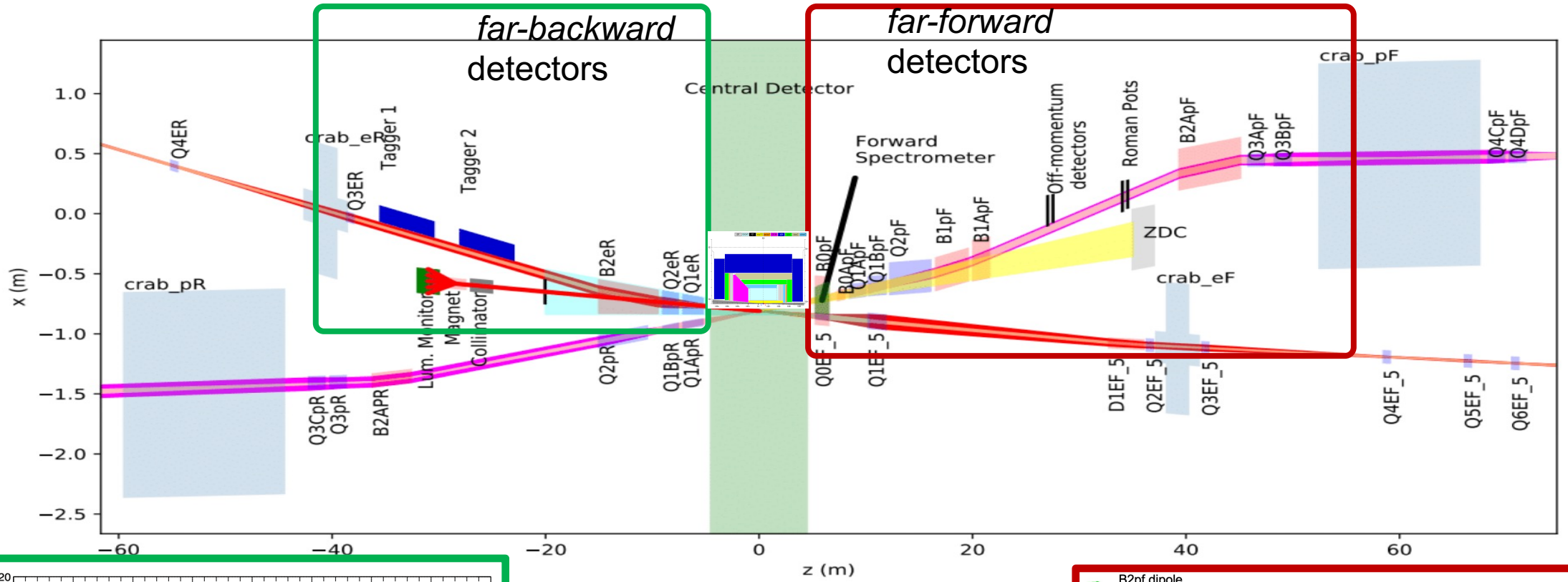
John Lajoie

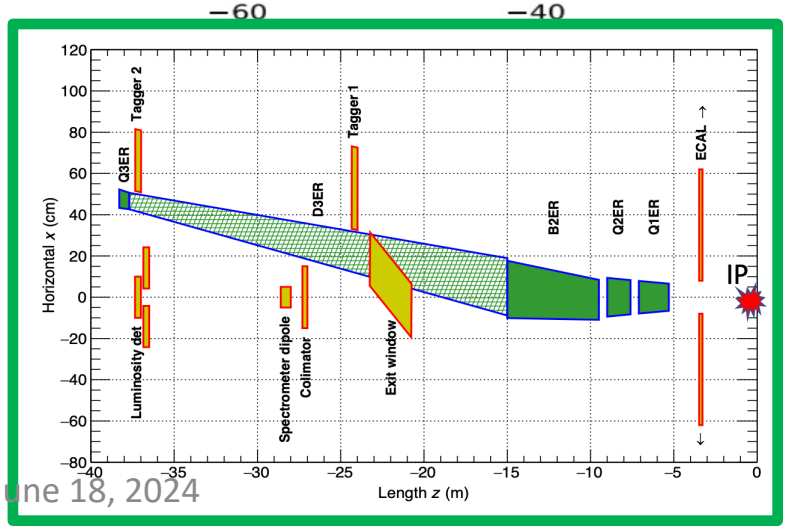
Detector polar angle / pseudo-rapidity coverage



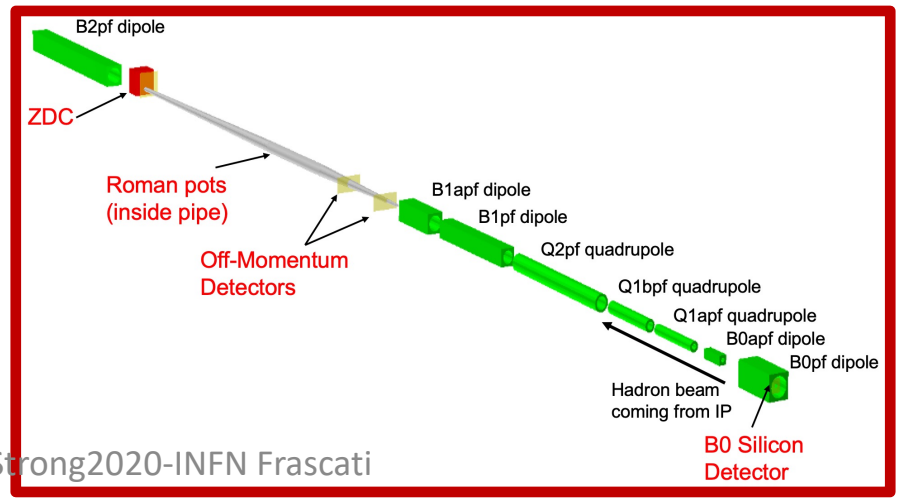
$$\eta \equiv -\ln\left[\tan\left(\frac{\theta}{2}\right)\right],$$

Reference Detector – Backward/Forward Detectors

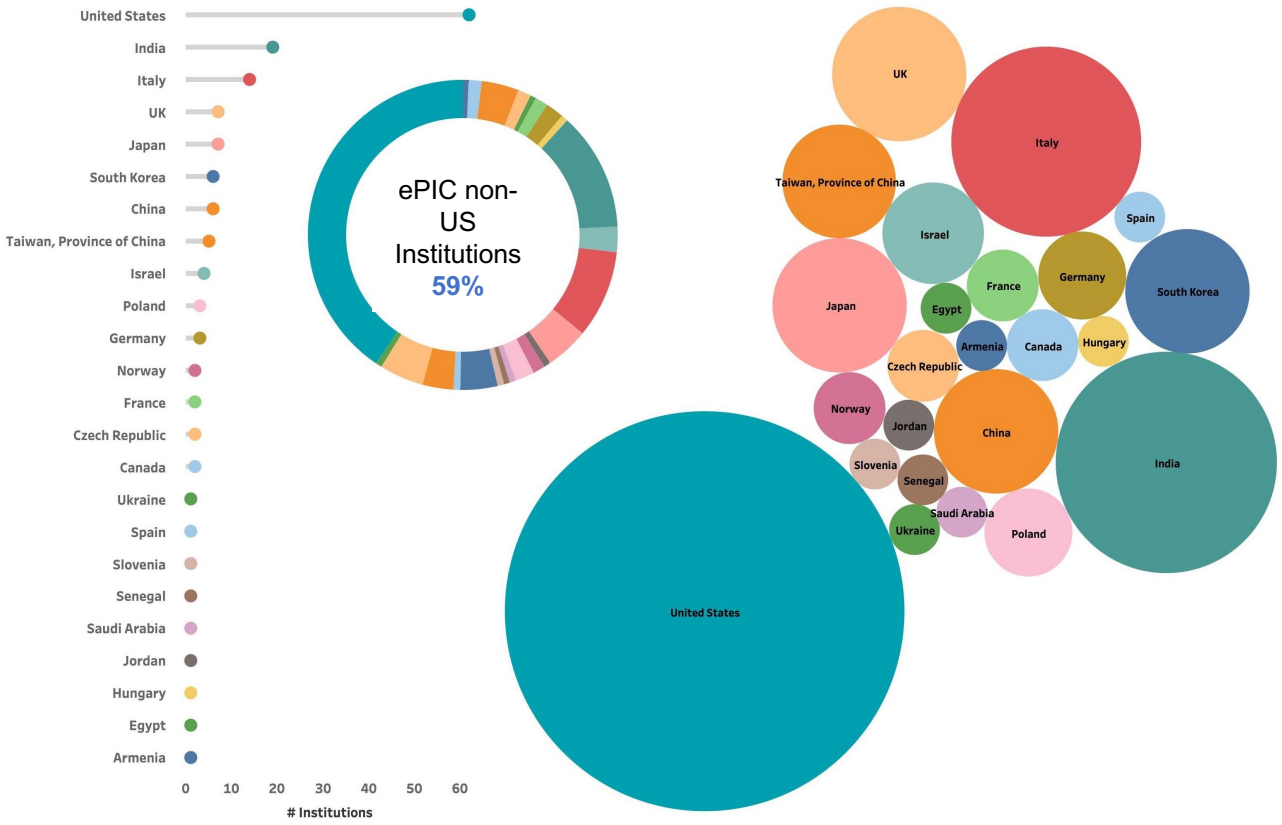




Extensive integration of forward and backward detector elements into the accelerator lattice



The ePIC Collaboration



ePIC formed a year ago.

ePIC is now 171 institutions including 11 new institutions that joined this July 2023.

Representing 24 countries

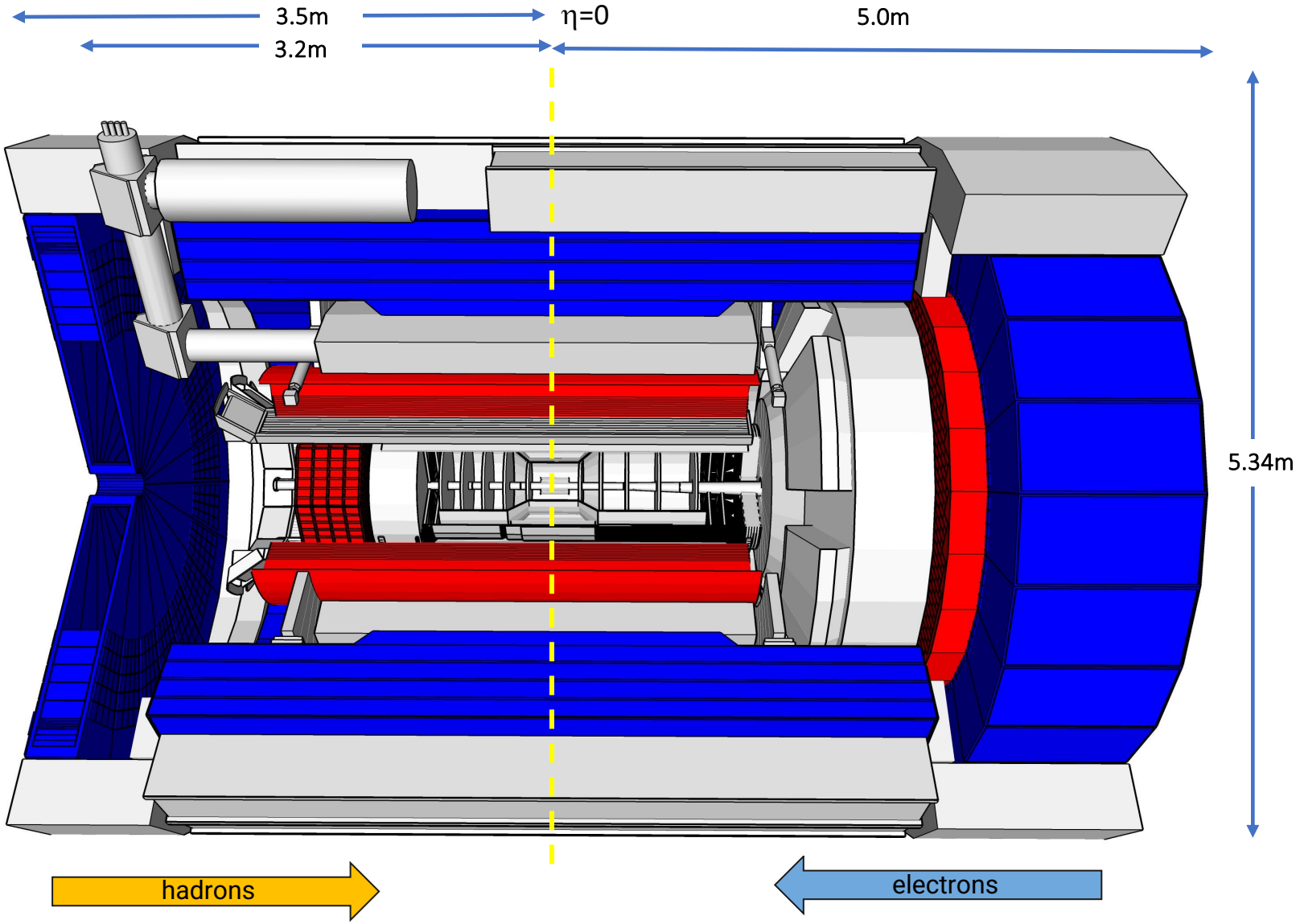
500+ participants

A global pursuit for a new experiment at the EIC!

ePIC Spokesperson:
John Lajoie (ORNL)

ePIC Deputy Spokesperson & Interim Technical Director
Silvia Dalla Torre (INFN Trieste)

ePIC Detector Design



Tracking:

- New 1.7T solenoid
- Si MAPS Tracker
- MPGDs (μRWELL/μMegas)

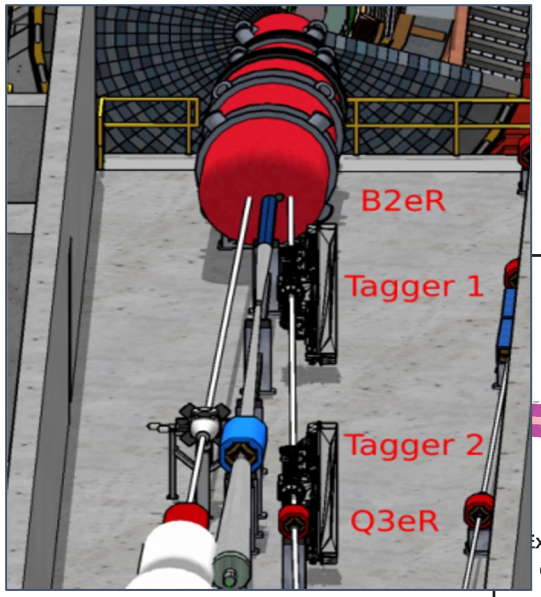
PID:

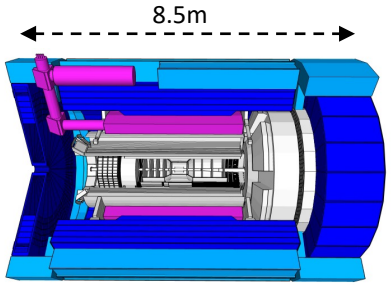
- hpDIRC
- pfRICH
- dRICH
- AC-LGAD (~30ps TOF)

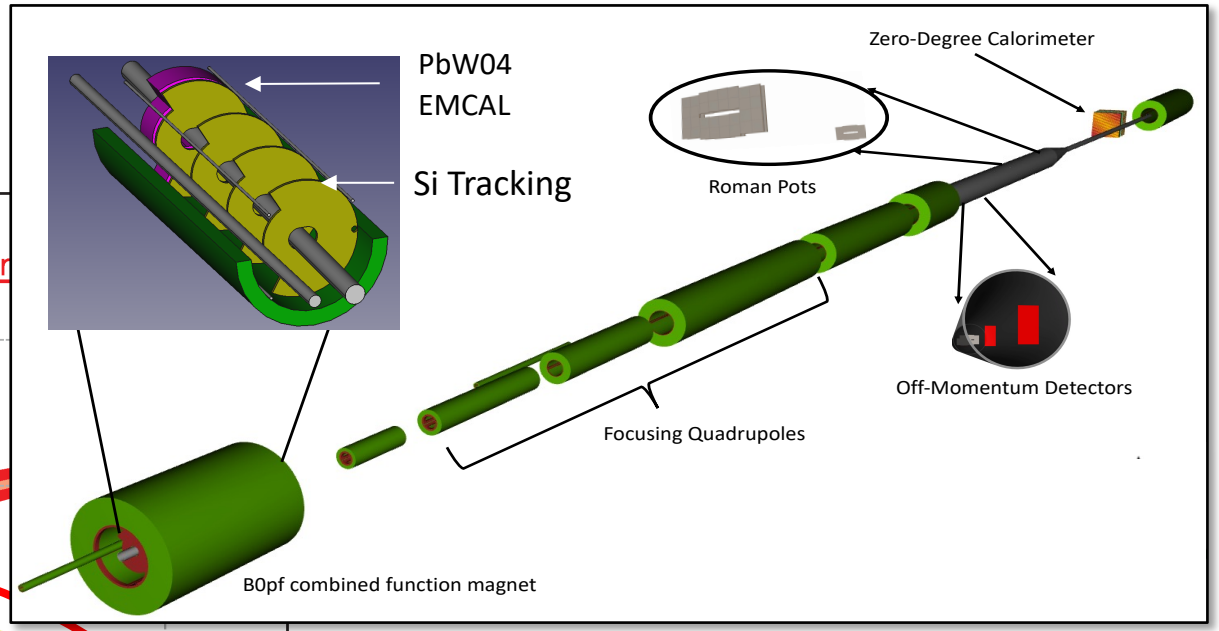
Calorimetry:

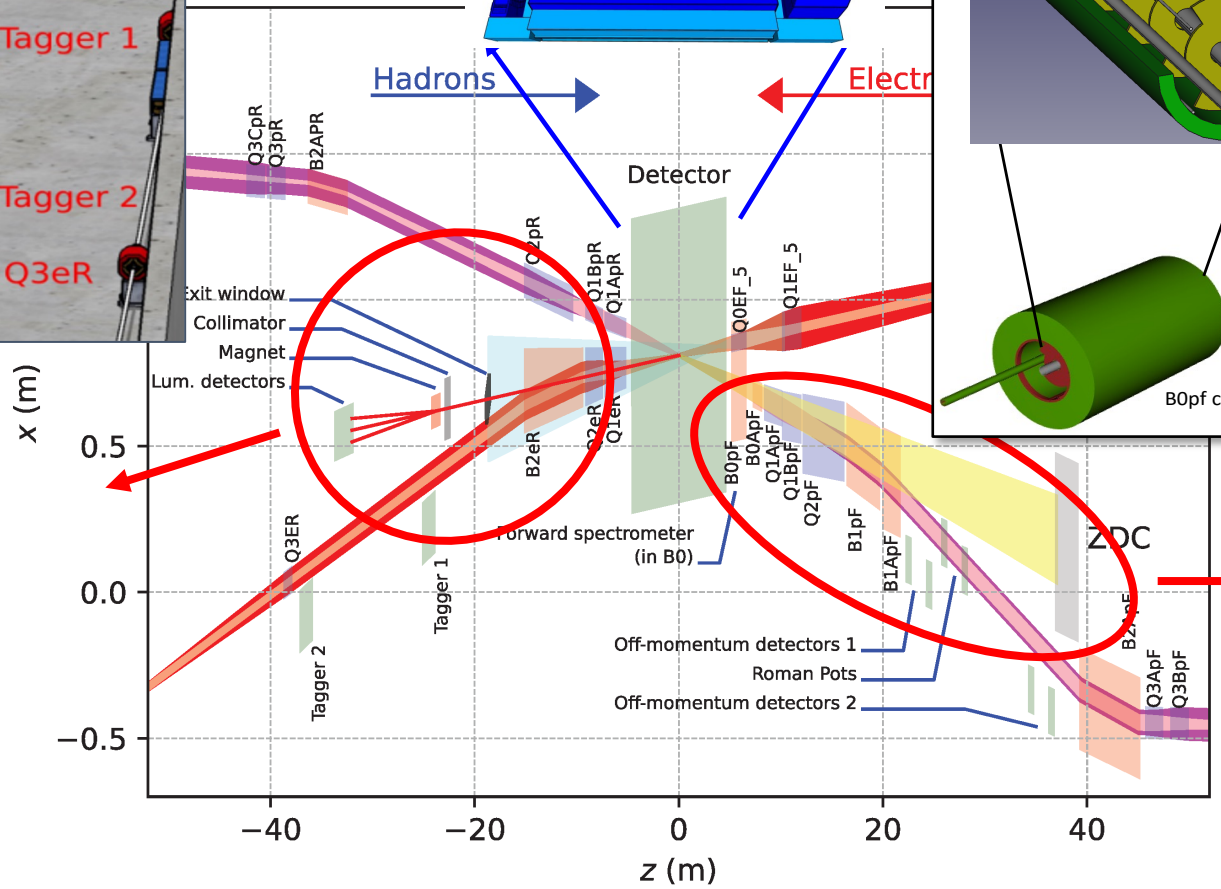
- Imaging Barrel EMCal
- PbWO4 EMCal in backward direction
- Finely segmented EMCal +HCal in forward direction
- Outer HCal (sPHENIX re-use)
- Backwards HCal (tail-catcher)

Far-Forward and Far-Backward Detectors









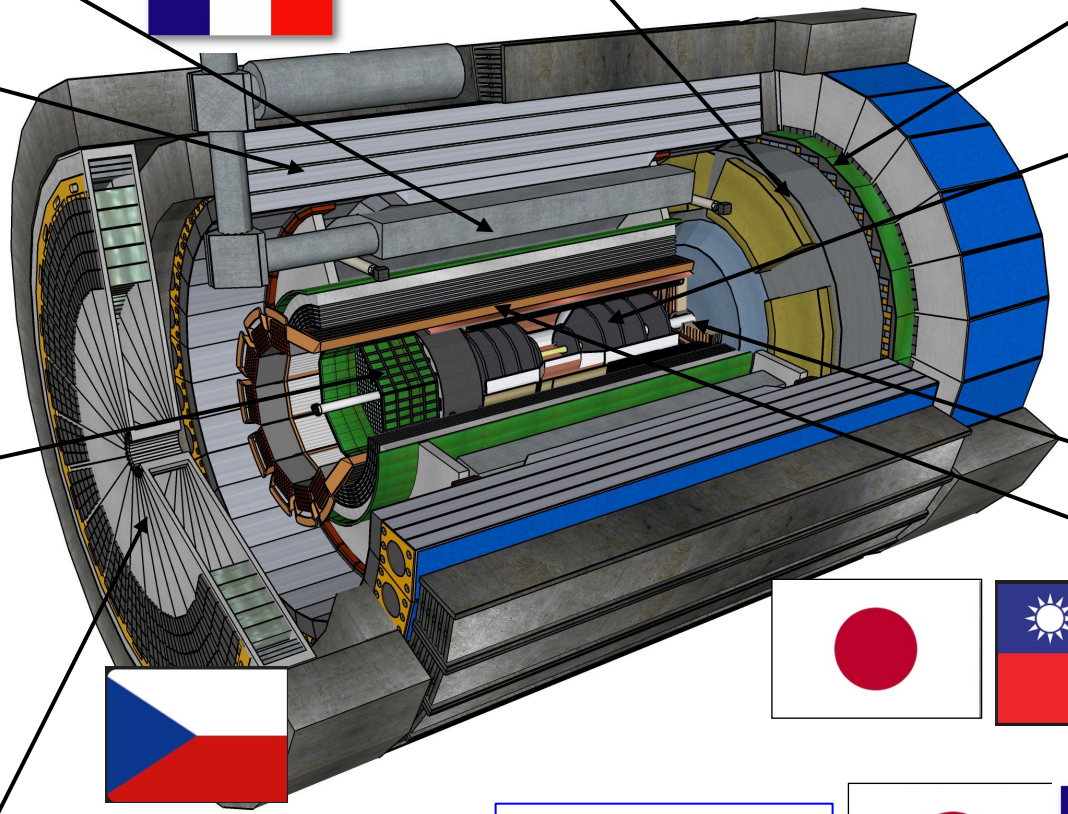
Far-Backward Detectors

- Luminosity monitor
- Low-Q^2 Tagging Detectors

Far-Forward Detectors

- B0 Tracking and Photon Detection
- Roman Pots and Off-Momentum Detectors
- Zero-Degree Calorimeter

Central Detector Non-DOE Interest & In-Kind



Superconducting Solenoid

Dual-radiator RICH

Forward Electromagnetic Calorimeter

Barrel Electromagnetic Calorimeter

Tracking Detectors

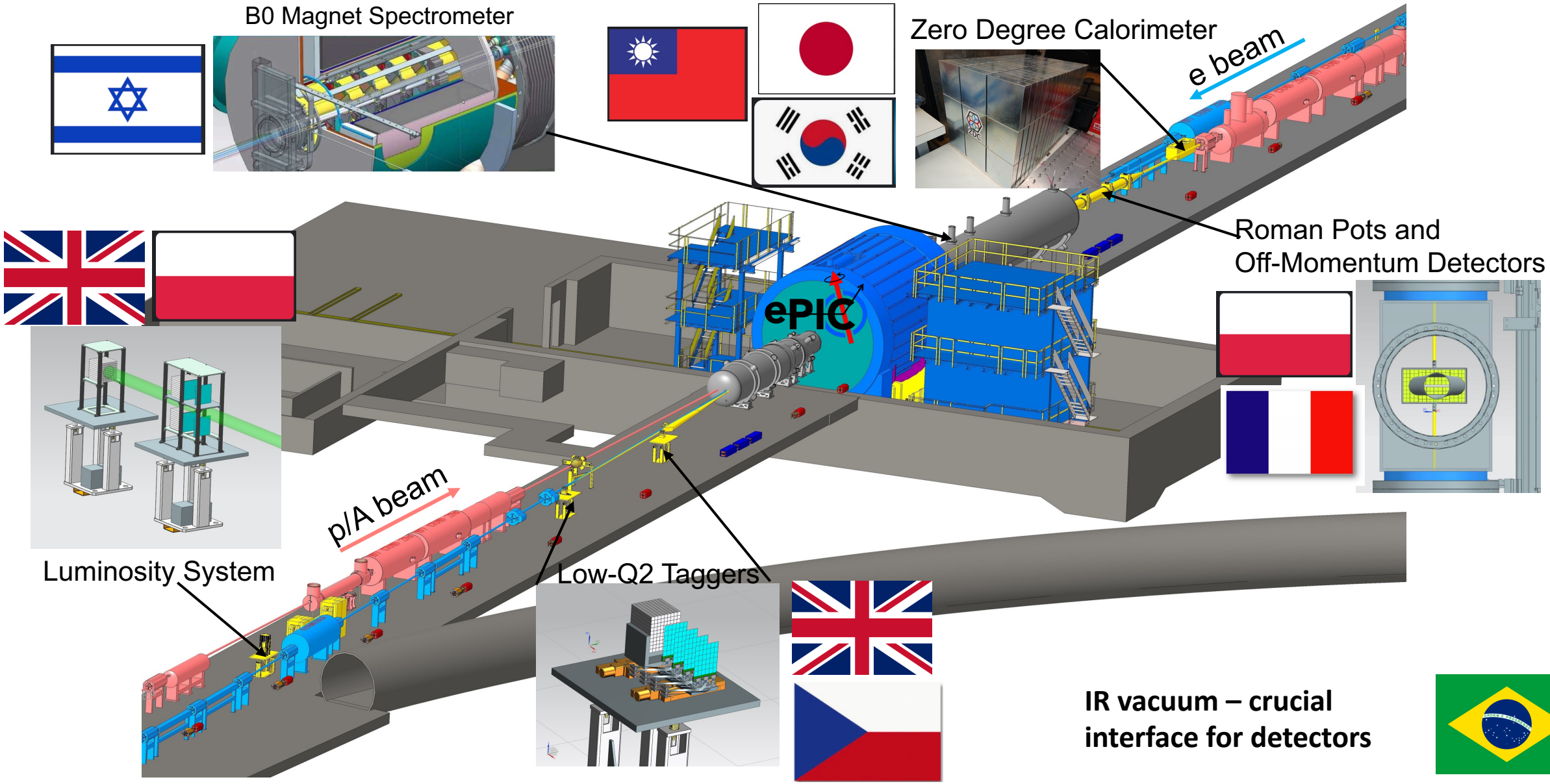
Backward Electromagnetic Calorimeter

Time-of-Flight

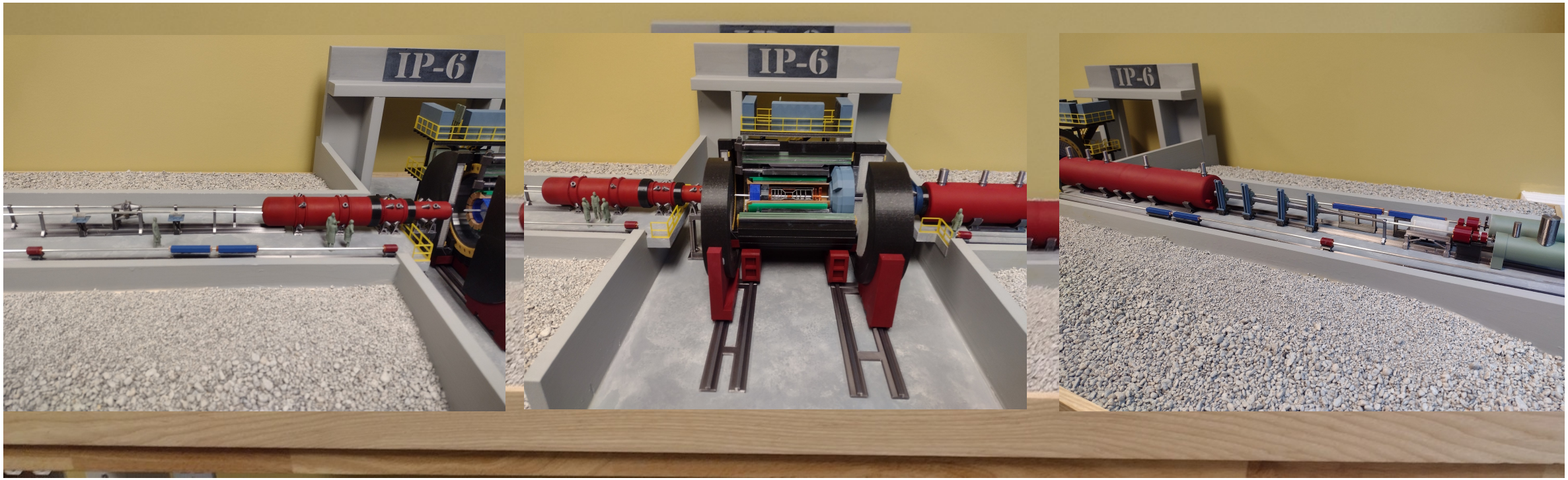
Backward Hadronic Calorimeter

Data-Acquisition Electronics

Far-Forward/Far-Backward Detectors Non-DOE Interest & In-kind



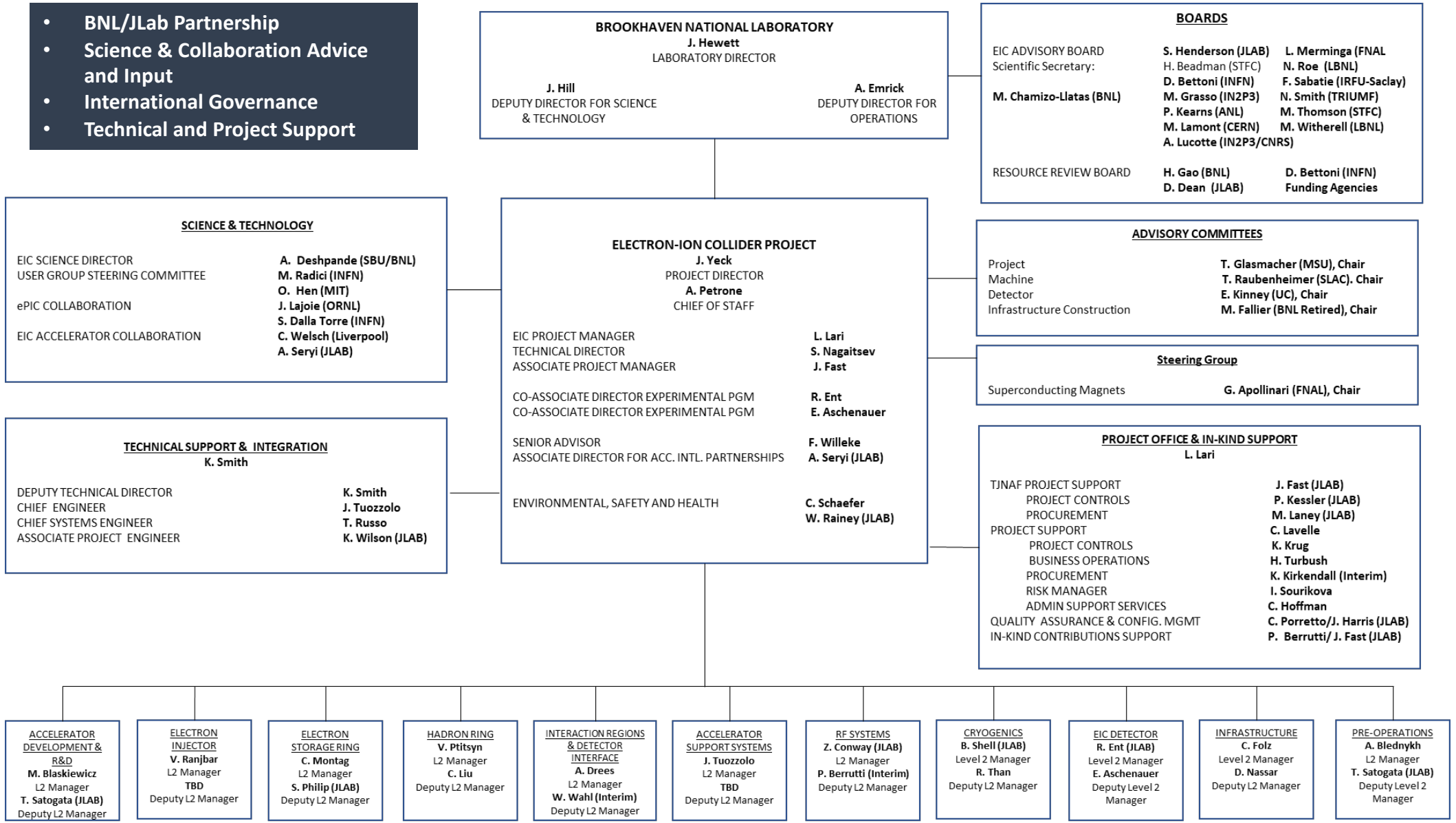
ePIC and the Interaction Region in 3D model



Based on a slide by ECA & RE

Project Organization

- BNL/JLab Partnership
- Science & Collaboration Advice and Input
- International Governance
- Technical and Project Support



Project Organization – Integrated BNL/JLAB

- Integrated BNL/JLab organization established in 2020.
- Continues to evolve and strengthen with the support of the host labs.
- An effective framework for developing execution strategies and identifying and resolving issues.
- Executive Management Team meetings include additional participants.
- New Technical Director after the Nov-2023 CD-3A review.

ELECTRON-ION COLLIDER PROJECT

J. Yeck
PROJECT DIRECTOR

A. Petrone
CHIEF OF STAFF

EIC PROJECT MANAGER	**L. Lari**
TECHNICAL DIRECTOR	**S. Nagaitsev**
ASSOCIATE PROJECT MANAGER	**J. Fast**
CO-ASSOCIATE DIRECTOR EXPERIMENTAL PGM	**R. Ent**
CO-ASSOCIATE DIRECTOR EXPERIMENTAL PGM	**E. Aschenauer**
SENIOR ADVISOR	**F. Willeke**
ASSOCIATE DIRECTOR FOR ACC. INTL. PARTNERSHIPS	**A. Seryi (JLAB)**
ENVIRONMENTAL, SAFETY AND HEALTH	**C. Schaefer** **W. Rainey (JLAB)**

Governance, Advice, and Support

SCIENCE & TECHNOLOGY

EIC SCIENCE DIRECTOR	**A. Deshpande (SBU/BNL)**
USER GROUP STEERING COMMITTEE	**M. Radici (INFN)**
	O. Hen (MIT)
ePIC COLLABORATION	**J. Lajoie (ORNL)**
	S. Dalla Torre (INFN)
EIC ACCELERATOR COLLABORATION	**C. Welsch (Liverpool)**
	A. Seryi (JLAB)

- Strong connections to the S&T communities.
- DOE, BNL, and JLab envision an EIC facility that is "fully international in character."
- The International Advisory Board provides oversight and advice on the construction of the facility, focusing on the accelerator.
- International Resource Review Board provides oversight of experiments.
- International Advisory Committees provide advice on the Project, Infrastructure, Machine, and Detector.
- Superconducting Magnet Steering Group

BOARDS

EIC ADVISORY BOARD	**S. Henderson (JLAB)**	**R. Pain (IN2P3/CNRS)**
Scientific Secretary:	**D. Bettoni (INFN)**	**F. Sabatie (IRFU-Saclay)**
M. Chamizo-Llatas (BNL)	**P. Kearns (ANL)**	**N. Smith (TRIUMF)**
	M. Lamont (CERN)	**M. Thomson (STFC)**
	L. Merminga (FNAL)	**M. Witherell (LBNL)**
RESOURCE REVIEW BOARD	**H. Gao (BNL)**	**D. Bettoni (INFN)**
	D. Dean (JLAB)	**Funding Agencies**

ADVISORY COMMITTEES

Project	**T. Glasmacher (MSU), Chair**
Machine	**T. Raubenheimer (SLAC). Chair**
Detector	**E. Kinney (UC), Chair**
Infrastructure Construction	**M. Fallier (BNL Retired), Chair**

Steering Group

Superconducting Magnets	**G. Apollina (FNAL), Chair**

EIC a facility truly international in character

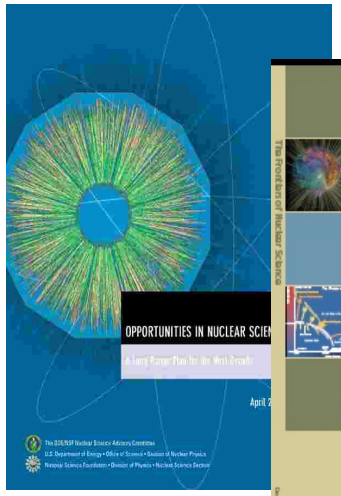
Jim Yech

Exciting news within these couple of months:

- State of NY gave EIC Project $100M for infrastructure building for the EIC
- EIC received CD3A – long lead procurement items ~$90M can now be bought.
- UK's science ministry announced a ~$75M contribution to accelerator and detector components for the EIC – first non-US in-kind contribution formalized

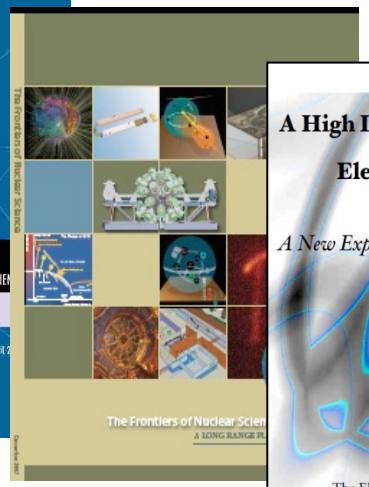
The Scientific Foundation for an EIC was Built Over Two Decades

2002



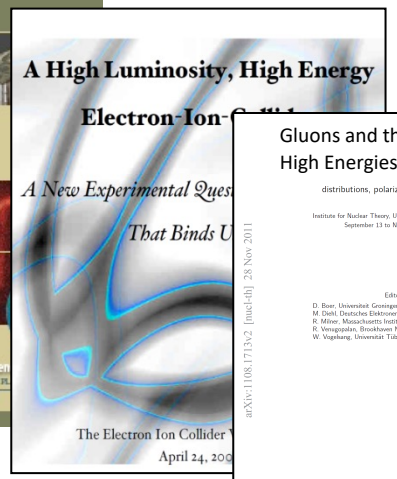
"…essential accelerator and detector R&D [for EIC] should be given very high priority in the short term."

2007



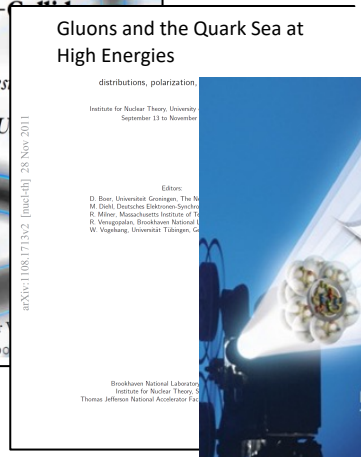
"We recommend the allocation of resources …to lay the foundation for a polarized Electron-Ion Collider…"

2009

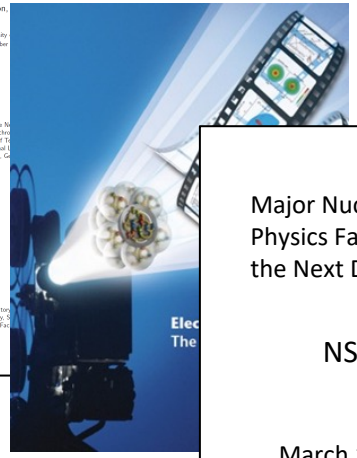


"..a new dedicated facility will be essential for answering some of the most central questions."

2010



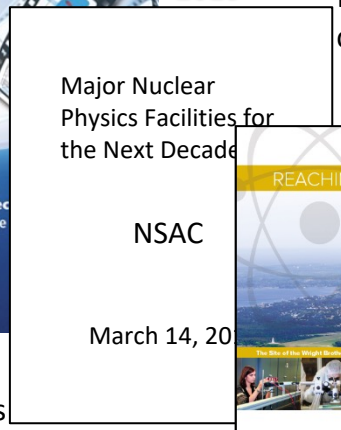
2012



"The quantitative study of matter in this new regime [where abundant gluons dominate] requires a new experimental facility: an Electron Ion Collider.."

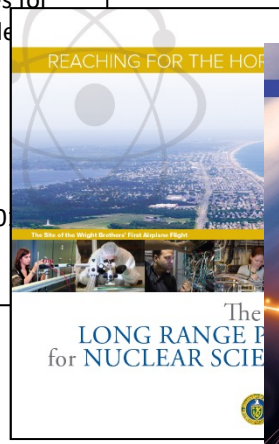
Electron-Ion Collider *absolutely central* to the nuclear science program of the next decade.

2013



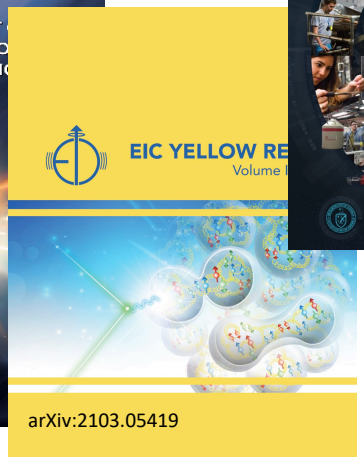
"a high-energy high-luminosity polarized EIC [is] the highest priority for new facility construction following the completion of FRIB."

2015



2018

2021



Science Requirements and Detector Concepts for the EIC – Drives the requirements of EIC detectors

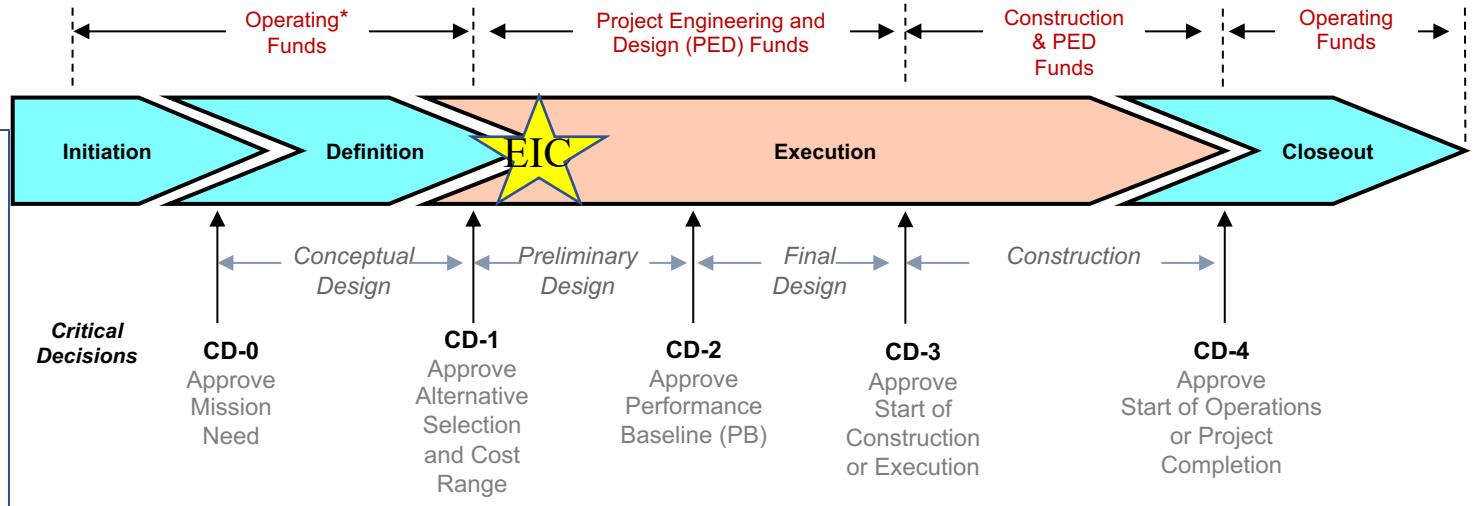
The science questions that an EIC will answer are central to completing an understanding of atoms as well as being integral to the agenda of nuclear physics today."

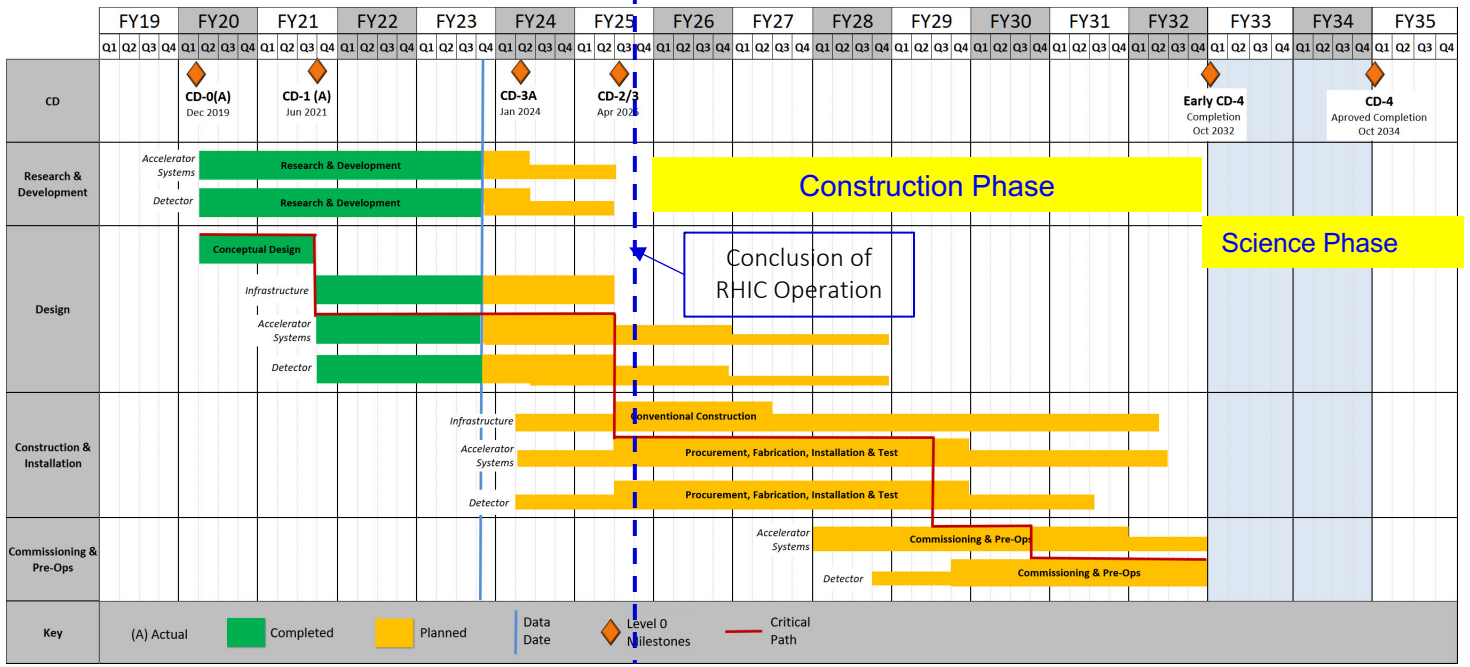
2023

Build expeditiously

Timeline:

EIC Critical Decision Plan	
CD-0/Site Selection	December 2019 ✓
CD-1	June 2021 ✓
CD-3A	March 2024 ✅
CD-3B	**March 2025**
CD-2/3	**End of 2025**
CD-4A	October 2032
CD-4	**October 2034**





CD-3A: (Approved)

Define Baseline:

technologies, Scope, Cost & Schedule

Long Lead Procurement (LLP) items

Design Maturity: ~90%

Plan is tracked through EVMS & Change control process

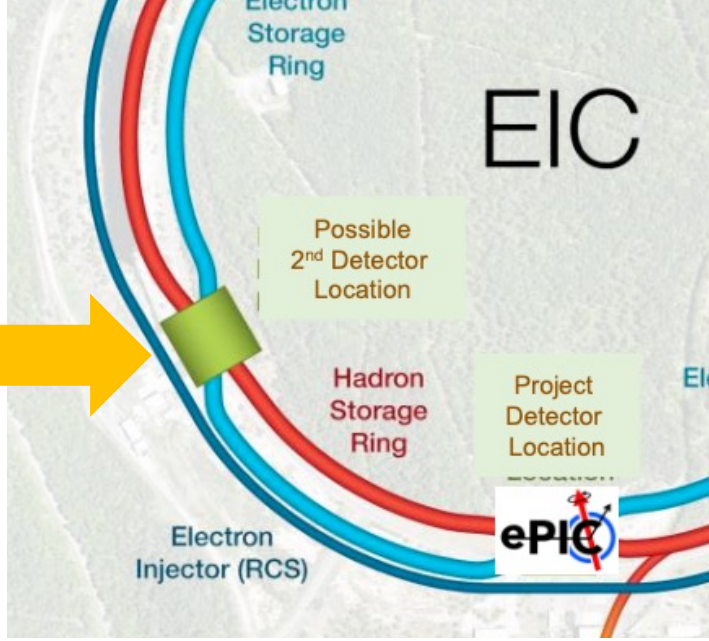
Start of construction for LLPs

… and then there is the 2nd Interaction region

National Academy Consensus Report: Recommended “up to two” detectors

No money for this in the EIC project, however, the accelerator design preserves the option for one in the future

The 2nd detector
Not in the EIC Project



EIC would be incomplete without the 2nd IR and 2nd detector
➔ my personal opinion

Can only be imagined when EIC project (machine+ePIC) moves forward successfully….

A set of workshops directed at physics of the 2nd detector led by EIC Users Group starting this/next year

Complementary detectors : 1 + 1 > 2

A 2nd detector with complementary acceptance, optimized for complementary technologies ➔ **Redundancy, cross-calibration and independent validation** of important results

- Complementary acceptance: establishing important discoveries – physics from “point of views”
- Complementary Technologies – systematic uncertainties improvement due to different Particle ID, Calorimetry, Tracking, magnetic field strengths and orientations.
  - H1/ZEUS, PHENIX/STAR, CDF/D0 and ATLAS/CMS vs. LHCb
  - Critical because most measurements at the EIC expected to be systematics limited
- Complementary analyses strategies of different collaborations build confidence in conclusions

And case would strengthen significantly if

- We identify science thrusts complementary *to* those of the ePIC detector:

Dream of 2nd detector ready ~5-7 years after EIC/ePIC start of operations

Summary & Outlook

- Electron Ion Collider, a high-energy **high-luminosity polarized e-p, e-A collider**, will be built in this decade and operate in 2030's.
  - Will address the most profound unanswered questions in QCD
  - Attempt to make this truly international in character

- Up to two hermetic (full acceptance(?) and complementary) detectors under consideration, although **EIC project has funds for 1 detector**.
  - A truly international experimental collaboration EPIC formed
  - A world-wide accelerator collaboration formed
  - An aggressive timeline : first collisions by ~2032; physics start by ~2033/34
  - High interest in having international partners both on detector and accelerator

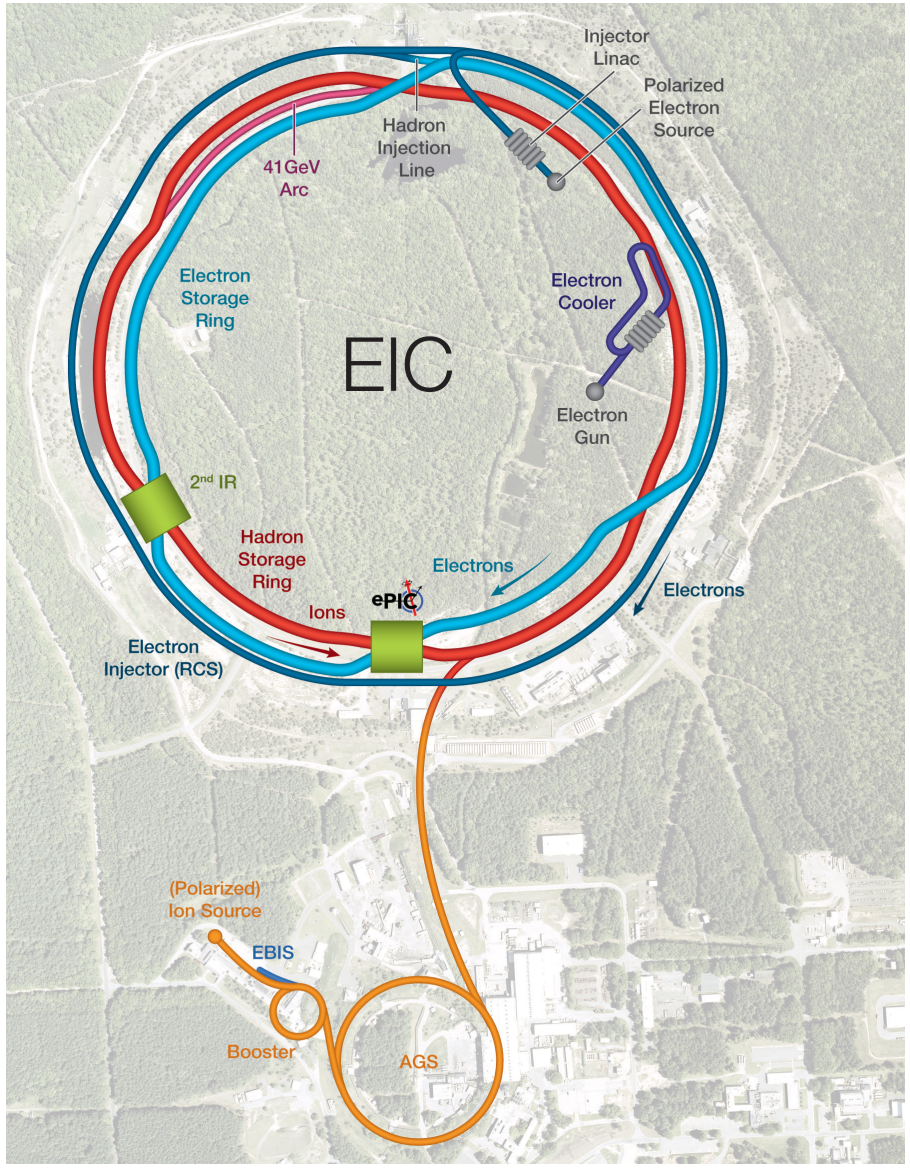
  - A second detector a few years later

- *For all early career scientists, graduate and undergraduate students: This machine is for you! Ample opportunity to contribute to machine, detector & physics of the EIC.*

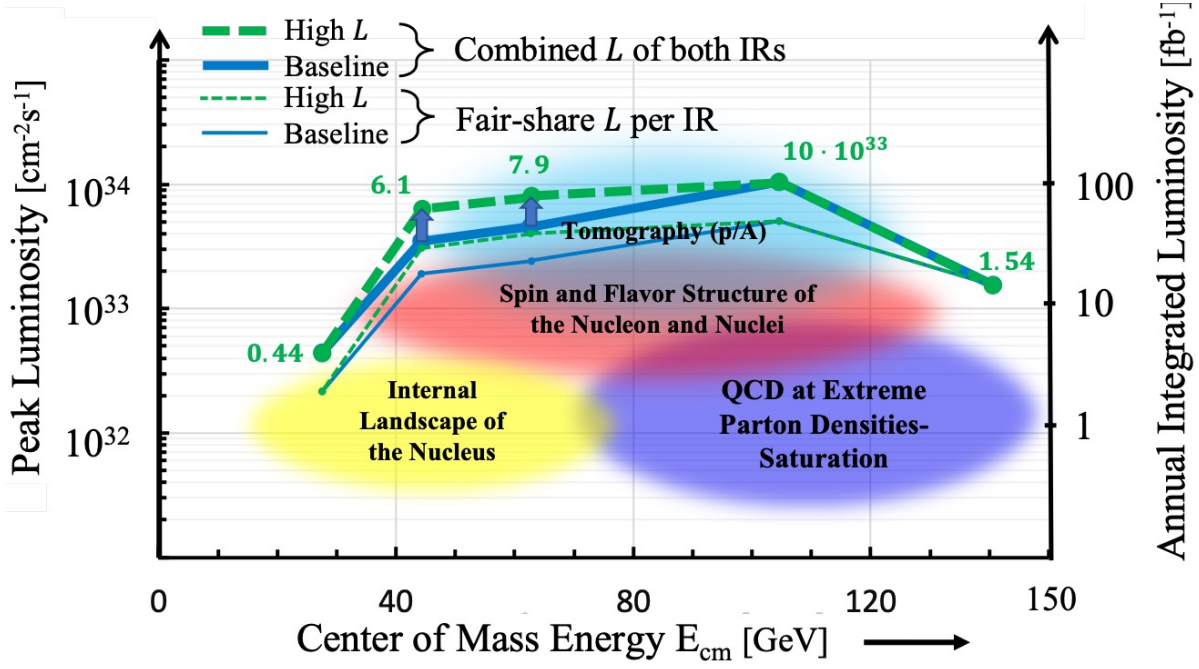
"New directions in science are launched by new tools much more often than by new concepts."

Freeman Dyson

EIC Accelerator Design



Center of Mass Energies:	20GeV - 140GeV
Luminosity:	10^{33} - 10^{34} $cm^{-2}s^{-1}$ / 10-100fb^{-1} / year
Highly Polarized Beams:	70%
Large Ion Species Range:	p to U
Number of Interaction Regions:	Up to 2!



The ePIC Detector

- Asymmetric beam energies
  - requires an asymmetric detector with electron and hadron endcap
  - tracking, particle identification, EM calorimetry and hadronic calorimetry functionality in all directions
  - very compact Detector, **Integration** will be key
- Imaging science program with protons and nuclei
  - requires specialized detectors integrated in the IR over 80 m
- Momentum resolution for EIC science requires a large bore 2T magnet
- Highest scientific flexibility
  - requires Streaming Readout electronics model