



The Electron Ion Collider (EIC) Science and Status

Abhay Deshpande

EIC Science Director

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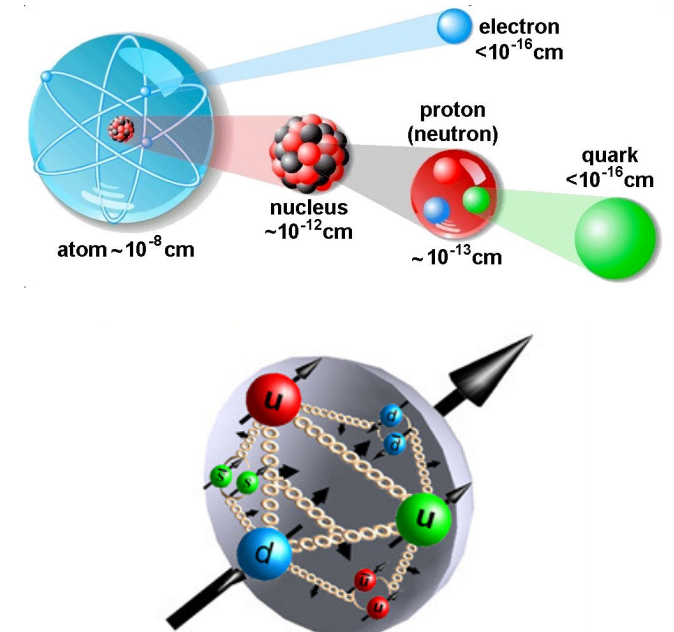
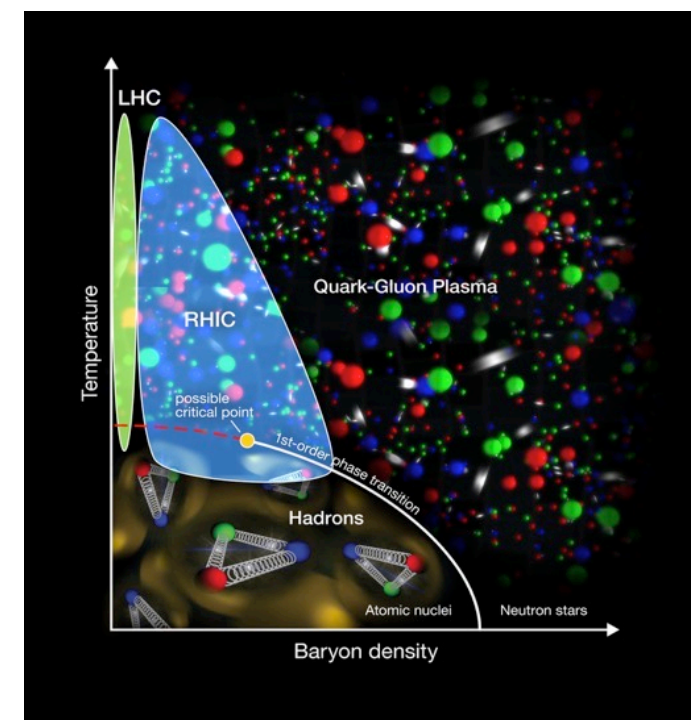
Associate Laboratory Director for Nuclear and Particle Physics, BNL

September 30, 2024



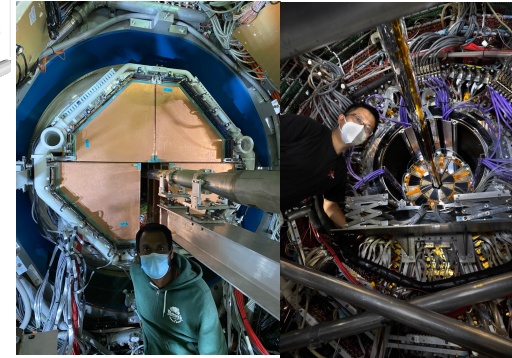
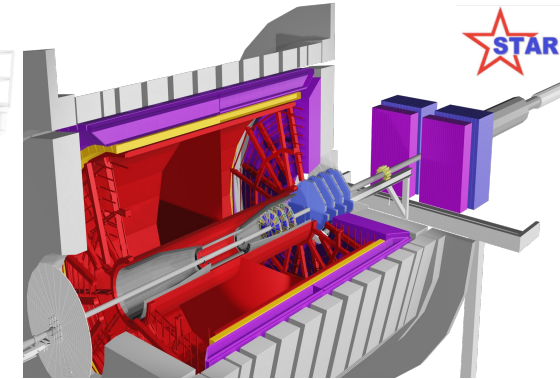
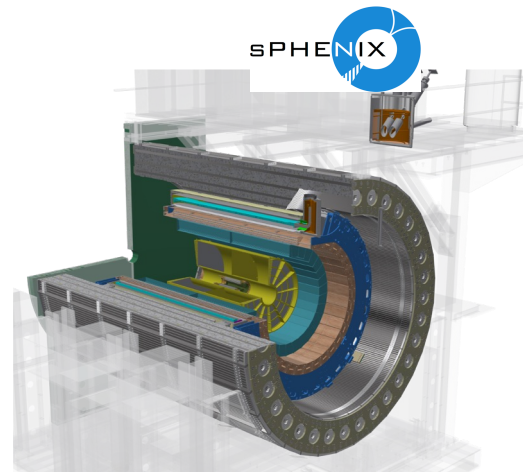
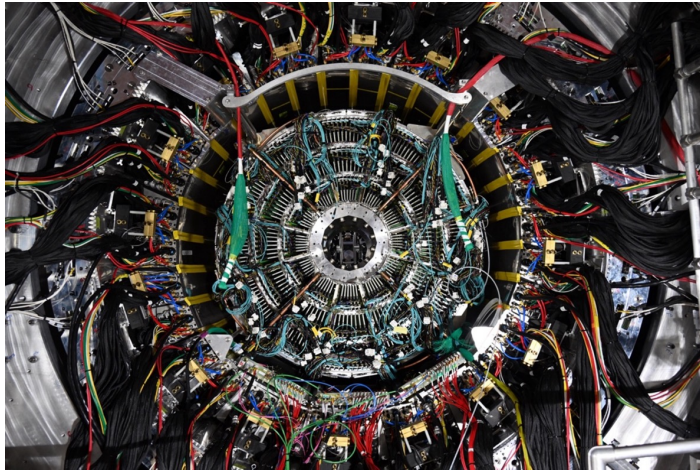
RHIC – a Unique Research Tool

- Heavy ion collisions
 - Established & now detailed study of Quark Gluon Plasma
 - Collide many different ion species from fixed target to collider energies
- Polarized proton collisions
 - The only polarized proton collider – study -- the internal spin structure of protons at high energy
 - Gluon's contribution to proton spin, transverse motion of quarks
- Arguably, the most versatile and advanced collider: reached 50 times its design luminosity & the expected ~60% proton polarization
- Operational since 2000, expected to shut down in ~2025



Completing the RHIC Mission with sPHENIX and STAR

- sPHENIX commissioned in 2023/4 will use energetic probes (jets, heavy quarks) to study quark-gluon plasma with unprecedented precision
 - How the "perfect" fluid emerges from the underlying interactions of quarks and gluons at high temperature
- sPHENIX a dedicated modern detector for heavy quark and jet studies – replaced the PHENIX experiment (2000-2016).
- 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 including glimpses of 3D quark gluon structure in polarized protons
- STAR continues to study: how dense nuclear environment affects quarks and gluons, their correlations, and their interactions and giving rise to non-linear effects?

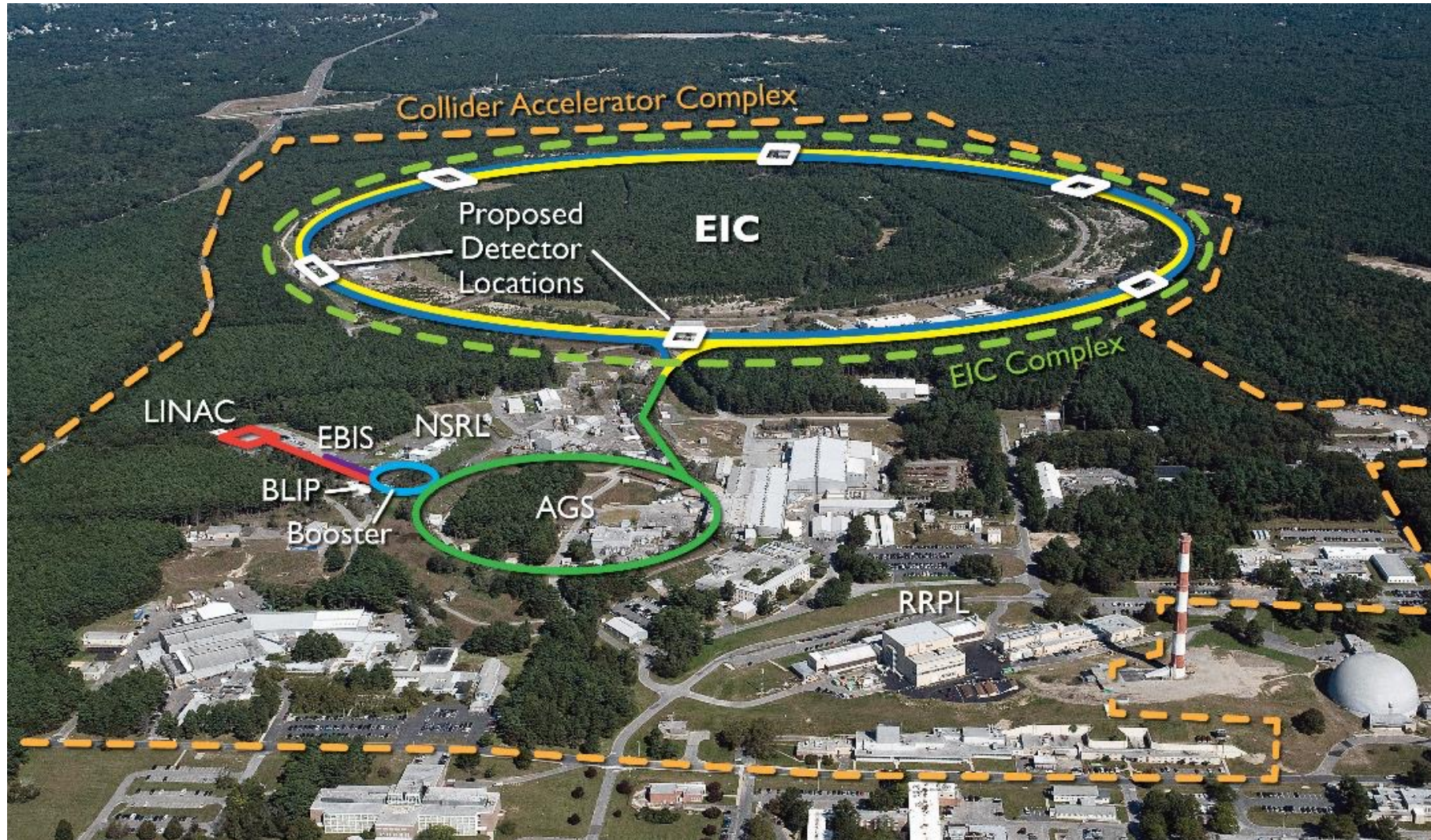


Synergies with the EIC science and contribute to EIC workforce development

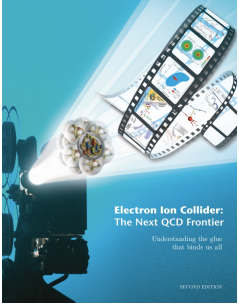
RHIC data taking scheduled for 2024–2025

sPHENIX and STAR with forward upgrade will fully utilize the enhanced (~50 times Au+Au design) luminosity of RHIC

EIC: to be realized jointly by BNL and Jefferson Lab



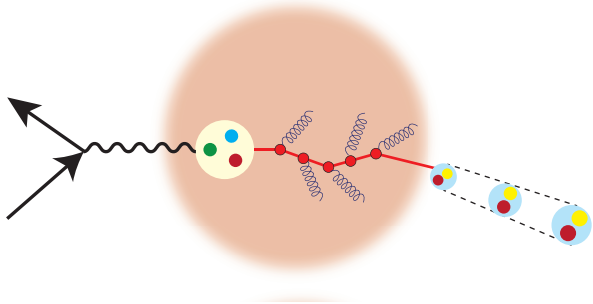
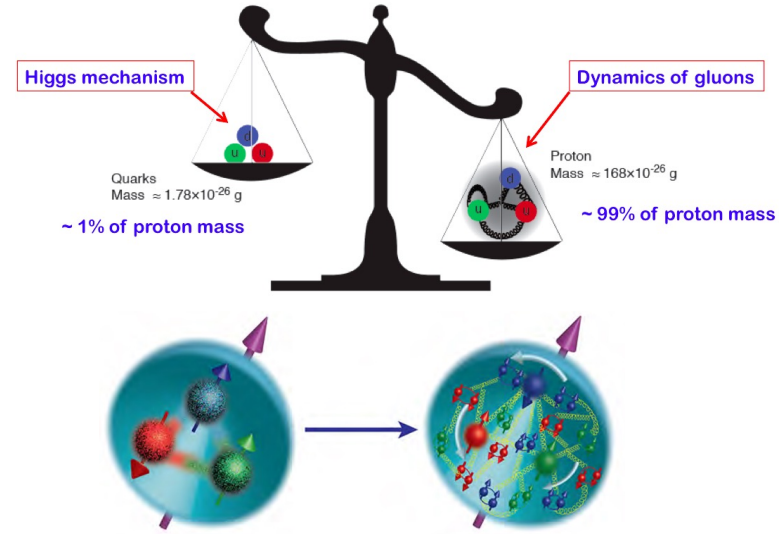
EIC benefits from \$2.4B class investments at BNL (RHIC and Injectors) & a highly successful RHIC program. RHIC will conclude operations in 2025. Electron Ion Collider installation will begin after RHIC ops concludes.



EIC Physics at-a-Glance

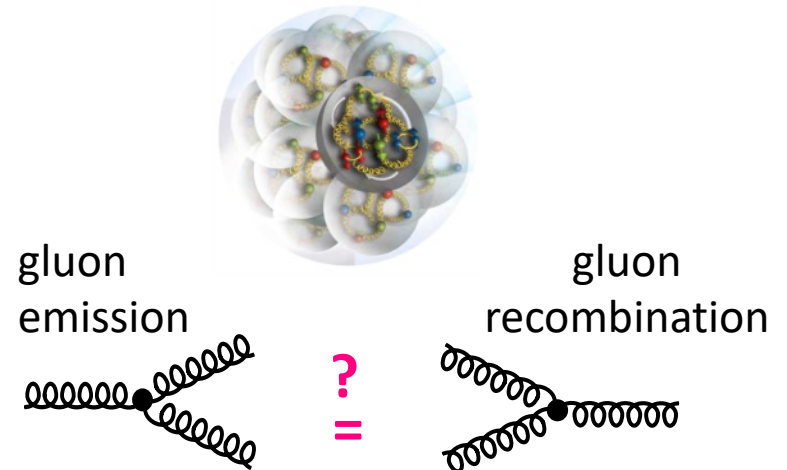
Eur. Phys. J. A 52 (2016) 9, 268 arXiv:1212.1701 (nucl-ex)

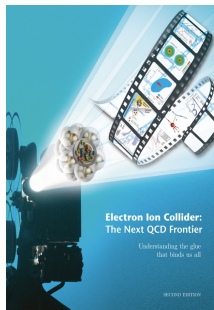
How are the sea quarks and gluons, and their spins, **distributed in space and momentum** inside the nucleon? How do the **nucleon properties (mass & spin) emerge** from their interactions?



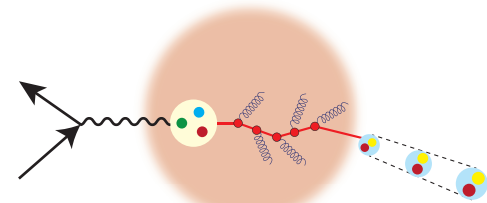
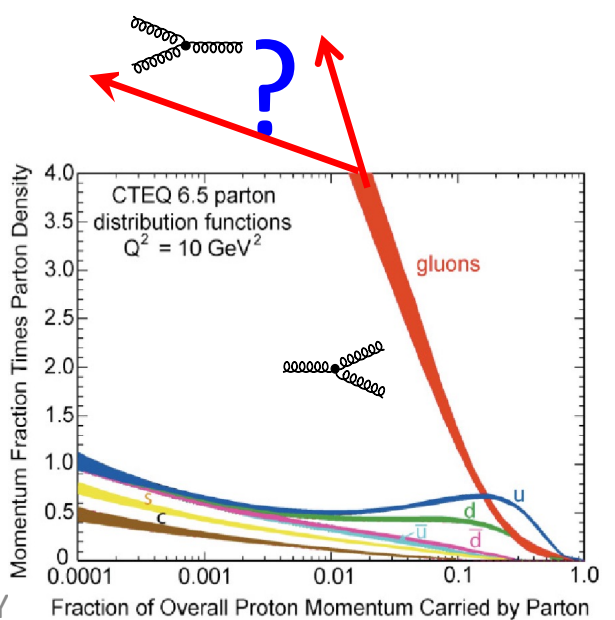
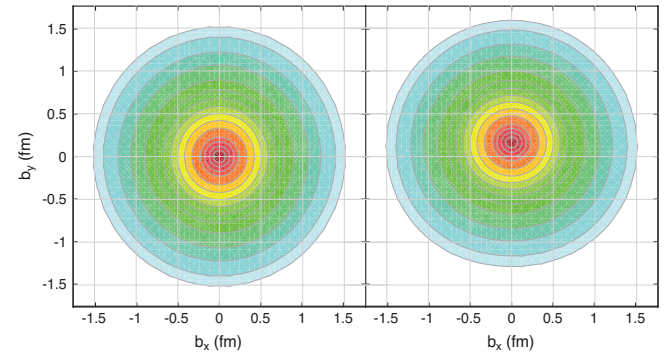
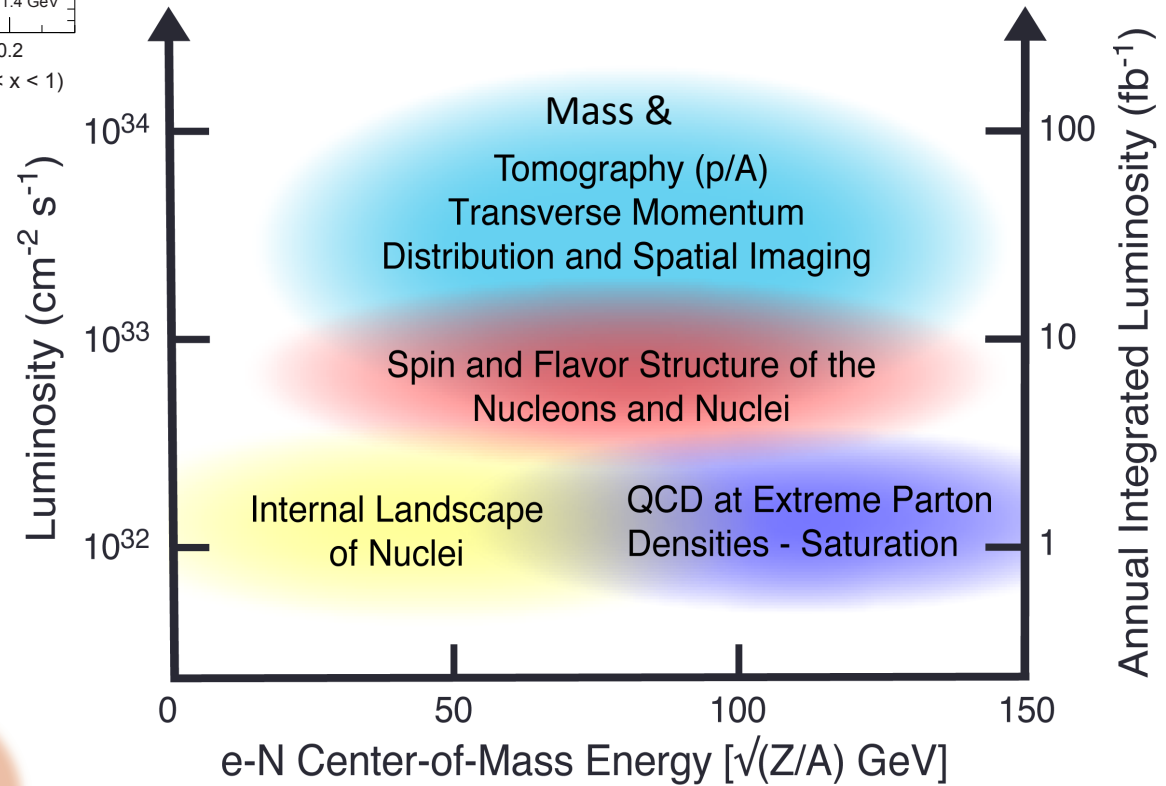
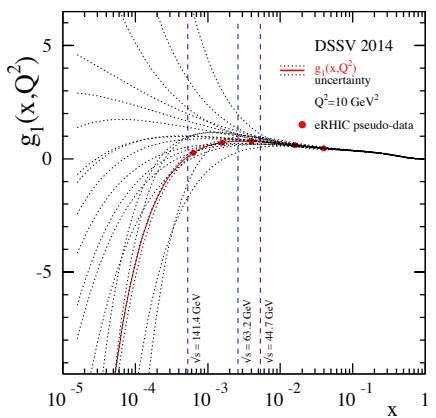
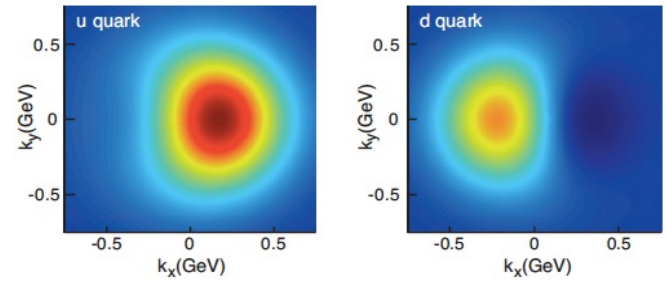
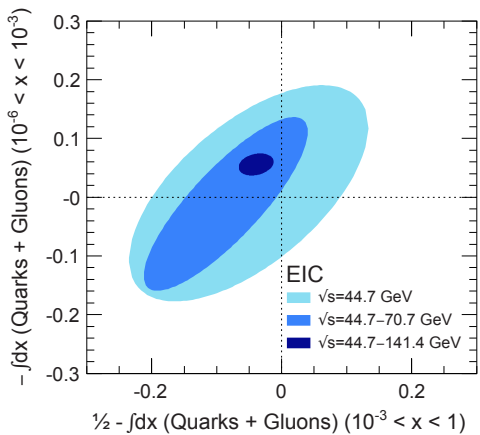
How do color-charged quarks and gluons, and colorless jets, **interact with a nuclear medium**? How do the **confined hadronic states emerge** from these quarks and gluons? How do the quark-gluon interactions create **nuclear binding**?

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?



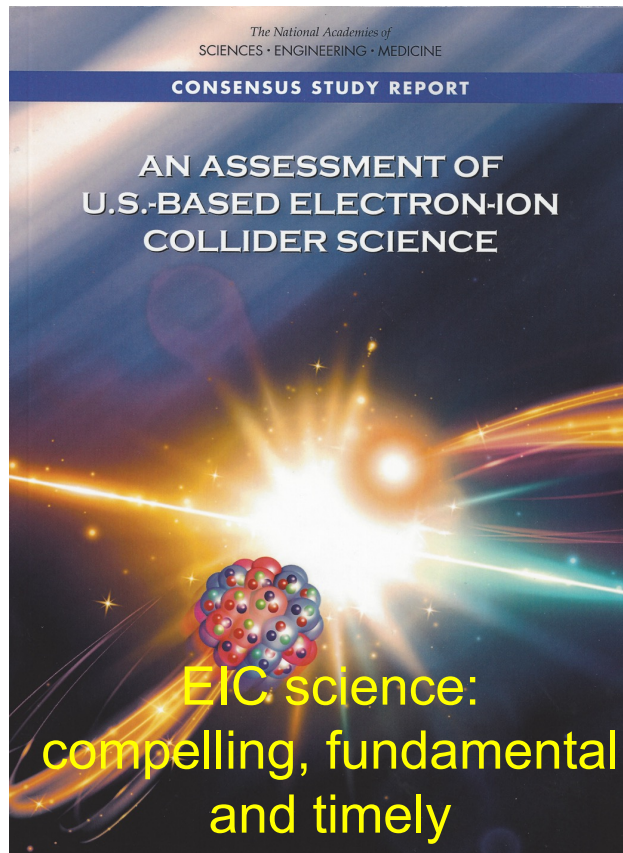


EIC science selected highlights





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?

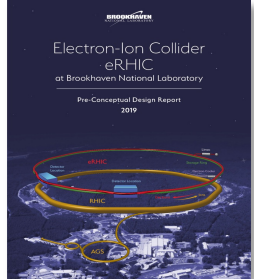
Machine Design Parameters:

- High luminosity: **up to 10^{33} - 10^{34} cm⁻²sec⁻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

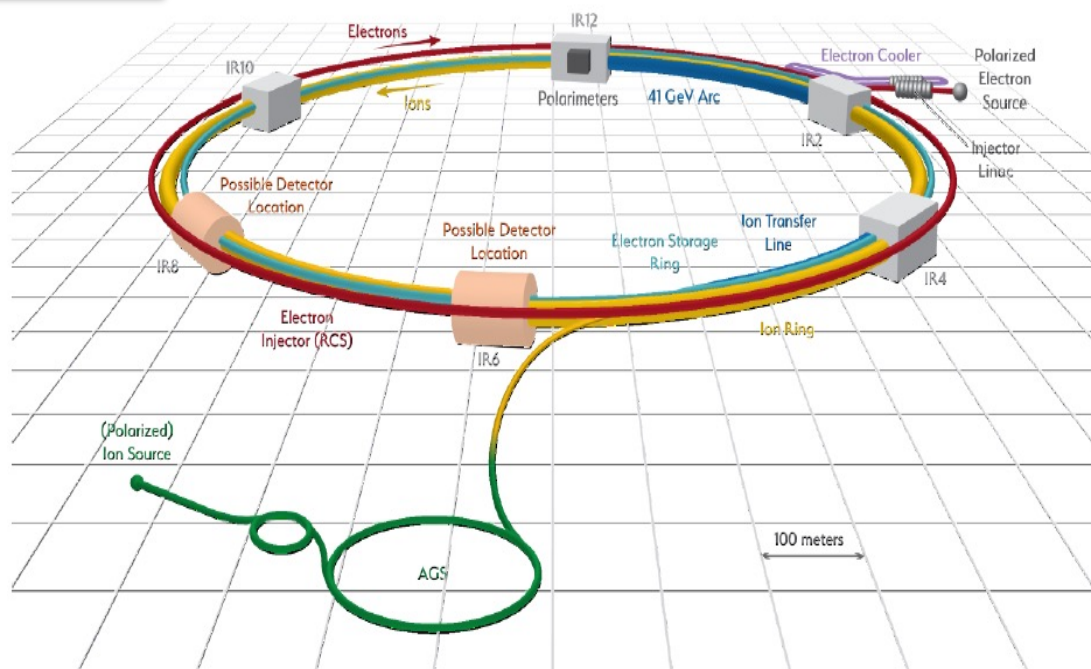
- Optimization of machine operations &
- Detector design & data acquisition (triggerless data collections)





The Electron Ion Collider: Partnership between BNL and JLab

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

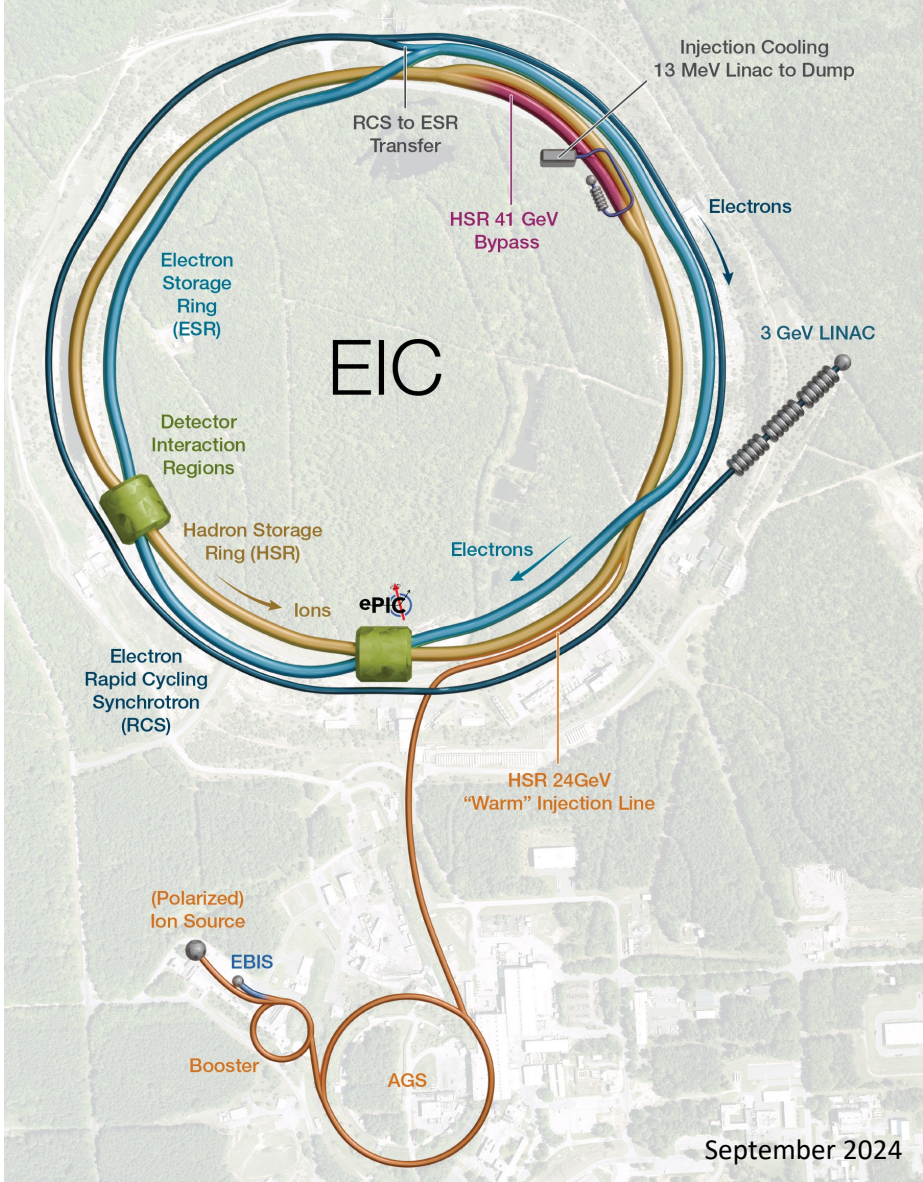
- Existing RHIC complex: Storage (Yellow), injectors (source, booster, AGS)
- Need few modifications
- RHIC beam parameters fairly close to those required for EIC@BNL

Electrons up to 18 GeV

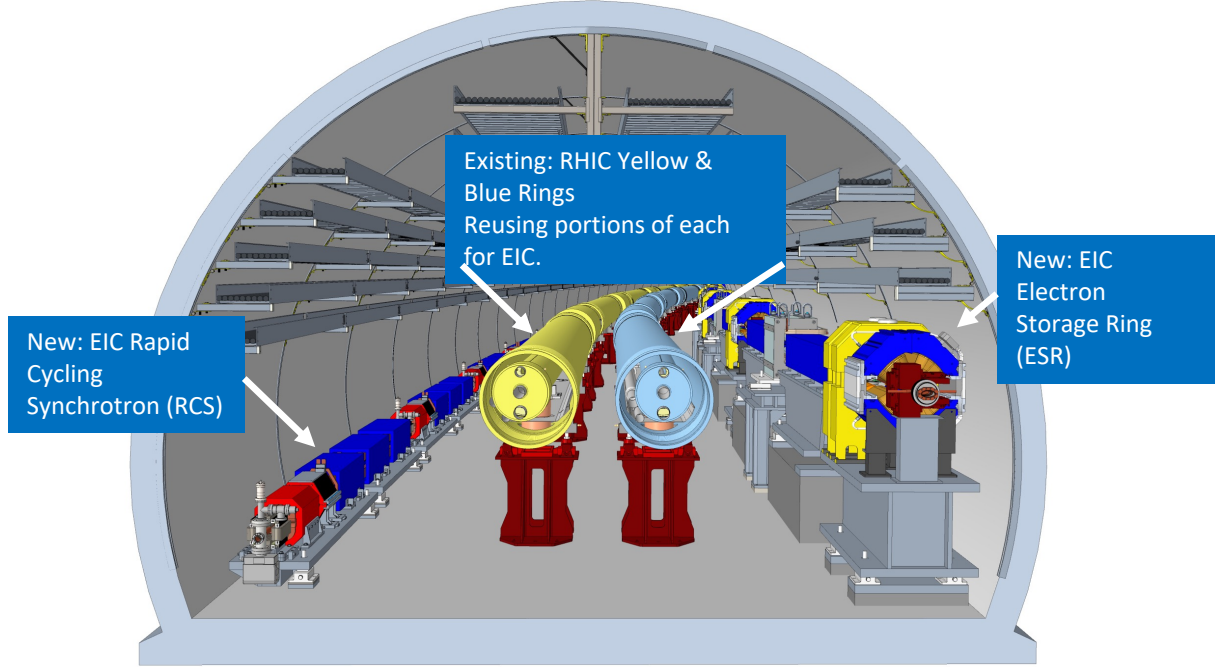
- Storage ring, provides the range $\sqrt{s} = 20\text{-}140$ GeV. Beam current limited by RF power of 10 MW
- Electron beam with variable spin pattern (s) accelerated in on-energy, spin transparent injector (Rapid-Cycling-Synchrotron) with 1-2 Hz cycle frequency
- Polarized e-source and a 400 MeV s-band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

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

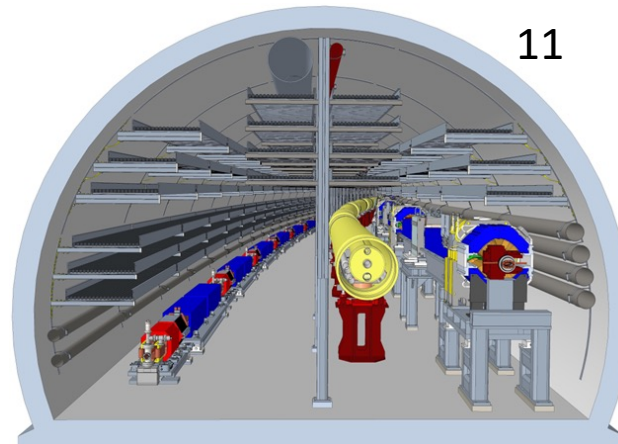
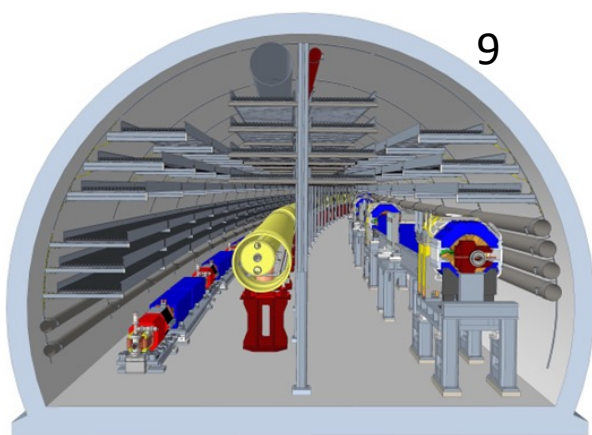
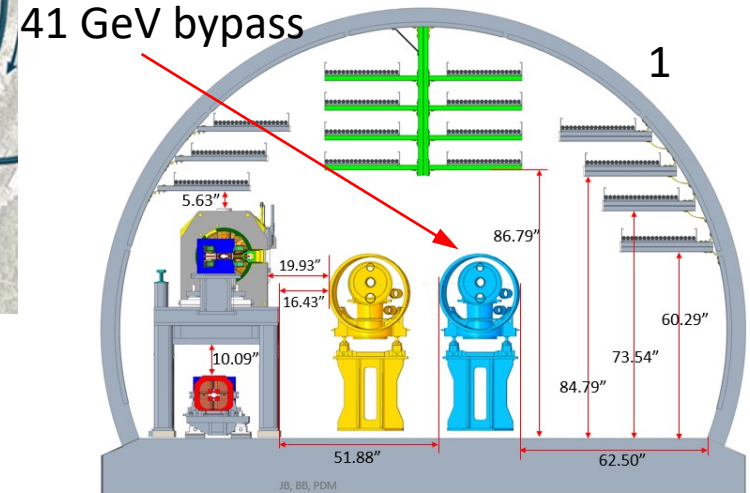
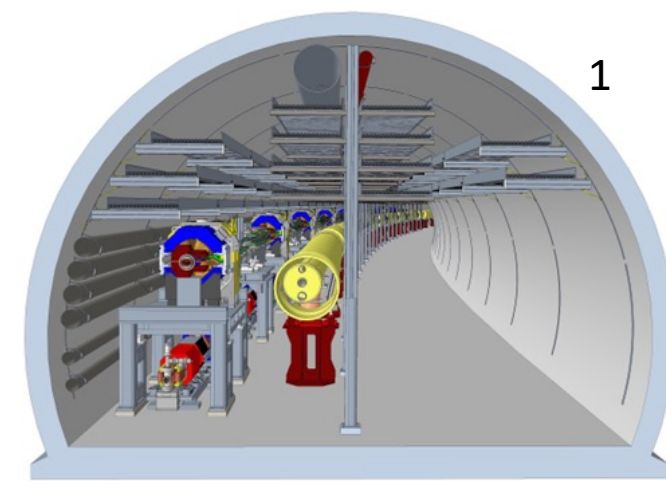
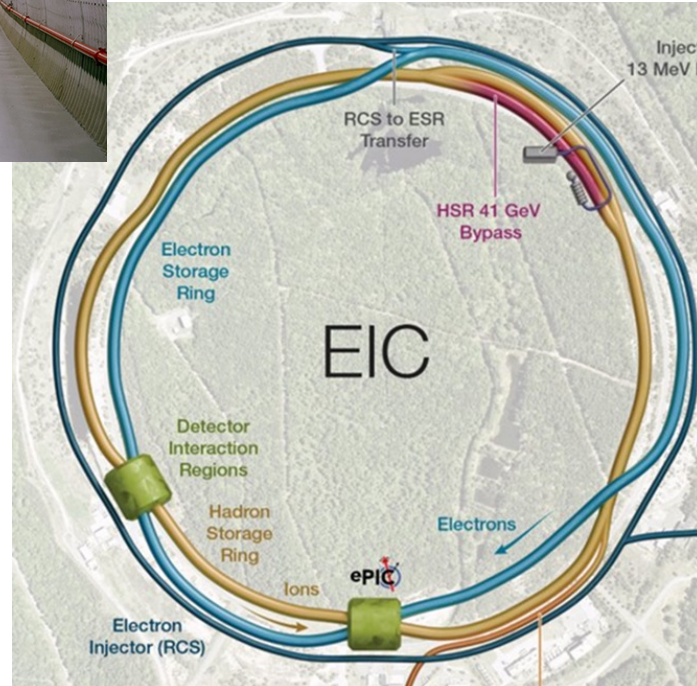
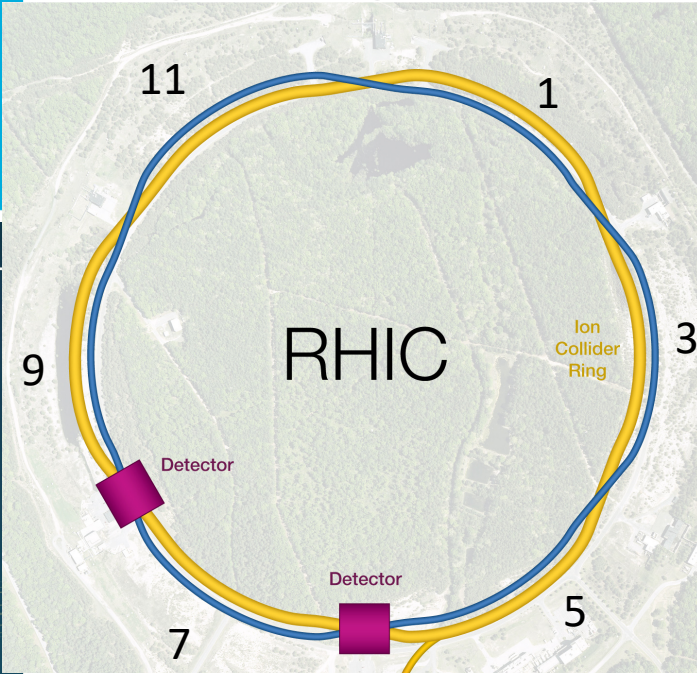
EIC Accelerator Design & Layout



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



Tunnel View



Electron-Ion Collider

S. Nagaitsev

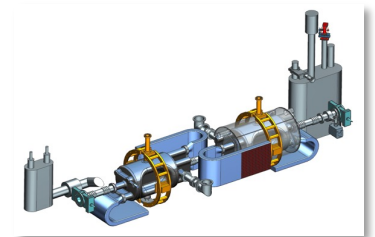
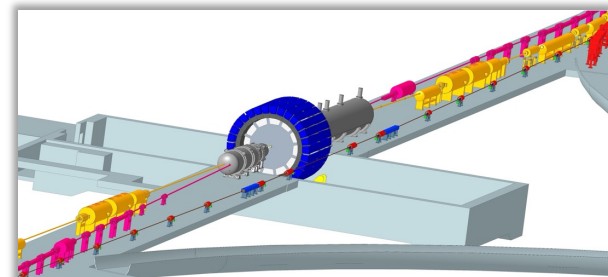
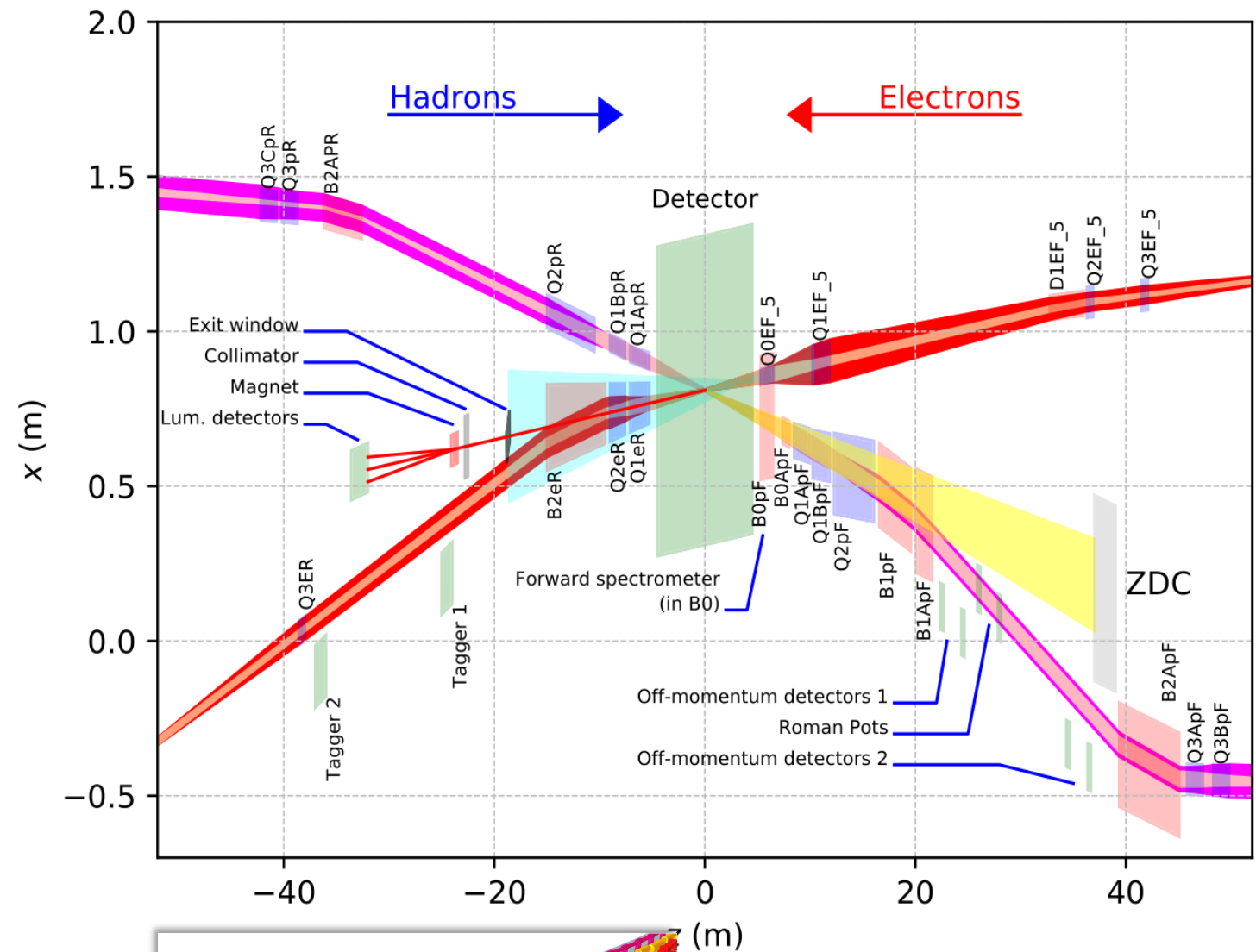
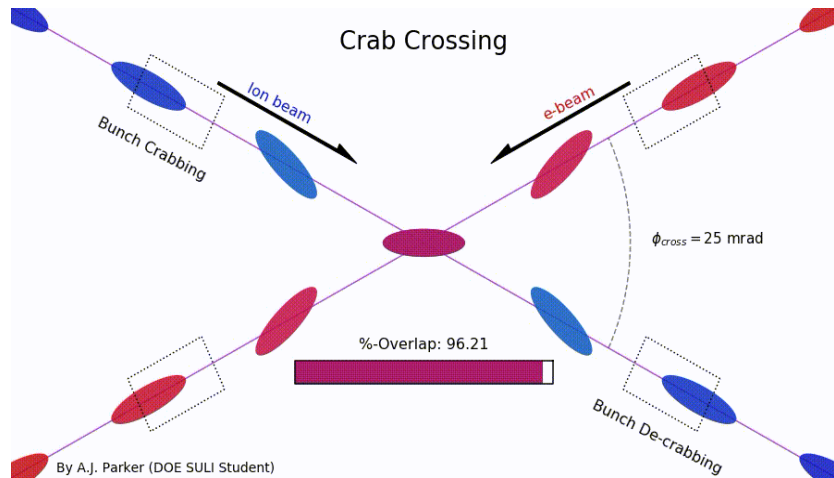
EIC IR6 Layout

High luminosity:

- 25 mrad crossing angle
- Small β^* for high luminosity with limited IR chromaticity contributions
- Large final focus quadrupole aperture

Machine Detector Interface

- Large detector acceptance
- Forward spectrometer
- No magnets within - 4.5 / +5 m from IP
- Space for luminosity detector, neutron detector, "Roman Pots"



Worldwide Interest in EIC

The EIC User Group:

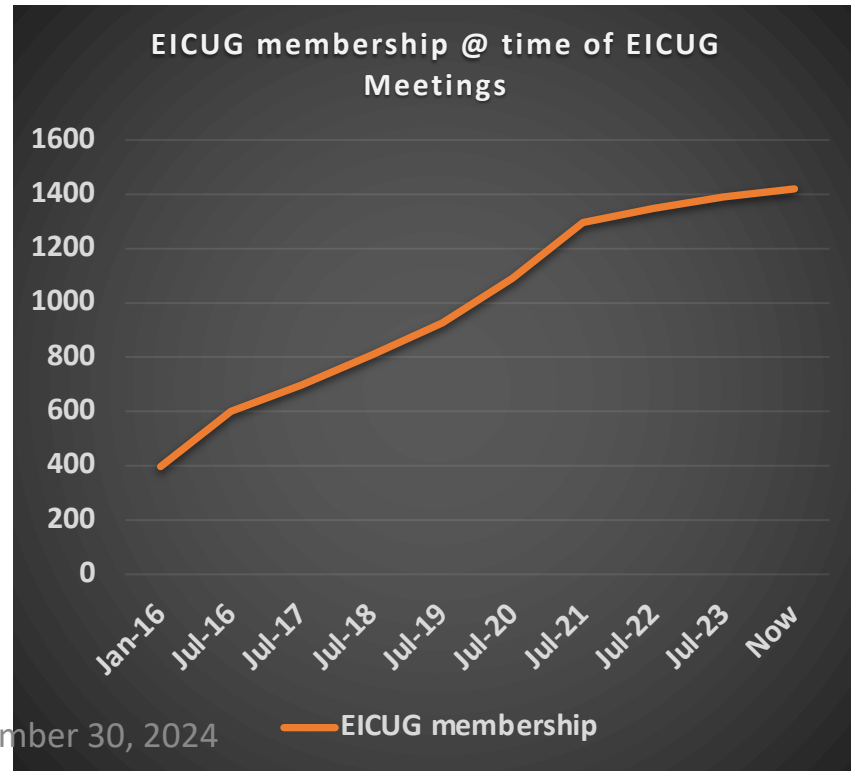
<https://eicug.github.io/>

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

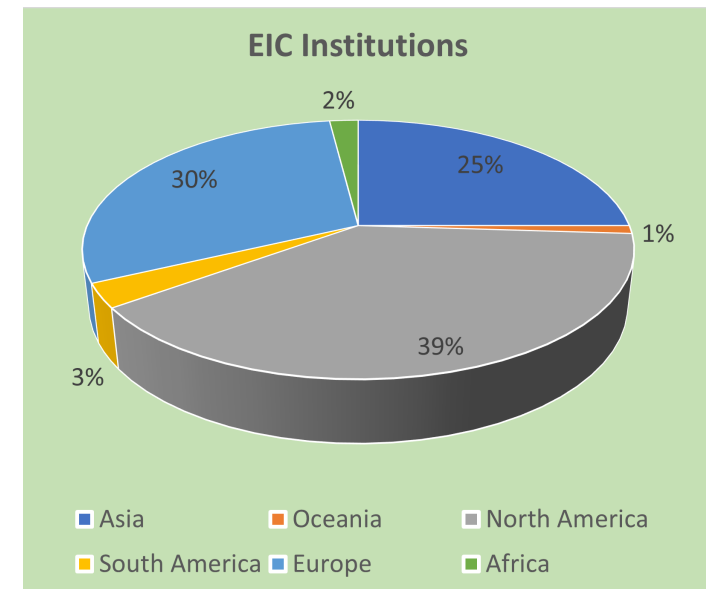
2021 VUU, VA & UCR, CA

2022 Stony Brook U, NY

2023 Warsaw, Poland

2024 Lehigh U, PA

EIC at IWSHO2024-Yerevan



Physics @ the EIC: Connections to High Energy Physics & Beyond

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

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

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

- Impact of precision measurements of unpolarized PDFs at high x/Q^2 , on LHC-Upgrade results(?)
- 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 HERA and with polarization**
- Polarized light nuclei in the EIC
- **Quark Exotica: 4,5,6 quark systems...? Much interest after recent Belle, LHCb led results.**
- **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** → novel observables, center of mass energy variability → adds additional control to the studies: Entanglement, entropy, connections to fragmentation, hadronization and their relation to confinement

Precision electroweak and BSM physics:

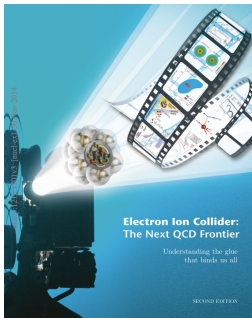
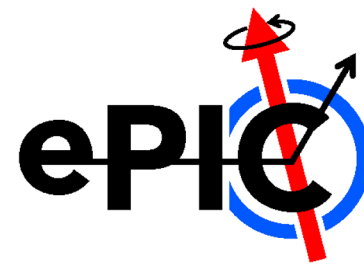
- Electroweak physics & searches beyond the SM: Parity, charge symmetry, lepton flavor violation
- LHC-EIC Synergies & complementarity

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

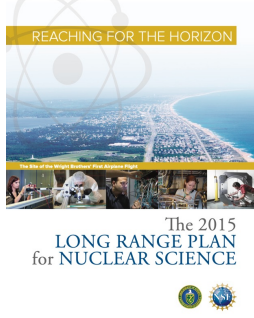
Detector design and new physics ideas....

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

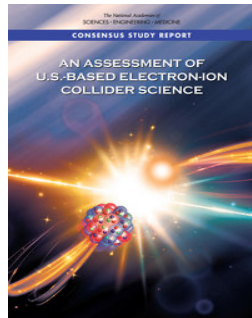
Detector Design Process Timeline



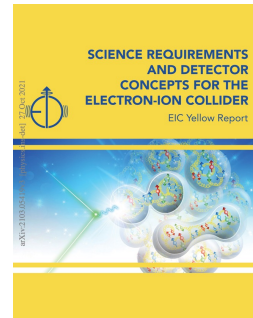
2012



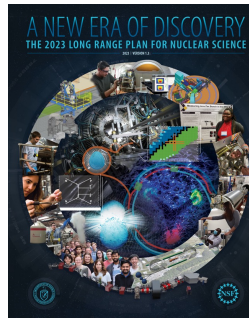
2015



2018



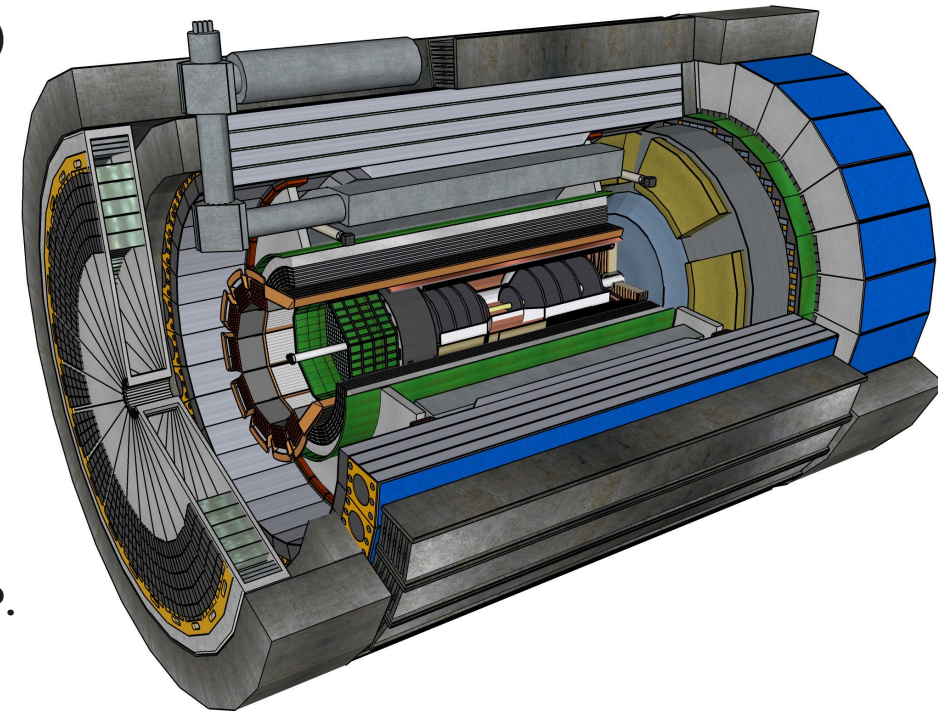
2020



2023

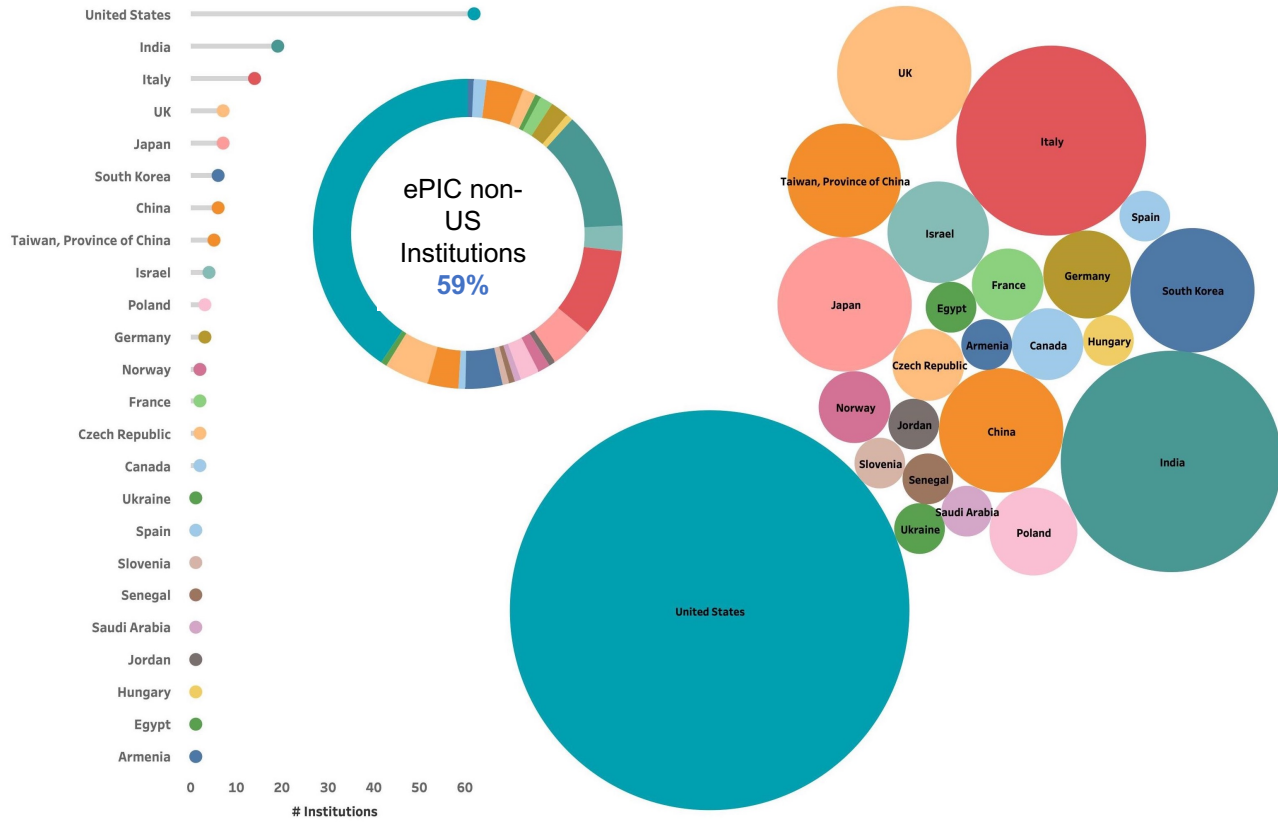
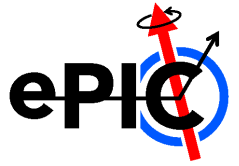
Detector and machine design parameters driven by physics objectives

- 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

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

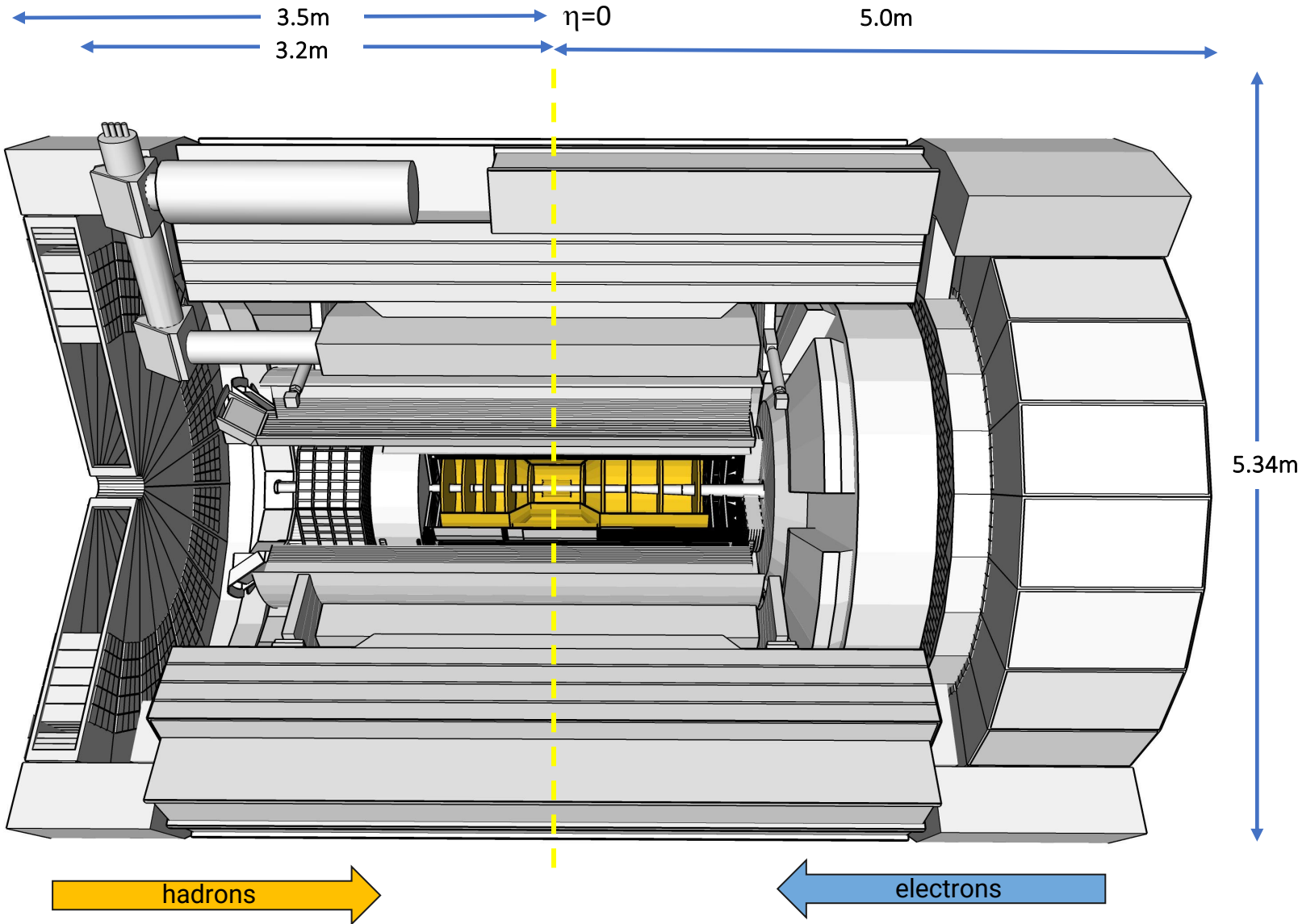
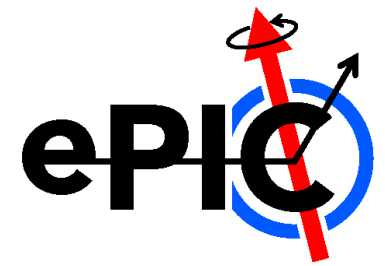
A global pursuit for a new experiment at the EIC!

**ePIC Spokesperson:
John Lajoie (ORNL)**

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



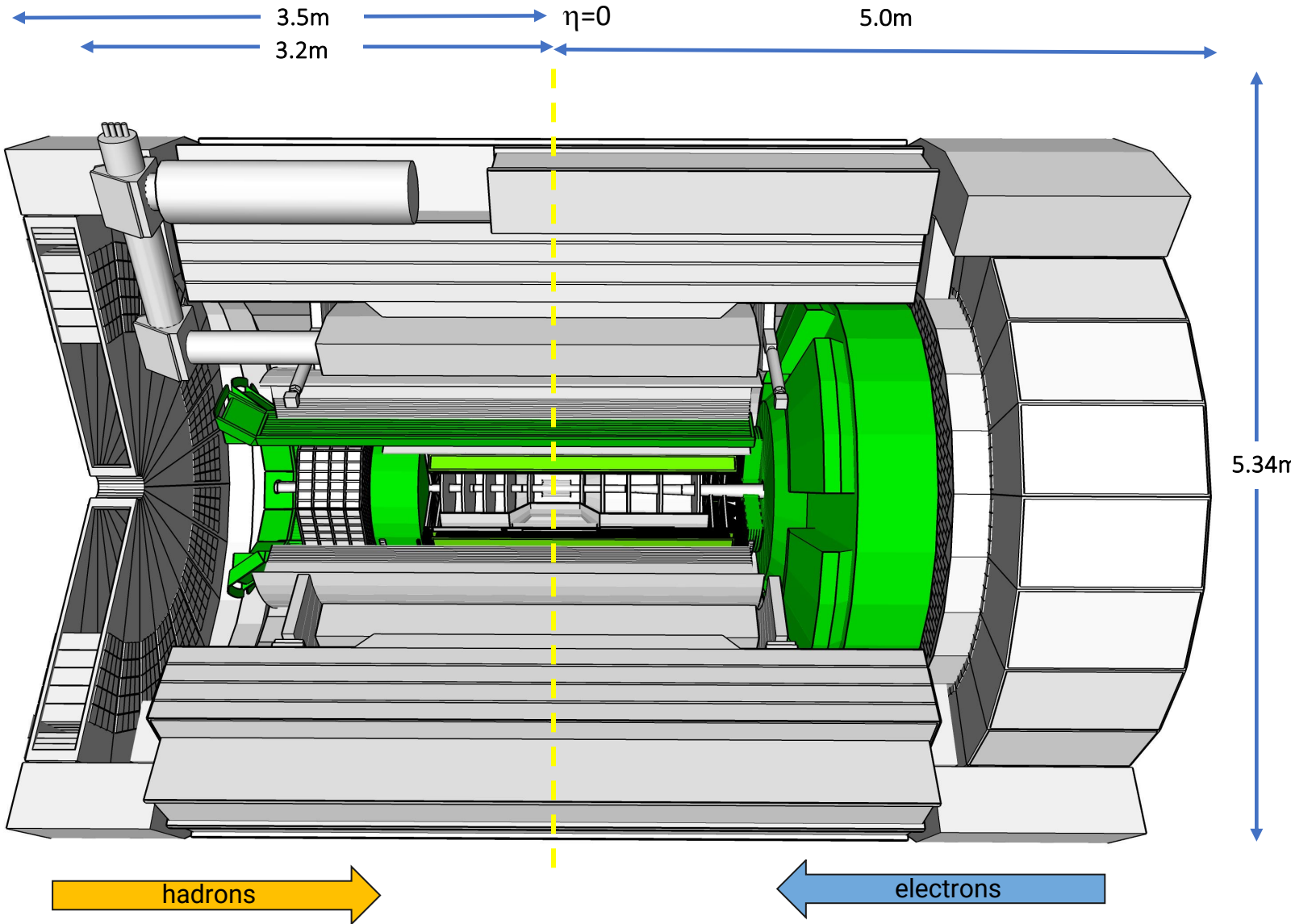
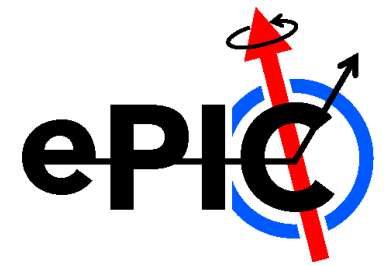
ePIC Detector Design



Tracking:

- New 1.7T solenoid
- Si MAPS Tracker
- MPGDs (μ RWELL/ μ Megas)

ePIC Detector Design



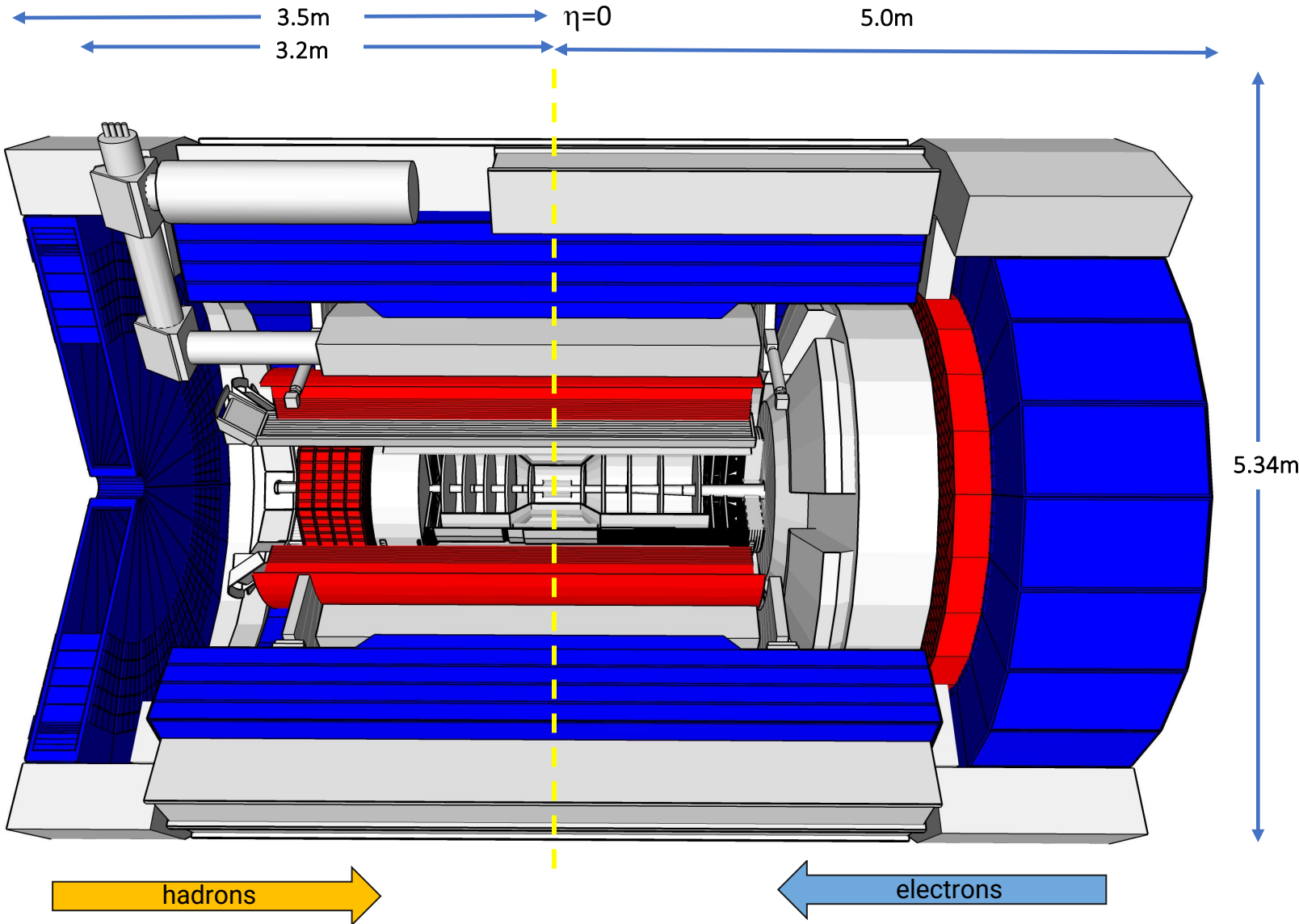
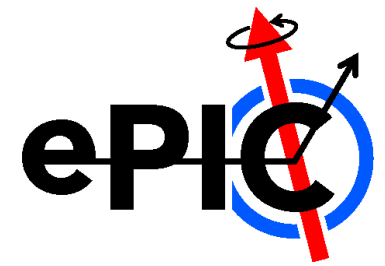
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PID:

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

ePIC Detector Design



Tracking:

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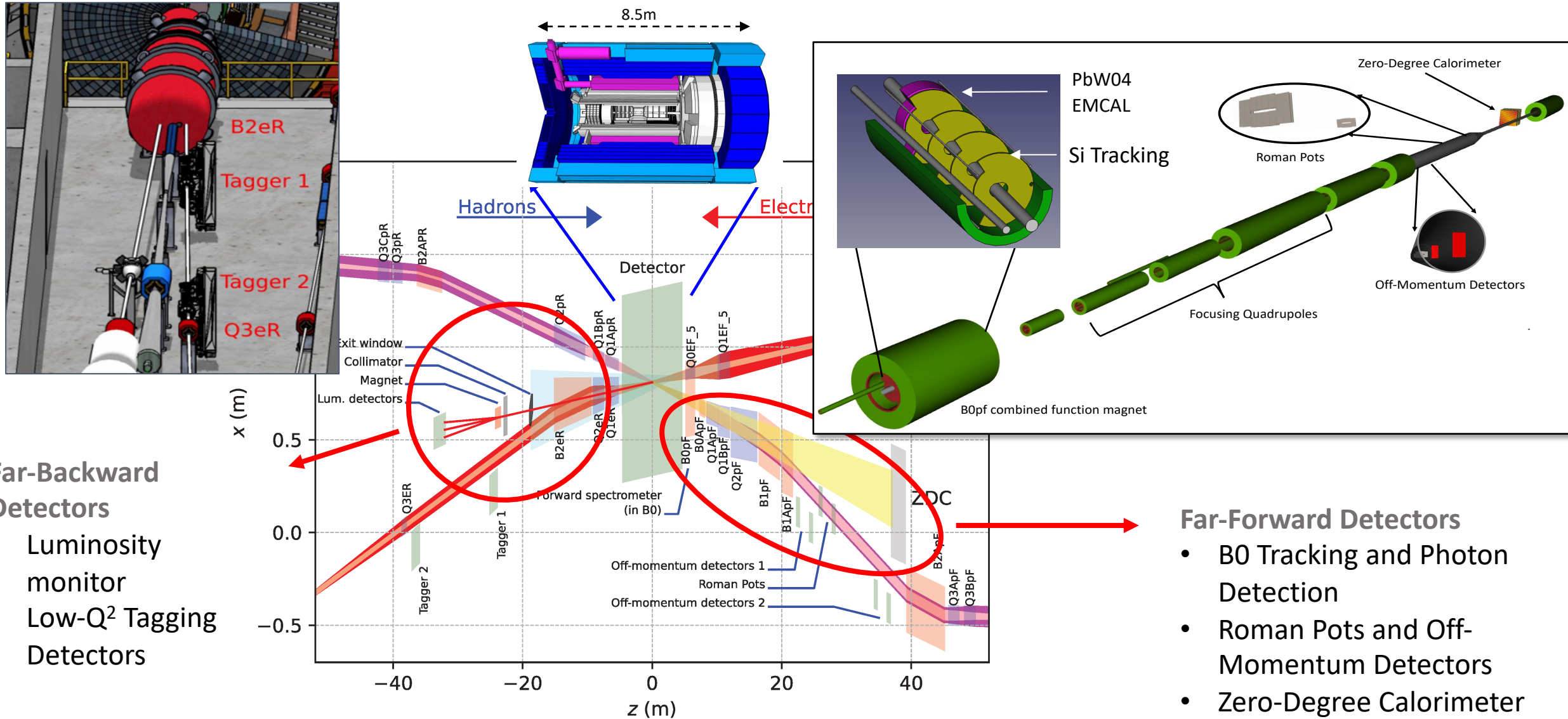
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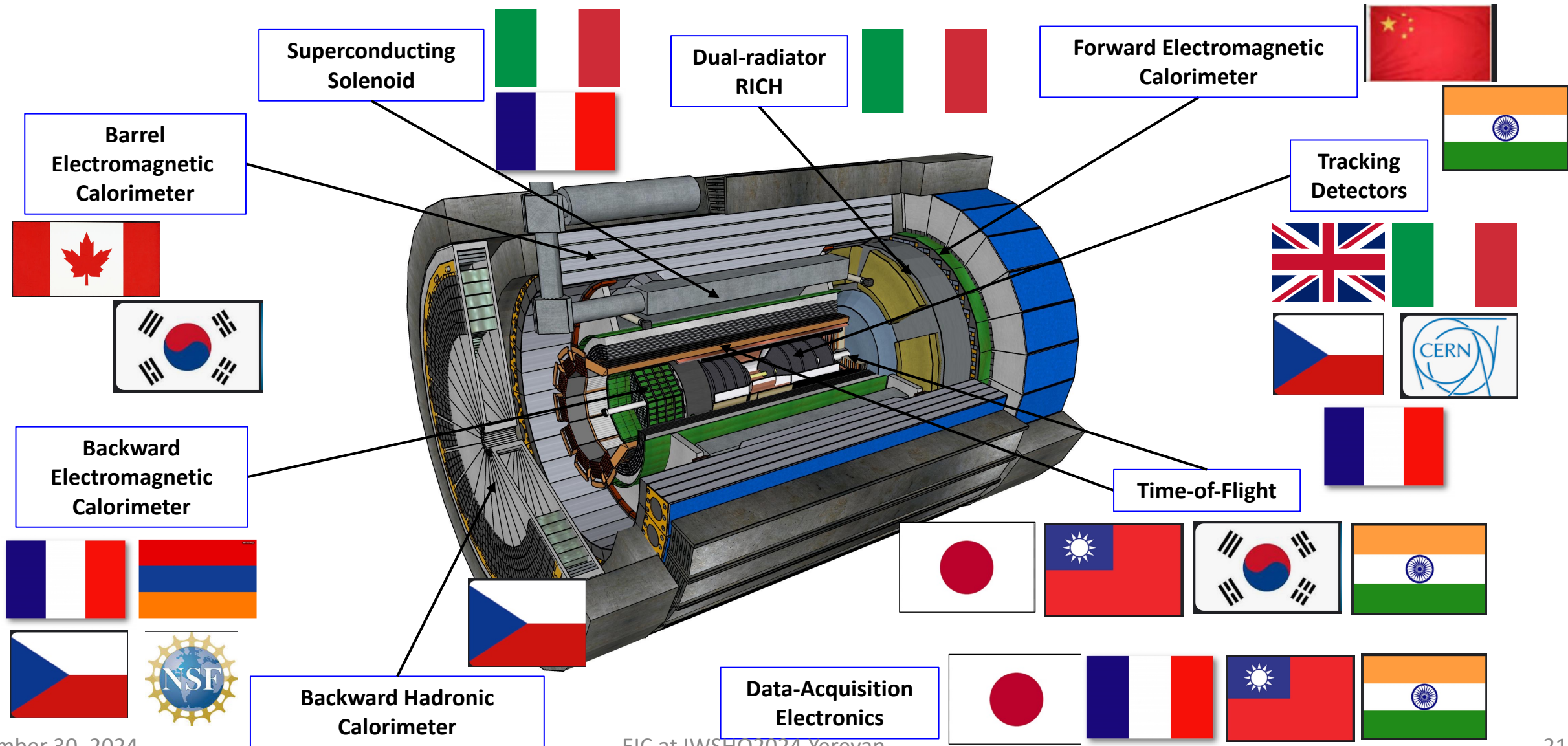
Calorimetry:

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

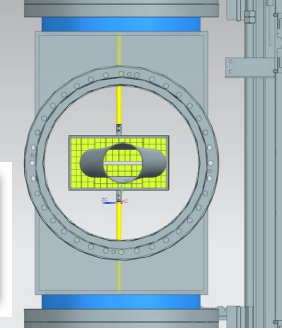
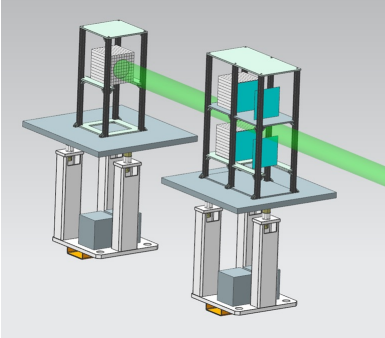
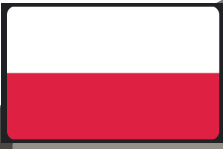
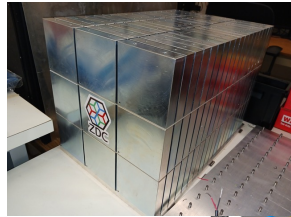
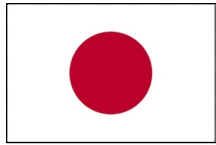
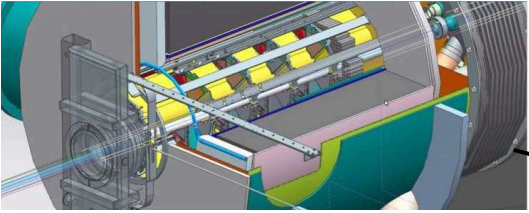
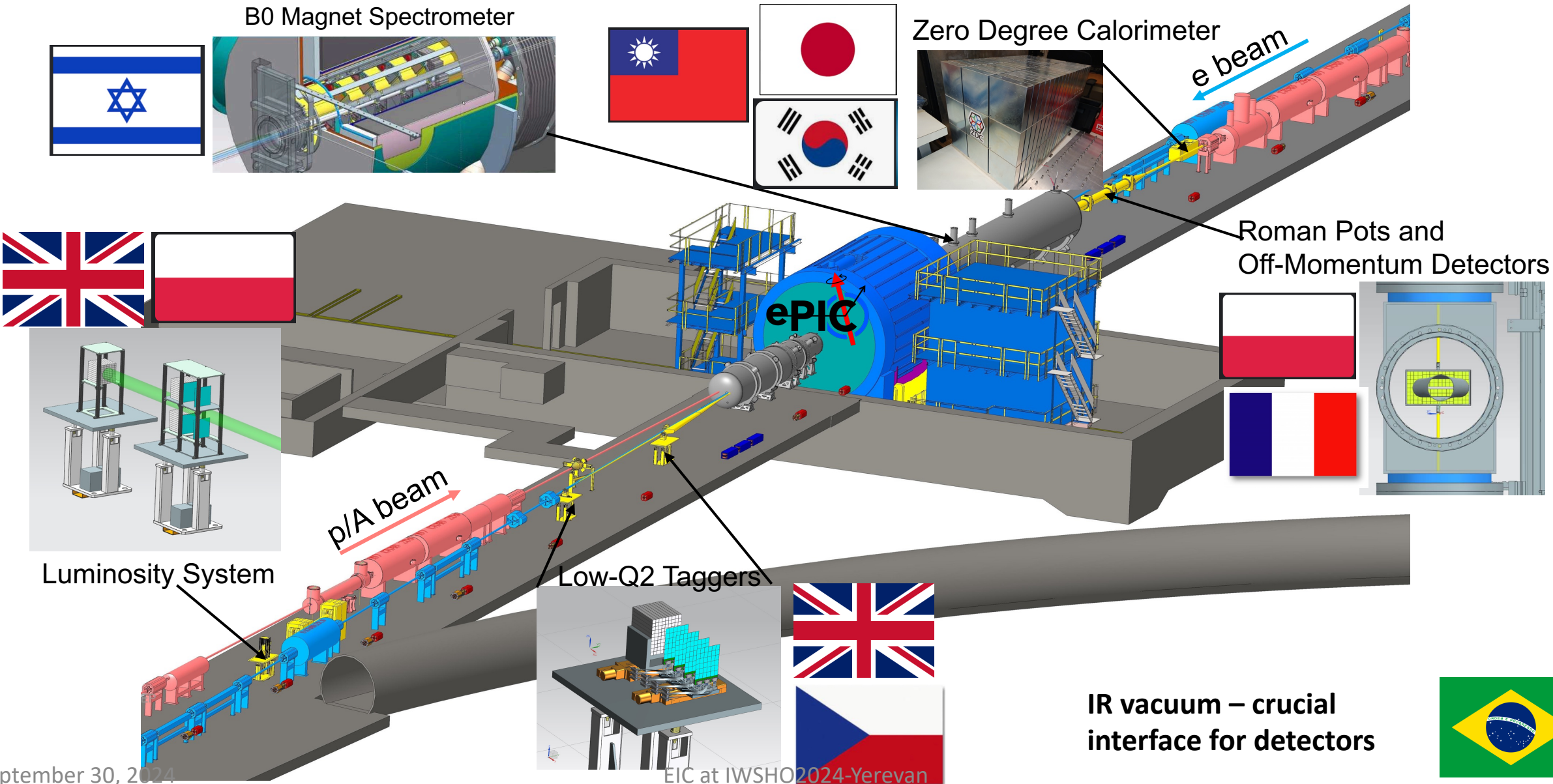
Far-Forward and Far-Backward Detectors



Central Detector Non-DOE Interest & In-Kind

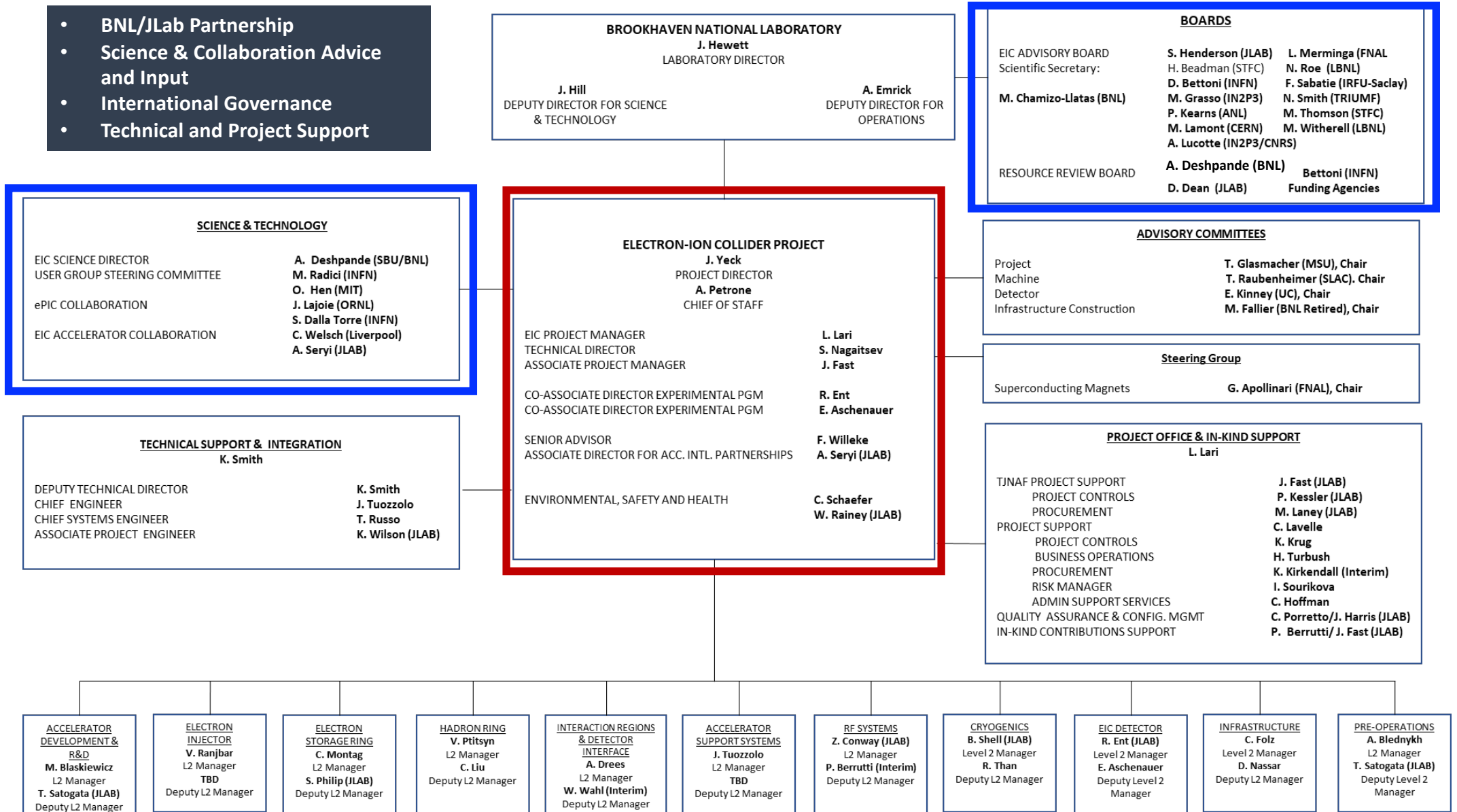


Far-Forward/Far-Backward Detectors Non-DOE Interest & In-kind



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
TECHNICAL DIRECTOR
ASSOCIATE PROJECT MANAGER

L. Lari
S. Nagaitsev
J. Fast

CO-ASSOCIATE DIRECTOR EXPERIMENTAL PGM
CO-ASSOCIATE DIRECTOR EXPERIMENTAL PGM

R. Ent
E. Aschenauer

SENIOR ADVISOR
ASSOCIATE DIRECTOR FOR ACC. INTL. PARTNERSHIPS

F. Willeke
A. Seryi (JLAB)

ENVIRONMENTAL, SAFETY AND HEALTH

C. Schaefer
W. Rainey (JLAB)

Governance, Advice, and Support

SCIENCE & TECHNOLOGY

EIC SCIENCE DIRECTOR
USER GROUP STEERING COMMITTEE

A. Deshpande (SBU/BNL)

M. Radici (INFN)

O. Hen (MIT)

J. Lajoie (ORNL)

S. Dalla Torre (INFN)

C. Welsch (Liverpool)

A. Seryi (JLAB)

ePIC COLLABORATION

EIC ACCELERATOR COLLABORATION

EIC ADVISORY BOARD

S. Henderson (JLAB)

D. Bettoni (INFN)

P. Kearns (ANL)

M. Lamont (CERN)

L. Merminga (FNAL)

R. Pain (IN2P3/CNRS)

F. Sabatie (IRFU-Saclay)

N. Smith (TRIUMF)

M. Thomson (STFC)

M. Witherell (LBNL)

RESOURCE REVIEW BOARD

A. Deshpande (BNL)

D. Dean (JLAB)

D. Bettoni (INFN)

Funding Agencies

ADVISORY COMMITTEES

Project
Machine
Detector
Infrastructure Construction

T. Glasmacher (MSU), Chair
T. Raubenheimer (SLAC), Chair
E. Kinney (UC), Chair
M. Fallier (BNL Retired), Chair

Steering Group

Superconducting Magnets

G. Apollina (FNAL), Chair

- 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

EIC a facility truly international in character

Exciting recent & near future news

- 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
- A few other announcements from Europe and Asia are eminent

The Scientific Foundation for an EIC was Built Over Two Decades

2002
 OPPORTUNITIES IN NUCLEAR SCIENCE
 Working Group Report for the Workshop
 April 2002

2007
 The Frontiers of Nuclear Science
 A LONG RANGE PLAN

2009
 A High Luminosity, High Energy
 Electron-Ion Collider
 A New Experimental Quest
 That Binds Us
 The Electron Ion Collider
 April 24, 2009

2010
 Gluons and the Quark Sea at High Energies
 distributions, polarization
 Institute for Nuclear Theory, University
 September 13 to November
 Editors:
 D. Boer, Universitat Göttingen, The Netherlands
 M. Diehl, DESY/SLAC, Electron-Positron Storage
 R. Milner, Massachusetts Institute of Technology
 R. Venugopalan, Brookhaven National Laboratory
 W. Vogelsang, Universität Tübingen, Germany

2012
 Major Nuclear Physics Facilities for the Next Decade
 NSAC
 March 14, 2012

2013
 Electron-Ion Collider
 absolutely central to the nuclear science program of the next decade.

2015
 “a high-energy high-luminosity polarized EIC [is] the highest priority for new facility construction following the completion of FRIB.”

2018
 AN ASSESSMENT OF U.S.-BASED ELECTRON-ION COLLIDER SCIENCE
 CONSENSUS STUDY REPORT
 The National Academies of SCIENCES • ENGINEERING • MEDICINE

2021
 EIC YELLOW REPORT
 Volume 1
 arXiv:2103.05419

2023
 A NEW ERA OF DISCOVERY
 THE 2023 LONG RANGE PLAN FOR NUCLEAR SCIENCE
 Build expeditiously

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

“We recommend the allocation of resources ...to lay the foundation for a polarized Electron-Ion Collider...”

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

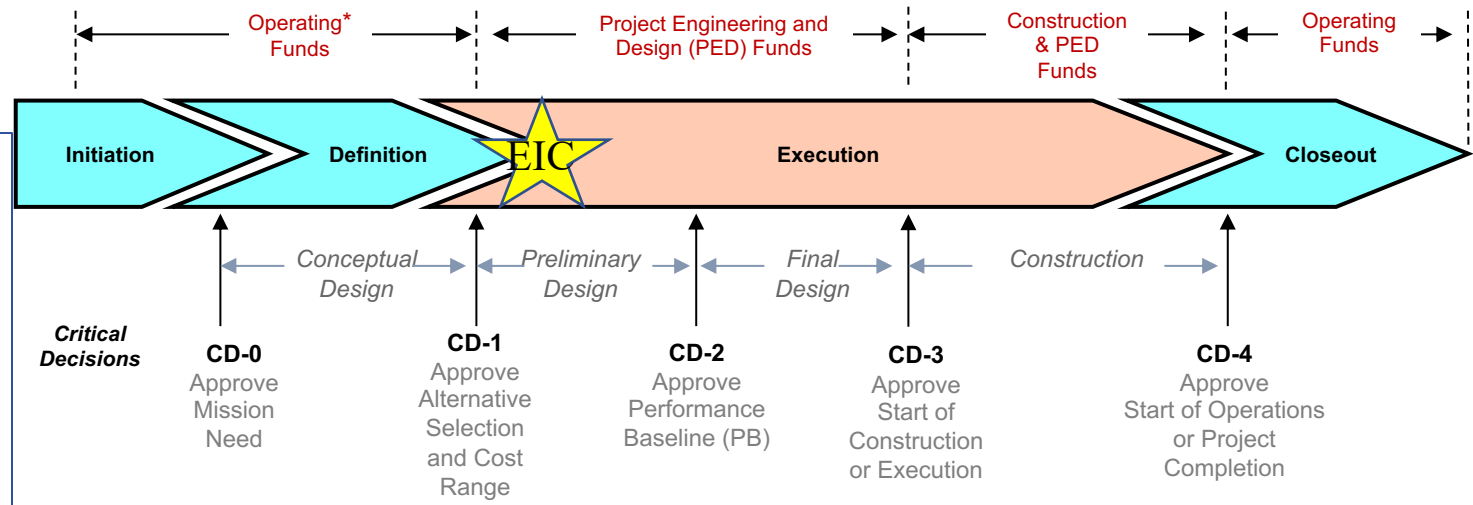
“The quantitative study of matter in this new regime [where abundant gluons dominate] requires a new experimental facility: an Electron Ion Collider..”

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)

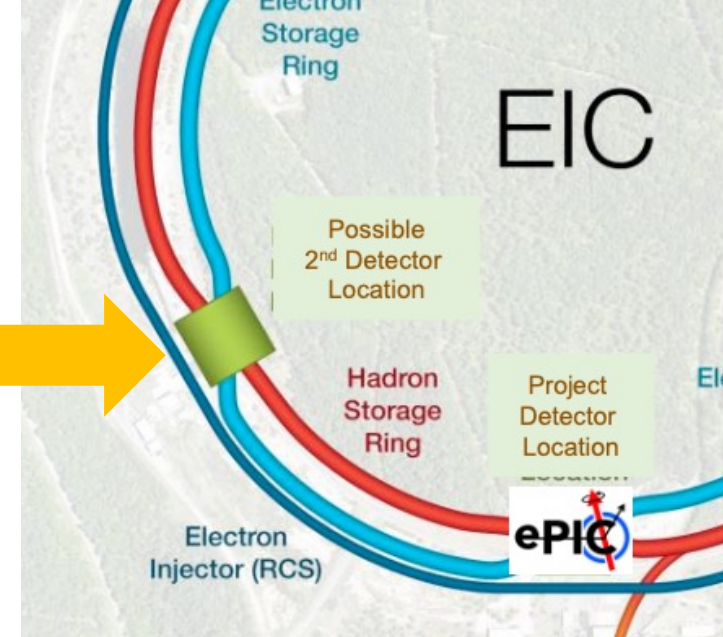
Define Baseline:
 technologies, Scope, Cost & Schedule
 Long Lead Procurement (LLP) items
 Design Maturity: ~90%
 Plan is tracked through EVMS
 & Change control process
 Start of construction for LLPs



	FY19		FY20		FY21		FY22		FY23		FY24		FY25		FY26		FY27		FY28		FY29		FY30		FY31		FY32		FY33		FY34		FY35																																							
	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4																																				
CD					CD-0(A) Dec 2019																																																																			
Research & Development					Research & Development								Construction Phase																																																											
Design					Conceptual Design		Infrastructure										Accelerator Systems										Detector														Conclusion of RHIC Operation				Science Phase																											
Construction & Installation									Infrastructure								Conventional Construction																				Accelerator Systems								Procurement, Fabrication, Installation & Test												Detector								Procurement, Fabrication, Installation & Test							
Commissioning & Pre-Ops																					Accelerator Systems								Commissioning & Pre-Ops												Detector								Commissioning & Pre-Ops																							
Key	(A) Actual	Completed	Planned	Data Date	Level 0 Milestones	Critical Path																																																																		

EIC at IWSHO2024-Yerevan

The 2nd detector Not in the EIC Project



National academy report suggested being prepared for up to two detectors

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

2nd IR: Can only be considered seriously when EIC project (machine+ePIC) moves forward successfully (after "CD2")

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
 - Confirmation of physics observation from different “point of views”
- Complementary **Technologies** : different 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. (beyond the three pillars of physics established for the EIC so far.

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

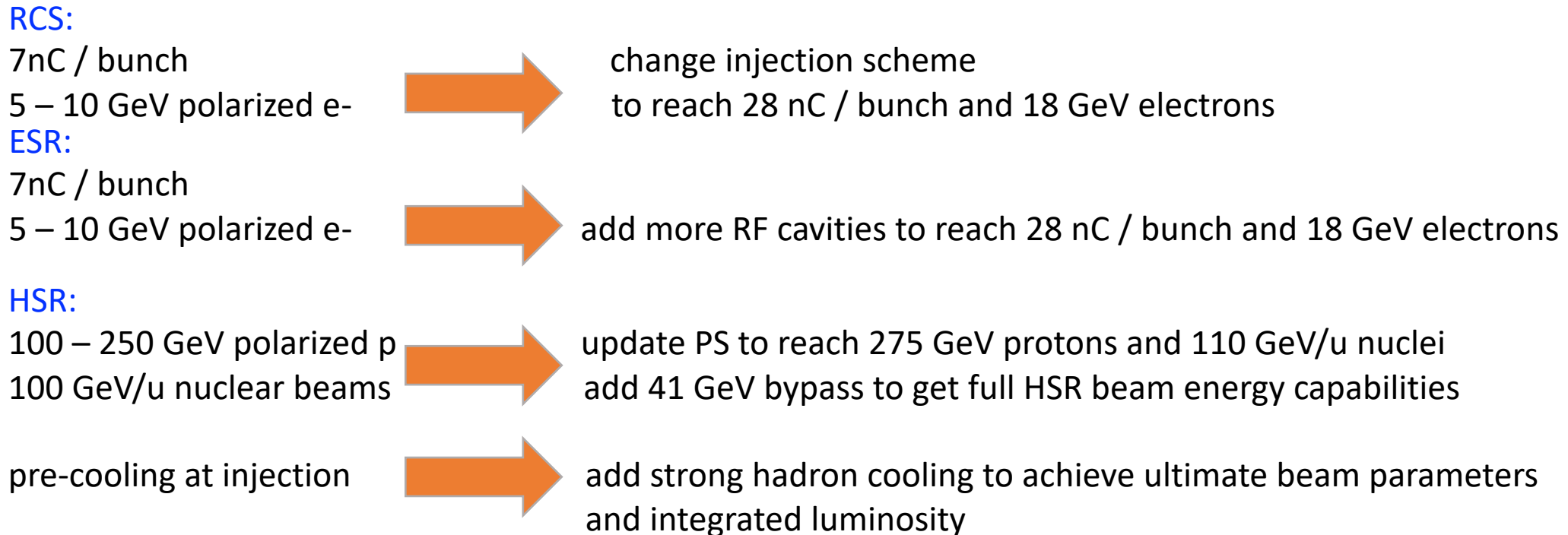
Summary & Outlook

- 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.*

Phase I and Phase II proposals

- Change in baseline (independent of phasing) since Nov 2023 DOE review:
 - Add injection cooler for hadrons; replace a 400-MeV NC commercial linac with a 3-GeV SRF (1.3 GHz) linac as injector to the RCS;
- Phase I:
 - HSR: no SHC, add precooler, no 41-GeV bypass
 - ESR: 5-10 GeV, 7 nC max (means fewer rf cavities and amps); maybe no crabs (may require lower proton bunch intensities)
 - RCS: operates with a 7-nC (single bunch), 3 → 5 or 10 GeV, ramps at 1 Hz
- Phase II:
 - HSR: add SHC, add 41-GeV bypass
 - ESR: add rf cavities and power to operate at 28 nC and 18 GeV; add crabs
 - RCS: upgraded to 28 nC and 3 → 18 GeV ramps (at 1 Hz);

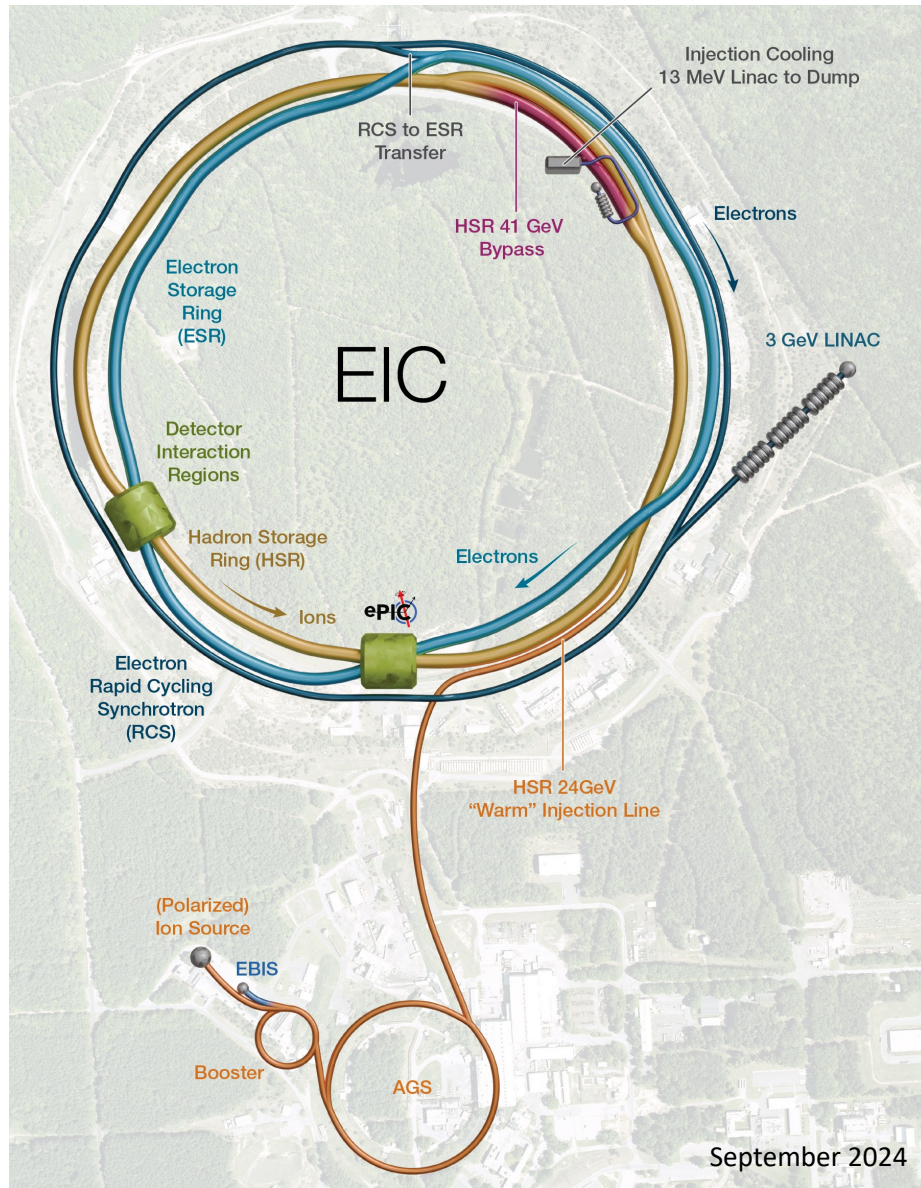
Accelerator at Phase 1 and Ultimate



Proposal for the Day-One Physics and the initial years of science is driven by

- Start of the promised NSAC/NAS science program
- Alignment with expected order in commissioning the collider and ramp up of performance that comes with gain of operational experience
- Access to new physics results early to get high impact publications, i.e. PRLs,

EIC Accelerator Design



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

