Status of EIC and Prospects beyond…

CFNS Workshop

Progress on the production of muon and photon beams for applications in muon-Ion Colliders.

March 26, 2024

Abhay Deshpande

Stony Brook University & Brookhaven National Laboratory

Relativistic Heavy Ion Collider (RHIC)

BNL's work-horse for nuclear physics for the past twenty years

Most complex and versatile accelerator complex in the world

The only collider with polarized proton beams at the highest energy

The only collider with (almost) all nuclei including - asymmetric collisions

Relativistic Heavy Ion Collider (RHIC) Complex

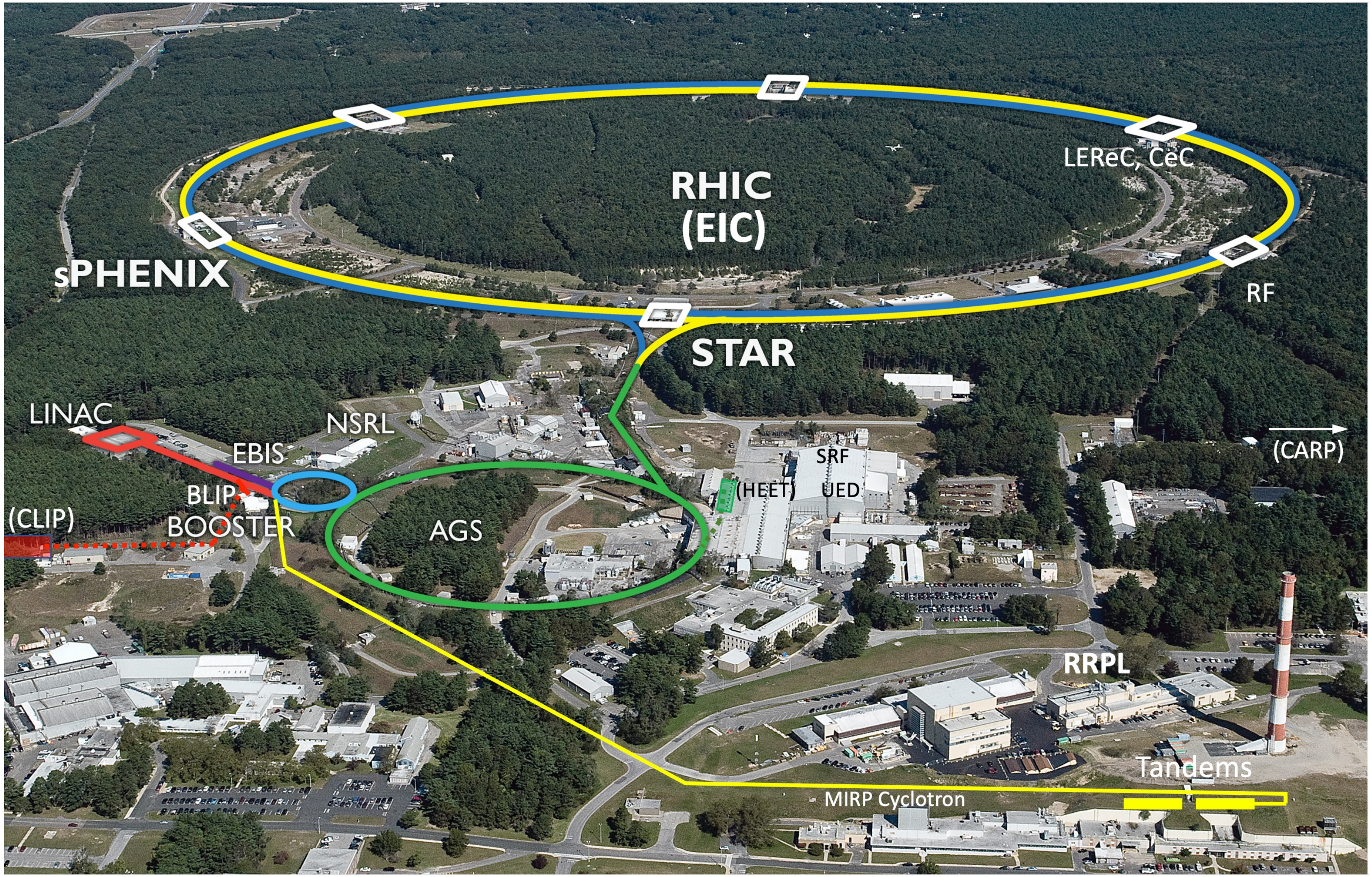
Uniquely flexible and only hadron collider in US for exploration of QCD phase diagram and proton spin

Injectors also used for application programs:

- Linac/BLIP for isotope production
- Booster/NSRL for space radiation studies
- Tandem for industrial/academic users

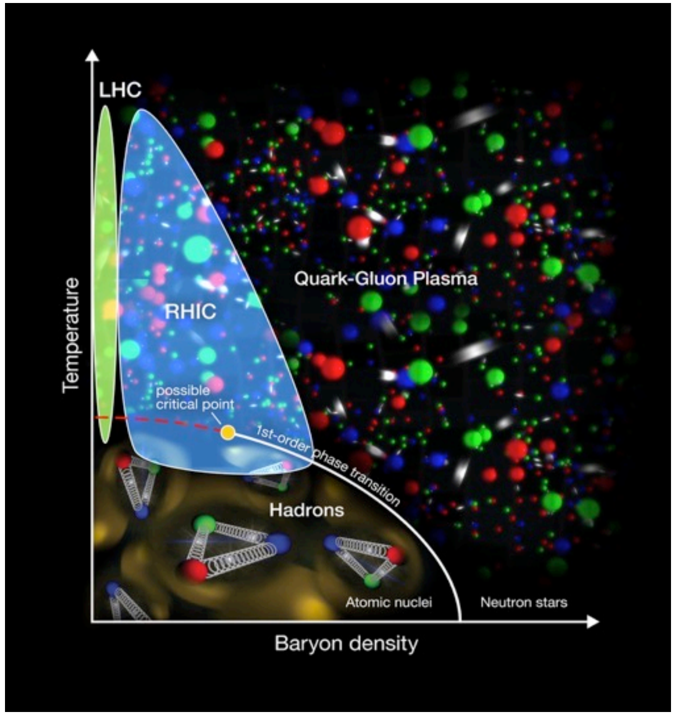
R&D for future facilities and application

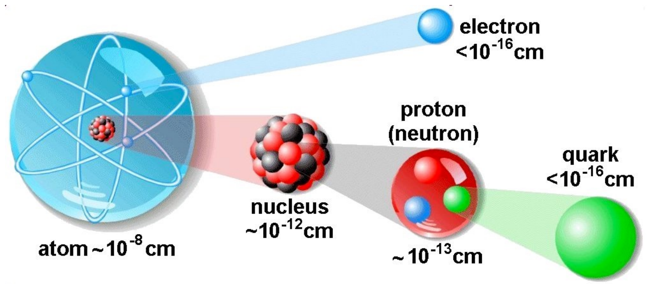
sources, cooling, pol. beams, …

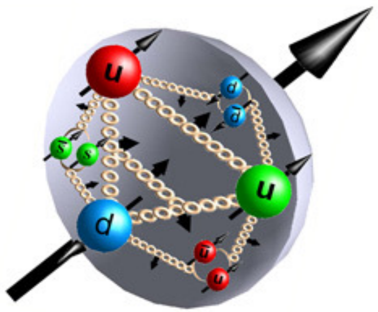


RHIC – a Unique Research Tool

- 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



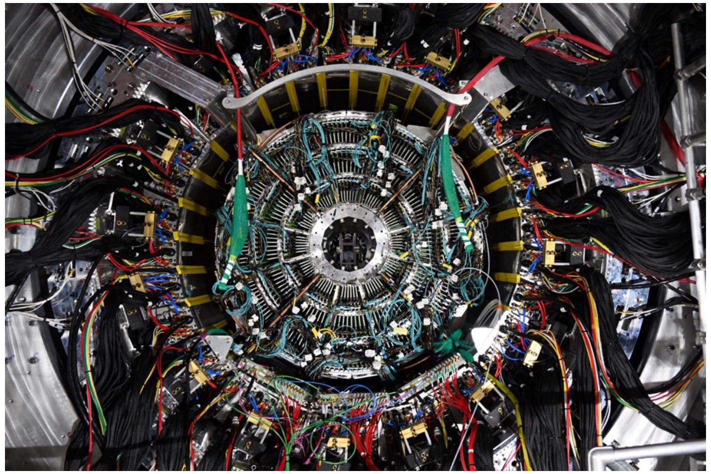


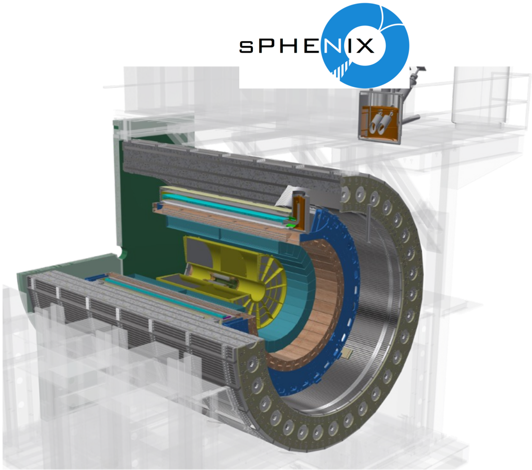


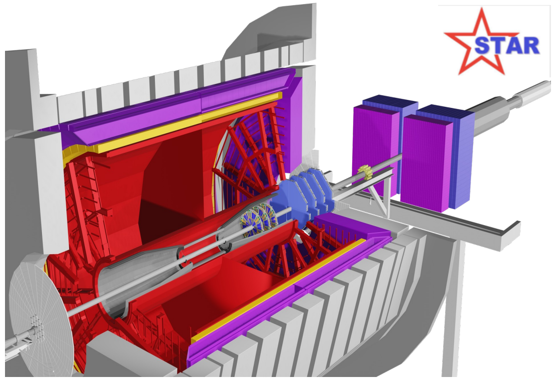
Completing the RHIC Mission with sPHENIX and STAR

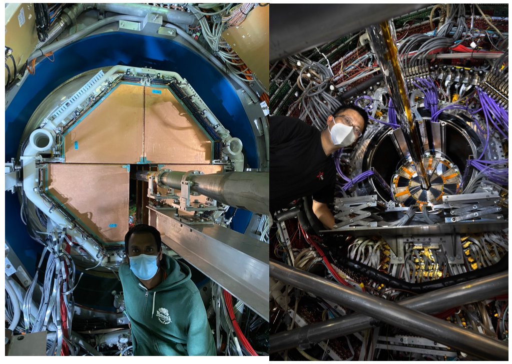
- sPHENIX will use energetic probes (jets, heavy quarks) to study quark-gluon plasma with unprecedented precision
  - How the structureless "perfect" fluid emerges from the underlying interactions of quarks and gluons at high temperature
- sPHENIX outer hadron calorimeter will be part of the EIC project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









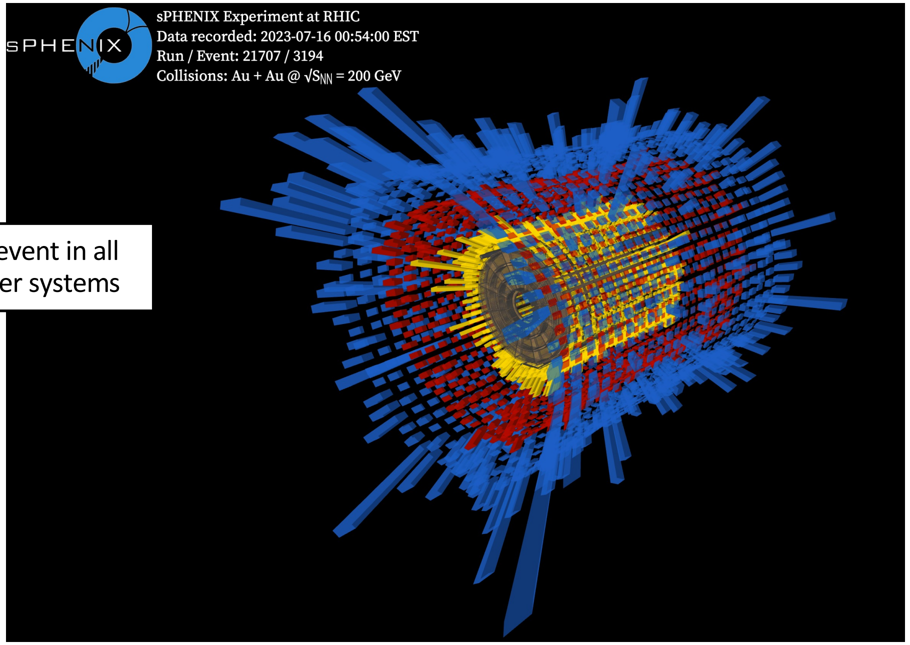
Synergies with the EIC science and contribute to EIC workforce development

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

sPHENIX commissioning 2023. Now ready for data for Run 24.

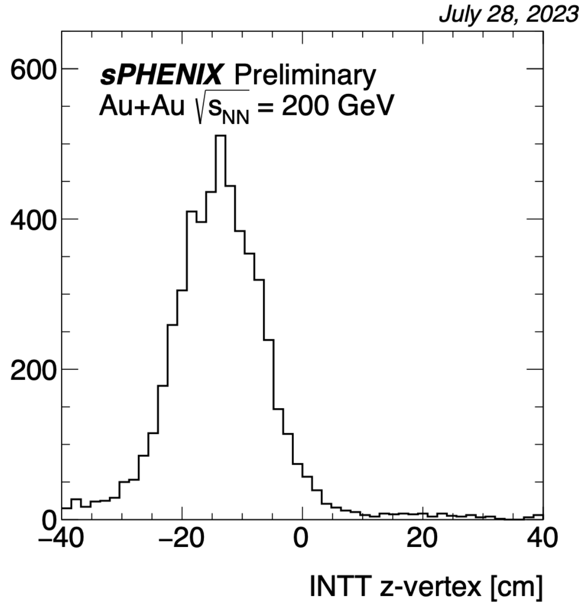
- Commissioning with beam started May-August 2023. Now ready for Run 24, expected ot begin in April 15, 2024. Length depends on the Budget allocation. Awaited.
- Ten sub-detectors* and DAQ commissioned
- SC magnet operated very stably
- All sPHENIX subsystems, including the MVTX, have taken RHIC data and stored in HPSS
- Excellent support from C-AD to provide wide variety of RHIC beam conditions
- Recent focus had been on operation of TPC at full HV and on MVTX response.

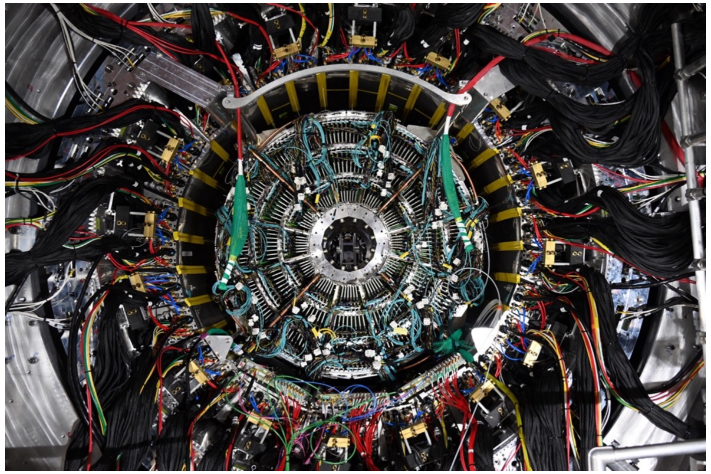
*MVTX, INTT, TPC, TPOT, EMCal, iHCal, oHCal, MBD, sEPD, ZDC/SMD



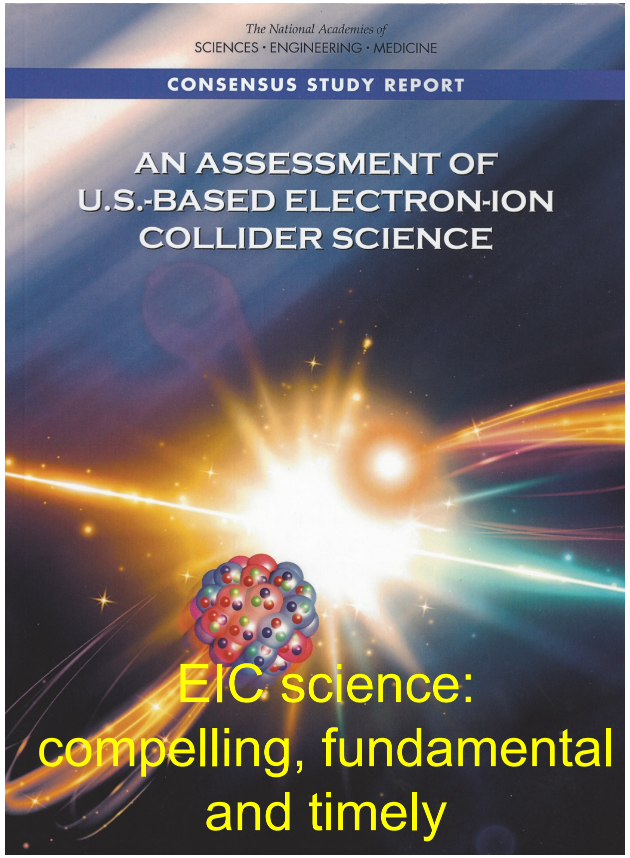
Central Au+Au event in all three calorimeter systems

Reconstruction of vertex location along beam axis using INTT silicon strip detector



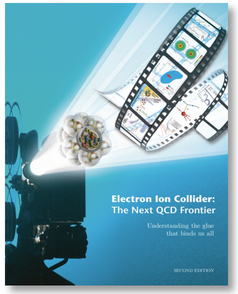


National Academy's Assessment, July 2018
Electron Ion Collider



Electron Ion Collider Science:

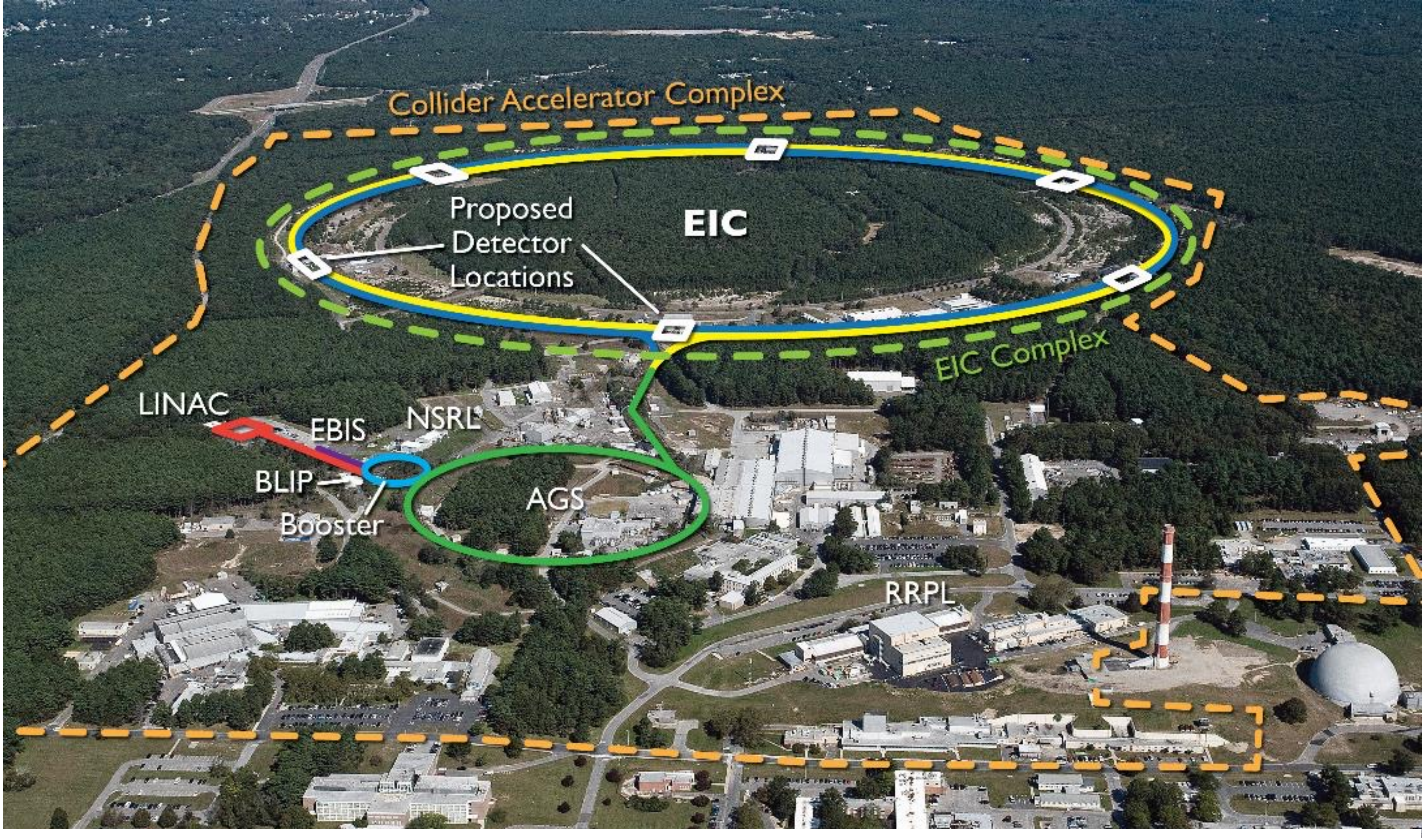
- Origin of nucleon spin
- Understanding the origin of mass
- Intense gluonic fields & novel gluonic matter



Machine Design Parameters:

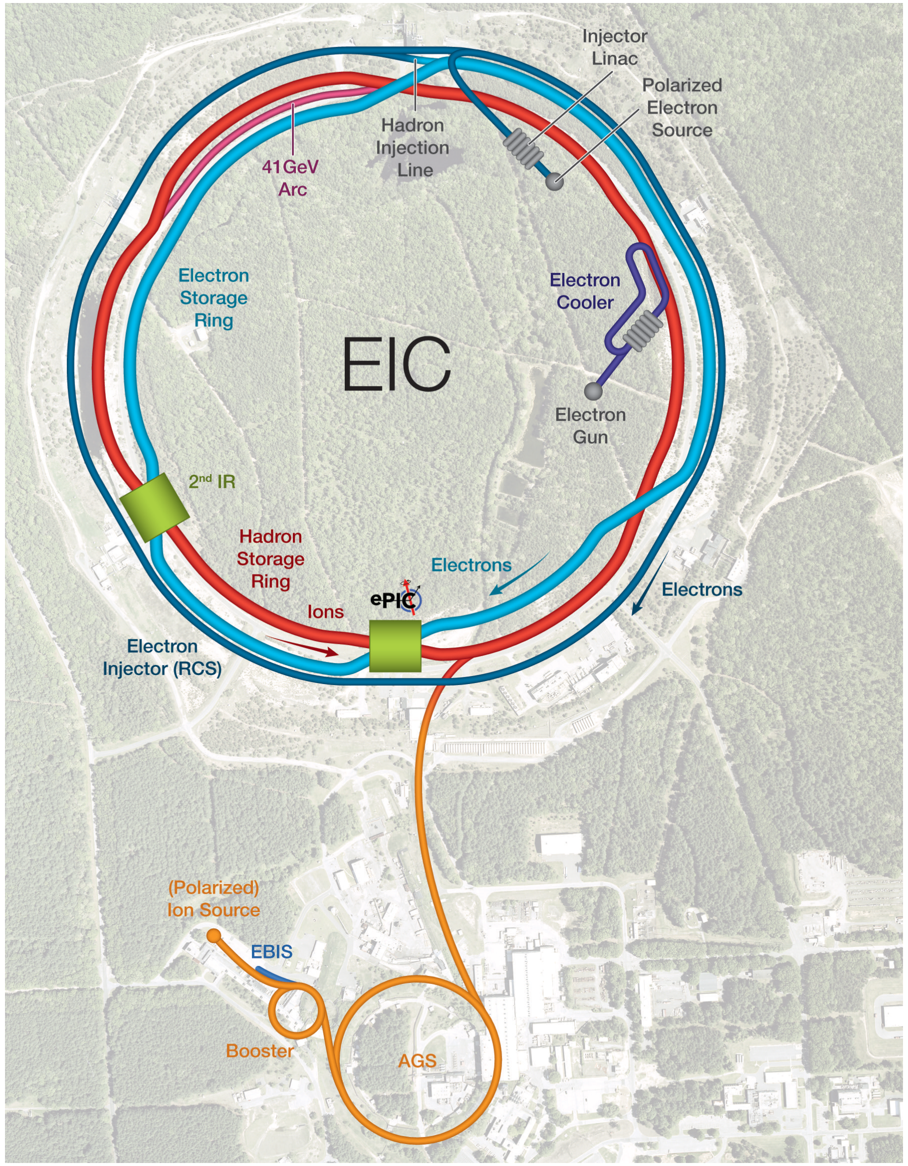
- High luminosity: up to 10^{33}-10^{34} $cm^{-2}sec^{-1}$
  - a factor ~100-1000 times HERA
- Broad range in center-of-mass energy: ~20-100 GeV upgradable to 140 GeV
- Polarized beams e-, p, and light ion beams with flexible spin patterns/orientation
- Broad range in hadron species: protons…. Uranium
- Up to two detectors well-integrated detector(s) into the machine lattice

Use of AI and ML in both operation, optimization of machine and data acquisition (triggerless data collections)

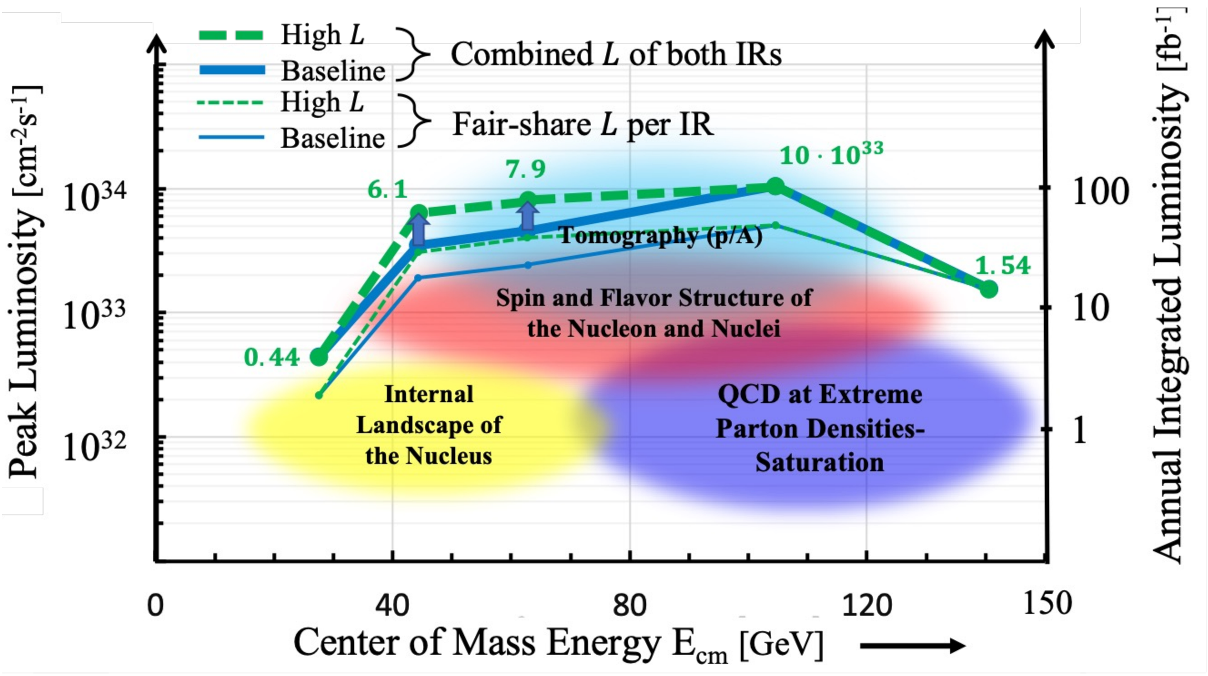


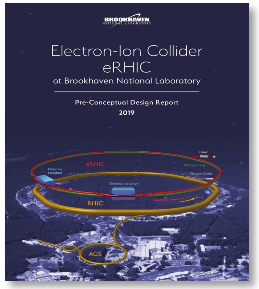
- EIC benefits from $B class investments at BNL and the highly successful RHIC program.
- RHIC will conclude operations in 2025. EIC installation will begin after RHIC ops concludes.

EIC Accelerator Design



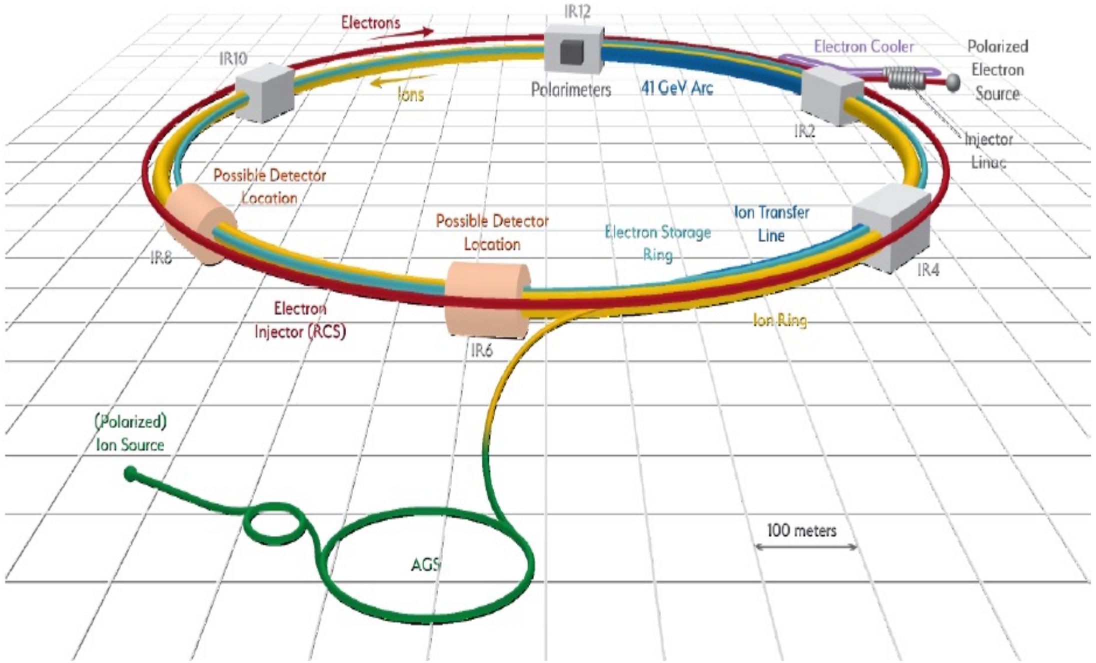
Center of Mass Energies:	20GeV - 140GeV
Luminosity:	10^{33} - 10^{34} $cm^{-2}s^{-1}$ / 10-100fb^{-1} / year
Highly Polarized Beams:	70%
Large Ion Species Range:	p to U
Number of Interaction Regions:	Up to 2!





The US Electron Ion Collider

CD0: Dec. 2019, CD1 July 2021



- ❖ 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

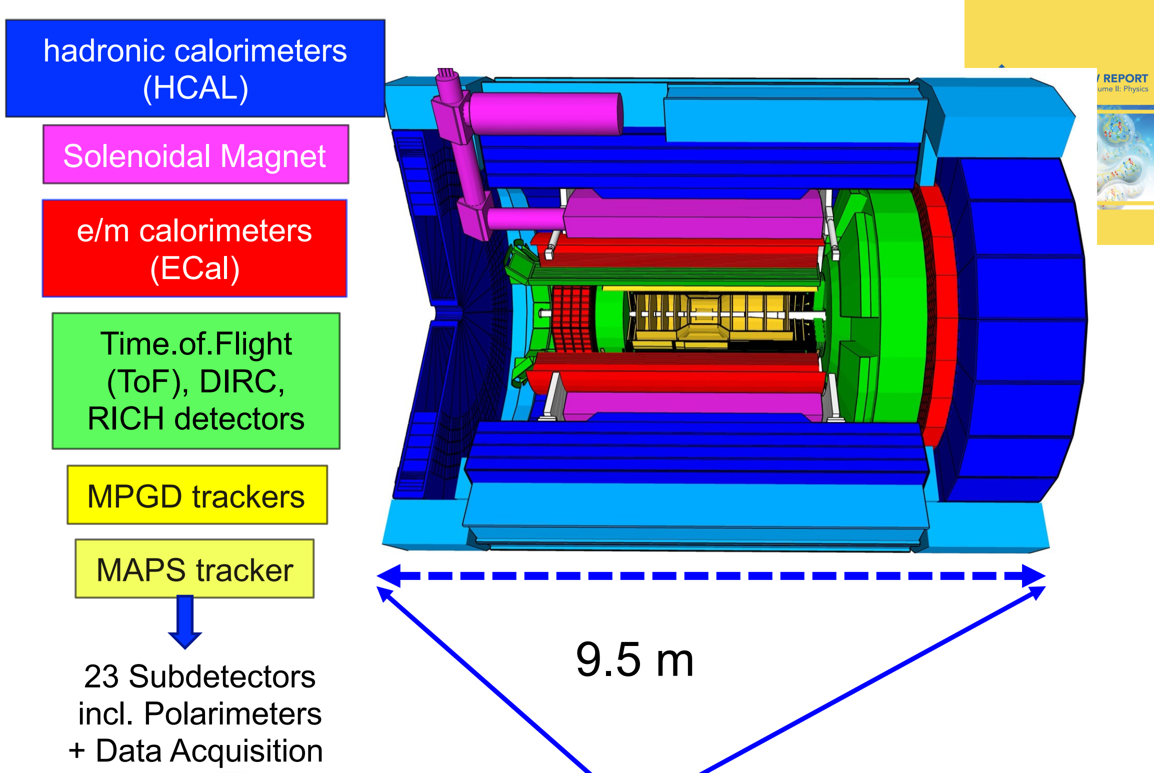
Electrons up to 18 GeV

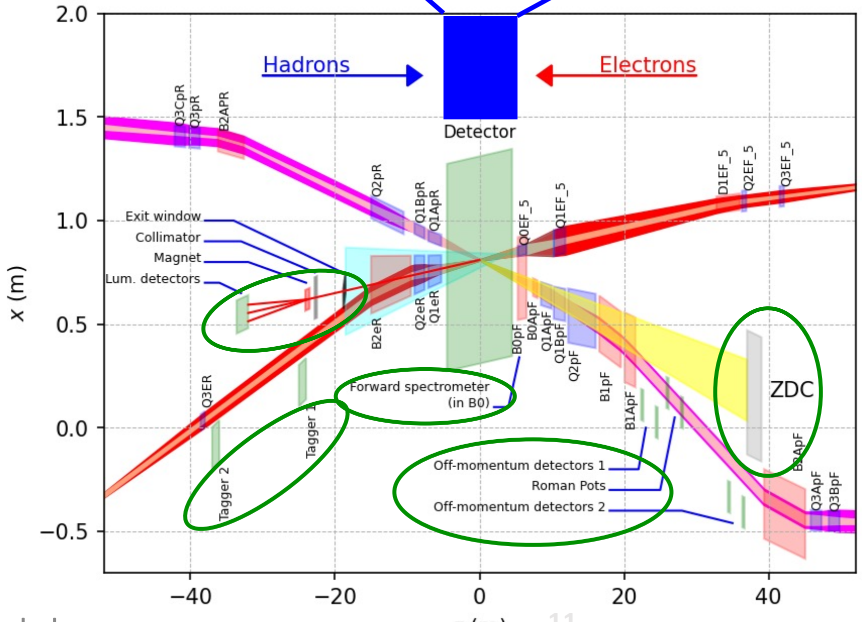
- ➢ Storage ring, provides the range sqrt(s) = 20-140 GeV. Beam current limited by RF power of 10 MW
- ➢ Electron beam with variable spin pattern (s) accelerated in on-energy, spin transparent injector (Rapid-Cycling-Synchrotron) with 1-2 Hz cycle frequency
- ➢ Polarized e-source and a 400 MeV s-band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

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

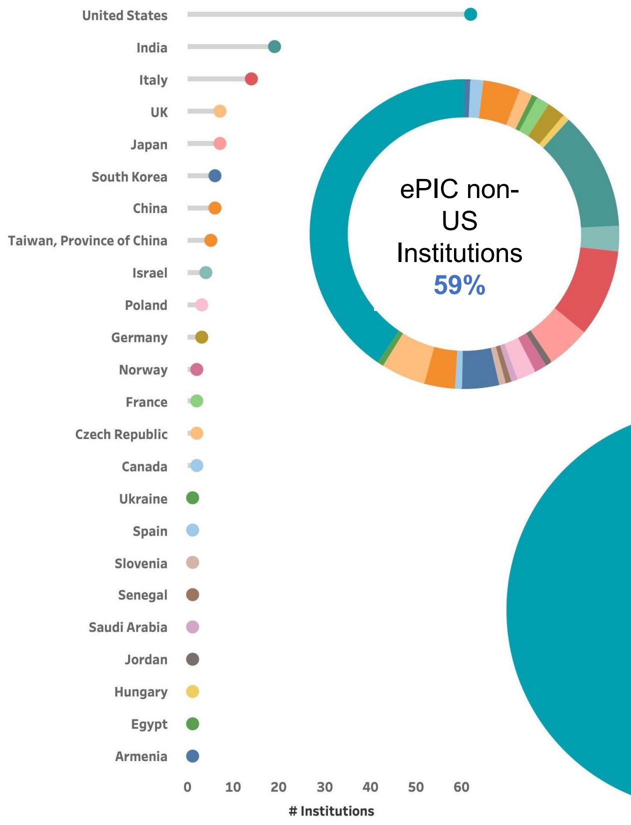
The ePIC Detector

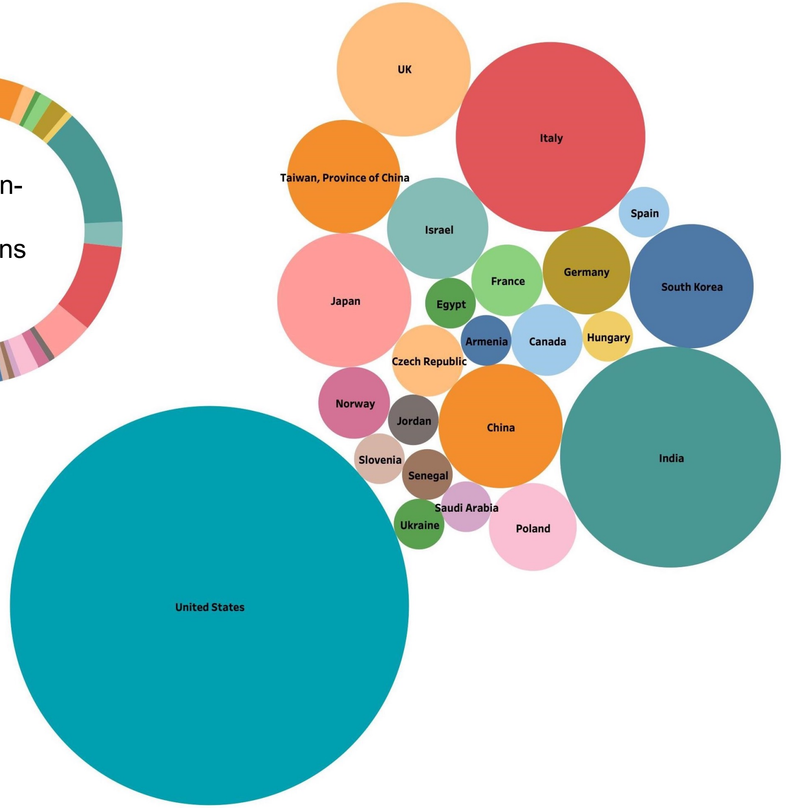
- ❑ Asymmetric beam energies
  - ➢ requires an asymmetric detector with electron and hadron endcap
  - ➢ tracking, particle identification, EM calorimetry and hadronic calorimetry functionality in all directions
  - ➢ very compact Detector, **Integration** will be key
- ❑ Imaging science program with 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





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!

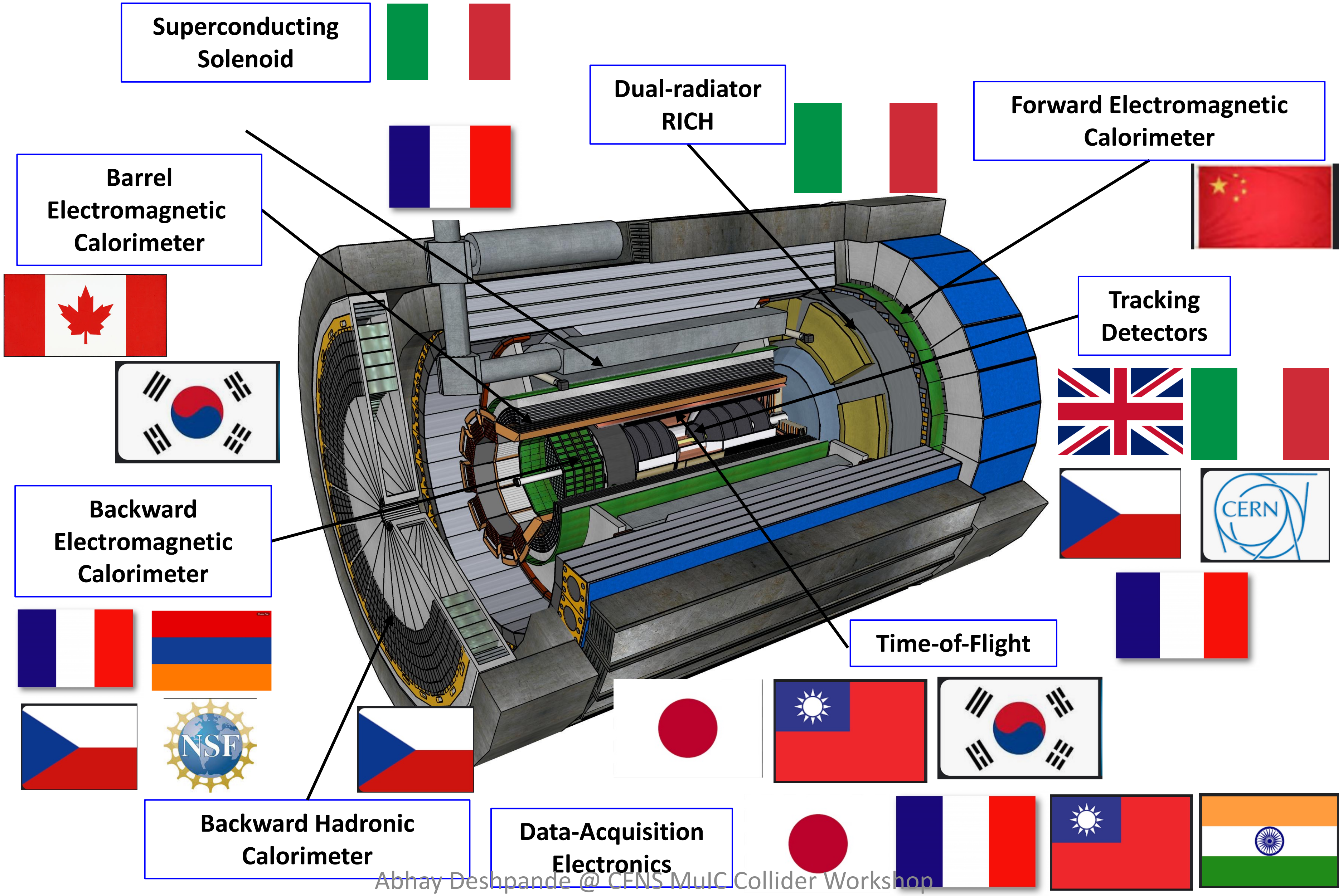
ePIC Spokesperson:
John Lajoie (ORNL)

ePIC Deputy Spokesperson:
Silvia Dalla Torre (INFN Trieste)

Central Detector Non-DOE Interest & In-Kind

US involved in all sub-systems not shown explicitly

ePIC Detector

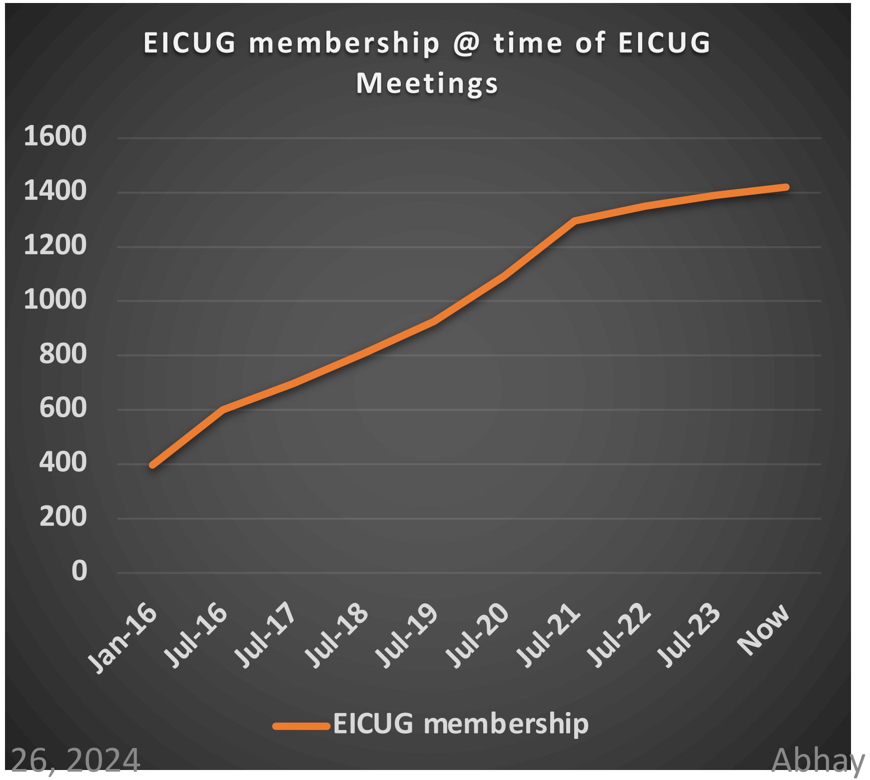


Worldwide Interest in EIC

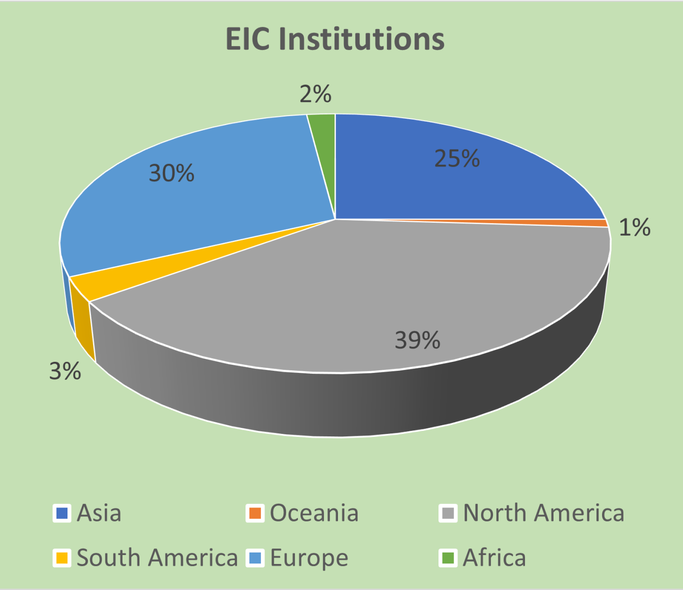
The EIC User Group:
https://eicug.github.io/

1450+ collaborators,
- **45+ countries,**
- **287 institutions**

as of January 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



NSAC LRP 2023 Recommendation

1. Capitalize on extraordinary opportunities made possible by investments in US…
   - ❖ Workforce development, Operate facilities (ATLAS@ANL, **CEBAF@Jlab**, FRIB, and **complete** the **RHIC Mission**

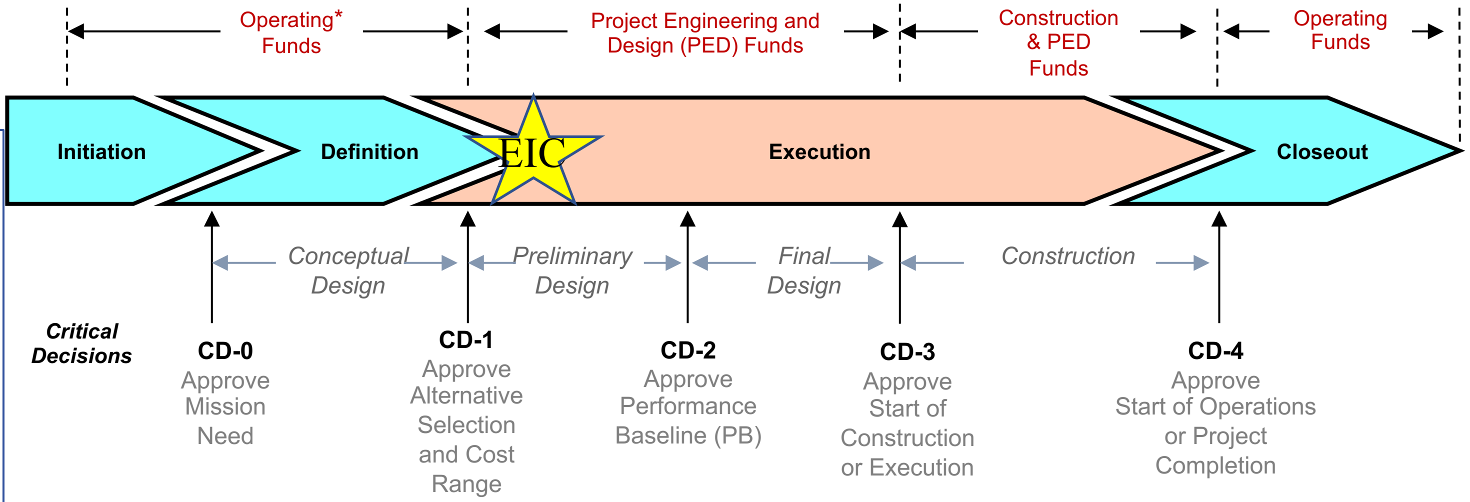
2. and 3.
   - ❖ Lead an international consortium for **neutrino-less double beta** decay experiment
   - ❖ Expeditious completion of **Electron Ion Collider (EIC**) as highest priority facility

4. Capitalize on the unique ways in which nuclear physics can advance discovery science and applications for the society by investing in additional projects and strategic opportunities (detector R&D, support computing, theory, lattice QCD…)

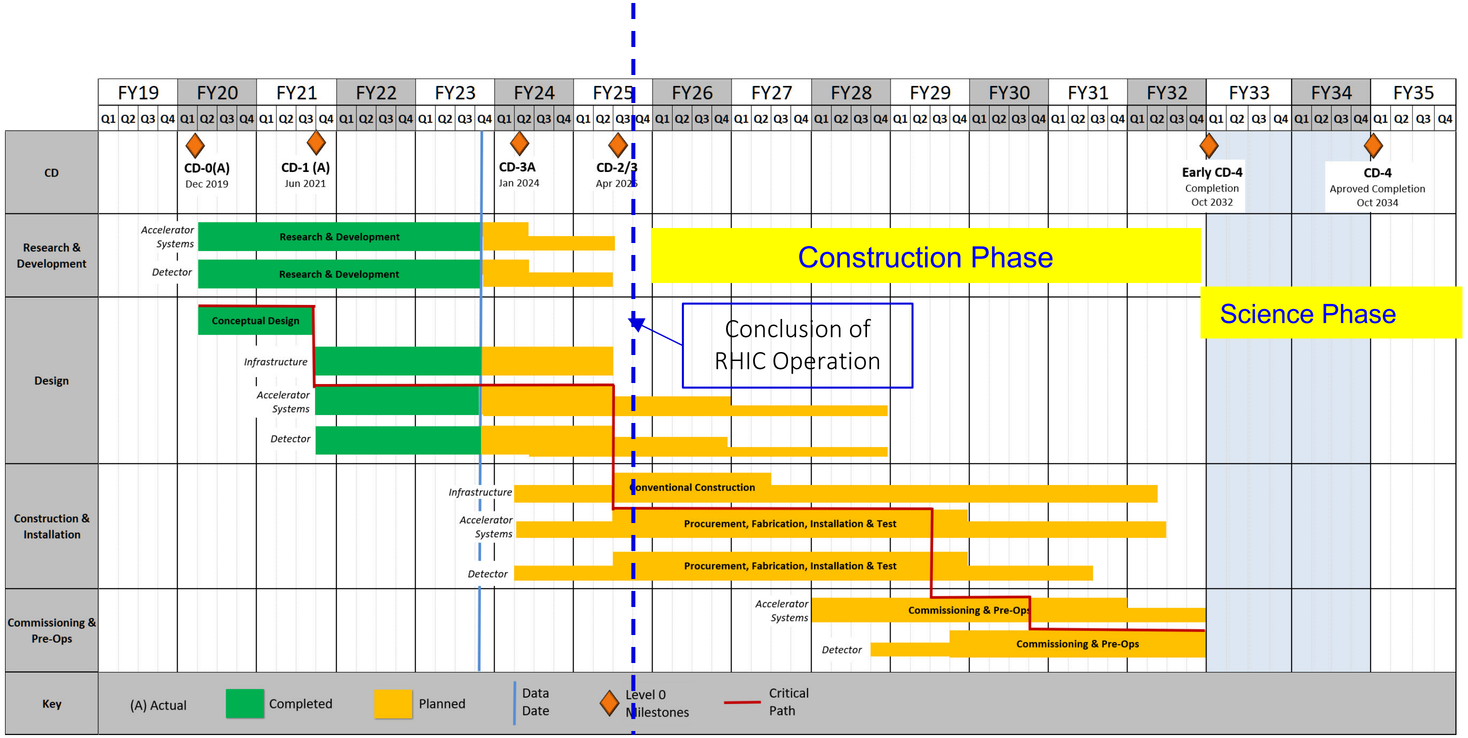
Timeline:

EIC Critical Decision Plan

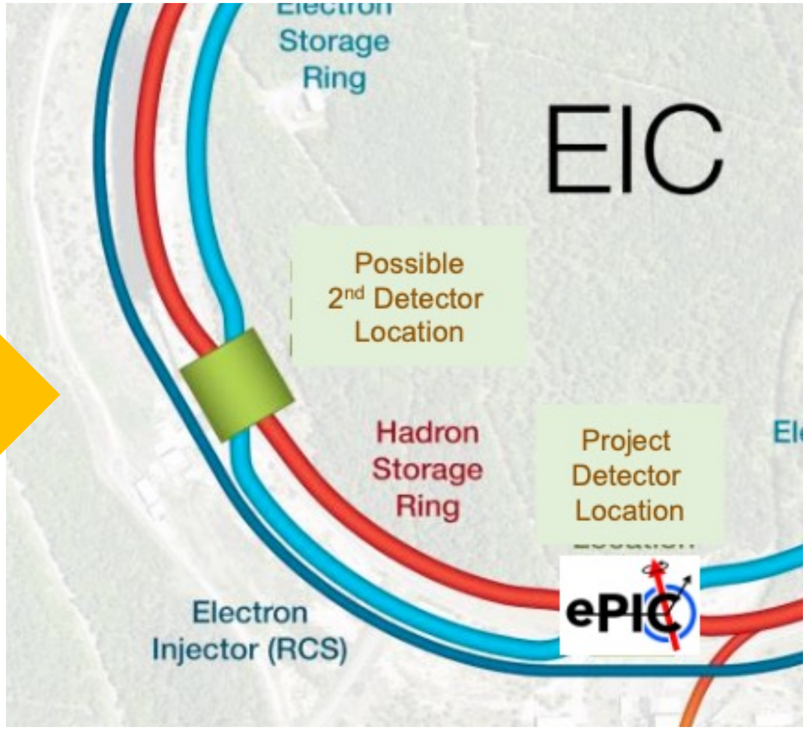
CD-0/Site Selection	December 2019 ✓
CD-1	June 2021 ✓
CD-3A	**March 2024**
CD-2/3	**April 2025**
CD-4A	October 2032
CD-4	**October 2034**



CD-3A: (review mid-November)
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



The 2nd detector



NSAC documents talk about possibly ~4 detectors

NAS Report: planning for up to 2 well-integrated detectors

EICUG desires 2 Detectors

EIC Project has 1 Machine, 1 IR and ~1 Detector

without negating the possibility of the 2nd IR/Detector

Vision for the 2nd detector: C^3

- Complementary (IR, detector technologies & design)
  - Continue to explore complementary ready and not-yet-ready technologies
  - Generic detector R&D program – Run through JLab
- Complementary (physics)
  - A significant list of physics topics (some-exclusive to 2nd IR, some-overlapping) exists: drill down and see which of those can *develop into strong pillars of science for the 2nd detector.*
  - New physics developing around the world : we need to monitor constantly
- Complementary (people)
  - New non-US/outside groups who may bring new interests & funding in future
  - New US groups – other than those with significant responsibilities in ePIC

Muons to replace electrons in the EIC? ➔ μIC

TeV scale deep inelastic scattering – way beyond HERA at DESY

- Muon significantly lower radiative corrections and such….
- Muons significantly difficult to handle… decays and all that, how to handle?

Can it achieve interesting luminosity?

Perception: not much work has occurred on muon collider detector/IR

Reality different?

MuIC proponents could get on fast, if you join forces

My thoughts based on what I heard at this workshop…
Include slides from select participants

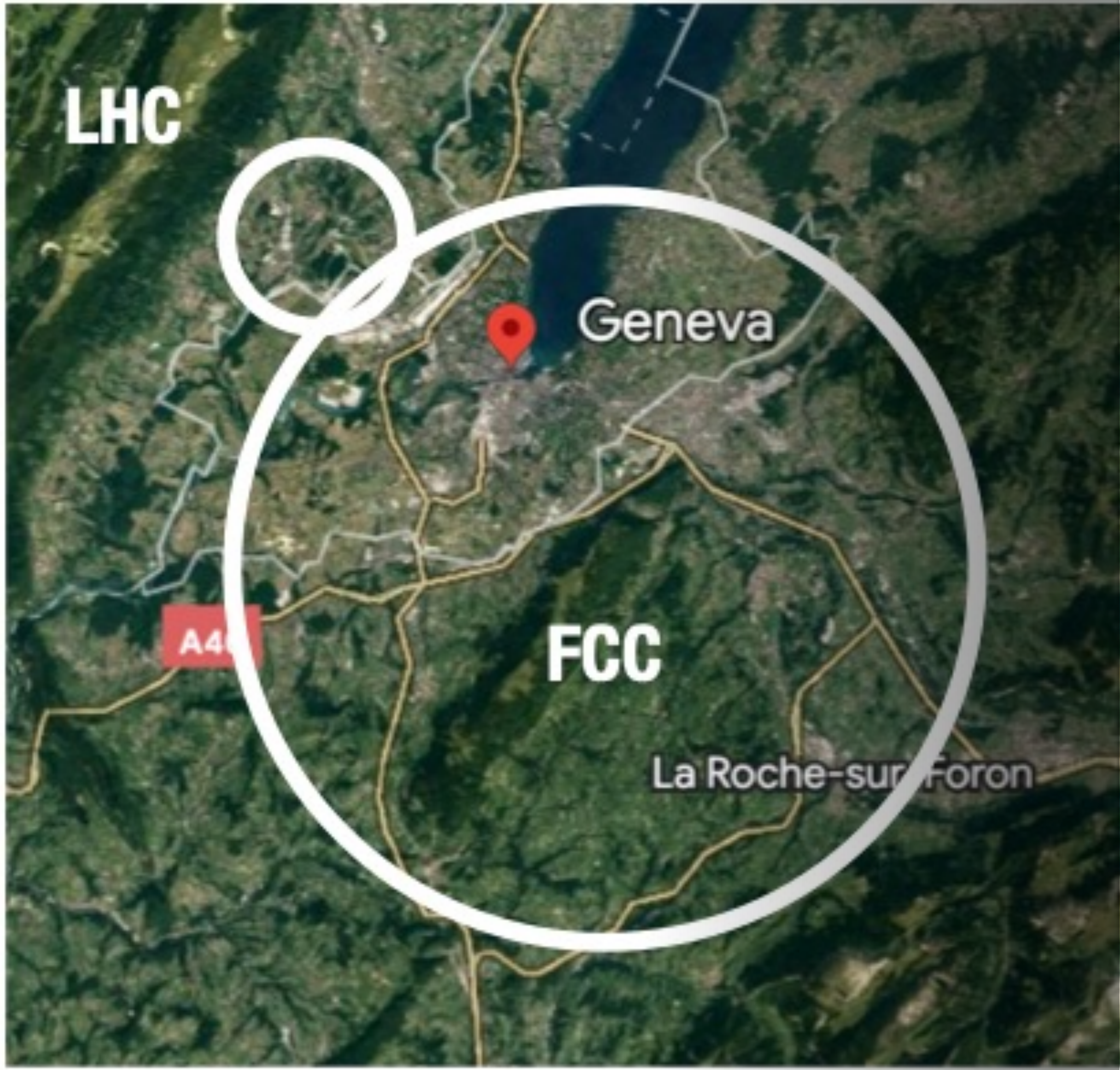
https://muic2023.rice.edu

For a fixed technology
→ go bigger

$$E_{\text{beam}} \sim 0.3 \cdot R \cdot B_{\text{dipole}}$$

For 100 TeV pp-collisions

LHC NbTi	8 T	190 km
Record NbSn3	15 T	100 km
Future HTS	20 T	80 km



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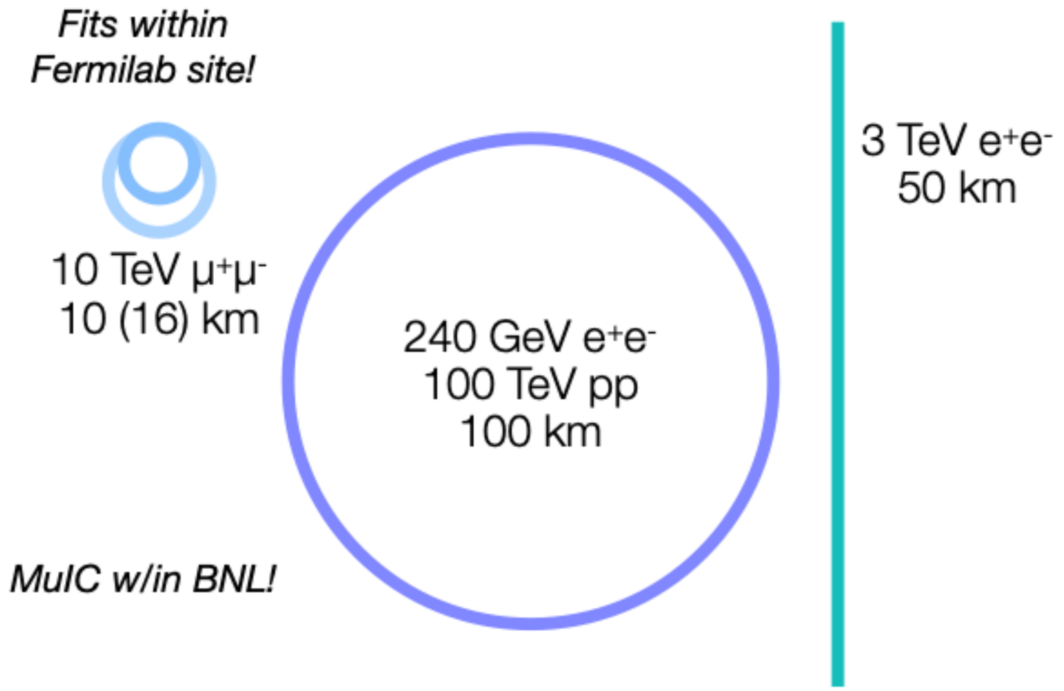
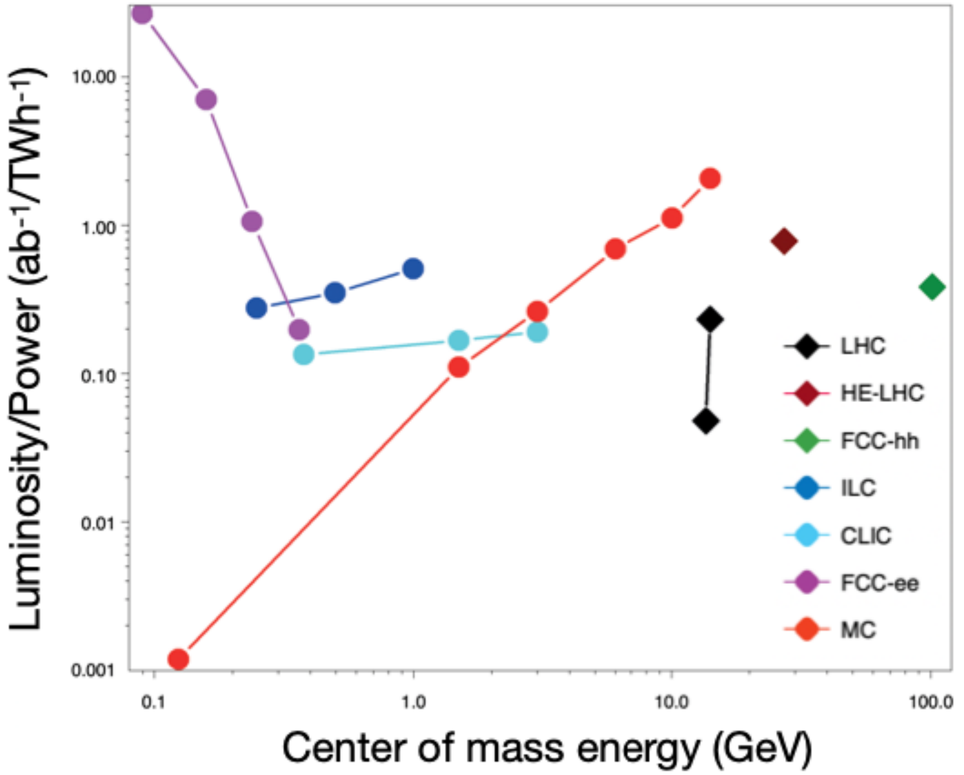
Muons break paradigm of larger and larger e^+e^- and pp machines

Colliding fundamental particles with no synchrotron radiation

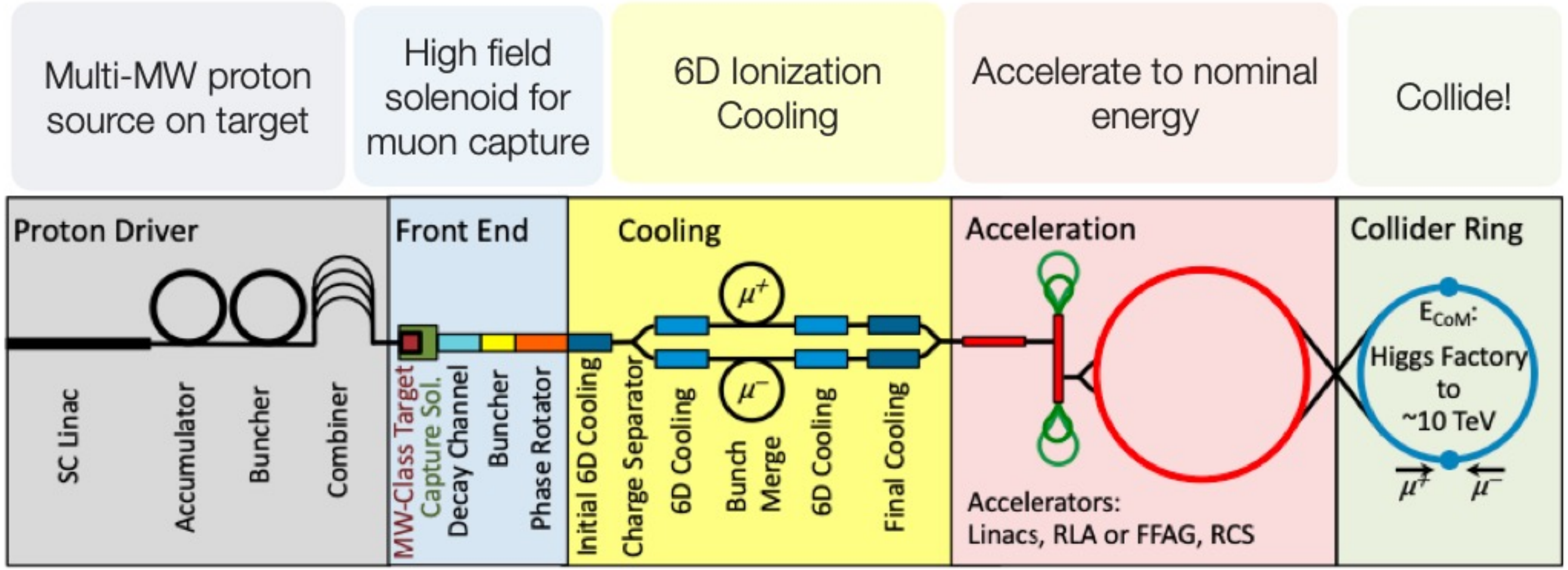




Challenge

Need to produce, cool, accelerate, and collide muons before they decay

Rest frame τ= 2.2 μs



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On the positive: exciting new development

In just the past year

- International Muon Collider Collaboration (CERN)
  - Second Annual Meeting June 2023 in Orsay
  - Rapid progress beyond MAP designs
- "MuCol" project funded by EU
  - Design study for collider complex at 10 TeV
  - Brings in ~7M Euro
- 4+ major meetings dedicated to muon colliders
- Very positive outcome from P5 planning process!

Exploring the Quantum Universe

Draft
Pathways to Innovation and Discovery in Particle Physics
Report of the 2023 Particle Physics Project Prioritization Panel

As part of this initiative, we recommend **targeted collider R&D** to establish the feasibility of a **10 TeV pCM muon collider**. A key milestone on this path is to design a muon collider demonstrator facility. If favorably reviewed by the collider panel, such a facility would open the door to building facilities at Fermilab that test muon collider design elements while producing exceptionally bright muon and neutrino beams. By taking up this challenge, the US blazes a trail toward a new future by advancing critical R&D that can benefit multiple science drivers and ultimately bring an unparalleled global facility to US soil.

- e+e- Higgs Factories “(nearly) shovel ready”
- For 10 TeV scale colliders
  - We don’t have the technology today & we’re not ready to make any decisions
  - We should begin R&D for $\mu^+\mu^-$ AND pp colliders as soon as possible
- “We urge to give high priority to the R&D topics aimed at the reduction of the cost and the energy consumption of future collider projects”

Collider	$\sqrt{s}$ (TeV)	Tunnel (km)	Power (MW)	Cost ($B)	Time to start (yrs)
ILC e+e-	0.24	20	140	7-12	<12
FCC-ee	0.24	100	290	12-18	13-18
μ-3	3	10	230	7-12	19-24
CLIC	3	50	550	18-30	19-24
μ-10	10	16	300	12-18	>25
FCC-hh	100	100	560	30-50	>25

*Cost without contingency/escalation
**Technically limited timelines
***No staging assumed

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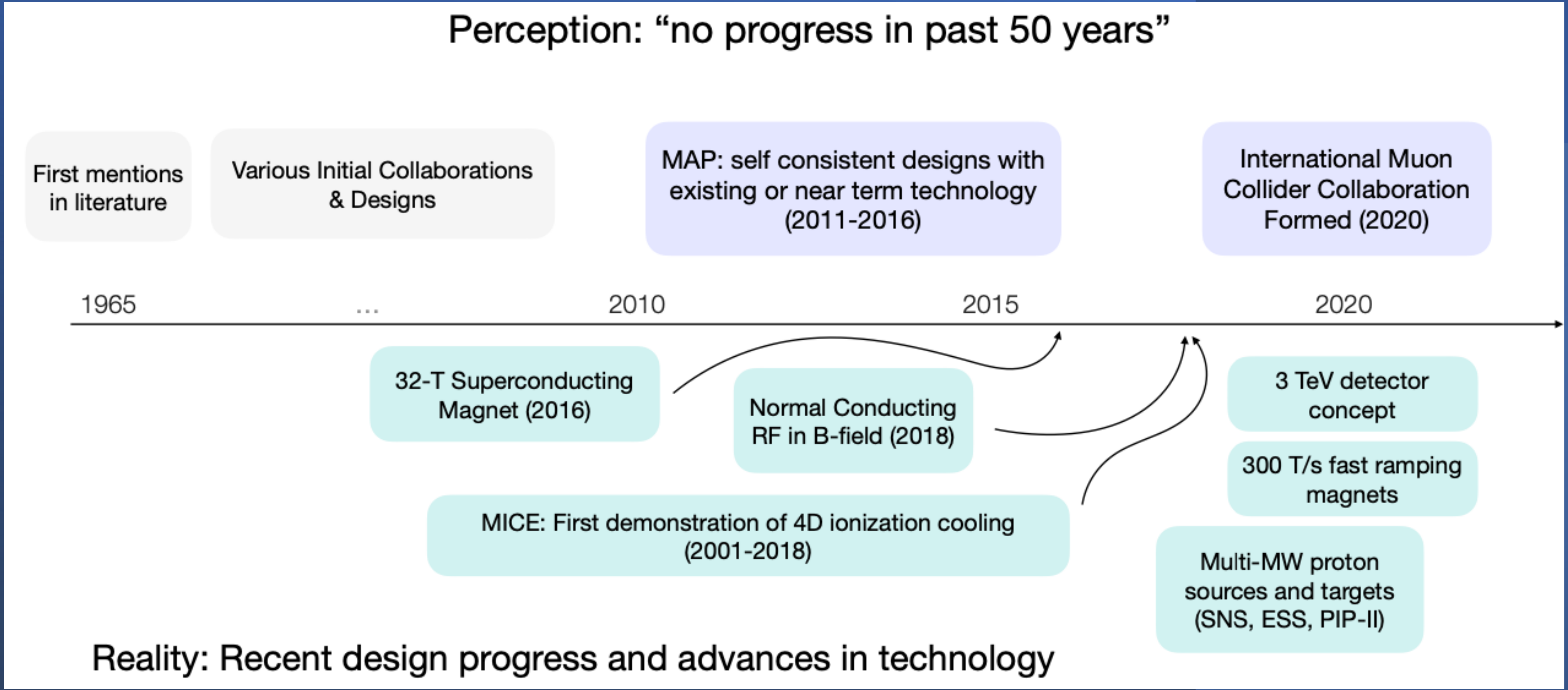
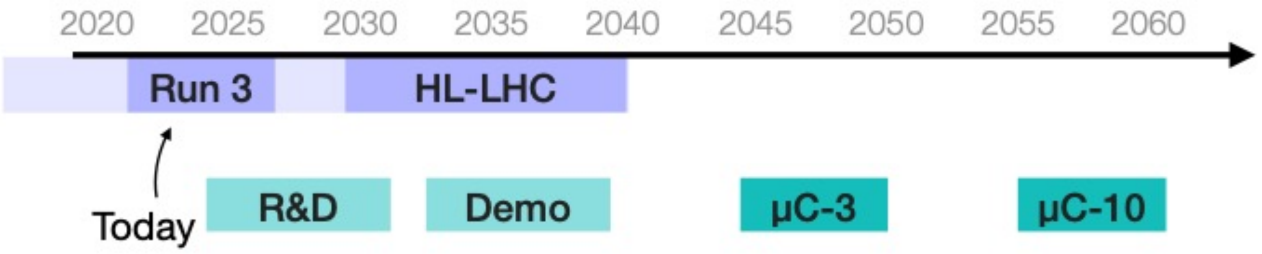
Perception vs. Reality

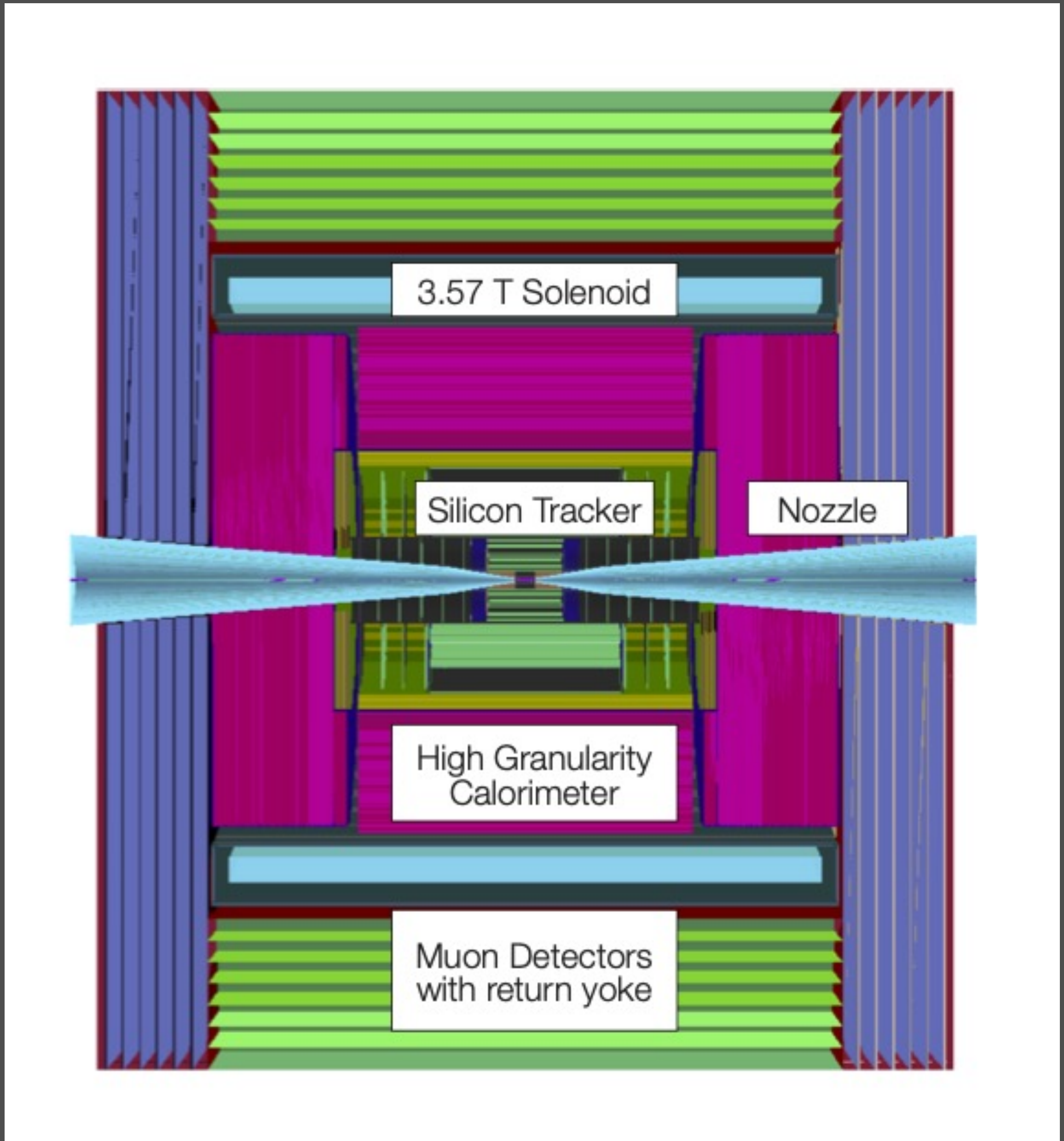


D. Stratakis at IMCC

- **Design work**
  - Ionization cooling
  - Optimize ACE for μC front end
  - Baseline FNAL design for μC
  - Neutrino flux mitigation for a FNAL MuC
- **Prototyping and tests**
  - Bunch compression & proton stripping
  - Target material & performance studies
  - Fast ramping magnet prototypes
  - Low-frequency SRF cavity prototyping & testing
- **Towards a Demonstrator**
  - Explore facility options for a full demo
  - Design & prototype (if possible) 1.5 cooling cell
  - Deliver a TDR for a demo facility with costs




International MUON Collider Collaboration
March 15, 2022
https://muoncollider.web.cern.ch
Promising Technologies and R&D Directions for the Future Muon Collider Detectors
Submitted to the Proceedings of the US Community Study on the Future of Particle Physics (Snowmass 2021)
Forward μ
Scoring plane
-100 0 100 200 300 400 500 600 700 800 900 1000 1100 1200


3.57 T Solenoid
Silicon Tracker
Nozzle
High Granularity Calorimeter
Muon Detectors with return yoke

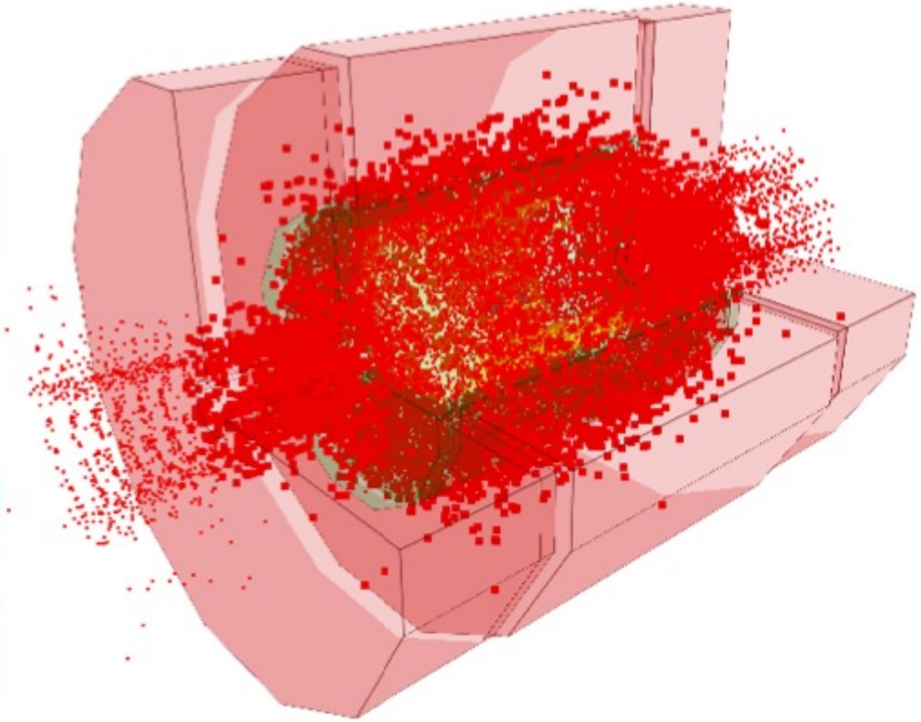
- **Circulate two bunches & re-fill when depleted**
- Time between collisions: t=L/c = 30 kHz
- Muons survive ~2000 turns

1000 x lower event rate than LHC

- **Beam induced background**
- Decays w/in 20 m of interaction point: ~10^7
- Total energy of decay products: ~ 50 EeV

N_{decay} decrease with Energy

Total E_{decay} doesn't depend on Energy



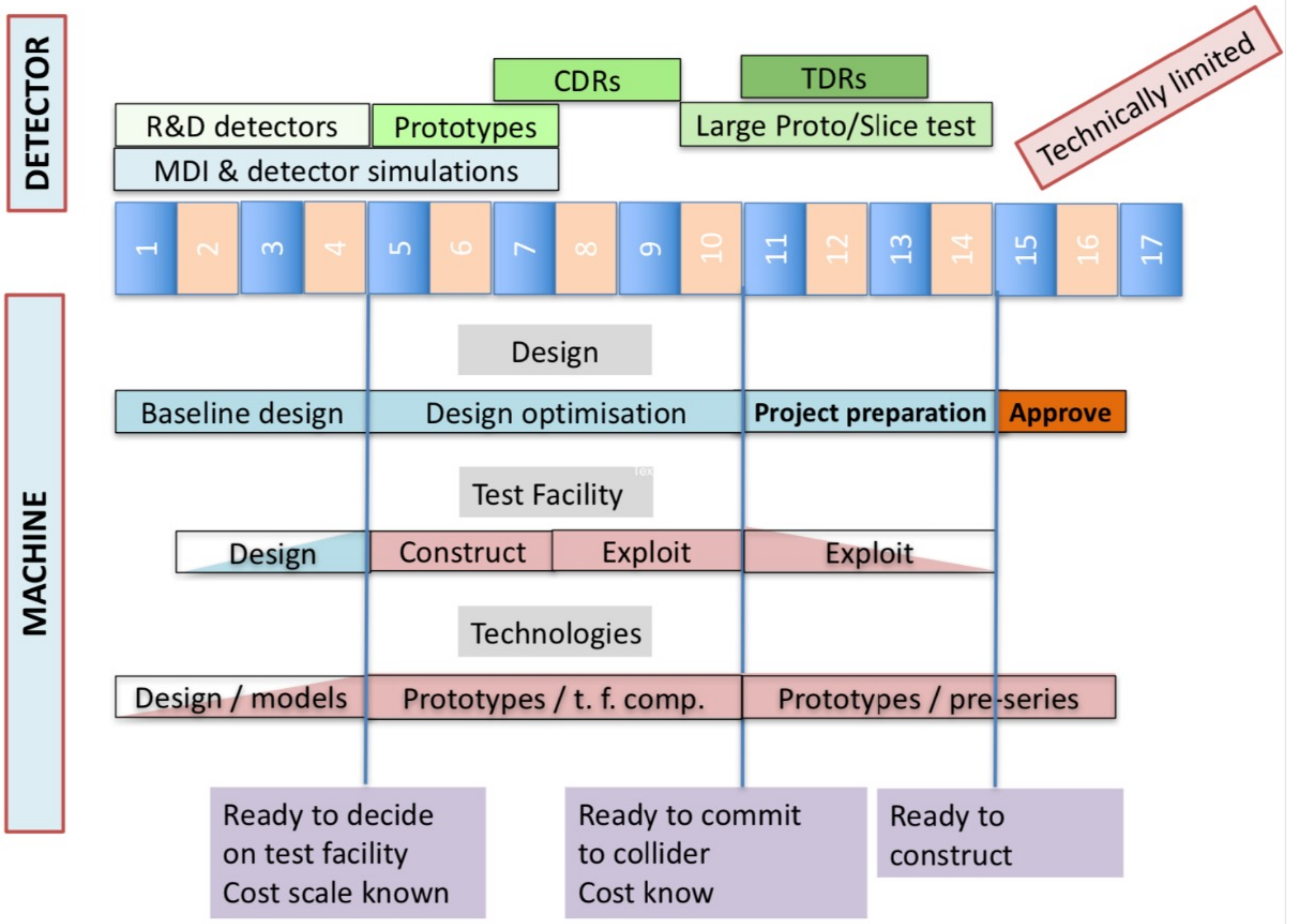


Fig. 10.5: Potential technically-limited time-line for a muon collider.

I would assume the same somewhat shorter for muIC?

2007.13391.pdf

Science of the muIC:

~ 1 TeV CM with mu-P
(and equivalently scaled for mu-Ion)

Compare simply to the studies so far made for the LHeC physics at CERN

2007.13391.pdf

LHeC science → MuIC
Assuming ~1 TeV CM (ep)

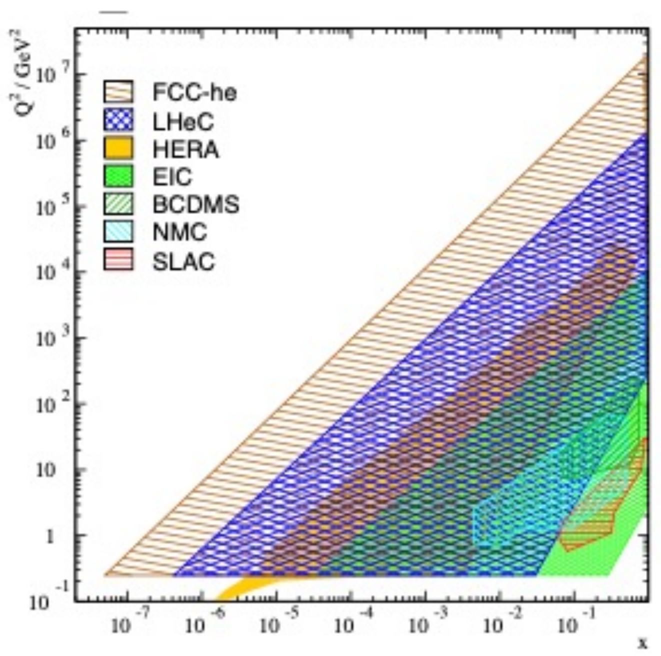


Figure 1.1: Coverage of the kinematic plane in deep inelastic lepton-proton scattering by some initial fixed target experiments, with electrons (SLAC) and muons (NMS, BCDMS), and by the ep colliders: the EIC (green), HERA (yellow), the LHeC (blue) and the FCC-eh (brown). The low Q^2 region for the colliders is here limited to about 0.2 GeV^2, which is covered by the central detectors, roughly and perhaps using low electron beam data. Electron taggers may extend this to even lower Q^2. The high Q^2 limit at fixed x is given by the line of inelasticity $y = 1$. Approximate limitations of acceptance at medium x, low Q^2 are illustrated using polar angle limits of $\eta = -\ln\tan\theta/2$ of 4, 5, 6 for the EIC, LHeC, and FCC-eh, respectively. These lines are given by $x = \exp\eta \cdot \sqrt{Q^2}/(2E_p)$, and can be moved to larger x when E_p is lowered below the nominal values.

Source of uncertainty	Uncertainty
Scattered electron energy scale $\Delta E'_e/E'_e$	0.1 %
Scattered electron polar angle	0.1 mrad
Hadronic energy scale $\Delta E_h/E_h$	0.5 %
Radiative corrections	0.3 %
Photoproduction background (for $y > 0.5$)	1 %
Global efficiency error	0.5 %

Table 3.1: Assumptions used in the simulation of the NC cross sections on the size of uncertainties from various sources. The top three are uncertainties on the calibrations which are transported to provide correlated systematic cross section errors. The lower three values are uncertainties of the cross section caused by various sources.

How much better could muon beam do?

2007.13391.pdf

Kinematic Coverage of a 1 TeV e-p machine

muIC won't be too different

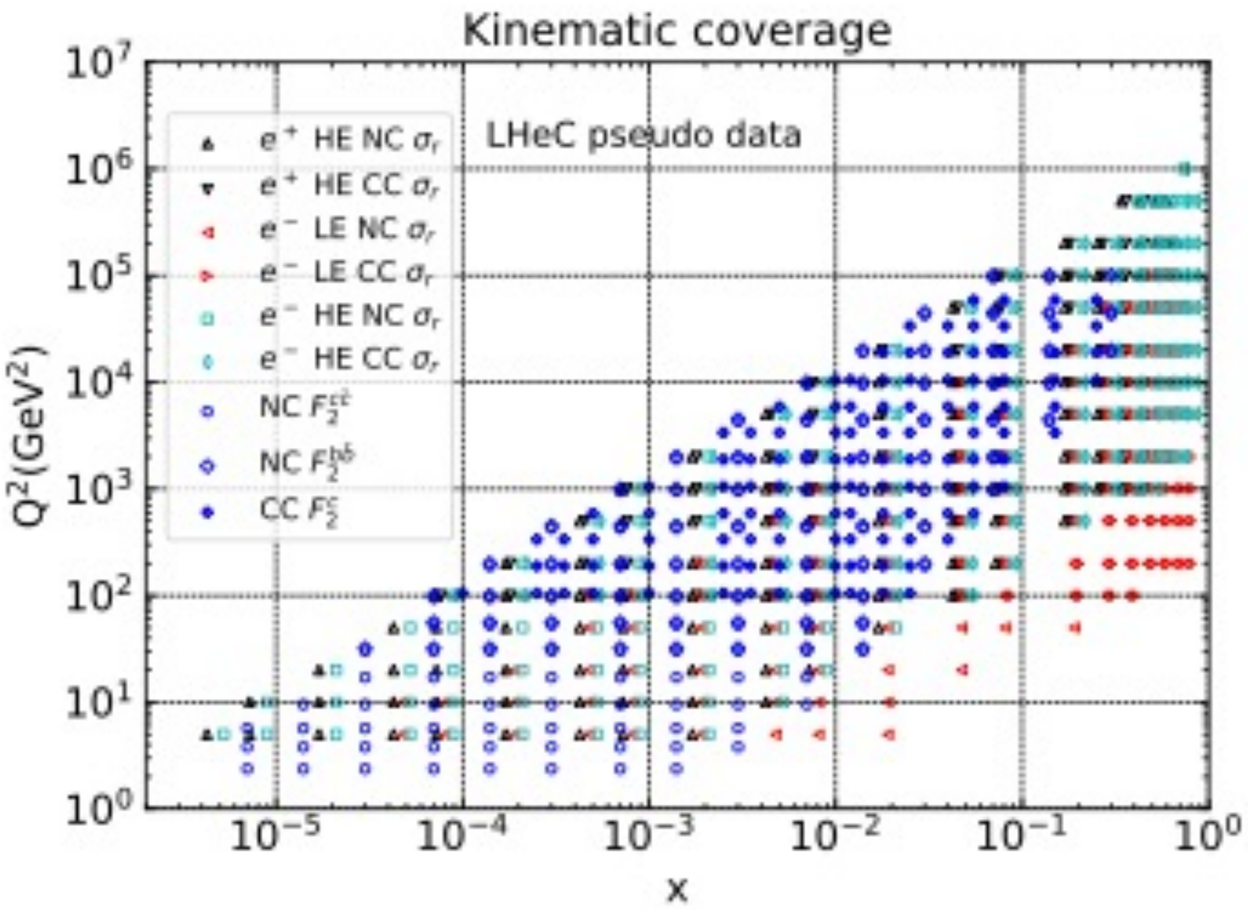


Figure 3.4: Illustration of the x, Q^2 values of simulated cross section and heavy quark density data used in LHeC studies. The red points illustrate the gain in acceptance towards large x at fixed Q^2 when E_p is lowered, see text.

Concluding thoughts:

- MuIC with somewhere between 600-1000 GeV Center of Mass would be a very attractive Stage in the construction and life of a future muon collider (2+ TeV).
- There is good science to be done in QCD, EW and possibly precision Higgs factory leading to sensitivities for physics beyond the SM
- Whether it happens at RHIC after EIC (starting from 2045) or somewhere else (FNAL main injector, or CERN PS), would make it only minimally differen.
- Recent recommendation for moving forward on a muon collider bodes well for thinking about such a muIC modulo all the technical hurdles that both needs to solve on the way….

Backup

Topics discussed

The workshop aims to foster a highly interactive environment for researchers in HEP and NP communities. The program consists of invited talks, each reserved with ample time for discussion. Topics include:

- Physics at muon colliders, TeV DIS machines and EIC
- Status and prospects of muon accelerators and colliders
- Concept and design options of muon-ion colliders
- Machine-detector interface, detector requirements for muon-based colliders vs. EIC, as well as their synergies
- Long range plan status in particle and nuclear physics, synergies and path forward.

Dedicated topical discussion sessions are also planned.

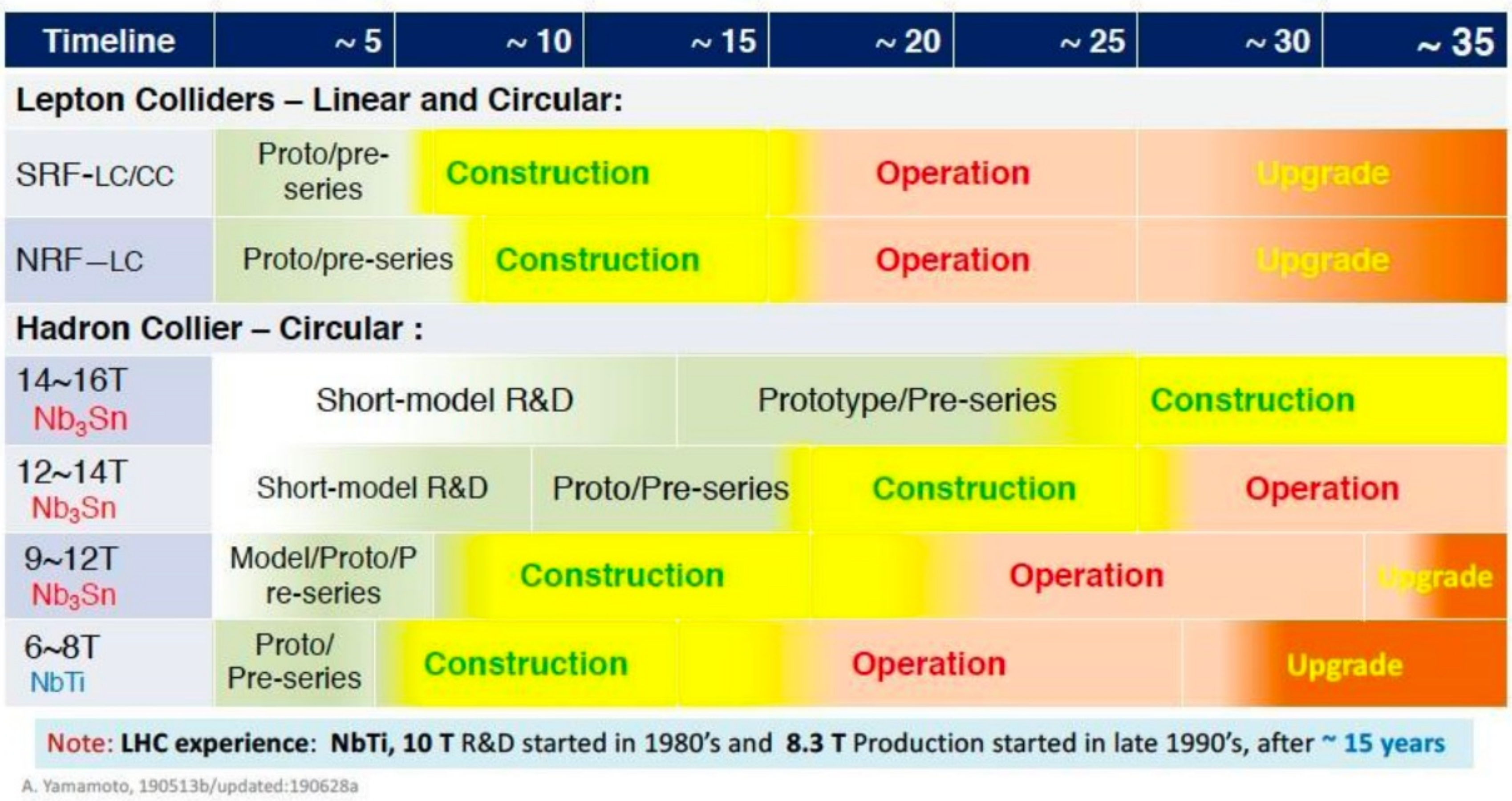


Fig. 10.4: A relative time-line expected for realizing future lepton and hadron colliders (from A. Yamamoto, presented at the Open Symposium in Granada, and updated based on the discussion that followed).