Center for Frontiers in Nuclear Science

Dreaming of a Muon Ion Collider: μIC

Based on the History, Science and Timelines of the EIC

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Outline of this talk

Physics of EIC

EIC project

  EIC Accelerator and detector (ePIC) timeline

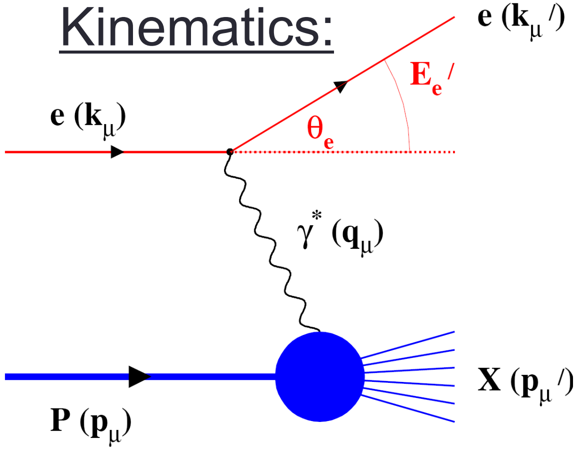
EIC realization timeline

Lessons learned

While Past performance is no guarantee of future success, I still would dare to extrapolate and advise toward realizing Fantasies of MuIC

Deep Inelastic Scattering: Precision and control

Kinematics:



$$Q^2 = -q^2 = -(k_\mu - k'_\mu)^2$$

$$Q^2 = 2E_e E'_e(1-\cos\Theta_{e'})$$

Measure of resolution power

$$y = \frac{pq}{pk} = 1 - \frac{E'_e}{E_e}\cos^2\left(\frac{\theta'_e}{2}\right)$$

Measure of inelasticity

$$x = \frac{Q^2}{2pq} = \frac{Q^2}{sy}$$

Measure of momentum fraction of struck quark

***Hadron*:**

$$z = \frac{E_h}{\nu}; p_t$$ with respect to γ^*

$$s = 4\,E_h\,E_e$$

High lumi & acceptance

Exclusive DIS

detect & identify *everything* e+p/A → e'+h(π,K,p,jet)+…

Semi-inclusive events:

e+p/A → e'+h(π,K,p,jet)+X

detect the scattered lepton in coincidence with identified hadrons/jets

Inclusive events:

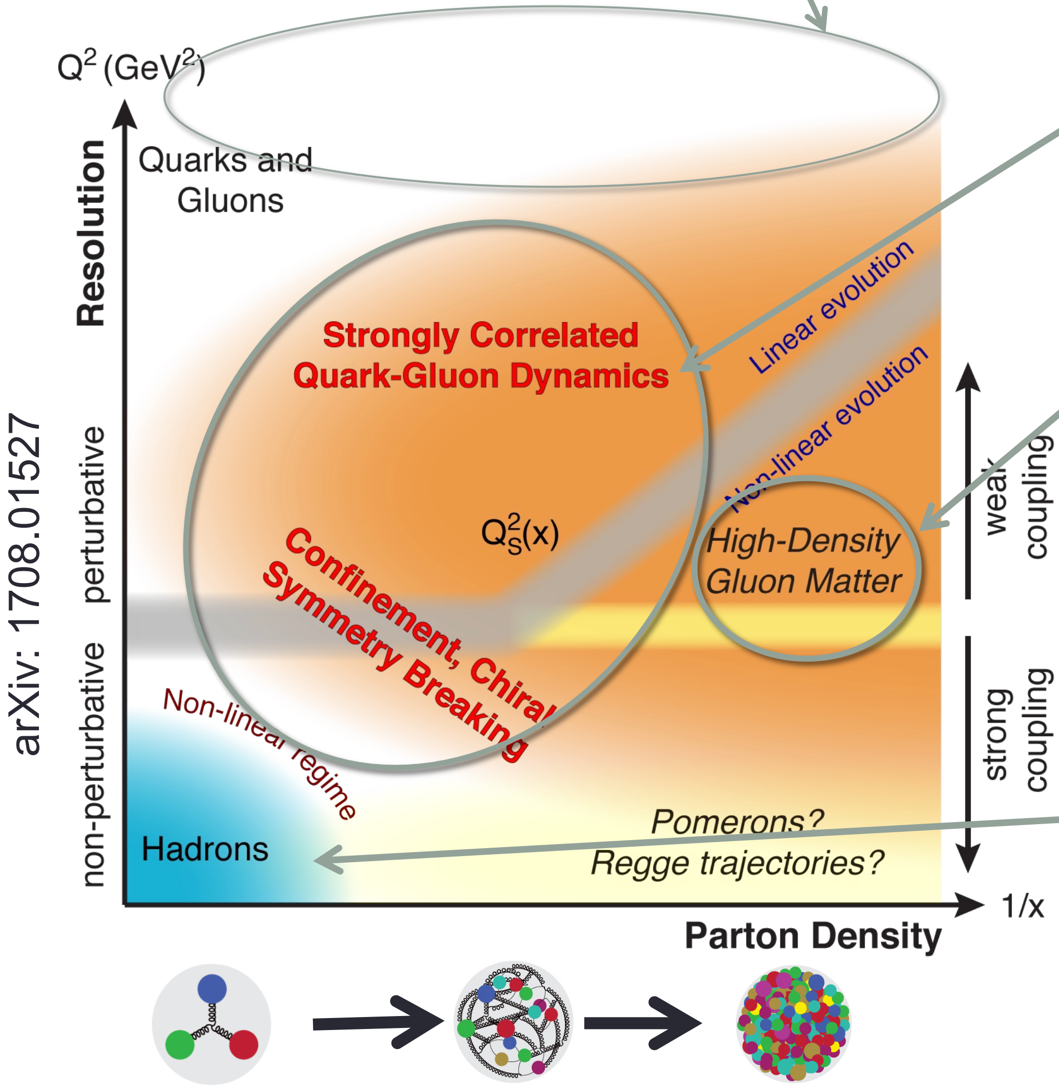
e+p/A → e'+X

detect *only the scattered lepton* in the detector

Low lumi & acceptance

QCD Landscape to be explored by a new future facility

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

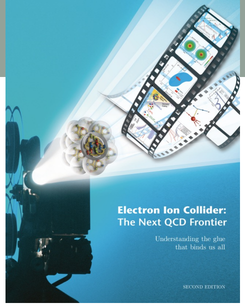


Systematically explore correlations in this region.

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

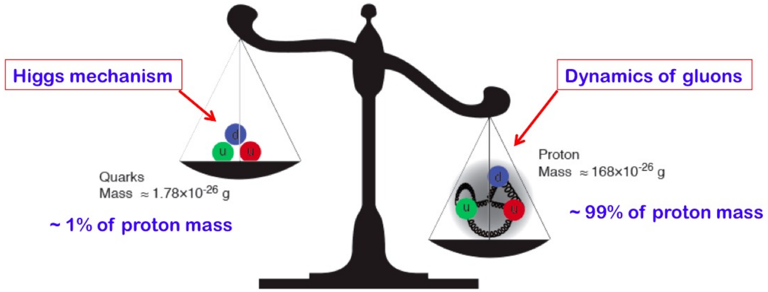
Strong QCD dynamics creates many-body correlations between quarks and gluons
→ hadron structure emerges

Need Precision and Control

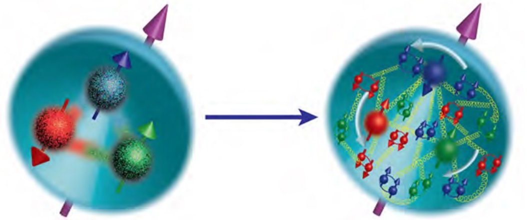


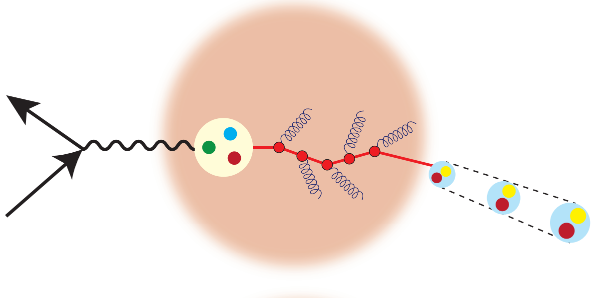
EIC Physics at-a-Glance

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



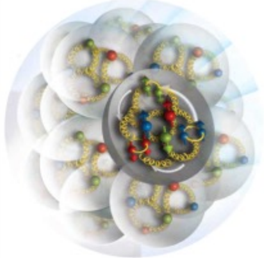
How are the sea quarks and gluons, and their spins, distributed in space and momentum inside the nucleon? How do the nucleon properties (mass & spin) emerge from their interactions?

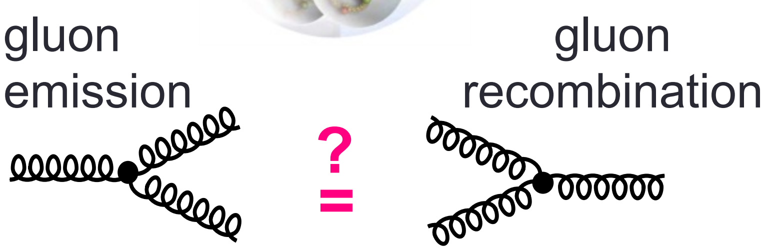


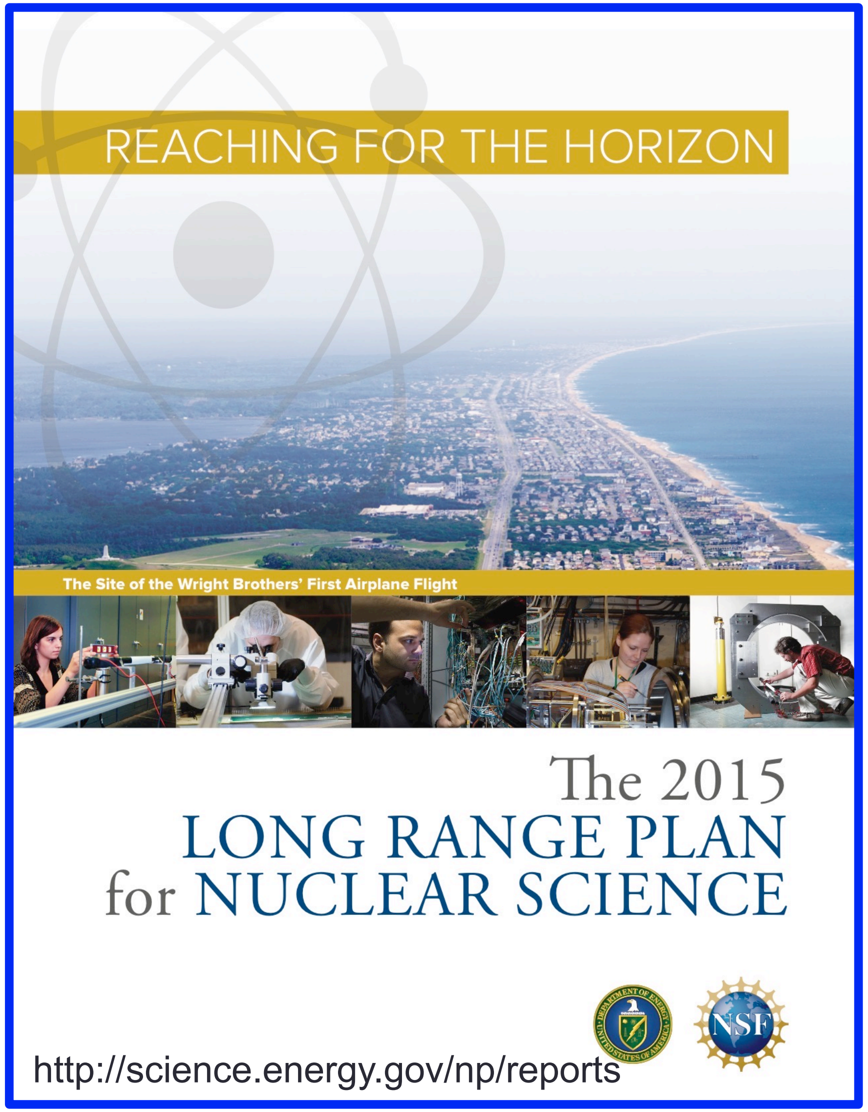


How do color-charged quarks and gluons, and colorless jets, interact with a nuclear medium? How do the confined hadronic states emerge from these quarks and gluons? How do the quark-gluon interactions create nuclear binding?

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?







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

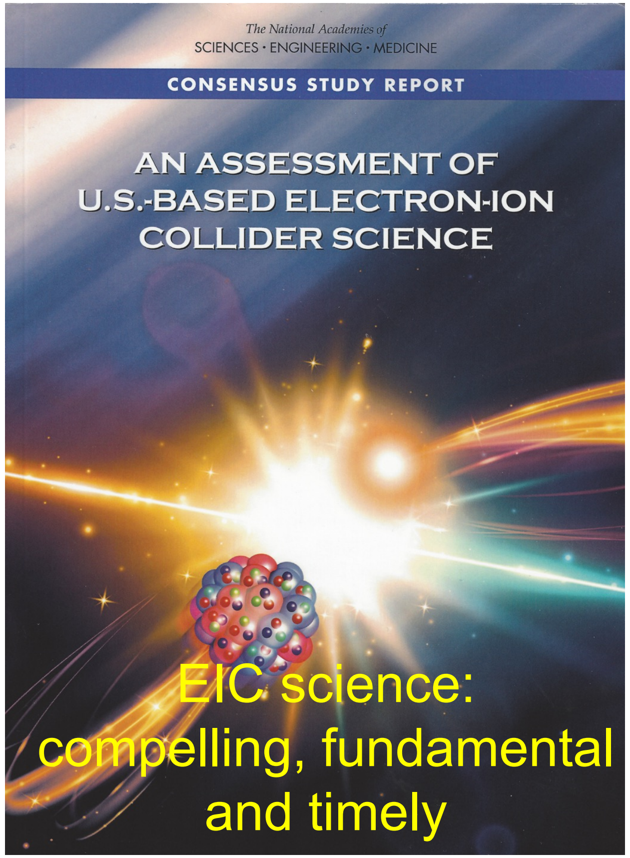
Gluons, the carriers of the strong force, bind the quarks together inside nucleons and nuclei and generate nearly all of the visible mass in the universe. Despite their importance, <u>fundamental questions remain</u> about the role of gluons in nucleons and nuclei. These questions can <u>only be answered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

<u>RECOMMENDATION:</u>
We recommend a high-energy high-luminosity polarized EIC as the highest priority for new facility construction following the completion of FRIB.

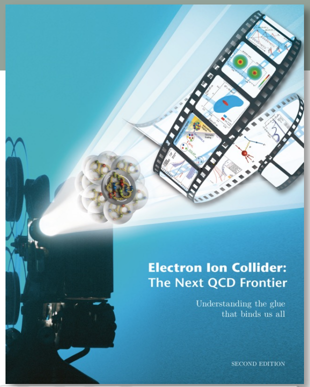
FRIB construction completed, operations began May 2022.

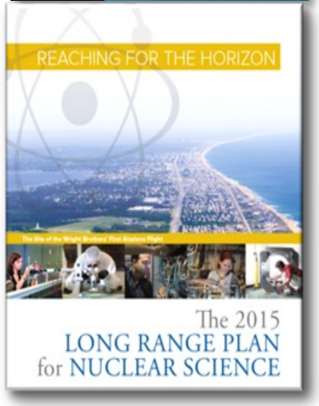
National Academy of Science, Engineering and Medicine

Assessment July 2018



EIC science:
compelling, fundamental and timely





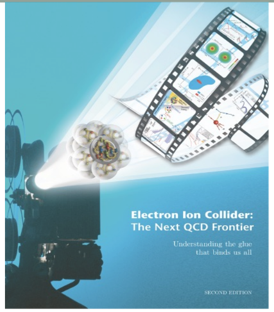
Physics of EIC

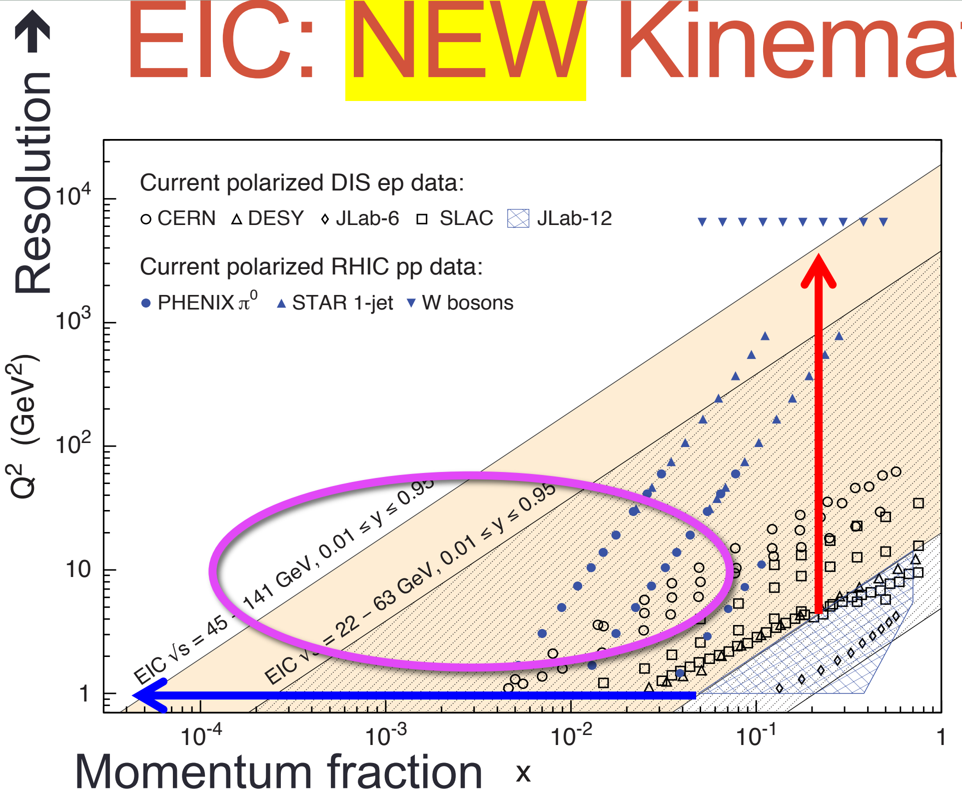
- Emergence of Spin
- Emergence of Mass
- Physics of high-density gluon fields

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: ~20-140 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

EIC: NEW Kinematic reach & properties



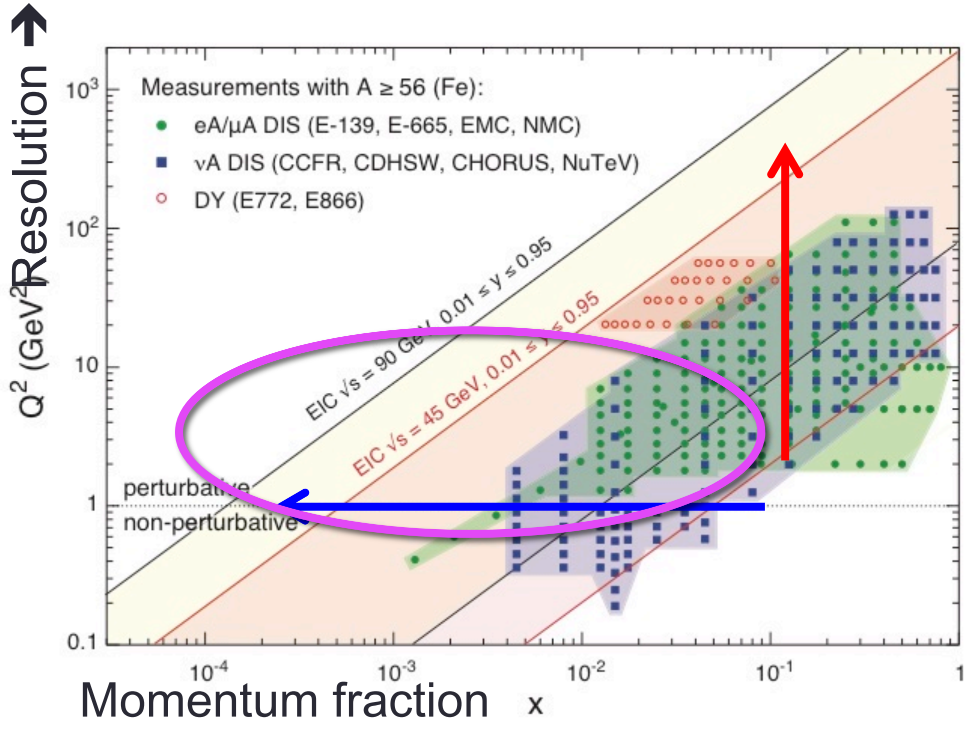


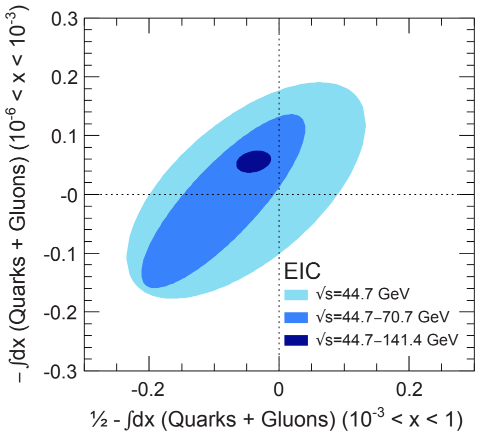
For e-N collisions at the EIC:

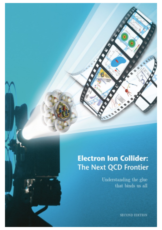
- ✓ Polarized beams: e, p, d/^{3}He
- ✓ Variable center of mass energy
- ✓ Wide Q^2 range → evolution
- ✓ Wide x range → spanning valence to low-x physics

For e-A collisions at the EIC:

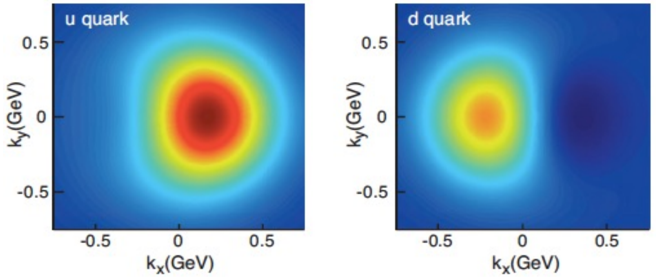
- ✓ Wide range in nuclei
- ✓ Luminosity per nucleon same as e-p
- ✓ Variable center of mass energy
- ✓ Wide x range (evolution)
- ✓ Wide x region (reach high gluon densities)

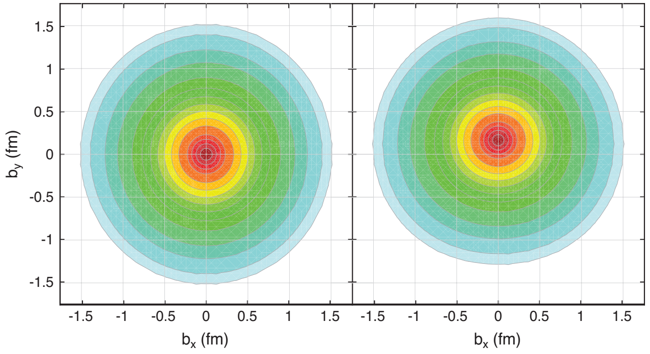


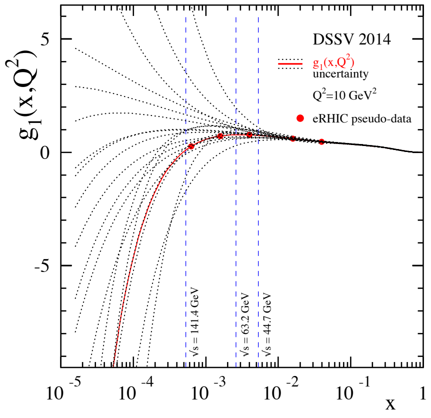


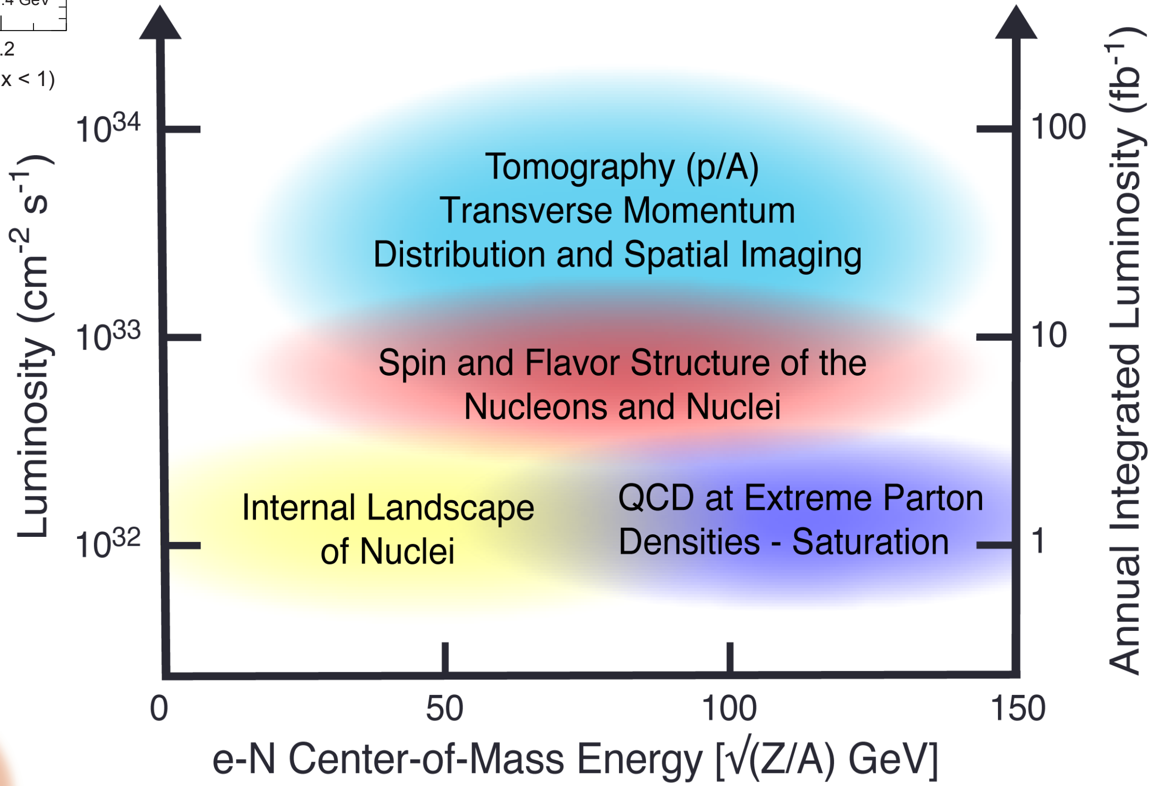


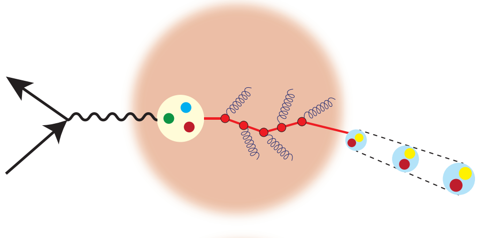
EIC science highlights

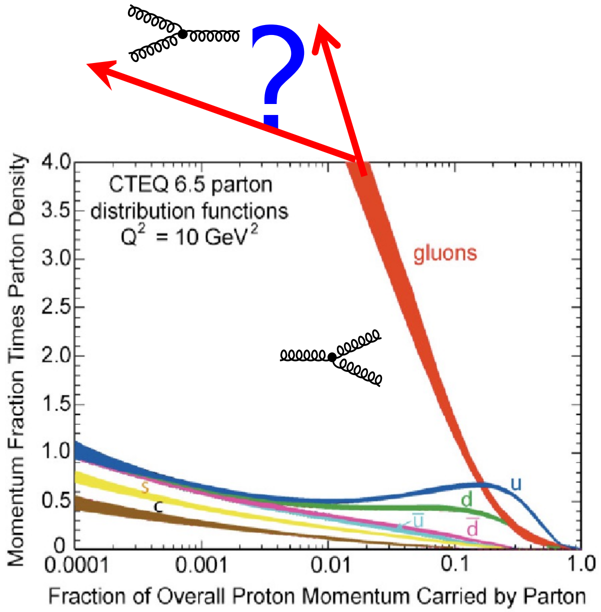






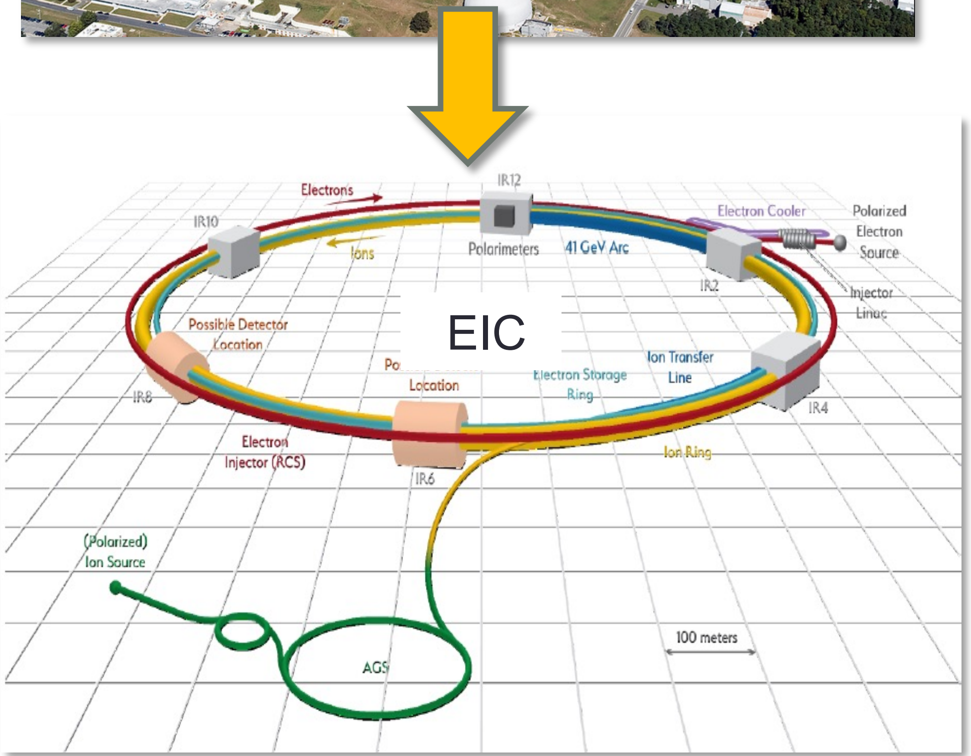




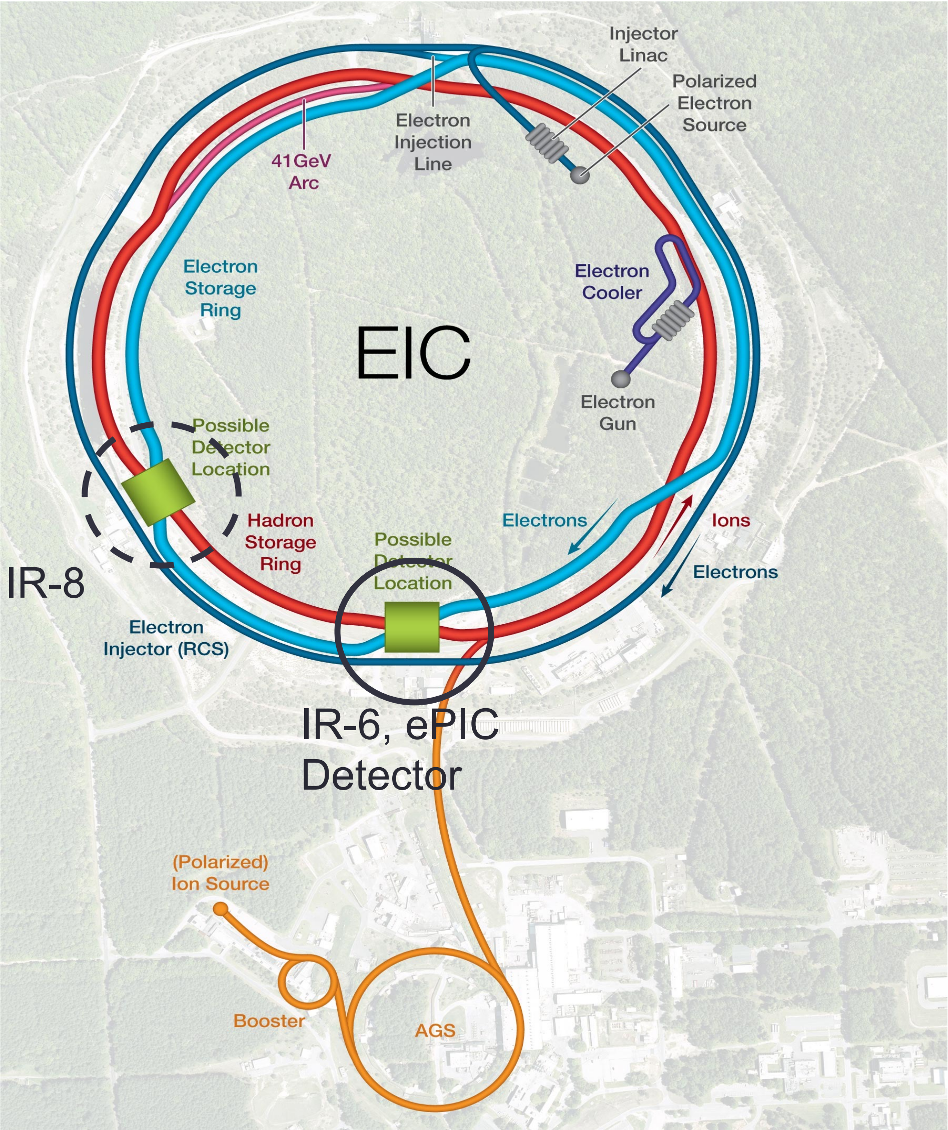


EIC Accelerator Design Overview

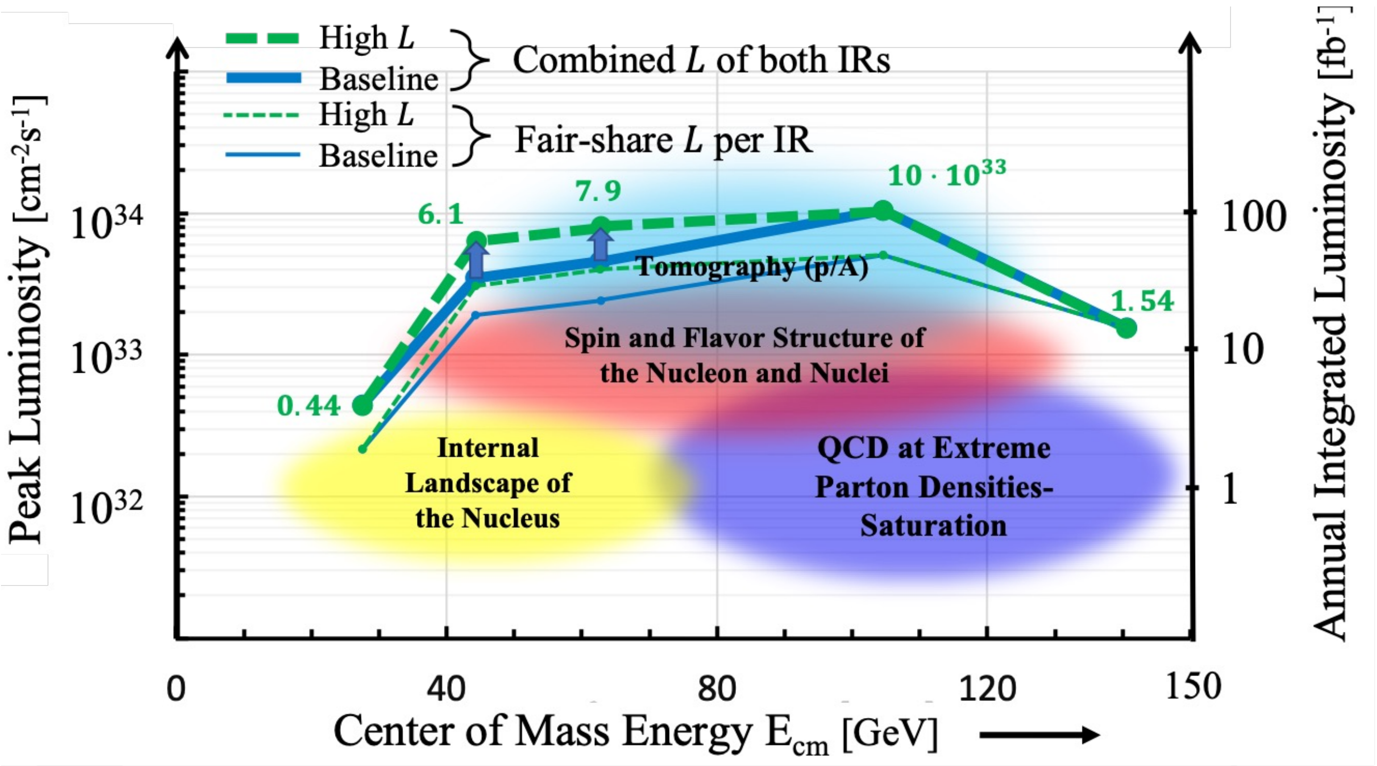
- **Hadron storage ring (HSR): 41-275 GeV** (**based on RHIC**)
  - up to 1160 bunches, 1A beam current (3x RHIC)
  - bright vertical beam emittance (1.5 nm)
  - strong cooling (coherent electron cooling, ERL)
- **Electron storage ring (ESR): 2.5–18 GeV** (**new**)
  - up to 1160 polarized bunches
    - high polarization by continual reinjection from RCS
  - large beam current (2.5 A) ➔ 9 MW SR power
  - superconducting RF cavities
- **Rapid cycling synchrotron (RCS): 0.4-18 GeV** (**new**)
  - 2 bunches at 1 Hz; spin transparent due to high periodicity
- **High luminosity interaction region(s)** (**new**)
  - L = 10^{34} $cm^{-2}s^{-1}$
  - superconducting magnets
  - 25 mrad crossing angle with crab cavities
  - spin rotators (produce longitudinal spin at IP)



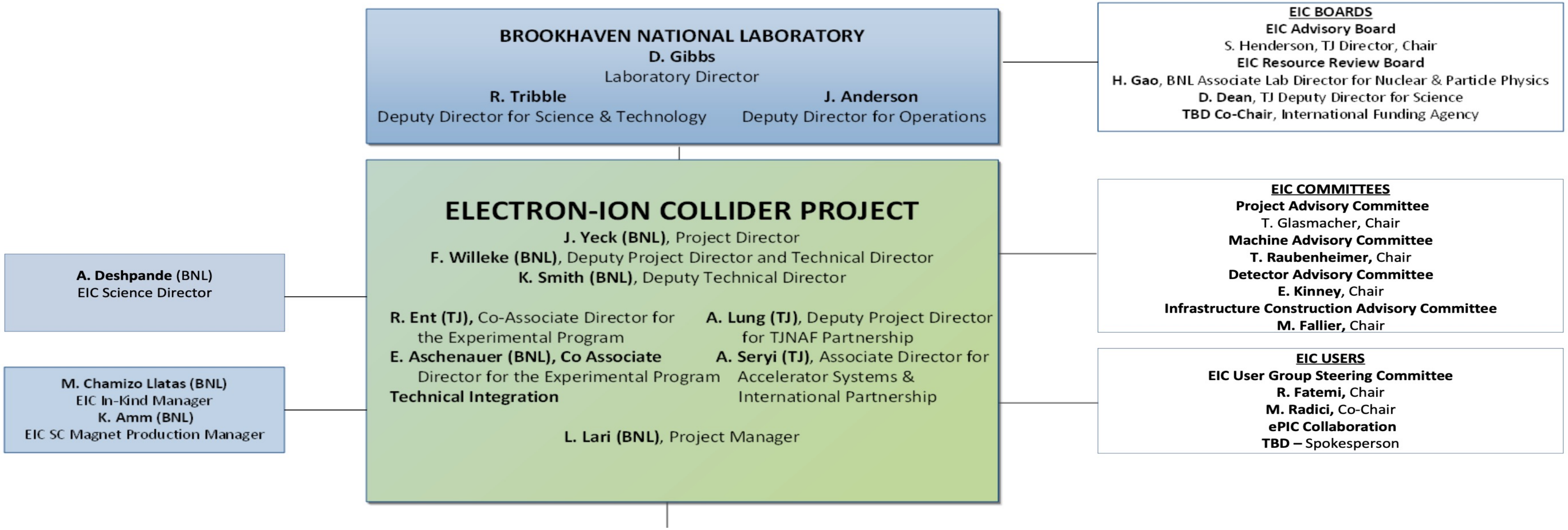
EIC Accelerator Design



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!



EIC Project – BNL/JLab, Boards, Advisory Committees



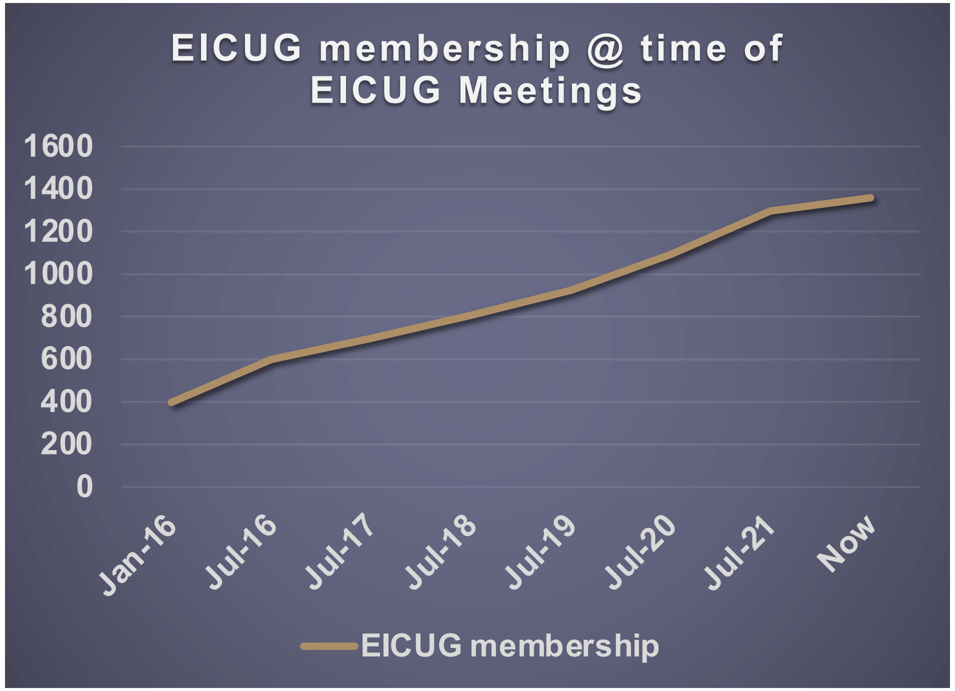
- DOE, together with BNL and JLab, envision an EIC facility that is “fully international in character.”
- EIC Advisory Board provides oversight and advice on the construction of the facility, focusing on the accelerator (BNL, TJNAF, LBNL, ANL, TRIUMF, IN2P3, CEA, STFC, INFN).
- EIC Project Advisory Committee provides advice on the successful delivery of the DOE Project (management, scope, schedule, cost, and performance).
- EIC Resource Review Board (RRB) to provide oversight of the experiments.

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

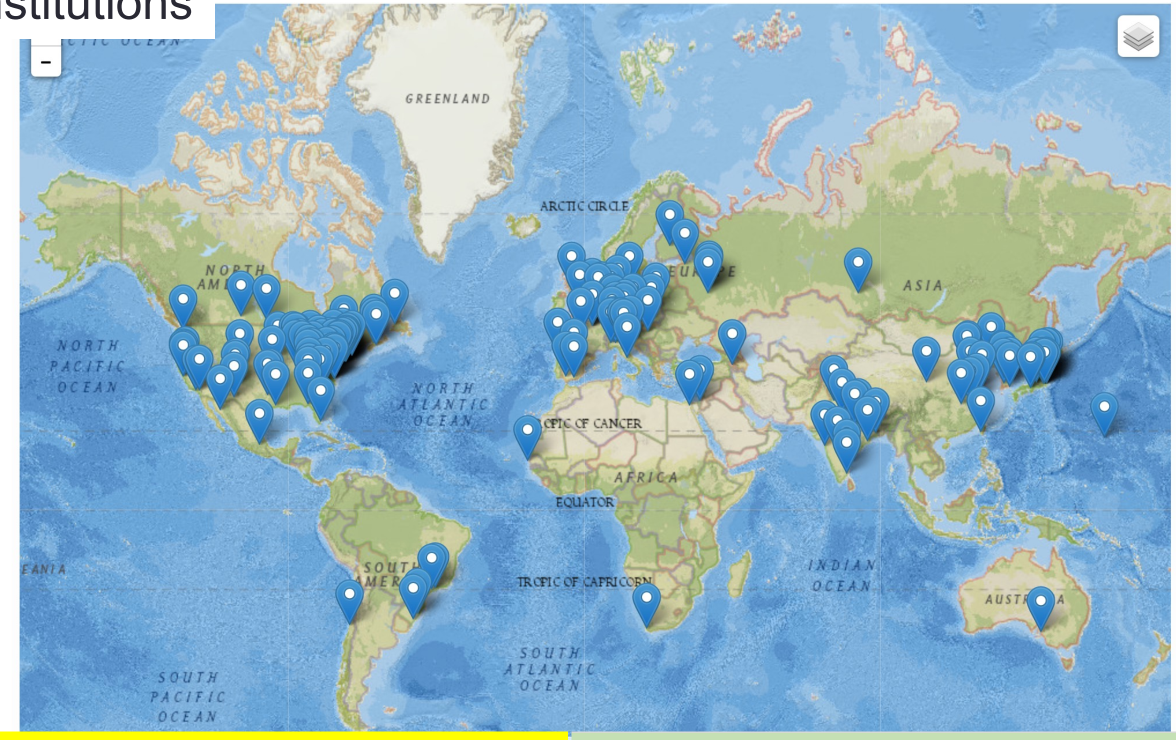
Formed in 2016, Currently:

- **1369 collaborators,**
- **36 countries,**
- **267 institutions**

International Participation Growing

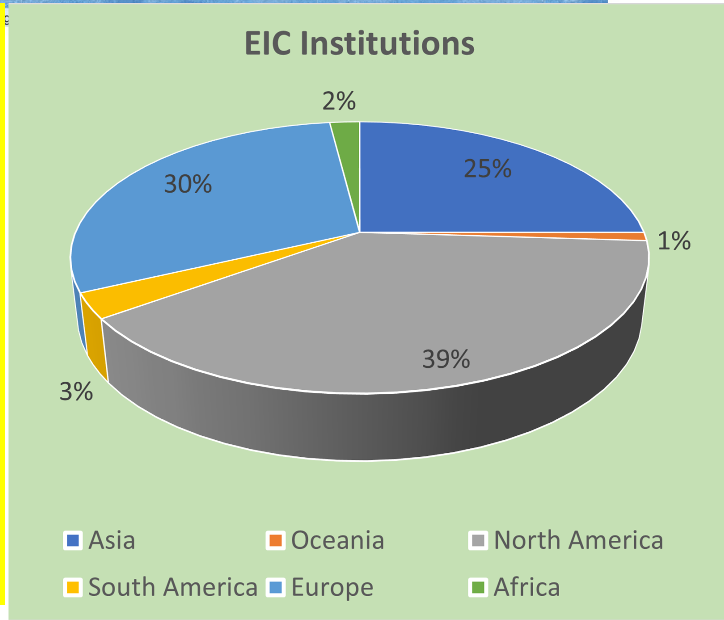


Institutions



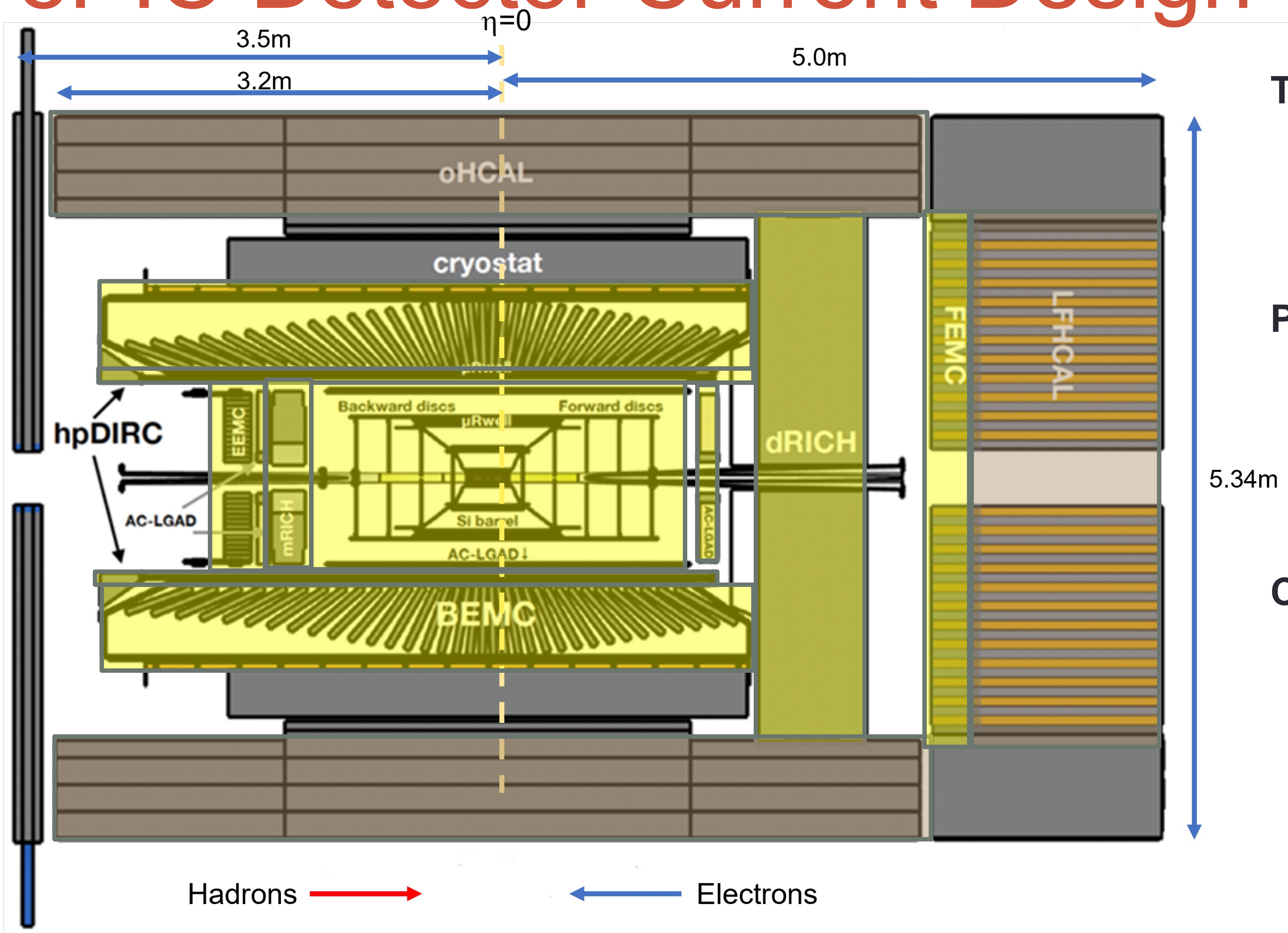
Annual EICUG meeting

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



ePIC Detector Current Design

Collaboration Setup
February 2023 : Elections
John Lejoie & Silvia Dalla Torre



Tracking:

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

PID:

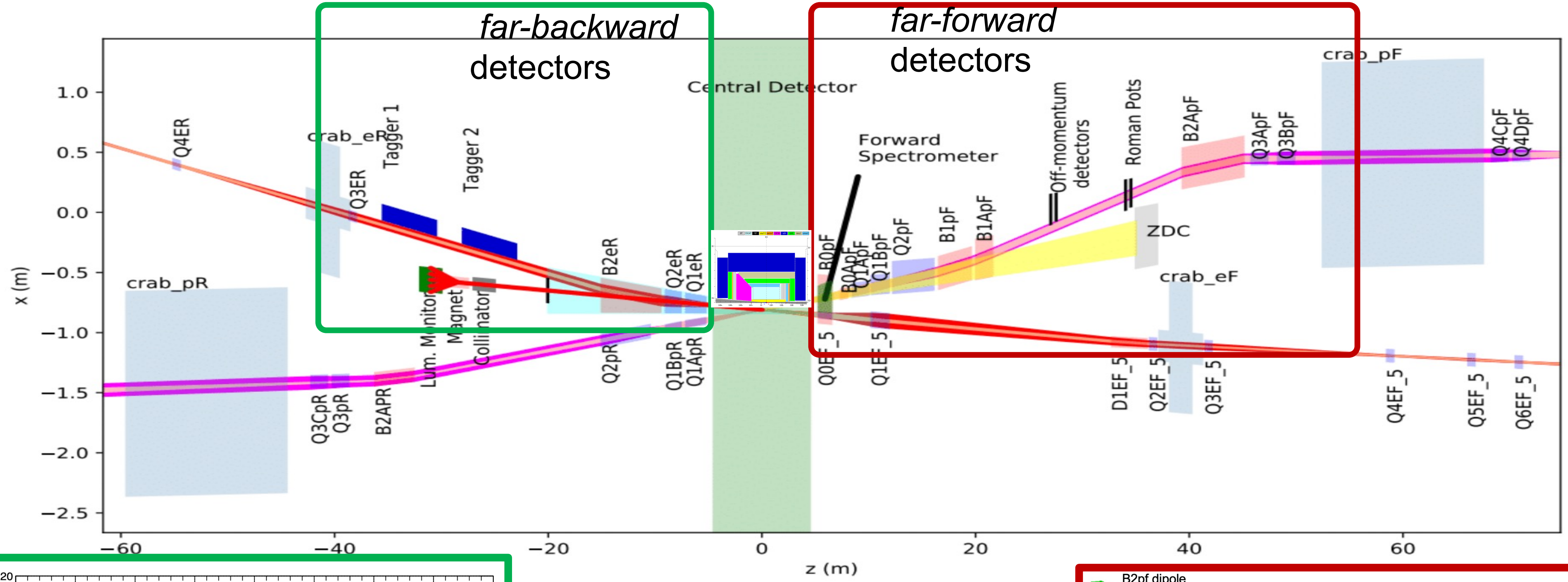
- hpDIRC
- mRICH/pfRICH
- dRICH
- AC-LGAD (~30ps TOF)

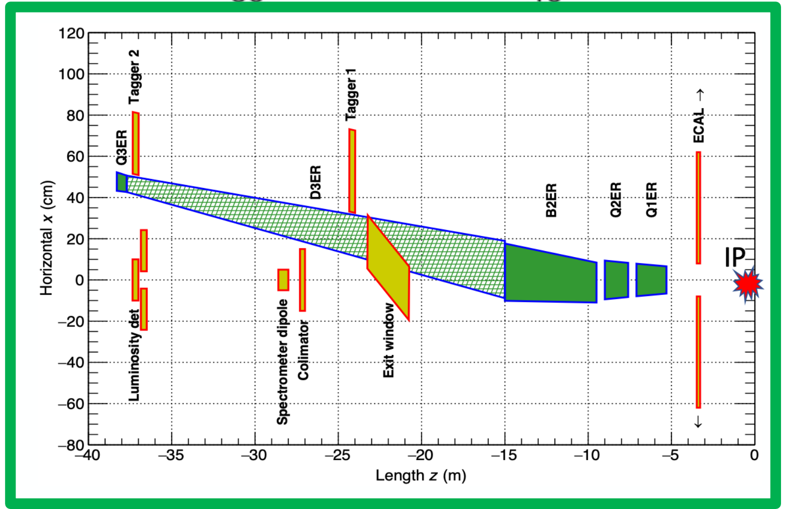
Calorimetry:

- SciGlass/Imaging Barrel EMCal
- PbWO4 EMCal in backward direction
- Finely segmented EMCal +HCal in forward direction
- Outer HCal (sPHENIX re-use)

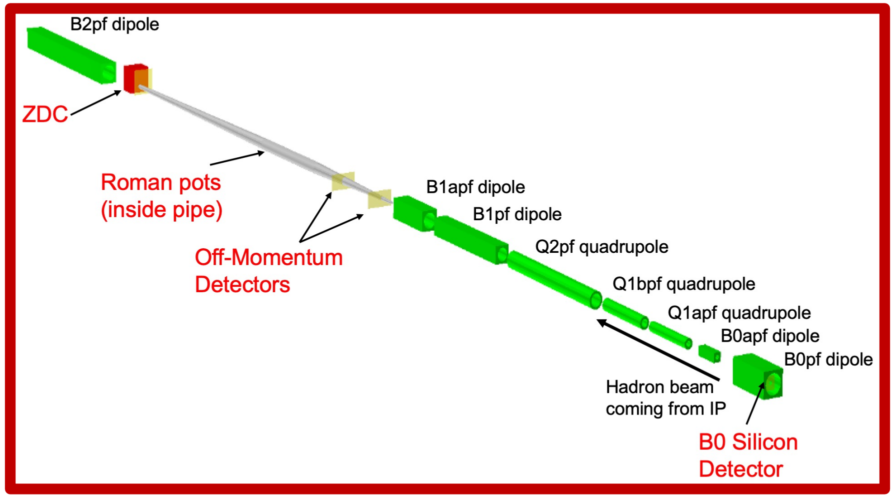
From John Lajoie @ Epiphany 2023

Reference Detector – Backward/Forward Detectors





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



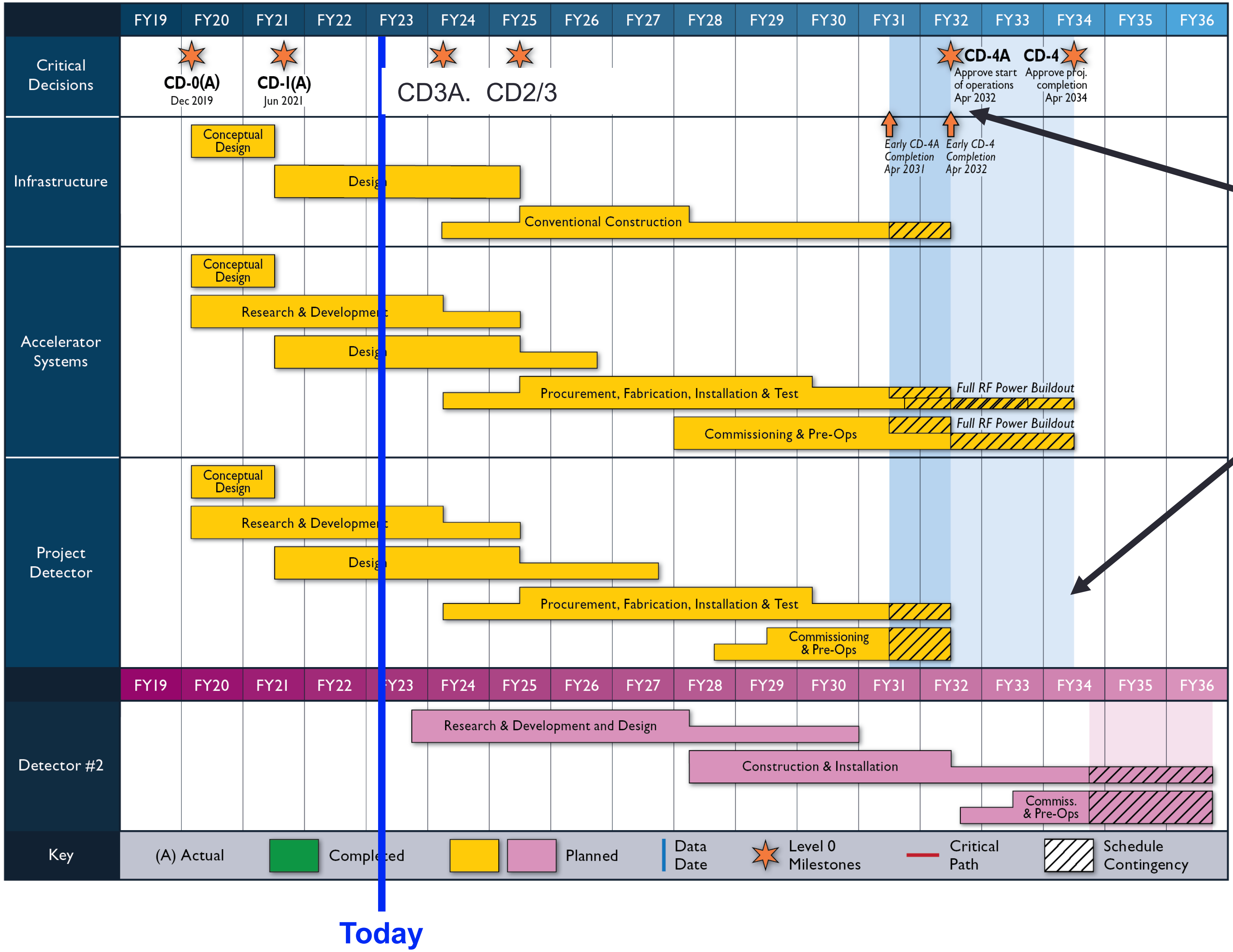
2^{nd} IR and 2^{nd} Detector

- Not in the EIC project
- Challenging parameters of EIC require careful attention to the post 2^{nd} IR era.
- No design decisions now should negate the possibility of the second IR and detector

Activities starting now: Led by EIC Users Group

- Kick off meeting at Temple University May 17-19, 2023
- What is a compelling physics case for the 2^{nd} IR?
- Balance between new physics and affirming important core physics (Detector 1)
- Complementary technologies ←→ generic detector R&D
- Need to get consensus amongst the EIC Users → acceptance in US NP community along with a buy-in from non-DOE sources (within and outside of the US)
- Proposals for a timeline and realization plans

Overall Schedule



CD4A early finish, collisions begin for machine tuning
Detector 1 needs to be ready to give feedback.

CD4 Machine delivers for physics
Detector 1 should be fully functional to start physics

2nd Detector and IR

- Current assumption realization trailing ~ 5 years behind Detector-1
- focus on complementary IR/physics & technologies

It is reasonable to assume that the EIC physics program will run for about 15 years starting 2035, and possibly extended by another ~5-10 years with detector upgrades.

So we are now in year 2050-2055.

You have 25-30 years to prepare for what comes next! Perfect timing….

Some personal thoughts/questions on muons – *unorganized but hopefully helpful…..*

Muons!

Historically extremely important… heavier sister/brother of electron

- many valuable complementary experiments have been performed in atomic, nuclear and particle physics
- 200 times larger mass ➔ significantly less radiation losses while acceleration ➔ hope to achieve much higher initial beam energy.
- On the flip side: it is unstable and has to be accelerated to high energy to be used in a collider experiment
- *Challenges here are the same as future Muon Collider! (Synergies)*

Some personal thoughts/questions on muons – *unorganized but hopefully helpful…..*

What is the optimal beam energy one would like to have? ➔ This is governed by the physics you pursue.

- Is LHeC center of mass energy a reasonable goal at this time?
- Science of LHeC starting from EIC (CM energy) has been given much thought over past decades…
  - could be a time saver
  - Community interested in this physics already exists

- LHeC is just a target, you should be flexible at this early stage including not *only* considering RHIC as a location of the future facility

Some personal thoughts/questions on muons – *unorganized but hopefully helpful…...*

Assuming you go in the direction of a LHeC:

- What luminosity is needed? What is enough luminosity?
- What are the schemes of muon production? Is there hope for enough luminosity?

- What sort of detector planning would one need? (very different than an EIC detector being considered)

Some personal thoughts/questions on muons –

unorganized but hopefully helpful…..

Can one imagine developing the muon beam of high enough energy to overcome at least some of the technical hurdles faced by muon collider enthusiasts? i.e. Can it (μIC) be viewed as an important R&D milestone for HEP (μ+ μ- collider) while still resulting in a significant physics program? ➔ this combination seems very potent to me.

Collaboration between **accelerator scientists** working on muon collider should look at this critically. **Experimental nuclear and particle** physicists should decide whether the resulting collisions are reasonable and physics communities (**theorists included**) from both sides should opine if this program is compelling.

Final thoughts: on timeline…. (are you ahead of the curve?)

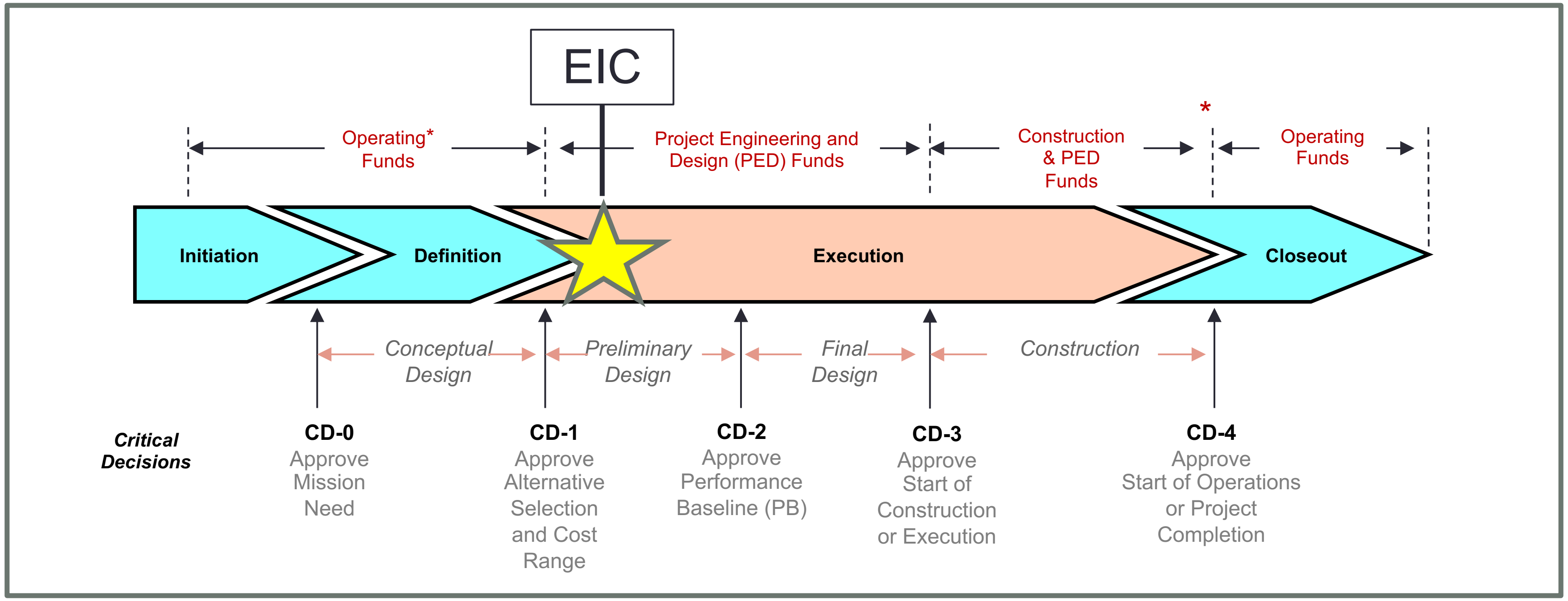
- EIC was being discussed (as polarized HERA or eRHIC) from 1995/6 in various small workshops until 1999/2000 when a dedicated workshops were held at Yale and RBRC. (Other options at lower energy @IUCF, MIT and GSI/Fair).
- Groups came came together from 2000-2001 @ MIT – first eRHIC white paper followed by multiple WS at RBRC/Indiana/MIT and eRHIC got its first mention in the LRP 2002. ➔ **[5-7 years since conception]**
- It went through one more LRP 2007 (strong mention, recommended significant accelerator and detector R&D) before it was recommended in LRP 2015/6 ➔ **[20 years since conception].**
- Going by currently planned timeline expected date of CD3 2025 [30 years sc]
- And CD4 – operations will start in ~2033 ➔ **[~ 40 years since conception or ~30 years since first mention in the LRP]**

The timeline is not to discourage you but infact challenge you. If the science is good, it needs to be done, and will get done.

My advice is to put your head down and develop a strong:

- Physics case and a collaboration
- Connection with HEP accelerator scientists to develop a ~300-500 GeV muon beam – see if it is useful towards their ultimate goal
- Accelerator **R&D** towards a TeV muon beam **coupled** with a strong **physics motivation** could be be a win-win for everyone

DOE Project Phases



Formal Process of DOE Gateway Reviews

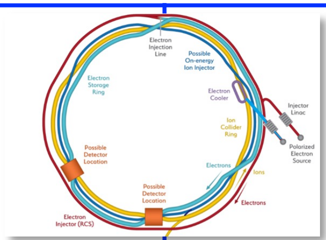
- CD-0, Mission Need ✓
- CD-1, Alternative Selection and Cost Range ✓

Partner and collaboration engagement needed to establish the baseline

- CD-2, Performance Baseline
- CD-3a, Long Lead Procurement

Complementarity for 1st-IR & 2nd-IR

	1st IR (IP-6)	2nd IR (IP-8)
Geometry:	ring inside to outside tunnel and assembly hall are larger Tunnel: ⃠ 7m +/- 140m	ring outside to inside tunnel and assembly hall are smaller Tunnel: ⃠ 6.3m to 60m then 5.3m
Crossing Angle:	25 mrad	35 mrad secondary focus
	different blind spots different forward detectors and acceptances different acceptance of central detector	
Luminosity:	optimize Doublet focusing FDD vs. FDF → impact of far forward p_T acceptance	
Experiment:	1.7-2.0 Tesla or 3(?) Tesla different subdetector technologies	



Perhaps other intersections with LQCD?

Physics @ the US EIC beyond the EIC's core science

Of HEP/LHC-HI interest to Snowmass 2021 (EF 05, 06, and 07 and possibly also EF 04)

New Studies with proton or neutron target:

- 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

Physics with nucleons and nuclear targets:

- Quark Exotica: 4,5,6 quark systems…? Much interest after recent **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 : novel new observables, energy variability
  - Entanglement, entropy, connections to fragmentation, hadronization and confinement

Precision electroweak and BSM physics:

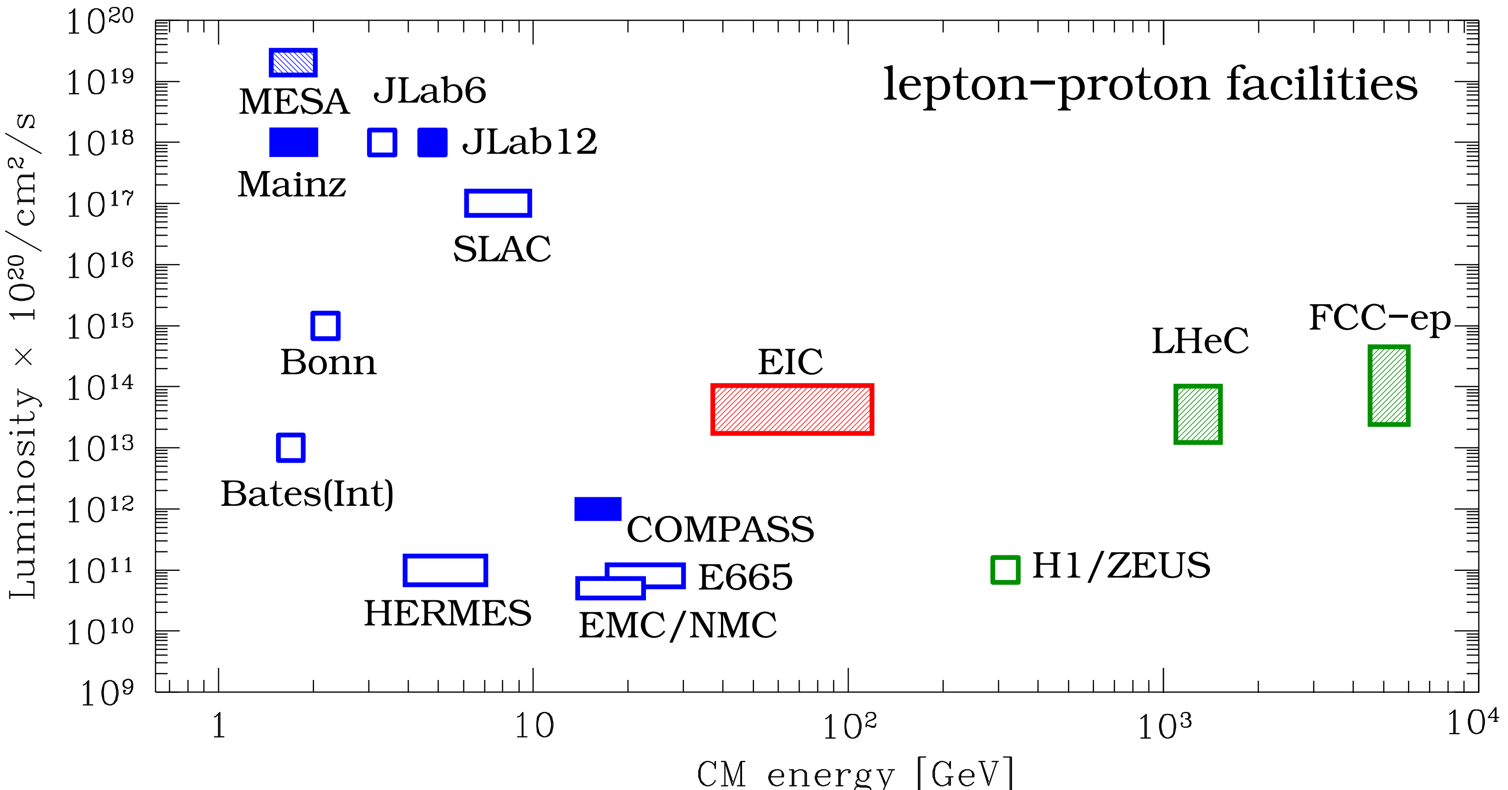
- Electroweak physics & searches beyond the SM: Parity, charge symmetry, lepton flavor violation
- LHC-EIC Synergies & complementarity

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

EIC's versatility, resolving power and intensity (luminosity) open new windows of opportunity to address some of the crucial and fundamental scientific questions in particle physics. The paper summarizes the EIC physics from the perspective of the HEP community participating in Snowmass 2021

- Beyond the Standard Model Physics at the EIC
- Tomography (1,3,5 d PDFs) of Hadrons and Nuclei at the EIC
- Jets at EIC
- Heavy Flavors at EIC
- Small-x Physics at the EIC

- High luminosity wide CM range
- Polarized e, p, and ion beams
- All nuclei



Towards high luminosity: optimizing a multidimensional parameter space

- Luminosity will always benefit from large beam currents
  ➔ maximize beam currents

- EIC luminosity benefits from reducing hadron emittance by “cooling” to maximize luminosity as normalized emittance from source is too large

- Minimizing number of bunches (1060, still a large number) will
  - Reduce demand on beam cooling (since cooling is hard)
  - Is detector friendly because bunch spacing is relatively large (12 ns)
  - Results in smaller beam divergence at IP ➔ helps with p_T acceptance