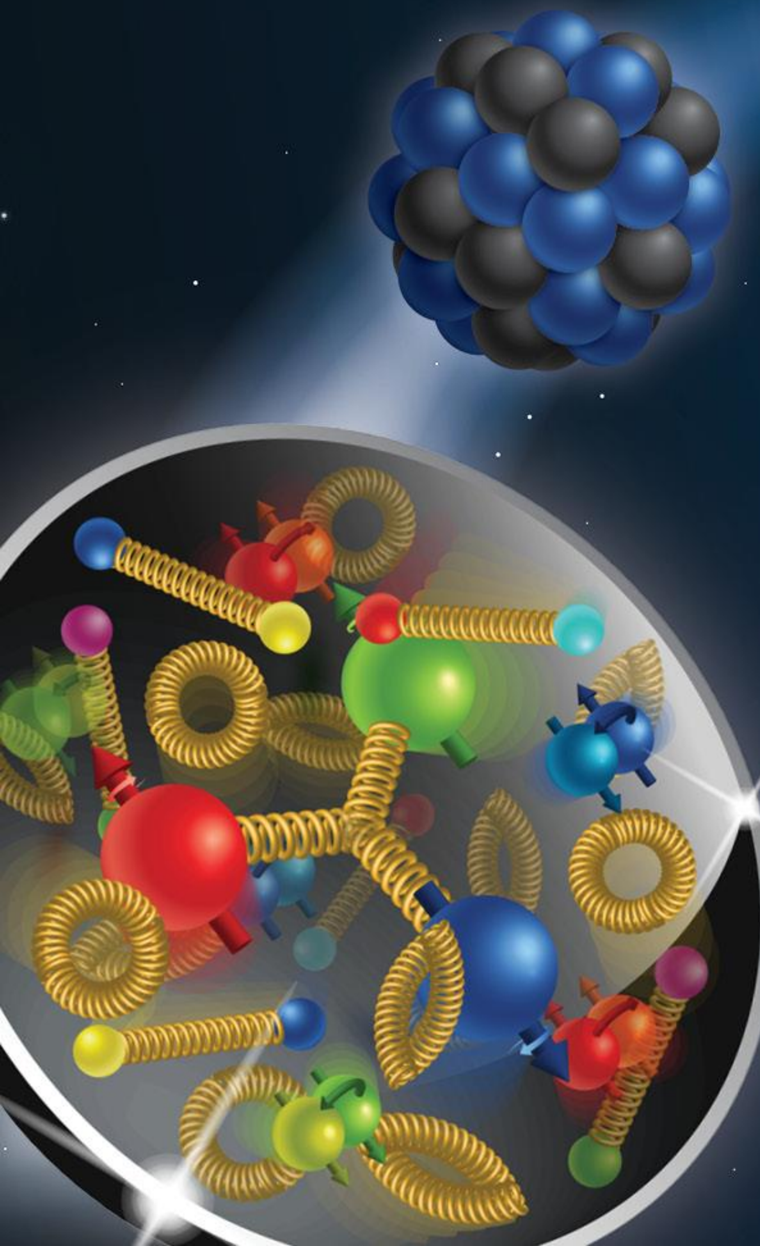


From RHIC to the EIC

Berndt Mueller (BNL)

QEIC Workshop

Mumbai, India

January 4, 2020

Electron Ion Collider – EIC at BNL

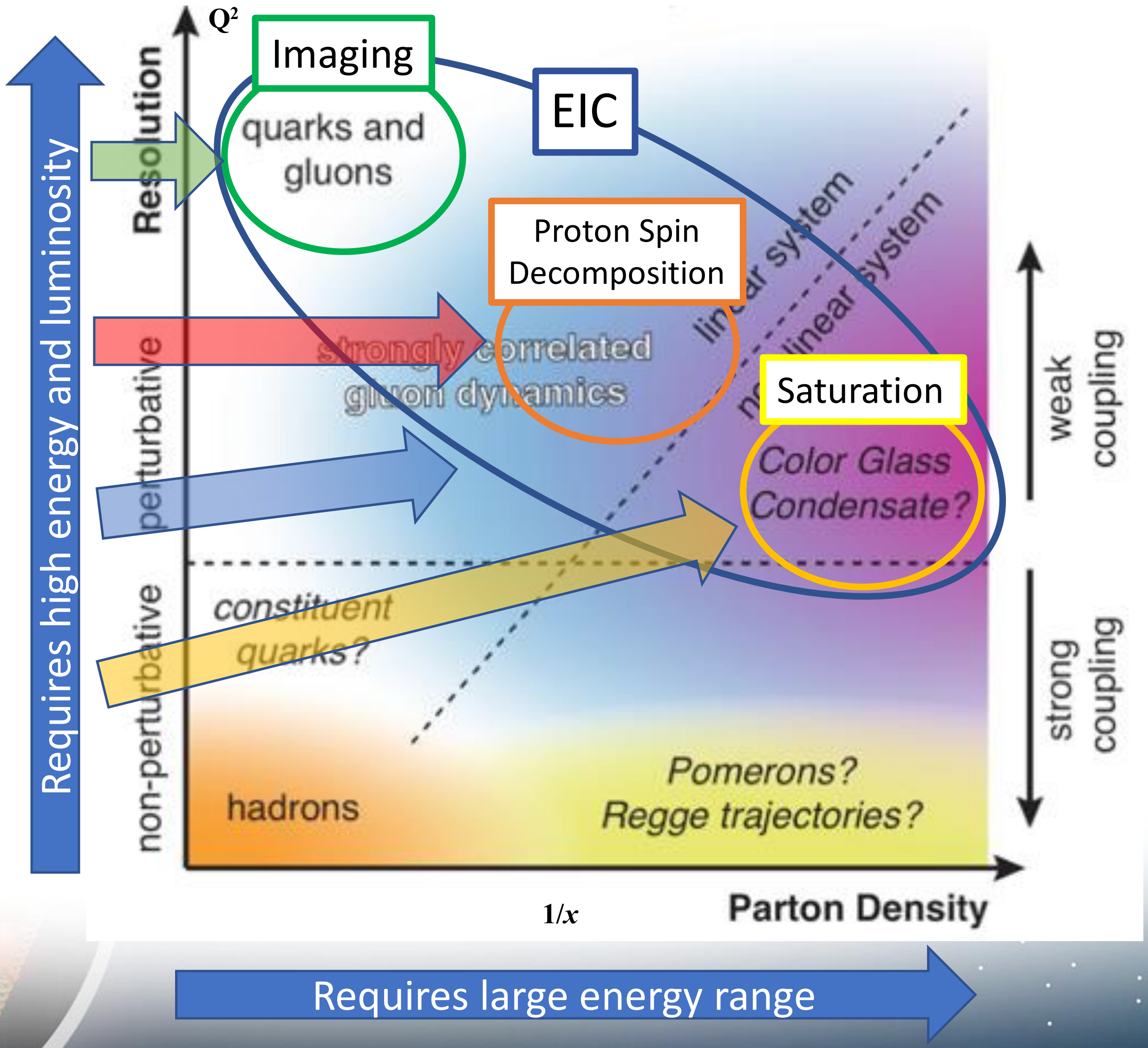
BROOKHAVEN NATIONAL LABORATORY

U.S. DEPARTMENT OF ENERGY | Office of Science

EIC Science

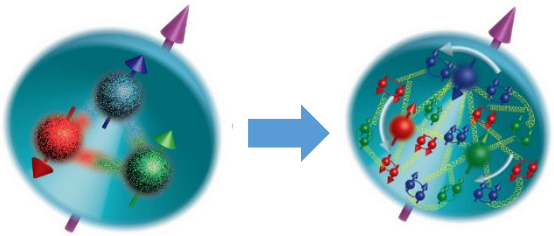
Answering four deep questions

- How do quarks and gluons form nuclei?
- How does the proton get its spin?
- How does the proton get its mass?
- What is the nature of dense gluon matter?

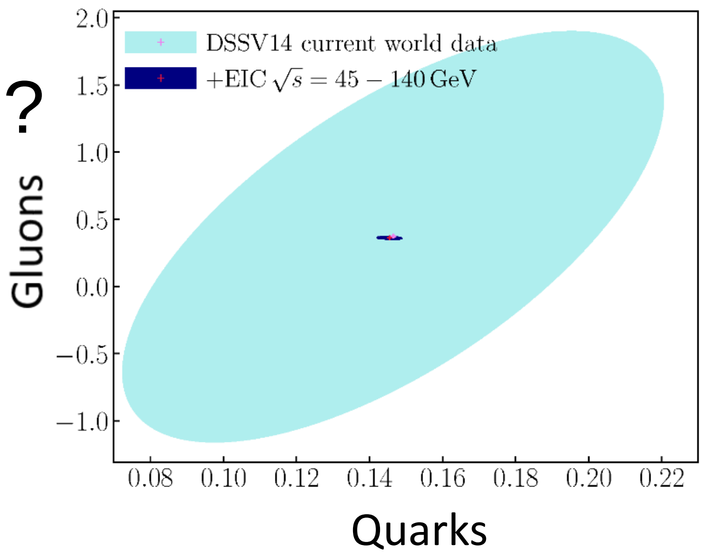


EIC science questions (1)

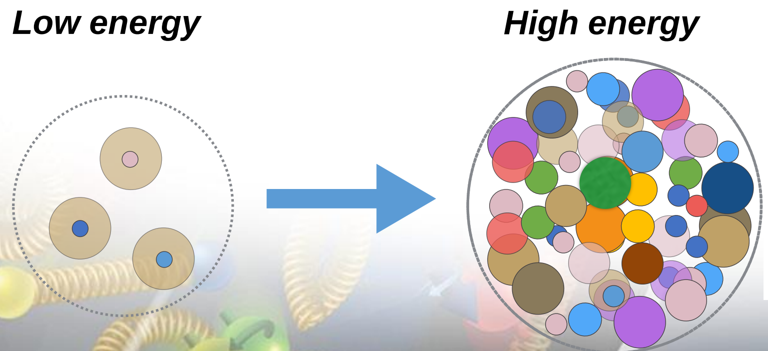
- How does the proton get its spin?

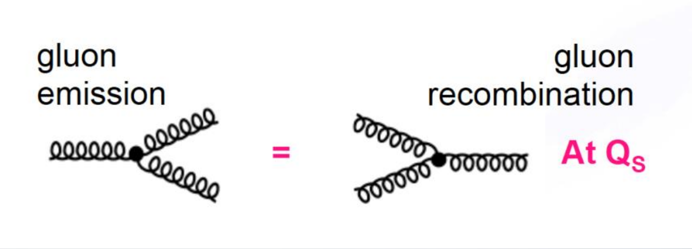


High E_{CM} for low momentum fraction '*x*'



- What is the nature of dense gluon matter?





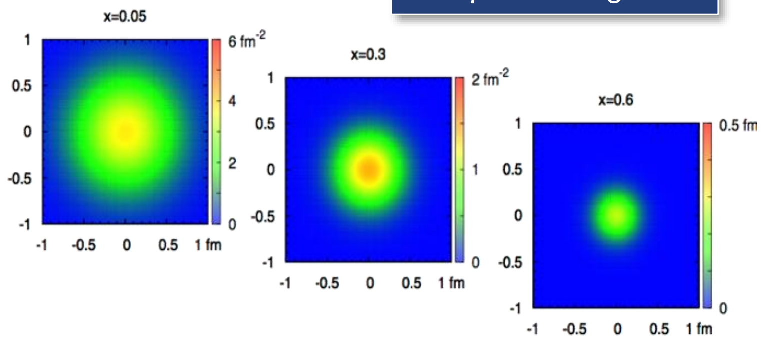
Onset scales with $(A/x)^{1/3}$

EIC science questions (2)

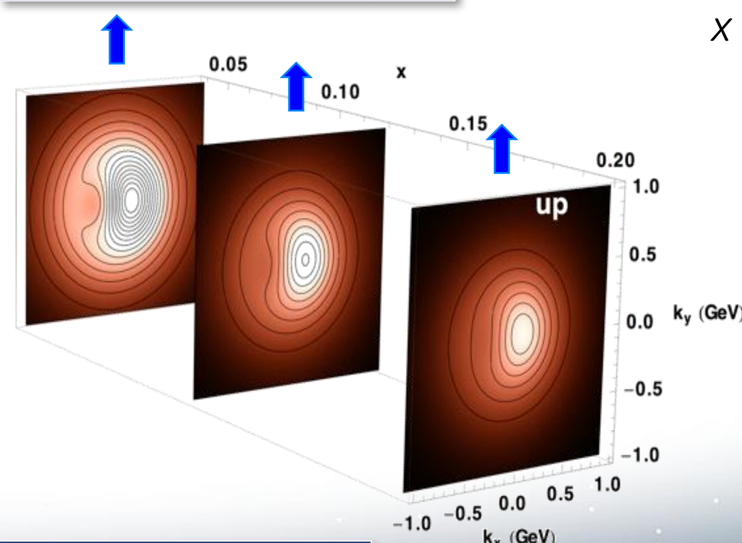
- How does the proton get its mass?
  - Requires detailed understanding of QCD dynamics
- How do quarks and gluons form nucleons and nuclei?

The EIC will answer these questions!

Spatial images



Momentum space images



Tomographic Imaging

EIC Requirements

The EIC science case drives the technical requirements for the EIC, the Key Performance Parameters (KPPs), which were developed by NSAC and endorsed in the NAS Study of the EIC Science Case:

- **Highly polarized (70%) electron and nucleon beams**
- **Ion beams from deuteron to the heaviest stable nuclei**
- **Variable center of mass energies from 20 to 100 GeV, upgradable to 140 GeV**
- **High luminosity of 10^{33} - 10^{34} $cm^{-2}s^{-1}$**
- **Possibility of having more than one interaction region.**

The BNL EIC design achieves these goals, without the need for an energy upgrade, with only minor modifications to RHIC by adding an electron accelerator and storage ring in the RHIC tunnel.

Relevance of the KMPs

- **High polarization:** Required for studies of the origins of the spin of proton and neutron
- **Heavy ion beams:** Required for the study of gluons at high densities
- **CM energies up to 140 GeV:** Full energy range required for maximum discovery potential (gluon density grows with CM energy)
- **High luminosity (10^{34} $cm^{-2}s^{-1}$):** Required for efficient imaging of nucleon structure by exclusive measurements
- **Possibly more than one interaction region:** Desirable to efficiently perform measurements that require different detector optimization, to provide experimental checks, and to accommodate a large user community

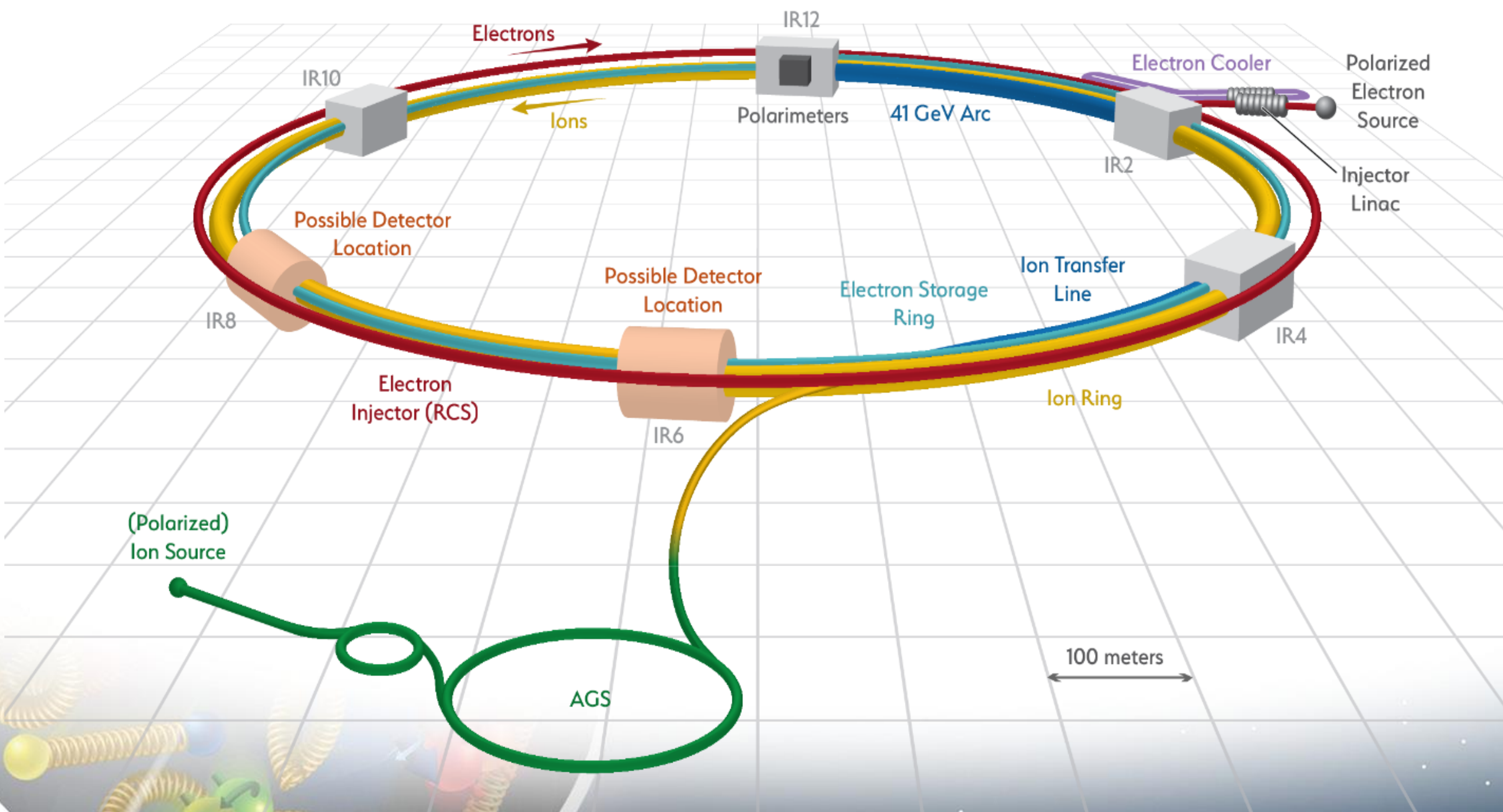
BNL's EIC Design

The BNL EIC design

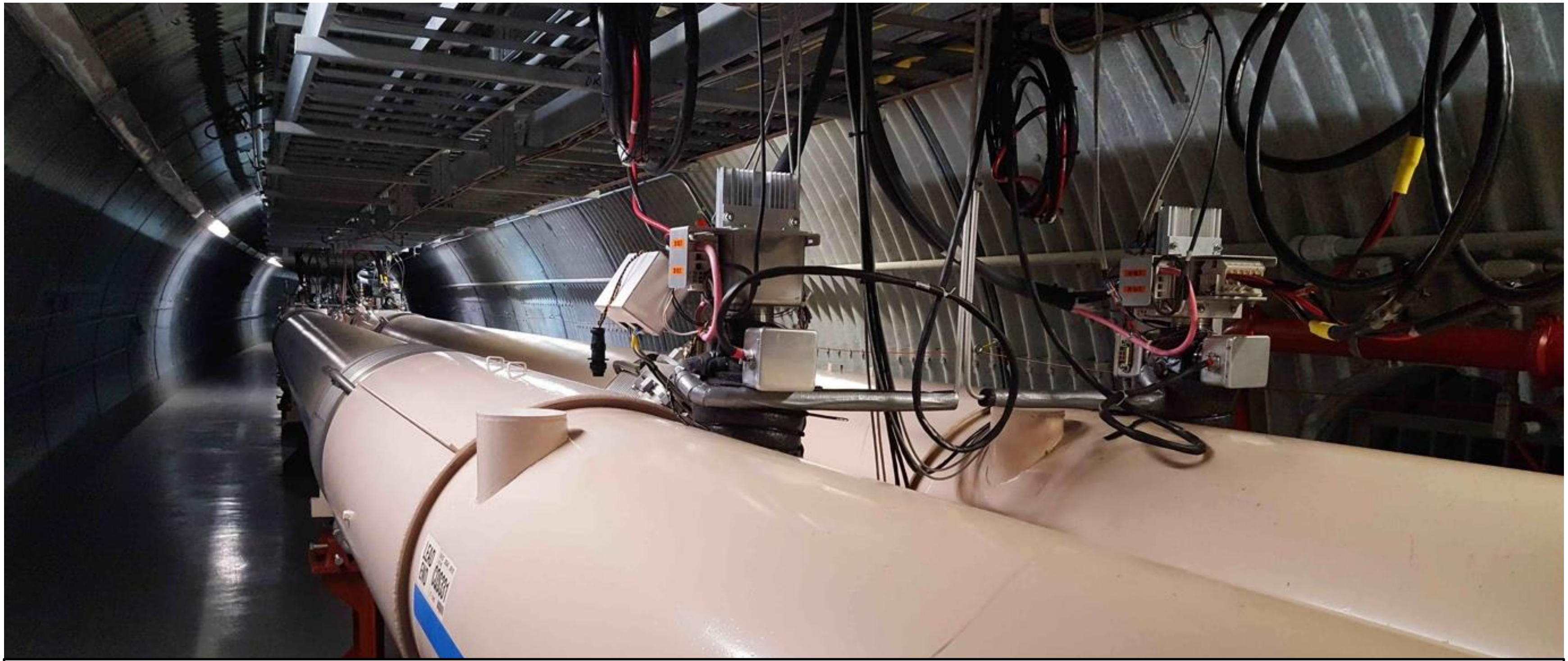
- **Meets all required machine parameters without the need of a future energy upgrade**
  - NSAC requirements to carry out the science are included in base design
- **Is cost effective – repurposes RHIC**
  - RHIC complex in excellent condition
  - Accelerator at peak performance
  - Satisfies hadron beam requirements for EIC
- **Requires minimal new civil construction**
  - Only utilities, utility buildings, and access roads needed
- **Is low-risk**
  - Proven accelerator science and technology
- **Is versatile and flexible**
  - Can optimize luminosity for the science
  - Staging possible with physics running

EIC @ BNL

The design aims at the construction of an Electron-Ion-Collider (eRHIC) leveraging the existing RHIC accelerator complex and its infrastructure.

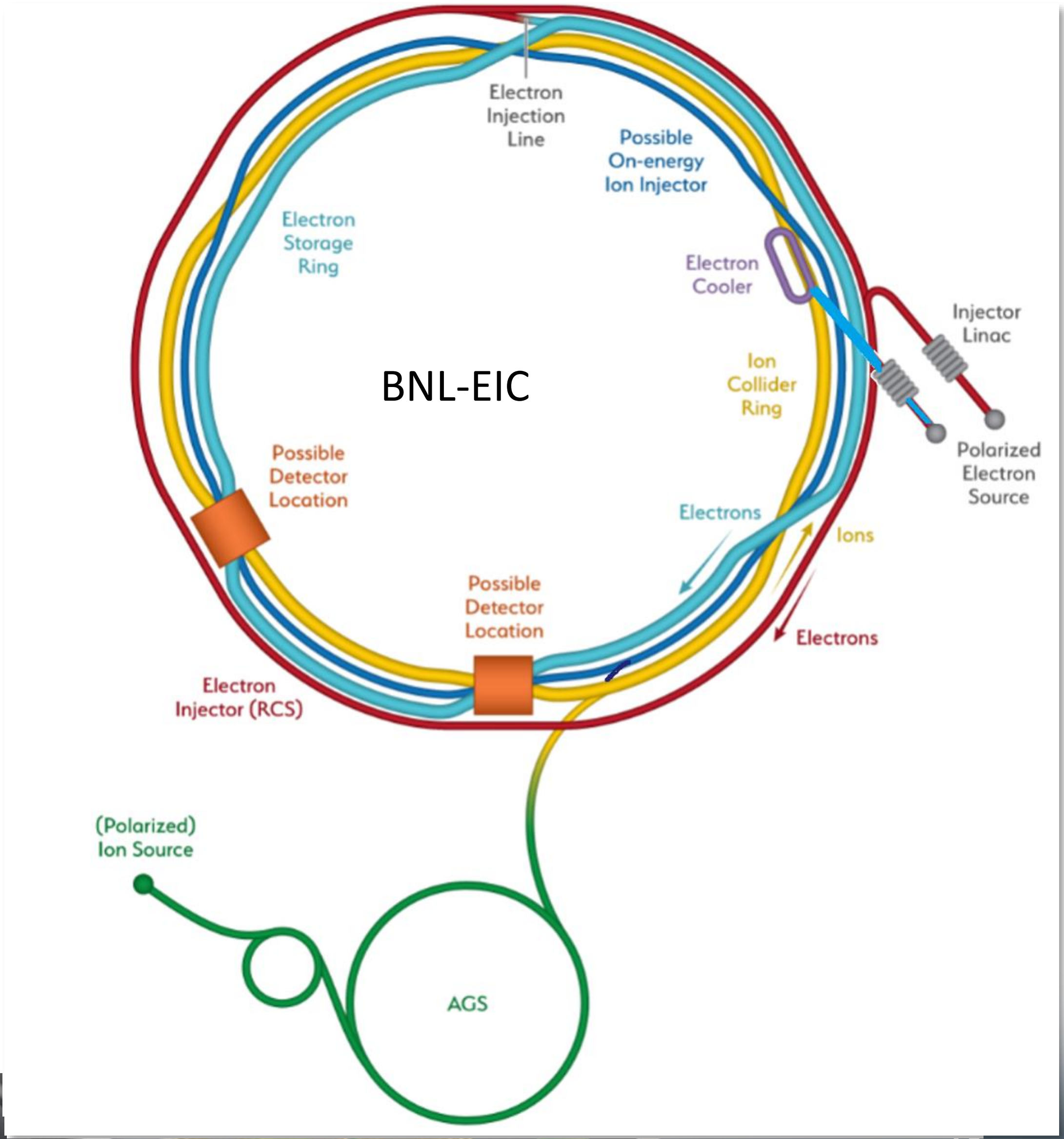


Building on RHIC

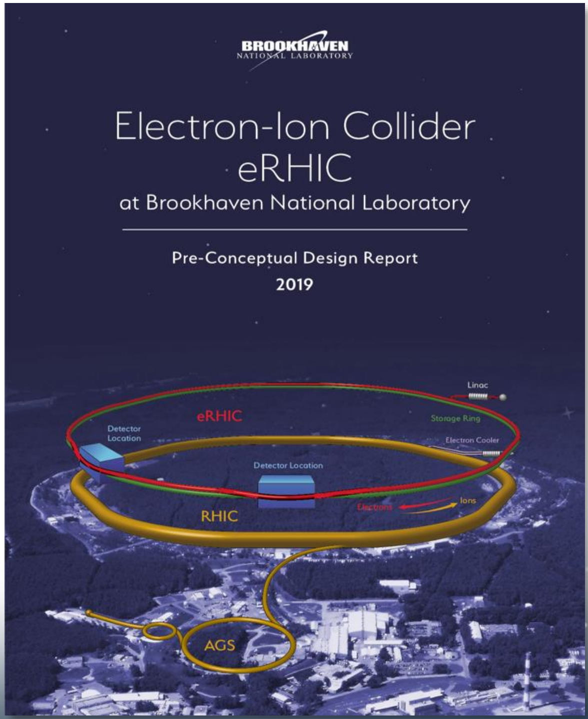


- High-performance hadron collider (the only one in the U.S.) with a superb record of scientific results, transformative discoveries, S&T innovations.
- Continuously upgraded, infrastructure with a history of major performance improvements (>40x the luminosity of the original design)
- Established portfolio of accelerator-based applications (isotopes, NSRL, …)

How RHIC is transformed into an EIC

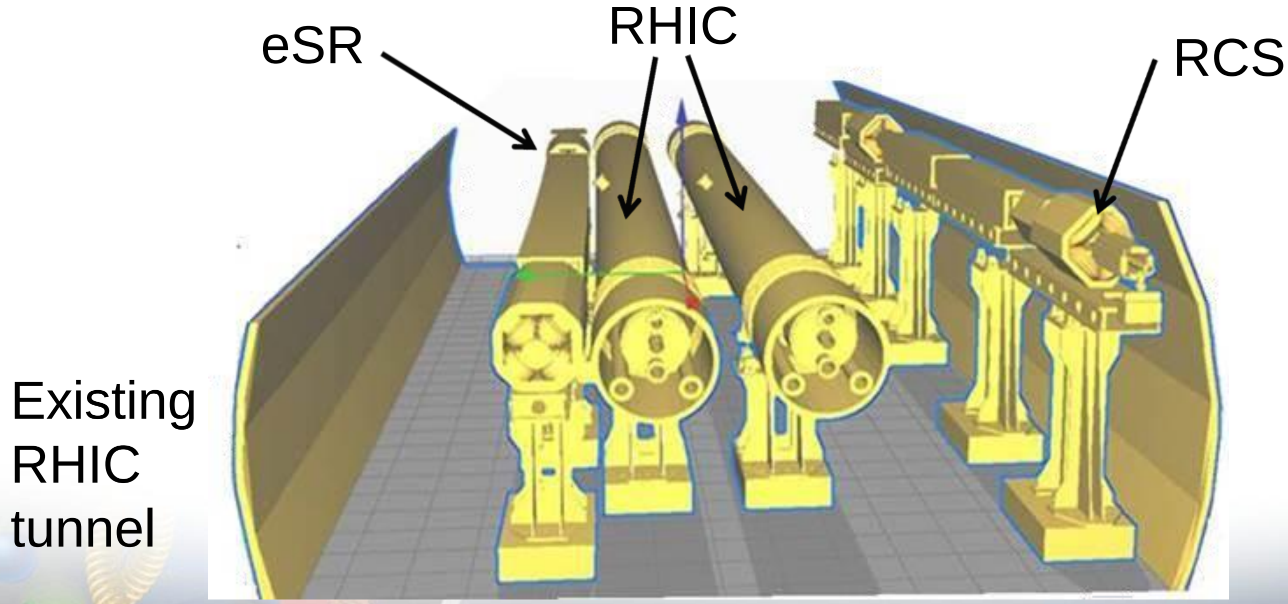


- Hadron Storage Ring
- Electron Storage Ring
- Electron Injector Synchrotron
- Possible on-energy Hadron injector ring
- Hadron injector complex



Major additions fit in RHIC tunnel

- Rapid Cycling Synchrotron (RCS) for electrons and Electron Storage Ring (eSR) fit into the existing RHIC tunnel
- Two detector halls available for interaction regions and detectors; one was included in independent cost review

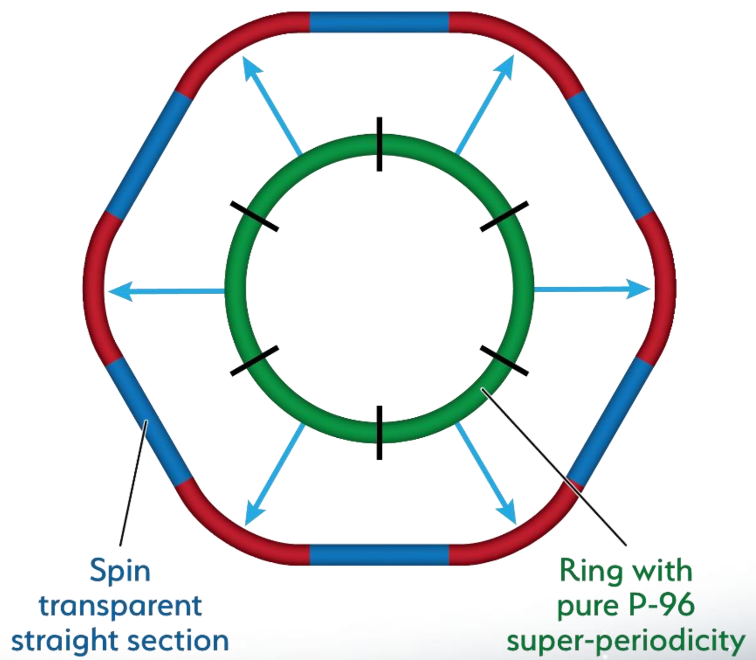


Robust, mature design

- EIC based on established concepts
  - storage ring collider
  - unequal species collision concepts taken from experiences at HERA, B-Factories, and RHIC
- Design
  - parameters are ambitious, but demonstrated at other machines
  - design choices based on studies of alternative solutions
  - studies of lattice sensitivity to imperfections confirm robust solutions
- Technology
  - implementation based on established technology
  - state-of-the-art hardware development by extensive R&D program
- Few challenges (e.g. strong hadron cooling) are backed up by more conservative alternatives that compare well in terms of cost and performance

Electron beam polarization

- 85% polarized electron source injects into 18 GeV, 1-2 Hz Rapid Cycling Synchrotron (RCS) using conventional magnets
- Highly symmetrical RCS avoids depolarization during acceleration
- Residual depolarization effects in the RCS due to deviations from ideal symmetry will be corrected with partial Siberian snakes
- Frequent injection of fresh bunches into storage ring maintains >80% polarization for all spin orientations for the duration of the store



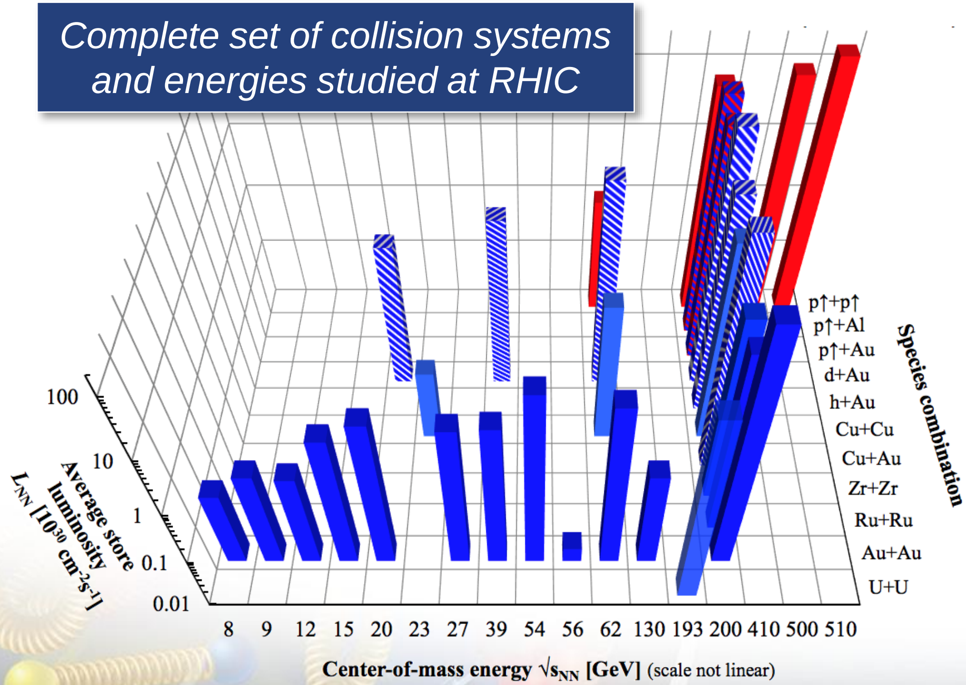
Light ion beam polarization

- Existing polarized proton source delivers protons with >80% polarization
- New polarized ^{3}He source (developed with MIT) has demonstrated 85% polarization
- Protons stored in RHIC have reached 60% polarization
- 80% polarization of protons, deuterons, and ^{3}He in RHIC storage ring will be achieved by:
  - Adding four Siberian snakes to the RHIC ring
  - Adding stronger snakes and skew quadrupoles to the AGS
  - Introducing a tune jump for polarized deuterons in RHIC

Full range of ion species

- RHIC accelerates ions from protons, deuterons, ^{3}He to Au and ^{238}U over a wide range of energies. All will be available at the EIC.
- Enabled by two decades of technological innovation

Complete set of collision systems and energies studied at RHIC



The electron beam ion source EBIS can produce virtually any desired ion species including polarized ^{3}He

Full range of beam energies

- No energy upgrade needed
- Protons up to 275 GeV
  - Existing superconducting magnet yellow ring with EIC interaction region magnets allows for protons up to 275 GeV
- Electrons up to 18 GeV
  - 18 GeV electron storage ring installed in the RHIC tunnel is readily achievable with
    - large ring circumference of 3.8 km
    - well established superconducting RF technology
- Electron energy range (2.5–18 GeV) and proton energy range (41–275 GeV) combine to make full EIC CM energy range accessible (20–140 GeV)

BNL design: Full luminosity

- BNL EIC design achieves full peak luminosity with:
  - **Bunch charges** $N_e \leq 1.7 \cdot 10^{11}$, $N_p \leq 0.7 \cdot 10^{11}$
  - **Stored bunches**, n_b=1160, requiring:
    - crossing angle collision geometry (25 mrad)
    - e-beam current limited by installed RF power compensating for synchrotron radiation losses (<10 MW)
  - **Beam size** at interaction point (7 μm)
- Beam size at final focus can be maintained by either
  - Option A: strong hadron cooling to prevent emittance growth due to intra-beam scattering

  or

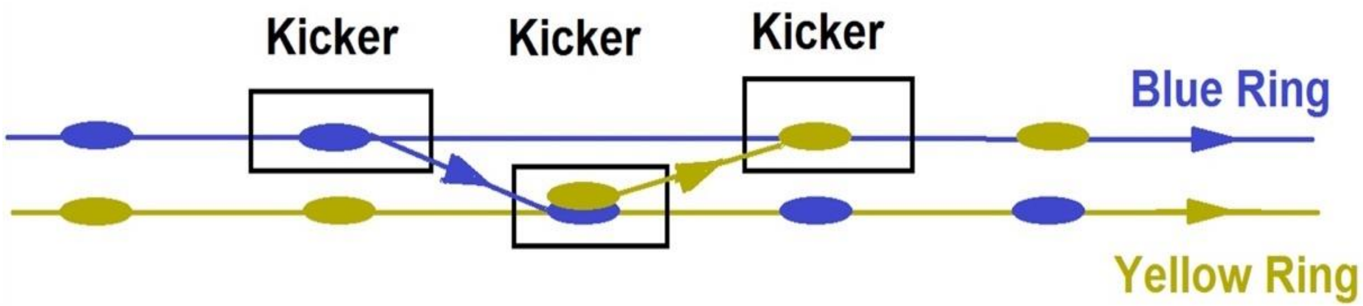
  - Option B: regular on-energy hadron replacement
- Selection between these two baseline alternatives by CD-1

Average Luminosity: Option A

- Long, uniform beam stores optimal for precision measurements
- Peak luminosity maintained over many hours by hadron cooling
- Heavy ions: existing stochastic cooling system preserves low beam emittance
- Protons: average luminosity is maximized by strong cooling
  - Coherent electron Cooling (CeC) using an intense electron beam provides high-bandwidth amplification
  - Conceptually designed using only existing technologies
  - Validated by simulations
  - Proof-of-Principle experiment under way at RHIC

Average Luminosity: Option B

- Low-risk alternative to CeC
  - Regular on-energy injections using existing blue RHIC ring restore average luminosity to >90% of peak luminosity
  - Moderate emittance growth requires replacing the stored proton beam only once per hour
  - Transfer takes only 13 μs, preserves the total charge stored in both rings, avoids transient injection effects

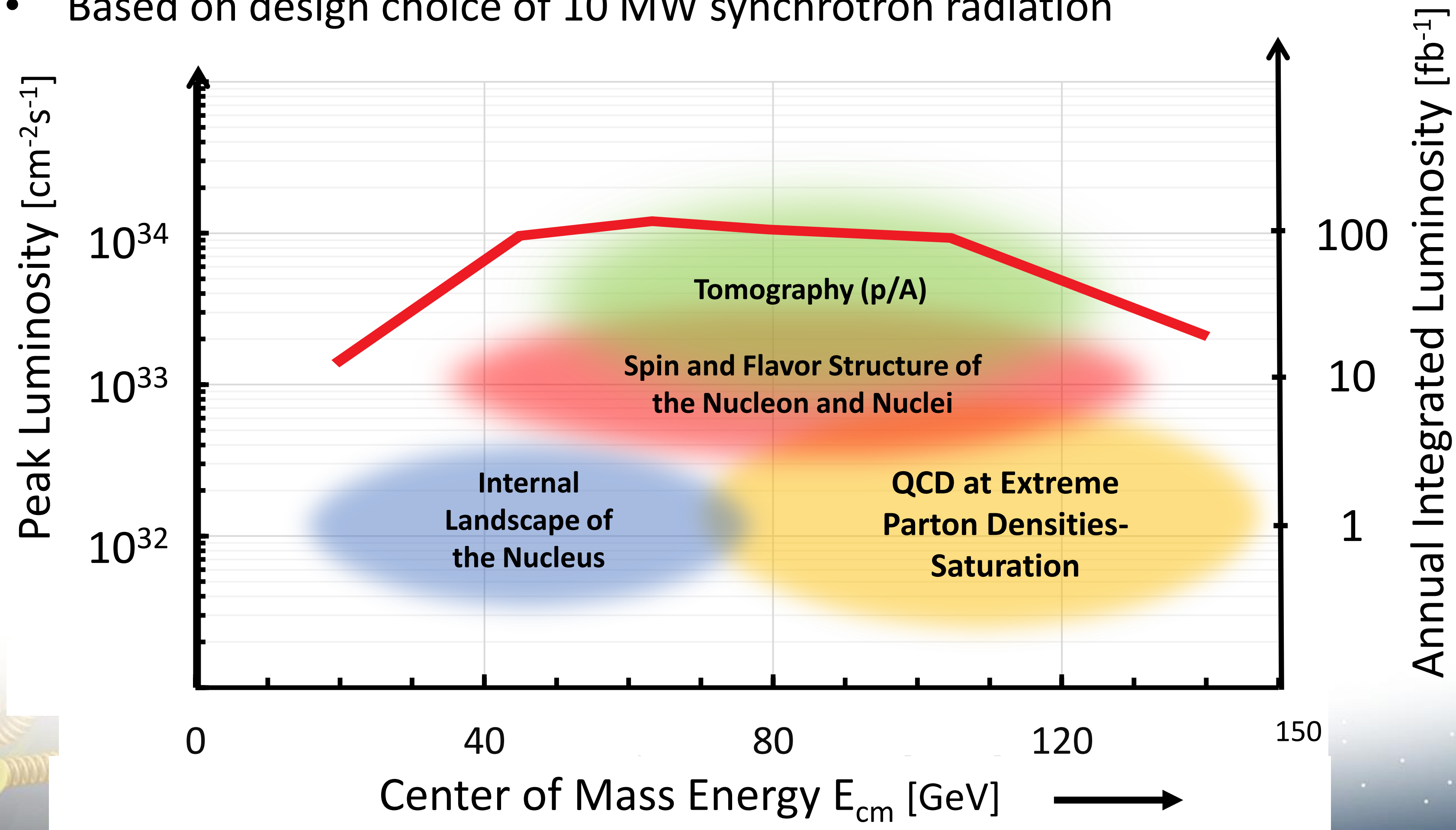


- Cost neutral to Option A, but less attractive for experiments, which prefer longer stores

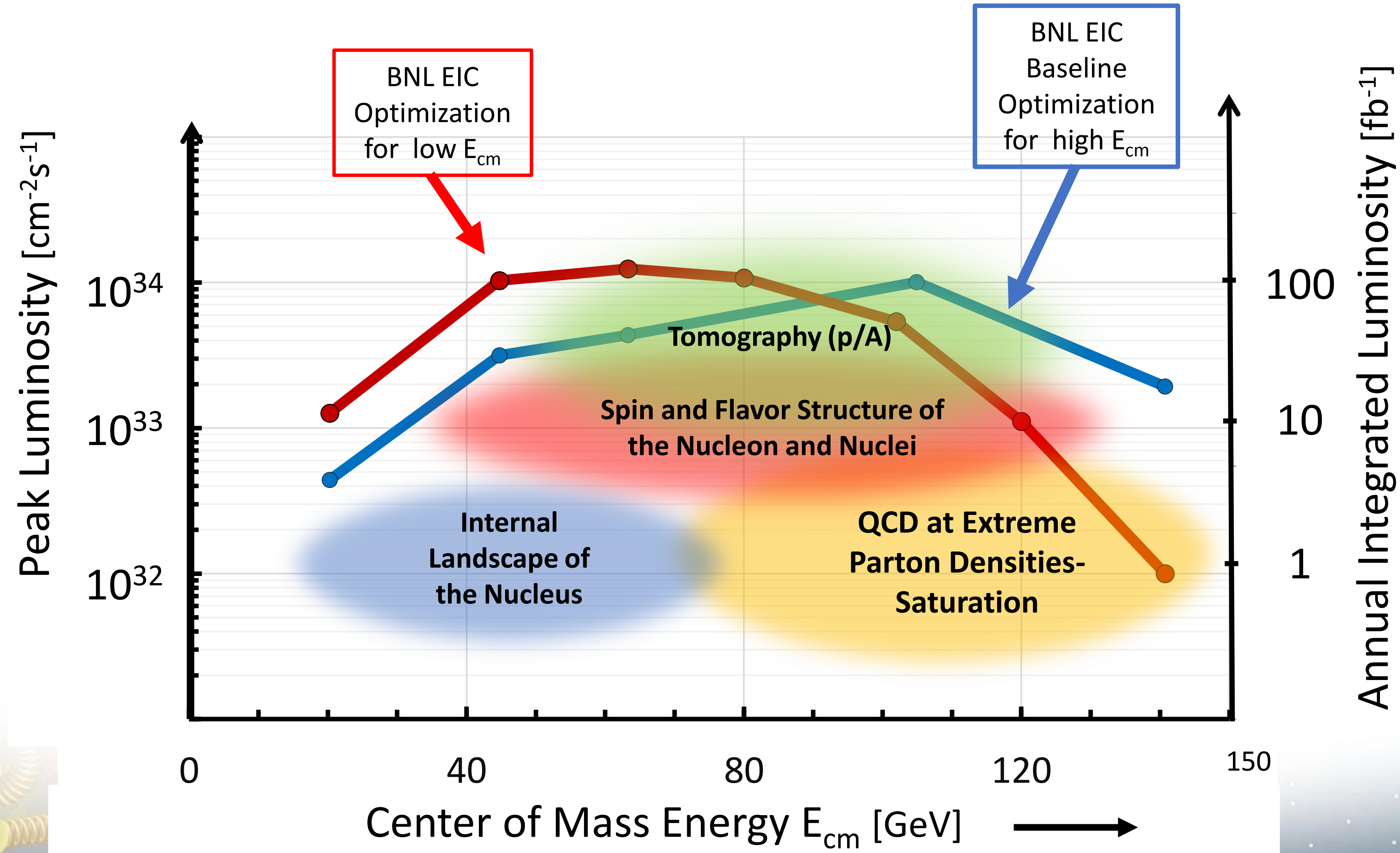
BNL EIC covers full science range

Collider capability envelope

- Based on design choice of 10 MW synchrotron radiation

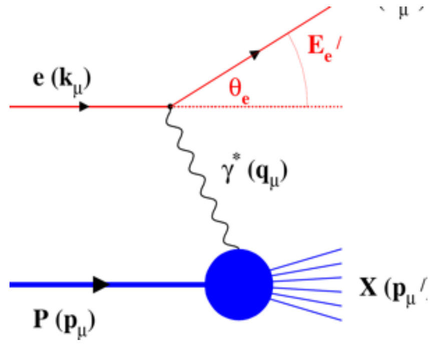


BNL EIC can be optimized for science



EIC Detectors

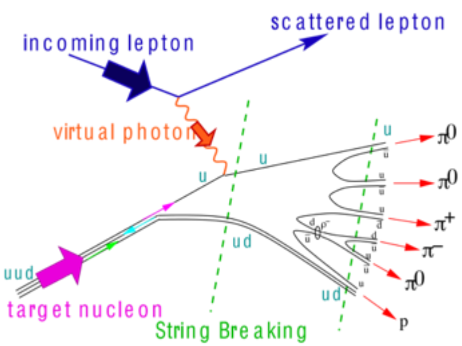
EIC Measurement Categories



Inclusive DIS

- Fine multi-dimensional binning
  → x, Q^2

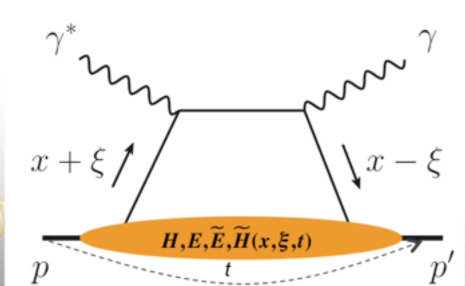
→ Reach to lowest x, Q^2 impacts distance of machine elements to IP



Semi-inclusive processes

- 5-dimensional binning
  → x, Q^2, z, p_T, ϕ

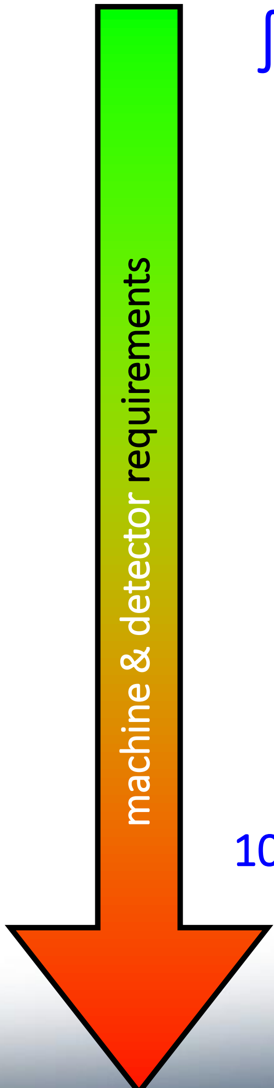
⟶ Needs to reach p_T > 1 GeV



Exclusive processes

- 4-dimensional binning
  → x, Q^2, t, θ, low proton p_T

→ Strong impact on IR design
→ Outside main detector elements



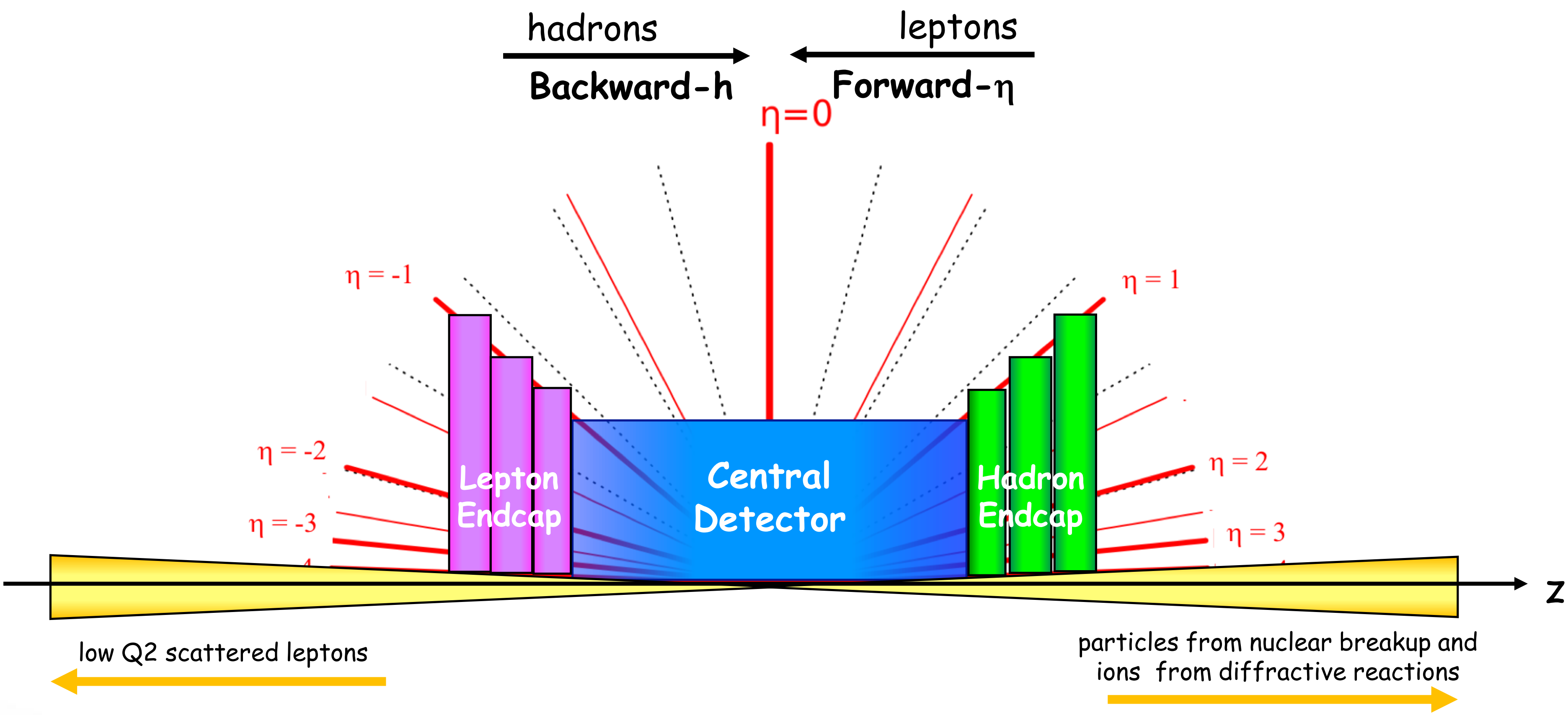
∫Ldt

1 fb^{-1}

10 fb^{-1}

10 - 100 fb^{-1}

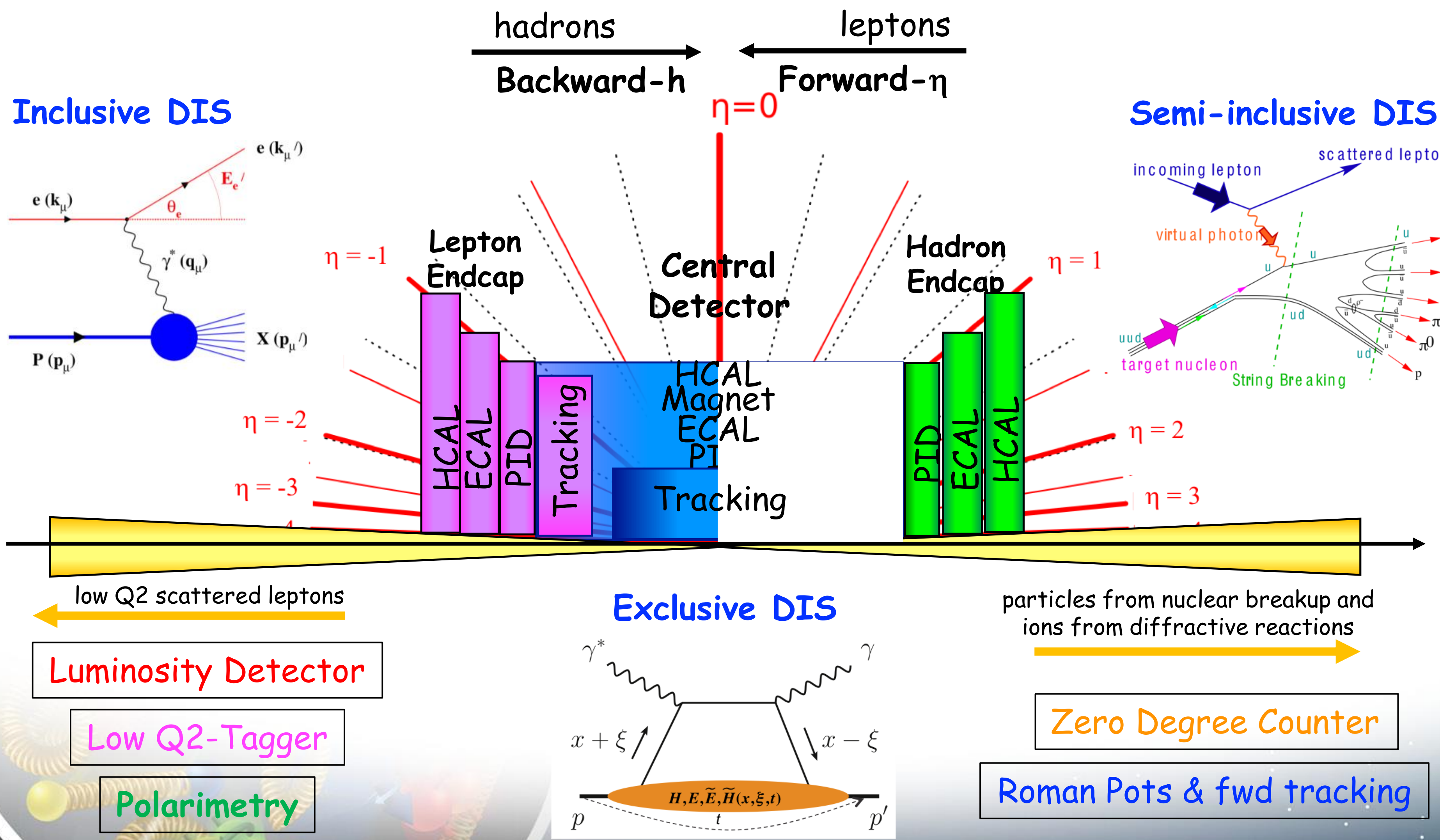
EIC General Detector Principles



For a high luminosity collider like the EIC control of systematics needs to be integrated into the detector from the start

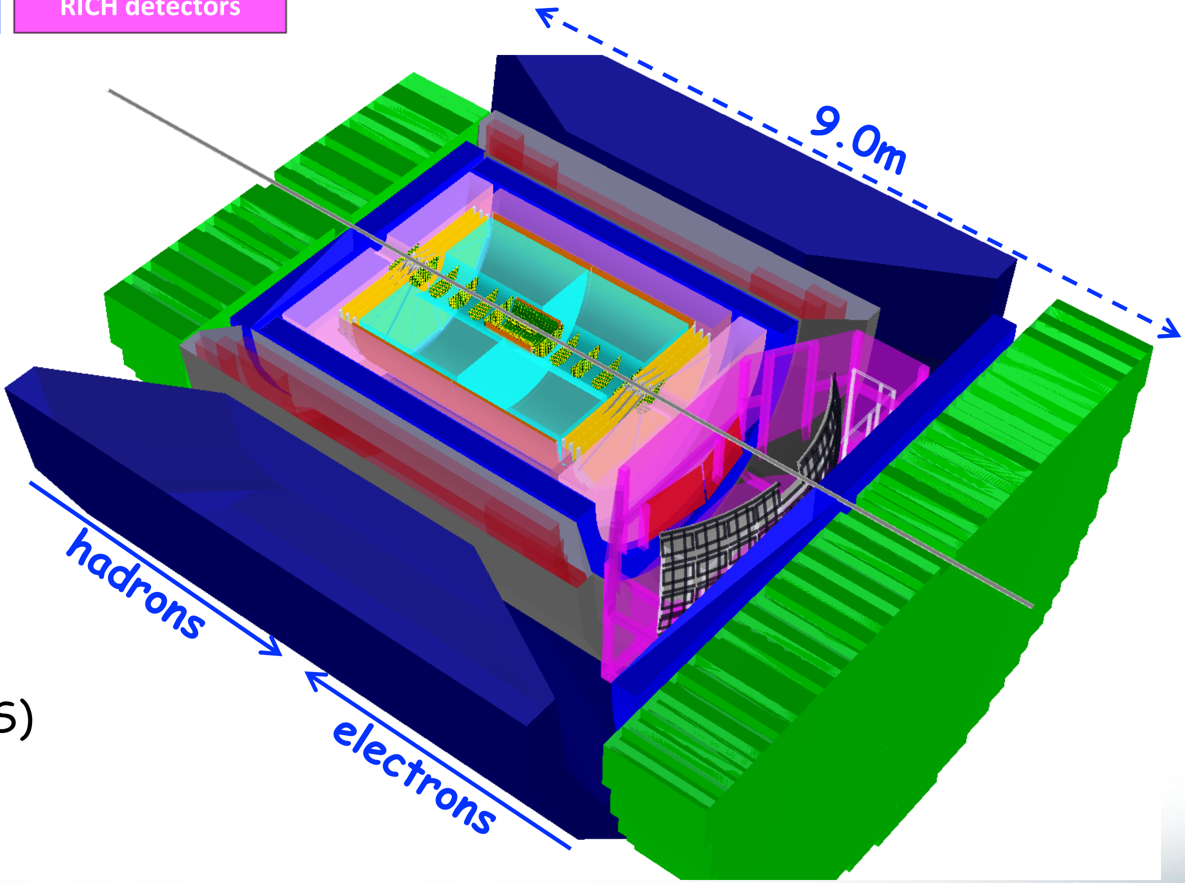
Accelerator, interaction region, and detector must be designed together

EIC Detector Functions



EIC Detector (Schematic)

Hadronic calorimeters | e/m calorimeters | RICH detectors



Hadron PID:

$-1<\eta<1$: RICH/DIRC + TPC
$1<\eta<3$: Dual-radiator RICH
$-1<\eta<-3$: Aerogel RICH

Lepton-ID:

$-3<\eta<3$: e/p
$1<|\eta|<3$: HCal & tracking
$|\eta|>3$: ECal+Hcal & tracking

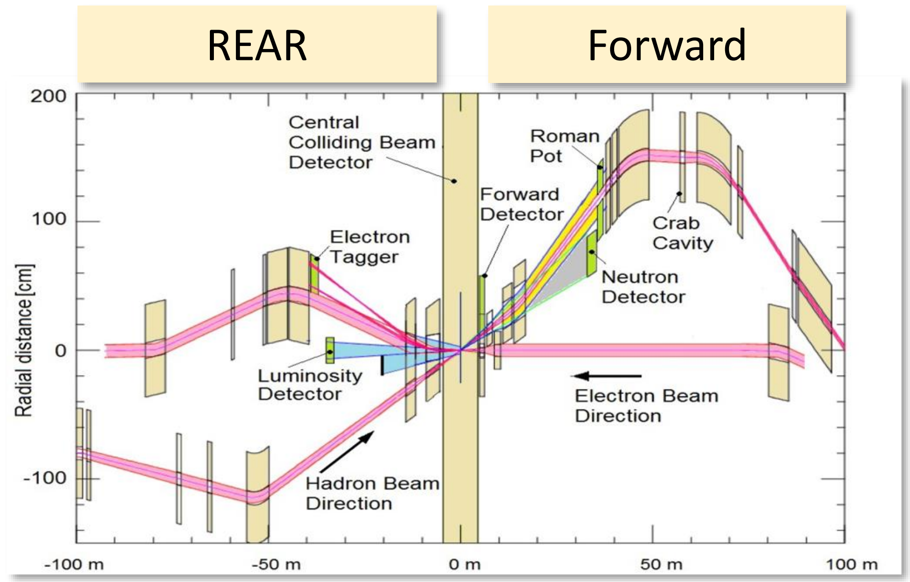
$-4<\eta<4$: Tracking (TPC+GEM+MAPS)

Silicon trackers | TPC | GEM trackers | 3 T solenoid coils

EIC Interaction region

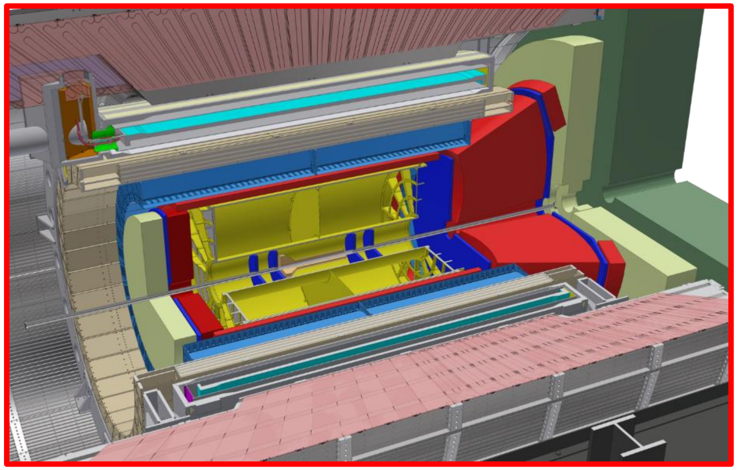
IR design requirements:

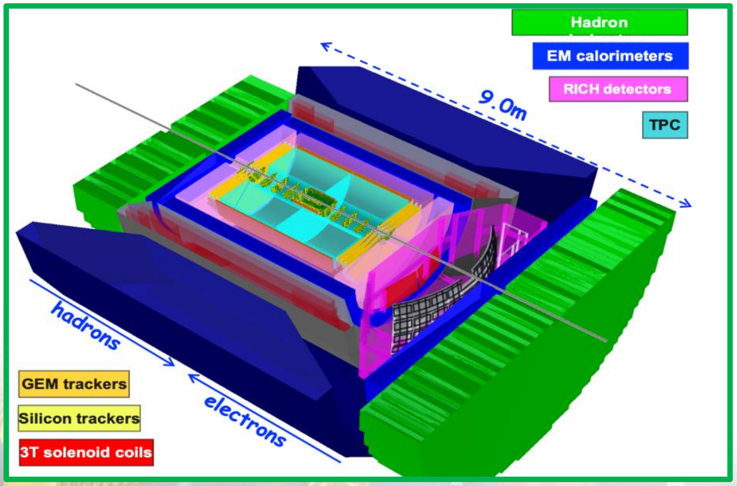
- Small β^* for high luminosity
- Large Detector acceptance
- Accommodate dipole spectrometer
- No accelerator magnets +/-4.5 m
- Crossing angle with crab cavities
- Minimize synchrotron radiation
- Accommodate spin rotators
- Space for luminosity monitor, neutron detector, “roman pots”



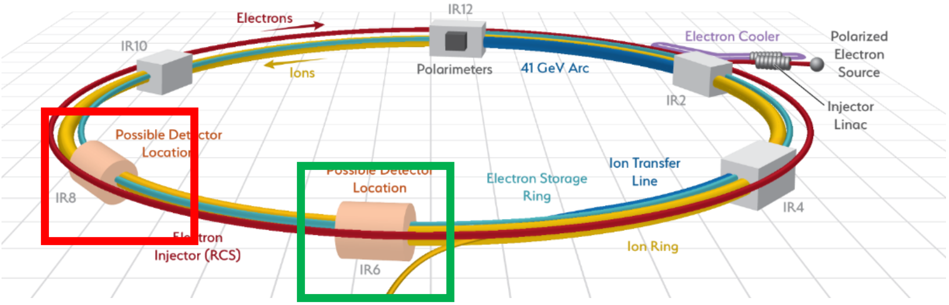
BNL design meets all requirements by incorporating novel types of magnets

BNL design: Detector concepts





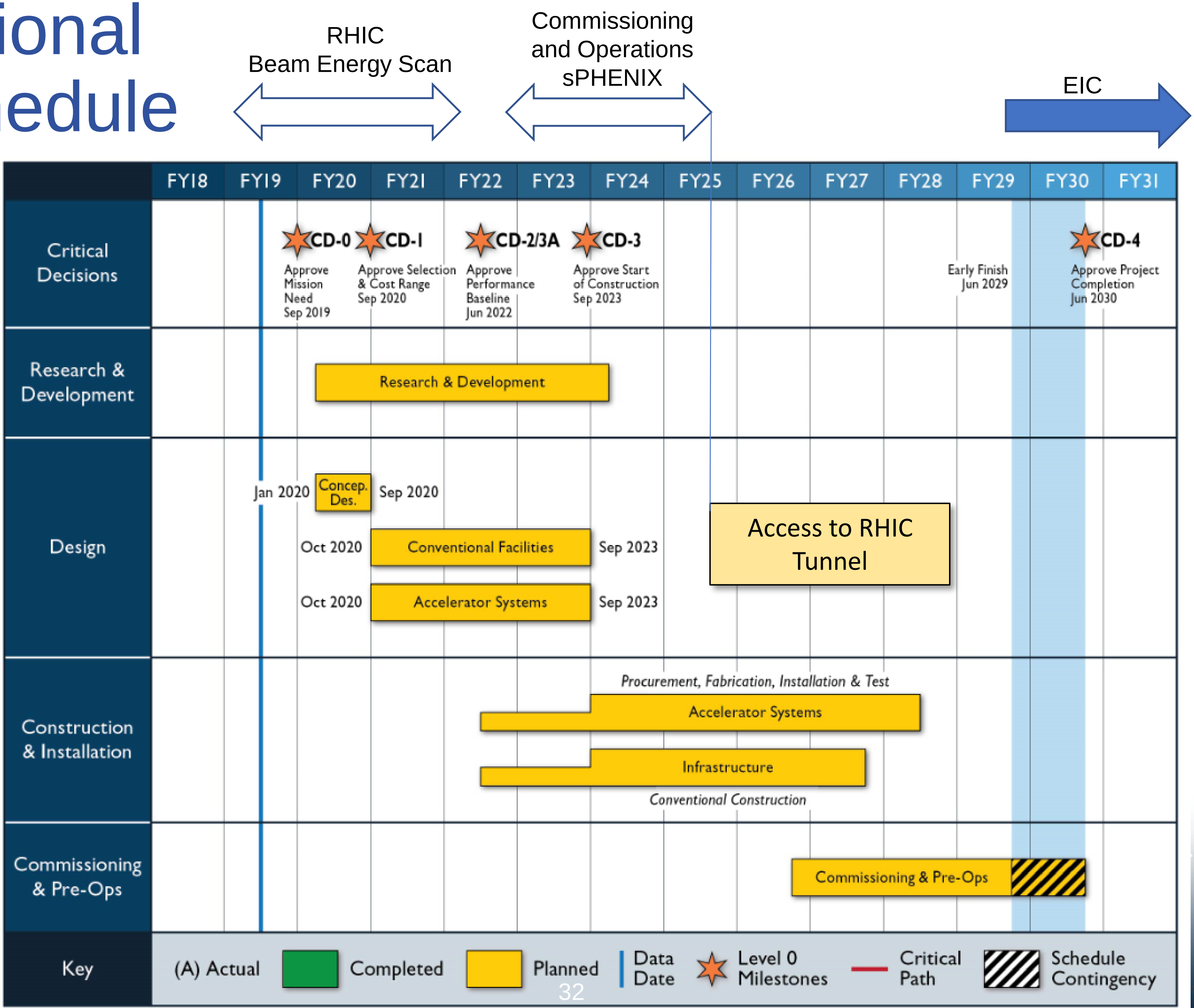
- Pre-conceptual design for EIC detector covers the full range of science in EIC white paper, NSAC long range plan and NAS report



- A second, possibly differently optimized detector could be built with international and/or inter-agency funding in existing Hall 2

EIC Schedule (Notional)

Notional Schedule



Summary

- BNL has developed a (pre-conceptual) design for an EIC that is:
  - Comprehensive
  - Cost-effective and low-risk
  - Meets all requirements
  - Dovetails on completion of RHIC program
  - Ready to proceed to the project stage
- There is wide room for international contributions:
  - Accelerator components
  - Detector design and construction
- With timely agency decision and adequate funding, an EIC at BNL could start taking data in 2030