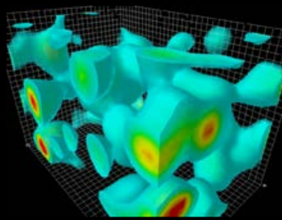


~~The EIC physics program at BNL~~

The Electron Ion Collider
BNL's Perspectives

Only the machine design "eRHIC" is BNL specific

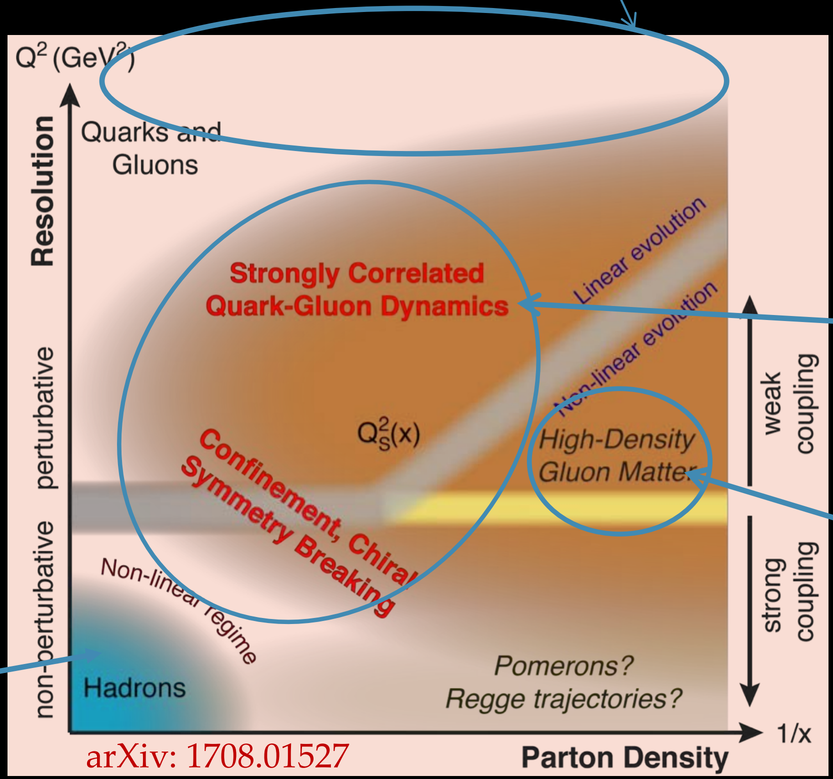
Abhay Deshpande
Stony Brook University & Brookhaven National Laboratory

Friday, December 22th, 2018

QCD Landscape to be explored by EIC

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

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



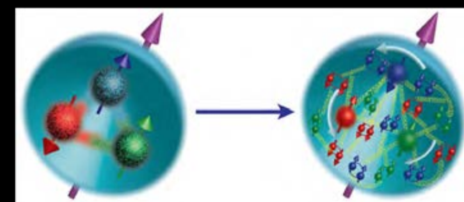
EIC will systematically explore correlations in this region.

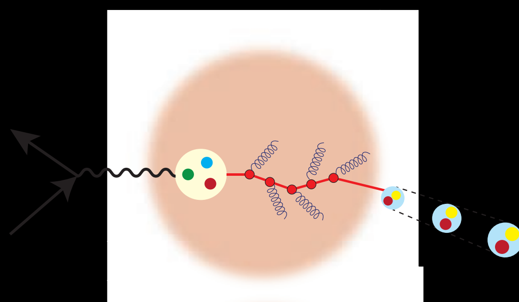
An exciting opportunity: Observation by EIC of a new regime in QCD of weakly coupled high density matter

A new facility is needed to investigate, with precision, the dynamics of gluons & sea quarks and their role in the structure of visible matter

How are the sea quarks and gluons, and their spins, distributed in space and momentum inside the nucleon?

How do the nucleon properties emerge from them and their interactions?

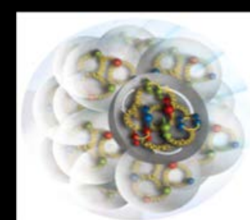




How do color-charged quarks and gluons, and colorless jets, interact with a nuclear medium?

How do the confined hadronic states emerge from these quarks and gluons?

How do the quark-gluon interactions create nuclear binding?

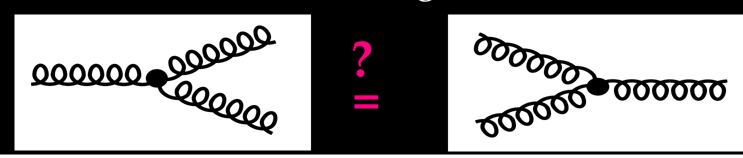


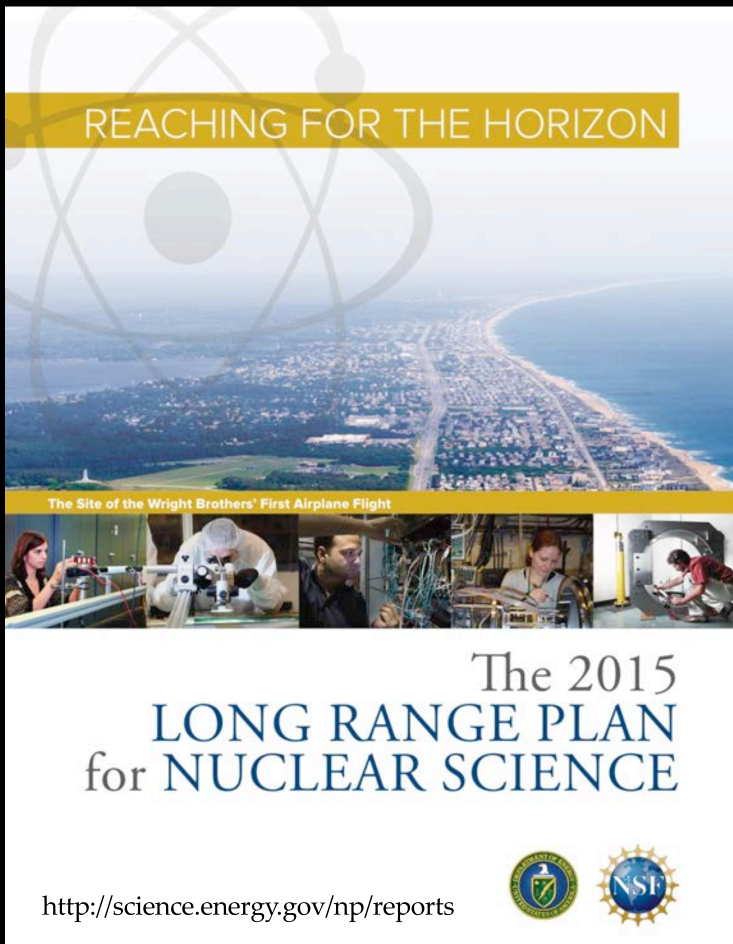
How does a dense nuclear environment affect the quarks and gluons, their correlations, and their interactions?

What happens to the gluon density in nuclei? Does it saturate at high energy, giving rise to a gluonic matter with universal properties in all nuclei, even the proton?

gluon emission

gluon recombination





RECOMMENDATION:

We recommend a high-energy high-luminosity polarized EIC as the highest priority for new facility construction following the completion of FRIB.

Initiatives:

Theory

Detector & Accelerator R&D

Detector R&D money ~1.3M/yr since 2011; significant increase anticipated soon.

Anticipated Now:

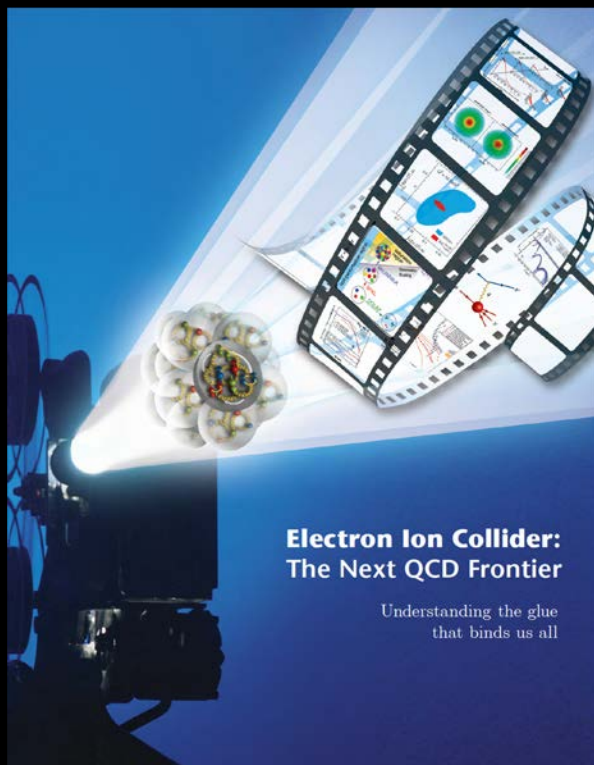
NEW Money for EIC Accelerator R&D already assigned $7m/yr

NAS Committee Statement of Task

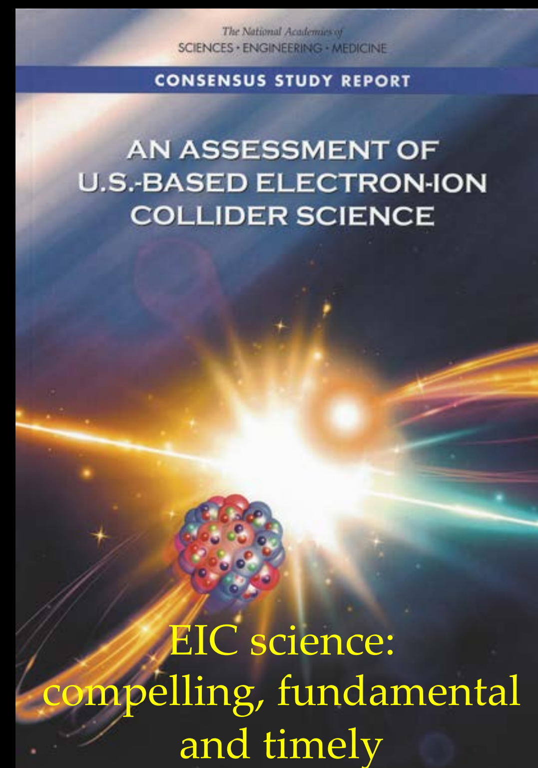
from DOE/NSF to NAS (End of 2016)

The committee will assess the scientific justification for a U.S. domestic electron ion collider facility, taking into account current international plans and existing domestic facility infrastructure. In preparing its report, the committee will address the role that such a facility could play in the future of nuclear physics, considering the field broadly, but placing emphasis on its potential scientific impact on quantum chromodynamics.

EIC Science Endorsed Unanimously by the NAS



Developed by US QCD community over two decades



EIC science: compelling, fundamental and timely

A consensus report
July 26, 2018

Developed by NAS with broad science perspective

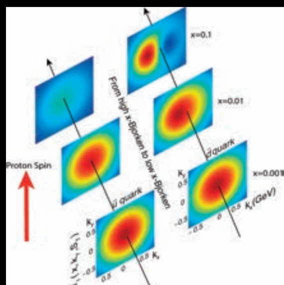
Findings of the NAS committee

- Finding 1: An EIC can uniquely address three profound questions about nucleons—neutrons and protons—and how they are assembled to form the nuclei of atoms:
  - How does the mass of the nucleon arise?
  - How does the spin of the nucleon arise?
  - What are the emergent properties of dense systems of gluons?
- Finding 2: These three high-priority science questions can be answered by an EIC with highly polarized beams of electrons and ions, with sufficiently high luminosity and sufficient, and variable, center-of-mass energy.
- Finding 3: An EIC would be a unique facility in the world and would maintain U.S. leadership in nuclear physics.
- Finding 4: An EIC would maintain U.S. leadership in the accelerator science and technology of colliders and help to maintain scientific leadership more broadly.
- Finding 5: Taking advantage of existing accelerator infrastructure and accelerator expertise would make development of an EIC cost effective and would potentially reduce risk.

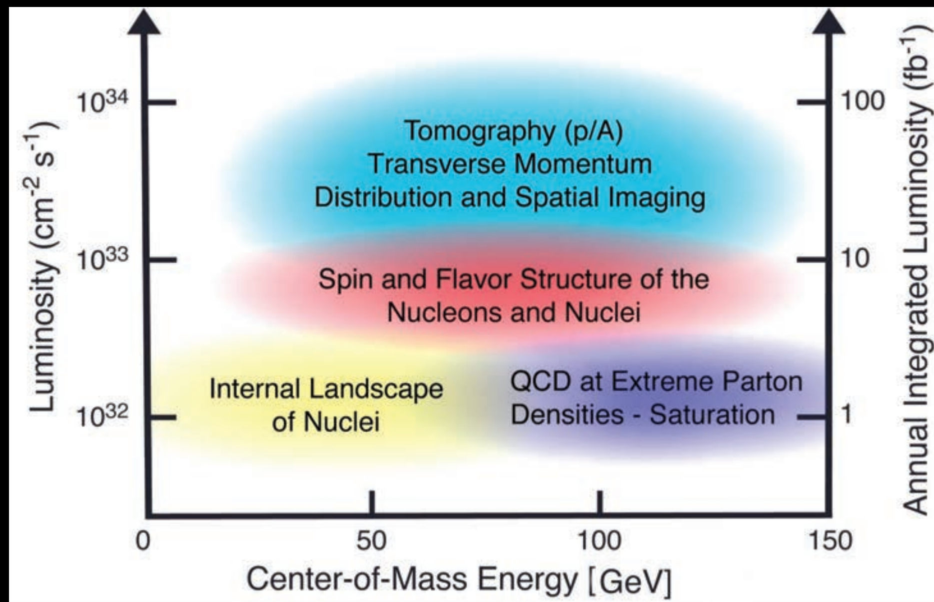
Findings of the NAS Committee (II)

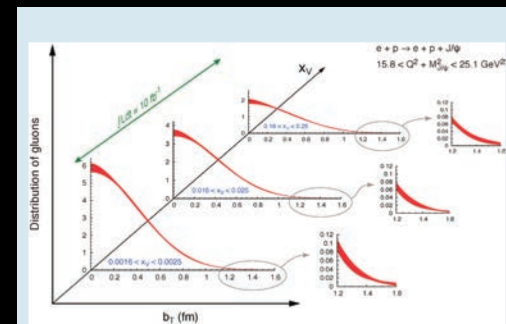
- Finding 6: The current accelerator R&D program supported by DOE is crucial to addressing outstanding design challenges.
- Finding 7: To realize fully the scientific opportunities an EIC would enable, a theory program will be required to predict and interpret the experimental results within the context of QCD, and furthermore, to glean the fundamental insights into QCD that an EIC can reveal.
- Finding 8: The U.S. nuclear science community has been thorough and thoughtful in its planning for the future, taking into account both science priorities and budgetary realities. Its 2015 Long Range Plan identifies the construction of a high-luminosity polarized EIC as the highest priority for new facility construction following the completion of the Facility for Rare Isotope Beams (FRIB) at Michigan State University.
- Finding 9: The broader impacts of building an EIC in the United States are significant in related fields of science, including in particular the accelerator science and technology of colliders and workforce development.

EIC science and required luminosity

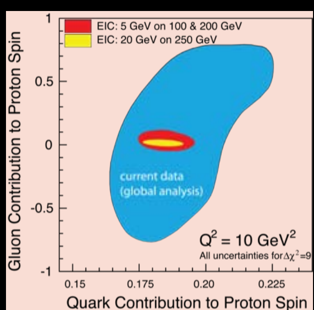


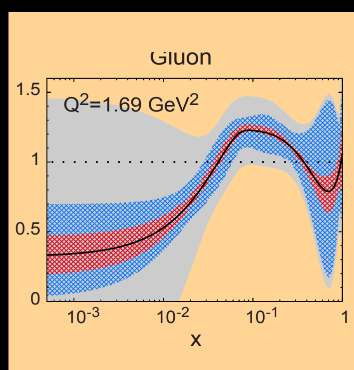
2+1D imaging of quarks and gluons, dynamics, and emergence of spin & mass

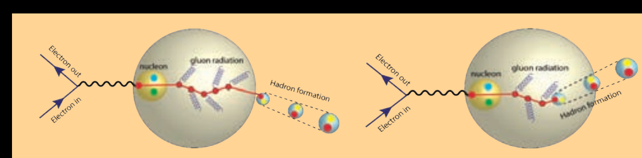




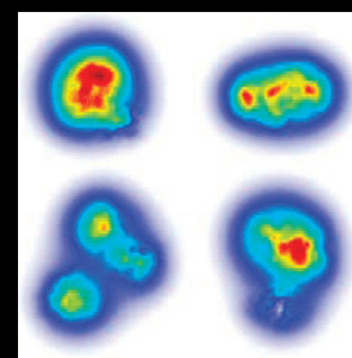
Gluon imaging in nucleons



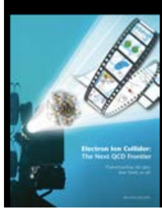




Color propagation, neutralization in nuclei & hadronization

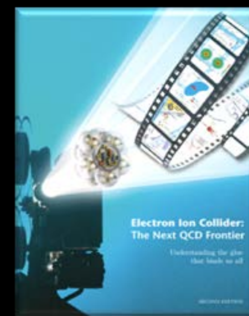


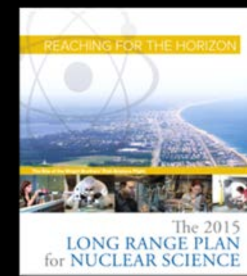
Gluons at high energy in nuclei:
(Gluon imaging in nuclei)



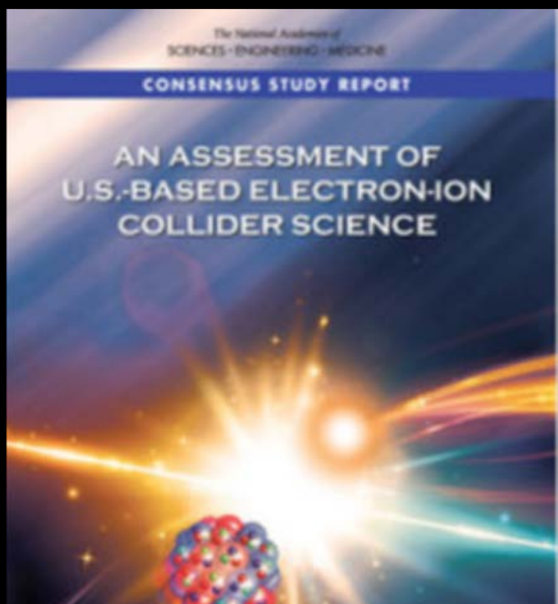
In order to definitively answer the compelling scientific questions elaborated in Chapter 2, including the origin of the mass and spin of the nucleon and probing the role of gluons in nuclei, a new accelerator facility is required, an electron-ion collider (EIC) with unprecedented capabilities beyond previous electron scattering programs. An EIC must enable the following:

- Extensive center-of-mass energy range, from ~20-~100 GeV, upgradable to ~140 GeV, to map the transition in nuclear properties from a dilute gas of quarks and gluons to saturated gluonic matter.
- Ion beams from deuterons to the heaviest stable nuclei.
- Luminosity on the order of 100 to 1,000 times higher than the earlier electron-proton collider Hadron-Electron Ring Accelerator (HERA) at Deutsches Elektronen-Synchrotron (DESY), to allow unprecedented three-dimensional (3D) imaging of the gluon and sea quark distributions in nucleons and nuclei.
- Spin-polarized (~70 percent at a minimum) electron and proton/light-ion beams to explore the correlations of gluon and sea quark distributions with the overall nucleon spin. Polarized colliding beams have been achieved before only at HERA (with electrons and positrons only) and Relativistic Heavy Ion Collider (RHIC; with protons only).





NAS Study endorses machine parameters suggested by the 2012 White Paper and 2015 NSAC Long Range Plan



Consensus Study Report on the US based Electron Ion Collider

Summary:

The science questions that an EIC will answer are central to completing an understanding of atoms as well as being integral to the agenda of nuclear physics today. In addition, the development of an EIC would advance accelerator science and technology in nuclear science; it would as well benefit other fields of accelerator based science and society, from medicine through materials science to elementary particle physics

Critical Decision Process DOE

PROJECT ACQUISITION PROCESS AND CRITICAL DECISIONS

Project Planning Phase		Project Execution Phase			Mission
Preconceptual Planning	Conceptual Design	Preliminary Design	Final Design	Construction	Operations

CD-0	CD-1	CD-2	CD-3	CD-4
Approve Mission Need	Approve Preliminary Baseline Range	Approve Performance Baseline	Approve Start of Construction	Approve Start of Operations or Project Closeout

Expected Soon (2019) → CD-0

Technical feasibility (~2029) → CD-4

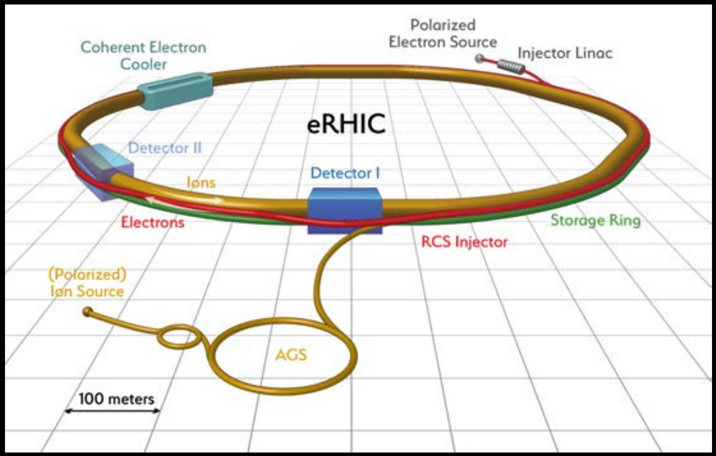
CD-0	CD-1	CD-2	CD-3	CD-4
Actions Authorized by Critical Decision Approval				
• Proceed with conceptual design using program funds • Request PED funding	• Allow expenditure of PED funds for design	• Establish baseline budget for construction • Continue design • Request construction funding	• Approve expenditure of funds for construction	• Allow start of operations or project closeout

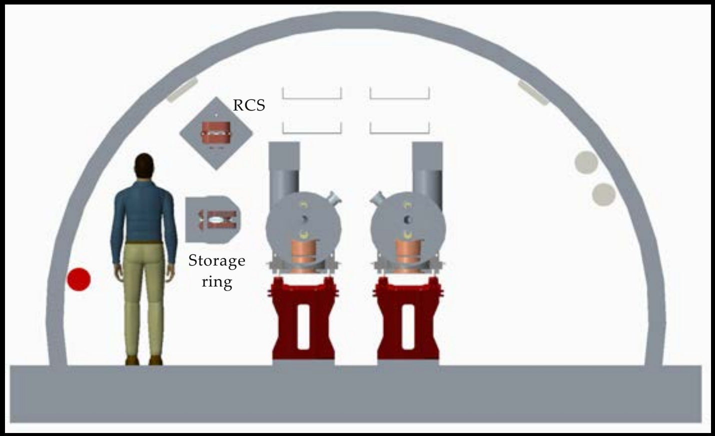
PED: Project Engineering & Design

The EIC Machines: eRHIC and JLEIC

Two designs, Patrizia will cover the JLEIC

pCDR eRHIC Design Concept





✧**Hadron Beam**

- ✧ entirely re-uses injection chain and one of RHIC rings (Yellow ring)
- ✧ partially re-uses components of other ion RHIC ring
- ✧ A $2.5B investment in RHIC is reused

✧**Electron Accelerator** added inside the existing RHIC tunnel:

- ✧ 5-18 GeV Storage Ring
- ✧ On-energy injector: 18 GeV Rapid Cycling Synchrotron
- ✧ Polarized electron source & 400 MeV injector LINAC: 10nC, 1 Hz

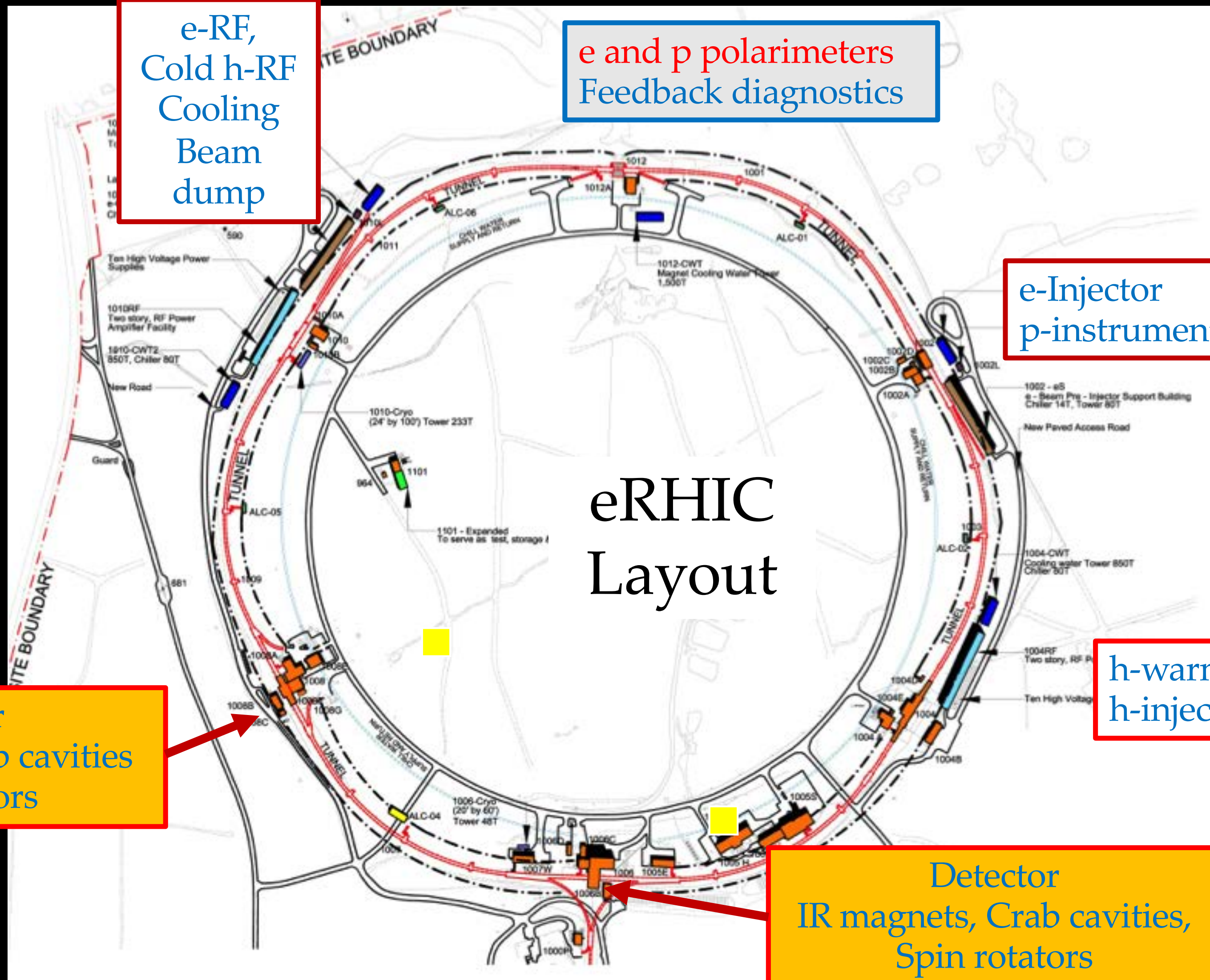
✧**Hadron cooling system** required for $L= 10^{34} cm^{-2} s^{-1}$
Without cooling the peak luminosity reaches $4.4\ 10^{33} cm^{-2} s^{-1}$

✧Wide Center of mass energy: 29-140 GeV

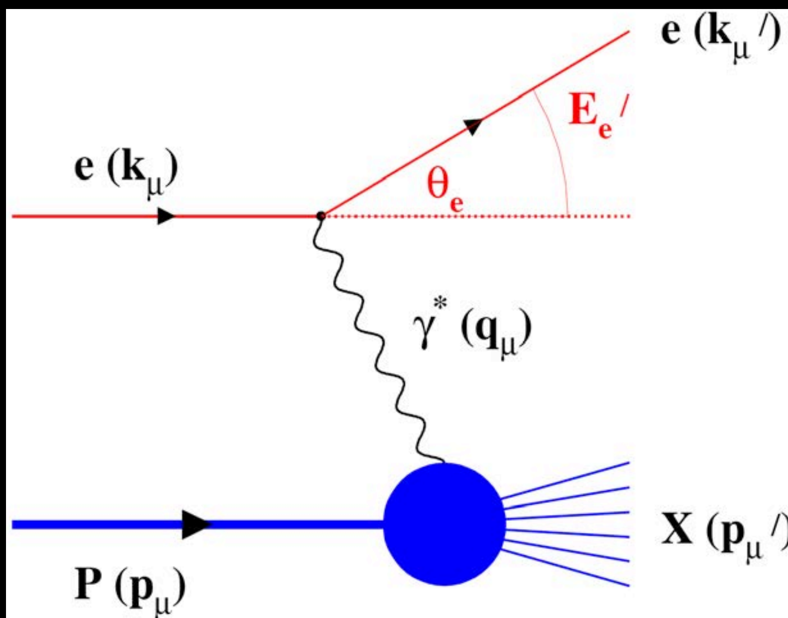
✧Large acceptance detectors integrated in the accelerator IR for forward particle detectors

✧Polarized e, p, D and ^{3}He beams planned for the physics program

eRHIC Infra-Structure



Deep Inelastic Scattering: Precision & Control



Kinematics:

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

Measure of resolution power

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

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

Measure of inelasticity

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

Measure of momentum fraction of struck quark

***Hadron*:**

$$z = \frac{E_h}{\nu};\ p_t$$

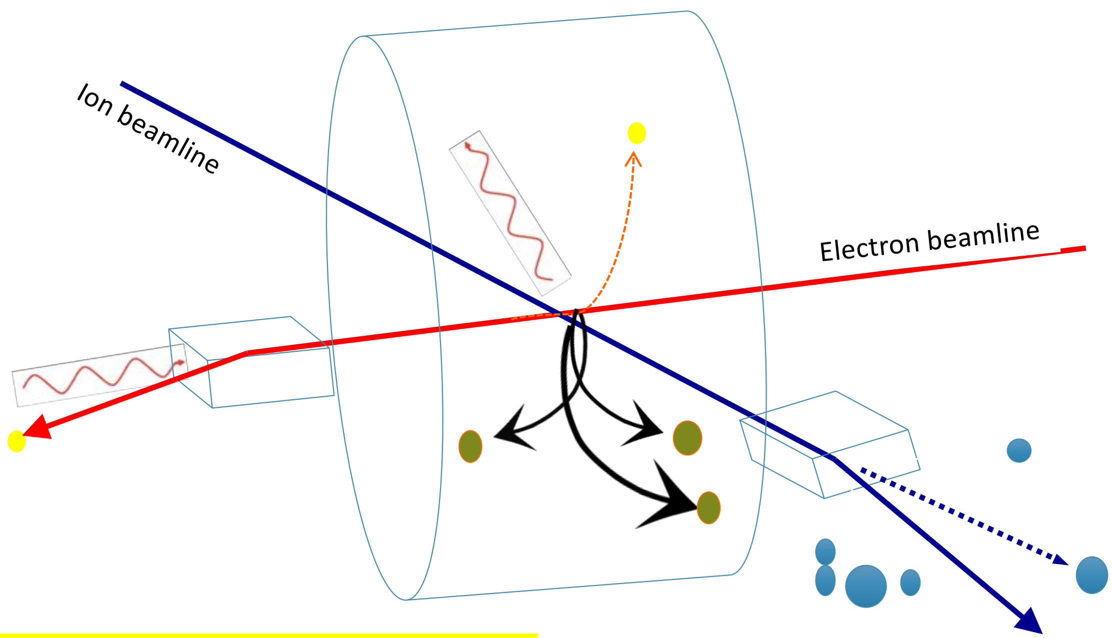
with respect to γ

Inclusive events: e+p/A → e′+X

Semi-Inclusive events: e+p/A → e′+h(π,K,p,jet)+X

Exclusive events: e+p/A → e′+ p′/A′+ h(π,K,p,jet)

Detector integration with the Interaction Region accelerator components:



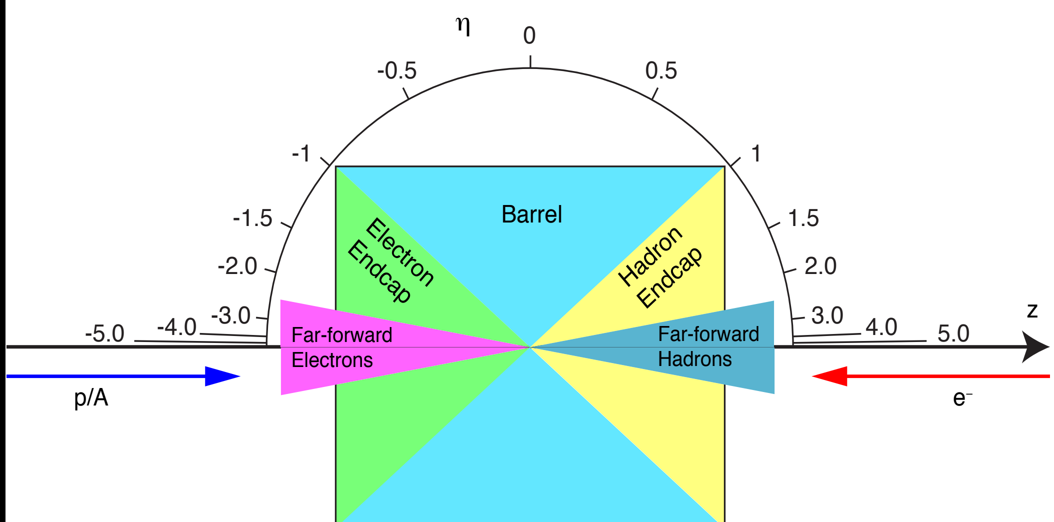
Total acceptance detector (and IR)

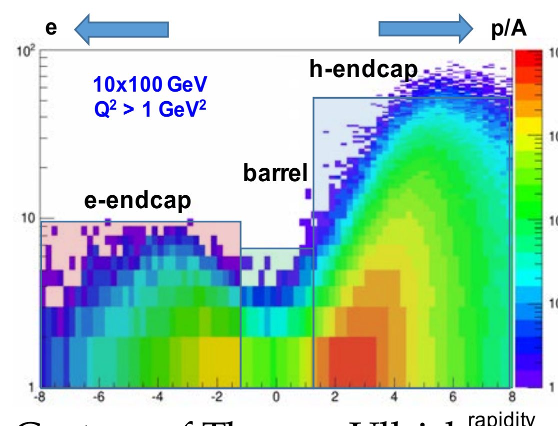
Crossing angles:
eRHIC: 25mrad
JLEIC : 40-50 mrad

Requirement are mostly site-independent with some slight differences in the forward region (IR integration)

In Short:

- Hermetic detector, low mass inner tracking, good PID (e and π/K/p) in wide range, calorimetry
- Moderate radiation hardness requirements, low pile-up, low multiplicity





Curtsey of Thomas Ullrich

Requirements for EIC Detectors

Requirement	Detector
Vertexing Event vertex, secondary vertices, track impact parameter	Vertex detector Central tracker and solenoid
Electron identification and measurement $-4 < \eta < +4$	Central tracker and solenoid Calorimeter
Jet measurement Excellent energy resolution, kinematic reconstruction $-4 < \eta < +4$	Central tracker and solenoid Calorimeter
Pion/kaon/proton separation Barrel PID needed for $p < 10$ GeV/c In forward direction needed for $p < 50$ GeV/c In backward direction needed for $p < 10$ GeV/c	Central tracker and solenoid Forward dipole/toroid TOF or Čerenkov
Forward proton/ion detection and measurement Large acceptance for momenta up to almost the beam energy	Roman pots with timing
Forward neutron detection and measurement Excellent energy and angle measurement	0^{o} calorimeter

Popular choices for the Major Subsystems

Vertex detector → Identify event vertex, secondary vertices, track impact parameters Silicon pixels, e.g. MAPS

Central tracker → Measure charged track momenta
Drift chamber, TPC + outer tracker or Silicon strips

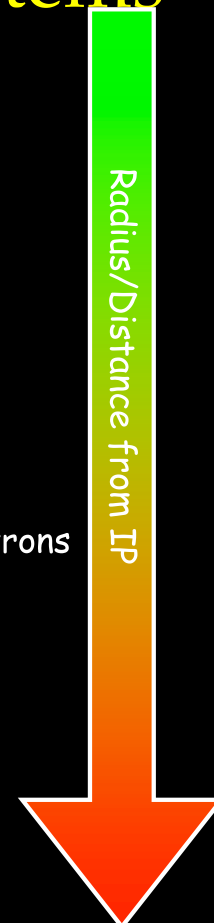
Forward tracker → Measure charged track momenta
GEMs, Micromegas, or Silicon strips, MAPS

Particle Identification → pion, kaon, proton separation
Time-of-Flight or RICH + dE/dx in tracker

Electromagnetic calorimeter → Measure photons (E, angle), identify electrons
Crystals (backward), Shashlik or Scintillator/Silicon-Tungsten

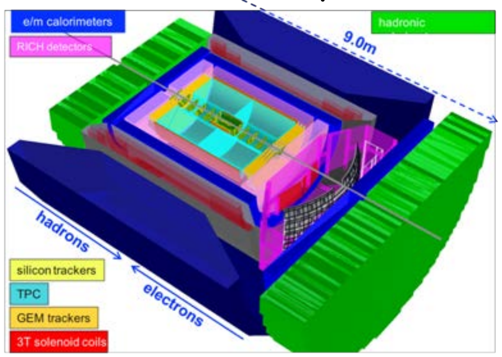
Hadron calorimeter → Measure charged hadrons , neutrons and K_L^0
Plastic scintillator or RPC + steel

+ Beam pipe, Solenoid, very forward and backward detectors

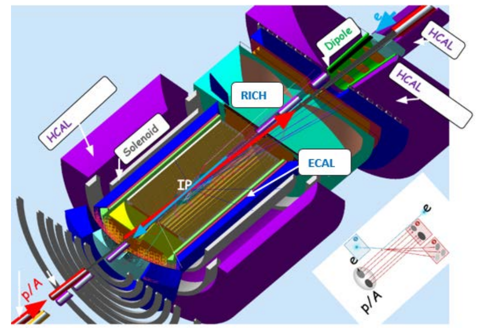


Current EIC General Purpose Detector Concepts

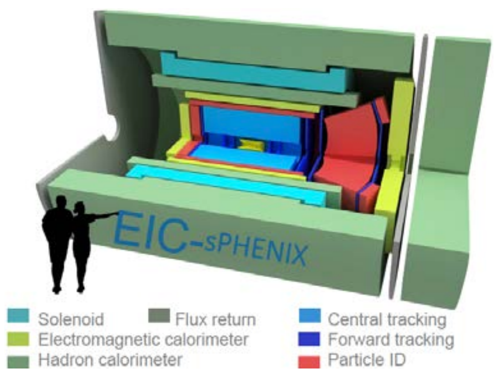
Brookhaven concept: BEAST



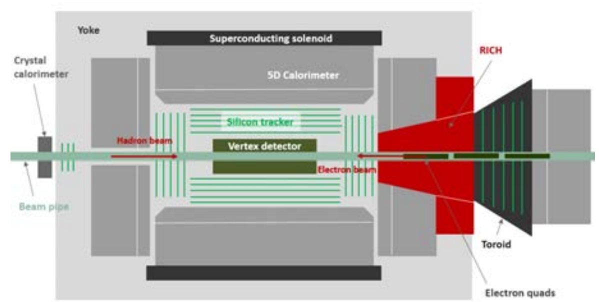
Jefferson lab concept: JLEIC



sPHENIX → EIC



Argonne concept: TOPSiDE



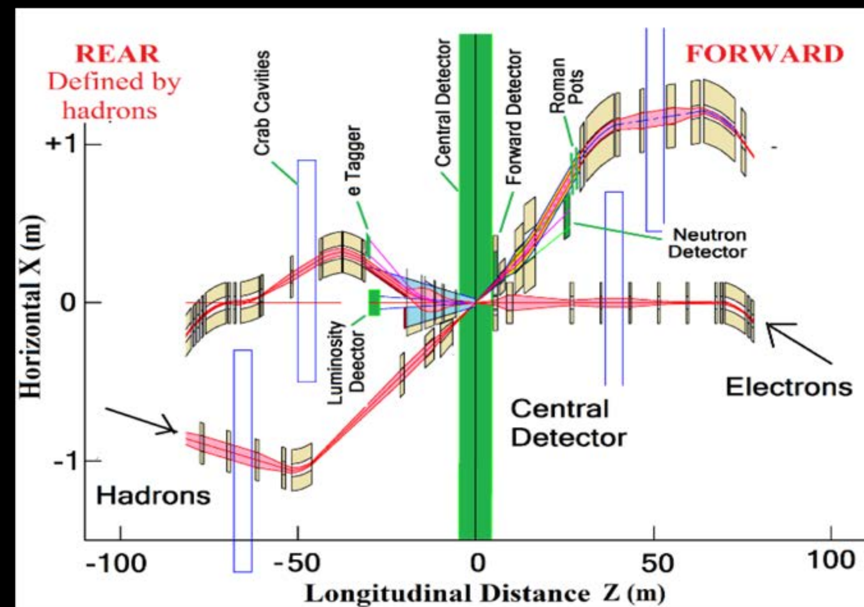
eRHIC – IR layout

C. Montag talk at EIC Collab meeting, Oct 2018

IR design requirements:

- Small β* for high luminosity
- Limited IR chromaticity contributions
- Large final focus quadrupole aperture
- Large detector acceptance
  ➔ Large quadrupole aperture, limited beam divergence
- Accommodate spectrometer in the low-β optics
- No accelerator magnets +/-4.5 m
- 25 mrad crossing angle, crab crossing, crab cavities 90° from IP
- Avoid synchrotron radiation:
  - no electron bends on the forward side
  - absorb SR far from IP
  - need mask against backscattered SR photons
- Accommodate spin rotators, spin matching
- Space for luminosity monitor, neutron detector, "Roman Pots"

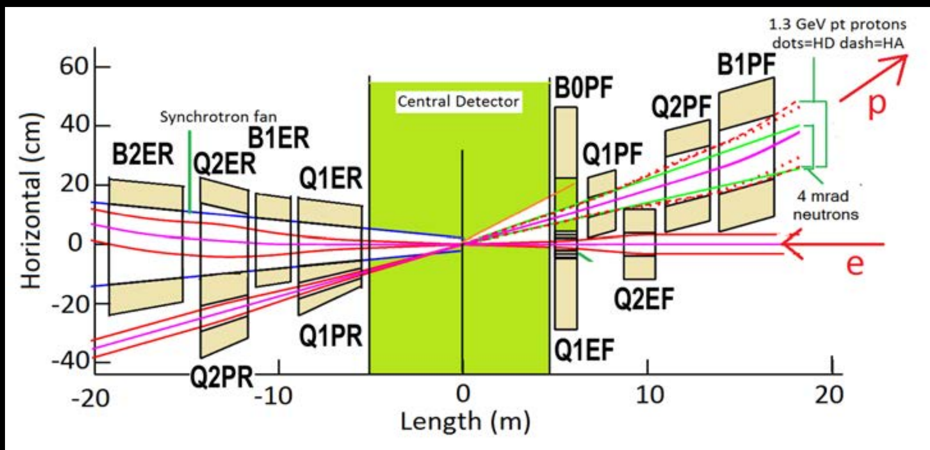
➔Design meets all requirements
➔ Very constrained systems, requires novel types of magnets in the IR

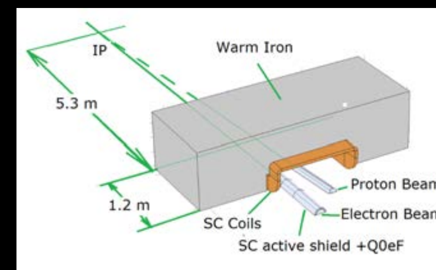


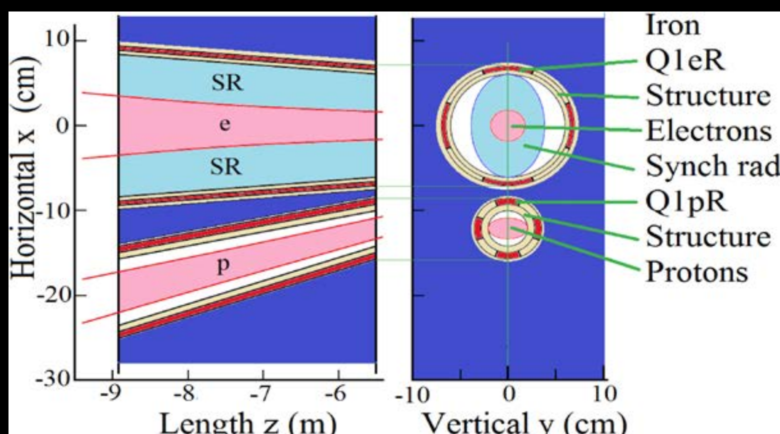
- Multi-stage separation:
- Electrons from protons
- Protons from neutrons
- Electrons from Bethe-Heitler photons (luminosity monitor)

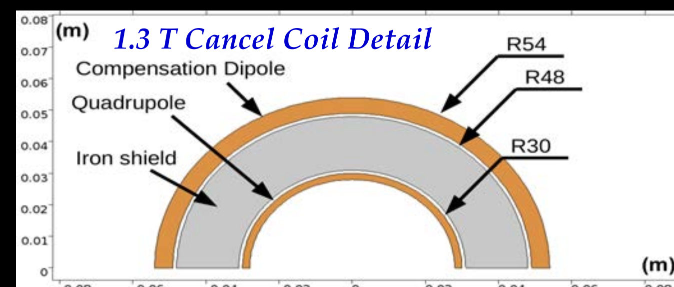
eRHIC – IR magnets

C. Montag talk at EIC Collab meeting, Oct 2018



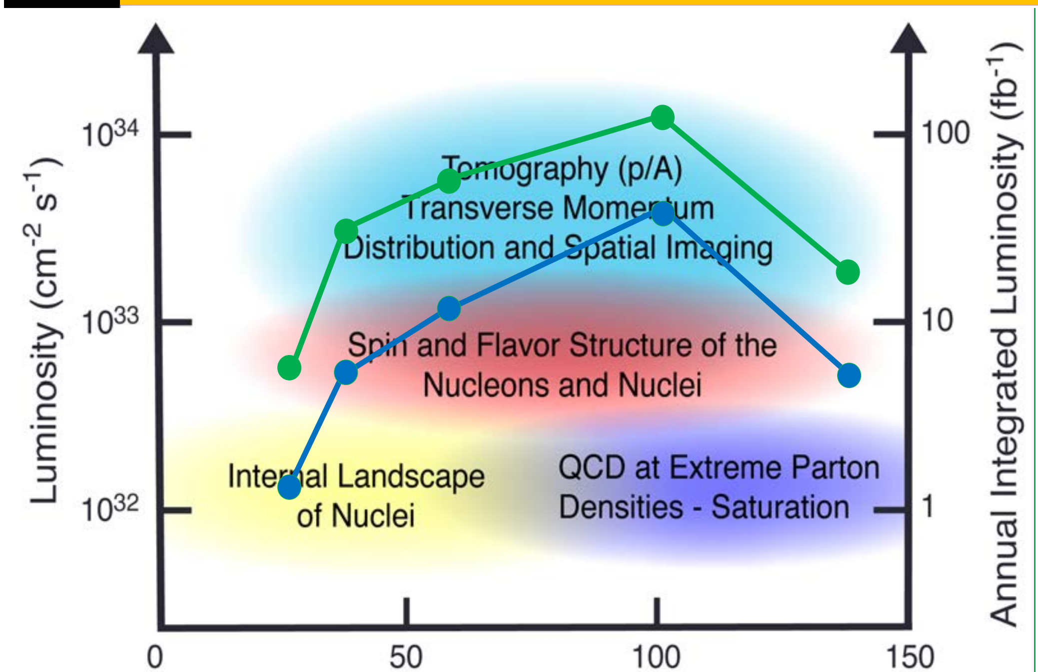






eRHIC Design Luminosity

Peak Luminosity vs CME
green: Nominal design (with cooling)
blue: Risk mitigation (no hadron cooling)



Center of Mass Energy [GeV]

Path to the high luminosity:

- ✧High beam currents
- ✧Many bunches (up to 1320)
- ✧Large beam-beam tune-shift
- ✧Flat beams
- ✧Short hadron bunches (5-7 cm)
- ✧25 mrad crossing angle with crab cavities
- ✧Strong hadron cooling for highest luminosity (10^{34})

Luminosity limiting factors are based on experience from previous and present colliders (HERA, RHIC, B-factories, LHC)

eRHIC pCDR has been completed in July 2018

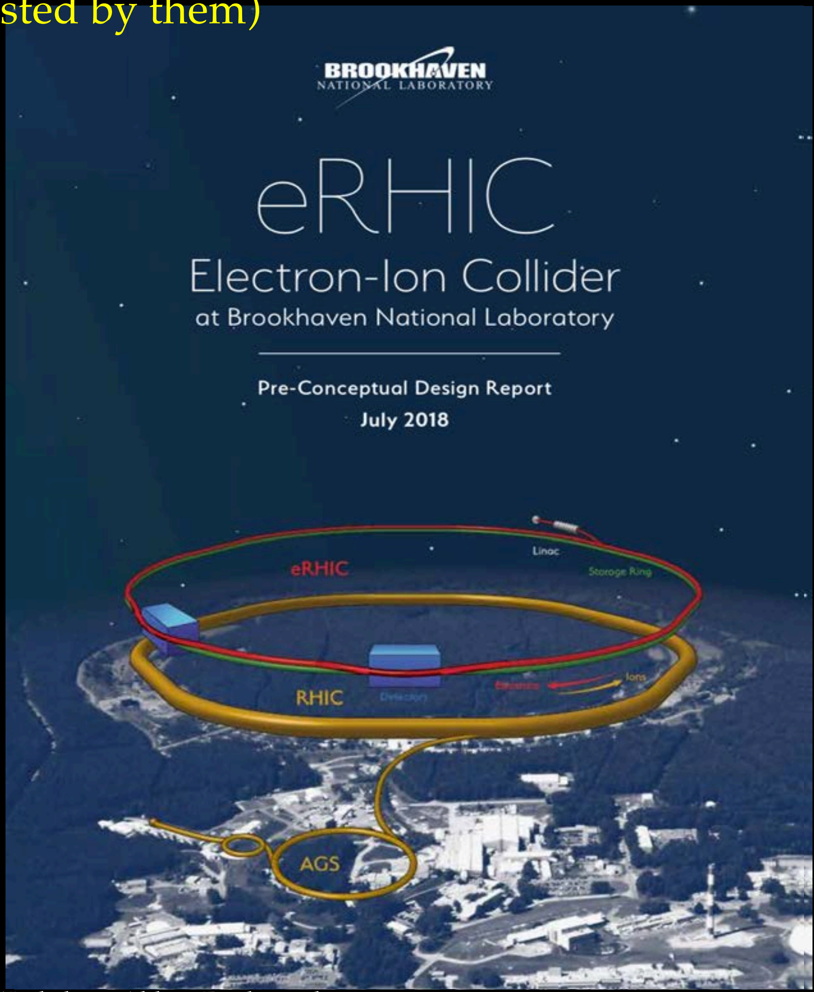
(Submitted to DOE as requested by them)

The **eRHIC Pre-Conceptual Design Report** has been finalized in the end of July 2018.

The detailed document (~770 pages)

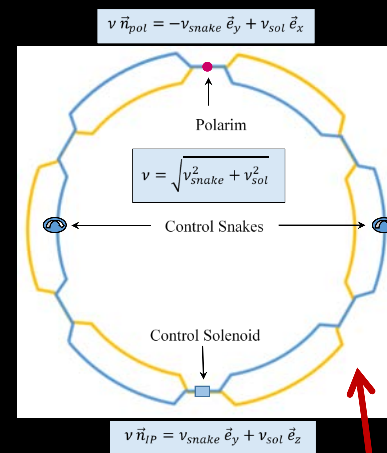
- Presents accelerator design which fully satisfies physics requirements
- Summarizes results of accelerator physics studies which validates reaching goal luminosity and high polarization
- Includes sufficiently deep description of accelerator systems, providing good basis for ongoing cost estimate work
- Evaluates required improvements in BNL/RHIC infrastructure

Presently available for eRHIC designers and collaborators. The public release is being coordinated with the Lab Management and DOE.



EIC R&D – examples:

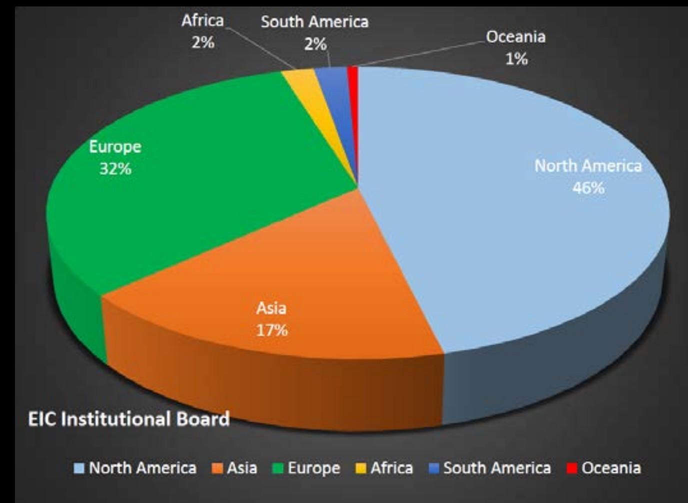
Joint effort BNL and Jlab with other institutions



- High-Priority EIC R&D topics defined by the Jones review panel
- A number of joint R&D funded by NP – FY17, significant progress achieved in:
  - Crab system design and experimental test
  - Electron cooler design
  - IR magnet design
  - Simulation software development
- Example of awarded FY18-19 proposals:
  - Crab cavity operation in a hadron ring (Lead: ODU, collaborators: JLab, BNL)
  - Strong hadron cooling
    - Development of innovative high-energy magnetized electron cooling for an EIC (Lead: JLab, collab.: BNL, FNAL, ODU)
    - Strong hadron cooling with micro-bunched electron beams (Lead: BNL, collaborators: JLab, SLAC, ANL)
  - Magnet design
    - High Gradient Actively Shielded Quadrupole (Lead: BNL, collaborators: JLab, LBNL)
    - Validation of EIC IR magnet parameters and requirements using existing magnet results (Lead: JLAB, collab.: SLAC, LBNL)
  - Benchmarking of EIC simulations
    - Development & test of simulation tools for EIC beam-beam interaction (Lead: BNL, collaborators: JLab, MSU, LBNL)
    - Experimental verification of spin transparency mode in an EIC (Lead: JLab, collaborator: BNL)
  - Electron complex
    - High Bandwidth Beam Feedback Systems for a High Luminosity EIC (Lead: ANL, collaborator: JLab)

The EIC Users Group: EICUG.ORG

Formally established in 2016
837 Ph.D. Members from 30 countries, 177 institutions
(Significant International interest ~32% Europe. ~17% Asia)



EICUG Structures in place and active.

EIC UG Steering Committee (w/ European Representative)
EIC UG Institutional Board
EIC UG Speaker's Committee (w/European Rep.)

Task forces on:
-- Beam polarimetry
-- Luminosity measurement
-- Background studies
-- IR Design

Annual meetings: Stony Brook (2014), Berkeley (2015), **ANL (2016), Trieste (2017), CAU (2018), Paris (2019)**

- December 4th, 2018, ~30 members of the EICUG from 10+ states went to the Hill and met with the staffers of the Senators and Representatives of their own state. One Italian user also joined in support.
- Conveyed excitement about the NAS report, thanked for their support of science, and seek the same for 2020+
- EICUG members carefully selected to map on with important committee representatives and other influential members of the house and senate:.

Representation to the Hill by ~30 EICUG members

EIC support, outreach and other news

European High Energy Physics Strategic Planning:

Rolf Ent (Jlab), Rik Yoshida(Jlab) and Abhay Deshpande (SBU/BNL) went to CERN in October 2018 to meet with Eckhard Elsen (CERN's Research and Technology Director)

- Very well informed about the US EIC status, very supportive, suggested strong involvement and input on EIC in the European High Energy Strategy Planning activity (ongoing now)
- EICUG presenting a science paper (led by its European contingent), and an accelerator design paper led by BNL and Jlab together
- EIC at the Plenary session of ECFA meeting November 2018

Recent success in funding of EIC as part of the Hadron studies in European Nuclear Physics $Eu 12M (Saclay, INFN and other major laboratories) over 3 years

A Consortium of 5 California Universities and 3 national labs supported by UC Chancellor's office for EIC

Center for Frontiers in Nuclear Science

http://www.stonybrook.edu/cfns

- Funded through a private donation from Simons Foundation and NY State
- International Advisory Committee: R. Milner (MIT, Chair), A. Caldwell (MPI, Munich), L. Elouadrhiri (Jlab), B. Jacak (UCB, LBNL), X. Ji (Shanghai.Maryland), Y. Kovchegov (OSU), Z.-E. Meziani (ANL), W. Nazarewicz (MSU), P. Newman (Birmingham), B. Pasquini (Pavia), F. Pilat (ORNL), G. Sterman (SBU), W. Vogelsang (Teubingen), Ex. Officio: B. Mueller (BNL), R. Yoshida (Jlab) and B. Surrow (EICUG) → **To be expanded internationally**
- Director: A. Deshpande
- Scientific Coordinator: J. H. Lee and J. Zhang
- Program Steering Committee: T. Hemmick, D. Kharzeev, K. Kumar, J. H. Lee, T. Ullrich, R. Venugopalan and A. Deshpande (Chair) **To be expanded internationally**
- Administrative Support: S. Delquaglio (SBU), M. Veri-Veteri (SBU), and R. Nieves (BNL)

Vision: to provide a "home" or "go-to" place for supporting the world-wide EIC Users / Enthusiasts

CFNS activities in the 1st year

(250+ international and national EICUG members visited us)

- EIC Physics 7 Topical Workshops:
  - 2 away from Long Island, 3 at Stony Brook, 2 at BNL: deepen the EIC physics topic or broaden it by seeking new avenues beyond the EIC Physics in the EIC White Paper
- Initiated a joint Post Doctoral Scientist program for EIC (50:50) with CFNS and a remote institution
  - 17 applications, 7 selected as excellent, will fund up to 5
- CFNS post doctoral program underway: Up to 4 post doctoral fellows at CFNS through SBU, augmented by up to 5 post doctoral fellows on EIC physics development at BNL through LDRD/PD
- SBU-BNL Joint Seminars: 2/month organized by 4 post docs (2 from BNL and 2 from SBU)
- Short and long term visitors program initiated

- EIC/QCD summer school planned in 2019 for about 30 students
- Minority outreach program for QCD and EIC related instrumentation under consideration

Summary: US EIC has momentum…

- The US EIC project has significant momentum on all fronts right now:
    - National Academy's positive evaluation → EIC science compelling, fundamental and timely
    - EICUG is energized, active and enthusiast: organized
        - EICUG led working groups on polarimetry, luminosity measurement, IR design evolving
    - Funding agencies taking note of the momentum: not just in the US but also internationally

- The science of EIC, technical designs (eRHIC and JLEIC) moving forward
    - Pre-CDRs prepared by BNL (eRHIC) and Jlab (under preparation) for the machine designs
    - CFNS, EIC^2 Centers established in the US to help EIC Users

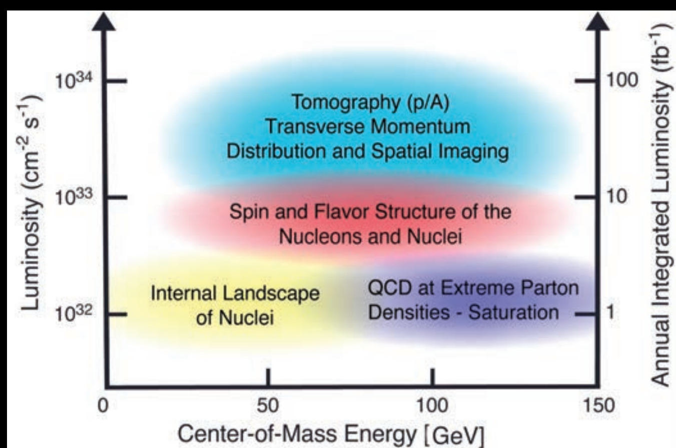
- CD0 for the EIC project very near. – We are waiting…

Invitation

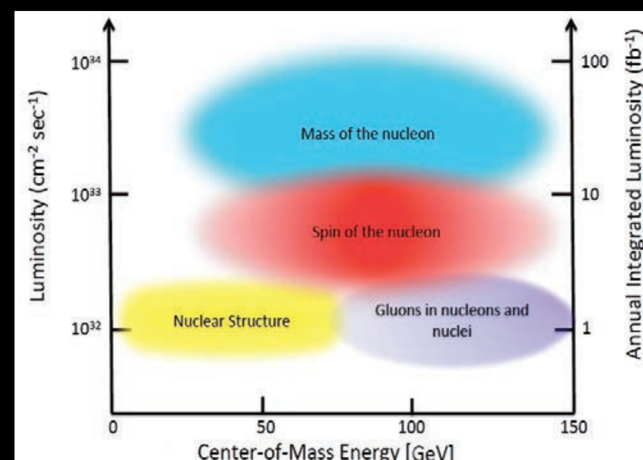
The 8th Biennial Workshop of the APS Topical Group on Hadronic Physics (GHP2019) will be held April 10-12, 2019 in Denver, CO. The workshop provides a great opportunity for nuclear and particle physicists to meet and discuss their common interests in hadronic interactions. The workshop precedes the APS April Meeting 2019 and will take place at the same venue, the Sheraton Denver Downtown Hotel.

The meeting website is at: https://www.jlab.org/indico/event/282/

EIC Physics Case
NAS report figure 2.4



NAS report figure 7.1



eRHIC and JLEIC key parameters at maximum Luminosity points

design parameter	eRHIC proton	eRHIC electron	JLEIC proton	JLEIC electron
center-of-mass energy [GeV]	105		44.7	
energy [GeV]	275	10	100	5
number of bunches	1320		3228	
particles per bunch [10^{10}]	6.0	15.1	0.98	3.7
beam current [A]	1.0	2.5	0.75	2.8
horizontal emittance [nm]	9.2	20.0	4.7	5.5
vertical emittance [nm]	1.3	1.0	0.94	1.1
β_x^* [cm]	90	42	6	5.1
β_y^* [cm]	4.0	5.0	1.2	1
tunes (Q_x, Q_y)	.315/.305	.08/.06	.081/.132	.53/.567
hor. beam-beam parameter	0.013	0.064	0.015	0.068
vert. beam-beam parameter	0.007	0.1	0.015	0.068
IBS growth time hor./long. [min]	126/120	n/a	0.7/2.3	n/a
synchrotron radiation power [MW]	n/a	9.2	n/a	2.7
bunch length [cm]	5	1.9	1	1
hourglass and crab reduction factor	0.87		0.87	
peak luminosity [10^{34} cm^{-2}s^{-1}]	1.05		2.1	
integrated luminosity/week [fb^{-1}]	4.51		9.0	

Assumptions on integrated luminosity: Accelerator is 75% of the time in colliding beam mode; 25% of the time is needed for injection, acceleration, run preparation as well as maintenance, machine development, and failures. The average luminosity within a luminosity run is very close to the peak luminosity (> 95%) due to strong hadron cooling.