eRHIC Update

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INT Program 18-3
October 22, 2018

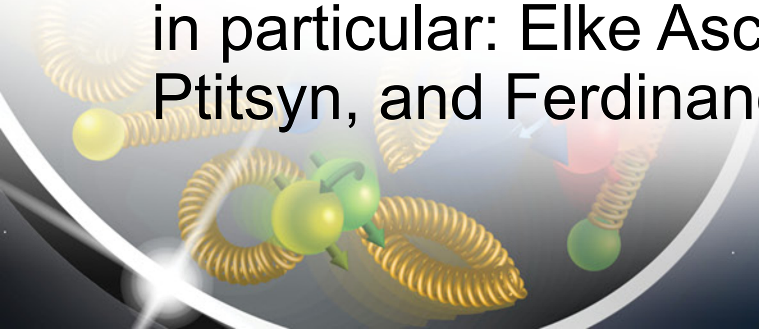
Electron Ion Collider – eRHIC

BROOKHAVEN NATIONAL LABORATORY
U.S. DEPARTMENT OF ENERGY | Office of Science

Outline

- Recent Updates to EIC Science
- eRHIC Design
- eRHIC Accelerator and Detector R&D
- EIC Program Considerations

I thank all those who helped assemble this presentation, in particular: Elke Aschenauer, Abhay Deshpande, Vadim Ptitsyn, and Ferdinand Willeke.



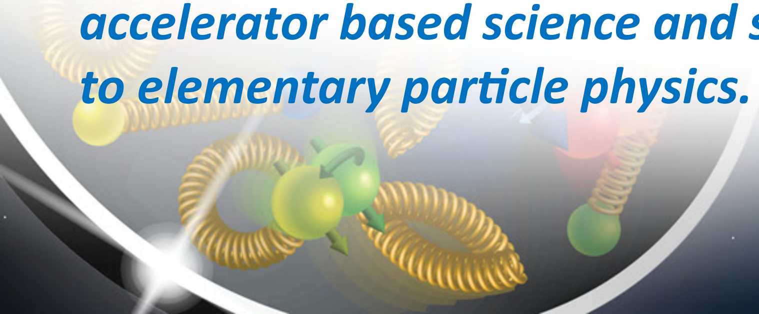
The Case for an EIC

NSAC Long Range Plan (2015) - Recommendation III

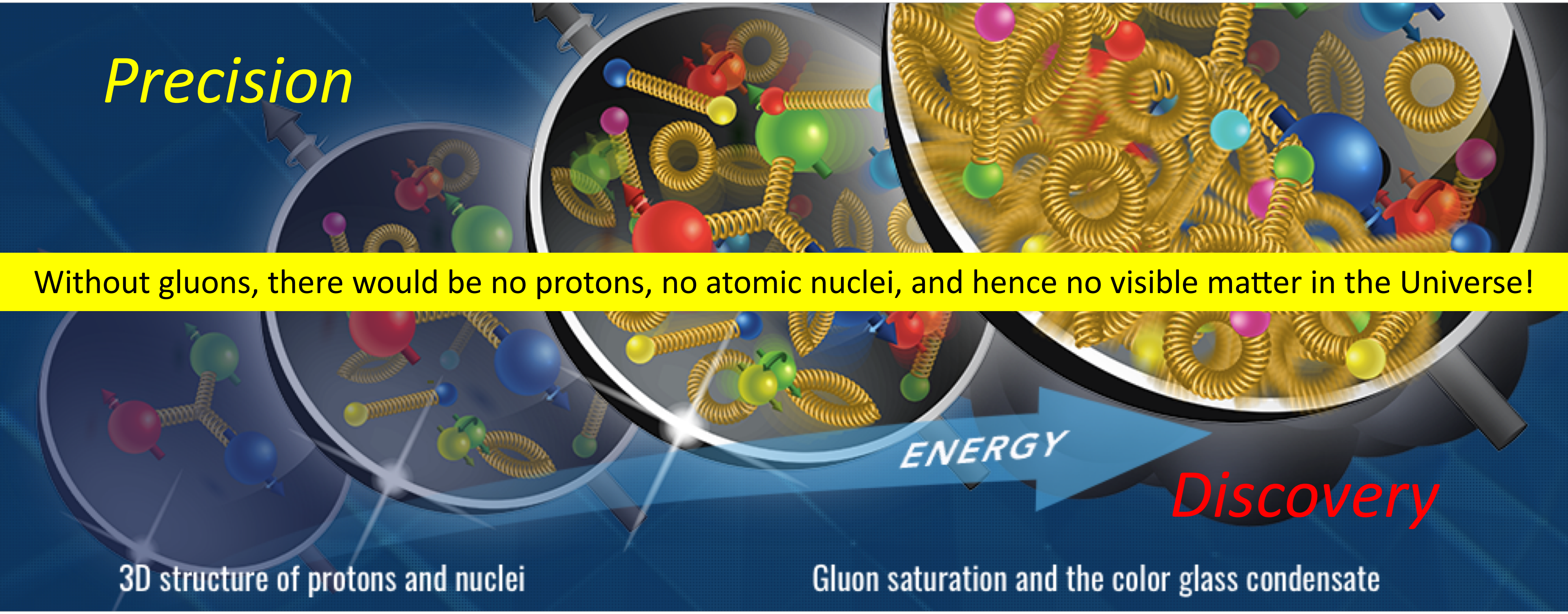
We recommend a high-energy, high-luminosity polarized Electron Ion Collider as the highest priority for new facility construction following the completion of FRIB.

National Academy of Sciences Consensus Report on the Science Case for a U.S. based Electron-Ion Collider (July 2018)

In summary, the committee finds a compelling scientific case for such a facility. 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.



EIC Science Pillars



Precision

Without gluons, there would be no protons, no atomic nuclei, and hence no visible matter in the Universe!

Discovery

3D structure of protons and nuclei

Gluon saturation and the color glass condensate

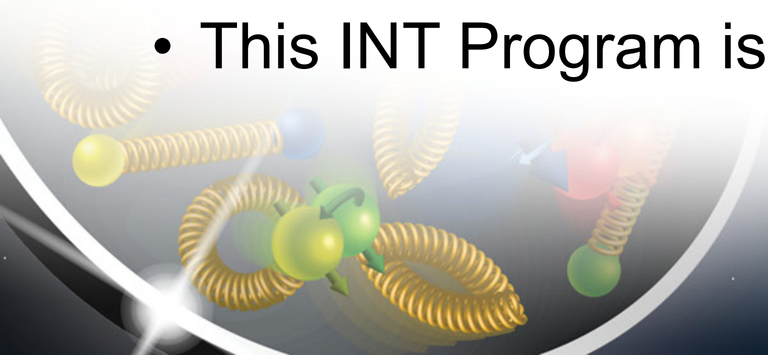
The EIC will collide high-energy electrons with high-energy protons or heavier atomic nuclei to produce "freeze-frame" snapshots of their inner structure, creating precise first-ever tomographic images of the "ocean" of gluons within. These images will tell us how gluons and quarks bind each other to form the particles that lie at the core of all atoms.

New experiments and advances in theory suggest that protons, neutrons, and nuclei appear as dense "walls" of gluons when probed at high energy, creating what are conjectured the strongest fields in nature. Discovering and studying this new form of matter, the "color glass condensate," will give us additional insight into why matter in this sub-atomic realm is stable.

The EIC will also drive technical innovations and support societal applications!

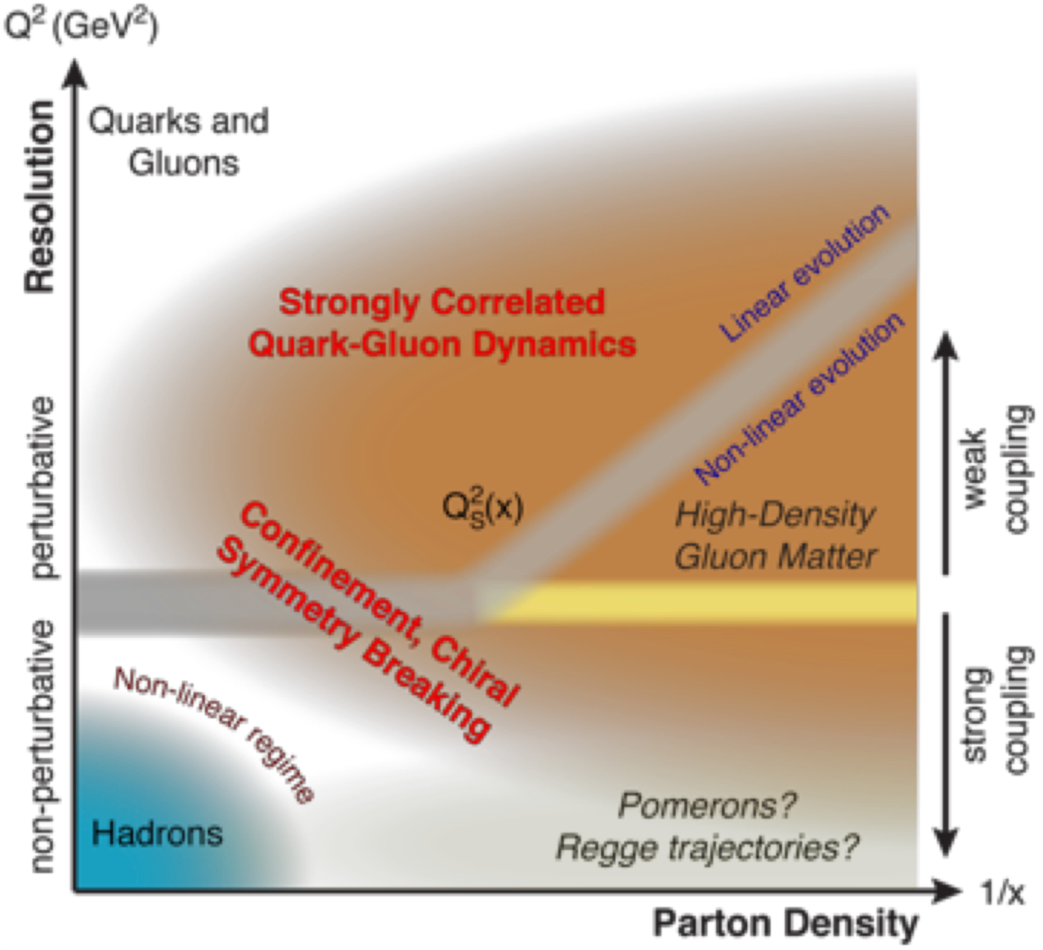
What Next?

- The *Justification Phase* of the EIC has ended
    - DOE, OMB and Congress have all the information they need
- We are entering the *Realization Phase*
    - We need to be able to state the science case for the EIC as crisply and compellingly as possible
    - We need a credible facility design that can be successfully built and operated
    - We need a plan to realize the science goals when the EIC is completed, maximizing the return on investment
    - We need to attract the widest global community of users
- This INT Program is one of the many steps on this path



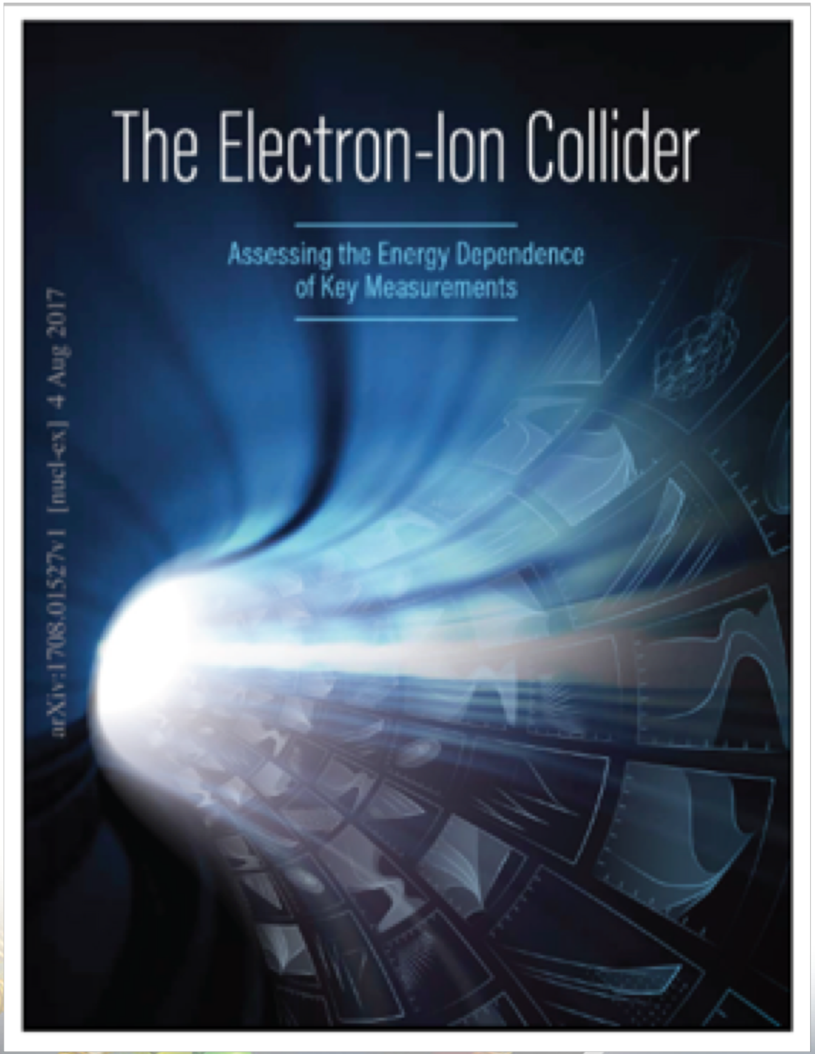
EIC Science
Recent Updates

EIC and the QCD landscape



With its wide kinematic range, access to polarization and nuclei, the EIC will enable the exploration of the full cold QCD matter landscape.

EIC Energy Range



The Electron-Ion Collider

Assessing the Energy Dependence of Key Measurements

arXiv:1708.01527v1 [nucl-ex] 4 Aug 2017

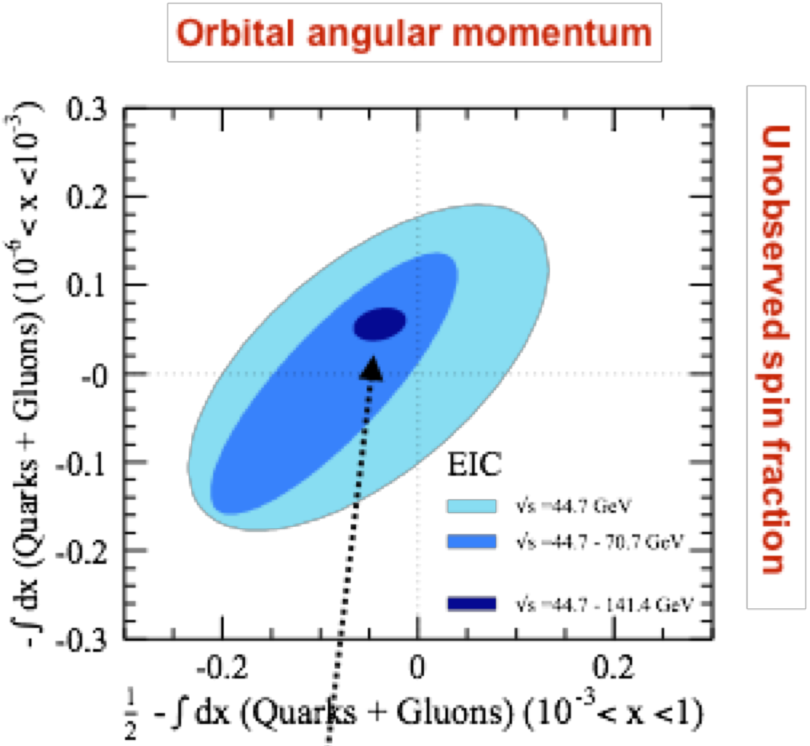
Reassessment of the relevance of the EIC energy range specified in the NSAC Long Range Plan (arXiv:1708.01527):

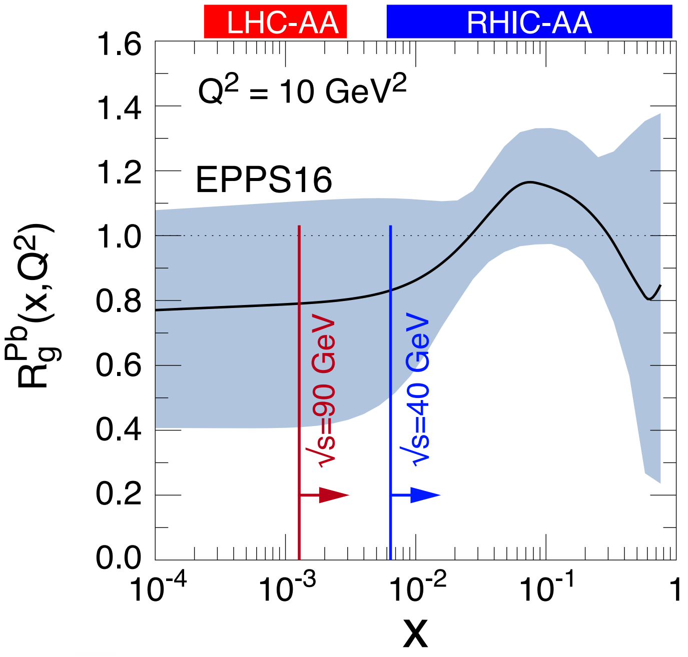
- Variable c. m. energies ~20–100 GeV upgradable to ~140 GeV (e-p)

The report analyzes the impact of the width of the energy range on a broad list of EIC measurements and concludes that the greater reach provided by the full energy (i.e. 140 GeV in e-p) greatly enhances the physics potential of an EIC and amplifies the discovery potential of these measurements.

The following slides show examples.

Value of √s reach





Full eRHIC CM energy required to disentangle different contributions to the proton spin with less than 10% uncertainty (ΔJ < 0.05ħ)

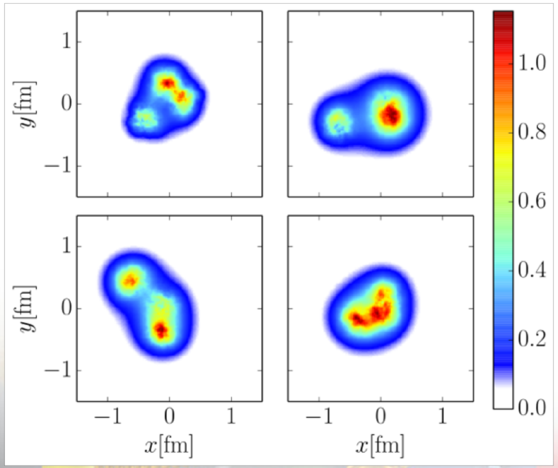
Full eRHIC CM energy required to constrain nuclear PDFs for the A+A and p+A programs at the LHC

Proton structure in pA, pp, and ep

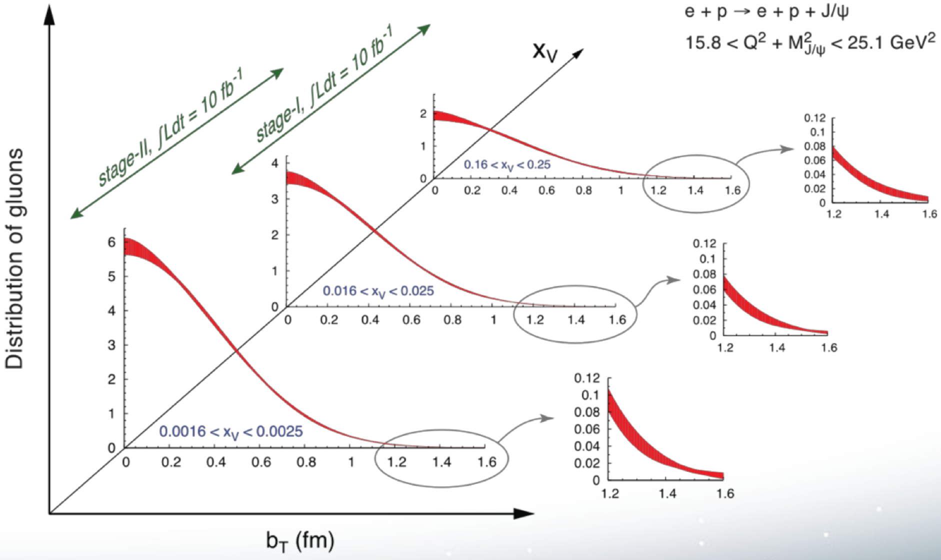
Data from pp and pA collisions at RHIC and LHC have shown that shape fluctuations of the proton at x = $10^{-2} - 10^{-3}$ are essential to explaining the observed collective behavior of pA and pp

eRHIC will map out the spatial quark and gluon structure of the proton

Simulated proton density fluctuations at x ~ 10^{-3}

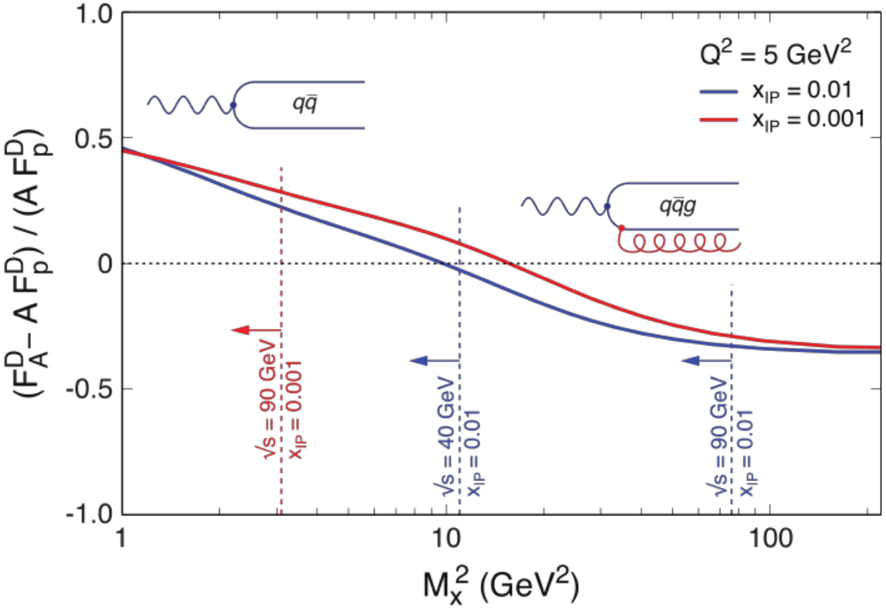


DVCS coherent and incoherent J/Ψ production



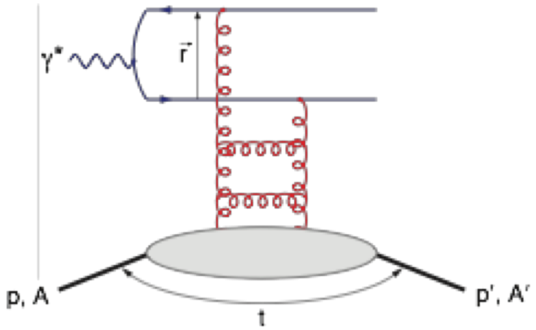
Nuclear opacity

The sign Change in $\sigma_{diff}/\sigma_{total}$ is characteristic of gluon saturation

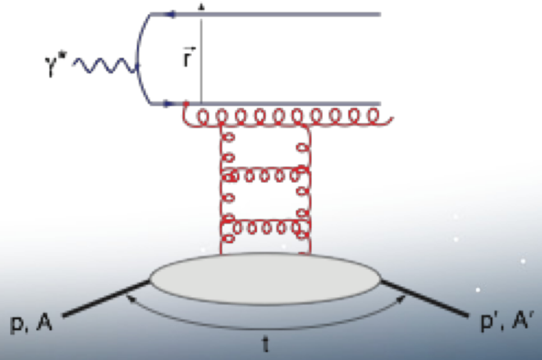


Observing the dependence on M_x over a large range in x and Q^2 is crucial: Sufficiently wide √s range is key.

A nucleus is “blacker” than a proton. Elastic scattering probability of a $q\bar{q}$ dipole is maximal in the “black” limit



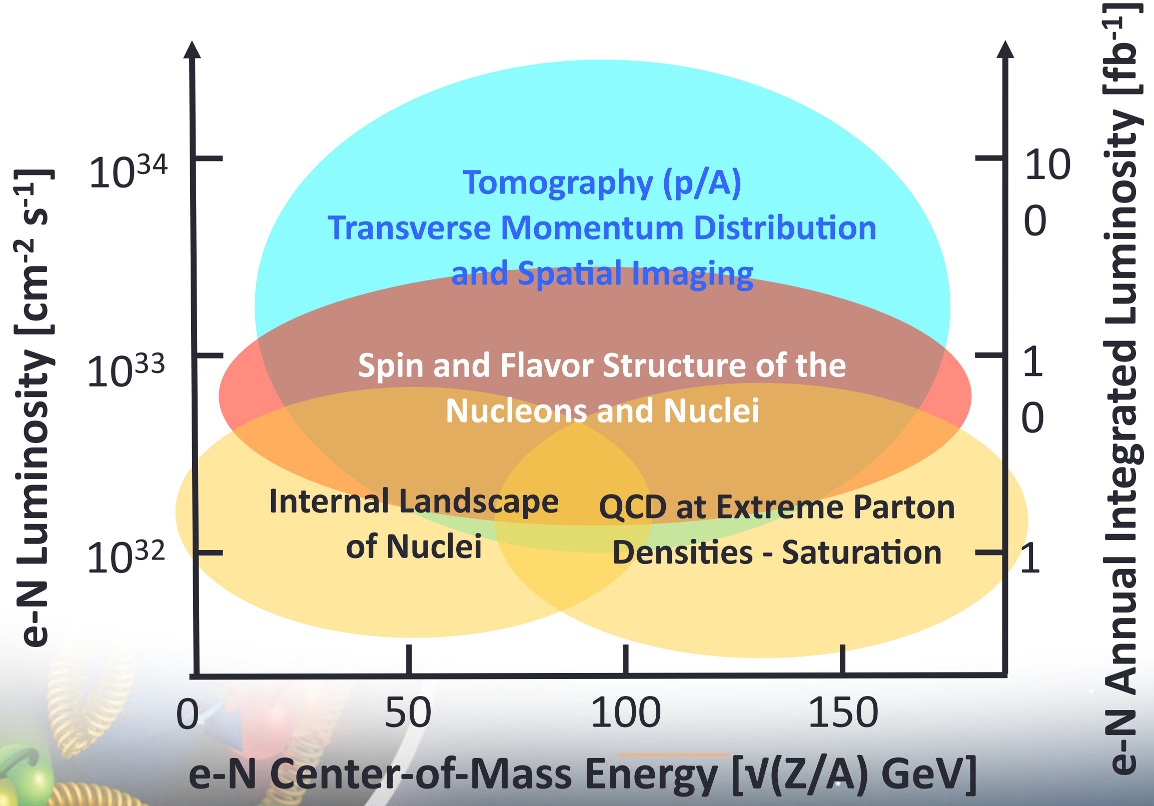
The $q\bar{q}g$ component vanishes in black disk limit



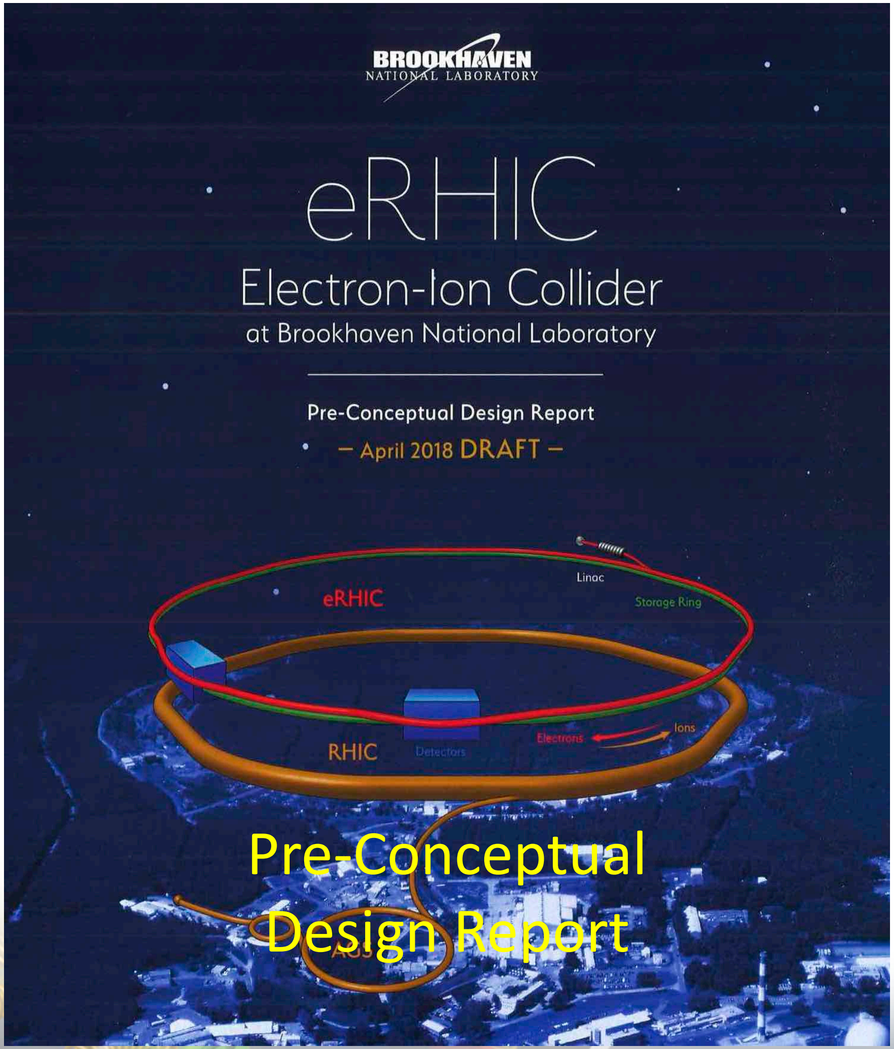
eRHIC Design

EIC Requirements

- **Large luminosity ($10^{33} - 10^{34}$ cm^{-2}s^{-1})**
- **Center of mass energy range (30−140) GeV**
- **Both hadron and electron beams are highly longitudinally spin polarized**
- **Large detector acceptance, in particular for small-angle scattered hadrons (optimized *high luminosity* & *high acceptance* running modes)**



eRHIC Design



BROOKHAVEN
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eRHIC
Electron-Ion Collider
at Brookhaven National Laboratory

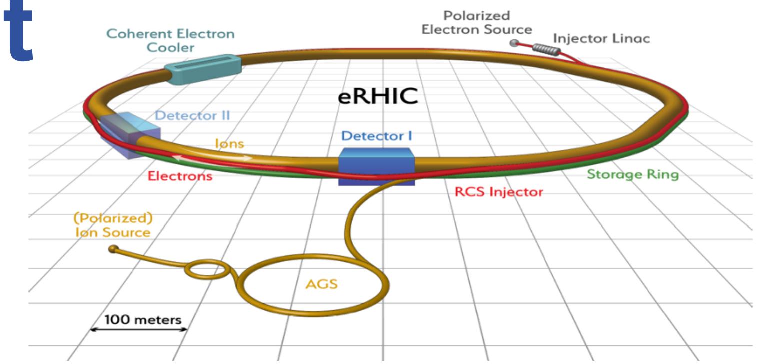
Pre-Conceptual Design Report
– April 2018 DRAFT –

Pre-Conceptual Design Report

The BNL design team has completed a Pre-conceptual Design Report for a facility based on the Ring-Ring concept that is capable of addressing the full range of science covered in the EIC White Paper with a low-risk, cost-effective solution for the first phase:

- Polarized (~70%) electrons, protons, and light nuclei (↑^{3}He, ↑d),
- Ion beams from deuterons to the heaviest stable nuclei,
- Variable CM energies ~20–100 GeV, an easy upgrade to ~140 GeV (e-p),
- Collision luminosity ~$10^{33\text{-}34}$ cm^{-2}s^{-1},
- Up to two interaction regions.

eRHIC Design Concept

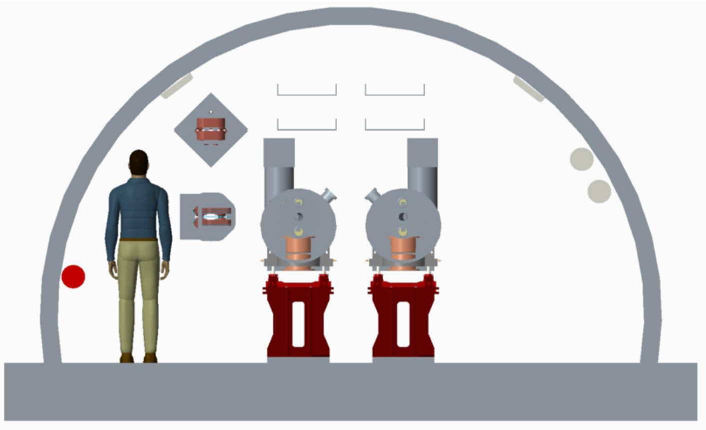


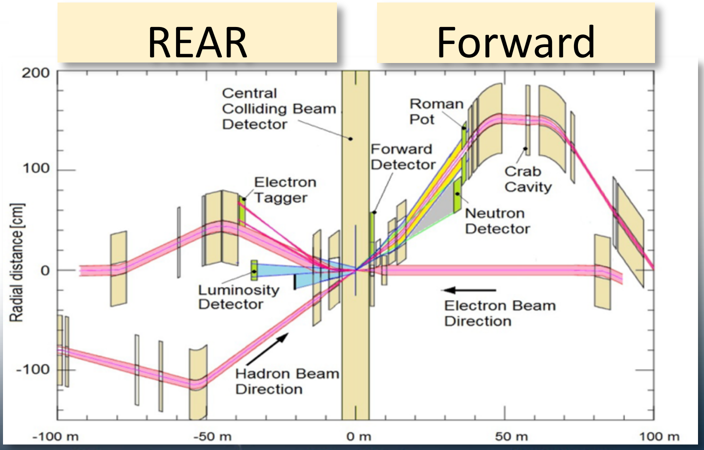
The eRHIC design goal has been adapted to reach the upper limit of the EIC White Paper luminosity range: **$L= 10^{34}$ cm^{-2}s^{-1}** with strong hadron cooling

- eRHIC is based on the RHIC complex: Storage ring (Yellow Ring), injectors, ion sources, infrastructure, which need only relatively few modifications and upgrades
- A (5-18) GeV electron storage ring & its injectors are added to the RHIC complex ➔ E_{cm} = (20-140) GeV
- To minimize risk, the eRHIC design is optimized under the assumption that each beam will have the parameters (in particular beam-beam tune-shift) that have been demonstrated in collisions in other colliders
- The requirement to store electron beams with a variable spin pattern requires an on-energy, spin transparent injector
- The total power of synchrotron radiation of the electron beam is assumed to be limited to 10 MW. This is a design choice.

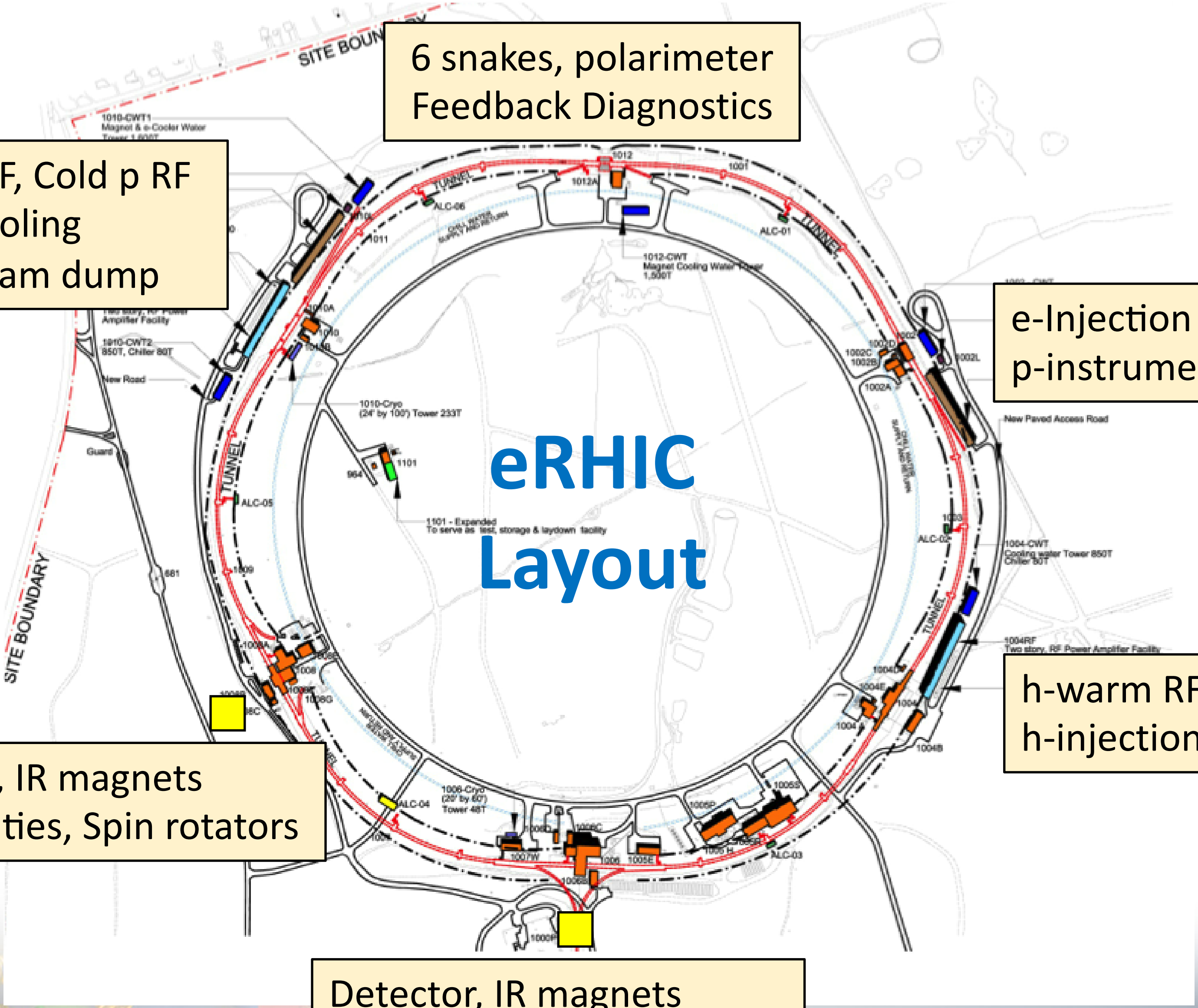
Key Additional Components

- **Electron Injector Synchrotron**
  - A comprehensive study resulted in the choice of a spin-transparent rapid cycling synchrotron in the RHIC tunnel
- **Electron Storage Ring**
  - Details given by Vadim – present plans call for a 10 MW limit on synchrotron radiation, which limits circulating current
- **IR Regions for Detectors**
  - Design satisfies requirements set by physics; uses 22 mr crab crossing and crab cavities





eRHIC Layout



6 snakes, polarimeter
Feedback Diagnostics

eRF, Cold p RF
Cooling
Beam dump

e-Injection
p-instrumentation

h-warm RF,
h-injection

Detector, IR magnets
Crab cavities, Spin rotators

Detector, IR magnets
Crab cavities, Spin rotators

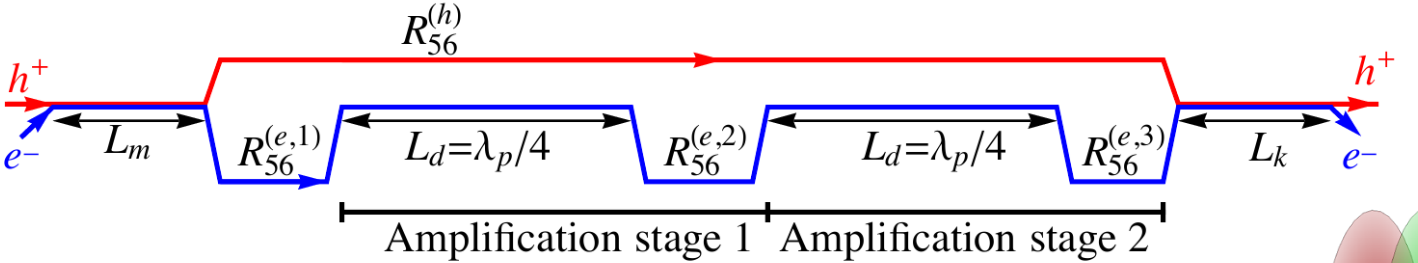
Strong Hadron Cooling

Necessary to reach highest luminosity in all EIC schemes.

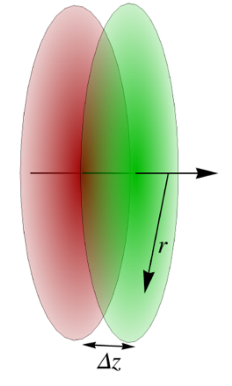
Several methods of strong hadron cooling have been studied:

- Bunched Beam Electron Cooling with an electron storage ring
- Coherent electron cooling with FEL amplifier or micro-bunching amplifier

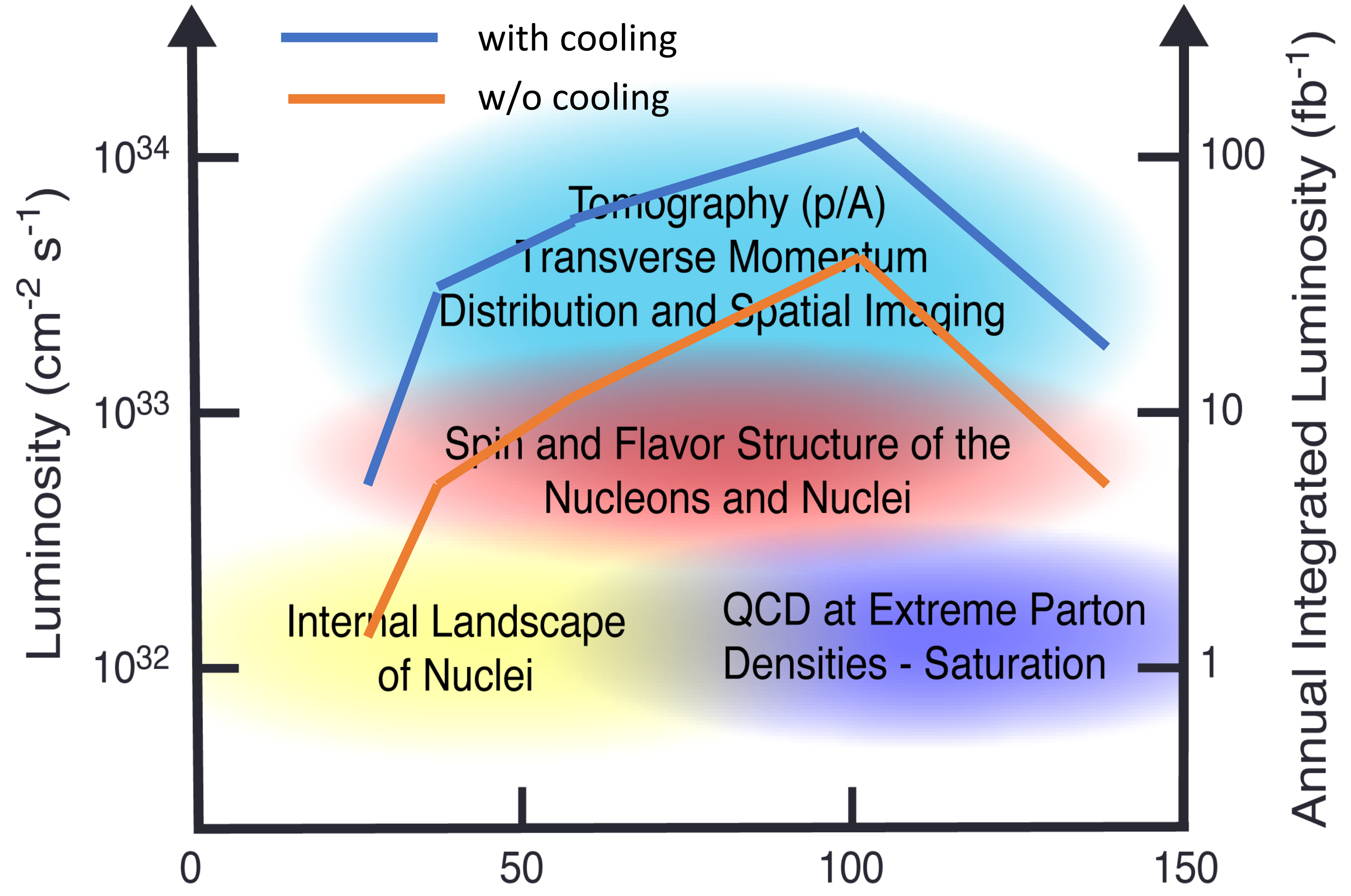
Most promising approach: micro-bunched electron beam cooling with two plasma amplification stages.



Predicted cooling rates with 100 mA electron current and flat beams are in the order of 1 hour which is sufficient for eRHIC. However, substantial R&D is needed before realization.

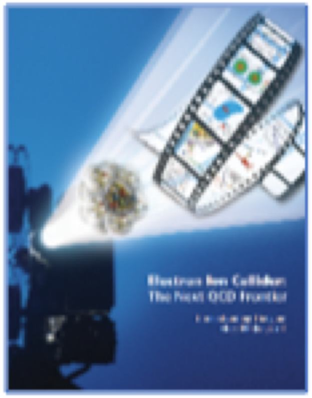


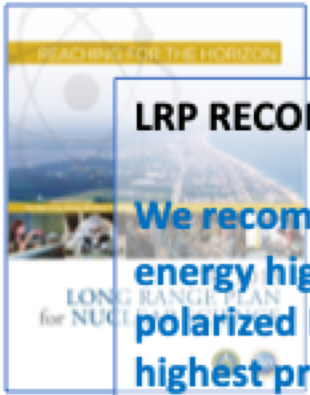
Luminosity versus CM Energy



Timeline (Past)

2011 **2012** **2013** **2014** **2015** **2016** **2017** **2018**





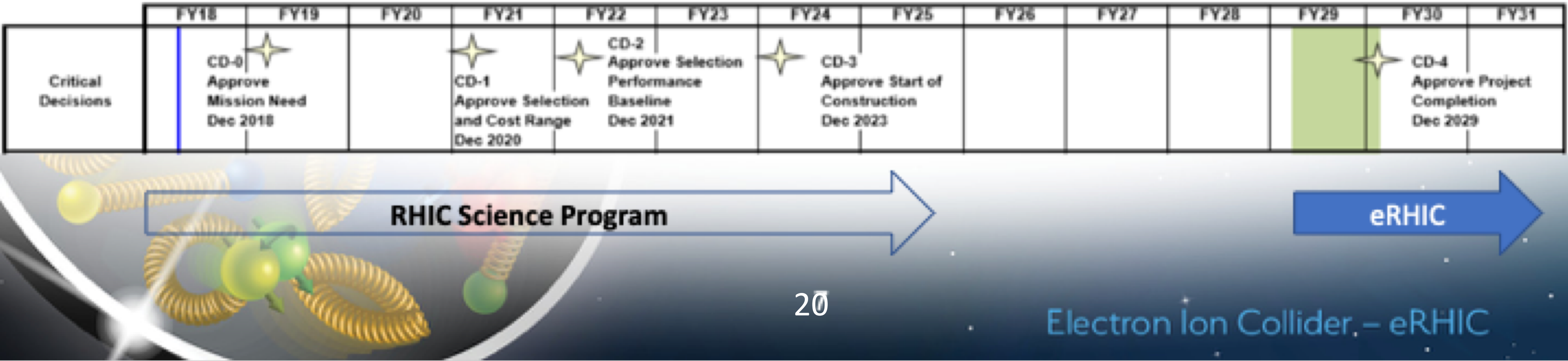
LRP RECOMMENDATION

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

NAS Review of the science case for a U.S.-based EIC:

...the committee finds a compelling scientific case for such a facility.

Timeline (Notional)



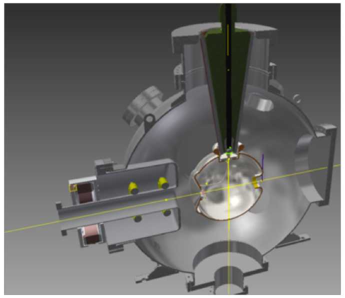
	FY18	FY19	FY20	FY21	FY22	FY23	FY24	FY25	FY26	FY27	FY28	FY29	FY30	FY31
Critical Decisions	CD-0 Approve Mission Need Dec 2018			CD-1 Approve Selection and Cost Range Dec 2020	CD-2 Approve Selection Performance Baseline Dec 2021		CD-3 Approve Start of Construction Dec 2023						CD-4 Approve Project Completion Dec 2029	

RHIC Science Program

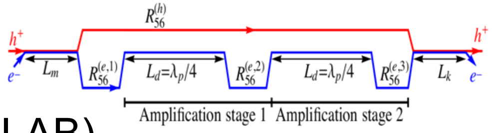
eRHIC

EIC Accelerator R&D @ BNL

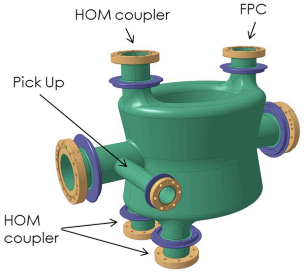
- Development of a **large cathode Inverted gun** for high average current, high bunch charge polarized electron beam



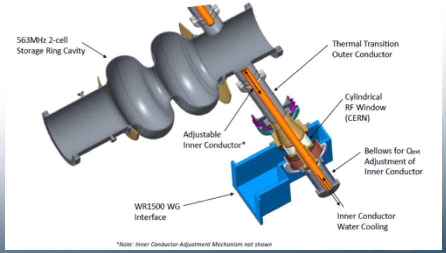
- Advanced coherent electron cooling with plasma amplification (in preparation)
- **Coherent electron cooling** with multi-staged microbunching is studied theoretically (Coll. BNL-JLAB-ANL-SLAC)



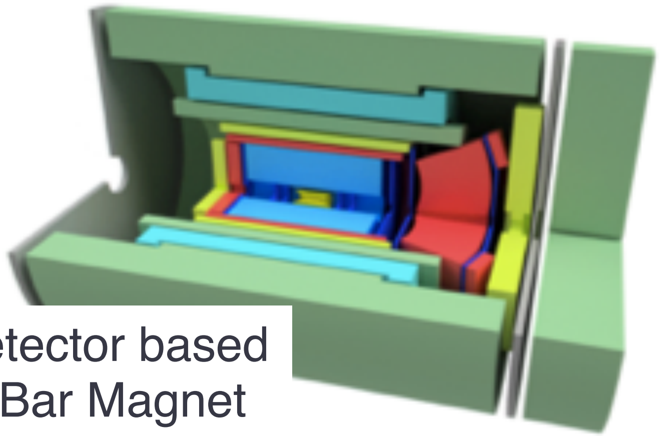
- **Development of simulation tools** for EIC (Coll. BNL-LBNL-MSU-JLAB)
- **Study of Spin transparency** mode in EIC (Collaboration with JLAB)
- **Crab-cavity in hadron ring:** SPS test (Coll. with JLAB & CERN)

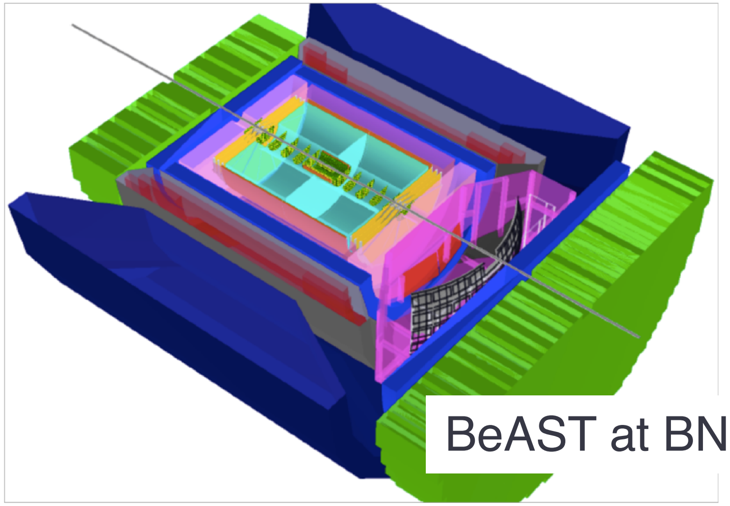


- **High Gradient actively shielded quadrupole** (Coll BNL-LBNL-JLAB)
- **Development of ^{3}He ion source polarimetry** (Coll BNL-MIT)
- **Study of storage ring based electron cooling** (Coll. BNL-JLAB)
- **Development of 1 MW variable coupling input coupler** for electron storage ring superconducting cavity (LDRD)

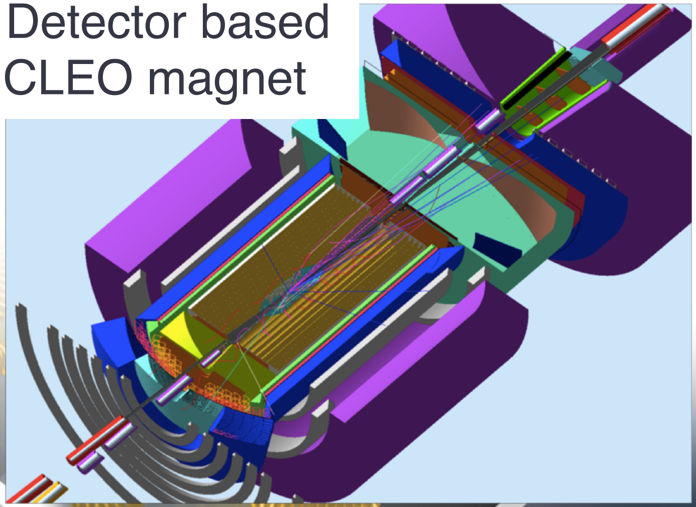


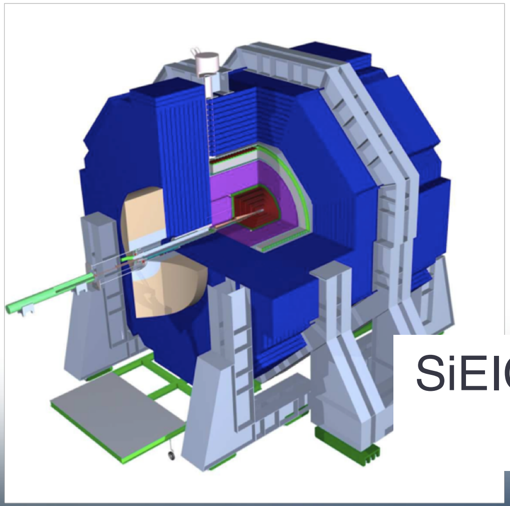
EIC Detector R&D


EIC Detector based on BaBar Magnet


BeAST at BNL

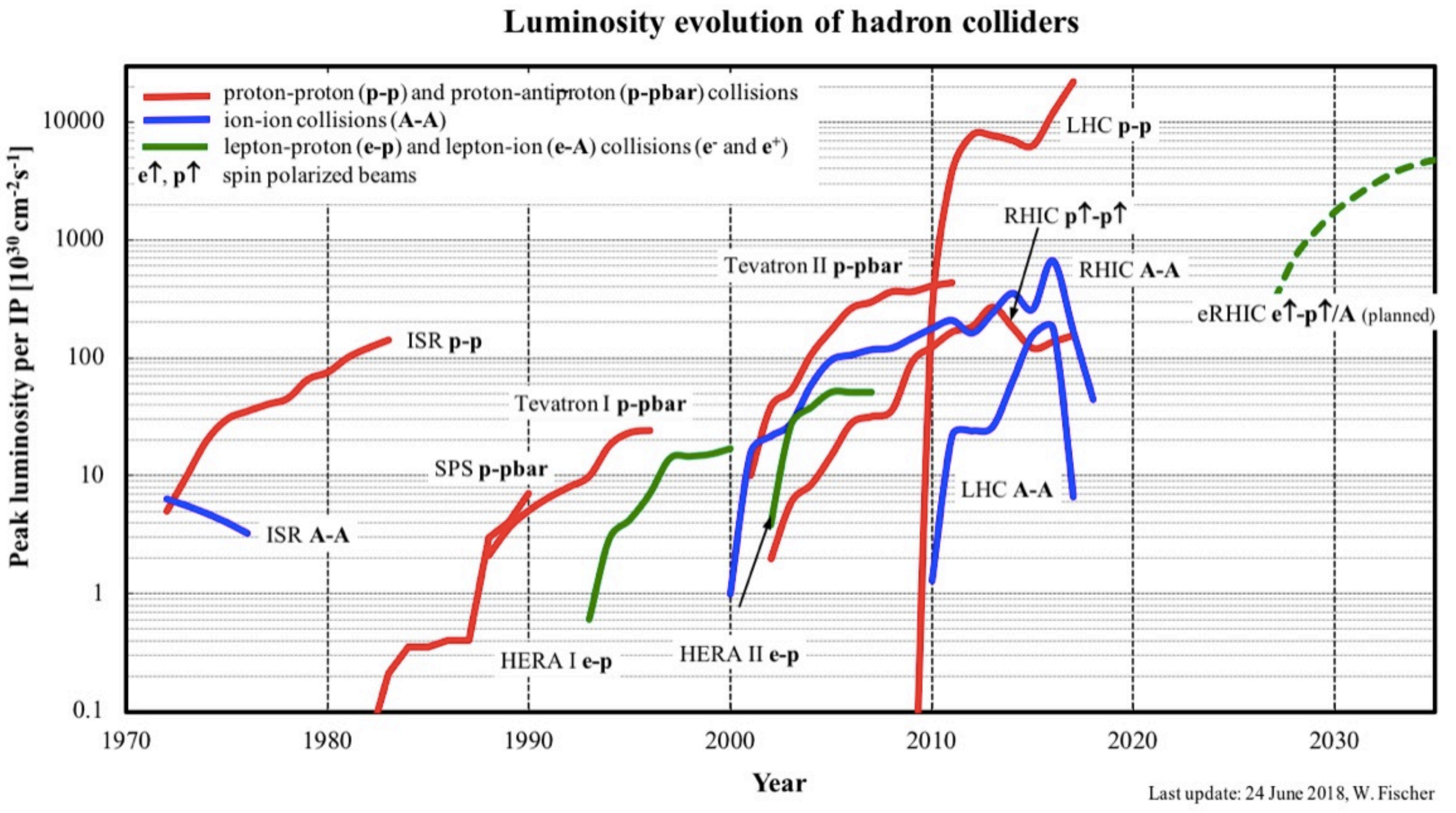
Ongoing $1M Generic EIC Detector R&D Program managed by BNL


EIC Detector based on CLEO magnet


SiEIC Detector (ANL)

EIC Program Considerations

Colliders start gradually



Integral Luminosity

For any collider, (integrated) luminosity evolves by a large factor over time. For eRHIC, we anticipate starting with 10^{33} cm^{-2} s^{-1} and increasing to 4.4×10^{33} cm^{-2} s^{-1} over a few years, finally reaching 10^{34} cm^{-2} s^{-1} after implementation of strong hadron cooling, for a 20-fold increase in integrated luminosity per year (from 5 fb^{-1} to 100 fb^{-1} per year).

	eRHIC		
	Initial operation	Without cooling	Nominal
Peak L, 10^{33} cm^{-2} s^{-1}	1.05	4.4	10
Average store L calculated, 10^{33} cm^{-2} s^{-1}	0.93	3.85	9.95
Contingency of average store L evaluation	20%	20%	0
Store length, h	11	10	several days
Time in store, %	60%	60%	75%
Integral L/week, fb^{-1}	**0.27**	**1.12**	**4.51**
Average L in the Run, 10^{33} cm^{-2} s^{-1}	0.56	2.31	7.46
Average L/Peak L	0.53	0.53	0.75

Collider Operations Models

LHC Model:

- Multi-year runs separated by long shutdowns allowing for major upgrades
- One dominant run mode (p+p) dominated by luminosity considerations
- Secondary programs (p+A, A+A) with limited luminosity needs

RHIC Model:

- Collider operates in every (fiscal) year since 2000
- Multiple systems in many years, often at multiple energies
- Annual incremental upgrades to collider and to detectors during ~6-month shutdown/maintenance period
- Systems and energies revisited as luminosity increases and detector systems acquire new capabilities

What will be the right operations model for the EIC?

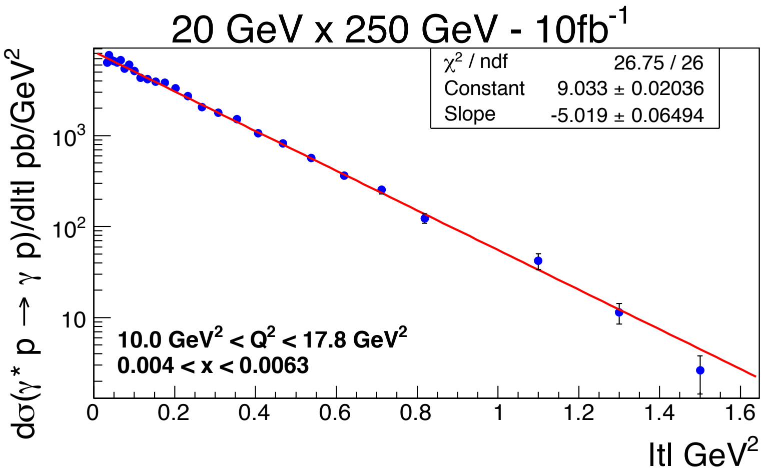
EIC: The first 5 years

It’s not too early to think about what the EIC science program could (should?) like in the first five years. DOE, Congress, science community will expect high-impact results in the first few years:

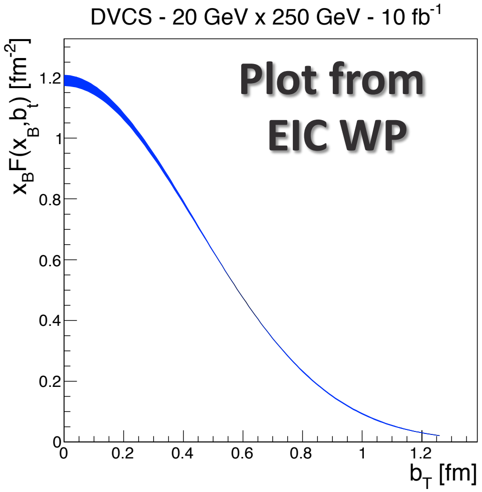
- What are the most important physics questions that can be addressed as the luminosity ramps up?
- What detector capabilities are required to carry out the measurements?
- Which collision systems will have the largest impact?
- Which collision energies will have the largest impact?
- What are the trade-offs?

eRHIC will yield early results

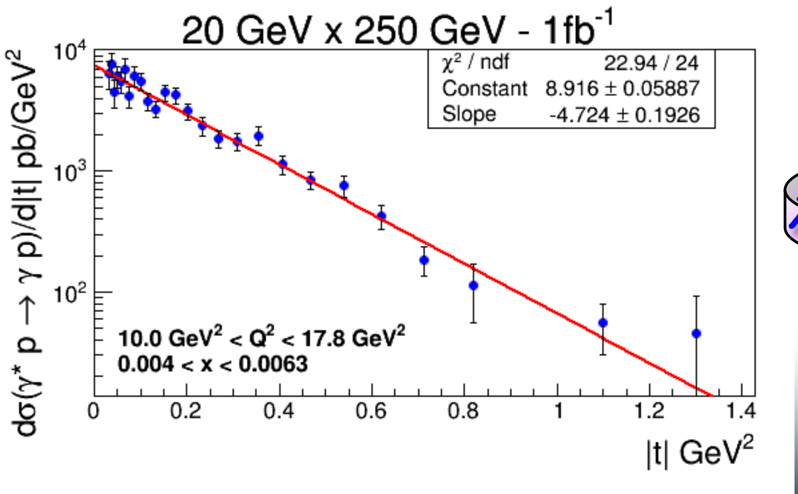
$10\ \mathrm{fb}^{-1} \rightarrow 1\ \mathrm{fb}^{-1}$ **$0.18 < |p_t|\ (\mathrm{GeV}) < 1.3$**



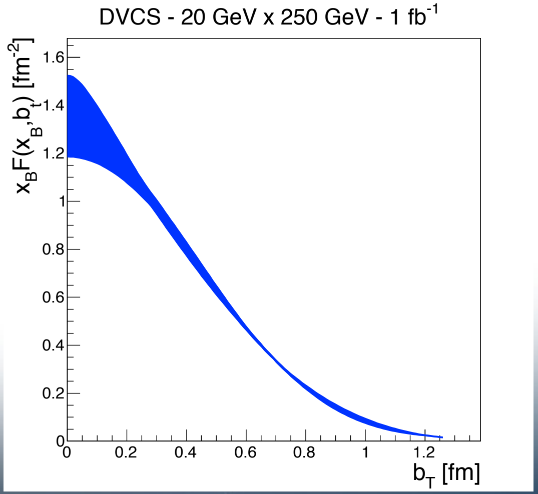
Fourier Transform



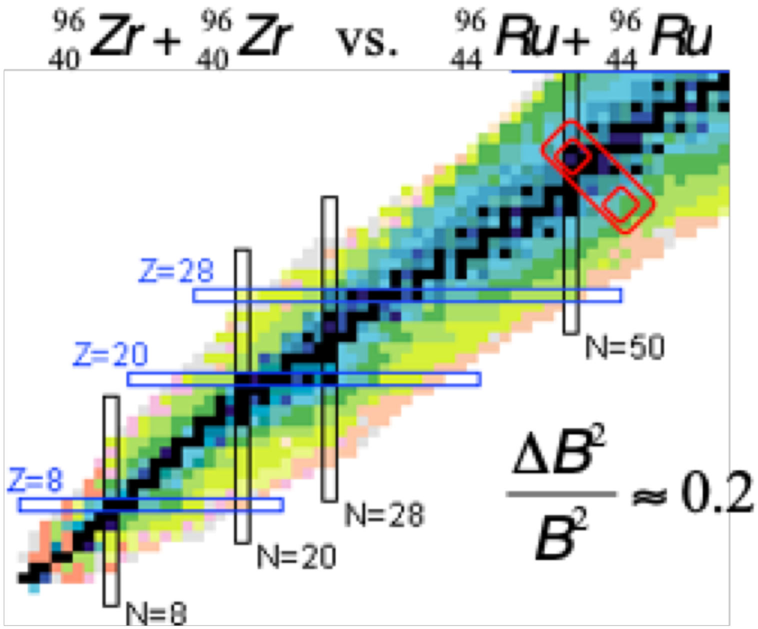
Plot from EIC WP



Fourier Transform



A Physics Question



In 2018 RHIC ran two isobar systems in shift-by-shift switch mode; $3\text{x}10^9$ collisions recorded for each system.

Goal: determine B-dependence of electric charge fluctuations (a rare signal of the chiral magnetic effect) with ~5% precision using the 10% difference in nuclear charge.

But: ^{96}Zr ($I_3 = -8$) and ^{96}Ru ($I_3 = -4$) differ by a factor 2 in isospin!

Could a comparison of e+ ^{96}Zr and e+ ^{96}Ru collisions be used to measure the effect of valence quark isospin on parton distributions in ways that are not easily accessible from final state observables?

Summary & Outlook

Over the past year, we have made significant progress in understanding the role of the energy range in realizing the full physics potential of an EIC. The new Center for Frontiers in Nuclear Science (CFNS) is supporting the effort by the EIC community to fully develop the EIC science program and train young scientists for their future role in it.

We have completed a pre-conceptual design report for the ring-ring version of eRHIC and are actively engaged in a broad program of EIC accelerator and generic detector R&D in close collaboration with many other institutions.

The energy and luminosity range of eRHIC would enable a robust physics program that addresses the goals of the 2015 NSAC Long Range Plans:

- fully access the sea-quark and gluon dominated regime
- reveal the dynamics of sea quarks and gluons in hadrons
- open up the phase space for new probes of nucleon / nuclear structure (jets, charge current, etc.)

Additional Slides

Electron Injector Synchrotron

- (5-18) GeV spin polarized electrons are required for injection into the storage ring.
- A comprehensive study resulted in the choice of a spin-transparent rapid cycling synchrotron in the RHIC tunnel
- High lattice quasi-symmetry suppresses depolarizing resonances during the ramp; a 200 ms ramp is sufficiently fast to cross resonances without loss of polarization
- Magnetic stray-field from the injector experienced by the storage ring have been calculated to be negligible
- Bypass around the detectors are accomplished without distorting the quasi symmetry

Electron Storage Ring

Composed of six FODO arcs with 60º /cell for 5-10 GeV

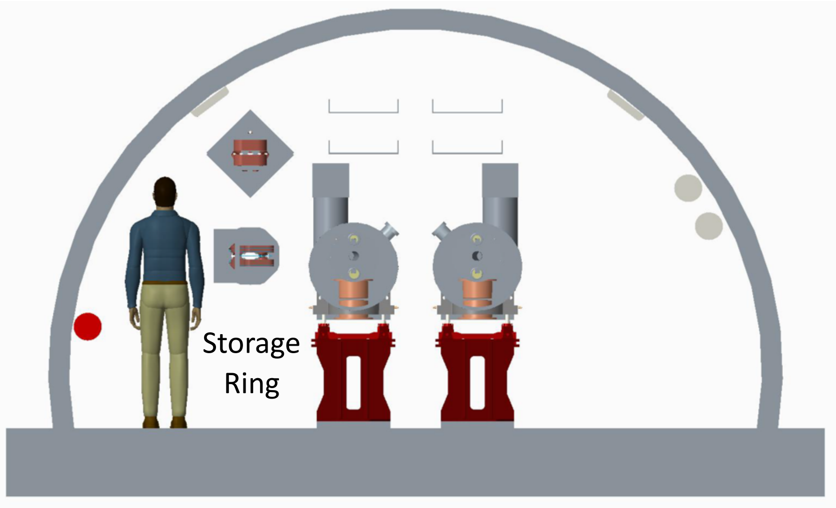
90º /cell for 18 GeV

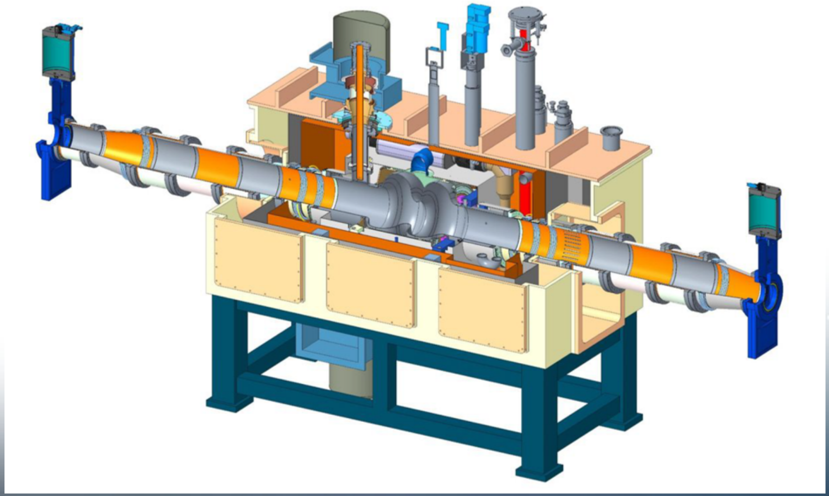
Super-bends for 5-10 GeV for emittance control

Six straight sections with simple layout

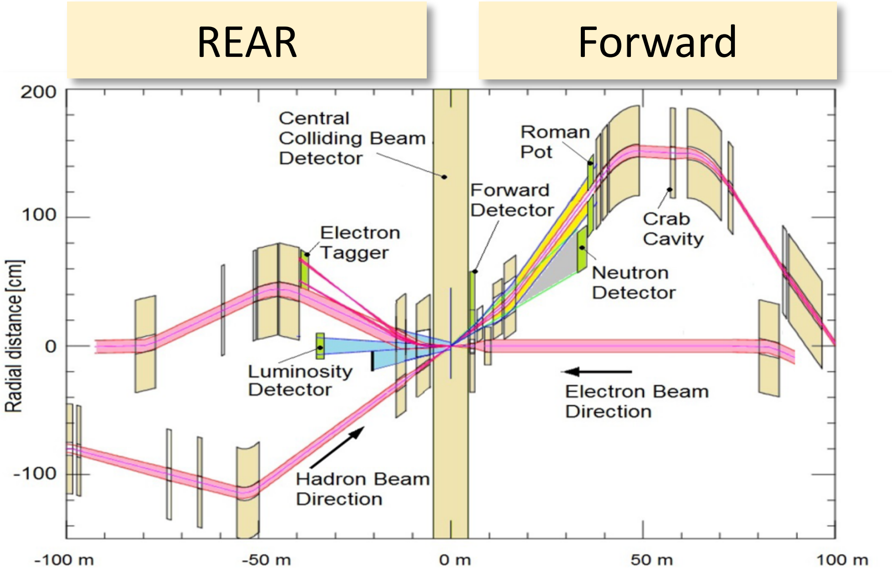
Radiate ~10 MW for maximum luminosity parameters at 10 GeV

Requires 11 superconducting 2-cell 563 MHz RF cavities





IR Layout



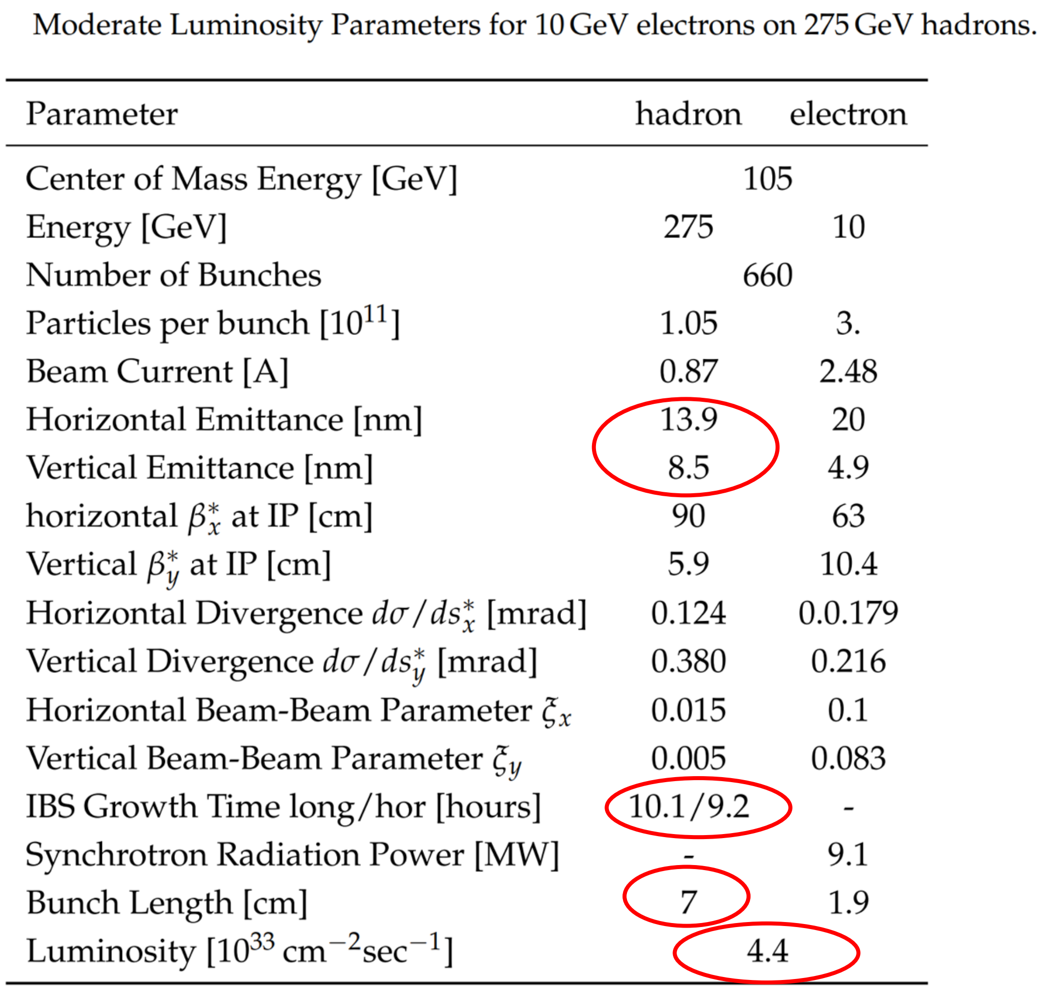
IR design requirements:

- Small β* for high luminosity
- Limited IR Chromaticity contributions
- Large final focus quadrupole aperture
- Large Detector acceptance
- Accommodate dipole spectrometer
- No accelerator magnets +/-4.5 m
- 22 mrad Crossing angle, crab crossing, crab cavities 90° from IP
- Minimize 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 by incorporating novel types of magnets in the IR

eRHIC w/o Strong Hadron Cooling

Solution with L = 4.4x10^{33} cm^{-2}s^{-1} and IBS growth rates of 10/9 h (long./hor.)

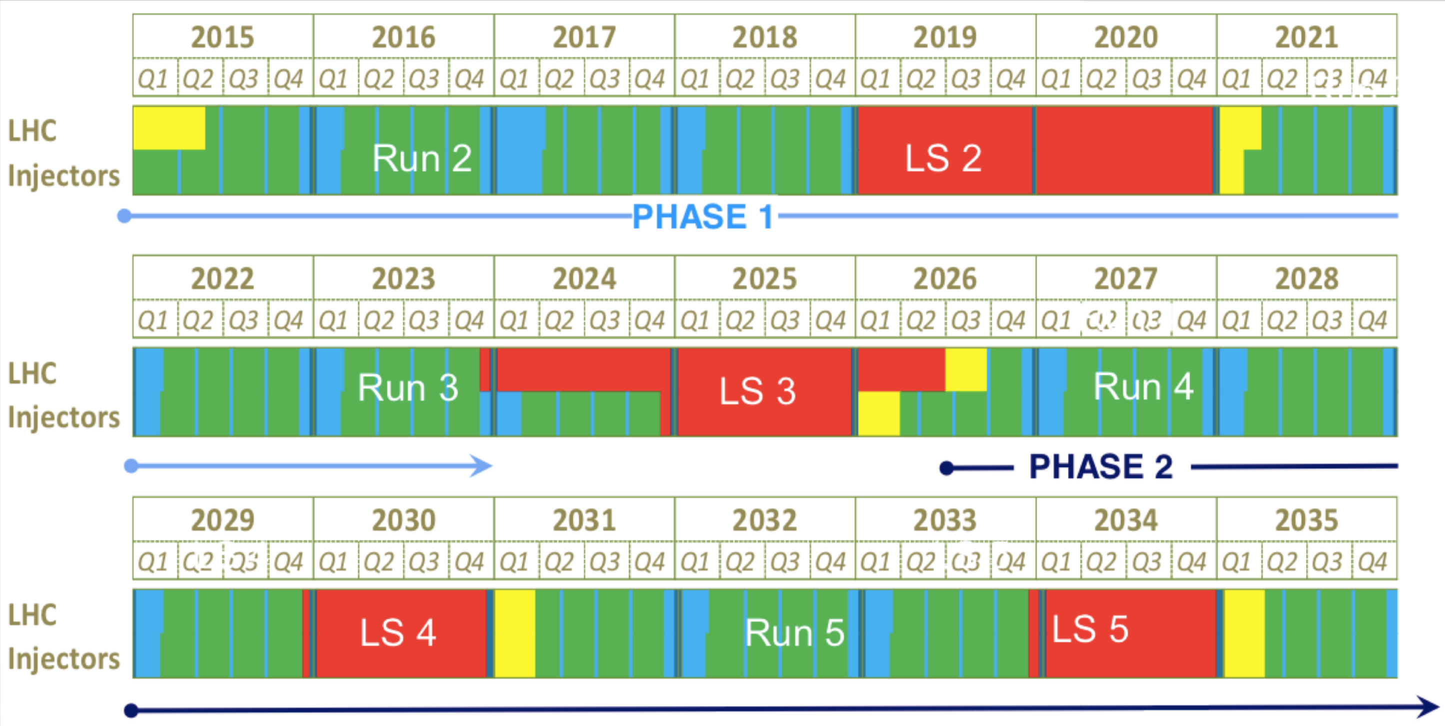


Moderate Luminosity Parameters for 10 GeV electrons on 275 GeV hadrons.

Parameter	hadron	electron
Center of Mass Energy [GeV]	105	
Energy [GeV]	275	10
Number of Bunches	660	
Particles per bunch [10^{11}]	1.05	3.
Beam Current [A]	0.87	2.48
Horizontal Emittance [nm]	13.9	20
Vertical Emittance [nm]	8.5	4.9
horizontal β_x^* at IP [cm]	90	63
Vertical β_y^* at IP [cm]	5.9	10.4
Horizontal Divergence $d\sigma/ds_x^*$ [mrad]	0.124	0.0.179
Vertical Divergence $d\sigma/ds_y^*$ [mrad]	0.380	0.216
Horizontal Beam-Beam Parameter ξ_x	0.015	0.1
Vertical Beam-Beam Parameter ξ_y	0.005	0.083
IBS Growth Time long/hor [hours]	10.1/9.2	-
Synchrotron Radiation Power [MW]	-	9.1
Bunch Length [cm]	7	1.9
Luminosity [10^{33} cm^{-2}sec^{-1}]	4.4	

Collider Operations Models: LHC

- Multi-year runs separated by long shutdowns allowing for major upgrades
- One dominant run mode (p+p) dominated by luminosity considerations
- Secondary programs (p+A, A+A) with limited luminosity needs



Collider Operations Models: RHIC

- Collider operates in every (fiscal) year since 2000
- Multiple systems in many years, often at multiple energies
- Annual incremental upgrades to collider and to detectors during ~6-month shutdown/maintenance period
- Systems and energies revisited as luminosity increases and detector systems acquire new capabilities

FY11	FY12	FY13	FY14	FY15
p+p, Au+Au	p+p, U+U, Cu+Au	p+p	Au+Au, ^{3}He+Au	p+p, p+Au, p+Al

FY16	FY17	FY18	FY19	FY20
Au+Au, d+Au	p+p, Au+Au	Zr+Zr, Ru+Ru, Au+Au	Au+Au (coll) Au+Au (FXT)	Au+Au (coll) Au+Au(FXT)

FY21	FY22	FY23	FY24	FY25
Au+Au, p+p	p+p ?	Au+Au	p+p, p+Au	Au+Au

EIC Program: First 4 years?

….making "reasonable" luminosity growth assumptions

Years 1 + 2: eAu at full energy will give the first results in unknown territory

  - **Nuclear PDFs**
  - **First look at saturation through di-hadrons and diffraction**

Year 3: Longitudinally polarized ep beams at full energy

- **$\int L \sim 5\ \mathrm{fb}^{-1}$ will give very important results on**
  - **Definitive spin structure of the proton**
  - **Unpolarized PDFs at large Q^2 and x**
  - **(Un-)polarized fragmentation functions**

Year 4: Split run between transverse polarized ep running at full energy and eA running for different nuclear beams and energies

- **$\int L \sim 5\ \mathrm{fb}^{-1}$ transverse polarized ep data will give very important**
  - **First results on the momentum and spatial 3-D structure of the proton**
- **$\int L \sim 5\ \mathrm{fb}^{-1}$ eA data with different nuclei and energies will**
  - **Measure A-dependence of nuclear PDFs**
  - **Study the evolution of Q_s with x and A**