Center for Frontiers in Nuclear Science

Ion- and Electron-Ion Colliders

Toward full understanding of QCD

Plenary ECFA Meeting
November 16th , 2018

Kick off with HI Experiments (physics goals & detector realization plan)
Detailed Discussion: CERN Townhall Meeting October 2018

Launch in to US Electron Ion Collider and cover all aspects requested in the PECFA invitation

Stony Brook University

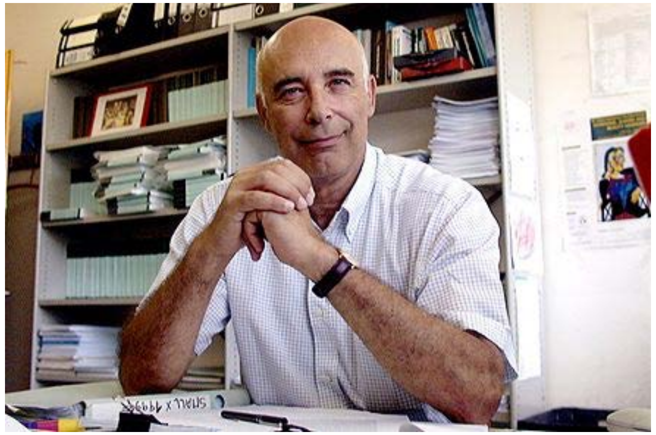
Abhay Deshpande

BROOKHAVEN NATIONAL LABORATORY

Complementarity of Probes in Physics

Guido always emphasized:

Standard Model of Physics was developed using **e+e-, p+p, and e+p collisions** over a **wide range in energy…..**



I observe that it is also true for QCD

We would not get the full understanding of QCD (The Standard Model of Strong Interactions) without studying it with **e+e-, p+p, e+p, e-A, and A+A** collisions over a **wide range of energies** AND also where possible with **polarized e, p, and light ion beams.**

QCD: The Holy Grail of Quantum Field Theories

- QCD : "nearly perfect" theory that explains nature's strong interactions, is a fundamental quantum theory of quarks and gluon fields
- QCD is rich with symmetries:

$$SU(3)_C \times SU(3)_L \times SU(3)_R \times U(1)_A \times U(1)_B$$

(1) (2) (3)

(1) Gauge "color" symmetry : unbroken but confined
(2) Global "chiral" flavor symmetry: exact for massless quarks
(3) Baryon number and axial charge (massless quarks) conservation
(4) Scale invariance for massless quarks and gluon fields
(5) Discrete C, P & T symmetries

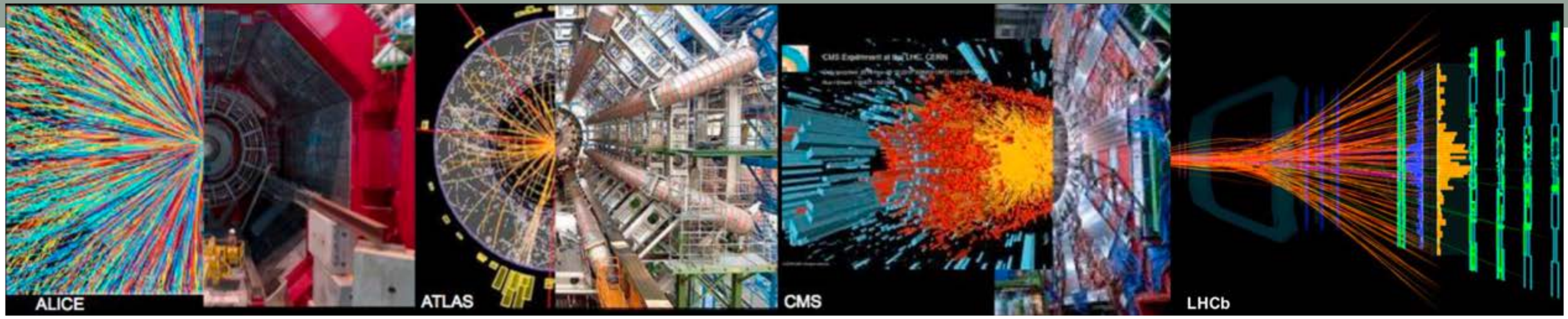
- Chiral, Axial, Scale & P&T symmetries broken by quantum effects: Most of the visible matter in the Universe emerges as a result
- Inherent in QCD are the deepest aspects of relativistic quantum field theories: (confinement, asymptotic freedom, anomalies, spontaneous breaking of chiral symmetry) ➔ all depend on non-linear dynamics in QCD

Non-linear Structure of QCD has Fundamental Consequences

Emergence of spin, mass & confinement, gluon fields

- Quark (Color) confinement:
  - Unique property of the strong interaction
  - Consequence of nonlinear gluon self-interactions
  - Clues: deconfinement in QGP @ LHC/RHIC & fragmentation/hadronization @ EIC
- Strong Quark-Gluon Interactions:
  - Confined motion of quarks and gluons – Transverse Momentum Dependent Parton Distributions (TMDs): *Measured at an EIC, and used in others including LHC*
  - Confined spatial correlations of quark and gluon distributions – Generalized Parton Distributions (GPDs): *Measured at an EIC, and used elsewhere*
- Ultra-dense color (gluon) fields:
  - Is there a universal many-body structure due to ultra-dense color fields at the core of **all** hadrons and nuclei?
  - *To be measured in light ion and asymmetric collisions at LHC/RHIC and at the EIC*
  - *Initial State of Heavy Ion Collisions*

LHC/RHIC & EIC are all essential for the deeper understanding of QCD

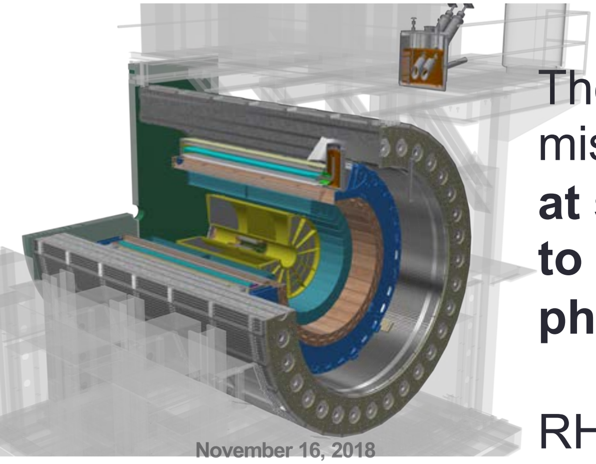


European Strategy for Particle Physics Update 2013:
Europe's top priority should be the exploitation of the full potential of the LHC, including the high-luminosity upgrade of the machine and detectors with a view to collecting ten times more data than in the initial design, by around 2030. This upgrade program will also provide further exciting opportunities for the study of flavour physics and the quark-gluon plasma.

Nuclear Physics European Collaboration Committee 2017

crucial that all aspects of the LHC heavy-ion program, including manpower support and completion of the detector upgrades, are strongly supported

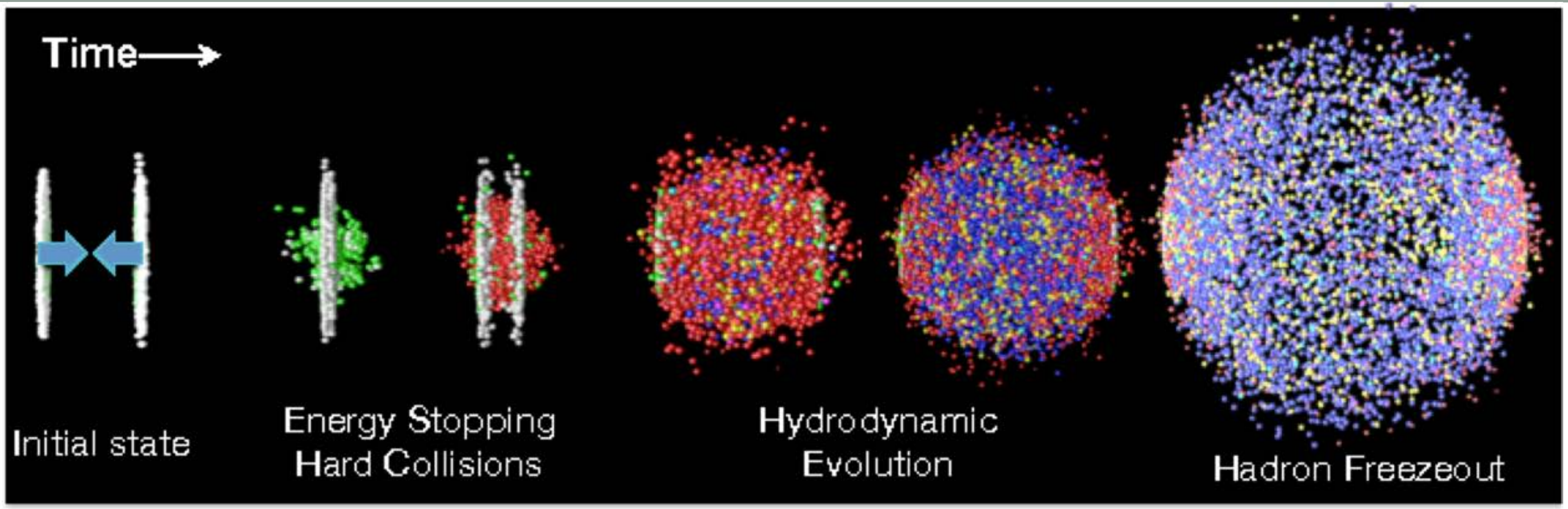
US Nuclear Science Advisory Committee's 2015 Long Range Plan



There are two central goals of measurements planned at RHIC, as it completes its scientific mission, and at the LHC: **(1) Probe the inner workings of QGP by resolving its properties at shorter and shorter length scales. The complementarity of the two facilities is essential to this goal, as is a state-of-the-art jet detector at RHIC, called sPHENIX. (2) Map the phase diagram of QCD with experiments planned at RHIC.**

RHIC provides unique capabilities for QGP studies and to study the proton spin

Heavy Ion Town-meeting CERN October 2018



Jan Fiete Grosse-Oetringhaus, CERN

Open Questions

- The quest for the QGP has turned into a precision exercise
- The questions remain puzzling and exciting

- What is the underlying dynamics?
  - Model describing long wavelength (ideal fluid) and short wave-length ("quenching") beha
- What are the (relevant) degrees of freedom / microscopic structure?
- How to derive behavior from QCD?

- QGP "onset" in light of the discoveries in small systems
  - Collectivity in small systems challenges two paradigms at once!
    1. How far down in systems size does the "SM of heavy ions" remain?
    2. Can the standard tools for min bias pp remain standard?

    Christian Bierl Workshop on at HL-LHC, 31
  - Collective effects in small and dilute systems?

Future physics opportunities for high-density QCD with ions and protons - Jan Fiete Grosse-Oetringhaus

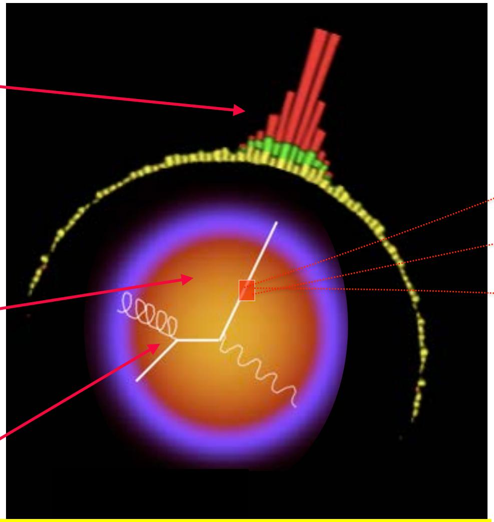
D. Morrison, BNL

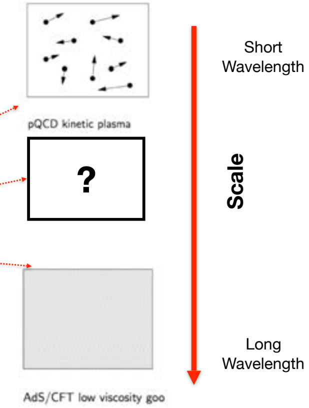
sPHENIX

Full characterization of final state

Different QGP initial conditions and evolution at RHIC and LHC

Same hard process



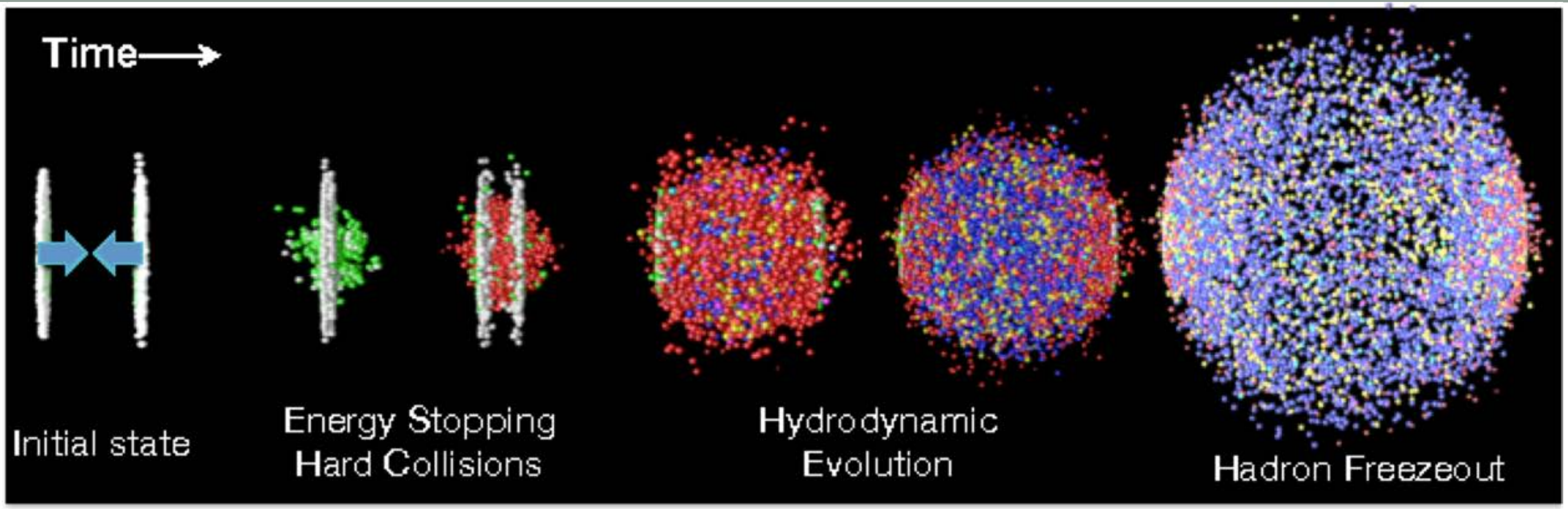


Jets, jet-structure, quarkonia, and parton energy loss

How does long-wavelength physics emerge from underlying gauge theory?

x

Heavy Ion Town-meeting CERN October 2018



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Christian Bierlich, Workshop on physic at HL-LHC, 31.10.17

Future physics opportunities for high-density QCD with ions and protons - Jan Fiete Grosse-Oetringhaus 6

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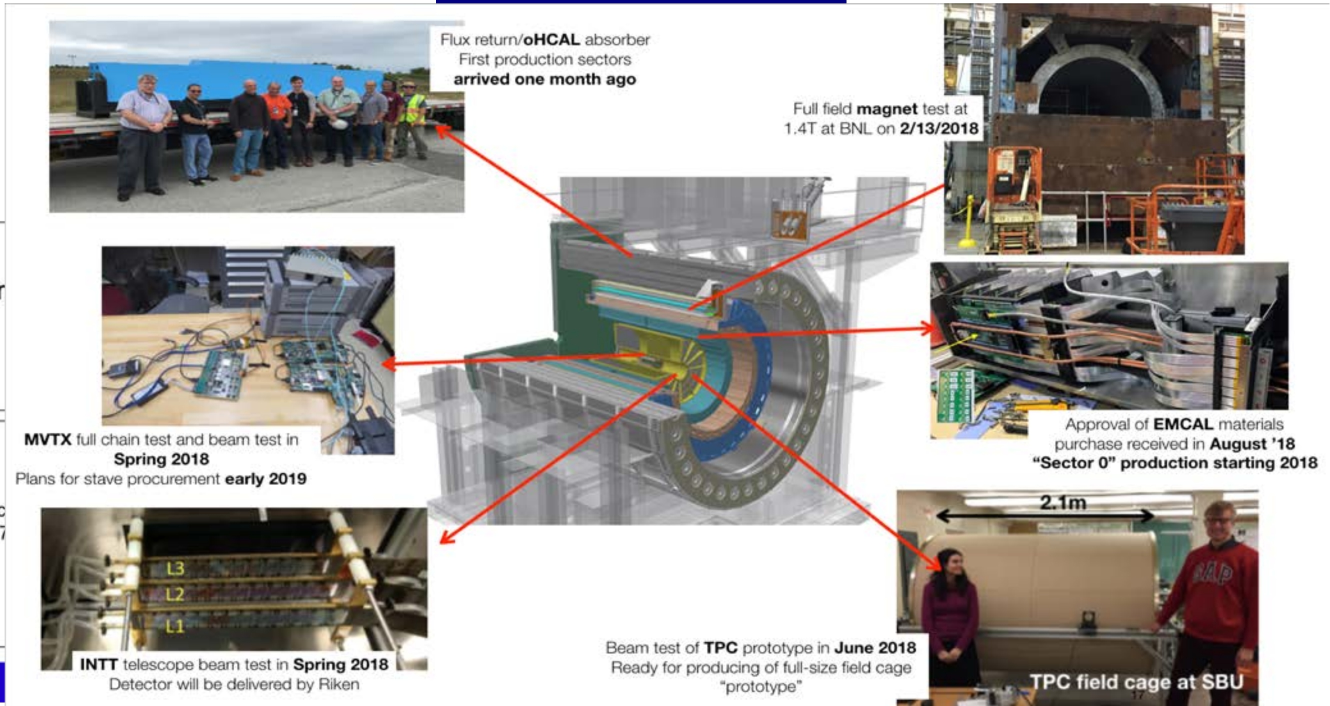

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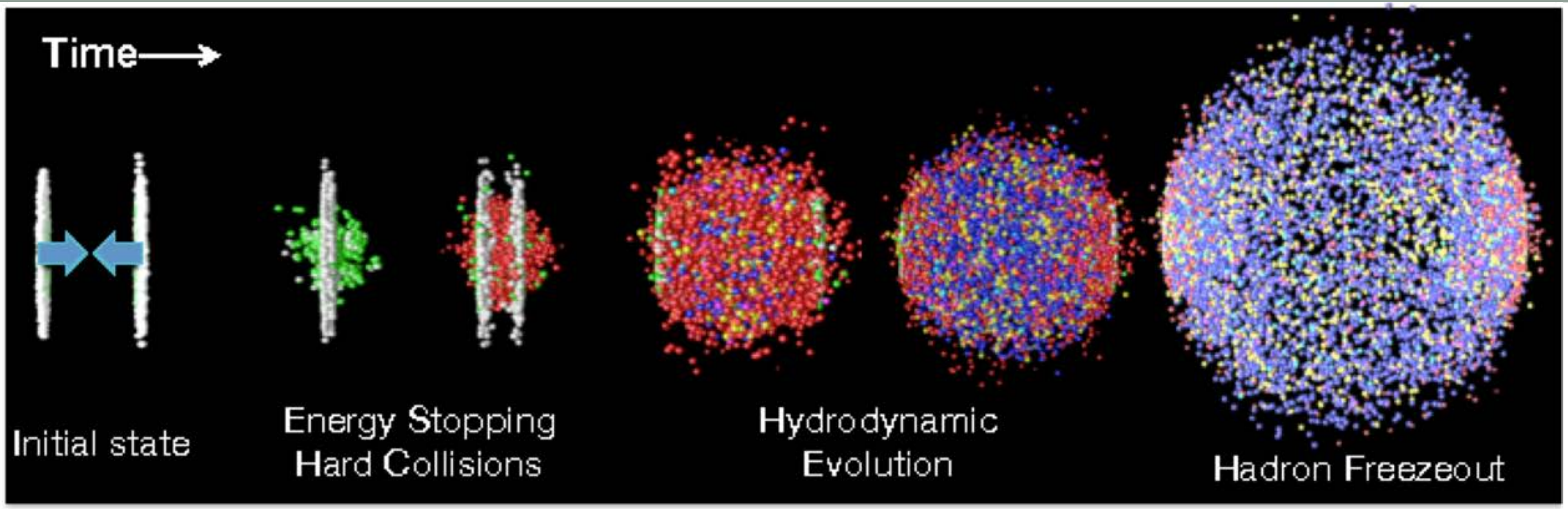

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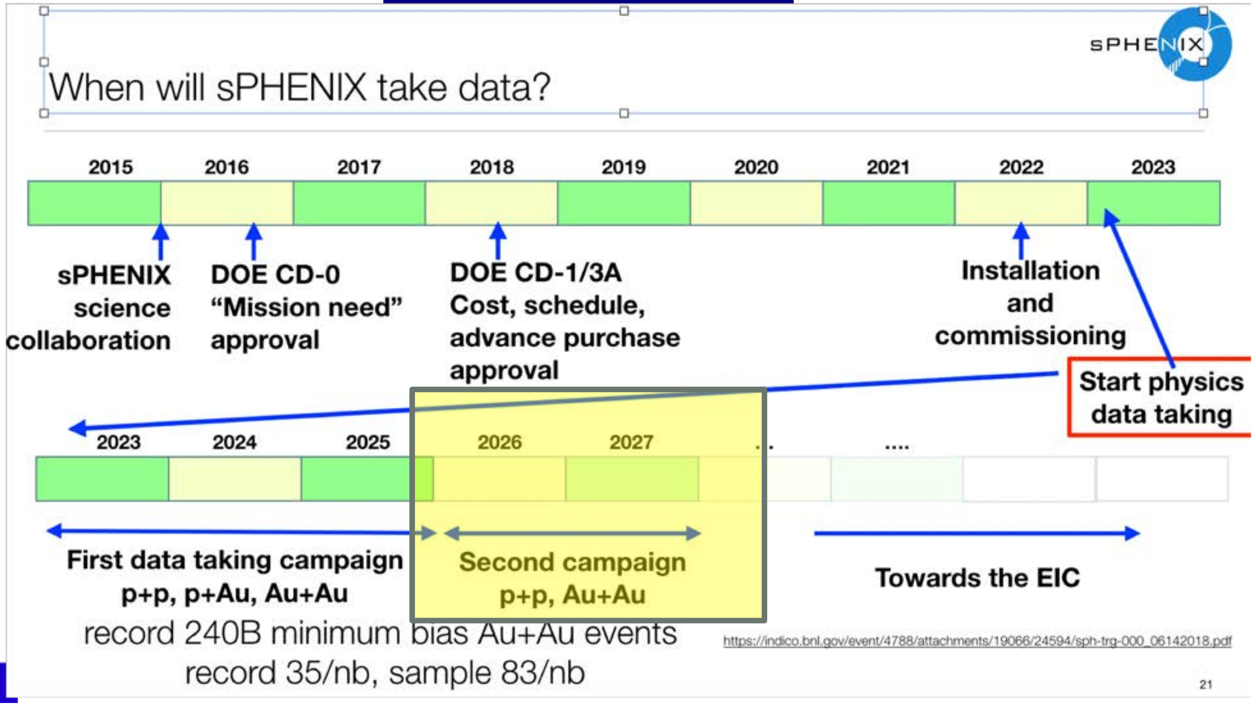
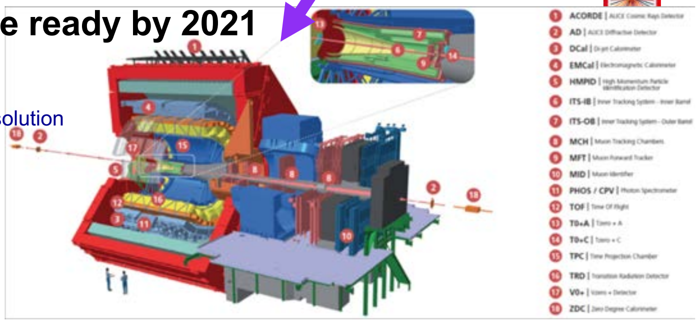


Run 2	Long shutdown 2	Run 3	Long Shutdown 3	Run 4	LS4

2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029

A Large Ion Collider Experiment

ALICE LS2 Upgrade ready by 2021



New Inner Tacking System (ITS)
- MAPS technology: improved resolution
- Less material,
- Faster readout

New TPC Readout Chambers
- New readout chambers using 4-GEM technology
- New electronics for continuous readout (SAMPA)

New Forward Muon Tracker (MFT)
- Vertex tracker at forward rapidity

Muon Arm
- New electronics (SAMPA)
- New electronics for Muon Trigger

Online Offline (O2) system
- new computing facility
- on line tracking & data compression
- 50kHz Pb-Pb event rate

Common Projects:
Common Readout Unit
SAMPA common FE chip

New Trigger Detectors (FIT, AD)
- + centrality, event plane

New Central Trigger Processor

Upgraded readouts for TOF, TRD, PHOS, EMCAL, CPV, HMPID

8

CMS Phase 1 Upgrade	CMS Phase 2 Upgrade

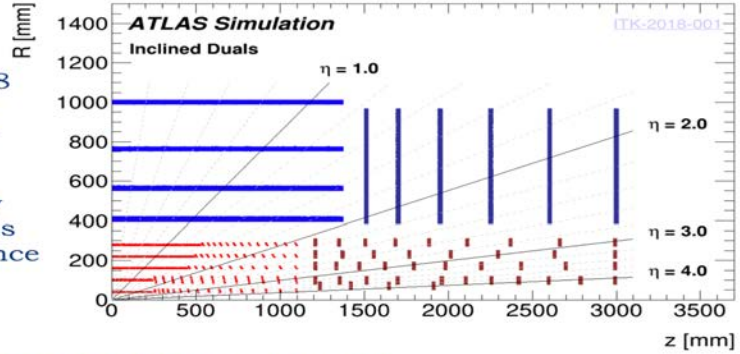
- 2016: Major upgrade of L1 trigger
- 2017: 4-Layer Pixel Detector
- 2018 Performance:
  - pp L1 100kHz
  - PbPb L1 **30kHz** (3x of 2015)
  - DAQ: 6 GB/s
    - Up to **6.5 kHz** MinBias events to tape (20x of 2015)

2024-26
- **Tracker |η|<4**
- **Muon ID up to |η|<3**
- High Granularity Calo **1.6<|η|<3.0**
- MIP timing detector
  - 4D vertexing
  - Possible p/K/π PID
- pp L1: 750 kHz
- DAQ: 60 GB/s

Yen-Jie Lee Future Plan from CMS 2

ATLAS Inner Tracker (ITk)

- η coverage of 8 units and all silicon design
- ~15 hits per track, approximately uniform across the η acceptance



- 5 pixel and 4 double-sided barrel layers
- 6 strip endcap disks
- Pixel endcap disks in the forward direction

To be installed before Run 4

3

Run 2	Long shutdown 2	Run 3	Long Shutdown 3	Run 4	LS4

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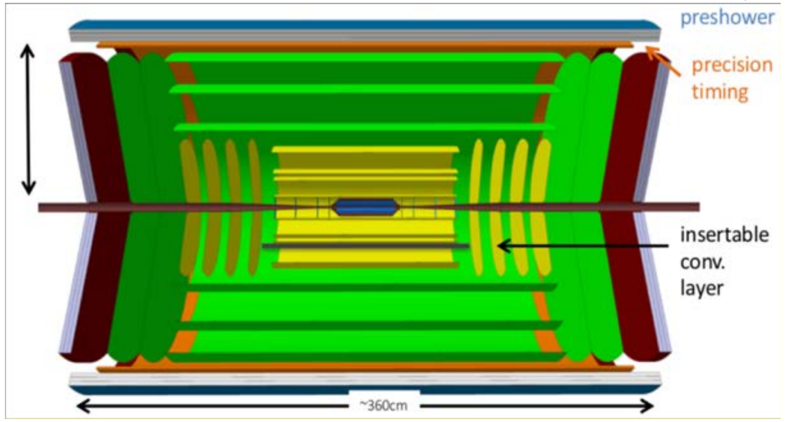
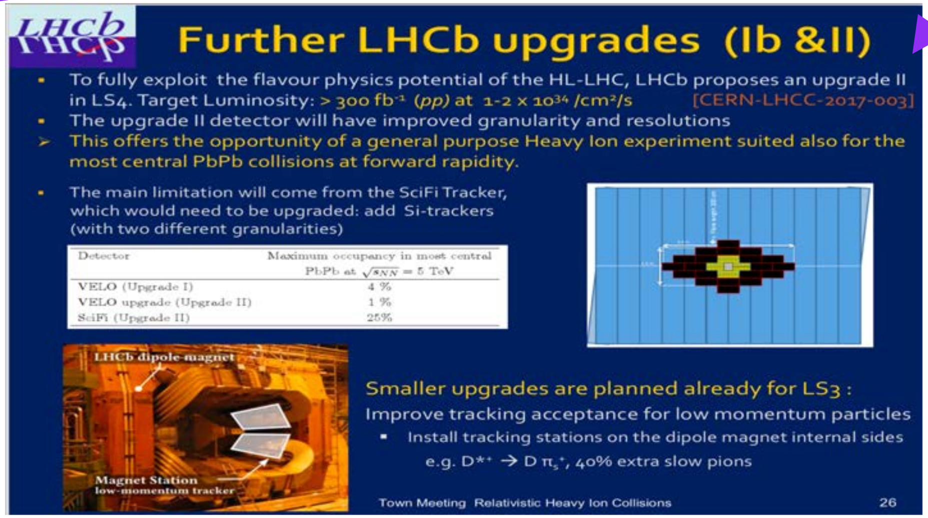
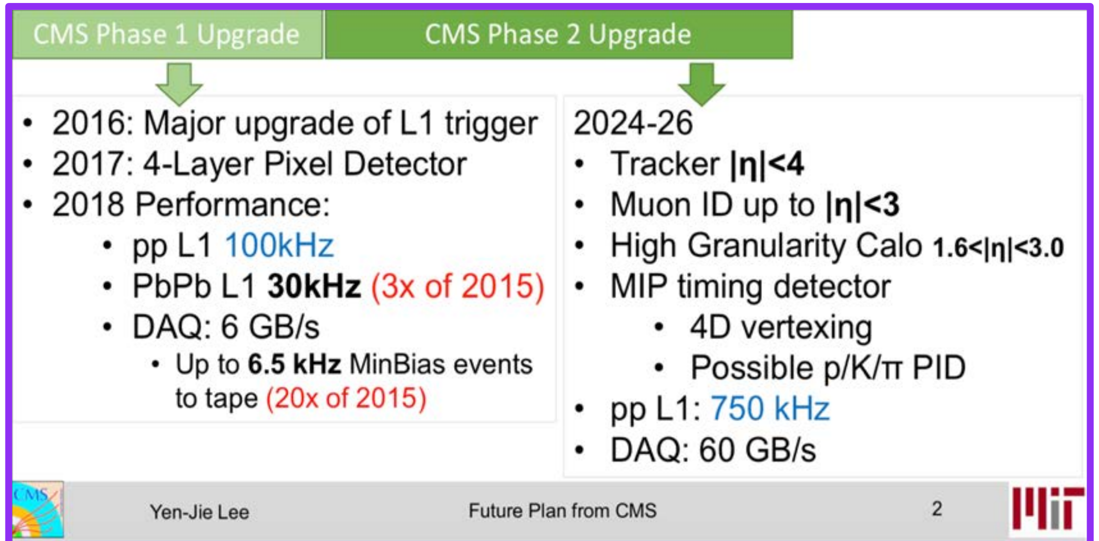
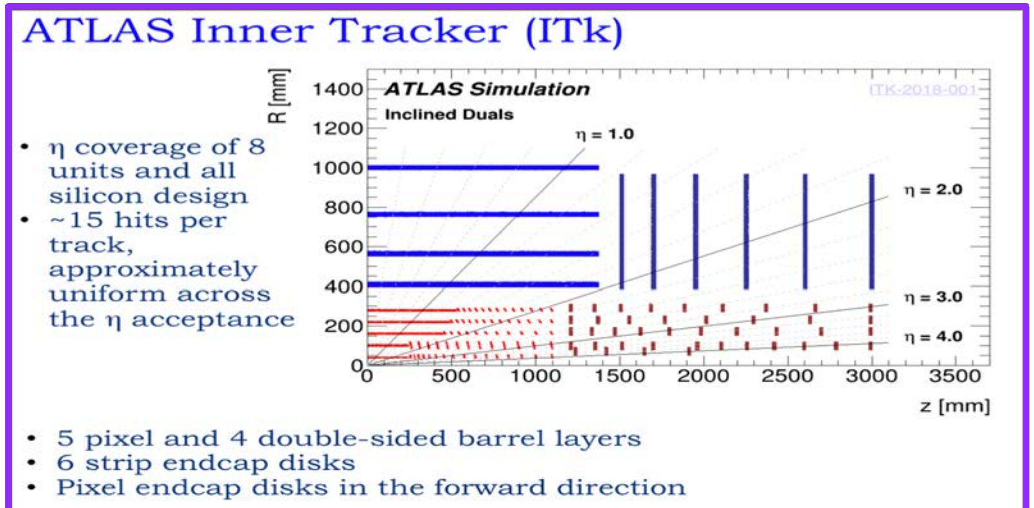
ALICE all MAPS detector during LS4



ALICE & LHCb already planning HI physics beyond 2030+







To be installed before Run 4

Connections of Heavy Ion Collisions to EIC Physics

CERN

Goals for HL-LHC Era

1. Characterize the macroscopic long-wavelength QGP properties with unprecedented precision
2. Access the microscopic parton dynamics underlying the QGP properties
3. Probing partonic content in nuclei and search for possible onset of parton saturation
4. Investigate unified picture of particle production from small to large systems

Replace "QGP" with "nuclei" **For EIC**

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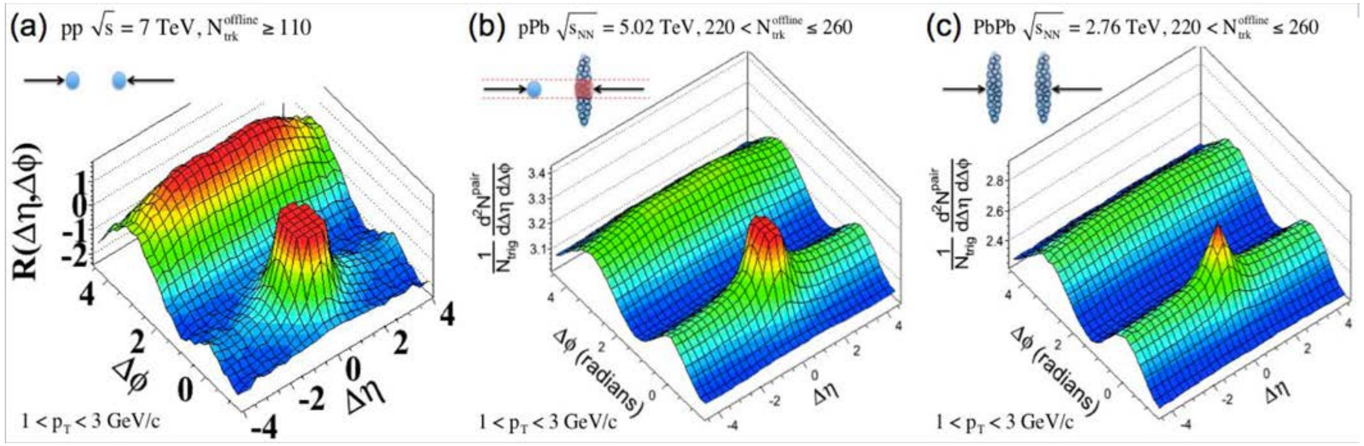
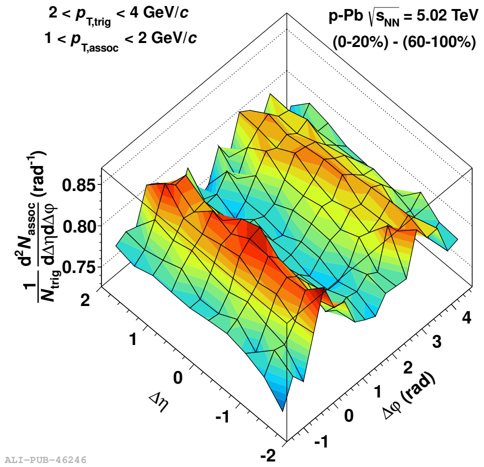
Replace "QGP" with "nuclei" **For EIC**

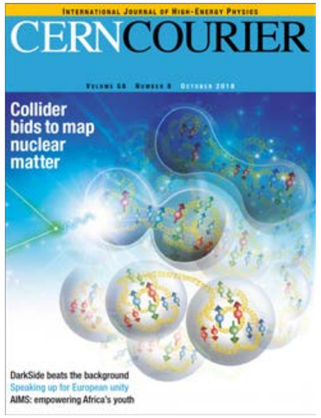
An explicit goal of the EIC

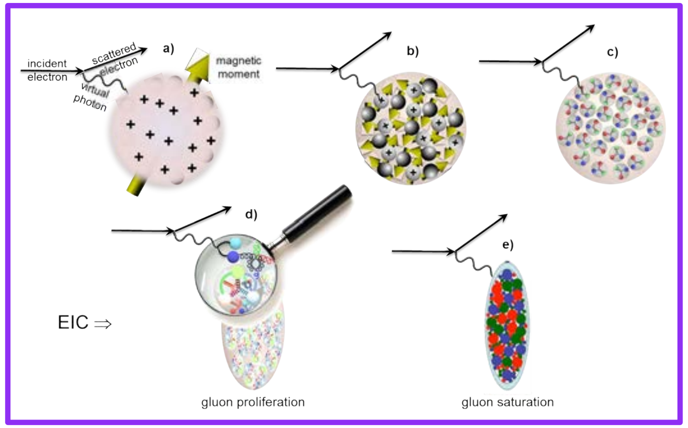
CMS

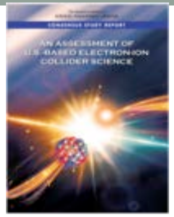


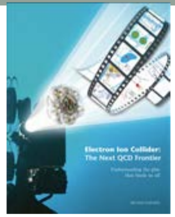


ALICE Collaboration, Phys. Lett. B719 (2013) 29



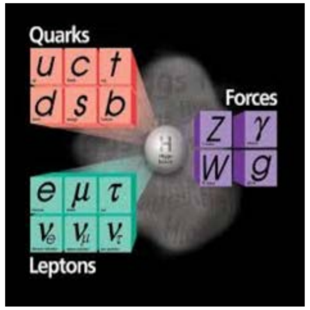


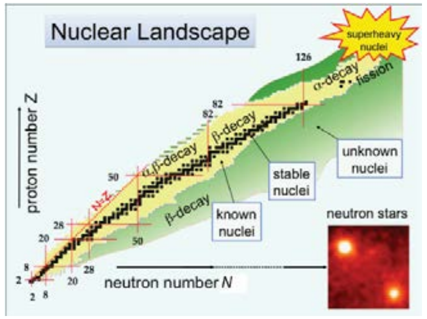




Electron Ion Collider: The next QCD frontier

To precisely understand the universal gluon dynamics in QCD and its consequences in the visible world.



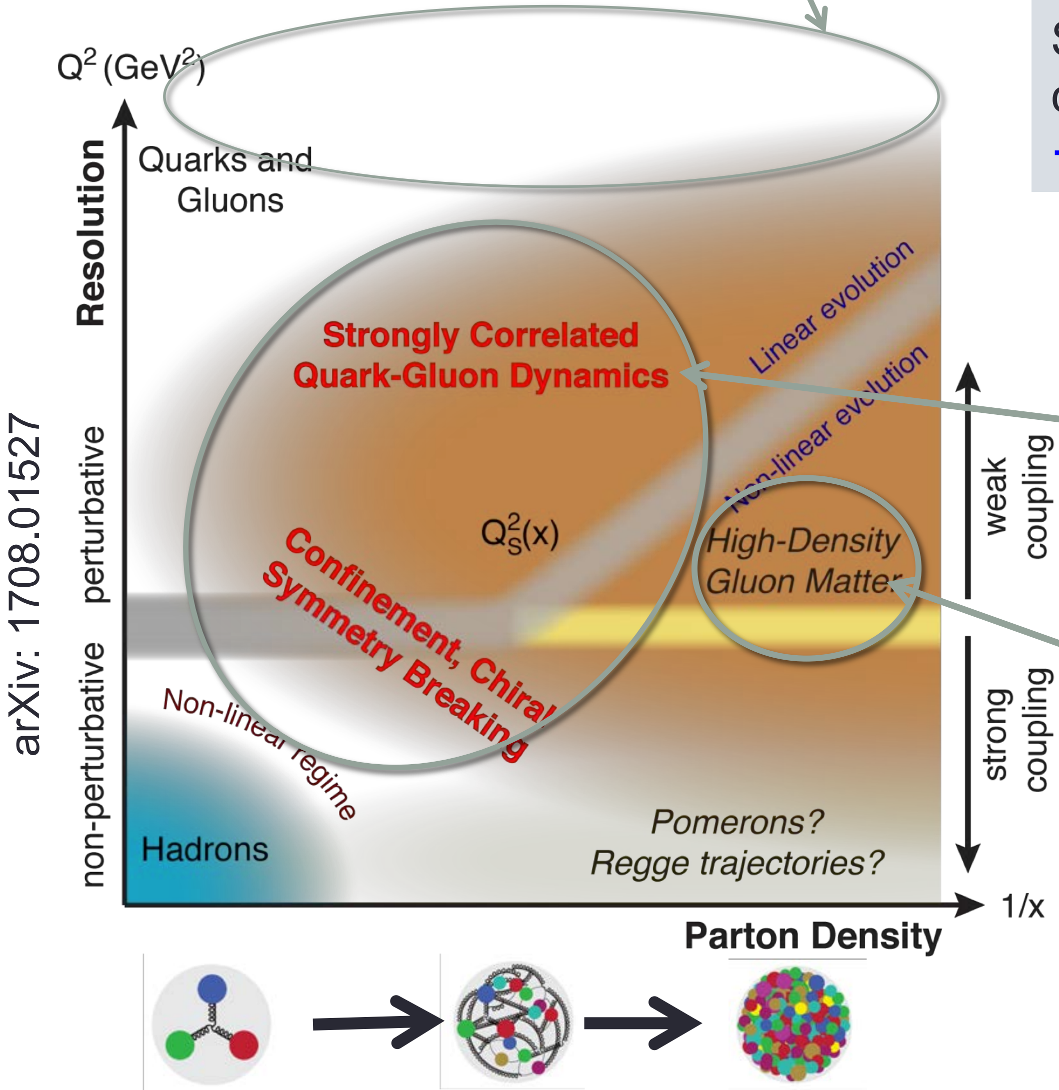


Stony Brook University

QCD Landscape to be explored by EIC

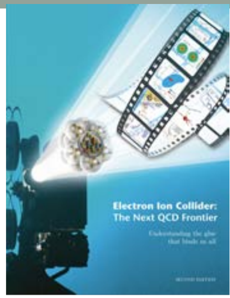
QCD at high resolution (Q^2) —weakly correlated quarks and gluons are well-described

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



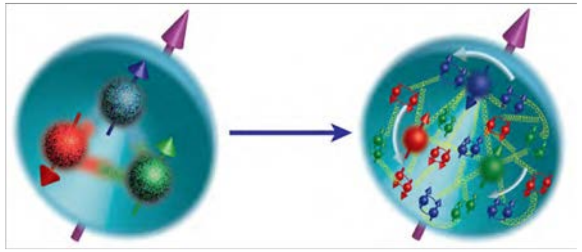
EIC will systematically explore correlations in this region.

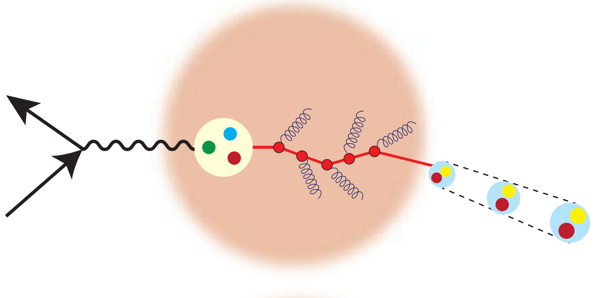
An exciting opportunity: Observation by EIC of a new regime in QCD of weakly coupled high density matter



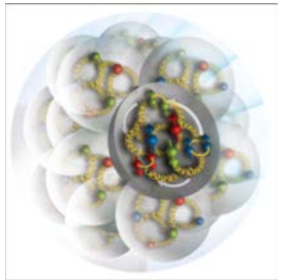
A new facility is needed to investigate, with precision, the dynamics of gluons & sea quarks and their role in the structure of visible matter

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?



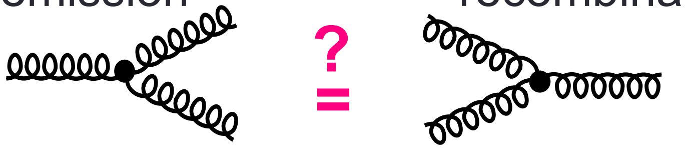


How do color-charged quarks and gluons, and colorless jets, interact with a nuclear medium?
How do the confined hadronic states emerge from these quarks and gluons?
How do the quark-gluon interactions create nuclear binding?

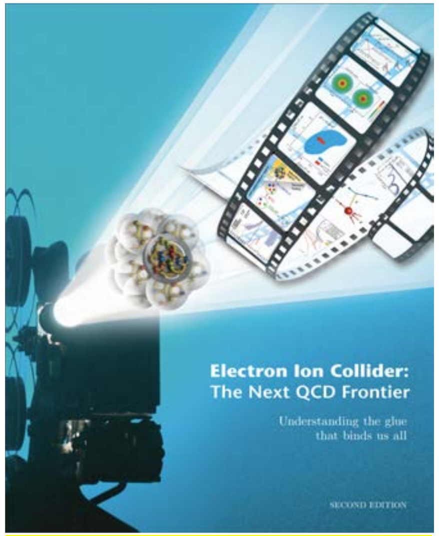


How does a dense nuclear environment affect the quarks and gluons, their correlations, and their interactions?
What happens to the gluon density in nuclei? Does it saturate at high energy, giving rise to a gluonic matter with universal properties in all nuclei, even the proton?

gluon emission ?= gluon recombination



The Electron Ion Collider



1212.1701.v3
A. Accardi et al
Eur. Phy. J. A, 52 9(2016)

For e-N collisions at the EIC:

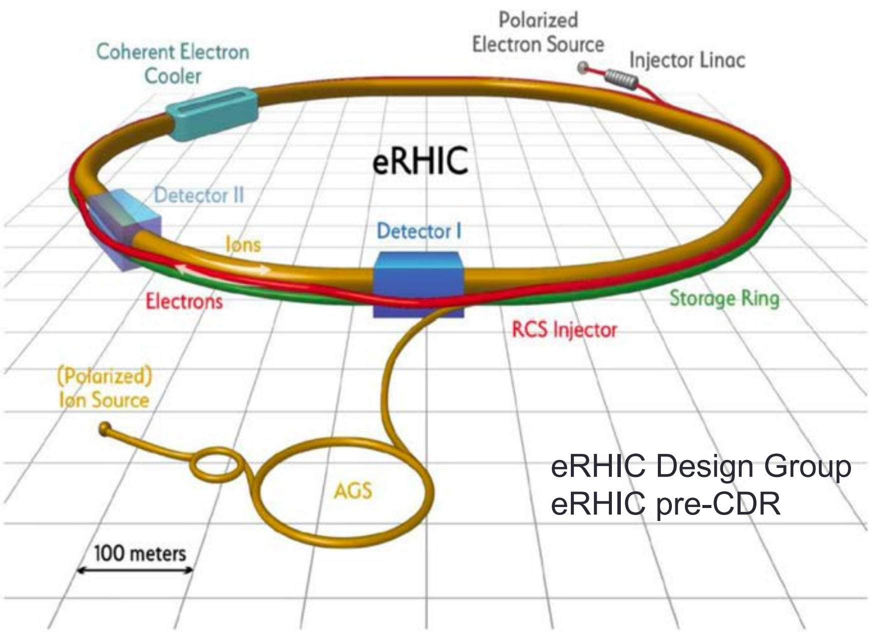
- ✓ Polarized beams: e, p, d/^{3}He
- ✓ e beam 5-10(20) GeV
- ✓ Luminosity L_{ep} ~ 10^{33-34} $cm^{-2}sec^{-1}$
  100-1000 times HERA
- ✓ 20-100 (140) GeV Variable CoM

For e-A collisions at the EIC:

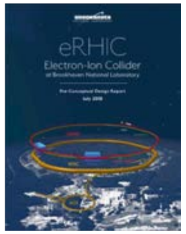
- ✓ **Wide range in nuclei**
- ✓ Luminosity per nucleon same as e-p
- ✓ Variable center of mass energy

World's first
Polarized electron-proton/light ion
and electron-Nucleus collider

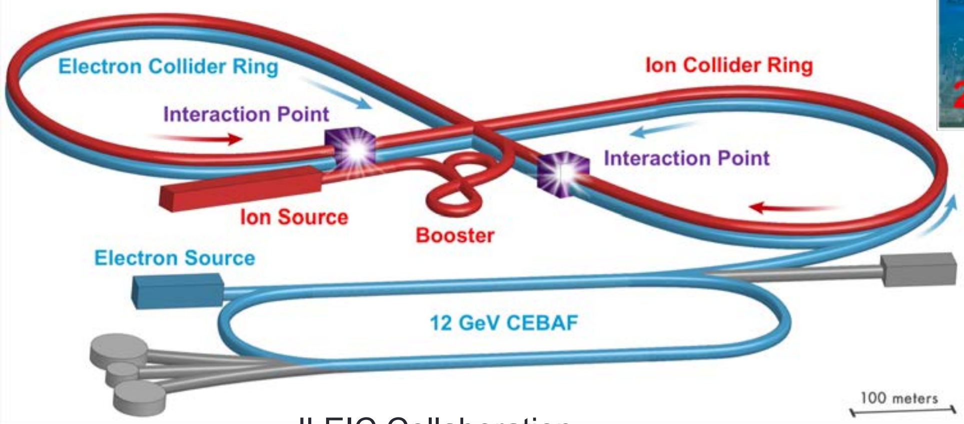
Both designs use DOE's significant investments in infrastructure

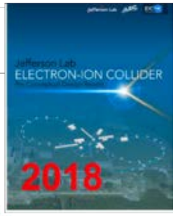


eRHIC Design Group
eRHIC pre-CDR



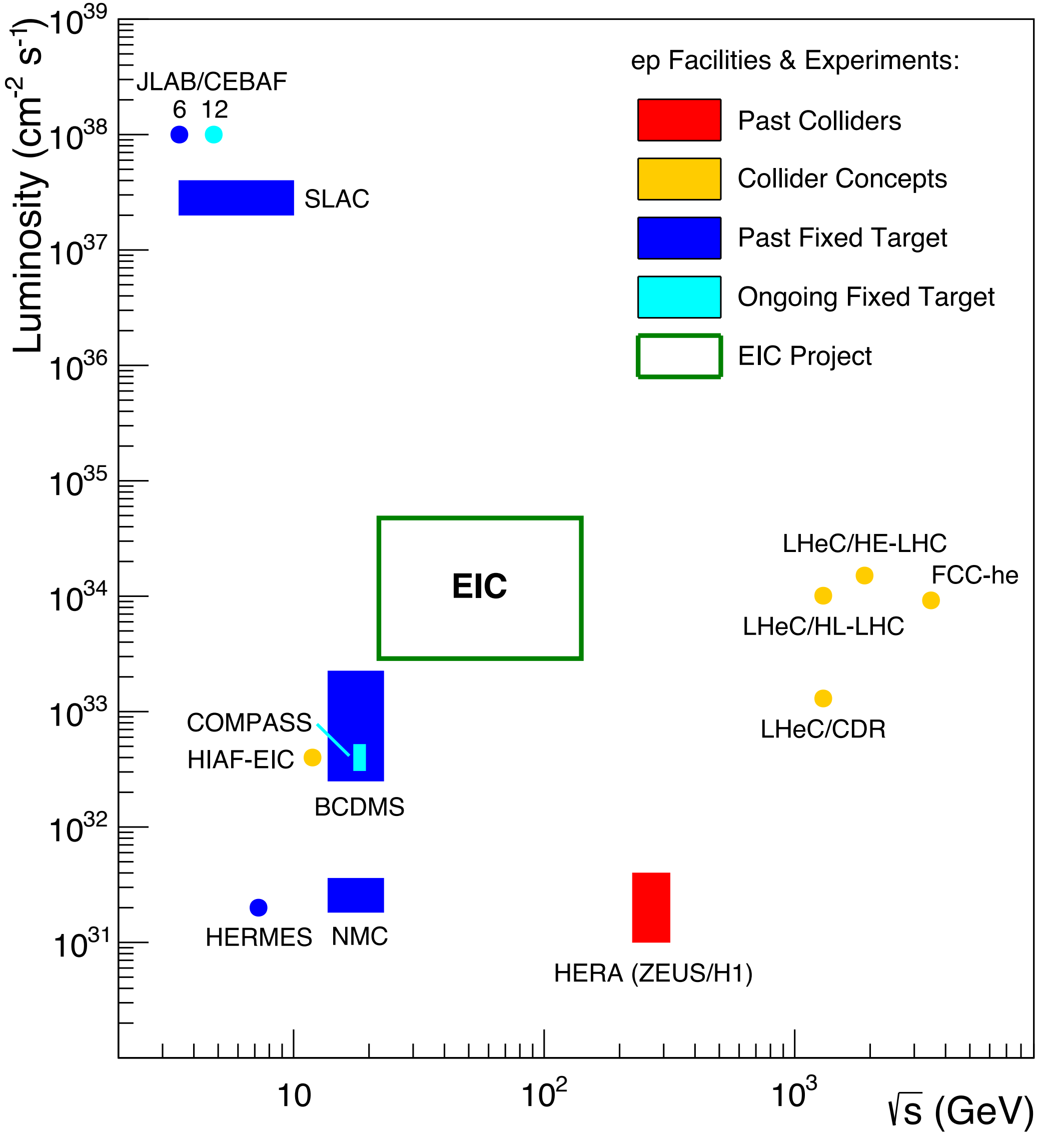
2018





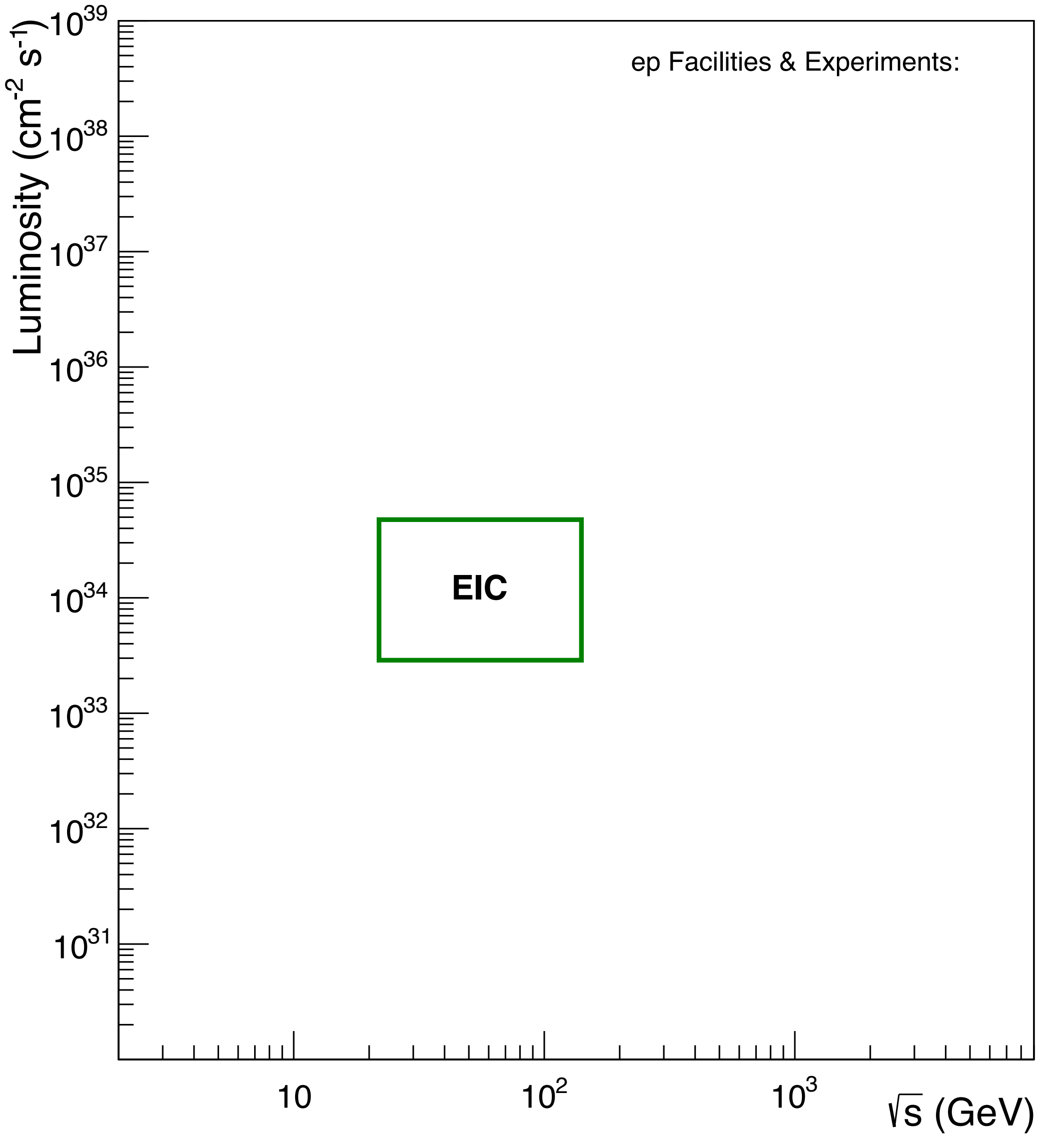
JLEIC Collaboration
JLEIC Pre-CDR about to be finalized

Uniqueness of EIC among all DIS Facilities



All DIS facilities in the world.

Uniqueness of EIC among all DIS Facilities



All DIS facilities in the world.

However,
if we ask for:

- high luminosity & wide range in $\sqrt{s}$
- polarized lepton & hadron beams
- nuclear beams

EIC stands out as unique facility …

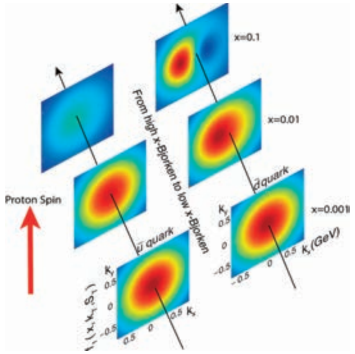
State of the art Accelerator Technology for EIC

EIC will be one of the most complex collider accelerators ever be built. It will push the envelope on many fronts including high degree of beam polarization, high luminosity, beam cooling, beam dynamics, crab cavities on for both beams, and interaction region with complex magnets integrated with the detectors.

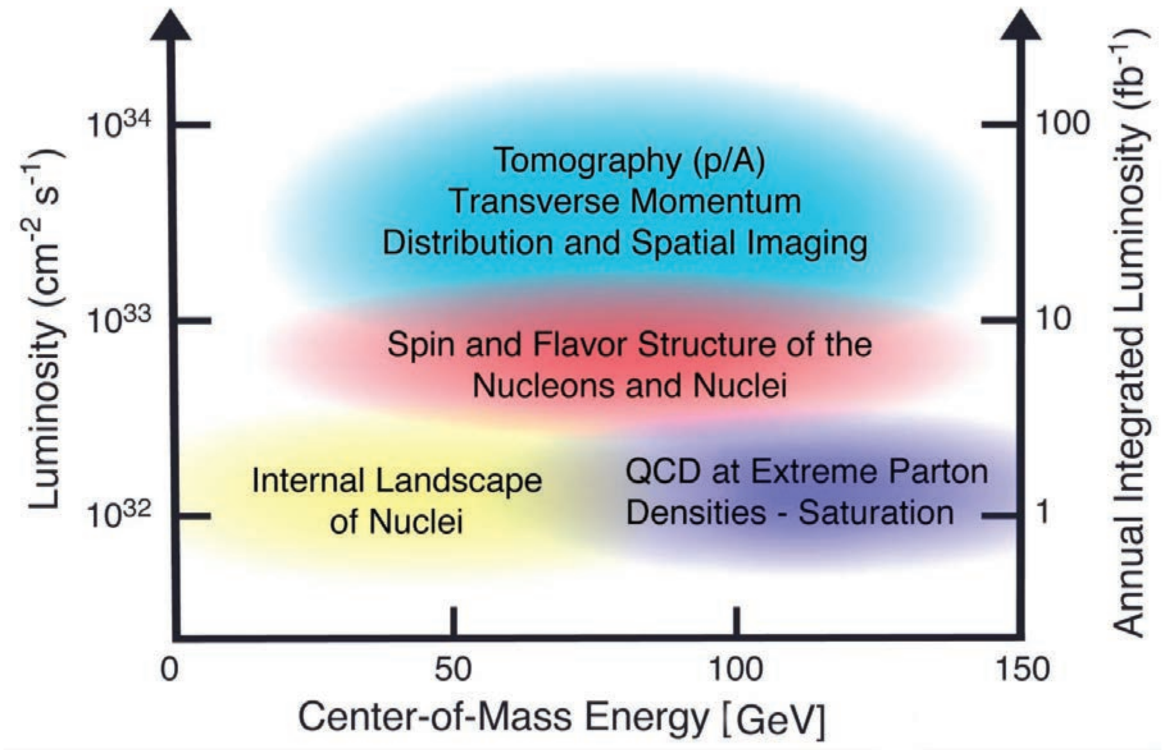
- **Beam cooling: Absolutely needed** to achieve the high collisions luminosity ~ $10^{33\text{-}34}$ $cm^{-2}sec^{-1}$
  - High current multi-pass energy recovery linac (ERL)
  - High current unpolarized electron injectors for the ERL
- **Interaction Region:**
  - **Magnets:** challenging magnet designs to meet the required high fields and field free regions
  - **Crab Cavities: M**aximize collisions rates. No experience yet for crab cavities in hadron beams (R&D @ CERN)
- **Storage Ring Magnets:** Challenging high field storage ring magnets needed
- **Polarized electron source:** High bunch charges for ring-ring concept
- **Simulation Codes**: Benchmarking the realistic EIC simulation tools against available data

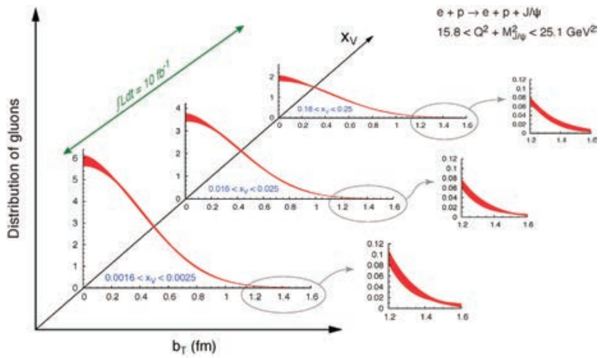
*Ample opportunity for joint accelerator research and development initiatives with Jlab/BNL and other labs around the world. (**Details in US EIC Accelerator Paper planned to be submitted to ESPP process next month).***

EIC science and required luminosity

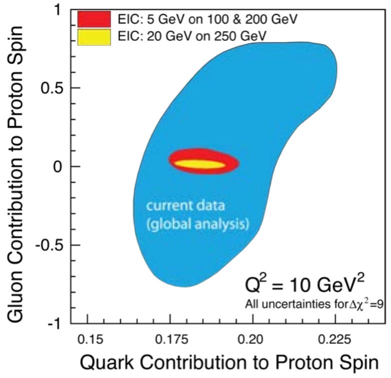


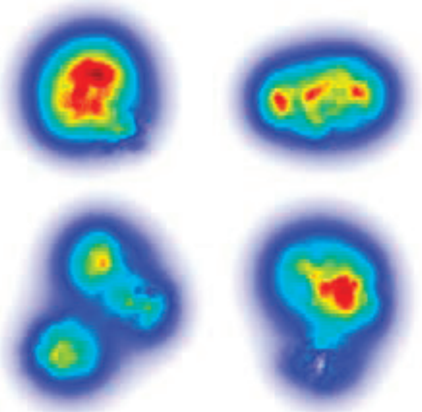
2+1D imaging of quarks and gluons, dynamics, and emergence of spin & mass



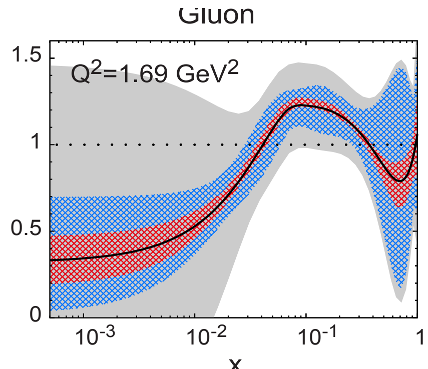


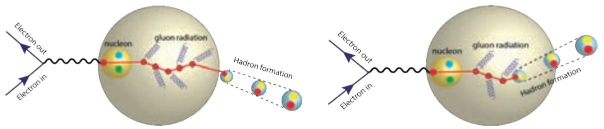
Gluon imaging in nucleons



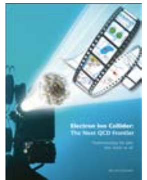


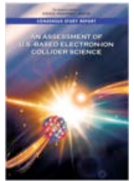
Gluons at high energy in nuclei:
(Gluon imaging in nuclei)





Color propagation, neutralization in nuclei & hadronization

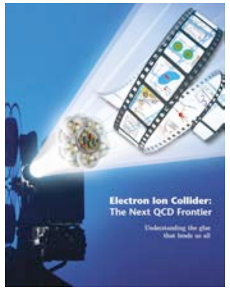




U.S. Electron-Ion Collider Planning 2007-18 (all links included)

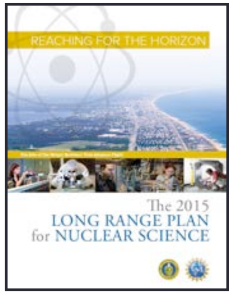
2007 NSAC Long-Range Plan

"An Electron-Ion Collider (EIC) with polarized beams has been embraced by the U.S. nuclear science community as embodying the vision for reaching the next QCD frontier"



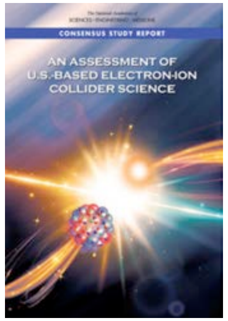
2013 Electron Ion Collider White Paper (arXiv:1212.1701.v3 from 2014)
(EIC Users Writing committee convened by Jefferson Lab and BNL)

2013 NSAC Subcommittee on Future Facilities
Identified EIC as **absolutely central** to the nuclear science program of the next decade



2015 NSAC Long Range Plan

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



2018 National Academy of Sciences – Assessment of U.S. Based Electron-Ion Collider Science

"…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."

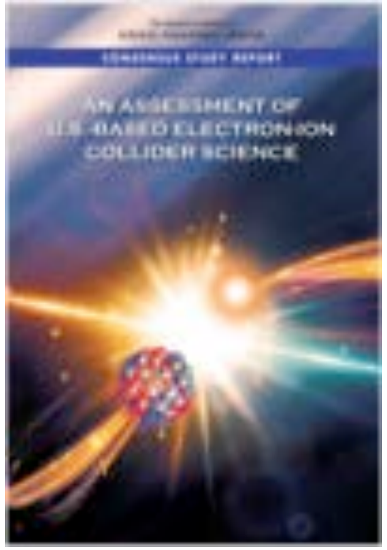
The National Academies of SCIENCES ENGINEERING MEDICINE

A very strong endorsement of the EIC Science: *Compelling, timely and fundamental*

July 2018

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?



[The Full Report]

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 sufficiently and variable, center-of-mass energy.

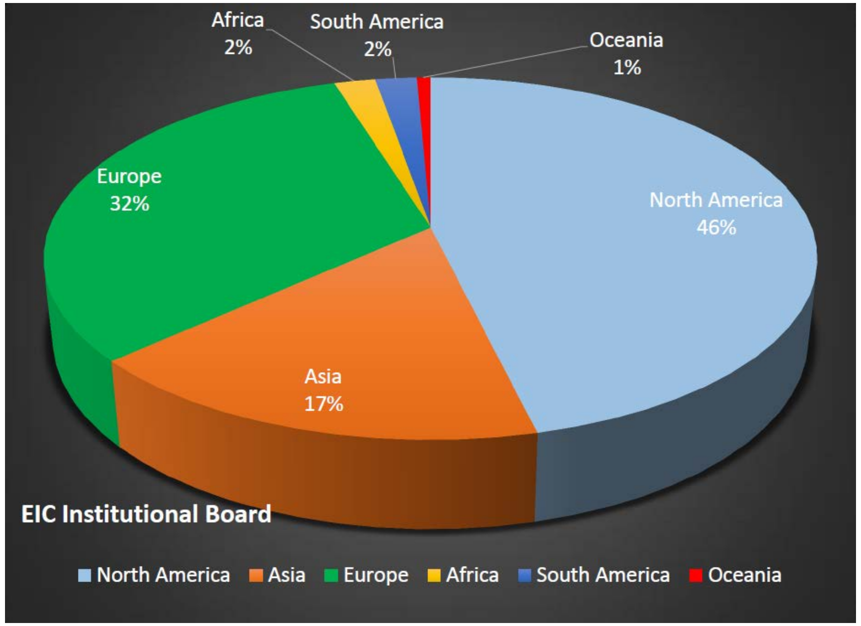
Finding 3: An EIC would be a unique facility in the world and would maintain U.S. leadership in nuclear physics

Findings 4-9 go on to support the importance of **accelerator research and science**, **societal impact**, **support for theory** to fully benefit from the data expected from the EIC, and **systematic approach of the US NP community in its planning process**: EIC after FRIB….

The EIC Users Group: EICUG.ORG

Formally established in 2016
826 Ph.D. Memners vfom 30 countries, 176 institutions
(Significant interest (32%) from Europe)

New:
Center for Frontiers in Nuclear Science (at Stony Brook/BNL)
EIC² at Jefferson Laboratory



EICUG Structures in place and active.

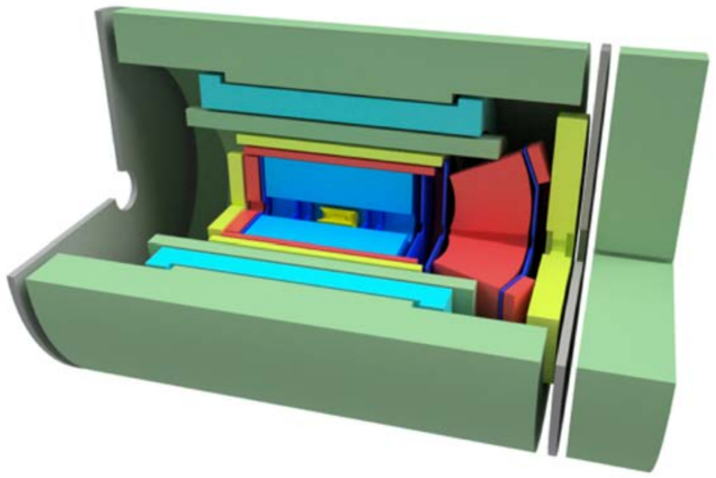
EIC UG Steering Committee (w/ European Representative)
EIC UG Institutional Board
EIC UG Speaker's Committee (w/European Rep.)

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

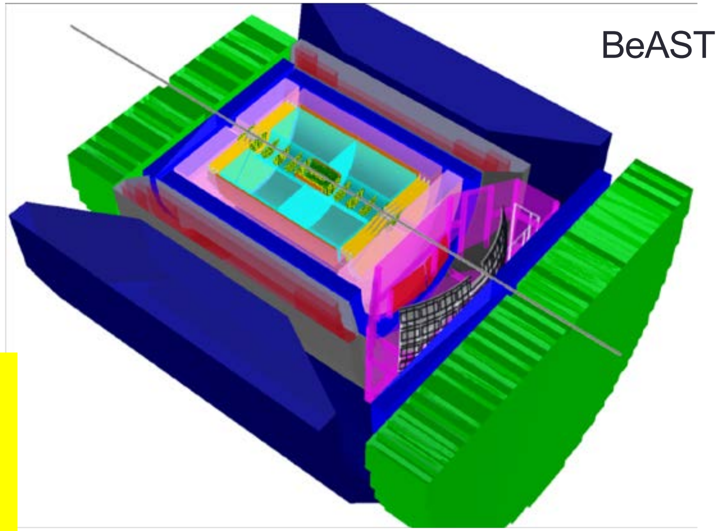
Annual meetings: Stony Brook (2014), Berkeley (2015), **ANL (2016)**, **Trieste (2017)**, **CAU (2018)**, **Paris (2019)**

EIC Detector Concepts, others expected to emerge

EIC Day 1 detector, with BaBar Solenoid

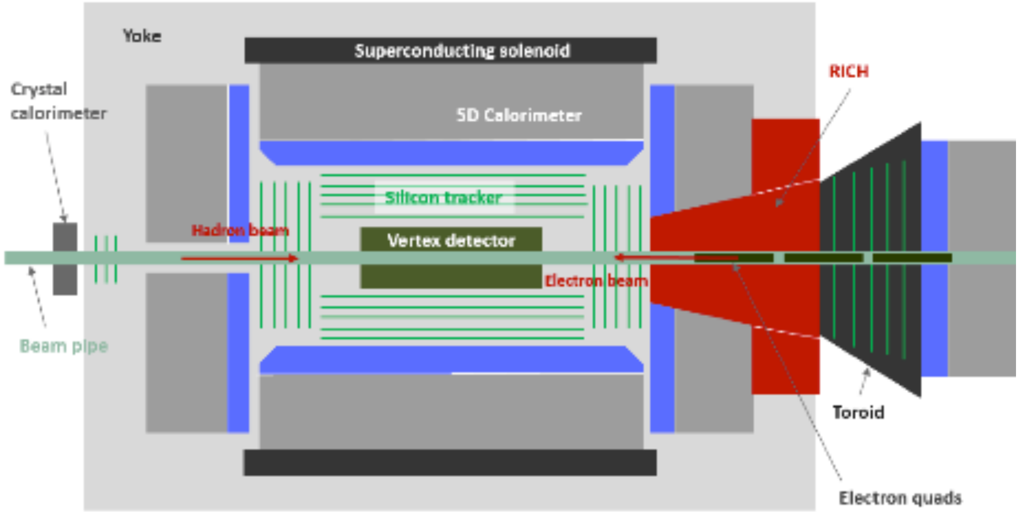


BeAST at BNL

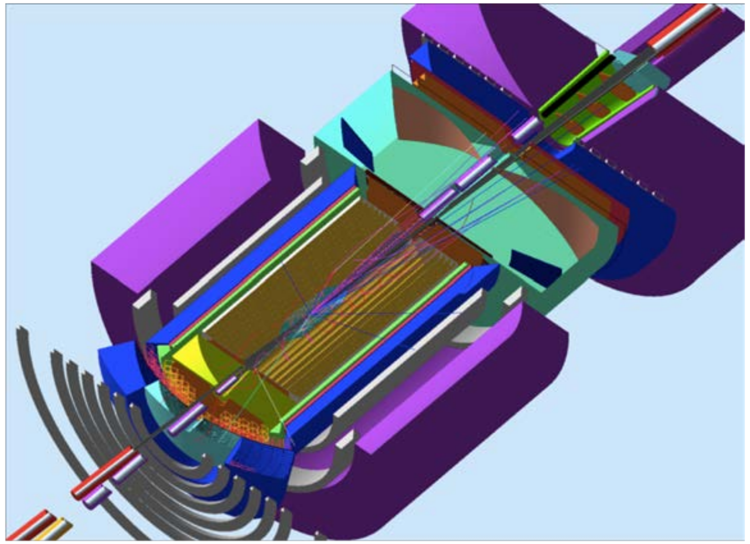


Ample opportunity and need for additional contributors and collaborators

TOPSiDE: Time Optimized PID Silicon Detector for EIC

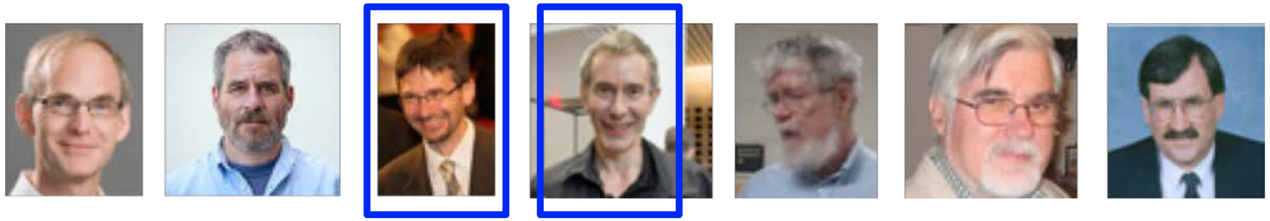


JLEIC Detector Concept, with CLEO Solenoid



EIC detector R&D effort

- Laboratory Directed Research & Development Programs (LDRDs) at BNL, JLAB, ANL
- R&D at Belle-II and Panda has some overlap with EIC
- CERN/LHC
  - R&D for phase-I upgrades ended, phase-II focus on radiation hardness and rate
  - R&D on key common with EIC challenges (PID, EMCal) :→ Opportunity?
- Generic EIC Detector R&D Program (See here)
  - Managed since 2011 by BNL, in association with JLab and DOE NP
  - Funded by DOE NP, through RHIC operations
  - Program non site specific and explicitly open to international participation
  - 13 (non-US – mostly European) of the 46 institutions have benefited and now European Contingent of EICUGs have successfully acquired European funding (Strong2020: NextDIS)
  - Standing EIC Detector Advisory Committee with internationally recognized detector experts



Current: Marcel Demarteau (ANL, Chair), Carl Haber (LBNL), **Peter Krizan (Ljubljana), Ian Shipsey (Oxford)**, Rick Van Berg (UPenn), Jerry Va'vra (SLAC), Glenn Young (JLab)

Path forward for the EIC:

Predictions are especially difficult when it comes to the future

The 2015 Long Range Plan for Nuclear Science

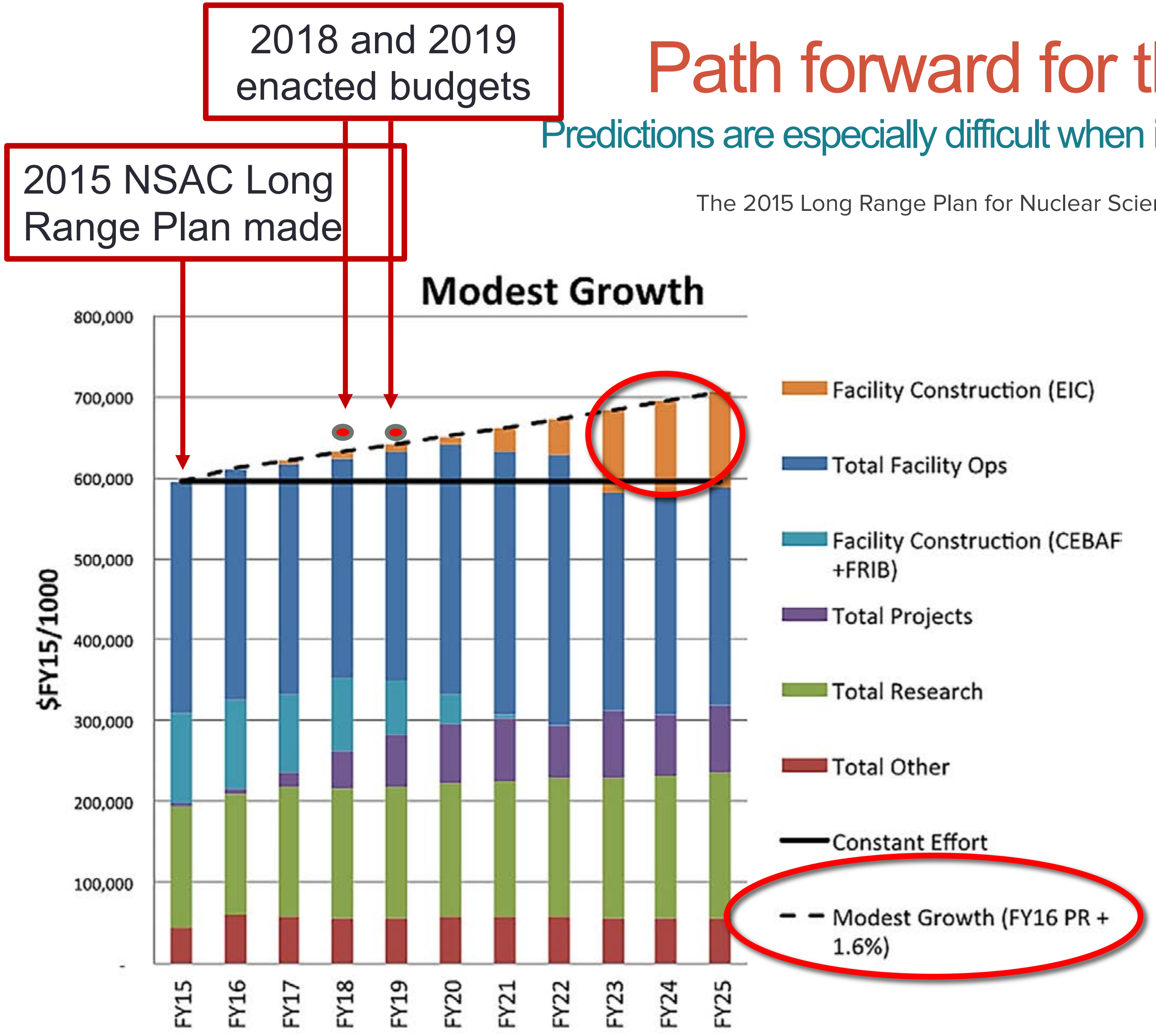


Figure 10.4: *DOE budget in FY 2015 dollars for the Modest Growth scenario.*

- Strong endorsement by the NAS (July 2018)
- BNL and JLab working together with the US DOE towards realizing the project.
- Technically driven schedule: the future
  - CD0 (critical decision process of the US DOE) in near future
  - EIC-Proposal's Technical & Cost review → Site selection → CD1-3
  - According to NSAC LRP 2015 major construction funds ("CD3") ~2023
  - *Earliest First* collisions in 2029/30

Summary

Robust plans for upgrades: synergetic heavy ion physics at LHC & RHIC next 10-**15**+ years:

- Characterizing and understanding QGP from small to large wavelength
- Diverse probes/techniques: heavy quarks, jets, energy loss, variation in initial state/energy, and appropriately required detector upgrades at **ALICE**, ATLAS, CMS and **LHCb** @ CERN, and a whole new detector sPHENIX@BNL

US EIC project is moving forward: steadily but surely

- Long range plan recommended it for construction in 2015
- National Academy Review positive (timely, compelling and fundamental) in 2018
- International EIC Users Group of 800+ Ph.D.'s now in place: seed for future collaboration
- A significant European contingent (~32%)
- US Department of Energy is anticipated to initiate the realization process (CD-process)
- Could have first collisions late 2020's (technically driven possible, fiscal always open question)

For the European PP Strategic discussions: A white paper led by EICUG's European contingent is being prepared. A separate machine design and accelerator R&D white paper for the EIC is being prepared buy BNL and Jefferson Lab together.

Thank you!

Thanks to those who actively helped:

EIC Users Group Steering Committee, Berndt Mueller, Robert McKeown, Rolf Ent, Elke Aschenauer, Dave Morrison, Barbara Erazmus, Federico Antinori, Boris Hippolyte, Richard Milner, and Tapan Nayak

And whose slides/presentations I used from various talks given elsewhere:

Jan Fiete Grosse-Oetringhaus, Yen-Jie Lee, Andrea Dainise, Dominik Derendarz, Burkhard Schmidt

Guideline/Charge from Prof. D'Hondt for this talk:

"*As a guideline for the presentation, it is important to inform the community about the* ***realism of the proposed future collider*** *project, from the* ***basic properties of the collider (and detector(s)) to elements of innovation****, from* ***physics goals to R&D challenges****, from costs and secured budgets to the required individual talents to face the challenges, potential computing requirements and challenges, a* ***timeline including R&D*** *and* ***construction milestones, and the potential formation of scientific collaborations***."

"*Surely you can mention the science and technology challenges (and opportunities) of the RHIC and ALICE programmes as a kick-off towards future (or upgraded) colliders. The session will have a focus on future colliders, therefore do not hesitate to place dedicated focus on the US EIC project. Indeed, the electron-proton part of future colliders is covered elsewhere.*"

National Academy Committee's Findings

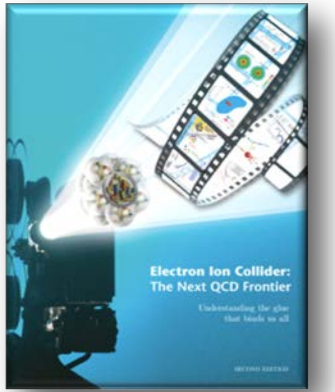
- Finding 1: An EIC can uniquely address three profound questions about nucleons—neutrons and protons—and how they are assembled to form the nuclei of atoms:
  - How does the mass of the nucleon arise?
  - How does the spin of the nucleon arise?
  - What are the emergent properties of dense systems of 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.

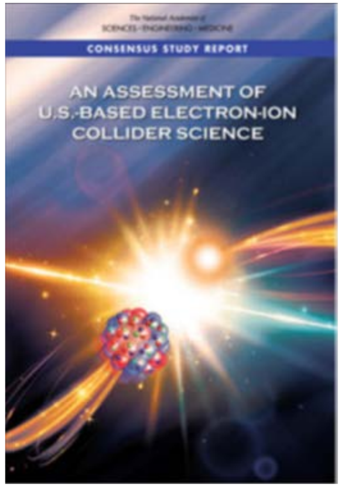
National Academy Committee's Findings

- 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.

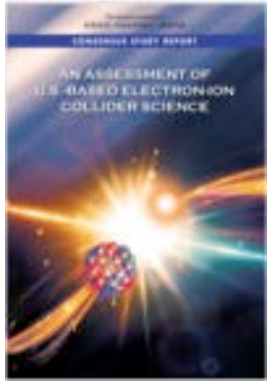
In order to definitively answer the compelling scientific questions elaborated in Chapter 2, including the origin of the mass and spin of the nucleon and probing the role of gluons in nuclei, a new accelerator facility is required, an electron-ion collider (EIC) with unprecedented capabilities beyond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

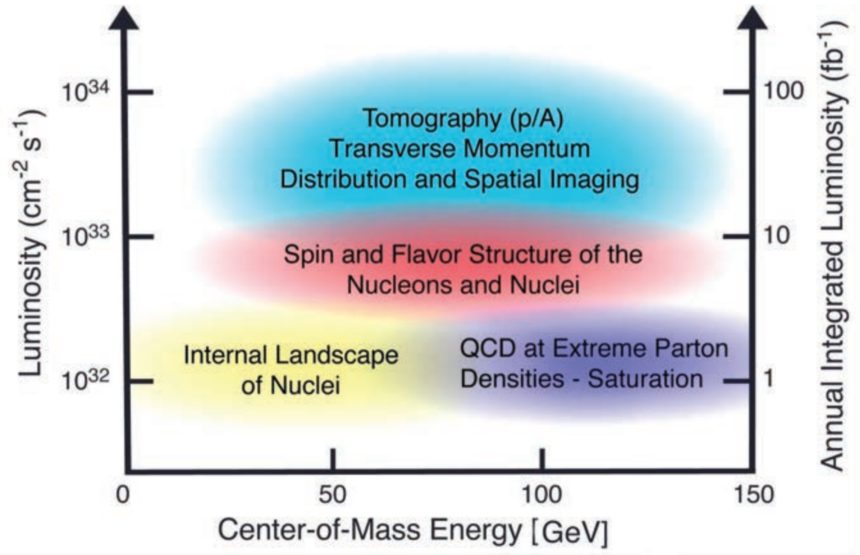




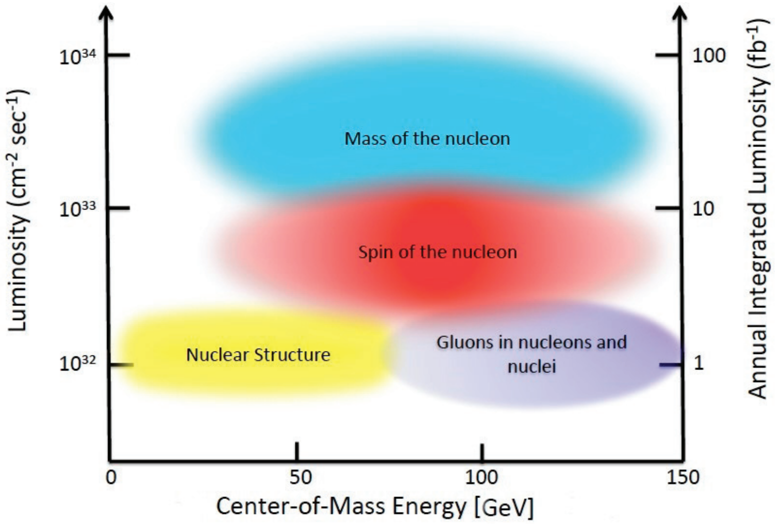
NAS Study endorses machine parameters suggested by the 2012 White Paper and 2015 NSAC Long Range Plan



EIC Physics Case
NAS report figure 2.4



NAS report figure 7.1



Critical Decision Process DOE

<table>
<tr><th colspan="6">PROJECT ACQUISITION PROCESS AND CRITICAL DECISIONS</th></tr>
<tr><td colspan="2">Project Planning Phase</td><td colspan="3">Project Execution Phase</td><td>Mission</td></tr>
<tr><td>Preconceptual Planning</td><td>Conceptual Design</td><td>Preliminary Design</td><td>Final Design</td><td>Construction</td><td>Operations</td></tr>
<tr><td colspan="6">CD-0: Approve Mission Need
CD-1: Approve Preliminary Baseline Range
CD-2: Approve Performance Baseline
CD-3: Approve Start of Construction
CD-4: Approve Start of Operations or Project Closeout</td></tr>
</table>

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

eRHIC Beam parameters at highest luminosity ($\sqrt{s} = 105 GeV$)

- Many bunches (up to 1320)
- High beam currents (1A p, 2.5A e)
- Flat beams
- Short hadron bunches (5cm with cooling, 7cm without)
- Crossing angle collisions with crab crossing

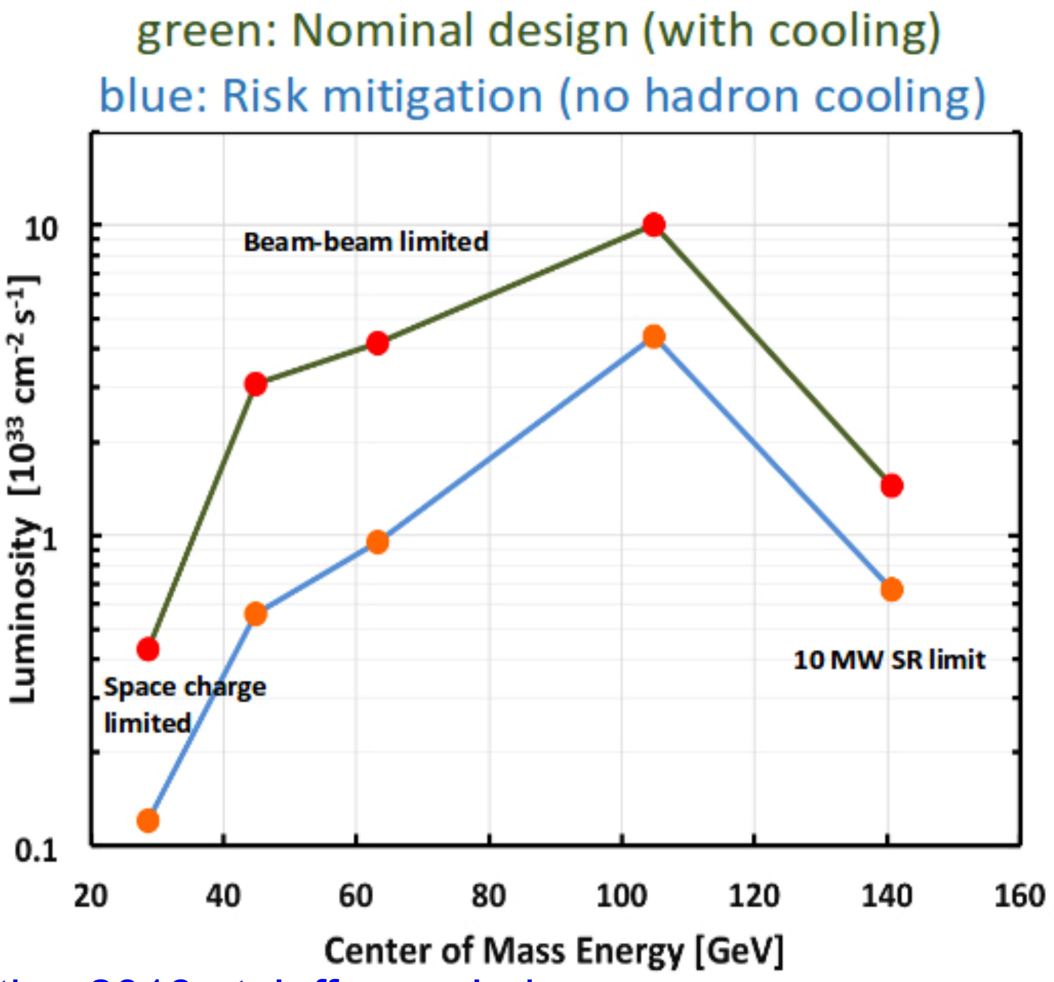
	Nominal Design (with cooling)		Risk Mitigation (no cooling)	
Species	p	e	p	E
Bunch frequency [MHz]	112.6		56.3	
Bunch intensity [10^11]	0.6	1.5	1.05	3.0
Number of bunches	1320		660	
Beam current [A]	1	2.5	0.87	2.5
Rms norm. emit. h/v [um]	2.7/0.38	391/20	4.1/2.5	391/95
Rms emittance h/v [nm]	9.2/1.3	20/1	13.9/8.5	20/4.9
β* h/v [cm]	90/4	42/5	90/5.9	63/10.4
IP rms beam size h/v [um]	91/7.2		112/22.5	
IR rms angular spread h/v [urad]	101/179	219/143	124/380	179/216
b-b parameter (/IP) h/v	0.013/0.007	0.064/0.099	0.015/0.005	0.1/0.083
Rms bunch length [cm]	5	1.9	7	1.9
Rms energy spread, 10^-4	4.6	5.5	6.6	5.5
Max space charge parameter	0.004	neglig.	0.001	neglig.
IBS growth time tr/long, h	2.1/2.0		9.2/10.1	
Polarization, %	80	70	80	70
Hourglass and crab crossing factor	0.87		0.85	
Peak luminosity [10^33 cm-2s-1]	**10.1**		**4.4**	
Integrated luminosity/week, fb^{-1}	**4.51**		**1.12**	

High luminosity: 10.1*$10^{33} cm^{-2} sec^{-1}$ with cooling, 4.4*$10^{33} cm^{-2} sec^{-1}$ without

Christophe Montag at the EIC Collaboration Meeting 2018 at Jefferson Lab

eRHIC: Luminosity versus Center-of-Mass Energy

Strong hadron cooling improves luminosity by factor 2.3 at $\sqrt{s} = 105\ GeV$ and beyond, and by factor 6-7 at lower energies



Christophe Montag at the EIC Collaboration Meeting 2018 at Jefferson Lab

eRHIC Summary

- eRHIC design reaches a peak luminosity of **L= 1.05·10^{34}cm^{-2}s^{-1}**
  with 2 hour IBS growth times
- However, this can only be achieved with strong hadron cooling, which is beyond state of the art, and is a topic of ongoing R&D.
- Without hadron cooling a peak luminosity of

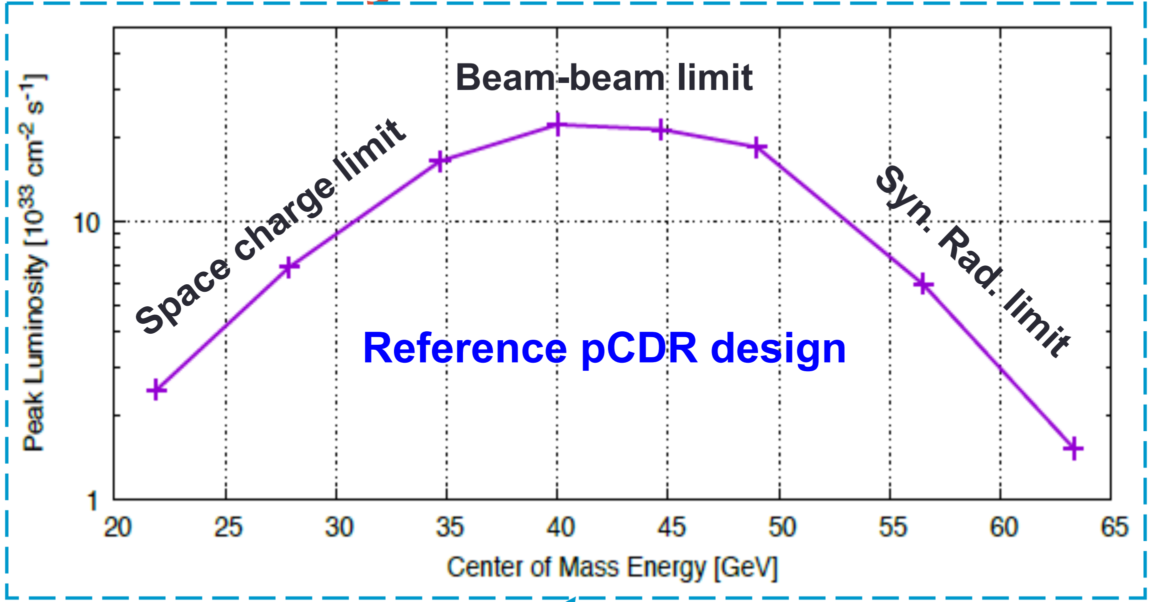
  $$\mathbf{L= 0.44 \cdot 10^{34} cm^{-2} s^{-1}}$$

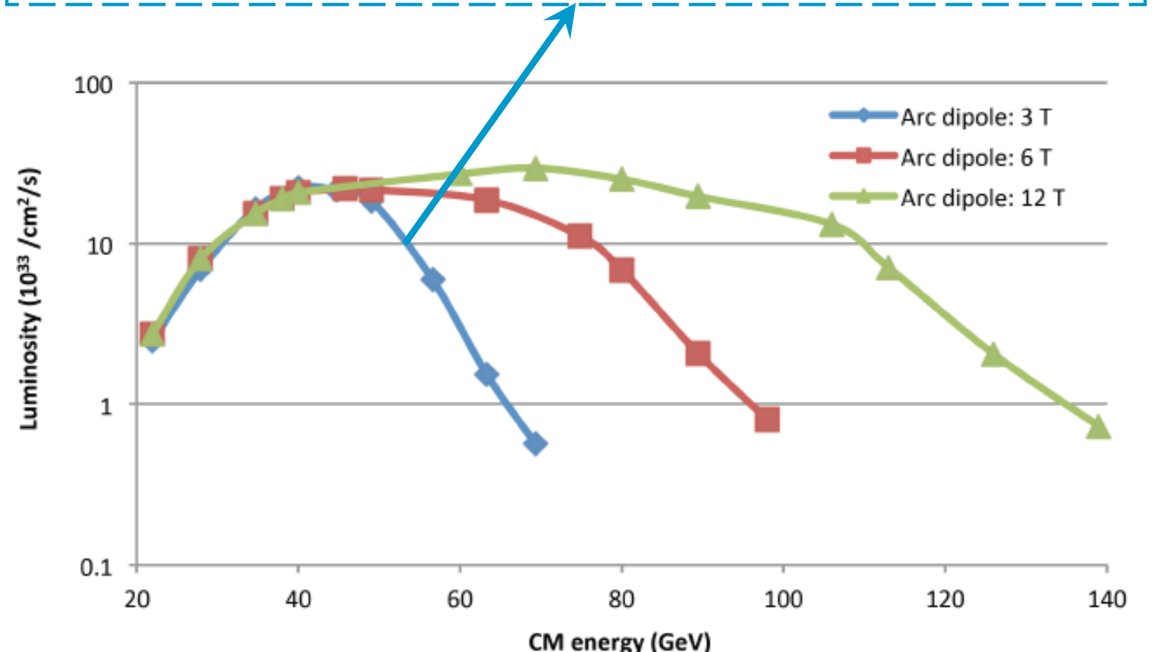
  is reached, with IBS growth times of 9 hours
- eRHIC design has progressed very well and a tremendous amount of design work was accomplished.
- There are still critical beam dynamic issues which require more effort. They could have an impact on achievable luminosity but do not constitute a risk of missing the EIC White Paper Requirement
- While a large amount of work is still ahead to arrive at a **Conceptual Design**, we believe that the present state of the eRHIC design matches well the expectations of a Pre-Conceptual Design

Christophe Montag at the EIC Collaboration Meeting 2018 at Jefferson Lab

JLEIC e-p Parameters and Luminosity Performance

CM energy	GeV	21.9 (low)		44.7 (medium)		63.3 (high)	
		p	e	p	e	p	e
Beam energy	GeV	40	3	100	5	100	10
Collision frequency	MHz	476		476		476	
Particles per bunch	10^{10}	0.98	3.7	0.98	3.7	0.98	0.93
Beam current	A	0.75	2.8	0.75	2.8	0.75	0.71
Polarization	%	80	80	80	80	80	75
Bunch length, RMS	cm	1	1	1	1	1	1
Norm. emitt., horiz./vert.	µm	0.3	24	0.5/ 0.1	54/ 10.8	0.9/ 0.18	432/ 86.4
Horiz, & verti. β*	cm	8/8	13.5/ 13.5	6/1.2	5.1/1	10.5/2.1	4/0.8
Vert. beam-beam param.		0.015	0.09	0.015	0.068	0.002	0.009
Laslett tune-shift		0.06		0.055		0.03	
Detector space, up/down	m	3.6/7	2.96/2.2	3.6/7	2.96/2.2	3.6/7	2.96/2.2
Hourglass(HG) reduction		1		0.87		0.86	
Lumi./IP, w/HG, 10^{33}	$cm^{-2}s^{-1}$	2.5		21.4		1.7	





Similar high performance for electron-ion (*e-A*) collisions

Fanglei Lin at EIC Collaboration Meeting at Jefferson Lab 2018

JLEIC Summary

- We continued JLEIC design and improved the design performance. Significant progress has been made in many design aspects.
- We completed documenting JLEIC self-consistent design with the CM energy up to 65 GeV. This 400-page pCDR has been delivered to lab leadership and reviewed by external visitors.
- We explored an alternative baseline design with the CM energy up to 100 GeV. The study shows no show-stopper in all accelerator-associated issues.
- Path forward for FY19
  - JLEIC with $\sqrt{s}$ = 100 GeV optimization: injector complex, collider ring optimization, filling pattern, bunch parameters, HE electron cooling, etc.
  - Continue program development and RD towards CD0

Fanglei Lin at EIC Collaboration Meeting at Jefferson Lab 2018

U.S. DEPARTMENT OF ENERGY | Office of Science

Jones Panel Priority Table:

Report of the Community Review of EIC Accelerator R&D for the Office of Nuclear Physics

February 13, 2017

2017

The **key EIC machine parameters** identified in the LRP were:

- Polarized (~70%) electrons, protons, and light nuclei,
- Ion beams from deuterons to the heaviest stable nuclei,
- Variable center of mass energies ~20-100 GeV, upgradable to ~140 GeV,
- High collision luminosity ~10^{33}-10^{34} $cm^{-2}sec^{-1}$, and
- Possibly have more than one interaction region.

11/2/2018 Richard Milner NSAC 35

R. Milner at NSAC Nov. 2 2018
Source:
M. Farkhondeh at the
EICUG meeting 2018

U.S. DEPARTMENT OF ENERGY | Office of Science

Technical Challenges for EIC

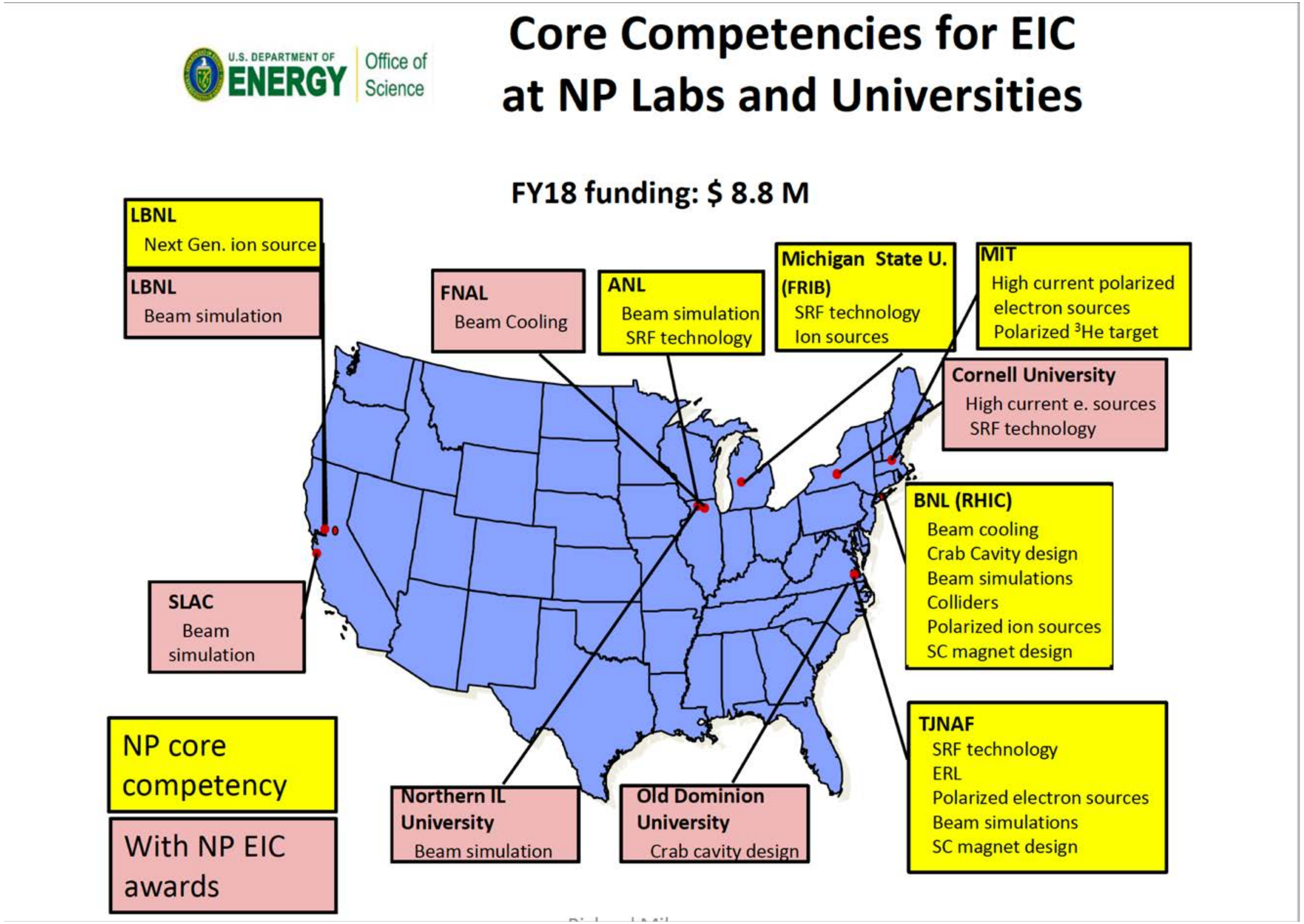
EIC will be one of the most complex collider accelerators ever to be built. It will push the envelope in many fronts including high degrees of beam polarizations, high luminosity, beam cooling, beam dynamics, crab cavities for both beams, and an interaction region with complex magnets.

Required Accelerator R&D Advances for EIC (list from the Jones panel report)

- Hadron cooling techniques
- Polarized electron sources
- Ring magnet demonstrations
- Interaction region magnet design and prototyping
- Machine-detector interfaces
- Superconducting RF technology
- Large scale cryogenics technology
- High current ERL linacs
- Crab cavity design, fabrication and testing (with beam)
- Beam and spin dynamics and benchmarking of simulation tools
- Electron cloud mitigation techniques

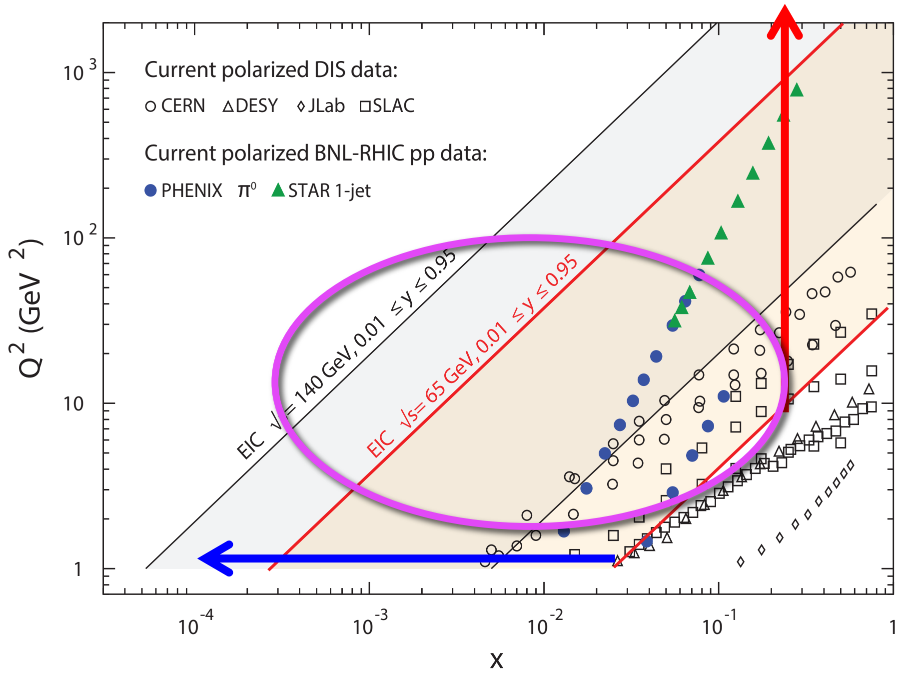
11/2/2018 Richard Milner NSAC 36

R. Milner at NSAC Nov. 2 2018
Source:
M. Farkhondeh at the
EICUG meeting 2018



R. Milner at NSAC Nov. 2 2018
Source:
M. Farkhondeh (DOE) at the
[EICUG meeting 2018]

EIC: Kinematic reach & properties

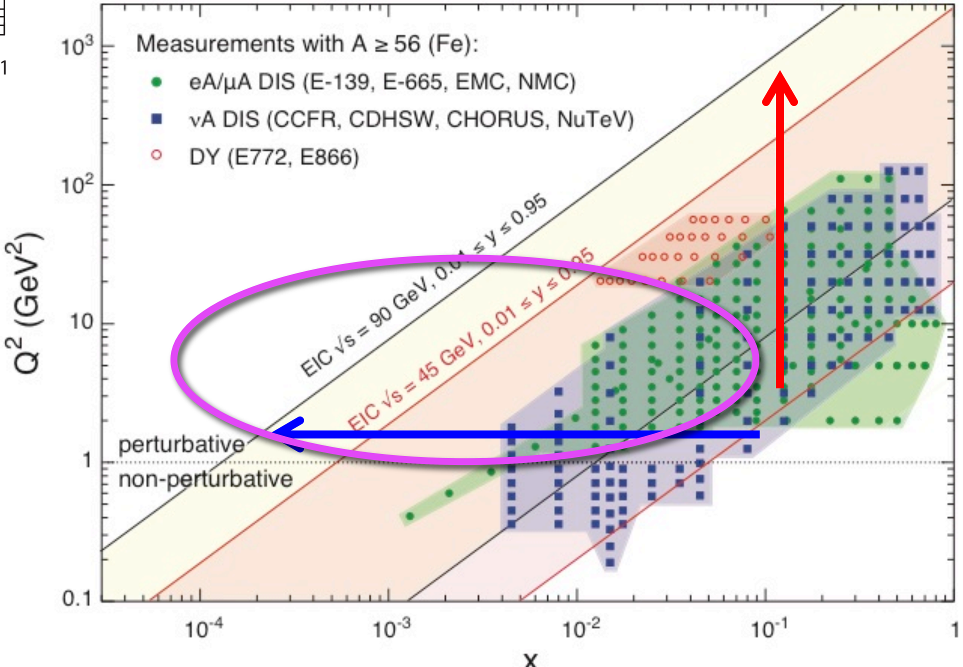


For e-N collisions at the EIC:

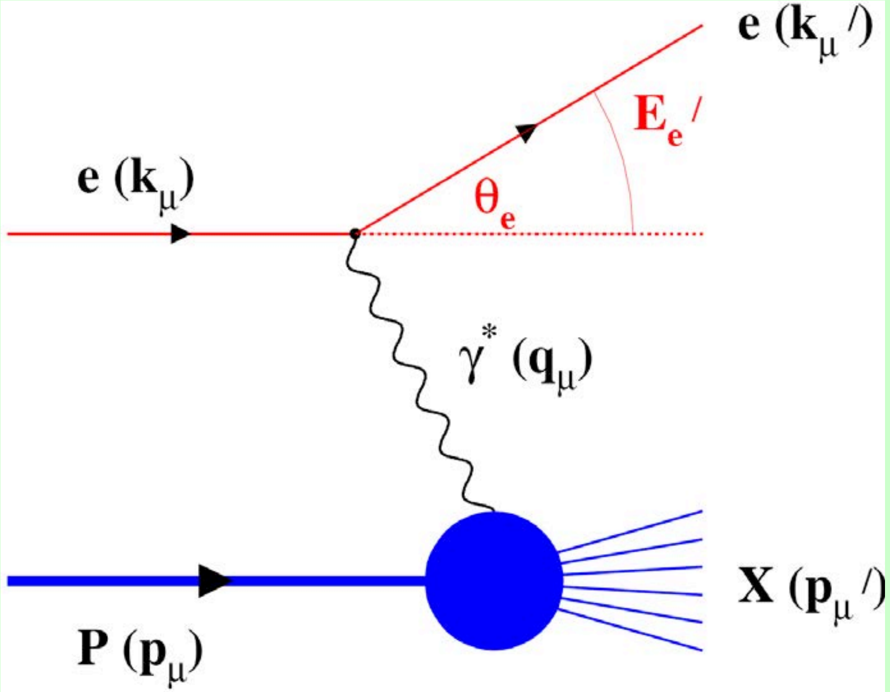
- ✓ **Polarized** beams: e, p, d/^{3}He
- ✓ Variable center of mass energy
- ✓ Wide Q^2 range → evolution
- ✓ Wide x range → spanning valence to low-x physics

For e-A collisions at the EIC:

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



Deep Inelastic Scattering: Precision & Control



Kinematics:

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

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

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

Inclusive events: e+p/A → e'+X

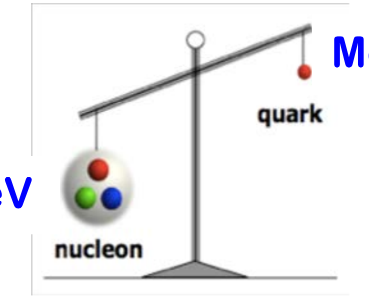
Semi-Inclusive events: e+p/A → e'+h(π,K,p,jet)+X

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

Understanding Nucleon Mass

$$M = E_q + E_g + \chi m_q + T_g$$

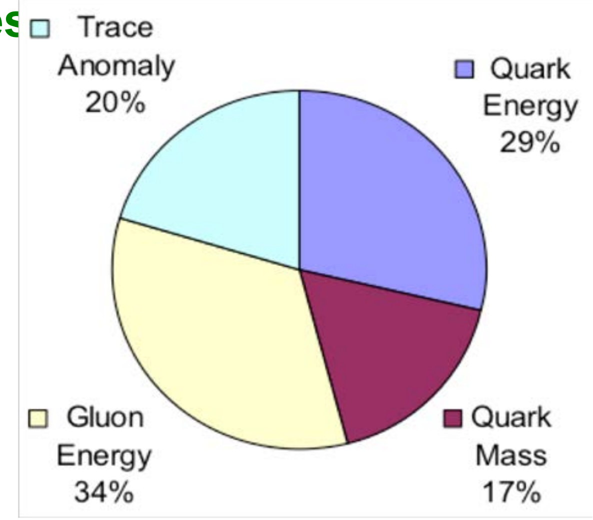
- Relativistic motion → $E_q + E_g$
- χ Symmetry Breaking → χm_q
- Quantum fluctuation → T_g
- Quark Energy → E_q
- Gluon Energy → E_g
- Quark Mass → m_q
- Trace Anomaly → T_g



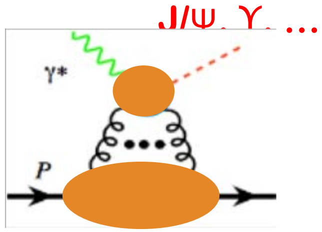
Mass component separation not yet agreed upon, but much interest in this is emerging

"… The vast majority of the nucleon's mass is due to quantum fluctuations of quark-antiquark pairs, the gluons, and the energy associated with quarks moving around at close to the speed of light. …" *The 2015 Long Range Plan for Nuclear Science*

- **Preliminary Lattice QCD res**



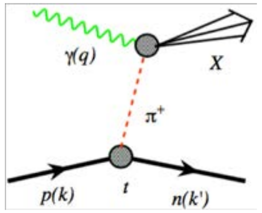
- **EIC's expected contribution in:**
  - Trace anomaly:
    Upsilon production near the threshold



  - Quark-gluon energy:
    $\propto$ *quark-gluon momentum fractions*

    In nucleon with DIS and SIDIS

    In pions and kaons with Sullivan process



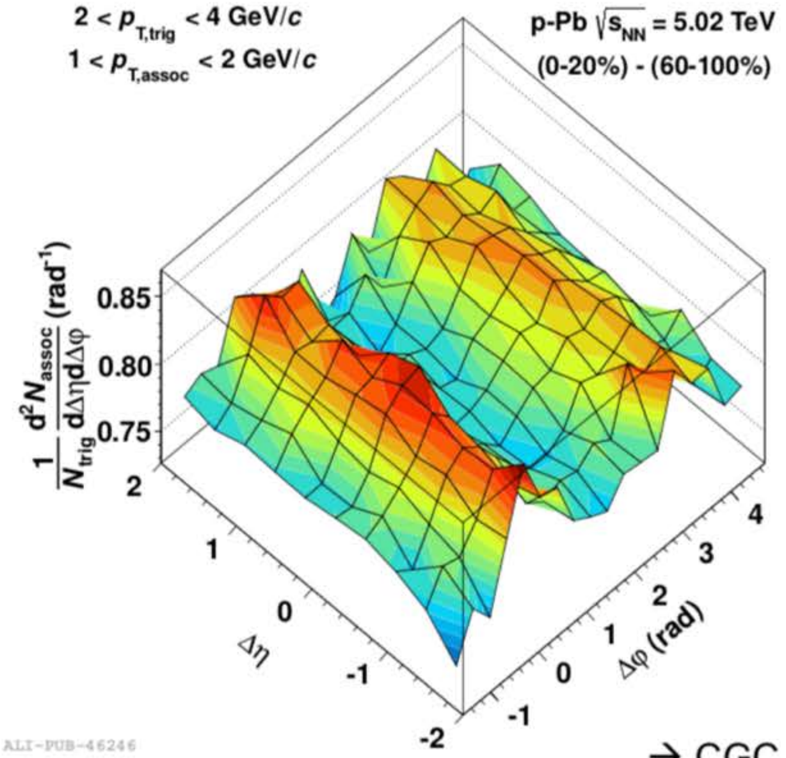
A Large Ion Collider Experiment

Double ridge structure in p-Pb collisions

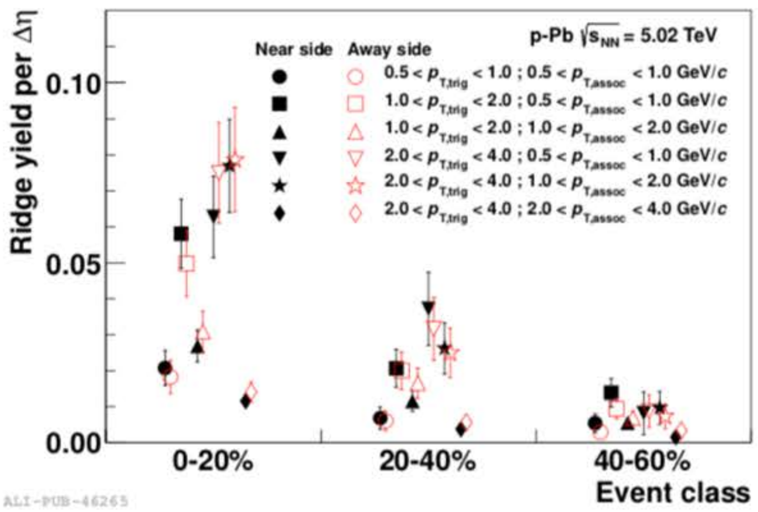
ALICE

ALICE Collaboration, Phys. Lett. B719 (2013) 29

→ Probing collective effects in small collision systems with two-particle correlations



- Ridge-like correlation structure elongated in pseudorapidity
- Similar ridges: away-side compared to near-side in p-Pb !
  - same centrality dependence
  - independently of transverse momentum

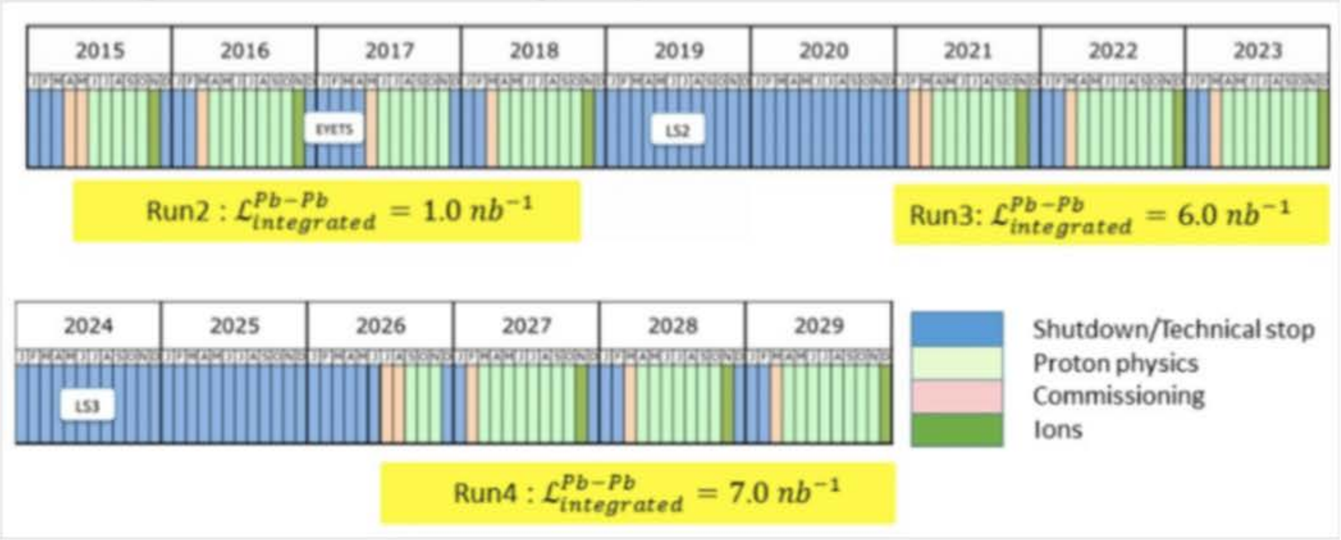


→ CGC or hydro models pointing to collectivity in p-Pb

A Large Ion Collider Experiment

ALICE LS2 Upgrades Ready by 2021

Timeline



- LS2:
  - LHC injector upgrades, Pb-Pb rate → 50 kHz (currently ~10 kHz)
  - ALICE upgrades
- Run 3 + Run 4:
  - experiments request > 10/nb (ALICE: 10/nb + 3/nb at 0.2 T)
  - in line with projections from machine group

A Large Ion Collider Experiment

An "all-MAPS" HI dedicated experiment beyond LS4

ALICE

he use of CMOS imaging technologies opens new opportunities

- Vertex detectors, large area tracking detectors and digital calorimeters
  - enhanced performance (very high-precision spatial and time resolution)

esign guidelines

Increase rate capabilities (factor 20 to 50 wrt to RUN4): $<L_{NN}>$ ~ up to 10^{34} $cm^{-2}s^{-1}$

Improve vertexing
- Ultra-thin wafer-scale sensors with truly cylindrical shape, inside beampipe
- spatial resolution ~ 1-3μm
- material thickness < 0.05% X_0 /layer

Improve tracking precision and efficiency
- About 10 layers with a radial coverage of 1m
- Spatial resolution of about 5μm up to 1m
- whole tracker could be less than 6% X_0 in thickness (at mid-rapidity)

Extended rapidity coverage (ideally up to 8 rapidity units)

ocus on relatively low p_T phenomena, $0.01 < p_T < 10$ GeV/*c*

soft electromagnetic and hadronic radiation

multiple heavy flavour hadrons (B_c, Ξ_{cc}, Ω_{ccc}, ...)

A Large Ion Collider Experiment

A new experiment "all-MAPS" detector beyond LS4

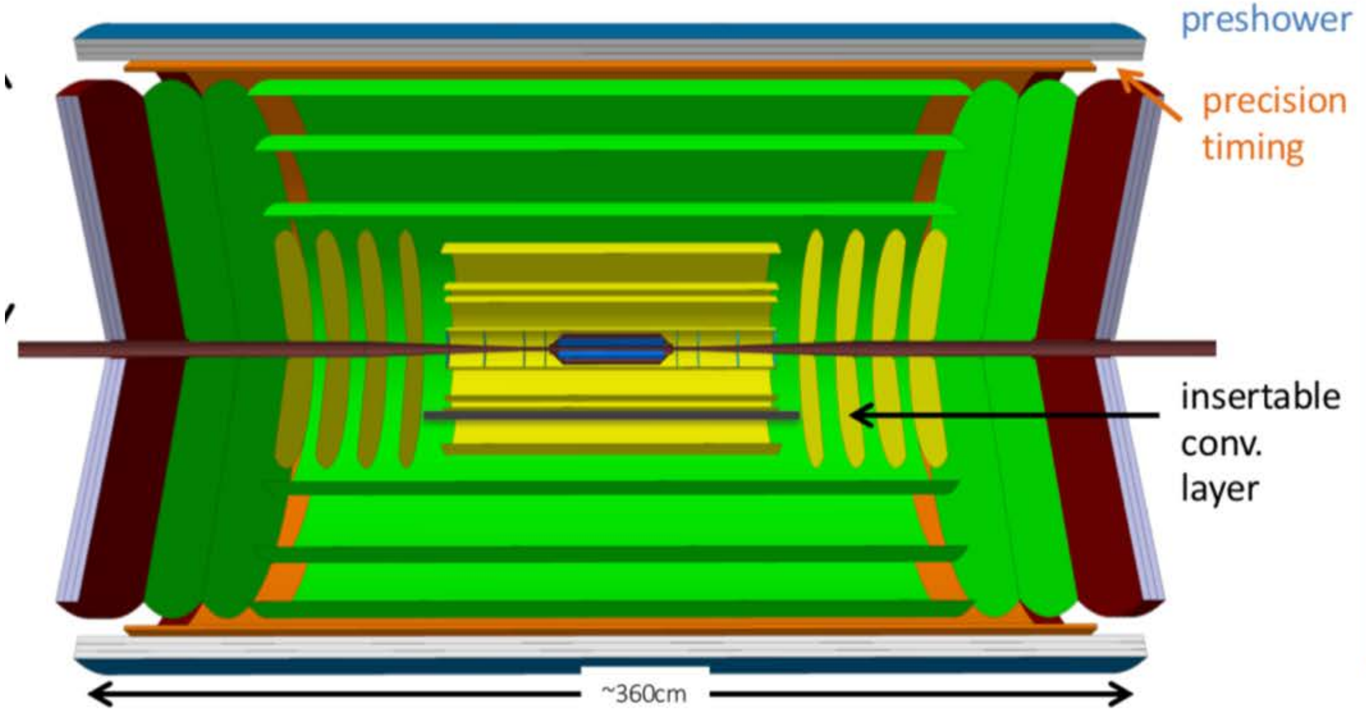
ALICE

Tracker: ~10 tracking barrel layers (blue, yellow and green) based on CMOS sensors

Hadron ID: TOF with outer silicon layers (orange)

Electron ID: pre-shower (outermost blue layer)

Extended rapidity coverage: up to 8 rapidity units + FoCal



Preliminary studies

Magnetic Field
- B = 0.5 or 1 T

Spatial resolution
- Innermost 3 layers: $\sigma \sim 1\mu m$
- Outer layers: $\sigma \sim 5\mu m$

Time Measurement
Outermost layer integrates high precision time measurement (σ_t < 30ps)