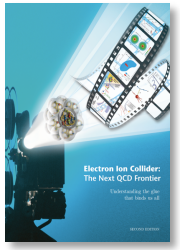
Center for Frontiers in Nuclear Science

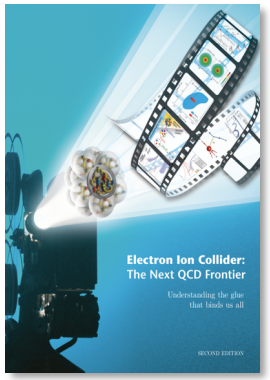
Perceiving the Emergence of Hadron Mass through **AMBER@CERN**

30 November to 4 December 2020
CERN, Geneve - Switzerland

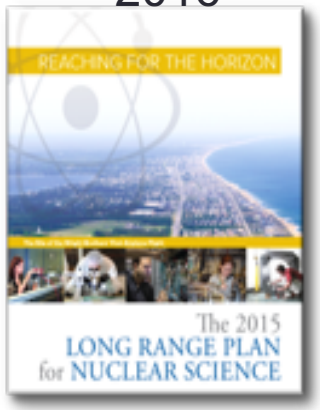



# Electron Ion Collider:
## *Science, Status and Opportunities for Collaboration*

2015

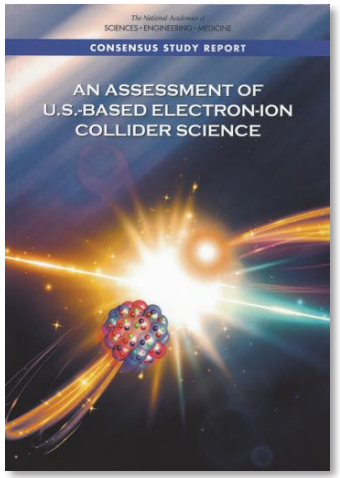



2016



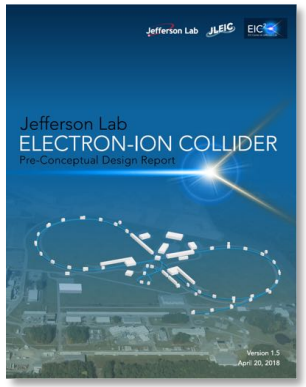

Physics of EIC

2018

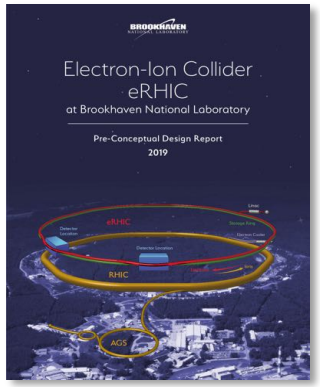



Evaluation

2019




2019 - future




Realization

# On the menu today:

- The science of Electron Ion Collider : an overview & highlights
- The EIC project (machine & detector design) status and plans
- EIC Users Group (science program, detector design and collaboration) aspirations
- Realization & opportunities for collaboration

# QCD: The Holy Grail of Quantum Field Theories

- QCD : "nearly perfect", fundamental quantum field theory of quarks and gluons that explains nature's strong interactions
- 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 Dynamics of QCD has Fundamental Consequences

- Quark (Color) confinement:
  - Unique property of the strong interaction
  - Consequence of nonlinear gluon self-interactions
- Strong Quark-Gluon Interactions:
  - Confined motion of quarks and gluons – Transverse Momentum Dependent Parton Distributions (TMDs)
  - Confined spatial correlations of quark and gluon distributions -- Generalized Parton Distributions (GPDs)

Emergence of spin, mass & confinement, gluon fields

→ Deeply connected to emergence of mass and spin of observed building blocks of nature

- Ultra-dense color (gluon) fields in all nucleons and nuclei?
  - Runaway growth in gluon number: Is it tamed by existing mechanisms in QCD?
  - Is there a universal many-body structure due to ultra-dense color fields?
  - Happens **in all** hadrons and nuclei? ➔ Universal?

***A-A, p-A, e-A, p-p, e/μ-p/A and e-e collisions are all essential for fully understanding of QCD***

# Emergent Dynamics in QCD

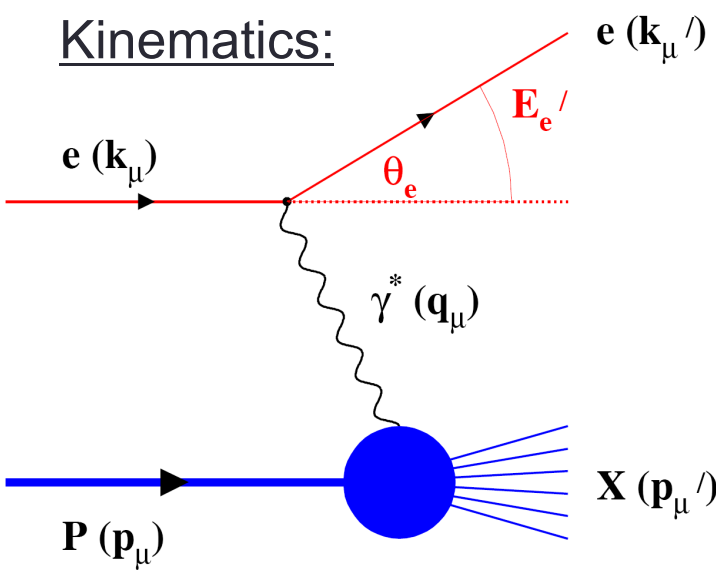
***Without gluons,* there would be no nucleons, no atomic nuclei… *no visible world!***

- Massless gluons & almost massless quarks, *through their interactions,* generate most of the mass of the nucleons
- Gluons carry ~50% of the proton's momentum, a significant fraction of the **nucleon's spin**, and are essential for the dynamics of confined partons
- Properties of hadrons are emergent phenomena resulting not only from the equation of motion but are also inextricably tied to the properties of the QCD vacuum. (Striking examples besides confinement are spontaneous symmetry breaking and anomalies).
- How do the nucleon-nucleon forces emerge from quark-gluon interactions? -- A mystery….

**Experimental insight and guidance crucial for complete understanding of *how* hadrons & nuclei emerge from quarks and gluons**

# Deep Inelastic Scattering: Precision and 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

$$s = 4\,E_t\,E_e$$

$$x = \frac{Q^2}{2pq} = \frac{Q^2}{sy}$$ Measure of momentum fraction of struck quark

High lumi & acceptance

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

***Hadron :***

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

**Semi-inclusive events**:
e+p/A → e'+h(π,K,p,jet)+X
detect the scattered lepton in coincidence with identified hadrons/jets

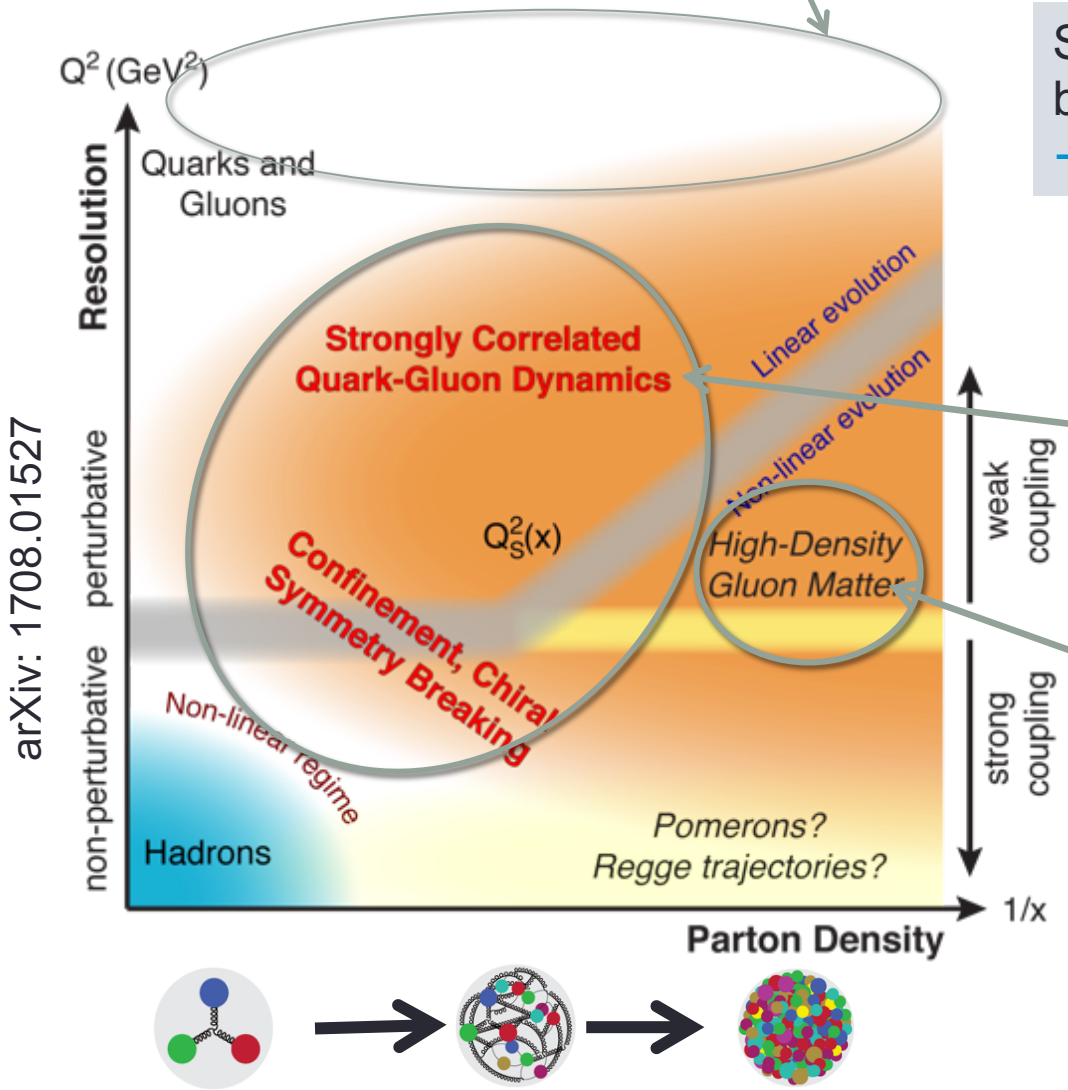
**Inclusive events**:
e+p/A → e'+X
detect *only the scattered lepton* in the detector

Low lumi & acceptance

# QCD Landscape to be explored by a future facility

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

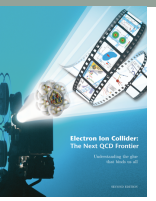



Systematically explore correlations in this region.

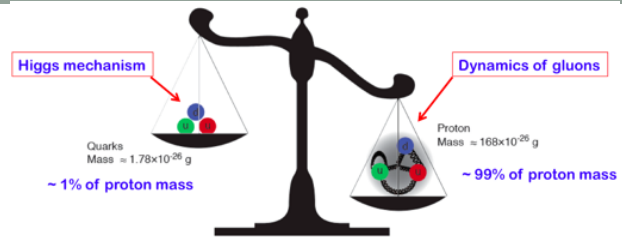
An exciting opportunity: Observation of a new regime in QCD of weakly coupled high-density matter

**Need Precision and Control**

arXiv: 1708.01527

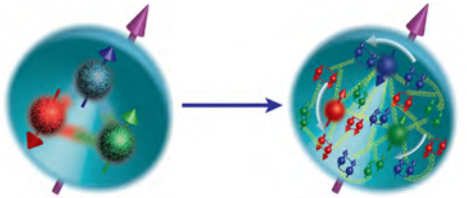


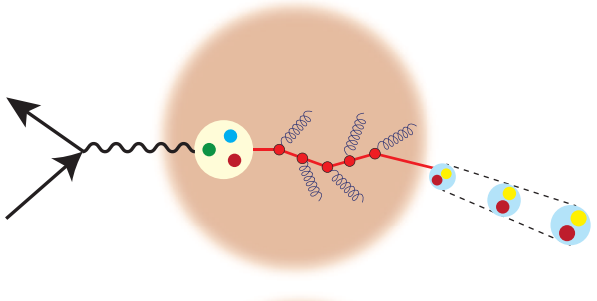

# EIC Physics at a Glance




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

How do the nucleon properties l(mass & spin) emerge from their interactions?





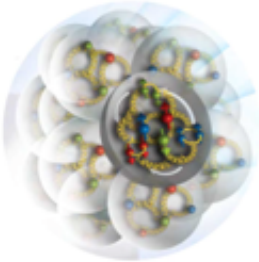
How do color-charged quarks and gluons, and colorless jets, interact with a nuclear medium?

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

How do the quark-gluon interactions create nuclear binding?

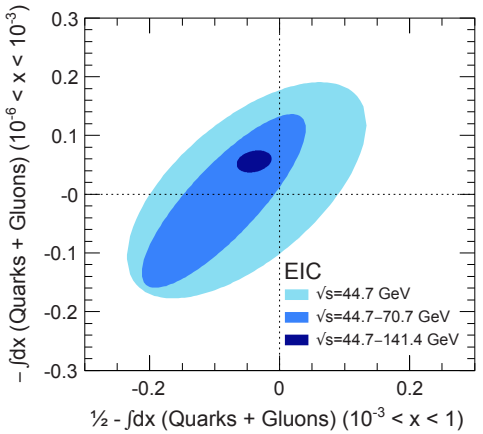
How does a dense nuclear environment affect the quarks and gluons, their correlations, and their interactions?

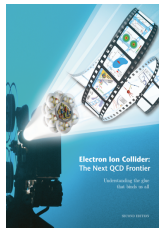
What happens to the gluon density in nuclei? Does it saturate at high energy, giving rise to a gluonic matter with universal properties in all nuclei, even the proton?

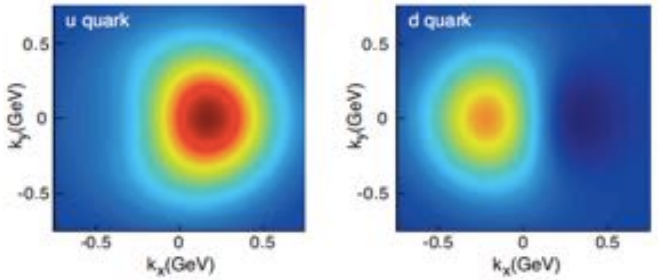


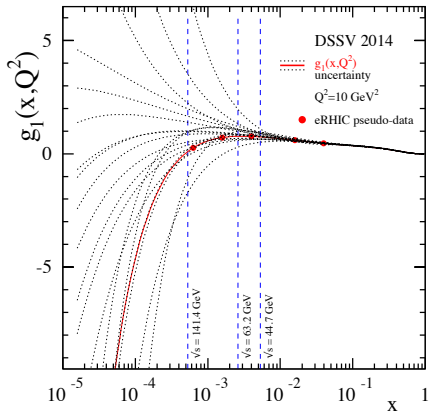
gluon emission ? = gluon recombination

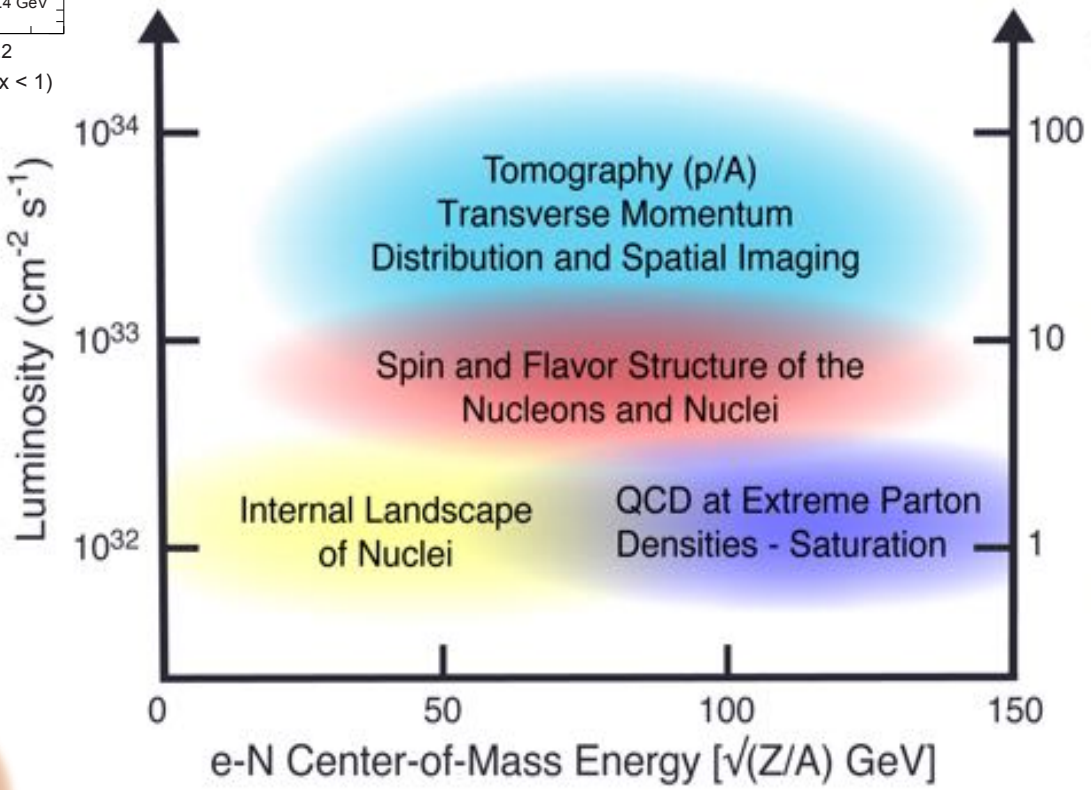
# EIC science highlights

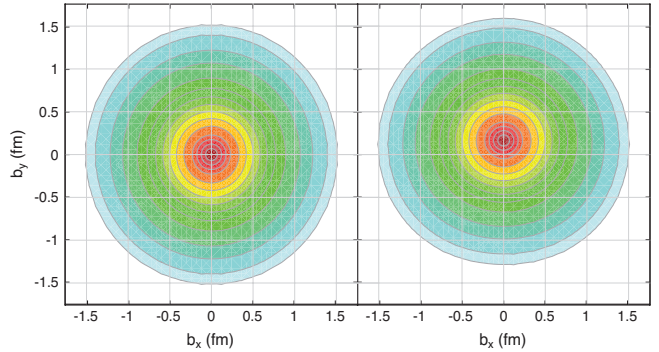


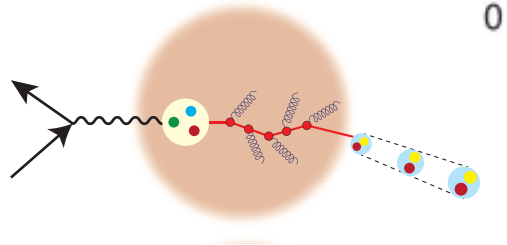



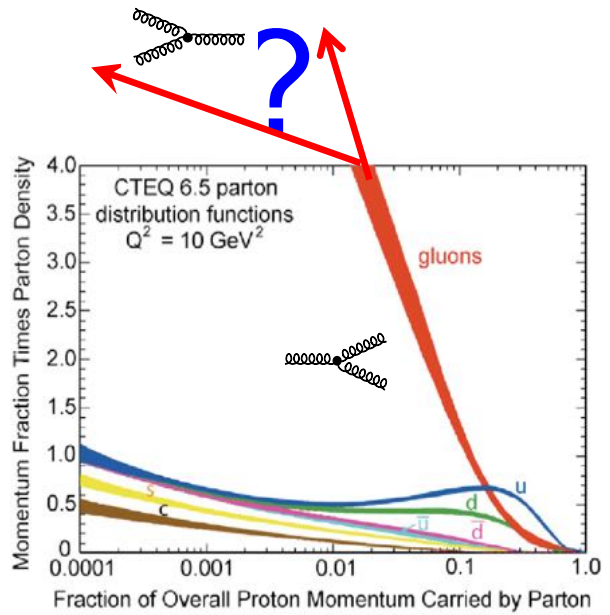


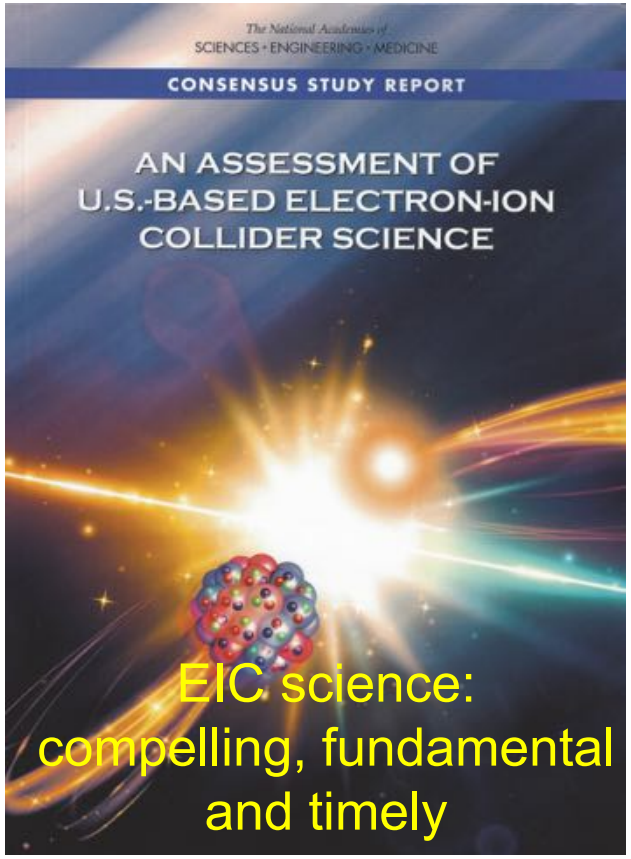



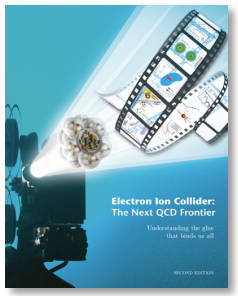





# National Academy's Assessment

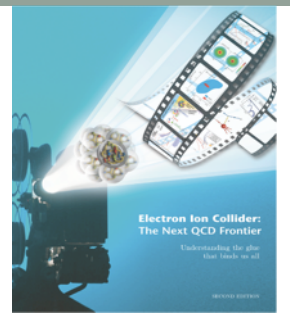


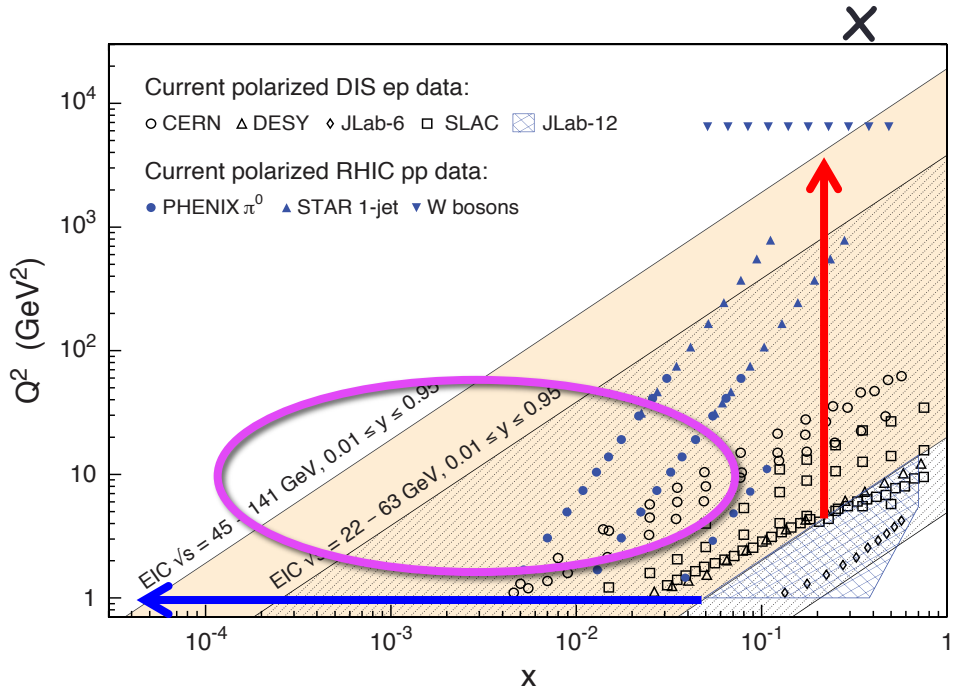




**Machine Design Parameters:**

- High luminosity: up to $10^{33}$-$10^{34}$ $cm^{-2}sec^{-1}$
  - a factor ~100-1000 times HERA
- Broad range in center-of-mass energy: ~20-100 GeV upgradable to 140 GeV
- Polarized beams e-, p, and light ion beams with flexible spin patterns/orientation
- Broad range in hadron species: protons…. Uranium
- Up to two detectors well-integrated detector(s) into the machine lattice

# EIC: Kinematic reach & properties



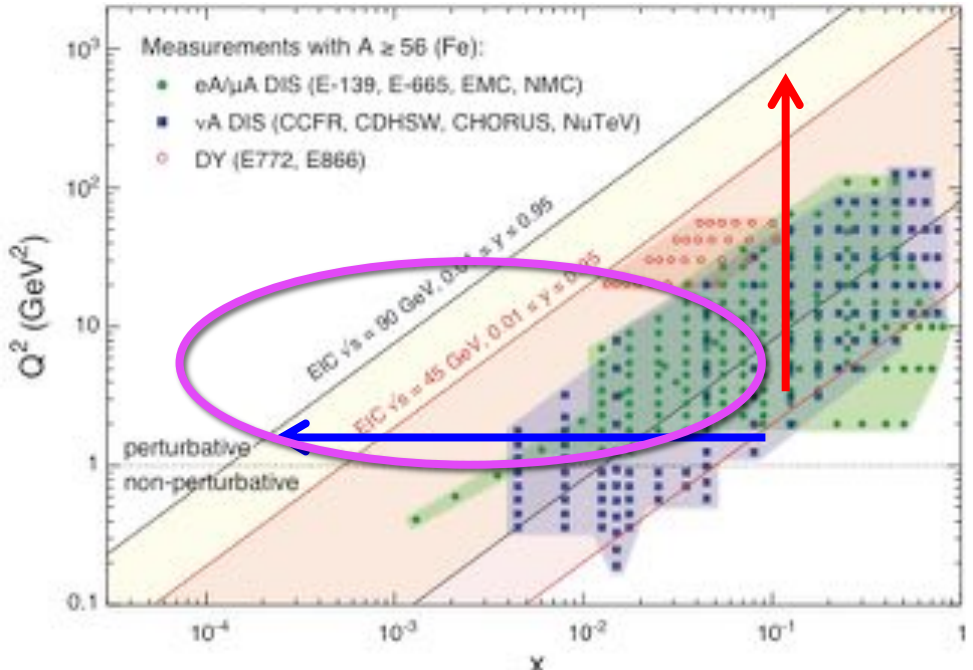




For e-N collisions at the EIC:

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

For e-A collisions at the EIC:

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



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

Of HEP/LHC-HI interest to Snowmass 2021 (EF 05, 06, and 07 and possibly also EF 04) ➔ **Interesting to High Energy Physicists at LHC**

**New Studies with proton or neutron target:**

- Impact of precision measurements of unpolarized PDFs at high $x/Q^2$, on LHC-Upgrade results(?)
- What role would TMDs in e-p play in W-Production at LHC? Gluon TMDs at low-x!
- Heavy quark and quarkonia (c, b quarks) studies with 100-1000 times lumi of HERA
- Does polarization of play a role (in all or many of these?)

**Physics with nucleons and nuclear targets:**

- Quark Exotica: 4,5,6 quark systems…? Much interest after recent LHCb led results.
- Physic of and with jets with EIC as a precision QCD machine:
  - Internal structure of jets
  - Studies with jets: Jet propagation in nuclei… energy loss in cold QCD medium
- Entanglement entropy & connection to fragmentation, hadronization, confinement
- Connection to p-A, d-A, A-A at RHIC and LHC
- Polarized light nuclei in the EIC

**Precision electroweak and BSM physics:**

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

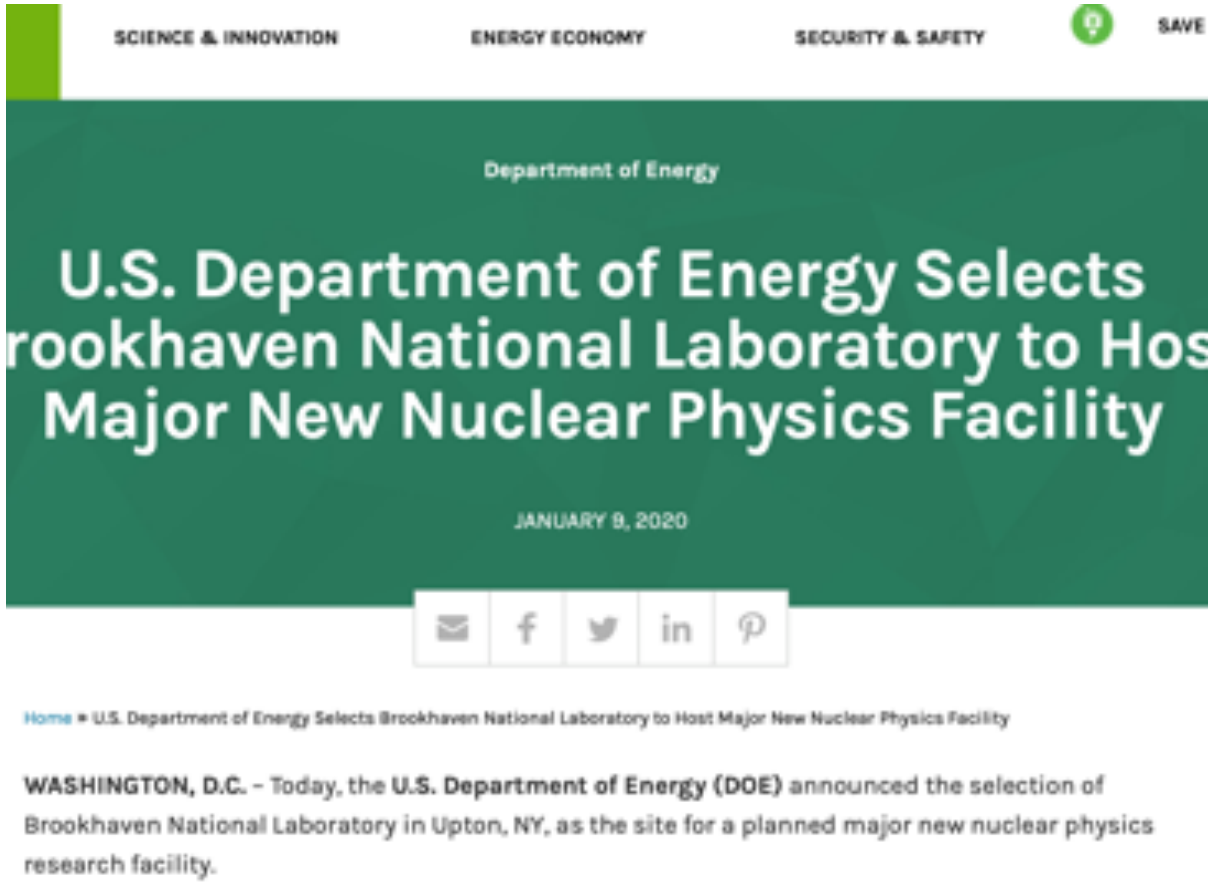
# EIC Status and Realization

- CD0 : December 19, 2019
- Site BNL : January 9, 2020
- BNL and JLab realize EIC as partners

- A formal EIC project is now setup at BNL
- BNL+Jlab management & scientists are working together to realize it on a fast timeline.

- CD1 anticipated March 2021
- CD2 September 2022 (final design)
- CD3 4th Quarter FY2023 (start construction)

- EIC CD4A Early Finish 4th Q FY2029
- EIC CD4B 3rd Q FY 2032



SCIENCE & INNOVATION ENERGY ECONOMY SECURITY & SAFETY SAVE

Department of Energy

U.S. Department of Energy Selects
rookhaven National Laboratory to Hos
Major New Nuclear Physics Facility

JANUARY 9, 2020

Home • U.S. Department of Energy Selects Brookhaven National Laboratory to Host Major New Nuclear Physics Facility

**WASHINGTON, D.C.** – Today, the **U.S. Department of Energy (DOE)** announced the selection of Brookhaven National Laboratory in Upton, NY, as the site for a planned major new nuclear physics research facility.

# BNL TJNAF Partnership

- The EIC Project captures project delivery experience from BNL and TJNAF
- BNL-TJNAF Partnering Agreement Approved- May 7, 2020
- EIC Project Executive Management Team (EMT) Established:
  Elke Aschenauer, Rolf Ent, Diane Hatton, Allison Lung, Andrei Seryi, Ferdinand Willeke, and Jim Yeck
- Abhay Deshpande, EIC Science Director, participates in the EMT meeting as an ex-officio member providing an additional connection to the User community.

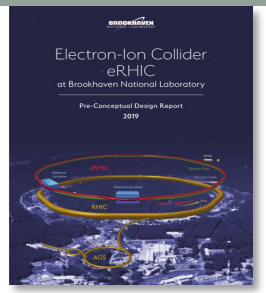

**BNL Visit to TJNAF – Feb 28, 2020**

**ELECTRON ION COLLIDER PROJECT**

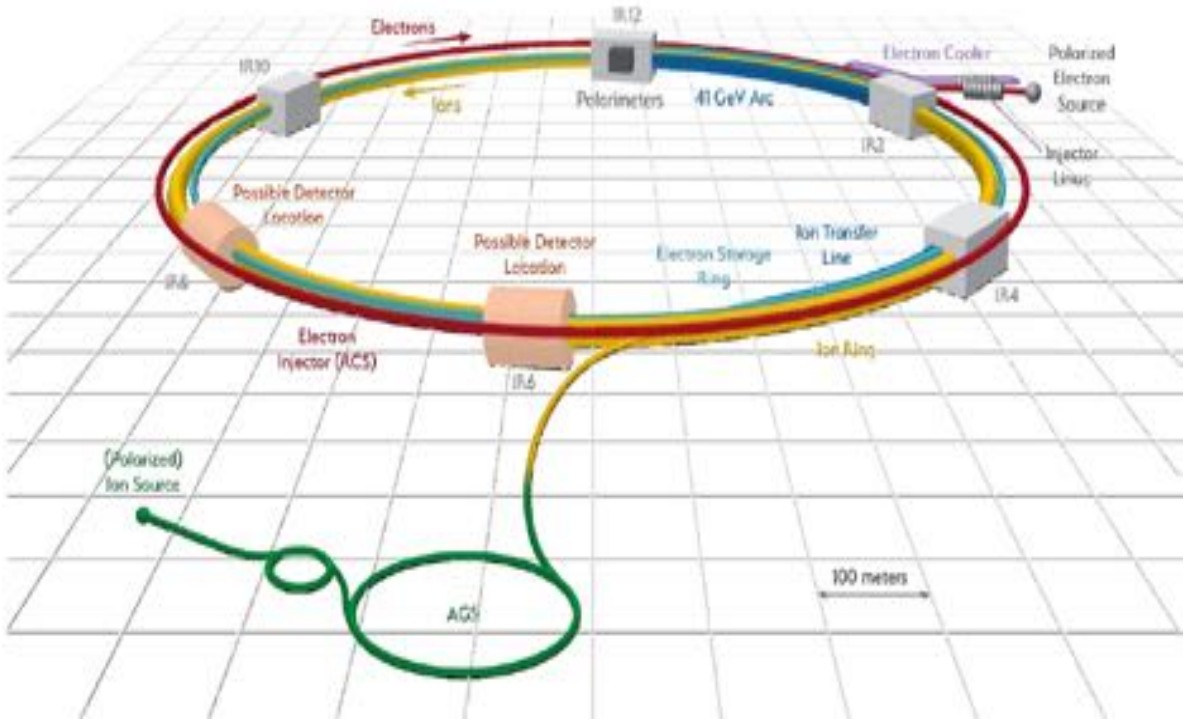
**J. Yeck (BNL)**, Project Director
**F. Willeke (BNL)**, Deputy Project Director and Technical Director

**R. Ent (TJ)**, Co-Associate Director for the Experimental Program
**E. Aschenauer (BNL)**, Co-Associate Director for the Experimental Program
**A. Lung (TJ)**, Deputy Project Director for TJNAF Partnership
**A. Seryi (TJ)**, Associate Director for Accelerator Systems & International Partnership
**D. Hatton (BNL)**, Project Manager

J.Yech, EIC project Director




# The US Electron Ion Collider




- Electron storage ring with frequent injection of fresh polarized electron bunches
- Hadron storage ring with strong cooling or frequent injection of hadron bunches

**Hadrons up to 275 GeV**

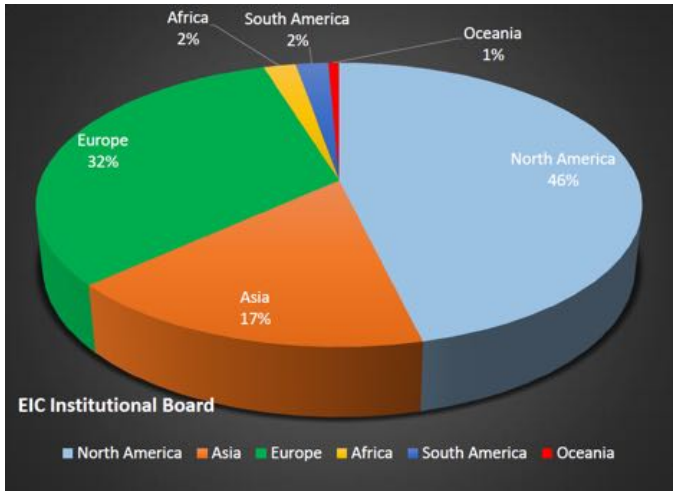
- Existing RHIC complex: Storage (Yellow), injectors (source, booster, AGS)
- Need few modifications
- RHIC beam parameters fairly close to those required for EIC@BNL

**Electrons up to 18 GeV**

- Storage ring, provides the range sqrt(s) = 20-140 GeV. Beam current limited by RF power of 10 MW
- Electron beam with variable spin pattern (s) accelerated in on-energy, spin transparent injector (Rapid-Cycling-Synchrotron) with 1-2 Hz cycle frequency
- Polarized e-source and a 400 MeV s-band injector LINAC in the existing tunnel

**Design optimized to reach $10^{34}$ $cm^{-2}sec^{-1}$**

# The EIC Users Group: EICUG.ORG




**Formally established in 2016, now we have:**
**~1200 Ph.D. Members from 33 countries, 230 institutions**
**New members welcome**


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, Institutional Board, Speaker's Committee, Election & Nominations Committee
**Task forces on**:
-- Beam polarimetry, Luminosity measurement
-- Background studies, IR Design

**Year long workshops: Yellow Reports for detector design**

Annual meetings: Stony Brook (2014), Berkeley (2015), **ANL (2016), Trieste (2017), CAU (2018), Paris (2019), FIU (2020), Warsaw (2021)**

# Experimental Program Preparations: Yellow Reports, Expressions of Interests & Proposals

- EIC Community's Yellow Report Initiative (Kickoff in December 2019, site)
  - Four workshops planned to advance the state and detail of the documented physics studies and detector concepts in preparation for the realization of the EIC.
  - Report ready February 2021
- BNL and TJNAF Jointly Leading Process for **Defining Detector(s) strategy**
  - Project contains machine, IR and 1 detector; Users aspire for two detectors: Carefully considered by Project
  - Call for "Potential Cooperation on the EIC Experimental Program" published in May
  - Includes two questionnaires, FAQ, and input received
  - **Expressions of Interest (EOIs) due November 1, 2020:**
- Following the EOI Response Deadline
  - Status report at 4th Yellow Report meeting in November 18-20, LBNL: **Summary – see later**
  - Responses evaluated and Call for Proposal(s) finalized
    - Assessment by an external committee including: members of the Users Group and Project Management with advice from Detector Advisory Committee (DAC)
    - Call for Detector Proposal(s) in March 2021

EIC EOI Site: https://www.bnl.gov/eic/EOI.php

# Yellow Reports Conveners

- Physics Conveners:
  - Adrian Dumitru (Baruch)
  - Olga Evdokimov (University of Illinois at Chicago)
  - Andreas Metz (Temple)
  - Carlos Muñoz Camacho (Orsay)
- Detector Conveners:
  - Ken Barish (UC Riverside)
  - Tanja Horn (CUA)
  - Peter Jones (Birmingham)
  - Silvia Dalla Torre (Trieste)
  - Markus Diefenthaler, ex-officio (JLab)

**Other YR meetings:**

March 2020 (Temple U)

May 2020 (Pavia)

July/August 2020 (FIU)

September 2020 (CUA)

November 2020 (LBNL)

YR Final: by February 23, 2021

# Physics Working Group Sub-conveners

## Inclusive

Theory: Nobuo Sato (JLab)
Experiment: Renee Fatemi (Kentucky), Barak Schmookler (Stony Brook)

## Semi-Inclusive DIS

Theory: Bowen Xiao (CCNU, China), Alexey Vladimirov (Regensburg)
Experiment: Anselm Vossen (Duke), Ralf Seidl (RIKEN), Justin Stevens (W&M)

## Jets, heavy quarks

Theory: Ivan Vitev (LANL), Frank Petriello (Argonne & Northwestern U.)
Experiment: Ernst Sichtermann (LBL), Brian Page (BNL), Leticia Mendez (ORNL)

## Exclusive

Theory: Tuomas Lappi (Jyvaskyla), Barbara Pasquini (Pavia)
Experiment: Raphaël Dupré (Orsay), Salvatore Fazio (BNL), Daria Sokhan (Glasgow)

## Diffractive & Tagging

Theory: Wim Cosyn (Florida), Anna Stasto (PSU)
Experiment: Or Hen (MIT), Douglas Higinbotham (JLab), Spencer Klein (LBNL)

# EXPERIMENTAL REQUIREMENTS

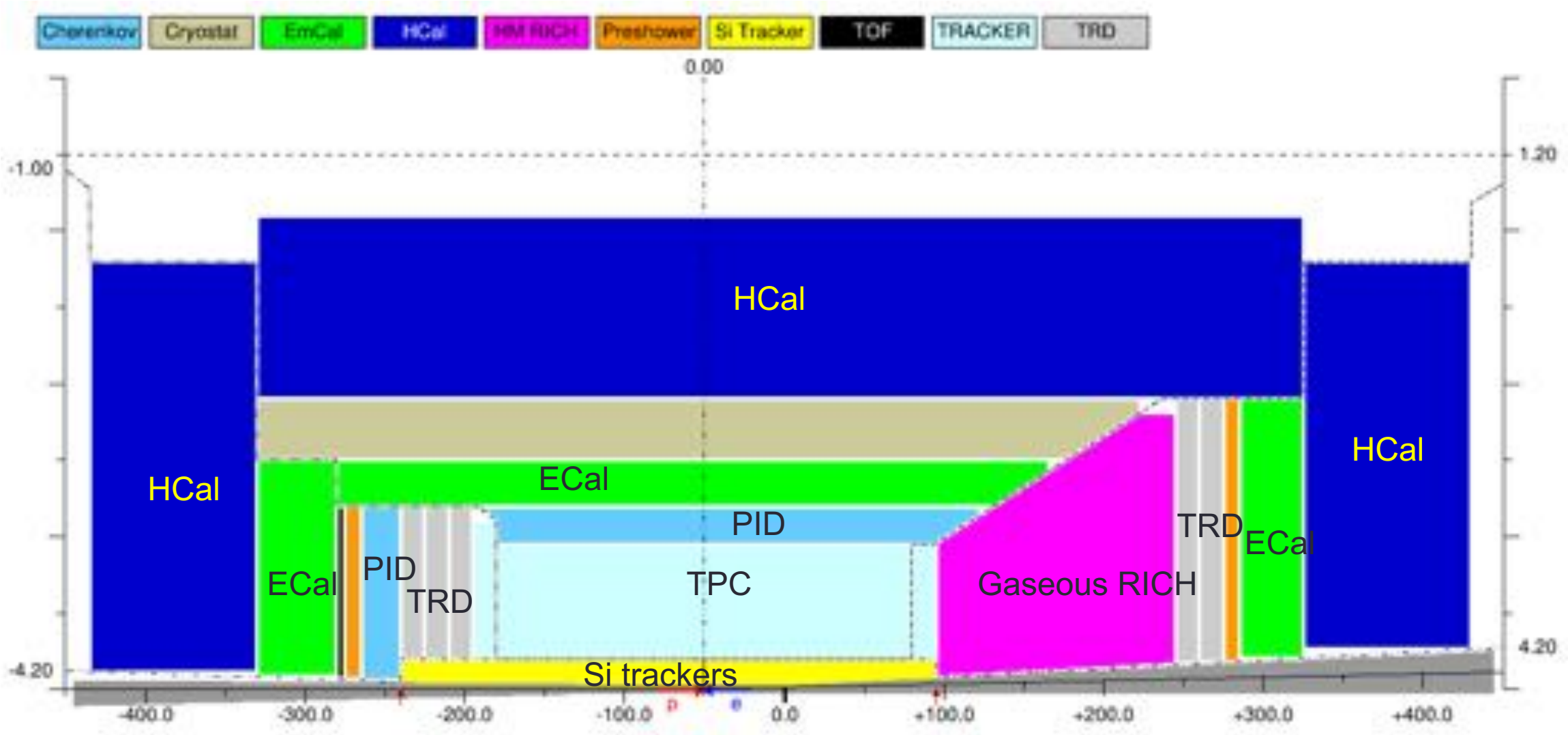
More and more demanding moving from inclusive to fully exclusive scattering

- **Inclusive measurements (DIS), required:**
  - Precise scattered electron identification (e.m. calorimetry, e/h PID) and extremely fine resolution in the measurement of its angle (tracking) and energy (calorimetry)
- **Semi-inclusive measurements (SI-DIS), also required:**
  - excellent hadron identification over a wide momentum and rapidity range (h-PID)
  - full $2\pi$ acceptance for tracking (tracking) and momentum analysis (central magnet)
  - excellent vertex resolution (low-mass vertex detector)
- **Exclusive measurements also required:**
  - Tracker with excellent space-point resolution (high resolution vertex) and momentum measurement (tracking),
  - Jet energy measurements (h calorimetry)
  - very forward detectors also to detect n and neutral decay products (Roman pots, large acceptance zero-degree calorimetry)
- **And luminosity control, e and A polarimeters, r-o electronics, DAQ, data handing**



S. Dalla Torre (INFN) & T. Horn (CUA)

# REFERENCE DETECTOR IN A CARTOON



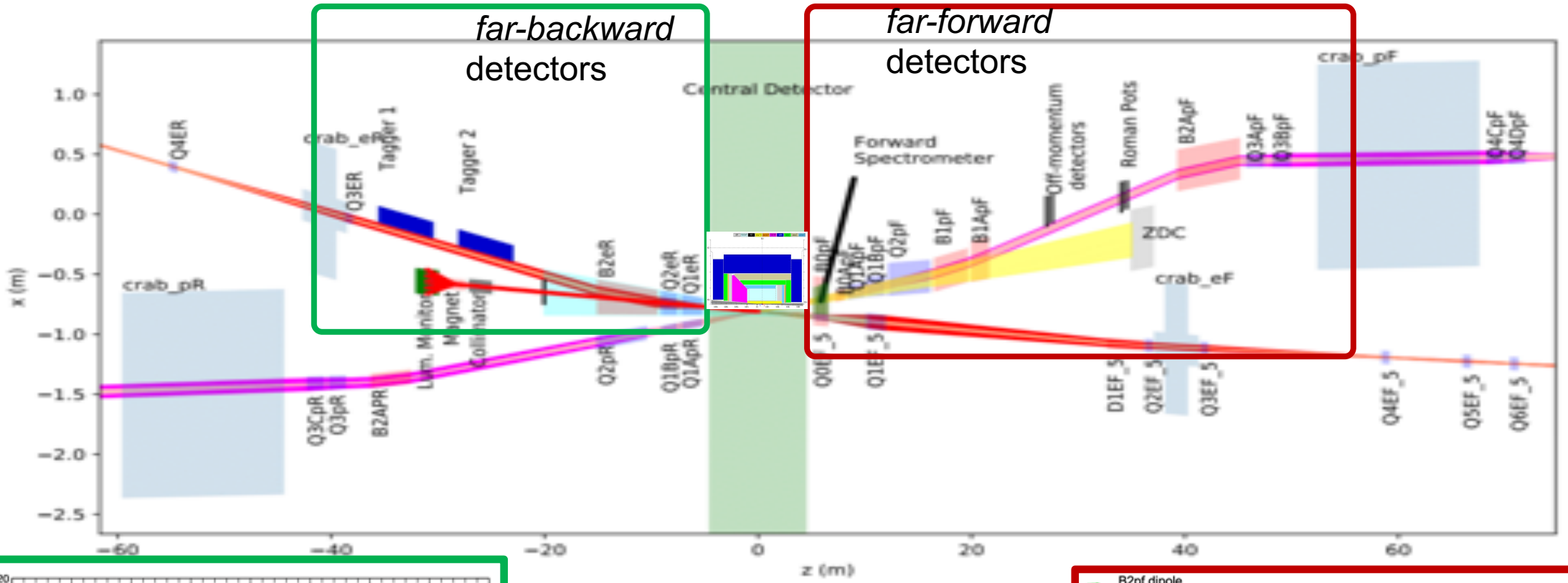


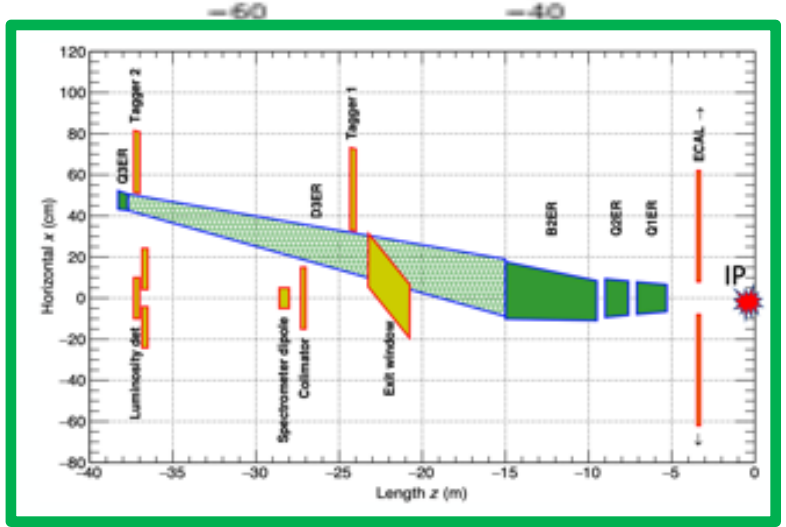

S. Dalla Torre & T. Horn

# Reference Detector – Backward/Forward Detectors

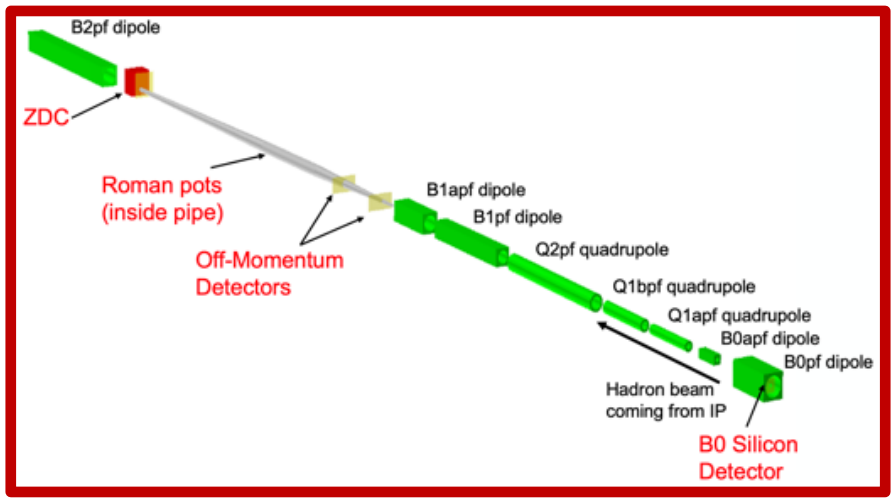
*far-backward* detectors

*far-forward* detectors

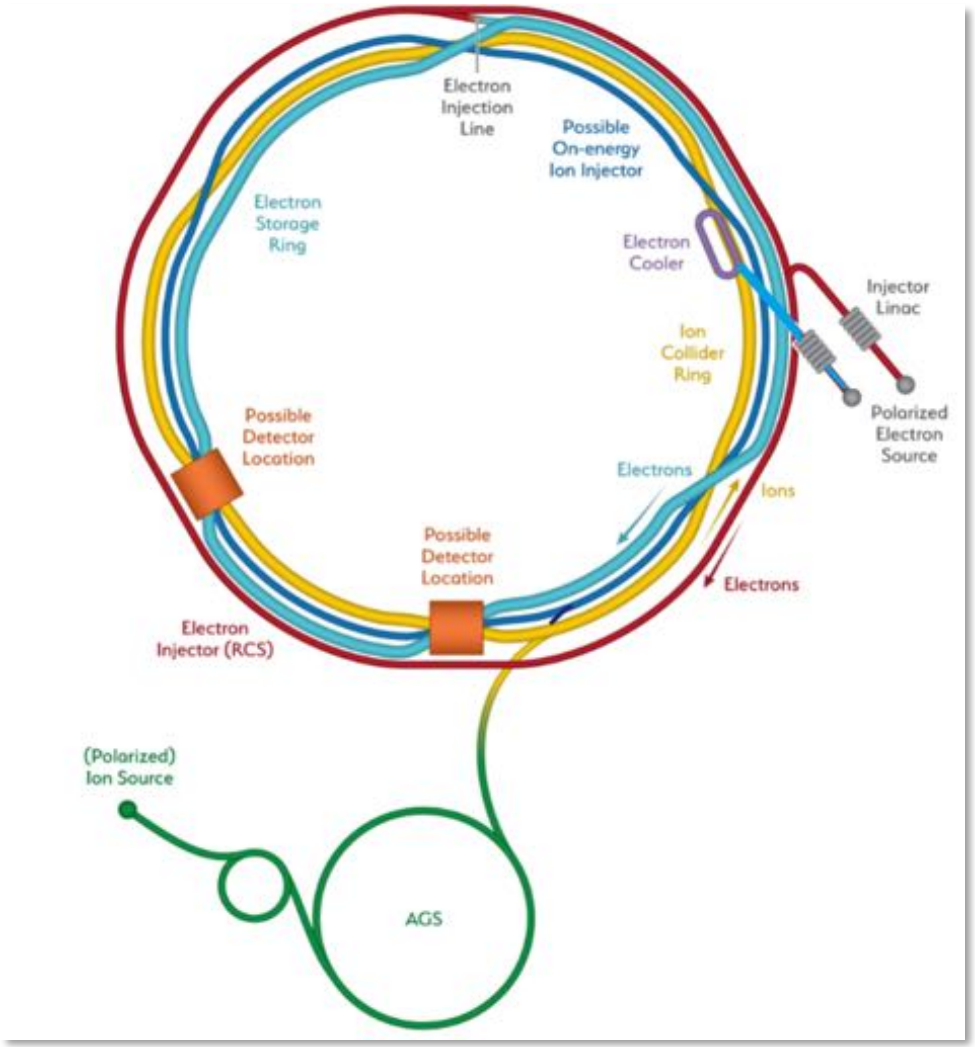



Extensive integration of forward and backward detector elements into the accelerator lattice



# Overview of EIC Project and Layout




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

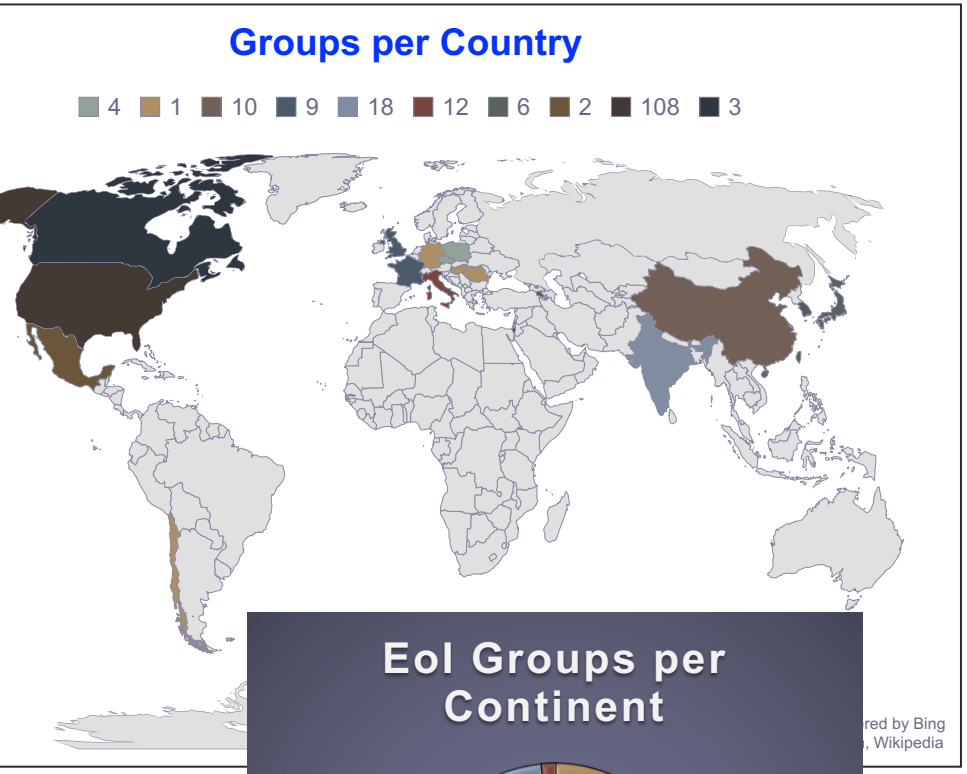
**EIC Project: 1 Machine, 1 IR, 1 Detector cost**
**Possibility of the 2nd IR and a 2nd Detectors to be preserved**

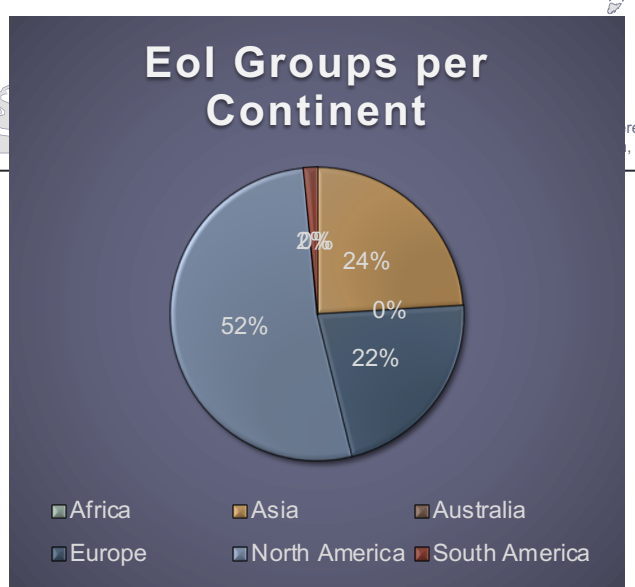
**Two possible locations – IP6 and IP8 – for detectors/IR**

Current Assumption: IP6 is "default" EIC detector location (as IP8 has sPHENIX).

Details of one or two detectors (designs, complementarity) to be finalized in the coming years.

# Expressions of Interest : analysis by EIC Project




Slide based on R. Ent's, LBNL YR meeting

- 46 Expressions of Interest received
- There is clearly large interest in EIC science and experimental equipment
  - Both domestically among universities and national labs
  - And international, with many countries represented (Canada, China, Czech, France, India, Italy, Japan, Korea, Poland, UK and institutional EoIs of Chile, Hungary, Mexico, Rumania, and group EoIs with Armenia, Israel, Saudi Arabia and Taiwan as members)
- With EIC science still a *decade* away, impressively many are committed to work on EIC.
- In-kind contributions suffice to maintain low-risk for a general-purpose EIC detector.
- It is clear we need to remain vigilant and follow up to secure in-kind contributions and even argue, based on our strong EIC science, for further contributions, if we want to be able to secure a second detector, with crisp arguments on why.
- Remain unified and make the case for collaboration internationally

# EIC Bilateral & Other Collaborative Initiatives Machine and Detector

**September 2020**

- SLAC – EIC: 9/30
- ORNL – EIC: 9/18
- **TRIUMF – EIC: 9/17**
- **CERN – EIC: 9/14**
- **DESY – EIC: 9/14**
- ANL – EIC: 9/8
- LBNL – EIC: 9/2

**June – August 2020**

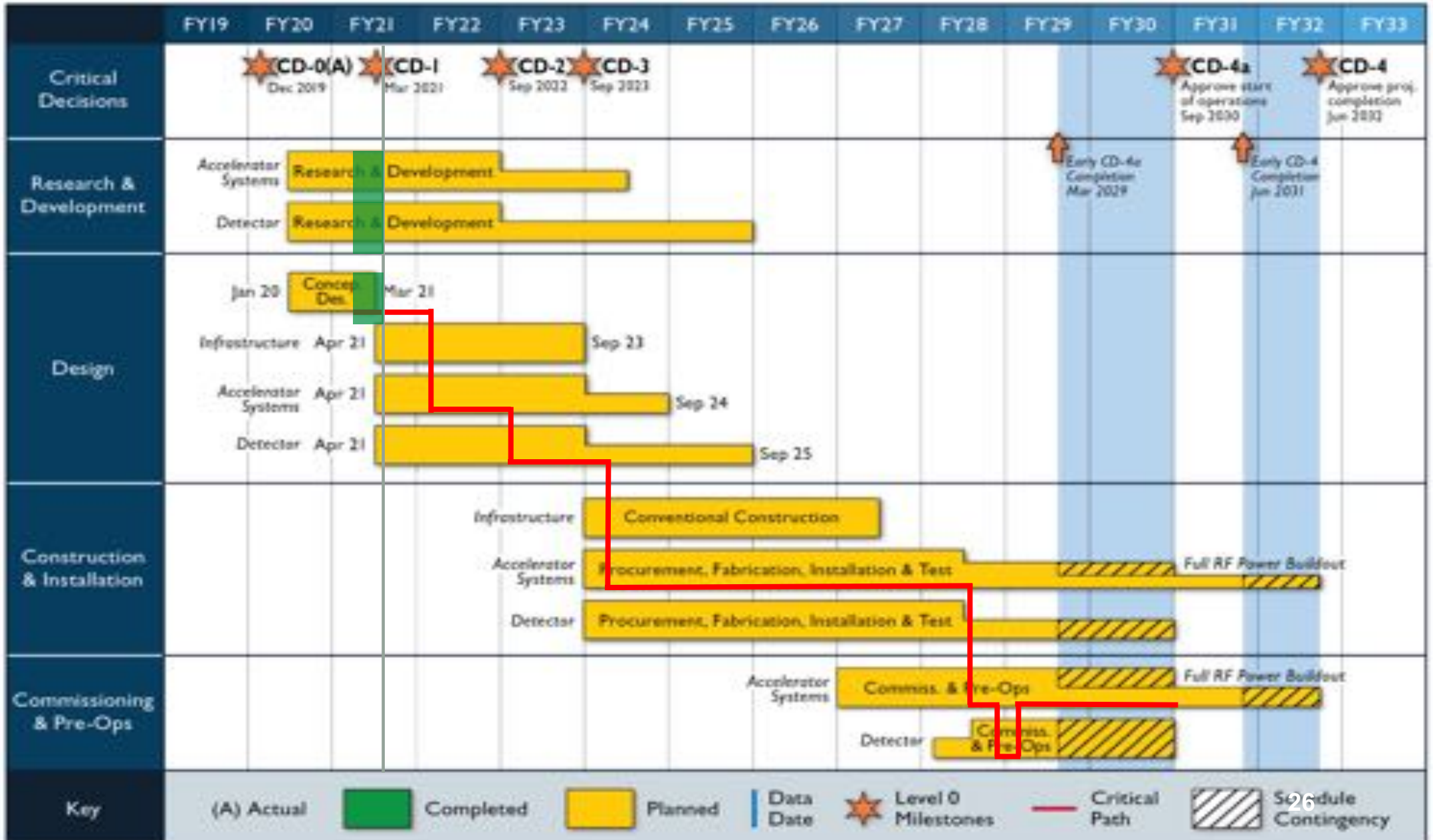
- **CERN FCC – EIC: 7/6**
- **INF Krakow – EIC: 7/2**
- ANL – EIC: 7/1
- **CEA-Saclay – EIC: 6/16**

**October 7-10, 2020**

**EIC Accelerator Collaboration Meeting**
**Cockcroft Institute in UK**
**https://www.cockcroft.ac.uk/events/eic20/**

Electron Ion Collider Project Launch, September 18, 2020
https://www.bnl.gov/newsroom/news.php?a=117399
**Movie Clip: CERN Director General Fabiola Gianotti (starts at 1:01:50)**

# Schedule


FY19
FY20
FY21
FY22
FY23
FY24
FY25
FY26
FY27
FY28
FY29
FY30
FY31
FY32
FY33
Critical Decisions
CD-0(A)
Dec 2019
CD-1
Mar 2021
CD-2
Sep 2022
CD-3
Sep 2023
CD-4a
Approve start of operations
Sep 2030
CD-4
Approve proj. completion
Jun 2032
Research & Development
Accelerator Systems
Research & Development
Detector
Research & Development
Early CD-4a Completion Mar 2029
Early CD-4 Completion Jun 2031
Design
Jan 20
Concep. Des.
Mar 21
Infrastructure
Apr 21
Sep 23
Accelerator Systems
Apr 21
Sep 24
Detector
Apr 21
Sep 25
Construction & Installation
Infrastructure
Conventional Construction
Accelerator Systems
Procurement, Fabrication, Installation & Test
Full RF Power Buildout
Detector
Procurement, Fabrication, Installation & Test
Commissioning & Pre-Ops
Accelerator Systems
Comms. & Pre-Ops
Full RF Power Buildout
Detector
Comms. & Pre-Ops
Key
(A) Actual
Completed
Planned
Data Date
Level 0 Milestones
Critical Path
Schedule Contingency

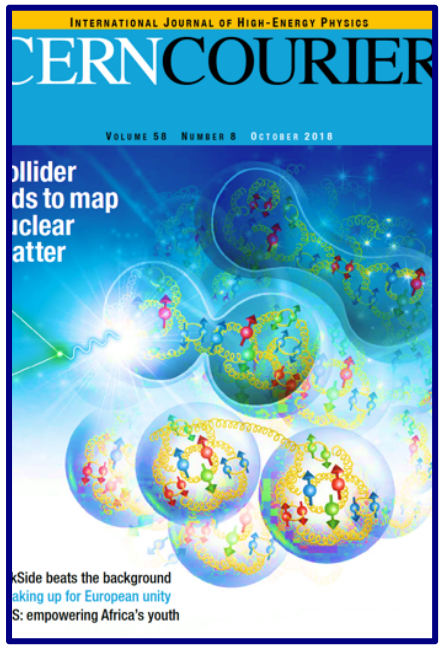
# Summary & Outlook

- Electron Ion Collider, a high-energy **high-luminosity polarized e-p, e-A collider**, funded by the DOE will be built in this decade and operate in 2030's.
  - Up to two hermetic full acceptance detectors under consideration, currently **EIC project has funds for 1 detector**, cost of a second detector from non-DOE sources
  - Community led detector design being developed through a Yellow Report Writing effort
  - Experimental collaboration(s) to be formed by late 2021

- EIC project assumes **an aggressive timeline** with support from both Labs and the DOE to have first collisions around 2030 (CD4A) & routine operation with high lumi, and polarization after 2032 (CD4B)

- **There is high interest in having international partners both on detector and accelerator**
  - Easiest & direct way to participate in the EIC Physics is through the EIC Users Group
  - Contact the EIC Project Management for contributions to the project (machine & detector)

R. Ent, T. Ullrich, R. Venugopalan
Scientific American (2015)
*Translated into multiple languages*




E. Aschenauer
R. Ent
October 2018

A. Deshpande
& R. Yoshida
June 2019
*Translated in to multiple languages*