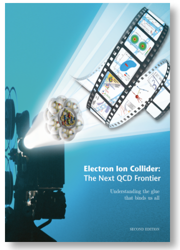
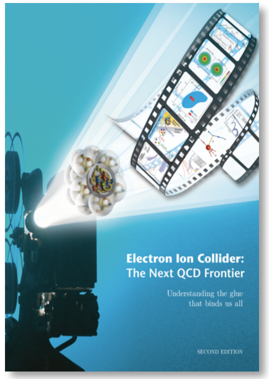
Center for Frontiers in Nuclear Science

IFIC
INSTITUT DE FÍSICA CORPUSCULAR



Electron Ion Collider:
Science, Status and Opportunities for Collaboration

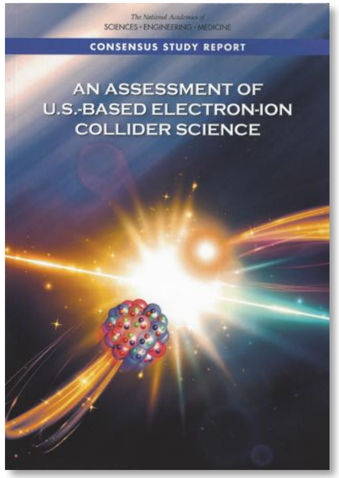
2015



2016

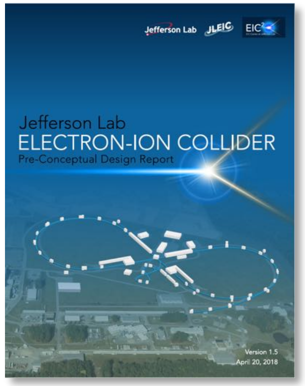
Physics of EIC

2018

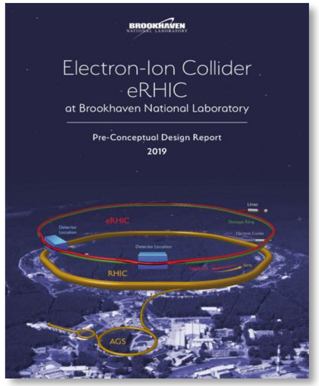


Evaluation

2019



2019 - future



Realization

Abhay Deshpande

On the menu today:

- The Science of Electron Ion Collider
- EIC Users Group (experimentalists, theorists & accelerator scientists)
- The EIC project (machine & detector design) statis and plans
- Opportunities for Collaboration

The Science Of Electron Ion Collider

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

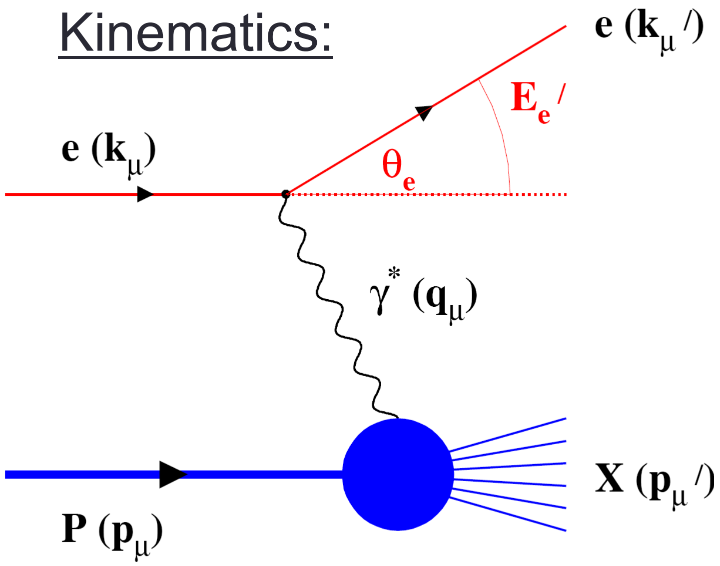
Emergence of spin, mass & confinement, gluon fields

- 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)
- Ultra-dense color (gluon) fields in all nucleons and nuclei?
  - Runaway growth in gluon number is tamed by existing mechanisms in QCD: Is there a universal many-body structure due to ultra-dense color fields at the core of **all** hadrons and nuclei?

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

Deep Inelastic Scattering: Precision and control

Kinematics:



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

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

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

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

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

Measure of momentum fraction of struck quark

Hadron :

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

with respect to γ

High lumi & acceptance

Exclusive DIS

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

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

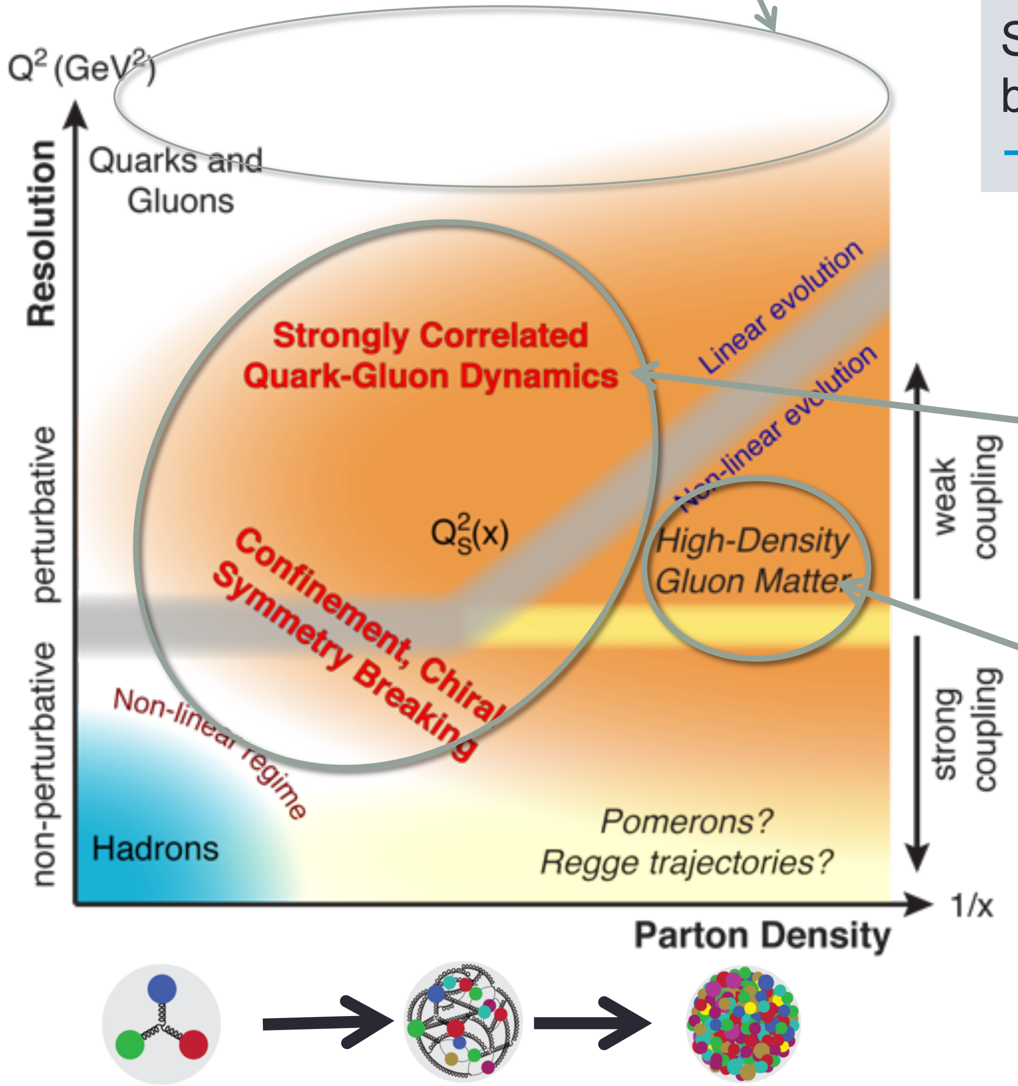
detect *only the scattered lepton* in the detector

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

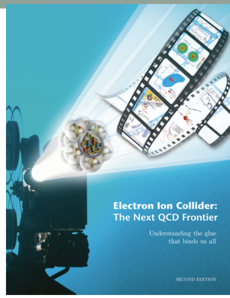


arXiv: 1708.01527

Systematically explore correlations in this region.

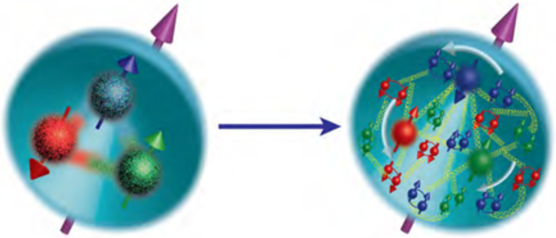
An exciting opportunity: Observation of a new regime in QCD of weakly coupled high-density matter

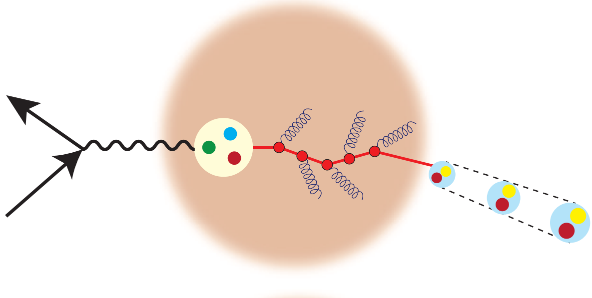
Need Precision and Control



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

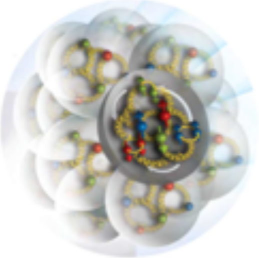
How are the sea quarks and gluons, and their spins, distributed in space and momentum inside the nucleon?
How do the nucleon properties like mass & spin emerge from them and their interactions?

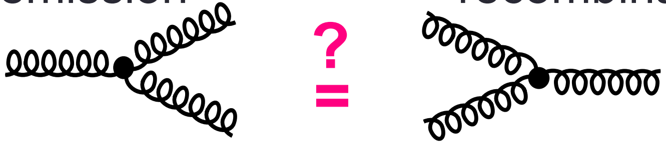




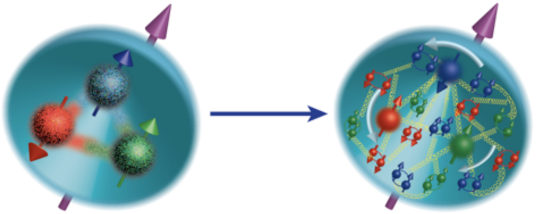
How do color-charged quarks and gluons, and colorless jets, interact with a nuclear medium?
How do the confined hadronic states emerge from these quarks and gluons?
How do the quark-gluon interactions create nuclear binding?

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?





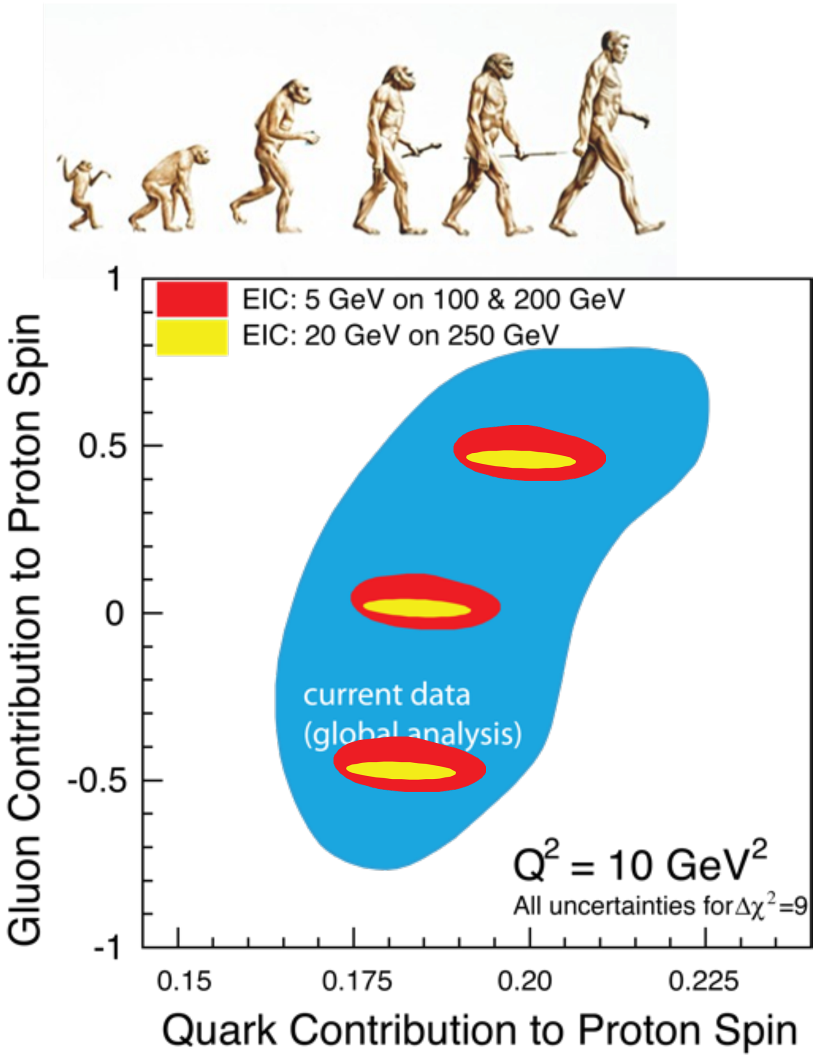
Nucleon Spin: Precision with EIC



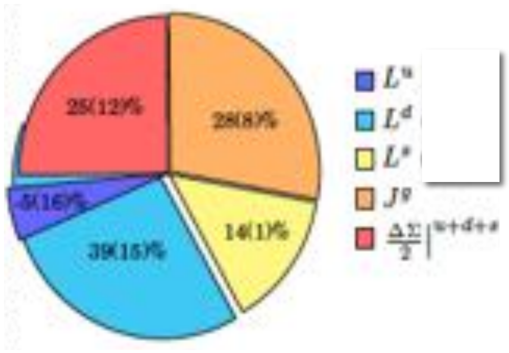
$$\frac{1}{2} = \left[\frac{1}{2}\Delta\Sigma + L_Q\right] + \left[\Delta g + L_G\right]$$

$\Delta\Sigma/2$ = Quark contribution to Proton Spin
L_Q = Quark Orbital Ang. Mom
Δg = Gluon contribution to Proton Spin
L_G = Gluon Orbital Ang. Mom

Precision in $\Delta\Sigma$ and Δg ➔ A clear idea Of the magnitude of L_Q+L_G



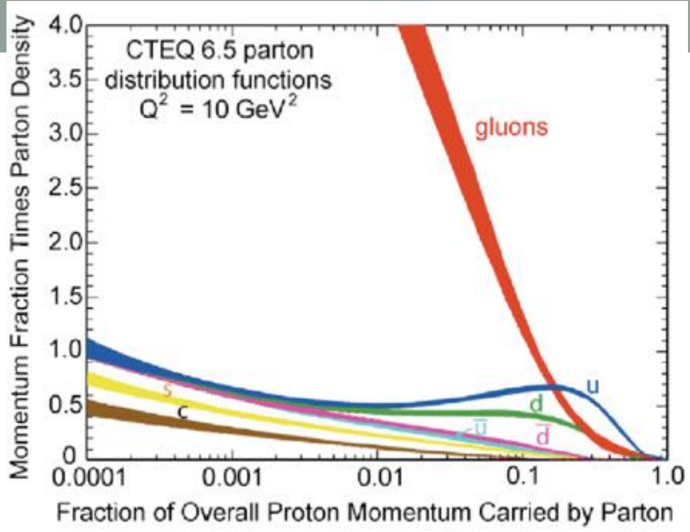
Spin in Lattice QCD:
Ab initio Calculations

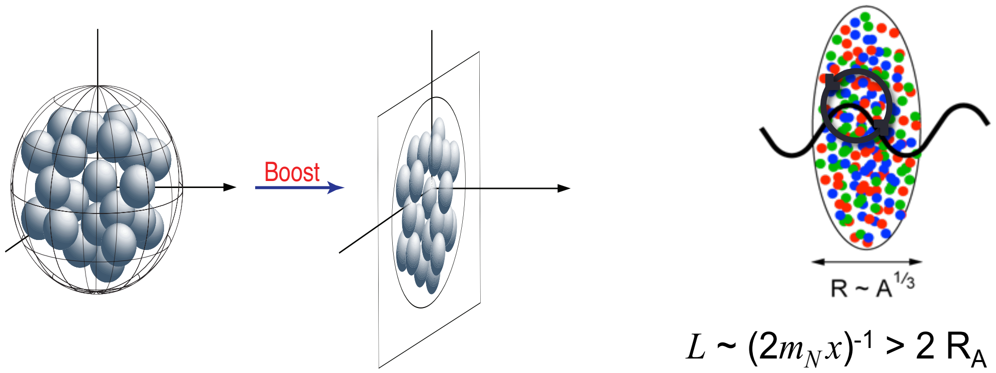


- **Gluon's spin contribution on Lattice: S_G = 0.5(0.1):** Yi-Bo Yang et al. PRL **118**, 102001 (2017)
- **J_q calculated on Lattice QCD:** χQCD Collaboration, PRD91, 014505, 2015

SIDIS: strange and charm quark spin contributions

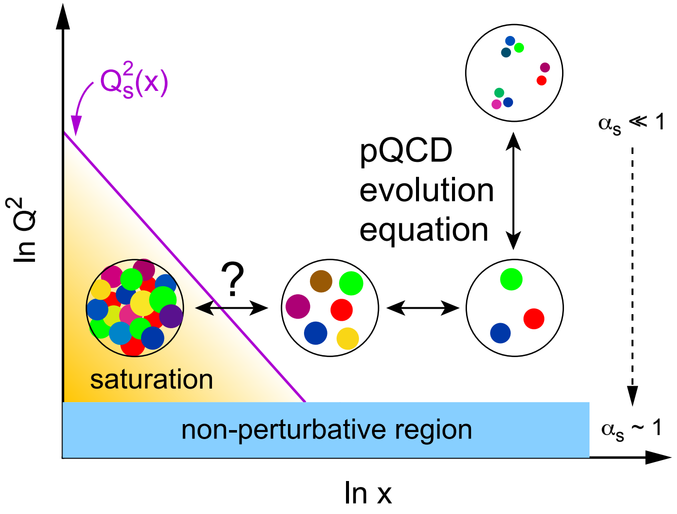
Low x physics with nuclei



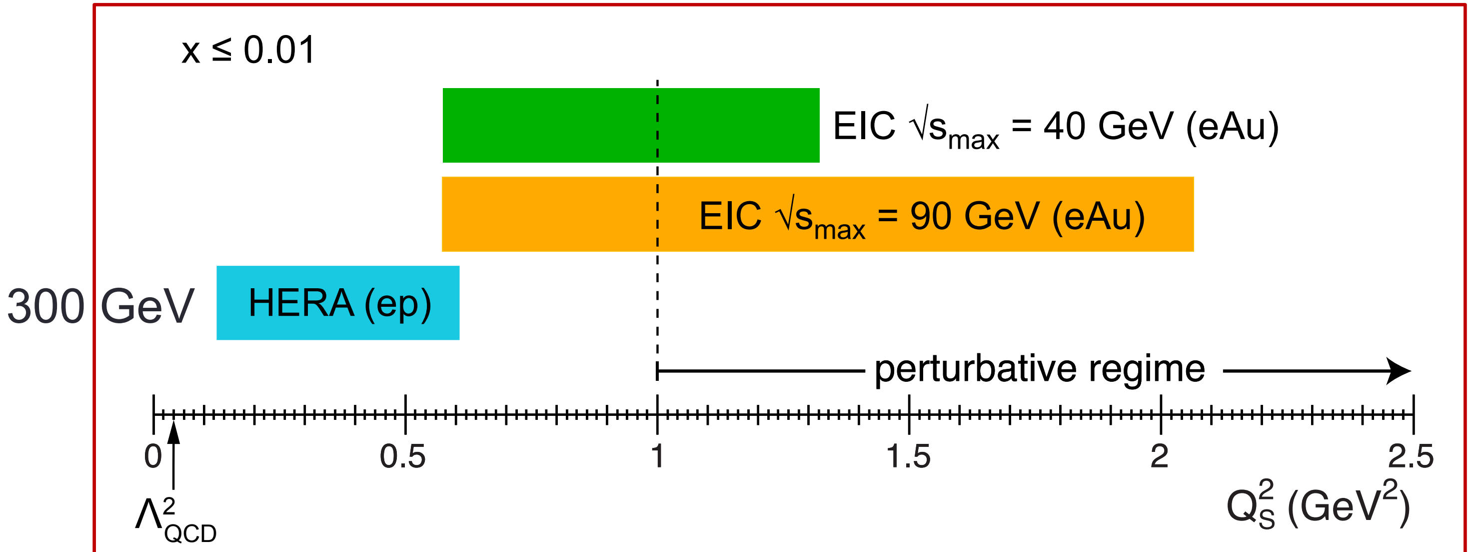


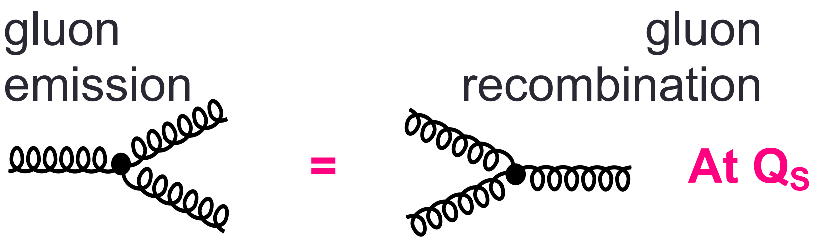
$$(Q_s^A)^2 \approx cQ_0^2 \left[\frac{A}{x}\right]^{1/3}$$

$L \sim (2m_N x)^{-1} > 2\,R_A \sim A^{1/3}$

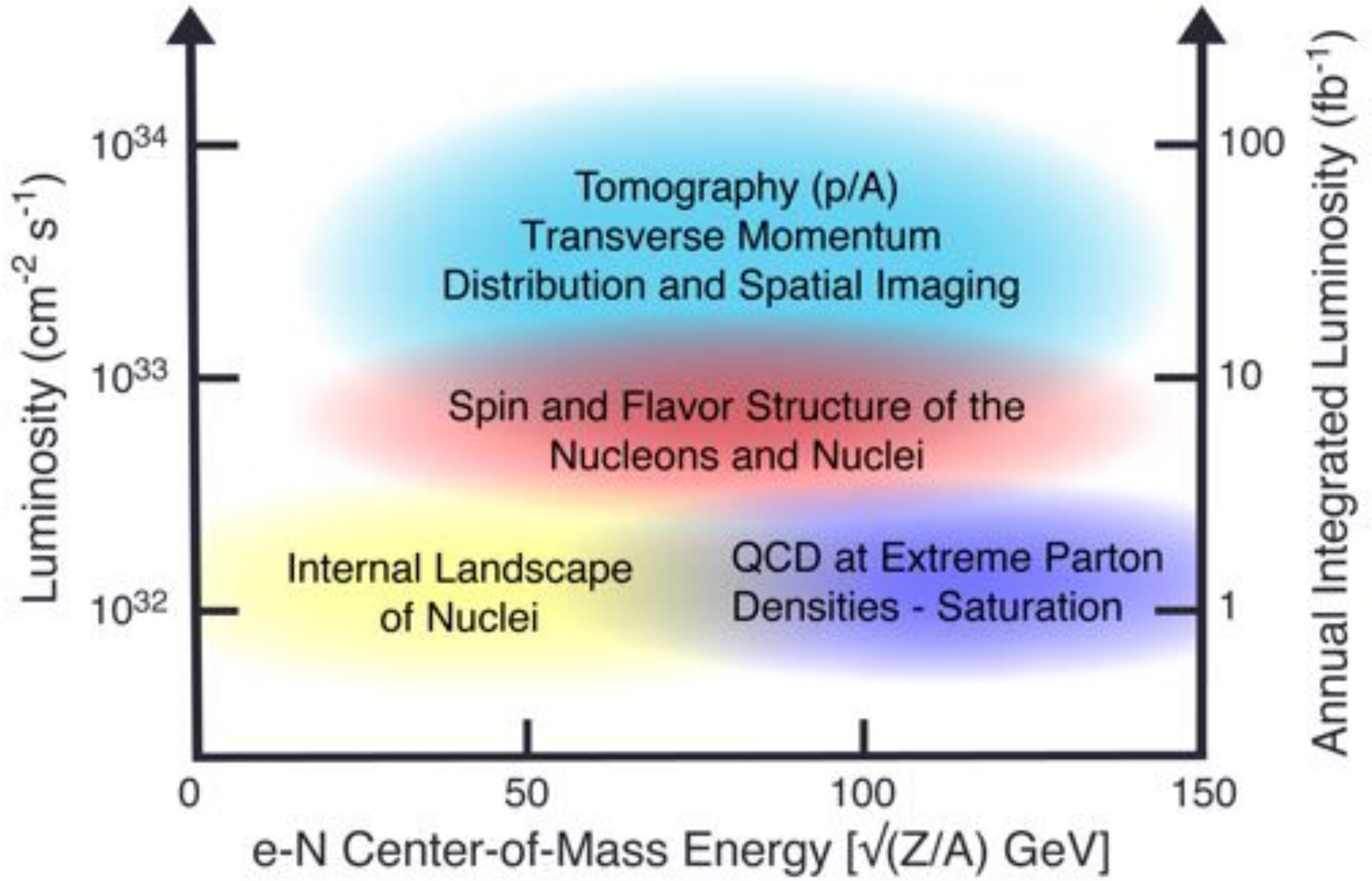


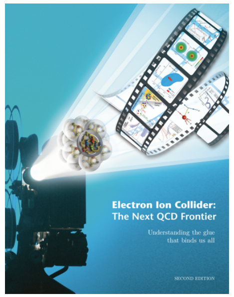
Accessible range of saturation scale $Q_s^{\,2}$ at the EIC with e+A collisions.
arXiv:1708.01527

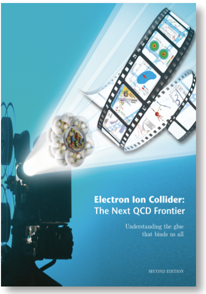




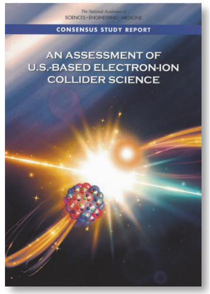
Summary: EIC Physics:
CM vs. Luminosity vs. Integrated luminosity







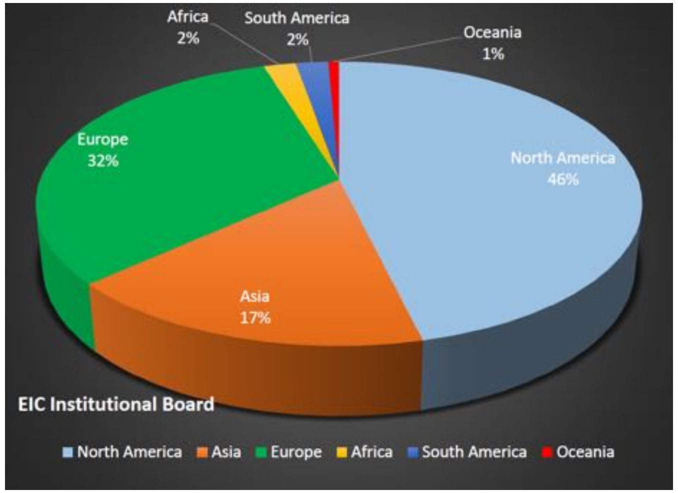
The EIC design parameters



Requirements for the US electron ion collider (EIC) were defined by a community led White Paper (1212.1701.v3). The EIC with those parameters was endorsed by the Nuclear Science Advisory Committee (NSAC) in 2015/6 & by the National Academy in its evaluation of EIC science in 2018.

- High luminosity: 10^{33}-10^{34} $cm^{-2}sec^{-1}$ a factor 100-1000 times HERA (@DESY)
- Broad range in center-of-mass energy: 20 – 140 GeV
- Polarized beams e-, p, D, ^{3}He… C, Be with flexible spin patterns & spin orientation
- Wide range in hadron species: protons…. Uranium
- Up to two well-integrated detector(s) into the machine lattice for max. acceptance

The EIC Users Group: EICUG.ORG



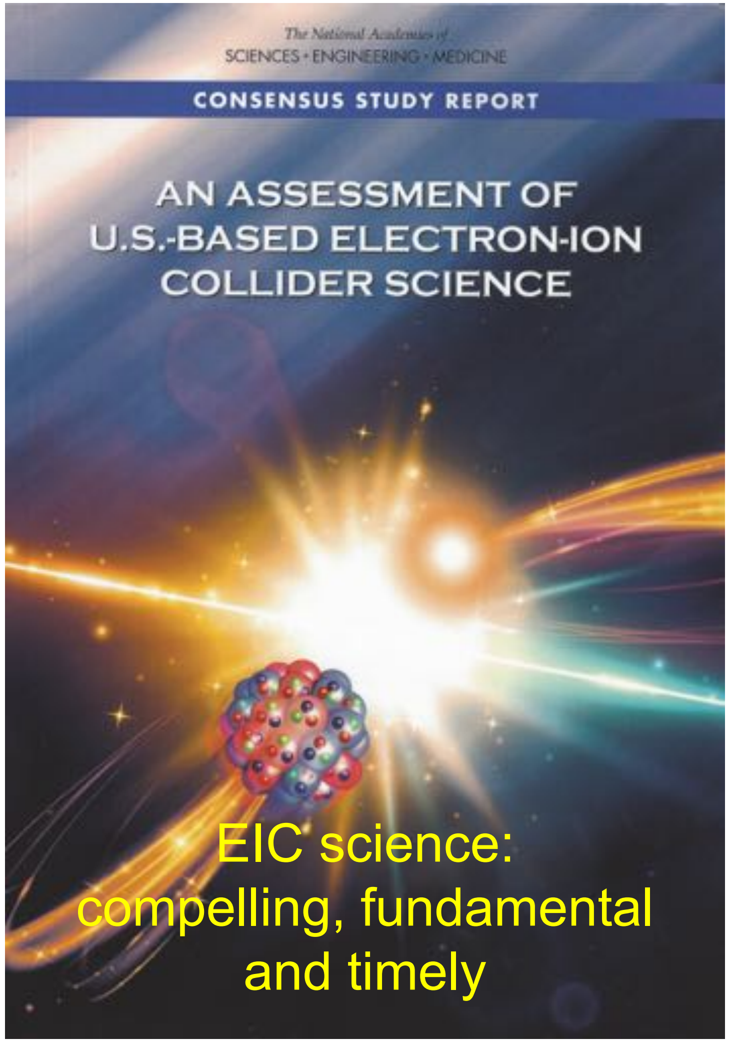
Formally established in 2016, now we have:
~1092 Ph.D. Members from 31 countries, 230 institutions
New members welcome

New:
Center for Frontiers in Nuclear Science (at Stony Brook/BNL)
EIC[2] 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)**



Consensus Study Report on the US based Electron Ion Collider

Summary:

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

EIC and the LHC:

Precision QCD → impact on studies at LHC in the 2030's

BSM physics investigations

Accelerator & Detector technologies

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

Recent initiatives in precision QCD & EW/BSM Physics at the EIC

LPC Workshop on **Physics Connections between LHC & EIC**: November 13-15, 2019 at FNAL : Synergies between HEP and EIC/NP common interests

(*A. Deshpande, T. Hobbs, J. Qiu, R. Yoshida, R. Boughezal, J. Campbell, O. Evdokimov, S. Hoeche, F. Petriello*)

- Precision QCD, Monte Carlo event generators, lattice QCD, advance computing, opportunities in Electroweak sector & BSM searches

CFNS Workshop on Electroweak and BSM physics at the EIC: May 6-7, 2020

Revisited topics of interest in EW physics

(*W. Deconick, Y. Ferlatova, C. Gal, M. Gericke, A. Deshpande*)

- Relevant HERA precisions QCD studies & BSM Searches, LF & LN violation studies, Parity violating e-p scattering ($g_1^{\gamma Z}$, $g_5^{\gamma Z}$), Charge Symmetry Violation, Dark photon searches

EIC Realization: Project & Its Status

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

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

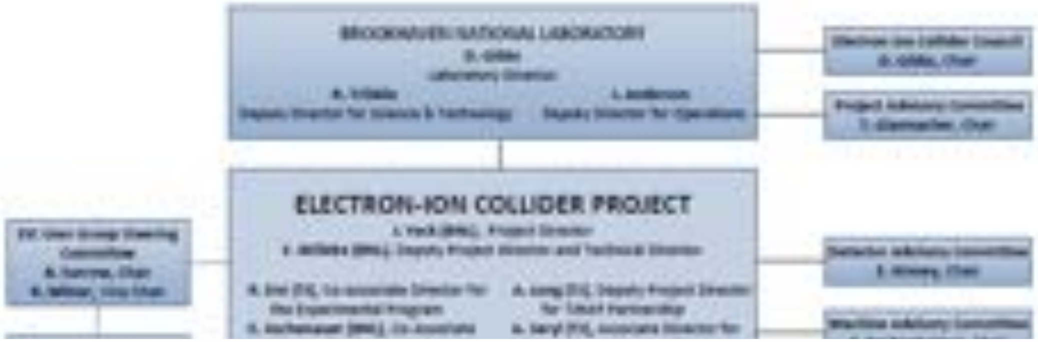
A. Lung (TJ), Deputy Project Director for TJNAF Partnership

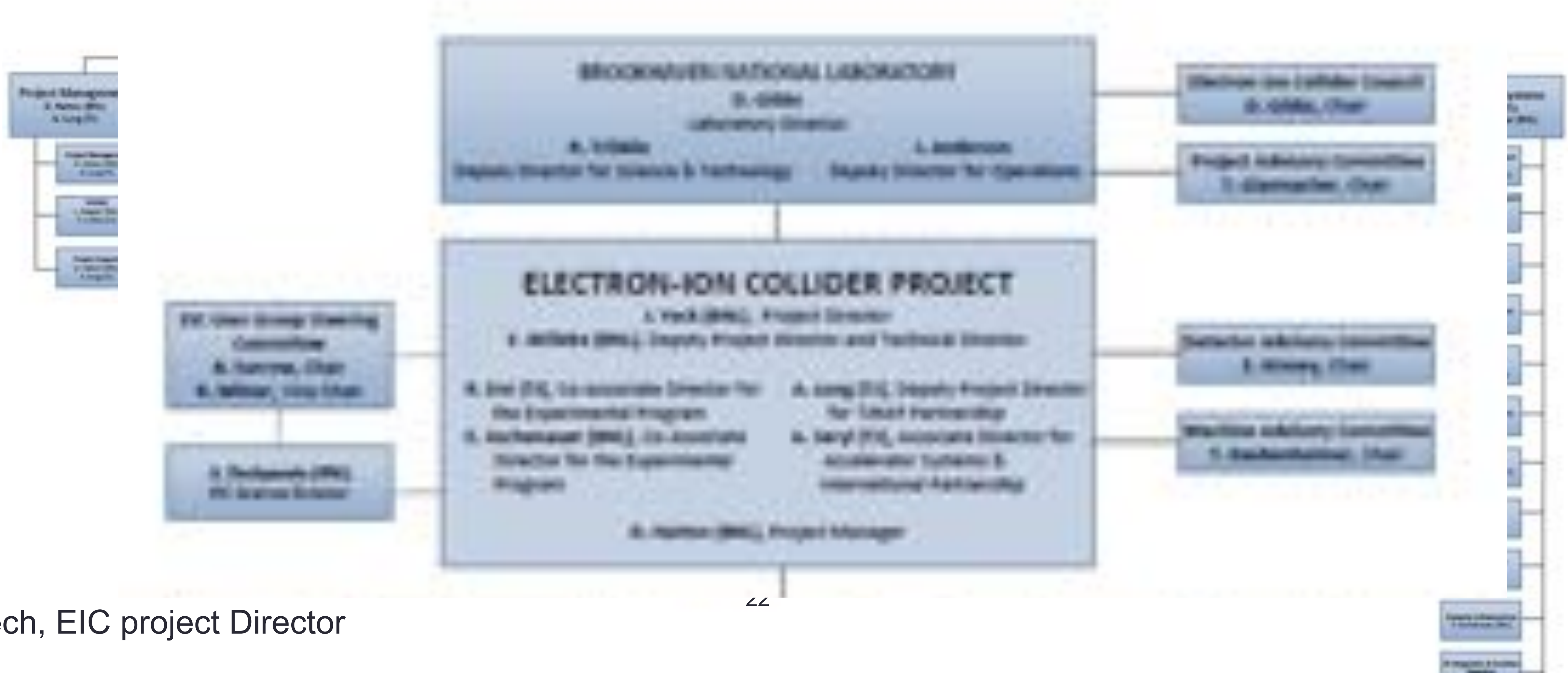
A. Seryi (TJ), Associate Director for Accelerator Systems & International Partnership

D. Hatton (BNL), Project Manager

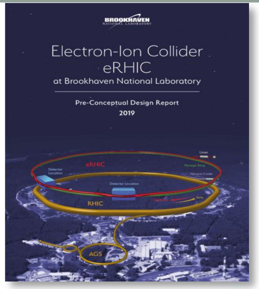
J.Yech, EIC project Director

EIC Project Organization

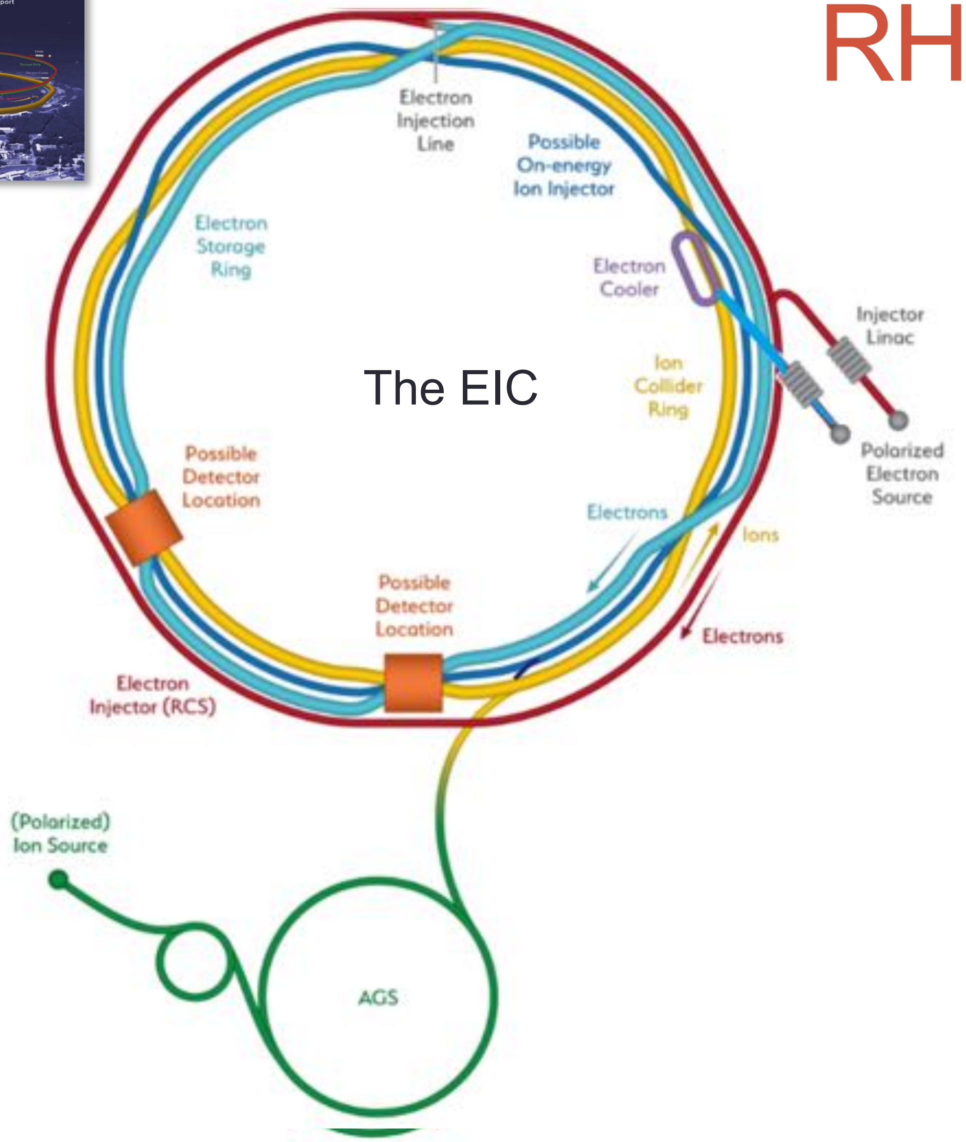


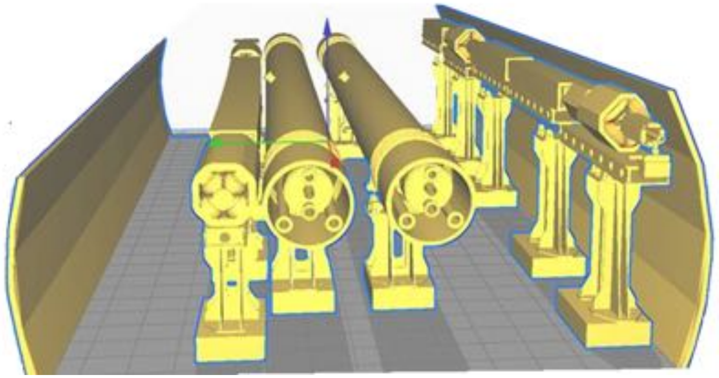


J.Yech, EIC project Director



RHIC → EIC

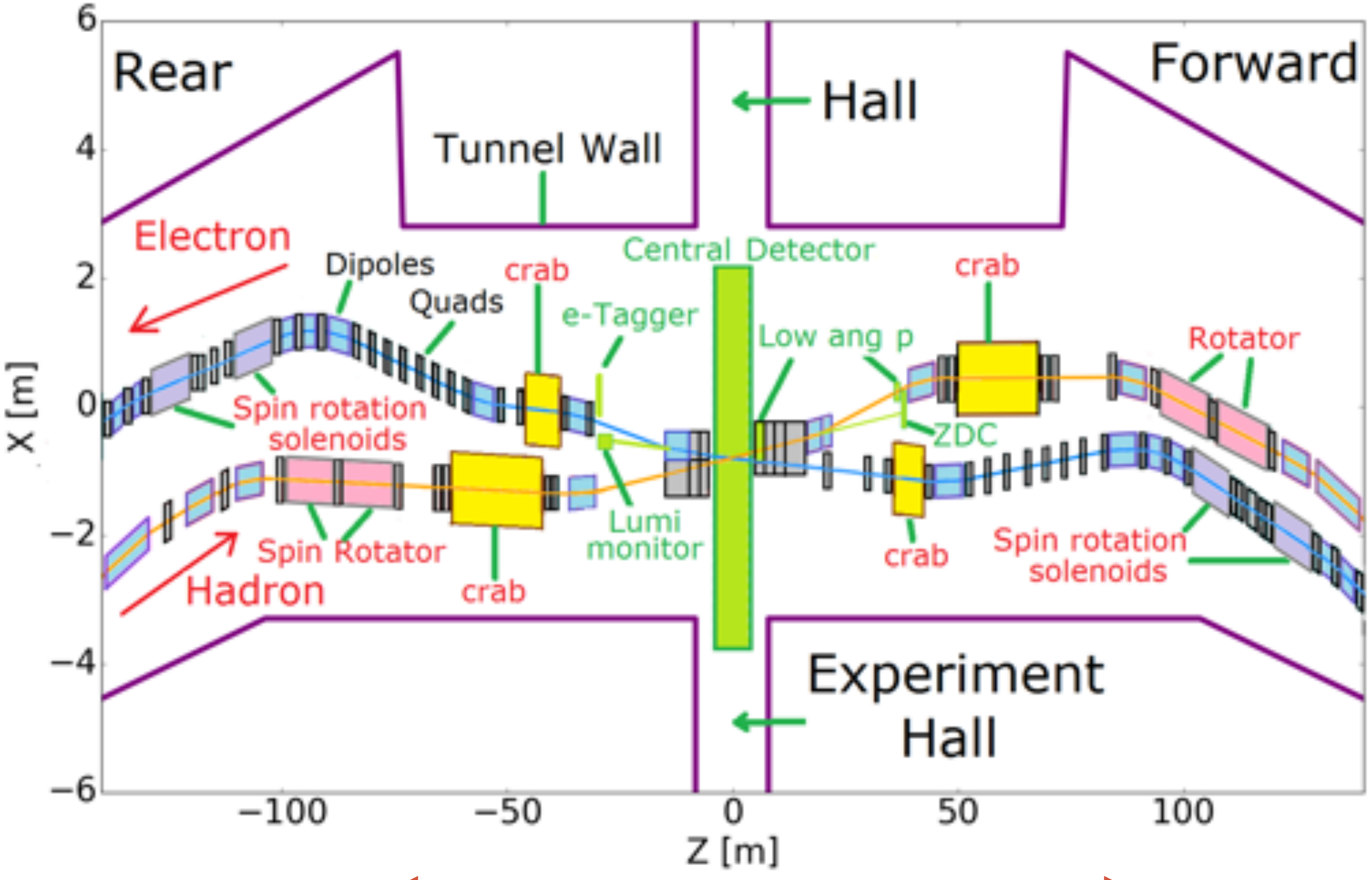




The strong hadron cooling facility completes the facility

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

Full Acceptance EIC Interaction Region Layout



Detector Components
Far beyond the central detector

Design

- All superconducting magnets
  - Only 5 magnets need collared Nb-Ti coils
  - All other magnets can be built with **direct wind** of Nb-Ti wire
- Full acceptance e.g. P_t =200 MeV/c-1.3 GeV/c
  - Neutrons 4 mrad
- Large Aperture Dipole w/ instrumented gap
- Modest IR chromaticity
- Hadrons up to β<200m

➔ Manageable dynamic aperture optimization

Experimental Program

Experimental Program Preparations

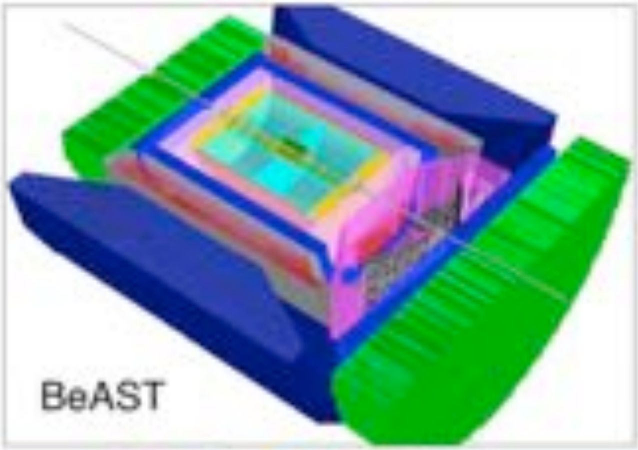
- EIC Community's Yellow Report Initiative (Kickoff in December 2019, site)
  - Four workshops planned to advance the state and detail of the documented physics studies and detector concepts in preparation for the realization of the EIC.

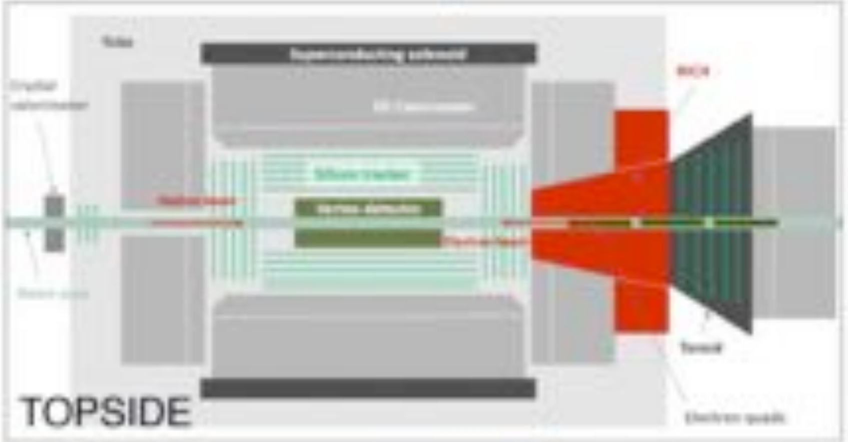
- BNL and TJNAF Jointly Leading Process for Defining Detector(s)
  - Call for "Potential Cooperation on the EIC Experimental Program" published in May
  - Includes two questionnaires, FAQ, and input received
  - Expressions of Interest (EOIs) due November 1, 2020

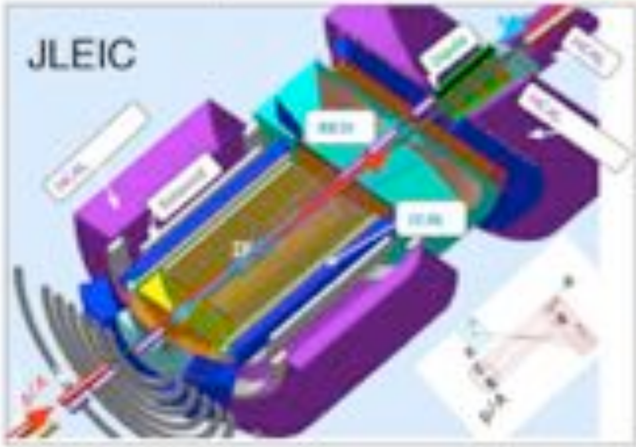
- Following the EOI Response Deadline
  - Status report at 4th Yellow Report meeting in November
  - Responses evaluated and Call for Proposal(s) finalized
    - Assessment by Members of the Users Group and Project Management with advice from Detector Advisory Committee (DAC)
    - Call for Detector Proposal(s) in March 2021

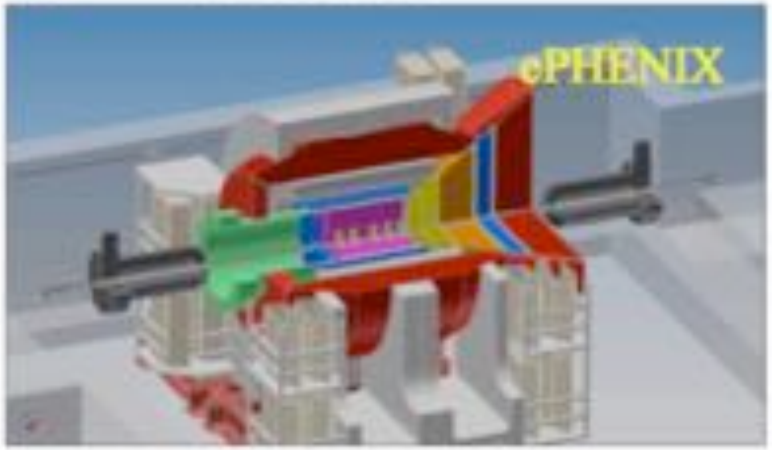
EIC EOI Site: https://www.bnl.gov/eic/EOI.php

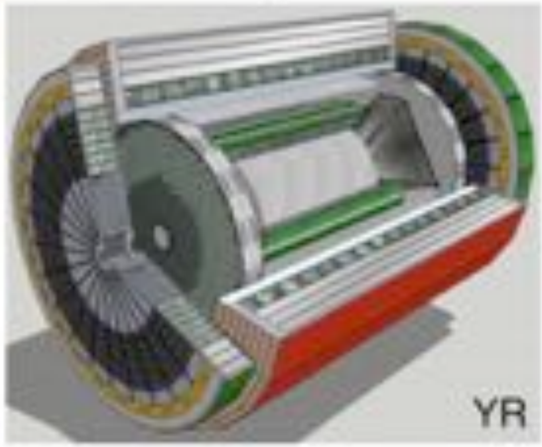
GALLERY OF DETECTOR CONCEPTS proposed over time











Several key elements are present in common

this previous activity is at the basis of the present central reference detector discussed in the following

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

EIC Detector Advisory Committee (DAC) Meeting, 28-29 September 2020

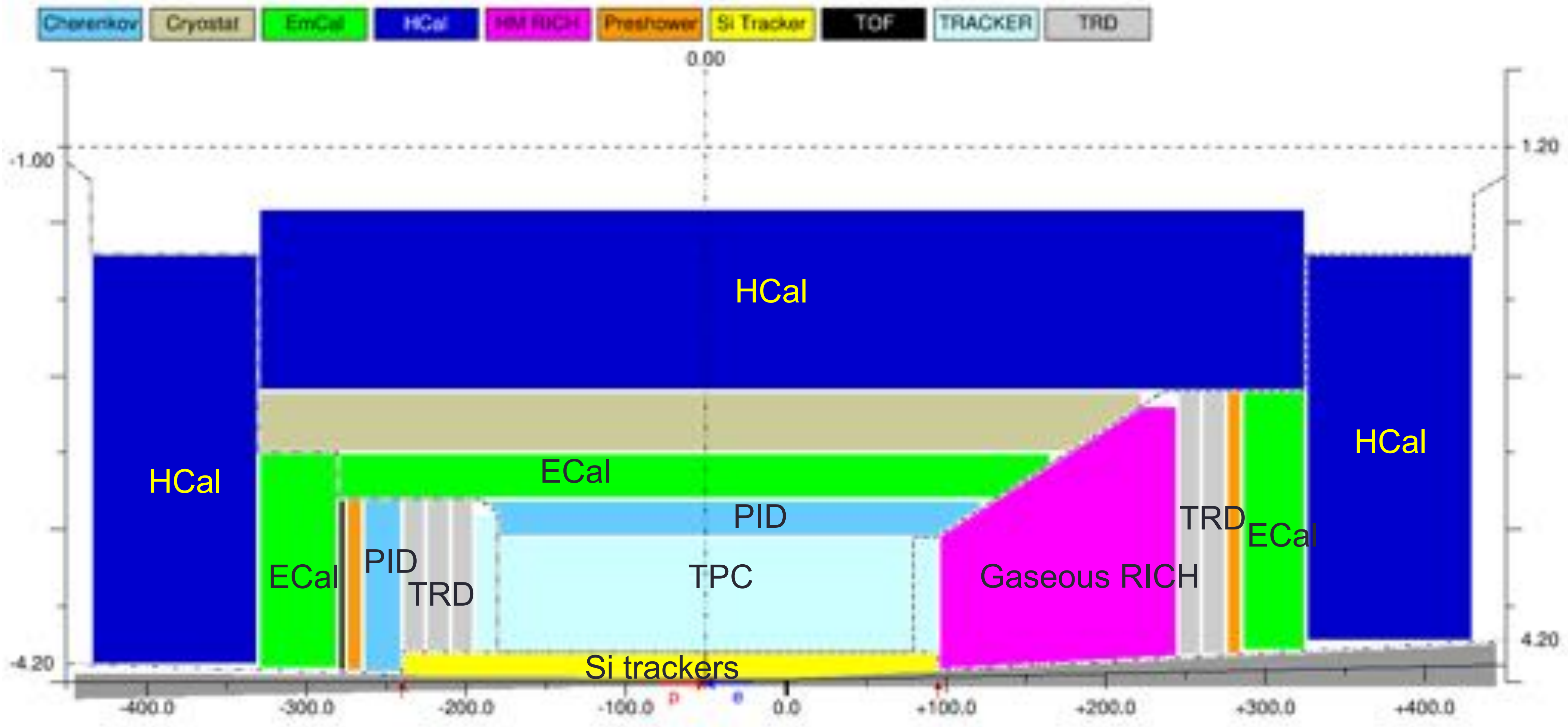
EXPERIMENTAL REQUIREMENTS

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 2π 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**

EIC Detector Advisory Committee (DAC) Meeting, 28-29 September 2020 S. Dalla Torre (INFN) & T. Horn (CUA)

REFERENCE DETECTOR IN A CARTOON



EIC Detector Advisory Committee (DAC) Meeting, 28-29 September 2020

S. Dalla Torre & T. Horn

EIC Detector

Physics Requirements, Collaboration Opportunities and Challenges

η	Nomenclature		Tracking (B = 1.5 T) Resolution	Allowed X/X_0	minimum-pT	Transverse pointing res.	Electrons and Photons Resolution σ_E/E	PID	min E photon	π/K/p p-Range (GeV/c)	Separation	HCAL Resolution σ_E/E	Energy
-4.0 to -3.5			not accessible										
-3.5 to -3.0, -3.0 to -2.5, -2.5 to -2.0	Central Detector	Backward Detector	σp/p ~ 0.2%×p ⊕ 5%	~5% or less X	to be determined		1%/E ⊕ 2.5%/√E ⊕ 1% (for 40 cm space)	π suppression up to 1:1E-4	20 MeV	≤ 10 GeV/c	≥ 3σ	50%/√E ⊕ 10% (Better resolution required more space and R&D)	~500 MeV
-2.0 to -1.5, -1.5 to -1.0			σp/p ~ 0.04%×p ⊕ 2%			dca(xy) ~ 40/pT µm ⊕ 10 µm	2%/E ⊕ (4-8)%/√E ⊕ 2% (Upper limit achievable with 60 cm space *Better resolution requires ~65 cm space allocated)	π suppression up to 1:(1E-3 - 1E-2)	50 MeV				
-1.0 to -0.5, -0.5 to 0.0, 0.0 to 0.5, 0.5 to 1.0		Barrel	σp/p ~ 0.04%×p ⊕ 1%		100 MeV/c with 50% acceptance (similar for pi and k)	dca(xy) ~ 30/pT µm ⊕ 5 µm	[illegible]	π suppression up to 1:1E-2	100 MeV (50 MeV if higher resolution)	≤ 6 GeV/c; ≤ 8 GeV/c		100%/√E ⊕ 10%	
1.0 to 1.5, 1.5 to 2.0		Forward Detector	σp/p ~ 0.04%×p ⊕ 2%		to be determined	dca(xy) ~ 40/pT µm ⊕ 10 µm	2%/E ⊕ (4-12)%/√E ⊕ 2% Upper limit achievable with 40cm space *Better resolution requires ~65 cm space allocated	3σ e/π up to 15 GeV/c	50 MeV	≤ 50 GeV/c (some approaching 3σ)		[illegible]	
2.0 to 2.5, 2.5 to 3.0, 3.0 to 3.5			σp/p ~ 0.2%×p ⊕ 5%										
3.5 to 4.0			not accessible										

- Most of the requirements are matched
- Investigation on going concerning aspects source of tension:
  - Crack (ECal, PID, …) @ ~ η=1
  - e/π suppression in the barrel
  - ECal resolution in $-1 < \eta < 1$
  - HCal resolution in $1 < \eta < 3.5$ (high E jets)
  - PID in Barrel: π/K 3σ sep. up to 10 GeV/c ?
- Intensive R&D & MC activity together with a rich variety of options are the tools to overcome the present open points

EIC Detector Advisory Committee (DAC) Meeting, 28-29 September 2020

S. Dalla Torre & T. Horn

Opportunities for Collaboration

EIC Project funds: The machine + 1 Interaction region + 1 detector

2nd IR and Detector (highly desirable by Users) but outside of the EIC Project

- Nothing in the EIC design prevents 2nd IR or Detector

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

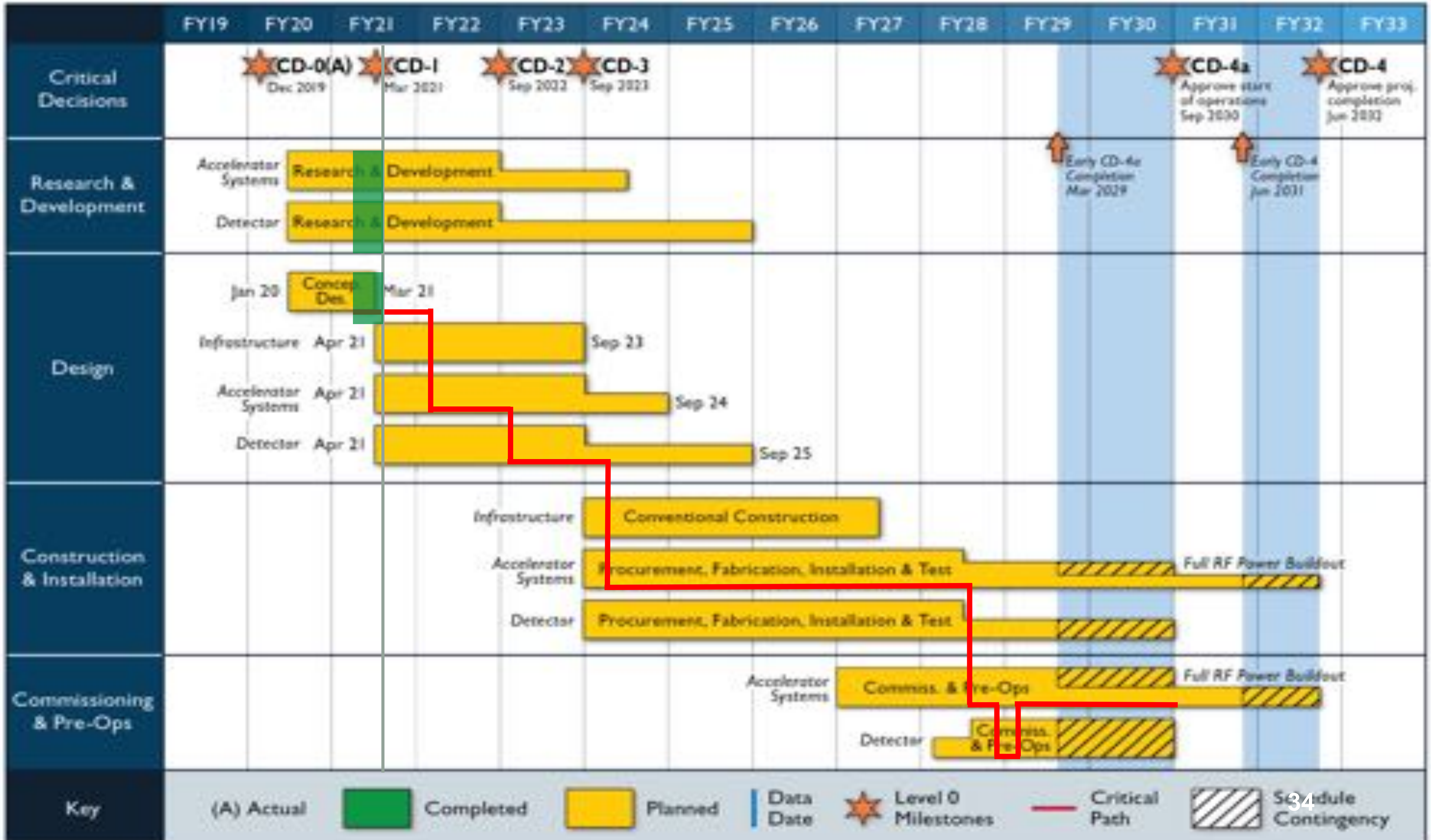
https://www.cockcroft.ac.uk/events/eic20/

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
Early CD-4a Completion Mar 2029
Early CD-4 Completion Jun 2031
Research & Development
Accelerator Systems
Research & Development
Detector
Research & Development
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
Commiss. & Pre-Ops
Full RF Power Buildout
Detector
Commiss. & 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)