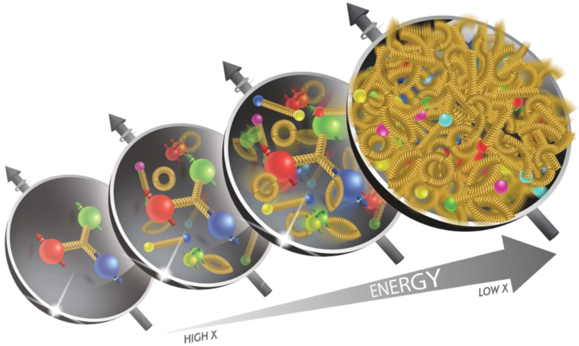
Istituto Nazionale di Fisica Nucleare
SEZIONE DI BARI



QCD@Work 10th edition

International Workshop on Quantum Chromodynamics
Theory and Experiment

workshop.qcd@ba.infn.it
agenda.infn.it/event/20170

LECCE (ITALY)
27-30
June 2022
Auditorium del Museo Provinciale
"Sigismondo Castromediano"

Low energy and nonperturbative QCD - Advances in perturbative QCD
Heavy quarks - QCD in extreme conditions of temperature and density
Holographic methods

Electron-Ion Collider

The next QCD facility

Domenico Elia

(INFN Bari, Italy)

Outline

- Science case for the Electron-Ion Collider
- EIC machine and design parameters
- EIC detector requirements
- EIC User Group’s activity and Project path
- Summary and Outlook

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Science case for the EIC

Assessment of US-based Electron-Ion Collider:
(National Academy of Science Report, 2018)

2012

2015

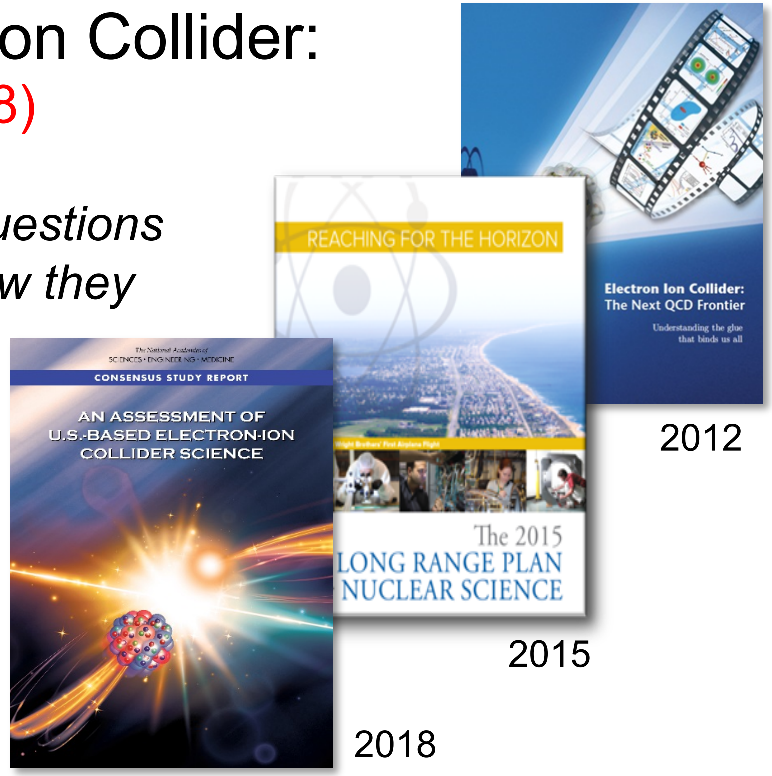
2018

Science case for the EIC

Assessment of US-based Electron-Ion Collider:
(National Academy of Science Report, 2018)

"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?"***



2012

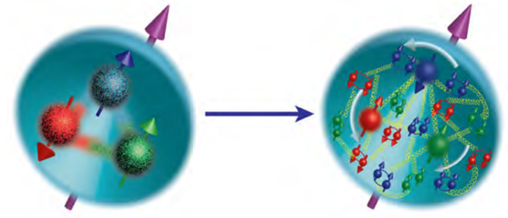
2015

2018

Science case for the EIC

Physics at the EIC:

a new facility to study the nucleon “glue”



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

Science case for the EIC

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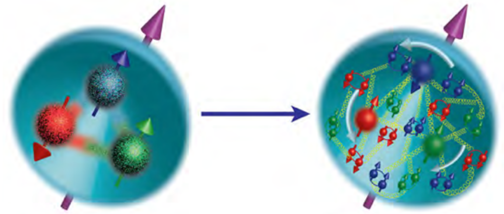

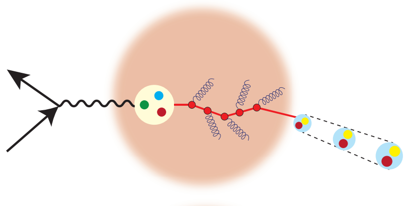

How do color-charged partons and colorless jets, interact with a nuclear medium? How do the confined hadronic states emerge from these quarks and gluons? How do the quark-gluon interactions create nuclear binding?

Science case for the EIC

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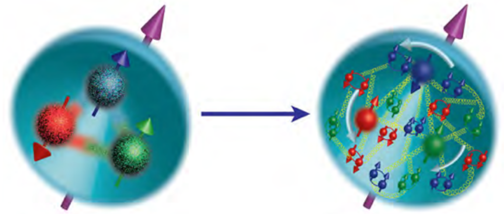
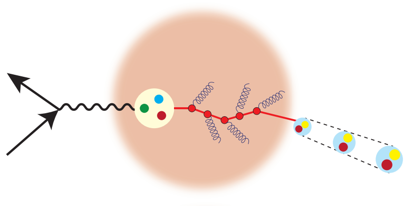
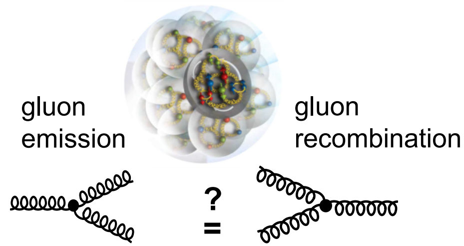




How do color-charged partons and colorless jets, interact with a nuclear medium? How do the confined hadronic states emerge from these quarks and gluons? How do the quark-gluon interactions create nuclear binding?

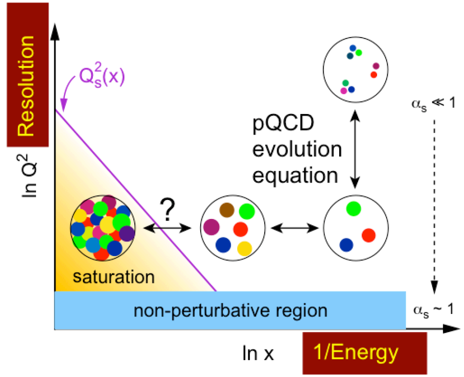
How does a dense nuclear environment affect the quarks and gluons distribution & interactions? Do gluons saturate at high energy in nucleons and nuclei? Properties of the novel gluonic matter?



Science case for the EIC

Deep Inelastic Scattering (DIS) processes:

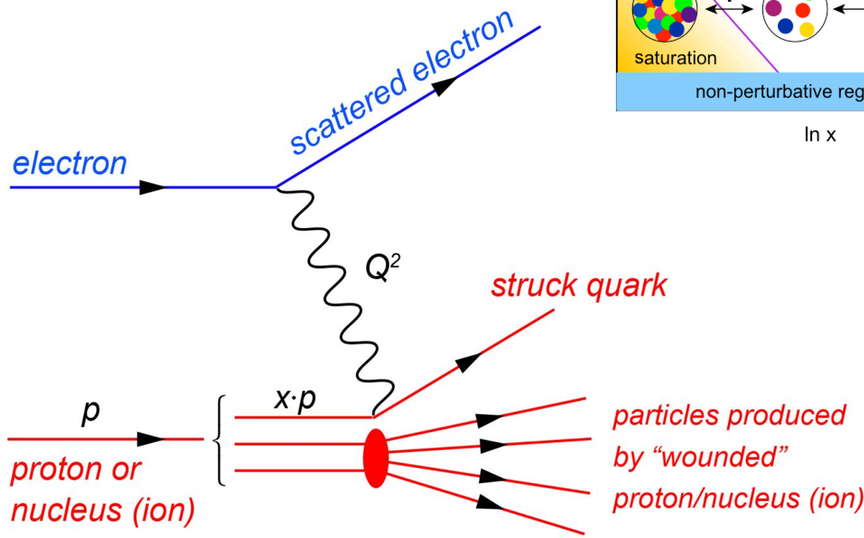
access physics with precision and control at the EIC



Most relevant variables:

Q^2 = *square of the momentum transferred by the electron to the quark*
→ measure of the resolution power

x = *fraction of the momentum of the proton (ion) carried by the struck quark*
→ matter at low-x: regime dominated by gluons, special importance for the EIC!

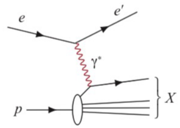


Science case for the EIC

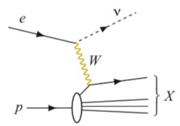
Deep Inelastic Scattering (DIS) processes:

access physics with precision and control at the EIC

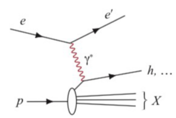
NC inclusive DIS
measure scattered electron



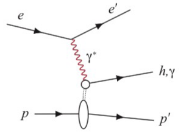
CC inclusive DIS
reconstruct kinematics via final state particles



Semi-inclusive DIS
measure part of the final state, need to identify at least one hadron



Exclusive DIS
measure whole final state, need for hermeticity



Much more information when:

- access to wider phase space domain made possible
- polarized particle scattering available
- part of the final state can be measured (Semi-Inclusive DIS, SIDIS)
- whole final state can be measured (Exclusive DIS)

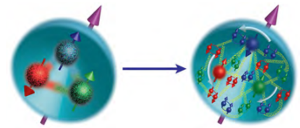
Extra bonus at the EIC: DIS in nuclei

- nPDF modifications
- gluon saturation and scale dependence from A (jets)
- hadronisation in cold nuclear matter

Science case for the EIC

Example: solving the “proton spin puzzle”

$$\frac{1}{2} = \underbrace{\frac{1}{2}\Delta\Sigma(\mu)+\Delta G(\mu)}_{\text{quark and gluon spin}}+\overbrace{L_q(\mu)+L_g(\mu)}^{\text{orbital angular momentum}}$$

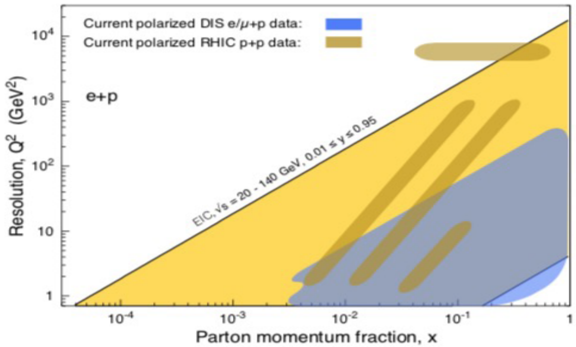


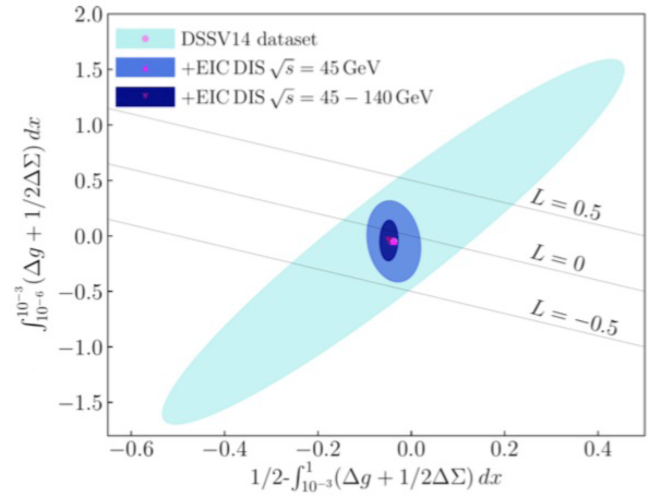
The spin is the interplay between parton intrinsic properties & their interactions
→ dynamic, not a static property!

- since late '80s we know $\Delta\Sigma$ is not the dominant term
- only 25% comes from quarks/anti-quarks – gluon contr. at 30%
- **big uncertainties! → no data on $\Delta\Sigma$ and ΔG for $x < 5 \times 10^{-3}$**

Key from EIC:

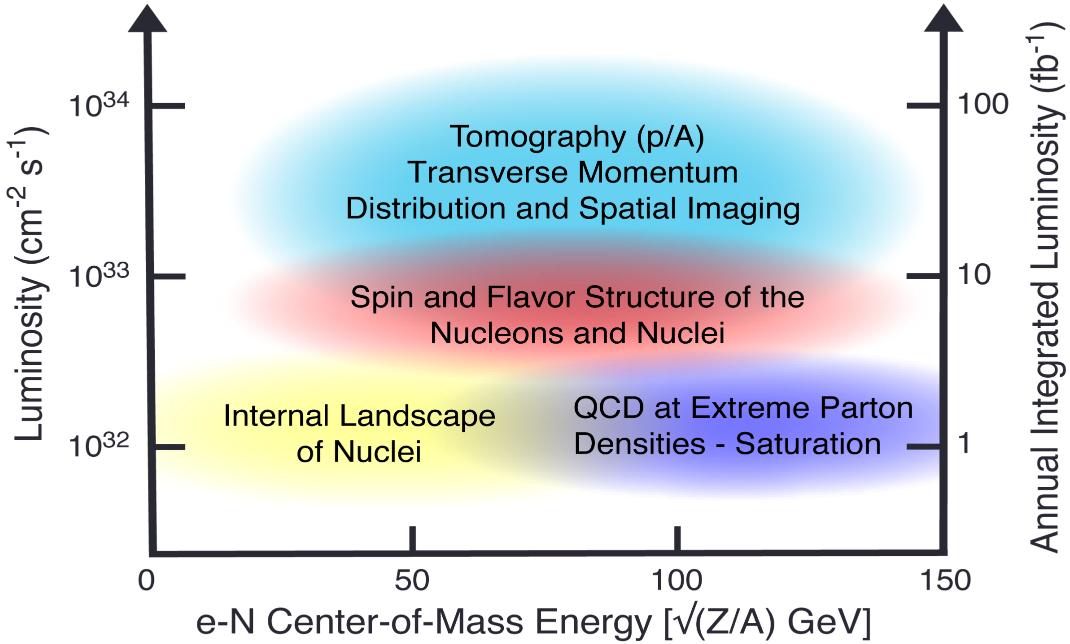
- polarized beams
- largely unexplored x-Q^2 region →





Science case for the EIC

EIC physics: CM energy vs Luminosity



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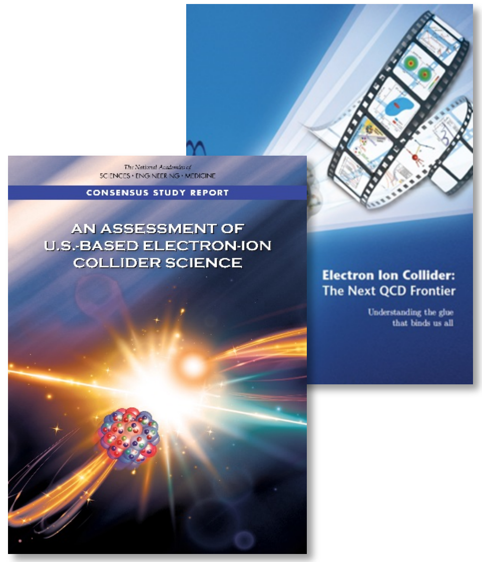
EIC machine

EIC design parameters:

requirements for the US EIC defined by a community led White Paper (2012), then endorsed by the Nuclear Science Advisory Committee (NSAC) in 2015/6 & by the National Academy in 2018.

- broad centre-of-mass energy range, $\sqrt{s}$ = 20-140 GeV
  - ✓ access gluon dominated region and wide kinematic range in x and Q^2
- polarized electron, proton and light nuclear beams, ~70%
  - ✓ access to spin structure and 3D spatial and momentum structure
- nuclear beams with heavy ions, up to U
  - ✓ access the highest gluon densities ($Q_s^2 \sim A^{1/3}$)
- high luminosity (~100-1000x HERA), $10^{33\text{-}34}$ cm^{-2} s^{-1}
  - ✓ access observables as a function of x, Q^2, A, ...

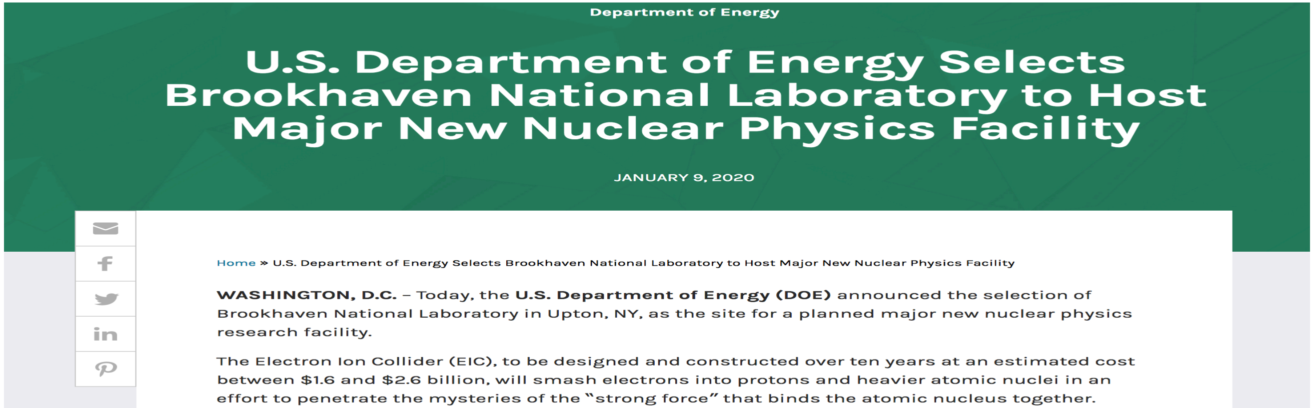


EIC machine

First big steps towards the EIC realization:

CD-0 approval (December 2019) and site selection (January 2020)

- BNL hosting site, BNL and JLab to realize EIC as partners
- CD-1 anticipated to June 2021



Department of Energy

U.S. Department of Energy Selects Brookhaven National Laboratory to Host 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.

The Electron Ion Collider (EIC), to be designed and constructed over ten years at an estimated cost between $1.6 and $2.6 billion, will smash electrons into protons and heavier atomic nuclei in an effort to penetrate the mysteries of the "strong force" that binds the atomic nucleus together.

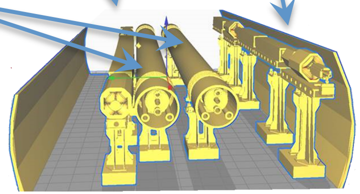
https://www.energy.gov/articles/us-department-energy-selects-brookhaven-national-laboratory-host-major-new-nuclear-physics

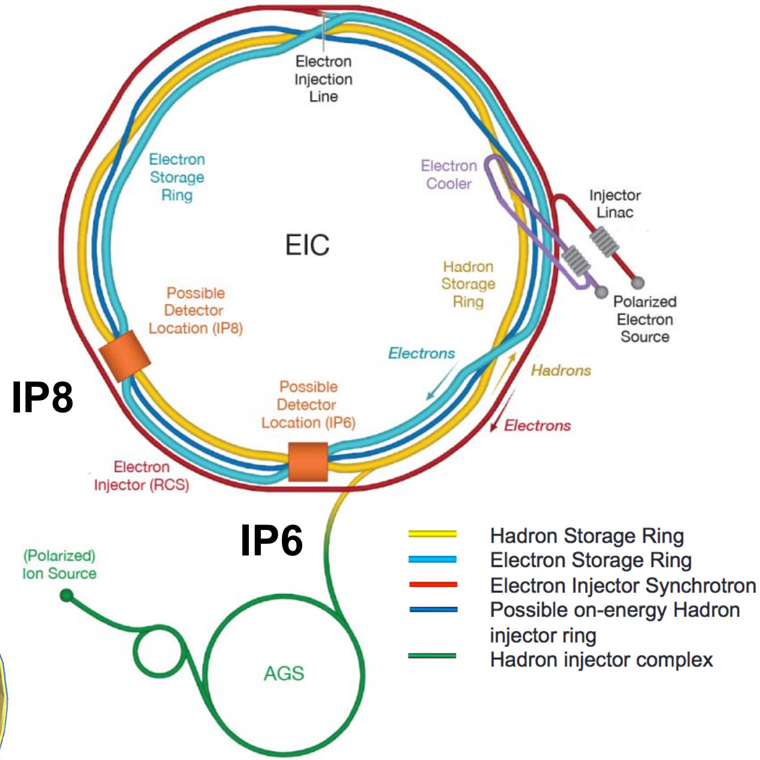
EIC machine

From RHIC to EIC @ BNL:

design using much of the RHIC facility plus

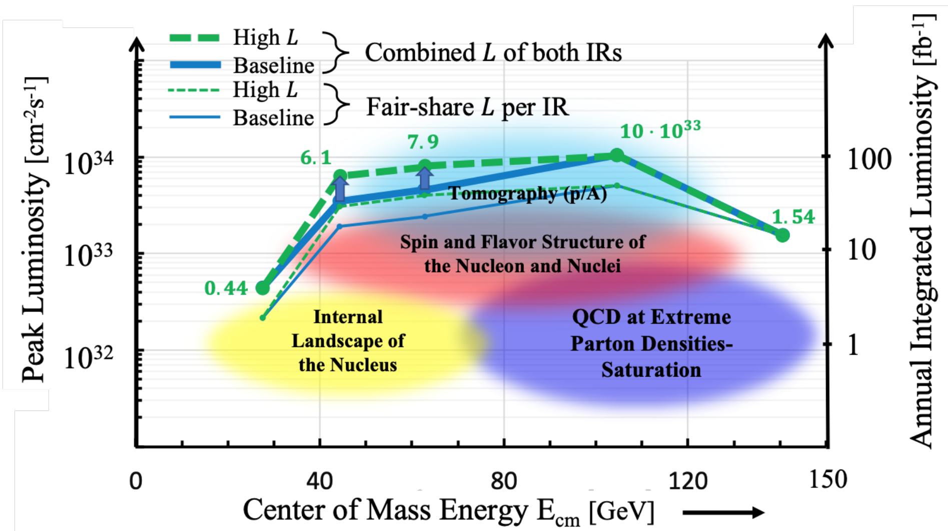
- three accelerator rings
  - ✓ existing RHIC ring (275 GeV)
  - ✓ new Rapid Cycling Electron Synchr (18 GeV)
  - ✓ new Electron Storage Ring (18 GeV)
- two injector complexes
  - ✓ existing Hadron injectors
  - ✓ new Electron injectors
- two detector halls (IP6 and IP8)
- innovative hadron cooling technique based on FEL

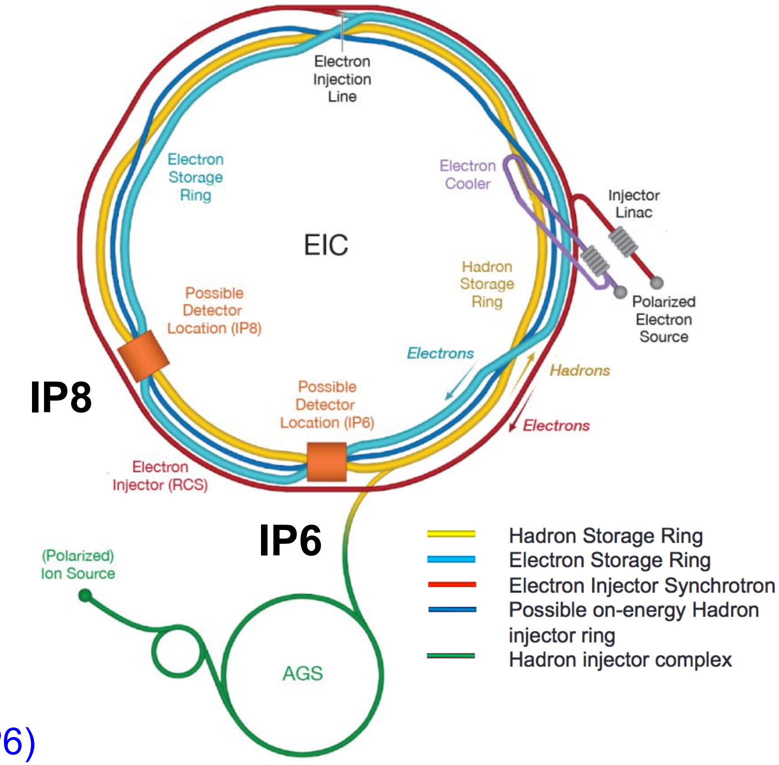




EIC machine

From RHIC to EIC @ BNL:
luminosity vs center-of-mass figure

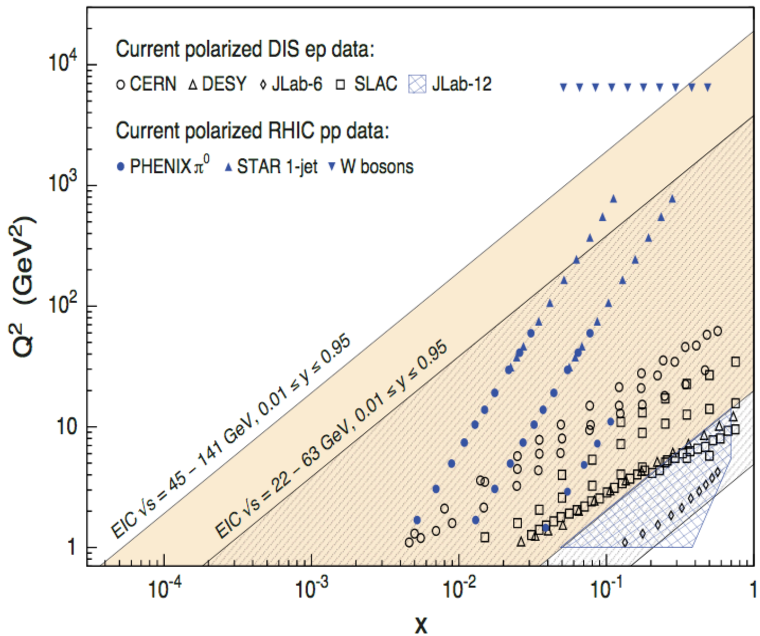


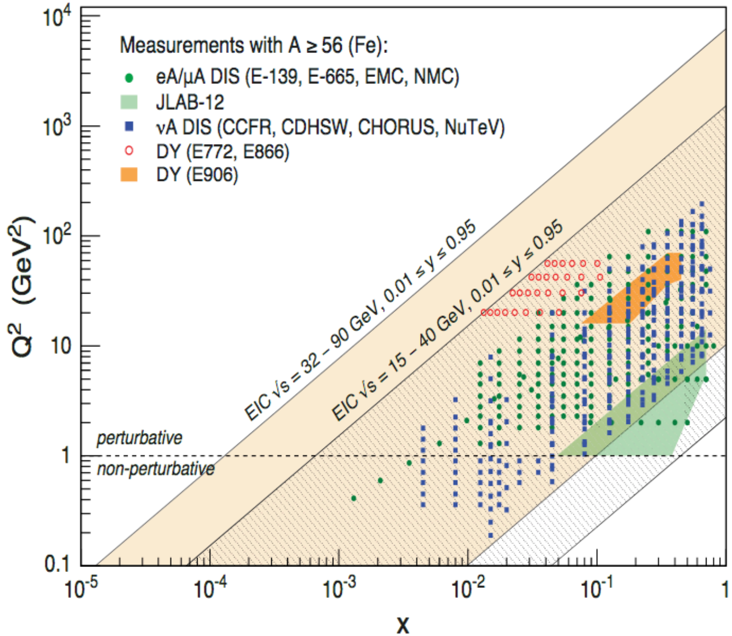


Currently DOE support is for 1 detector and 1 IR (located in IP6)

EIC machine

Uniqueness of the US EIC among all DIS facilities:





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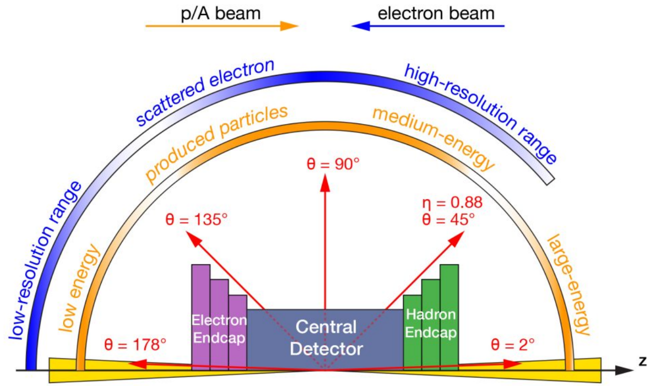
EIC detector requirements

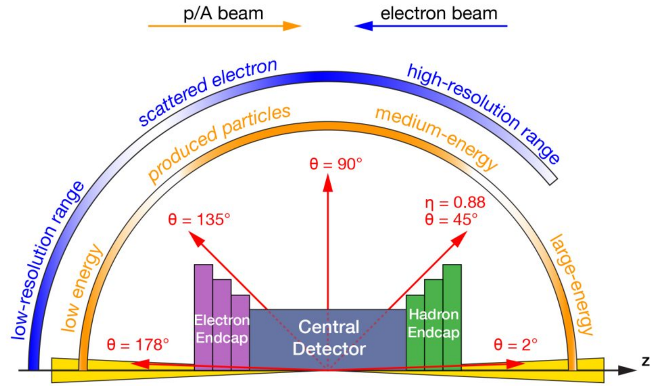
Dictated by the physics scope:

ie what has to be detected

- scattered electron (central and backward)
- hadrons associated with struck parton (central)
- hadrons associated with initial ion (forward)



EIC detector requirements



Dictated by the physics scope:

ie what has to be detected

- scattered electron (central and backward)
- hadrons associated with struck parton (central)
- hadrons associated with initial ion (forward)

that translates in the following:

- 4π hermeticity
  - ✓ with low-mass inner tracker and moderate radiation hardness (wrt LHC)
- good momentum and vertex position resolution
  - ✓ scattered electron in the backward, hadrons in the forward, HF and jets in the central region
- excellent PID up to 50 GeV/c for π/K/p in the forward, up to 10 GeV in the central region
  - ✓ critical for SIDIS measurements → TMDs → 3D-imaging
- excellent/good EM in backward/central, good hadro calorimetry
  - ✓ critical for low-x measurements → PDF mapping → spin

Tracking central:

$$\sigma(p_T)/p_T(\%) \approx 0.01 p_T \otimes 0.5$$

EM calo

backward: $\sigma(E)/E \approx \frac{2\%}{\sqrt{E}} \otimes (1-3)\%$

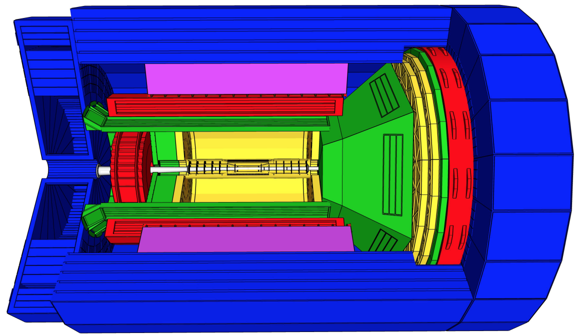
central: $\sigma(E)/E \approx \frac{10\%}{\sqrt{E}} \otimes (1-3)\%$

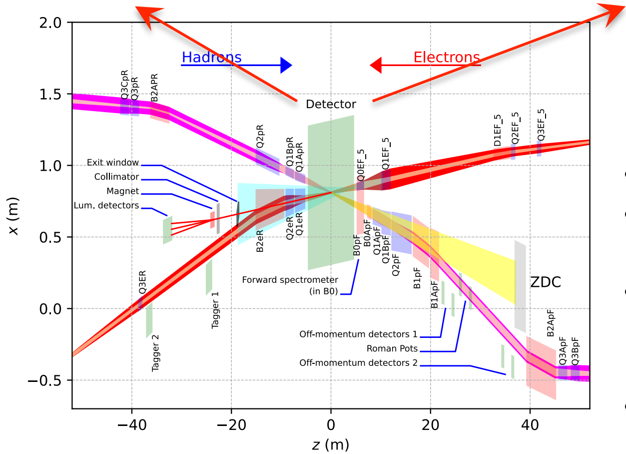
EIC detector requirements

First detector baseline:
the EIC Yellor Report baseline

Result of the first “collective” effort of the EIC community in 2020!
(completely during pandemic ...)

https://arxiv.org/abs/2103.05419





Note need of
- larger acceptance for diffraction
- neutron tagging for nuclear breakup
- forward proton measurement at small angles: ZDC, Roman-Pots, low Q^2 tagger
- luminosity monitor

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EICUG and EIC Project path

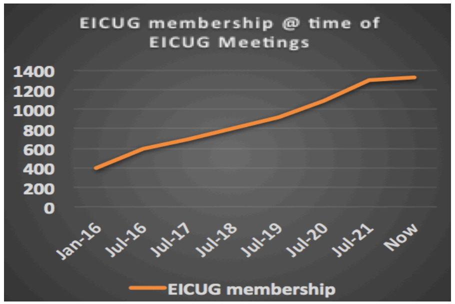
The EIC User Group:

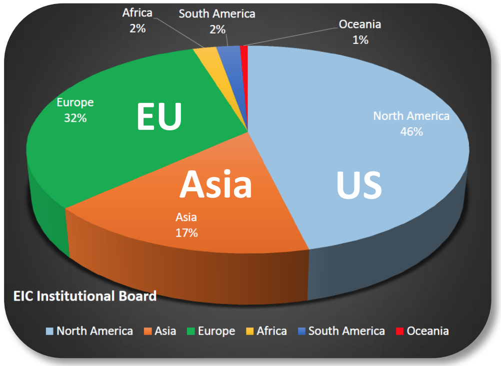
an international growing community

https://eicug.github.io

Formally established in 2016, by now:

- ~1330 collaborators
- ~36 countries
- 266 Institutions





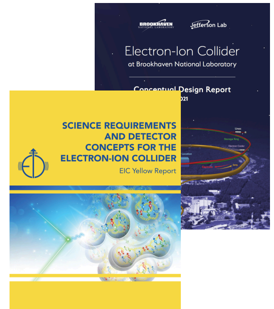
EICUG Structures in place and active:
EICUG Steering Committee, Institutional Board, Speaker's Committee, Election & Nominations Committee

EICUG and EIC Project path

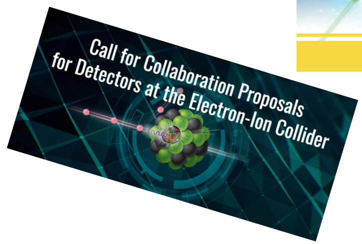
Experimental programme preparation:

extremely intense activity along the last couple of years

- call for Expression of Interest
  - ✓ for potential cooperation on the EIC Experimental Programme, deadline November 2020
- EICUG Yellow Report initiative
  - ✓ Yellow Report and EIC Conceptual Design Report published in March 2021



- call for Collaboration Proposals for Detectors at the EIC
  - ✓ 3 proto-collaborations formed (ATHENA, ECCE, CORE)
  - ✓ proposal submitted end of 2021
  - ✓ evaluation of Proposals finalized in March 2022: ECCE selected
- currently working in a join “Detector-1” Collaboration
  - ✓ for a common baseline detector at the EIC and in view of
- start in 2023 with TDR activity for CD-2



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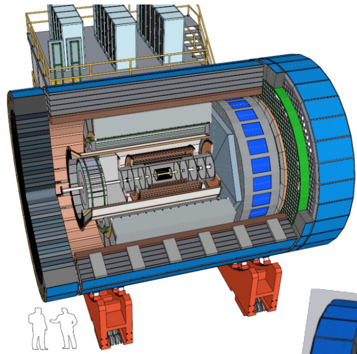
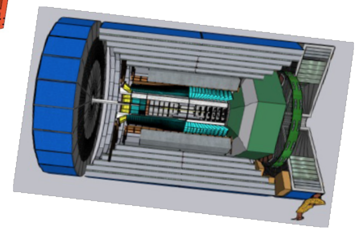
EICUG and EIC Project path

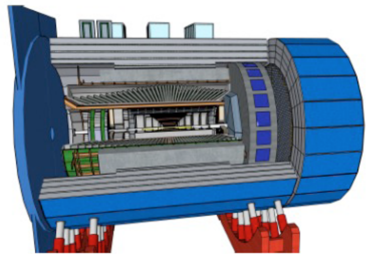
Response to call for Detector Proposal:



ATHENA (https://sites.temple.edu/eicatip6/)
- Focus on becoming the **"project detector"@IP6**
- **New 3 T magnet** and the YR Reference Detector
- Leadership: S. Dalla Torre (INFN Trieste, B. Surrow (Temple)
- ~117 collaborating institutions from Armenia, Canada, China, Czech, France, Germany, Italy, India, Poland, Romania, UK



CORE (https://eic.jlab.org/core/)
- An EIC Detector proposal based on a **new 3 T compact magnet for the 2nd EIC detector @ IP8**
- Contacts: Ch. Hyde (ODU) and P. Nadel-Turonski (SBU)
- Smaller-scale effort, ~20-30 active collaborators



ECCE (https://www.ecce-eic.org)
- **Project detector @IP6 or the 2nd EIC detector @ IP8 using existing 1.5T "Babar" solenoid**
- Leadership: O. Hen (MIT), T. Horn (CUA), J. Lajoie (Iowa State)
- ~98 collaborating institutions from Armenia, Canada, Chile, China, Croatia, Czech, France, Germany, Israel, Japan, Senegal, Korea, Russia, Slovenia, Taiwan, UK

EICUG and EIC Project path

Detector technologies at the EIC:

Relevant synergies with LHC, see also: https://indico.ph.tum.de/event/7014/

- **MAPS** μVertex for primary/secondary vtx: barrel & end-caps (ALICE ITS3)
- **MicroPattern Gas Detectors**: large rapidity, spatial resolution ~100 μm
- Electromagnetic Calorimetry for kinematic reconstruction, precise energy measurements e, γ; e/π & π^0/γ separation. Various technologies/locations:
  - ✓ **W/SciFi w/o PMT, PbWO4, SiGlass; AstroPix & Pb/SciFi**
  - ✓ High resolution Crystal Cal for e-endcap
  - ✓ Barrel EMCal 6 layers AstroPix and Pb/SciFi
- Particle Identification – extremely important for most EIC physics
  - ✓ Hadron ID: hpDIRC in Barrel, forward EndCap: dual RICH, backward Endcap: modular RICH or pF RICH; **SiPM** for all RICHes (and also for Calorimeters)
  - ✓ TOF for short lever arm (**AC-LGAD, LAPPD**), AC-LGAD also for Roman Pots
- Streaming Readout (including AI/ML)

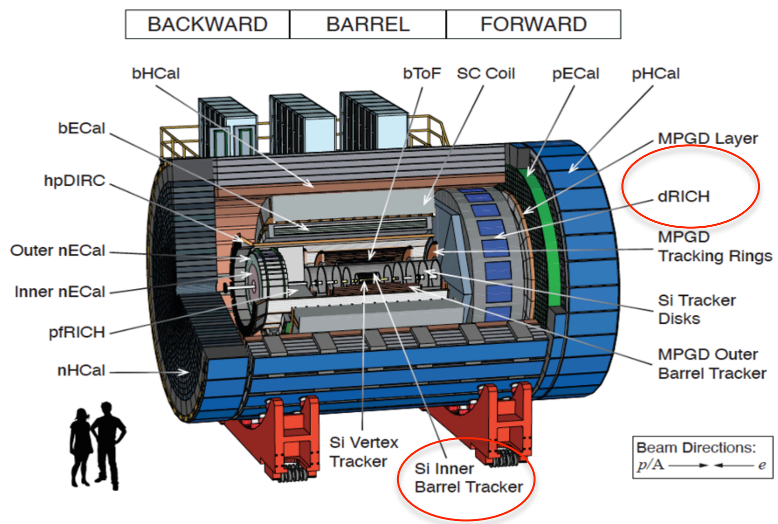
EICUG and EIC Project path

INFN involvement in EIC:

- started in the very early phases (< 2019)
- various roles in the EIC User Group
  - ✓ Steering Committee (vice-chair and members)
  - ✓ Institutional Board (vice-chair)
  - ✓ Conference Committee
- Yellor Report initiative 2020
  - ✓ Detector and Simulation conveners
  - ✓ Tracking and PID conveners, Physics conveners
- Detector Proposal (ATHENA) 2021-22
  - ✓ proto-collaboration spokesperson
  - ✓ Tracking and PID conveners, Physics conveners
- Detector 1 Collaboration 2022
  - ✓ leading the Collaboration formation process
  - ✓ contributing to Tracking/PID/Simulation/ Physics WGs

Main detector interest/contributions:

- Silicon Vertex tracker (MAPS in 65 nm technology)
- Forward PID (dual RICH)
- computing/simulation and streaming readout

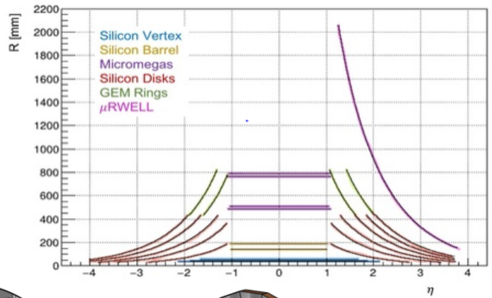


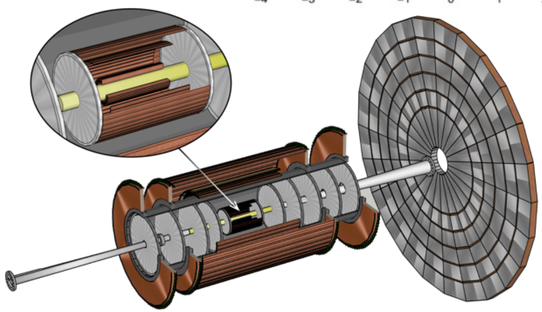
EICUG and EIC Project path

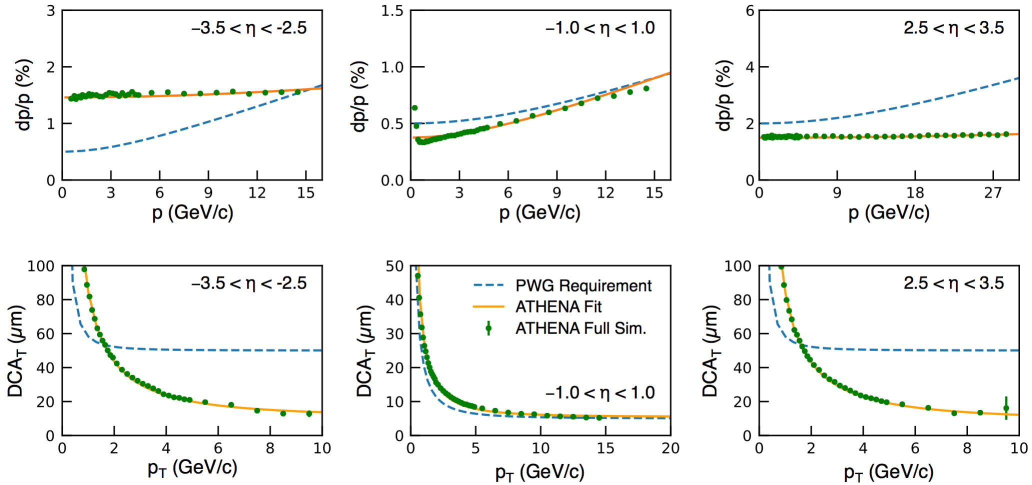
Detector performance at-a-glance:

ATHENA tracking: see also poster by S. Kumar

- **Tracking (ATHENA):**





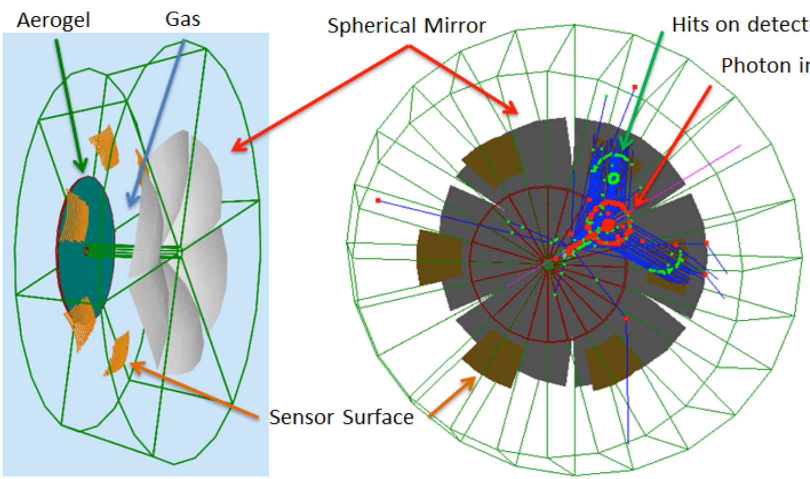


- Si Vertex Tracker: 3 layers / first layer @ R~33 mm, material 0.05% X_0 per layer
- Si inner barrel Tracker: 2 layers / material 0.55% X_0 per layer
- FW and BW Si Tracker disks: 5 (BW) + 6 (FW) / material 0.24% X_0 per disk
- MPGD in the Outer barrel, outer disks and Forward endcap

EICUG and EIC Project path

Detector performance at-a-glance:

- **dRICH: the (forward) dual radiator RICH**



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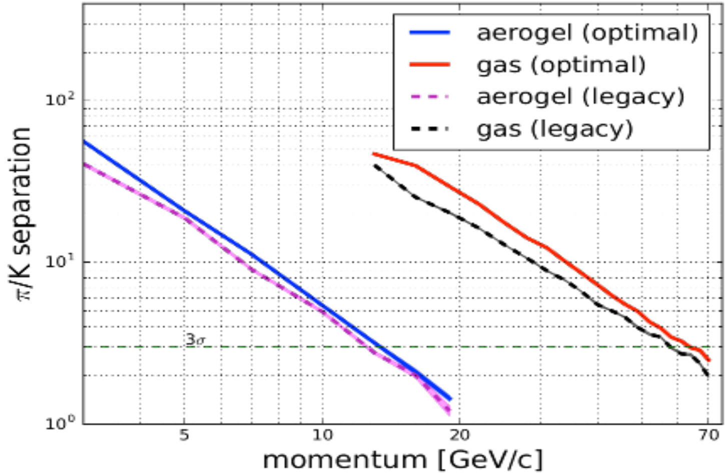
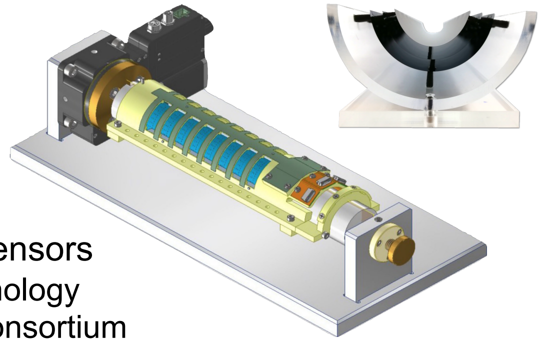


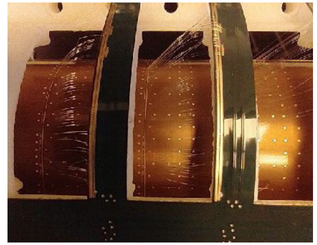
- **radiators:** aerogel (n ~ 1.02) and C_2F_6 (n ~ 1.0008)
- **mirrors:** 6 sectors, outward-reflecting
- **sensors:** 3x3 mm^2 pixel, 0.5 m^2 / sector
  - single-photon detection in high-intensity B-field (~ 1 T)
  - out of acceptance → less constraints

Common solution for forward PID in all proposals

EICUG and EIC Project path

R&D activity within INFN:





Silicon vertex

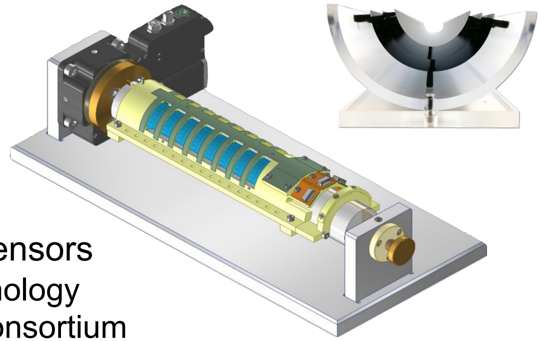
same idea/constraints as ALICE ITS3:

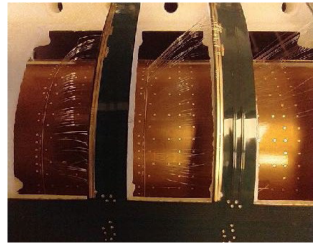
- available sensor design: ITS3 65nm CMOS monolithic sensors
  - ✓ crucial interaction with ALICE ITS3 to access the technology
  - ✓ members of EIC_NET and ALICE in the EIC Silicon Consortium
- bent silicon for innermost layers
- large area staves & discs

- **Bending and interconnection tests with ALPIDE**
- **Test of new structures in 65 nm**

EICUG and EIC Project path

R&D activity within INFN:





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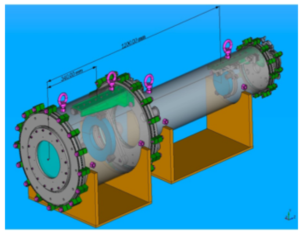
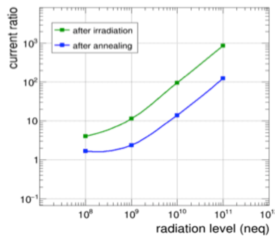
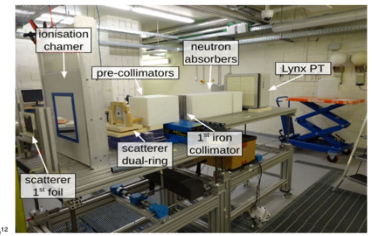
dRICH prototype and SiPM:

synergies with CLAS12@JLab and ALICE 3:

- study of dual radiator performance
- investigate options for optical components
- test of photo-sensors
  - ✓ test on SiPM (radiation tolerance, annealing)
  - ✓ expore alternative options (LAPPDs)







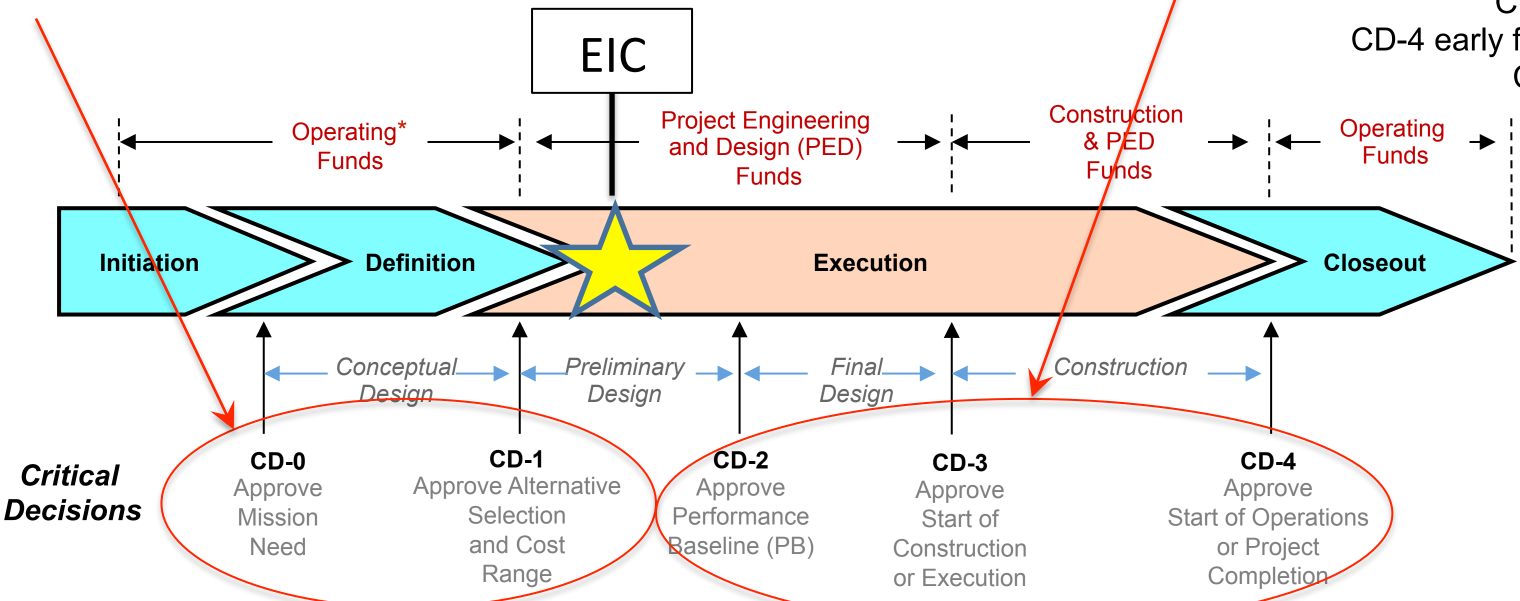
- **dRICH prototype test beam**
- **SiPM irradiation, annealing tests**

EICUG and EIC Project path

DOE project decision process:

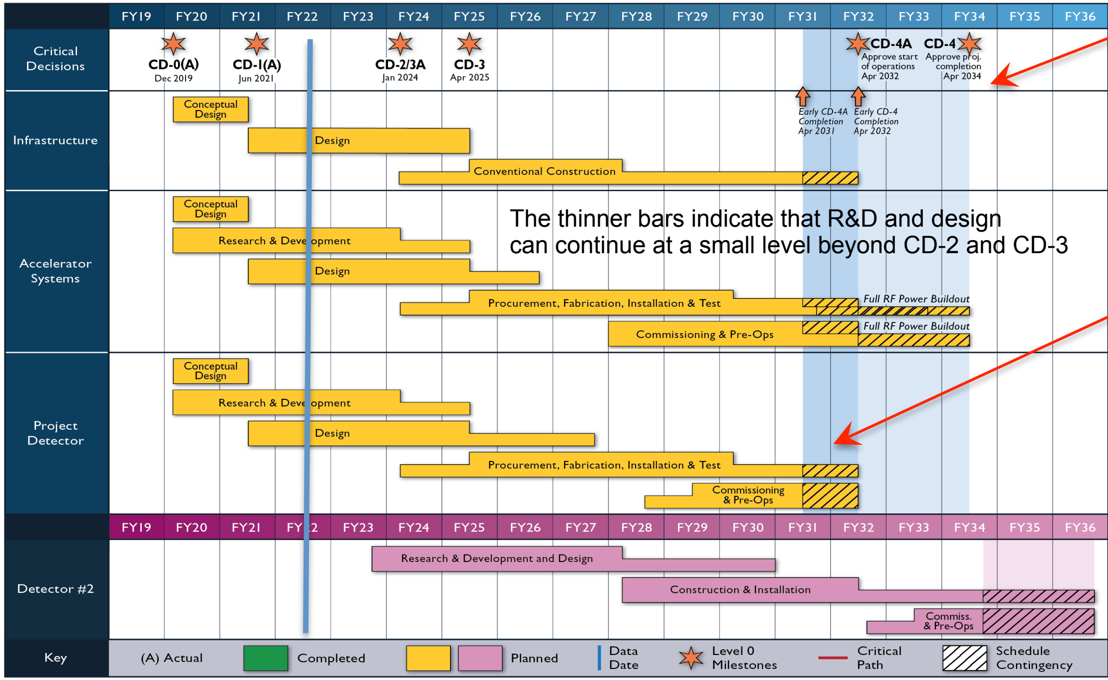
CD-0: approve mission need, Dec 2019
CD-1: June 2021

EIC Critical Decision Plan at CD-1
CD-2/3a Apr 2023
CD-3 Jul 2024
CD-4a early finish Jul 2030
CD-4a Jul 2031
CD-4 early finish Jul 2031
CD-4 Jul 2033



EICUG and EIC Project path

Latest EIC reference schedule:



CD-4 (Apr 2034):
machine delivers for physics → Detector 1 should be fully functional to start physics

CD-4a early finish (Apr 2031):
collisions begin for machine tuning → Detector 1 needs to be ready to give feedback

2nd Detector and IR:
current assumption ~3-5 years behind Detector 1 (focus on complementarity for physics&technologies)

Summary and Outlook

- The US Electron-Ion Collider will be built in the next ~10 years:
  - ✓ a high-energy, high-luminosity polarized e-p, e-A collider @ BNL
  - ✓ an hermetic full acceptance detector based on state-of-the-art technologies
  - ✓ opening a large variety of precision QCD studies and more
  - ✓ construction to start in ~2025, first beams in ~2031 and physics ~2034
- A wide and dedicated International community at work:
  - ✓ more than 1300 physicists from ~270 institutions in the EICUG
  - ✓ large effort since Yellow Report (2020) and following Detector Proposals
- Large perspectives for progress with the EIC, with an incredibly broad range of scientific and technological challenges!

Istituto Nazionale di Fisica Nucleare
SEZIONE DI BARI

Summary and Outlook

Thank You!

- Large perspectives for progress with the EIC, with an incredibly broad range of scientific and technological challenges!