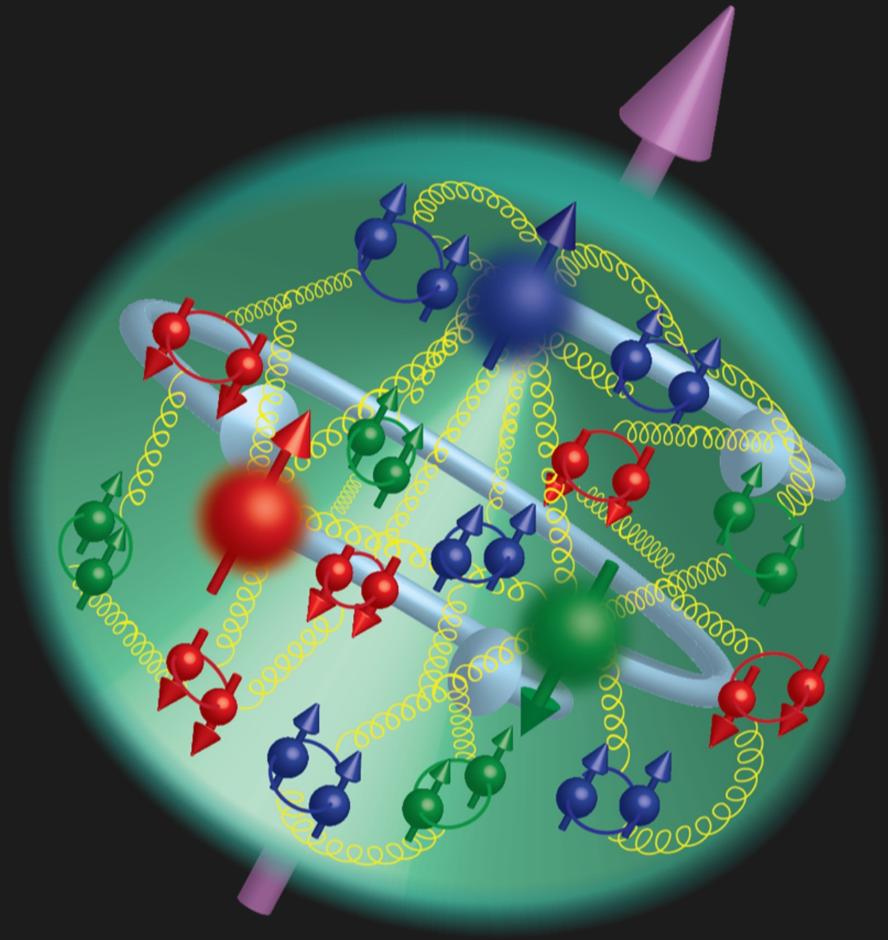
14th LHCP Conference, Jun 3 – 7, 2024
Future Projects Session

The EIC: Theoretical Motivations and Experimental Challenges

Maria ŻUREK, Argonne National Laboratory
on behalf of the ePIC Collaboration

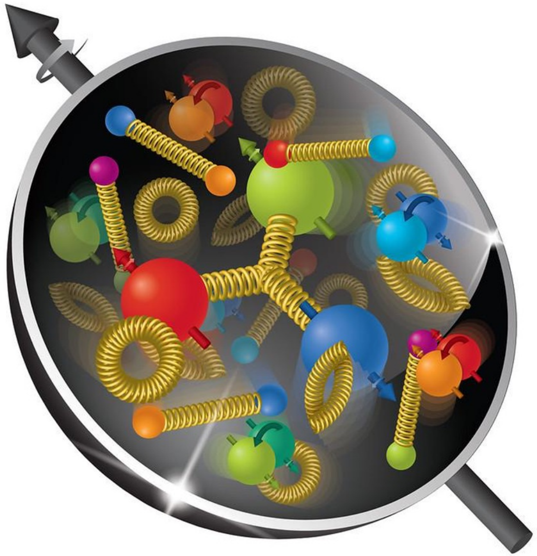


(Selected) Theoretical Motivations

The Physics Quest of the EIC

- How do the **nucleon properties like mass and spin emerge** from their partonic structure?

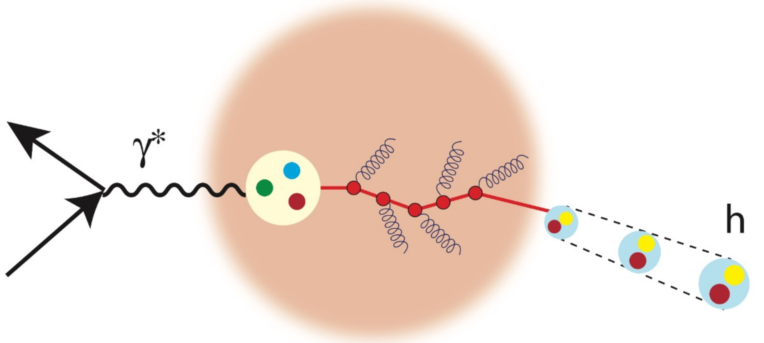
- How are the sea quarks and gluons, and their spins, distributed in space and momentum inside the nucleon?

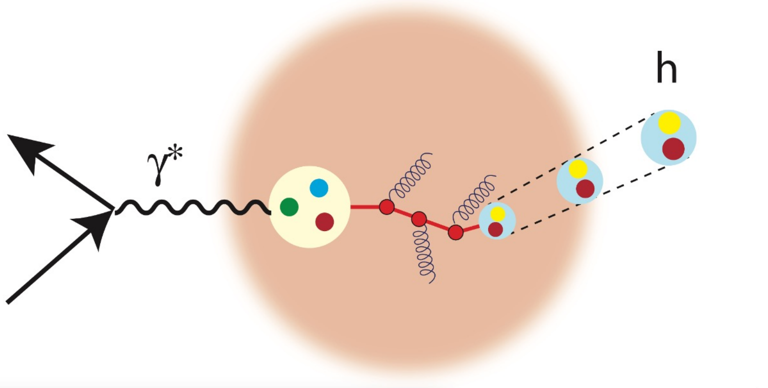


The Physics Quest of the EIC

- In what manner do color-charged quarks and gluons, along with colorless jets, interact with the nuclear medium?

- What is the mechanism through which quark-gluon interactions give rise to nuclear binding?

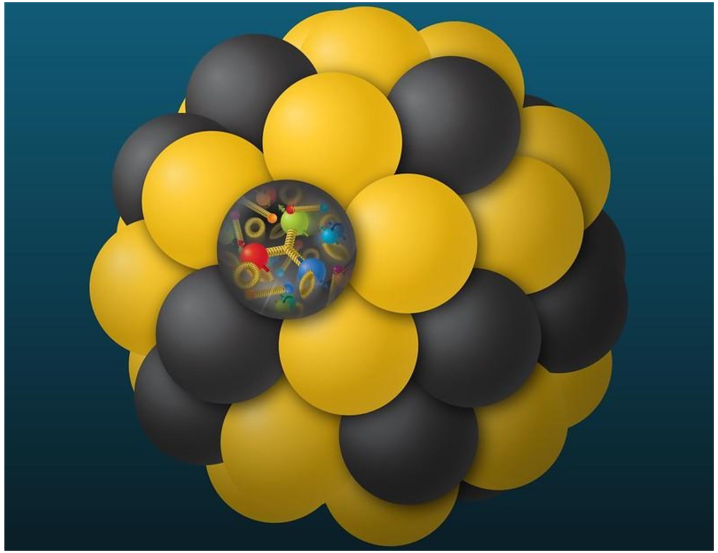




The Physics Quest of the EIC

- What impact does a high-density nuclear environment have on the interactions, correlations, and behaviors of quarks and gluons?

- Is there a **saturation point** for the density of gluons in nuclei at high energies, and does this lead to the **formation of gluonic matter** with universal properties across all nuclei, including the proton?

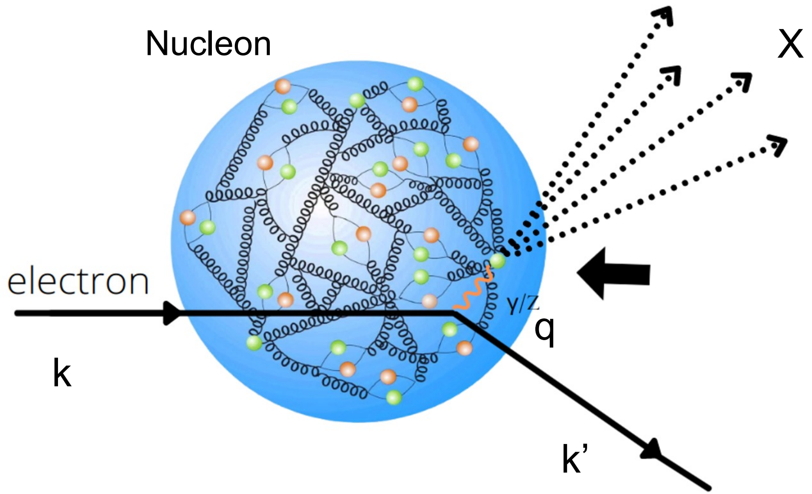


Deep Inelastic Scattering

e + p → e' + X

Golden process to probe nucleons and nuclei with electron beam providing the unmatched precision of EM interactions

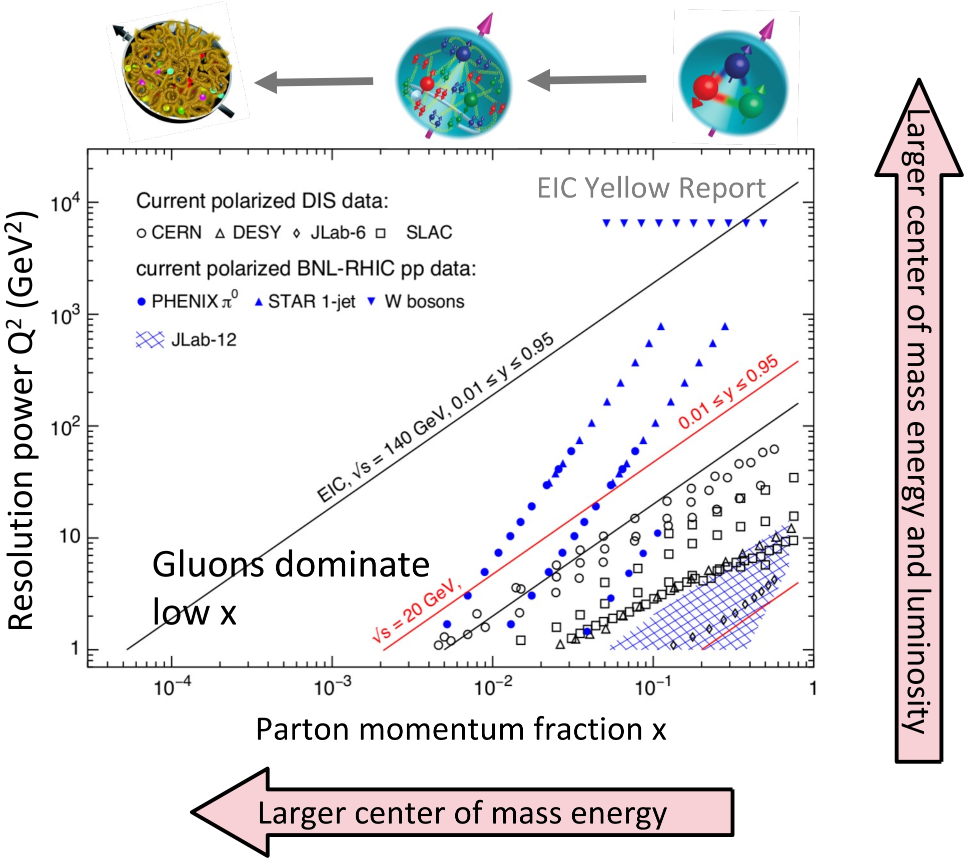
- Access to **partonic kinematics** through scattered lepton on event level
- **Initial and final state effects** can be cleanly disentangled



$$Q^2 = s \cdot x \cdot y$$

Q^2 - resolution power (virtuality of the photon)
s - center-of-mass energy squared
x - the fraction of the nucleon's momentum that the struck quark caries
y - inelasticity

Probing Uncharted Territory



Center-of-mass energy √s: 29 – 140 GeV

Explore QCD landscape over large range of resolution (Q^2) and quark/gluon density (1/x)

Unraveling the Mystery of the Origin of the Nucleon Spin

$$\boxed{\Delta\Sigma/2}+\boxed{\Delta G}+\boxed{\ell_q}+\boxed{\ell_g}=\hbar/2$$

Quark spins

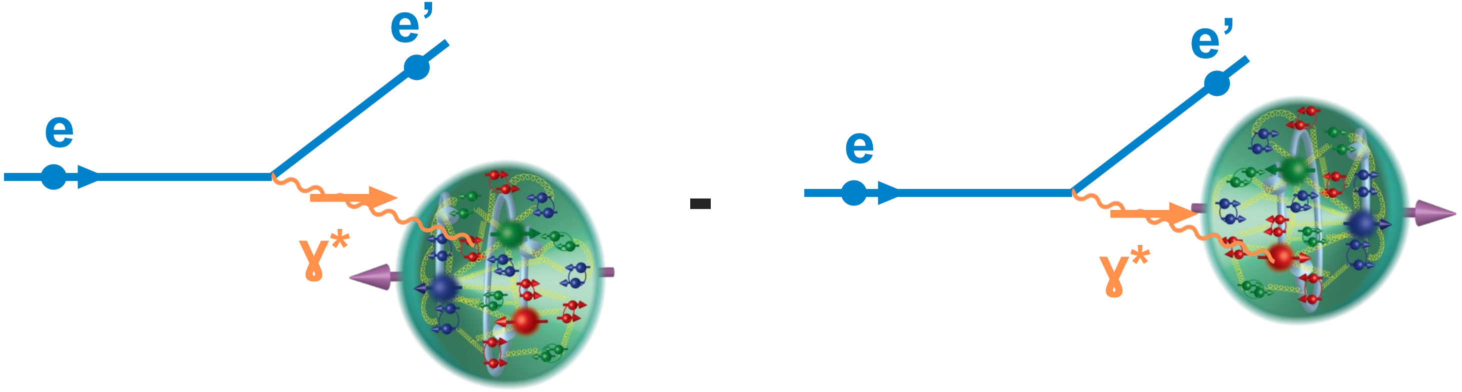
Gluon spins

Quark orbital angular momentum

Gluon orbital angular momentum

Access to gluon spin with the measurement of the g_1 structure function

- Difference of cross-sections with **different longitudinal spin orientation** of e and proton

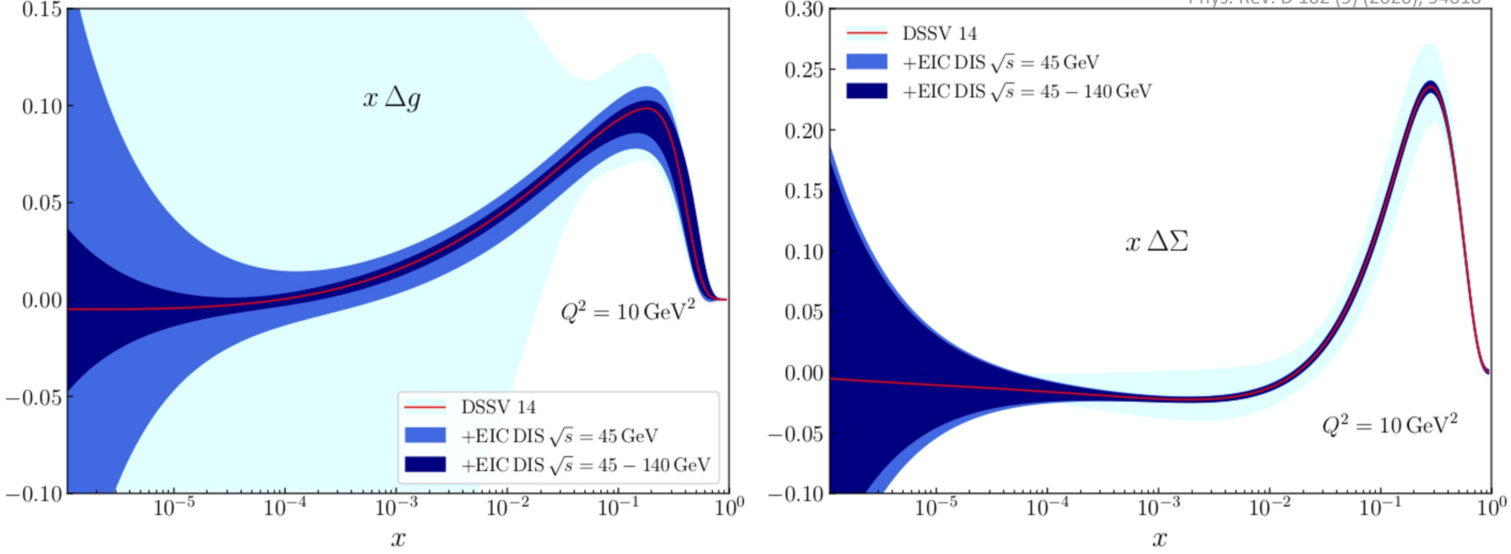


Access to quark contribution of OAM – through exclusive processes

Unraveling the Mystery of the Origin of the Nucleon Spin

Impact of the projected EIC DIS A_{LL} pseudodata ($L = 10\ fb^{-1}$) on the gluon helicity and quark singlet helicity

Phys. Rev. D 102 (9) (2020), 94018



Current world data: Helicity distributions known for **x > ~0.01** with good precision

Deep insight with EIC: In addition to golden channel g_1, direct access to gluons in higher-order photon-gluon fusion: dijet, heavy-quark

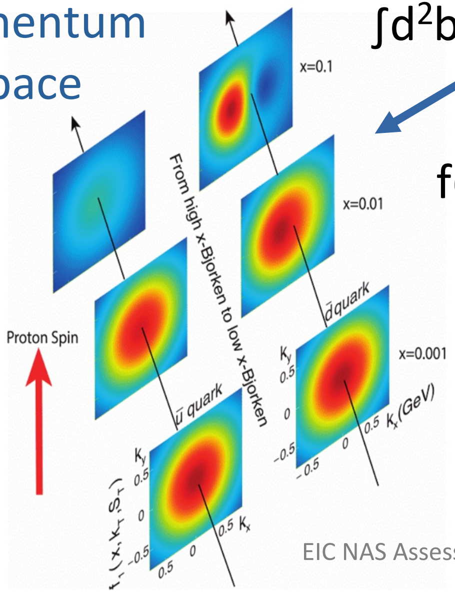
Spatial and Momentum Structure of Nucleons and Nuclei in 3D

Wigner functions

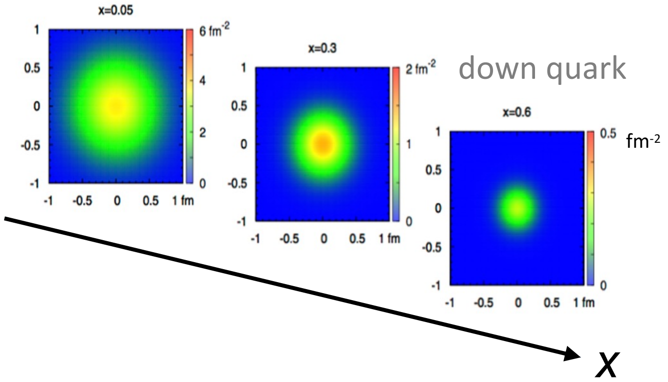
$W(x,b_T,k_T)$

$\int d^2b_T$ → Momentum space: $f(x,k_T)$

$\int d^2k_T$ → Coordinate space: $f(x,b_T)$



EIC NAS Assessment

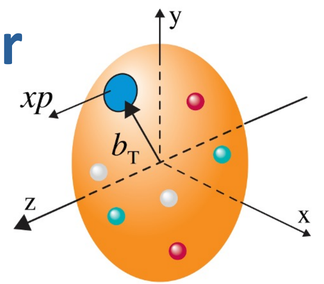


→ Access to e.g., spin-orbit correlations

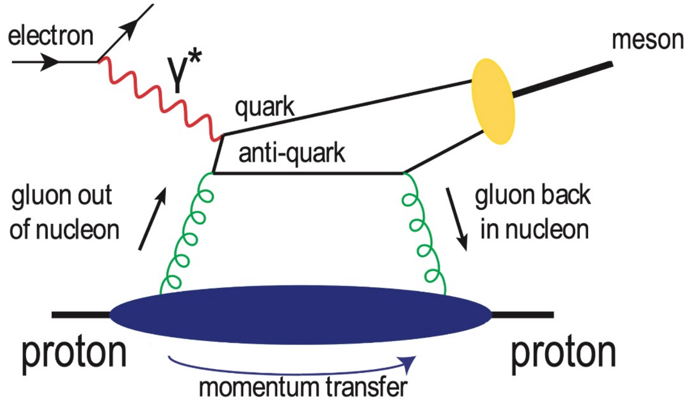
Spin-dependent 3D momentum space images from semi-inclusive scattering

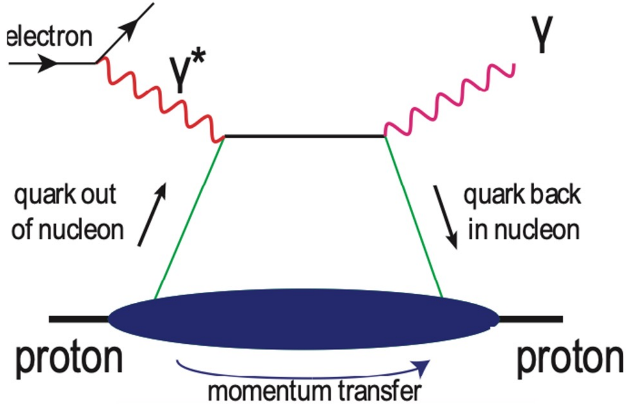
Spin-dependent 2+1D coordinate space images from exclusive scattering

Tomographic Image of Quarks and Gluons within Matter



Spatial imaging of Quarks and Gluons via exclusive reactions where the nucleon is left intact in the final state



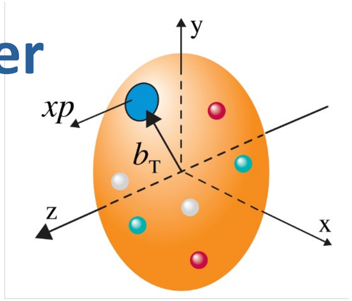


EIC NAS Assessment

Deeply Virtual Meson production: quark-antiquark bound state is produced

Deeply Virtual Photon scattering: real photon is produced

Tomographic Image of Quarks and Gluons within Matter



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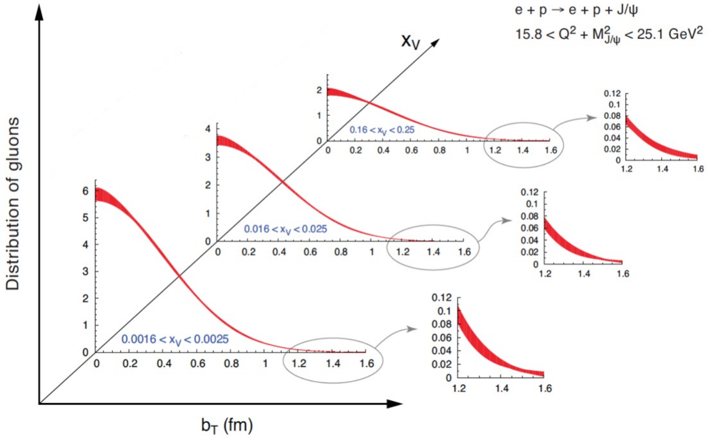

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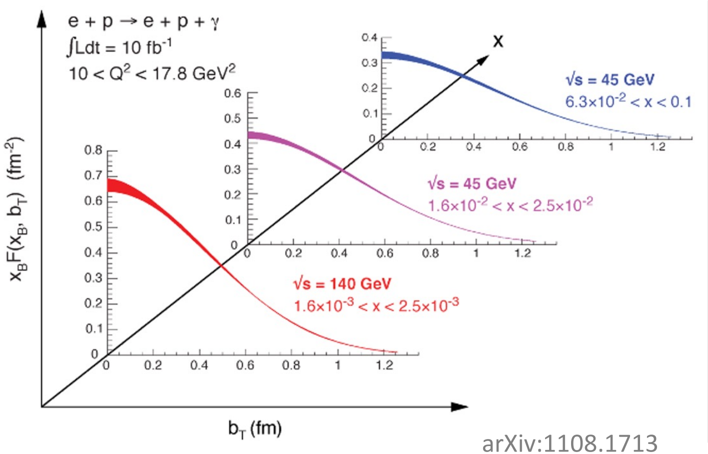


arXiv:1108.1713

Deeply Virtual J/ψ production: quark-antiquark bound state is produced

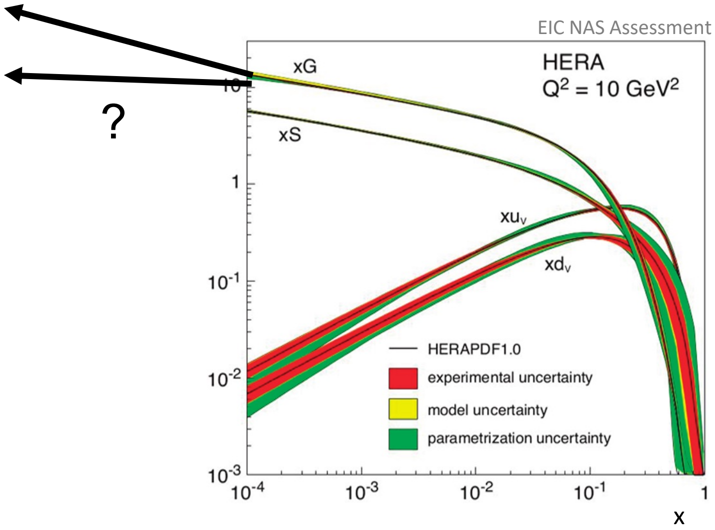
Deeply Virtual Photon scattering: real photon is produced

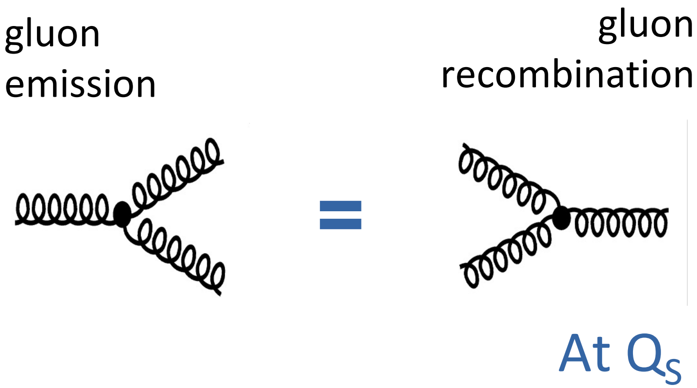
First ever tomographic images of ocean of gluons within matter

Probing non-linear gluon dynamics

What happens to the gluon density in nuclei?

- Number of gluon **grows in the low-x limit**
- At some point the **density becomes so large** that gluons lose their individual identity and are **strongly overlapping**

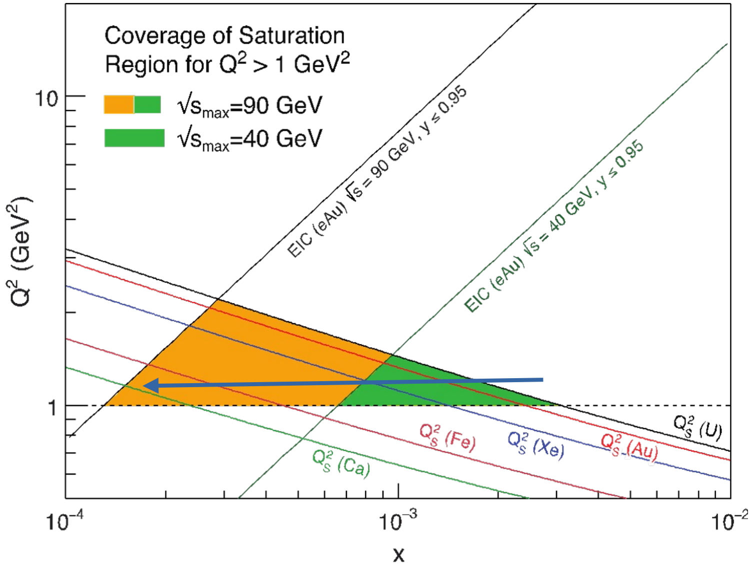




Probing non-linear gluon dynamics

- EIC provides a unique opportunity to have very high gluon densities
  electron – heavy nuclei (e.g., Pb) collisions
- Combined with an unambiguous observables, e.g., di-hadrons (jets) in ep and eA
- **EIC will allow to map the transition from a linear to non-linear QCD regime**

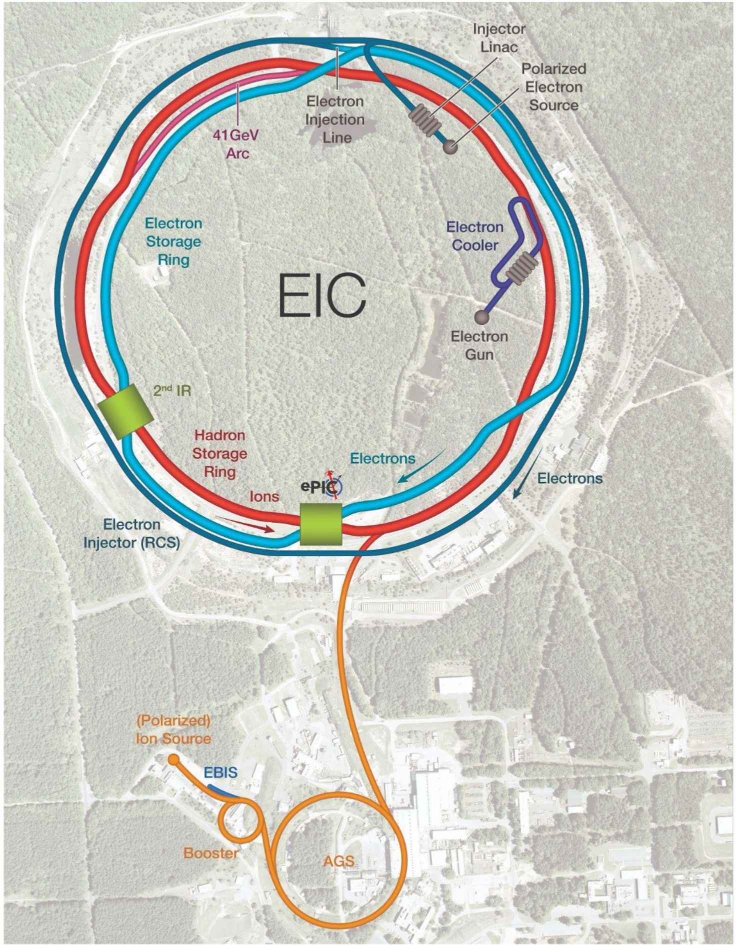
EIC Yellow Report



Q_S - resolution scale at which the number density so large that gluons are no longer independent

$$Q_s^2 \propto \left(\frac{A}{x}\right)^{1/3}$$

Experimental Realizations and Challenges


Injector
Linac
Polarized
Electron
Source
Electron
Injection
Line
41GeV
Arc
Electron
Storage
Ring
EIC
Electron
Cooler
Electron
Gun
2nd IR
Hadron
Storage
Ring
Electrons
Electrons
ePIC
Ions
Electron
Injector (RCS)
(Polarized)
Ion Source
EBIS
Booster
AGS

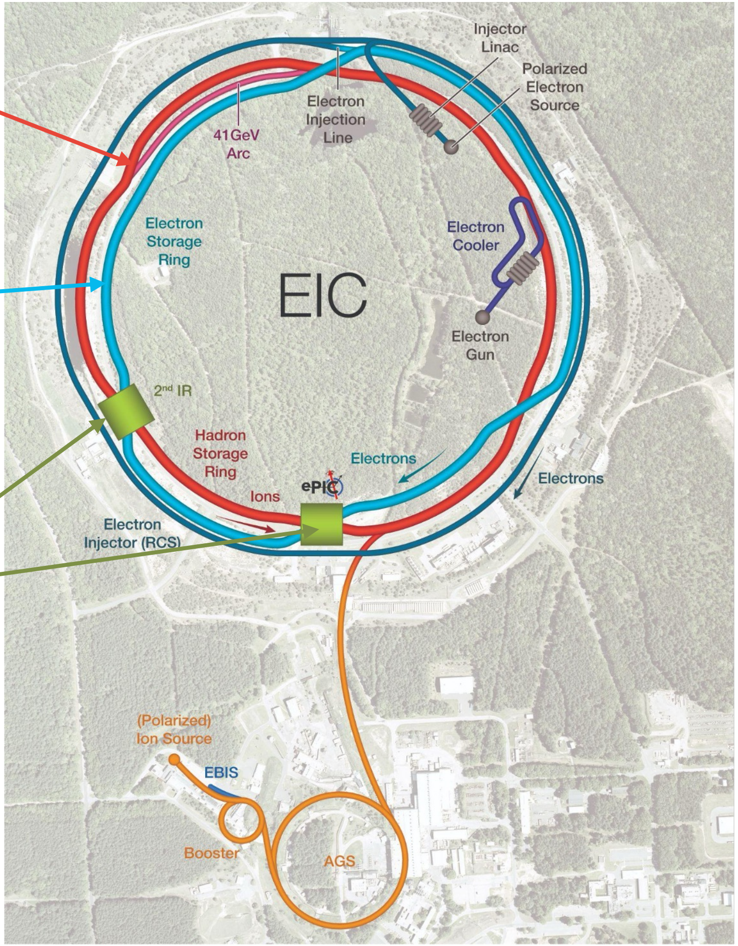
Hadron Storage Ring (RHIC Rings)
41, 100-275 GeV

Electron Storage Ring **5–18 GeV**

- Polarized electron source
- 400 MeV injector linac
- Rapid Cycling Synchrotron design to avoid depolarizing resonances

High luminosity Interaction Region(s)

- **Luminosity:**
  $L= 10^{33}–10^{34} cm^{-2} sec^{-1}$
  $10 – 100\ fb^{-1}/year$
- **Highly Polarized Beams:** 70%
- 25 mrad (IP1) crossing angle with crab cavities
- Bunch Crossing ~ 10.2 ns/98.5 MHz



Hadron Storage Ring (RHIC Rings)
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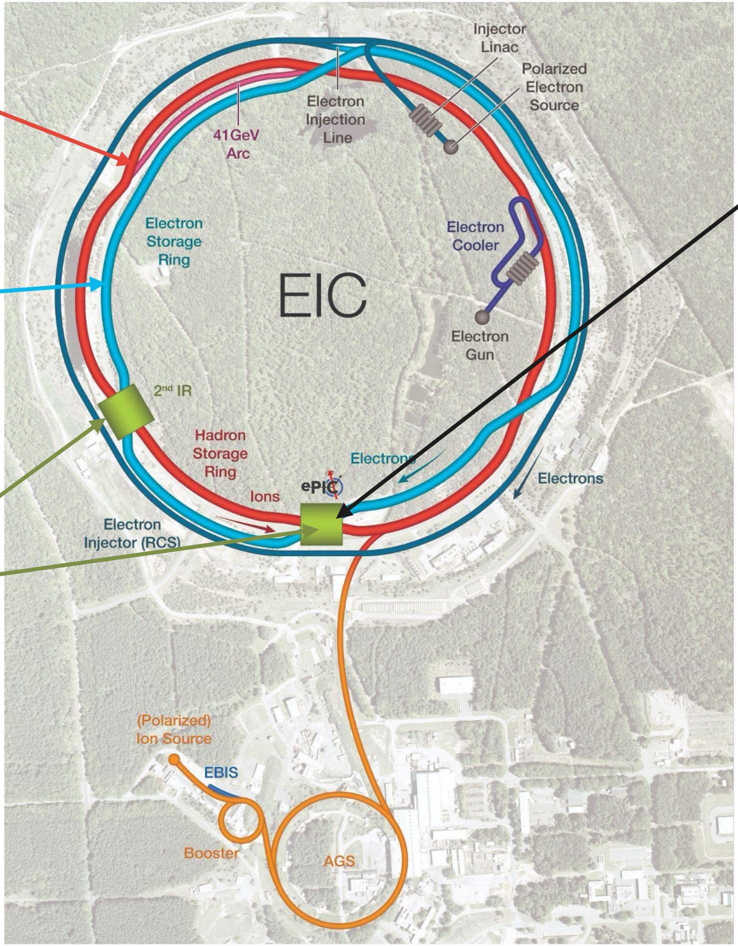


Detector located at 6 o'clock of the EIC Ring

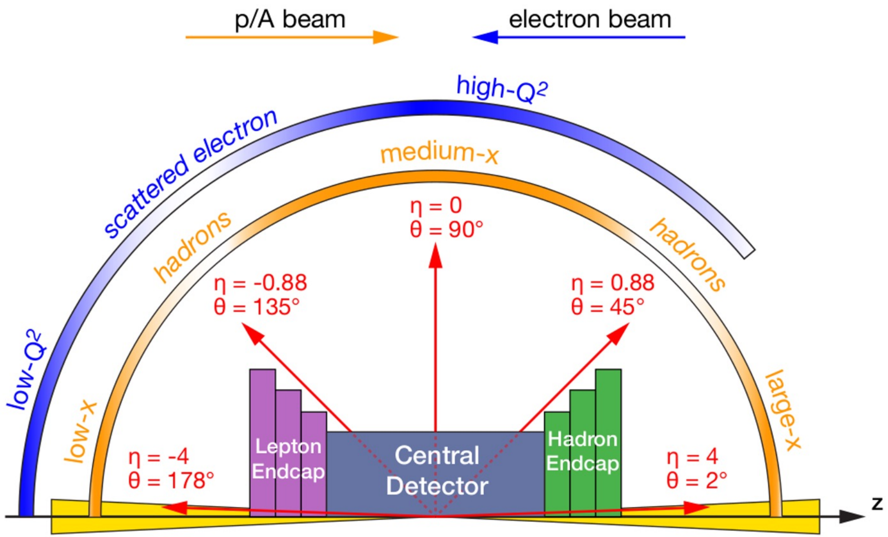
The **ePIC Collaboration** formed in July 2022 is dedicating to the realization of the project detector

- 177 Institutions, 26 countries, 4 world's region
- Currently: > 850 collaborators (from 2024 survey)

EIC Detector Challenges and Requirements

p: 41, 100-275 GeV

e: 5-18 GeV



Large center-of-mass energy range: 29-140 GeV

- Large detector acceptance

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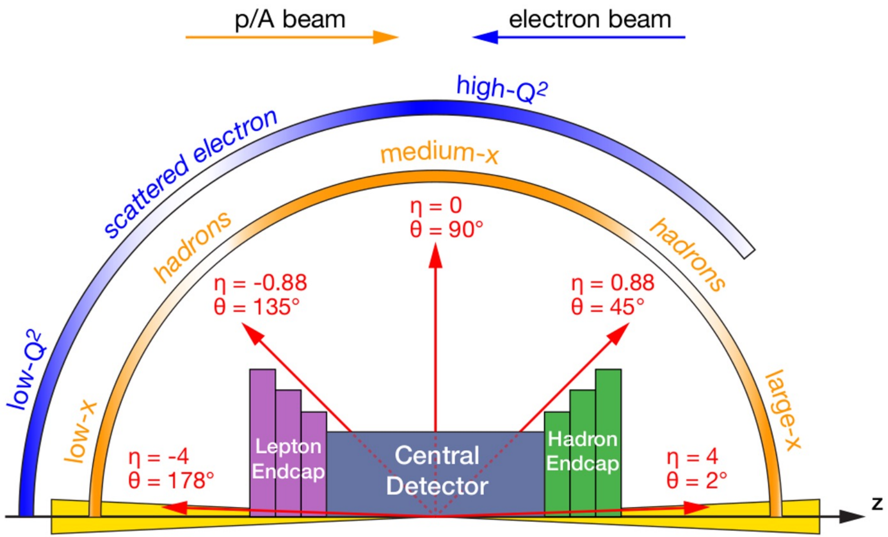

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- Large detector acceptance

Asymmetric beams

- **Asymmetric detector**: barrel with electron and hadron end caps
- Large central **coverage** (-4 < η < 4) **in tracking, particle identification**, em and hadronic **calorimetry**
  - High precision low mass tracking
  - Good e/h separation critical for scattered electron ID
  - Separation of e, p, K, p on track level

EIC Detector Challenges and Requirements

p: 41, 100-275 GeV

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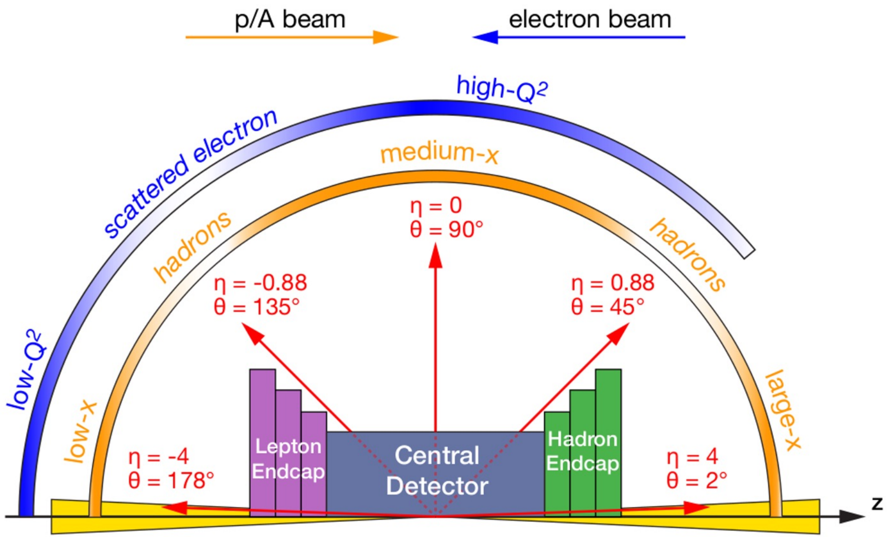

luminosity detectors
low Q2 tagger

Far-forward: particle from nuclear breakup and exclusive process

Large center-of-mass energy range: 29-140 GeV

- Large detector acceptance

Asymmetric beams

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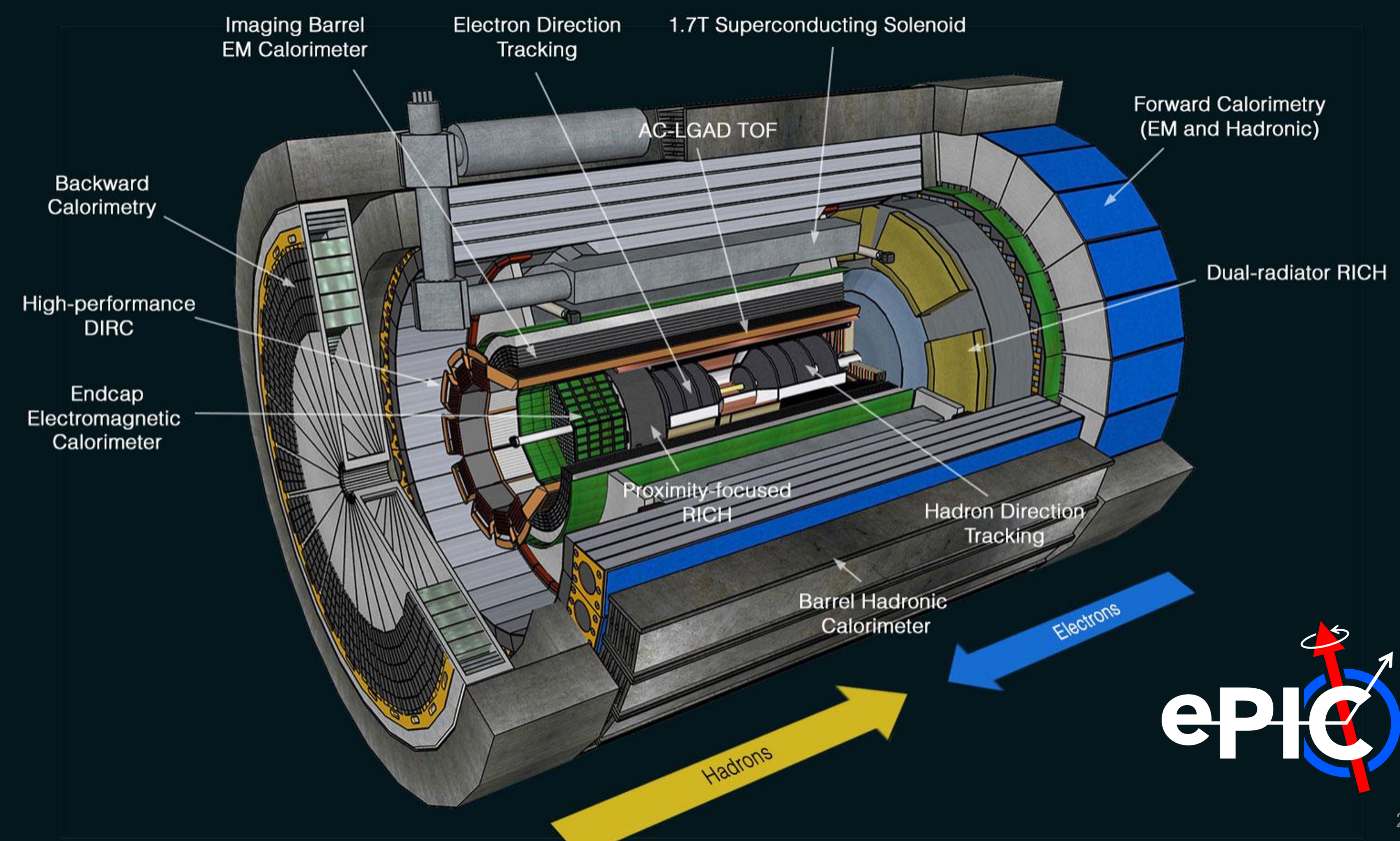
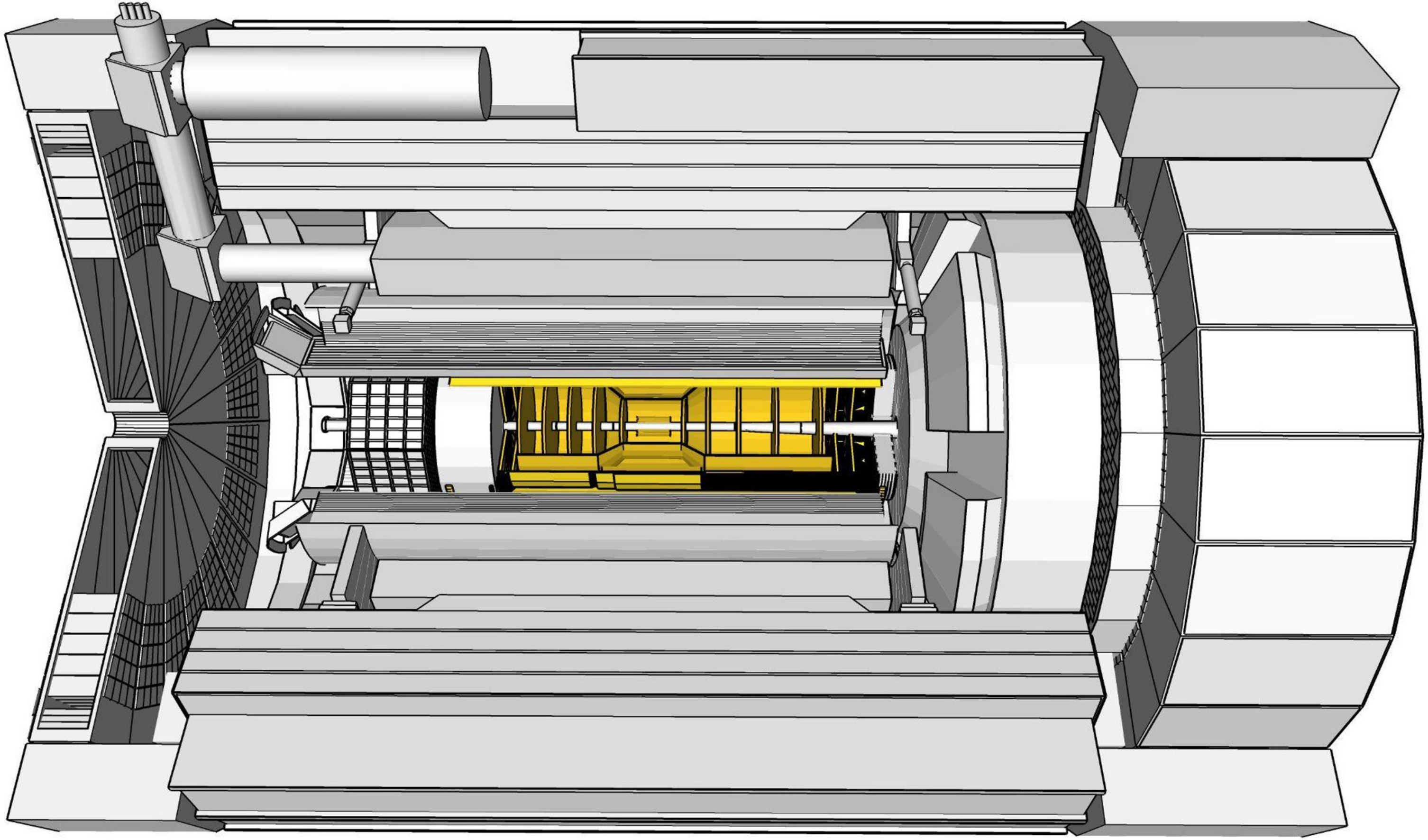
Imaging science program with large ion species range: protons-U

- Specialized detectors **integrated in the Interaction Region over 50m**


Imaging Barrel
EM Calorimeter
Electron Direction
Tracking
1.7T Superconducting Solenoid
AC-LGAD TOF
Forward Calorimetry
(EM and Hadronic)
Backward
Calorimetry
High-performance
DIRC
Dual-radiator RICH
Endcap
Electromagnetic
Calorimeter
Proximity-focused
RICH
Hadron Direction
Tracking
Barrel Hadronic
Calorimeter
Electrons
Hadrons

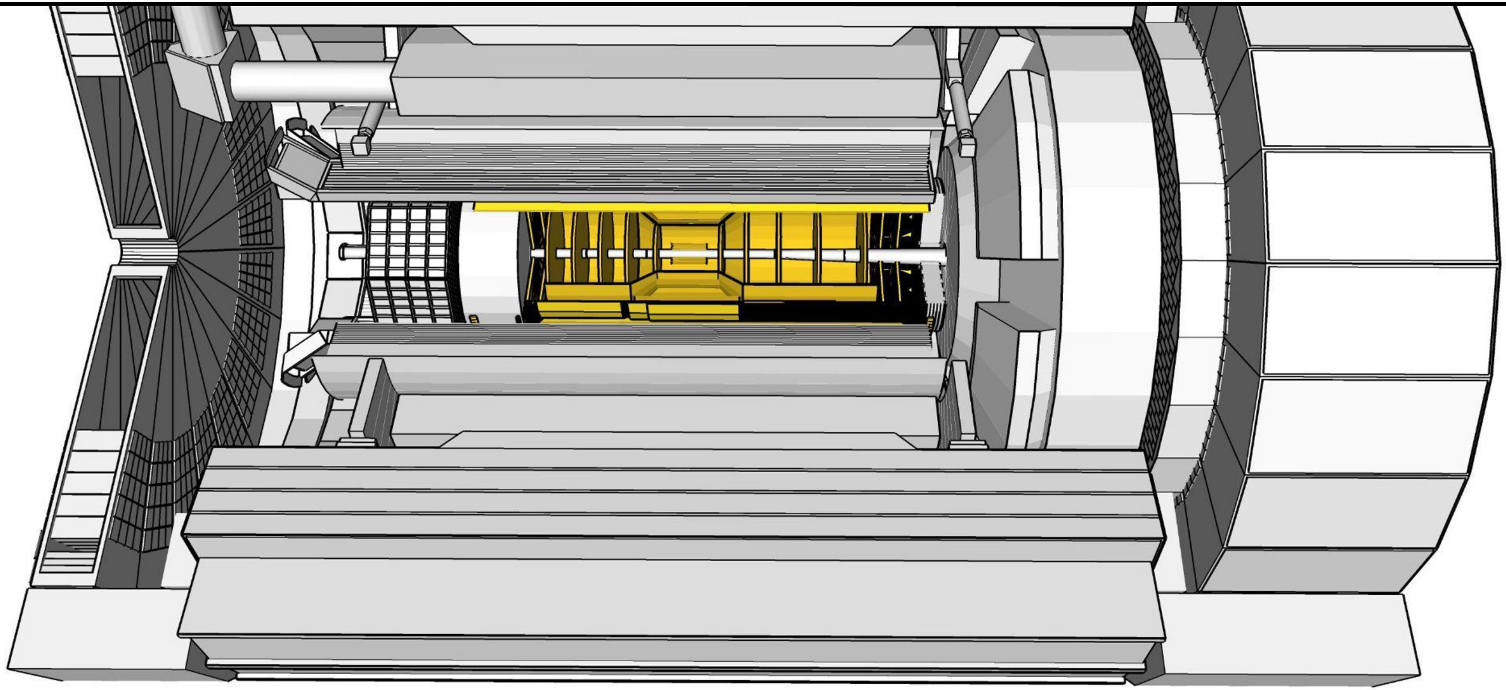
Tracking



Tracking

Challenges: High precision low mass tracking

- High spatial-resolution and efficiency and large-area coverage (8 m^2 of Silicon Vertex Detector):
  - High pixel granularity
  - Very low material budget constraints also at large η (challenge for services)



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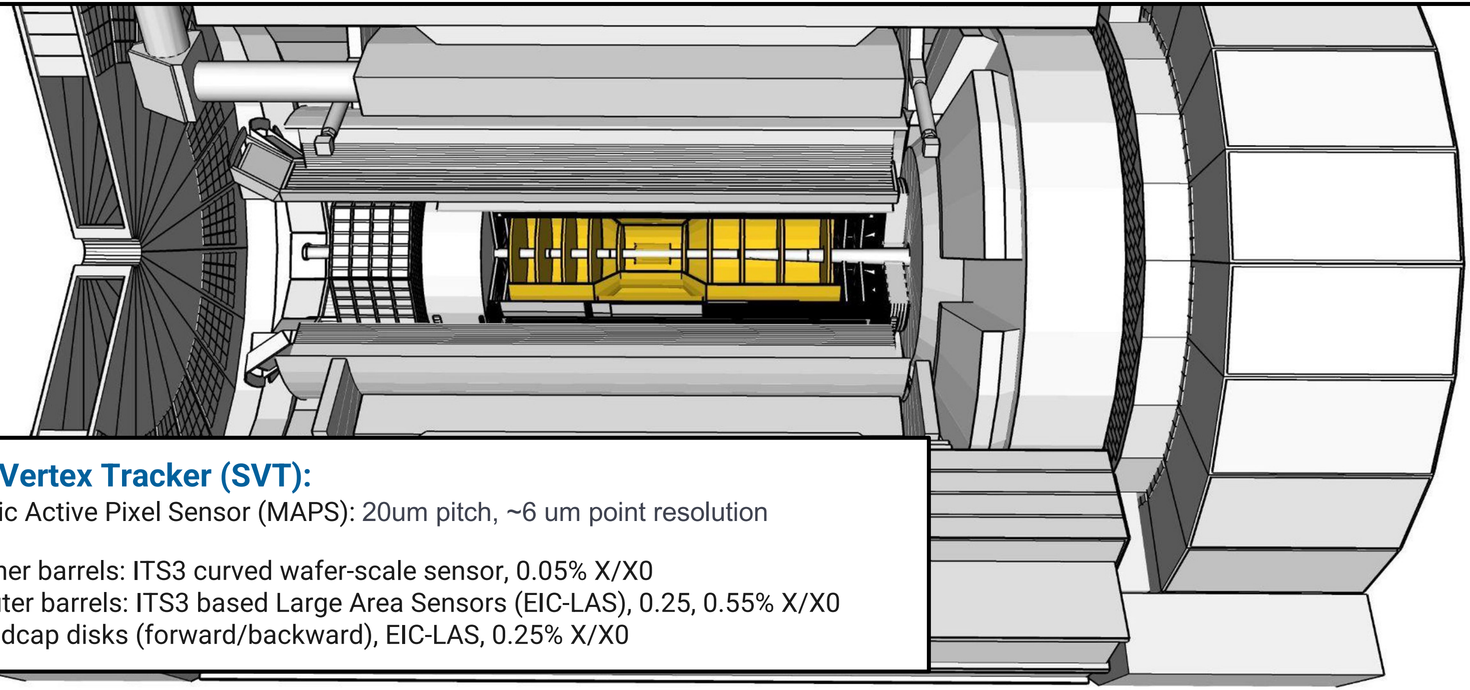

Silicon Vertex Tracker (SVT):

Monolithic Active Pixel Sensor (MAPS): 20um pitch, ~6 um point resolution

- 3 inner barrels: ITS3 curved wafer-scale sensor, 0.05% X/X0
- 2 outer barrels: ITS3 based Large Area Sensors (EIC-LAS), 0.25, 0.55% X/X0
- 5 endcap disks (forward/backward), EIC-LAS, 0.25% X/X0

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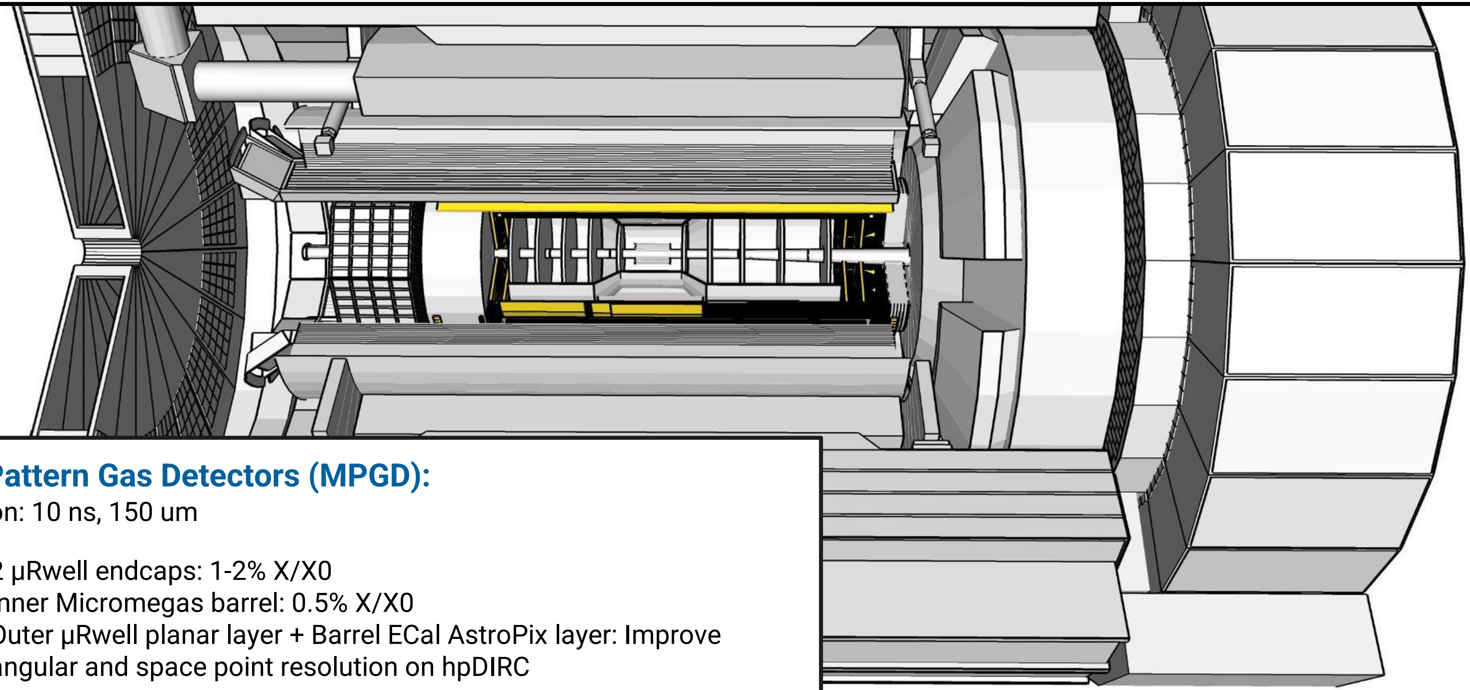

Micro Pattern Gas Detectors (MPGD):

Resolution: 10 ns, 150 um

- 2 μRwell endcaps: 1-2% X/X0
- Inner Micromegas barrel: 0.5% X/X0
- Outer μRwell planar layer + Barrel ECal AstroPix layer: Improve angular and space point resolution on hpDIRC

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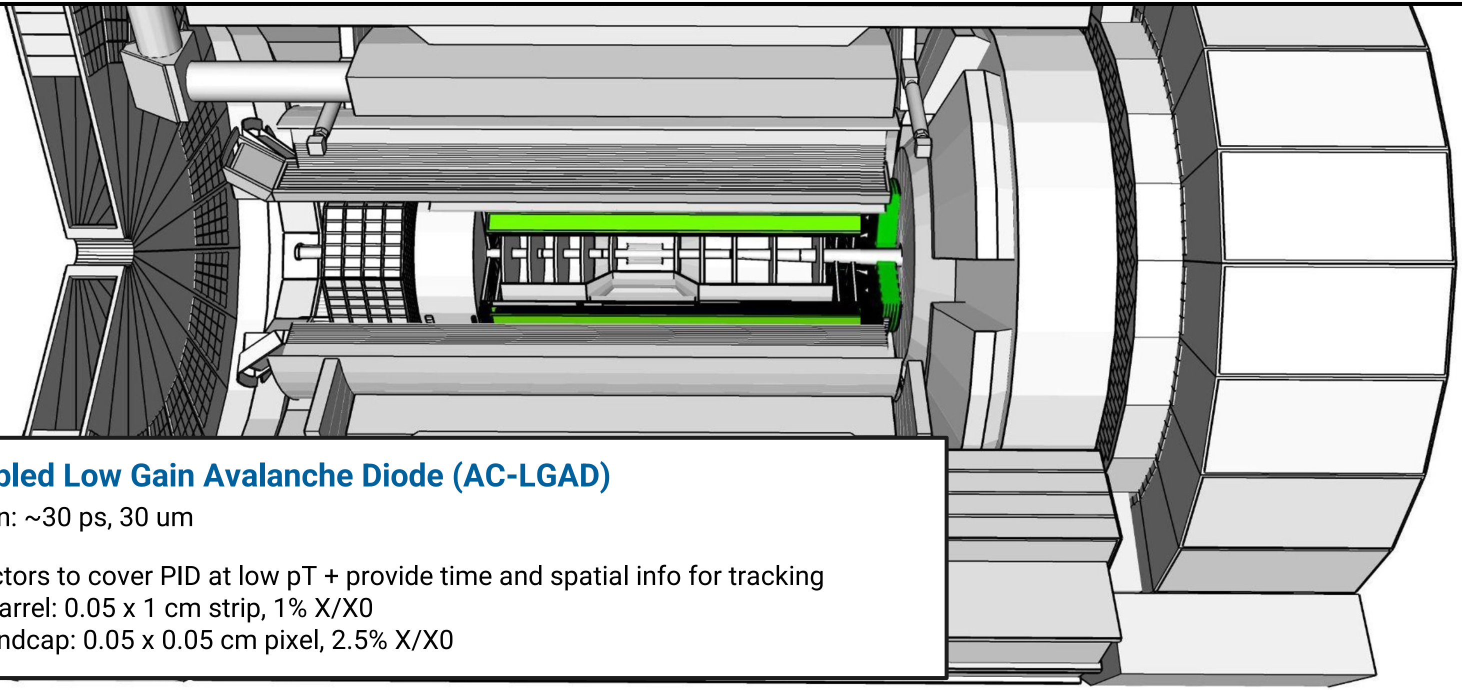


AC-coupled Low Gain Avalanche Diode (AC-LGAD)

Resolution: ~30 ps, 30 um

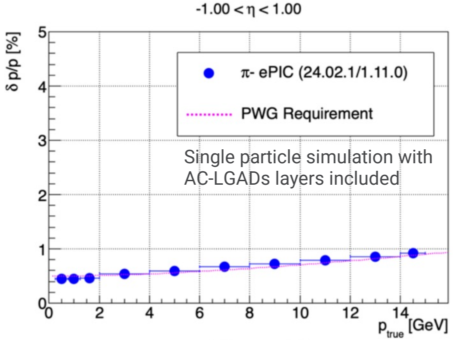
ToF detectors to cover PID at low pT + provide time and spatial info for tracking

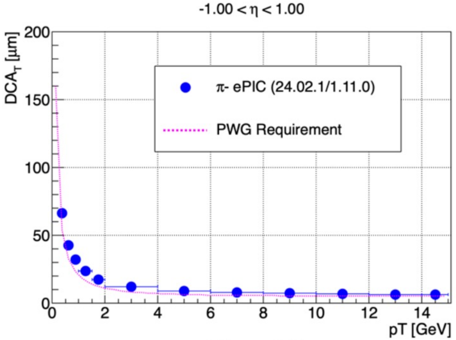
- Barrel: 0.05 x 1 cm strip, 1% X/X0
- Endcap: 0.05 x 0.05 cm pixel, 2.5% X/X0

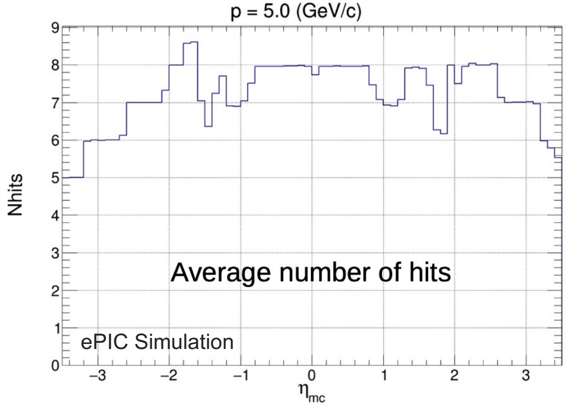
Tracking Performance

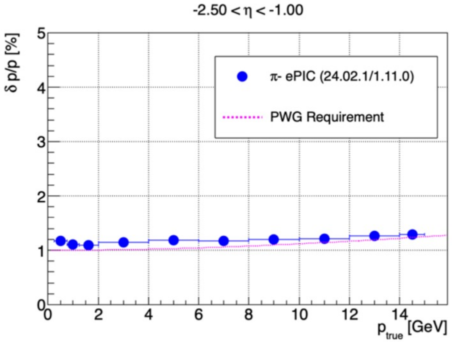
Momentum

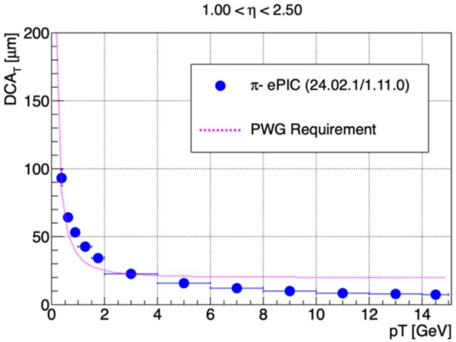
Distance of Closest Approach (DCA_T)







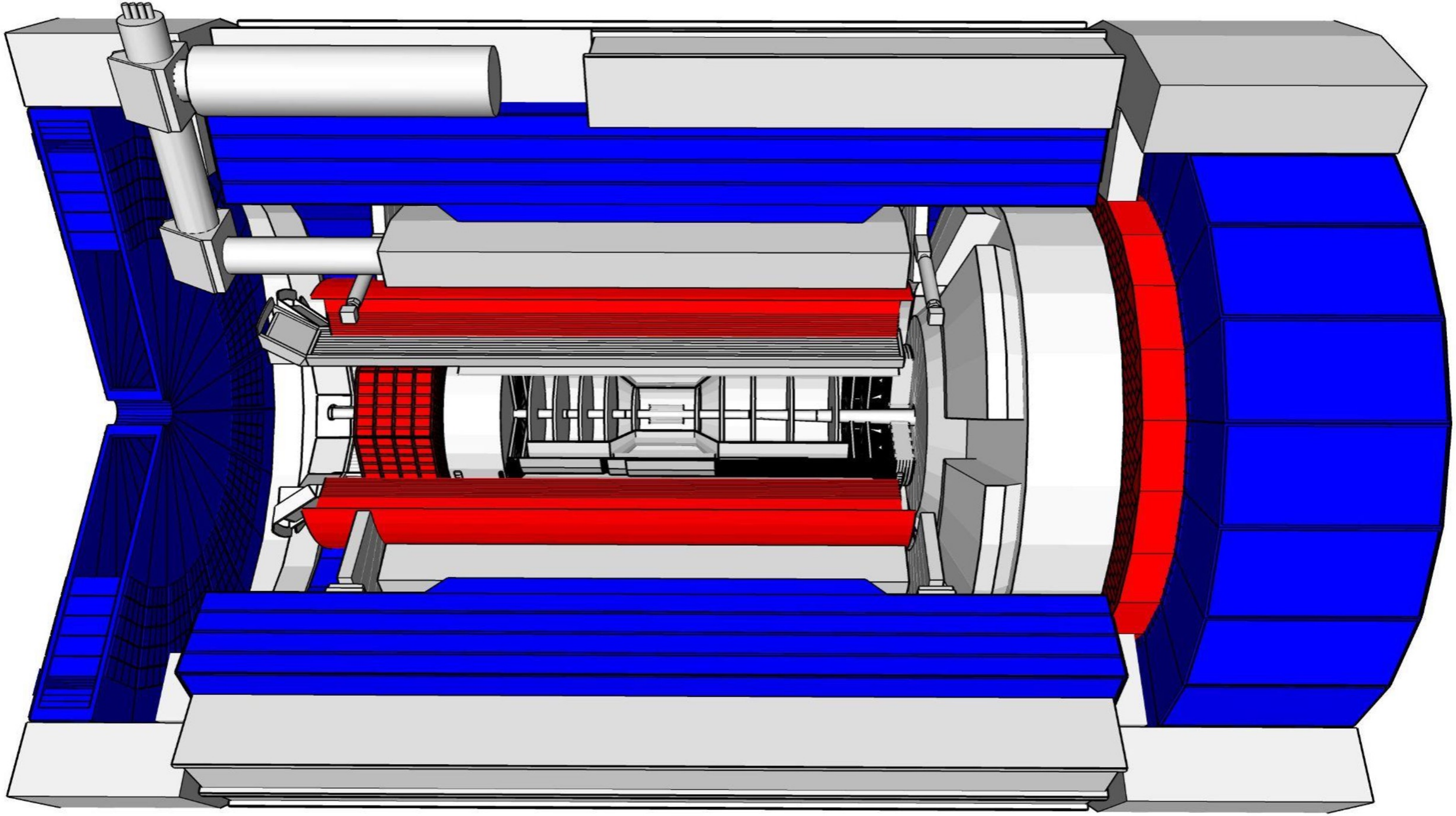




	Momentum Resolution	Spatial Resolution
Backward (-3.5 to -2.5)	~0.10%×p⊕2.0%	~ 30/pT μm ⊕ 40 μm
Backward (-2.5 to -1.0)	~ 0.05%×p⊕1.0%	~ 30/pT μm ⊕ 20 μm
Barrel (-1.0 to 1.0)	~0.05%×p⊕0.5%	~ 20/pT μm ⊕ 5 μm
Forward (1.0 to 2.5)	~0.05%×p⊕1.0%	~ 30/pT μm ⊕ 20 μm
Forward (2.5 to 3.5)	~0.10%×p⊕2.0%	~ 30/pT μm ⊕ 40 μm

- Backward/Forward momentum resolution in extreme η regions complemented by calorimetric resolution
- Meets PWG requirements elsewhere

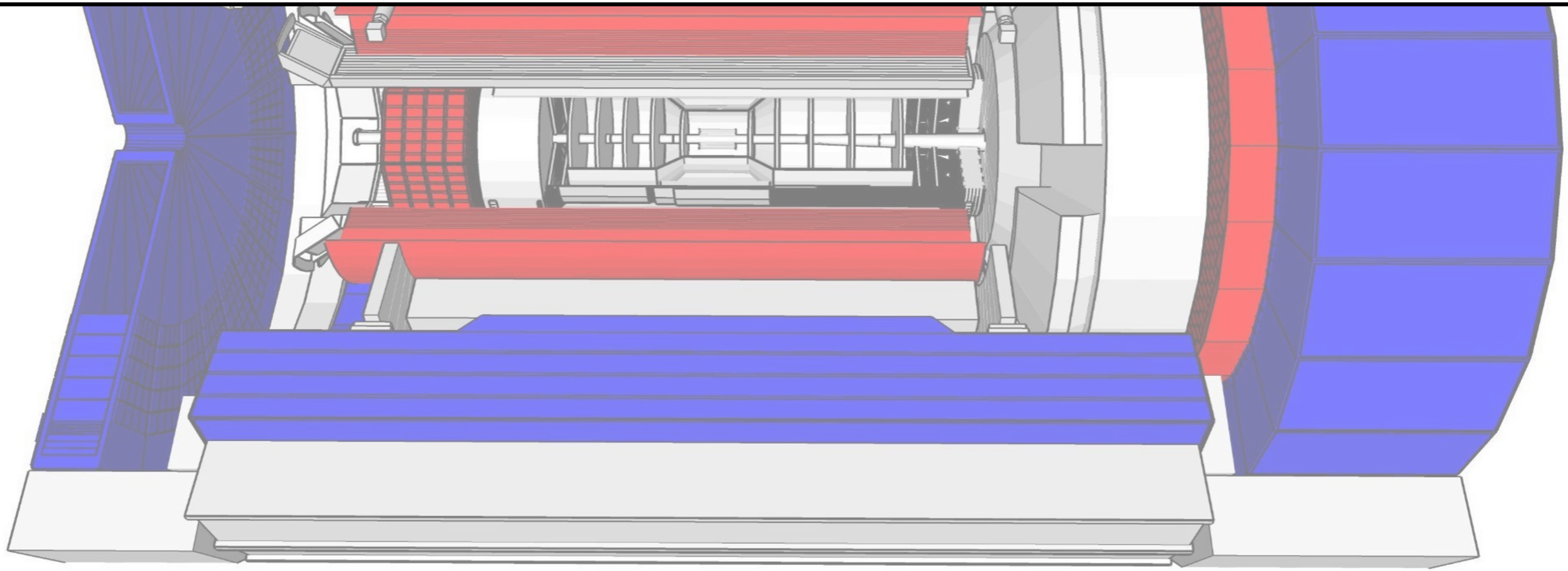
Calorimetry



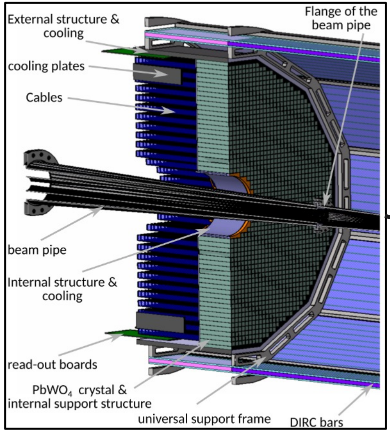
Calorimetry

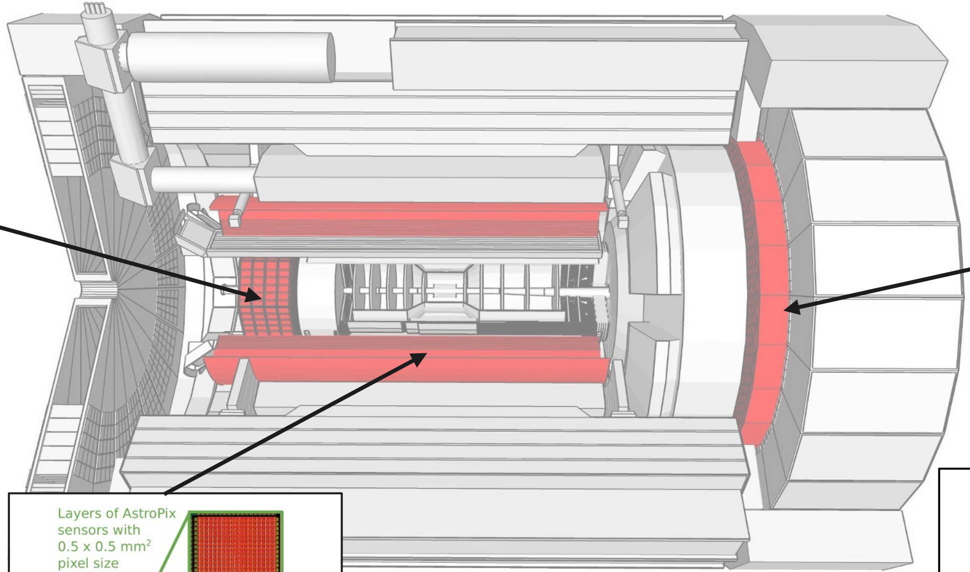
Challenges:

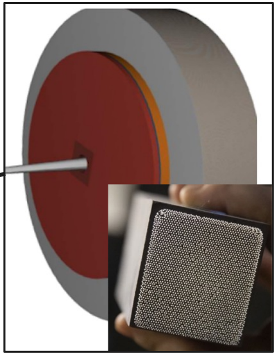
- Detect the **scattered electron** and **separate them from π** (up to 10^{-4} suppression factor in backward and barrel ECal)
- Improve the electron **momentum resolution at backward rapidities** (2-3% $/\sqrt{E} \oplus$ (1−2)% for backward ECal)
- Provide **spatial resolution of two photons sufficient to identify decays $\pi^0 \rightarrow \gamma\gamma$** at high energies from ECals
- Contain the **highly energetic hadronic final state and separate clusters** in a dense hadronic environment in Forward ECal and HCal



Electromagnetic Calorimetry

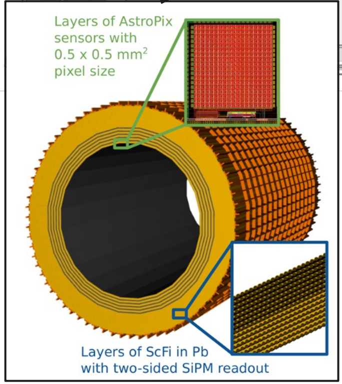






Backward EMCal $PbWO_4$ crystals

- 2 × 2 × 20 cm^3 crystals
- Readout: SiPMs 10μm pixel
- Depth: ~20 X0
- Cooling to keep temperature stable within ± 0.1 ^oC



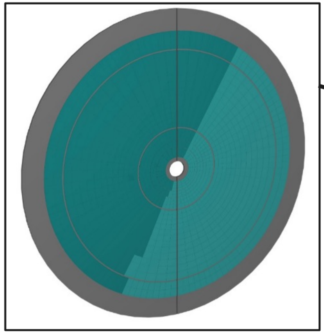
Imaging Barrel Calorimeter

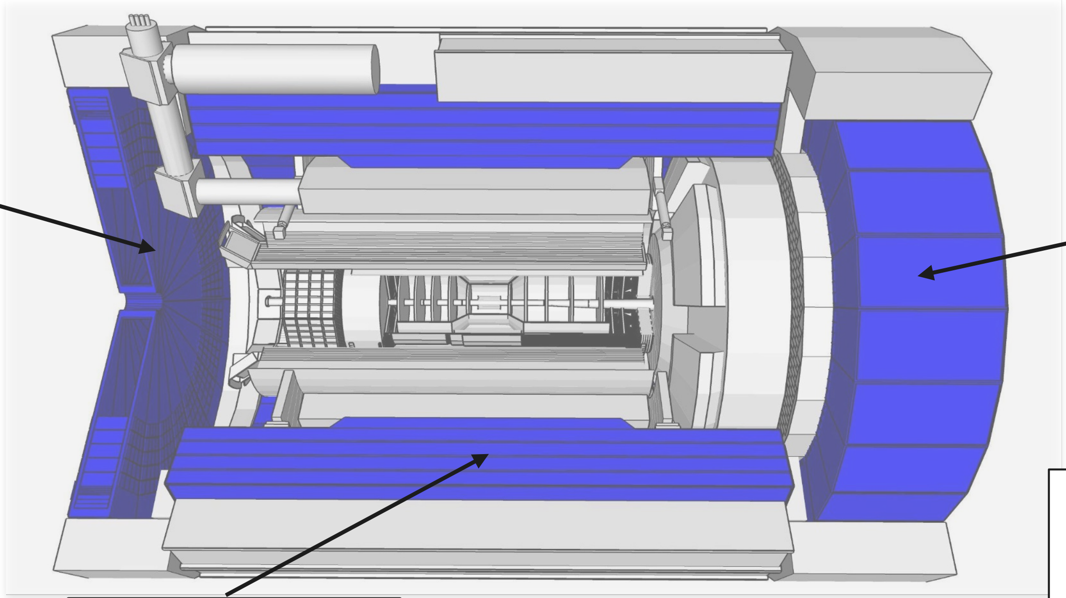
- 4(+2) layers of AstroPix MAPS sensor, 500x500 μm
- Interleaved with scintillating fiber/Pb layers
  - 2-side SiPM readout, 50 μm pixel
- Depth: ~17.1 X0

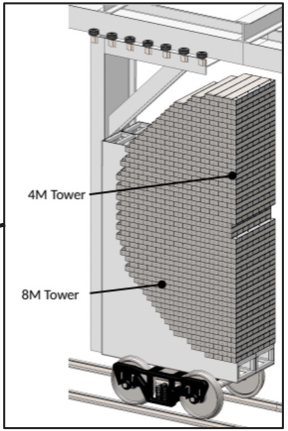
High granularity W/SciFi EMCal

- Tungsten powder mixed with epoxy + scintillating fibers
- 5 cm x 5 cm x 17 cm blocks
- 4 independent towers per block
- Readout: 4 SiPM per tower, 50 μm pixel
- Depth: ~23 X0

Hadronic Calorimetry







Backwards HCal

- Steel + large scintillator tiles sandwich
- SiPM readout
- Exact design still in progress

Barrel HCAL (sPHENIX re-use)

- Tilted Steel/Scintillator plates with SiPM readout

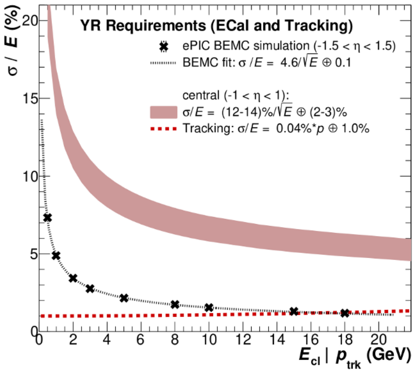
Refurbish for EIC
- Minor radiation damage replace SiPMs
- Upgrade electronics to HGCROC
- Reading out each tile individually

Longitudinally separated HCAL with high-η insert

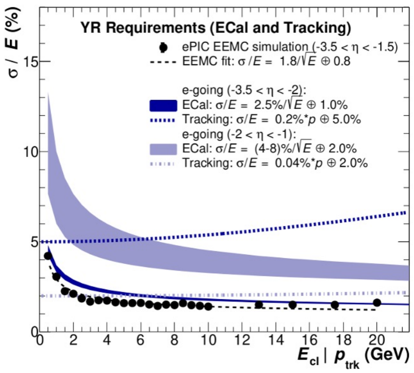
- Steel + Scintillator SiPM-on-tile
- Highly segmented longitudinally
- 65 layers per tower
  - 565,760 SiPMs
- Stackable for “easy” construction
- Highly segmented insert

Calorimetry Performance

Barrel

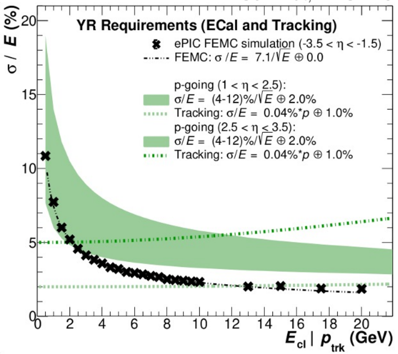


Endcap (e-going)

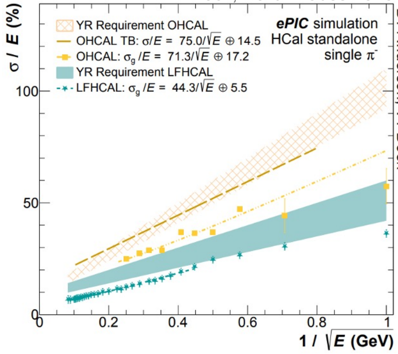


Endcap (p-going)

N. Schmidt, RAUM23

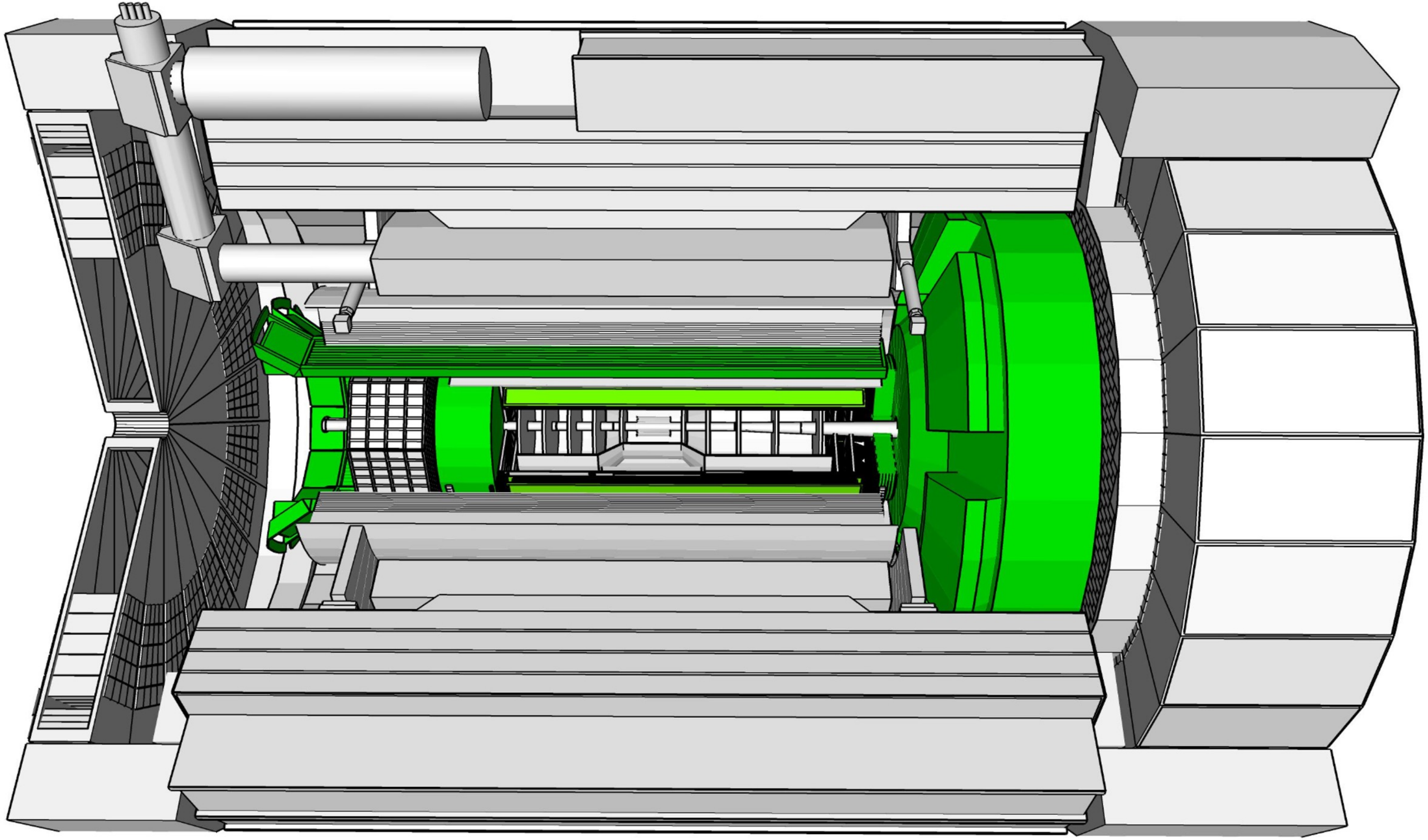


F. Bock, Hard Probes 2023



D. Anderson, F. Bock

Particle Identification

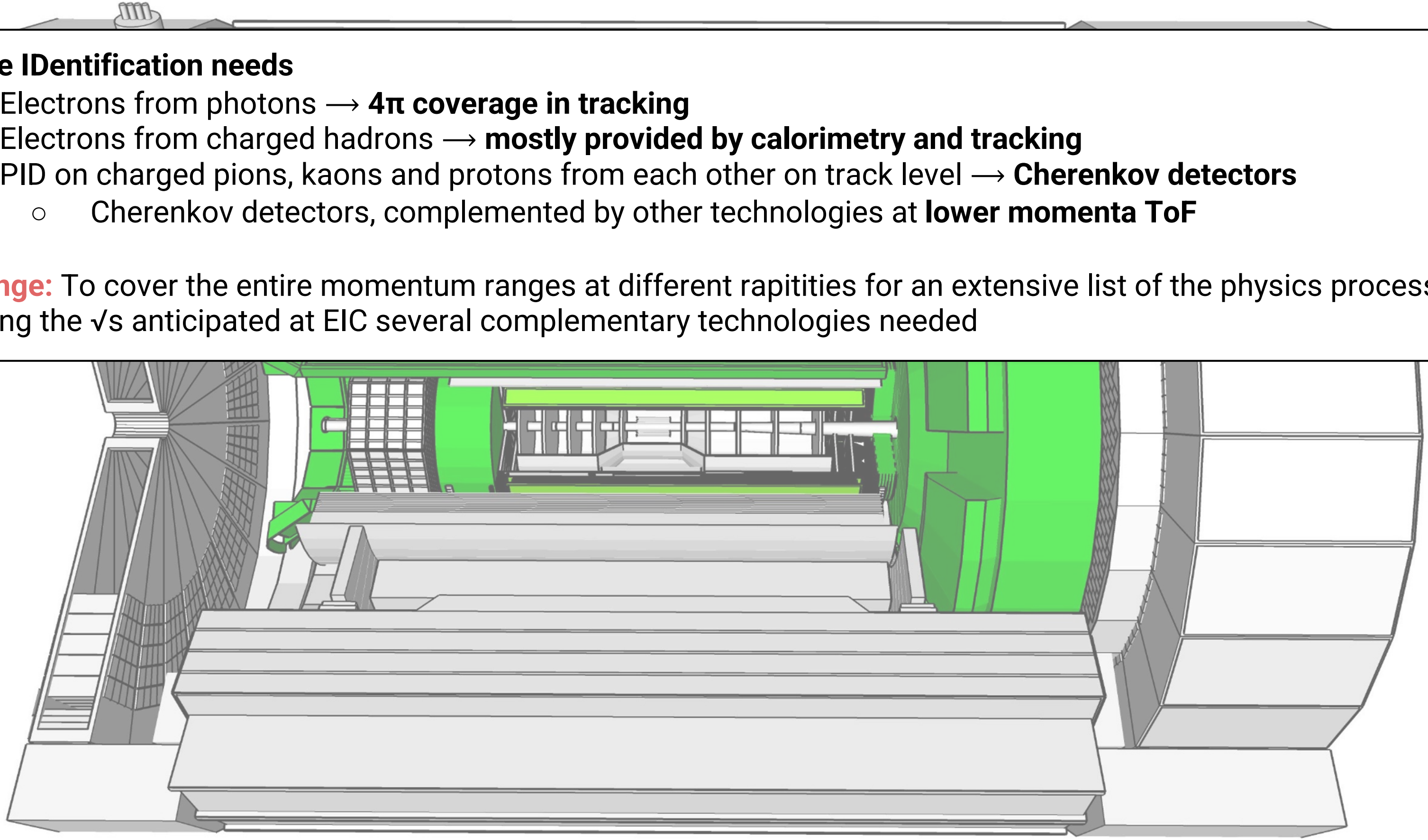


Particle Identification

Particle IDentification needs

- Electrons from photons ⟶ **4π coverage in tracking**
- Electrons from charged hadrons ⟶ **mostly provided by calorimetry and tracking**
- PID on charged pions, kaons and protons from each other on track level ⟶ **Cherenkov detectors**
  - Cherenkov detectors, complemented by other technologies at **lower momenta ToF**

Challenge: To cover the entire momentum ranges at different rapitities for an extensive list of the physics processes spanning the √s anticipated at EIC several complementary technologies needed



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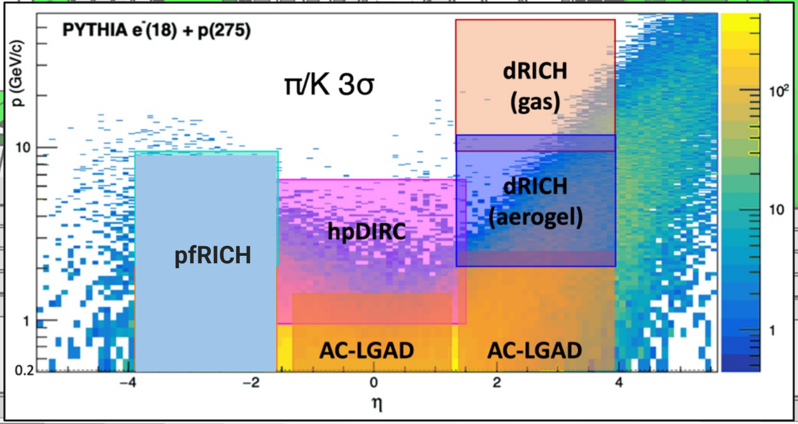
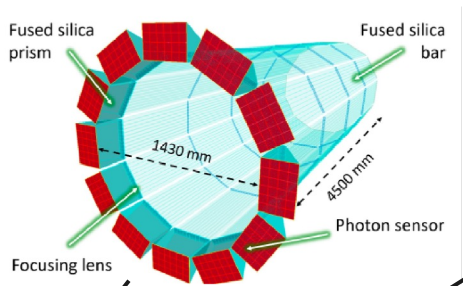


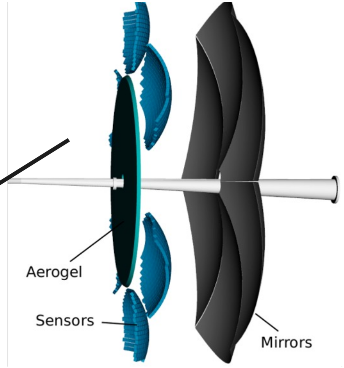
Particle Identification

High-Performance DIRC

- Quartz bar radiator (BaBAR bars)
- light detection with MCP-PMTs
- Fully focused
- π/K 3б separation at 6 GeV/c



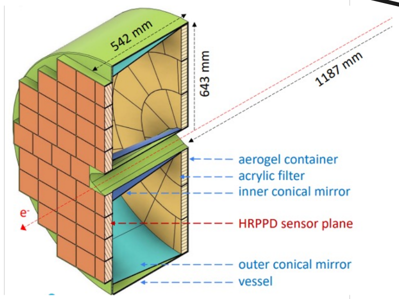
Dual-Radiator RICH (dRICH)

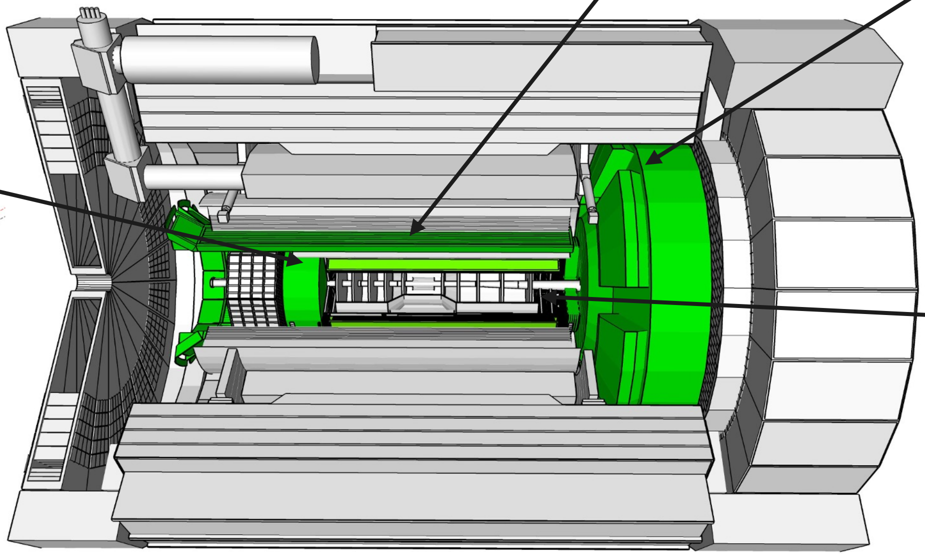


- C_2F_6 Gas Volume and Aerogel
- Sensors tiled on spheres (SiPMs)
- π/K 3б sep. at 50 GeV/c

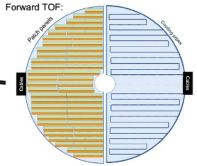
Proximity Focusing RICH

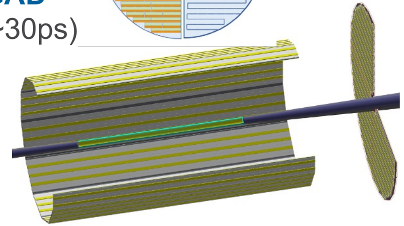
- Proximity gap >40 cm
- up to 7 GeV/c 3б π/K sep.
- High Rate Picosecond Photodetector (HRPPD) sensors
  - Provide also reference time (~20ps) for ToF





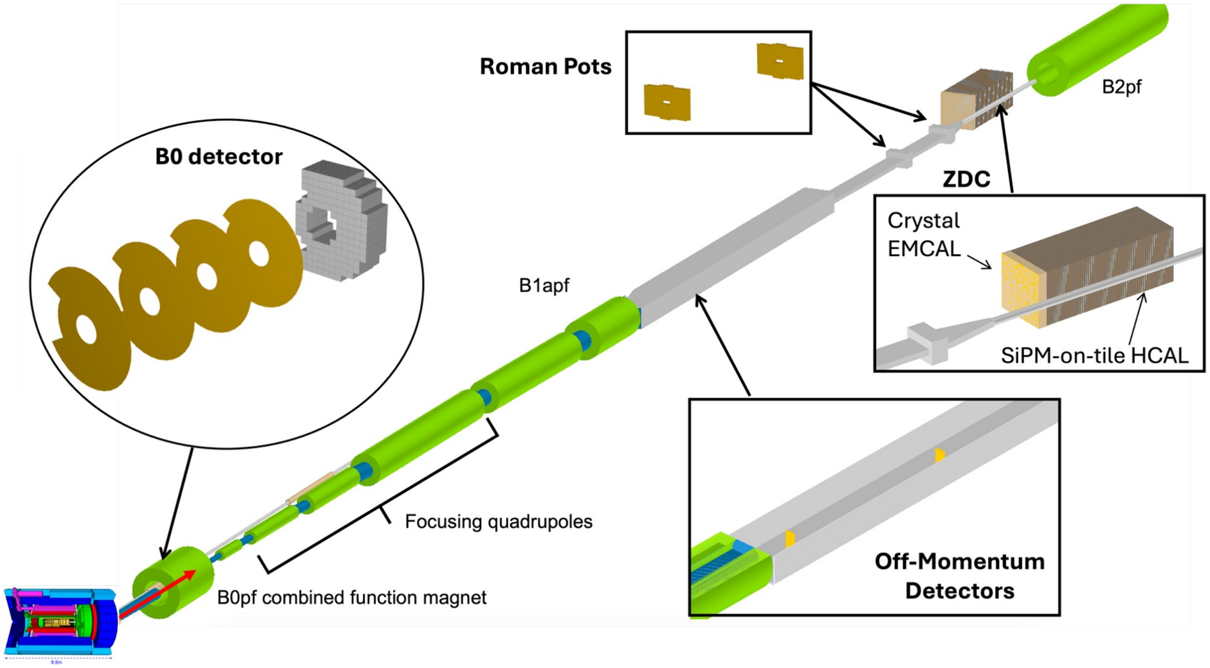
AC-LGAD TOF (~30ps)





- Accurate space point for tracking ~30 um
- Forward disk and central barrel

Far-Forward Detectors



Detector	Acceptance
Zero-Degree Calorimeter (ZDC)	θ < 5.5 mrad (η > 6)
Roman Pots (2 stations)	0.0 < θ < 5.0 mrad (η > 6)
Off-Momentum Detectors (2 stations)	θ < 5.0 mrad (η > 6)
B0 Detector	5.5 < θ < 20.0 mrad (4.6 < η < 5.9)

Challenge:

The extended detector's array required to enable primary physics objectives: Detect particles from nuclear breakup and exclusive processes

Subsystems:

- **B0 detector:** Full reconstruction of charged particles and photons
- **Off-momentum detectors:** Reconstruction of charged spectators from breakup of light nuclei
- **Roman pot detectors:** Charged particles near the beam
- **Zero-degree calorimeter:** Neutral particles at small angles

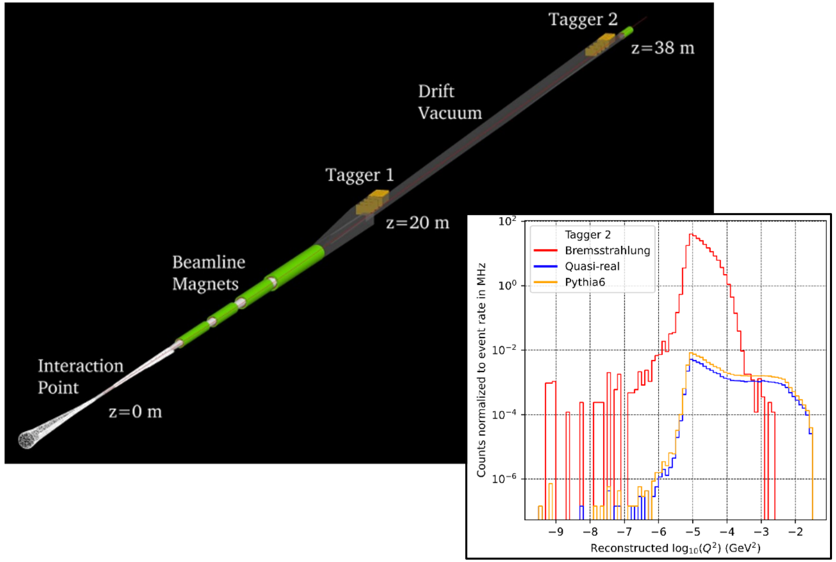
Far-Backward Detectors

Low-Q^2 tagger

Challenge: Allow quasi real (Q<<1) physics with electron detection in very forward rapidity

- high, non-uniform Bremsstrahlung background

Pixel-based trackers (Timepix4), with rate capability of > 10 tracks per bunch and calorimeters for calibration



Luminosity Spectrometer

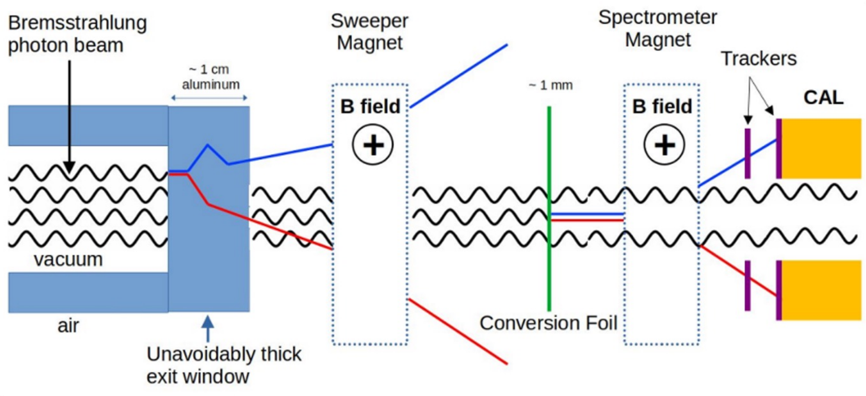
Challenge: Precise luminosity determination (<1%)

From Bremsstrahlung processes

e+p → e γ p

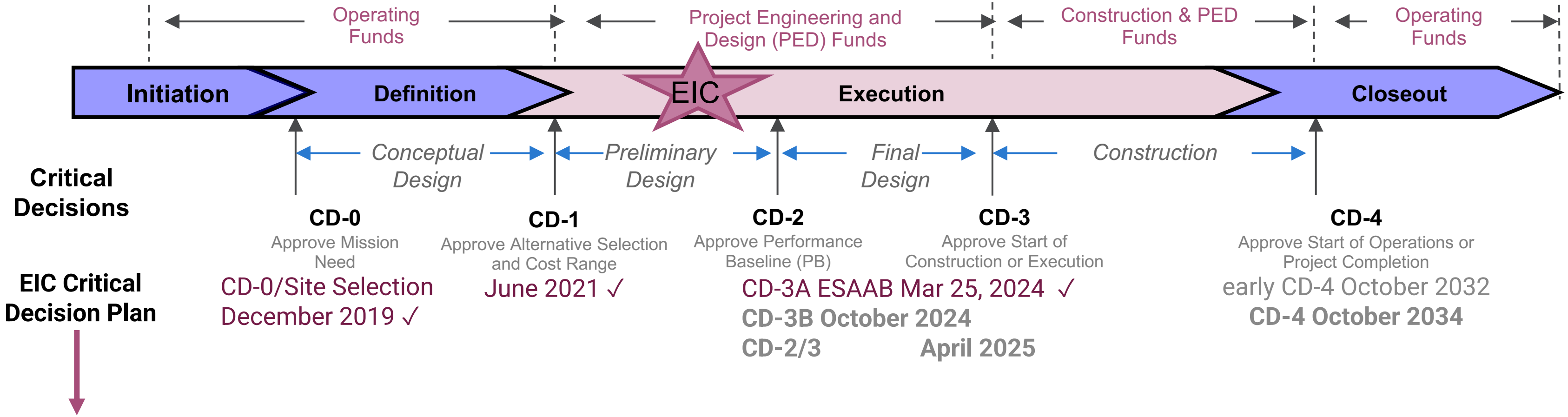
e+Au → e γ Au

AC-LGAD and Scintillating Fiber $23X_0$ ECal



Schedule

Schedule



Sep 2022 EIC received $138M DOE Inflation Reduction Act funding: **CD-3A** (approve start of long-lead procurements)

Updated Project Schedule:

Based on the actual appropriated FY24 funding ($98M), on uncertain FY25 budget scenarios (President's Budget is only ~$113M)

- **January 7 – 9, 2025 Path to CD-2/CD-3 status review**, including CD-3B Approval by spring 2025?
- **CD-2 Approval Late 2025**, Possibility of CD-3C as needed.
- **CD-3 one year later** → end of FY26

Summary

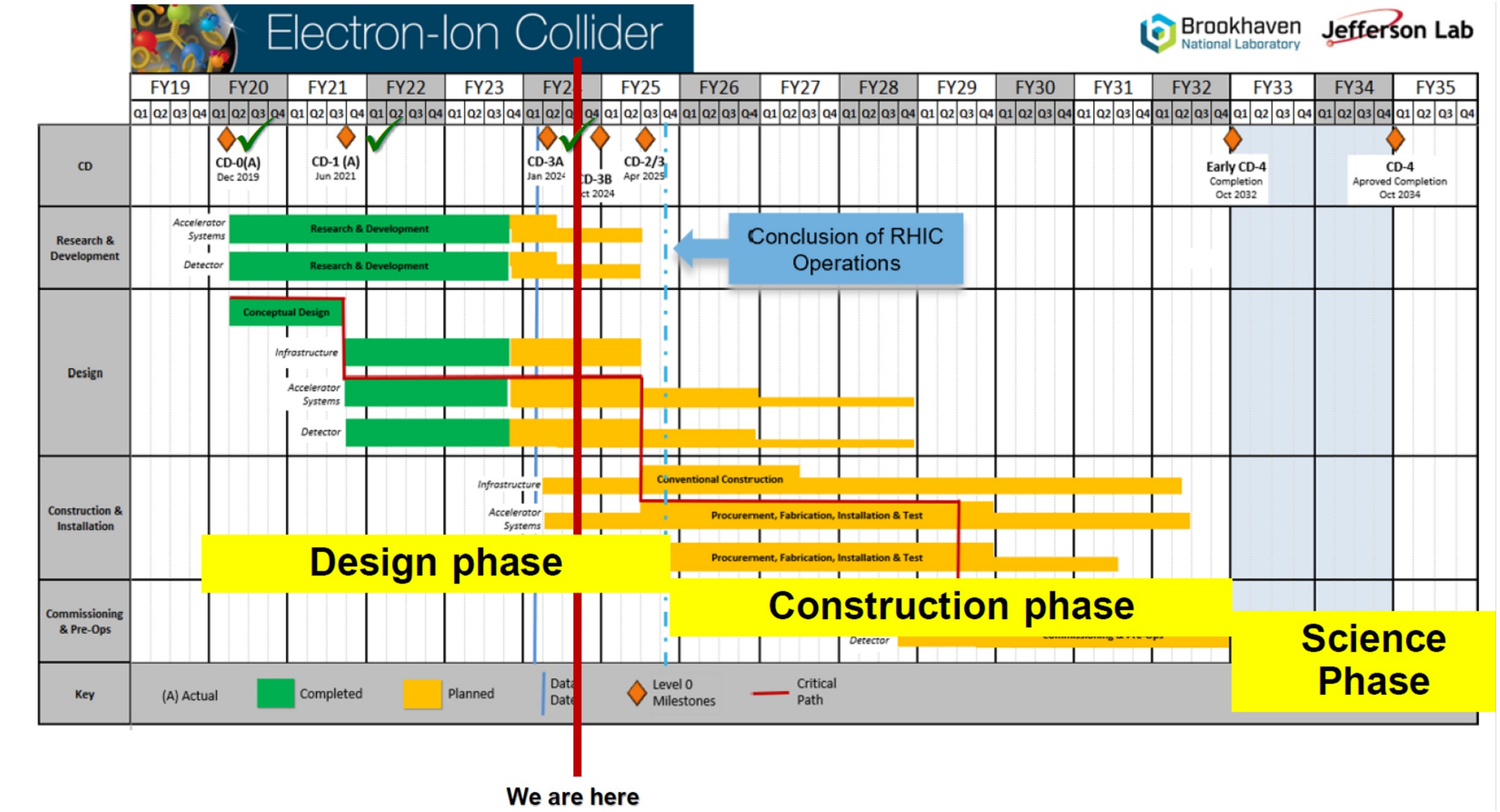
EIC science program will profoundly impact our understanding of the most fundamental inner structure of the matter that builds us all

Access to EIC Physics through

- Large kinematic coverage
- Polarized electron and hadron beams and unpolarized nuclear beams with high luminosities
- Detector setup fulfilling specific requirements of the polarized e-p/A collider

The EIC project is progressing towards construction, with the ePIC collaboration established and dedicated to its mission.

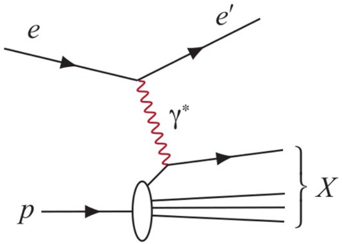
Backup



Electron-Ion Collider
Brookhaven National Laboratory
Jefferson Lab
FY19 FY20 FY21 FY22 FY23 FY24 FY25 FY26 FY27 FY28 FY29 FY30 FY31 FY32 FY33 FY34 FY35
CD
CD-0(A) Dec 2019
CD-1 (A) Jun 2021
CD-3A Jan 2024
CD-3B Oct 2024
CD-2/3 Apr 2025
Early CD-4 Completion Oct 2032
CD-4 Aproved Completion Oct 2034
Research & Development
Accelerator Systems
Detector
Research & Development
Research & Development
Conclusion of RHIC Operations
Design
Conceptual Design
Infrastructure
Accelerator Systems
Detector
Construction & Installation
Infrastructure
Conventional Construction
Accelerator Systems
Procurement, Fabrication, Installation & Test
Procurement, Fabrication, Installation & Test
Commissioning & Pre-Ops
Detector
Key
(A) Actual
Completed
Planned
Level 0 Milestones
Critical Path
Design phase
Construction phase
Science Phase
We are here

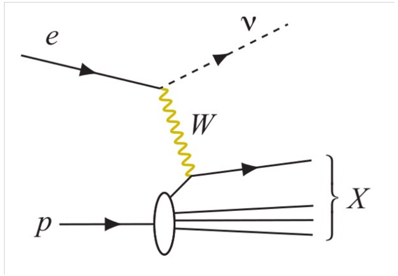
Experimental Processes to Access EIC Physics

DIS event kinematics - scattered electron or final state particles (CC DIS, low y)



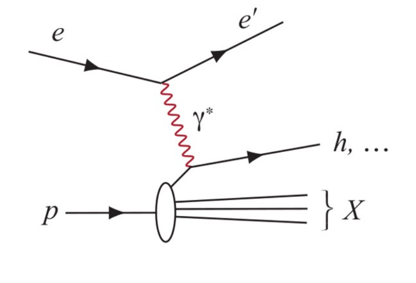
Neutral Current DIS

- Detection of scattered electron with high precision - event kinematics



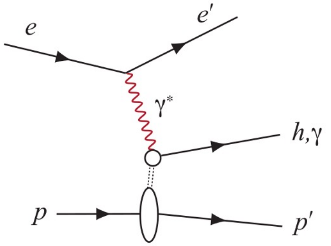
Charged Current DIS

- Event kinematics from the final state particles (Jacquet-Blondel method)



Semi-Inclusive DIS

- Precise detection of scattered electron in coincidence with at least 1 hadron



Deep Exclusive Processes

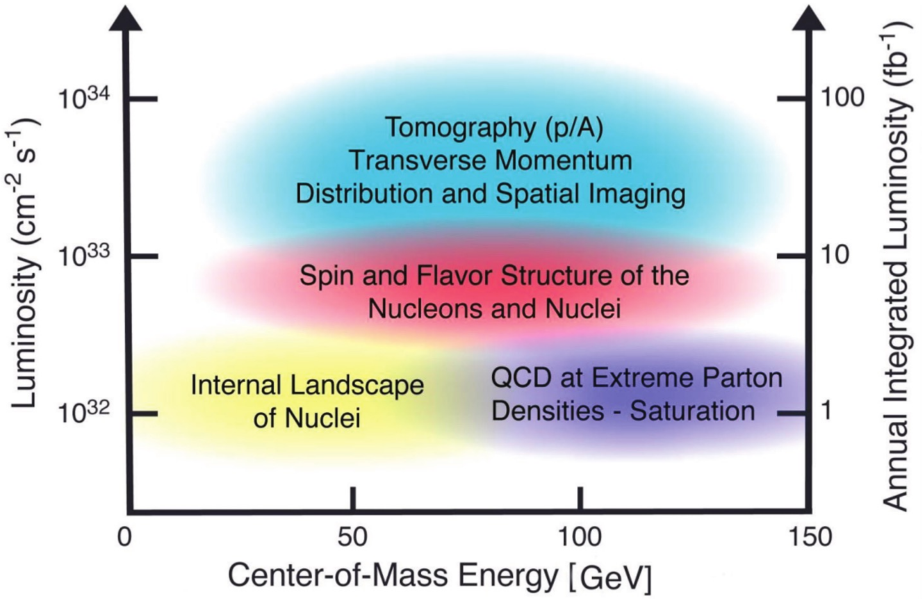
- Detection of all particles in event

Parton Distributions in nucleons and nuclei

Spin and Flavor structure of nucleons and nuclei | **Tomography Transverse Momentum Dist.**

QCD at Extreme Parton Densities - Saturation | **Tomography Spatial Imaging**

Experimental Access to EIC Physics



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