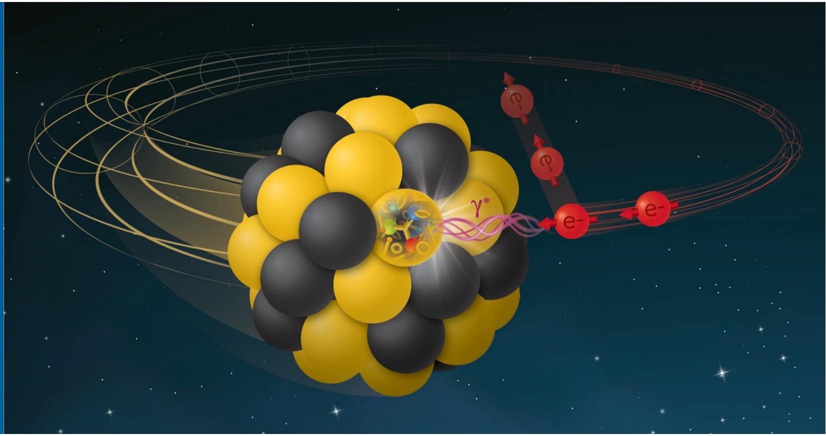
EPIC – LEVERAGING THE EIC ON DAY 1



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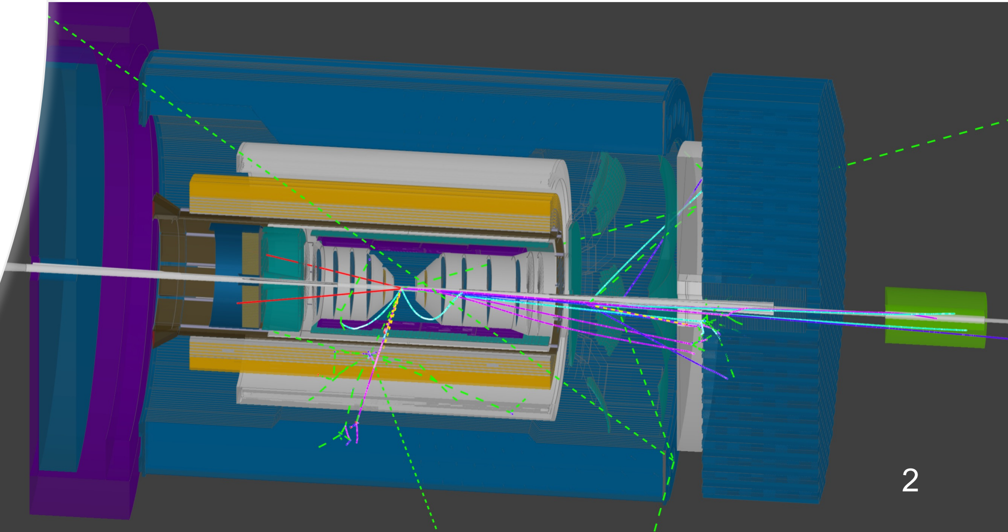
Monday, October 7, 2024

EPIC IN A NUTSHELL

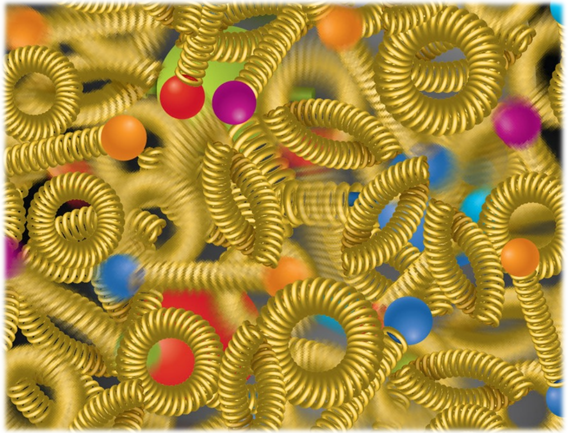
- ePIC is the primary experiment at the Electron-Ion Collider (EIC).
- It is a highly integrated, multi-purpose experiment.
- The ePIC Experiment is being realized by the ePIC Collaboration, jointly with the EIC Project.
- The collaboration, formed in 2022/2023, is international in scope

In our presentation, we will summarize the status and planning for ePIC



THE DYNAMICAL NATURE OF NUCLEAR MATTER

Proton structure emerges from the complex dynamics of its constituents



Nuclear Matter – Interactions and structures are inextricably mixed up

Observed properties – such as mass and spin – emerge out of the complex system

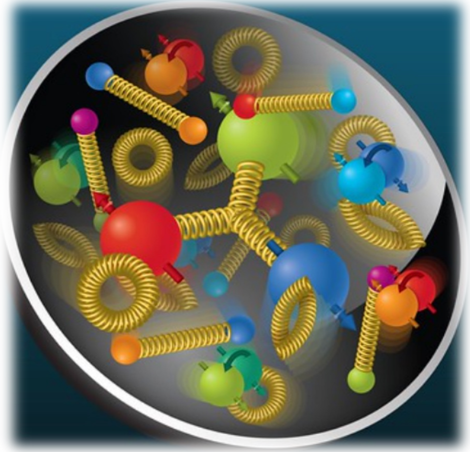
Ultimate goal – Understand how matter at its most fundamental level is made

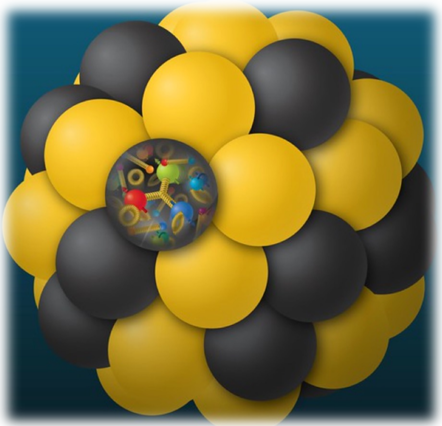
To reach goal – precisely image quarks and gluons and their interactions

Explore the nucleon in terms of the quark and gluon dynamics.

EIC SCIENCE IN A NUTSHELL

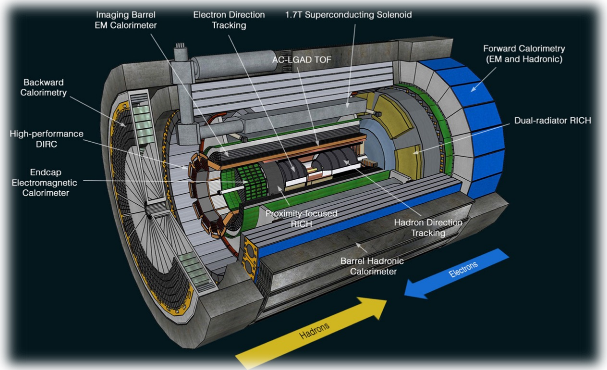
Detailed mapping of the quark & gluon dynamics that account for > 99% of the mass of our visible universe!



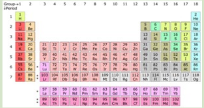
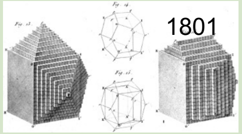
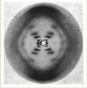
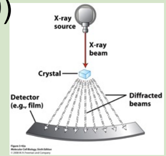
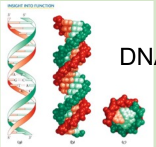
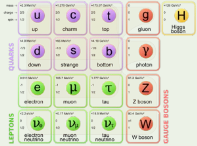
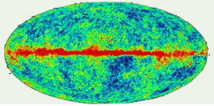
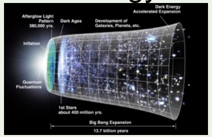
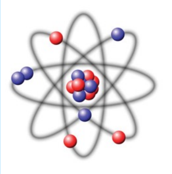
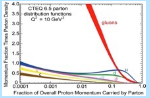
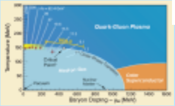
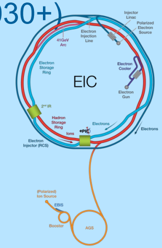


EIC will provide transformational insights into the heart of matter.

Development of cutting-edge technologies to build a state-of experiment, leveraging advances in accelerator, detector, readout, and computing technologies.

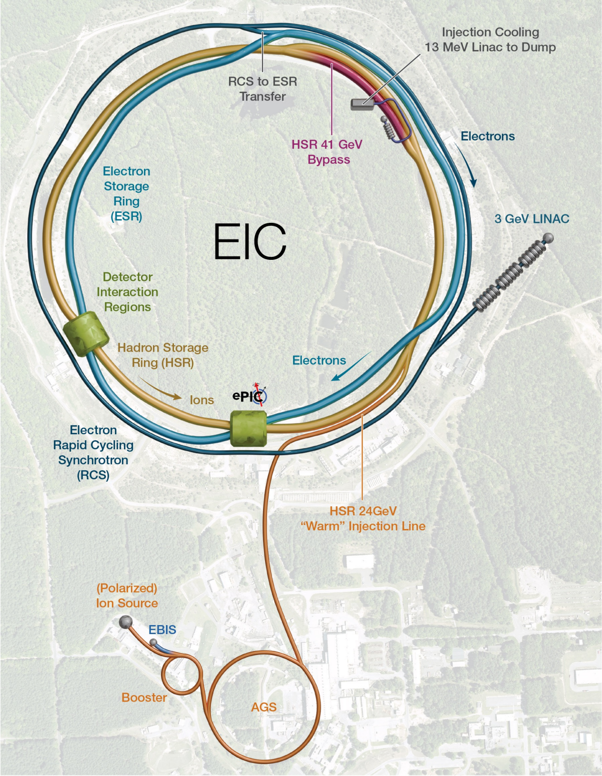


EIC BRINGS A NEW FRONTIER IN SCIENCE!

Dynamical System	Fundamental Knowns	Unknowns	Breakthrough Structure Probes (Date)	New Sciences, New Frontiers
Solids 	Electromagnetism Atoms 	Structure  1801	X-ray Diffraction (~1920)  	Solid state physics Molecular biology  DNA
Universe 	General Relativity Standard Model 	Quantum Gravity, Dark matter, Dark energy. Structure CMB 1965 	Large Scale Surveys CMB Probes (~2000)  	Precision Observational Cosmology 
Nuclei and Nucleons 	Perturbative QCD Quarks and Gluons $\mathcal{L}_{QCD} = \bar{\psi}(i\partial\!\!\!/ - gA\!\!\!/)\psi - \frac{1}{2}\mathrm{tr}\, F_{\mu\nu}F^{\mu\nu}$	Non-perturbative QCD Structure  2017  	Electron-Ion Collider (2030+) 	**Structure & Dynamics in QCD** 

A Frontier Accelerator in the USA

THE ELECTRON-ION COLLIDER



World's first collider of:

- Polarized electrons and polarized protons,
- Polarized electrons and light ions (d, 3He),
- Electrons and heavy ions (up to Uranium).

A versatile machine:

- Versatile range of beam polarizations, up to 70%,
- Versatile range of beam species,
- Versatile range of center of mass energies, Ecm = 29 – 140 GeV.

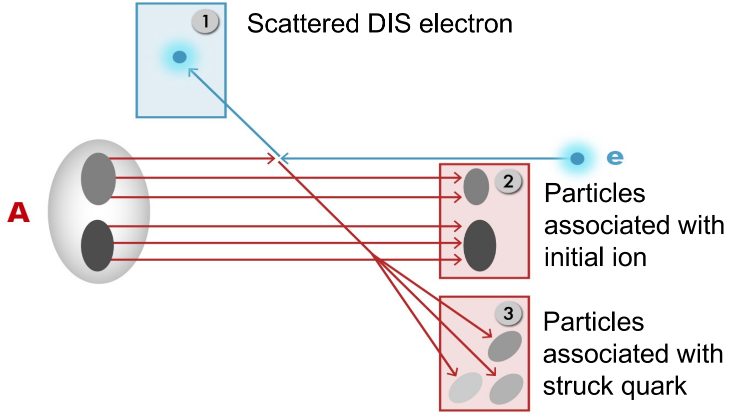
High luminosity up to L = 1034 cm-2 s-1 = 10 kHz/μb:

- The e-p cross section at peak luminosity is about 50 μb. This corresponds to a signal event rate of about 500 kHZ.

BNL and Jefferson Lab are the host laboratories for the EIC Experimental Program, sharing leadership roles.

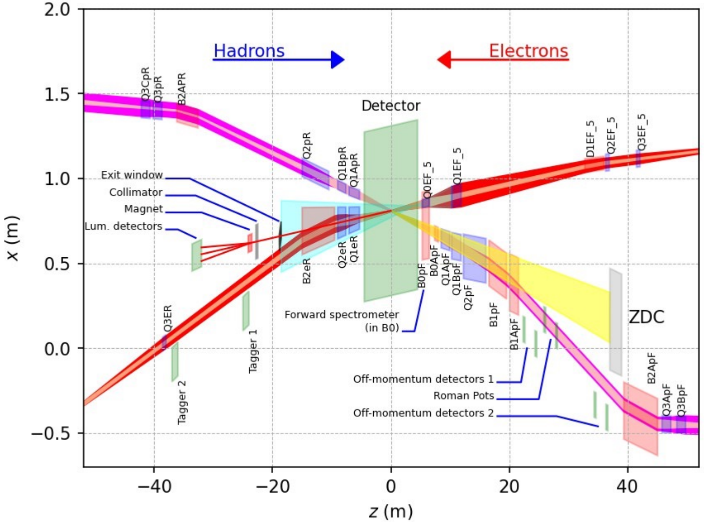
MAXIMIZING THE PHYSICS REACH

The aim is to get **near-full acceptance** for all final state particles, with good resolution.



Experimental challenges:

- Beam elements limit forward acceptance.
- Central Solenoid not effective for forward

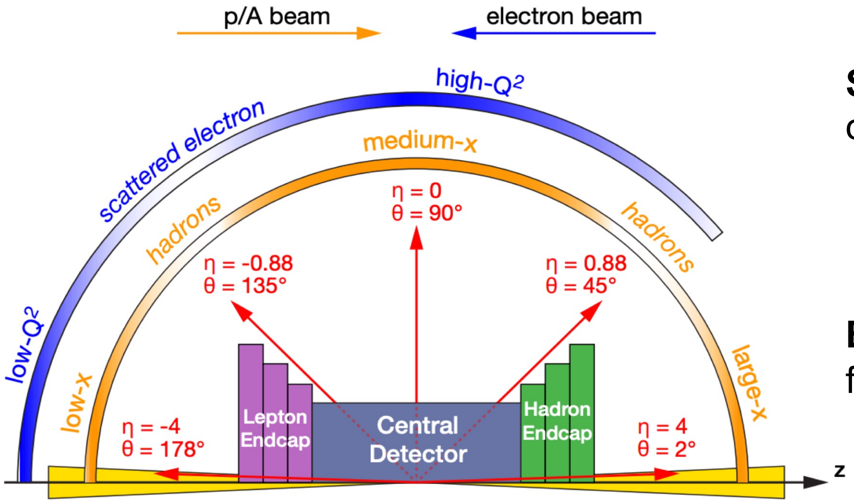


Possible to get close to full acceptance for the whole event:

- Beam crossing angle of 25mrad creates room for forward dipoles.
- Dipoles create space for detectors in the forward ion and electron direction and analyze the forward particles.

SO THE EPIC DETECTOR IS … 90 METERS LONG!

PHYSICS-DRIVEN DETECTOR DESIGN



Inclusive DIS requires fine binning in x_B, Q^2:

- Large coverage ($-3.5 < \eta < 3.5$) for wide phase space reach
- Excellent EM-calorimetry with PID support for e/π separation.
- Fine resolution tracking with low mass

Semi-inclusive DIS requires multidimensional binning in five or more variables (x_B, Q^2, z, p_T, φ_h , …):

- Fine p_T resolution.
- Extended PID systems for hadron identification,
- Hadron calorimetry to attempt TMD studies with jets.

Exclusive processes require multidimensional binning in four or more variables (x_B, Q^2, t, φ_h , …):

- Extend acceptance at extremely small scattering angles by far forward detectors.
- Fine vertex resolution by tracking.

THE CENTRAL EPIC DETECTOR

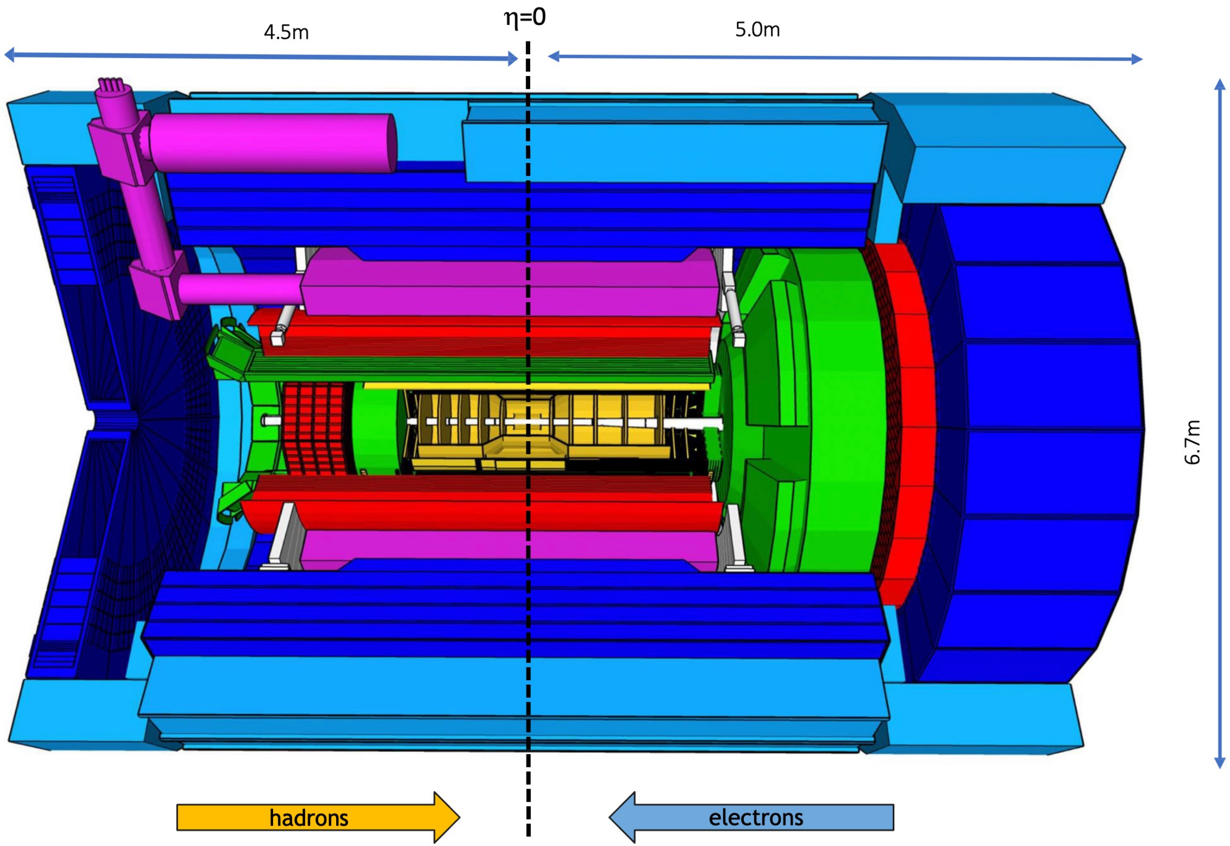
Magnet
- New 1.7 T SC solenoid, 2.8 m bore diameter

Tracking
- Si Vertex Tracker MAPS wafer-level stitched sensors (ALICE ITS3)
- Si Tracker MAPS barrel and disks
- Gaseous tracker: MPGDs (μRWELL, MMG) cylindrical and planar

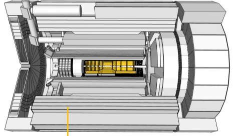
PID
- high performance DIRC (hpDIRC)
- dual RICH (aerogel + gas) (forward)
- proximity focussing RICH (backward)
- ToF using AC-LGAD (barrel+forward)

EM Calorimetry
- imaging EMCal (barrel)
- W-powder/SciFi (forward)
- $PbWO_4$ crystals (backward)

Hadron calorimetry
- FeSc (barrel, re-used from sPHENIX)
- Steel/Scint – W/Scint (backward/forward)



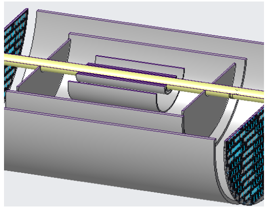
EPIC TRACKING DETECTORS

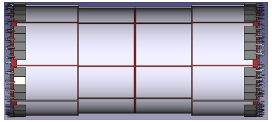


Overview Slide from EIC Project

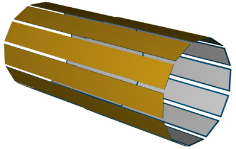
ePIC

μVertex Tracker | Barrel Tracker | Outer Barrel MPGD Tracker | EndcapTracker

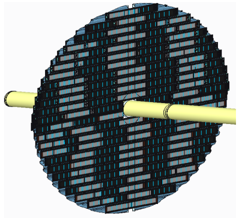




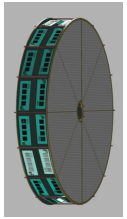
MicroMegas Tracker



μRWELL Tracker



MAPS Disks



μRWELL Disks

Main Function

μVertex Tracker / Barrel Tracker: Excellent momentum 0.05%pT⊕0.5% and spatial resolution 20μm/pT⊕ 5μm

μVertex Tracker: Displaced vertex reconstruction

MicroMegas Tracker: Provide redundancy and pattern recognition for tracking

μRWELL Tracker: Tracking close to hpDIRC detector to improve angular and space point resolution. Redundancy and pattern recognition for tracking

MAPS Disks: Excellent momentum 0.05 (0.10)% pT⊕1.0 (2.0)% and spatial resolution 30μm/pT⊕ (20 – 40) μm

μRWELL Disks: Provide redundancy and pattern recognition for tracking

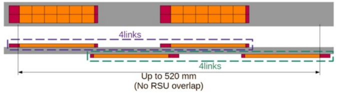
Proven Technology

μVertex Tracker: Monolithic Active Pixel Sensor → ALICE ITS3 MOSAIX sensor (65 nm) small pixels (~18 mm) and power consumption (<20 mW/cm^2)

MicroMegas Tracker: Cylindrical resistive Micromegas technology Used: ATLAS NSW, CLAS12, SPHENIX, MINOS& T2K TPC

world's first at ePIC

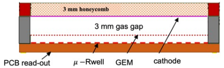
Barrel Tracker: EIC Large Area Sensor (LAS), modification of ITS3 sensor with 5 or 6 RSU forming staves as the basic building elements for the Barrel



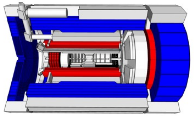
μRWELL Tracker: 24 planar Thin-gap & double amplification (GEM & μRWELL) modules & 2D-strip readout

MAPS Disks: EIC Large Area Sensor (LAS), staves as the basic building elements for the MAPS disks

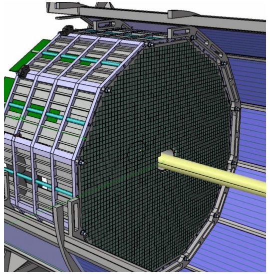
μRWELL Disks: GEM- μRwell hybrid configuration with increased gain



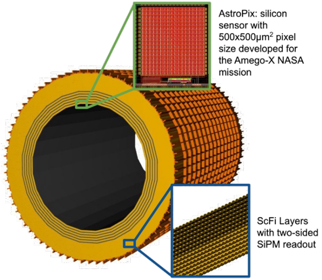
EPIC CALORIMETRY



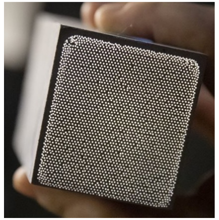
Backward ECal



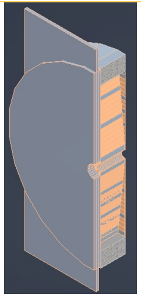
Barrel ECal



Forward ECal

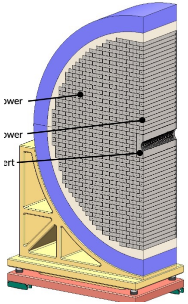


Backward HCal



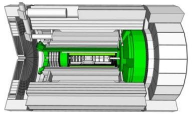
Barrel HCal

Forward HCal

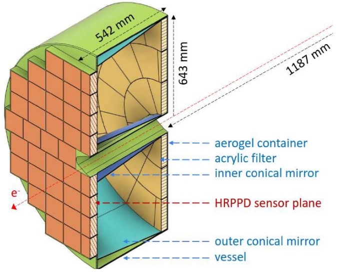


	Backward ECal	Barrel ECal	Forward ECal	Backward HCal	Barrel HCal	Forward HCal
Main Function	scattered lepton detection → very high-precision	scattered lepton and γ detection, hadronic final state characterization	lepton and γ detection, hadronic final state characterization → π^0, γ separation	muon and neutral detection → improved jet Energy reconstruction	muon and neutral detection → improved jet Energy reconstruction	particle-flow measurements
Proven Technology	PbWO4 – crystals → long lead procurement	Pb/SciFi sampling part using SiPMs combined with imaging section (6 layers) interleaving Pb/SciFi with ASTROPIX	Tungsten-powder + SciFi SPACAL design Developed through EIC R&D and applied successfully in sPHENIX	Steel + Scintillator SiPM-on-tile	Steel + Scintillator design re-used from sPHENIX	longitudinal segmented Steel + Scintillator SiPM-on-tile Pioneered by CALICE analog HCal High resolution insert next to beam-pipe
world's first at ePIC	SiPM as Photonsensors	Use of ASTROPIX in Calorimetry				first-time full-size CALICE like calorimeter in collider experiment

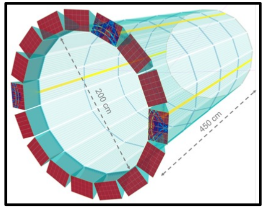
EPIC PARTICLE IDENTIFICATION DETECTORS



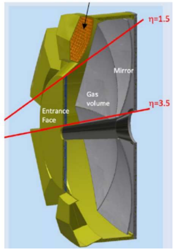
Backward RICH



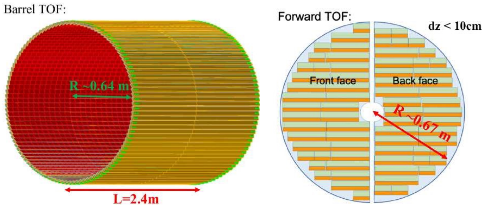
Barrel DIRC



Forward RICH



Time-of-Flight (Barrel, Forward)



Main Function

Backward RICH
- e, π, K, p separation

→ π/K 3σ sep. up to 9 GeV/c and 10-20 ps timing → ToF

Barrel DIRC
- e, π, K, p separation

→ π/K 3σ sep. at 6 GeV/c

Forward RICH
- e, π, K, p separation

→ π/K 3σ sep. up to 50 GeV/c

Time-of-Flight
- e, π, K, p separation through 20-35 ps ToF

Barrel: $0.15 < p_T < 1.5$ GeV/c

Forward: $0.15 < p_T < 2.5$ GeV/c
- Accurate space point for tracking

Proven Technology

Backward RICH: Classical single volume proximity focusing aerogel RICH with long proximity gap (~30 cm)

Barrel DIRC: High Performance DIRC
- Quartz bar radiator
  → Reuse of BaBAR DIRC bars
- light detection with MCP-PMTs
- Fully focused

Forward RICH: Dual Radiator RICH
- Aerogel and C_2F_6 gas
- Spherical Mirrors (6 Azimuthal Sectors)
- Photon-Sensors tiled on spheres

world's first at ePIC

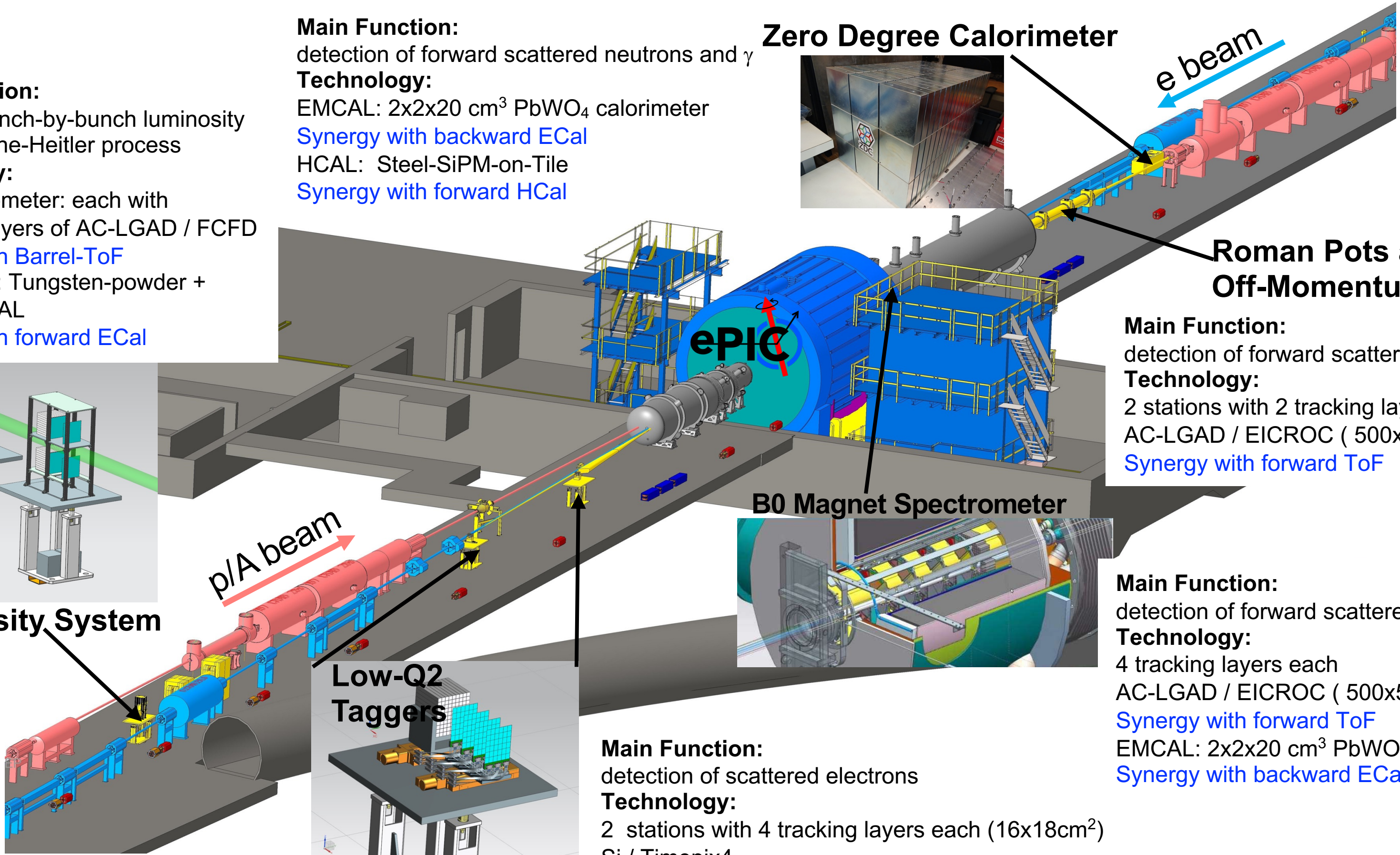
Backward RICH: Photonsensors: HRPPDs for Time-of-Flight

Forward RICH: First use of SiPMs as Photonsensors in a RICH

Time-of-Flight: First time use of AC-LGAD (Low Gain Avalanche Detector) in collider detector

Overview Slide from EIC Project

EPIC FAR-FORWARD/FAR-BACKWARD DETECTORS



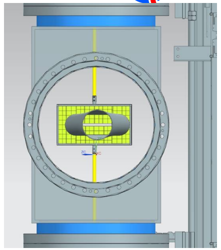
Zero Degree Calorimeter

Main Function:
detection of forward scattered neutrons and γ
Technology:
EMCAL: 2x2x20 cm^3 $PbWO_4$ calorimeter
Synergy with backward ECal
HCAL: Steel-SiPM-on-Tile
Synergy with forward HCal

Luminosity System

Main Function:
measure bunch-by-bunch luminosity through Bethe-Heitler process
Technology:
Pair-spectrometer: each with
2 tracking layers of AC-LGAD / FCFD
Synergy with Barrel-ToF
Calorimeter: Tungsten-powder + SciFi SPACAL
Synergy with forward ECal

Roman Pots and Off-Momentum



Main Function:
detection of forward scattered protons and nuclei
Technology:
2 stations with 2 tracking layers each
AC-LGAD / EICROC (500x500 μm^2 pixel)
Synergy with forward ToF

B0 Magnet Spectrometer

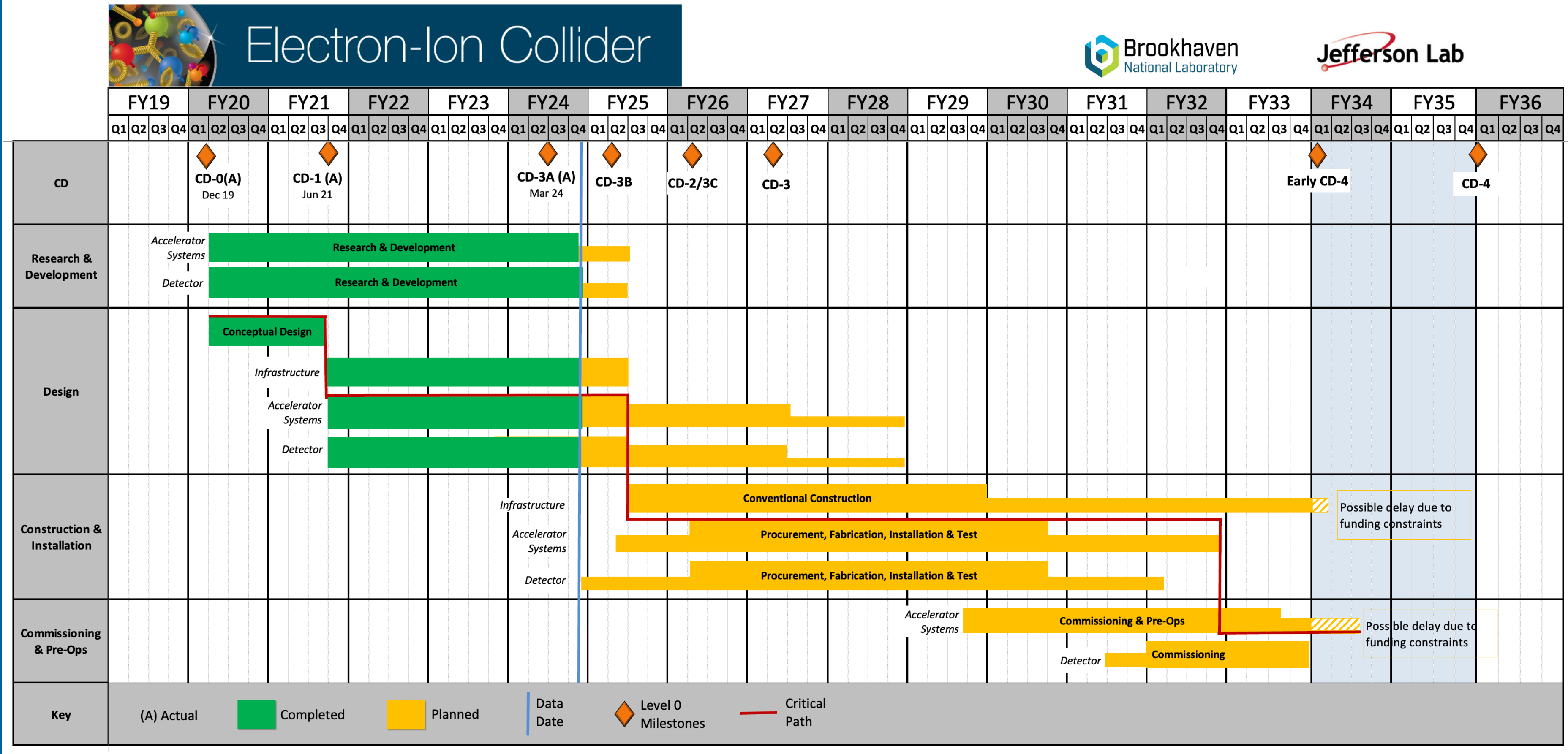
Main Function:
detection of forward scattered protons and and γ
Technology:
4 tracking layers each
AC-LGAD / EICROC (500x500 μm^2 pixel)
Synergy with forward ToF
EMCAL: 2x2x20 cm^3 $PbWO_4$ calorimeter
Synergy with backward ECal

Low-Q2 Taggers

Main Function:
detection of scattered electrons
Technology:
2 stations with 4 tracking layers each (16x18cm^2)
Si / Timepix4
Calorimeter: Tungsten-powder + SciFi SPACAL
Synergy with forward ECal

Overview Slide from EIC Project

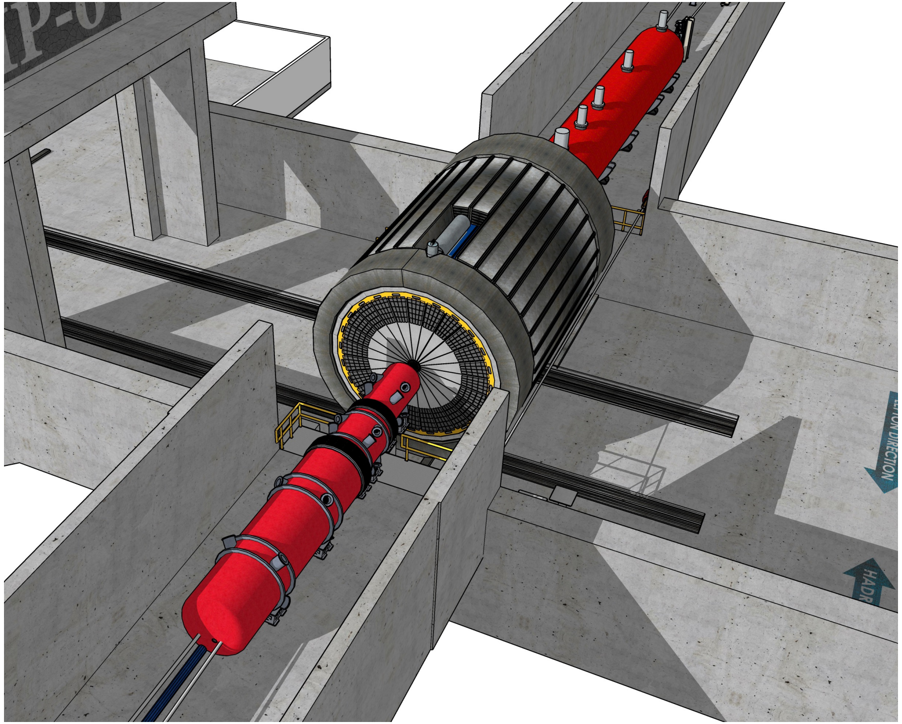
HIGH LEVEL INSTALLATION SCHEDULE



THE HIGHLY-INTEGRATED EPIC EXPERIMENT

Integrated Interaction and Detector Region (90 m)

Get close to full acceptance for all final state particles, and measure them with good resolution. All particles count!



Compute-Detector Integration

Seamless data processing from detector readout to analysis using streaming readout and streaming computing.

Definition of Streaming Readout

- Data is digitized at a fixed rate with thresholds and zero suppression applied locally.
- Data is read out in continuous parallel streams that are encoded with information about when and where the data was taken.
- Event building, filtering, monitoring, and other data processing is deferred to computing.

Advantages of Streaming Readout

- Simplification of readout (no custom trigger hardware and firmware) and increased flexibility.
- Event building from holistic detector information.
- Continuous data flow provides detailed knowledge of backgrounds and enhances control over systematics.

COMPUTE-DETECTOR INTEGRATION TO MAXIMIZE SCIENCE

ePIC

Broad ePIC Science Program:

- Plethora of observables, with less distinct topologies where every event is significant.
- High-precision measurements: Control of systematic uncertainties of paramount importance.

Streaming Readout Capability Due to Moderate Signal Rate:

- **Capture every collision signal**, including background.
- Event selection using all available detector data for holistic reconstruction:
  - **Eliminate trigger bias** and provide accurate estimation of uncertainties during event selection.
- Streaming background estimates ideal to reduce background and related systematic uncertainties. High-precision measurements: **Control of systematic uncertainties paramount**.

	EIC	RHIC	LHC → HL-LHC
Collision species	$\vec{e}+\vec{p}$, $\vec{e}+A$	$\vec{p}+\vec{p}/A$, $A+A$	$p+p/A$, $A+A$
Top x-N C.M. energy	140 GeV	510 GeV	13 TeV
Peak x-N luminosity	10^{34} cm^{-2} s^{-1}	10^{32} cm^{-2} s^{-1}	$10^{34} \rightarrow 10^{35}$ cm^{-2} s^{-1}
x-N cross section	**50 µb**	**40 mb**	**80 mb**
$dN_{ch}/d\eta$	0.1-Few	~3	~6
Charged particle rate	**4M N_{ch}/s**	**60M N_{ch}/s**	**30G+ N_{ch}/s**

Accelerating the science turnaround

COMPUTE-DETECTOR INTEGRATION

Problem: Data for physics analyses and the resulting publications available after O(1year) due to complexity of NP experiments (and their organization).

- Alignment and calibrations, reconstruction and validation time-consuming.

Goal: Rapid turnaround of 2-3 weeks for data for physics analyses.

- Timeline driven by alignment and calibrations.
- Preliminary information from detector groups indicates that 2-3 weeks are realistic.

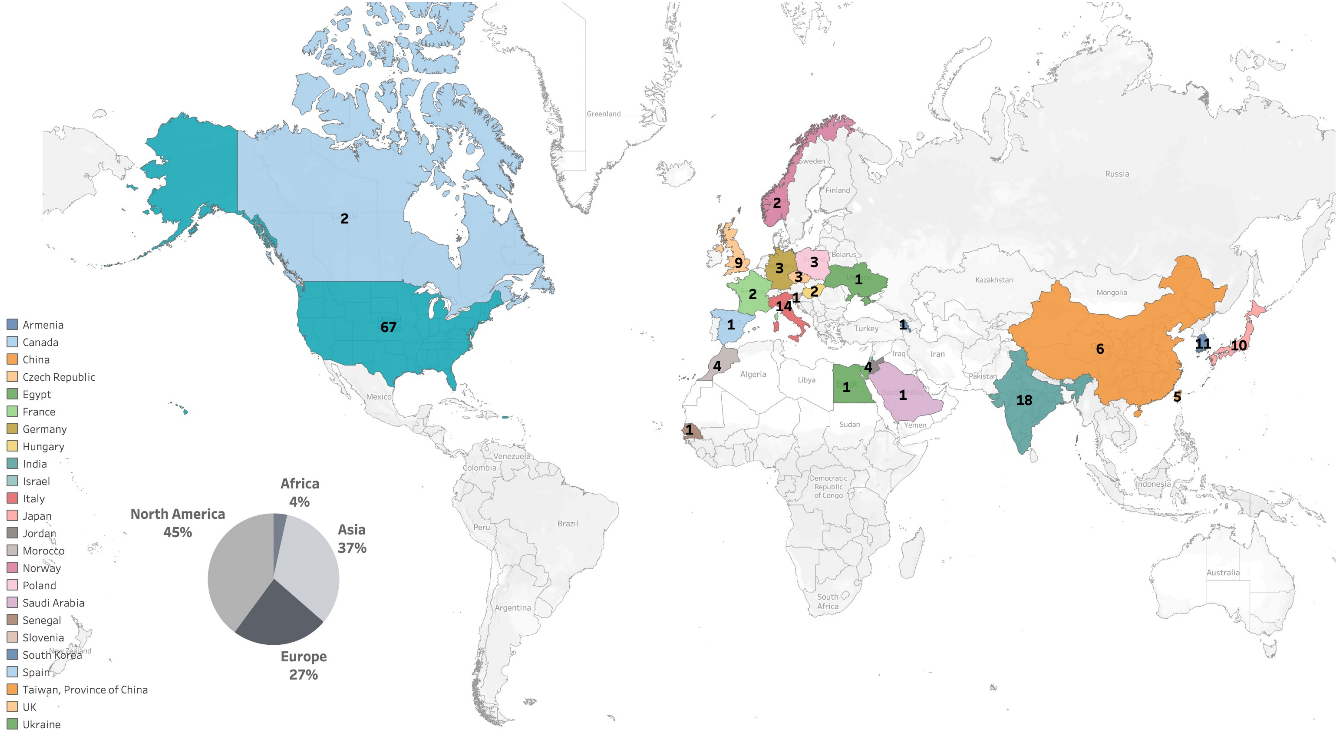
Solution: Compute-detector integration

Streaming readout for continuous data flow of the full detector information.

AI for autonomous alignment and calibration as well as autonomous validation for rapid processing.

Heterogeneous computing for acceleration (CPU, GPU).

THE EPIC COLLABORATION



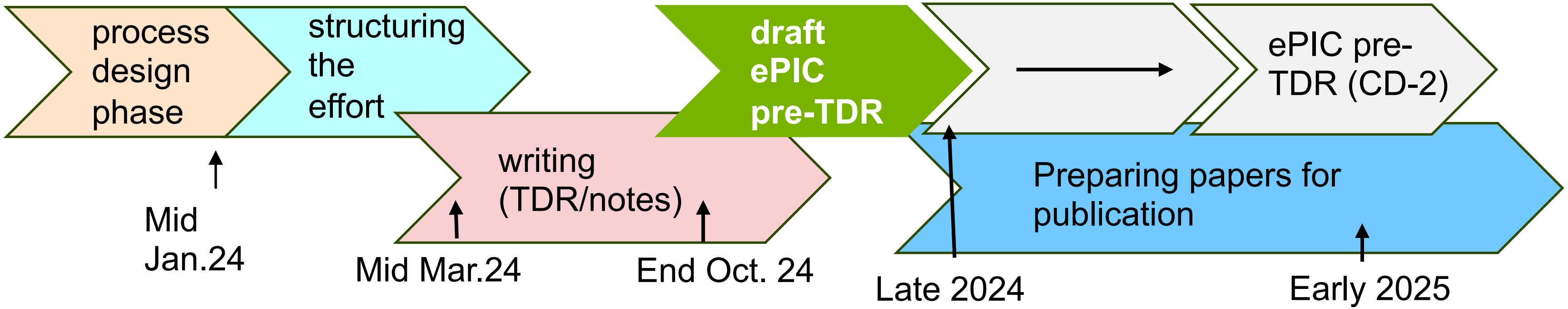
ePIC initiated in
July 2022.

Currently (from 2024 Institutional Survey):

> 850 collaborators
from
173 institutions
from
25 countries
from
4 world regions.

(PRE)TDR STRATEGY AND PUBLICATIONS

The EIC (pre)TDR is the top priority for the ePIC Collaboration,



Timeline driven by the EIC Project (CD-2/CD-3).

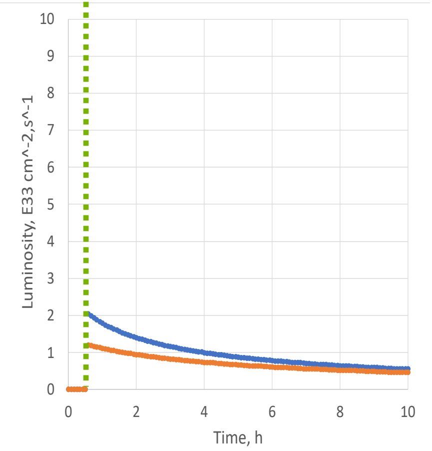
Extended versions of the sections on the detector, physics performance, and software & computing will be published in scientific journals.

Discussion between the EIC Project and ePIC based on phasing of EIC operations

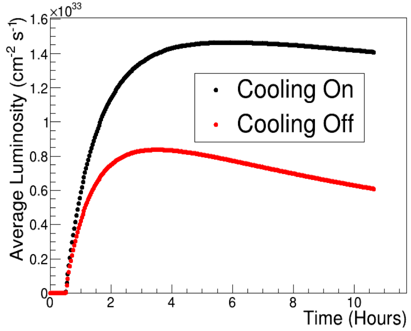
EARLY SCIENCE PROGRAM

- **Phase I: Under Discussion**
  - HSR: no strong hadron cooling (SHC), add precooler, no 41-GeV bypass
  - ESR: 5-10 GeV, 7 nC max (means fewer rf cavities and amps); maybe no crabs (may require lower proton bunch intensities)
  - RCS: operates with a 7-nC (single bunch), 3 –> 5 or 10 GeV, ramps at 1 Hz
- **Phase II: Under Discussion**
  - HSR: add SHC, add 41-GeV bypass
  - ESR: add rf cavities and power to operate at 28 nC and 18 GeV;
  - RCS: upgraded to 28 nC and 3 -> 18 GeV ramps (at 1 Hz);
- **Early science program driven by:**
  - Start of EIC Science program.
  - Alignment with expected order in commissioning the collider and ramp up of performance that comes with gain of operational experience.
  - Having access to new physics results early to get high impact publications.

e-p Luminosity in EIC Phase I



Luminosity w/wo SHC



This work is supported by the U.S. Department of Energy, Office of Science, Office of Nuclear Physics, under contract DE-AC02-06CH11357.

EPIC – LEVERAGING THE EIC ON DAY 1

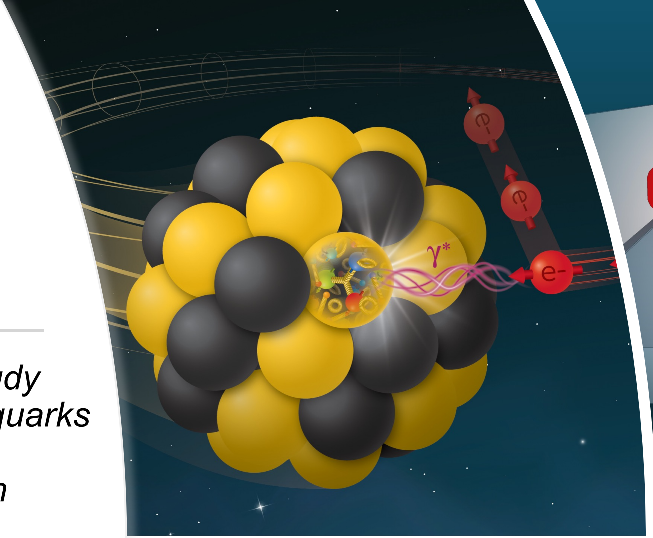
The EIC will enable us to embark on a precision study of the nucleon and the nucleus at the scale of sea quarks and gluons. We will explore nucleon structure and observed properties in terms of the quark and gluon dynamics.

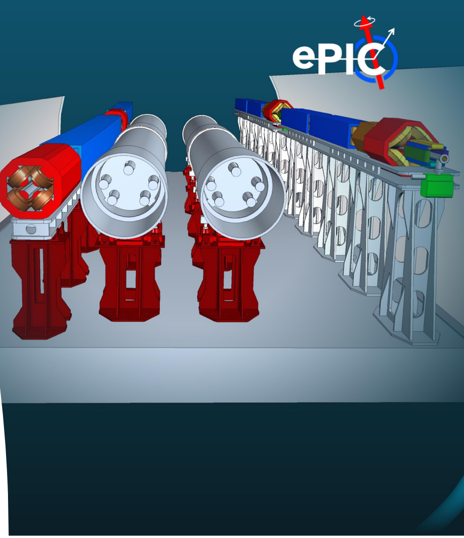
The ePIC collaboration is large for NP: over 850 scientists from 173 institutions across 25 countries in four world regions

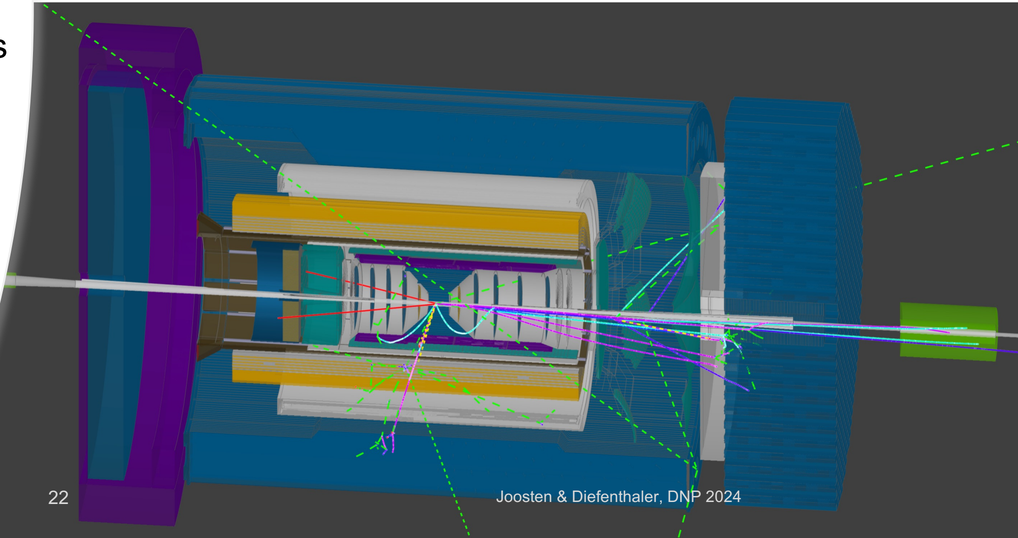
ePIC, together with the EIC Project, is realizing **a highly integrated, multi-purpose detector:**

- The detector is design to maximize its physics reach
- State-of-the-art technologies and computing ensure that ePIC will deliver on EIC Science from its start

The EIC (pre)TDR is the current top priority ePIC; timeline driven by the CD-2/CD-3 Project timeline.

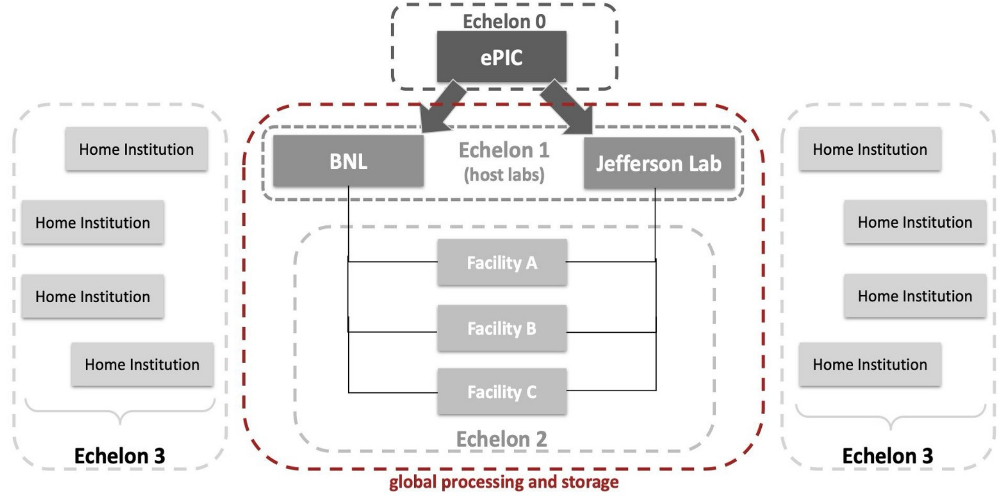






BACKUP

THE EPIC STREAMING COMPUTING MODEL



Echelon 0: ePIC Streaming DAQ.

Echelon 1: Two host labs, two primary ePIC computing facilities.

Echelon 2: Global contributions leveraging commitments to ePIC computing from labs and universities, domestically and internationally.

Echelon 3: Supporting the analysis community *where they are* at their home institutes, primarily via services hosted at Echelon 1 and 2.

COMPUTING USE CASES AND THEIR ECHELON DISTRIBUTION

Use Case	Echelon 0	Echelon 1	Echelon 2	Echelon 3
Streaming Data Storage and Monitoring	✓	✓		
Alignment and Calibration		✓	✓	
Prompt Reconstruction		✓		
First Full Reconstruction		✓	✓	
Reprocessing		✓	✓	
Simulation		✓	✓	
Physics Analysis		✓	✓	✓
AI Modeling and Digital Twin		✓	✓	

Prompt := rapid low-latency processing.

Prompt processing of newly acquired data typically begins in seconds, not tens of minutes or longer.

Assumed Fraction of Use Case Done Outside Echelon 1	
Alignment and Calibration	50%
First Full Reconstruction	40%
Reprocessing	60%
Simulation	75%

- **Echelon 1** sites uniquely perform the **low-latency streaming workflows** consuming the data stream from Echelon 0:
  - Archiving and monitoring of the streaming data, prompt reconstruction and rapid diagnostics.
- Apart from low-latency, Echelon 2 sites fully participate in use cases:
  - Tentative resource requirements model assumes a **substantial role for Echelon 2**.

COMPUTING RESOURCE NEEDS AND THEIR IMPLICATIONS

Processing by Use Case [cores]	Echelon 1	Echelon 2
Streaming Data Storage and Monitoring	-	-
Alignment and Calibration	6,004	6,004
Prompt Reconstruction	60,037	-
First Full Reconstruction	72,045	48,030
Reprocessing	144,089	216,134
Simulation	123,326	369,979
Total estimate processing	**405,501**	**640,147**

Storage Estimates by Use Case [PB]	Echelon 1	Echelon 2
Streaming Data Storage and Monitoring	71	35
Alignment and Calibration	1.8	1.8
Prompt Reconstruction	4.4	-
First Full Reconstruction	8.9	3.0
Reprocessing	9	9
Simulation	107	107
Total estimate storage	**201**	**156**

Computing Resource Needs in 2034 for EIC Phase I

O(1M) core-years to process a year of data:

- Optimistic scaling of constant-dollar performance gains would reduce the numbers about 5x:
  - Based on current LHC measure of 15% per year.
  - But the trend is towards lower gains per year.
- Whatever the gains over time, processing scale is substantial!
- Motivates attention to leveraging distributed and opportunistic resources from the beginning.

~350 PB to store data of one year.

ePIC is compute intensive experiment, must ensure ePIC is not compute-limited in its science.

STREAMING DAQ AND COMPUTING MILESTONES

Streaming DAQ Release Schedule:

PicoDAQ **FY26Q1**
- Readout test setups

MicroDAQ: **FY26Q4**
- Readout detector data in test stand using engineering articles

MiniDAQ: **FY28Q1**
- Readout detector data using full hardware and timing chain

Full DAQ-v1: **FY29Q2**
- Full functionality DAQ ready for full system integration & testing

Production DAQ: **FY31Q3**
- Ready for cosmics

Streaming Computing Milestones:

Start development of streaming orchestration, including workflow and workload management system tool.
Start streaming and processing streamed data between BNL, Jefferson, DRAC Canada, and other sites.

Support of test-beam measurements, using variety of electronics and DAQ setups:
- Digitization developments will allow detailed comparisons between simulations and test-beam data.
- Track progress of the alignment and calibration software developed for detector prototypes.
- Various JANA2 plugins for reading test-beam data required. Work started on an example.

Establish autonomous alignment and calibration workflows that allows for validation by experts.

Analysis challenges exercising end-to-end workflows from (simulated) raw data.

Streaming challenges exercising the streaming workflows from DAQ through offline reconstruction, and the Echelon 0 and Echelon 1 computing and connectivity.
Analysis challenges exercising autonomous alignment and calibrations.

Data challenges exercising scaling and capability tests as distributed ePIC computing resources at substantial scale reach the floor, including exercising the functional roles of the Echelon tiers, particularly Echelon 2, the globally distributed resources essential to meeting computing requirements of ePIC.