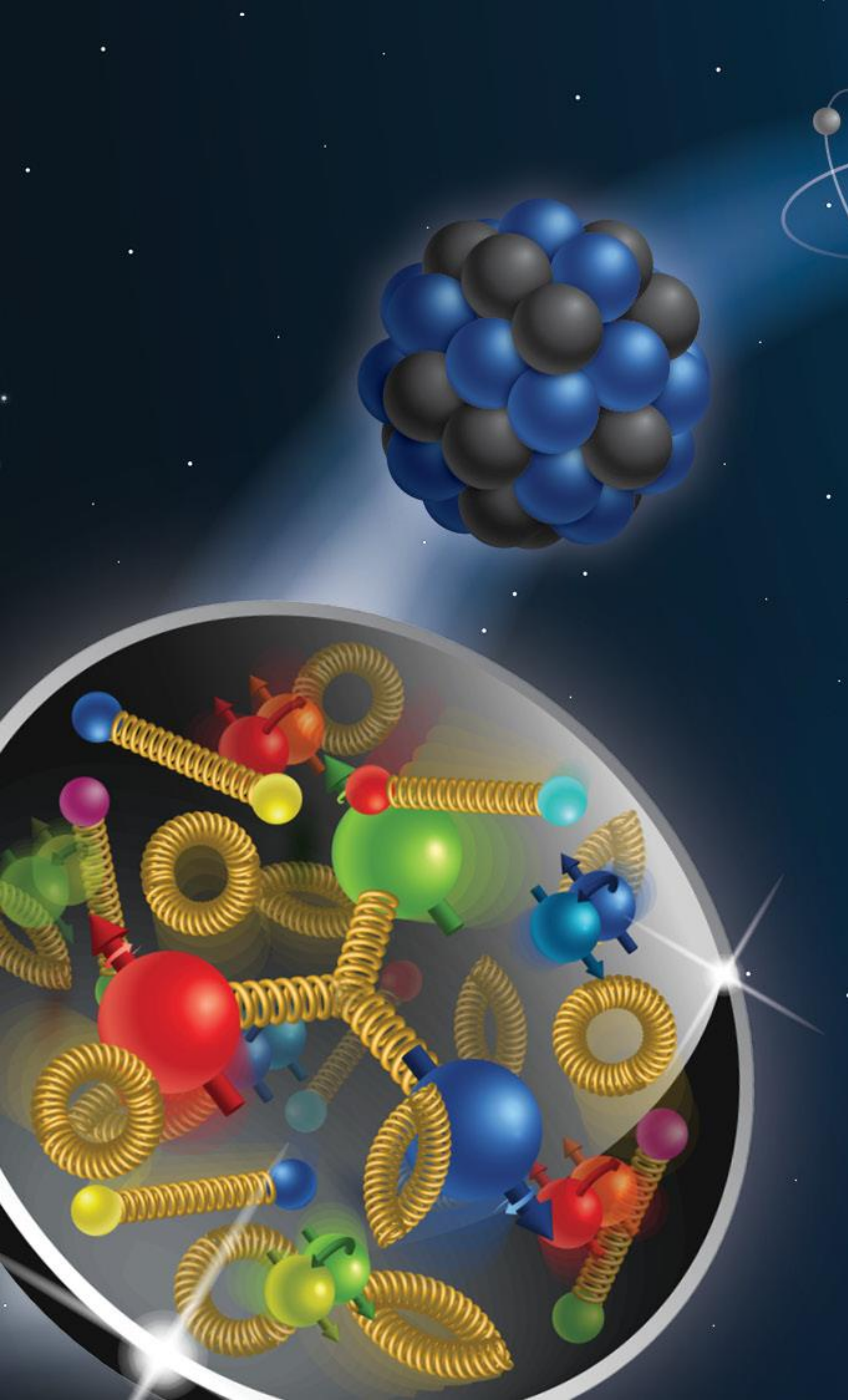


ePIC
a Detector for EIC
and
Detector R&D

Elke-Caroline Aschenauer (BNL)

Co-Associate Director for the EIC Experimental Program

What is the EIC Facility

What is the EIC:

A high luminosity (10^{33} – 10^{34} $cm^{-2}s^{-1}$) polarized electron proton / ion collider with $\sqrt{s_{ep}}$ = 28 – 140 GeV

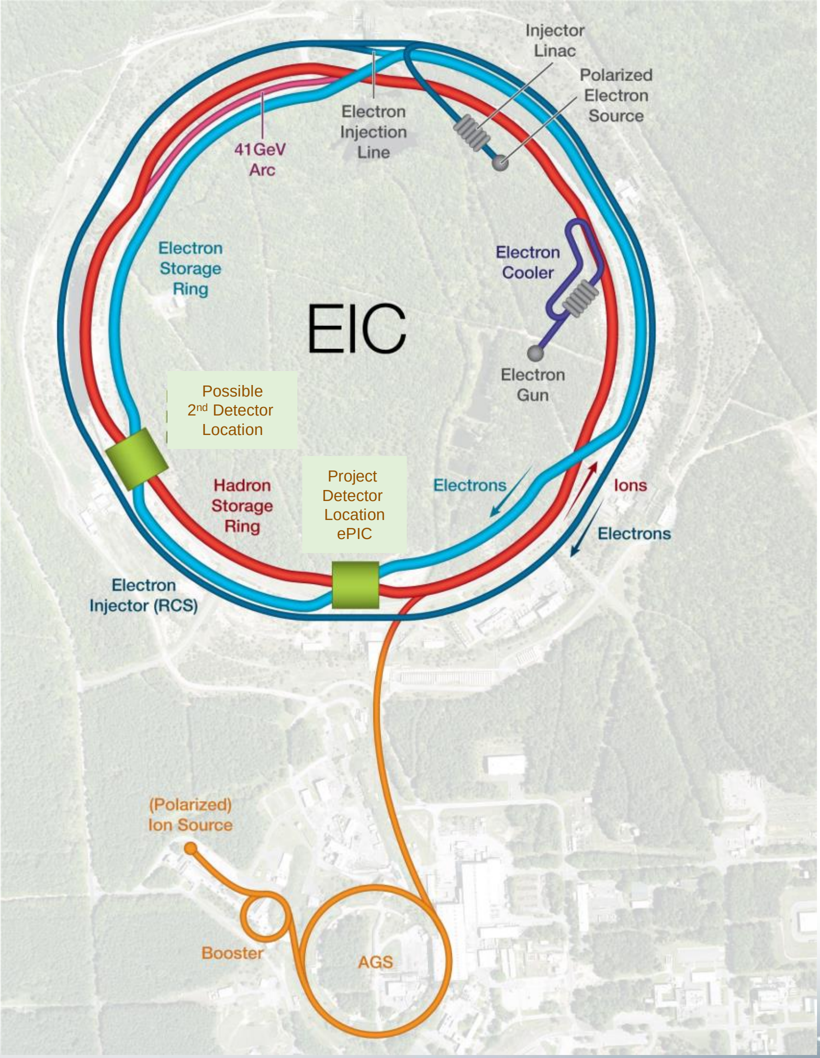
What is special:

EIC is the ONLY new collider in foreseeable future.
Allows to remain at frontier of Accelerator S&T.

factor 100 to 1000 higher luminosity as HERA
both electrons and protons / light nuclei polarized,
nuclear beams: d to U
Fixed Target Facilities i.e.:
at minimum > 2 decades increase in kinematic coverage in x and Q^2

Science Program: An EIC can uniquely address three profound questions about nucleons — neutrons and protons — and how they are assembled to form the nuclei of atoms:

State of the art general purpose collider detector

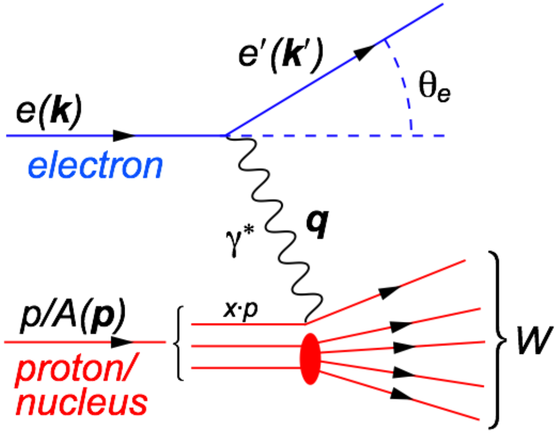


What is needed to address the EIC Physics

The Golden Process:

Deep Inelastic Scattering (DIS):

- As a probe, electron beams provide unmatched precision of the electromagnetic interaction
- Direct, model independent determination of parton kinematics of physics processes



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

s: center-of-mass energy squared

Q^2: resolution power

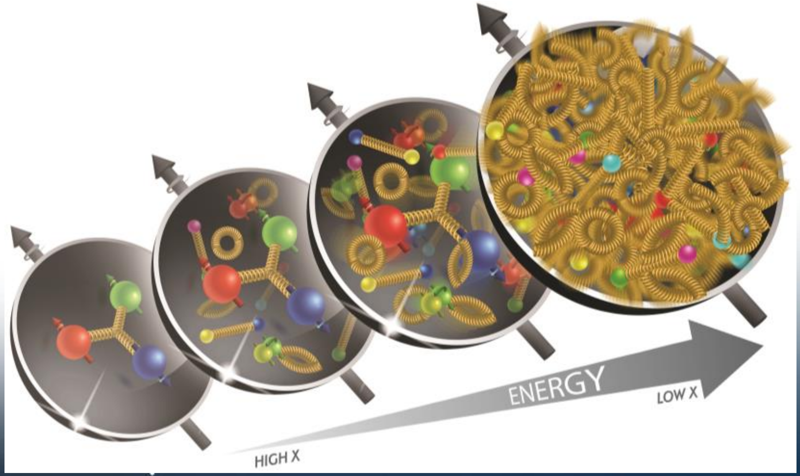
x: the fraction of the nucleon's momentum carried by the struck quark (0<x<1)

y: inelasticity

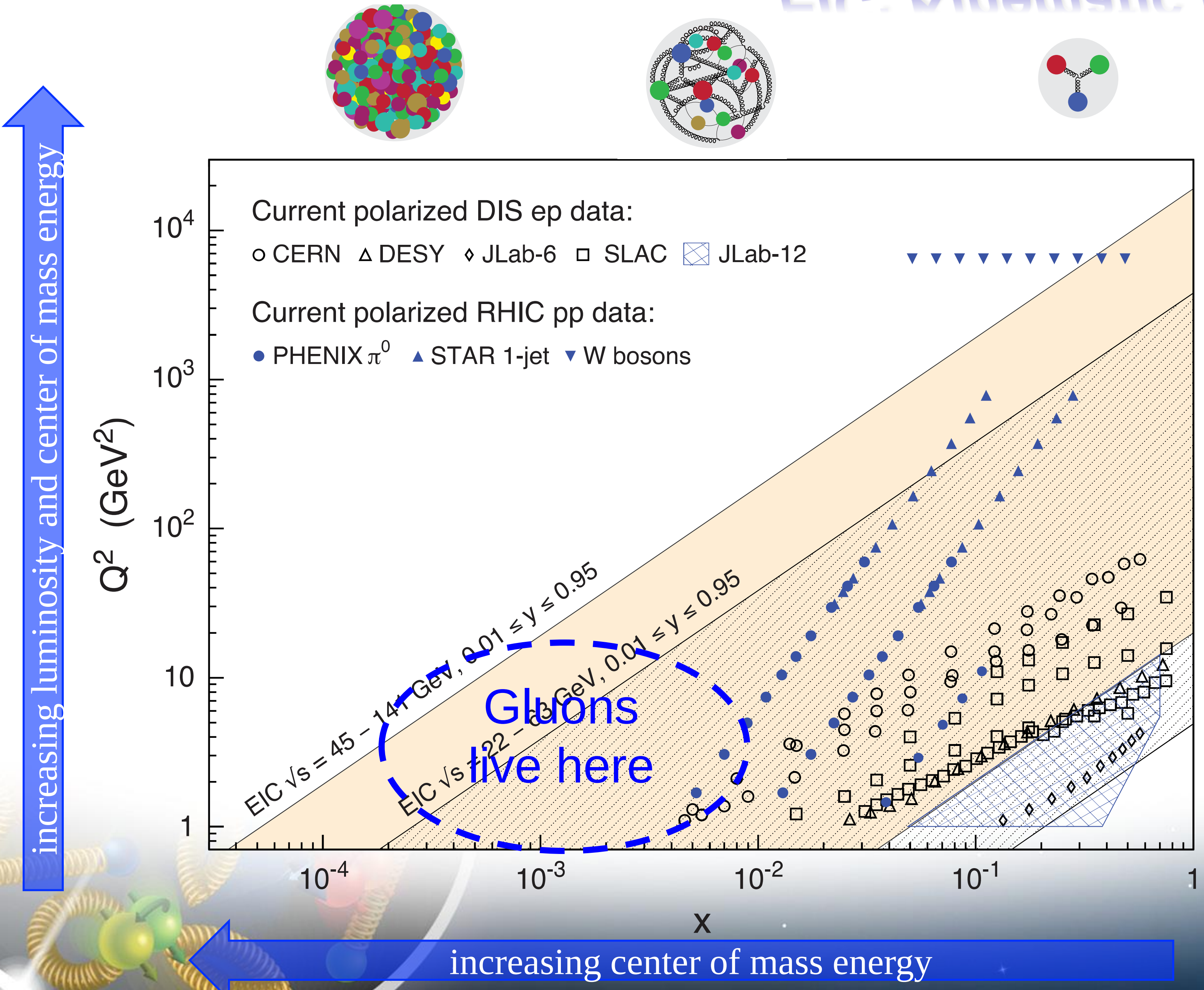
large kinematic coverage:

→ center-of-mass energy √s: 30 – 140 GeV

→ access to *x* and Q^2 over a wide range



EIC: Kinematic Plane



Gluons live here

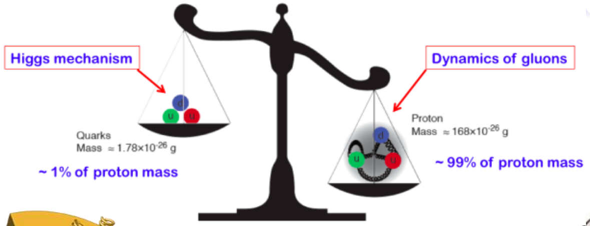
increasing luminosity and center of mass energy

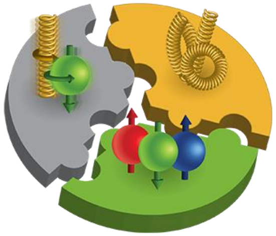
increasing center of mass energy

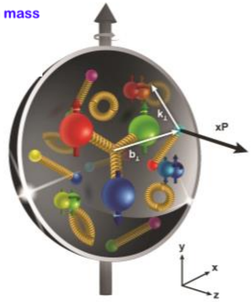
The EIC Physics

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

How do the nucleon properties emerge from them and their interactions?







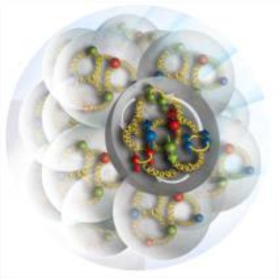
How do color-charged quarks and gluons, and colorless jets, interact with a nuclear medium?

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

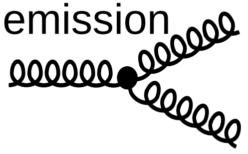
How do the quark-gluon interactions create nuclear binding?

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?

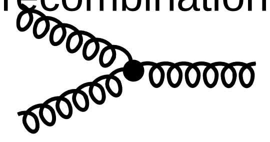


gluon emission



? =

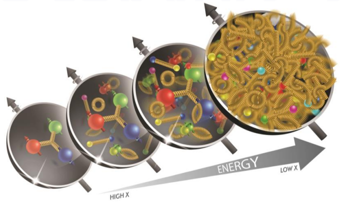
gluon recombination



Accelerator Performance Needs for NAS Science

wide center-of-mass energy √s: 20 – 140 GeV :

- map the out nucleon and nuclei structure from high to low x

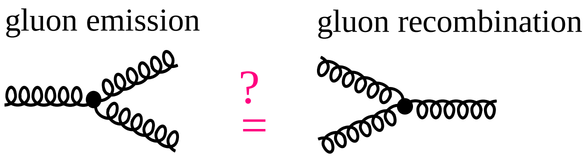


polarized electron and hadron (p, He-3) beams:

- access to spin structure of nucleons and nuclei
- Spin vehicle to access the spatial and momentum structure of the nucleon
- Full specification of initial and final states to probe q-g structure of NN and NNN interaction in light nuclei

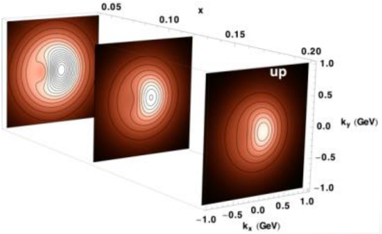
nuclear beams: d to Pb

- accessing the highest gluon densities → saturation
- quark and gluon interact with a nuclear medium



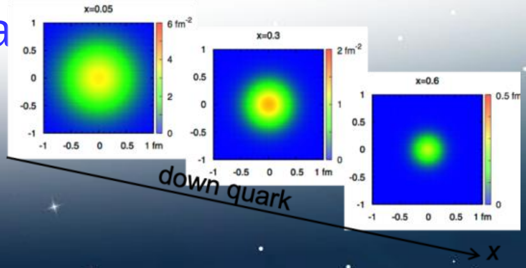
high luminosity 10^{33}-10^{34} cm^{-2}s^{-1} :

- mapping the spatial and momentum structure of nucleons and nuclei
- access to rare probes, i.e. Ws

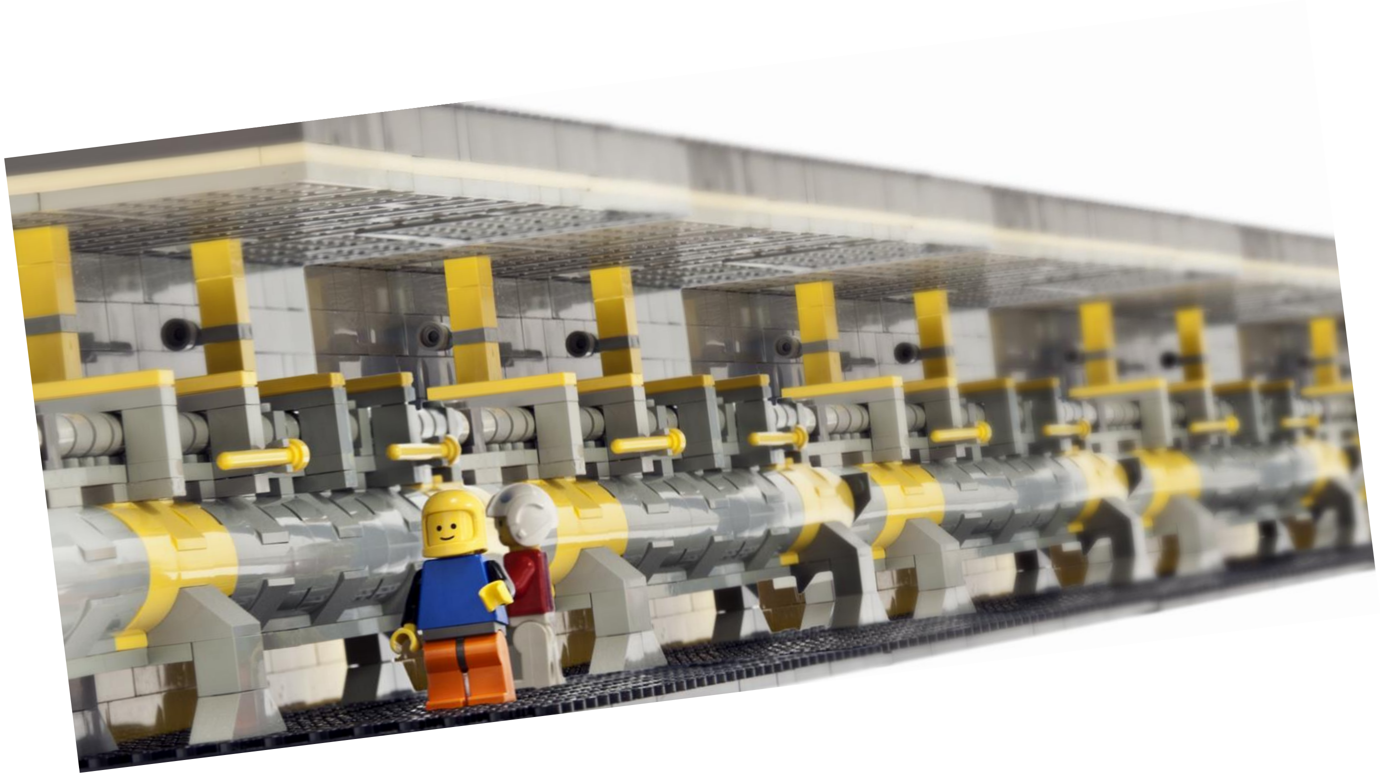


large acceptance (0.2 – 1.3 GeV) through forward focusing IR ma

- spatial imaging of nucleons and nuclei



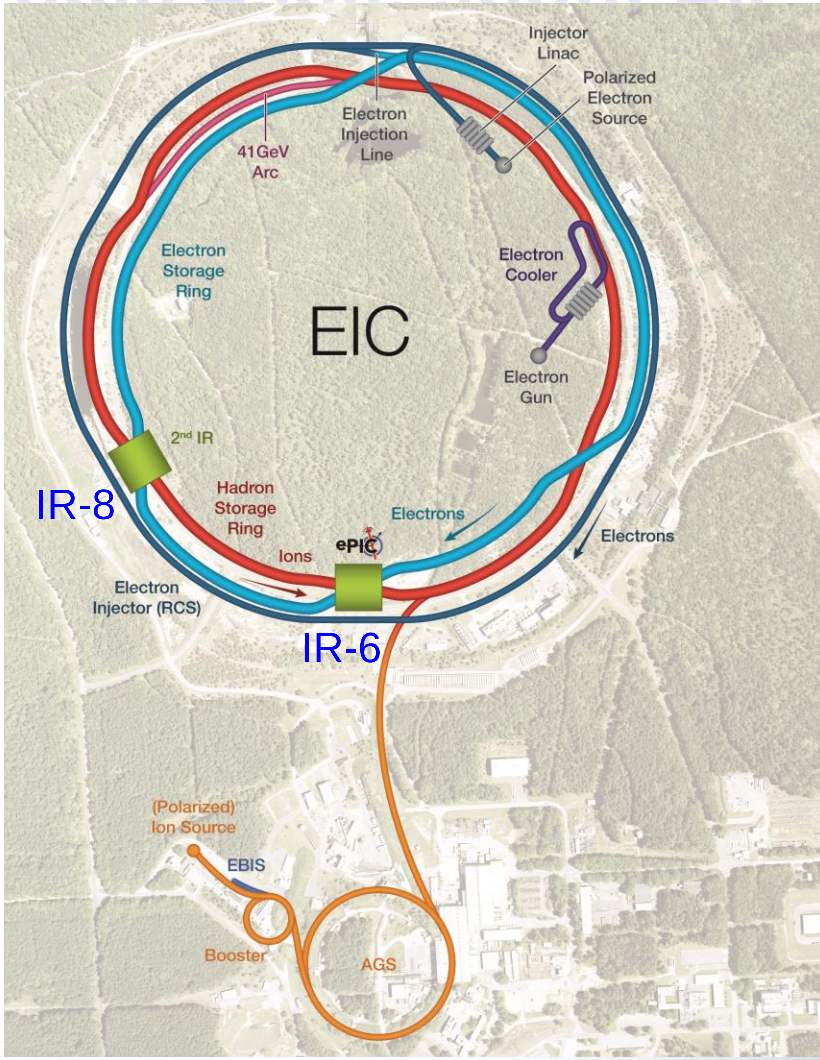
The EIC Accelerator



Some Facts about EIC

Project Design Goals

- High Luminosity: $L = 10^{33} – 10^{34} \mathrm{cm}^{-2}\mathrm{sec}^{-1}$, 10 – 100 fb^{-1}/year
- Highly Polarized Beams: 70%
  - → requires high precision polarimetry
- Large Center of Mass Energy Range: E_{cm} = 29 – 140 GeV
  - → Large Detector Acceptance
- Large Ion Species Range: protons – Uranium
  - → Requires forward detectors integrated in beam lattice
- Good Background Conditions
- Accommodate a Second Interaction Region (IR) → IR-8

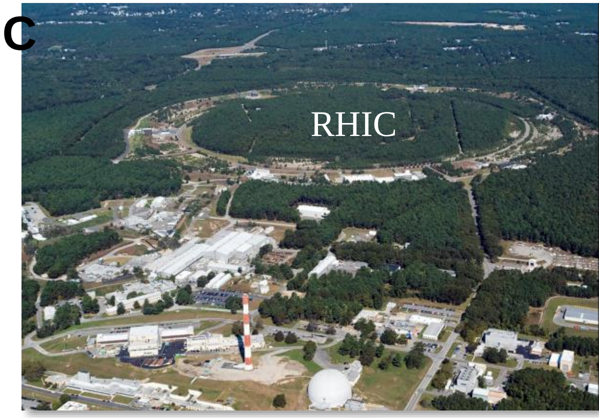


p: 41 GeV, 100 to 275 GeV p/A beam →

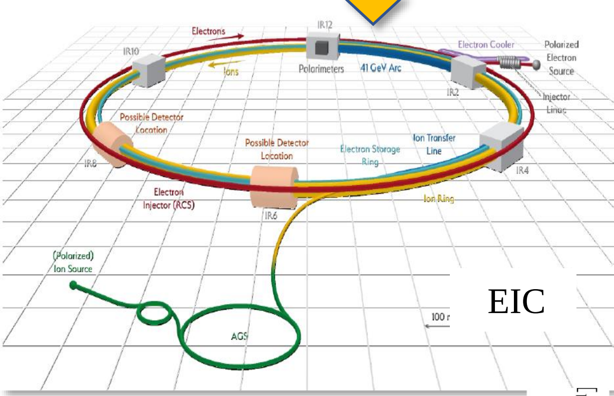
← e beam **e: 5 GeV to 18 GeV**

EIC Design Overview

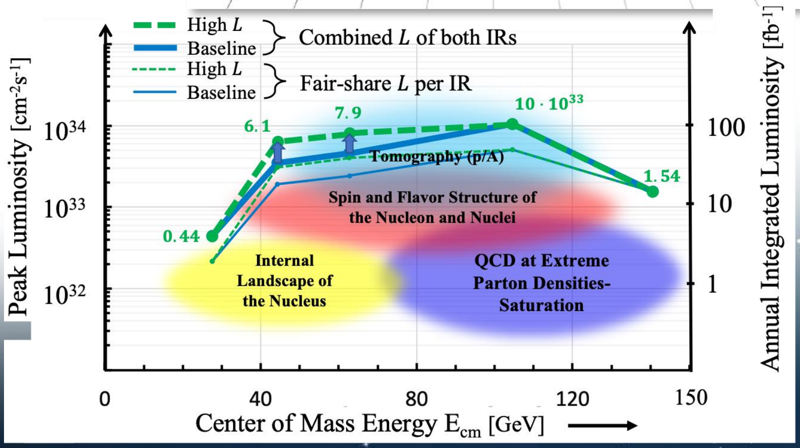
- Based on **existing, well maintained, well performing RHIC**



- **Hadron storage Ring (RHIC Rings) 40-275 GeV**
  - Superconducting magnets (existing)
  - 1160 bunches, 1A beam current (3x RHIC)
  - Bright vertical beam emittance 1.5 nm ("flat beams")
  - Strong cooling (coherent electron cooling)



- **Electron Storage Ring 2.5–18 GeV**
  - Large beam current, 2.5 A, 9 MW S.R. power, S.C. RF
  - Need to inject polarized bunches
- **Electron rapid cycling synchrotron, 1Hz, (0.4- 18) GeV**
  - Spin transparent due to high quasi periodicity
- **High luminosity Interaction Region(s)**
  - Superconducting final focus magnets
  - 25 mrad crossing angle with crab cavities
  - Spin Rotators (longitudinal spin)
  - Forward hadron instrumentation

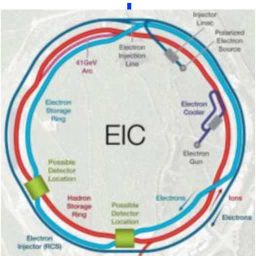


The EIC: A Unique Collider

EIC	LHC /RHIC
collide different beam species: ep & eA → consequences for beam backgrounds → hadron beam backgrounds, i.e. beam gas events → synchrotron radiation	collide the same beam species: pp, pA, AA → beam backgrounds → hadron beam backgrounds, i.e. beam gas events, high pile up
asymmetric beam energies → boosted kinematics → high activity at high $\|\eta\|$	symmetric beam energies → kinematics is not boosted → most activity at midrapidity
Small bunch spacing: 10ns	moderate bunch spacing: 25 ns
crossing angle: 25mrad	no significant crossing angle yet (150 μrad now)
wide range in center of mass energies → factor 6	LHC limited range in center of mass energies → factor 2 RHIC wide range in center of mass energies : → factor 26 in AA and 8 in pp
both beams are polarized → stat uncertainty: $\sim 1/(P_1 P_2 (\int L\, dt)^{1/2})$	no beam polarization → stat uncertainty: $\sim 1/(\int L\, dt)^{1/2}$

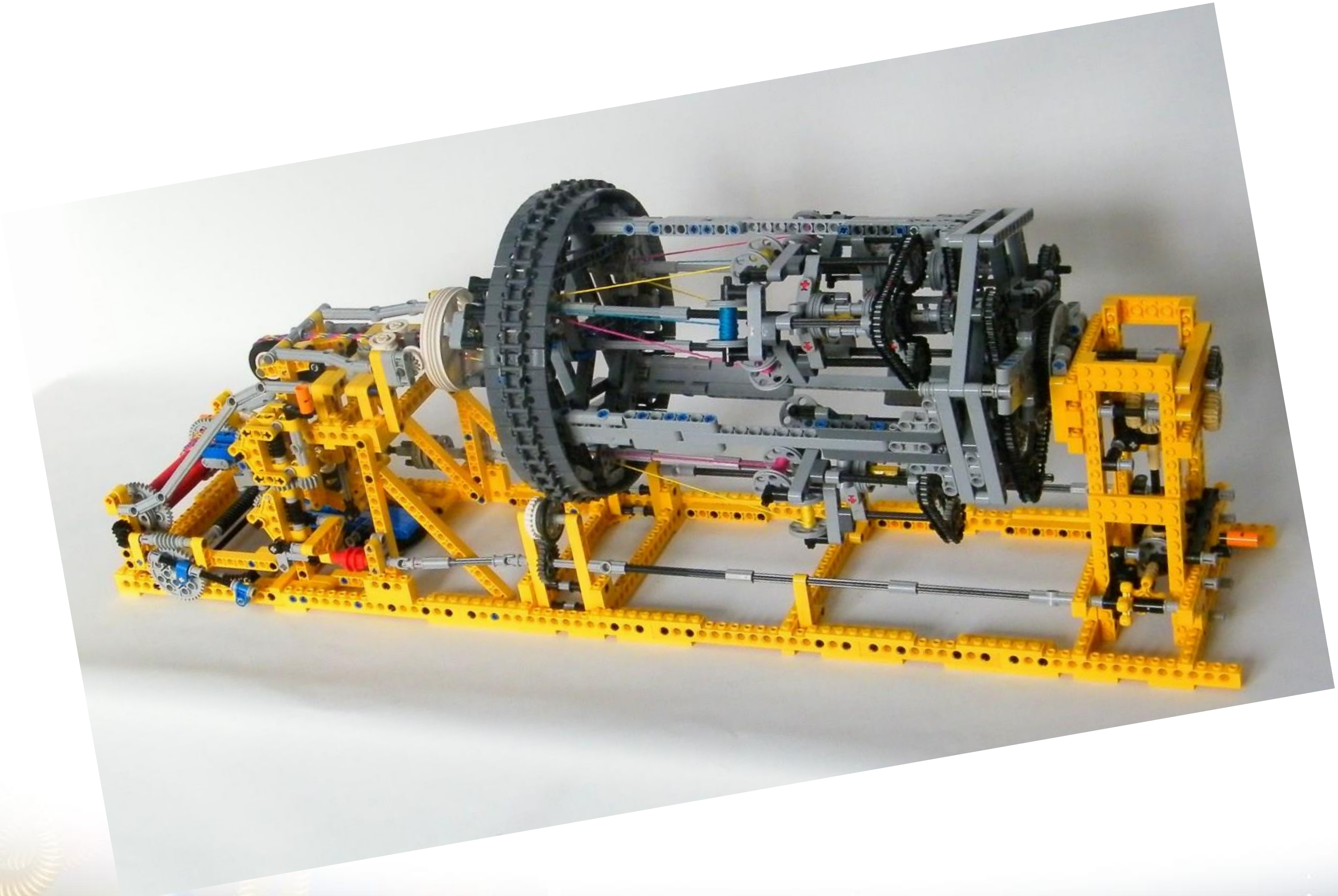
→ **Differences impact detector acceptance and possible detector technologies**

Complementarity for 1st-IR & 2nd-IR



<table>
<tr><th></th><th>1st IR (IP-6)</th><th>2nd IR (IP-8)</th></tr>
<tr><td>Globally:</td><td colspan="2">same accelerator highlights and challenges</td></tr>
<tr><td>Geometry:</td><td>ring inside to outside</td><td>ring outside to inside</td></tr>
<tr><td>Crossing Angle:</td><td>25 mrad</td><td>35 mrad
→ more difficult to get acceptance at high η</td></tr>
<tr><td></td><td colspan="2">different blind spots
different far-forward detector acceptances</td></tr>
<tr><td>Luminosity:</td><td colspan="2">same luminosity at both IRs
same center-of-mass energy coverage</td></tr>
<tr><td>IR-Design:</td><td>$0.2\ \text{GeV} < p_T < 1.3\ \text{GeV}$</td><td>$2^{nd}$ Focus
→ improved low p_T acceptance at far-forward Roman Pots
$x_L \sim 1 \rightarrow p_T \sim 0$</td></tr>
<tr><td>Experiment:</td><td colspan="2">complementarity through
different subdetector technologies</td></tr>
</table>

EIC Detector Concept



EIC Experimental program preparation

Year-long EIC User Group driven EIC Yellow Report activity (December 2019 – February 2021

- Science Requirements and Detector Concepts for the EIC arXiv:2103.05419 & Nucl. Phys. A 1026 (2022) 122447

BNL and TJNAF Jointly Leading Efforts Towards Experimental Program		
2020	Call for Expressions of Interest (EOI) https://www.bnl.gov/eic/EOI.php	May 2020
	EOI Responses Submitted	November 2020
	Assessment of EOI Responses	On-going[&]
2021	Call for Collaboration Proposals for Detectors https://www.bnl.gov/eic/CFC.php	March 2021
	BNL/TJNAF Proposal Evaluation Committee	Spring 2021
	Collaboration Proposals for Detectors Submitted	December 2021
2022	Decision on Project Detector – baseline "ECCE"	March 2022
	Process to consolidate ECCE & ATHENA to the EIC Project Detector	Spring 2022
	ePIC Collaboration* Formed – 160 institutions	July 2022
2023	ePIC Charter ratified & elected Leadership Team	February 2023
	Resources Review Board Meeting	April 2023
	ePIC Detector remaining technology choices made	April 2023

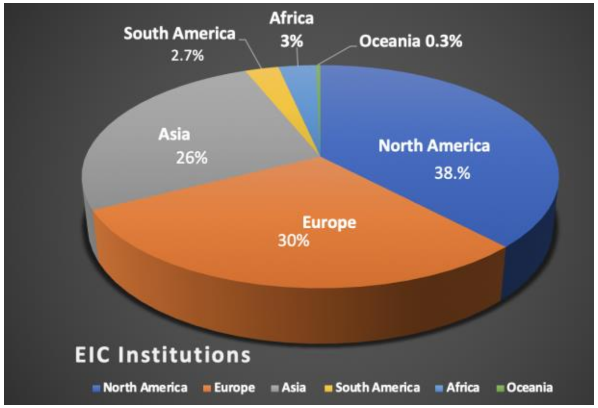
[&] Remains ongoing until formal agreements are in place – it originally led to confirmation that in-kind level assumed for the EIC detector was in range.

World-Wide Interest in EIC & ePIC

The EIC Users Group: EICUG.ORG

Formed 2016 400 Users → Now

1440 collaborators, 40 countries, 295 institutions
(Experimentalists 897, Theory 362, Acc. Sci. 156)



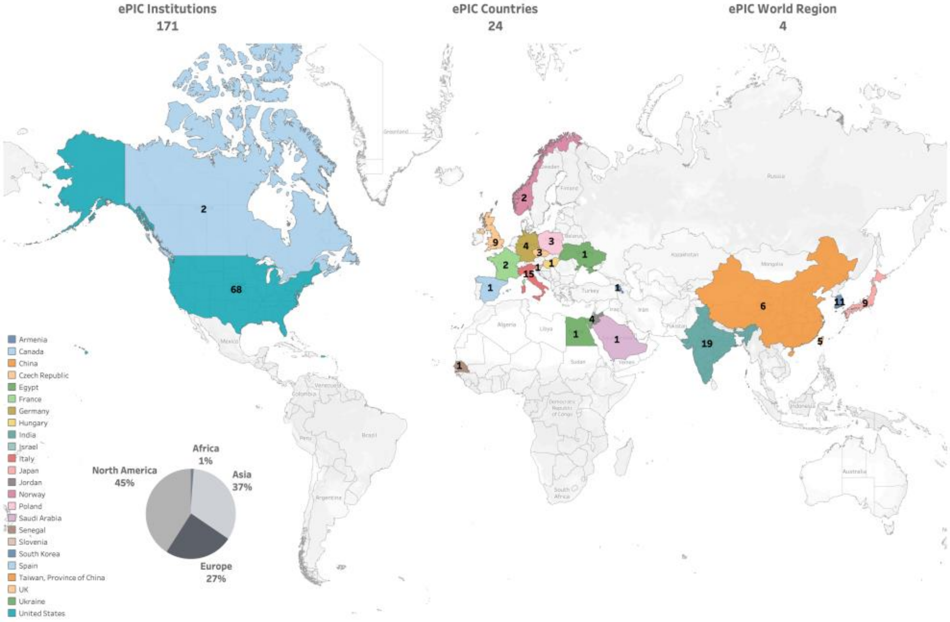
Location of Institutions

Leaflet | Tiles © Esri — National Geographic, Esri, DeLorme, NAVTEQ, UNEP-WCMC, USGS, NASA, ESA, METI, NRCAN, GEBCO, NOAA, iPC

ePIC Collaboration

fully formed December 2022
→ Collaboration Charter ratified
Collaboration Leadership:
John Lajoie ORNL Spokesperson
Silvia Dalla Torre Deputy- Spokesperson
ePIC to become CERN recognized experiment
Details:
https://wiki.bnl.gov/EPIC/index.php?title=Main_Page

ePIC now 171 institutions from 24 countries including 13 new institutions since July 2023



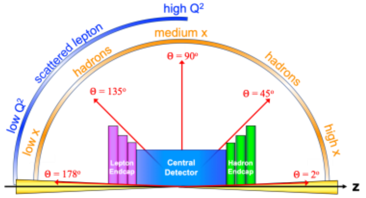
Experimental Equipment Scope

- High Luminosity: L= $10^{33} – 10^{34}$ cm^{-2}sec^{-1}, 10 – 100 fb^{-1}/year
- Highly Polarized Beams: 70%

  → requires high precision electron and hadron polarimetry
- Large Center of Mass Energy Range: E_{cm} = 29 – 140 GeV

  → Large Detector Acceptance
- Asymmetric beam energies

  → require an asymmetric detector Barrel with electron and hadron endcap → 9.5 m



→ equal coverage ($-4 < \eta < 4$) Tracking, particle dentification, electromagnetic and hadronic calorimetry

  - High precision low mass tracking
  - good e/h separation critical for scattered electron identification
  - separate e, p, K, p on track level

- Science program required momentum resolution

  → requires a large bore 2T magnet (1.7 T magnet operation point, stretch goal 2T) with a bore radius of 1.2 m.
- Imaging science program → Large Ion Species Range: protons – Uranium

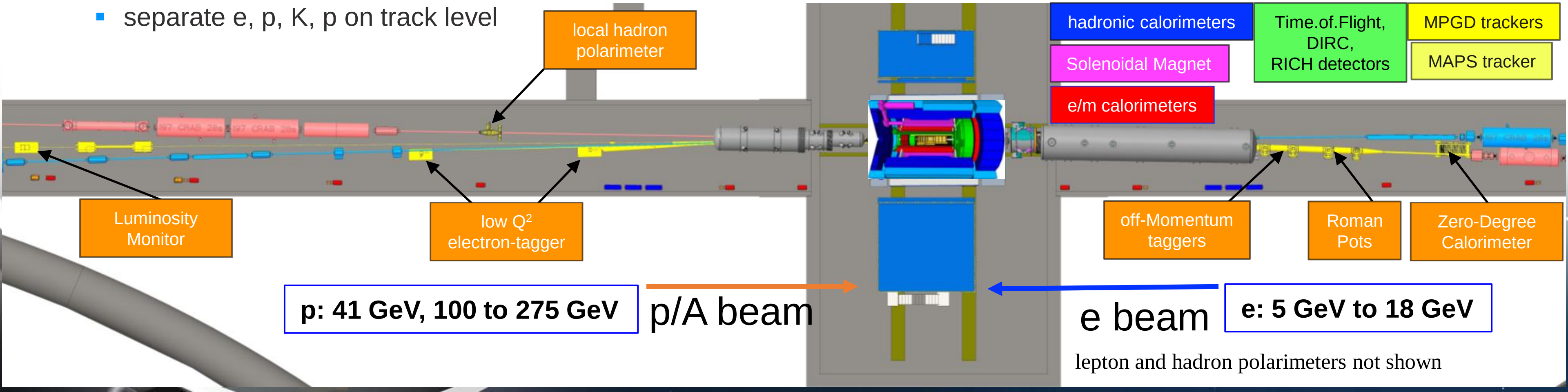
  → requires specialized detectors integrated in the Interaction Region over 80 m
- Streaming readout electronics model

  → highest scientific flexibility
- very compact Detector → **Integration** is key
- Good Background Conditions

  Details see:

  https://indico.bnl.gov/event/20473/contributions/85389/attachments/51976/88992/eca.EIC.Background.ePIC.pptx

25 different Subsystems incl. Polarimetry



hadronic calorimeters

Solenoidal Magnet

e/m calorimeters

Time.of.Flight, DIRC, RICH detectors

MPGD trackers

MAPS tracker

local hadron polarimeter

Luminosity Monitor

low Q² electron-tagger

off-Momentum taggers

Roman Pots

Zero-Degree Calorimeter

p: 41 GeV, 100 to 275 GeV

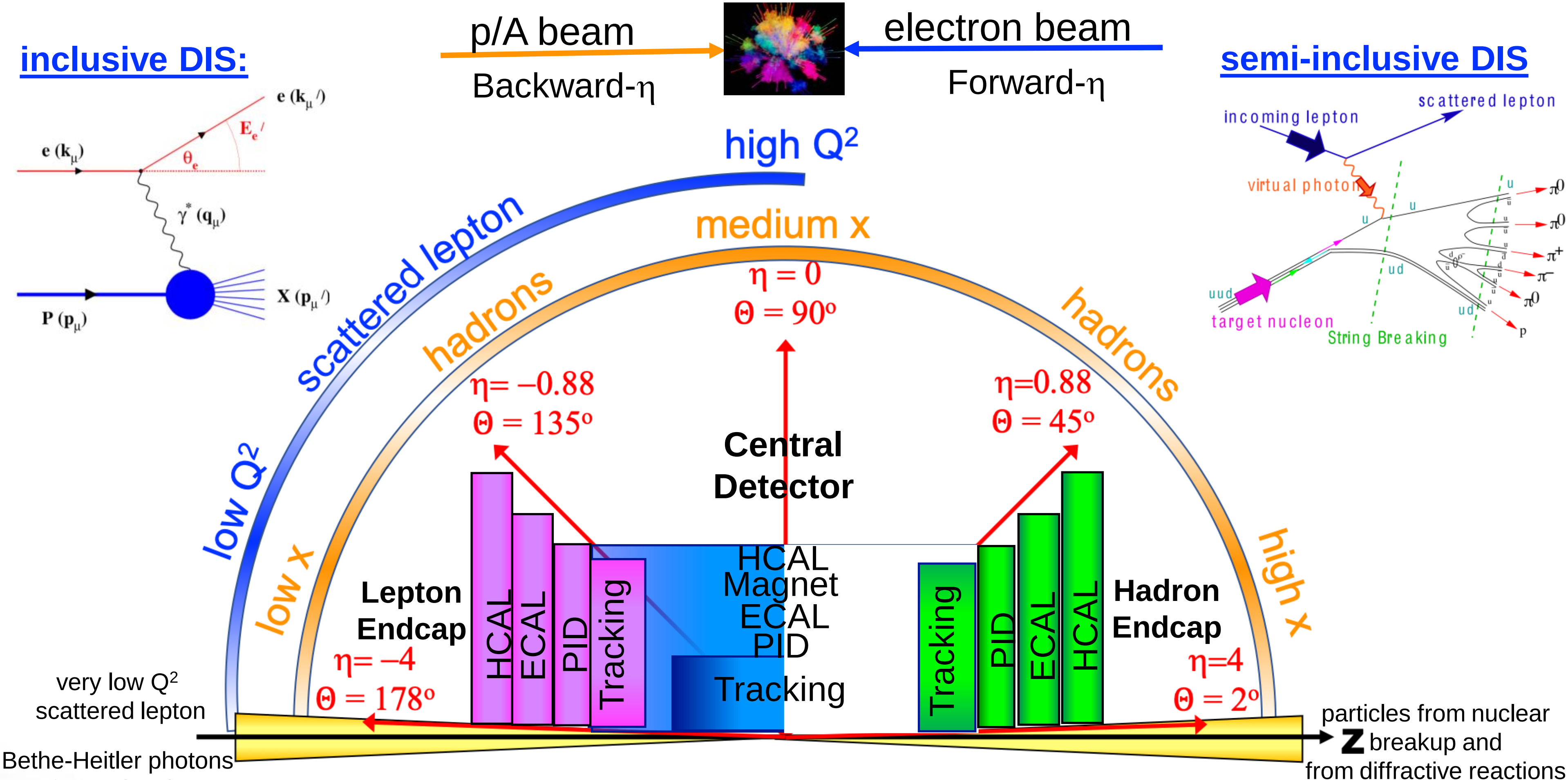
p/A beam

e beam

e: 5 GeV to 18 GeV

lepton and hadron polarimeters not shown

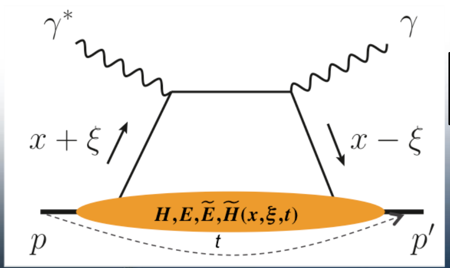
EIC General Purpose Detector: Concept



inclusive DIS:

semi-inclusive DIS

exclusive DIS



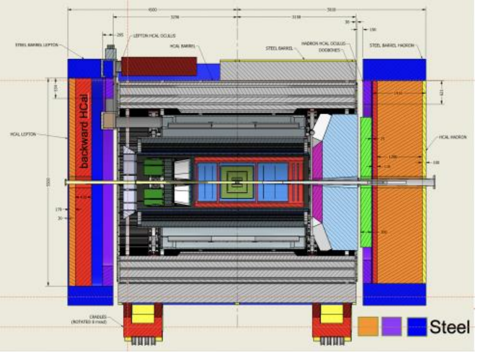
Luminosity Detector

Low Q²-Tagger

ZDC

Forward Tracking

MARCO Magnet Design Details



B_0	1.5 T	1.7 T	2.0 T	Units
Current	2942	3335	3924	A
T_{op}	4.7	4.7	4.7	K
B_{peak}	2.00	2.27	2.67	T
Temp. margin	3.06	2.82	2.45	K
Load line margin	59.6	54.2	46.1	%
$I / I_c(T, B_{peak})$	17.9	22.1	29.3	%

Robust and safe operating parameters

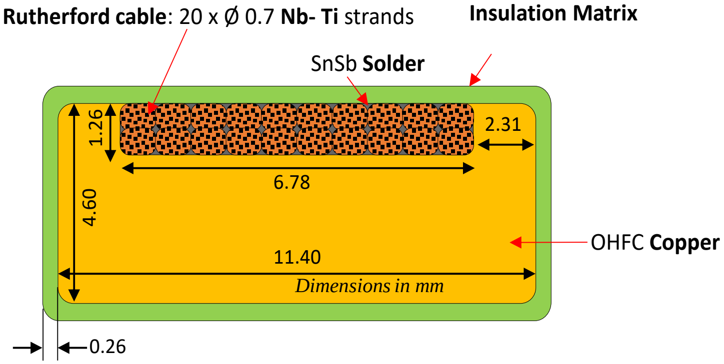
Order of conductor samples put in place based on these specifications !

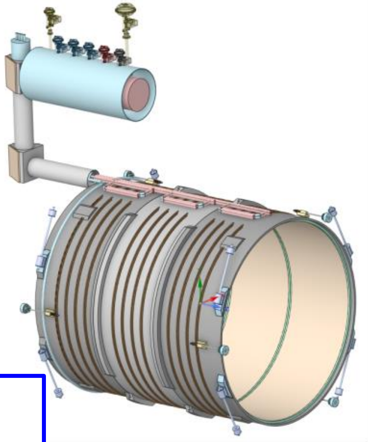
Working on sample conductor qualification

- *Discussed with test facilities around the world*
- *Already have estimated cost from at least one test facility*

Conductor is similar to the conductor used for 11.7 T MRI magnet at CEA, Saclay

Coil is divided in 3 modules with 6 layers each. This is done mainly to accommodate possible conductor length. Flux return steel layout fully defined to minimize forces and fringe fields (~10G)





Mechanical

2D and 3D mechanical analysis done on the overall magnet assembly, coils, mandrel and tie-rods.

All the stresses, displacement are well within the acceptable limits.

Cryogenic

Redundant cooling system is used to ensure that thermosiphon works properly

How we work:

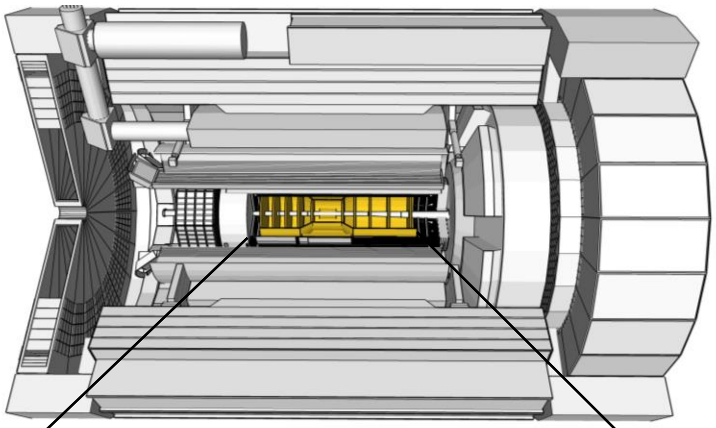
- Collaboration of Jefferson Lab, CEA Saclay and Brookhaven National Lab, the review committee also concluded:
  - The collaboration between CEA-Saclay, JLab and BNL has continued to make excellent progress and the review committee strongly supports extending this collaboration into the procurement, fabrication and commissioning phases
- 30% Design done as in-kind contribution by CEA Saclay in collaboration with Jefferson Lab Magnet Group
- BNL provides subject matter expert information on infrastructure and integration
- 60% and 90% design done as contract with CEA Saclay augmented with Jefferson Lab work and further in-kind contributions of CEA Saclay
- Expectation is that vendor contract may follow similar pattern for vendor oversight.
- Further discussions are ongoing on international engagement on magnet construction phase

ePIC Tracking Detectors

Monolithic Active Pixel Silicon Tracker:

- 1 single technology: 65-nm MAPS
  - small pixels (10 μm) and power consumption (<20 mW/cm^2) low material budget (0.05% to 0.55% X/X_0 / layer)
  - based on ALICE ITS3 development
  - MAPS Vertex layers
  - MAPS Barrel, forward and backward disks

→ synergy with ALICE-3 especially with the R&D on fast MAPS

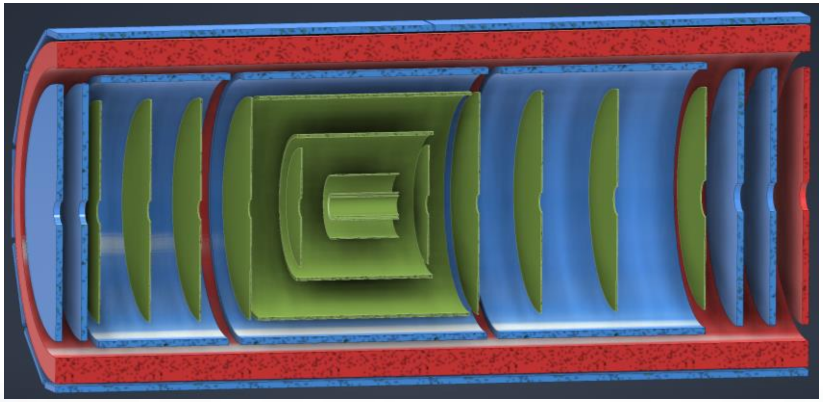


Multi Pattern Gas Detectors:

- additional space points at large radii
- Cylindrical microMEGAS
  - → Additional space point for pattern recognition / redundancy
  - → Ongoing geometry optimization

world's first at ePIC

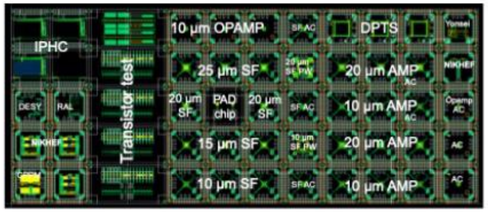
- μRWELL planar layer just before hpDIRC
  - → Impact point and direction for the ring seeding of hpDIRC
  - → Additional space point for pattern recognition / redundancy

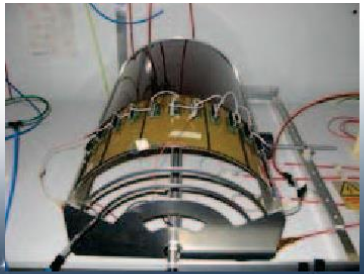


🟩 MAPS Barrel + Disks
🟦 MPGD Barrels + Disks
🟥 AC-LGAD based ToF

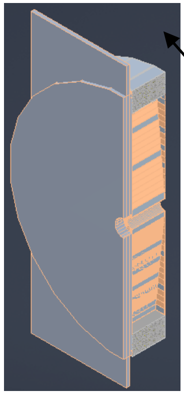
Two MPGD disks each beyond Si disks in forward and backward direction

→ To provide sufficient hits under large backgrounds to compensate for large Si integration time frame



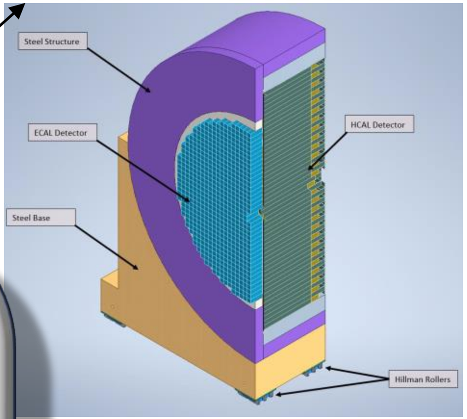


ePIC Calorimetry



Backwards HCal
Steel/Sc Sandwich
tail catcher

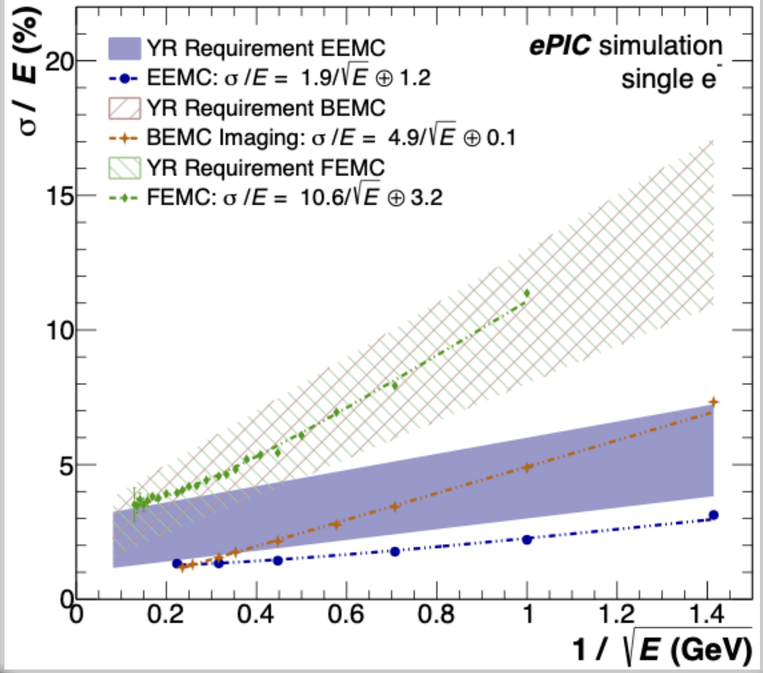
Barrel HCAL
(re-used from
sPHENIX)

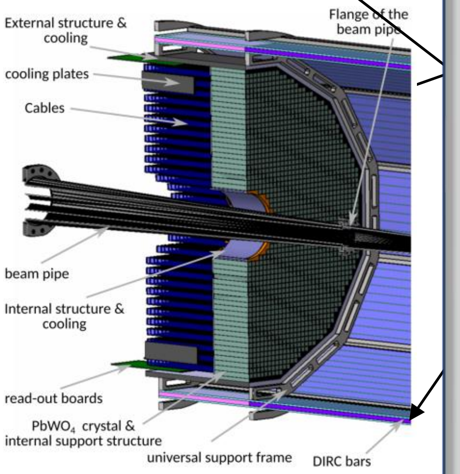


Forward ECal
High granularity
Tungsten/SciFi matrix
SiPMs as photonsensors

Forward HCAL
ngitudinally separated Steel/Sc &
W/Sc sandwich
th SiPMs embedded in Scintillator
→ first large scale realization of a
CALICE inspired design

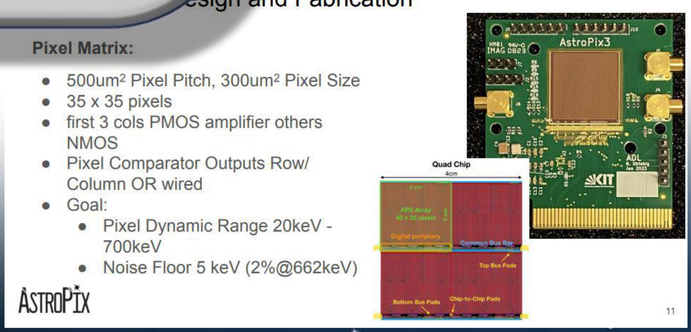
Excellent Energy Resolution





Backward Ecal
High-precision, PbWO4
SiPMs as photonsensor
→ synergy with future
crystal calorimeters

Barrel ECal: Pb/SciFi with a
hybrid imaging part (using 6 layers of
ASTROPIX)
Recent Technology Choice
Review 03/14/23, ePIC Decision 04/21/23



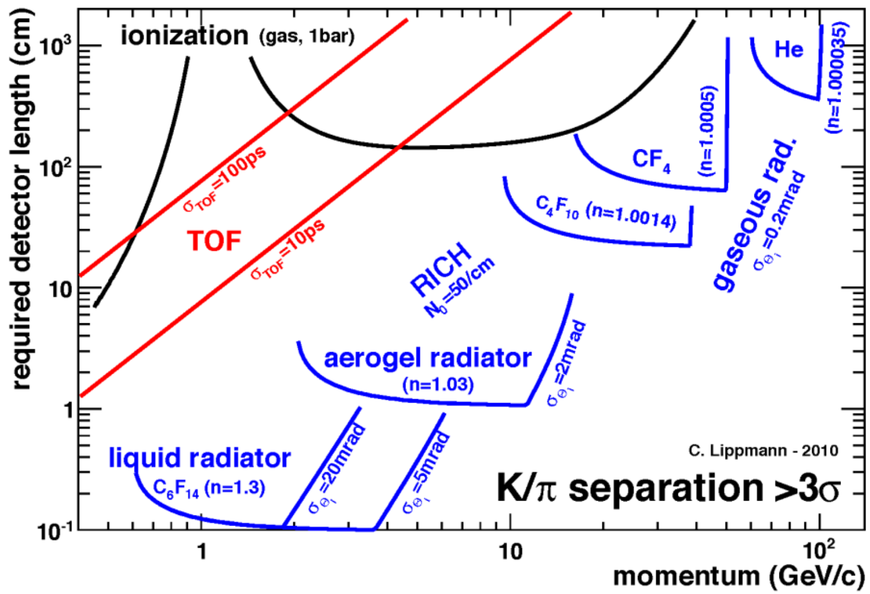
esign and Fabrication

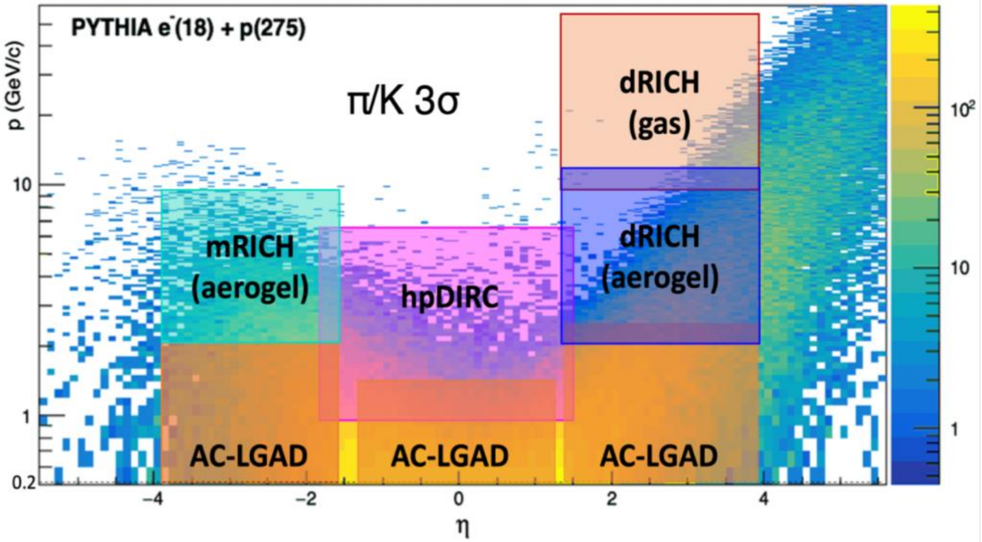
Pixel Matrix:

- 500um^2 Pixel Pitch, 300um^2 Pixel Size
- 35 x 35 pixels
- first 3 cols PMOS amplifier others NMOS
- Pixel Comparator Outputs Row/ Column OR wired
- Goal:
  - Pixel Dynamic Range 20keV - 700keV
  - Noise Floor 5 keV (2%@662keV)

Particle ID

- In general, need to separate:
  - Electrons from photons → 4π coverage in tracking
  - Electrons from charged hadrons → mostly provided by calorimetry
  - Charged pions, kaons and protons from each other → Cherenkov detectors
    - Cherenkov detectors, complemented by other technologies at lower momenta Time-of-flight or dE/dx





Need more than one technology to cover the entire momentum ranges at different rapidities

Physics requirements:

Rapidity	π/K/p and π0/γ	e/h	Min pT (E)
-3.5 – -1.0	7 GeV/c	18 GeV/c	100 MeV/c
-1.0 – 1.0	8-10 GeV/c	8 GeV/c	100 MeV/c
1.0 – 3.5	50 GeV/c	20 GeV/c	100 MeV/c

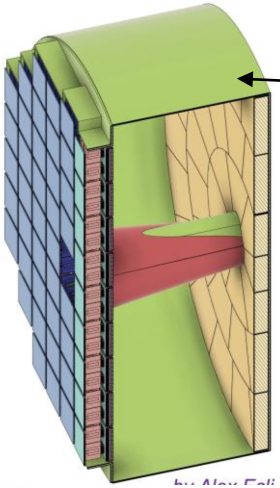
ePIC Particle Identification Detectors

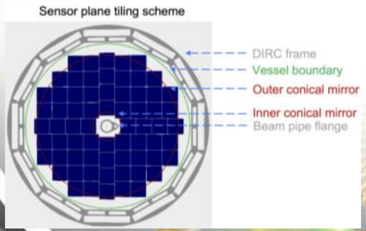
Backward RICH:
- Aerogel Cherenkov Det.
- e, π, K, p separation

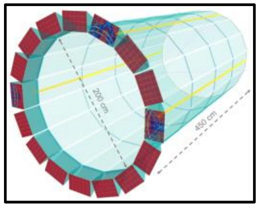
→ π/K 3σ sep. at 10 GeV/c
- Photon-sensor:
  LAPPDs to include TOF

world's first at ePIC

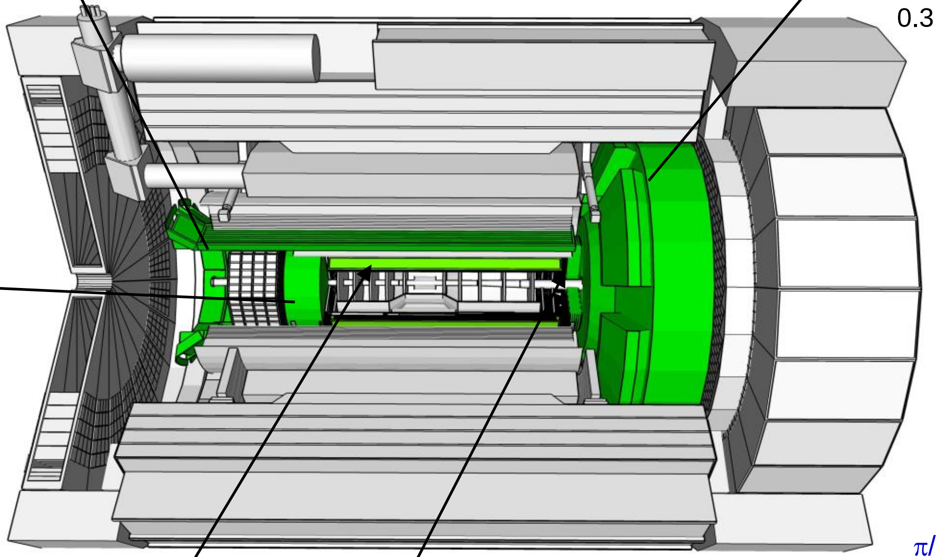
Single volume proximity focusing aerogel RICH with long proximity gap (~30 cm)




Sensor plane tiling scheme



hpDIRC (High Performance DIRC)
- Quartz bar radiator → Reuse of BaBAR DIRC bars
- light detection with MCP-PMTs
- Fully focused
- π/K 3σ sep. at 6 GeV/c



dual Radiator RICH

Aerogel
z: 4cm
radius: 110 cm
air gap
0.3 mm acrylic filter

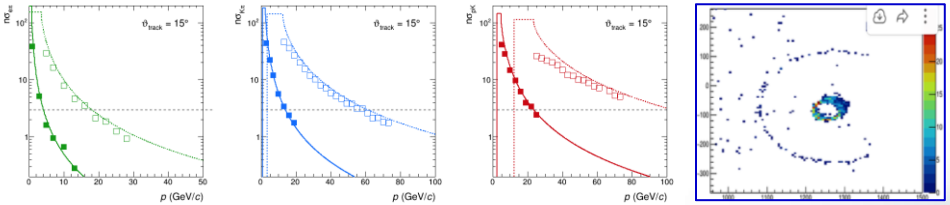
Spherical Mirrors
6 Azimuthal Sectors

C_2F_6 Gas Volume
120 cm length
radius: 185 cm
Tapered bore radius
Al vessel

Sensors tiled on spheres
→ SiPMs as Photonsensors

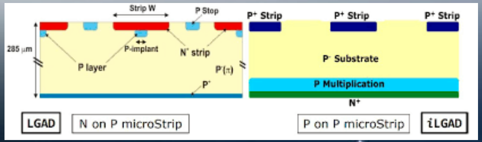
world's first at ePIC

π/K 3σ sep. at 50 GeV/c



AC-LGAD (Low Gain Avalanche Detector)
- 20-35 psec
- Accurate space point for tracking
- forward disk and central barrel
- R&D and PED by International consortium HEP & NP

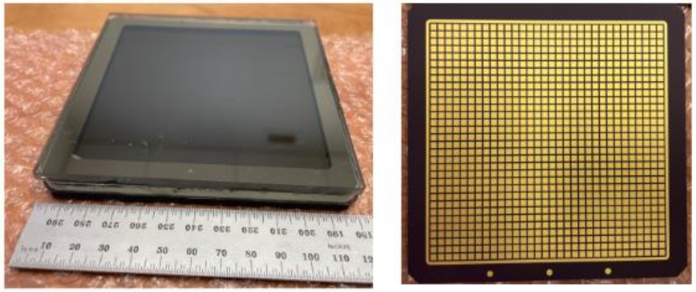
world's first at ePIC



ePIC paving the way to new era of single photon sensors for Cherenkov Imaging

HRPPDs: Large-size MCP-PMTs by INCOM

- Engineering contribution by ePIC
- 10 x 10 cm^2
- DC-DC coupled
- Being established within ePIC



DC-coupled HRPPDs by Incom Inc.

Establishing LAPPDs/HRPPDs as devices for RICHs and at the same time for ToF measurements and cooperating with industry on the engineering design

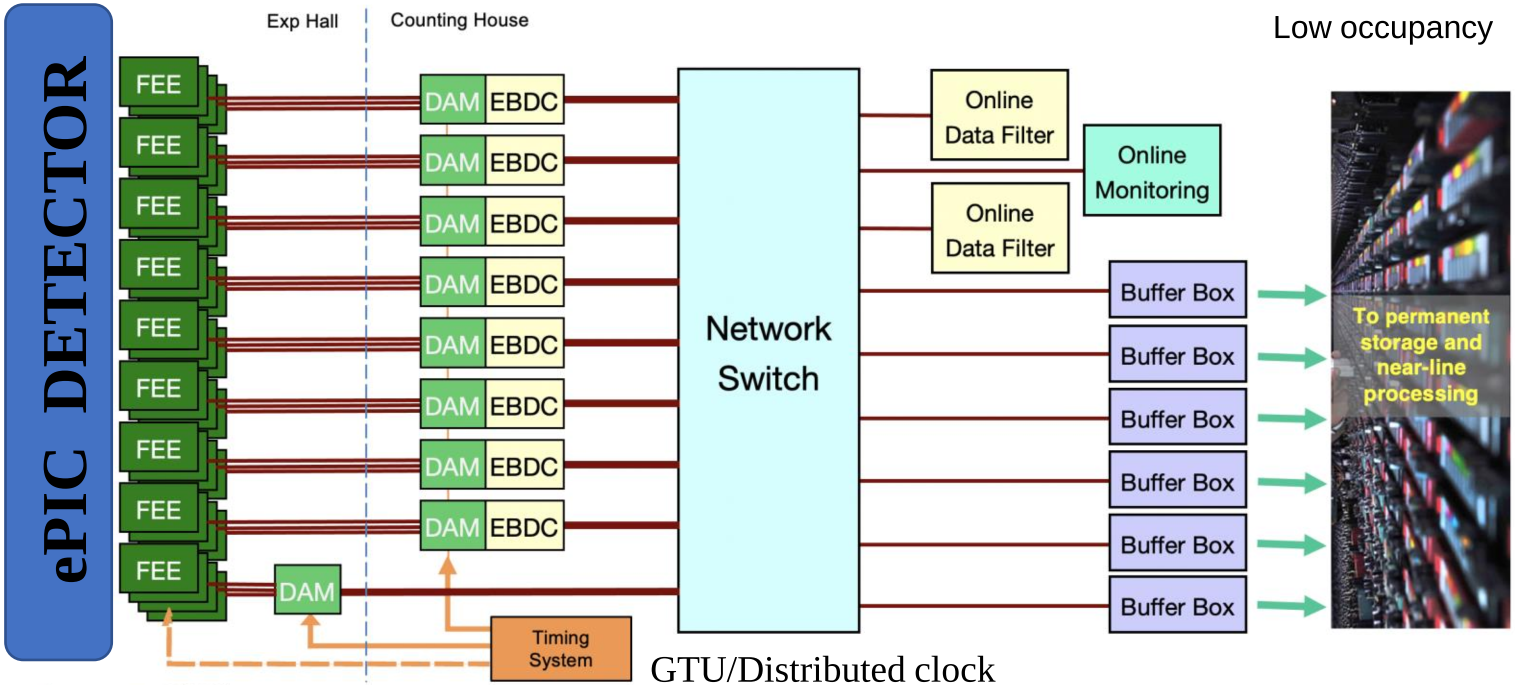
SiPMs as single photon detectors

- Never used so far for RICHes in experiments due to the dark-count rates increasing with radiation dose
- Robust R&D with ePIC:
  - Thermal annealing (in situ) demonstrated also in repeated cycles
  - SiPMs usage in RICHs in now an open path

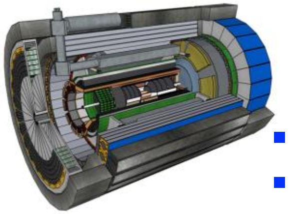
Using SiPMs as sensors for Cherenkov imaging devices is spear headed by the R&D of ePIC INFN groups

ePIC Streaming DAQ

Bunch Crossing ~ 10.2 ns/98.5 MHz
Interaction Rate ~500 kHz
Low occupancy



GTU/Distributed clock
(jitter ~5ps)



- No External trigger
- All collision data digitized but aggressively zero suppressed at FEB
- Low / zero deadtime
- Event selection can be based upon full data from all detectors (in real time, or later)
- Collision data flow is independent and unidirectional-> no global latency requirements
- Avoiding hardware trigger avoids complex custom hardware and firmware
- Data volume is reduced as much as possible at each stage ensuring that biases are controlled
- Integrate AI/ML as close as possible to subdetectors → cognizant Detector

Streaming Computing Model

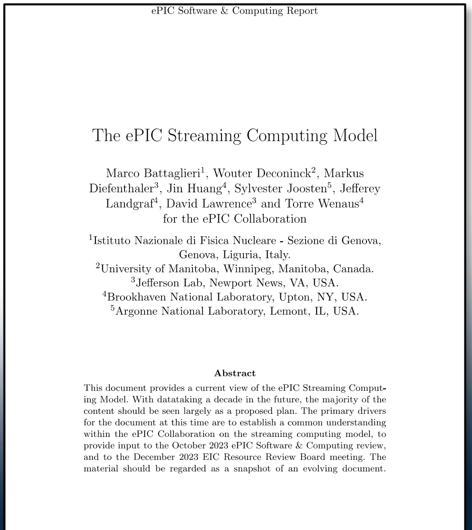
- Defined requirements and high-level design for a **computing model** that enables **rapid data processing for physics analyses.**
- **Compute-detector integration** using:

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

AI for autonomous alignment and calibration as well as reconstruction and validation.

Heterogeneous computing for acceleration.

- Started documenting a streaming computing model that can be redefined further with international partners.
- Initial version of the ePIC Streaming Computing Model has been presented in recent ePIC Software & Computing Review.



ePIC Software & Computing Report

The ePIC Streaming Computing Model

Marco Battaglieri[1], Wouter Deconinck[2], Markus Diefenthaler[3], Jin Huang[4], Sylvester Joosten[5], Jefferey Landgraf[4], David Lawrence[3] and Torre Wenaus[4]
for the ePIC Collaboration

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[2]University of Manitoba, Winnipeg, Manitoba, Canada.
[3]Jefferson Lab, Newport News, VA, USA.
[4]Brookhaven National Laboratory, Upton, NY, USA.
[5]Argonne National Laboratory, Lemont, IL, USA.

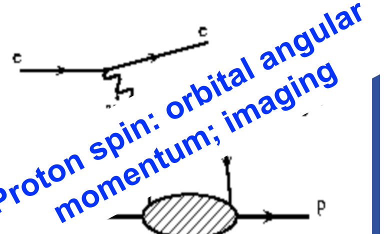
Abstract

This document provides a current view of the ePIC Streaming Computing Model. With datataking a decade in the future, the majority of the content should be seen largely as a proposed plan. The primary drivers for the document at this time are to establish a common understanding within the ePIC Collaboration on the streaming computing model, to provide input to the October 2023 ePIC Software & Computing review, and to the December 2023 EIC Resource Review Board meeting. The material should be regarded as a snapshot of an evolving document.

https://indico.bnl.gov/event/20960/contributions/82385/attachments/50619/86546/ePIC-StreamingComputingModel.pdf

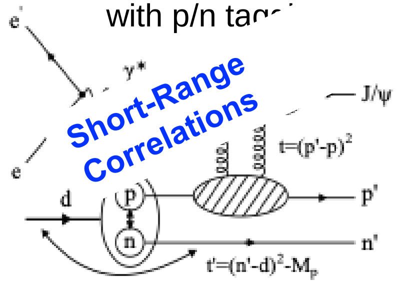
Far-forward physics at EIC

e+p DVCS



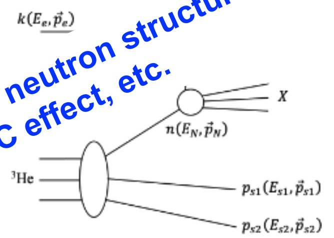
Proton spin: orbital angular momentum; imaging

e+d exclusive J/Psi with p/n tag



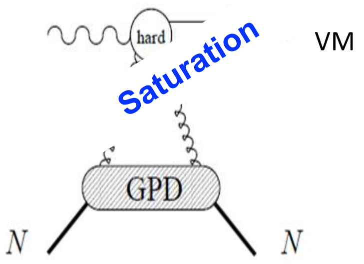
Short-Range Correlations

spectator tagging in light nuclei



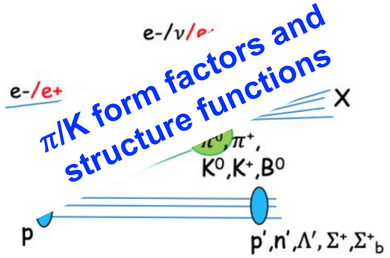
Free neutron structure, EMC effect, etc.

coherent/incoherent VM production



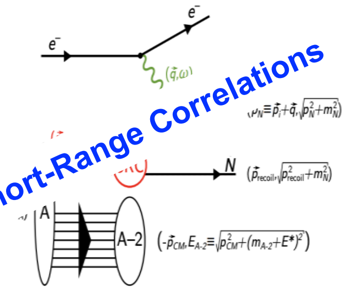
Saturation

Sullivan process



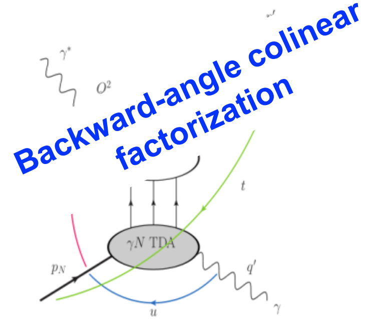
π/K form factors and structure functions

Quasi-elastic electron scattering



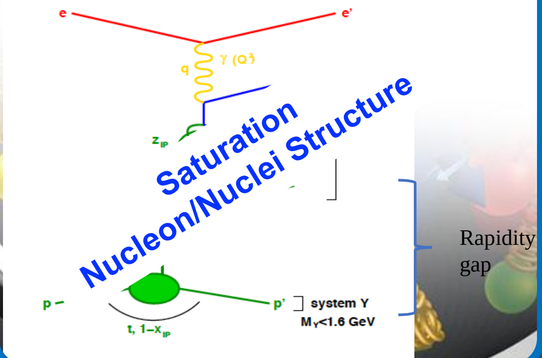
Short-Range Correlations

u-channel backward exclusive electroproduction



Backward-angle colinear factorization

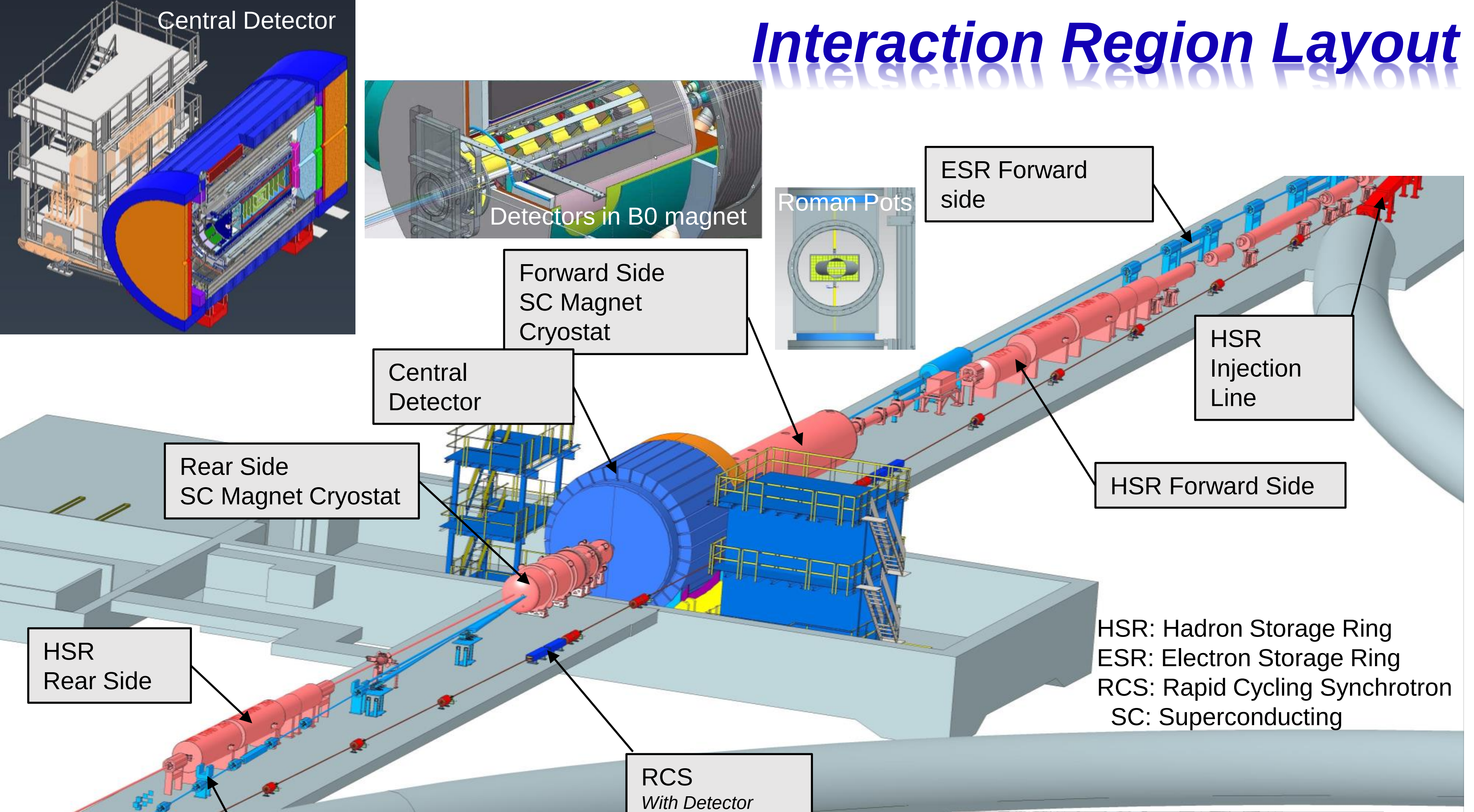
Diffraction



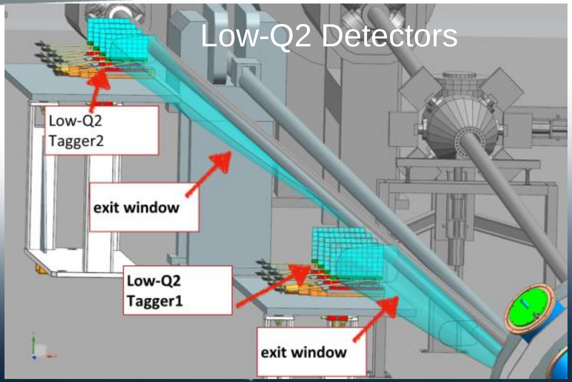
Saturation Nucleon/Nuclei Structure

All these processes require the detection of protons, neutrons, γ and hadrons at small scattering angles

Interaction Region Layout

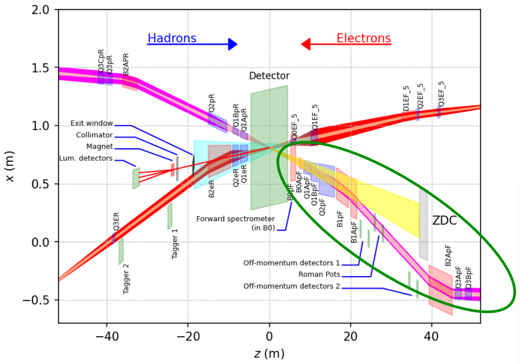


HSR: Hadron Storage Ring
ESR: Electron Storage Ring
RCS: Rapid Cycling Synchrotron
SC: Superconducting

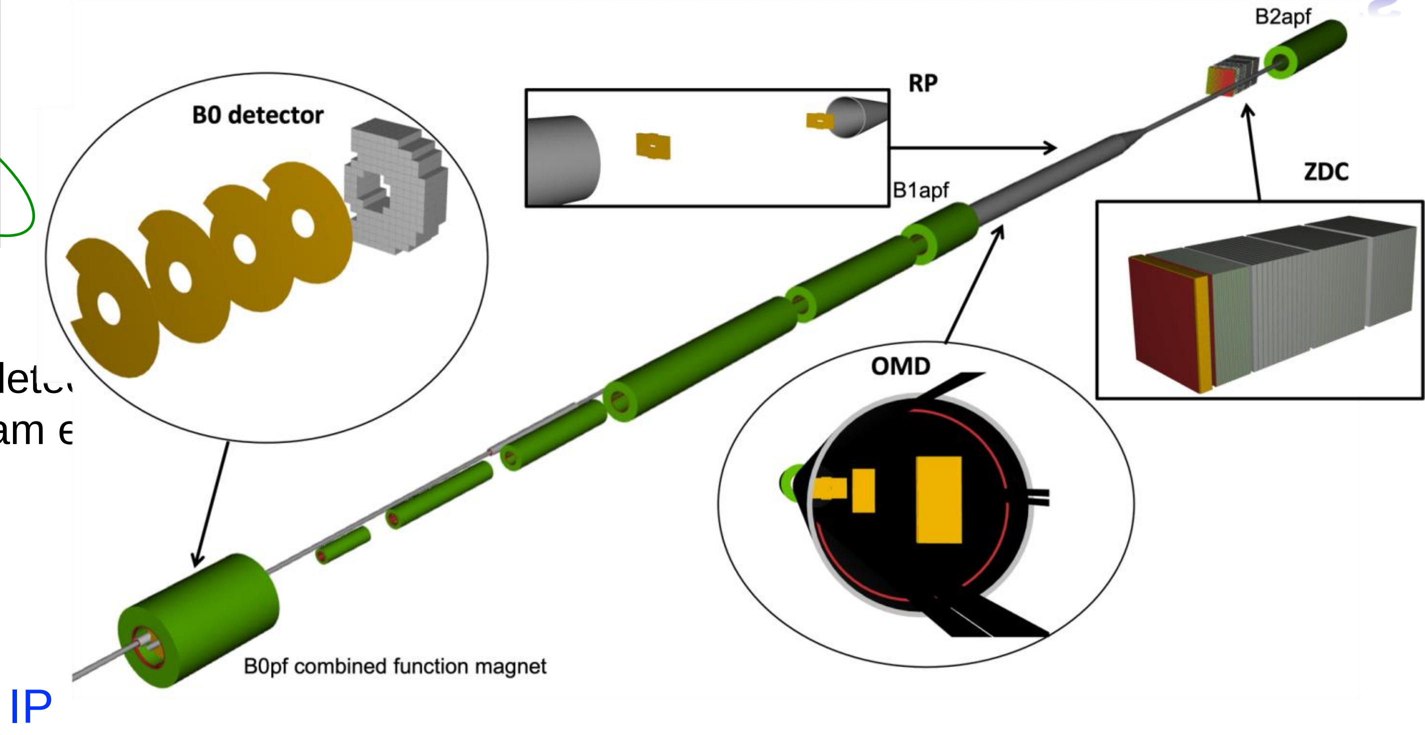


every cm counts… → integration and communication with accelerator team is crucial

Far –Forward Detectors



IP magnets & ancillary dete
GEANT including all beam e



Technologies defined

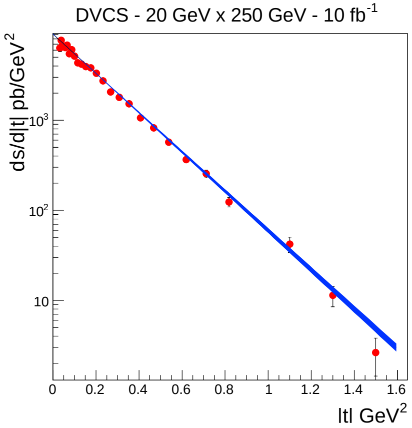
- Silicon: AC-LGAD
- B0-ECal: PbWO4
- ZDC:
  - ECAL (PbWO4)
  - HCAL (Steel+Sc.)

	Particles	Angle [mrad]		Distance from IP
B0-tracker	Charged particles Photons (tagged)	5.5 - 20		ca 6-7 m
Off-momentum	Charged particles	0-5.0	0.4< xL< 0.65	ca 23-25 m
Roman Pots	Protons Light nuclei	0*-5.0	0.6 < xL< 0.95	ca 27-30 m
ZDC	Neutrons Photons	0-4.0 (5.5)		ca 35 m

Impact of reduced scattered proton acceptance

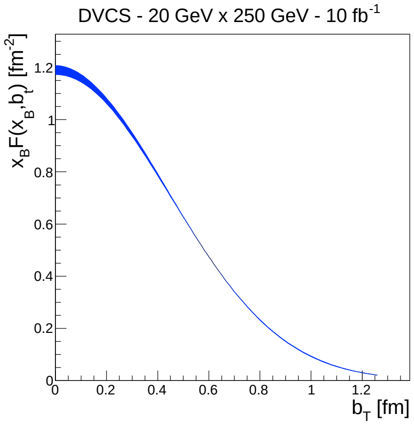
Measurement

Physics Observable



Plots from EIC WP:

Fourier Transform

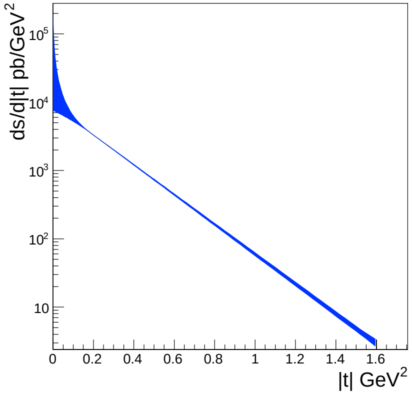


Requirement:

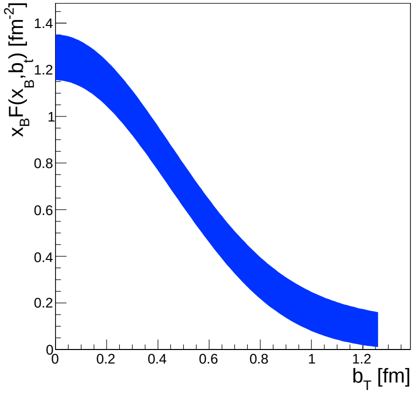
$\int L_{int} = 10 fb^{-1}$

$0.18 < p_t$ (GeV) < 1.3

$0.03 < |t|$ (GeV^2)< 1.6

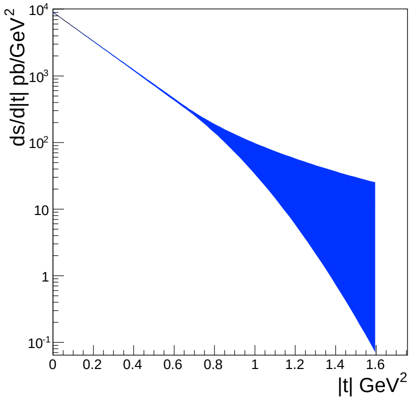


Plots with reduced lower p_t-acceptance

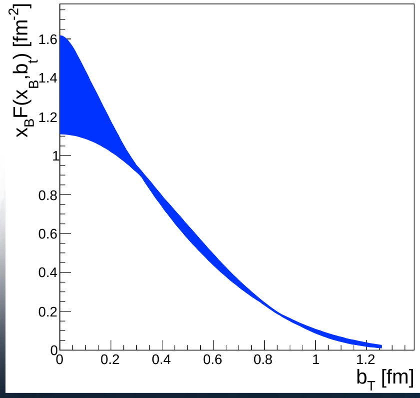


$\int L_{int} = 10 fb^{-1}$

$0.44 < |p_t|$ (GeV) < 1.3



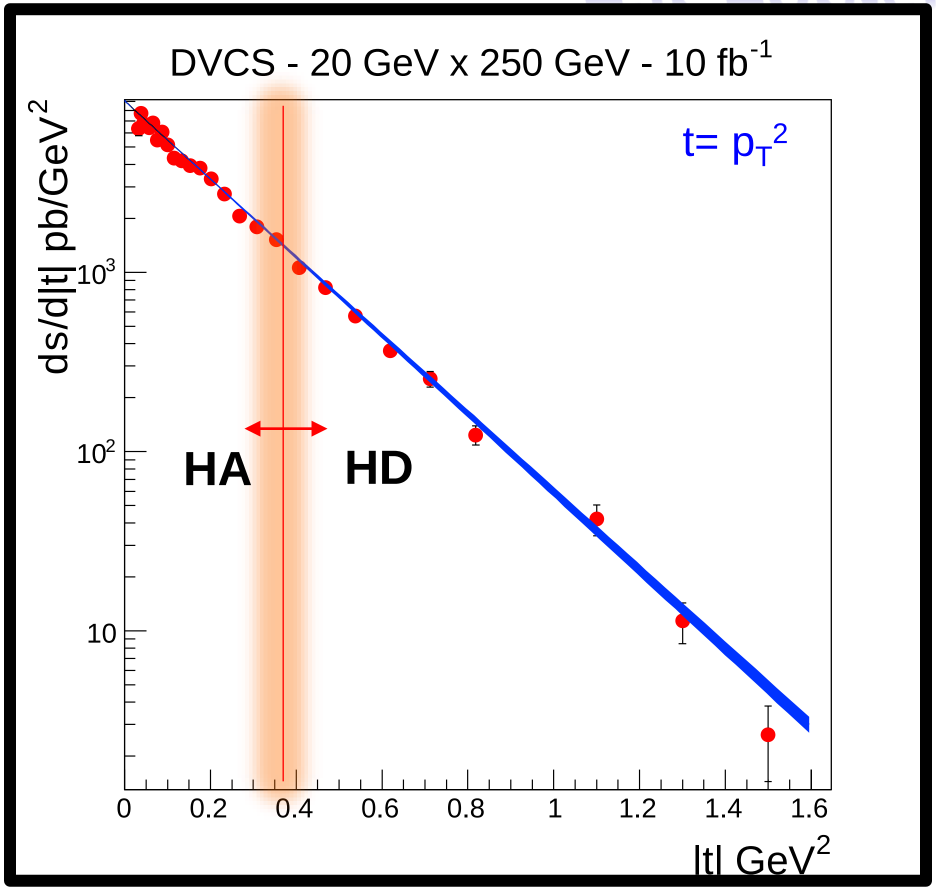
Plots with reduced high p_t-acceptance



$\int L_{int} = 10 fb^{-1}$

$0.18 < |p_t|$ (GeV) < 0.8

Far-Forward Detectors: Roman Pots



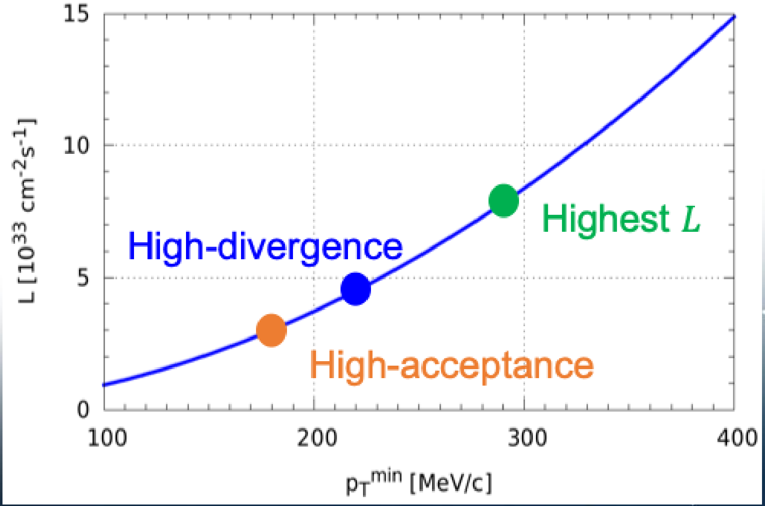
need two configurations:

→ high acceptance:
measure the low-t region
lowest t impacted by beam optics

→ high divergence
measure high-t tail
highest t reach driven by IR magnet design → bore size

Note: $\boxed{\sigma(z) = \sqrt{\varepsilon \cdot \beta(z))}}$

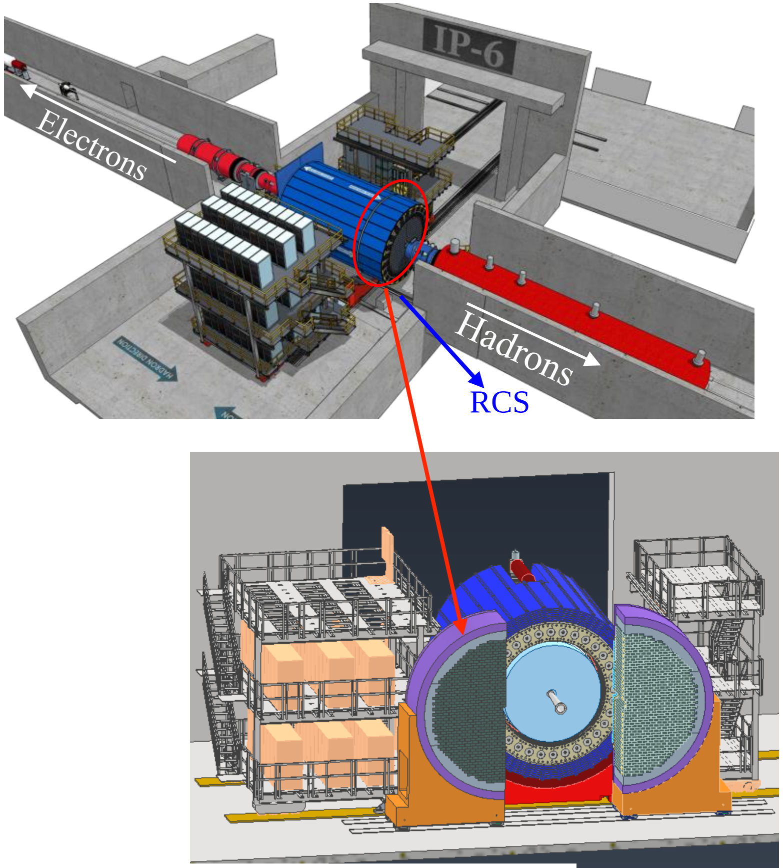
→ high luminosity and low p_T acceptance for forward scattered particles are anticorrelated
Luminosity increases if $\beta^* \downarrow$ &divergence $\sigma'^* \uparrow$
Highest luminosity → smallest low p_T acceptance at RPs

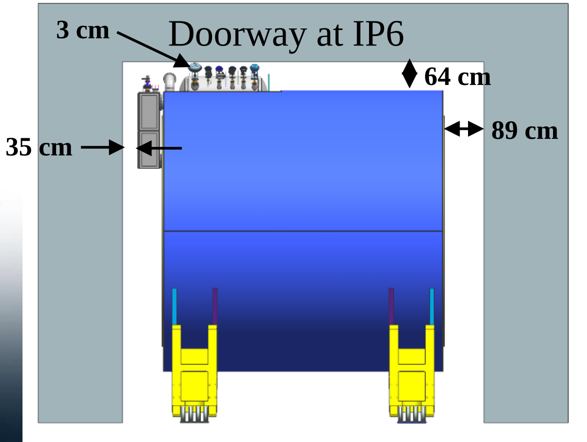


IR-Integration Constrains

Space Constrains:

- ❑ Detector: -4.5 m – IP – +5m not negotiable
- ❑ Detector aligned with electron beam
  → 8 mrad rotation
- ❑ <50 cm space to 1st IR-magnets occupied by vacuum pumps, valves, …..
- ❑ IP moved 81 cm towards ring inside compared to RHIC; y: 432 cm above floor
- ❑ RCS to IP: radial distance 335.2 cm at a height of 372 cm above floor
  - ➢ Maximum outer radius ~ 3.2 m
- ❑ limited installation possible in Collider Hall
  - ➢ endcap hadron calorimeters need to be split transverse to beam pipe for access to barrel part of detector
  - ➢ RCS vacuum needs to be broken
- ❑ 9.5 m long detector does not fit through the door
  - ➢ Door-Size: 823 cm x 823 cm
  - ➢ endcaps need to remain in collider hall, if central detector rolls in assembly hall



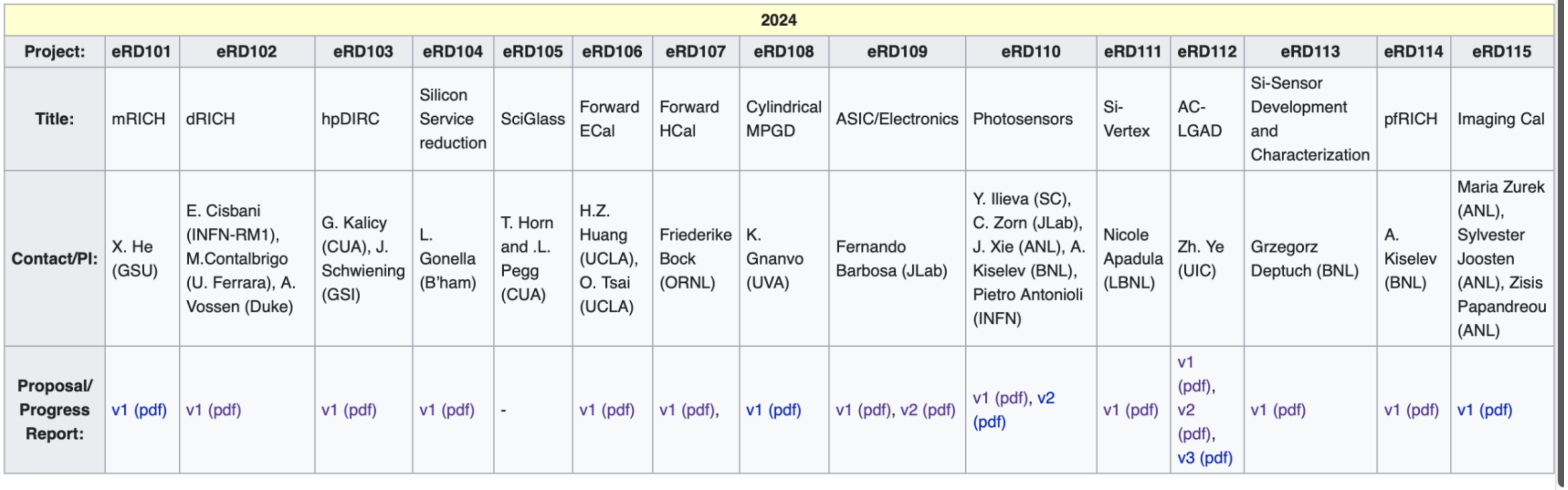


EIC Detector R&D Programs

Two tier Detector R&D program is critical for success of the EIC facility

- Generic EIC Detector R&D program (2011 – 2021)
    - Excellent experience (https://wiki.bnl.gov/conferences/index.php/EIC_R%25D)
    - Reduced the overall Risk level of EIC detector technology to Low/Moderate
    - Engaged 75 institutions (50% domestic, 50% international) from 10 countries
- DOE/NP has restarted generic detector R&D program (2021 - …..) (https://www.jlab.org/research/eic_rd_prgm)
- R&D as part under EIC Project

https://wiki.bnl.gov/conferences/index.php?title=Proposals



2024														
Project:	**eRD101**	**eRD102**	**eRD103**	**eRD104**	**eRD105**	**eRD106**	**eRD107**	**eRD108**	**eRD109**	**eRD110**	**eRD111**	**eRD112**	**eRD113**	**eRD114**	**eRD115**
Title:	mRICH	dRICH	hpDIRC	Silicon Service reduction	SciGlass	Forward ECal	Forward HCal	Cylindrical MPGD	ASIC/Electronics	Photosensors	Si-Vertex	AC-LGAD	Si-Sensor Development and Characterization	pfRICH	Imaging Cal
Contact/PI:	X. He (GSU)	E. Cisbani (INFN-RM1), M.Contalbrigo (U. Ferrara), A. Vossen (Duke)	G. Kalicy (CUA), J. Schwiening (GSI)	L. Gonella (B'ham)	T. Horn and .L. Pegg (CUA)	H.Z. Huang (UCLA), O. Tsai (UCLA)	Friederike Bock (ORNL)	K. Gnanvo (UVA)	Fernando Barbosa (JLab)	Y. Ilieva (SC), C. Zorn (JLab), J. Xie (ANL), A. Kiselev (BNL), Pietro Antonioli (INFN)	Nicole Apadula (LBNL)	Zh. Ye (UIC)	Grzegorz Deptuch (BNL)	A. Kiselev (BNL)	Maria Zurek (ANL), Sylvester Joosten (ANL), Zisis Papandreou (ANL)
Proposal/ Progress Report:	v1 (pdf)	v1 (pdf)	v1 (pdf)	v1 (pdf)	-	v1 (pdf)	v1 (pdf),	v1 (pdf)	v1 (pdf), v2 (pdf)	v1 (pdf), v2 (pdf)	v1 (pdf)	v1 (pdf), v2 (pdf), v3 (pdf)	v1 (pdf)	v1 (pdf)	v1 (pdf)

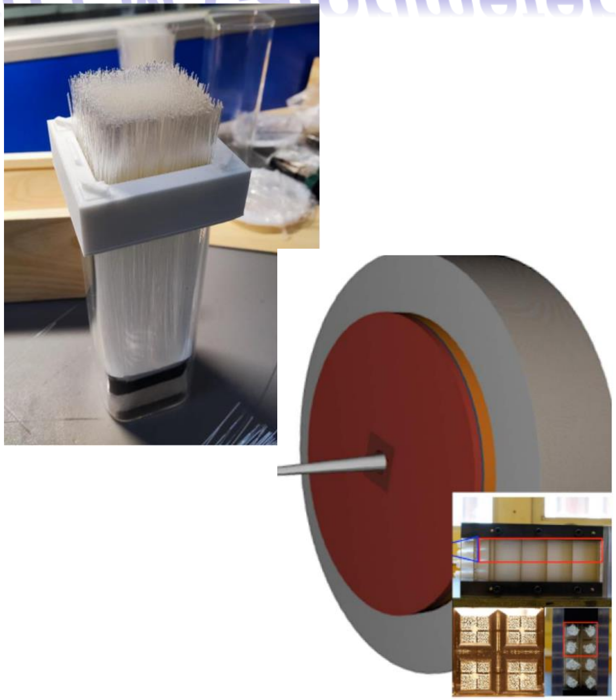
Strong synergies with CERN

CERN – EIC R&D Day November 2021 https://indico.cern.ch/event/1063927/

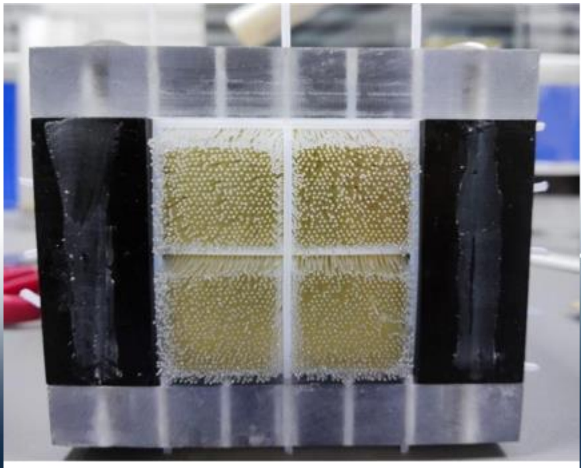
- MAPS: ALICE-3 – ITS-3 development
- MPGD: long-term CERN R&D program RD51
- PID: LHC-b and ALICE-3
- Photon-sensors: LAPPDs with LHC-b
- DAQ: strong developments on streaming DAQs for all LHC experiments
- AI/ML and high-performance distributed computing

Example: eRD106 – Forward EM Calorimeter

- **Milestones**
  - FY23: Optimize uniformity and efficiency of light collection with SiPM readout
- **Status**
  - The major delay at UCLA site where university grant/contract office was negotiating the terms of agreement with BNL contract office (3-4 month delay)
  - Comparison of new Bicron with Kuraray fibers 1/15/23
  - Shear tests complete 3/30/23
  - Acquire Sc. fibers, W powder, meshes and tooling for prototype test 02/27/23
  - Start production of blocks for test beam prototype 04/01/23
  - Perform UV scan to check uniformity LY 05/30/23
  - QA Production all blocks done 07/15/23
  - Compression tests complete 7/30/23
  - Mechanical/optical/electrical integration with readout complete 8/15/23
  - Light guides for prototype produced 8/30/23
- N.B. Sc. Fibers are LLP items



High granularity W/SciFi **forward EMCal**



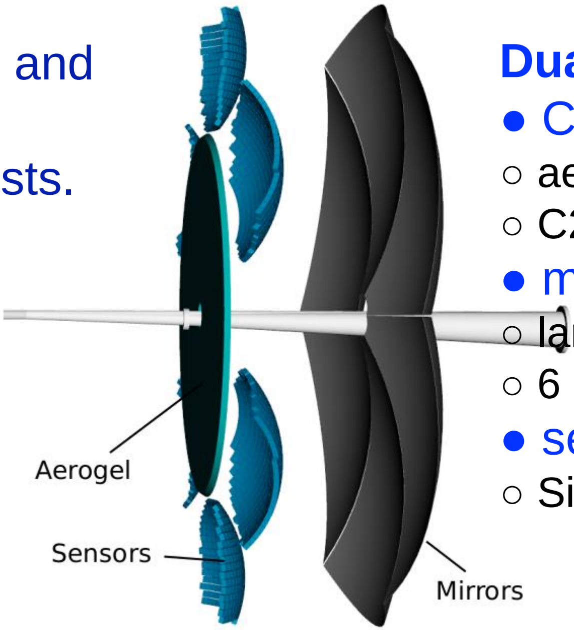
Example: eRD102 – dRICH

Milestones

- FY23: Characterization of realistic mirror and aerogel components and assessment of dRICH prototype performance in beam tests.

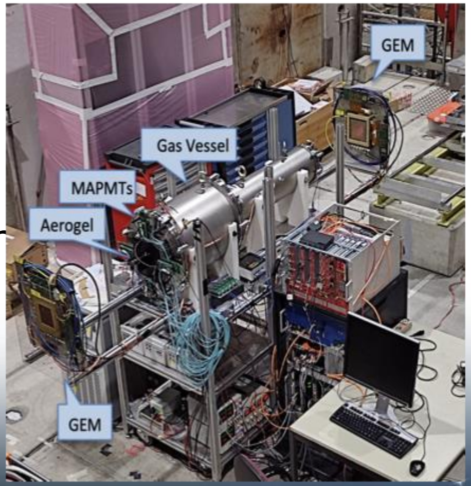
Status

- Characterization of realistic mirror and aerogel components, achieved (*April 23*)
- Projected performance of the baseline detector as integrated into ePIC achieved with the general revision of the dRICH simulation framework (*June 23*)
- Assessment of the dRICH prototype performance with the EIC-driven detection plane, for which a new test-beam campaign has been organized (October 23) with the primary scope to operate the new EIC-driven readout plane (SiPM sensors and ALCOR digitalization).

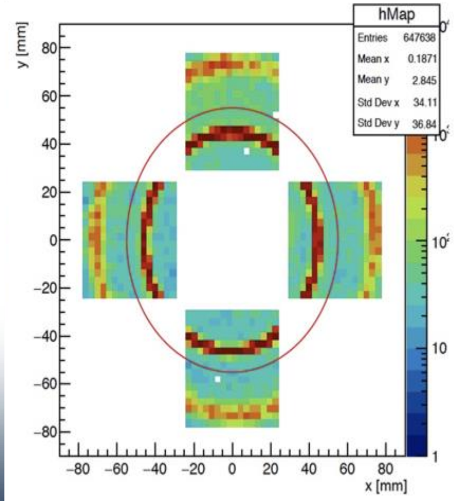


Dual RICH

- ● Cherenkov radiator
  - ○ aerogel
  - ○ C2F6
- ● mirrors
  - ○ large outward reflecting
  - ○ 6 open sectors
- ● sensors
  - ○ SiPM (~1T field)



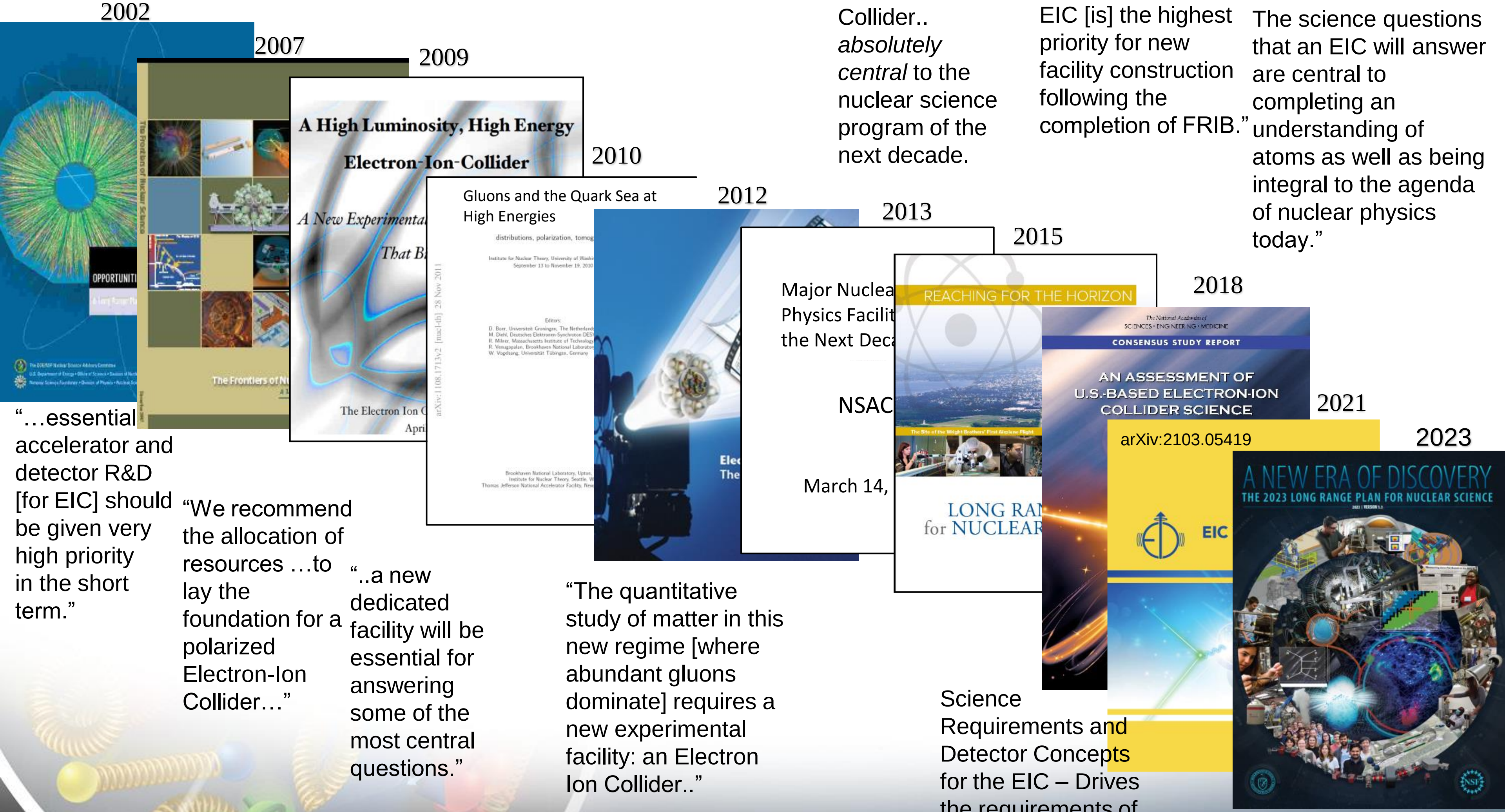
dRICH baseline prototype at the SPS beam



The EIC Project

Created by Håkan Forss @hakanforss http://hakanforss.wordpress.com

The EIC Scientific Foundation was Built Over two Decades



"…essential accelerator and detector R&D [for EIC] should be given very high priority in the short term."

"We recommend the allocation of resources …to lay the foundation for a polarized Electron-Ion Collider…"

"..a new dedicated facility will be essential for answering some of the most central questions."

"The quantitative study of matter in this new regime [where abundant gluons dominate] requires a new experimental facility: an Electron Ion Collider.."

Electron-Ion Collider.. *absolutely central* to the nuclear science program of the next decade.

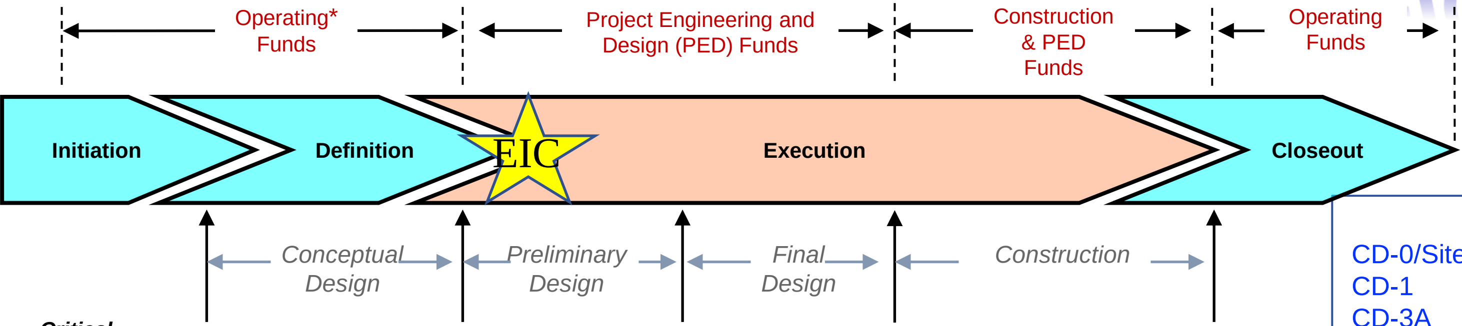
"a high-energy high-luminosity polarized EIC [is] the highest priority for new facility construction following the completion of FRIB."

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."

Science Requirements and Detector Concepts for the EIC – Drives the requirements of EIC detectors

We recommend the expeditious completion of the EIC as the highest priority for facility construction.

EIC Schedule



Critical Decisions

CD-0
Approve Mission Need

CD-2
Approve Performance Baseline (PB)

CD-3
Approve Start of Construction or Execution

CD-4
Approve Start of Operations or Project Completion

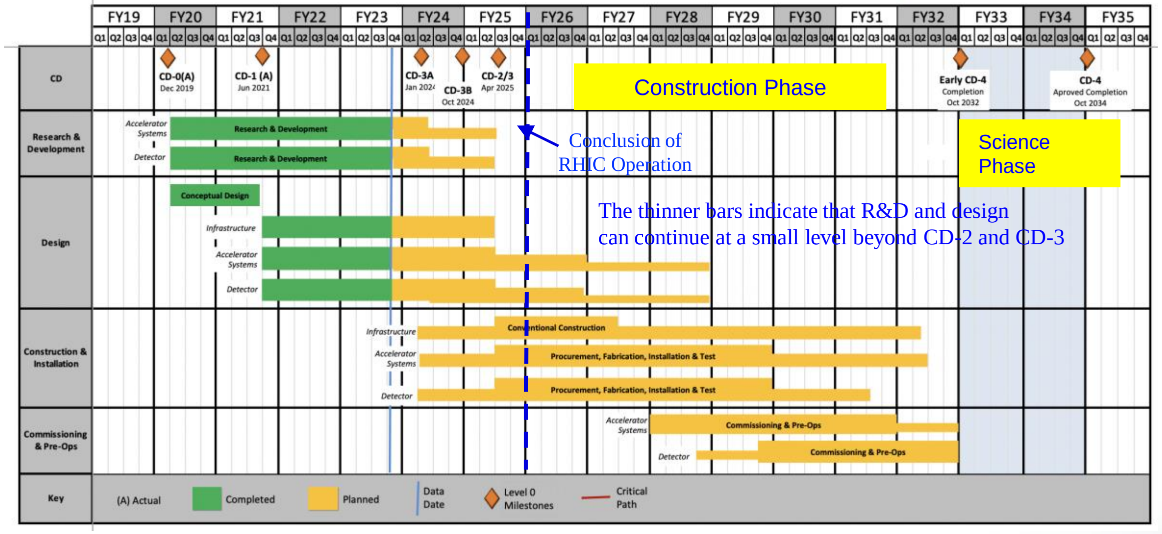
EIC Critical Decision Plan

CD-0/Site Selection	December 2019 ✓
CD-1	June 2021 ✓
CD-3A	January 2024
CD-3B	**October 2024**
CD-2/3	**April 2025**
early CD-4	October 2032
CD-4	**October 2034**

CD-3A/3B:
Approve start of long-lead procurements
CD-3A items passed final design review
All interfaces related to them are frozen
Waiting for ESAAB meeting for authorization

CD-2:
Approve prelim. design for all subdetectors
Design Maturity: >60%
Need “pre-”TDR (or draft TDR)
Baseline project in scope, cost, schedule

CD-3:
Approve final design for all subdetectors
Design Maturity: ~90%
Need full TDR



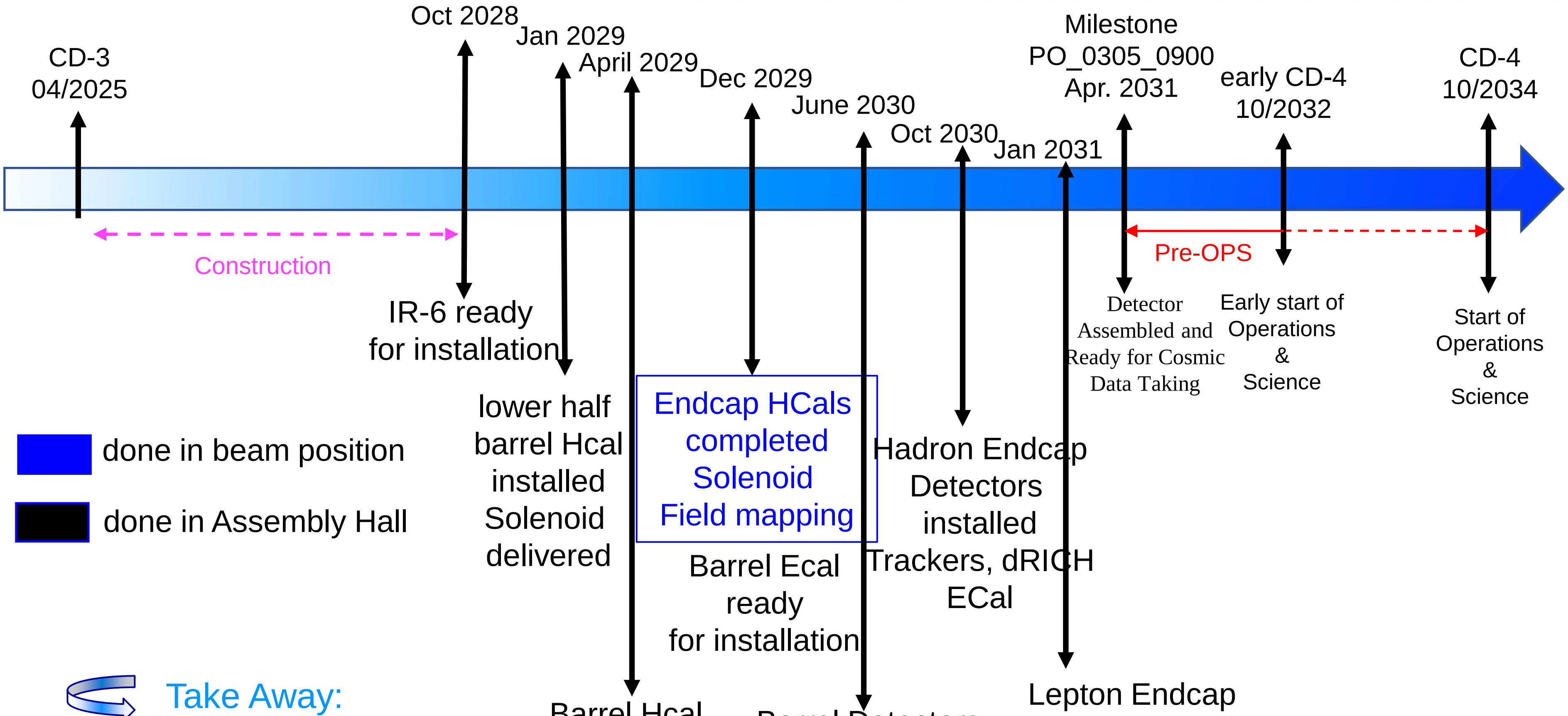
Conclusion of RHIC Operation

The thinner bars indicate that R&D and design can continue at a small level beyond CD-2 and CD-3

<u>Speculation</u> based on EIC accelerator complexity, on still uncertain FY24 and FY25 budget scenarios, and projected RHIC FY24-25 run:

- CD-3B Approval Dec. 2024
- RHIC operations conclude at end of FY25, in September 2025
- CD-2/3 Approval Dec. 2025, Possibility of CD-3C as needed.

High Level Installation Schedule



CD-3
04/2025

Construction

Oct 2028

IR-6 ready
for installation

Jan 2029

lower half
barrel Hcal
installed
Solenoid
delivered

April 2029

Dec 2029

Endcap HCals
completed
Solenoid
Field mapping

Barrel Ecal
ready
for installation

June 2030

Oct 2030

Hadron Endcap
Detectors
installed
Trackers, dRICH
ECal

Jan 2031

Milestone
PO_0305_0900
Apr. 2031

Detector
Assembled and
Ready for Cosmic
Data Taking

Pre-OPS

early CD-4
10/2032

Early start of
Operations
&
Science

CD-4
10/2034

Start of
Operations
&
Science

🟦 done in beam position

⬛ done in Assembly Hall

Barrel Hcal
& Solenoid
installed
followed by low
power test

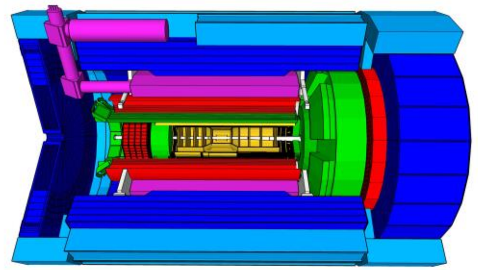
Barrel Detectors
installed
ECal, DIRC,
ToF, Trackers

Lepton Endcap
Detectors
installed
Trackers, bRICH
ECal

Take Away:

- Solenoid and Barrel HCal need to be ready by Jan 2029
- all other subdetectors need to be ready between 06/29 to 06/30 depending on their location in the detector

Note that this assumes the present best-known schedule, dates may shift with schedule/funding actuals



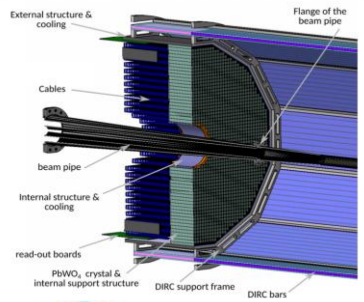
CD-3A Scope Overview for Detector Systems

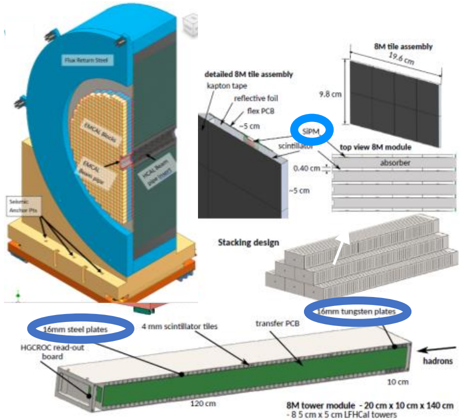
Detector Systems CD-3A Scope

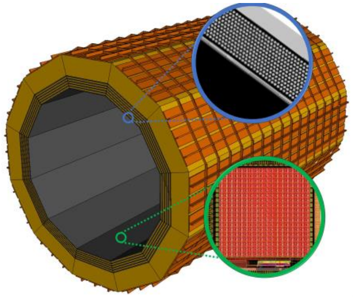
- WBS 6.10.05: Lead Tungstate Crystals for the Detector Backward EM Calorimeter
    - CD-3A scope is first two years of procurements (1500 pieces)
- WBS 6.10.05: Scintillating Fibers for the Detector Barrel and Forward EM Calorimeters
    - CD-3A scope is 1875 km first of four phases
- WBS 6.10.06: Silicon Photomultipliers for the Detector Forward Hadronic Calorimeter
    - CD-3A scope is one phase (320K SiPMs) out of two for the forward Hadron Calorimeter
- WBS 6.10.06: Steel and Tungsten Plates for the Detector Forward Hadro Calorimeter
    - CD-3A scope is first of two phases (~50%)
- WBS 6.10.07: Detector Solenoid Magnet Design and Fabrication and Conductor
    - CD-3A scope is for the conductor and the full magnet construction.

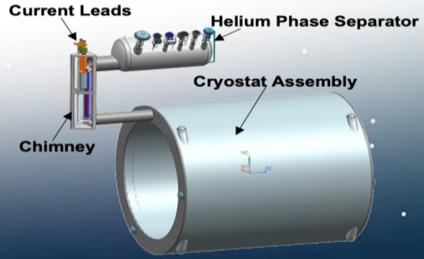
- Designs driving CD-3A Detector Systems scope are stable – final des reviews are completed for all LLP scope. Review committees concurı is minimal risk of change that could impact CD-3A LLPs following cor award.

- CD-3A Detector System scope justifications are based on:
    - Reduction of cost and technical risk
    - Limited world-wide vendors
    - Production times and capability and/or labor-intensive manufacturing tasks
    - Evade competition by other projects around the world









Let’s get to work and built the EIC

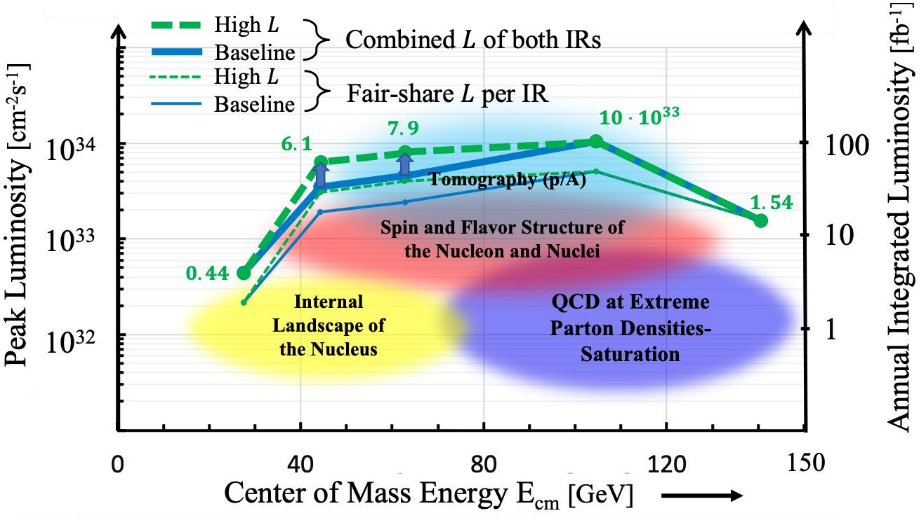
Please join us

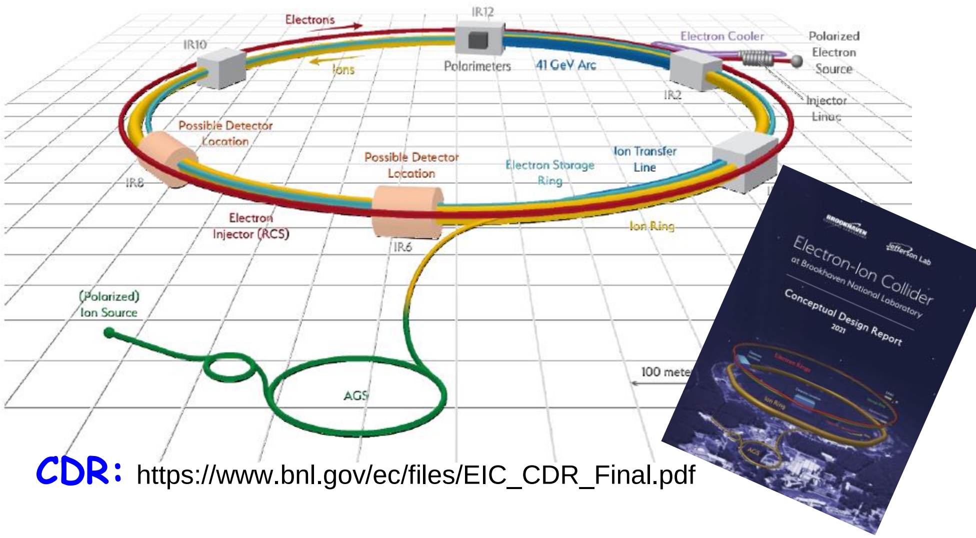
Engineers, Designers, Technicians, Administrators, Experimentalists, Theorists, Accelerator Physicists, ……

Jobs:
BNL: https://jobs.bnl.gov/search-jobs/eic?orgIds=3437&kt=1
JLab: https://www.jlab.org/recruiting
Science: https://www.bnl.gov/eic/


BACK UP

EIC Machine Parameters

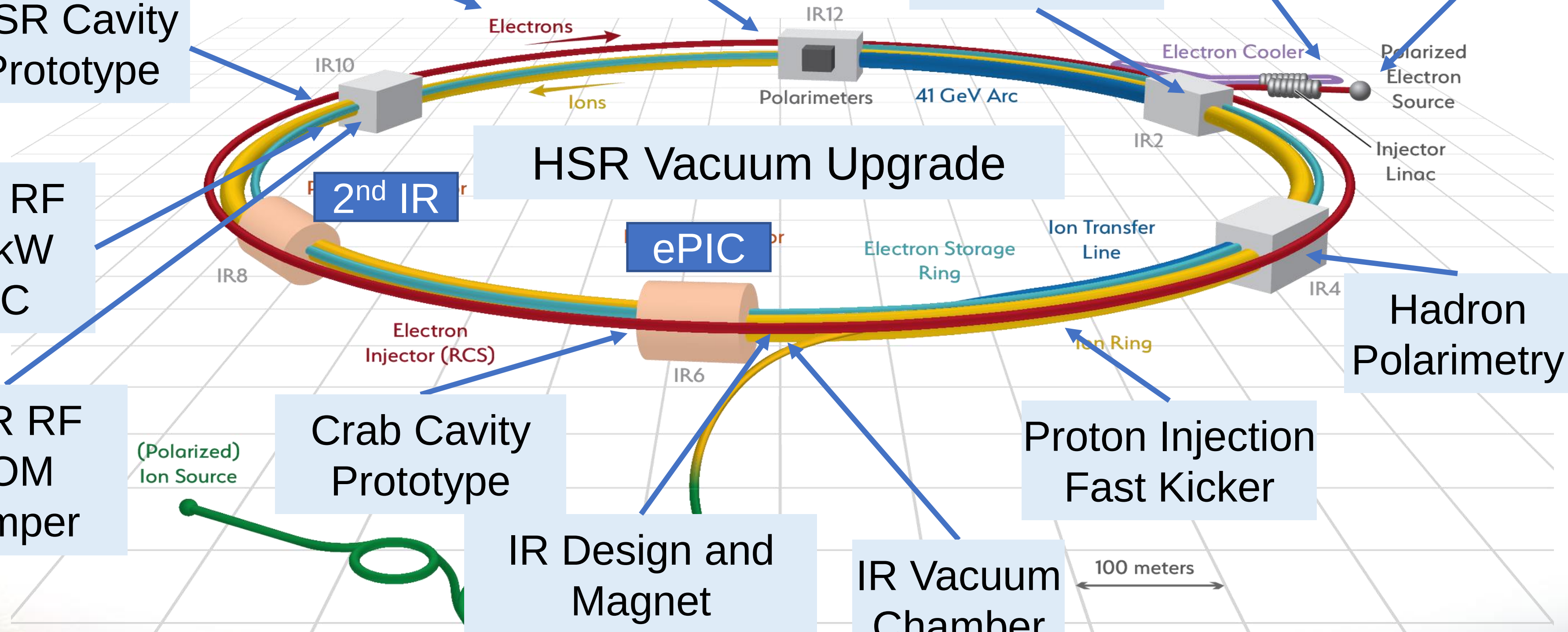




CDR: https://www.bnl.gov/ec/files/EIC_CDR_Final.pdf

Double Ring Design Based on Existing RHIC Facilities	
Hadron Storage Ring: 40, 100 - 275 GeV	**Electron Storage Ring: 5 - 18 GeV**
RHIC Ring and Injector Complex: p to Pb	9 MW Synchrotron Radiation
1A Beam Current	Large Beam Current - 2.5 A
10 ns bunch spacing and 1160 bunches	
Light ion beams (p, d, ^{3}He) polarized (L,T)	Polarized electron beams
Nuclear beams: d to U	**Electron Rapid Cycling Synchrotron**
Requires Strong Cooling: new concept →CEC	Spin Transparent Due to High Periodicity
One High Luminosity Interaction Region(s)	
25 mrad Crossing Angle with Crab Cavities	

Accelerator Science and Technology – Ongoing EIC R&D



ESR Vacuum R&D

Electron Injection Fast Kicker

Cooler Electron Source

Strong Cooling

Polarized e^- Source

ESR Cavity Prototype

HSR Vacuum Upgrade

2nd IR

ePIC

ESR RF 500kW FPC

Hadron Polarimetry

ESR RF HOM Damper

Crab Cavity Prototype

Proton Injection Fast Kicker

IR Design and Magnet Prototyping

IR Vacuum Chamber

Existing tunnel and experiment halls

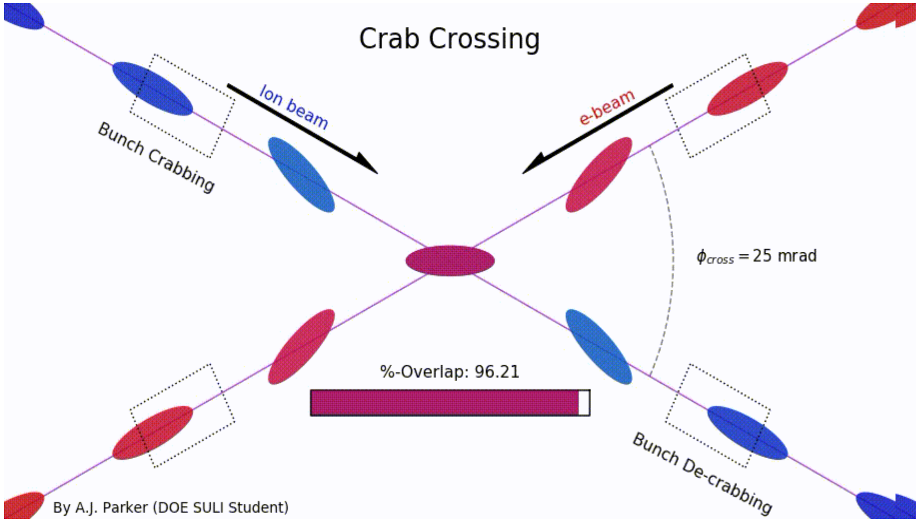
Why a Crossing Angle

- ❑ Brings focusing magnets close to IP
  → high luminosity
- ❑ Beam separation without separation dipoles
  → reduced synchrotron radiation background

But significant loss of luminosity

Solution: Crab crossing

- ❑ Head-on collision geometry is restored by rotating the bunches before colliding (“crab crossing”)
- ❑ Bunch rotation (“crabbing”) is accomplished by transversely deflecting RF resonators (“crab cavities”)
- ❑ Actual collision point moves laterally during bunch interaction

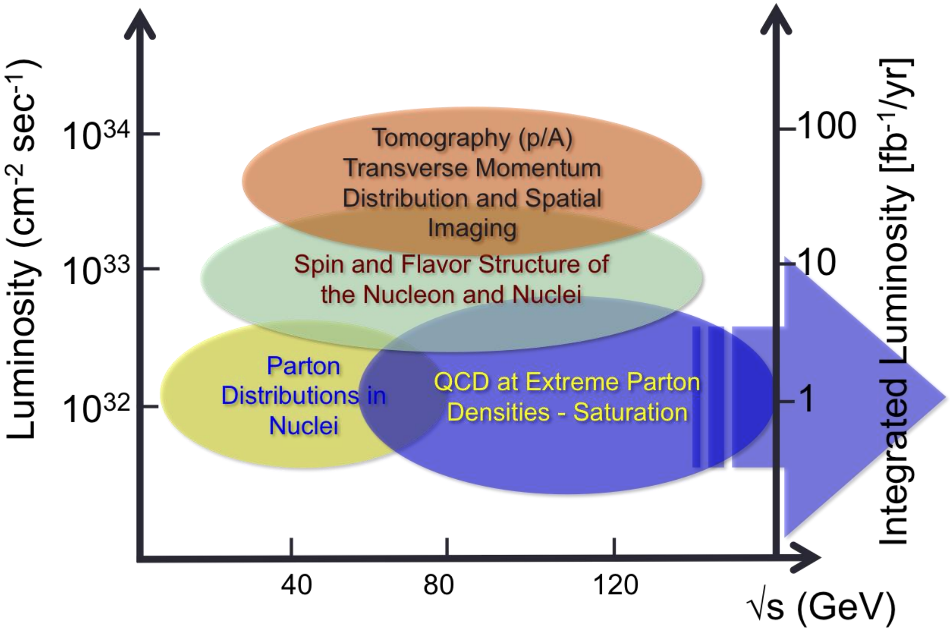


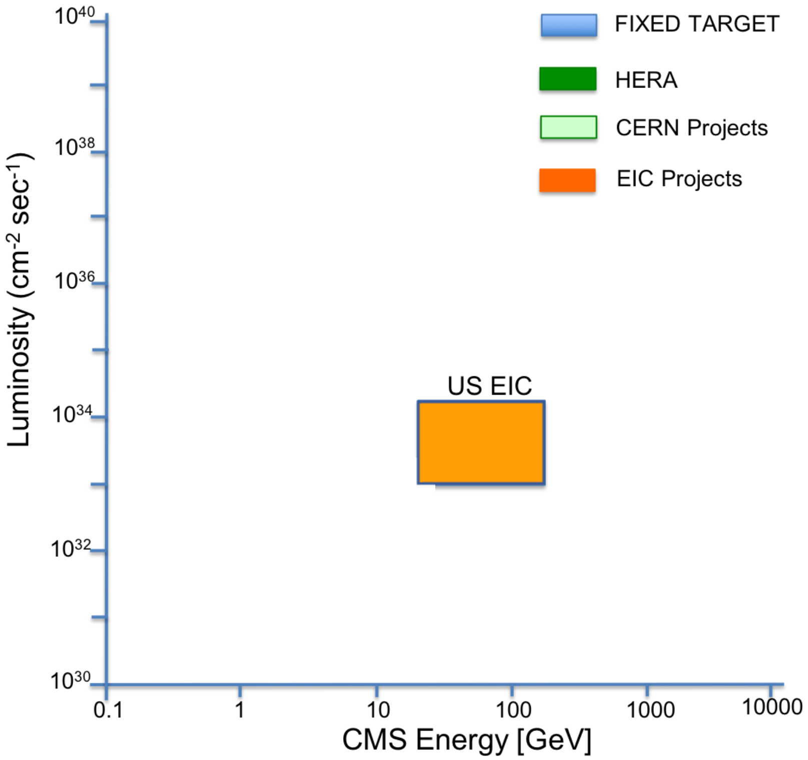
By A.J. Parker (DOE SULI Student)

→ Completely new concept for a collider

What is needed experimentally?

Luminosity - √s Energy and EIC Physics:





US-EIC:
polarization, ion species together with its luminosity and √s coverage makes it a completely unique machine world-wide.

What is needed experimentally?

experimental measurements categories to address EIC physics:

Parton Distributions in nucleons and nuclei

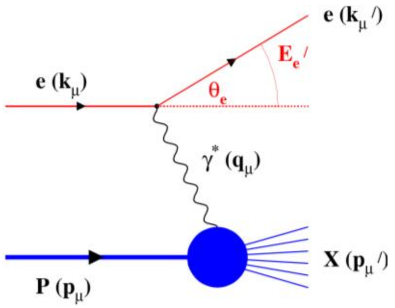
QCD at Extreme Parton Densities - Saturation

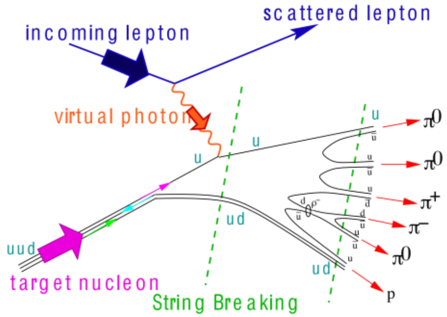
Spin and Flavor structure of nucleons and nuclei

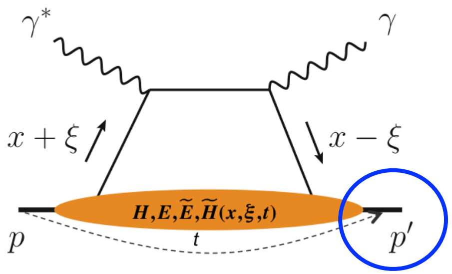
Tomography Transverse Momentum Dist.

QCD at Extreme Parton Densities - Saturation

Tomography Spatial Imaging







inclusive DIS

- measure scattered lepton

→ event kinematics
  - → e-ID: e/h separation
  - → reach to lowest x, Q^2 impacts Interaction Region design

semi-inclusive DIS

- measure scattered lepton and hadrons in coincidence
- multi-dimensional binning: x, Q^2, z, p_T, Θ
  - → particle identification over entire kinematic region is critical
  - → Jets: excellent E_T, jet-energy scale

exclusive processes

- measure all particles in event
- multi-dimensional binning: x, Q^2, t, Θ
- proton p_t: 0.2 - 1.3 GeV
  - → cannot be detected in main detector
  - → strong impact on Interaction Region design

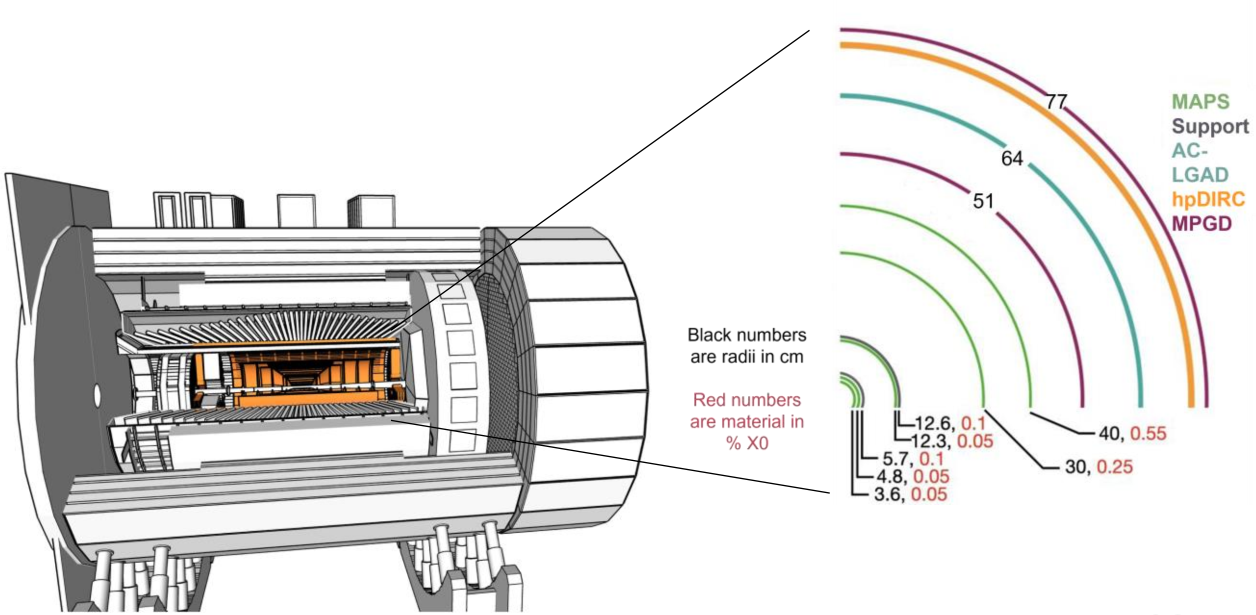
$\int Ldt$: 1 fb^{-1}

10 fb^{-1}

10 - 100 fb^{-1}

machine & detector requirements

ePIC Tracking Detectors



Black numbers are radii in cm

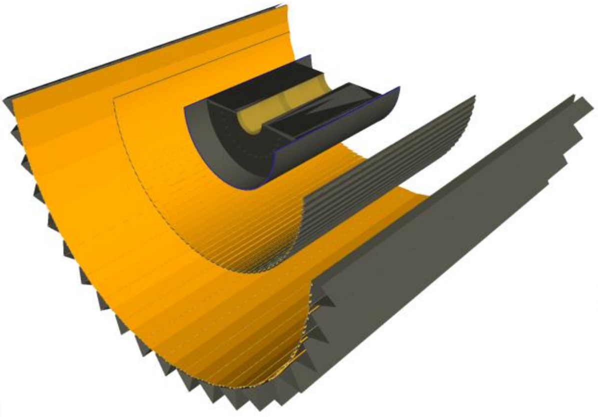
Red numbers are material in % X0

Si Tracker based on ALICE ITS3 65nm MAPS sensors.

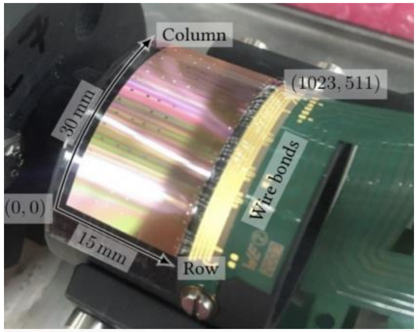
Five layers in barrel, supplemented by MPGDs for pattern recognition.

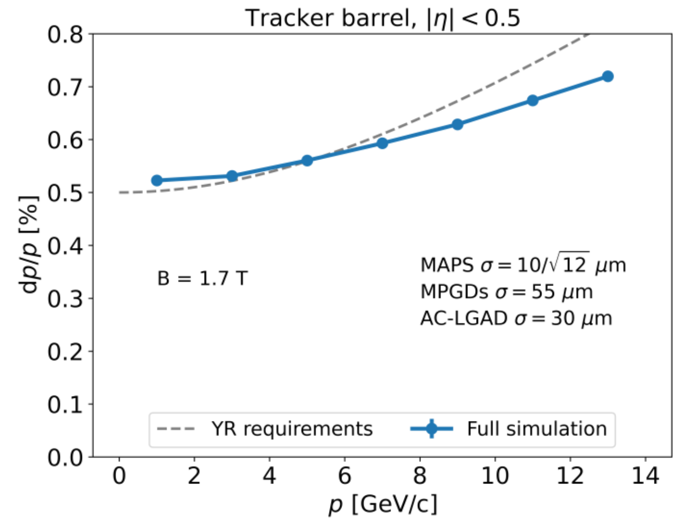
Five discs in forward/backward directions (+MPGD in forward)

Meets EICUG Yellow Report design requirements.



First “µITS3” assembly at CERN



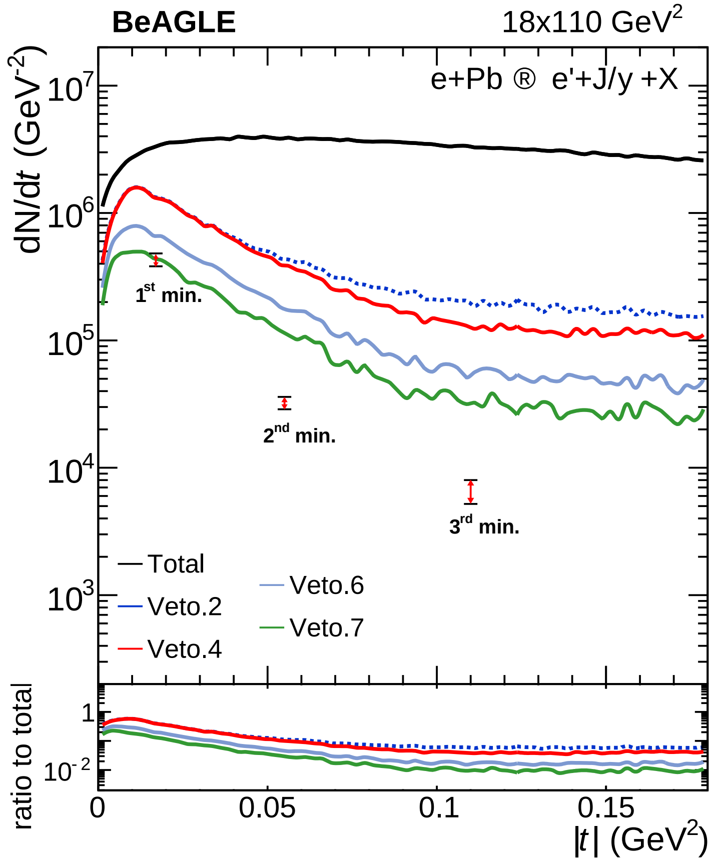


IR Requirements from Physics

<table>
<tr><th></th><th>Hadron</th><th>Lepton</th></tr>
<tr><td>Machine element free region</td><td colspan="2">High Luminosity → beam elements need to be close to IP
EIC: +/- 4.5 m for main detector
beam elements $< 1.5^o$ in main detector volume</td></tr>
<tr><td>Beam pipe</td><td colspan="2">Low mass material i.e. Beryllium</td></tr>
<tr><td>Integration of Detectors</td><td>Local Polarimeter</td><td>Low Q^2-tagger
Acceptance: $Q^2 < \sim 0.1$ GeV</td></tr>
<tr><td>Zero Degree Calorimeter</td><td>60cm x 60cm x 2m @ ~30 m</td><td></td></tr>
<tr><td>scattered proton/neutron acc.
all energies for ep</td><td>Proton:
$0.18 \text{ GeV} < p_t < 1.3$ GeV
$0.5 < x_L < 1$ ($x_L = E'_p/E_{Beam}$)
Neutron: $p_t < 1.3$ GeV</td><td></td></tr>
<tr><td>scattered proton/neutron acc.
all energies for eA</td><td>Proton and Neutron:
$\Theta < 6$ mrad ($\sqrt{s}$=50 GeV)
$\Theta < 4$ mrad ($\sqrt{s}$=100 GeV)</td><td></td></tr>
<tr><td rowspan="2">Luminosity</td><td colspan="2">Relative Luminosity: $R = L^{++/--}/L^{+-/-+} < 10^{-4}$
→ Flexible spin patters for both beams
1: +-+--+-++-+-   2: -+-++-+--+-+   3: ++--++--++--   4: --++--++--++</td></tr>
<tr><td></td><td>γ acceptance: +/- 1 mrad
→ $\delta L/L < 1\%$</td></tr>
</table>

🟦 most demanding

Vetoing Incoherent Events



Veto.1:
- no neutron in ZDC

Veto.2:
- Veto1 + no proton in Roman Pots

Veto.3:
- Veto2 + no proton in off-momentum detector

Veto.4:
- Veto3 + no proton in B0

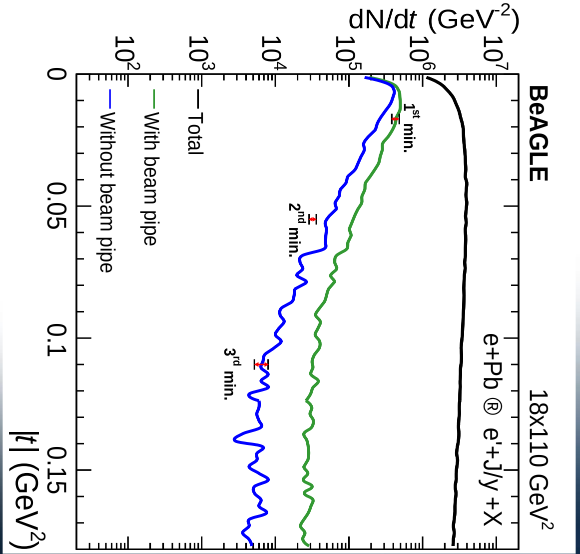
Veto.5:
- Veto4 + no anything in preshower

Veto.6:
- Veto5 + no photon ***E>50MeV*** in ZDC

Veto.7:
- Veto6 + no activities $(|\eta| < 4.0 \;\&\; p_T > 100\,\mathrm{MeV/c} \;\&\; E > 50\,\mathrm{MeV})$ other than e- and J/ψ in the main detector

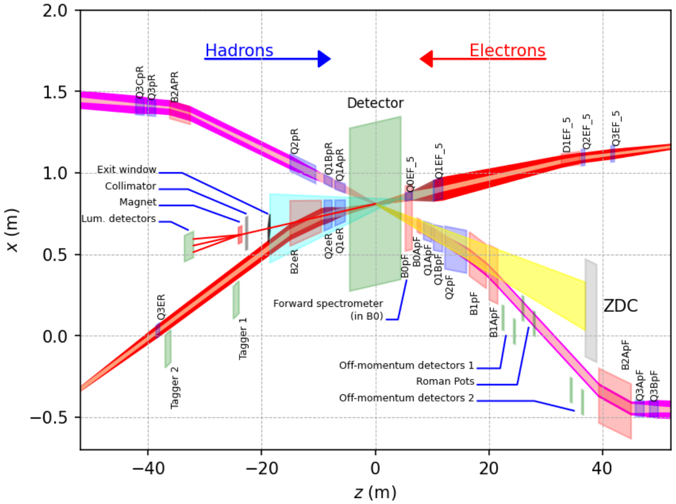
With these requirements, the rejection power is found to be not enough to reach the three minimum positions.

Beam pipe design and material critical to vetoing power



Progress – Interaction Region

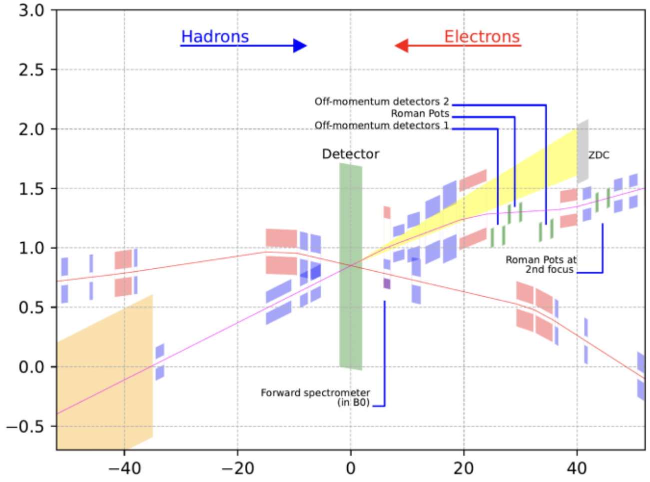
1st IR (IP-6)



IR Highlights and Challenges

- ❑ High Luminosity → High current (~ 2.5 A)
- ❑ High number of bunches (1160, ~10 ns separation)
  - ➢ Avoid parasitic collisions at IR
    - Crossing angle
    - Both focusing elements close to IP
- ❑ Small β^* values (h: 80/7.2 cm, e:45/5.6 cm)
  - ➢ Strong final focus magnets close to IR
  - ➢ Aperture: challenging magnet designs
- ❑ Polarization
  - ➢ Lattice constraints to enable polarized beams
  - ➢ Polarized hadrons / electons
    - Polarimetry (local and global)
    - Spin rotators & Snakes
  - ➢ electrons: Frequent on-energy bunch replacements
- ❑ Experimental detector
  - ➢ Forward detectors
  - ➢ Experimental solenoid & compensation

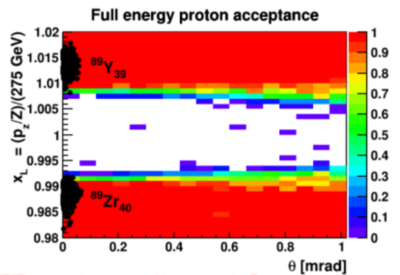
2nd IR (IP-8)



- ❑ The same highlights and challenges as IP-6
- ❑ Different: **pre-conceptual** design with 35mr crossing angle and secondary focus for science complementary checks.
- ❑ Further study needed for the feasibility of the IR magnets → Nb3Sn magnets are being evaluated as an option.

2nd focus enables:

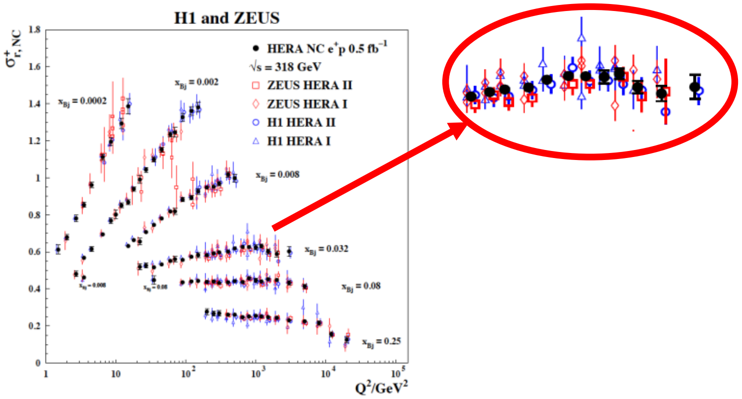
enhanced low P_T acceptance, DVCS on nuclei, Light ion tagging, Diffraction, improved Gluon imaging by detection of (A-1) nuclei



2nd Detector: Complementary is Key

What do we want from “Complementary”

- **Cross-checking important results (obvious!)**
  - Many examples of wrong turns in history of nuclear and particle physics.
  - Independent cross checks (detector, community, analysis tools) are essential for timely verifications and corrections

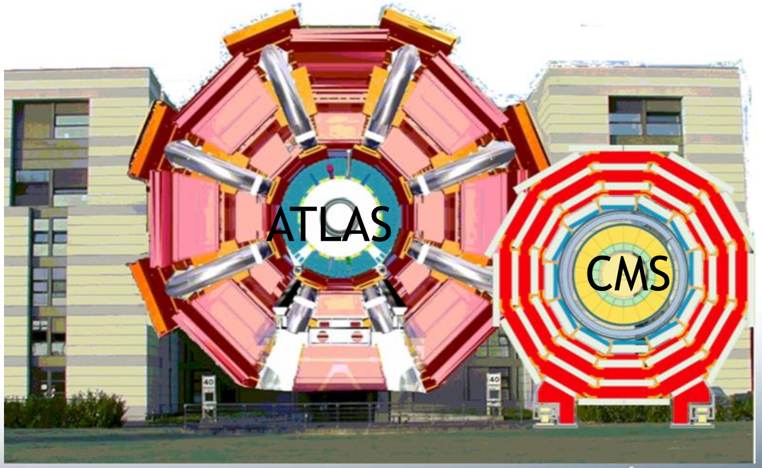


- **Cross Calibration**
  - Combining data gave well beyond the √2 statistical improvement …
  - Different dominating H1, ZEUS systematics…
  - Effectively use H1 electrons with ZEUS hadrons

    … not all optimal solutions have to be in one detector…

- **Technology Redundancy**

  ... by applying different detector technologies and philosophies to similar physics aims
  - mitigates technology risk vs. unforeseen backgrounds
  - differently optimizes precision and systematics



- **Different primary physics focuses**

  ... EIC has unusually broad physics program
  (from exclusive single particle production to high multiplicity eA or γA with complex nuclear fragmentation)

  → Impossible to optimize for the full program in a single detector.

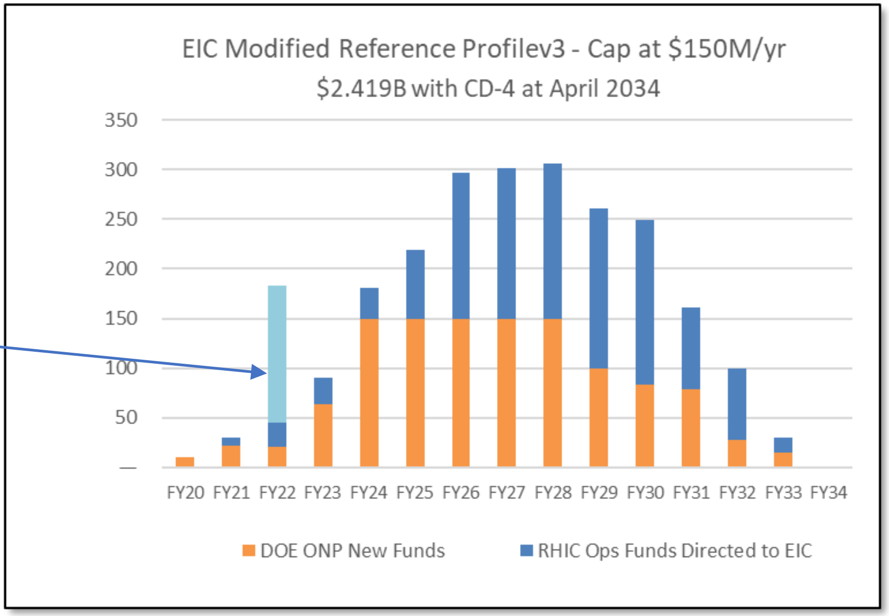
  → Impact on IR design

Latest News on the Funding and Schedule

Inflation Reduction Act:

- $217M to Nuclear Physics in FY22 to be spent by FY27.
- Includes EIC (to get to CD-2) – $138.24M.

(IRA funds can ONLY be used for project scope, but NOT to add scope)



Schedule: CD-3A = January 2024; CD-2= January 2025, CD-3 = April 2025; CD-4 Project Completion = 2034
RHIC operations conclude and EIC tunnel work starts in June 2025

Cost: CD-1 cost range of $1.7B-$2.8B

→ The DOE funding to ensure CD-2/3A timeline (baselining, start of long-lead procurement items) and CD-3 (start of construction) seems secured.