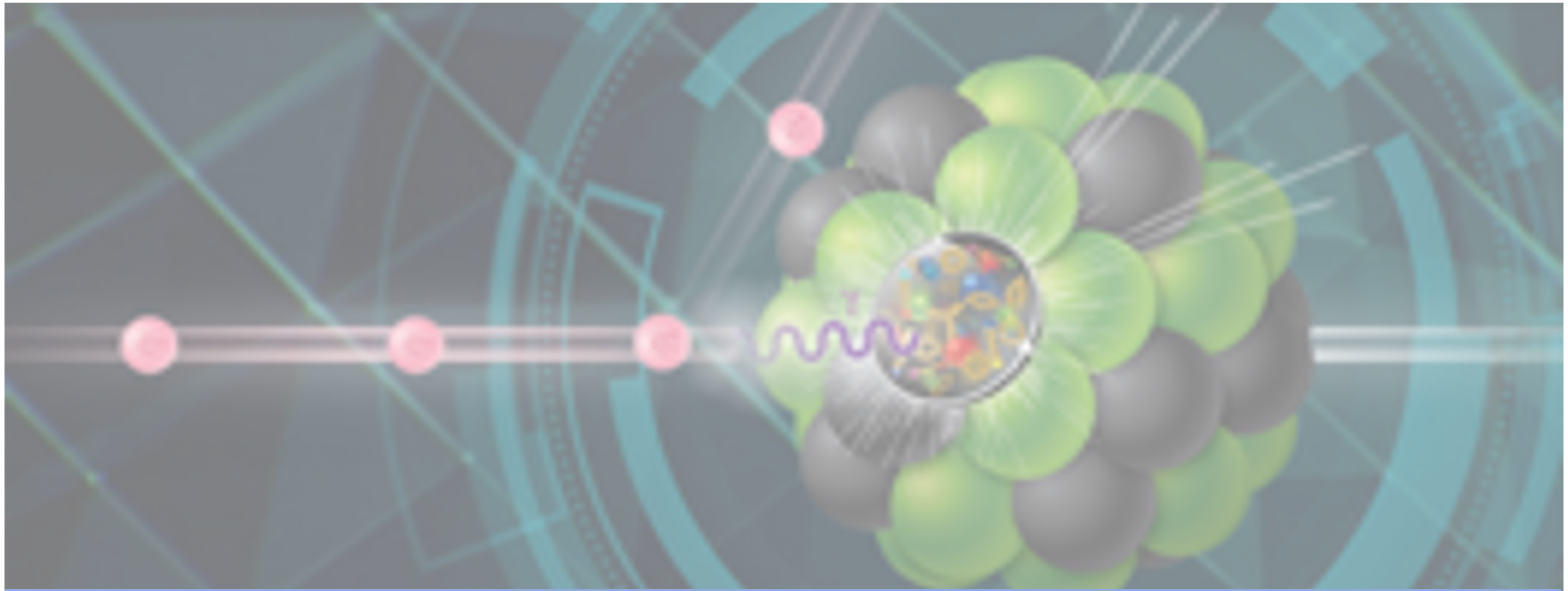


Overlap with Detector R&D for ePIC@EIC

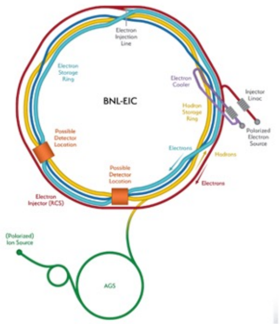
Synergy workshop between ep/eA and pp/pA/AA physics experiments
CERN 29 February 1 March 2024

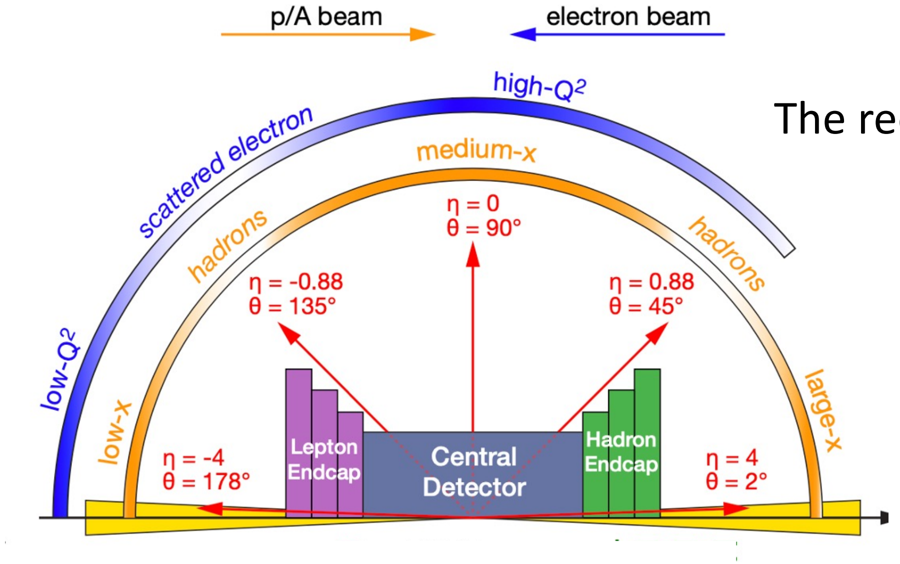
P. Antonioli for the ePIC Collaboration

INFN-Bologna

How I tried to organize this talk...

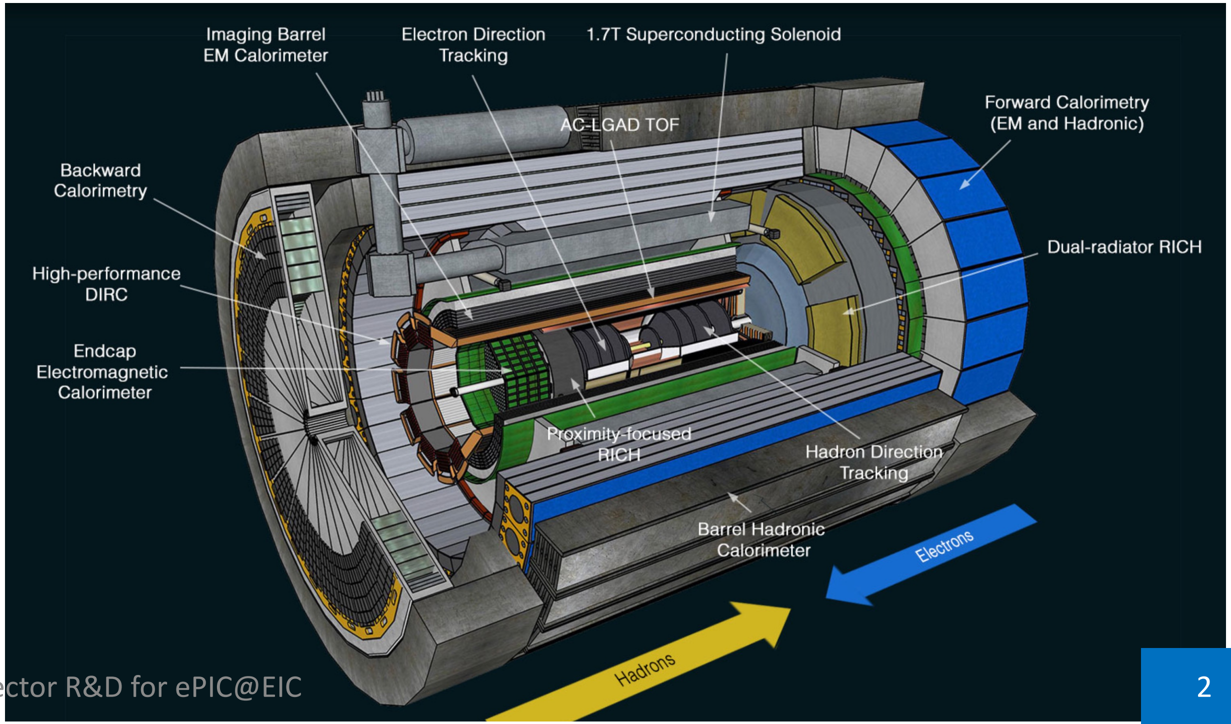
EIC fundamentals: the machine and the science program (*and timeline*)



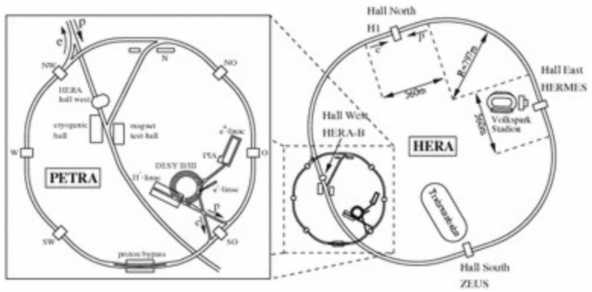


The requirements for an EIC detector (*and some physics highlights, emphasis on eA*)

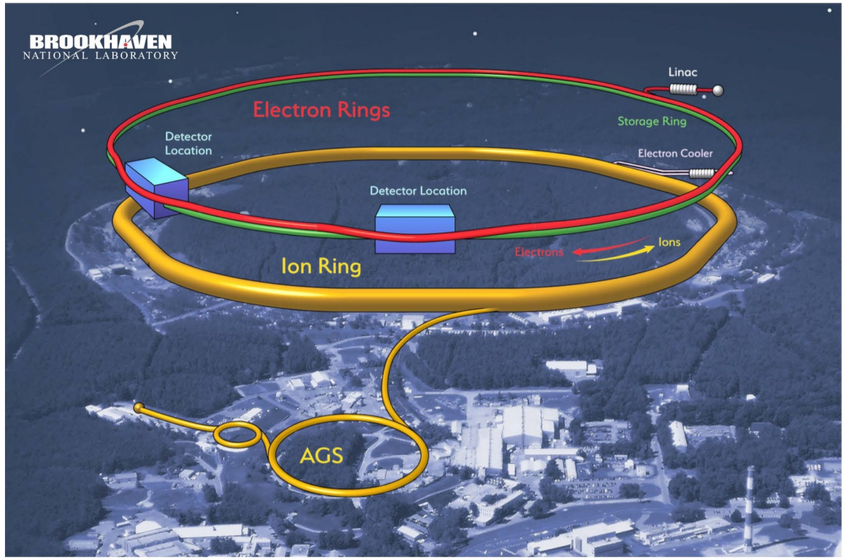
The ePIC detector (*and some R&D highlights, emphasis on PID*)

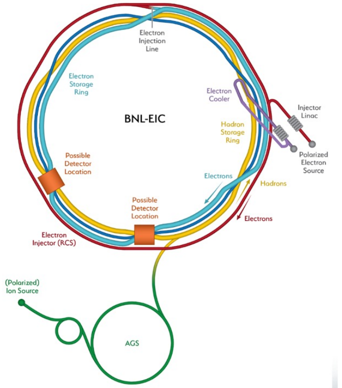


A new microscope for nucleons is coming!



SLAC-MIT, HERA, ...





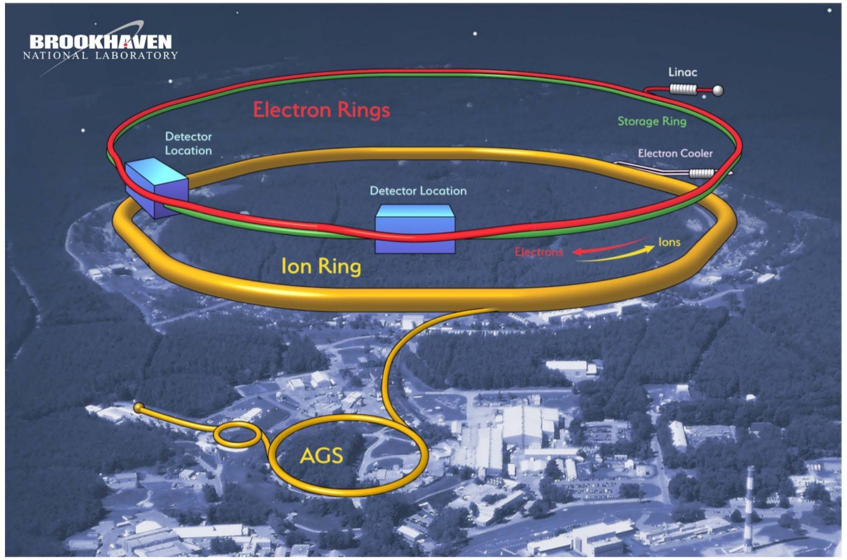
EIC 2031+

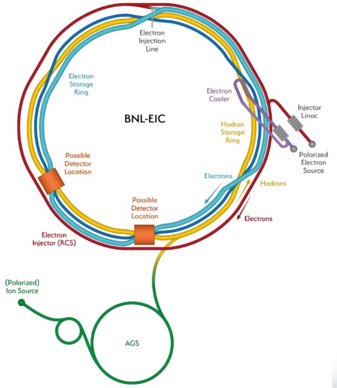
Three-ring design

- Hadron storage ring (HSR) 41-275 GeV
- Electron storage ring (ESR) up to 18 GeV (requires SC RF-cavities)
- Electron rapid cycling synchroton (RCS) (400 MeV to 18 GeV)
  [One existing hadron RHIC ring not used]

A new microscope for nucleons is coming!

"When HERA started in 1992, we only had vague notions of the structure of the proton," says Rolf-Dieter Heuer, director for particle-physics research at DESY. "The measurements from HERA showed that the interior of the proton is like a thick, bubbling soup in which gluons and quark–antiquark pairs are continuously emitted and annihilated."



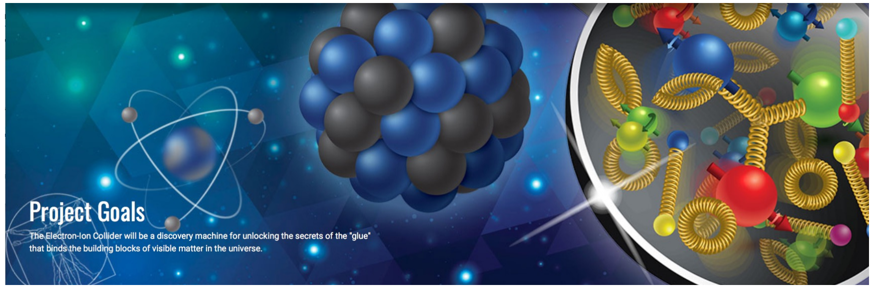


EIC 2031+

Three-ring design
- Hadron storage ring (HSR) 41-275 GeV
- Electron Storage ring (ESR) up to 18 GeV (requires SC RF-cavities)
- Electron rapid cycling synchroton (RCS) (400Mev to 18 GeV)

[One existing hadron RHIC ring not used]

EIC physics: a machine to study the nucleon "glue"

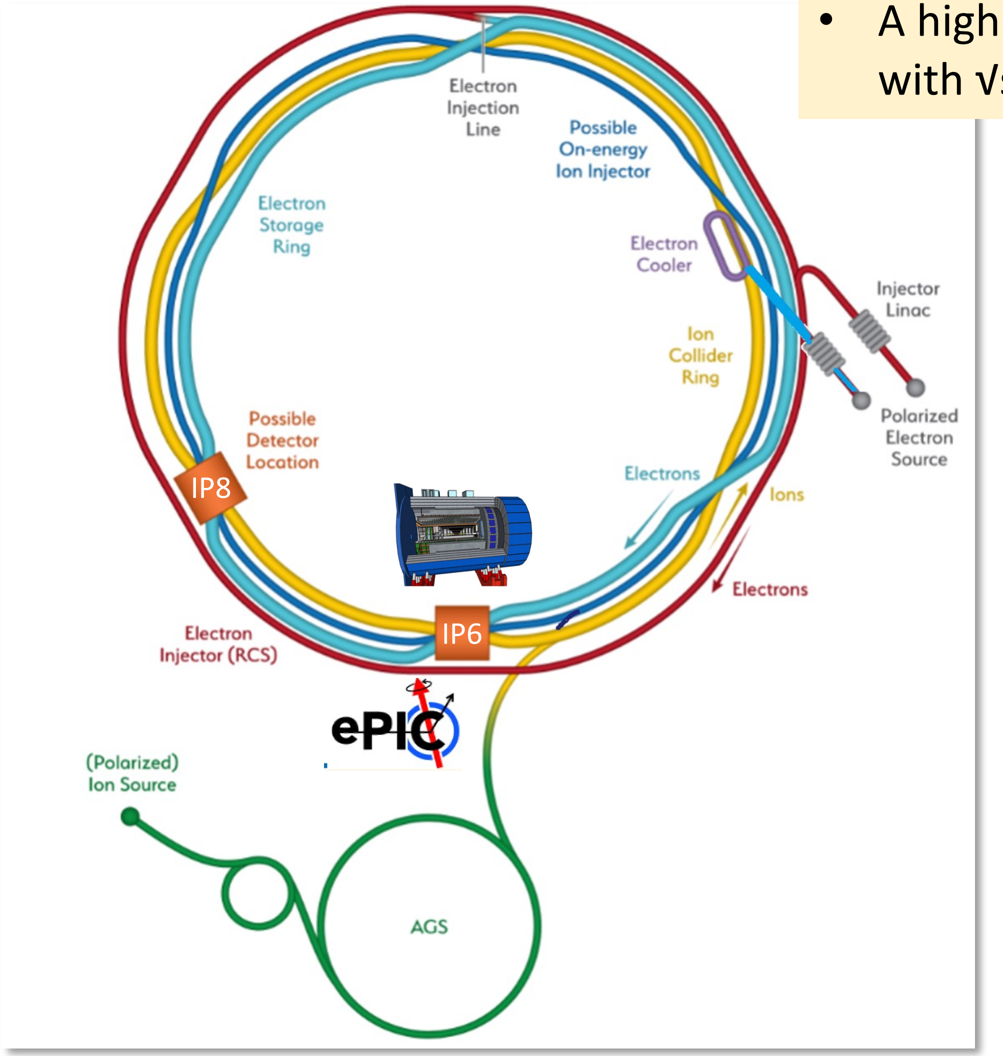


- How do the **nucleonic properties such as mass and spin emerge from partons** and their underlying interactions?
- **How are partons inside the nucleon distributed** in both momentum and position space?
- How do **color-charged quarks and gluons**, and jets, interact with a nuclear medium?
- How do the **confined hadronic states emerge** from these quarks and gluons?
- How do the **nuclear binding emerge** from quark-gluon interactions?
- How does a dense nuclear environment affect the dynamics of 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 gluonic matter or a gluonic phase with universal properties in all nuclei and even in nucleons?

For a comprehensive EIC science program overview see for example:
M. Zurek, "Shedding light on visibile matter: an Overview of the EIC Science", April 3, 2023
E. Aschenauer, "The electron-ion collider: A collider to unravel the mysteries of visible matter", December 14, 2024

The collider (I)

- Evolution of RHIC (pp/pA/AA) facility at BNL → electron ring (E_e = 5-18 GeV)
- A high luminosity ($10^{33} – 10^{34}$ $cm^{-2}s^{-1}$) polarized electron proton / ion collider with $\sqrt{s_{ep}}$ = 29 – 140 GeV

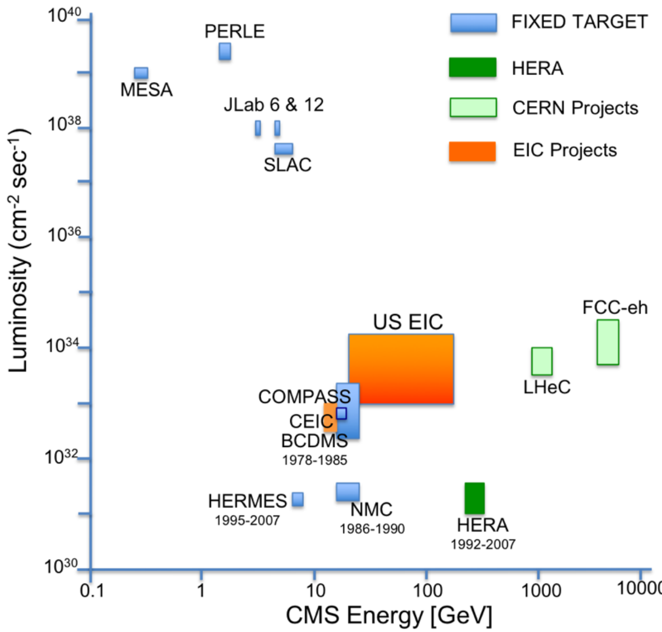


2.25 B$ project

EIC key points

with respect to HERA:

- luminosity x 100 to 1000 higher
- both (p, d, ^{3}He) and e polarized
- nuclear beams (d to U)



with respect to fixed target facilities:

- more than 2 decades increase in kinematic coverage in x and Q^2

Currently DoE supports EIC project for one detector, but the facility might support two detectors/IRs (IP6/IP8)

The collider (I)

- Evolution of RHIC (pp/pA/AA) facility at BNL → electron ring (E_e = 5-18 GeV)
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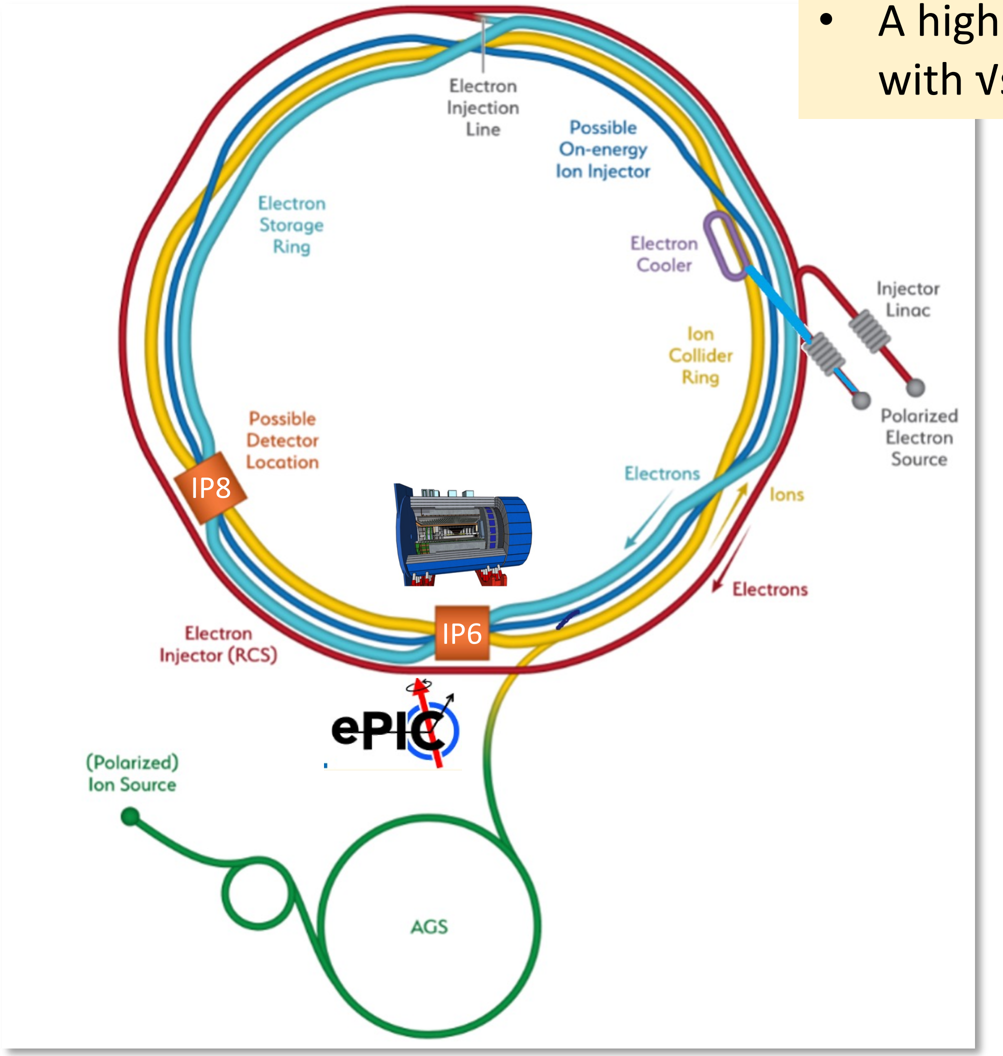
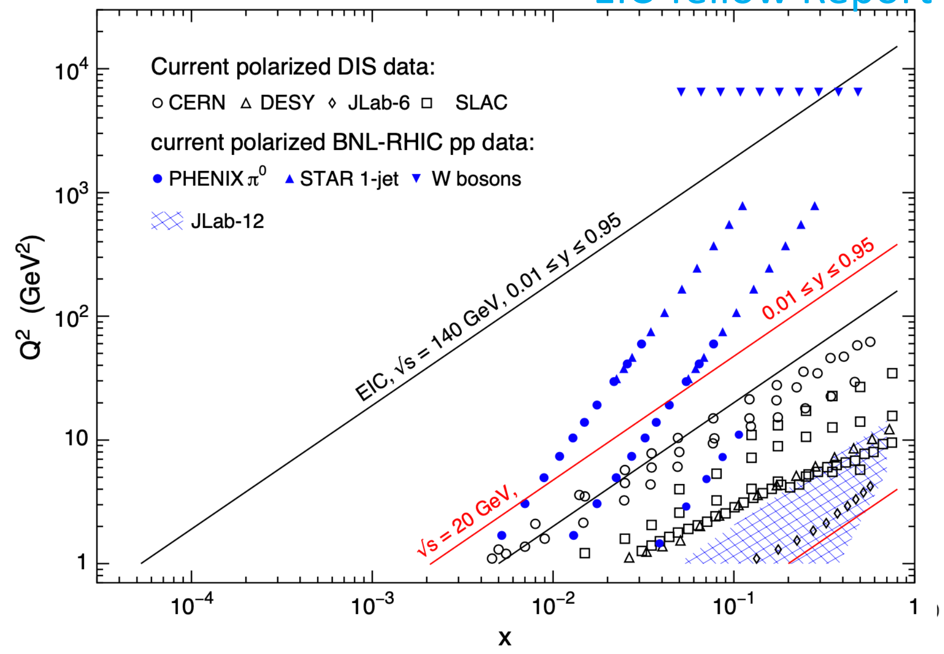


2.25 B$ project

EIC Yellow Report



EIC key points

with respect to HERA:

- luminosity x 100 to 1
- both (p, d, ^{3}He) and e
- nuclear beams (d to

with respect to fixed target facilities:

- more than 2 decades increase in kinematic coverage in x and Q^2

Currently DoE supports EIC project for one detector, but the facility might support two detectors/IRs (IP6/IP8)

The collider (2)

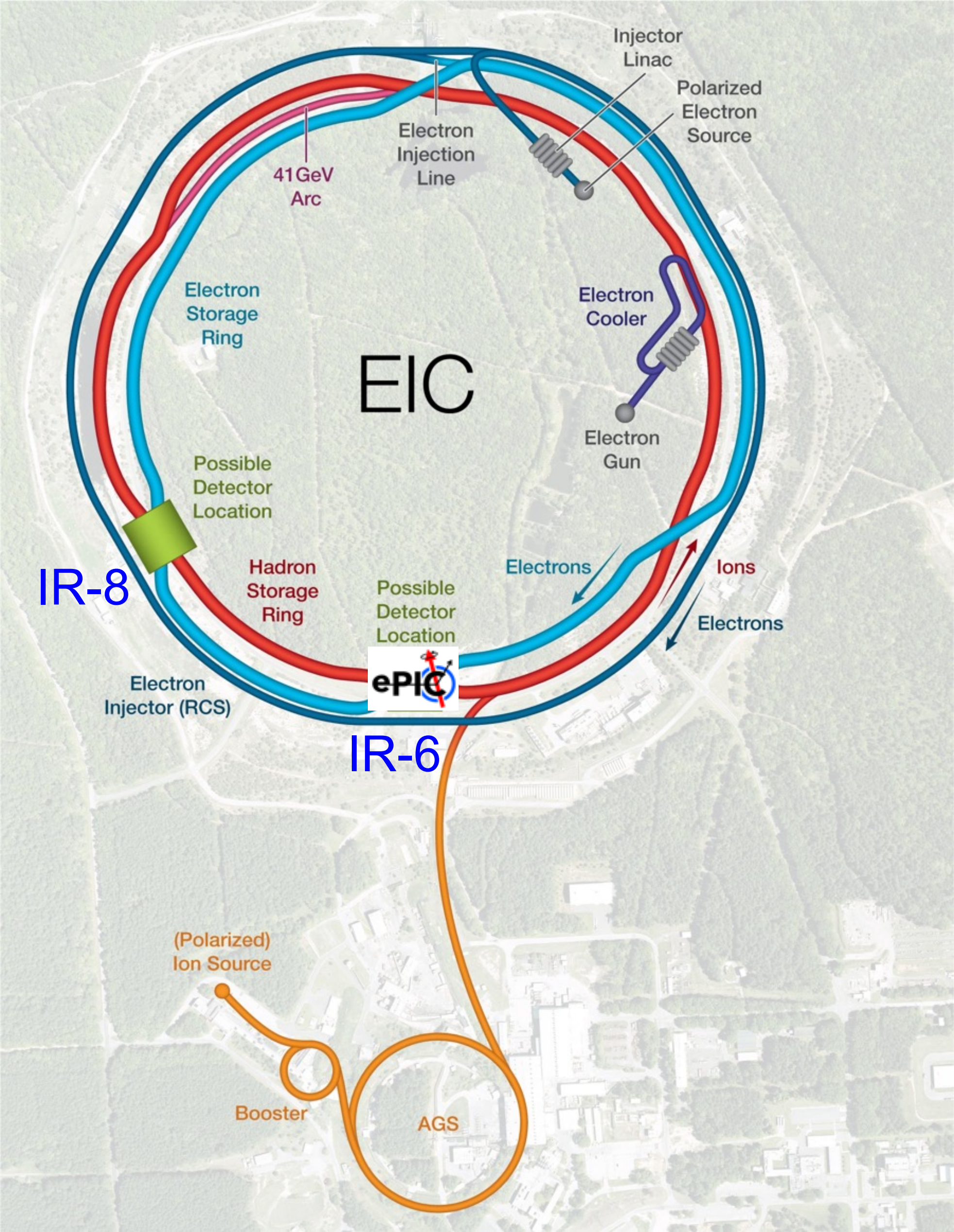
- High Luminosity: L= $10^{33} – 10^{34} cm^{-2} sec^{-1}$, 10 – 100 fb^{-1}/year
- Highly Polarized Beams: 70%
  - → **requires high precision polarimetry**
- Large Center of Mass Energy Range:
  E_{cm} = 29 – 140 GeV
  - → **Large Detector Acceptance**
- Large Ion Species Range: protons – Uranium
  - → **unique opportunity to study Q_s evolution with x**

p: 41 GeV, 100 to 275 GeV

p/A beam

e beam

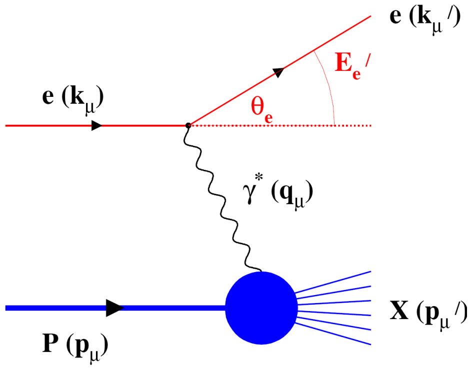
e: 5 GeV to 18 GeV



DIS processes → physics

Parton Distributions in nucleons and nuclei

QCD at Extreme Parton Densities - Saturation



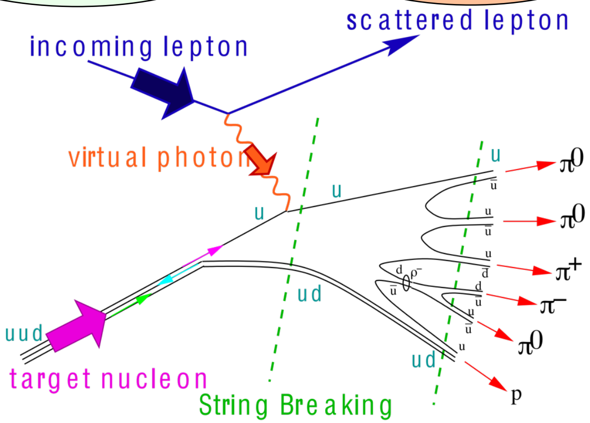
inclusive DIS

measure scattered electron
→ e/h PID
→ eCAL calorimetry

∫Ldt: 1 fb^{-1}

Spin and Flavor structure of nucleons and nuclei

Tomography Transverse Momentum Dist.



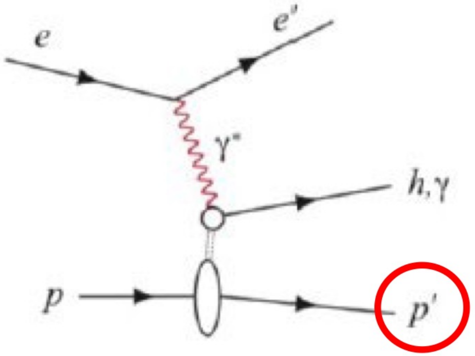
semi-inclusive DIS

measure electron and hadrons
→ hadron PID

10 fb^{-1}

QCD at Extreme Parton Densities - Saturation

Tomography Spatial Imaging



exclusive processes

measure all particles
→ hermeticity
→ design IR

10 - 100 fb^{-1}

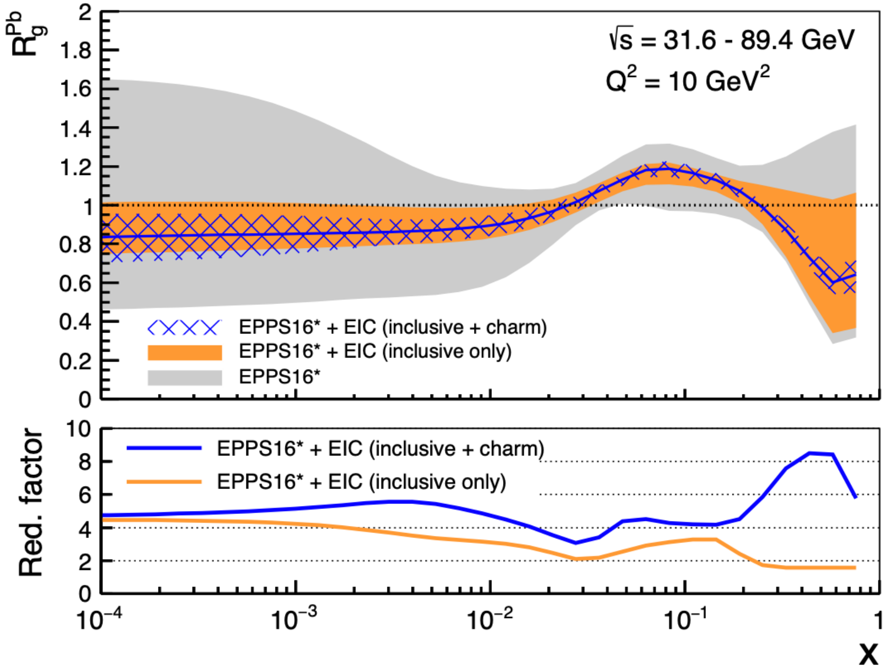
EIC extra-bonus: DIS in nuclei
- nPDF modifications
- gluon saturation (and its scale dependency from A) [jets]
- hadronisation in cold nuclear matter

Highlight 1 (nuclei): gluon saturation & nPDF

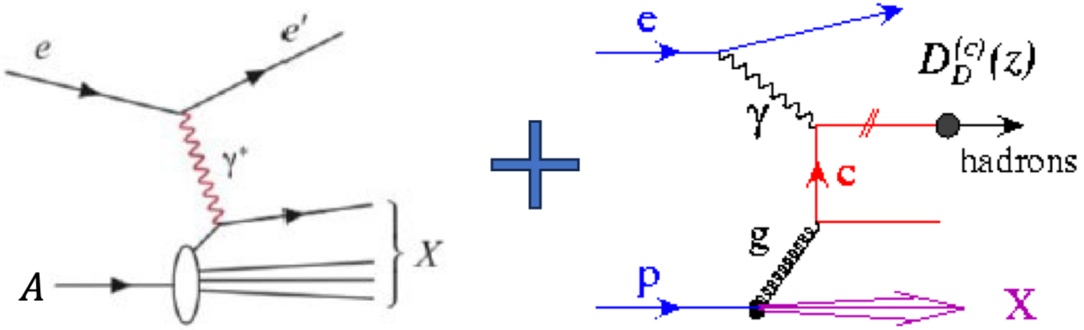
DGLAP and saturation models offer different prediction (Q^2 , A, x dependence)
channels → di-hadron angular correlations, diffractive particle production in eA
strategy→ large Q^2 span at fixed x performing A scan!

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

Detector requirements:
- good tracking + forward calorimeters
- + very forward instrumentation



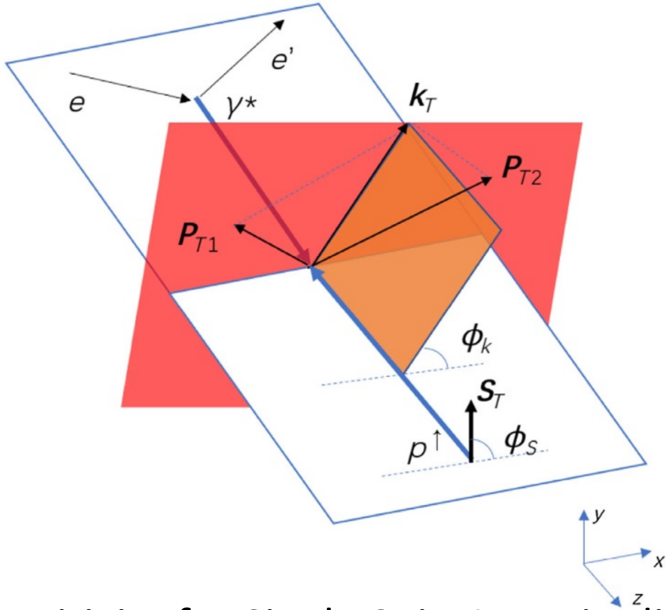
E. C. Aschenauer et al., Phys. Rev. D **96** (2007) 114005



- tag of scattered electron as a prerequisite
- **charm** → tag photon-gluon fusion → direct access to gluon

Detector requirements:
- vertexing (charm tagging)
- electron identification
- y resolution over large space!

Highlight 2: access to gluon Sivers function: TMD

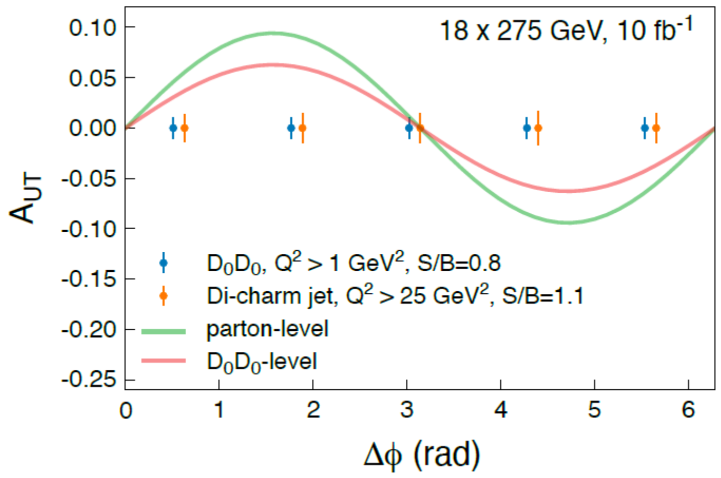


$$\frac{d\sigma}{dx\, dQ^2\, dz\, d\phi_S\, d\phi_h\, dp_T^h}$$

- **6-fold differential cross sections in SIDIS**
- **Azimuthal asymmetries and their modulations**

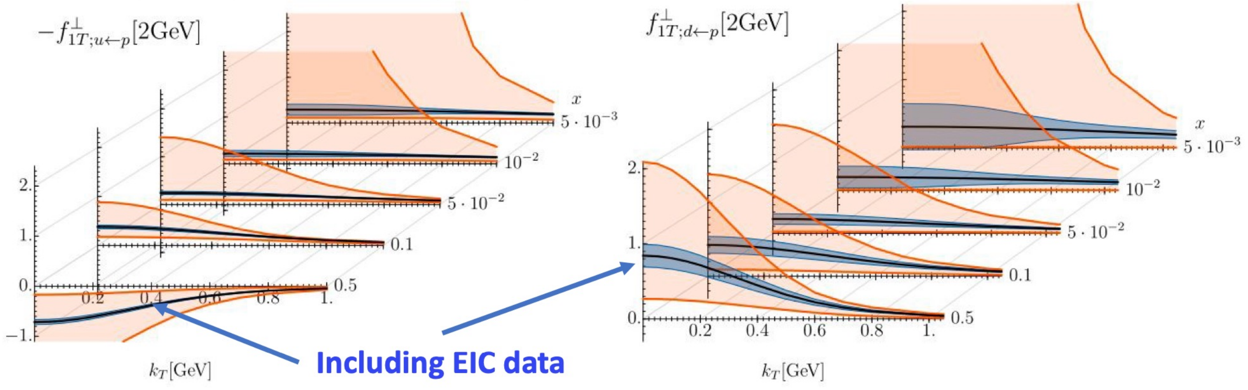
- access to Sivers TMD (D. W. Sivers, Phys. Rev. D 41, 83 (1990))
- access to gluon Sivers TMD via di-hadron and di-jet
- The Sivers function $f^{\perp}_{1T}$ encapsulates the correlations between a parton's transverse momentum inside the proton and the spin of the proton
- GSF (Gluon Sivers functions) poorly known (U. D'Alesio et al, JHEP 119 (2015))

Sensitivity for Single Spin Asym in di-charm
ATHENA simulation



Expected impact on *u* and *d* quark Sivers distributions

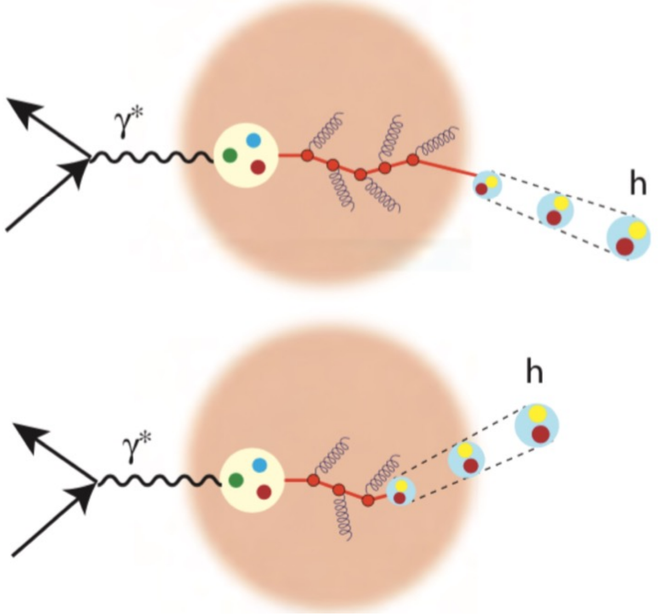
R. Seidl, et al., NIMA 1049 (2023) 168017



Detector requirements:
azymuthal acceptance, PID, vertexing (HF), tracking, HCAL (for jets)

Highlight 3: hadronization in CNM

EIC White Paper
https://arxiv.org/abs/1212.1701



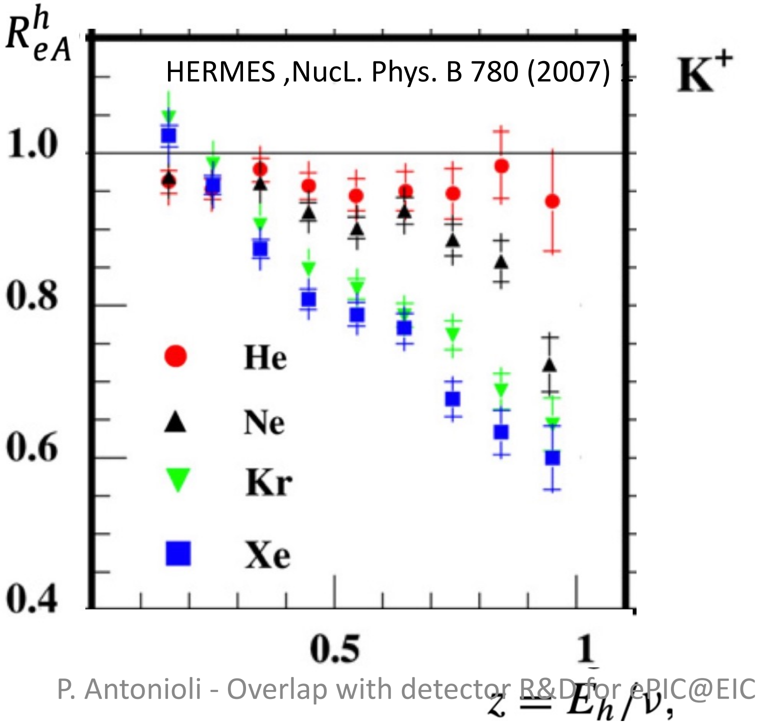
Basic idea: use Q^2 and $\nu=q{\cdot}p/M$ to control **where** hadronization happens

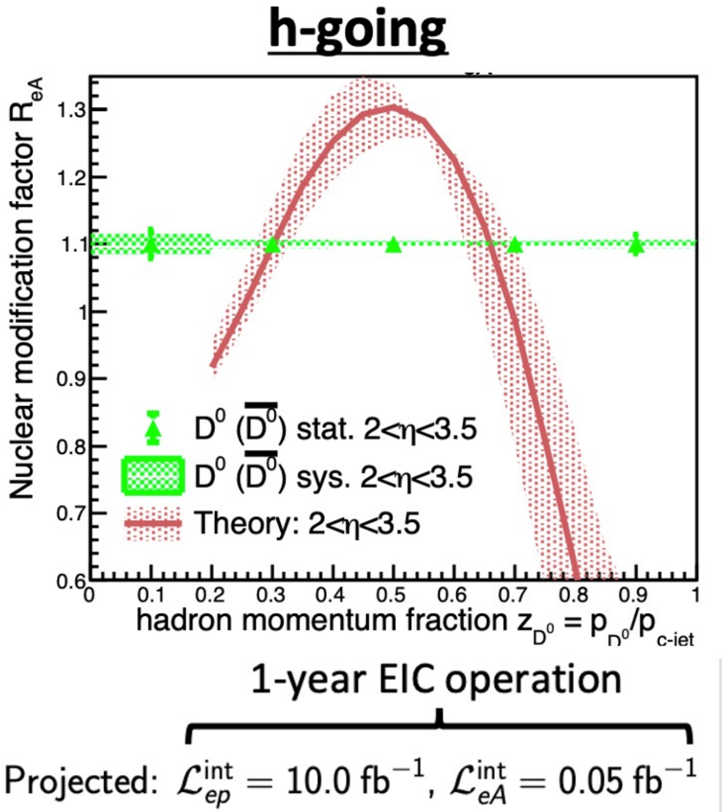
- effect foreseen for D^0/π (based on different FF) might be there also for HF baryons
- usually pre-hadron and absorption in CNM discussed for mesons (Kopeliovich et al., Nucl.Phys. A740 (2004) 211-245)
- role of **di-quark** for baryon hadronization (Adamov et al., Phys.Rev. D64 (2001) 014021)

Results for <u>light hadrons only</u> at <u>much lower energy</u> (fixed target e beam 27.6 GeV)

Detector requirements:
PID and HF-tagging

$$R^{\pi}_{eA}(\nu, Q^2, z) = \frac{\left.\frac{N^{\pi}(\nu,Q^2,z)}{N^e(\nu,Q^2)}\right|_A}{\left.\frac{N^{\pi}(\nu,Q^2,z)}{N^e(\nu,Q^2)}\right|_D}$$





ECCE simulation: more details C. Wong @ DIS2022
Theory curves from: Li H, Liu Z and I. Vitev, PLB 816 (2021) 136261

Physics → detector requirements

- Hermetic detector, low mass inner tracking
- Moderate radiation hardness requirements (w.r.t. for example LHC!)
- Electrons & jets in approx 8 η units
- Good momentum resolution
  - central: $\sigma(p)/p = 0.05\,\%\,p \oplus 0.5\,\%$
  - fwd/bkd: $\sigma(p)/p = 0.1\% \oplus 0.5\,\%$
- Good impact parameter resolution
- Excellent EM energy resolution
  - central: $\sigma(E)/E = 10\,\%/\sqrt{E}$
  - backward: $\sigma(E)/E < 2\,\%/\sqrt{E}$
- Good hadronic energy resolution
  - forward: $\sigma(E)/E \approx 50\,\%/\sqrt{E}$
- Excellent PID π/K/p
  - forward: up to 50 GeV/c
  - central: up to 8 GeV/c
  - backward: up to 7 GeV/c
- Low pile-up, low multiplicity., low int. rate (500 kHz at full lumi)

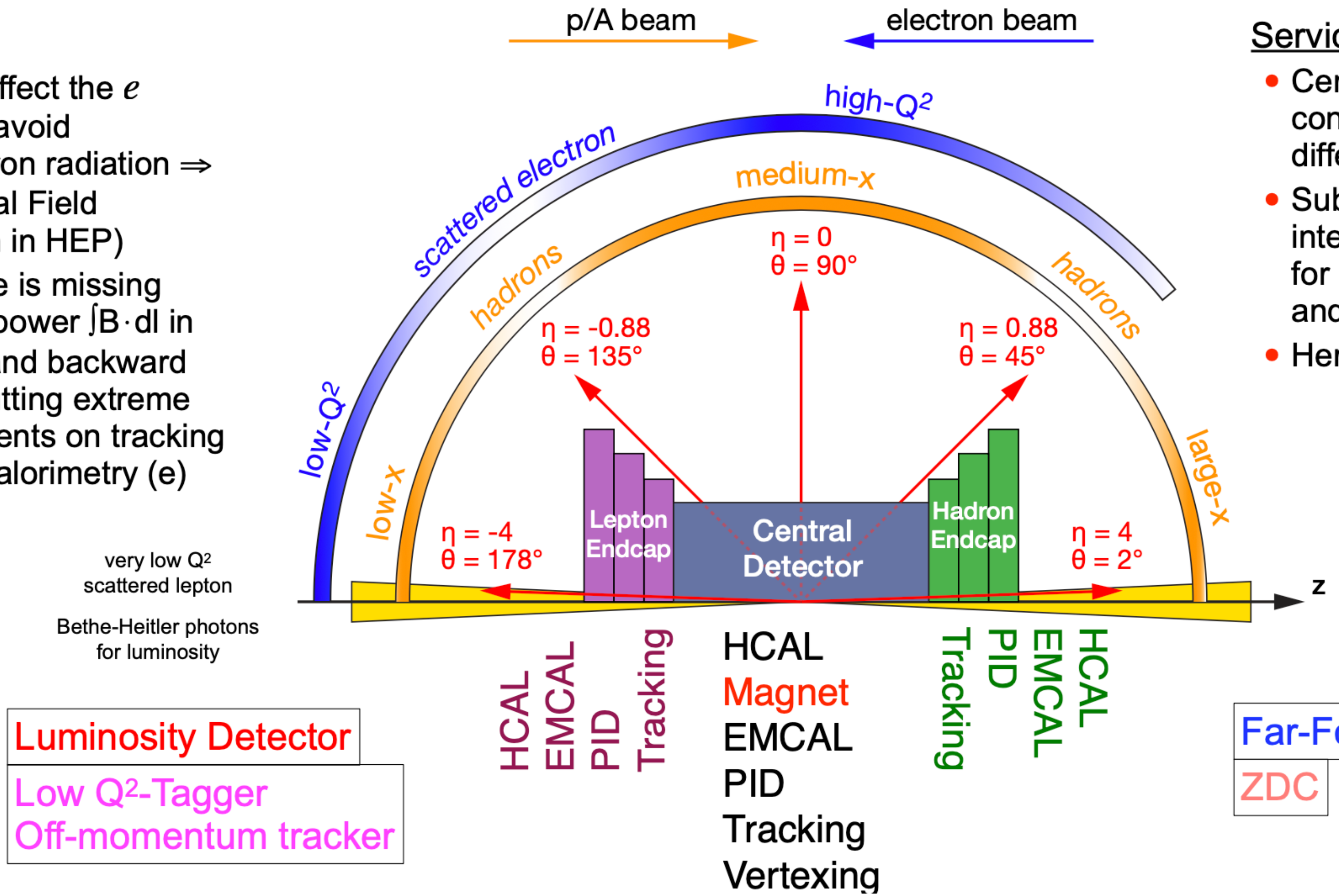
Hermeticity, low material budget tracker and PID make EIC detector design challenging

EIC Yellow Report: Nucl. Phys. A 1026 (2022) 122447, arXiv:2103.05419

Physics → Detector requirements (II)

Magnet

- Cannot affect the *e* beam to avoid synchrotron radiation ⇒ Solenoidal Field (common in HEP)
- Downside is missing bending power $\int B \cdot dl$ in forward and backward region putting extreme requirements on tracking (h) and calorimetry (e)



Services

- Central detector will contain > 16 different subsystems
- Substantial integration challenge for power, cooling, and data services
- Hermeticity?!

credit: T. Ulrich

EIC Yellow Report: Nucl. Phys. A 1026 (2022) 122447, arXiv:2103.05419

Most remarkable difference w.r.t. to LHeC detector (arXiv:2007.1449) is PID

ePIC design (barrel)

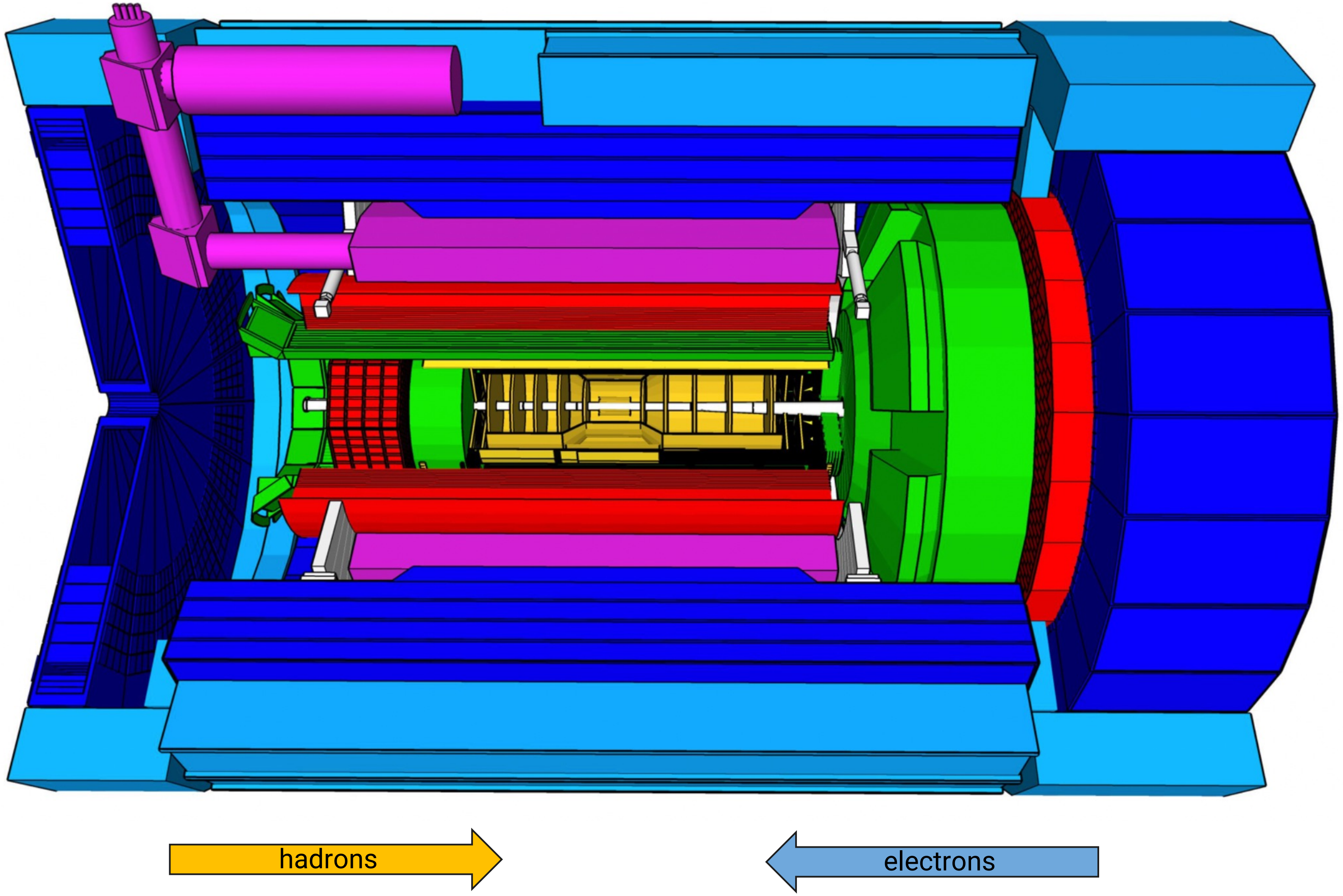
Magnet
- New 1.7 T SC solenoid, 2.8 m bore diameter

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)



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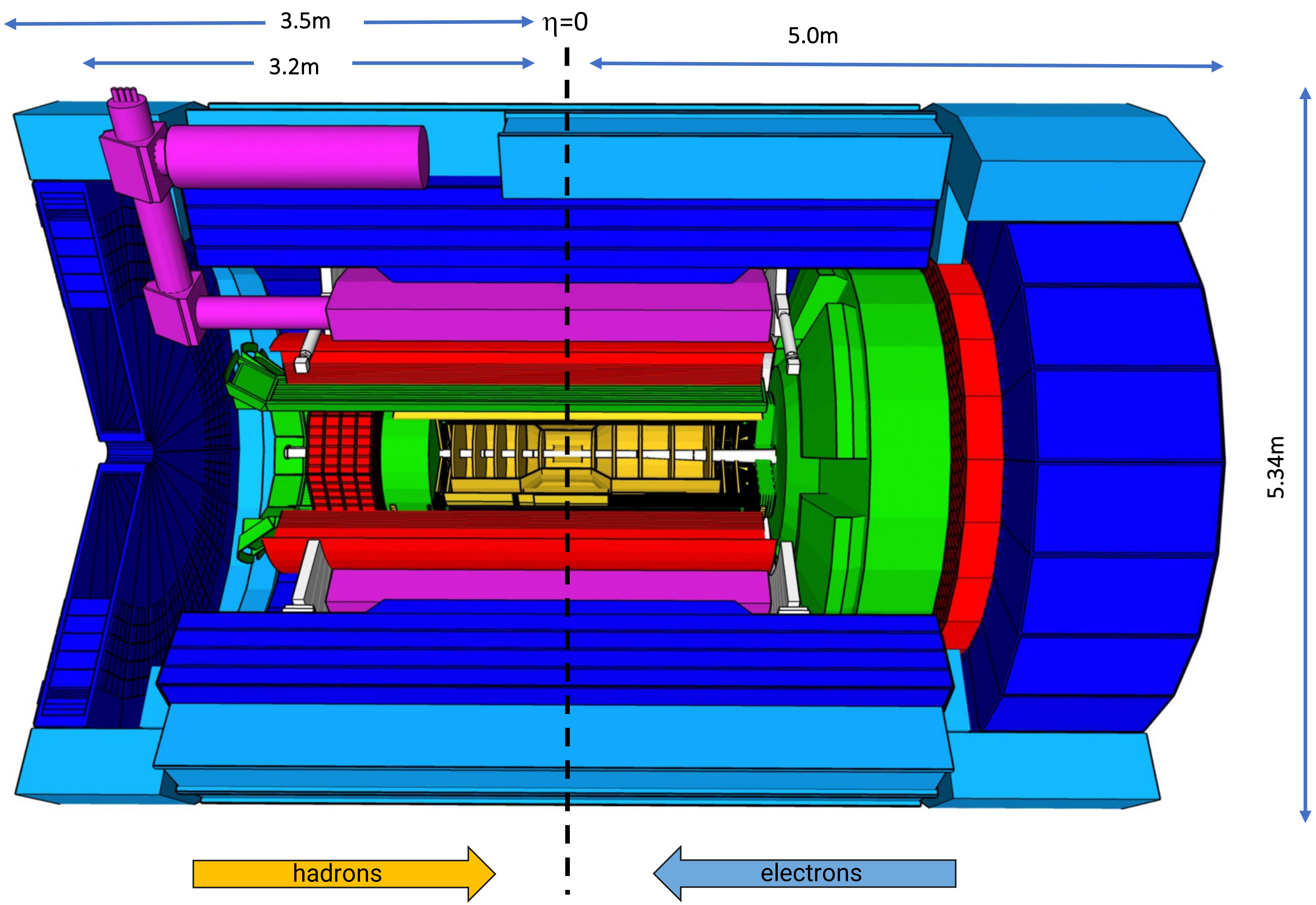
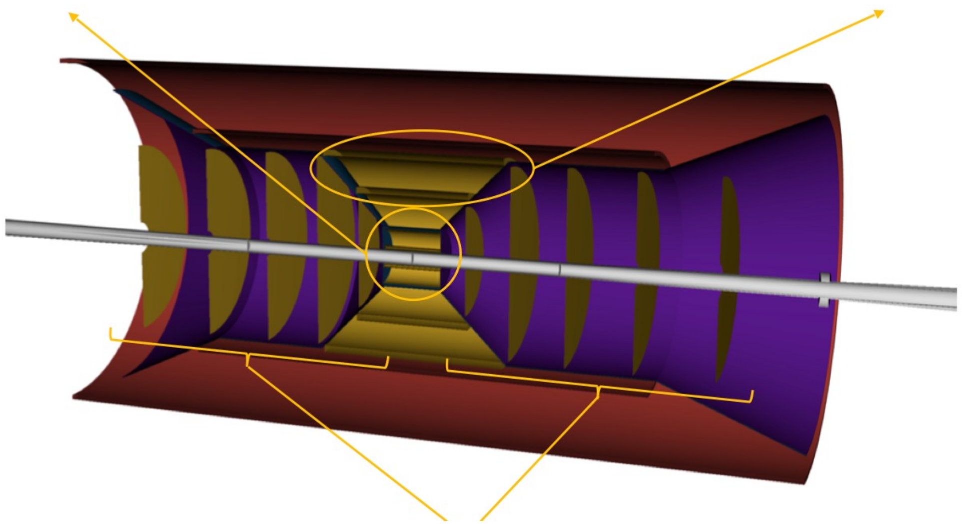
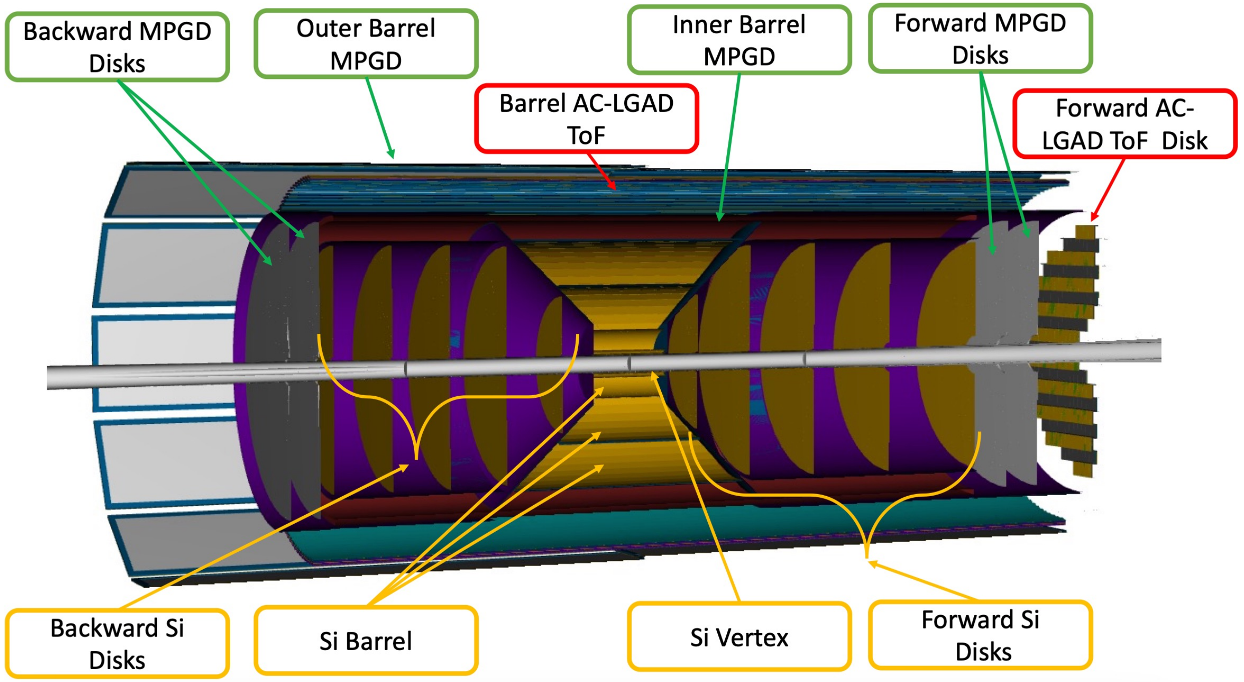


ePIC tracking: SVT and MPGD

Inner barrel (IB): 3 layers   Outer barrel (OB): 2 layers



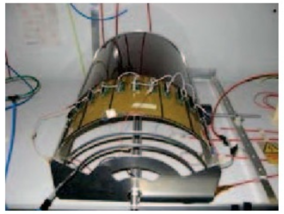
Electron/Hadron Endcaps (EE,HE)
5 disks on either side of IP



- one technology: MAPS @ 65 nm (ALICE ITS3)
- IB: First layer @ R ~ 3.6 cm - Material: 0.05% X/X_0 / layer
- OB: Material: 0.55% X/X_0 / layer
- EE/EH Material: 0.24% X/X_0 / layer
- pixel size O(20x20 μm^2)
- Total area 8.5 m^2

arXiv:2302.01447

- additional hit points for track reconstruction (~150 μm)
- fast timing hits for background rejection (~10-20 ns)
- MicroMega + uRWELL
- provide hit point over large angular range for PID
- new ASIC SALSA for readout (derived from ALICE SAMPA for TPC)

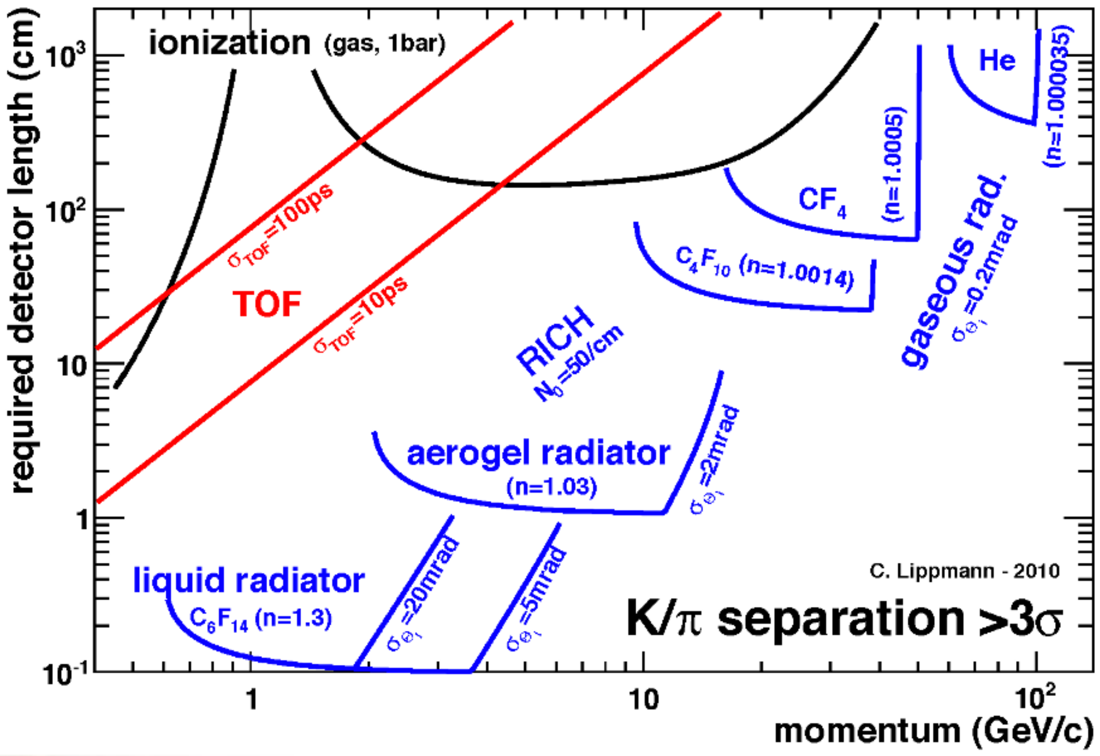


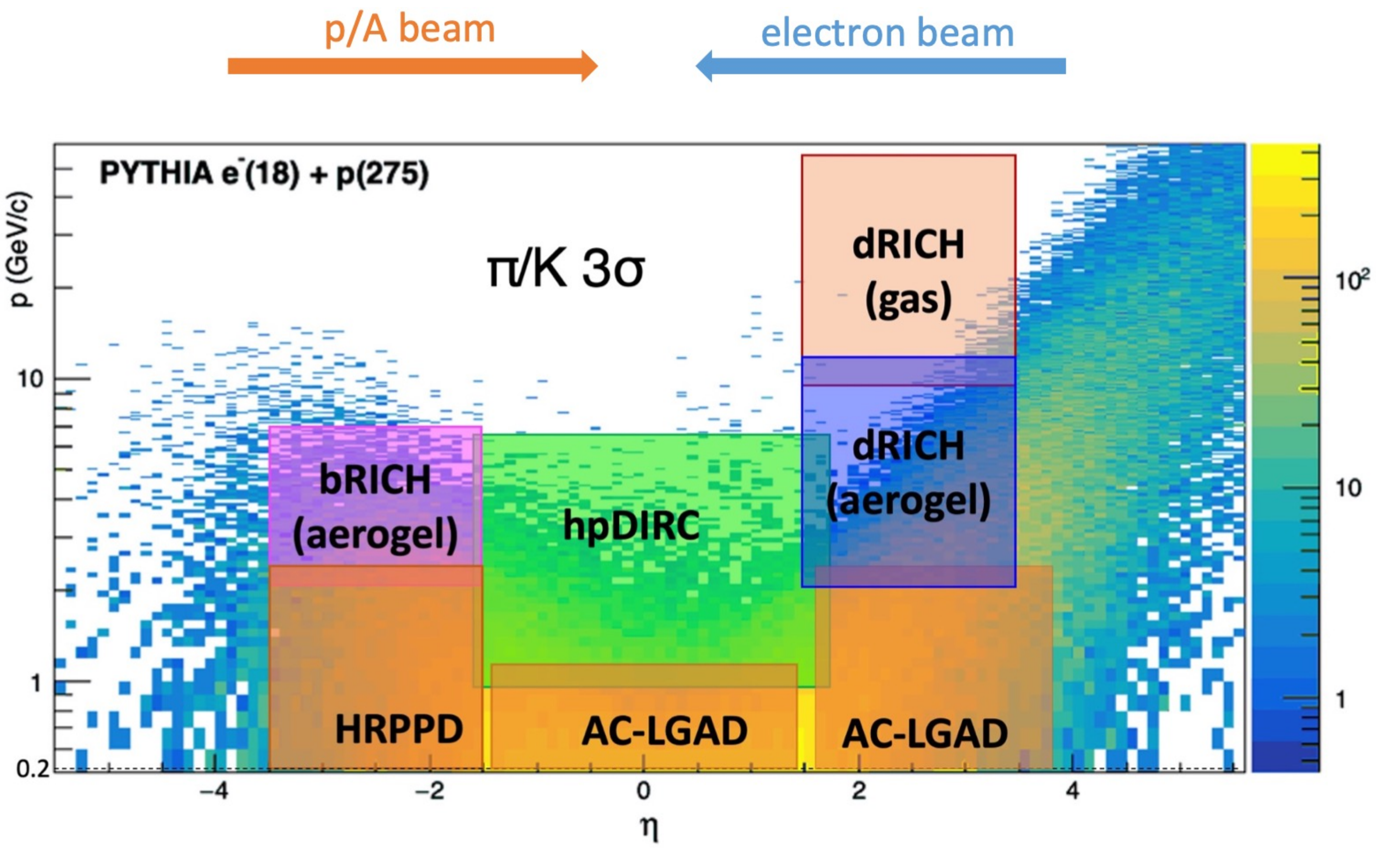
PID critical for EIC science

e-π separation
Cherenkov PID complements ECAL effort, especially at low momenta/backward region

hadron identification: SIDIS (→ TMD) , heavy flavour
ToF complements Cherenkov PID

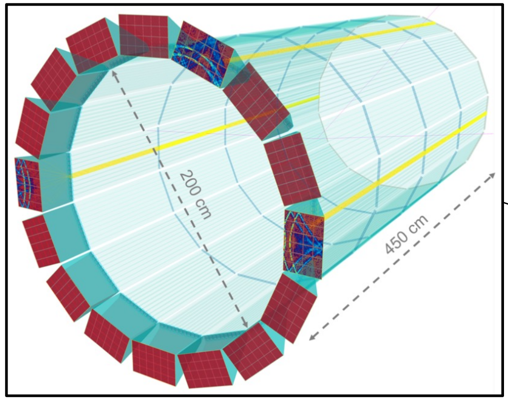
C. Lippmann, NIM A 666 (2012), 148





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

ePIC PID sub-systems

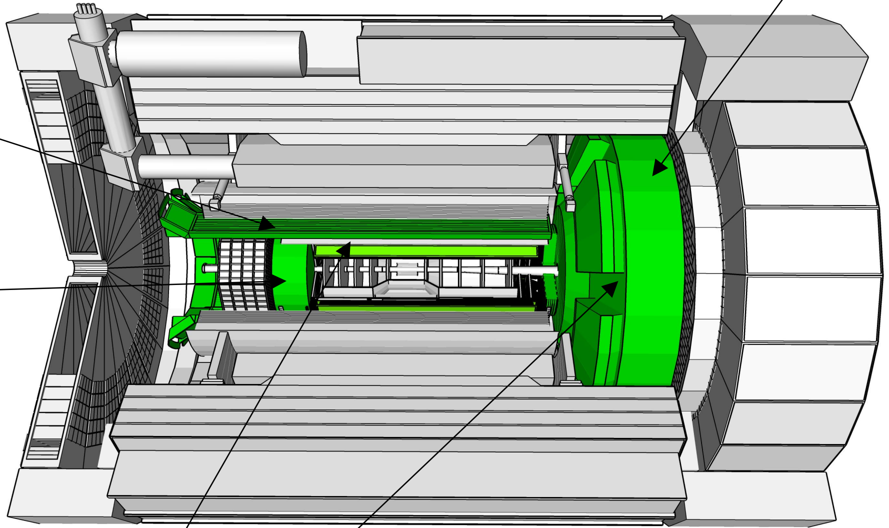


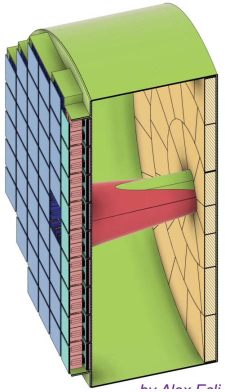
hpDIRC (High Performance DIRC)

- Quartz bar radiator → Reuse of BaBAR DIRC bars
- photosensor: MCP-PMTs
- p/K 3s sep. at 6 GeV/c

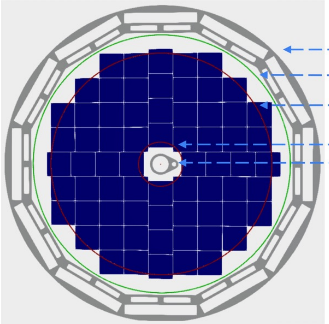
Backward RICH: pfRICH

- <u>Aerogel</u> Cherenkov Det.
- e, π, K, p separation → π/K 3σ sep. up to 7 GeV/c
- Photosensor:: **HRPPDs** to include TOF
- RICH with long proximity gap (~40 cm)





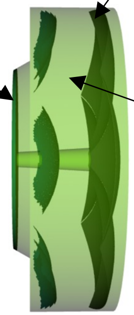
Sensor plane tiling scheme



dual radiator Forward RICH: dRICH

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

Spherical Mirrors
6 Azimuthal Sectors

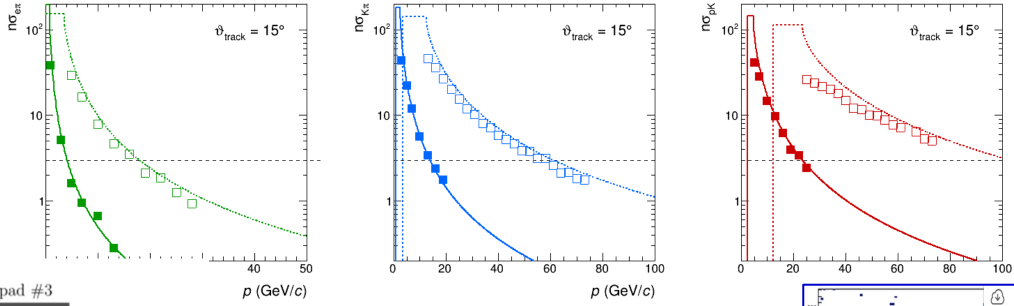


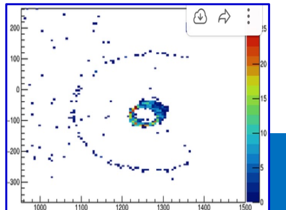
C_2F_6 Gas Volume
120 cm length
radius: 185 cm

Photosensor: **SiPMs**

dRICH sim.

π/K 3σ sep. up to 50 GeV/c

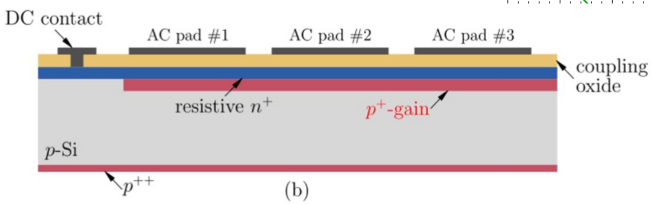




TOF

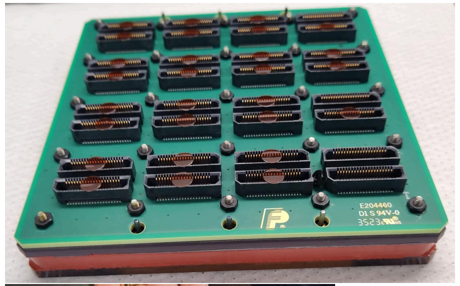
AC-LGAD (Low Gain Avalanche Detector)

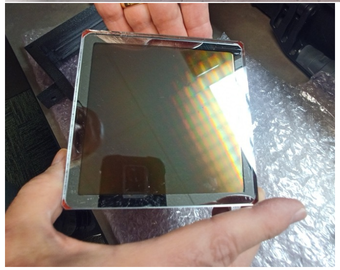
- 20-35 psec / σ=30 μm
- Accurate space point for tracking
- forward disk and central barrel

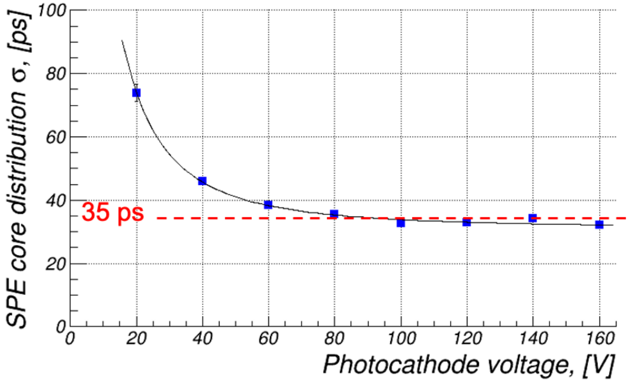


Photosensors R&D

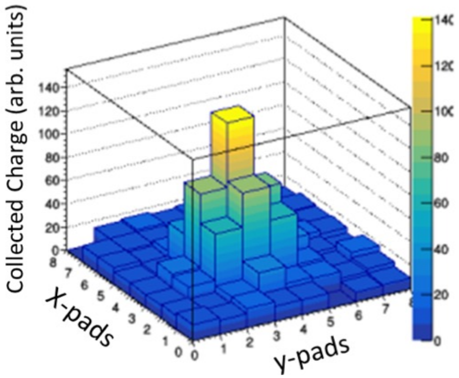
HRPPD: large area microchannel plates
provided by INCOM with ePIC/EIC contributing to engineering

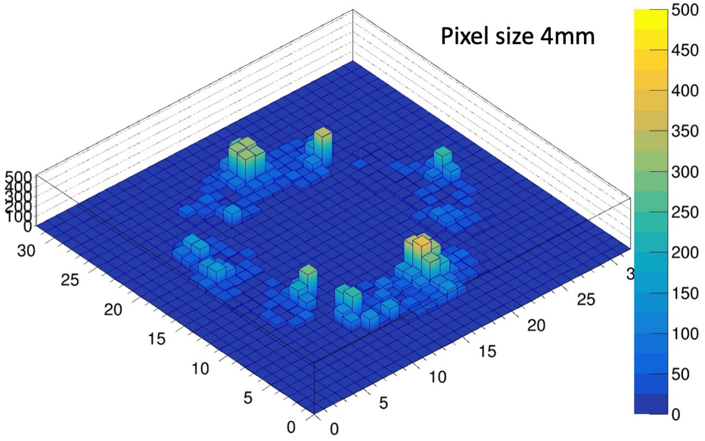






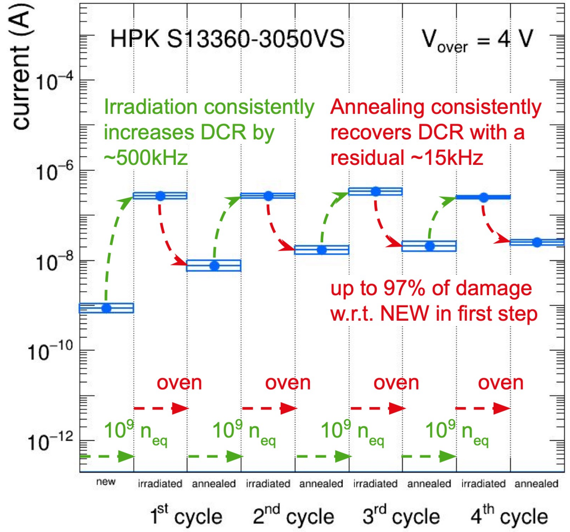
one photon → a multi-pixel cluster

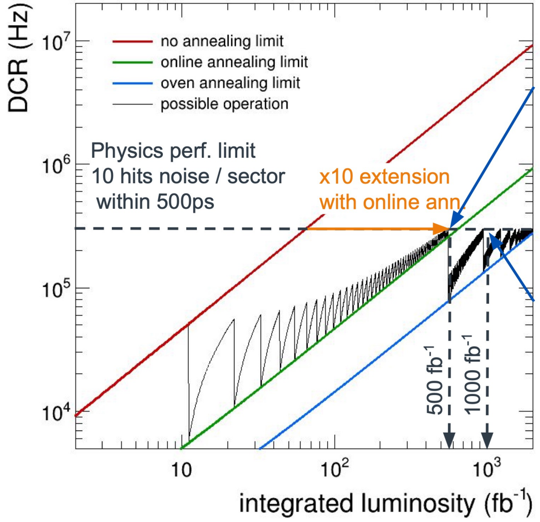


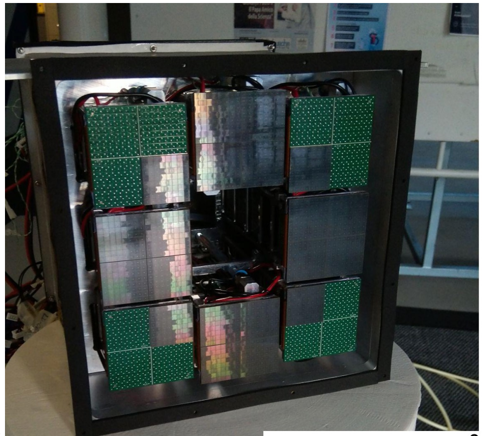


Single event with multiple photon clusters

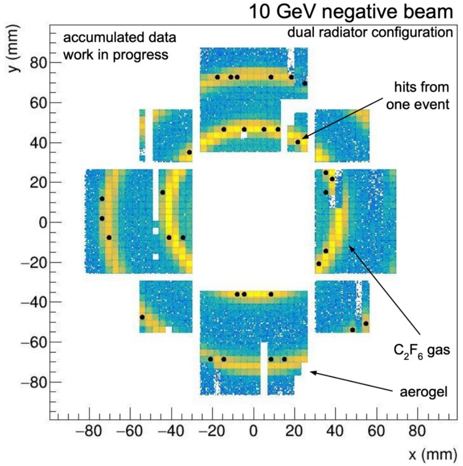
SiPM:
so far not used in RICH detectors, robust R&D to prove annealing cycles can manage DCR increase due to (moderate) radiation load





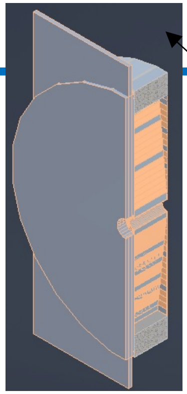


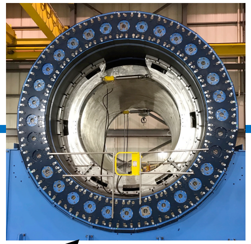
20 x 20 x 20 cm^3



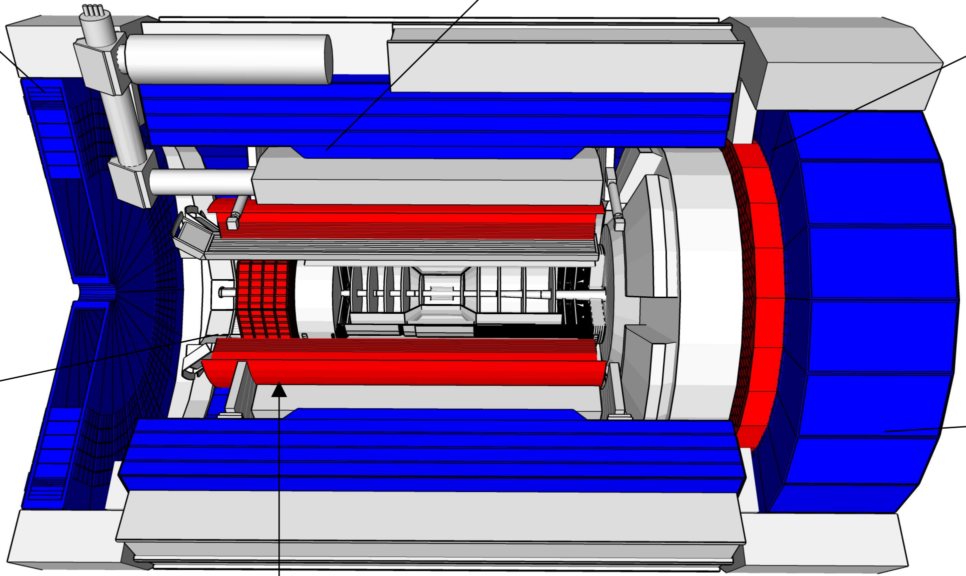
ePIC calorimetry

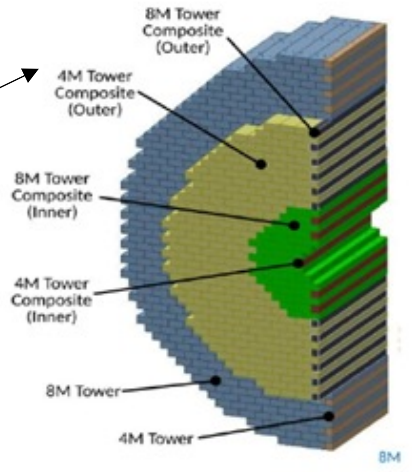
Backwards HCal
Steel/Scint Sandwich (10 layers)
(STAR re-use of scint. tiles)





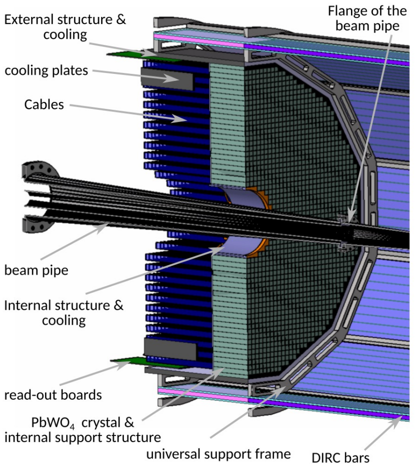
Barrel HCAL
sPHENIX re-use
new SiPM



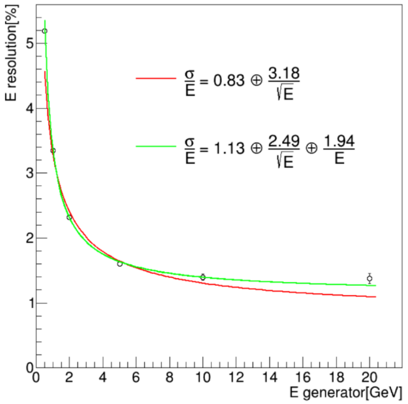


High granularity W-powder/SciFi EMCal:) keeps EM energy resolution at ~10%/√ E + 2%

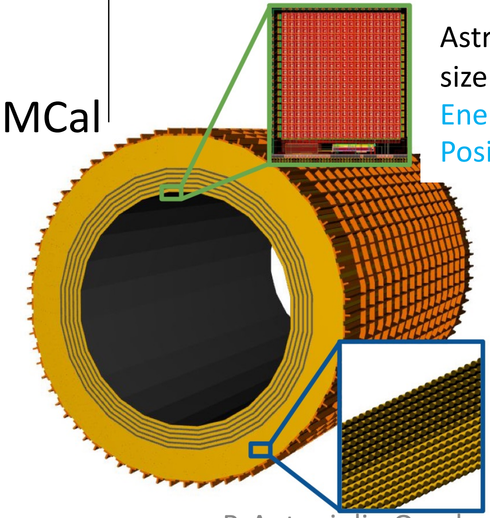
Longitudinally separated HCAL Steel/Sc & W/Sc sandwich with SiPMs embedded in Scintillator



Backwards EMCal. $PbW0_4$ crystals



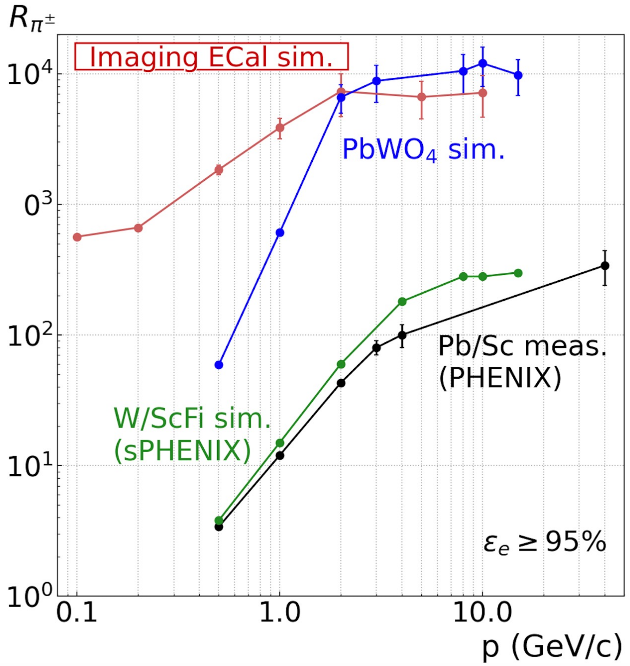
Barrel EMCal



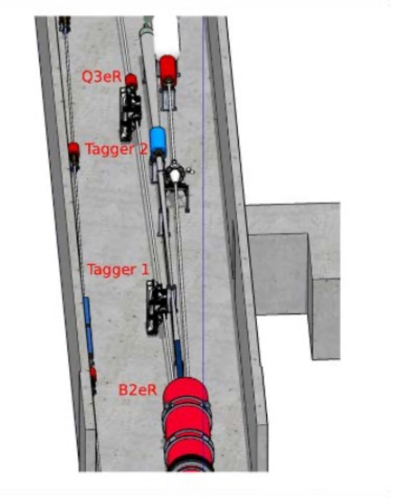
AstroPix: silicon sensor with 500x500 μm^2 size (NASA design). 4(+2) layers
Energy resolution - SciFi/Pb Layers: $5.3\% /\sqrt{E} \oplus 1.0\%$
Position resolution: O(pixel size)

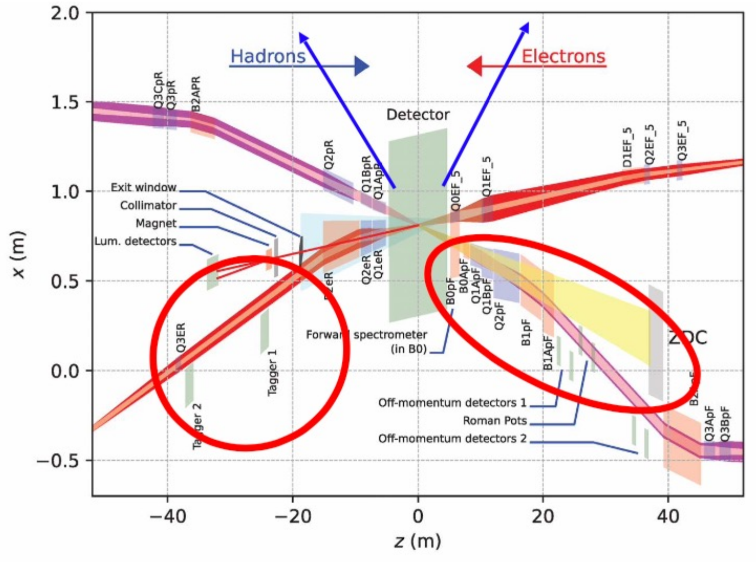
All calorimeters read with SiPM

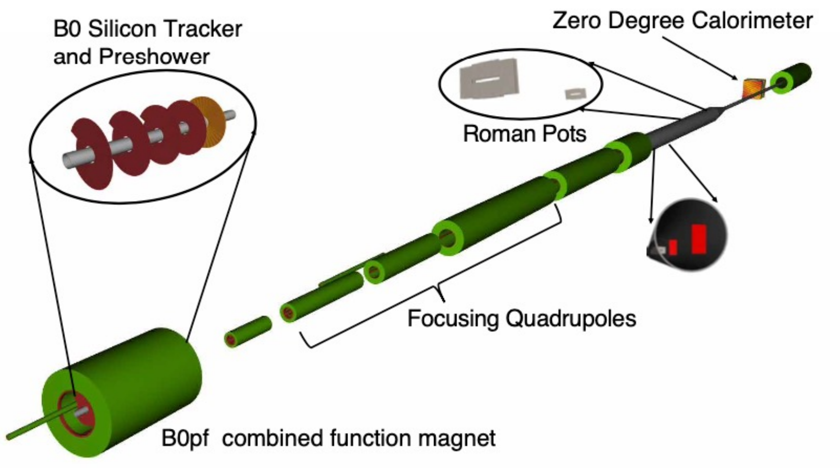
SciFi layers in Pb (GlueX design) with two-sided SIPM readout



ePIC, extended design (out of barrel)





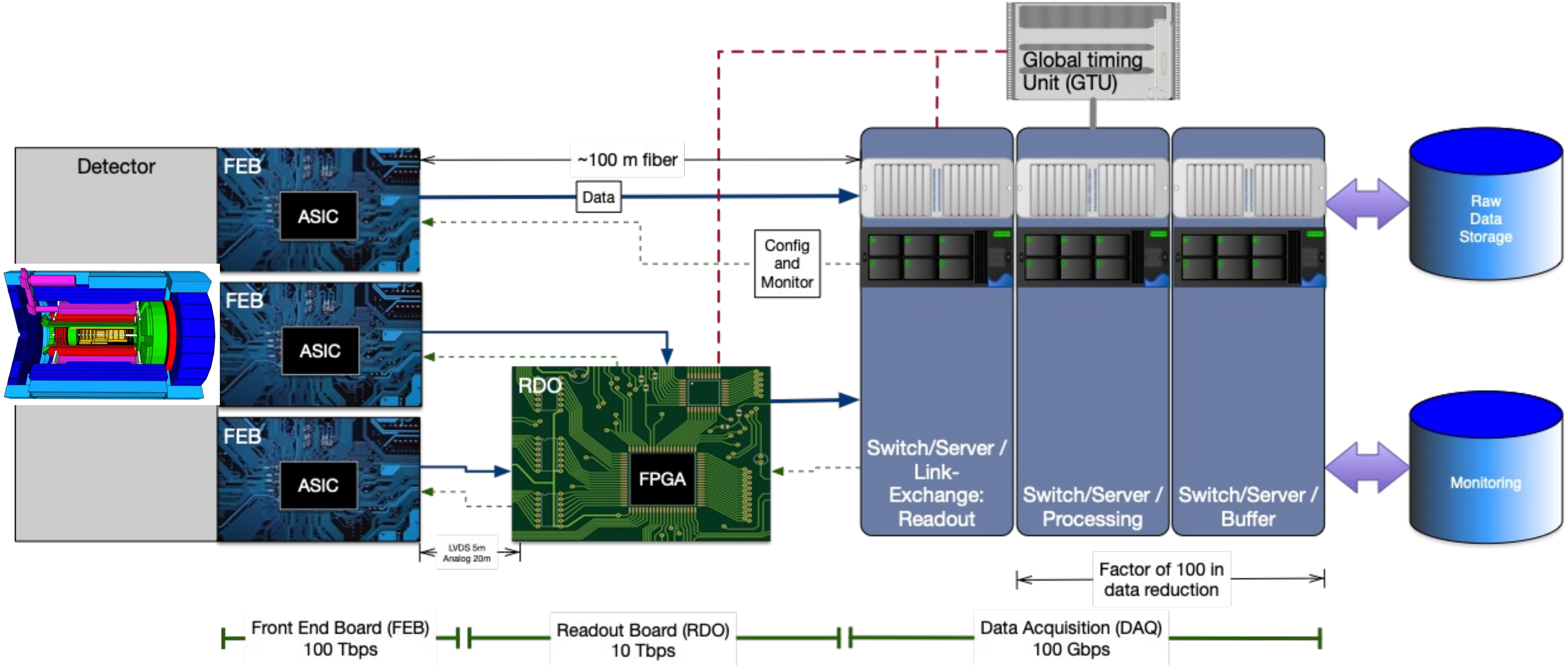


EIC physics includes final-states particles at $|\eta| > 4.5$.

- Need sub-systems integrated within and alongside the accelerator beam line
- **Far-Backward**
  - Luminosity monitor
  - Low-Q^2 tagging detectors $\Rightarrow$ scattered electron at small angles
- **Far-Forward**
  - B0 spectrometer $\Rightarrow$ silicon tracking system and photon EM calorimetry
  - Off-Momentum Detector (OMD) $\Rightarrow$ for particles from nuclear breakup
  - Roman Pots (RP) $\Rightarrow$ for tagging and reconstruction of protons
  - Zero-Degree Calorimeter (ZDC) $\Rightarrow$ for photons and neutrons

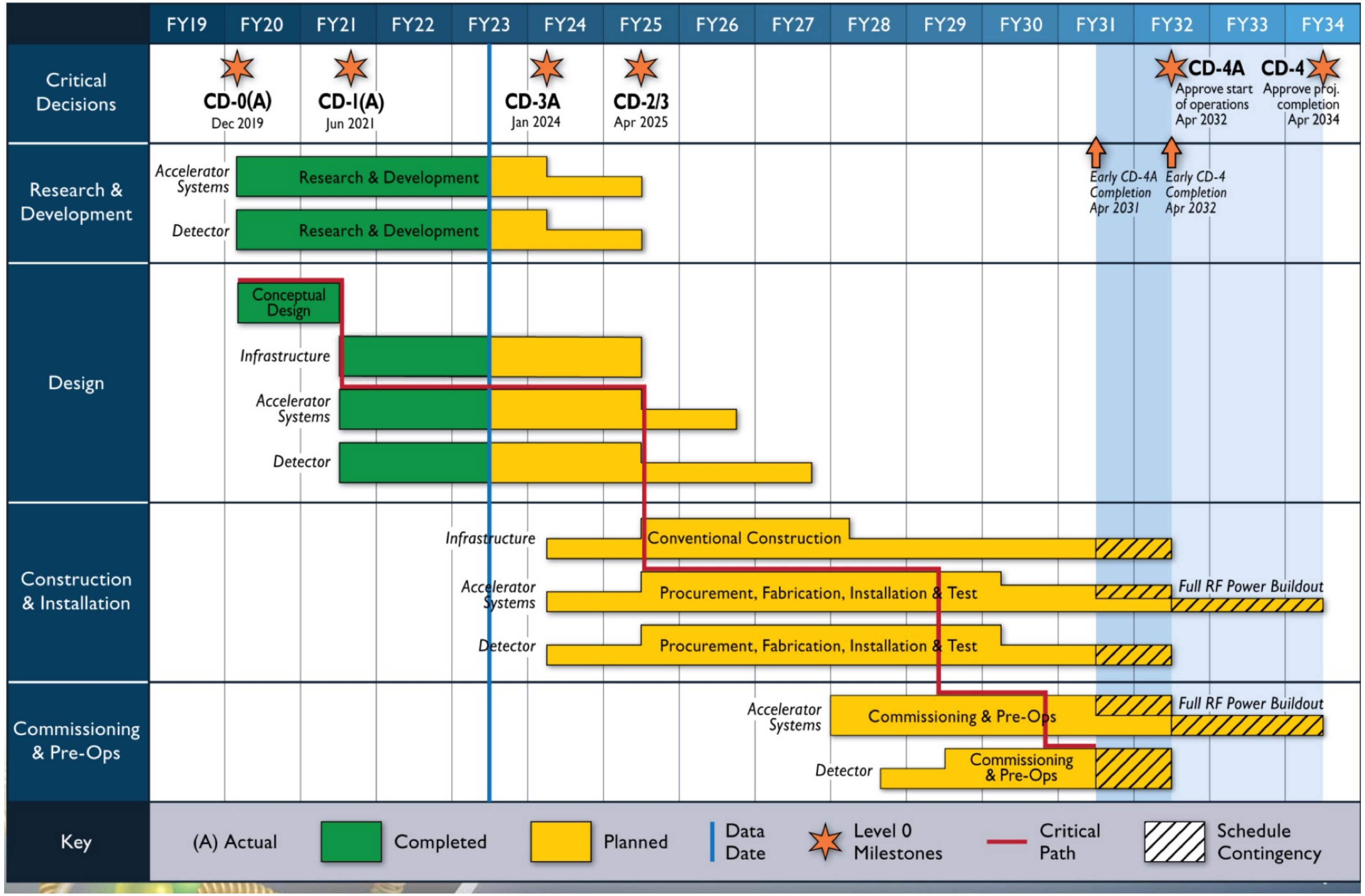
For exclusive physics instrumentation along the beamline is crucial

Streaming readout architecture and electronics



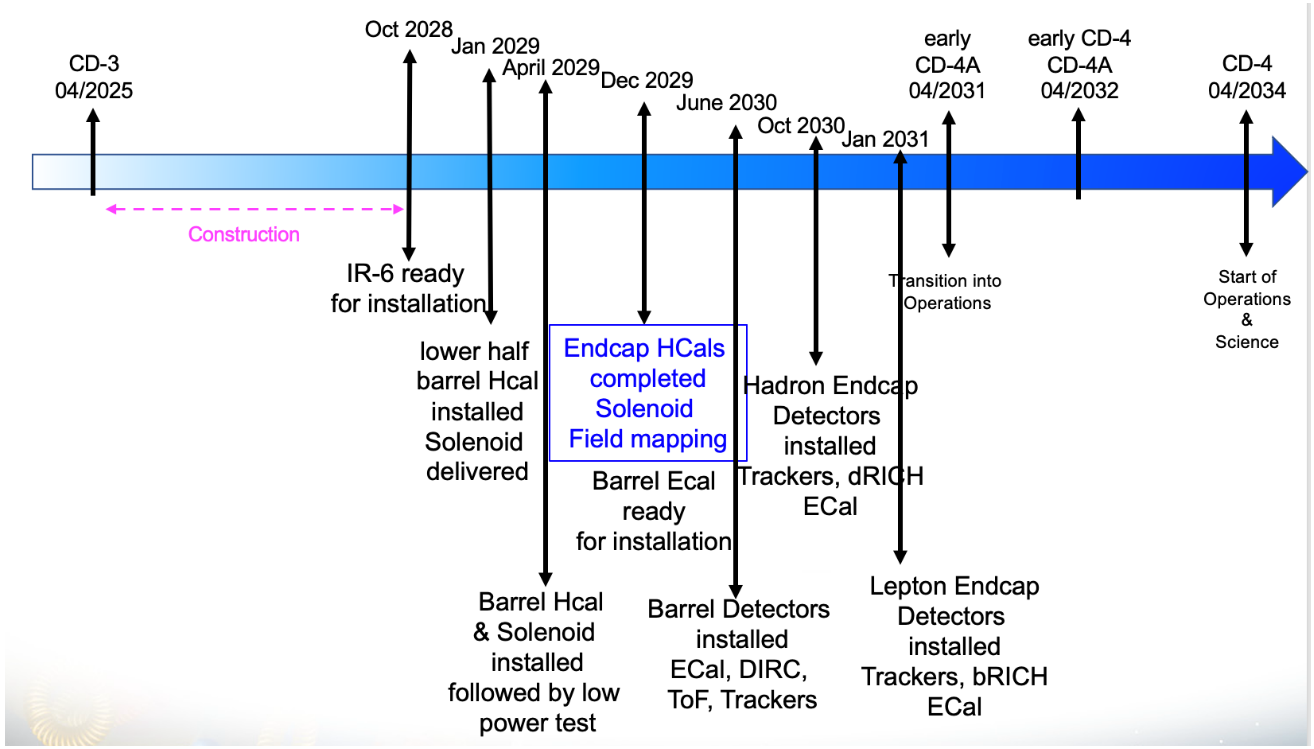
- **Triggerless** streaming architecture gives much more flexibility to do physics
- on-going **ASIC** developments for several detectors: SALSA (MPGD), ALCOR (dRICH), EICROC (AC-LGAD), CalSIPM (H2GCROC), HRPPD (HGCROC)
- Integrate **AI/ML** as close as possible to subdetectors → cognizant detector

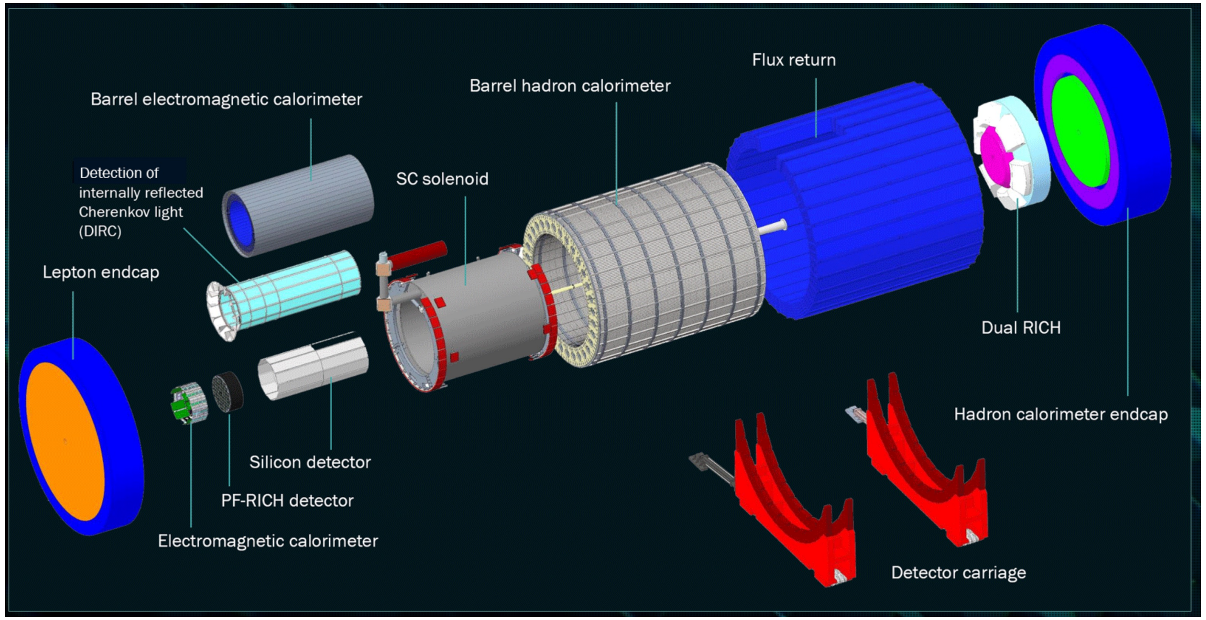
New microscope for nucleons delivery time



- construction starts following RHIC shutdown (2025)
- **7 years** from operations
- first year for machine commissioning
- 2032-2034 toward full luminosity

new microscope for nucleons installation schedule

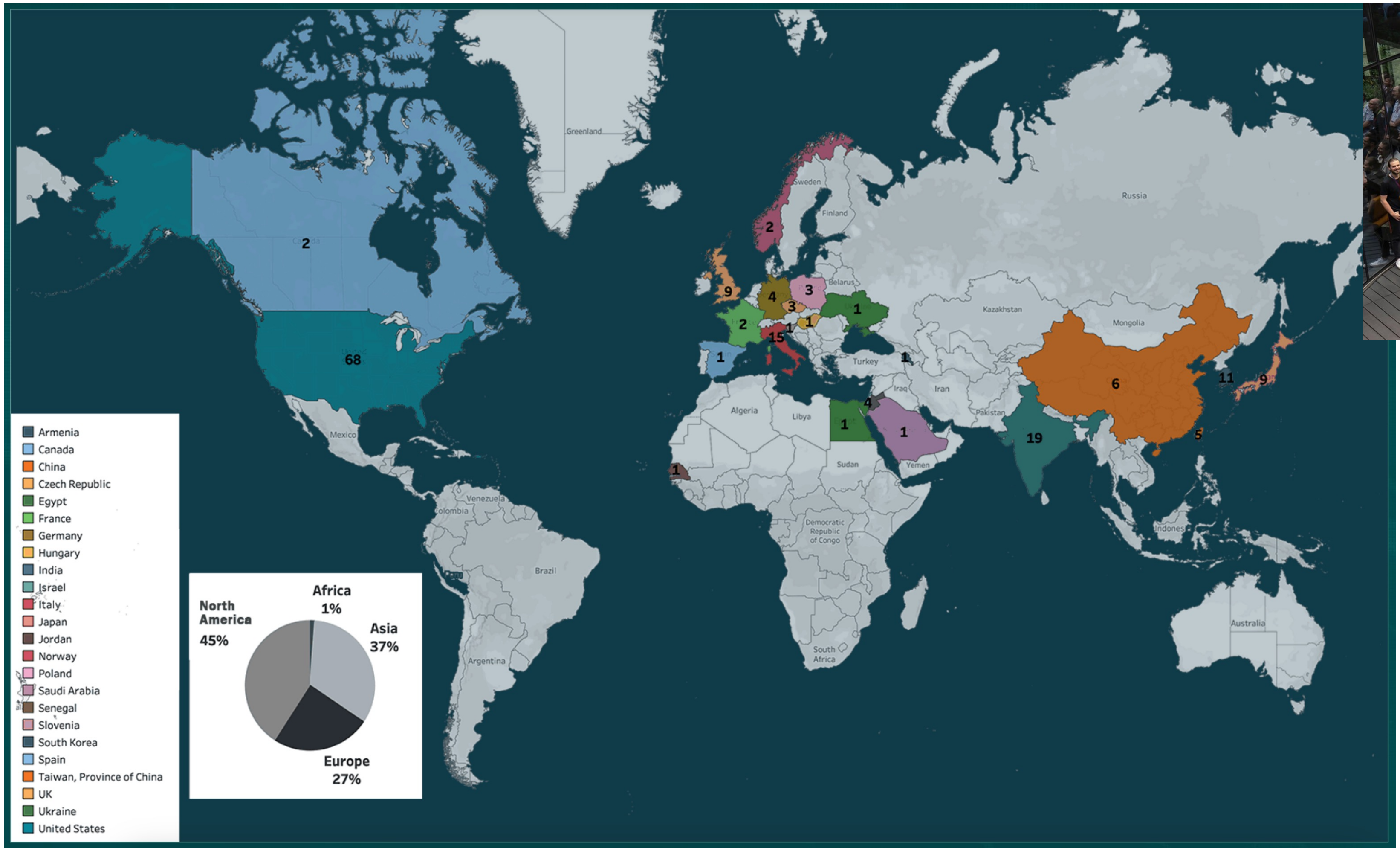




- Solenoid and Barrel HCal by Jan 2029
- all other subdetectors need to be ready between 06/29 to 06/30

With this schedule R&D not expected to extend beyond 2027

A new Collaboration in HEP/NP!



171 institutions from 24 countries
500+ members

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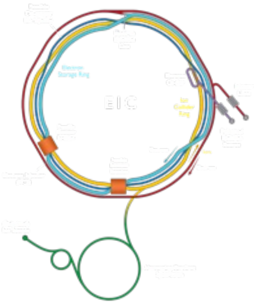
Minimal thoughts given this workshop/talk

- **R&D overlap?** timescale for LHeC matters w.r.t. to "overlap"
- MAPS technology currently developed in ALICE/ITS3 will be largely used in ePIC and it is expected to be used in ALICE3 --> see next talk by Walter Snoeys
- besides MAPS, detector R&D in ePIC is particularly innovative for photosensors applied to PID detectors, intensive use of SiPM in calorimeters and certain choices of calorimeters design (barrel ECAL PbSciFi with hybrid imaging part, forward HCAL à la CALICE) [link with DRD, see Didier’s talk]
- ePIC detector has much more emphasis on PID than "LHeC detector" PID is very relevant for several aspects of EIC science, does this apply to LHeC science?
- depending on LHeC timescale detector R&D overlap might be there for Detector 2 and/or ePIC upgrades. However, several **overlap** likely apply to ALICE (ALICE3) and LHCb upgrades under discussion for LHC Run5/6

overlap if not in time can be in technology: depending on actual LHeC detector timescale, some technologies will likely further ***evolve*** (ex: BSI SiPM, HRPPD, ...)

Summary and outlook



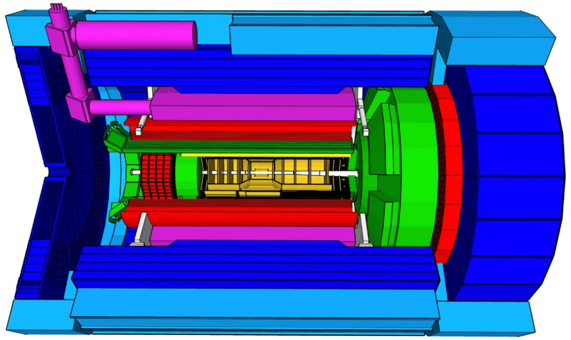
- **EIC project well on track**
  TDR (both for the accelerator and the detector) to be submitted by 2024

- **ePIC Collaboration** for "Detector 1" since 2022 and is maturing detector design toward TDR

- **ePIC detector** addresses the challenges of an EIC detector to deliver physics goals

- **ePIC** will be innovative: several novel technologies that will advance the state of the art

- construction and installation **timelines/schedule** understood



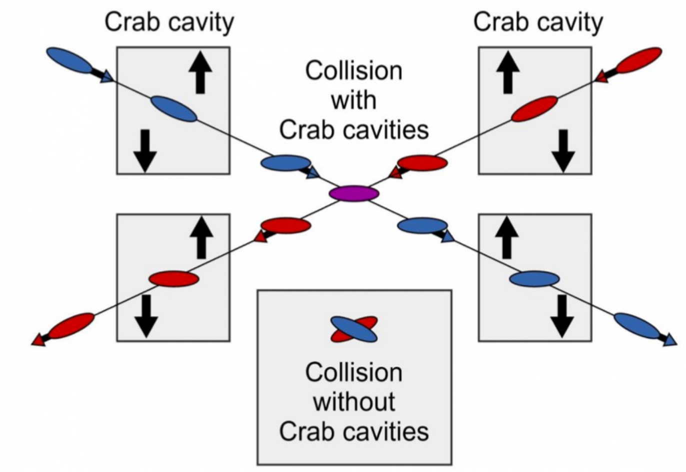
credits for several slides and input: E. Aschenauer, S. Fazio, J. La Joie, S. Dalla Torre, T. Ulrich, M. Zurek

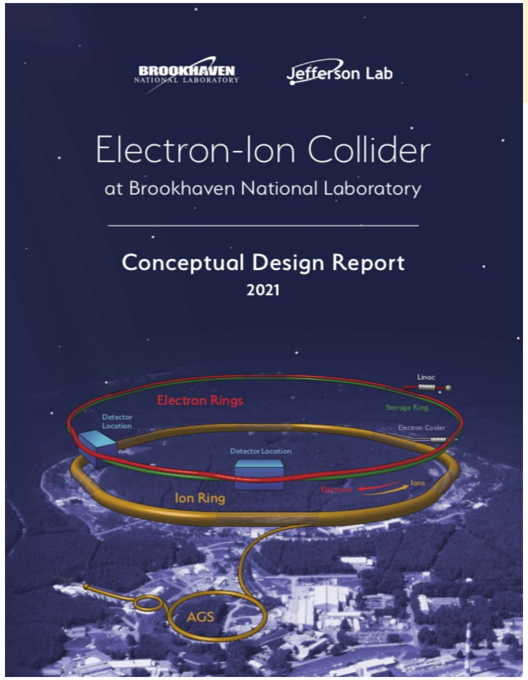

Backup

Collider params

Hadron Storage Ring: 40 – 275 GeV
Electron Storage Ring: 5 – 18 GeV

→ 25 mrad Crossing Angle





Machine Conceptual Design Report:
https://www.bnl.gov/ec/files/EIC_CDR_Final.pdf

Params at maximum lumi

Parameter	hadron	electron
Center-of-mass energy [GeV]	104.9	
Energy [GeV]	275	10
Number of bunches	1160	
Particles per bunch [10^{10}]	6.9	17.2
Beam current [A]	1.0	2.5
Horizontal emittance [nm]	11.3	20.0
Vertical emittance [nm]	1.0	1.3
Horizontal β-function at IP β^*_x [cm]	80	45
Vertical β-function at IP β^*_y [cm]	7.2	5.6
Horizontal/Vertical fractional betatron tunes	0.228/0.210	0.08/0.06
Horizontal divergence at IP $\sigma^*_{x'}$ [mrad]	0.119	0.211
Vertical divergence at IP $\sigma^*_{y'}$ [mrad]	0.119	0.152
Horizontal beam-beam parameter ξ_x	0.012	0.072
Vertical beam-beam parameter ξ_y	0.012	0.1
IBS growth time longitudinal/horizontal [hr]	2.9/2.0	-
Synchrotron radiation power [MW]	-	9.0
Bunch length [cm]	6	0.7
Hourglass and crab reduction factor [17]	0.94	
Luminosity [10^{34} cm^{-2}s^{-1}]	1.0	

→ Hadron beams cooling with innovative technique (Coherent Electron Cooling using FEL)
V.N. Litvinenko and Y. S. Derbenev, PRL 102 (2009) 114801

Yellow report requirements

η	Nomenclature			Tracking				Electrons and Photons			π/K/p PID		HCAL		Muons
				Min p_T	Resolution	Allowed X/X_0	Si-Vertex	Min E	Resolution σ_E/E	PID	p-Range (GeV/c)	Separation	Min E	Resolution σ_E/E	
-6.9 — -5.8	↓ p/A	Auxiliary Detectors	low-Q² tagger		$\delta\theta/\theta < 1.5\%$; $10^{-6} < Q^2 < 10^{-2}$ GeV²										
…															
-4.5 — -4.0			Instrumentation to separate charged particles from γ						2%/√E+(1-3)%						
-4.0 — -3.5				100 MeV π 135 MeV K				50 MeV						~50%/√E+6%	
-3.5 — -3.0		Central Detector	Backwards Detectors		$\sigma_p/p \sim 0.1\% \times p+2.0\%$	~5% or less				π suppression up to 1:10⁴	≤ 7 GeV/c	≥ 3σ	~500 MeV	~45%/√E+6%	Useful for bkg, improve resolution
-3.0 — -2.5							σ_{xy}~30μm/p_T+40μm								
-2.5 — -2.0					$\sigma_p/p \sim 0.05\% \times p+1.0\%$		σ_{xy}~30μm/p_T+20μm								
-2.0 — -1.5									7%/√E+(1-3)%						
-1.5 — -1.0															
-1.0 — -0.5			Barrel		$\sigma_p/p \sim 0.05\% \times p+0.5\%$		σ_{xyz} ~ 20 μm, $d_0(z) \sim d_0(r\varphi)$ ~ 20/p_T GeV μm + 5 μm		(10-12)%/√E+(1-3)%		≤ 10 GeV/c			~85%/√E+7%	
-0.5 — 0.0															
0.0 — 0.5															
0.5 — 1.0											≤ 15 GeV/c				
1.0 — 1.5			Forward Detectors		$\sigma_p/p \sim 0.05\% \times p+1.0\%$		σ_{xy}~30μm/p_T+20μm			3σ e/π	≤ 30 GeV/c			~35%/√E	
1.5 — 2.0											≤ 50 GeV/c				
2.0 — 2.5															
2.5 — 3.0					$\sigma_p/p \sim 0.1\% \times p+2.0\%$		σ_{xy}~30μm/p_T+40μm				≤ 30 GeV/c				
3.0 — 3.5							σ_{xy}~30μm/p_T+60μm				≤ 45 GeV/c				
3.5 — 4.0	↑e	Auxiliary Detectors	Instrumentation to separate charged particles from γ												
4.0 — 4.5															
…															
> 6.2			Proton Spectrometer		$\sigma_{intrinsic}(\lvert t\rvert)/\lvert t\rvert < 1\%$; Acceptance: $0.2 < p_T < 1.2$ GeV/c										