AC-LGAD Detectors for Spatial and Timing Measurements at EIC

Zhenyu Ye

yezhenyu@uic.edu

University of Illinois at Chicago

Electron-Ion Collider

BROOKHAVEN NATIONAL LABORATORY

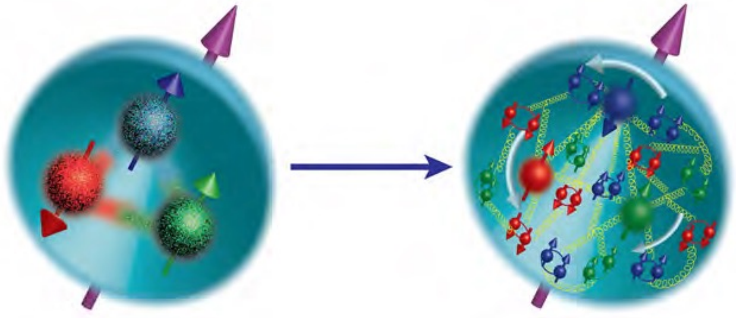
Jefferson Lab

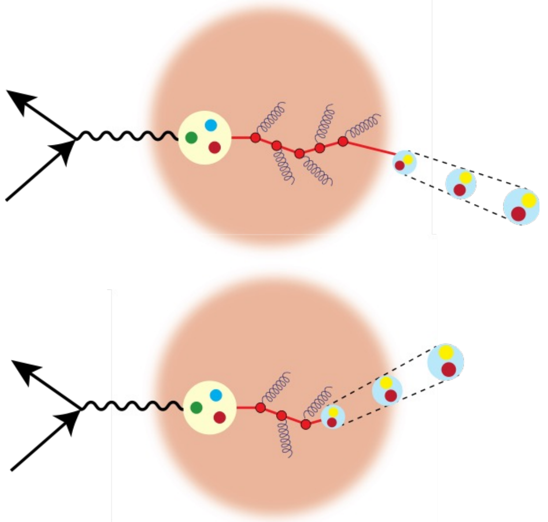
U.S. DEPARTMENT OF ENERGY Office of Science

EIC - Physics Program

[5] EIC Yellow Report

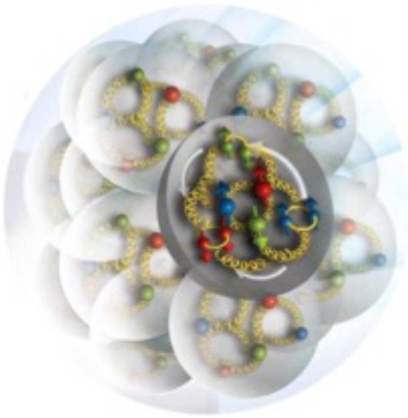
How are the gluons and sea quarks, and their spins, distributed in space and momentum inside the nucleon? What is the role of orbital motion in building the nucleon spin?





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?



Precision EW, Beyond Standard Model, …

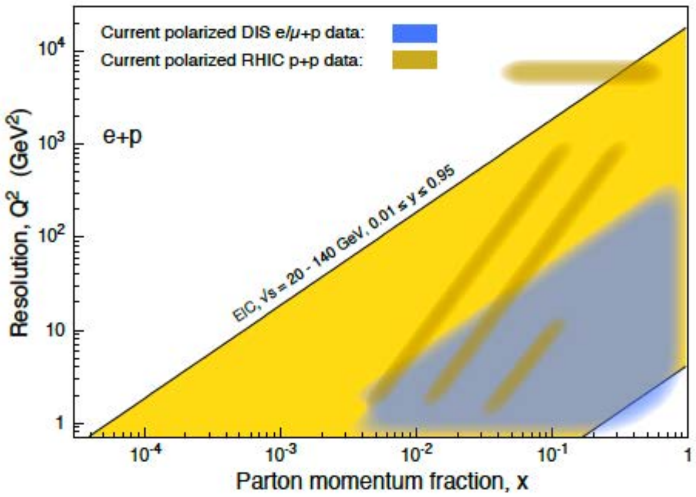
EIC - Accelerator

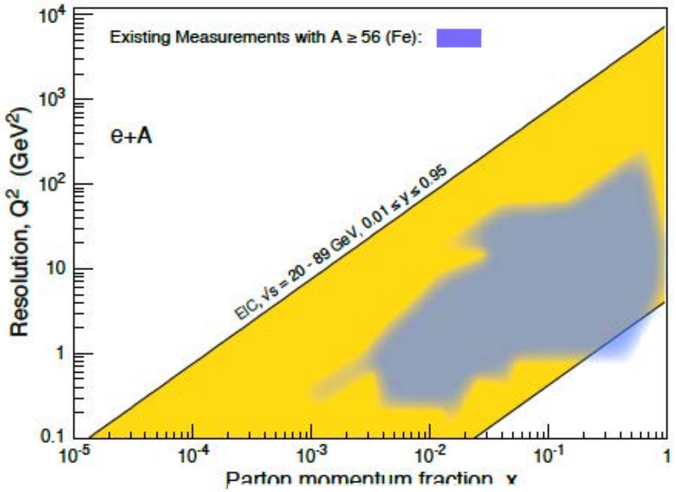
Push limits of accelerator technologies

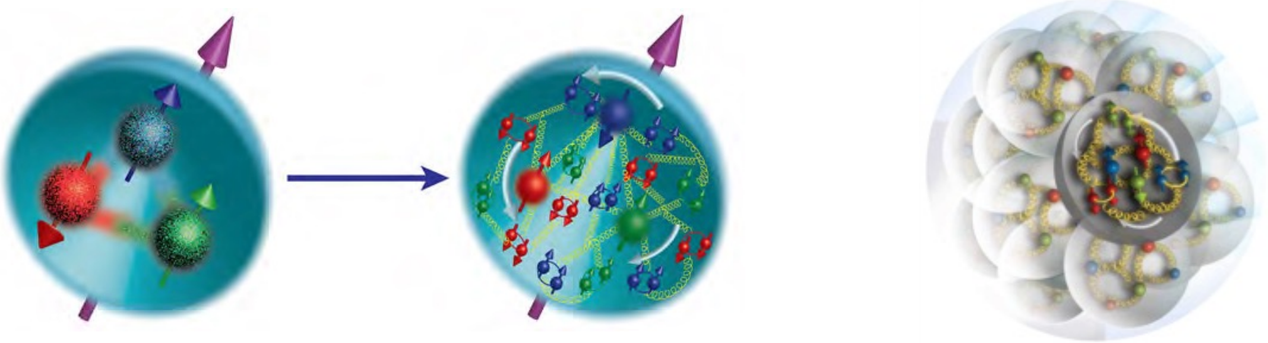
[4] EIC CDR

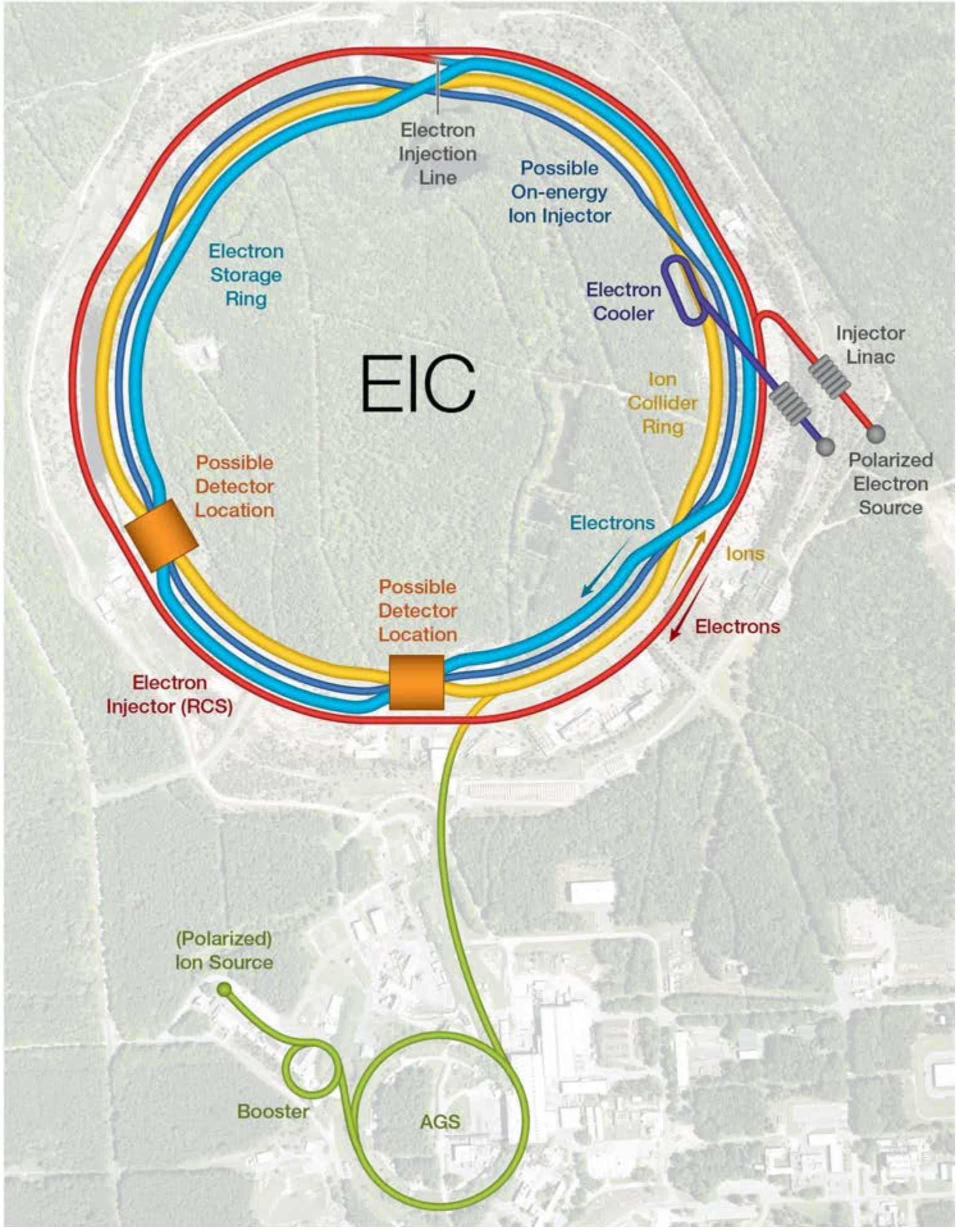
EIC is on the **highest priority** of US Nuclear Physics

- **High luminosity**: L= 10^{33}–10^{34} cm^{-2}s^{-1}, 10–100 fb^{-1}/year
- **Highly polarized** electron and light ion beams: ~70%
- **Large center of mass energy range**: E_{cm} = 20–140 GeV
- **Large ion species range**: proton – Uranium







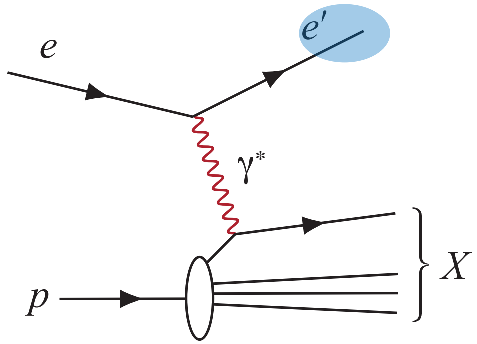


Electron Beam: 5-18 GeV
Ion: 40, 100-275 GeV

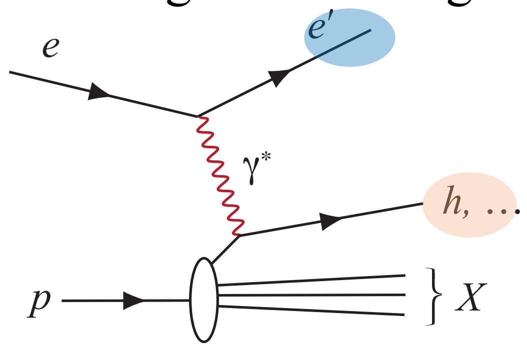
Physics Processes and Particle Detection

[6] EIC DPAP

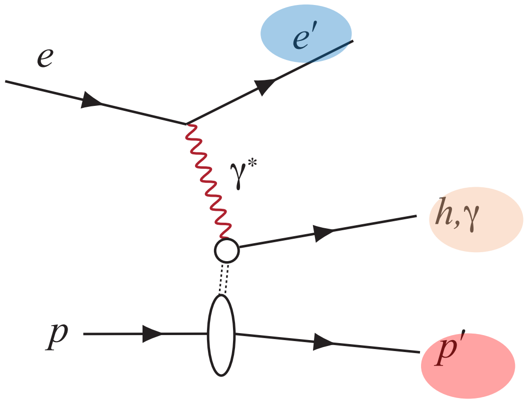
- Physics Processes in eN scatterings
  - Inclusive DIS : scattered electron only
  - Semi-inclusive DIS: scattered electron, one or more final state hadrons
  - Exclusive: all the final state particles including the recoiling nucleon



Inclusive DIS

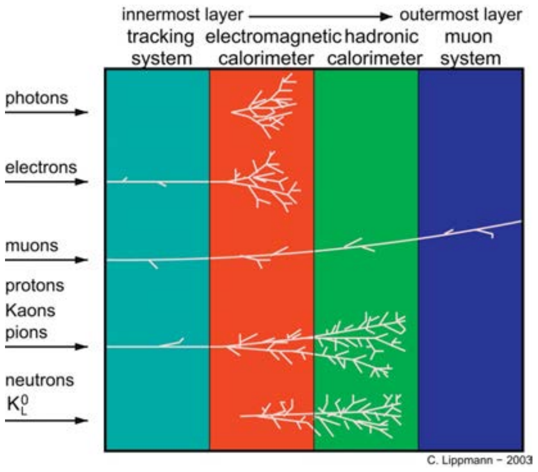


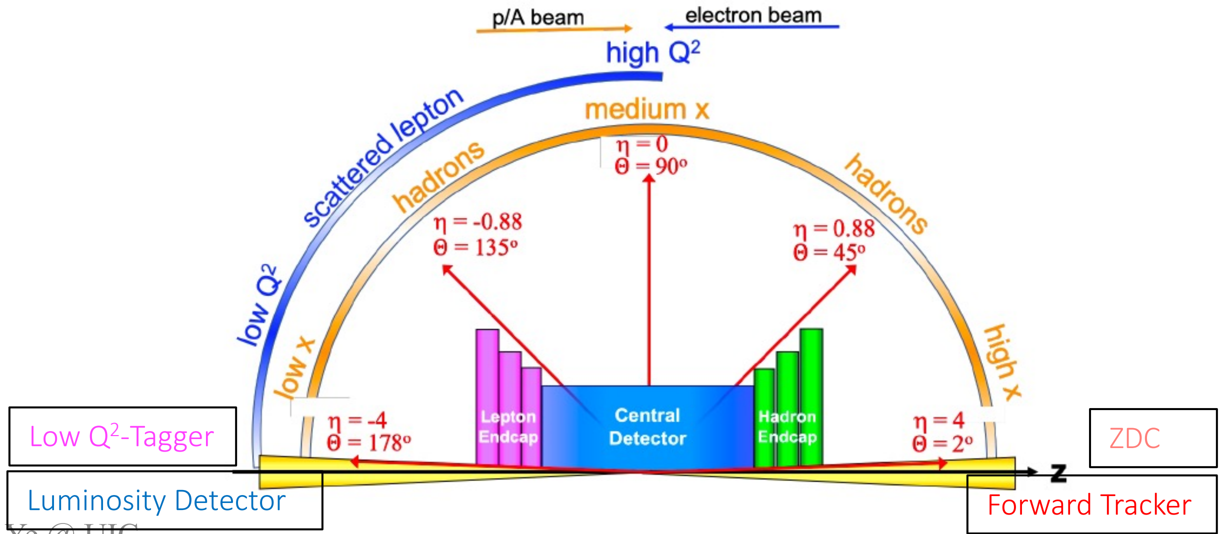
Semi-inclusive DIS



Exclusive

- Final state particles:
  - electrons
  - hadrons
  - photons
  - jets
  - muons
  - neutrinos
  - …





EIC – Detector Requirements

η	Nomenclature	Tracking						Electrons and Photons			π/K/p		HCAL		Muons
		Resolution	Relative Momentun	Allowed X/X_0	Minimum-p_T (MeV/c)	Transverse Pointing Res.	Longitudinal Pointing Res.	Resolution σ_E/E	PID	Min E Photon	p-Range	Separation	Resolution σ_E/E	Energy	
< -4.6	Low-Q2 tagger														
-4.6 to -4.0		Not Accessible													
-4.0 to -3.5			Reduced Performance												
-3.5 to -3.0	Backward Detector		$\sigma_p/p \sim 0.1\% \times p \oplus 2\%$	~5% or less	150-300			$1\%/E \oplus 2.5\%/\sqrt{E} \oplus 1\%$	π suppression up to $1:10^{-4}$	20 MeV	≤ 10 GeV/c	≥ 3σ	$50\%/\sqrt{E} \oplus 10\%$	~500MeV	Muons useful for background suppression and improved resolution
-3.0 to -2.5															
-2.5 to -2.0			$\sigma_p/p \sim 0.02\% \times p \oplus 1\%$												
-2.0 to -1.5						dca(xy) ~ $40/p_T$ μm ⊕ 10 μm	dca(z) ~ $100/p_T$ μm ⊕ 20 μm	$2\%/E \oplus (4\text{-}8)\%/\sqrt{E} \oplus 2\%$	π suppression up to $1:(10^{-3}\text{-}10^{-2})$	50 MeV					
-1.5 to -1.0															
-1.0 to -0.5	Barrel		$\sigma_p/p \sim 0.02\% \times p \oplus 5\%$		400	dca(xy) ~ $30/p_T$ μm ⊕ 5 μm	dca(z) ~ $30/p_T$ μm ⊕ 5 μm	$2\%/E \oplus (12\text{-}14)\%/\sqrt{E} \oplus (2\text{-}3)\%$	π suppression up to $1:10^{-2}$	100 MeV	≤ 6 GeV/c		$100\%/\sqrt{E} \oplus 10\%$		
-0.5 to 0.0															
0.0 to 0.5															
0.5 to 1.0															
1.0 to 1.5	Forward Detectors		$\sigma_p/p \sim 0.02\% \times p \oplus 1\%$		150-300	dca(xy) ~ $40/p_T$ μm ⊕ 10 μm	dca(z) ~ $100/p_T$ μm ⊕ 20 μm	$2\%/E \oplus (4^{*}\text{-}12)\%/\sqrt{E} \oplus 2\%$	3σ e/π up to 15 GeV/c	50 MeV	≤ 50 GeV/c		$50\%/\sqrt{E} \oplus 10\%$		
1.5 to 2.0															
2.0 to 2.5															
2.5 to 3.0			$\sigma_p/p \sim 0.1\% \times p \oplus 2\%$												
3.0 to 3.5															
3.5 to 4.0	Instrumentation to separate charged particles from photons		Reduced Performance												
4.0 to 4.5		Not Accessible													
> 4.6	Proton Spectrometer														
	Zero Degree Neutral Detection														

4π hermetic detector in $-4 < \eta < 4$ with light inner tracking detectors:

- Excellent momentum and impact parameter resolution
- Excellent PID for e/h and pi/K/p separation
- Excellent EM calorimeter resolution in backward direction
- Good hadronic calorimeter resolution in forward region

EIC Project Detector (ePIC)

Advance detector technologies

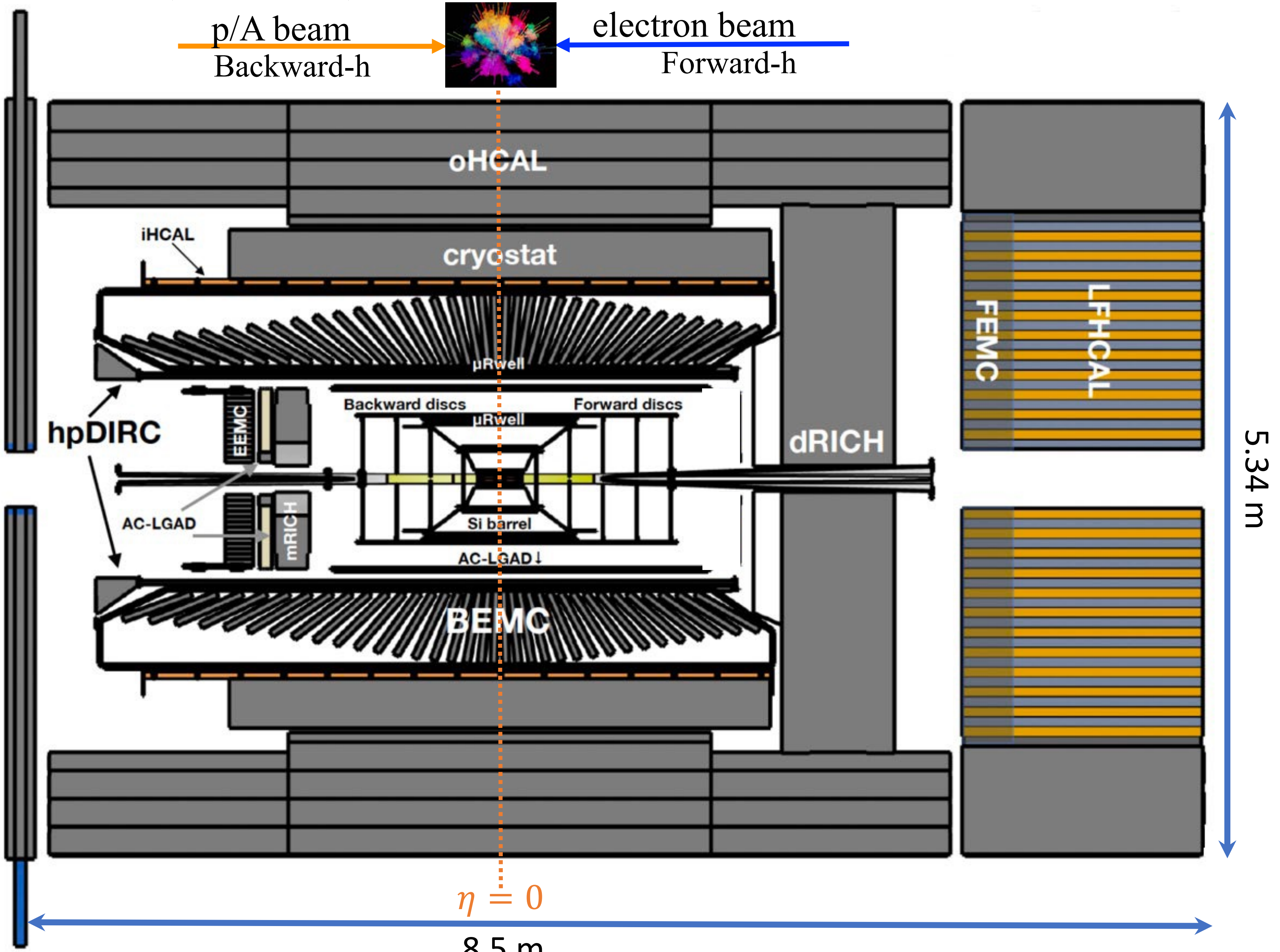
[6] EIC DPAP

Tracking and Vertexing:
- MAPS (~3 μm)
- AC-LGAD (~30 μm)
- MPGD (~150 μm)

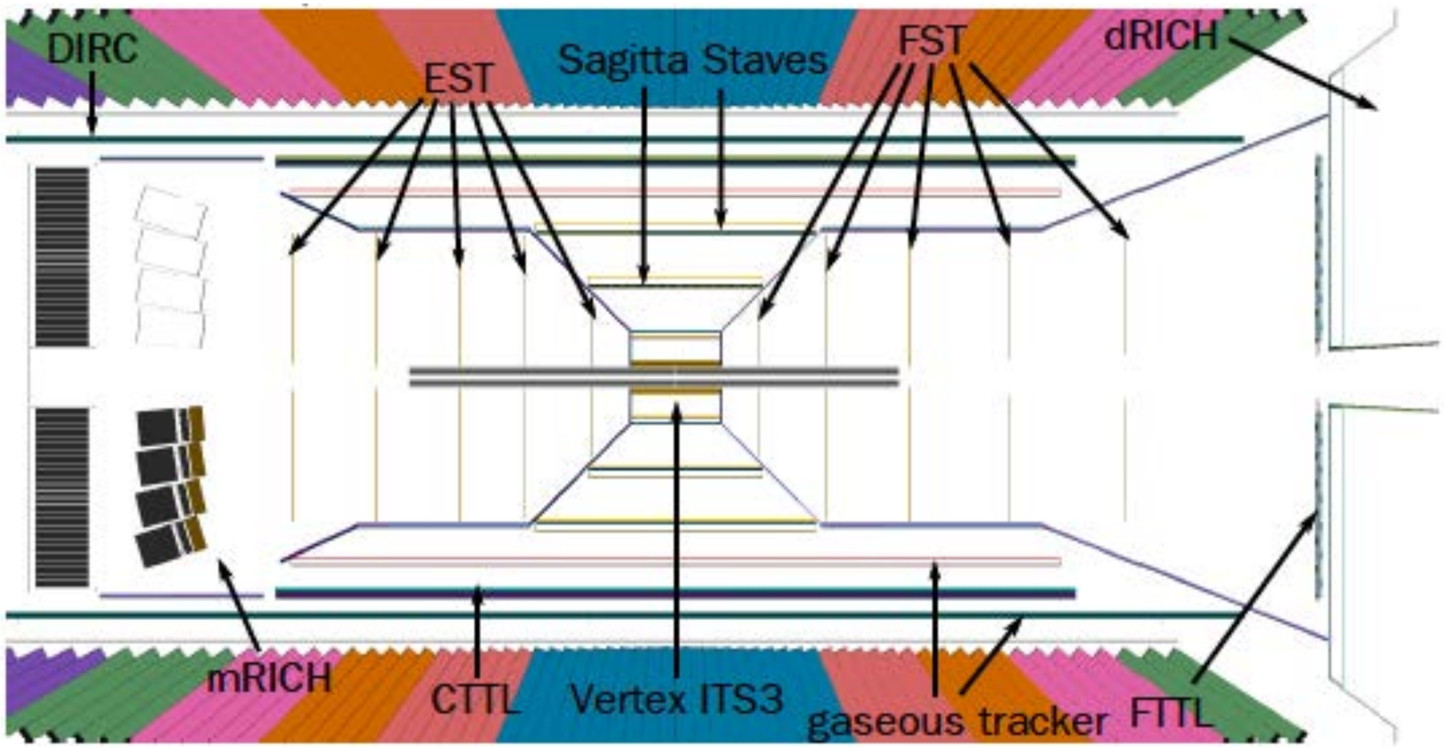
PID:
- AC-LGAD TOF (~30 ps)
- hpDIRC
- pfRICH
- dRICH

Calorimetry:
- PbWO EEMCal
- Imaging Barrel EMCal
- Inner HCal (instrumented frame)
- Outer HCal (sPHENIX re-use)
- FEMC
- LFHCAL

Differences to LHC
- lower momentum
- lower occupancy
- less irradiation



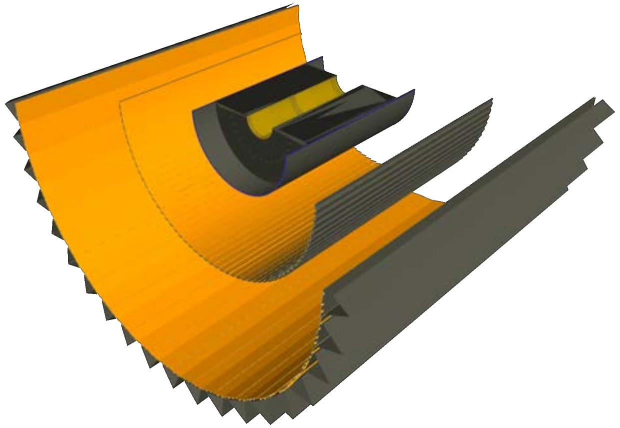
ePIC: Tracking and Vertexing

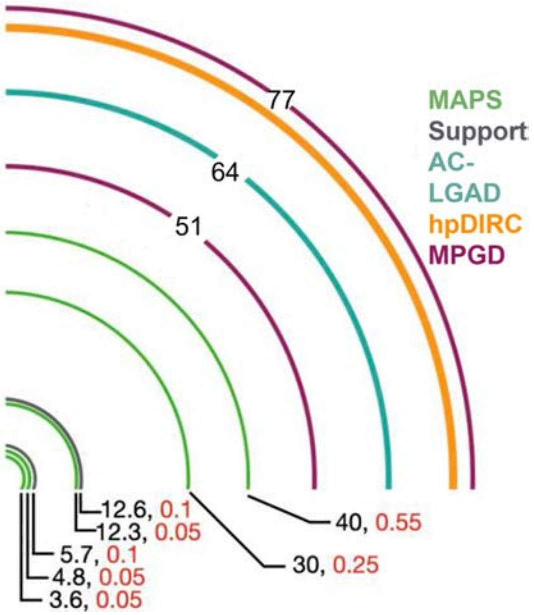


Technology mix

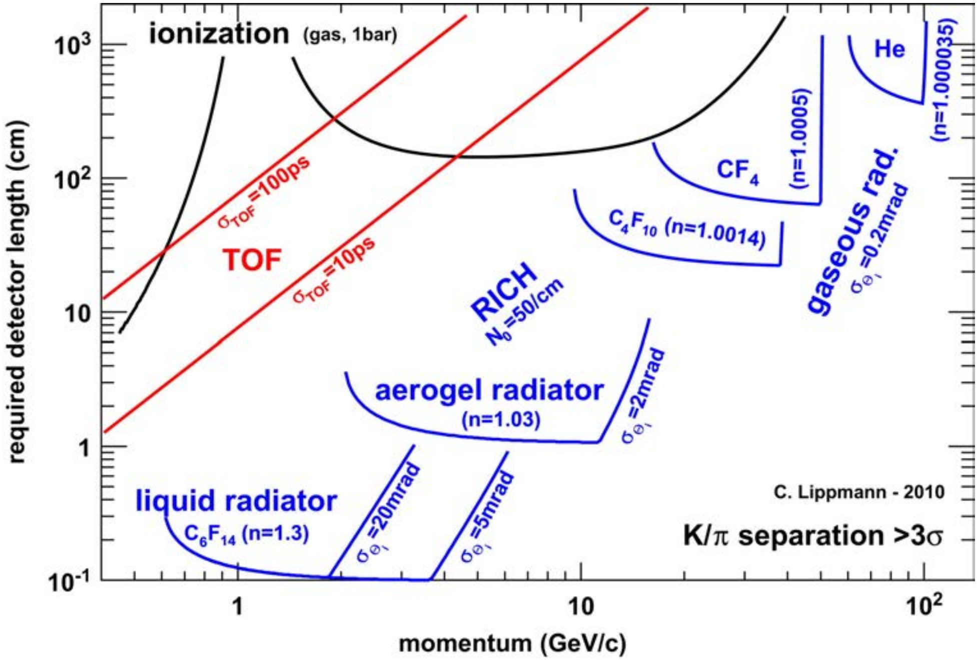
- **MAPS based Si-detectors**:
  $\sigma = 3\ \mu m \quad X/X_0 \sim 0.05 - 0.55\%/\text{layer}$
- **Gaseous tracker**:
  $\sigma = 150\ \mu m \quad X/X_0 \sim 0.2\%/\text{layer}$
- **AC-LGADs**:
  $\sigma = 30\ \mu\text{m},\ X/X_0 \sim$ 1-4 % /layer

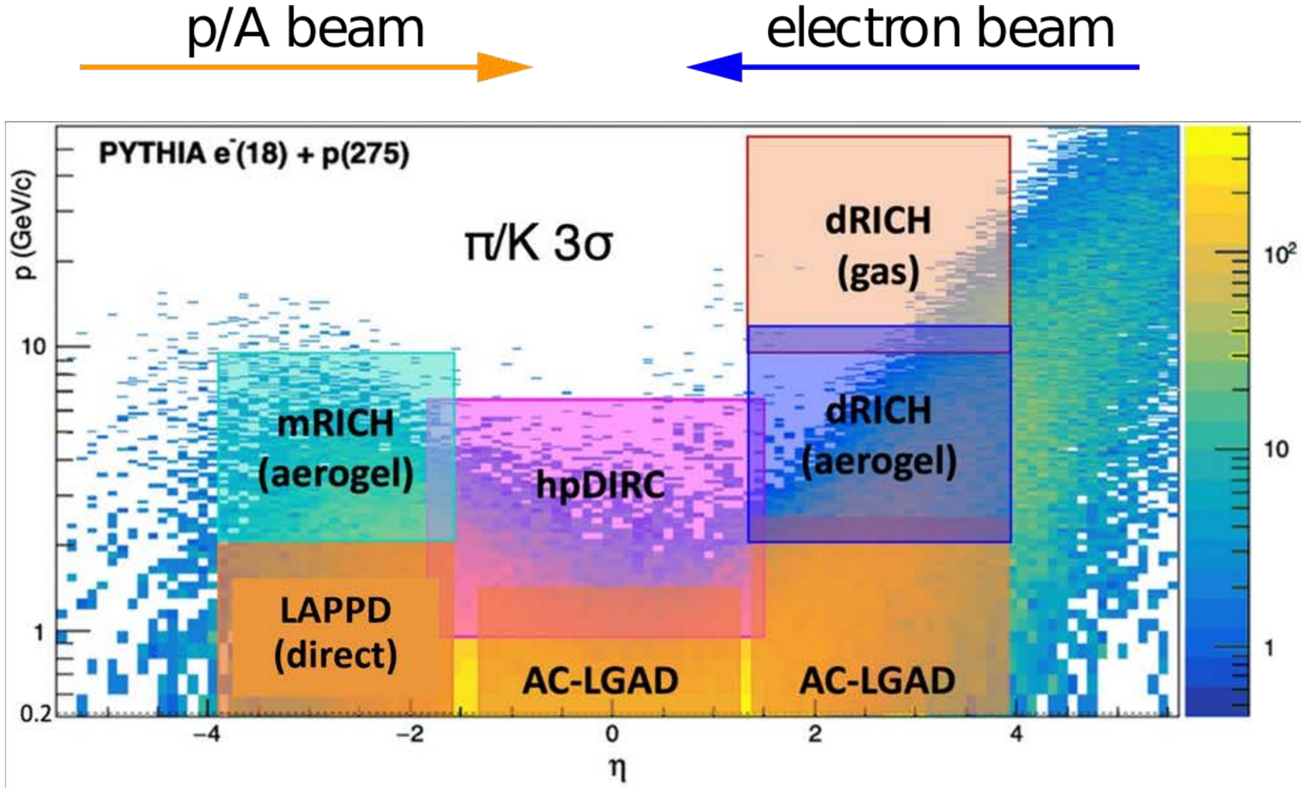
- **mid-rapidity:**
  Ultra thin MAPS based Si-detectors, gaseous detectors & AC-LGADs
- **Forward and Backward:**
  MAPS based Silicon discs & AC-LGADs
- Outer layers placed to provide seeds for tracking & ideal track points before/after PID detectors
- New Magnet with BABAR dimensions B = 1.7-2T





ePIC: Particle Identification



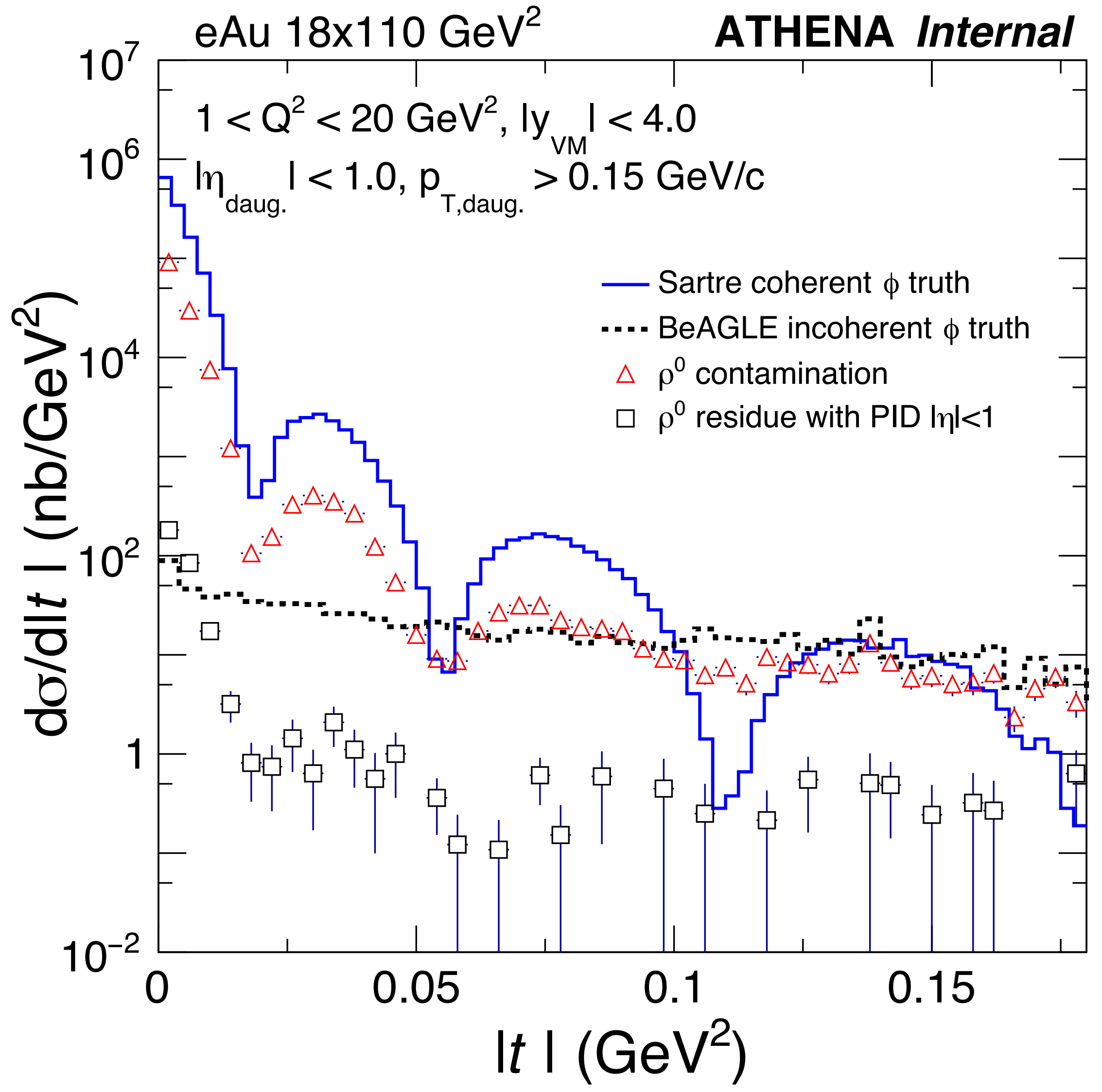


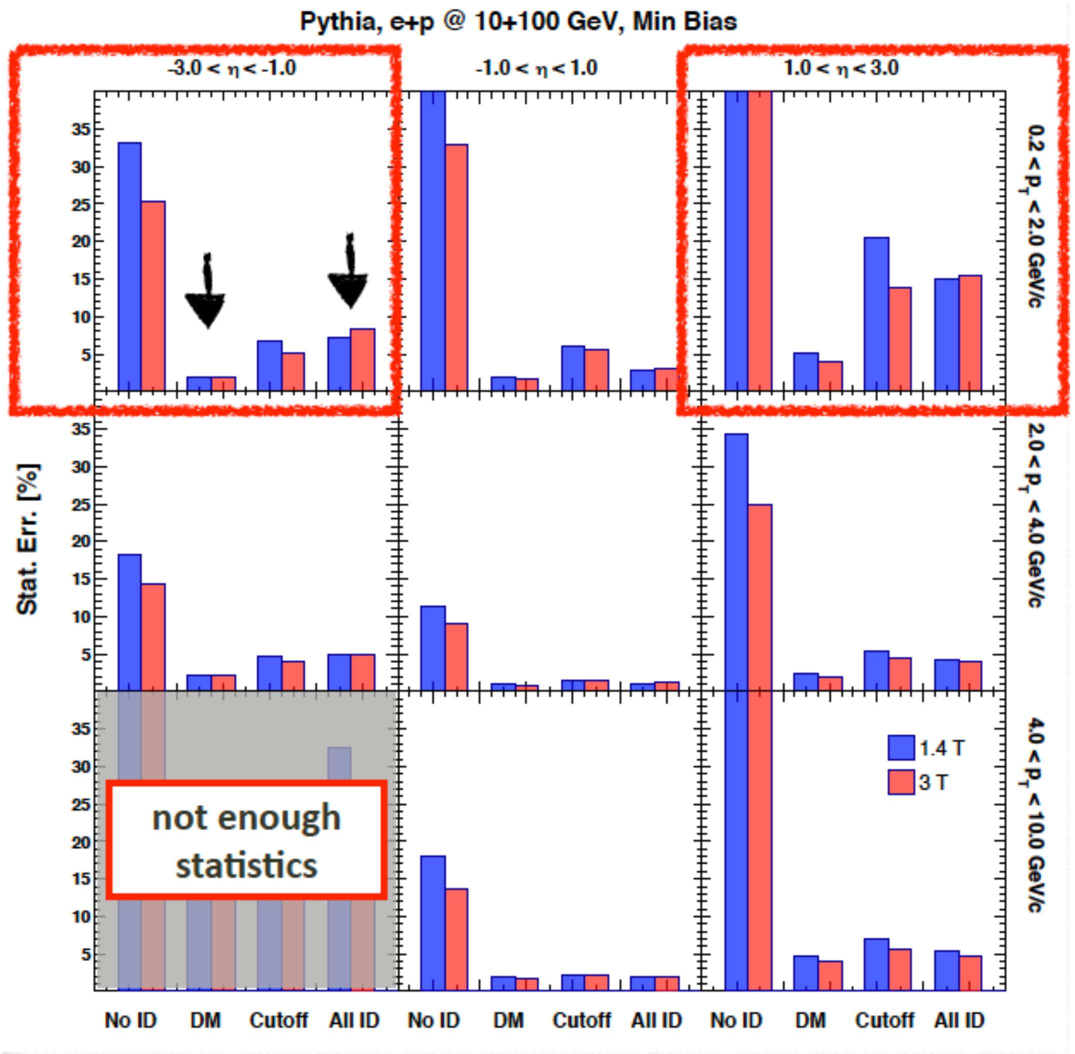
majority of particles are low momentum (<2 GeV/c)

Use multiple detector technologies to cover the wide kinematic range

- Backward: pfRICH + LAPPD TOF
- Barrel: hpDIRC + AC-LGAD TOF
- Forward: dRICH +AC-LGAD TOF

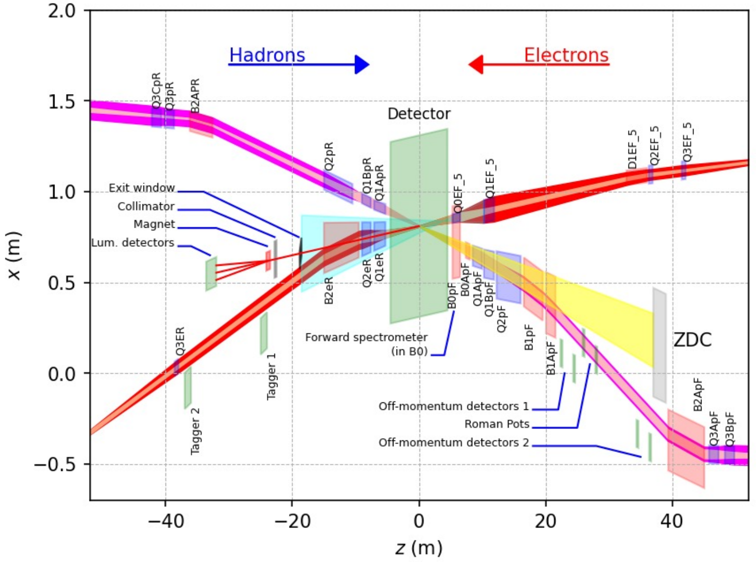
ePIC: Particle Identification

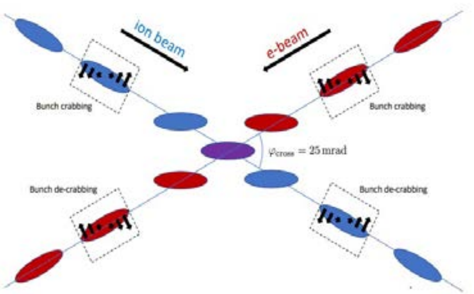


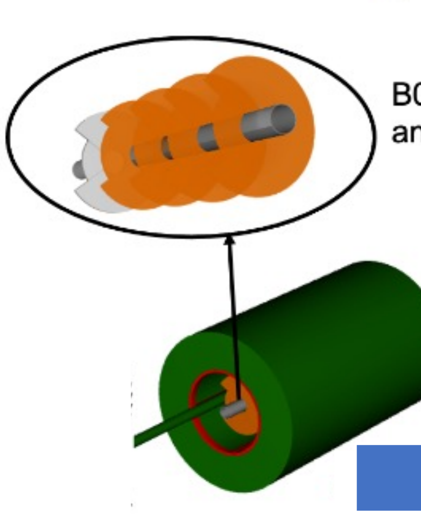


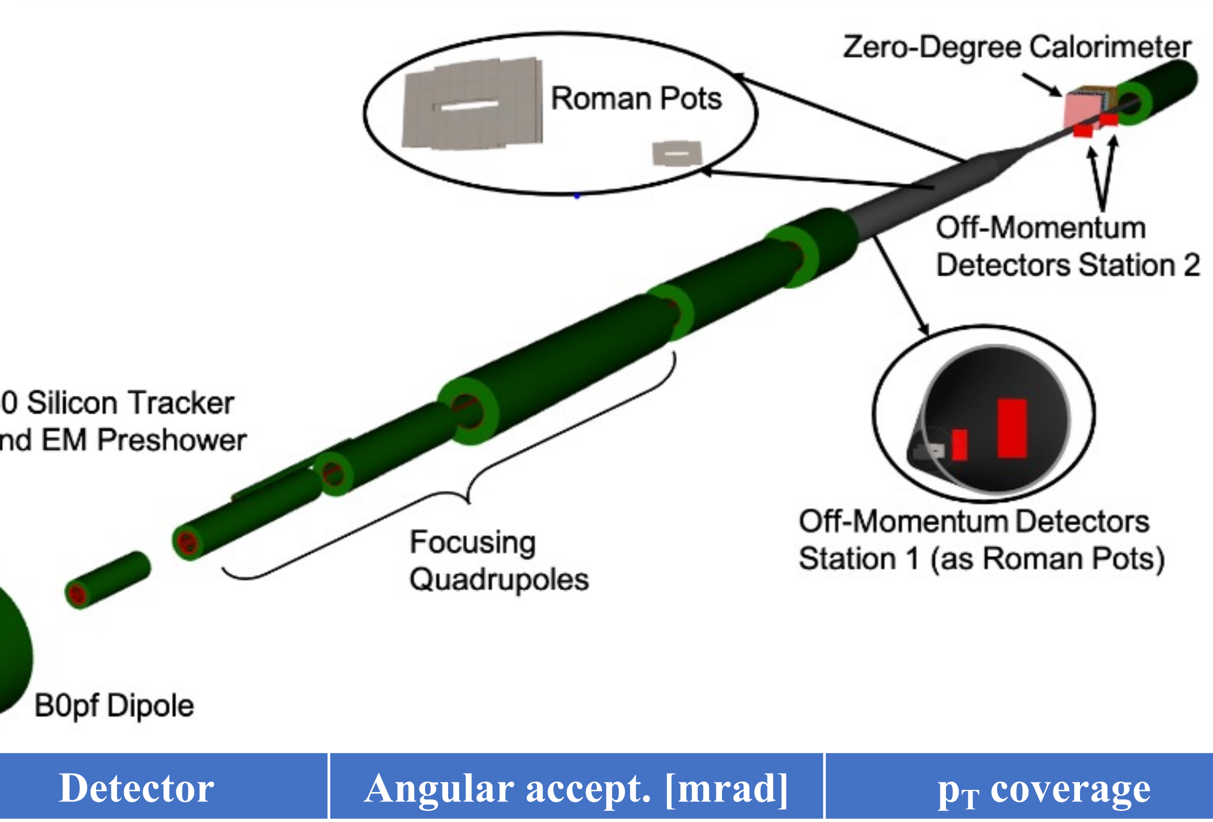
Low p_T PID by TOF is crucial for certain physics measurements

ePIC: Far-Forward Detectors



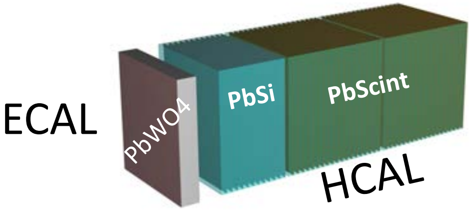






Technologies defined

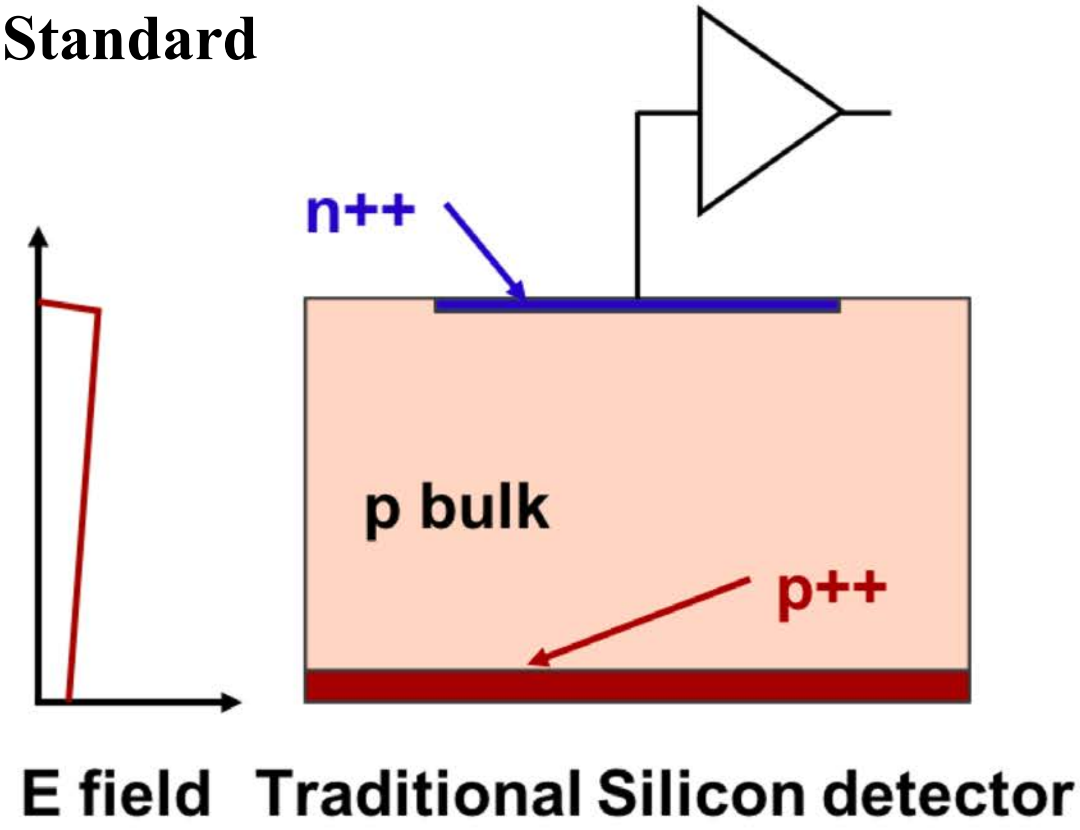
- Silicon: AC-LGAD & MAPS
- ZDC:
  - ECAL (PbWO4)
  - HCAL (PbSi + PbScint)



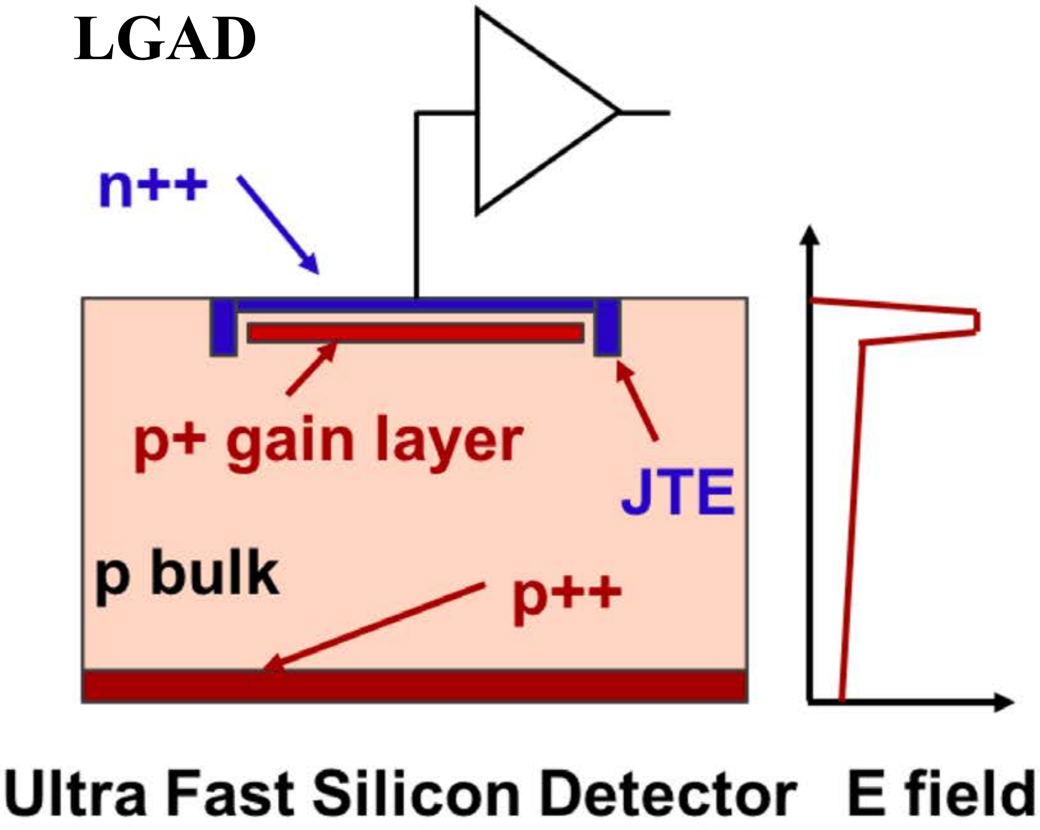
Detector	Angular accept. [mrad]	p_T coverage
ZDC @ ~30m	θ<5.5 ($\eta > 6$)	p_T<1.3 GeV
Roman Pots	0*<θ<5.0 ($\eta > 6$)	*Low p_T(t) cutoff (beam optics)
Off-Momentum Detectors	0.< θ < 5.0 ($\eta > 6$)	Low-rigidity particles from nuclear breakups
B0 forward spectrometer	5.5 < θ < 20.0 (4.6< η < 5.9)	High p_T(t)

Low Gain Avalanche Diode

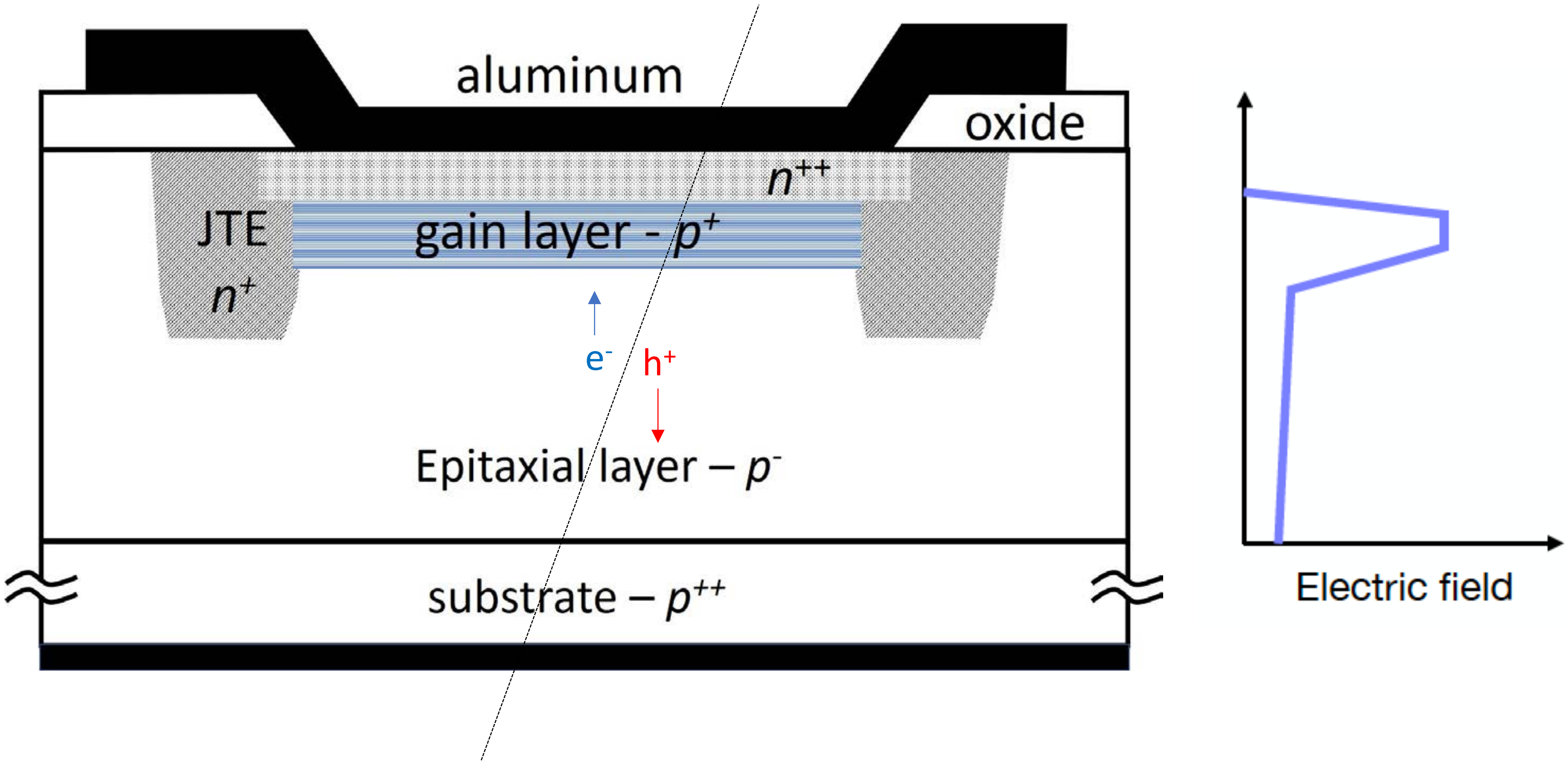
Standard



LGAD

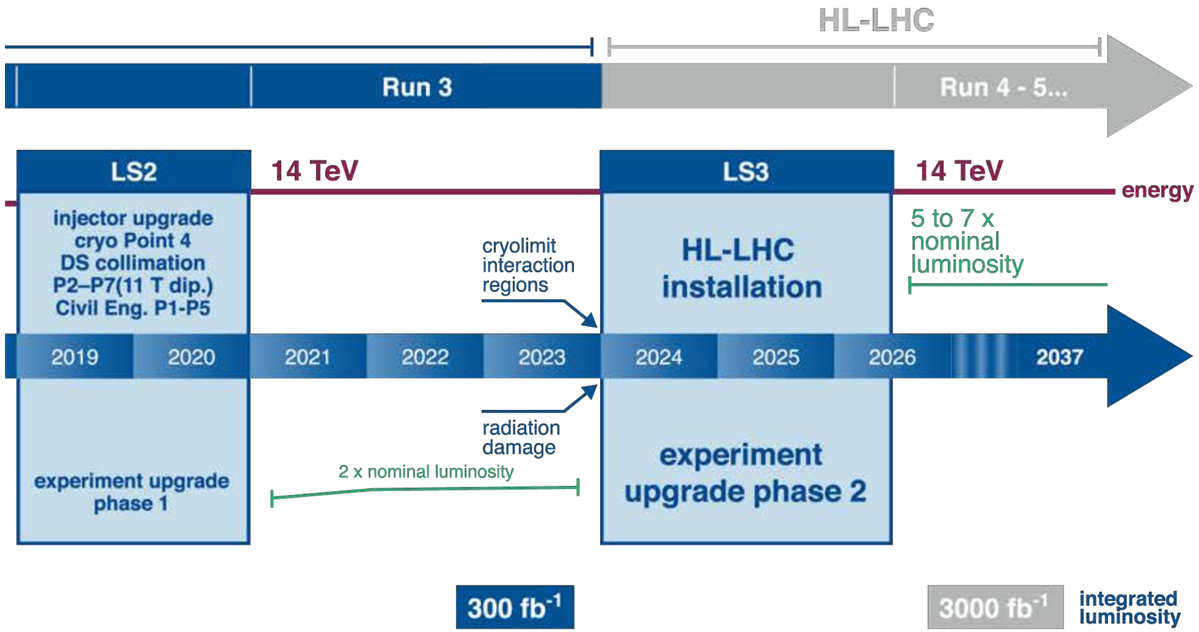


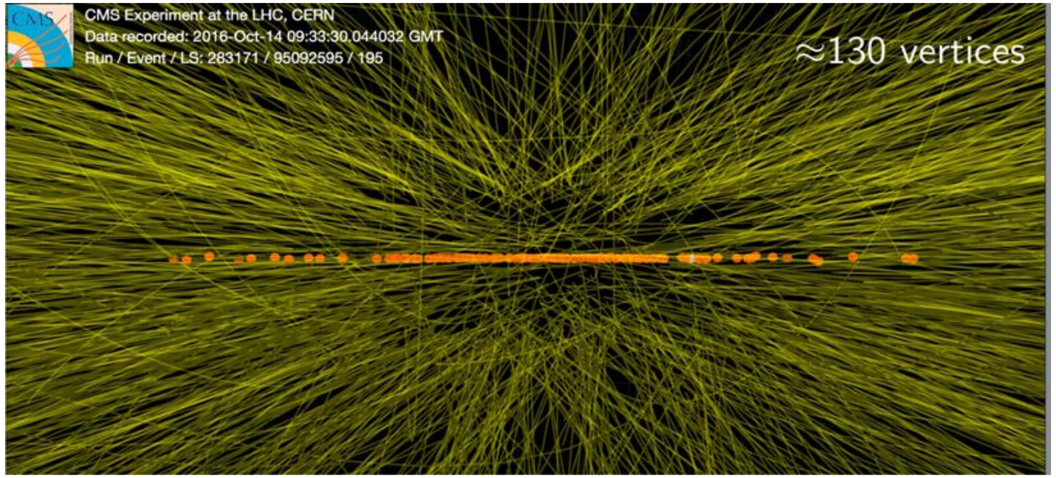
Low Gain Avalanche Diode

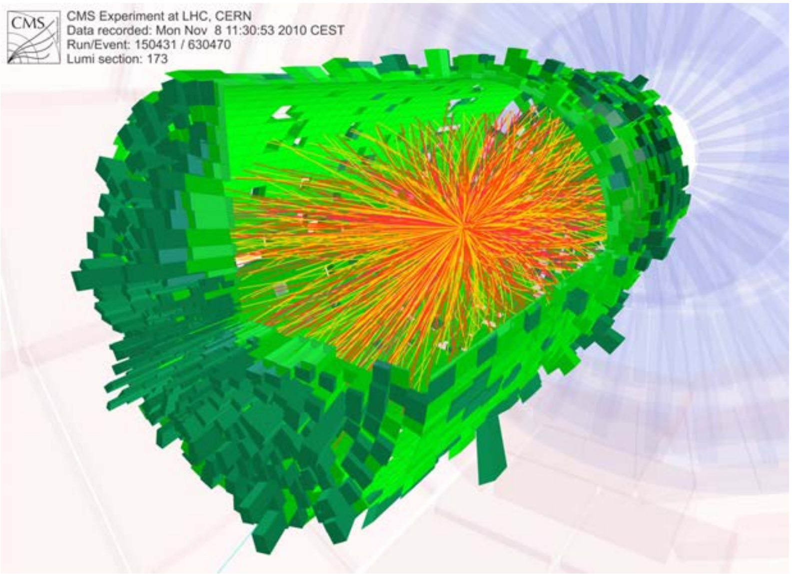


Ultra-fast silicon detectors with a highly doped p+ gain layer
Moderate internal gain : 10-30

High Luminosity LHC Era

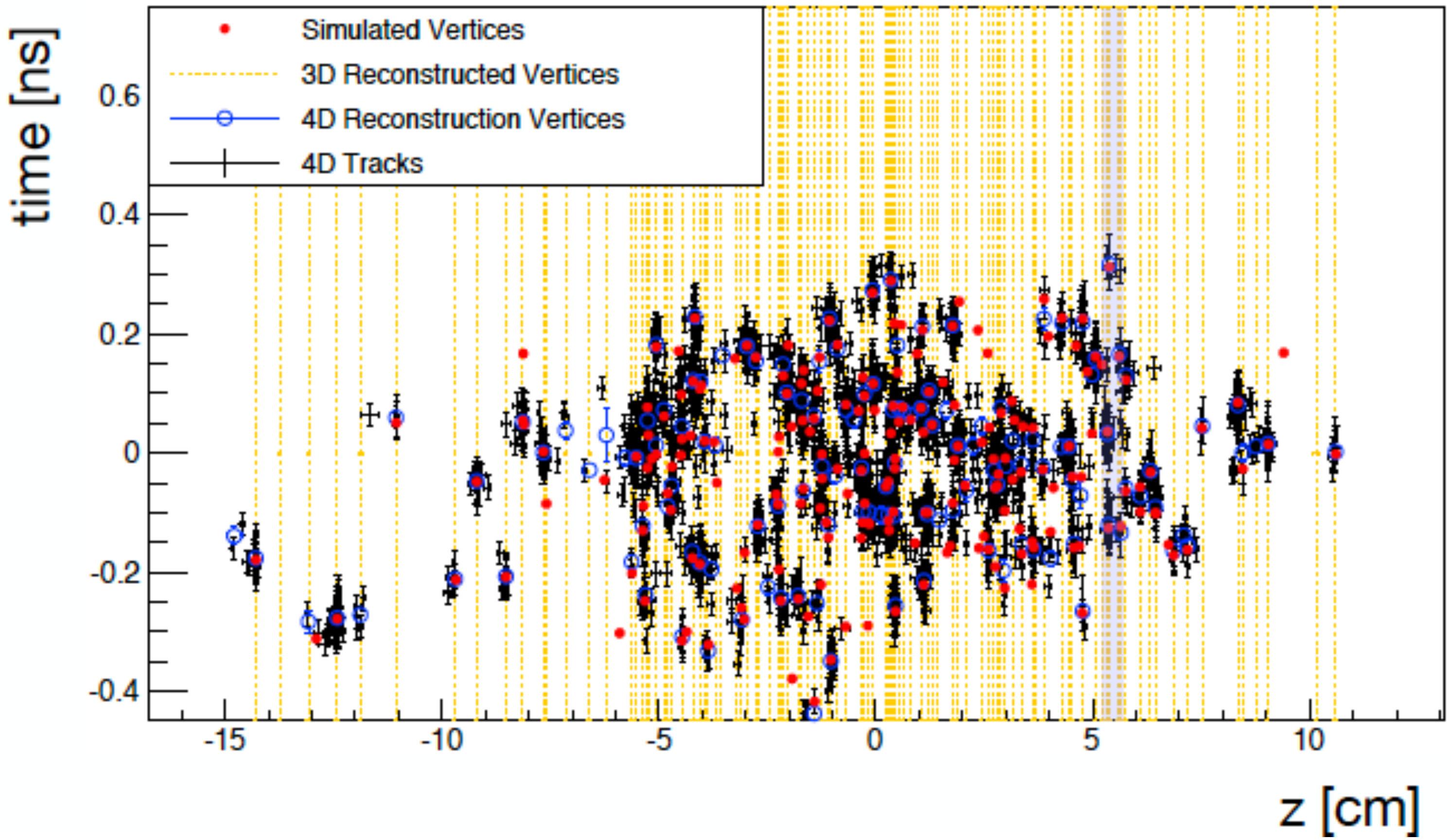


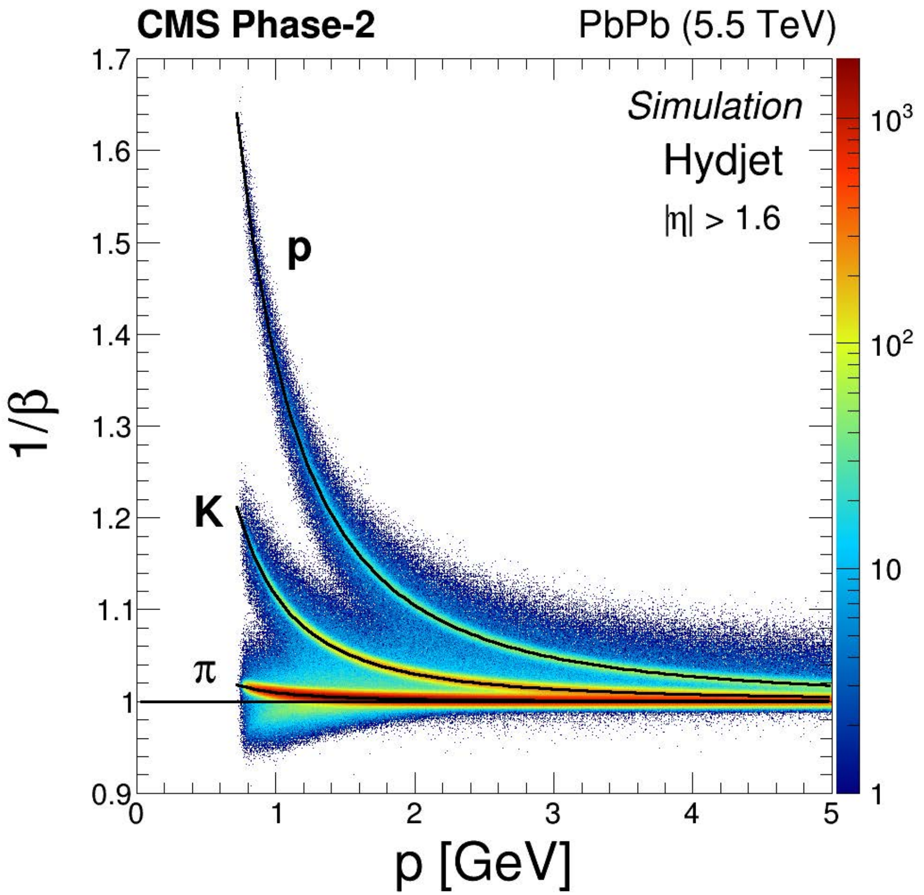




- **Dealing with the effects of pileup interactions in pp collisions will be a major challenge of the HL-LHC era.**
- **Sharping the tools for new discoveries as well as better measurement precision.**

Role of Precise Timing at HL-LHC





- Per-particle timing allows 4D track and vertex reconstruction to reduce pile-up contributions
  - Significant benefit to CMS pp physics program
- Precise timing provides particle ID for low p_T hadrons
  - New opportunities in Heavy Ion physics for CMS

CMS Phase-2 Upgrades for HL-LHC

Trigger/HLT/DAQ

- Track information in L1-Trigger
- L1-Trigger: 12.5 ms latency – output 750 kHz
- HLT output 7.5 kHz

Barrel ECAL/HCAL

- Replace FE/BE electronics
- Lower ECAL operating temp. (8 °C)

Muon Systems

- Replace DT & CSC FE/BE Electronics
- Complete RPC coverage in region $1.5<h<2.4$
- Muon tagging $2.4<h<3$

New Endcap Calorimeters

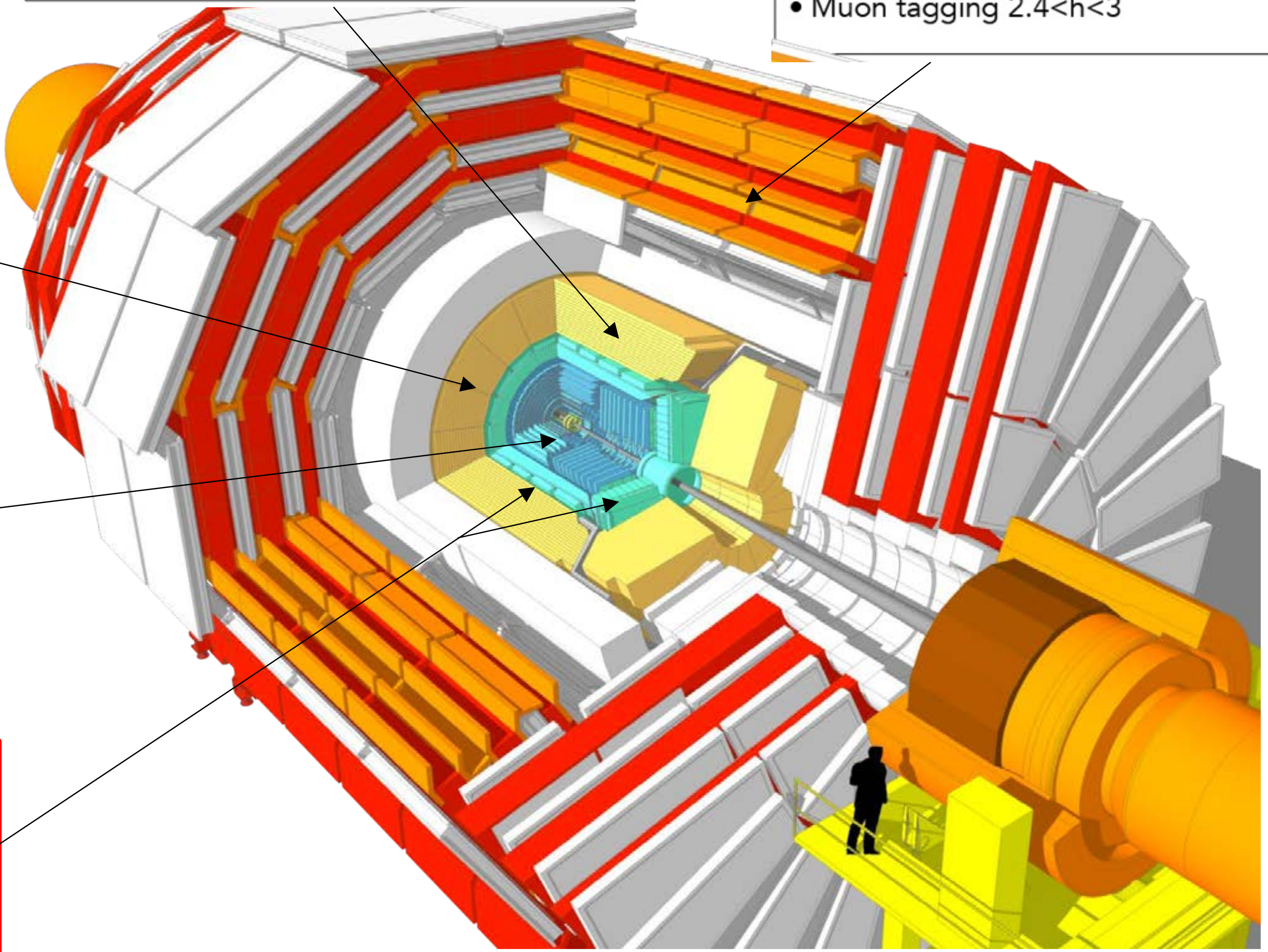
- Rad. tolerant – high granularity
- 3D capable

New Tracker

- Rad. tolerant – high granularity – significant less material
- 40 MHz selective readout (pT>2 GeV) in Outer Tracker for L1 -Trigger
- Extended coverage to $h=4$

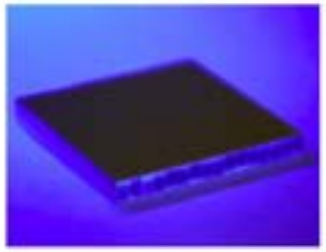
MIP Precision Timing Detector

- Barrel: Crystal +SiPM
- Endcap: Low Gain Avalanche Diodes

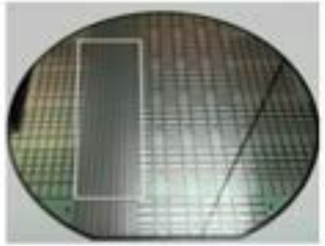


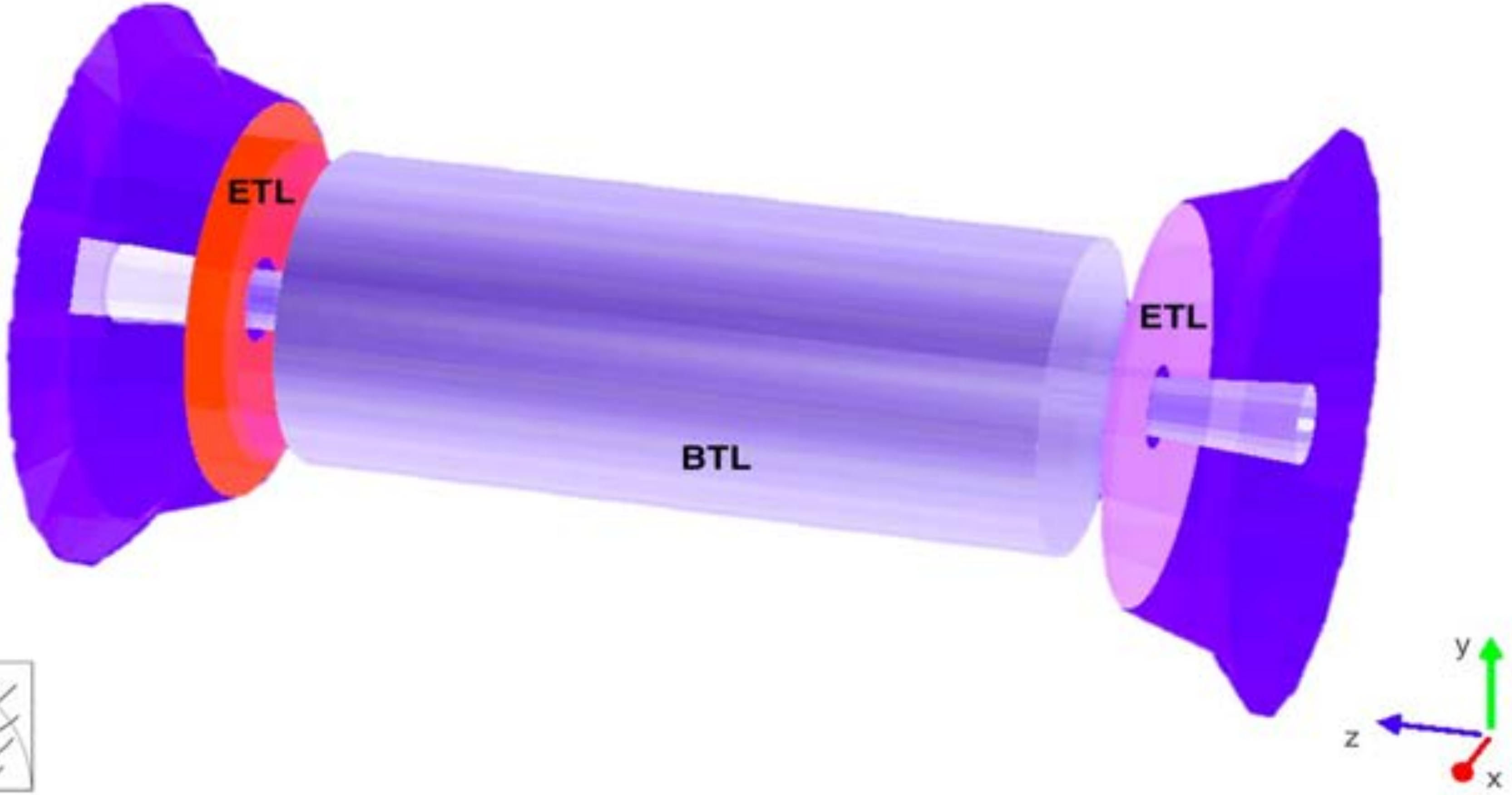
CMS MIP Timing Detector (MTP) for HL-LHC

BTL: LYSO bars + SiPM readout:
- TK/ ECAL interface: $|\eta| < 1.45$
- Inner radius: 1148 mm (40 mm thick)
- Length: ±2.6 m along z
- Surface ~38 m^2; 332k channels
- Fluence at 4 ab^{-1}: 2x10^{14} n$_{eq}$/cm^2



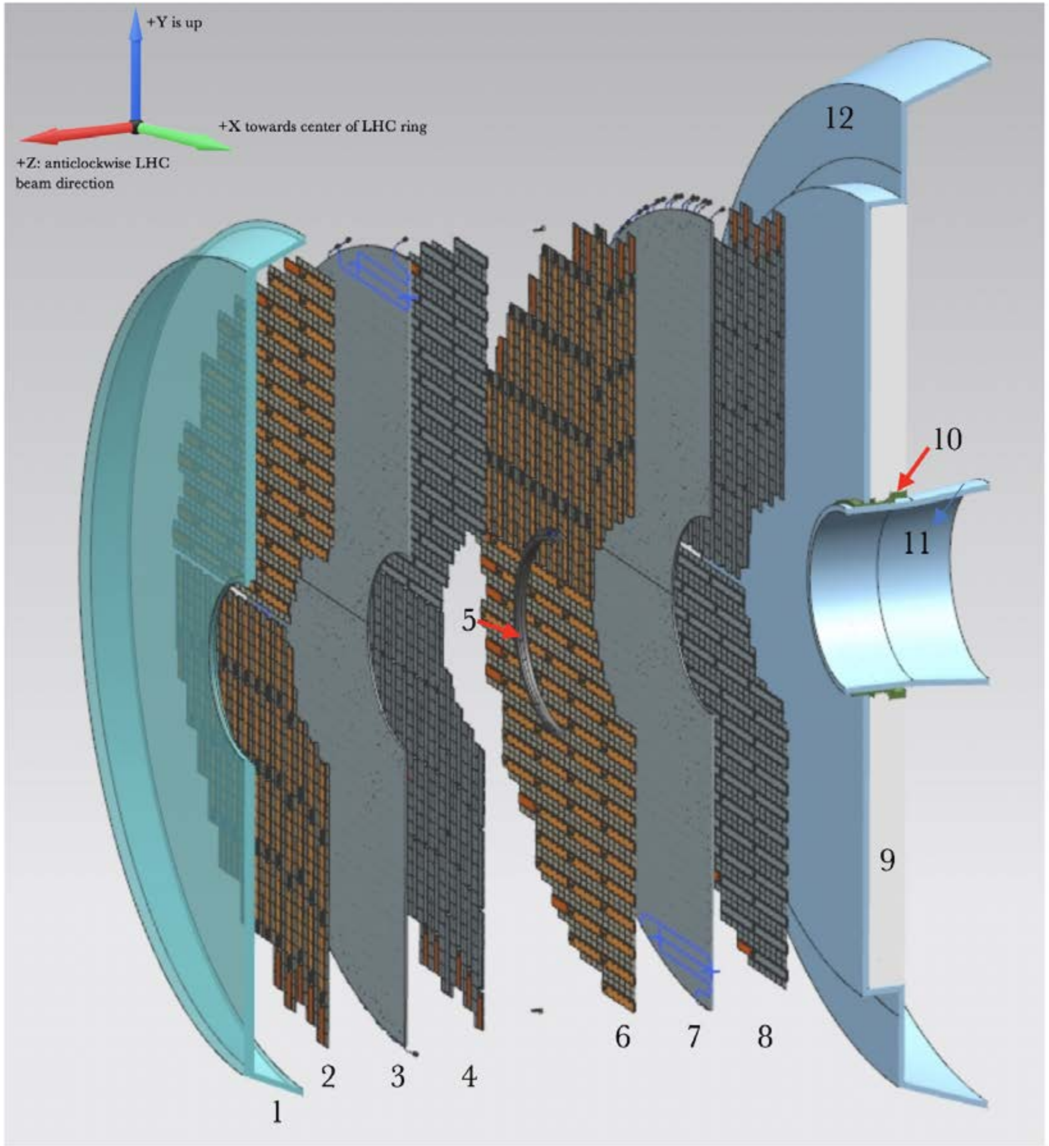
ETL: Si with internal gain (LGAD):
- On the HGC nose: $1.6 < |\eta| < 3.0$
- Radius: 315 < R < 1200 mm
- Position in z: ±3.0 m (45 mm thick)
- Surface ~15.8 m^2; ~6M channels
- Fluence at 4 ab-1: up to 2x10^{15} n$_{eq}$/cm^2



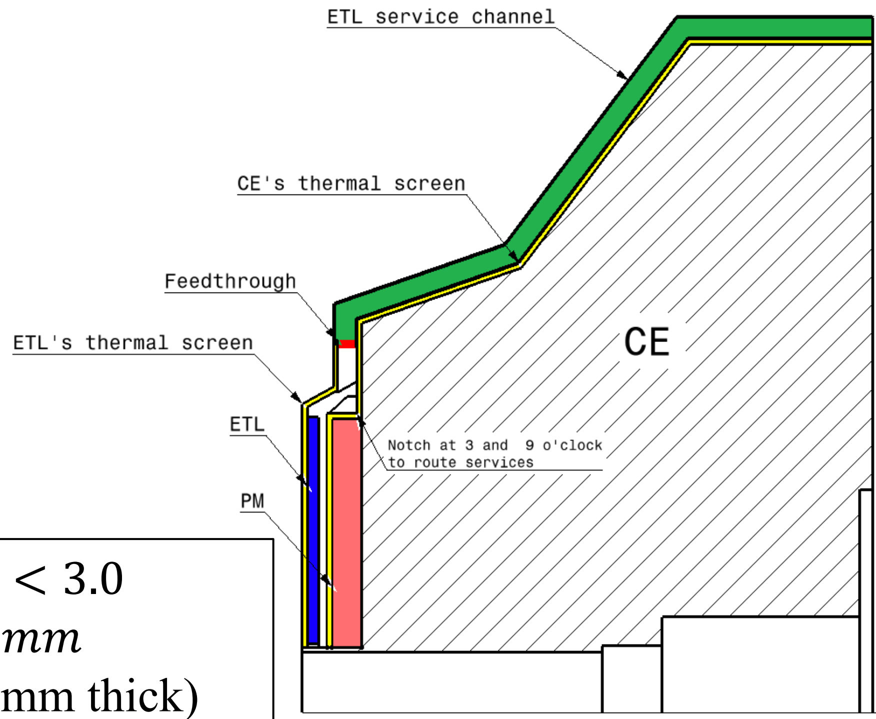


- **Thin layer between the tracker and calorimeters**
- **Hermetic coverage for $|\eta| < 3.0$**
- **Time resolution of 30 ps for minimum ionizing particles (MIPs) before irradiation**
- **Sufficient radiation tolerance to maintain σ_t<60 ps up to 3000 fb^{-1}.**

Endcap Timing Layer – Layout



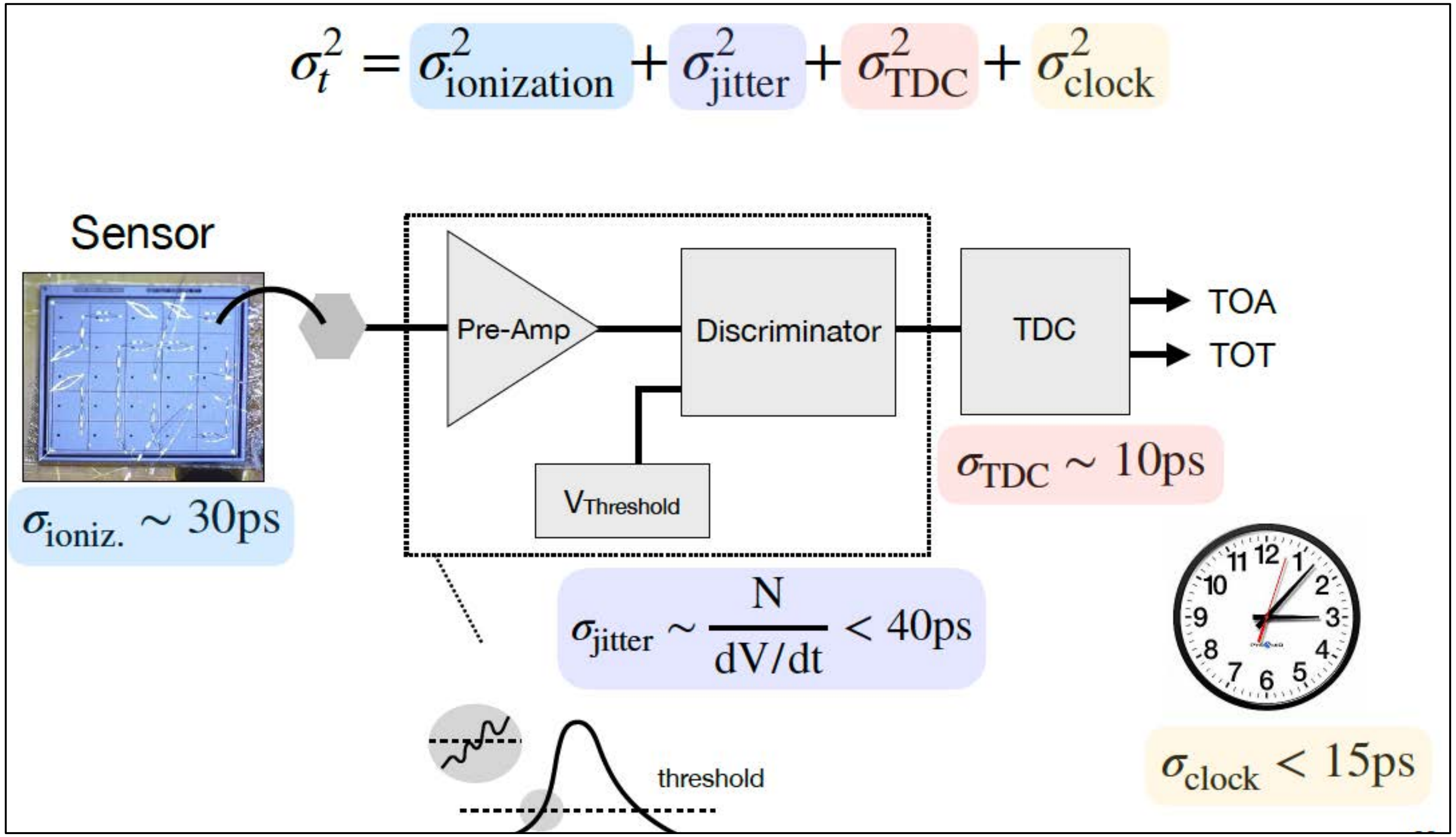
1: ETL Thermal Screen
2: Disk 1, Face 1
3: Disk 1 Support Plate
4: Disk 1, Face 2
5: ETL Mounting Bracket
6: Disk 2, Face 1
7: Disk 2 Support Plate
8: Disk 2, Face 2
9: HGCal Neutron Moderator
10: ETL Support Cone
11: Support cone insulation
12: HGCal Thermal Screen



- On the CE nose: $1.6 < |\eta| < 3.0$
- Radius: $315 < R < 1200\ mm$
- Position in Z: $\pm 3.0\ m$ (45 mm thick)
- Surface $\sim 15.8\ m^2$; ~8.6M channels
- Weight 282 kg/side; Power: 26kW/side

- **Two disks on each side allowing up to 2 time measurements per track**
  - **45 ps per hit → 30 ps per track**
- **Stageable, serviceable, maintainable**

Endcap Timing Layer – Time Resolution Contributions

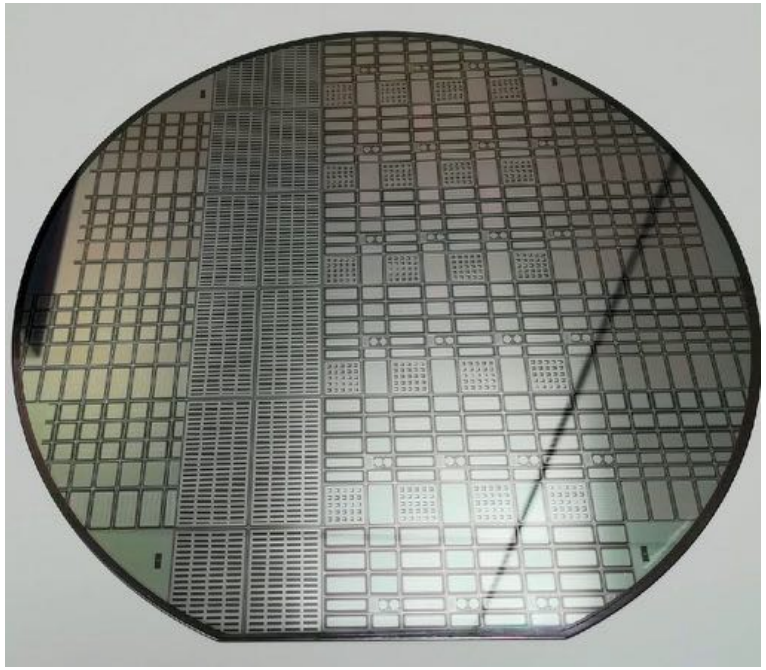


- $\sigma_{ionization}$: random variation in particle energy deposition, determining the amplitude and the shape of the signal
  ~30 ps up to 1x10^{15} n_{eq}/cm^2, and
  ~40 ps up to 2x10^{15} n_{eq}/cm^2
- σ_{jitter}: mostly due to electronics noise and depends on the amplifier slew rate (dV/dt)
  jitter <40 ps before irradiation.
  No degrading in ETROC0 performance observed up to 100 Mrad
- σ_{TDC}: the effect of the TDC binning
- σ_{clock}: contribution from clock distribution

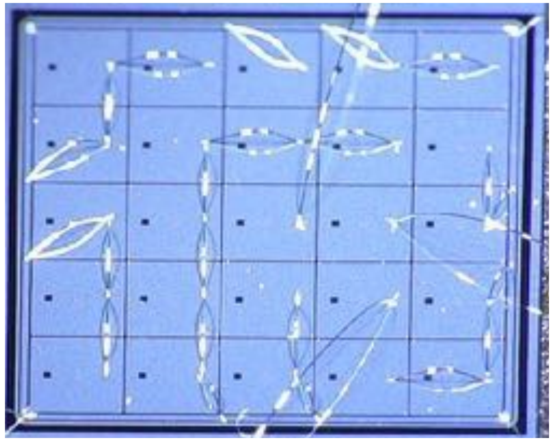
CMS Endcap Timing Layer - LGAD Sensor

Key Sensor Characteristics		
Depletion region thickness	$50\ \mu m$	Minimize rise time, sufficient charge, gain uniformity
Pad size	$1.3\times 1.3\ mm^2$	Minimize capacitance, Occupancy ~1%
Sensor size	$2\times 4\ cm^2$ (16×32)	Optimize wafer usage
Interpad gap	$< 90\ \mu m$	Fill factor > 85%
Time resolution after irradiation	$< 40\ ps$	Up to $1.7\times 10^{15}\ n_{eq}/cm^2$

FBK UFSD3



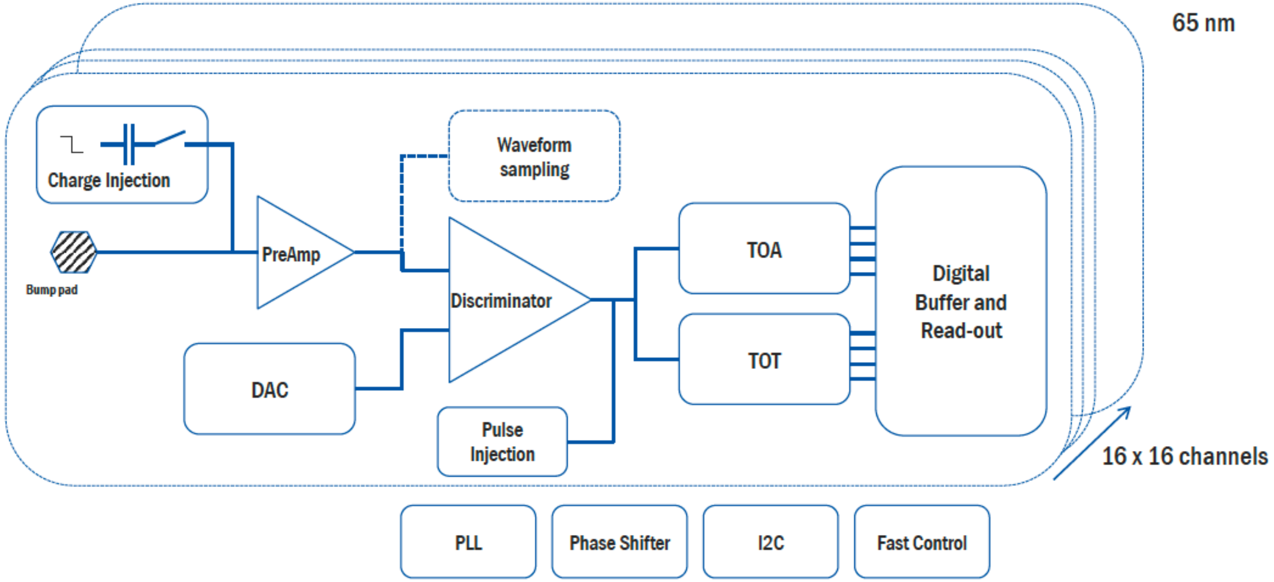
5x5 array from HPK

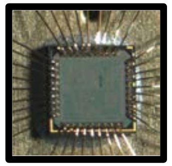


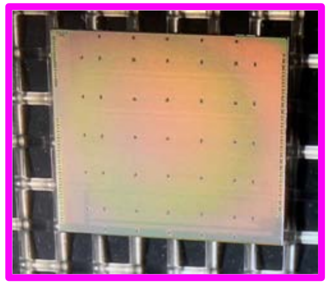
Recent prototypes from Hamamatsu (HPK) and Fondazione Bruno Kessler (FBK) focus on

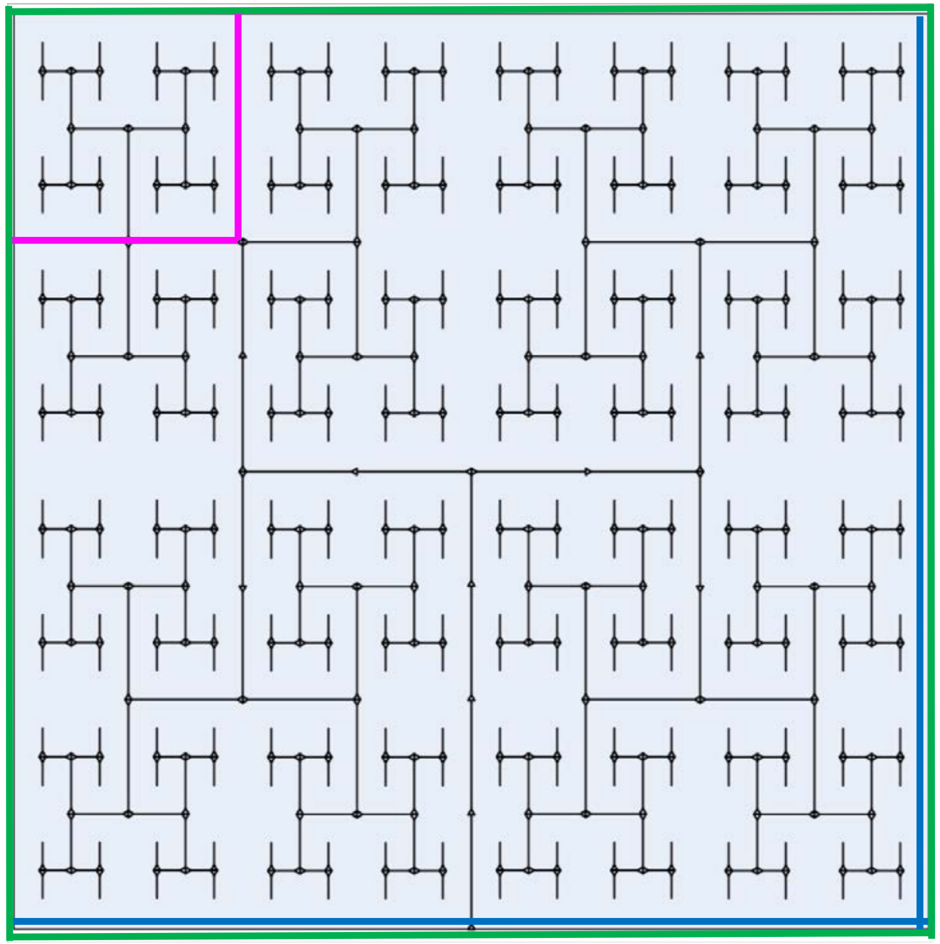
- **improving the radiation hardness**
- **increasing fill factor**
- **large arrays**

Endcap Timing Layer –Readout ASIC (ETROC)









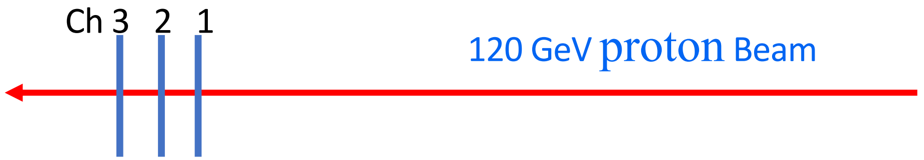
- **Dedicate balance act from:**
  - **Low noise & fast rise time**

$$\sigma_{jitter} \sim \frac{e_n C_d}{Q_{in}} \sqrt{t_{rise}} < 40\ ps$$

  - **Power budget: 1 W/chip, 4 mW/channel**
- **ETROC innovations:**
  - **Low power single TDC for both time of arrival and time over threshold measurements**
  - **Flexible low & high-power modes**

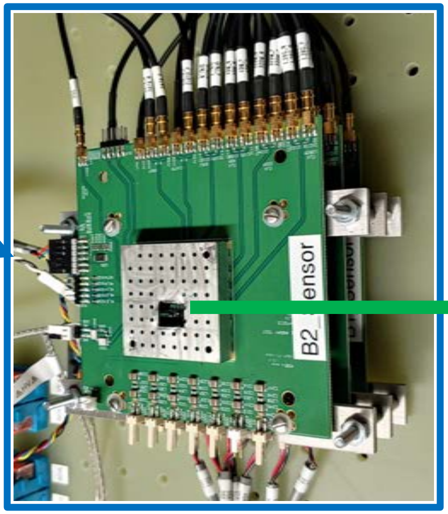
✓ **ETROC0 : single analog channel**
✓ **ETROC1: with TDC and 4x4 clock tree**
❑ **ETROC2: 16x16 full size full functionality**
❑ **ETROC3: 16x16 pre-production**

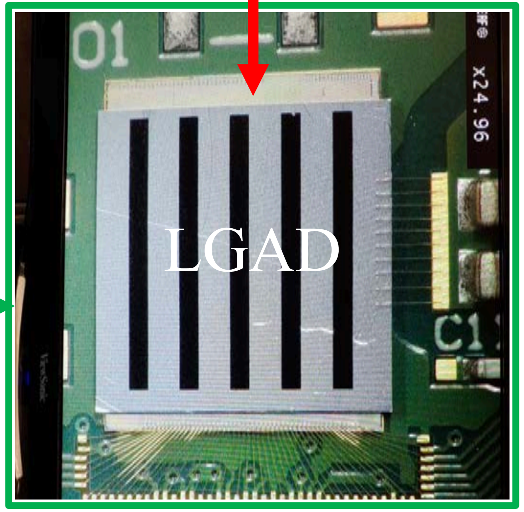
ETROC1+LGAD – Test Beam Results

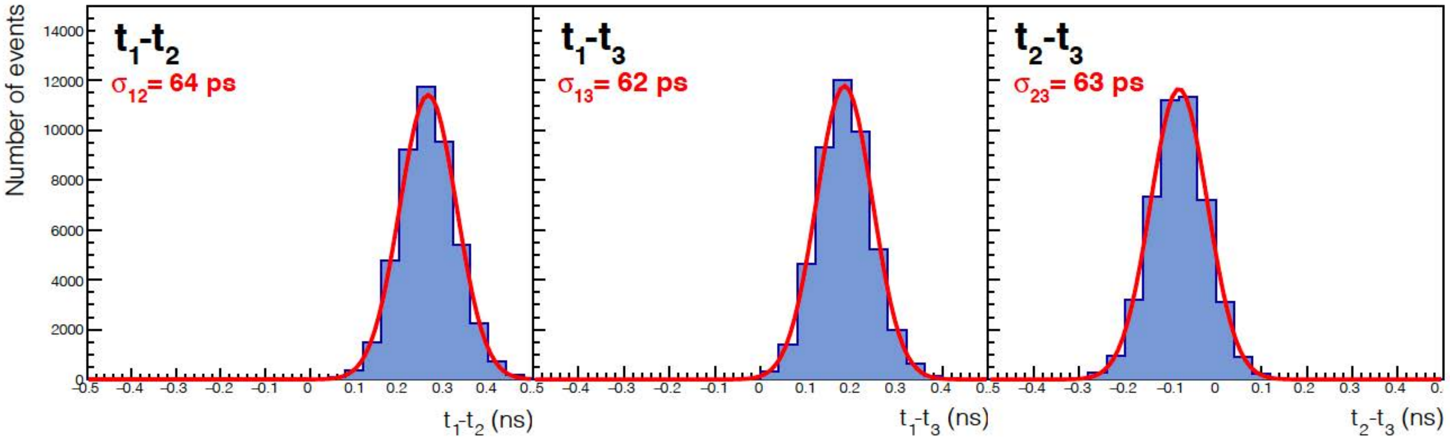


ETROC1 Test Board

ETROC1





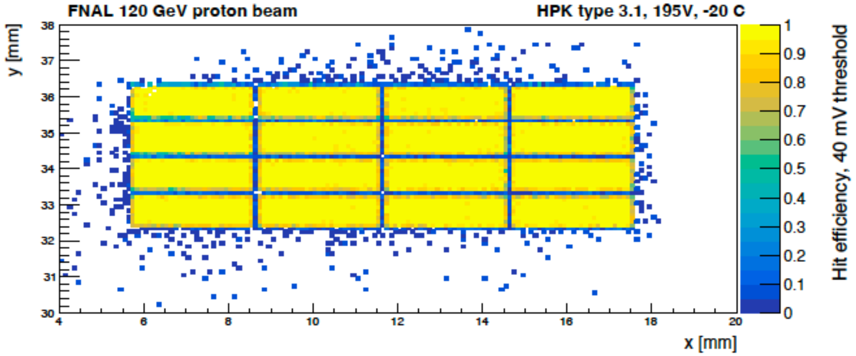


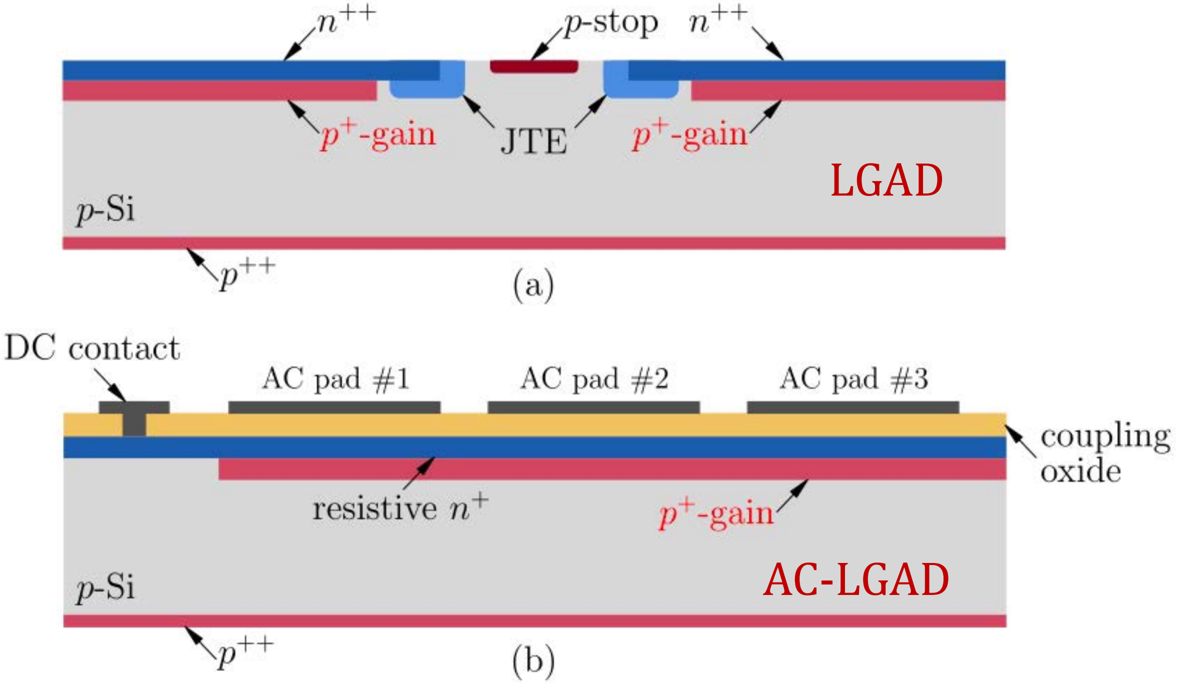
From preliminary analysis of the data from ongoing beam test at FNAL, the resolution of single LGAD+ETROC1 devices with large signal amplitude is 42-46 ps.

$$\sigma_i = \sqrt{0.5 \cdot (\sigma_{ij}^2 + \sigma_{ik}^2 - \sigma_{jk}^2)}$$

AC-Coupled LGAD

- Due to the presence of JTE and the gap between LGAD cells, 100% fill factor can not be achieved in LGAD. The position resolution is limited to be $\sqrt{1/12}$ of cell size.



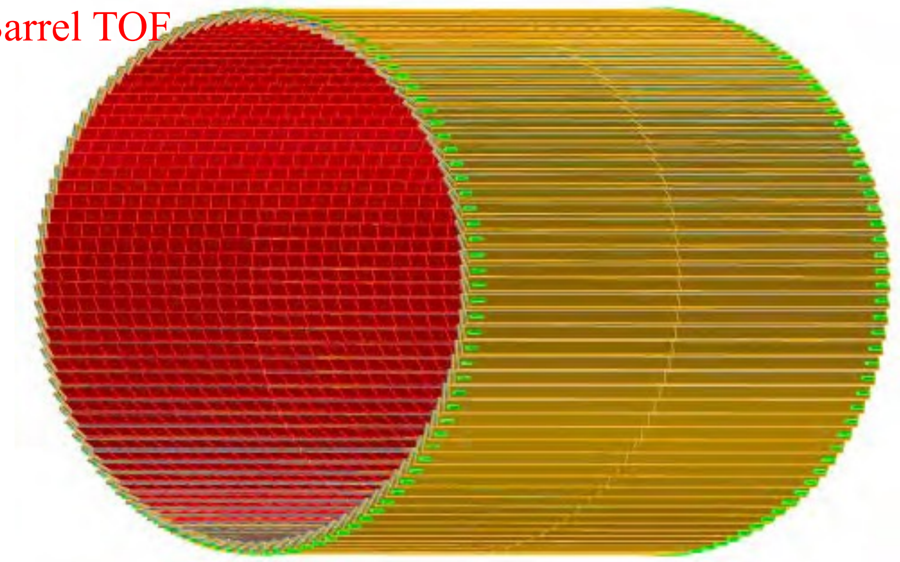


- AC-LGAD: replacement of the segmented n^{++} layer by a less doped but continuous n^{+} layer. Electrical signals in the n^{+} layer are AC-coupled to neighboring metal electrodes that are separated from the n^{+} layer by a thin insulator layer.

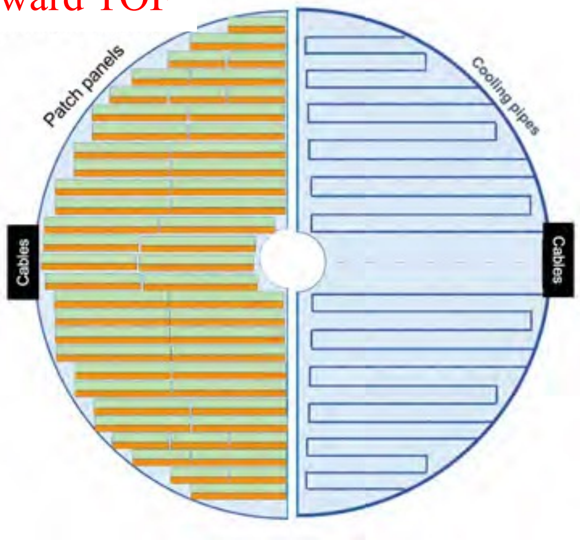
- AC-LGAD not only provides a timing resolution of a few tens of picoseconds, but also 100% fill factor and a spatial resolution that are orders of magnitude smaller than the cell size. Therefore, it is a good candidate for 4D detectors at future high energy experiments.

AC-LGAD Detectors for ePIC

Barrel TOF



Forward TOF



Roman Pots

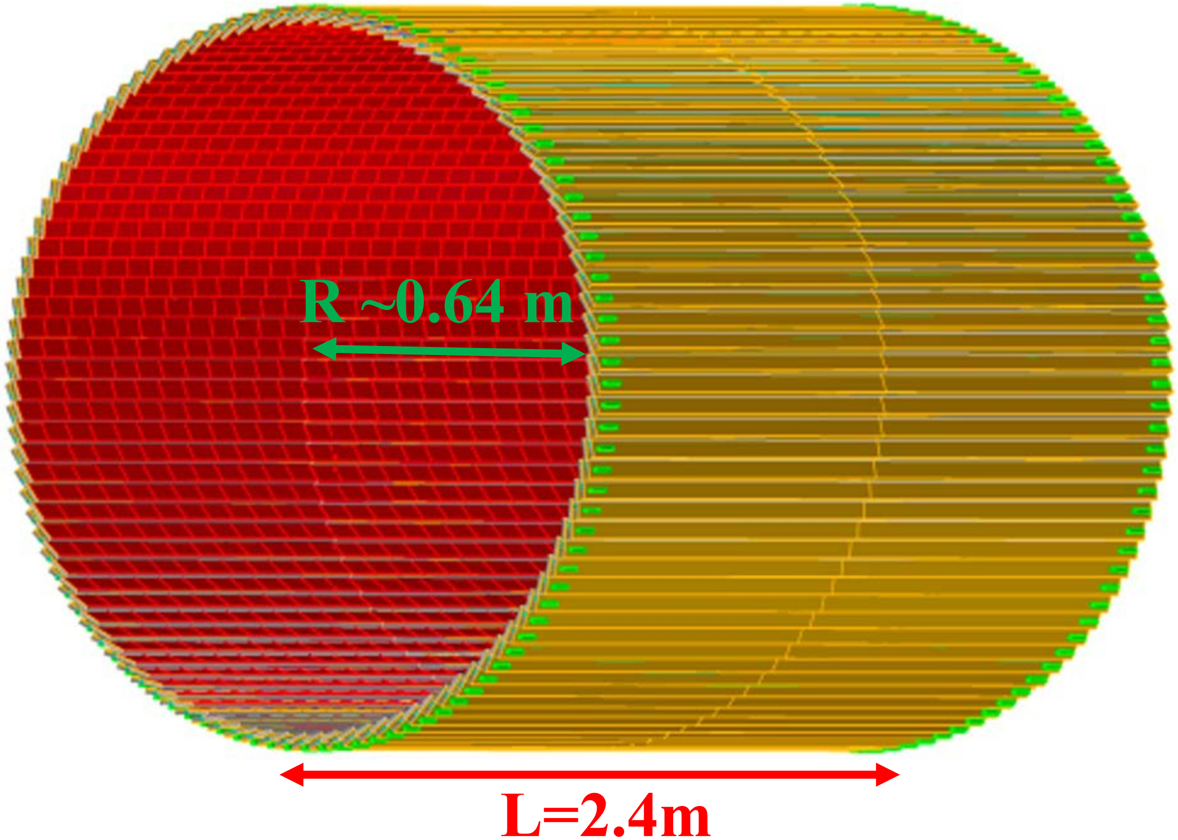
	Area (m^2)	Channel size (mm^2)	# of Channels	Timing Resolution	Spatial resolution	Material budget
Barrel TOF	10.9	0.5*10	2M	30 ps	30 μm in $r \cdot \varphi$	0.01 X0
Forward TOF	2.22	0.5*0.5	6 M	25 ps	30 μm in x and y	0.08 X0
B0 tracker	0.07	0.5*0.5	0.3M	30 ps	20 μm in x and y	0.05 X0
RPs/OMD	0.14/0.08	0.5*0.5	0.6M/0.3M	30 ps	140 μm in x and y	no strict req.

Requirements on timing and spatial resolutions and material budget are still being evaluated and are subject to change as the design matures, and we will continue to explore common designs for these detectors where possible to reduce cost and risk.

Barrel TOF Layout

More details: https://indico.bnl.gov/event/16765/

ePIC Barrel TOF (~1% X_0)

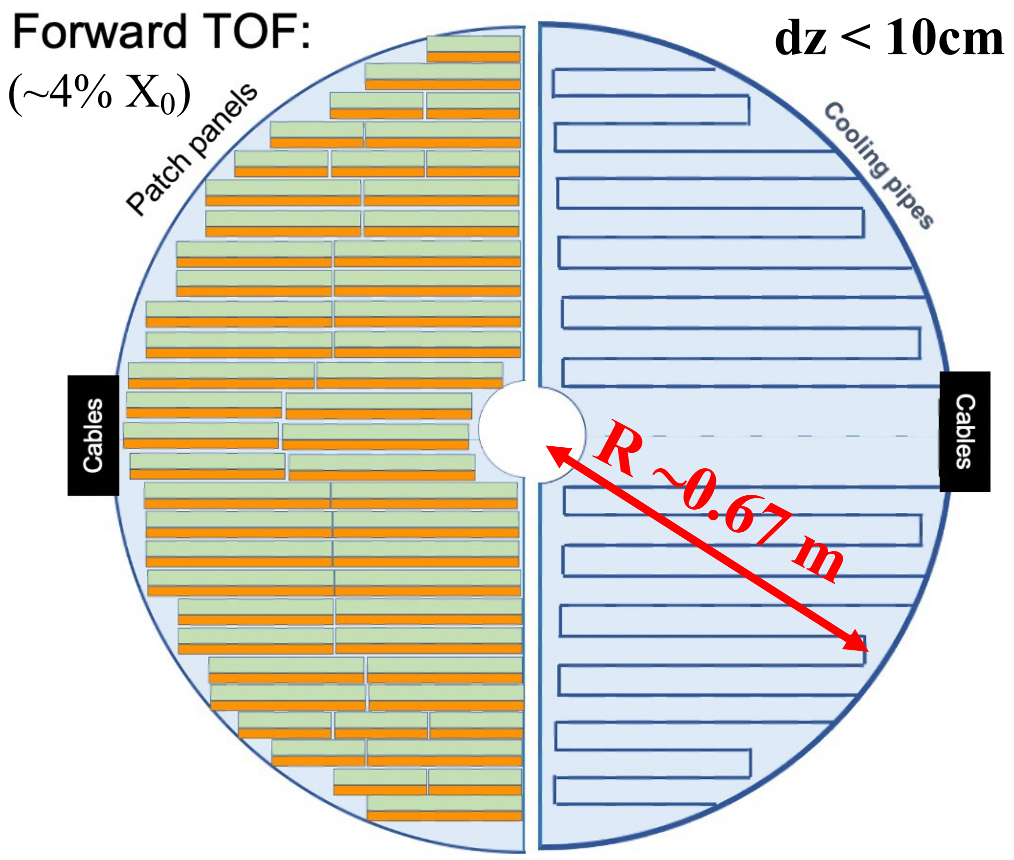


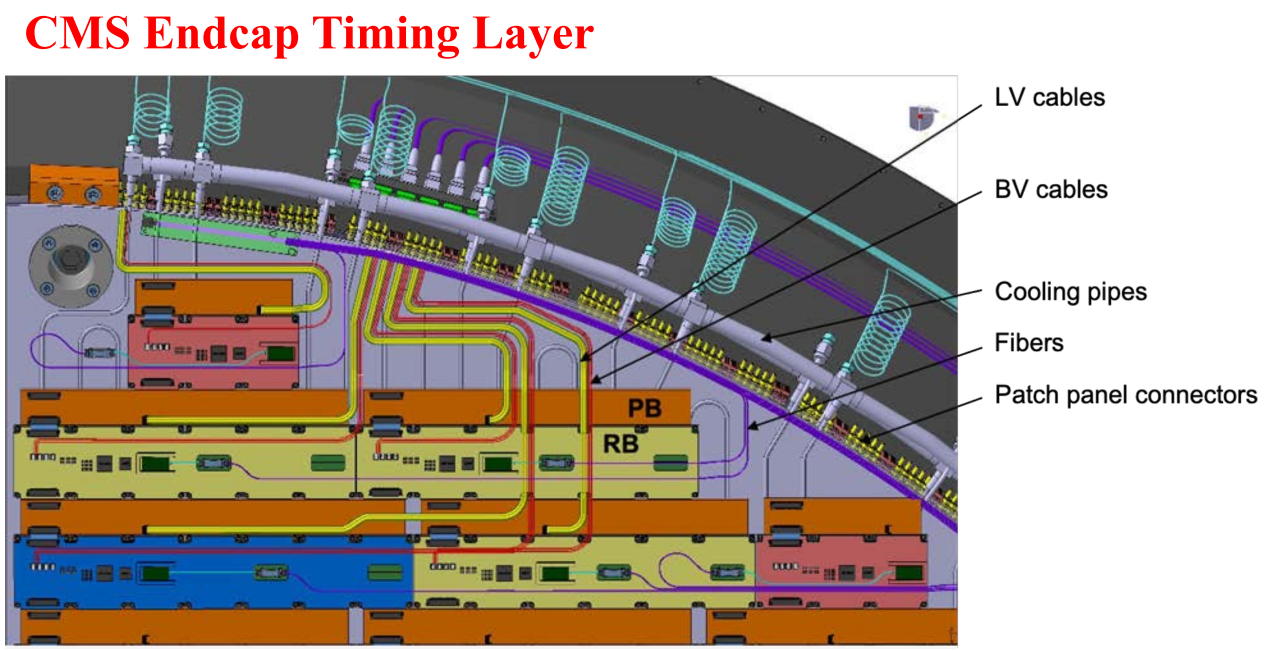
STAR Intermediate Silicon Tracker

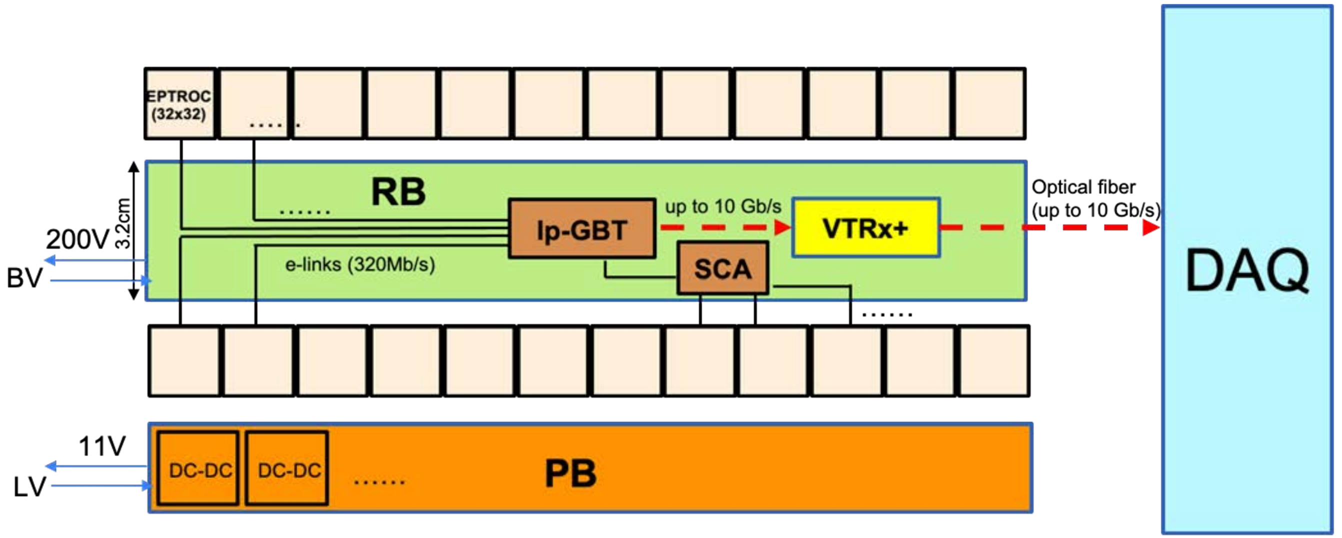
- 288 staves, each with 32 strip sensors wire-bonded to 64 frontend ASICs on low mass Kapton flex and CF support
- Power consumption: ~4 kW for 500µm x 1cm strips (2.4 kW for ASIC, 1.0 kW for DC-DC, 0.6 kW for sensor+cable+RB)

Forward TOF Layout

More details: https://indico.bnl.gov/event/17336/

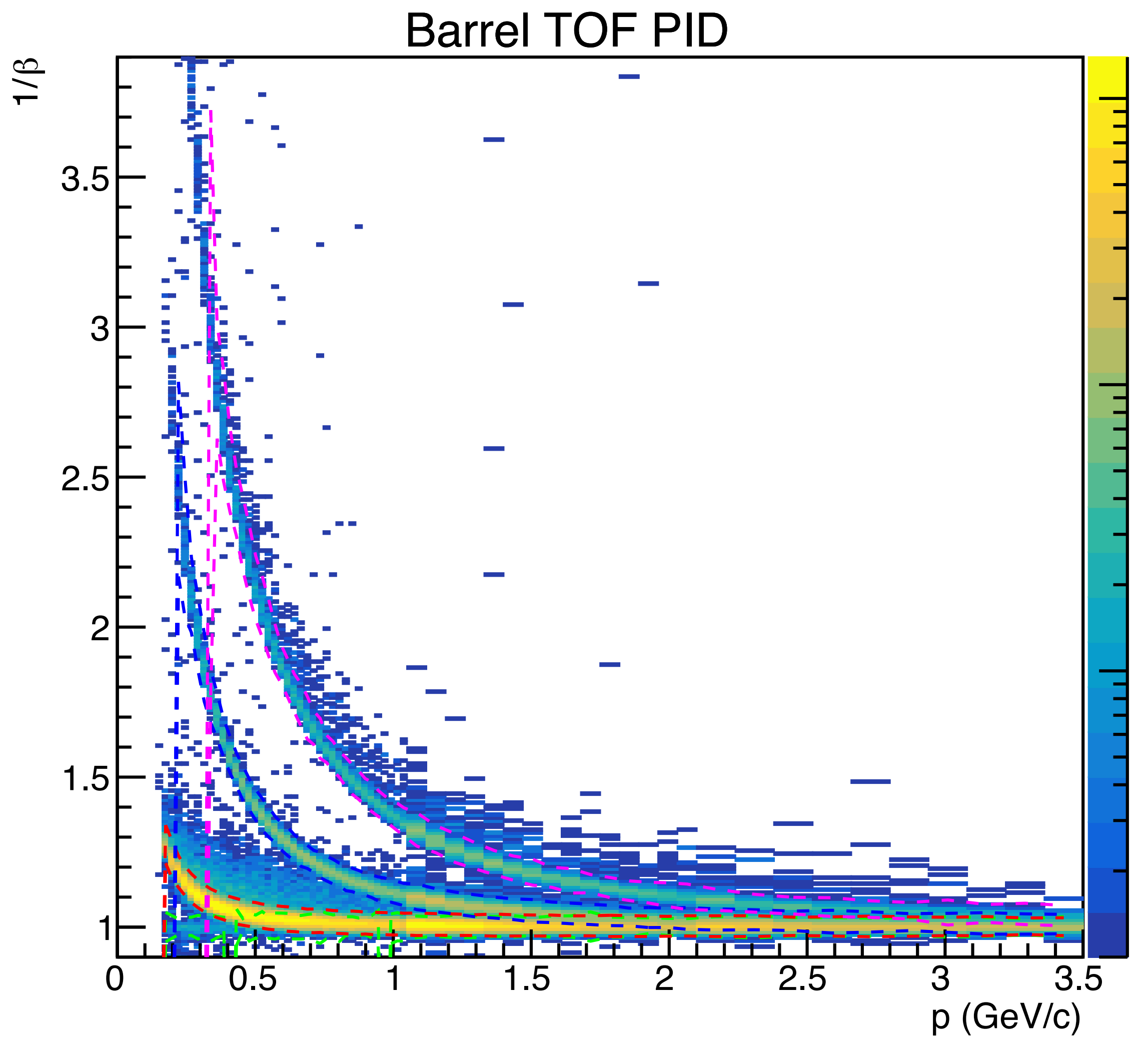


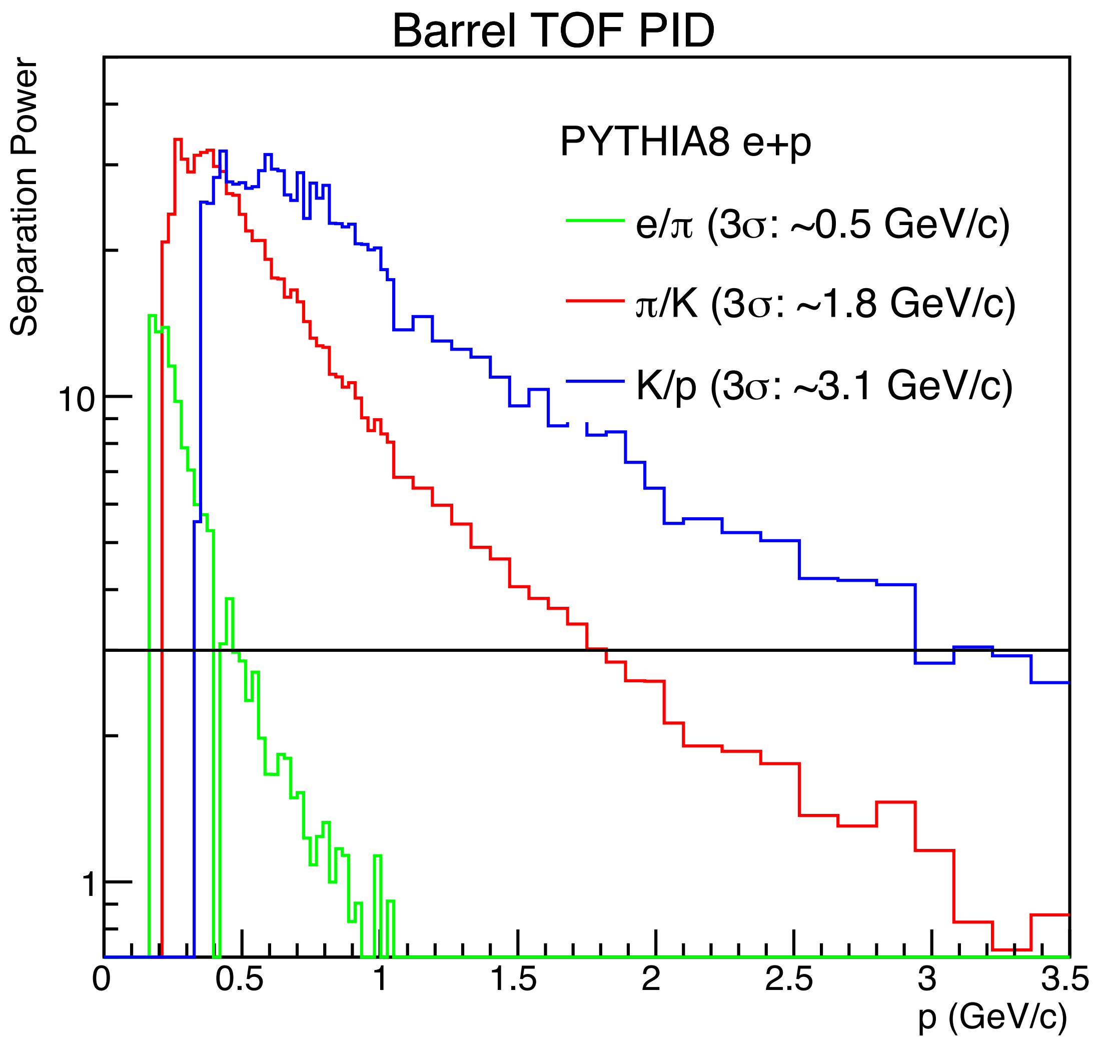




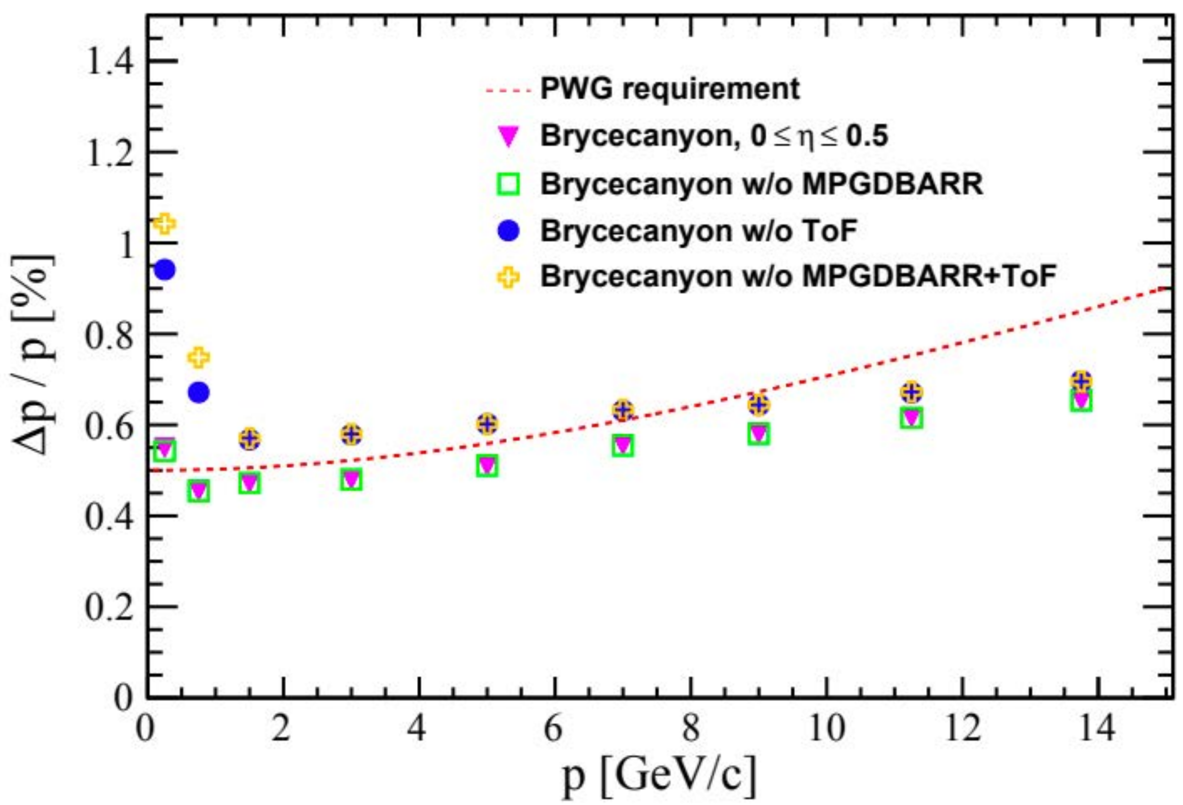
- 212 modules, each with 24 to 96 bump-bonded pixel sensor + ASIC assemblies on Al disk
- Power consumption: 13 kW for 500x500 μm^2 pixels (6 kW for 800 x 800 μm^2)

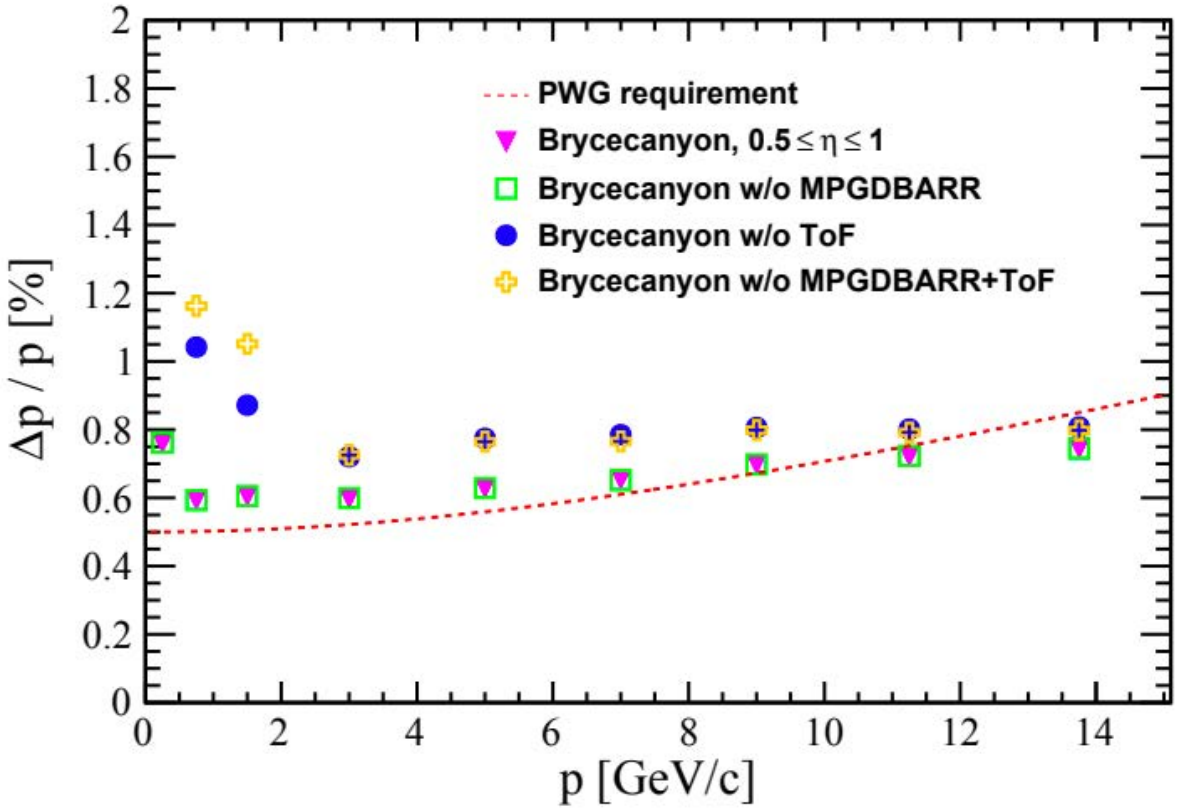
Barrel TOF PID Performance





Barrel TOF Impact on Tracking





Both MPGD + ToF alive

ToF alive MPGD dead

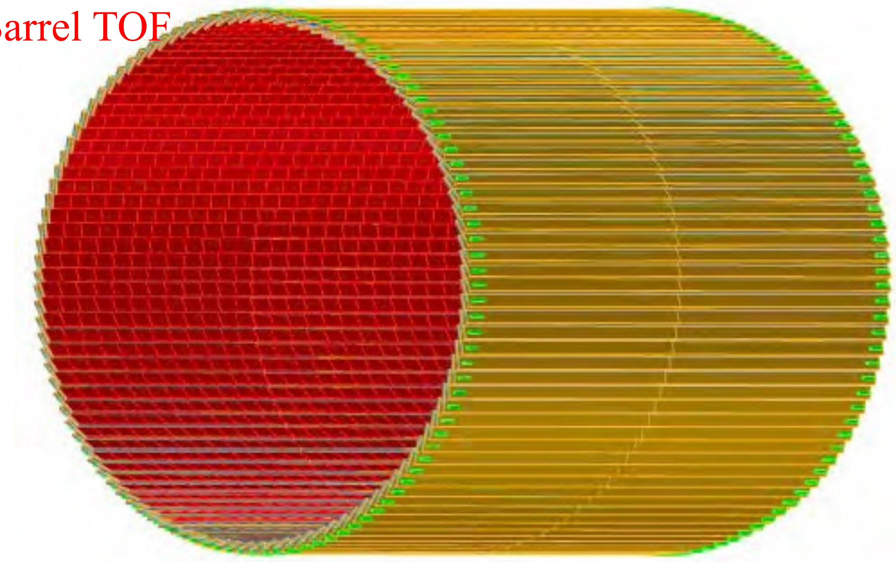
MPGD Alive ToF dead

MPGD dead ToF dead
(Si only)

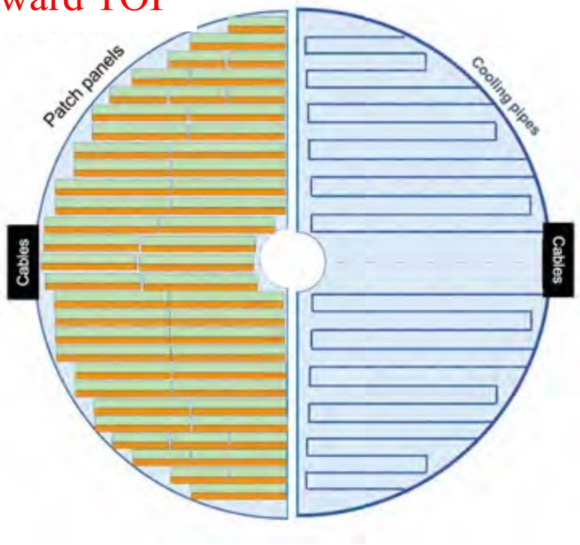
- 2 Bands appear → ToF and no ToF

AC-LGAD Detectors for ePIC

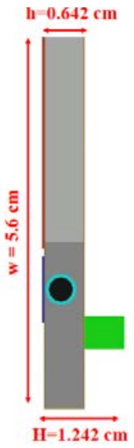
Barrel TOF

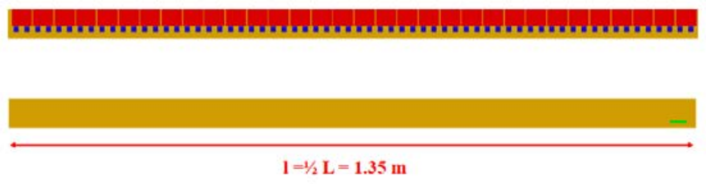


Forward TOF

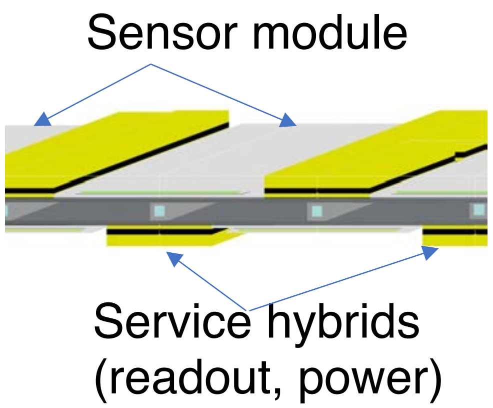


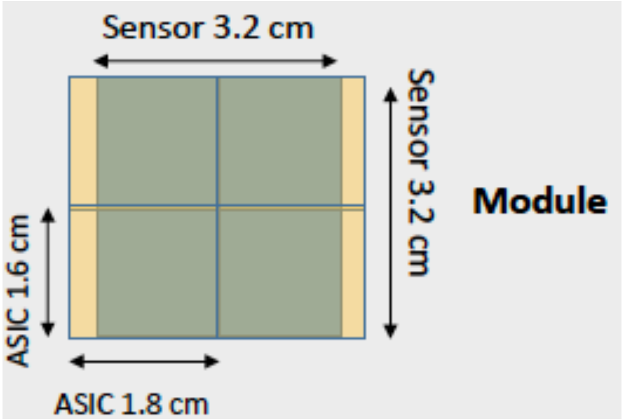
Roman Pots





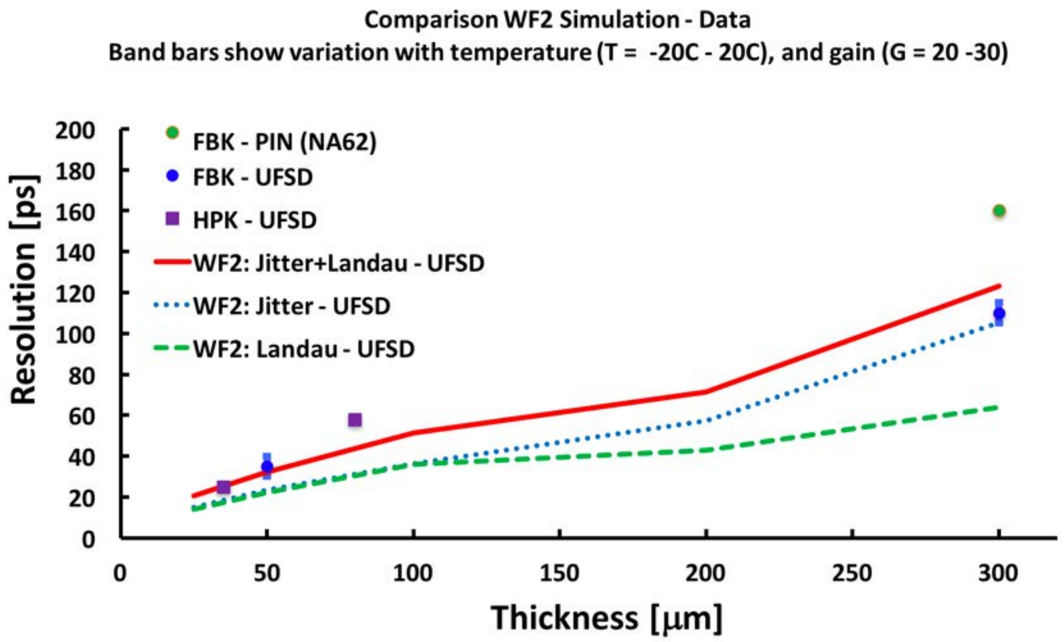
- 32 AC-LGAD sensors, each 3.2*4 cm^2 read out by 2 ASICs
- Low mass flexible Kapton PCB distributes power and I/O signals from a low mass connector(s) at the edge
- Liquid coolant in Al cooling tube takes away heat from the ASICs

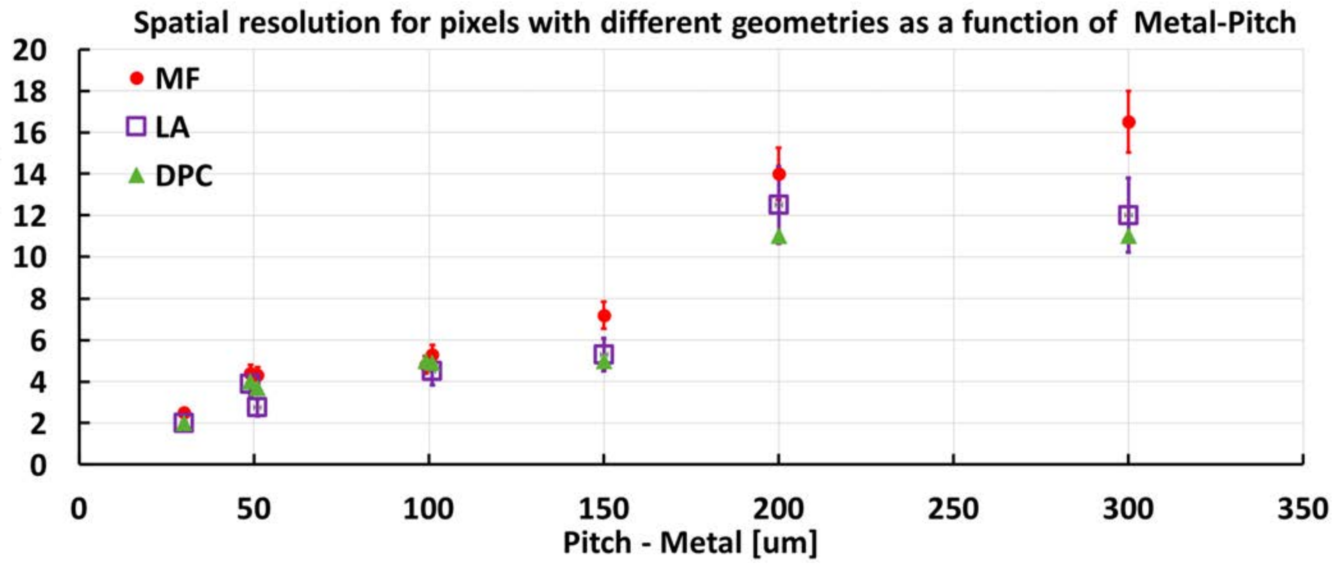




AC-LGAD Sensor R&D

Nicolo Cartiglia



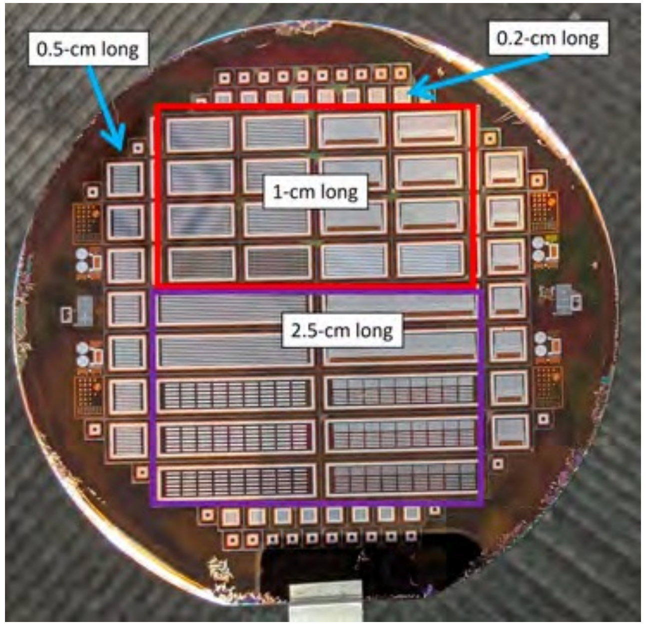


- **R&D Goals**
  - 15-20 ps timing resolution, O(3-50μm) position resolution where needed
  - Minimal readout channel density (long strip, rectangular pixel) for reduced power, material and cost
- **Plan**
  - Produce and test sensors with thinner active volume to achieve the desired timing resolution
  - Optimize implantation parameters and AC-pad segmentation through simulation and real device studies
  - Engage commercial vendors to improve fabrication process and yield

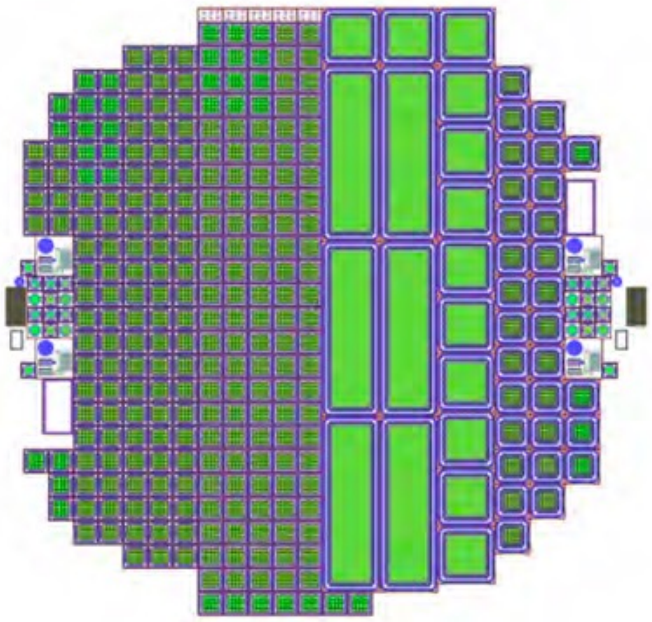
AC-LGAD Sensor R&D

- Production of medium/large area sensors with different doping concentration, pitch and gap sizes between electrodes and Si thickness to optimize performance by BNL IO and HPK.
  - 1st BNL (06/2021-11/2021): 5-25 mm strips with 500 μm pitch, 100-300 μm electrode width, 50 μm active Si
  - 2nd BNL (06/2022-11/2022): 5-25 mm strips with 500-700 μm pitch, 50-100 um electrode width, 20-50 μm Si
  - 3rd BNL (08/2022-12/2022): pixels with 500-700 μm pitch, various electrode shapes, 20-50 μm Si
  - 1st HPK (06/2022-04/2023): strip+pixel sensors with different electrode width, active thickness and n^+ doping
  - 4th BNL (02/2023-06/2023): deep gain layer to increase signal amplitudes

1st/2nd BNL Production

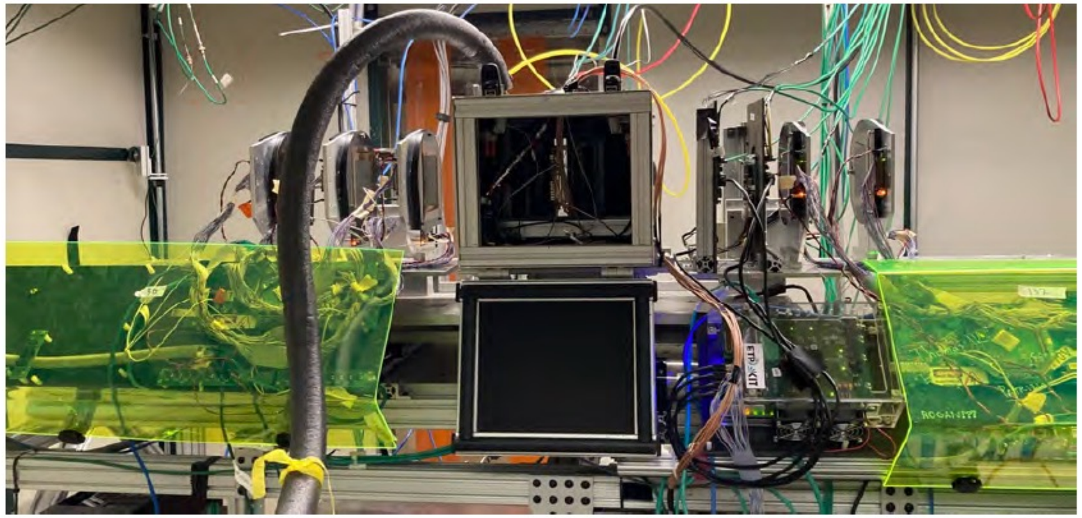


3rd BNL Production



Joint HPK Production

eRD112: AC-LGAD Sensor R&D



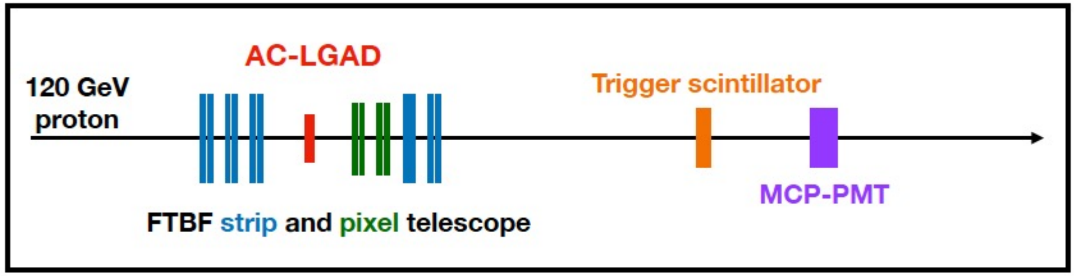


Figure 7: Picture (top) and diagram (bottom) of the FTBF silicon telescope and reference instruments used to characterize AC-LGAD performance. The telescope comprises five pairs of orthogonal strip layers and two pairs of pixel layers, for a total of up to 14 hits per track.

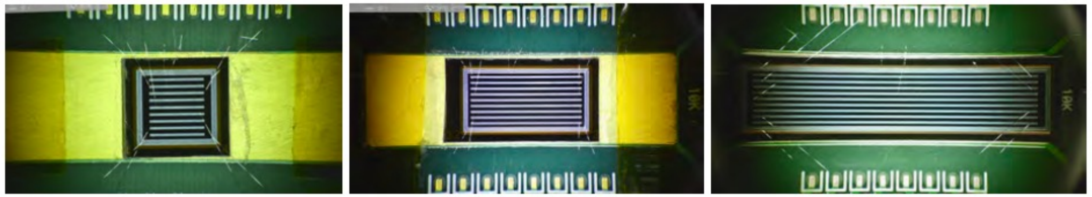
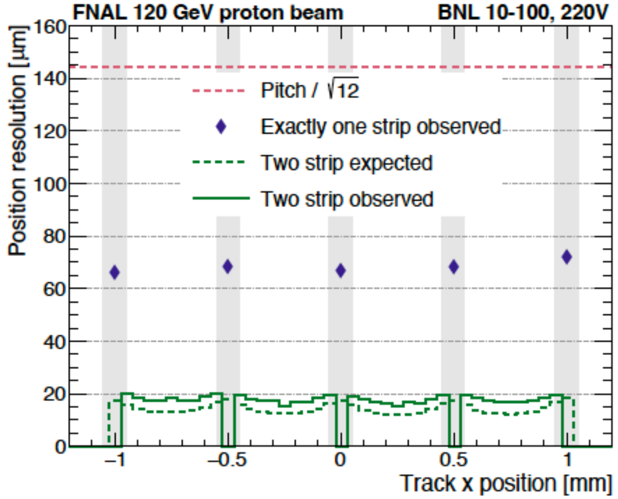
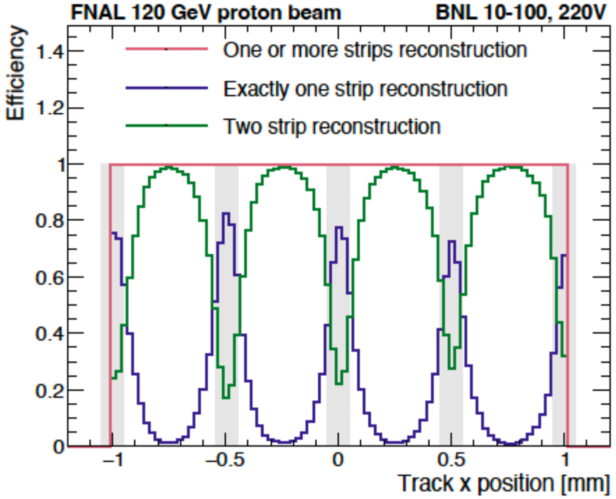
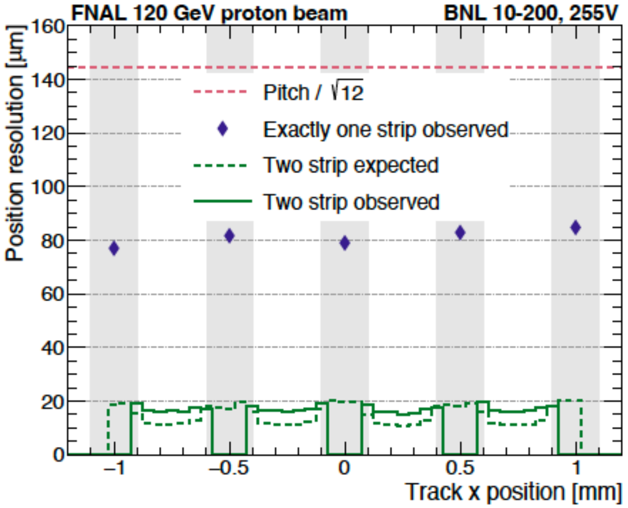
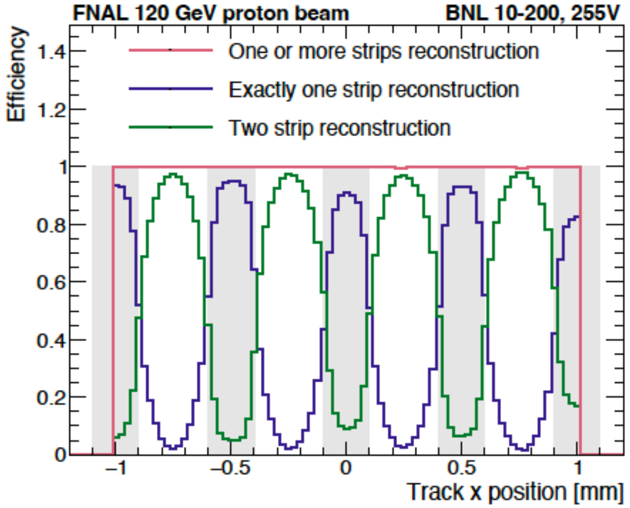


Figure 8: Three AC-LGAD strip sensors wire-bonded on Fermilab test board and tested at FTBF: BNL 5-200 (left), BNL 10-200 (middle) and BNL 25-200 (right). See text for details.









arXiv:2211.09698

eRD112: AC-LGAD Sensor R&D

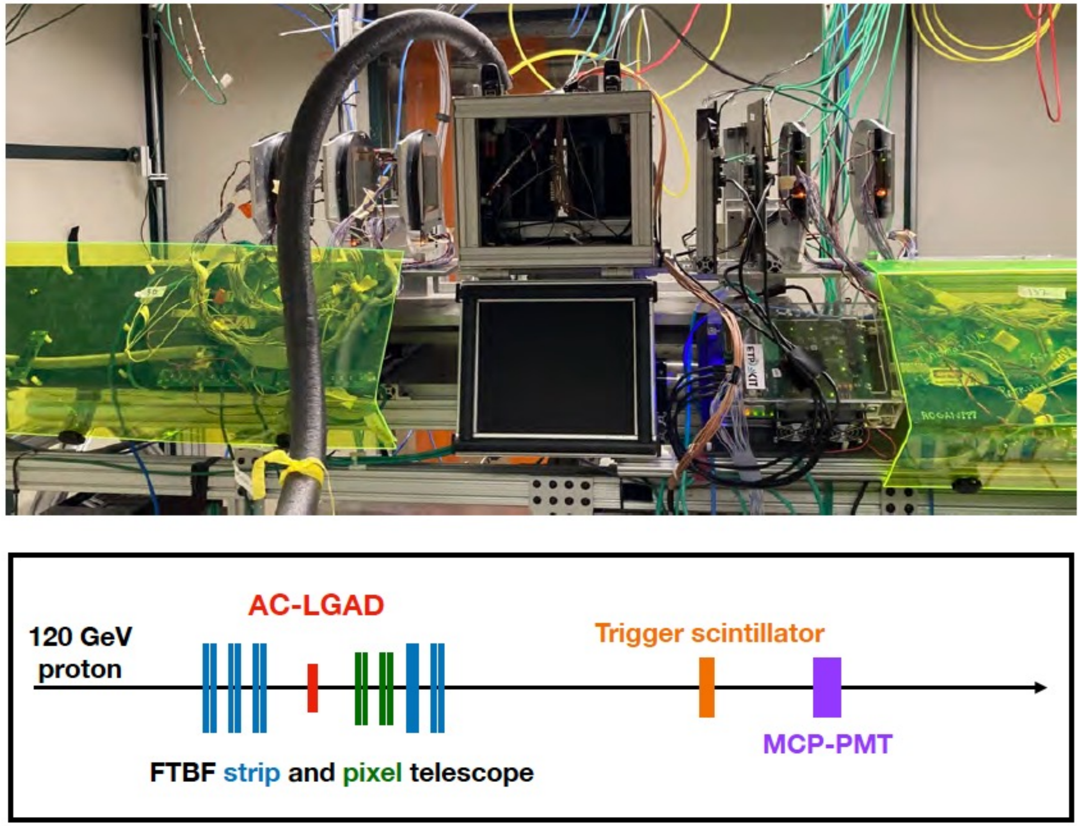


Figure 7: Picture (top) and diagram (bottom) of the FTBF silicon telescope and reference instruments used to characterize AC-LGAD performance. The telescope comprises five pairs of orthogonal strip layers and two pairs of pixel layers, for a total of up to 14 hits per track.

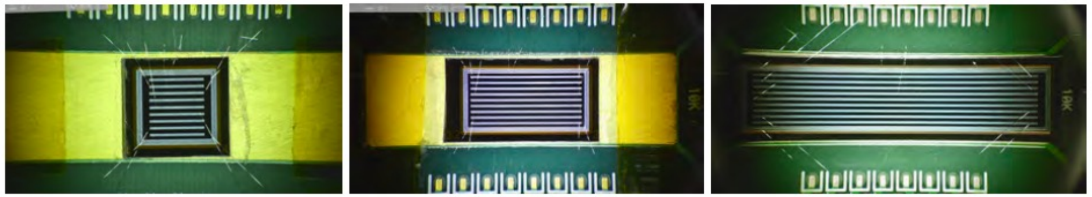
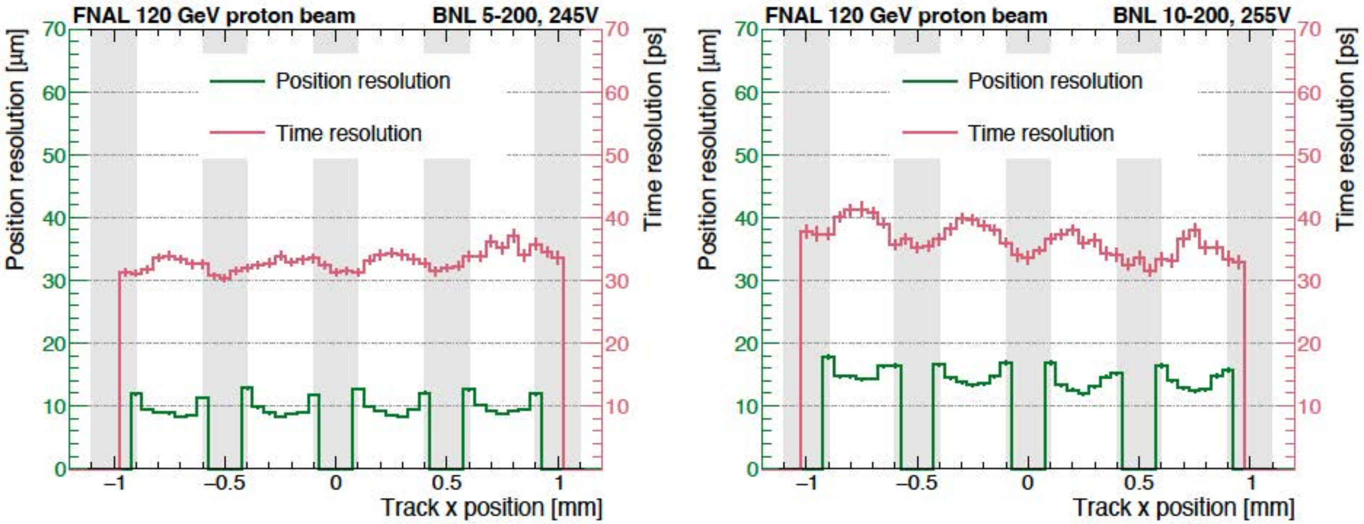


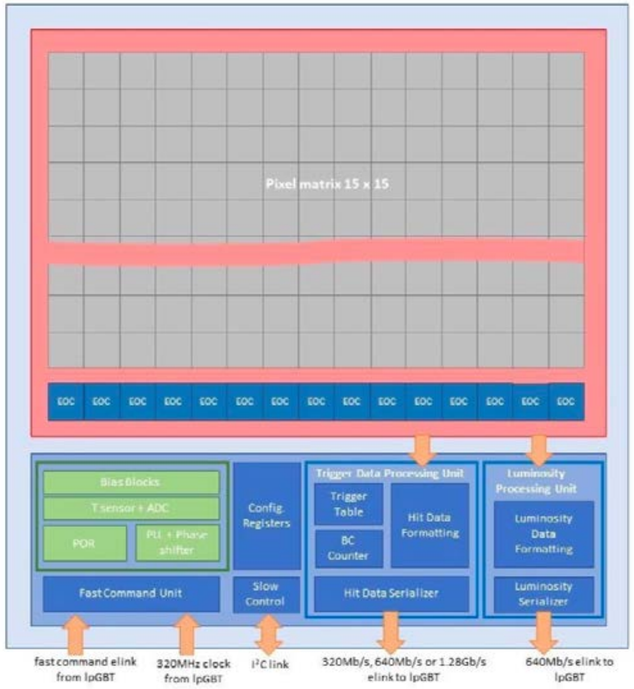
Figure 8: Three AC-LGAD strip sensors wire-bonded on Fermilab test board and tested at FTBF: BNL 5-200 (left), BNL 10-200 (middle) and BNL 25-200 (right). See text for details.

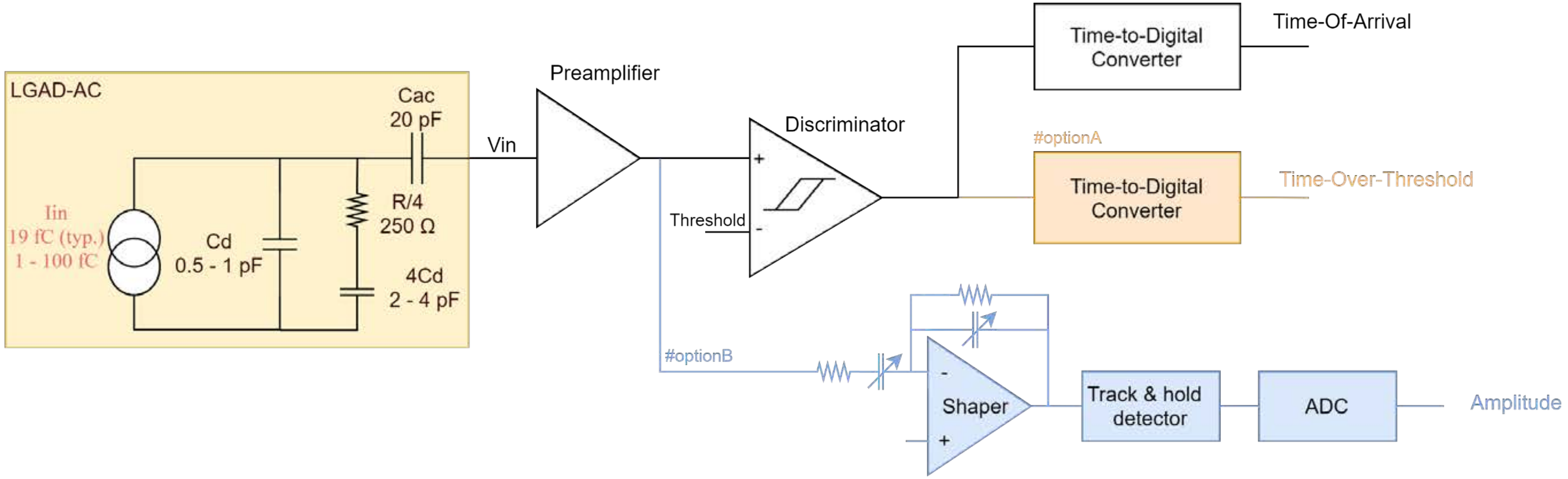


- Timing and spatial resolutions of 1 cm long strip sensors from 1st BNL production demonstrate good performance, making strip sensors a promising candidate for EIC applications.
- Production of medium/large area sensors by BNL IO and HPK with different doping concentration, pitch and gap sizes between electrodes and Si thickness to optimize performance.

arXiv:2211.09698

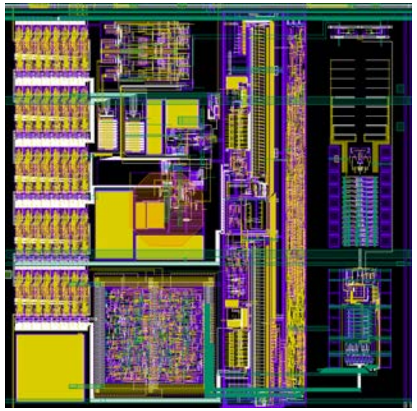
Frontend ASIC R&D

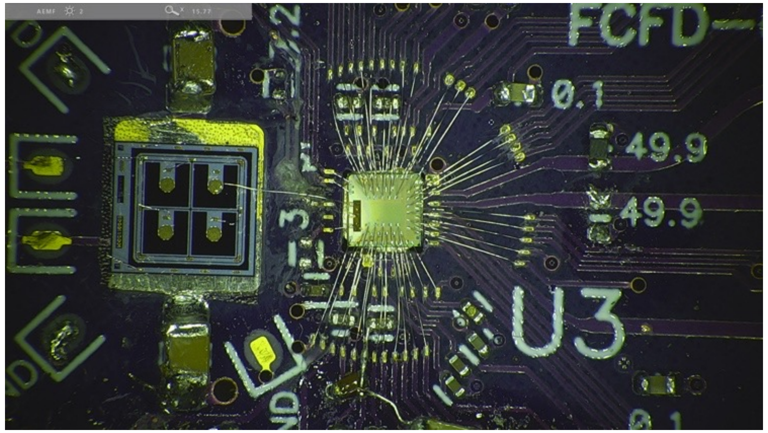


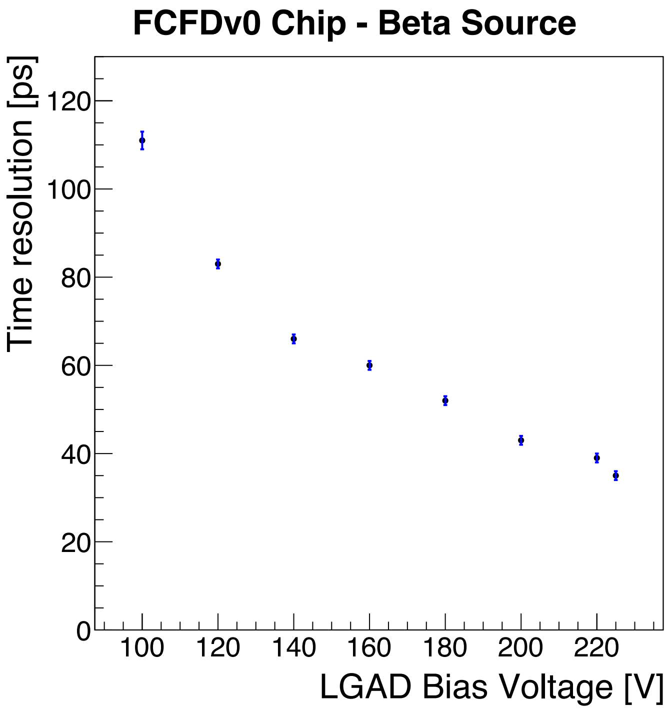


- **R&D Goals**
  - 15-20 ps jitter with minimal (1 mW/ch) power consumption, match AC LGAD sensors for EIC
- **Plan**
  - Continue the ASIC prototyping efforts and utilize the design and experience in ASICs for fast-timing detectors from ATLAS and CMS, and investigate common ASIC design and development for RP/B0 and ToF

Frontend ASIC R&D







EICROC by Omega/Irfu/AGH

- Preamp, discri. taken from ATLAS ALTIROC
- I2C slow control taken from CMS HGCROC
- TOA TDC adapted by IRFU Saclay
- ADC adapted to 8bits by AGH Krakow
- Digital readout: FIFO depth8 (200 ns)

FCFD by Fermilab

- Adapt the Constant Fraction Discriminator (CFD) principle in a pixel paired with a TDC, one time measurement gives the final answer.
- Charge injection consistent with simulations: ~30 ps at 5 fC, and <10 ps at 30 fC
- Tested with laser, beta source and beam

On-going Work

Simulation [1]

- Geometry, digitization, reconstruction
- Timing resolution
- Spatial resolution (granularity)
- Material budget

R&D [2]

- Sensor: BNL/HPK
- ASIC: EICROC, FCFD, UCSC/SCIPP
- ASIC/Sensor integration
- Low-density mechanical structure
- Low-mass service hybrid

Project Engineering and Design [3]

- Mechanical engineering
  - Mechanical structure and cooling
- Electric engineering (via DAQ group)
  - Prototype readout board, cables
  - Precision clock distribution

[1] https://wiki.bnl.gov/EPIC/index.php?title=TOFPID
[2] https://wiki.bnl.gov/conferences/index.php/ProjectRandDFY23
[3] https://www.overleaf.com/read/vftxyvjtjrvp

Summary and Outlook

- **AC-LGAD** is the selected technology by EIC Detector-1 for timing and tracking in central and far-forward detectors. Other fast timing technologies could be considered for Detector-2
  - **Opportunity**: new detector technology development; multi-million and multi-year projects.
  - **Challenge**: strict detector performance requirements; tight schedule.

    TOF WG Mailing list: eic-projdet-tofpid-l@lists.bnl.gov
    Indico page: https://indico.bnl.gov/category/414

- **eRD112**: develop sensor, ASIC, and other key components for AC-LGAD detectors at EIC
  - **Approach**: having common design and with combined R&D efforts for different detectors when possible.

  eRD112 Mailing list: https://mailman.rice.edu/mailman/listinfo/lgads-eic
  Indico page: https://indico.bnl.gov/category/323/

Timeline – What is Coming for EIC

CD-0 approval	December 19, 2019
Community-wide Yellow Report effort	Dec 2019 – Feb. 2021
CD-1 review (includes CDR)	January 26-29, 2021
Call for Collaboration Proposals for Detectors	March 6, 2021
CD-1 approval	June 29, 2021
DOE/OPA Status Review	October 19-21, 2021
Status Update to Federal Project Director	June 28-30, 2022
Cost and Schedule Event(s)	May-June 2022
Technical Subsystem Reviews	Jan. – Dec. 2022
OPA Status Review	January 2023
Preliminary Design Complete & Review	May 2023
Final Design/Maturity Readiness for CD-3A Items	May 2023
CD-3A review (expectation), requires pre-TDR	~October 2023
CD-3A (expectation)	~January 2024
CD-2/3 review (expectation), requires TDR	~January 2025
CD-2/3 (expectation)	~April 2025

- **You are welcome to join eRD112 and other EIC detector/physics efforts.**

EIC Users Group and ePIC Collaboration Meeting @ Warsaw, July 25-31, 2023

References

[1] Electron Ion Collider: The Next QCD Frontier - Understanding the glue that binds us all (2012), arXiv:1212.1701

[2] Reaching for the Horizon: The 2015 Long Range Plan for Nuclear Science (2015), link

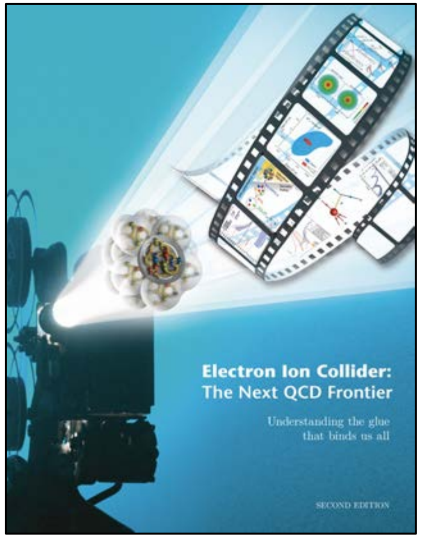
[3] An Assessment of U.S.-based Electron-Ion Collider Science (2018), link

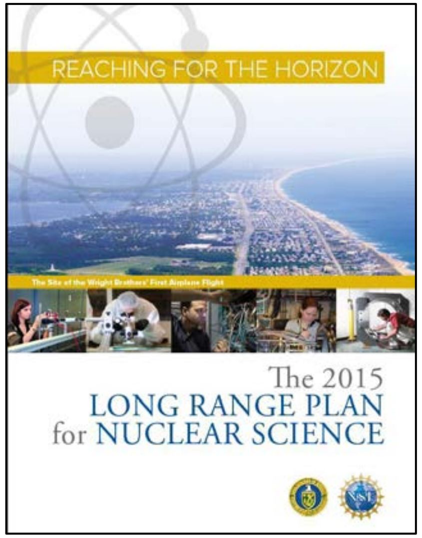
[4] Electron Ion Collider Conceptual Design Report (2021), link

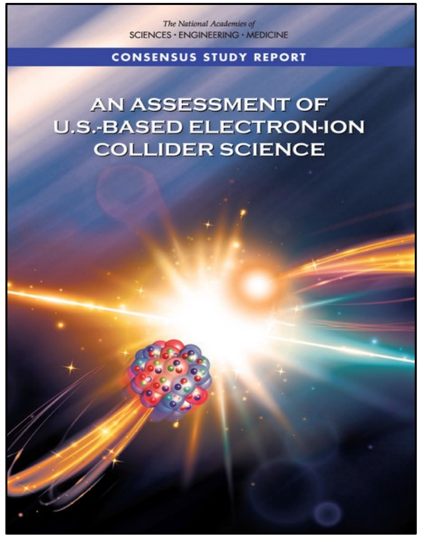
[5] Science Requirements and Detector Concepts for the Electron-Ion Collider: EIC Yellow Report, arXiv:2103.05419

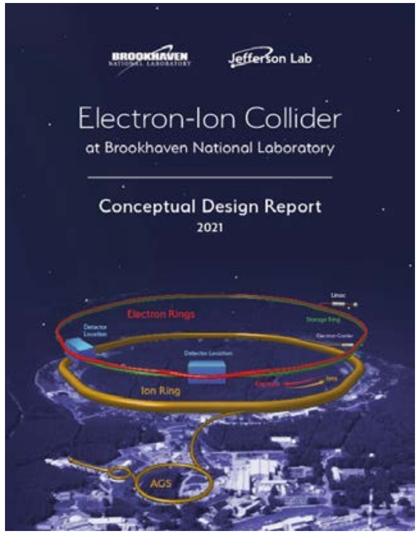
[6] EIC Detector Proposals and Advisory Panel Report (2022), link

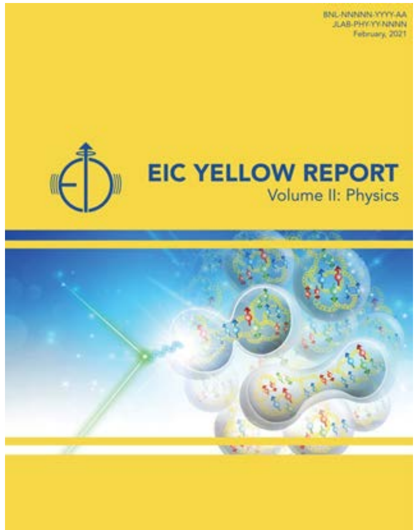
[7] eRD112: EIC AC LGAD R&D Proposal (2022), link





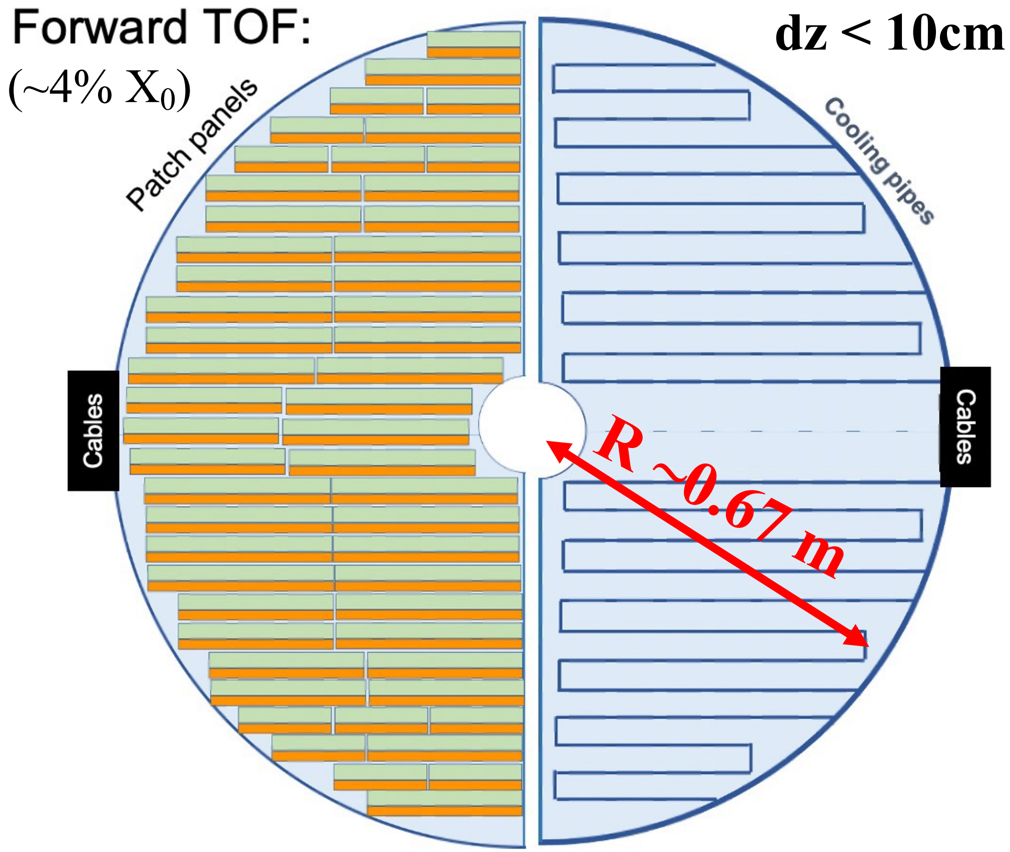




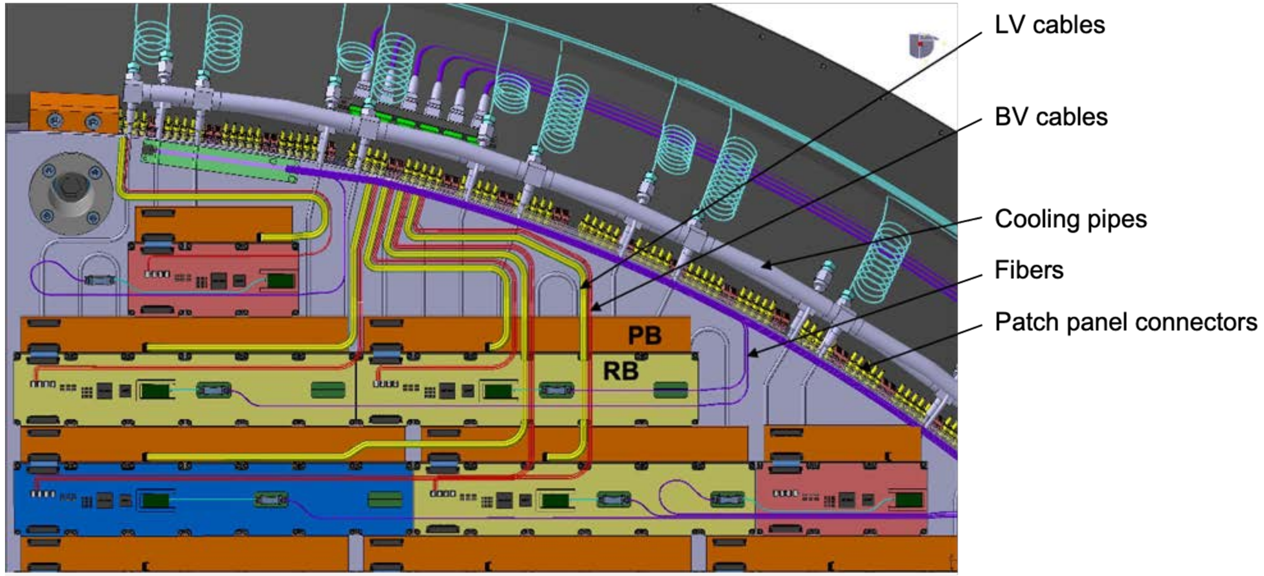


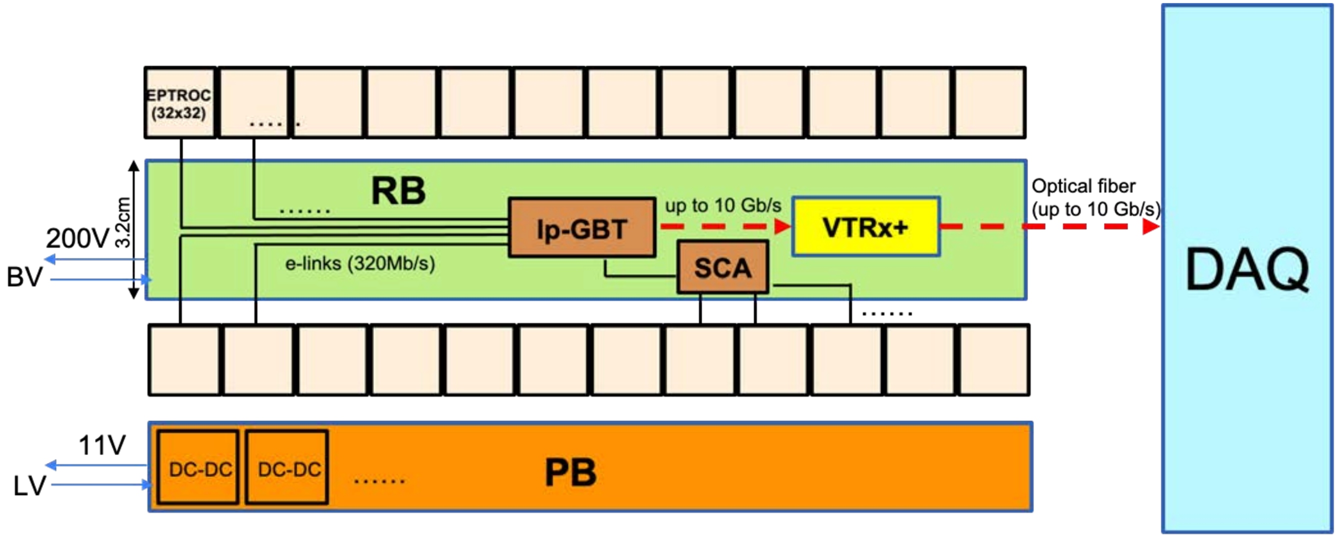
Forward TOF Layout

More details: https://indico.bnl.gov/event/17336/



CMS Endcap Timing Layer

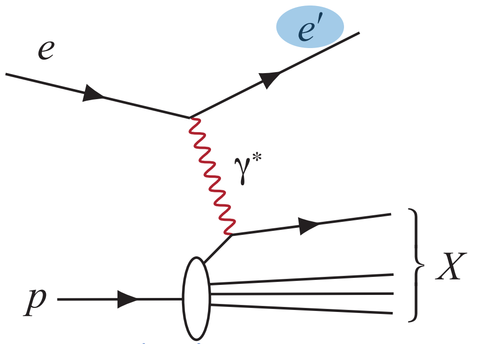




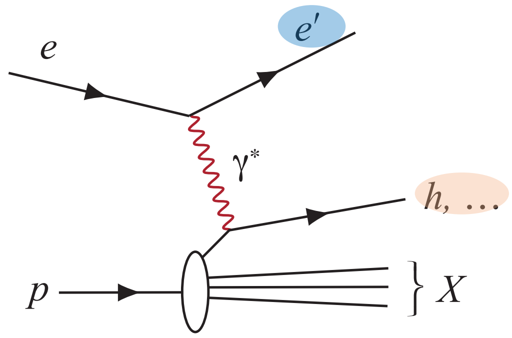
- 212 modules, each with 24 to 96 bump-bonded pixel sensor + ASIC assemblies on Al disk
- Power consumption: 13 kW for 500x500 μm^2 pixels (6 kW for 800 x 800 μm^2)

EIC - Particle Production

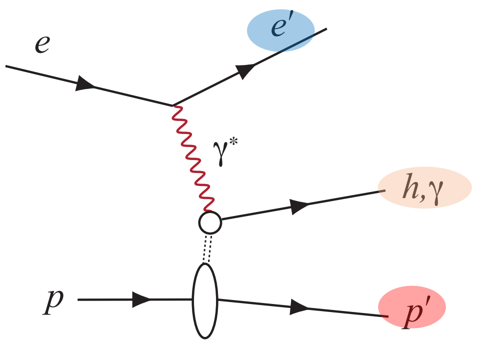
[6] EIC DPAP



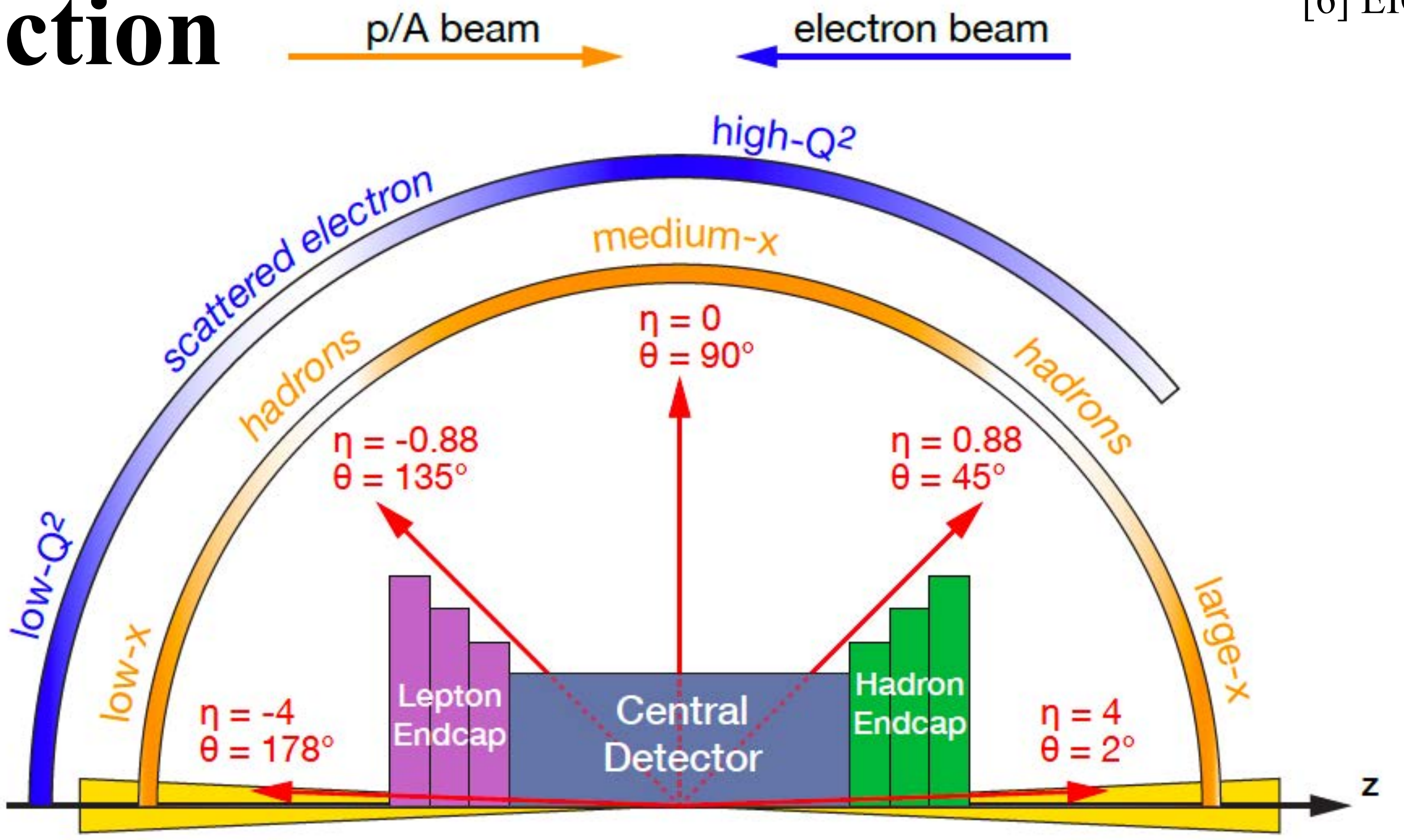
Inclusive DIS

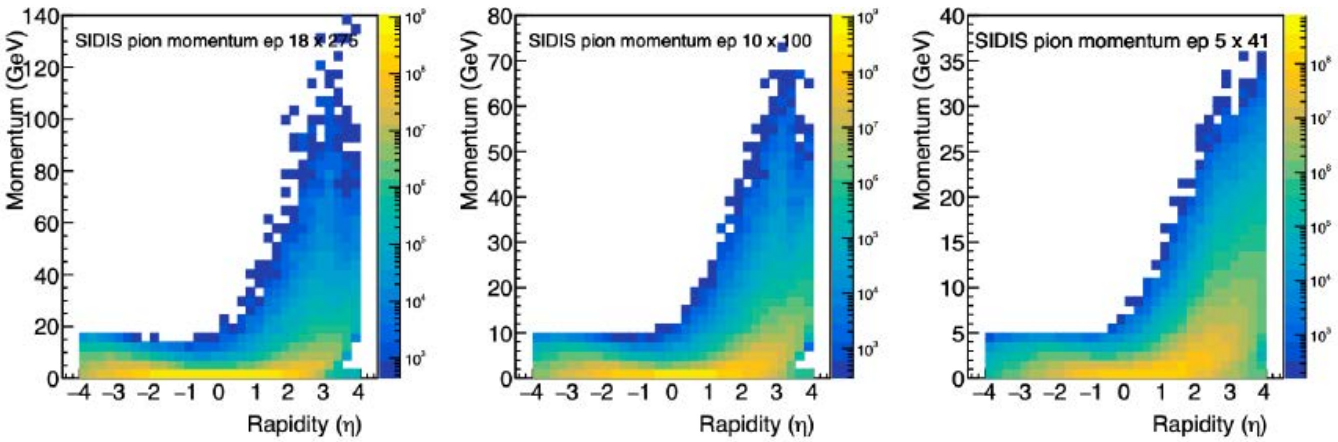


Semi-inclusive DIS



Exclusive





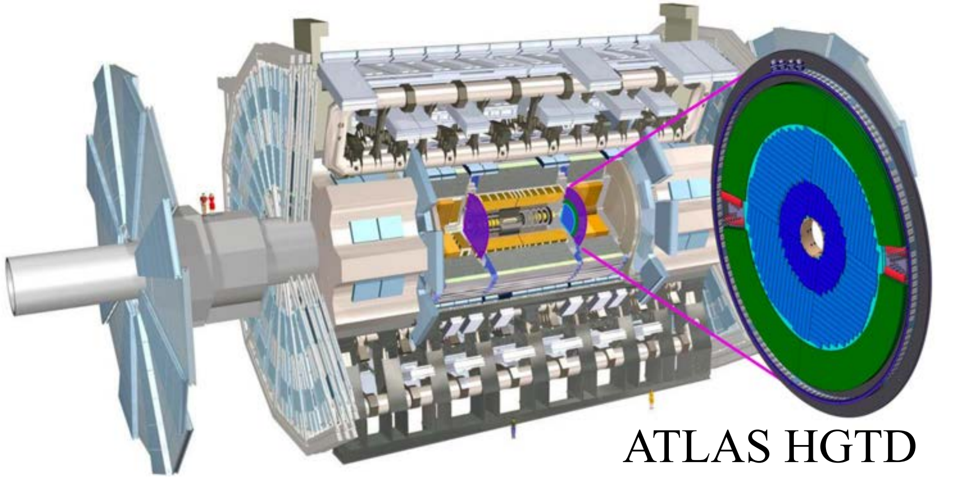
AC-LGAD for EIC

- Precise timing detectors based on DC-LGAD being built by ATLAS (6.4 m^2) and CMS (14 m^2) for data taking in 2028+.

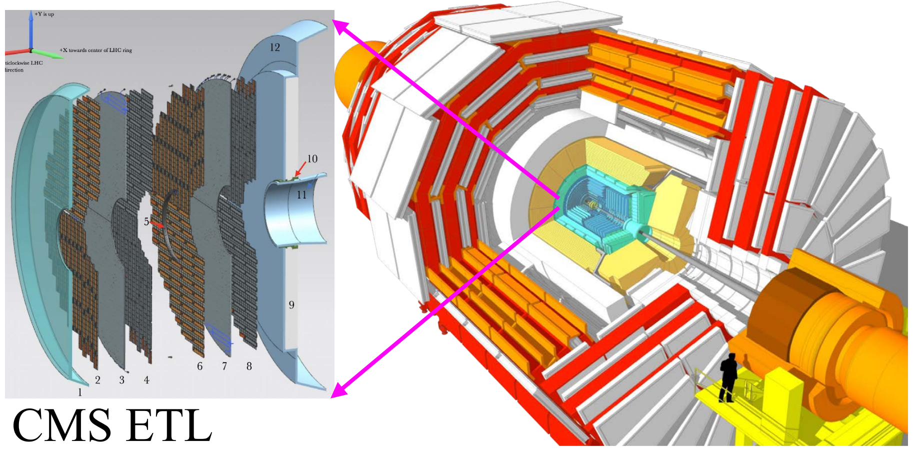
- AC-LGAD can not only provide precise timing resolution similar to DC-LGAD, but also 100% fill factor and much better spatial resolution thanks to charge sharing.

- AC-LGAD proposed for EIC experiments
  - TOF PID and tracking for central detectors
  - timing and tracking for forward detectors

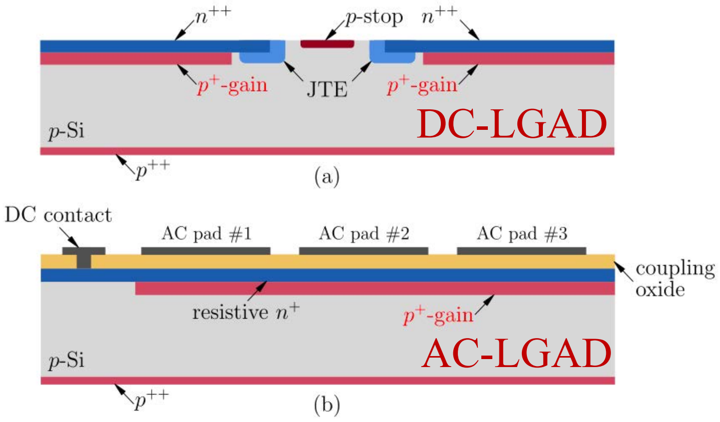
  with common designs in sensor, ASIC etc. where possible.

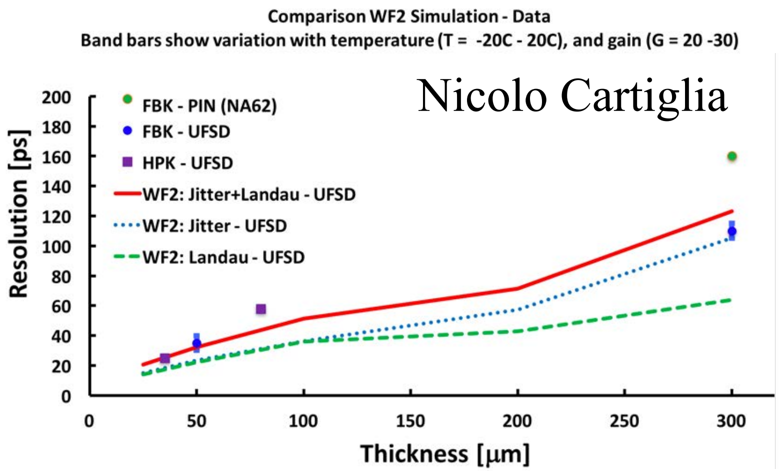


ATLAS HGTD

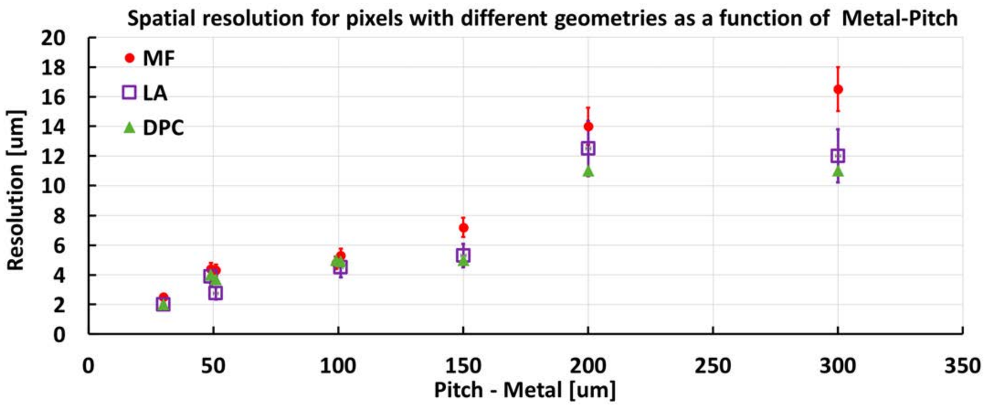


CMS ETL

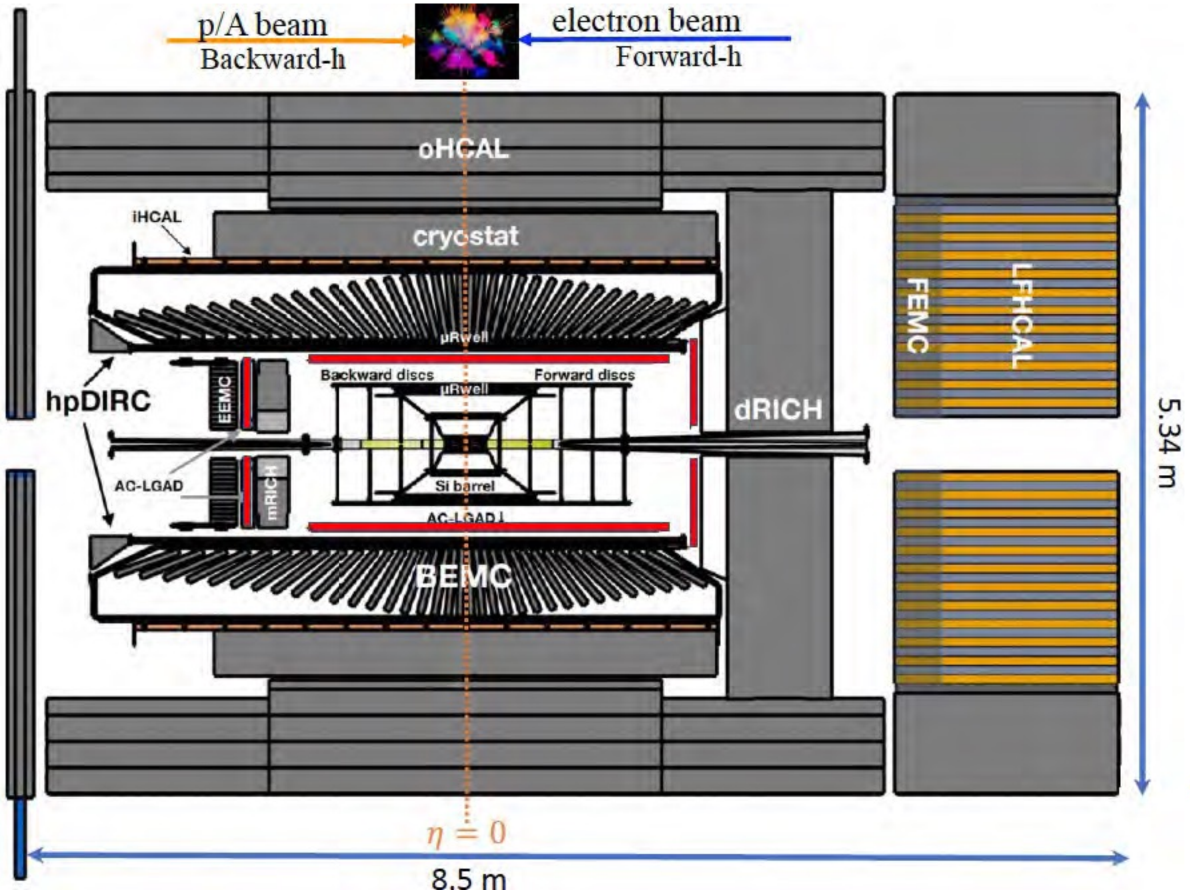


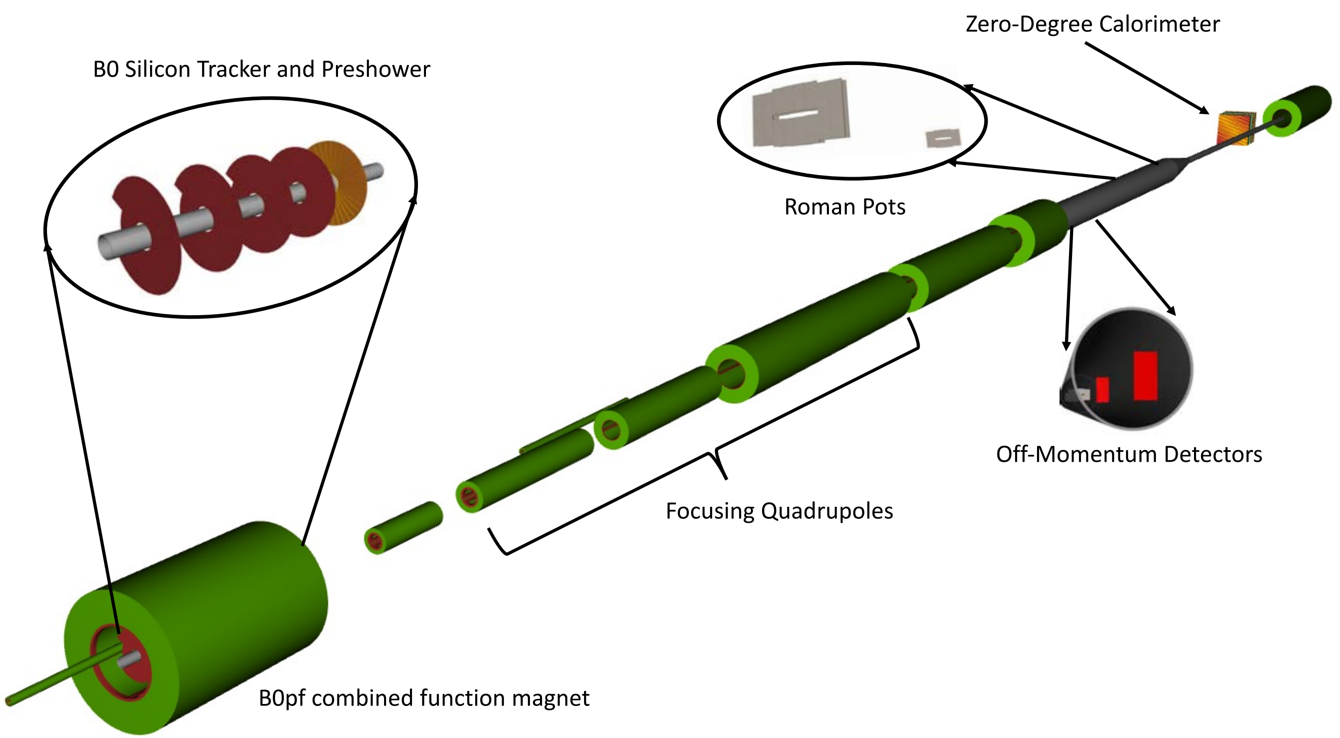


Nicolo Cartiglia



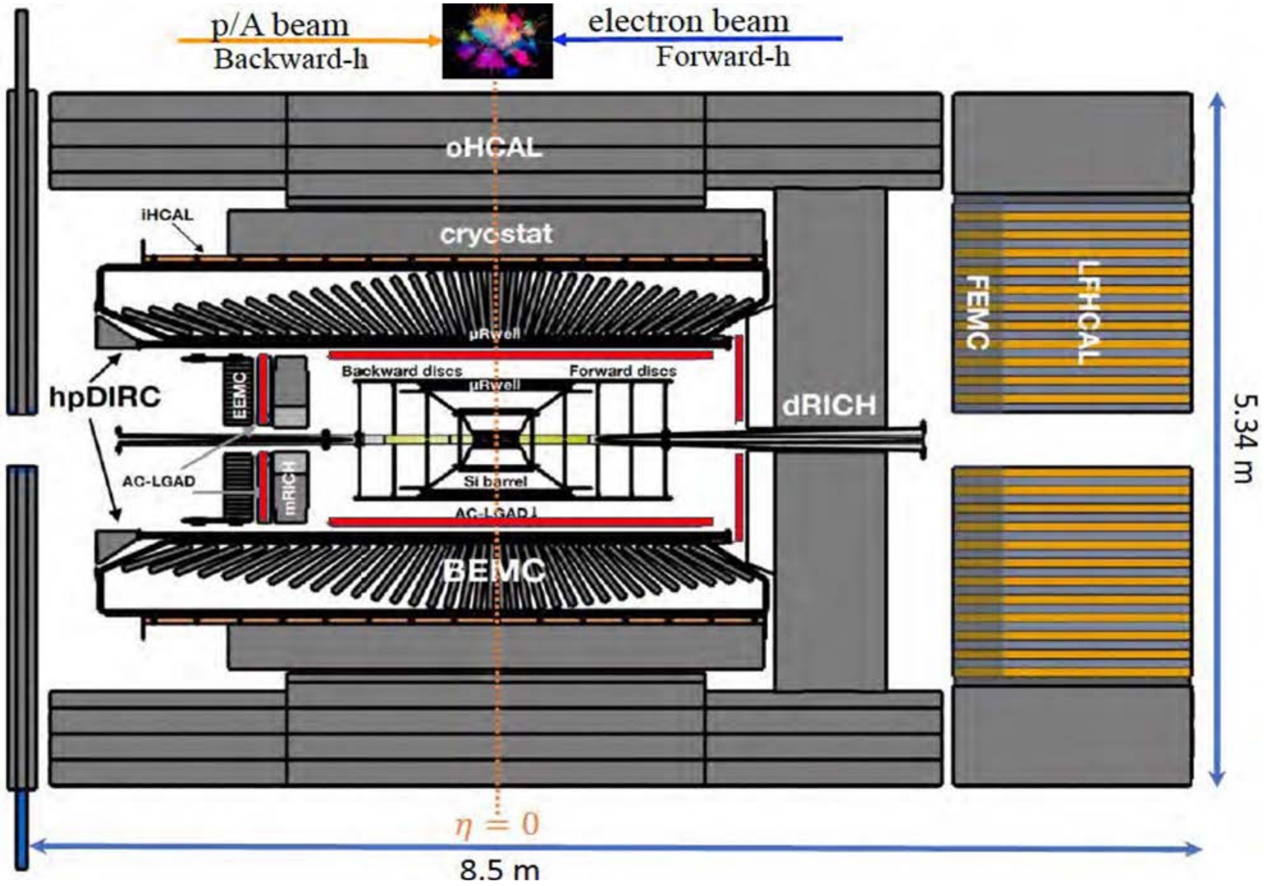
AC-LGAD Detectors for EPIC

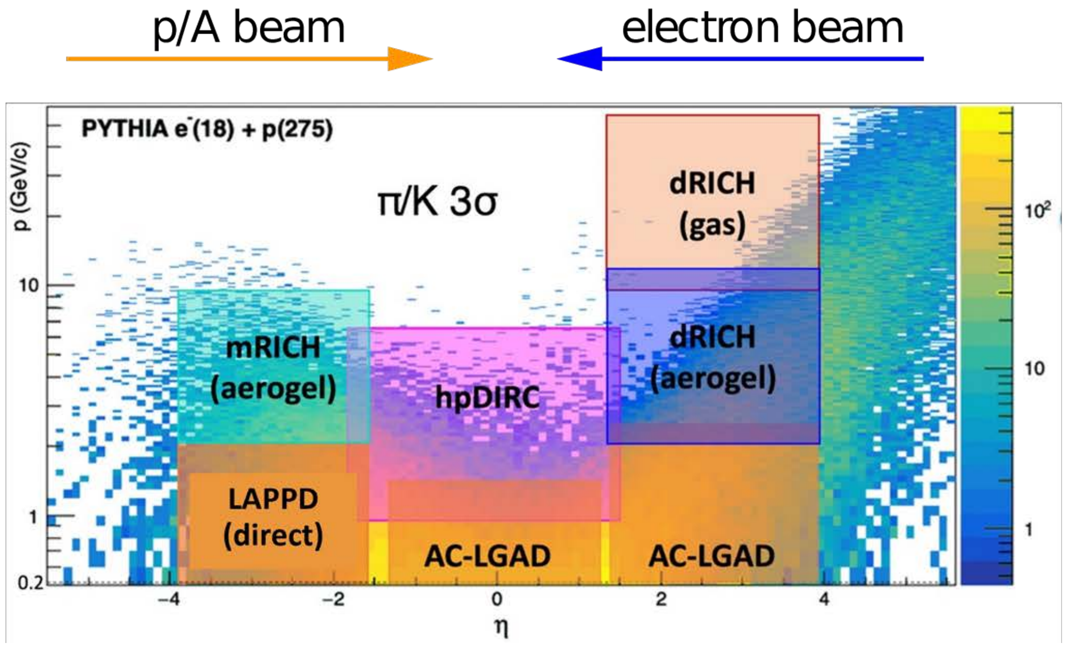




	Area (m^2)	Channel size (mm^2)	# of Channels	Timing Resolution	Spatial resolution	Material budget
Barrel TOF	10.9	0.5*10	~2 M	30 ps	30 μm in $r \cdot \varphi$	0.01 X0
Forward TOF	1.20/2.22	0.5*0.5	~6 M	25 ps	30 μm in x and y	0.04 X0
B0 tracker	0.07	0.5*0.5	~0.3M	30 ps	20 μm in x and y	0.01 X0
RPs/OMD	0.14/0.08	0.5*0.5	~0.6M/0.3M	30 ps	140 μm in x and y	no strict req.

AC-LGAD TOF Overview





majority of particles are low momentum (<2 GeV/c)

	PID coverage (π/K)
Forward ($1.5<\eta<3.5$)	$0.15 < p < 2.5$ GeV/c
Barrel ($\|\eta\|<1.4$)	$0.15 < p_T < 1.5$ GeV/c

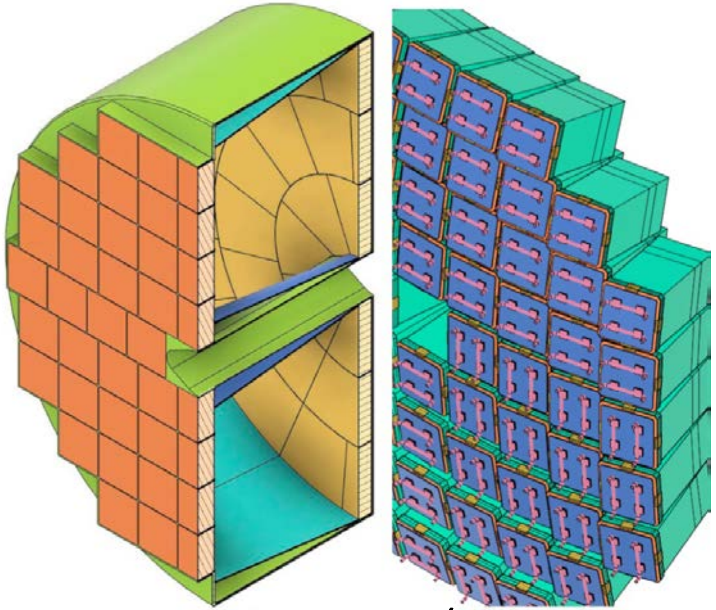
Baseline design:

- 500 μm x 1 cm strip, ~1% X_0 for barrel
- 500 x 500 μm^2 pixel, 8% X_0 for forward
- 25 ps single hit time resolution
- ~30 μm spatial resolution

- Barrel TOF: improve momentum resolution when single hit is missing in Si layers
- Forward TOF: expect positive impact on momentum and angular resolution when included in tracking

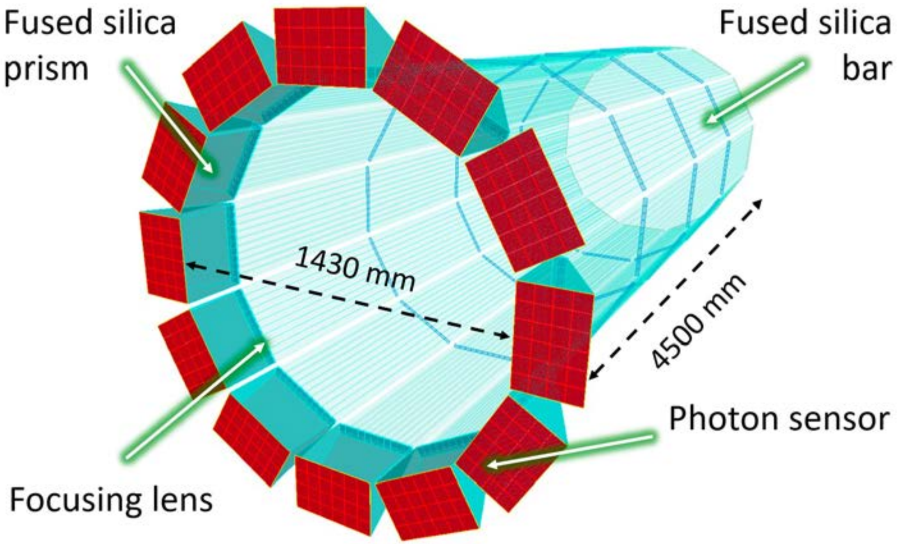
EIC Detector-1 Design: Particle Identification

pfRICH **mRICH**



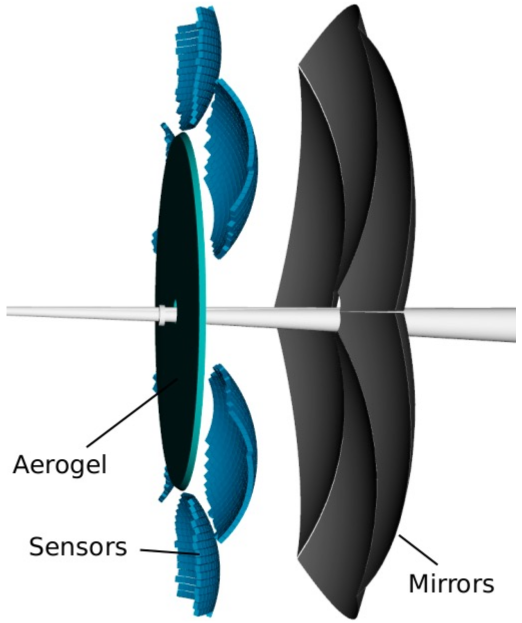
p<10 GeV/c

hpDIRC

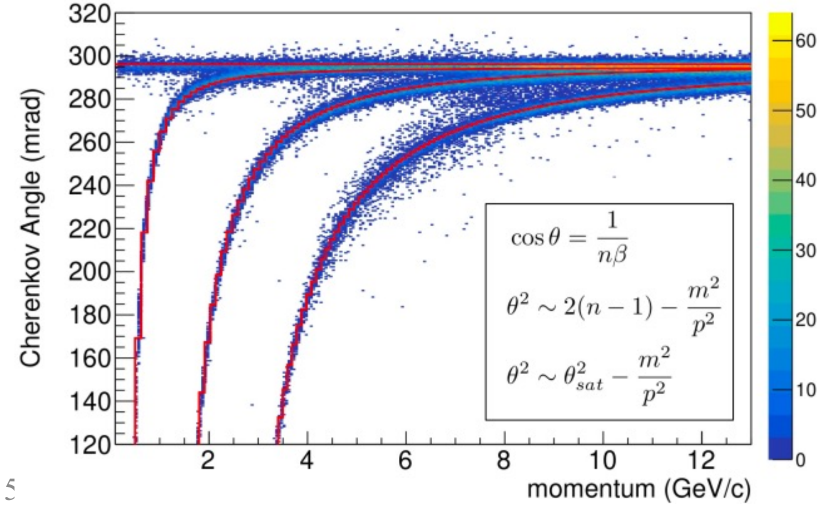


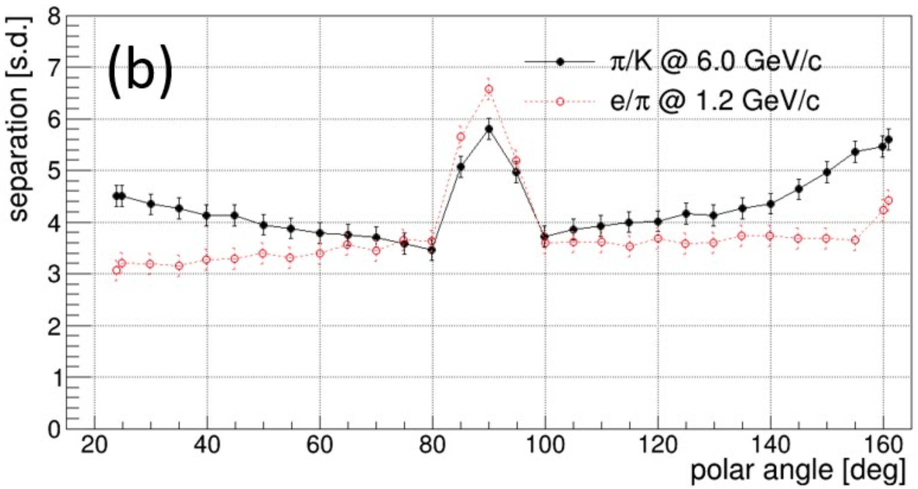
p<6 GeV/c

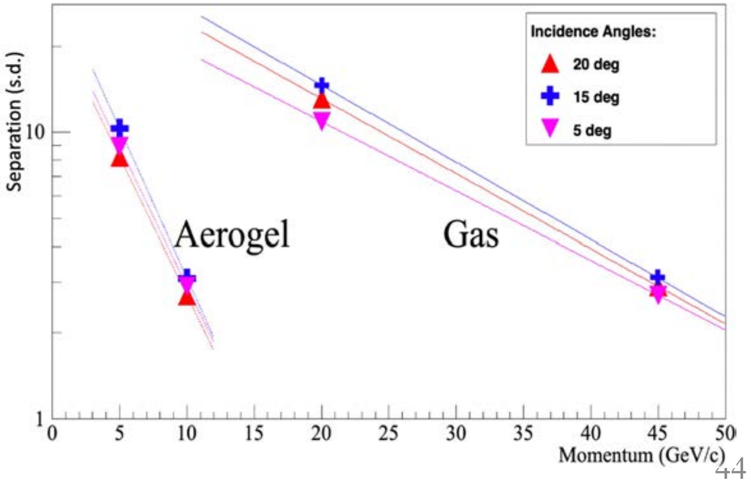
dRICH



p<50 GeV/c

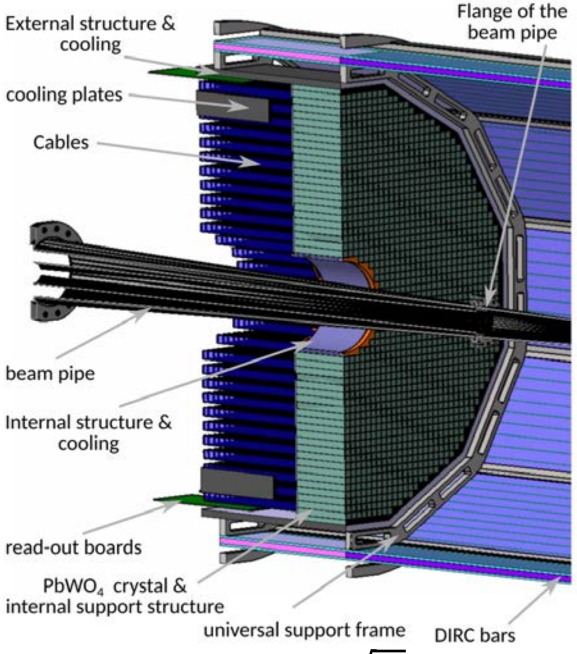






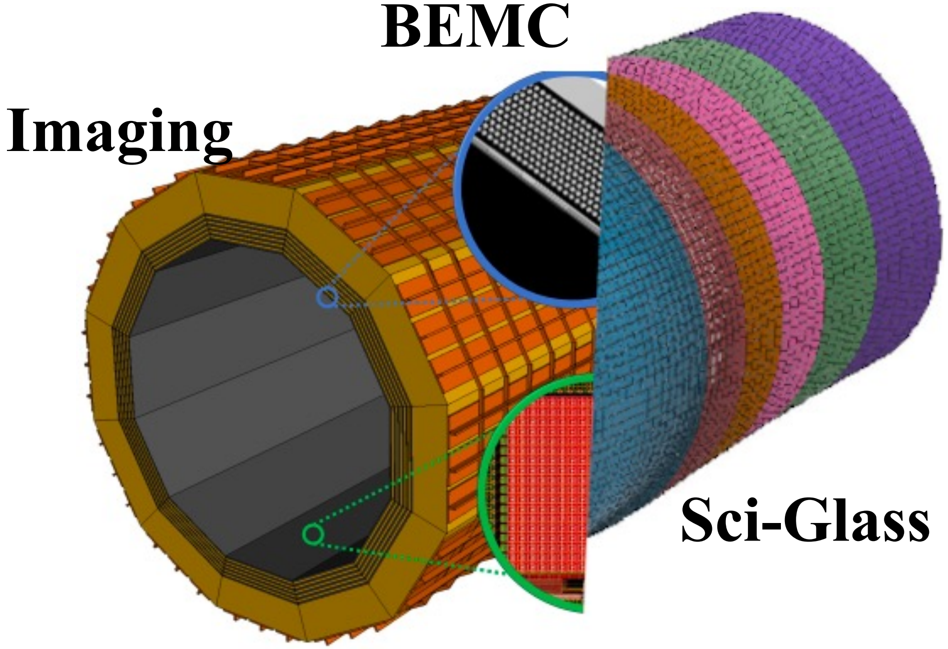
EIC Detector-1 Design: EM Calorimeters

EEMC



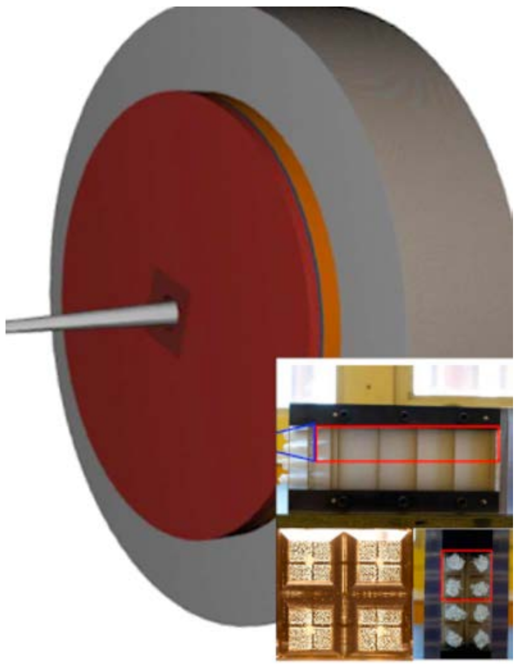
$1\%E \oplus 2.5\%/\sqrt{E} \oplus 1\%$

BEMC



$2\%E \oplus 4-8\%/\sqrt{E} \oplus 2\%$

FEMC



$2\%E \oplus 4-12\%/\sqrt{E} \oplus 2\%$

Endcap regions:

- **EEMC** - homogenous high resolution $PbWO_4$ crystal ECal
- **FEMC** - highly granular W-Scintilating Fiber calalorimeter

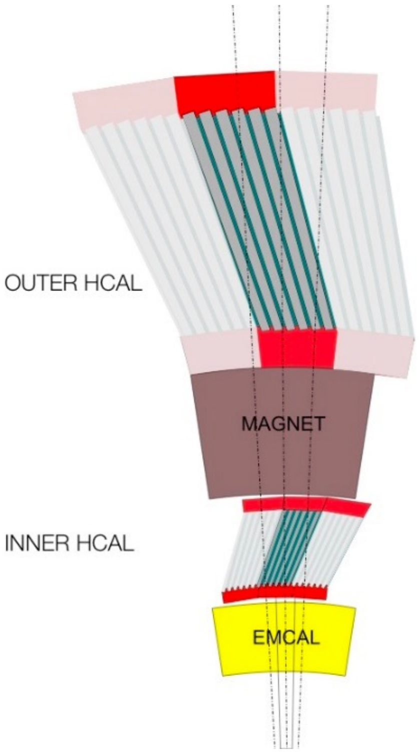
Barrel region - alternatives:

- **Sci-Glass:** homogenous, projective Sci-Glass ECal
- **Imaging:** 6 layers of 0.5x0.5mm Astro-Pix Silicon layers, interleaved with Pb-SciFi calorimeter

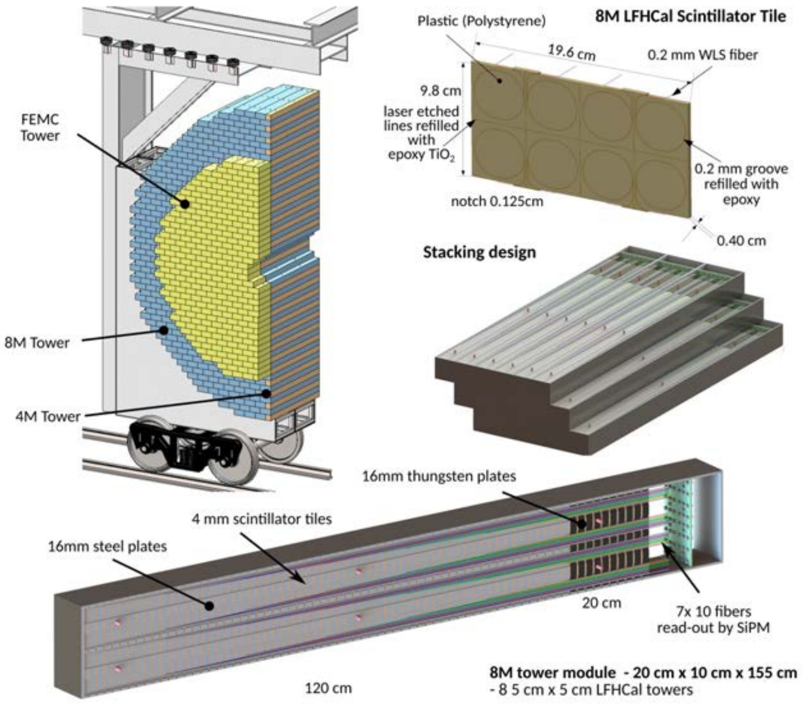
EIC Detector-1 Design: Hadronic Calorimeters

- Designed to complement tracking in Particle-Flow algorithm
- **OHCAL/IHCAL**
  - Fe/Scint sampling calorimeter
  - partial sPHENIX re-use & magnet flux return
- **LFHCAL**
  - Fe/Scint & W/Scint sampling calorimeter
  - Highly segmented (7 long. segments)
  - W-segment as colimator
- High granularity inserts under discussion for forward E&HCal
- Electron end-cap HCAL as neutral veto, shallow Fe/Scint calo

BHCAL



LFHCAL

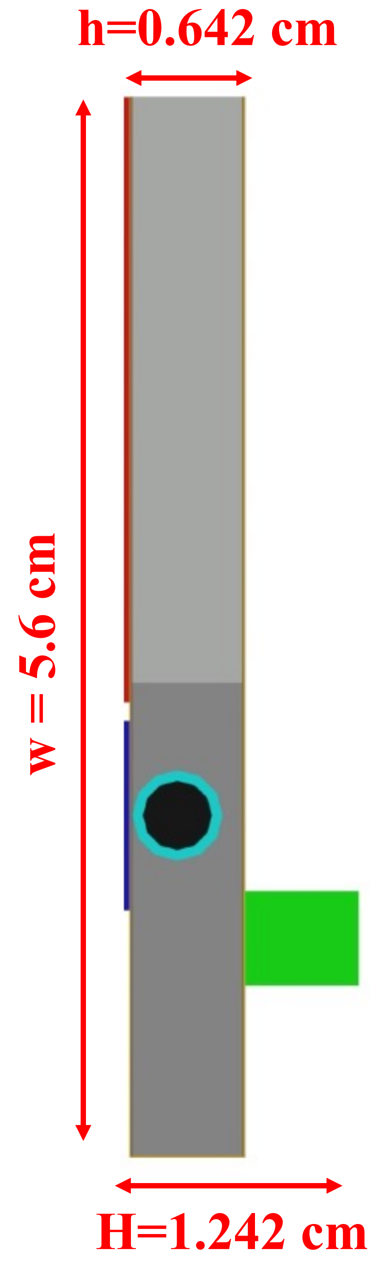


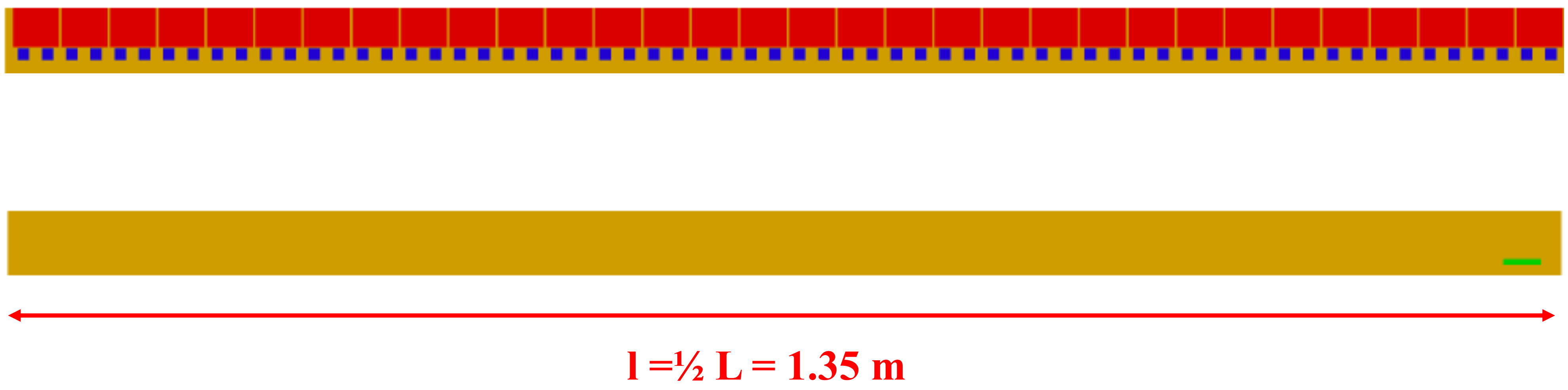
	Barrel HCal	LFHCAL
η	[-1 .. 1]	[1 .. 4]
σ_E/E	~75%/√E + 15%*	~33%/√E + 1.4%
depth	~4-5 λ_I	~7-8 λ_I

*Based on prototype beam tests and earlier experiments

EPIC Barrel TOF Module

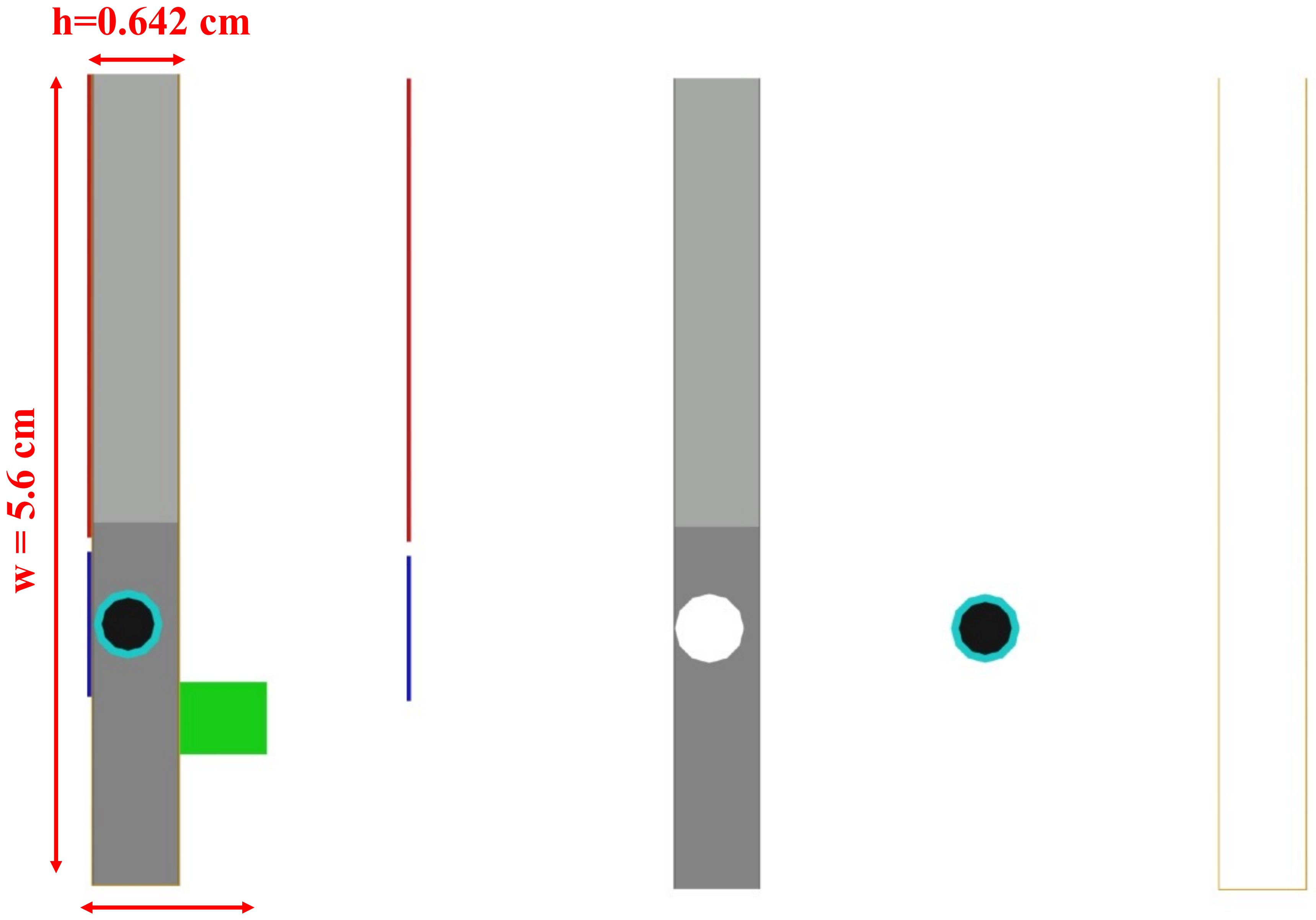
>95% coverage in Z





- **32 AC-LGAD sensors**, each 3.2*4 cm^2 read out by **2 ASICs**
- **Low mass flexible Kapton PCB** distributes power and I/O signals from a low mass connector(s) at the edge
- **Liquid coolant** in **Al cooling tube** takes away heat from the ASICs

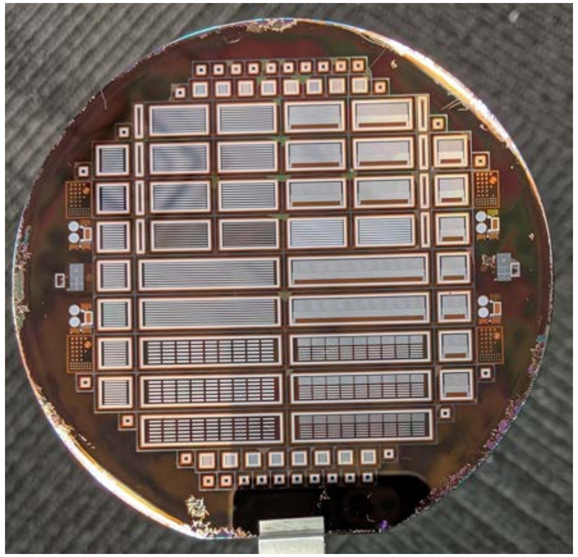
EPIC Barrel TOF Module



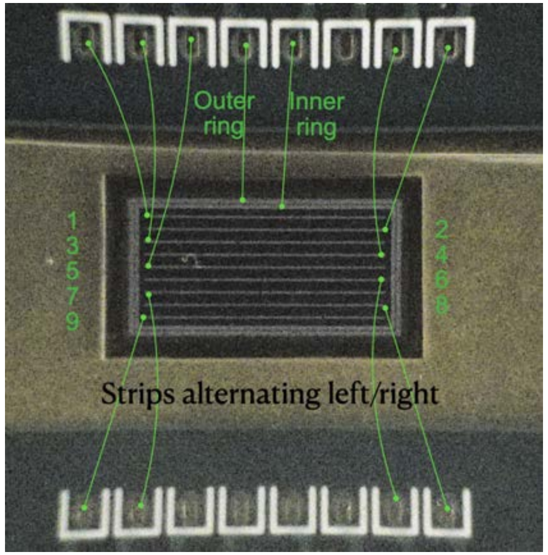
- AC-LGAD sensor
- Frontend ASICs
- Carbon foam+
  Carbon honeycomb+
  CF skins
- Al cooling tube
- Liquid coolant
- Kapton PCB
- Connector

Sensor R&D

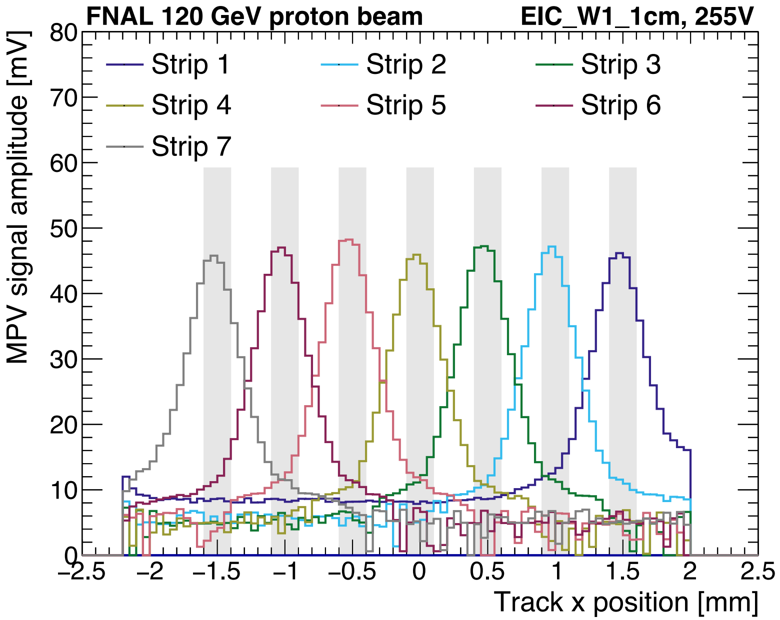
- **R&D Goals**
  - 15-20 ps timing resolution, O(~30μm) position resolution where needed
  - Minimal readout channel density (strip, rectangular pixel) for reduced power, material and cost
- **Plan**
  - Produce and test large area sensors with thinner active volume to achieve the desired timing resolution
  - Optimize implantation parameters and AC-pad segmentation through simulation and real device studies
  - Engage commercial vendors to improve fabrication process and yield



AC-LGAD Sensor Wafer by BNL IO 2021



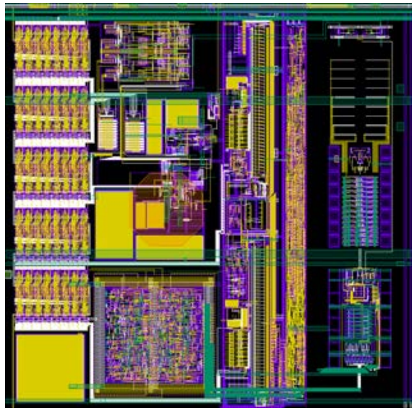
500 um*1cm strip AC-LGAD sensor mounted on test board

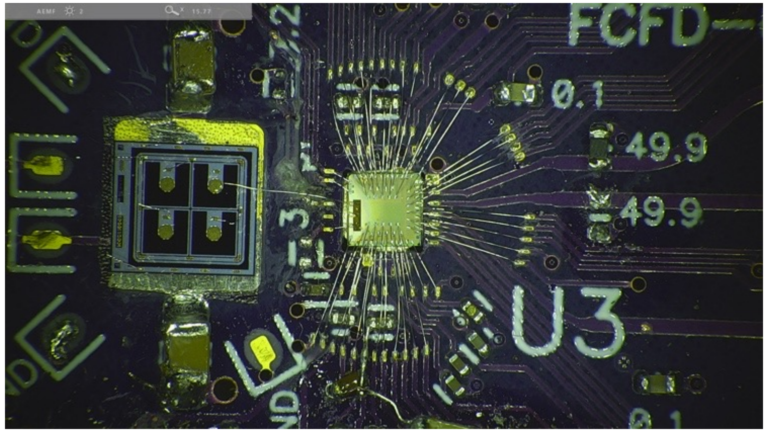


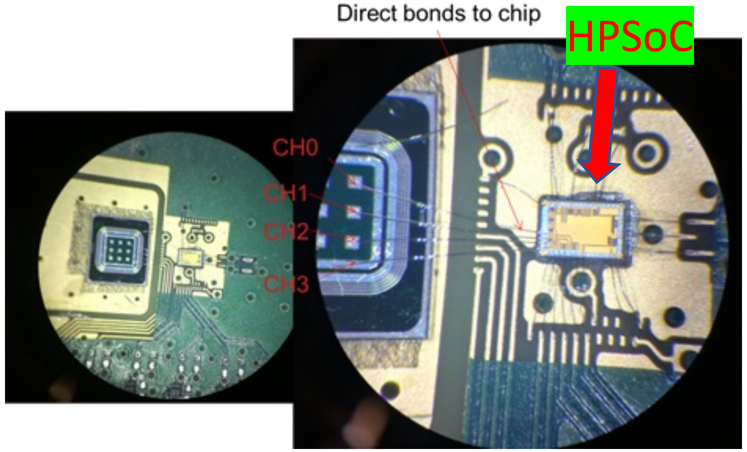
Signal amplitude vs x position at 2022 Fermilab test beam

eRD112: ASIC R&D

- **R&D Goals**
  - 15-20 ps jitter with minimal (1-2 mW/ch) power consumption, match AC-LGAD sensors for EIC
- **Plan**
  - Utilize the design and experience in ASICs for fast-timing detectors from ATLAS and CMS, and investigate common ASIC design and development for TOF/Tracking and RP/B0







EICROC by Omega/Irfu/AGH
- Preamp, discri. taken from ATLAS ALTIROC
- I2C slow control taken from CMS HGCROC
- TOA TDC adapted by IRFU Saclay
- ADC adapted to 8bits by AGH Krakow
- Digital readout: FIFO depth8 (200 ns)

FCFD by Fermilab
- Adapt the Constant Fraction Discriminator (CFD) principle in a pixel paired with a TDC, one time measurement gives the final answer.
- Charge injection consistent with simulations: ~30 ps at 5 fC, and <10 ps at 30 fC
- Tests with beta sources and beam are planned

HPSoC by Nalu Scientific LLC

Parameter	Specification
Channel no.	100+ (pitch 300-500 μm)
Process	65nm CMOS
Sample rate	10 GSa/s
Bandwidth	2 GHz
No. bits	10
Supply Voltage	1.0V (2.5V for digital I/O)
Timing accuracy	5ps
Front-End stage	Embedded TIA
Buffer length/channel	256 samples
Power/channel	<2mW
On-chip integration	Sampling, Digitization, Calibration, Feature Extraction, Data Fusion

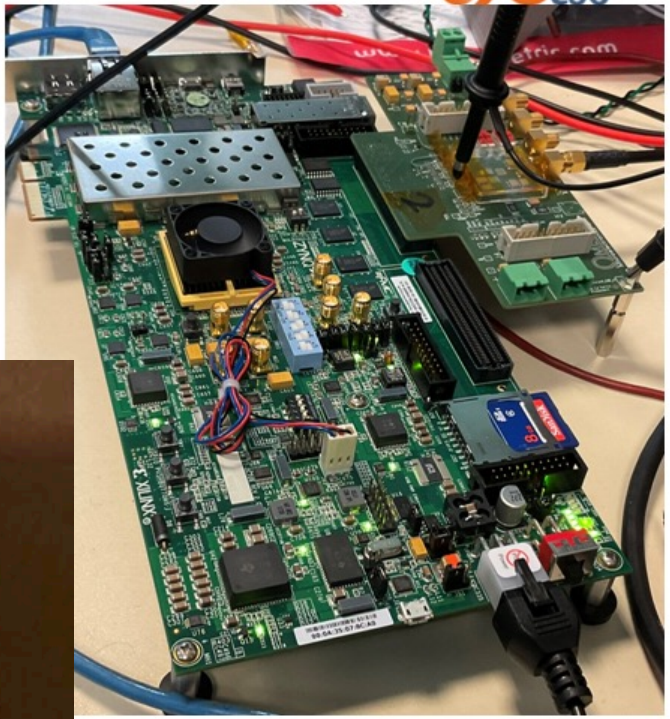
eRD112: Frontend ASIC R&D

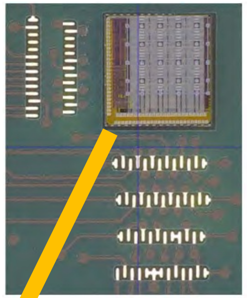
- A first ASIC prototype that is compatible with EIC Roman Pot requirements and can read out an AC-LGAD with 500 micron pitch and 20 ps time resolution.

EICROC0 (submitted in 3/2022, received in 7/2022) by OMEGA/CEA-Irfu/AGH/IJCLab

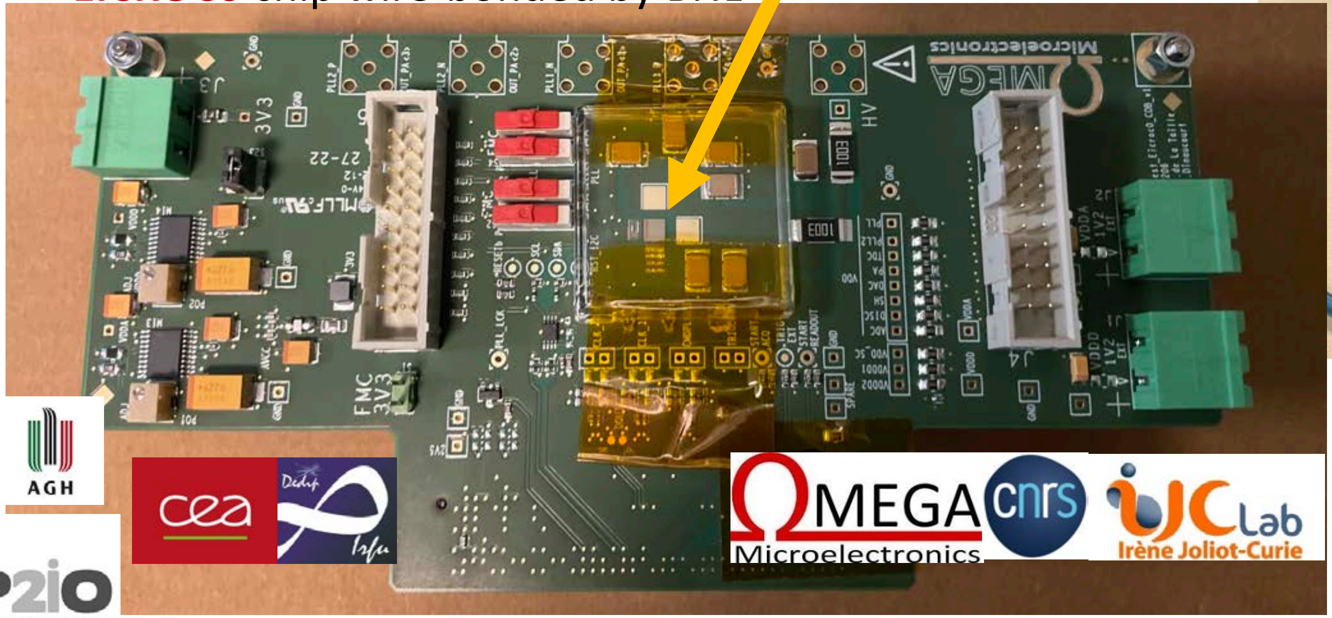
- 4 x 4 channels with 500x500 um^2 pitch
- Preamp, discri. taken from ATLAS ALTIROC
- I2C slow control taken from CMS HGCROC
- TDC (TOA) adapted by CEA-Saclay/Irfu
- ADC (40 MHz) adapted to 8bits by AGH Krakow
- Digital readout: FIFO depth8 (200 ns)

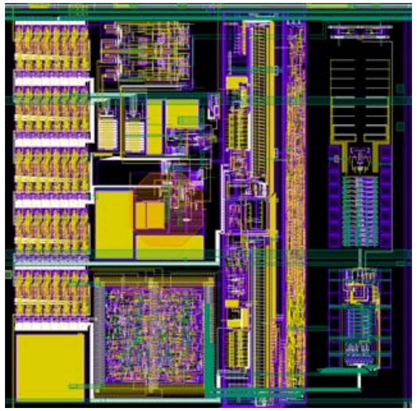
EICROC0 Test bench at IJCLab





EICROC0 chip wire-bonded by BNL





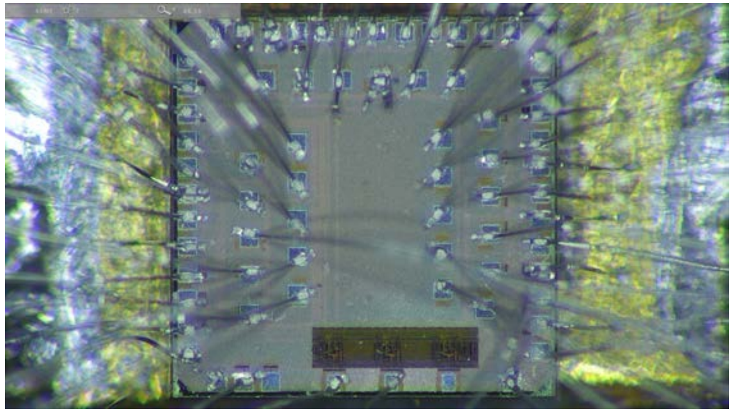
EICROC0, *1 channel implantation*

AGH, cea, Irfu, P2IO Physique des 2 Infinis et des Origines, OMEGA Microelectronics, cnrs, IJCLab Irène Joliot-Curie

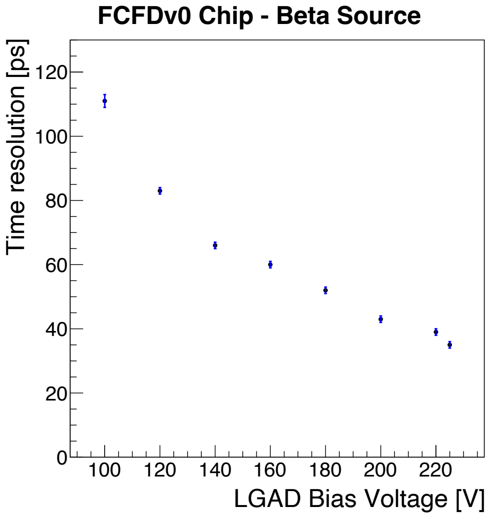
eRD112: Frontend ASIC R&D

FCFDv0 (Fermilab CFD v0)

- Adapt the Constant Fraction Discriminator (CFD) principle in a pixel when a CFD is paired with a TDC, one time measurement gives the final answer.
- Charge injection and beta source tests consistent with expectation. Tests with beam are planned

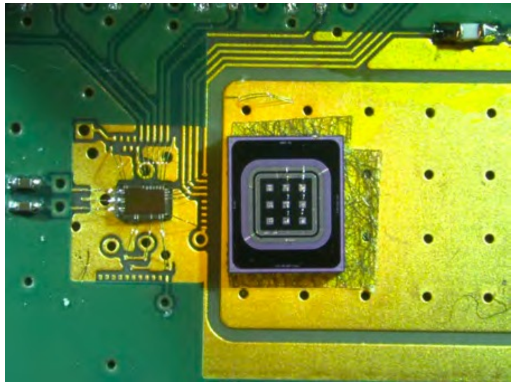


FCFD0

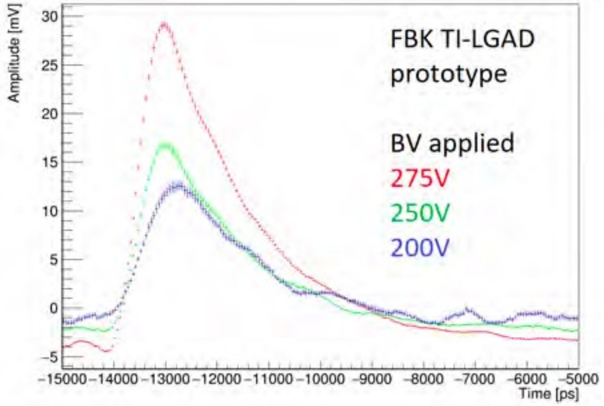


ASIC Efforts at UC Santa Cruz

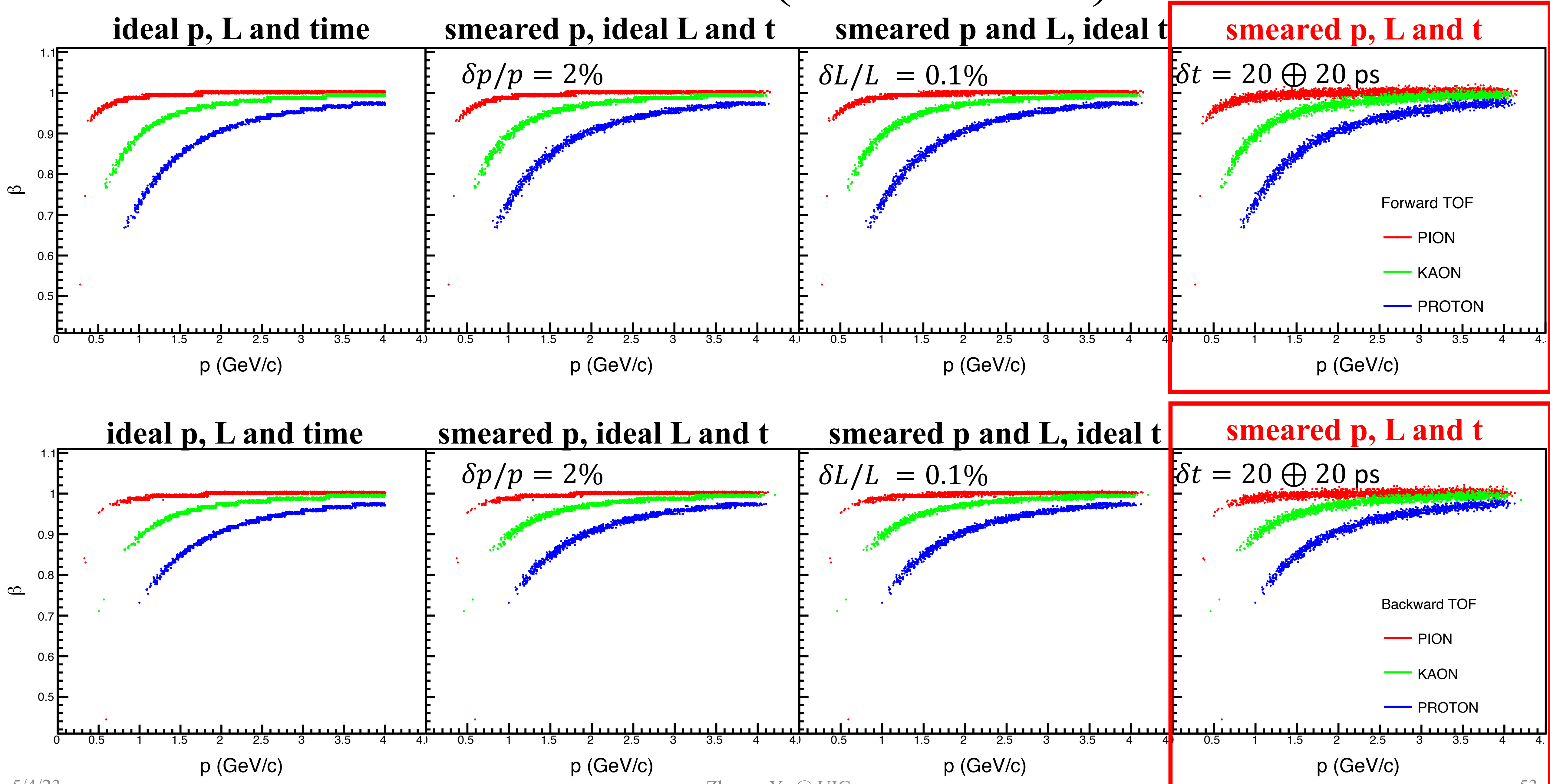
Institution		Technology	Output	# of Chan	Funding	Specific Goals	Status
INFN Torino	FAST	110 nm CMOS	Discrim. & TDC	20	INFN	Large Capacitance TDC	Testing
NALU Scientific	HPSoC	65 nm CMOS	Waveform	5 (Prototype) > 81 (Final)	DoE SBIR	Digital back-end	Testing
Anadyne Inc	ASROC	Si-Ge BiCMOS	Discrim.	16	DoE SBIR	Low Power	Simulations, final Layout, Board design



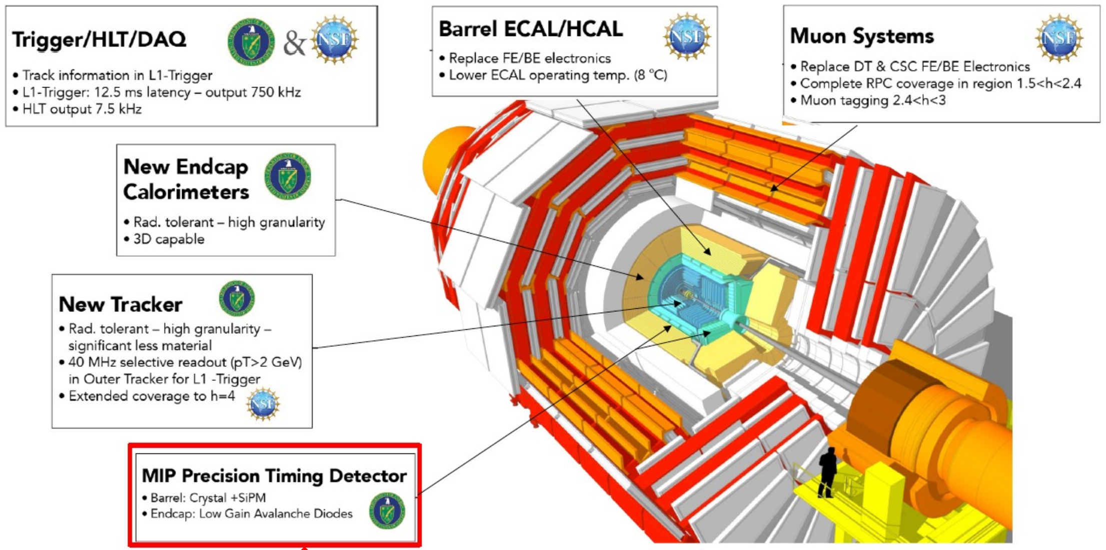
HPSoC

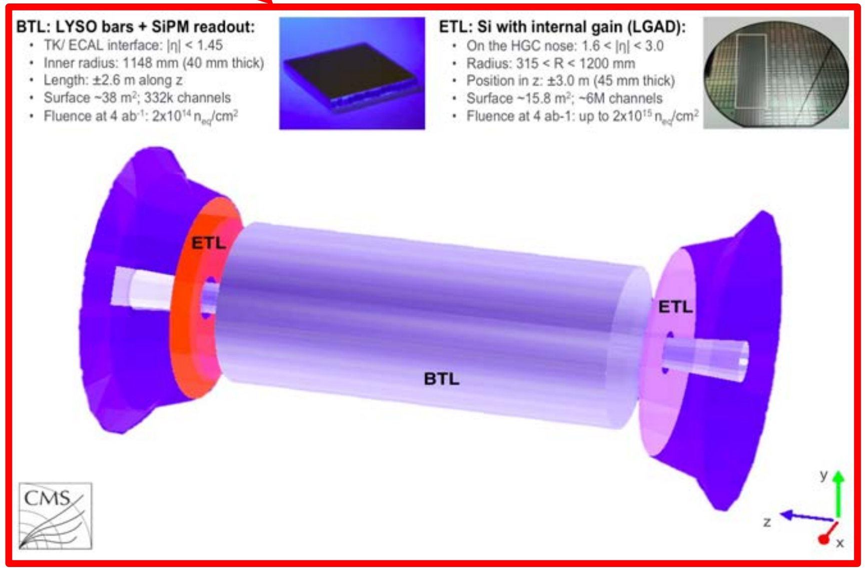


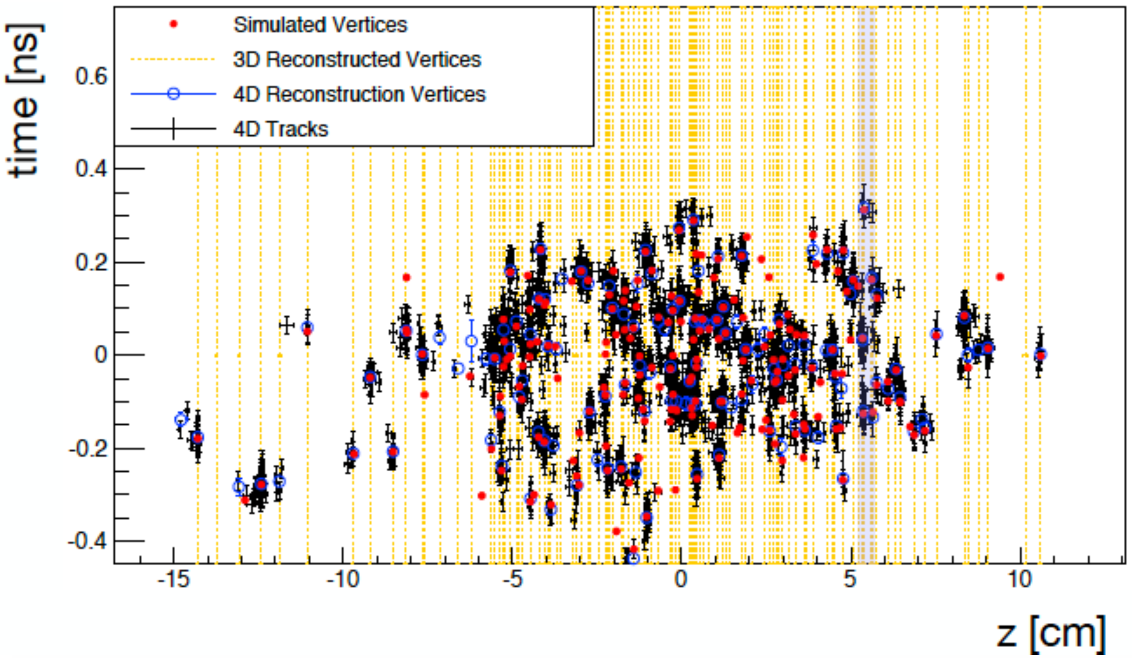
Forward and Backward TOF (eta=+/-2.25)

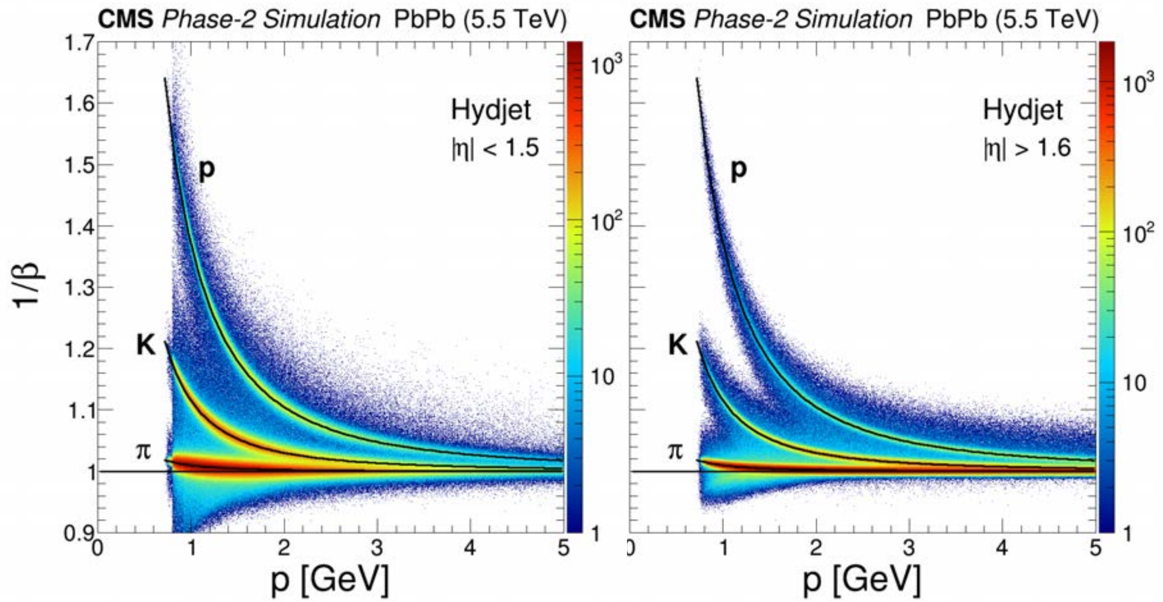


LGAD for CMS at HL-LHC

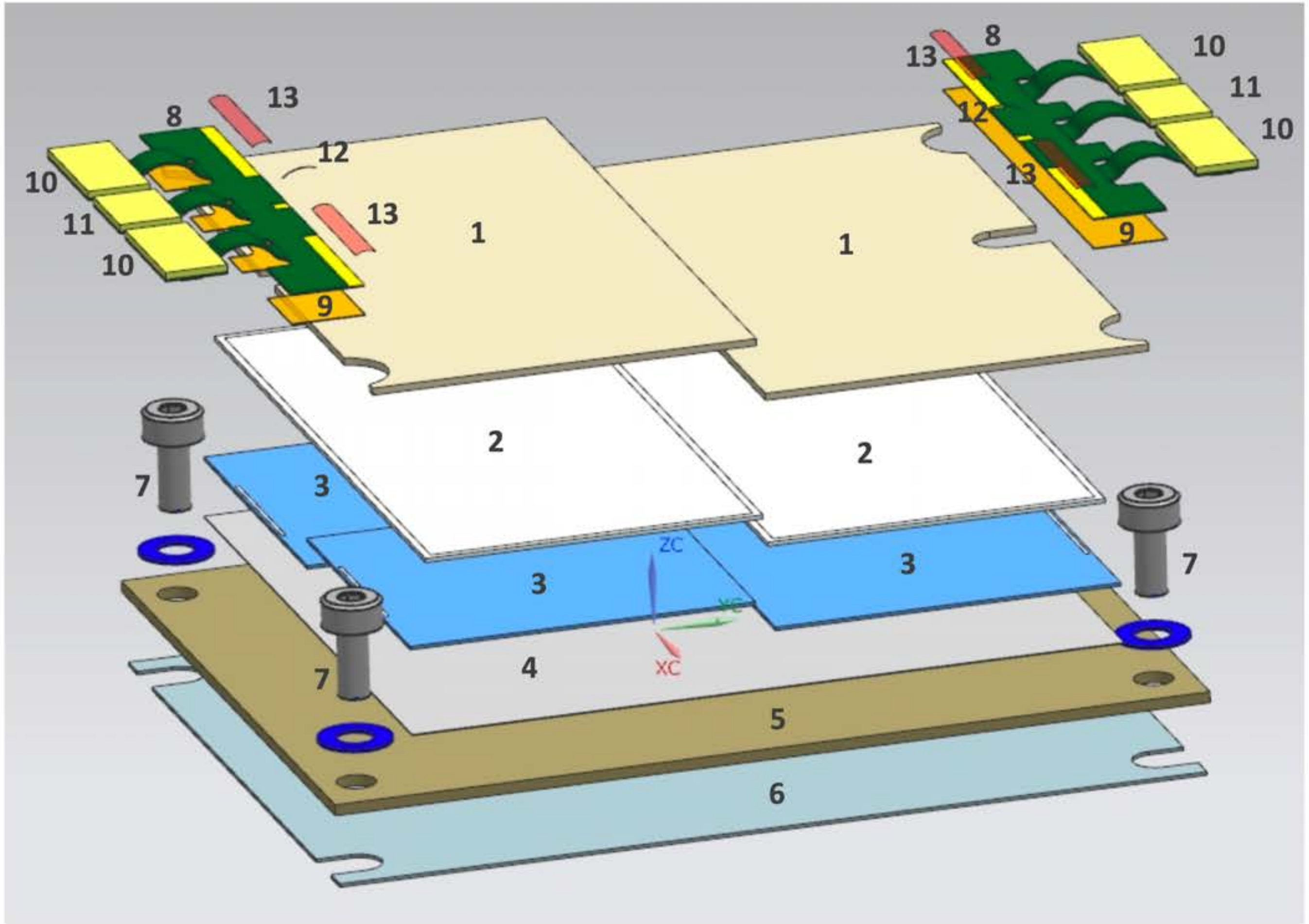








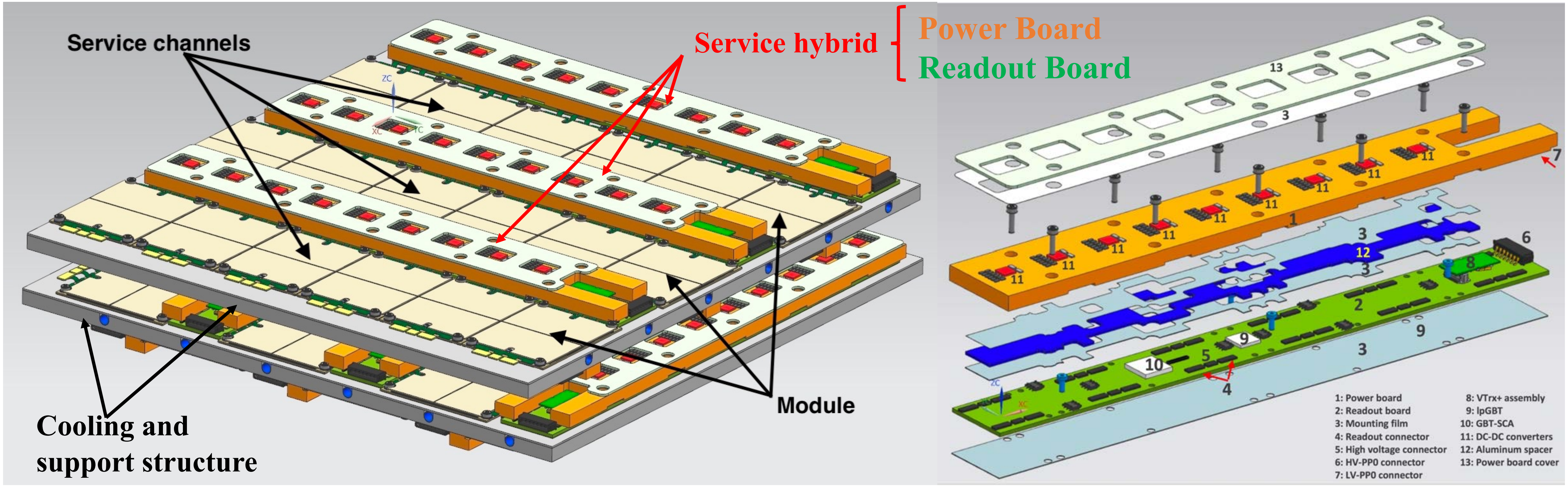
Endcap Timing Layer – Module Design



1: AlN module cover
2: LGAD sensor
3: ETL ASIC
4: Mounting film
5: AlN carrier
6: Mounting film
7: Mounting screw
8: Front-end hybrid
9: Adhesive film
10: Readout connector
11: High voltage connector
12: LGAD bias voltage wirebond
13: ETROC wirebonds

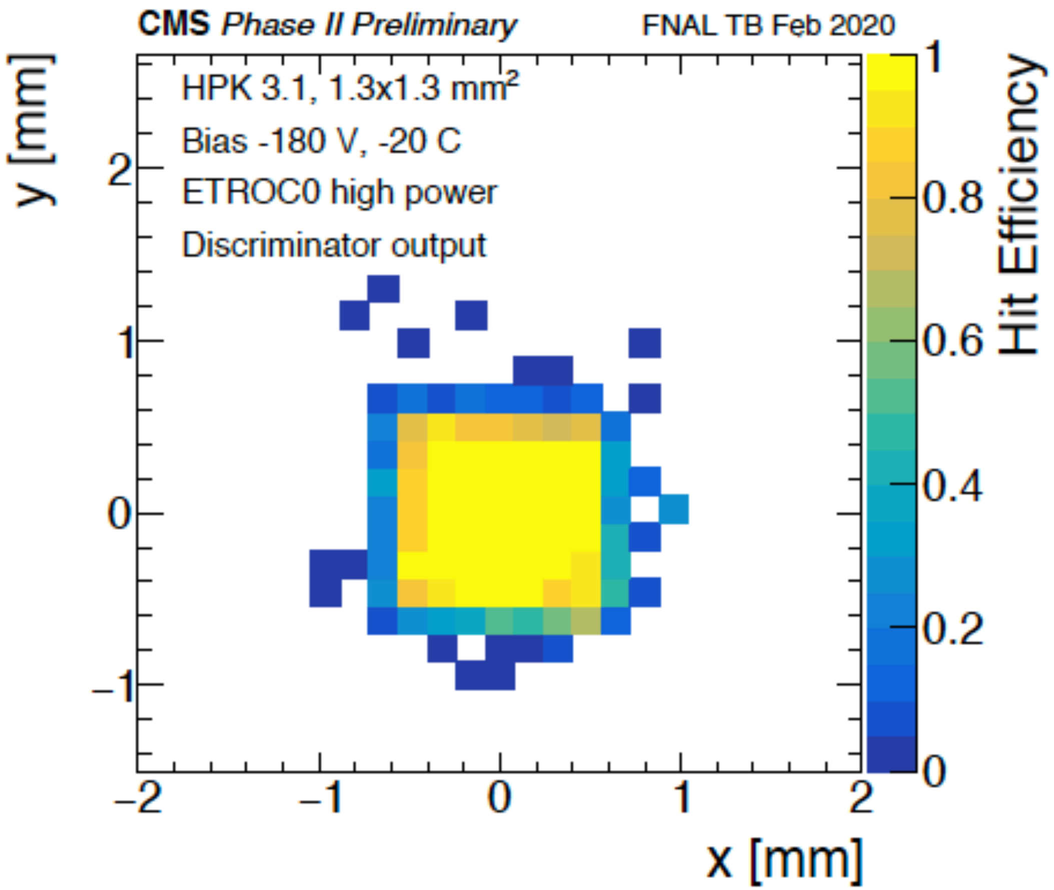
ETL consists of ~9000 modules. LGAD sensors and ETROC chips are bump-bonded together and attached to AlN base plate with thermal adhesive film to make one module. Electric connection between flexible circuits and LGAD/ETROCs are made through wire-bonding.

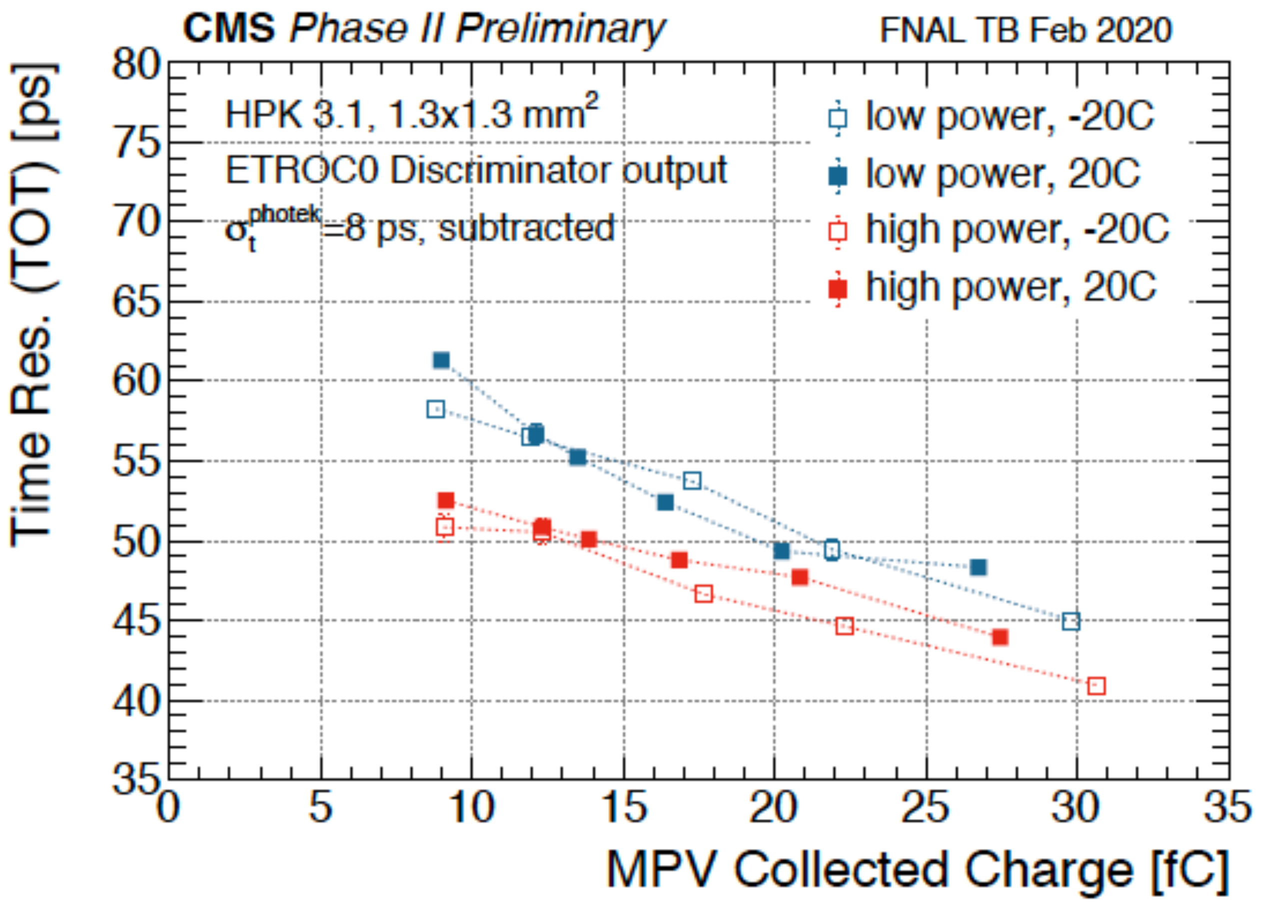
Endcap Timing Layer – Service Hybrid



- **Service Hybrid** is an assembly of two PCBs, a Power Board and a Readout Board, servicing 12 modules.
- **Power Board** distributes low voltages provided by power supplies to ETROCs, slow control adapter chip, lpGBT, and VTRx+. The voltages are regulated by radiation hard and B-tolerant DC-DC converters on the power board.
- **Readout Board** distributes bias voltages to LGAD sensors, receives and distributes fast control signals and slow controls to ETROCs, and route data and monitoring information from ETROCs to backend DAQ.

ETROC1+LGAD – Test Beam Results





- **For pre-radiated sensor and ETROC0 operating above 20 fC, ~100% efficiency across the sensor area and time resolution of 40-50 ps have been achieved.**
- **Irradiation effects will be reduced by operating at lower temp (-30 ^{o}C) and mitigated by increasing the sensor bias voltage and by the high power mode of ETROC. Time resolution will be maintained below 50 ps.**