AC-LGAD ToF (and 4D Tracker)

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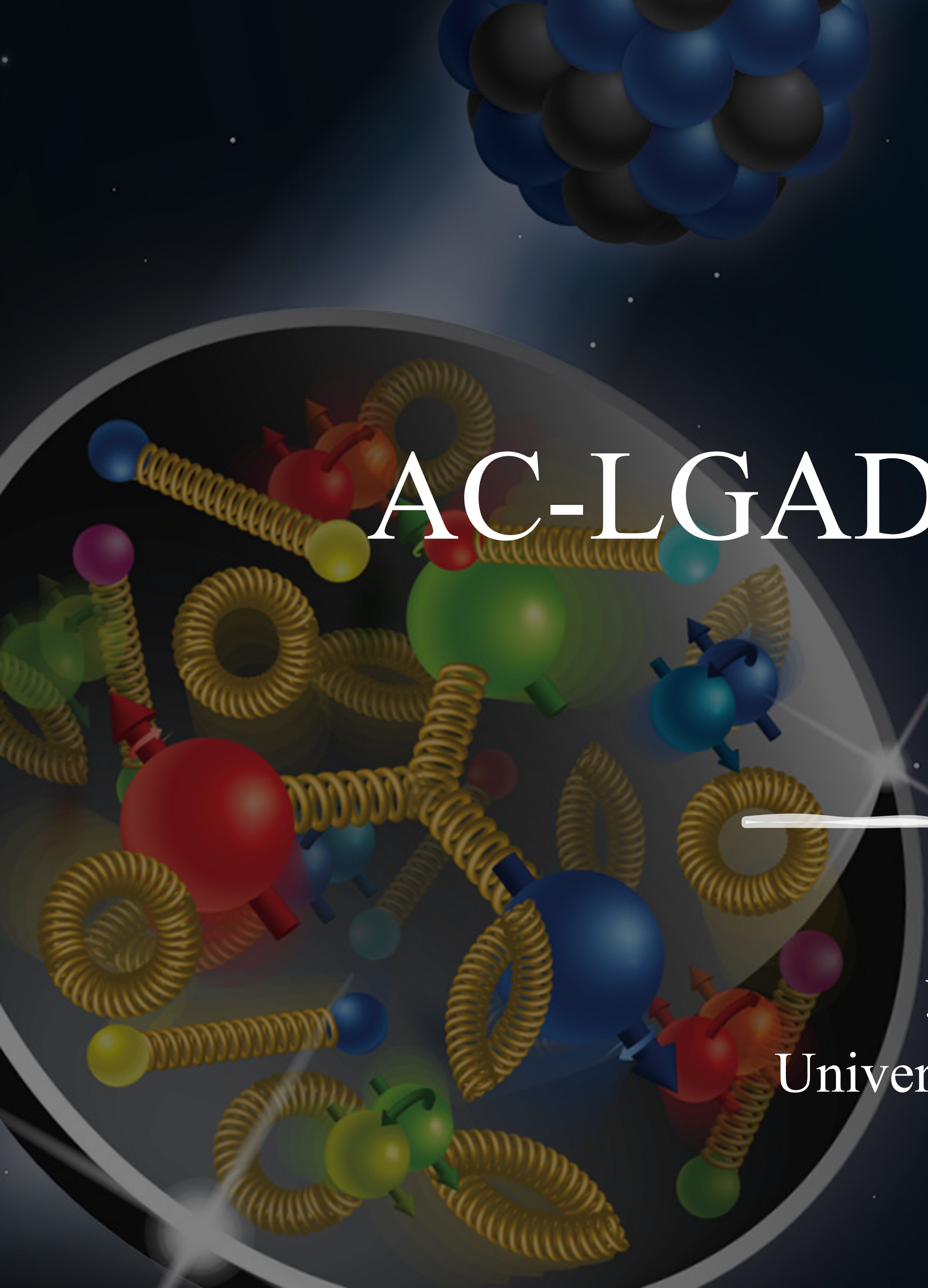
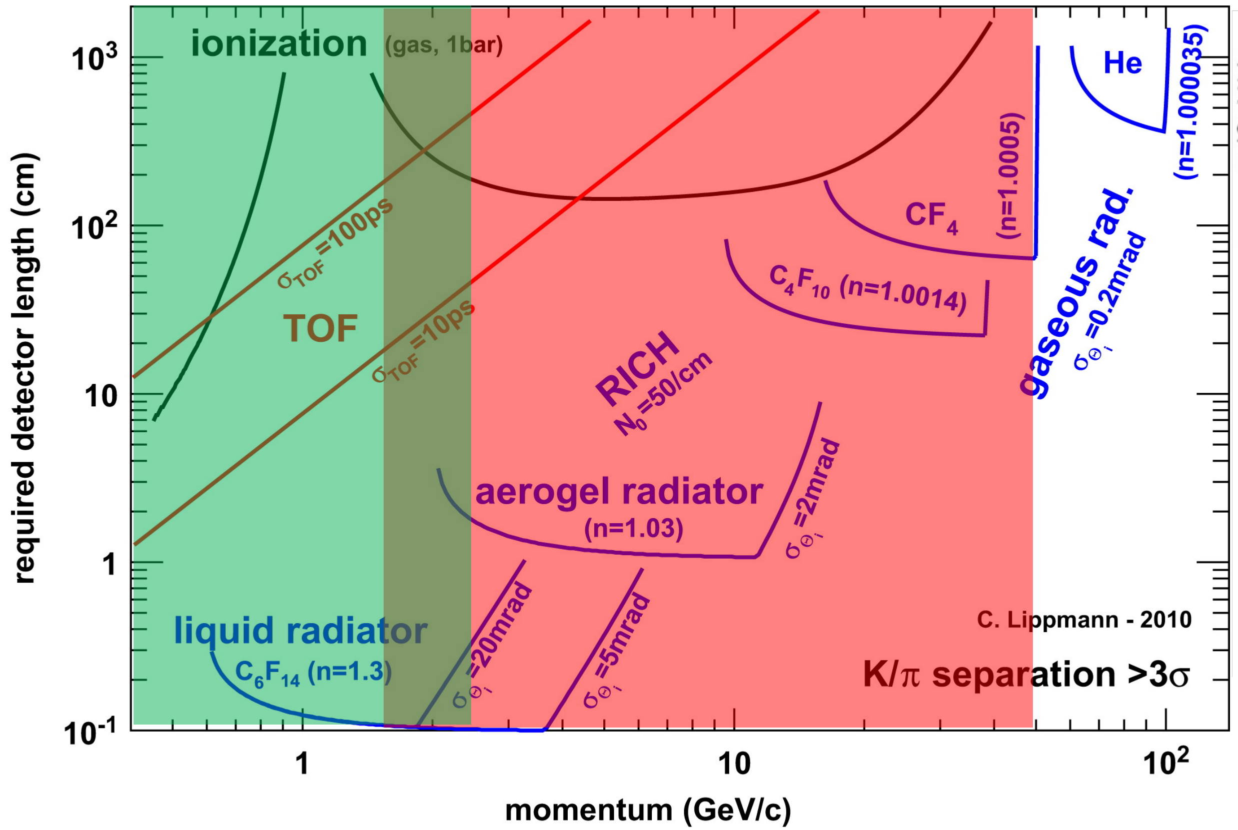
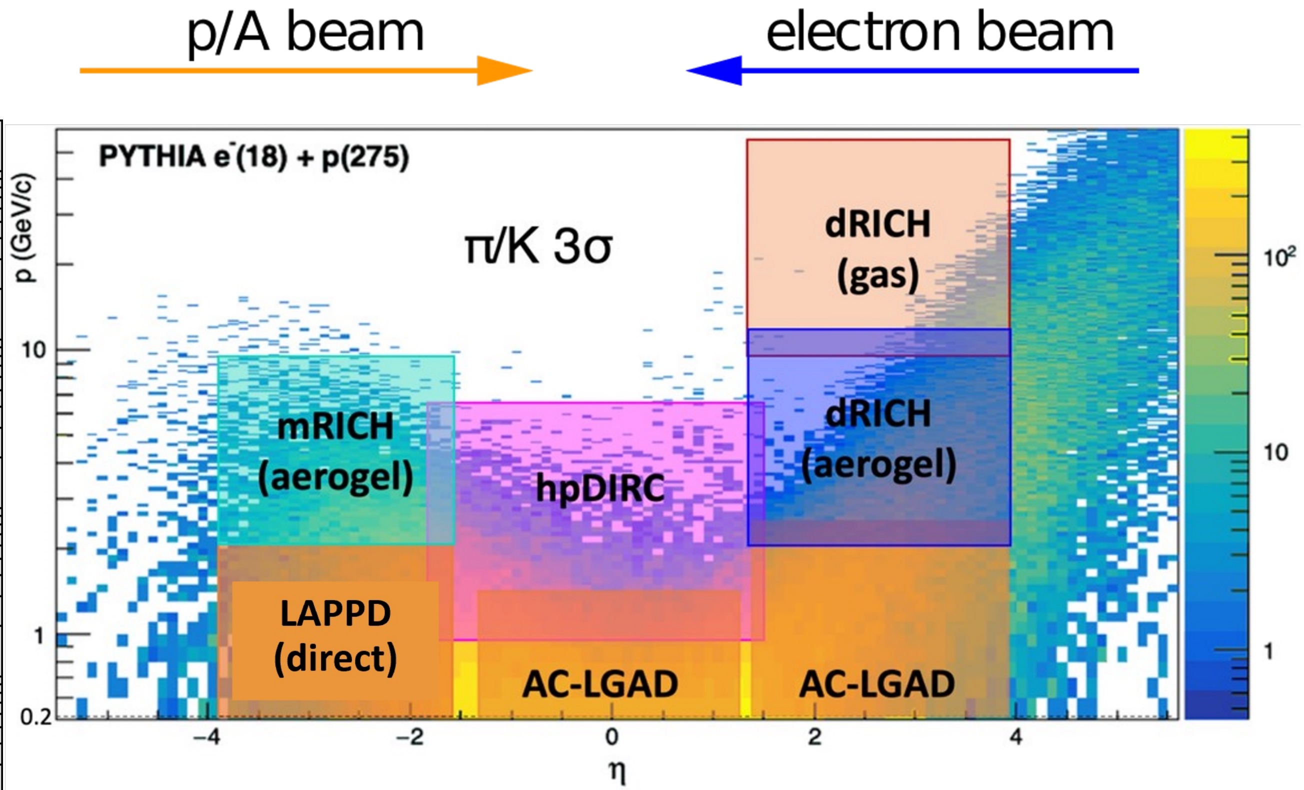


Electron-Ion Collider

BROOKHAVEN NATIONAL LABORATORY
Jefferson Lab
U.S. DEPARTMENT OF ENERGY | Office of Science

Particle Identification for EIC





PID is crucial for EIC physics programs. Use TOF and Cherenkov to cover the wide kinematic range for particle identification

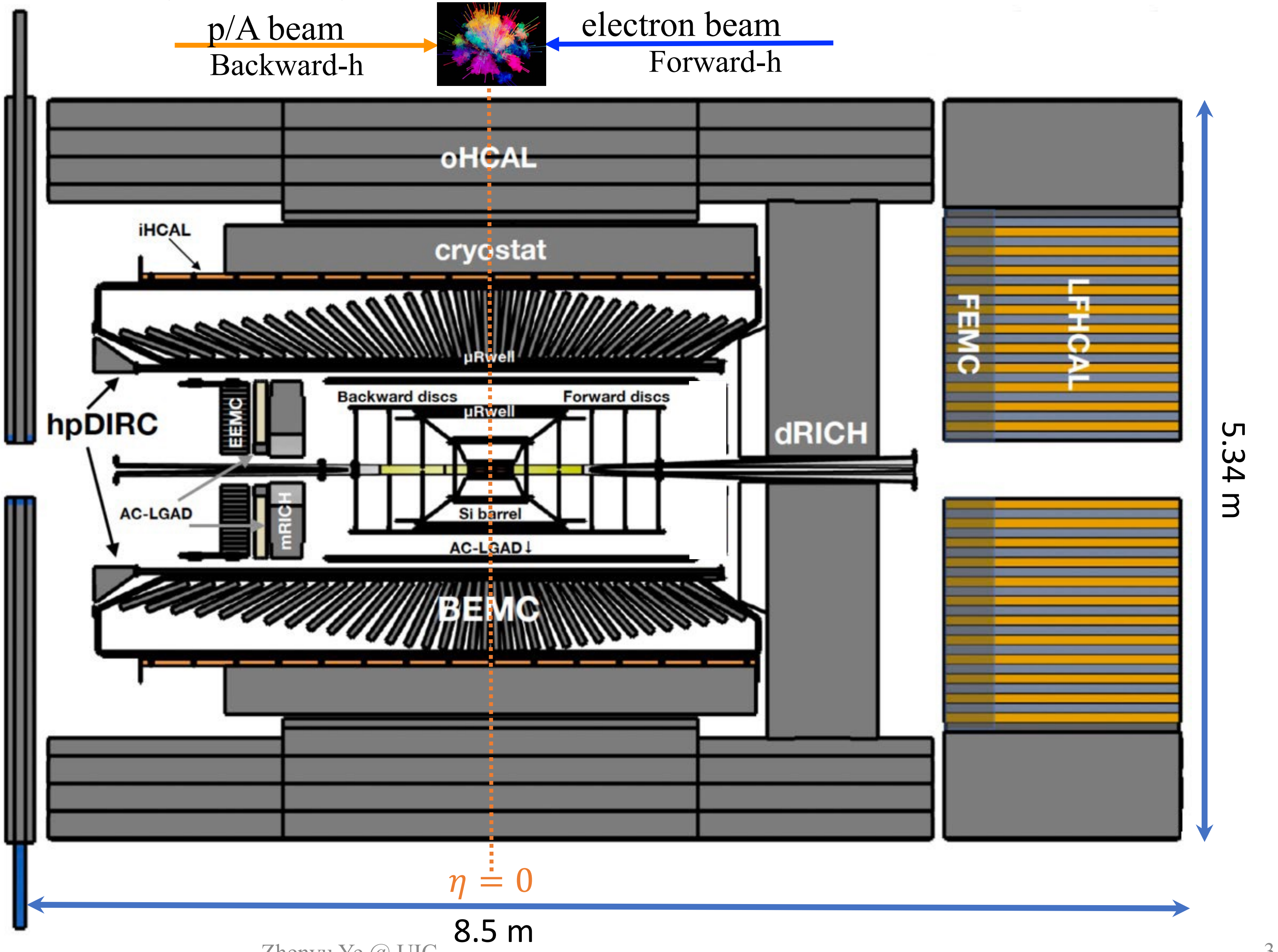
EIC Project Detector (ePIC)

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

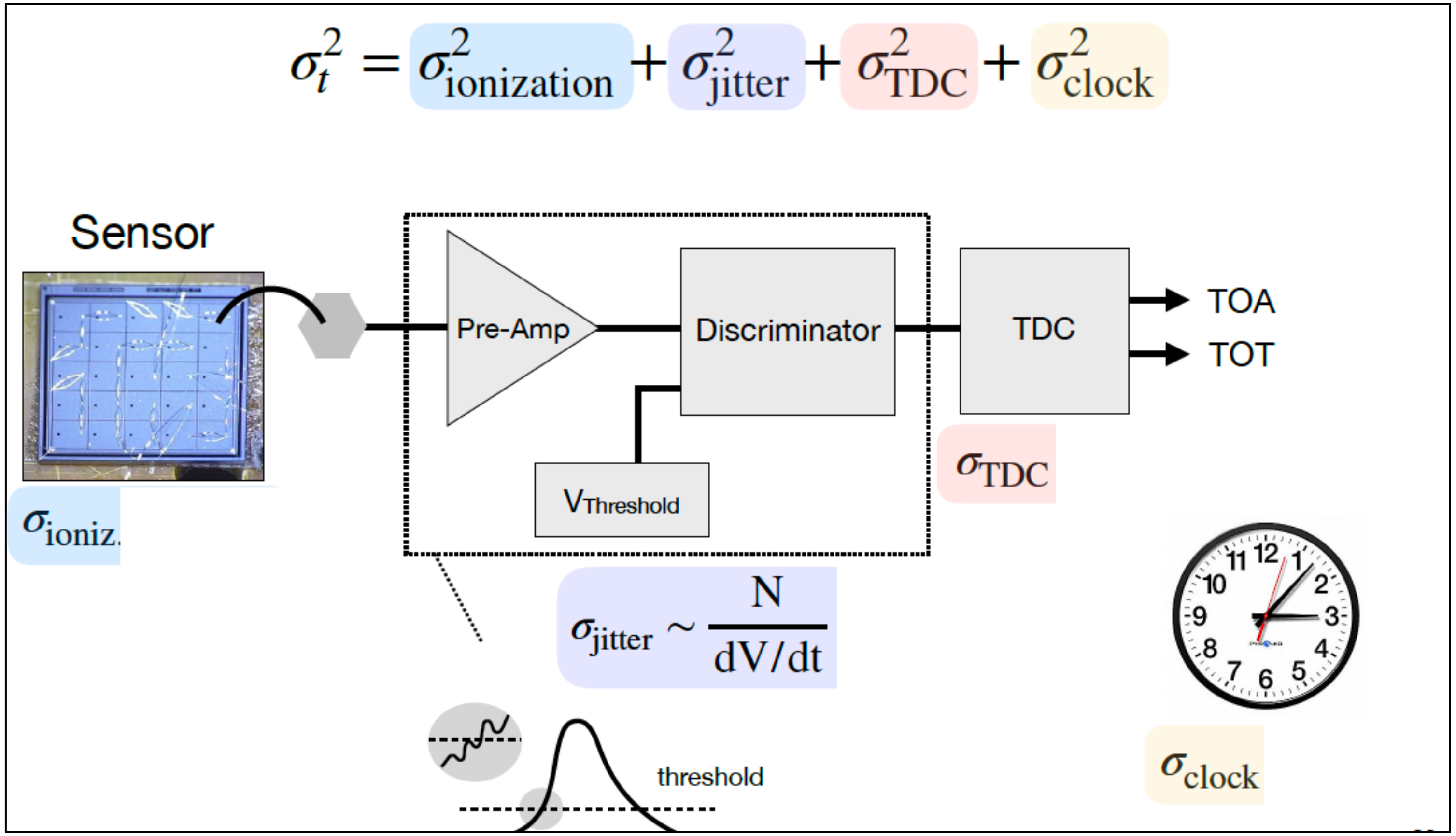
PID:
- AC-LGAD TOF (~30 ps)
- hpDIRC
- pfRICH
- dRICH

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

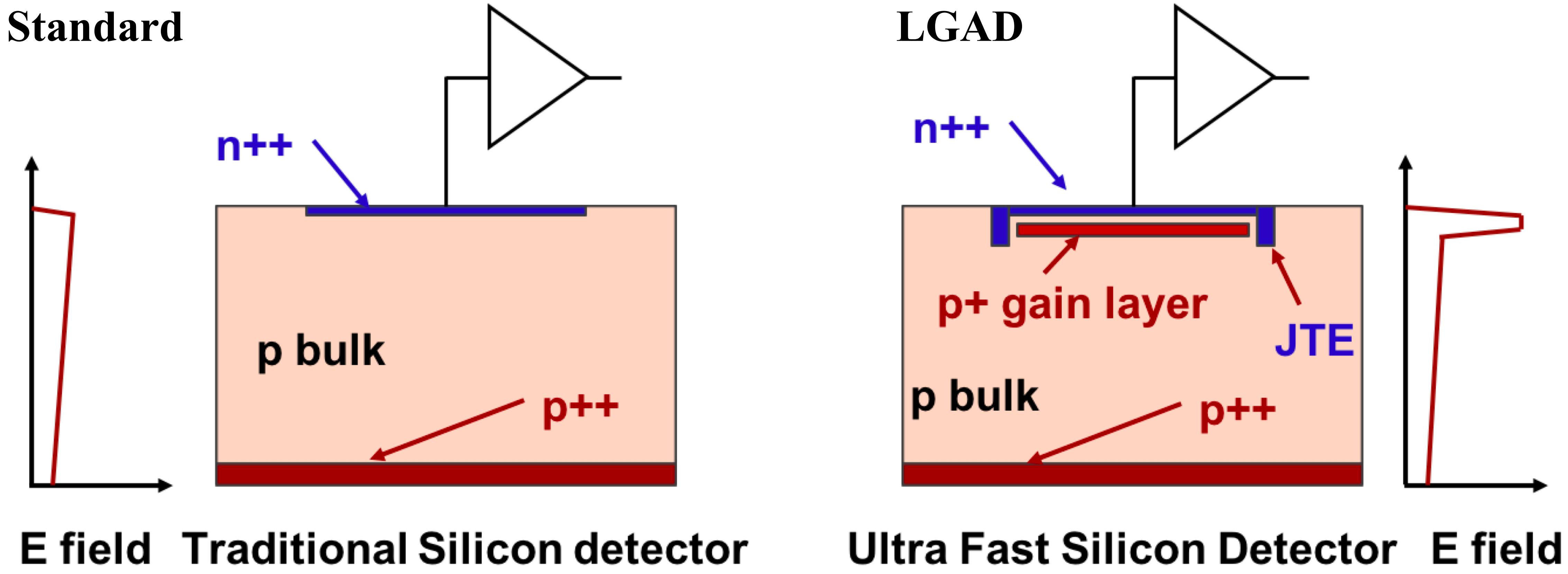


Time Resolution Contributions to TOF Detectors



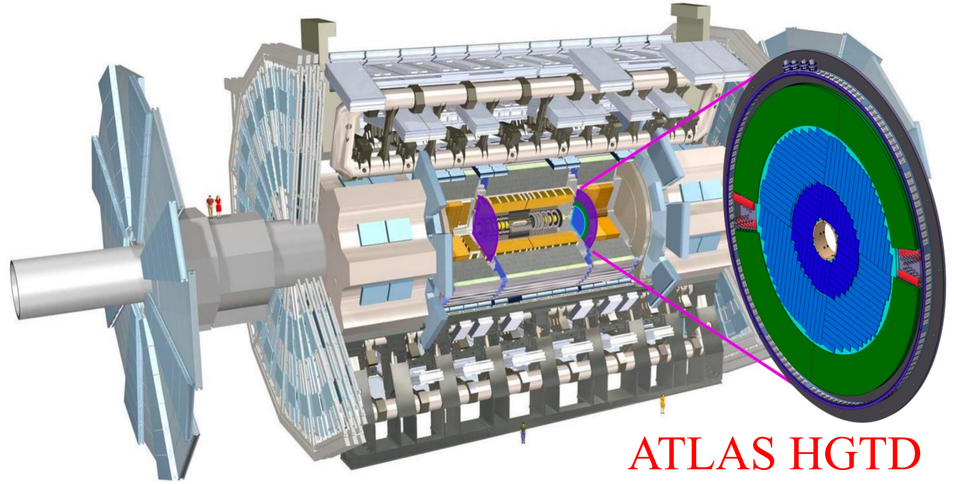
- $\sigma_{ionization}$: random variation in particle energy deposition in the sensors, determining the amplitude and the shape of the signal
- σ_{jitter}: mostly due to electronics noise and depends on the amplifier slew rate (dV/dt)
- σ_{TDC}: the effect of the TDC binning
- σ_{clock}: contribution from clock distribution

Low Gain Avalanche Diode (LGAD)

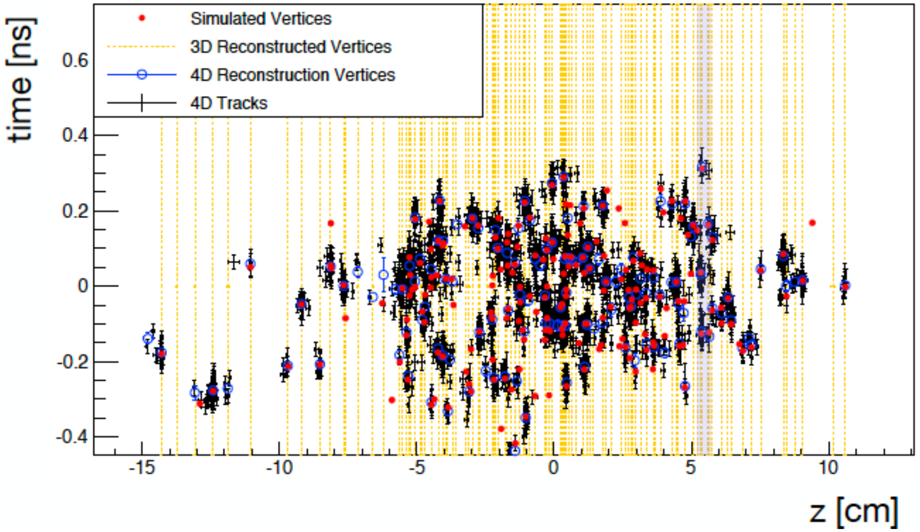


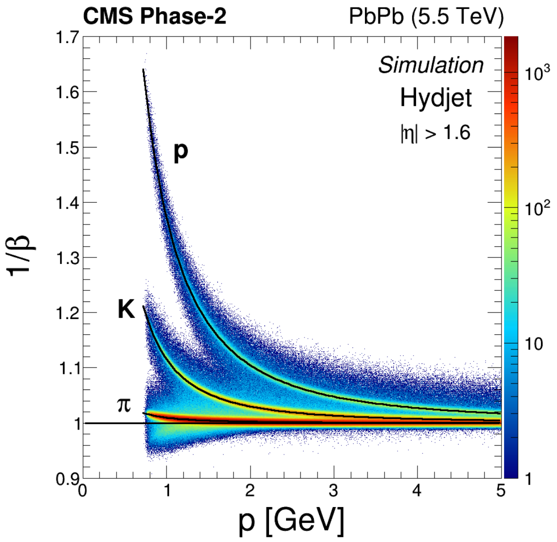
LGAD Detectors for LHC

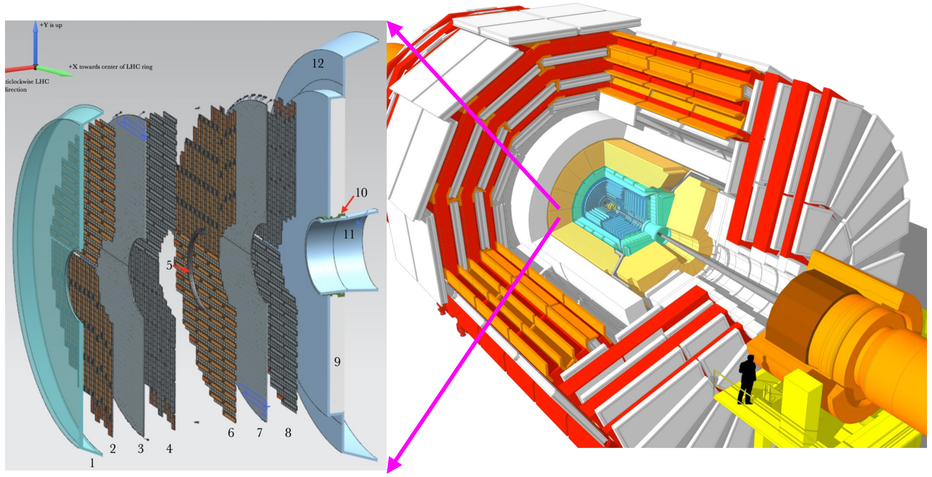
- Precise timing detectors based on DC-LGAD at ATLAS (6 m^2) and CMS (14 m^2) for HL-LHC.



ATLAS HGTD





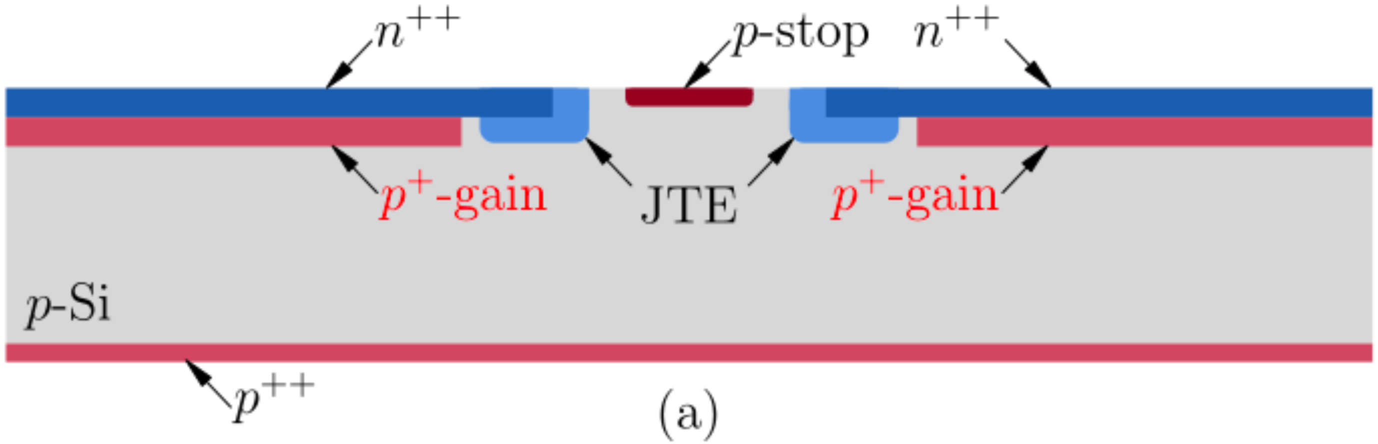


CMS ETL

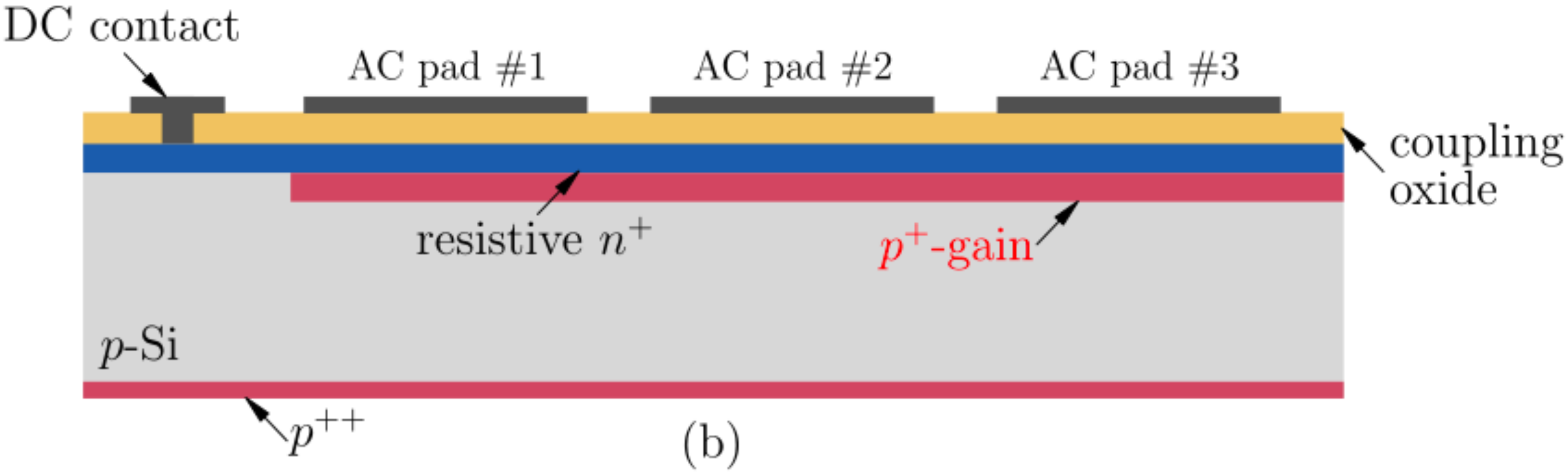
- Per-particle timing allows 4D track and vertex reconstruction to reduce pile-up contributions
  - Significant benefit to pp physics program
- Precise timing provides particle ID for low p_T hadrons
  - New opportunities in heavy ion collisions

AC-coupled LGAD

(DC-)LGAD

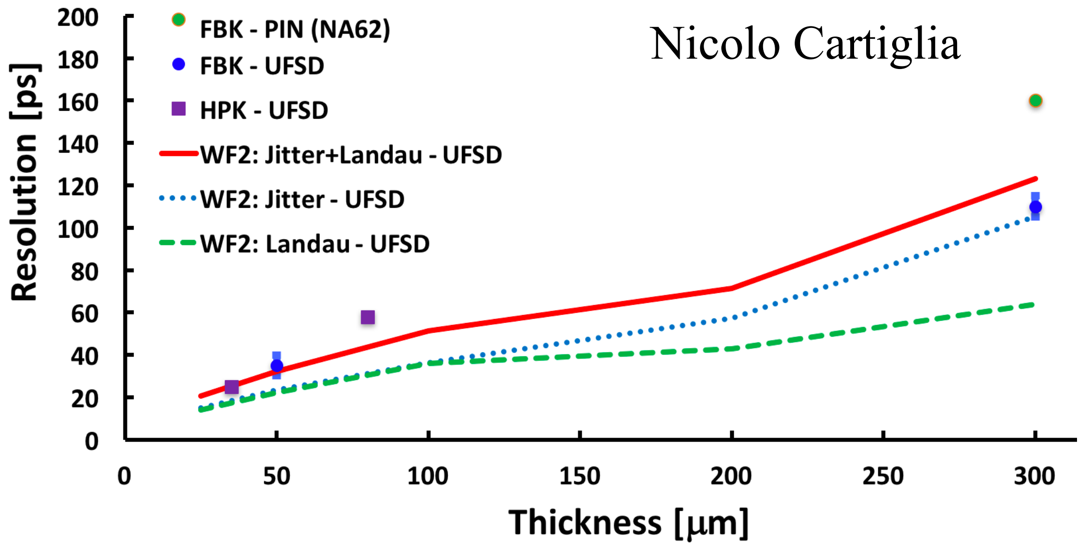


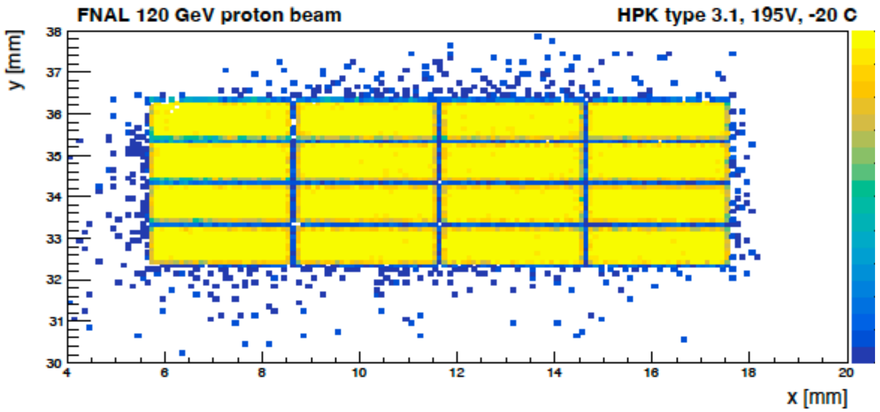
AC-LGAD



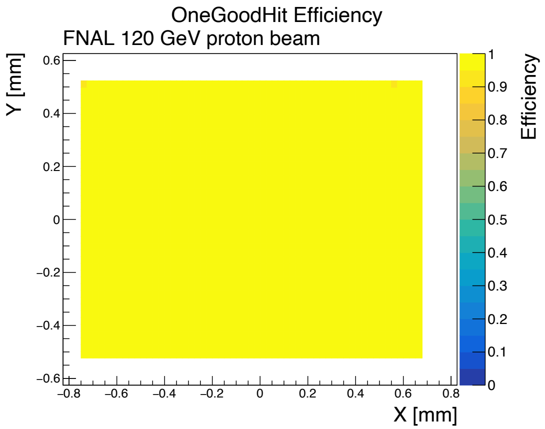
AC-LGAD for Timing and Spatial Measurements

- AC-LGAD provide not only precise timing resolution similar to DC-LGAD, but also 100% fill factor and much better spatial resolution through charge sharing than DC-LGAD.
- Good candidate for **4D trackers** at future high energy experiments (EIC, HL-LHC, FCC-ee/hh)

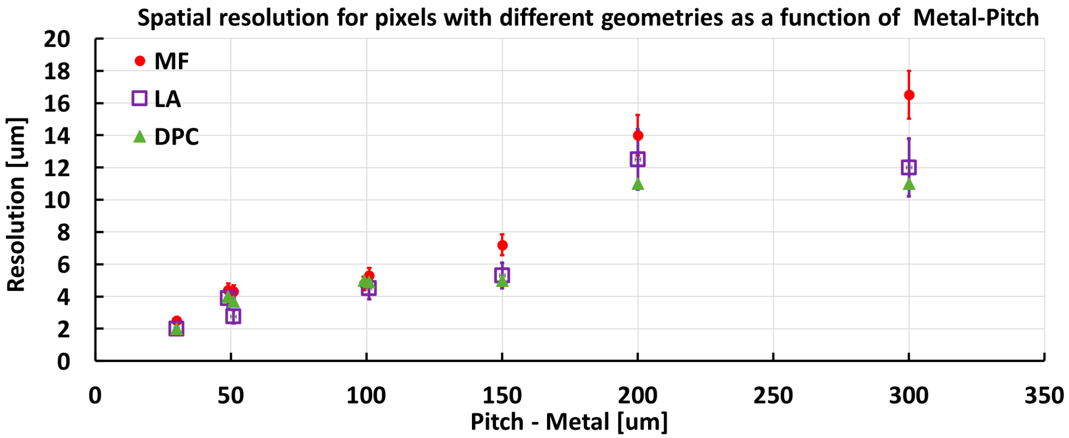




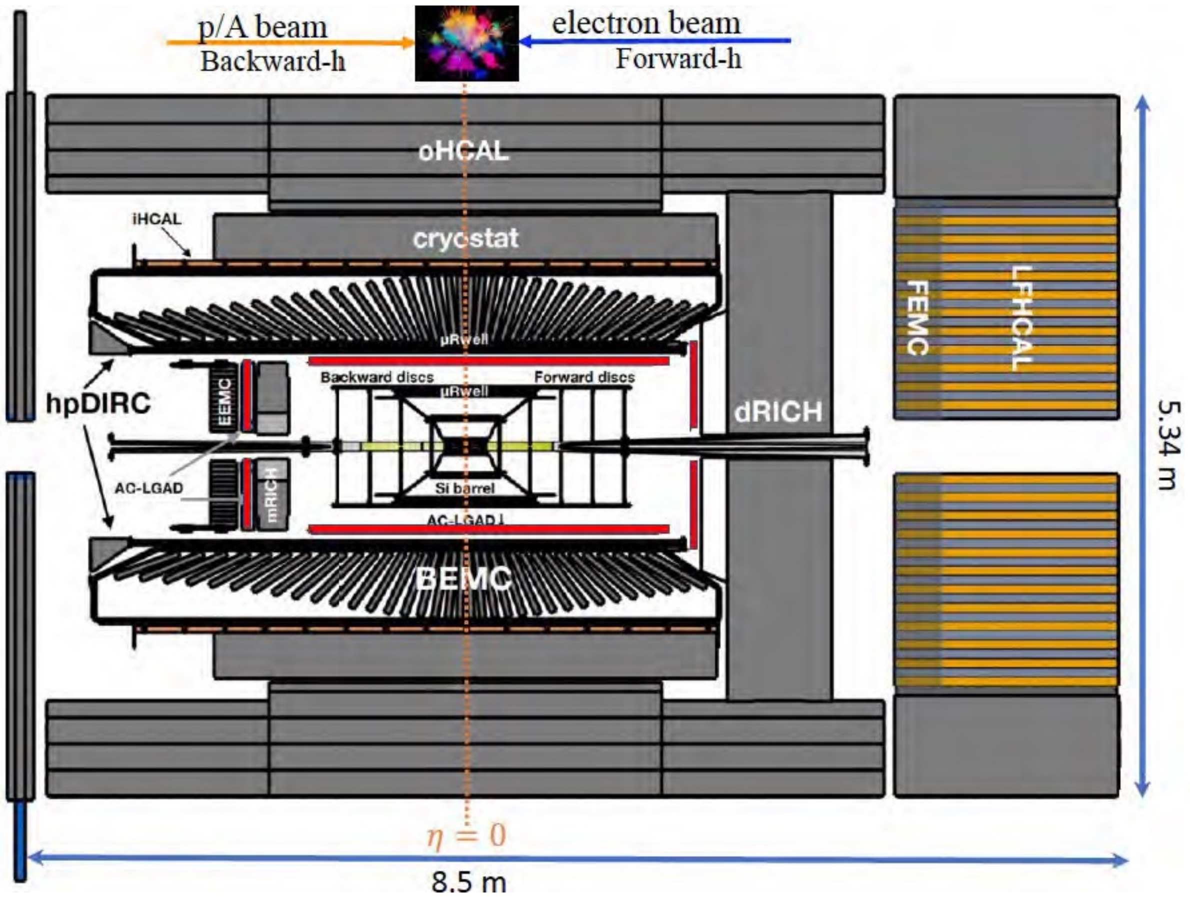
DC-LGAD

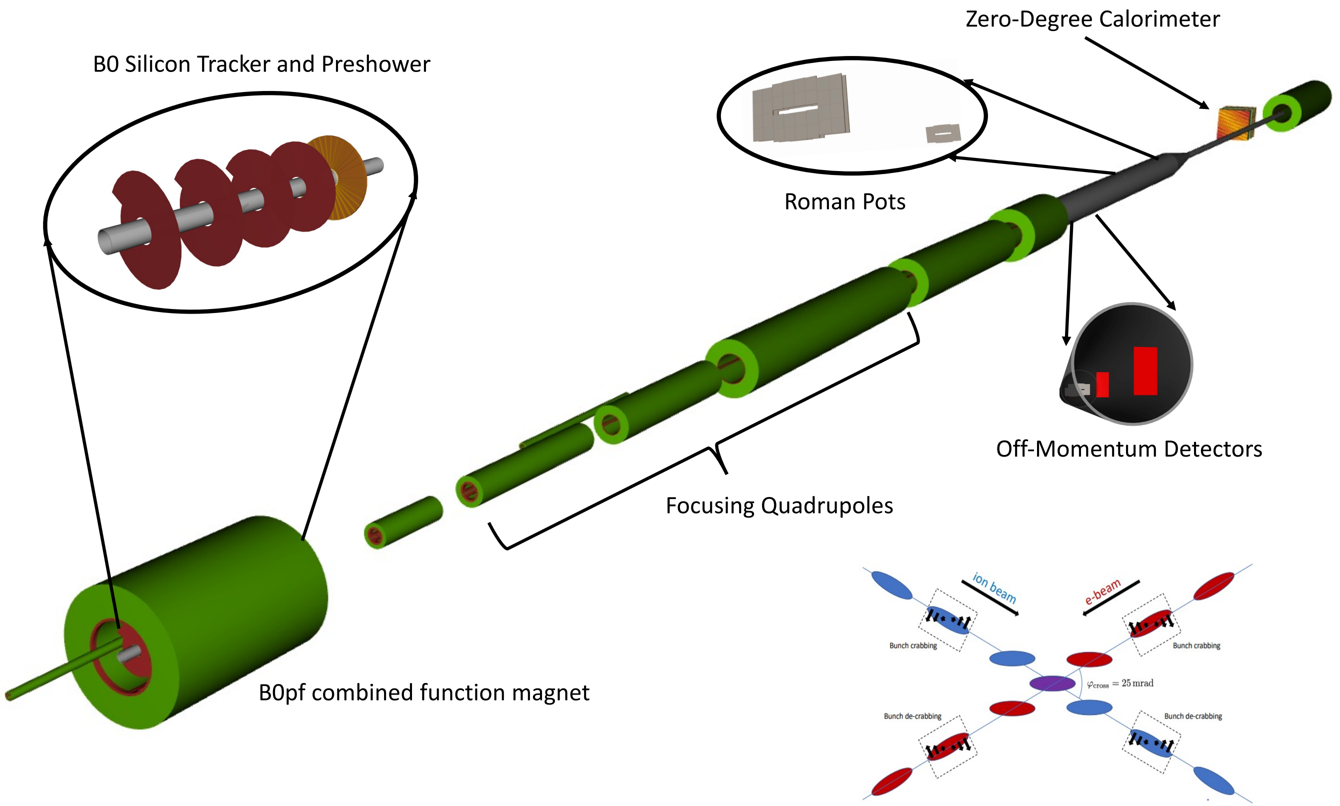


AC-LGAD



AC-LGAD Detectors for ePIC



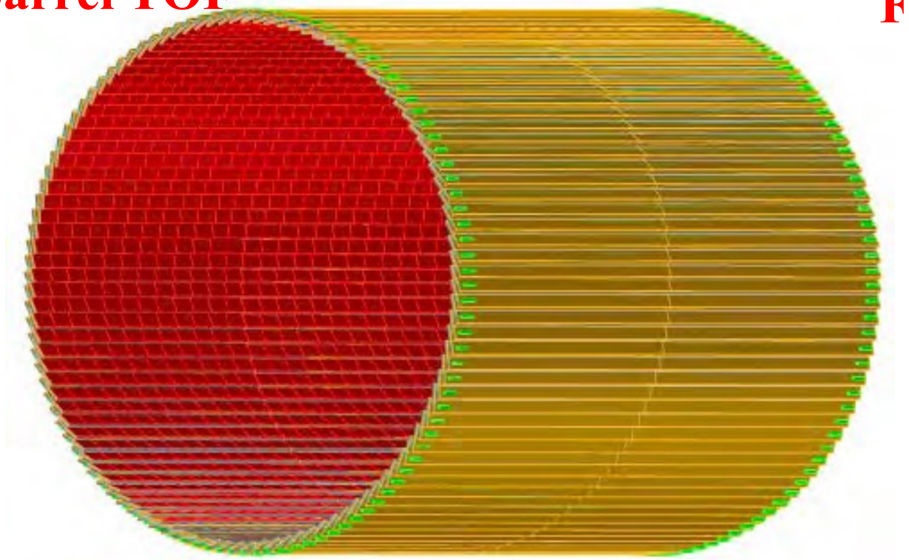


Detector	Angular accept.	p_T coverage
Backward TOF	$-3.7 < \eta < -1.7$	0.15 < p <2.8 GeV
Barrel TOF	$-1.4 < \eta < 1.4$	0.15 < p_T < 1.8 GeV
Forward TOF	$1.7 < \eta < 3.7$	0.15 < p < 2.8 GeV

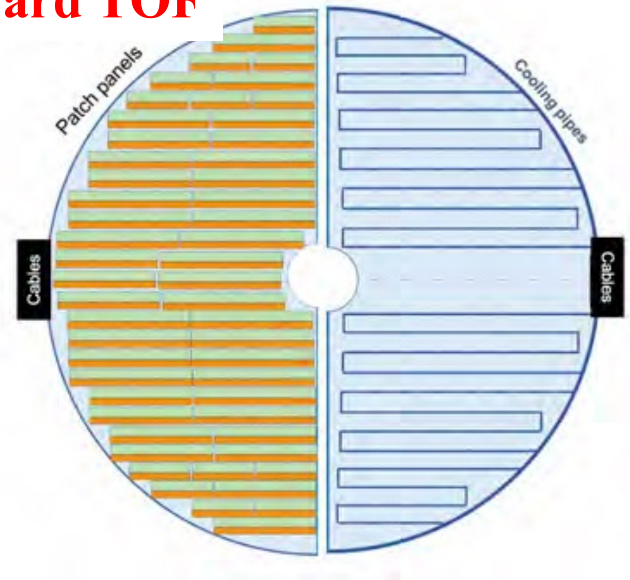
Detector	Angular accept.	p_T coverage
B0 Detector	$4.6 < \eta < 5.9$	Higher p_T
Roman Pots	$\eta > 6$	Low p_T cut-off from beam optics
Off-Momentum	$\eta > 6$	Low-rigidity from nucl. breakups

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	0.5*10	~2 M	30 ps	30 μm in $r \cdot \varphi$	0.01 X0
Forward TOF	2	0.5*0.5	~6 M	25 ps	30 μm in x and y	0.05 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.

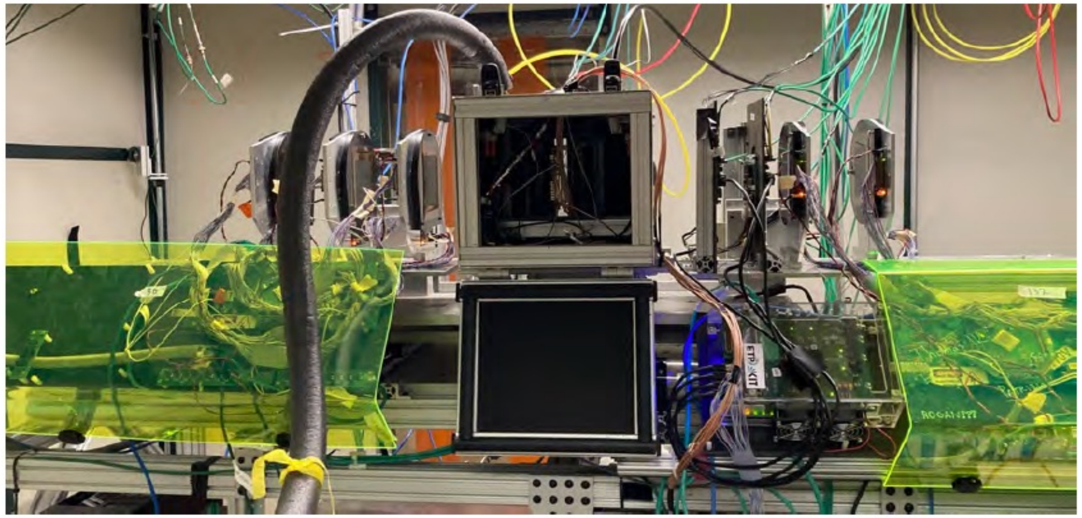
Requirements on timing and spatial resolutions and material budget are still being evaluated and are subject to change as the design matures, and we will continue to explore common designs for these detectors where possible to reduce cost and risk.

Open Questions to be addressed for CD-2/3

- **AC-LGAD sensor:**
  - Goal: large area sensors that meet timing/spatial resolution requirements with minimal # channels
  - Approach: utilize BNL IO to optimize the sensor design (pitch, electrode width, n-layer doping density, active volume thickness); engage commercial vendors to verify sensor quality and production cost/yield
- **Frontend readout ASIC:**
  - Goal: low jitter (15-20ps) and low power (~1 mW/channel), streaming readout with TDC and ADC outputs
  - Approach: custom-designed EICROC and FCFD, ASICs from 3rd party institutions
- **Sensor/ASIC integration:**
  - Goal: reliable and cost-effective way to establish connections between AC-LGAD sensor and frontend ASIC
  - Approach: bump-bonding, wire-bonding, interposer
- **Flex and frontend electronics:**
  - Goal: low jitter clock to frontend ASICs (<5 ps), low X_0 flexible PCB to route power/signal to sensor/ASIC
  - Approach: design a precise clock distribution system in concert with EPIC DAQ group, design and prototype flexible PCB that meet the requirements; work with EPIC DAQ to define the streaming readout scheme
- **Mechanical structure with cooling:**
  - Goal: light-weight structure with cooling that meet the material budget, thermal and mechanical requirements
  - Approach: finite element analysis and prototyping with carbon-fiber composite and PEEK materials

eRD112: AC-LGAD Sensor R&D

arXiv:2211.09698



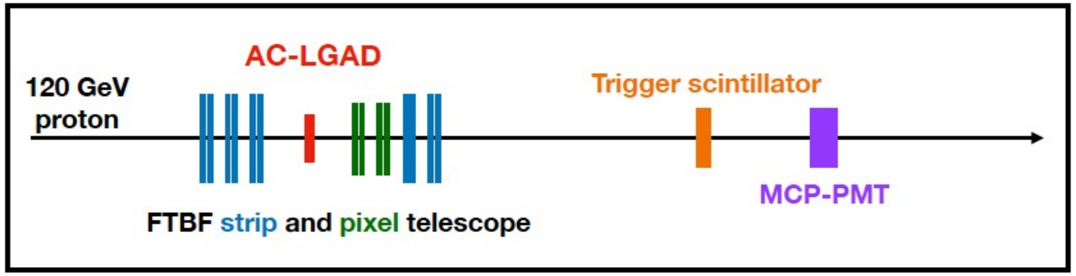


Figure 7: Picture (top) and diagram (bottom) of the FTBF silicon telescope and reference instruments used to characterize AC-LGAD performance. The telescope comprises five pairs of orthogonal strip layers and two pairs of pixel layers, for a total of up to 14 hits per track.

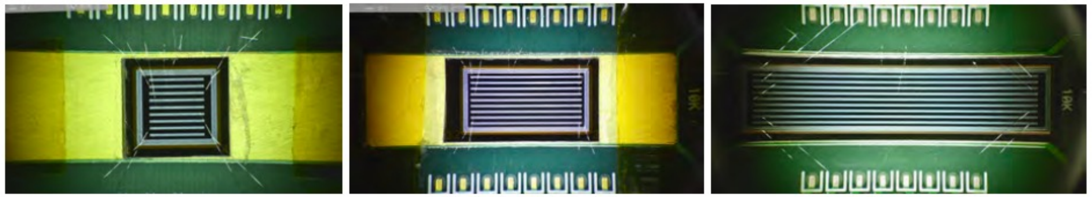
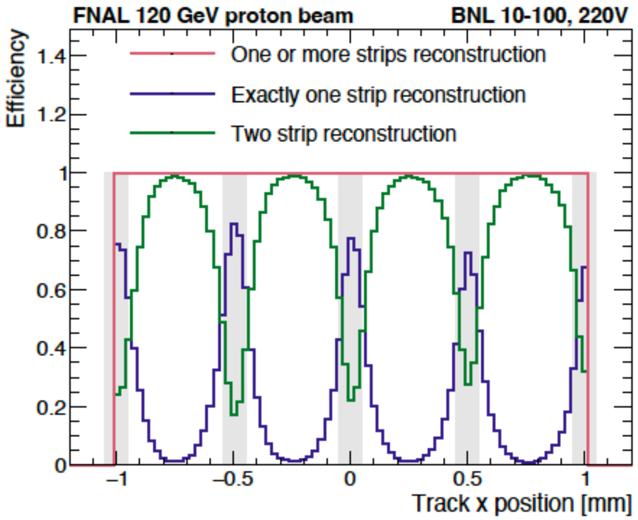
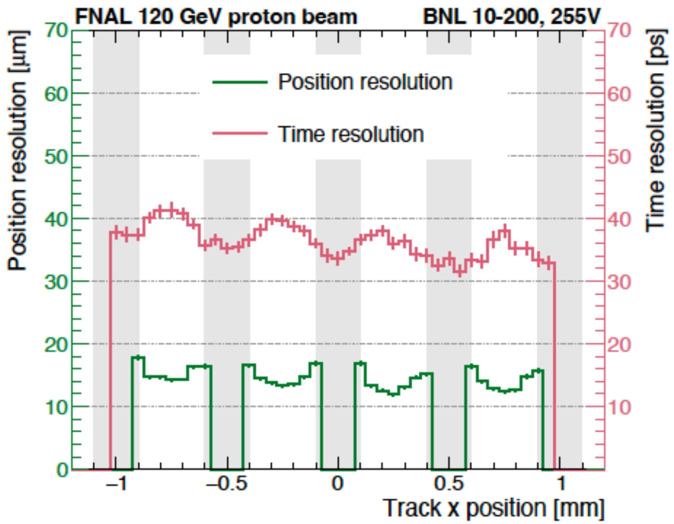


Figure 8: Three AC-LGAD strip sensors wire-bonded on Fermilab test board and tested at FTBF: BNL 5-200 (left), BNL 10-200 (middle) and BNL 25-200 (right). See text for details.



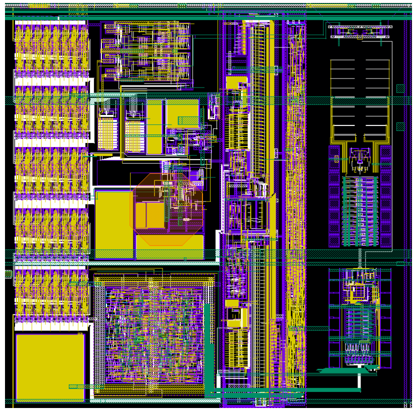


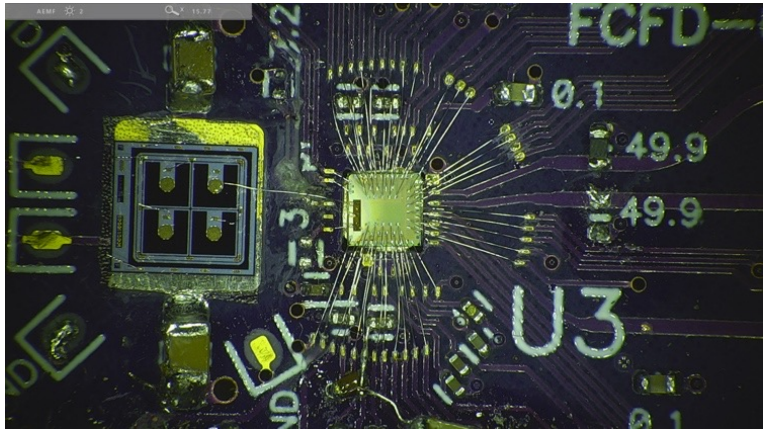
Production of medium/large area sensors by BNL IO and HPK with different doping concentration, pitch and gap sizes and Si thickness to optimize performance.

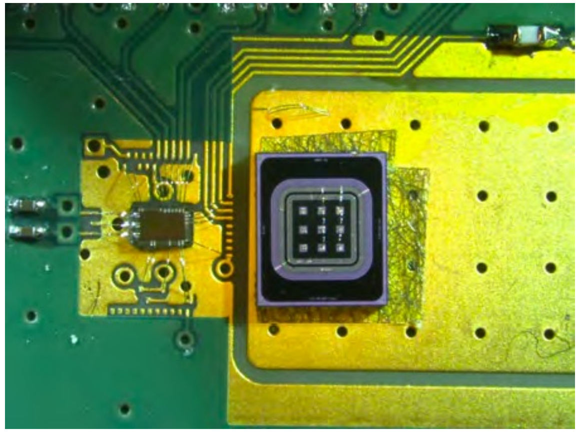
- 1st BNL (06/2021-11/2021): 5-25 mm strips with 500 μm pitch, 100-300 μm electrode width, 50 μm active Si
- 2nd BNL (06/2022-11/2022): 5-25 mm strips with 500-700 μm pitch, 50-100 um electrode width, 20-50 μm Si
- 3rd BNL (08/2022-12/2022): pixels with 500-700 μm pitch, various electrode shapes, 20-50 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 gain

eRD109: Frontend ASIC R&D

- **R&D Goals**
  - 15-20 ps jitter with minimal (1 mW/ch) power consumption, match AC LGAD sensors for ePIC
- **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







EICROC by Omega/IJCLab/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

ASICs by SCIPP

Developer	ASIC	Technology
INFN Torino	FAST	110 nm CMOS
NALU Scientific	HPSoC	65 nm CMOS
Anadyne Inc	ASROC	Si-Ge BiCMOS

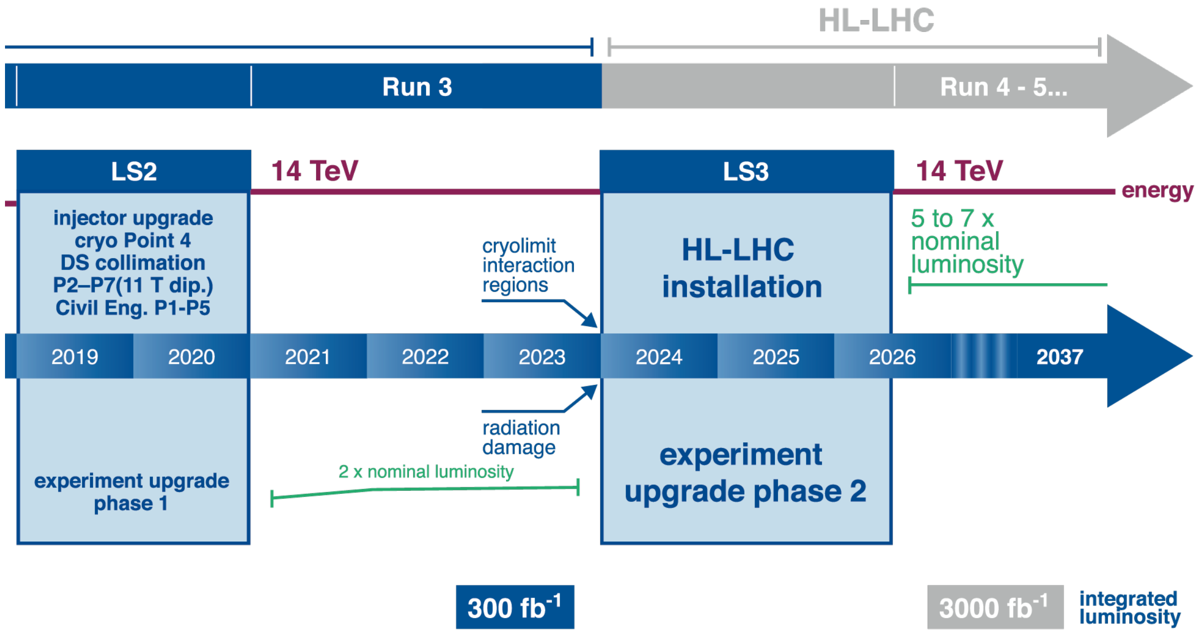
Summary

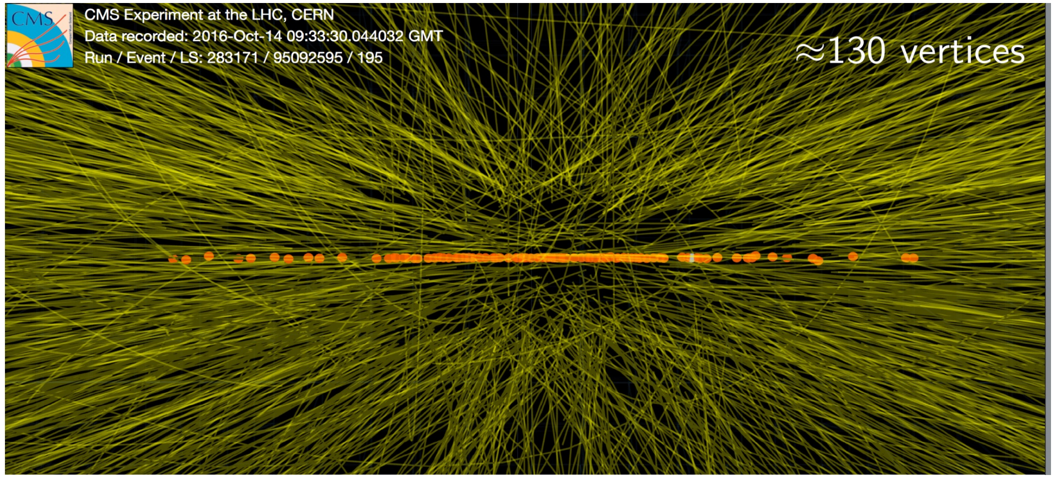
- **AC-LGAD** is a very promising candidate for **4D trackers** at future high energy experiments.

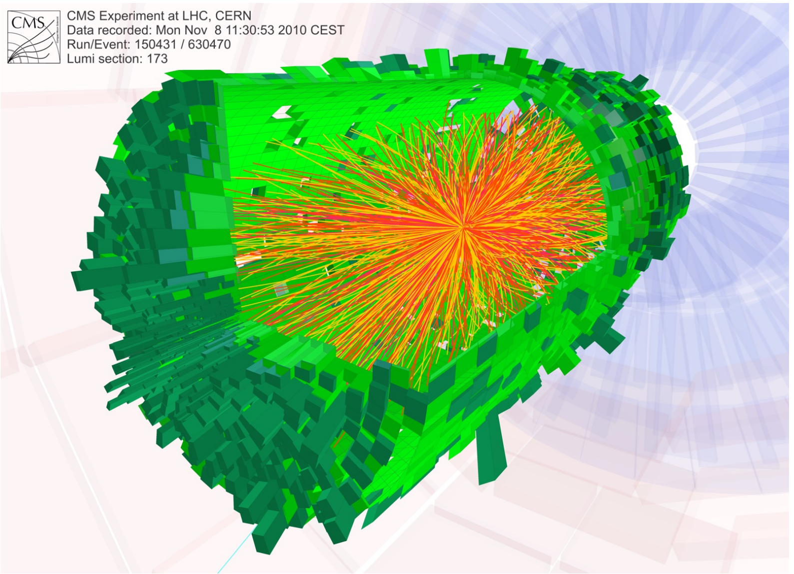
- The first large-scale application of AC-LGAD will be **ePIC TOF and Far-Forward detectors**, supported by a large and active community both domestically and internationally.
  - **USA**: Brookhaven National Laboratory, Fermi National Accelerator Laboratory, Los Alamos National Laboratory, Oak Ridge National Laboratory, Ohio State Univ., Purdue Univ., Rice Univ., Univ. of California Santa Cruz, Univ. of Illinois at Chicago
  - **Japan**: Hiroshima University, RIKEN, University of Tokyo
  - **India**: IIT Mandi, National Institute of Science Education and Research
  - **Taiwan**: National Central Univ., National Cheng Kung Univ., National Taiwan Univ.
  - **China**: South China Normal Univ., Univ. of Science and Technology of China
  - …

- Work on-going to develop and optimize the key components to meet the ePIC requirements. Great potential for further development and alternative designs for the **2nd EIC detector** and other facilities, e.g., HL-LHC, FCC-ee/hh.

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.**