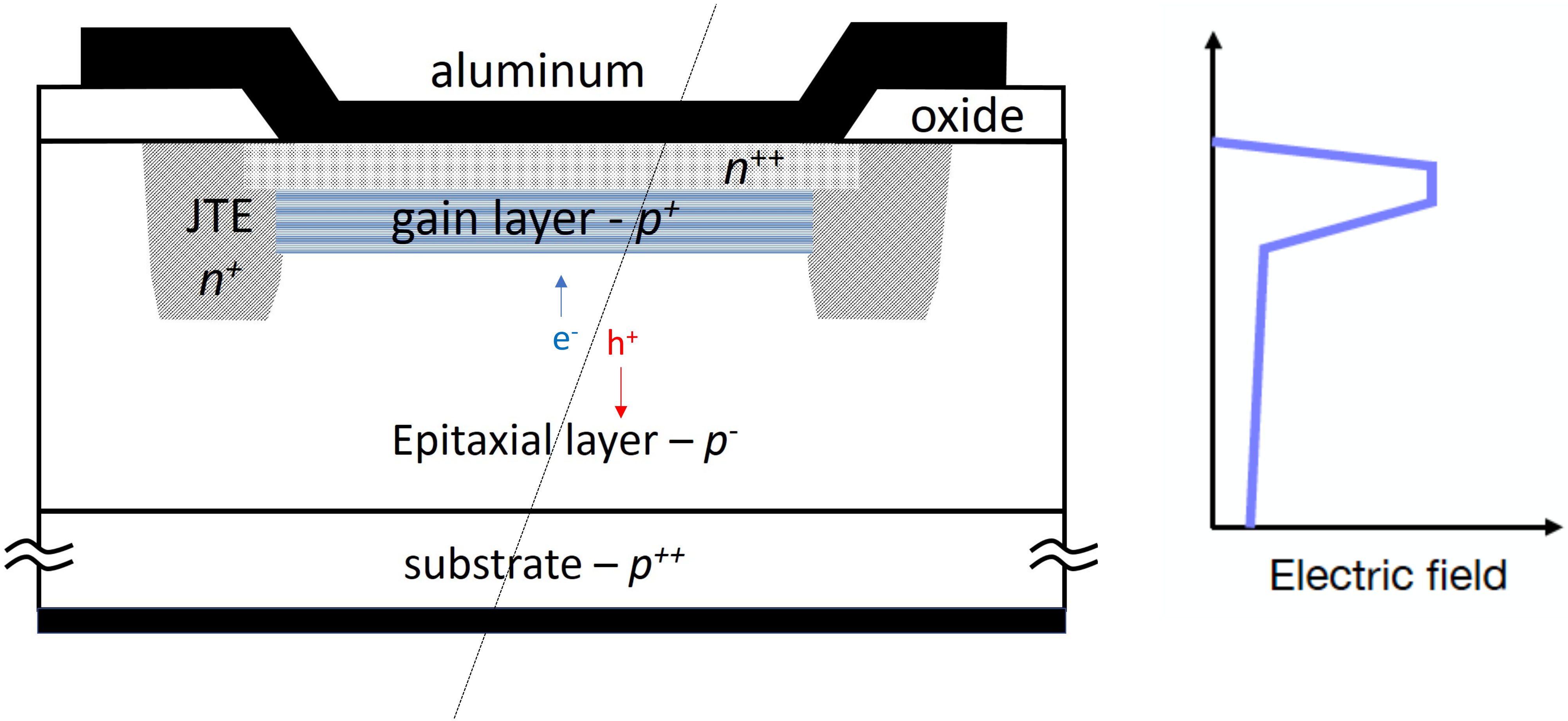
LGADs for LHC and EIC

Zhenyu Ye
University of Illinois at Chicago

Xiaoxun: We would like to hear the research on CMS MTD LGAD and in particular the technologies applied for ATHENA proposal.

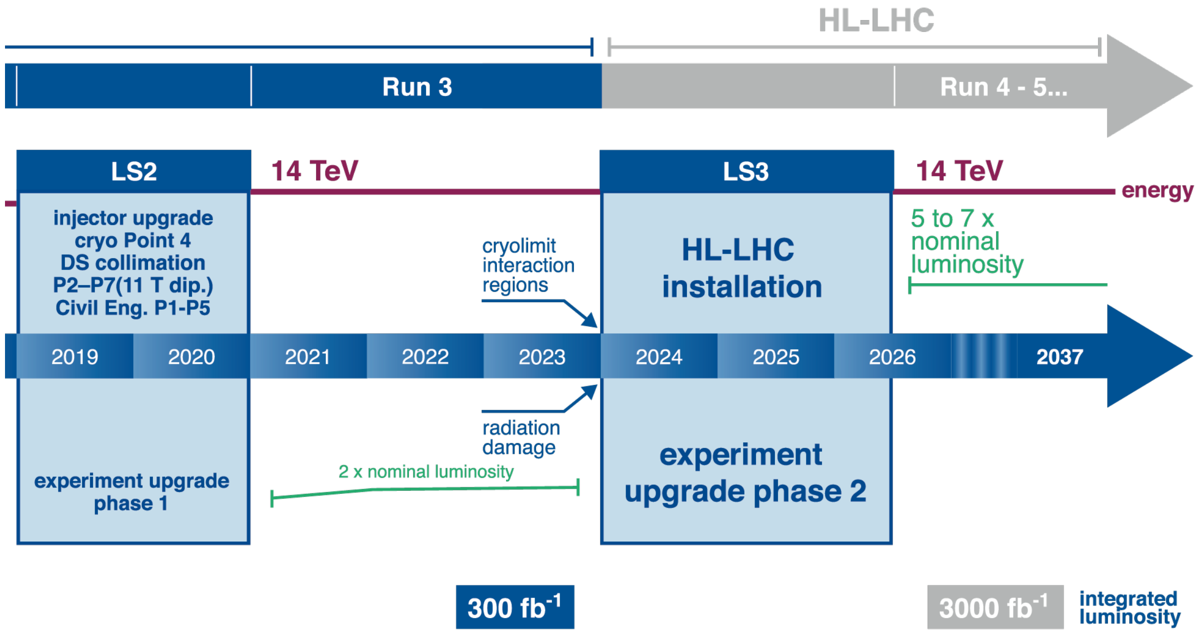
- **LGAD for CMS MIP Timing Detector**
- **AC-LGAD for EIC**

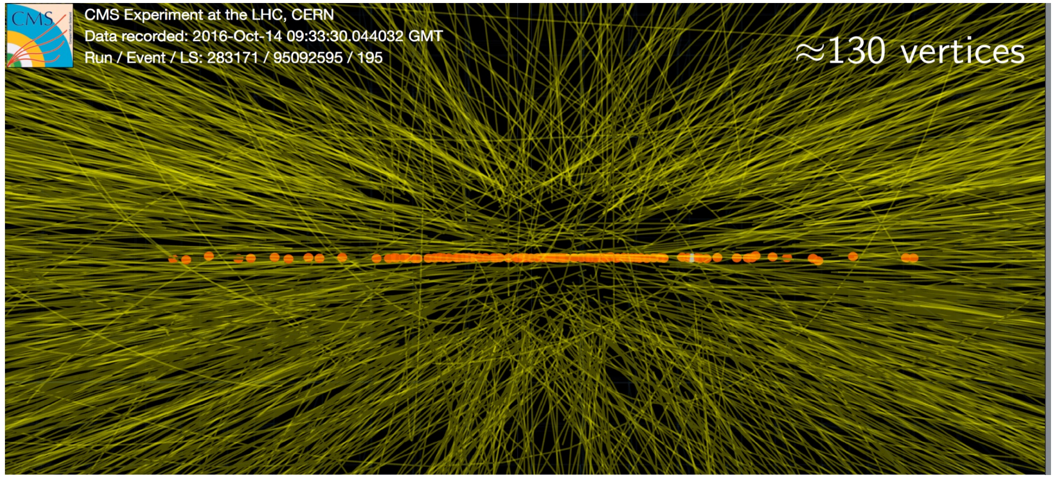
Endcap Timing Layer – Low Gain Avalanche Detector

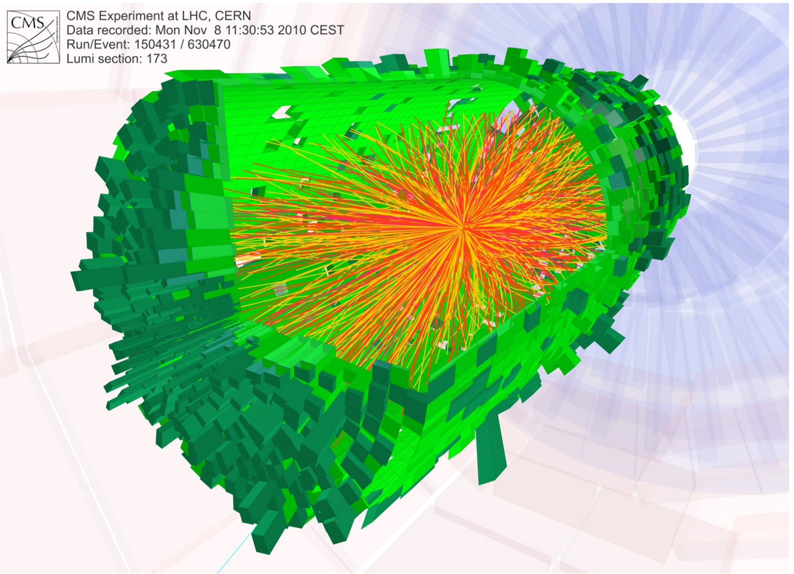


Ultra-fast silicon detectors with a highly doped p+ gain layer
Moderate internal gain : 10-30

High Luminosity LHC Era

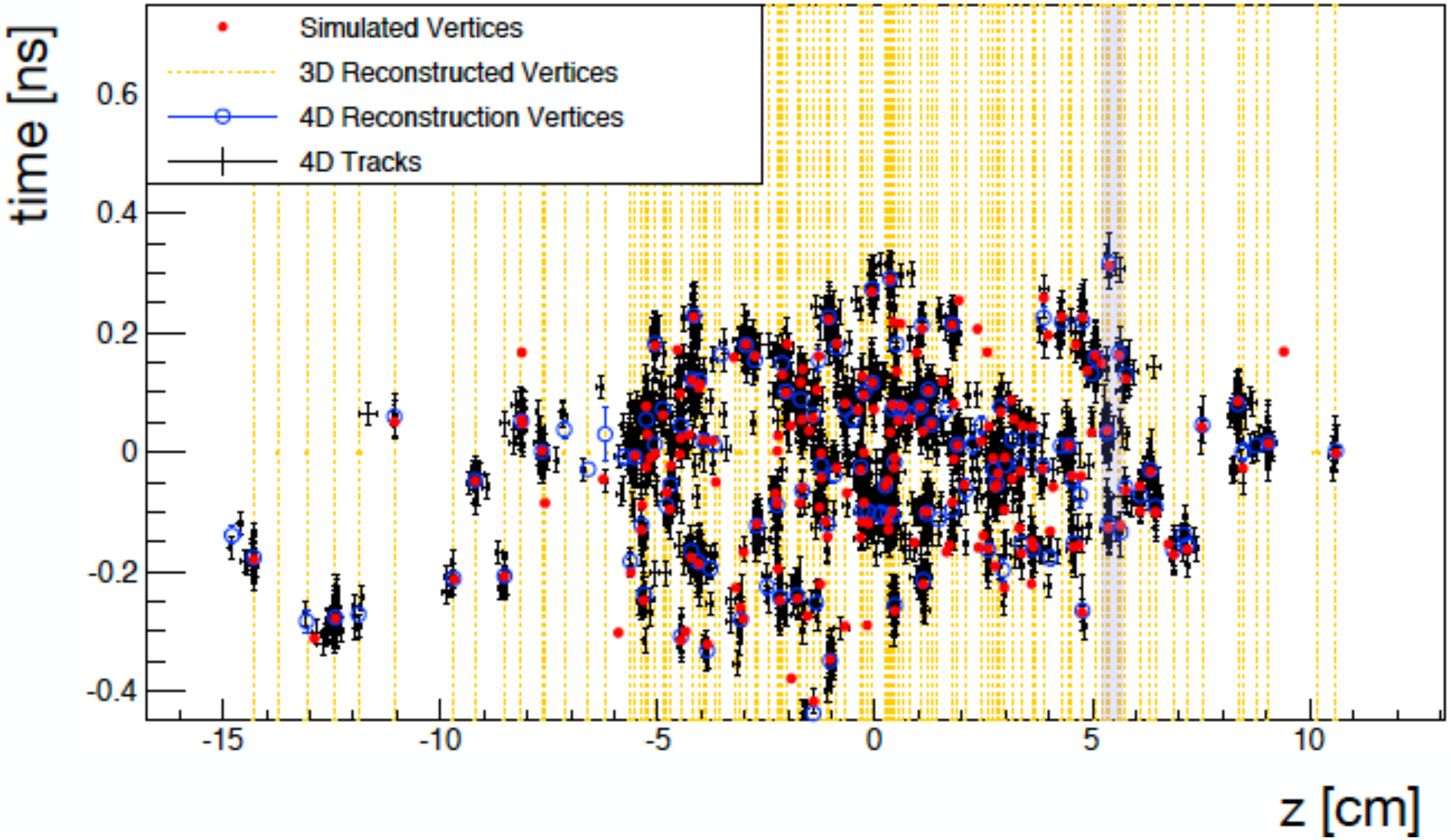






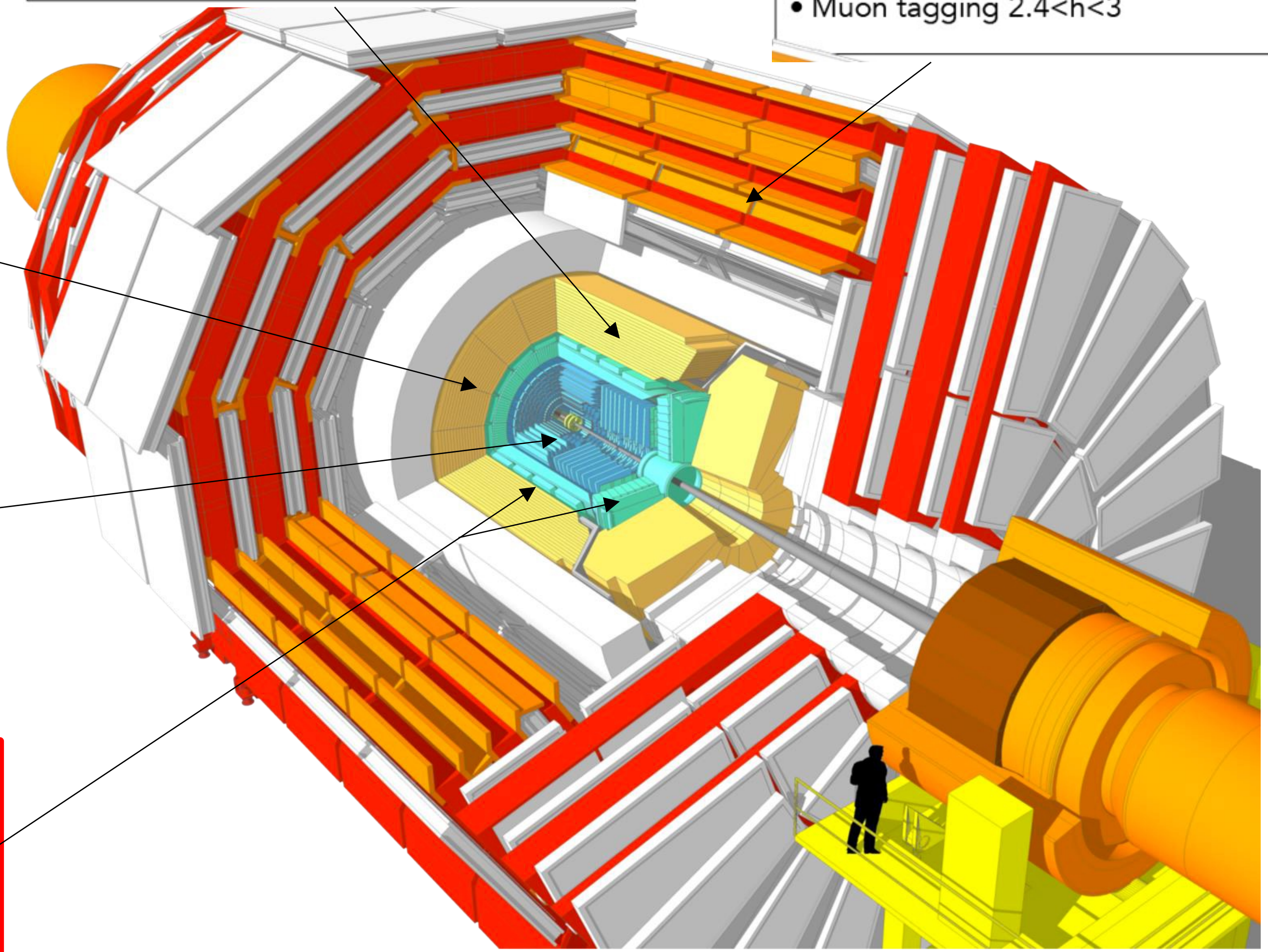
- **Dealing with the effects of pileup interactions in pp collisions will be a major challenge of the HL-LHC era.**
- **Sharping the tools for new discoveries as well as better measurement precision.**

Role of Precise Timing at HL-LHC



- **PU interactions significantly overlap in space, but are more separable in space + time.**
- **Per-particle timing allows 4D track and vertex reconstruction**
  - **PU reduced in each time slice; every object reconstruction is improved**
  - **Significant benefit to CMS physics program**

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

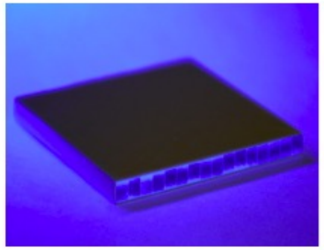
MIP Precision Timing Detector

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

CMS MTD Overview

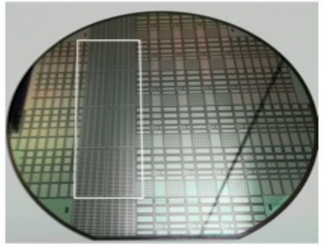
BTL: LYSO bars + SiPM readout:

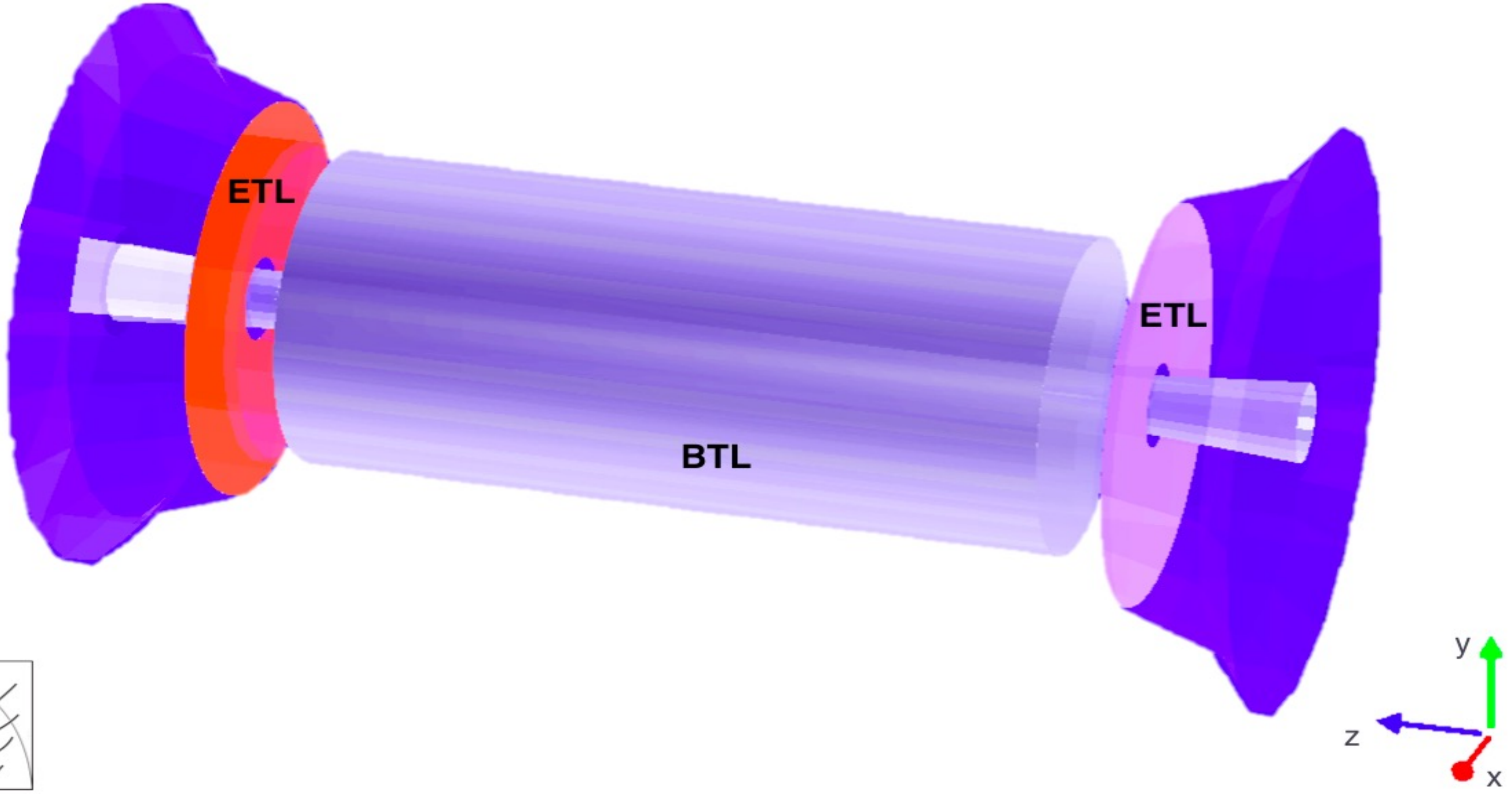
- TK/ ECAL interface: |η| < 1.45
- Inner radius: 1148 mm (40 mm thick)
- Length: ±2.6 m along z
- Surface ~38 m^2; 332k channels
- Fluence at 4 ab^{-1}: $2x10^{14}$ n_{eq}/cm^2



ETL: Si with internal gain (LGAD):

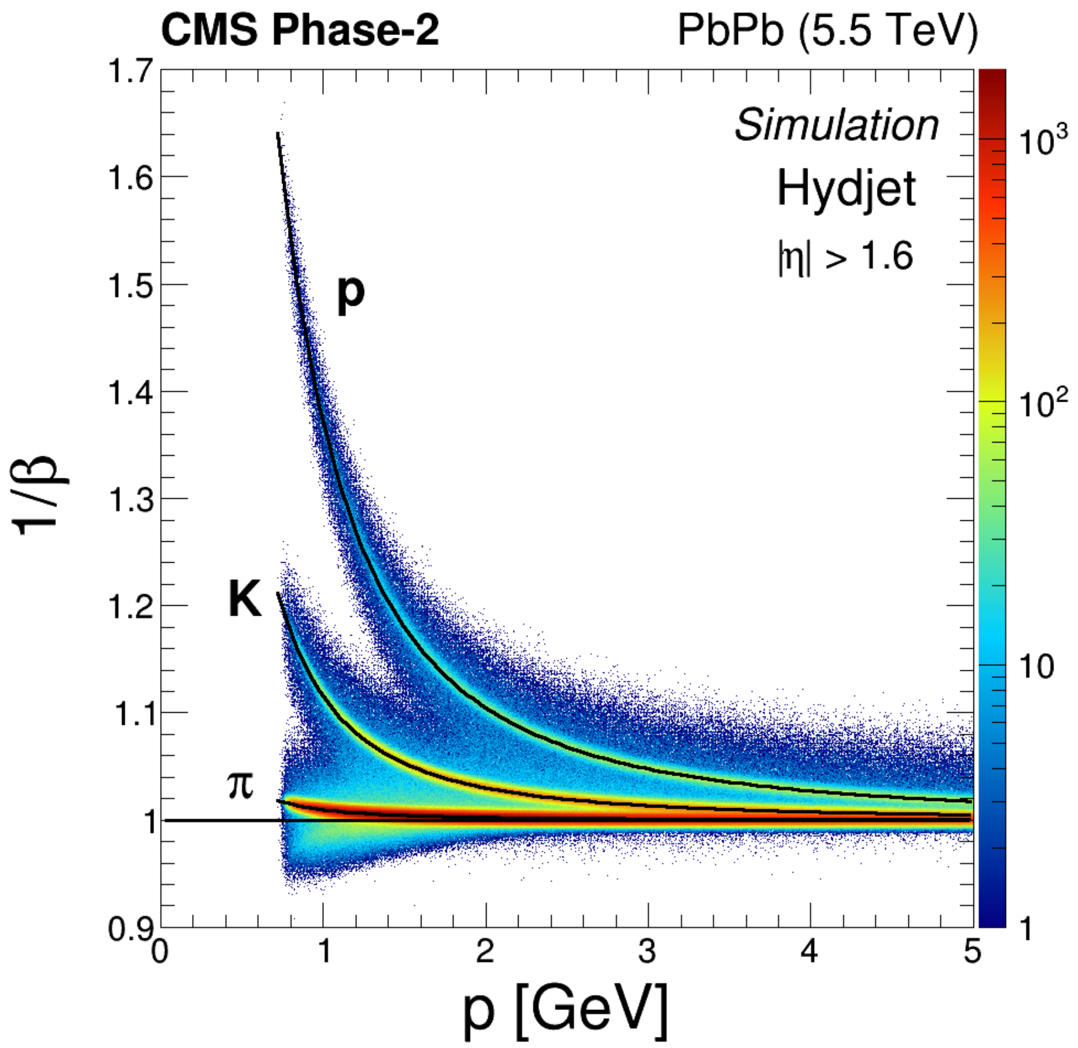
- On the HGC nose: 1.6 < |η| < 3.0
- Radius: 315 < R < 1200 mm
- Position in z: ±3.0 m (45 mm thick)
- Surface ~15.8 m^2; ~6M channels
- Fluence at 4 ab-1: up to $2x10^{15}$ n_{eq}/cm^2

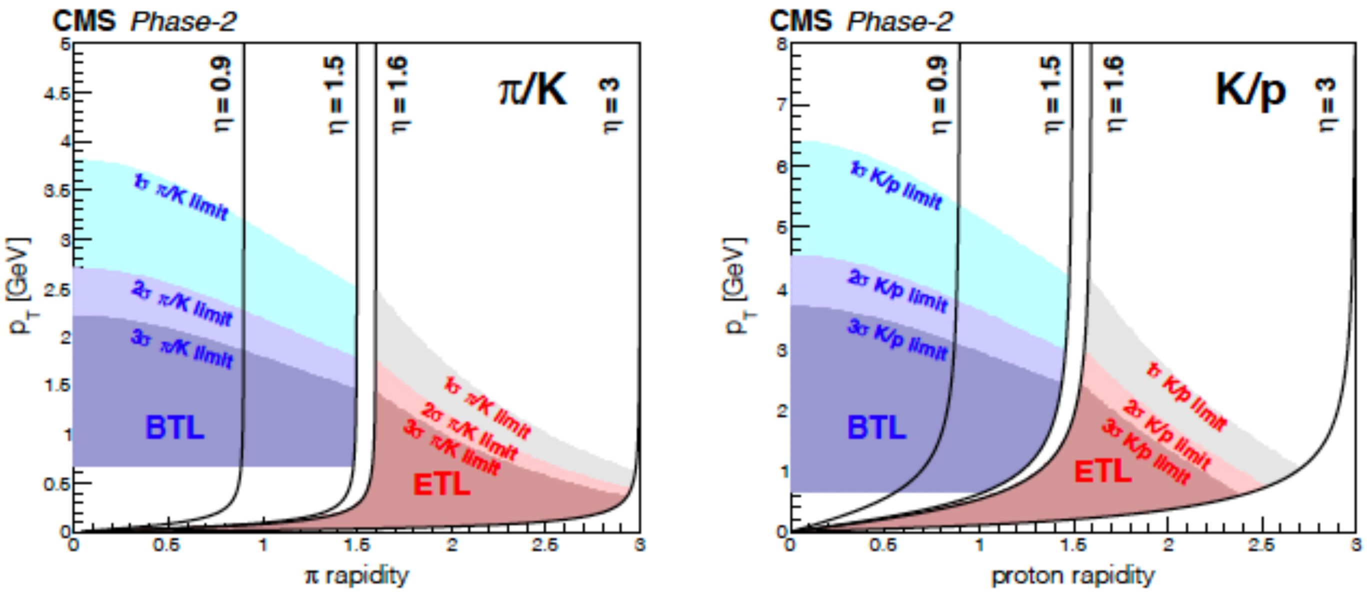




- Thin layer between the tracker and calorimeters
- Hermetic coverage for |η| < 3.0
- Time resolution of 30 ps for minimum ionizing particles (MIPs) before irradiation
- Sufficient radiation tolerance to maintain σ_t<60 ps up to 3000 fb^{-1}.

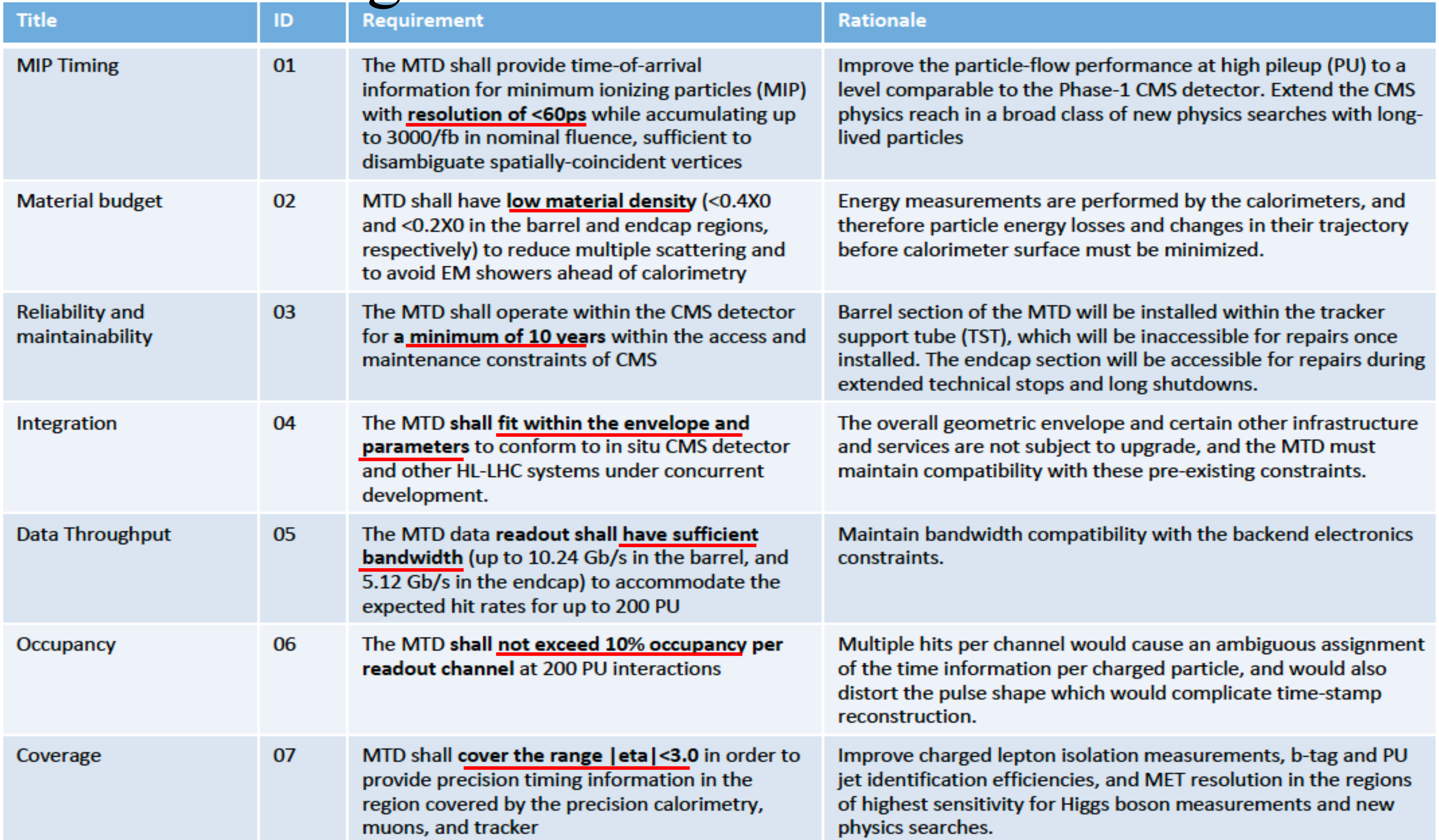
Opportunities from Precise Timing for Heavy Ion Physics





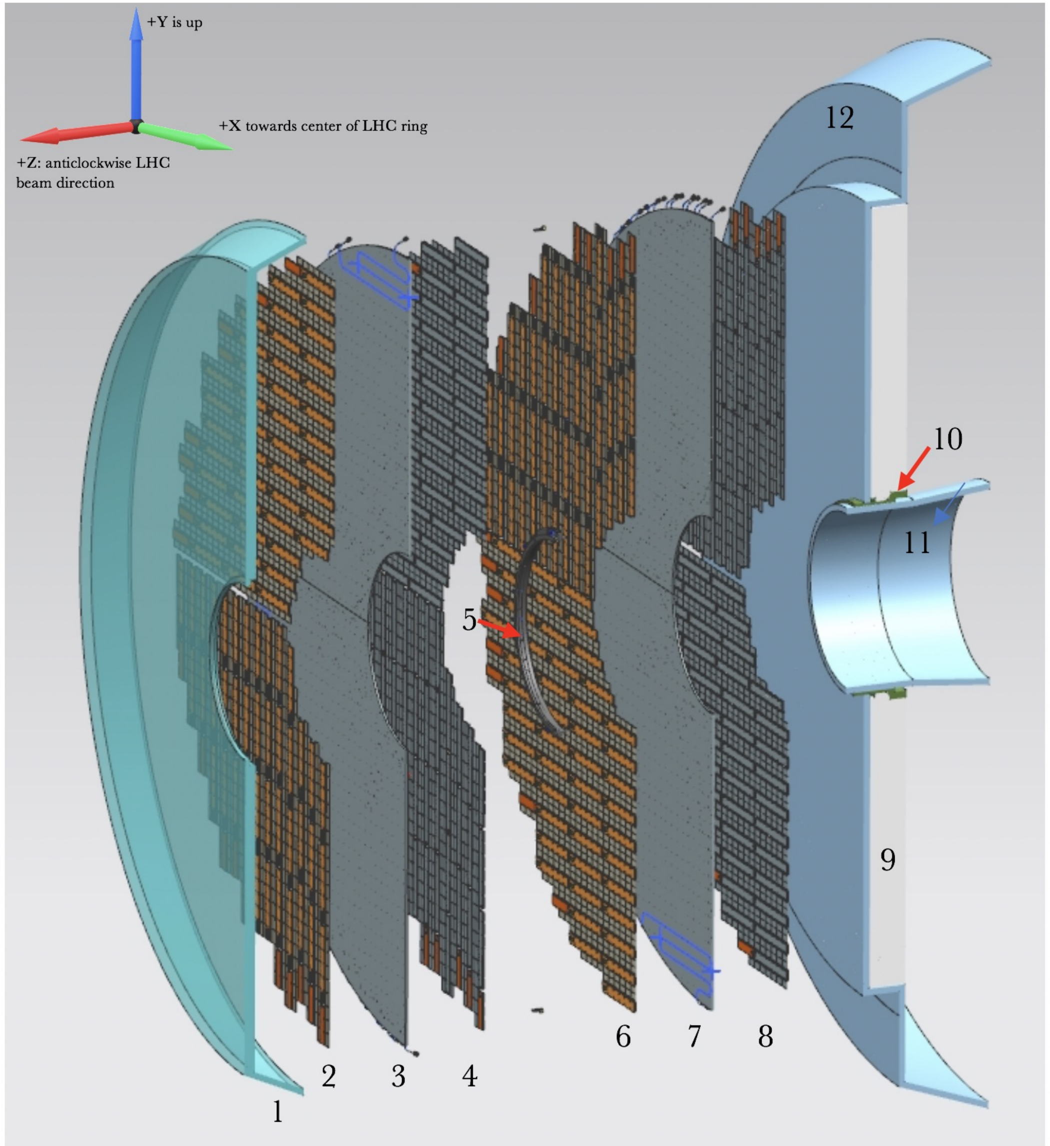
- **Precise timing provides particle ID for low p_T hadrons and thus new physics capabilities for Heavy Ion Physics.**
- **The CMS MTD will offer unique opportunity because of its excellent timing resolution and wide rapidity coverage.**

CMS MTD Design Considerations

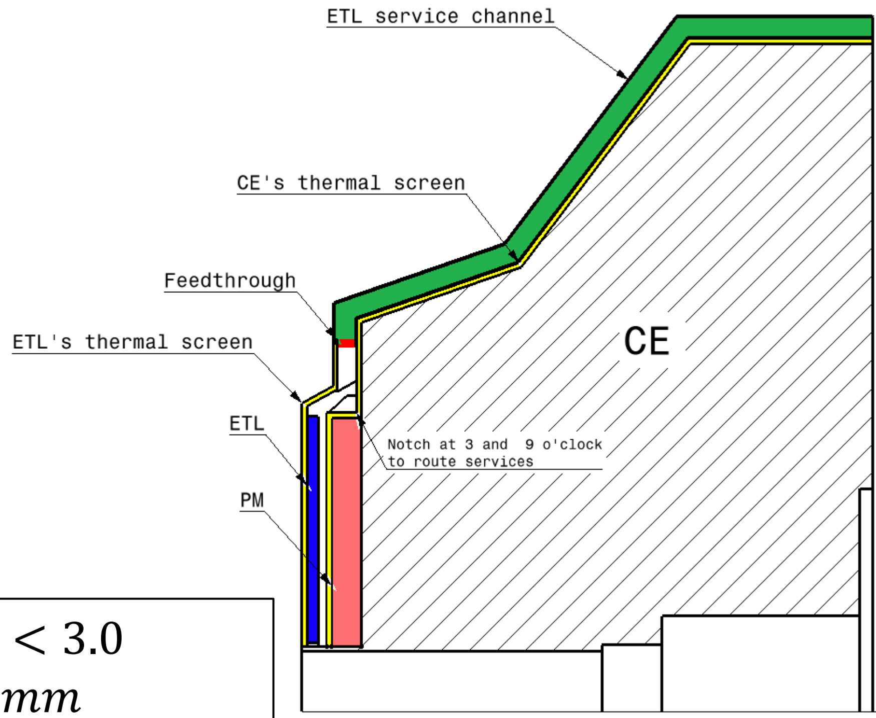


Title	ID	Requirement	Rationale
MIP Timing	01	The MTD shall provide time-of-arrival information for minimum ionizing particles (MIP) with **resolution of <60ps** while accumulating up to 3000/fb in nominal fluence, sufficient to disambiguate spatially-coincident vertices	Improve the particle-flow performance at high pileup (PU) to a level comparable to the Phase-1 CMS detector. Extend the CMS physics reach in a broad class of new physics searches with long-lived particles
Material budget	02	MTD shall have **low material density** (<0.4X0 and <0.2X0 in the barrel and endcap regions, respectively) to reduce multiple scattering and to avoid EM showers ahead of calorimetry	Energy measurements are performed by the calorimeters, and therefore particle energy losses and changes in their trajectory before calorimeter surface must be minimized.
Reliability and maintainability	03	The MTD shall operate within the CMS detector for **a minimum of 10 years** within the access and maintenance constraints of CMS	Barrel section of the MTD will be installed within the tracker support tube (TST), which will be inaccessible for repairs once installed. The endcap section will be accessible for repairs during extended technical stops and long shutdowns.
Integration	04	The MTD **shall fit within the envelope and parameters** to conform to in situ CMS detector and other HL-LHC systems under concurrent development.	The overall geometric envelope and certain other infrastructure and services are not subject to upgrade, and the MTD must maintain compatibility with these pre-existing constraints.
Data Throughput	05	The MTD data **readout shall have sufficient bandwidth** (up to 10.24 Gb/s in the barrel, and 5.12 Gb/s in the endcap) to accommodate the expected hit rates for up to 200 PU	Maintain bandwidth compatibility with the backend electronics constraints.
Occupancy	06	The MTD **shall not exceed 10% occupancy per readout channel** at 200 PU interactions	Multiple hits per channel would cause an ambiguous assignment of the time information per charged particle, and would also distort the pulse shape which would complicate time-stamp reconstruction.
Coverage	07	MTD shall **cover the range |eta|<3.0** in order to provide precision timing information in the region covered by the precision calorimetry, muons, and tracker	Improve charged lepton isolation measurements, b-tag and PU jet identification efficiencies, and MET resolution in the regions of highest sensitivity for Higgs boson measurements and new physics searches.

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



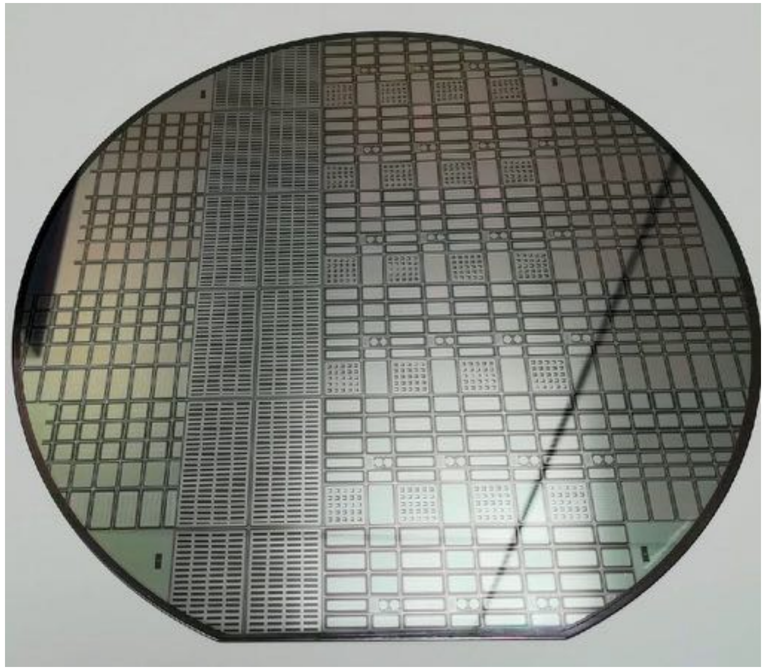
- On the CE nose: $1.6 < |\eta| < 3.0$
- Radius: $315 < R < 1200\ mm$
- Position in Z: $\pm 3.0\ m$ (45 mm thick)
- Surface ~$15.8\ m^2$; ~8.6M channels
- Weight 282 kg/side; Power: 26kW/side

- **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 - 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	$2 \times 4\ cm^2\ (16 \times 32)$	Optimize wafer usage
Interpad gap	$< 90\ \mu m$	Fill factor > 85%
Time resolution after irradiation	$< 40\ ps$	Up to $1.7 \times 10^{15}\ n_{eq}/cm^2$

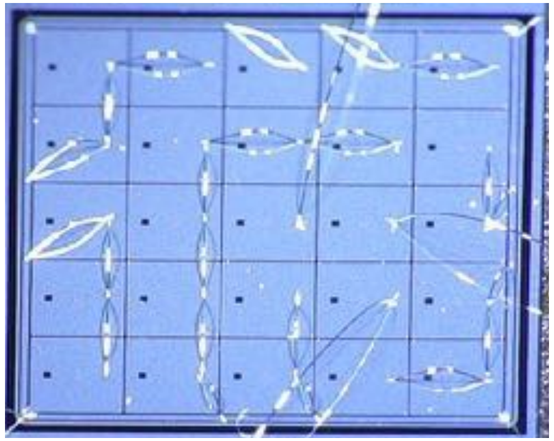
FBK UFSD3



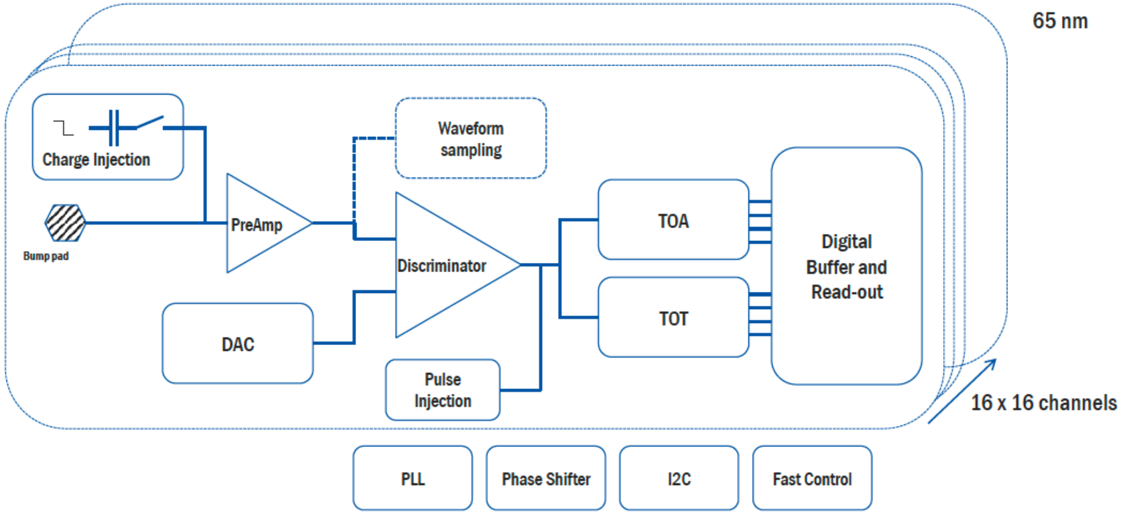
Recent prototypes from Hamamatsu (HPK) and Fondazione Bruno Kessler (FBK) focus on

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

5x5 array from HPK



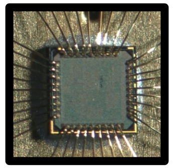
Endcap Timing Layer –Readout ASIC (ETROC)

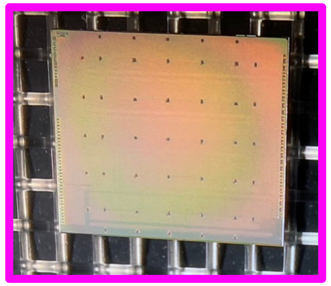


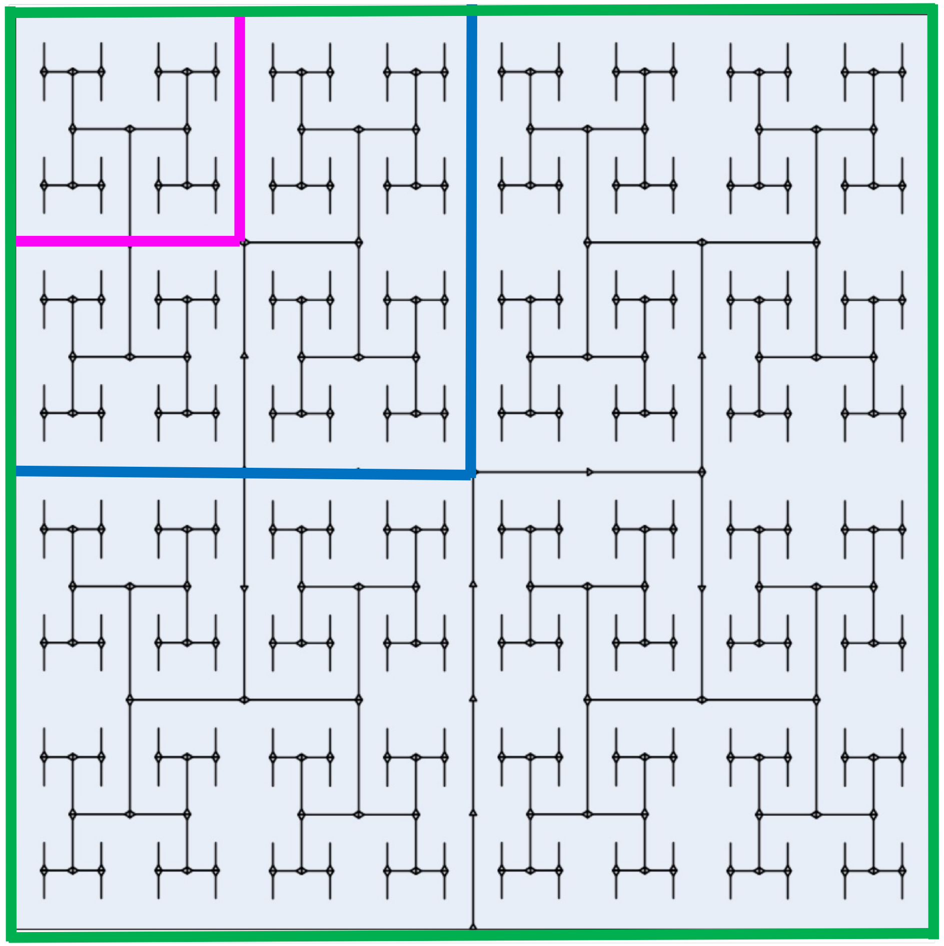
- **Dedicate balance act from:**
  - **Low noise & fast rise time**

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

  - **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**

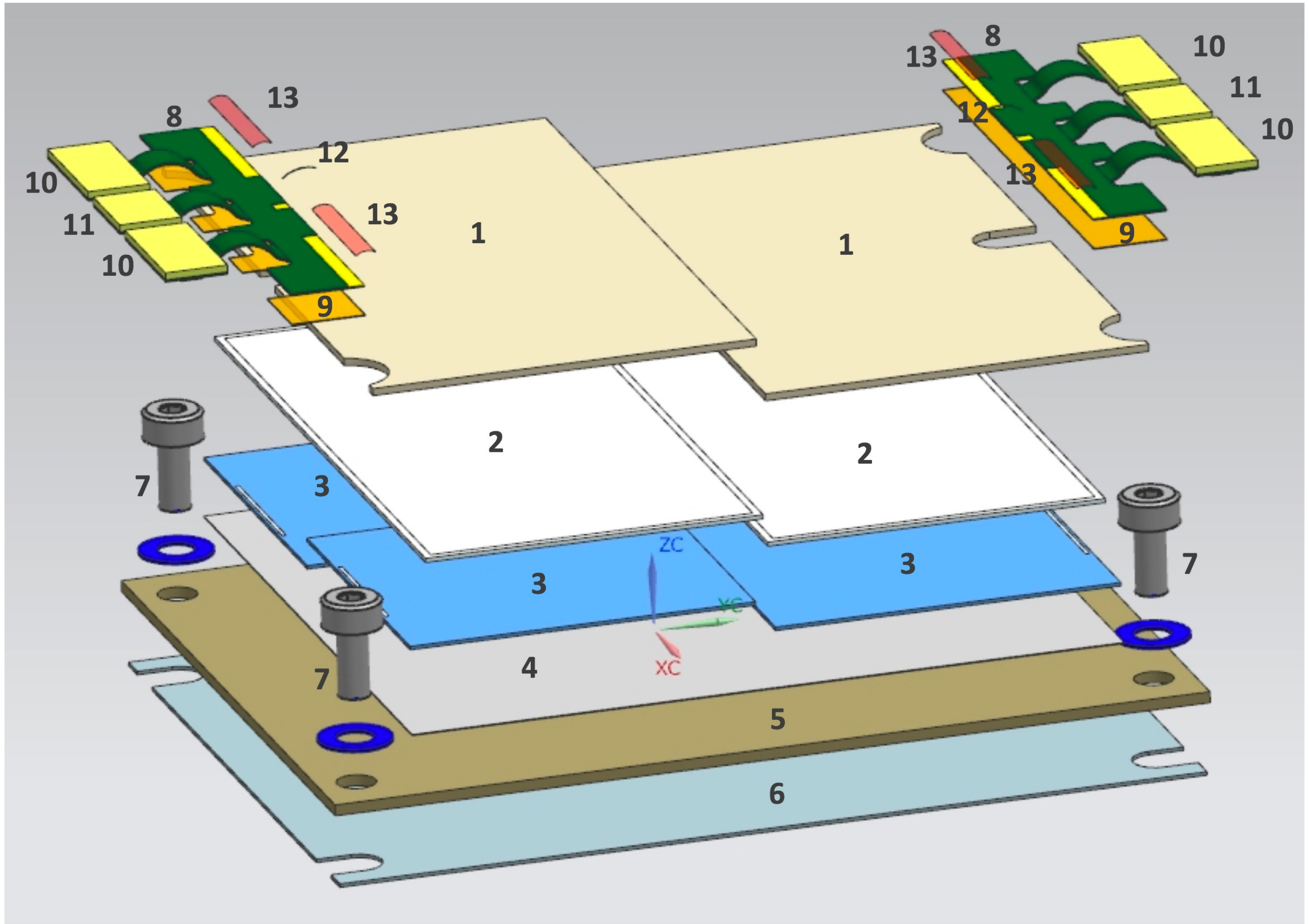






✓ **ETROC0 : single analog channel**
✓ **ETROC1: with TDC and 4x4 clock tree**
☐ **ETROC2: 16x16 full functionality**
☐ **ETROC3: 16x16 full size chip**

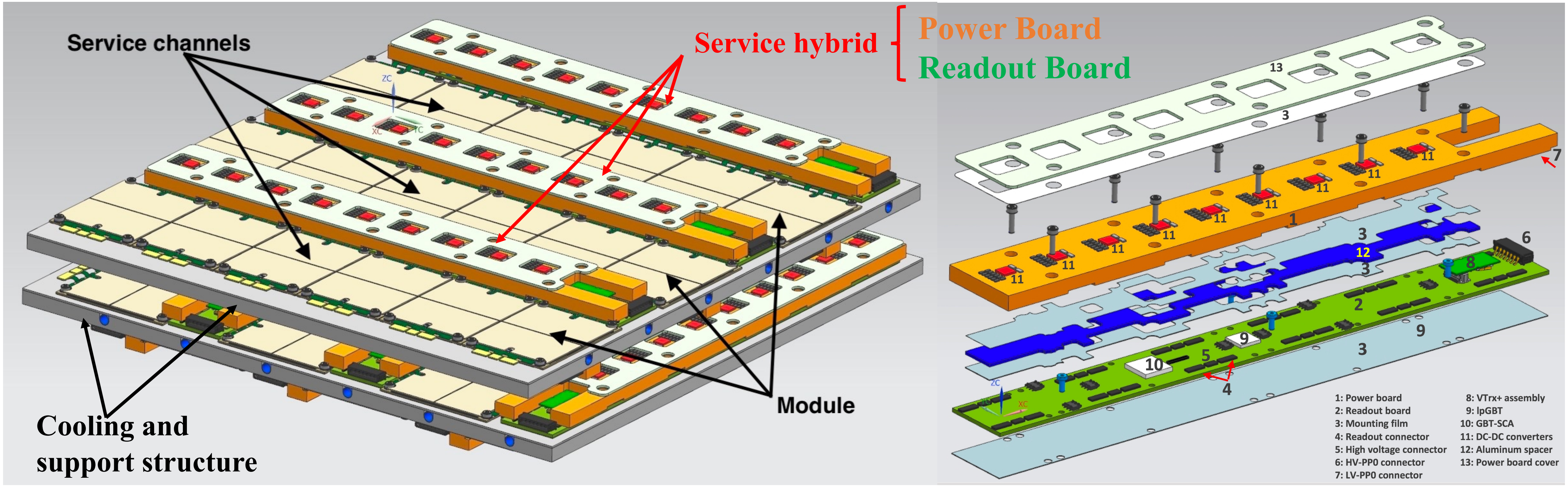
Endcap Timing Layer – Module Design



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

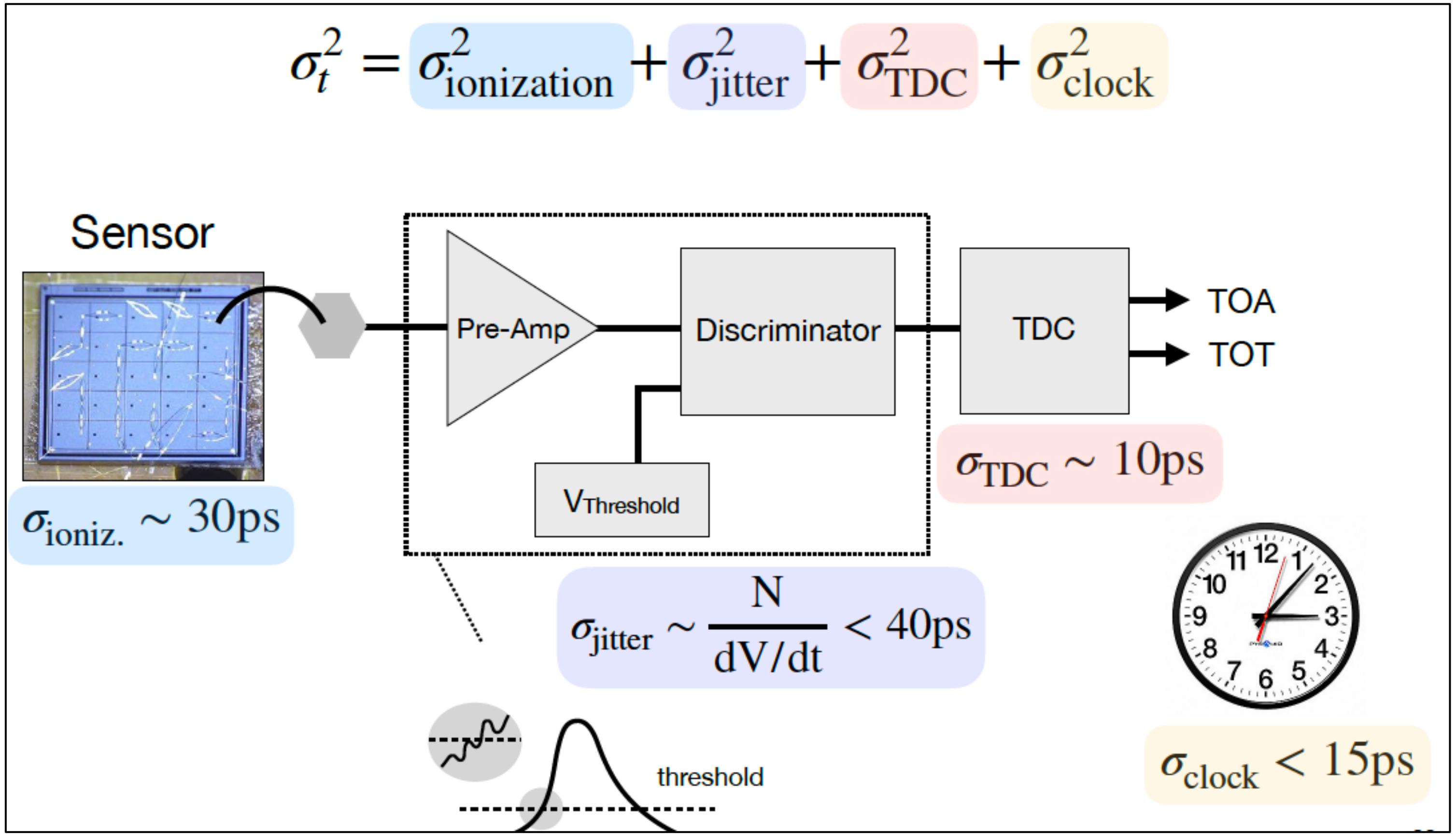
ETL consists of ~9000 modules. LGAD sensors and ETROC chips are bump-bonded together and attached to AlN base plate with thermal adhesive film to make one module. Electric connection between flexible circuits and LGAD/ETROCs are made through wire-bonding.

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.

Endcap Timing Layer – Time Resolution Contributions



$$\sigma_t^2 = \sigma^2_{\text{ionization}} + \sigma^2_{\text{jitter}} + \sigma^2_{\text{TDC}} + \sigma^2_{\text{clock}}$$

$\sigma_{\text{ioniz.}} \sim 30\text{ps}$

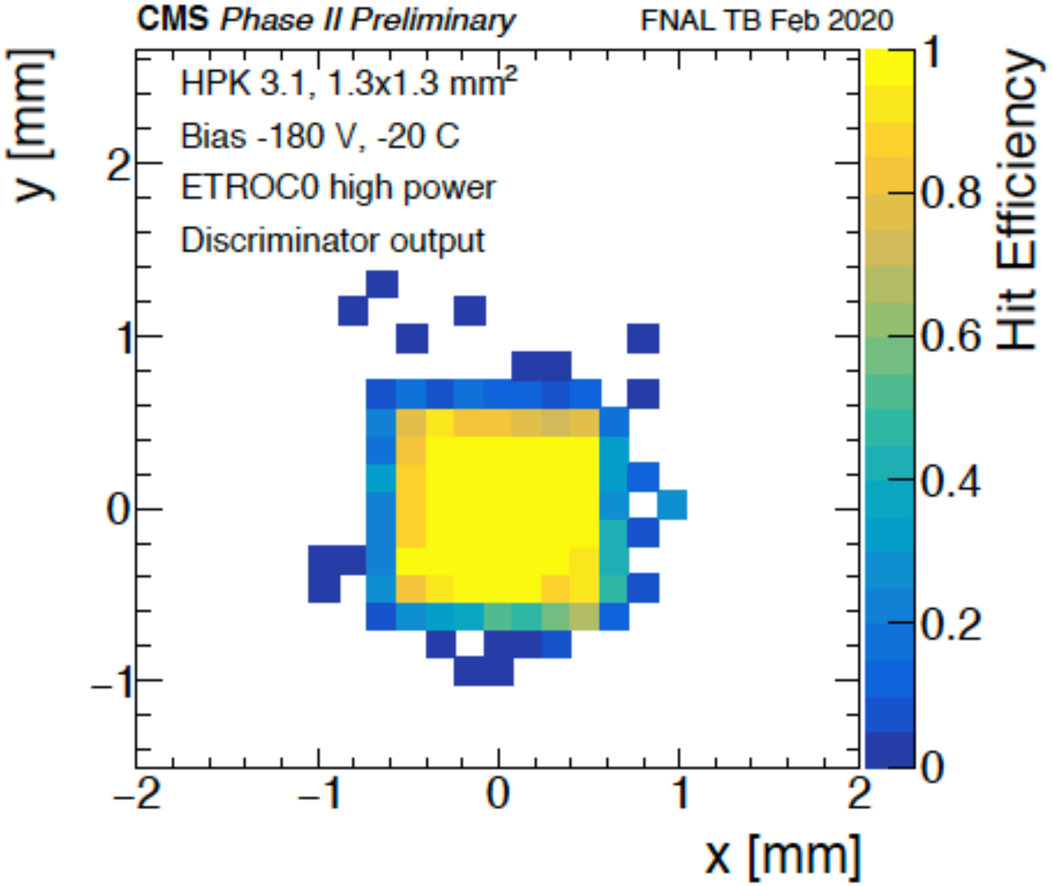
$\sigma_{\text{TDC}} \sim 10\text{ps}$

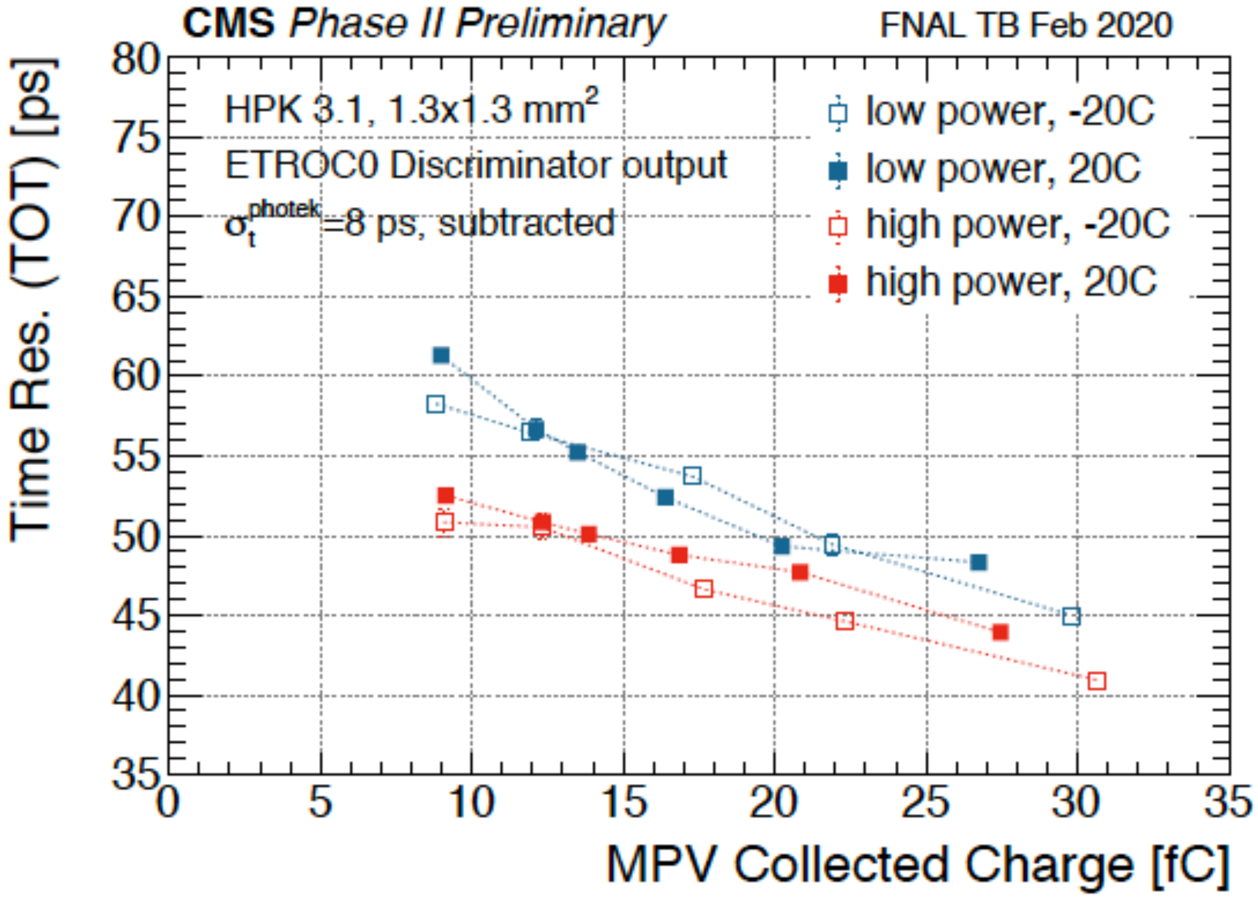
$\sigma_{\text{jitter}} \sim \frac{N}{dV/dt} < 40\text{ps}$

$\sigma_{\text{clock}} < 15\text{ps}$

- $\sigma_{ionization}$: random variation in particle energy deposition, determining the amplitude and the shape of the signal
  ~30 ps up to $1\text{x}10^{15}$ n_{eq}/cm^2, and
  ~40 ps up to $2\text{x}10^{15}$ 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

ETROC1+LGAD – Test Beam Results

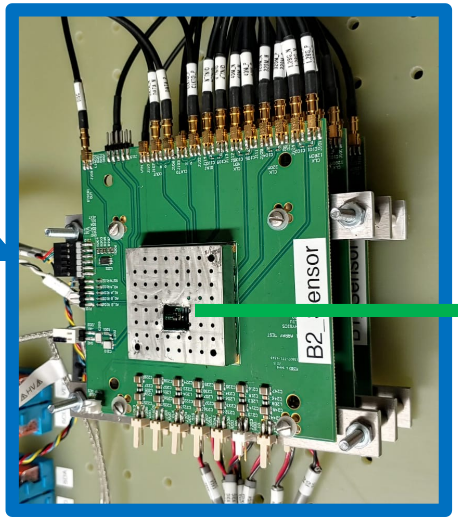




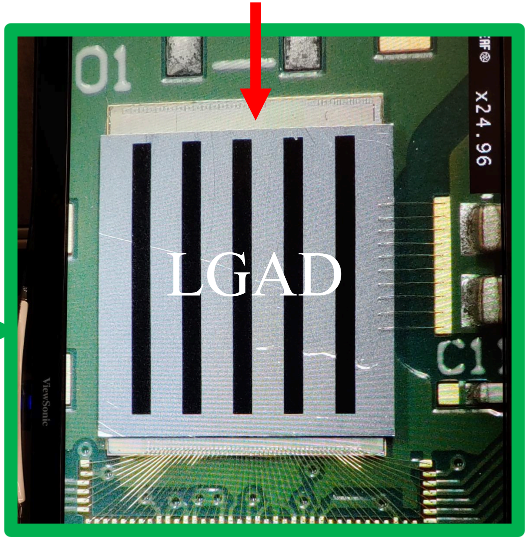
- **For pre-radiated sensor and ETROC0 operating above 20 fC, ~100% efficiency across the sensor area and time resolution of 40-50 ps have been achieved.**
- **Irradiation effects will be reduced by operating at lower temp (-30 ^{o}C) and mitigated by increasing the sensor bias voltage and by the high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

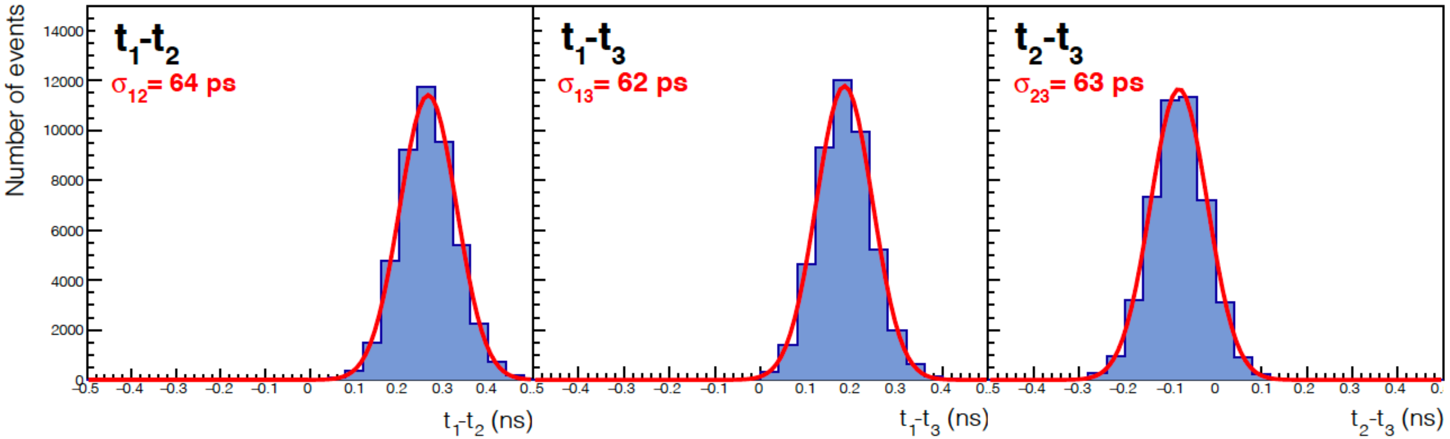
ETROC1+LGAD – Test Beam Results

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.

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

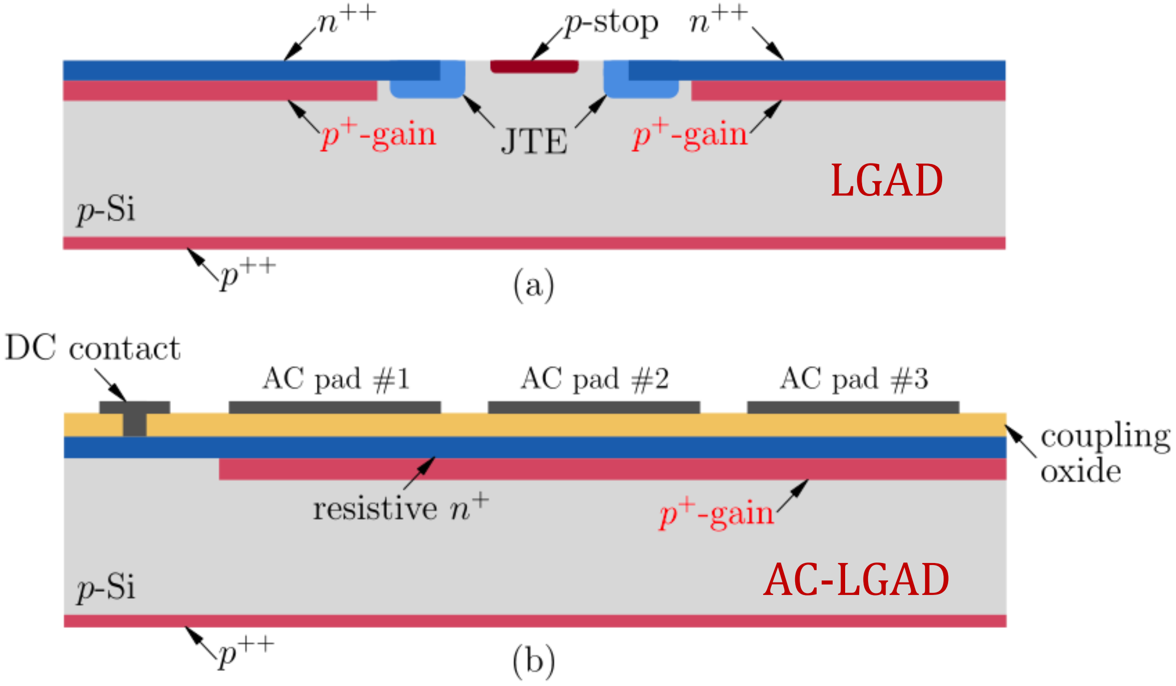
CMS MTD - Summary

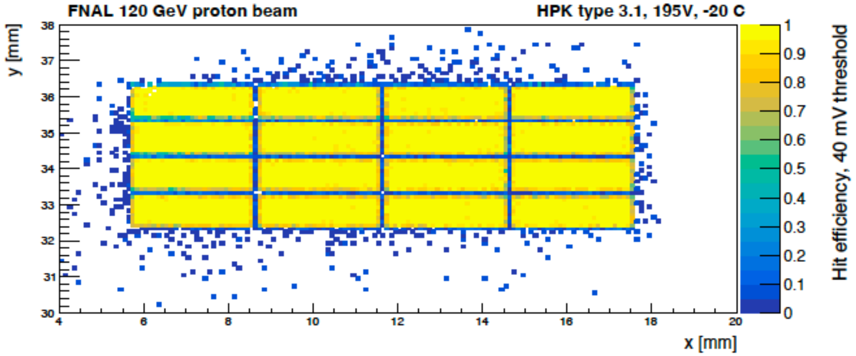
- **MTD is designed to provide precision timing for CMS during the LHC Run4 and beyond (2026+)**
  - Single layer of LYSO:Ce scintillators combined with SiPM at $R = 1.15m$ in the barrel
  - Two disks of LGAD sensors at $z = \pm 3\ m$ on each side of the endcap regions

- MTD will cover a wide rapidity region ($|\eta| < 3$) with a timing resolution of 30-40 ps in LHC Run4, providing unique opportunities for heavy ion physics
  - Performance consistent with the designed values has been demonstrated in test beam
  - Performance will be maintained through optimized design and operation to mitigate the radiation damage effects

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.





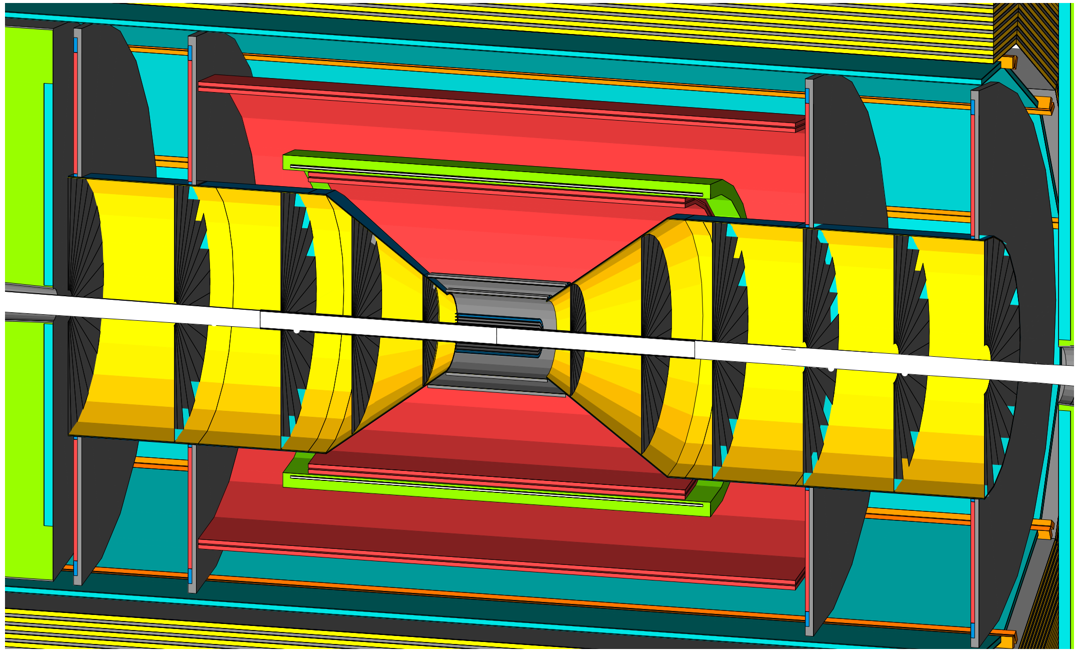
- AC-LGAD: replacement of the segmented n^{++} layer by a less doped but continuous n^{+} layer. Electrical signals in the n^{+} layer are AC-coupled to neighboring metal electrodes that are separated from the n^{+} layer by a thin insulator layer.

- 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 for EIC

- AC LGAD detectors proposed for EIC
  - Roman Pots and B0
  - TOF for PID (and tracking)

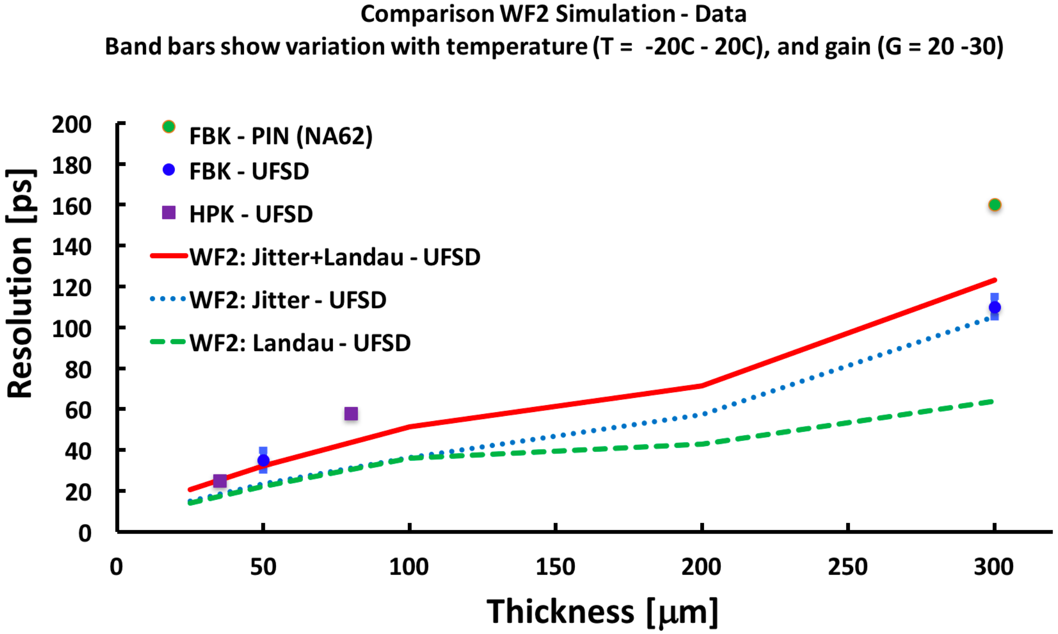
- Have common designs in sensor, ASIC etc. when possible, combine R&D efforts

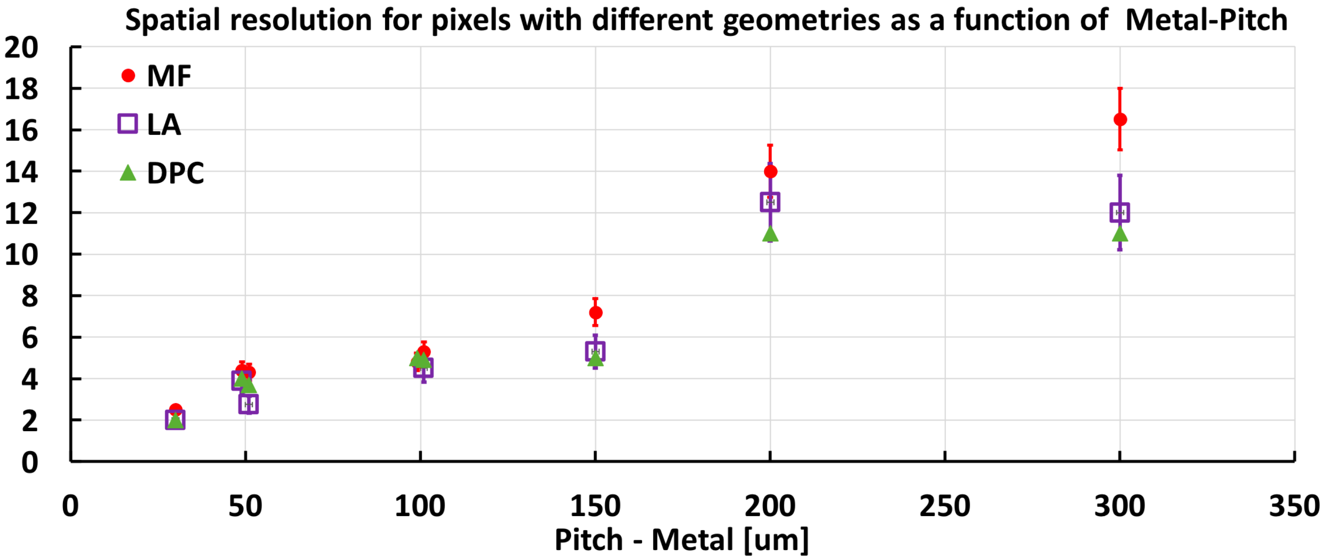


	Time resolution / hit	Position resolution / hit	Material budget / layer
Barrel ToF (Tracker)	<30 ps	(3-30 μm for Tracker)	$< 0.01\ X_0$
Endcap ToF (Tracker)	<25 ps	(30-50 μm for Tracker)	e-direction $< 0.05 X_0$ h-direction $< 0.15 X_0$
Roman Pots	<50 ps	$< 500/\sqrt{12}\ \mu m$	N/A
B0	<50 ps	$O(50)\ \mu m$	$< 0.01\ X_0$

eRD112: AC-LGAD Sensor R&D

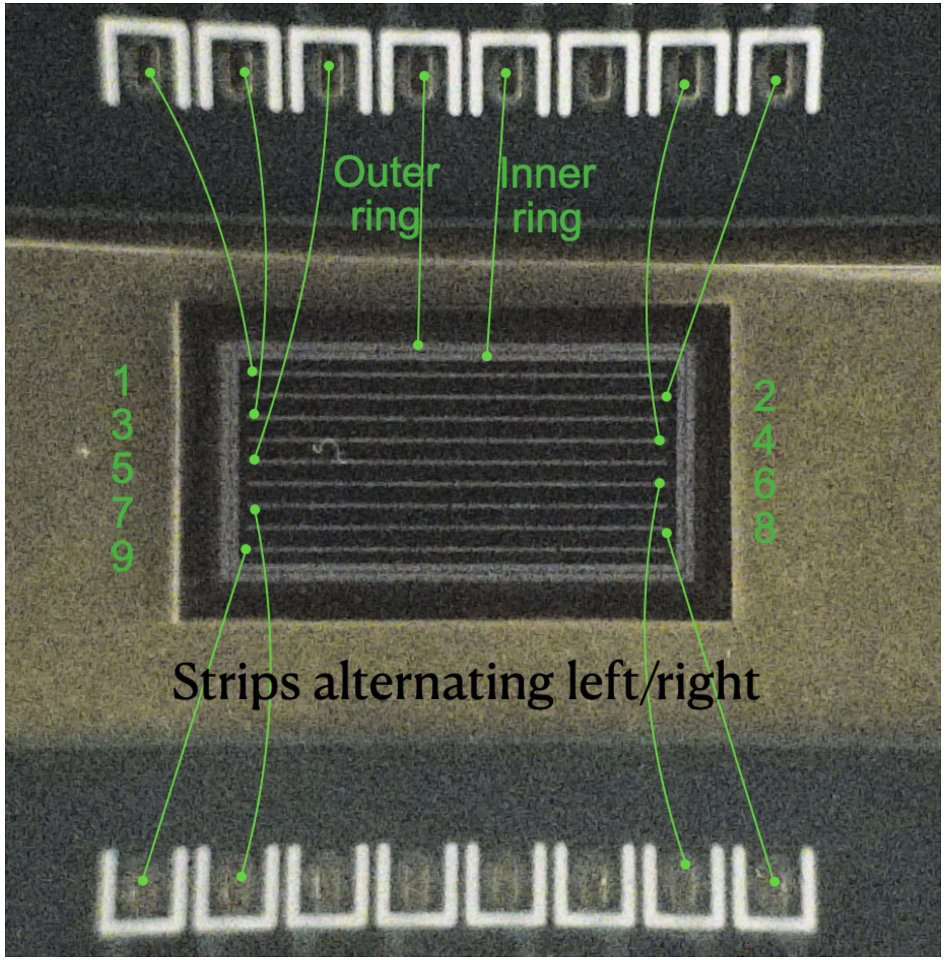
Nicolo Cartiglia



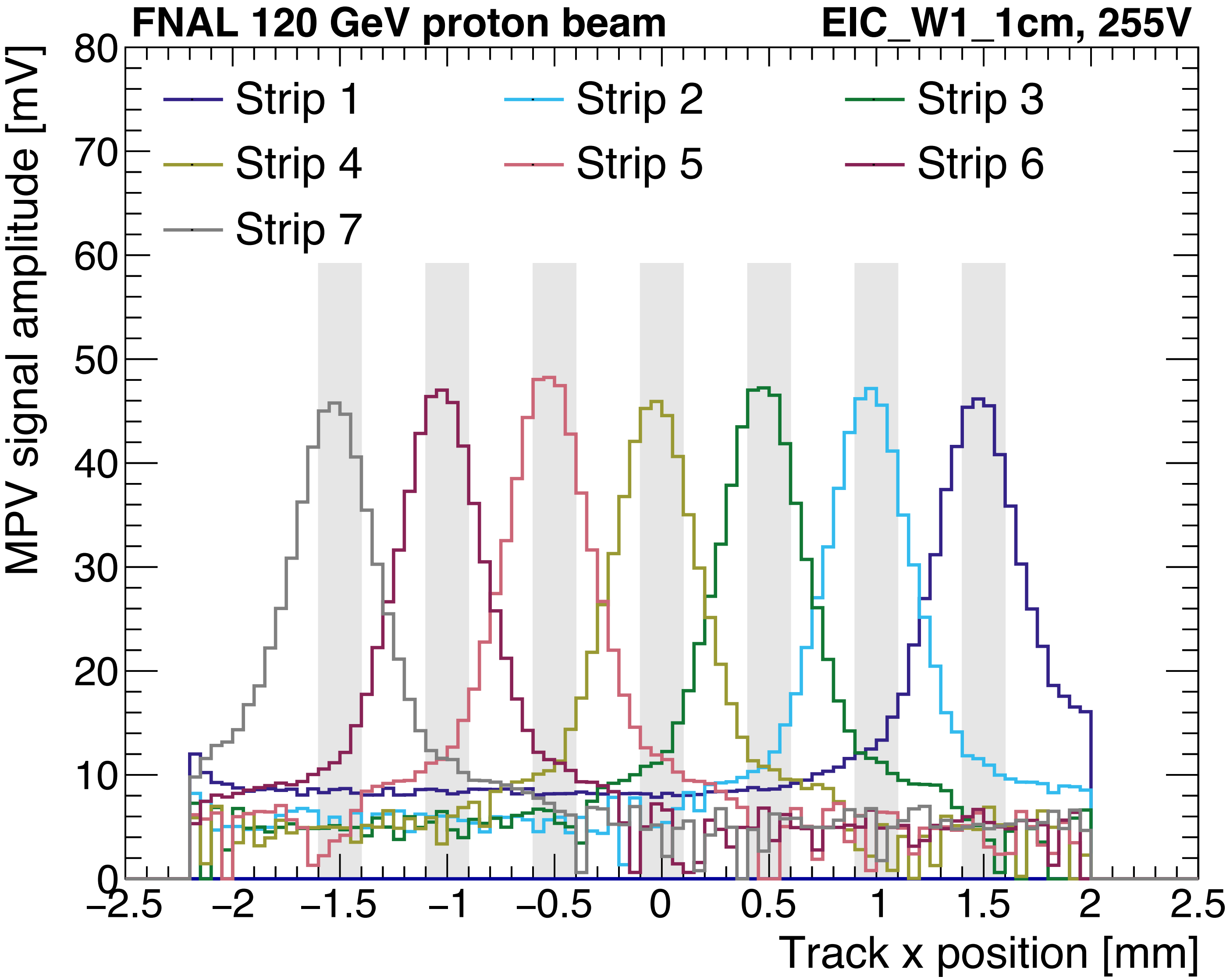


- **R&D Goals**
  - 15-20 ps timing resolution, O(3-50μm) position resolution where needed
  - Minimal readout channel density (long strip, rectangular pixel) for reduced power, material and cost
- **Plan**
  - Produce and test sensors with thinner active volume to achieve the desired timing resolution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

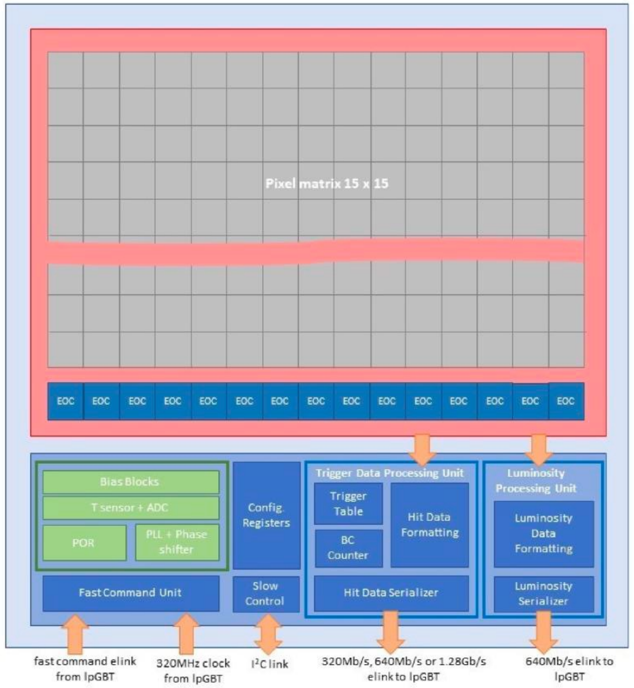
BNL/UIC Long Strip AC-LGAD Sensor at Test Beam

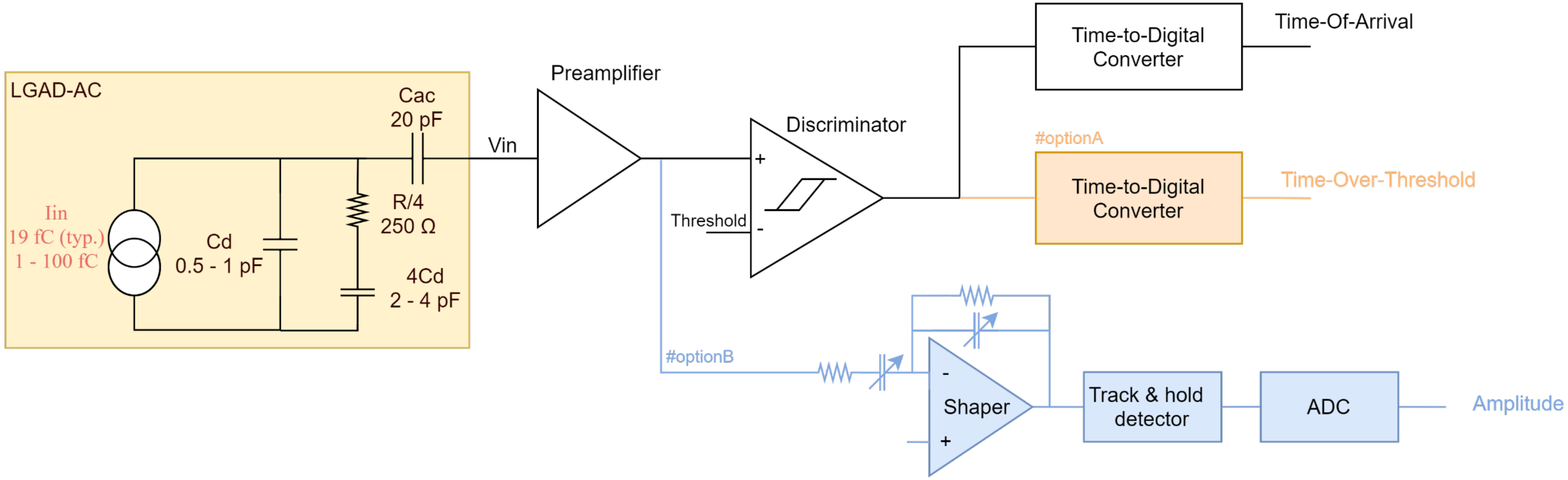


BNL/UIC: 1 *cm* length, 500 μm pitch



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**
  - Continue the ASIC prototyping effort for RPs by IJCLAB/Omega (1st submission in FY22 funded externally)
  - 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

Summary and Outlook

- AC-LGAD is a proposed technology for TOF and far-forward detectors (RPs/B0) at EIC.
  - Opportunity: new detector technology development.
  - Challenge: strict detector performance requirements; very tight schedule.