



北京大学
PEKING UNIVERSITY

The CMS MIP Timing Detector for Phase 2 Design, status, and recent results

2026 International Conference on Instrumentation for Colliding Beam Physics
Hefei – 13 October 2026

C. Quaranta^a on behalf of the CMS Collaboration

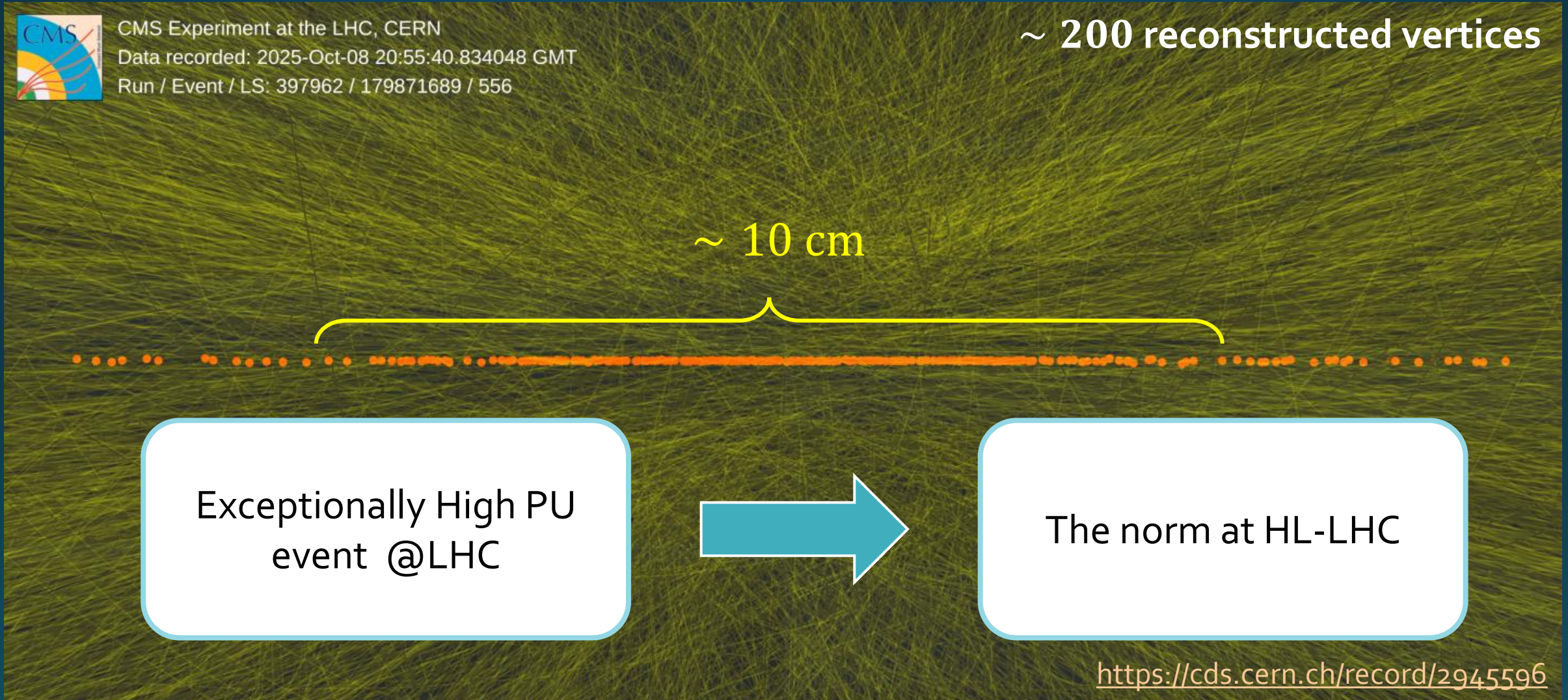
^aPeking University



The HL-LHC Pile Up Challenge



proton-proton interactions per bunch crossing (*pile-up*, PU): 60 (LHC Run3) → 140-200



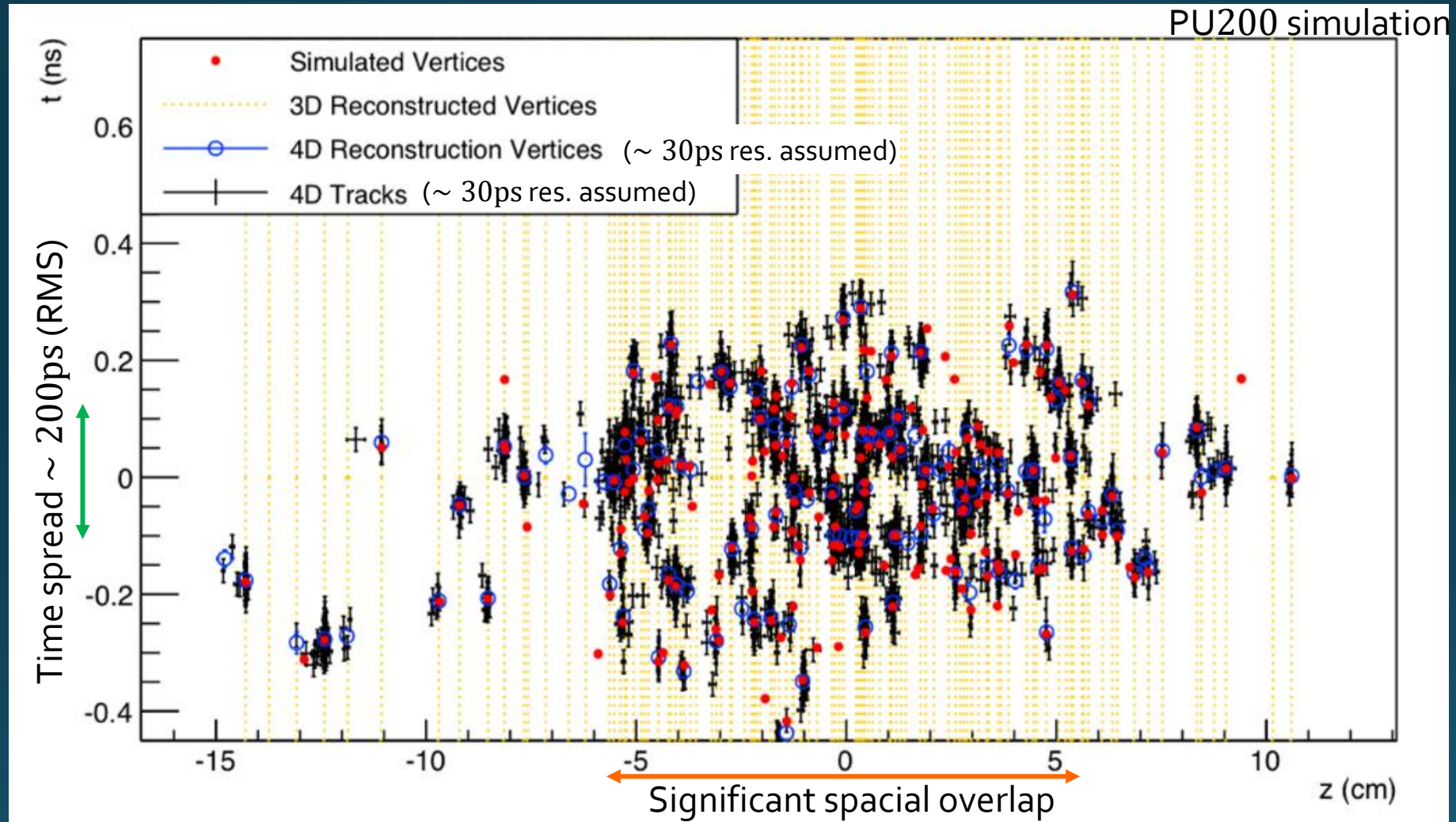
Exceptionally High PU
event @LHC



The norm at HL-LHC

<https://cds.cern.ch/record/2945596>

Timing information for vertex reconstruction



<https://cds.cern.ch/record/2667167/>

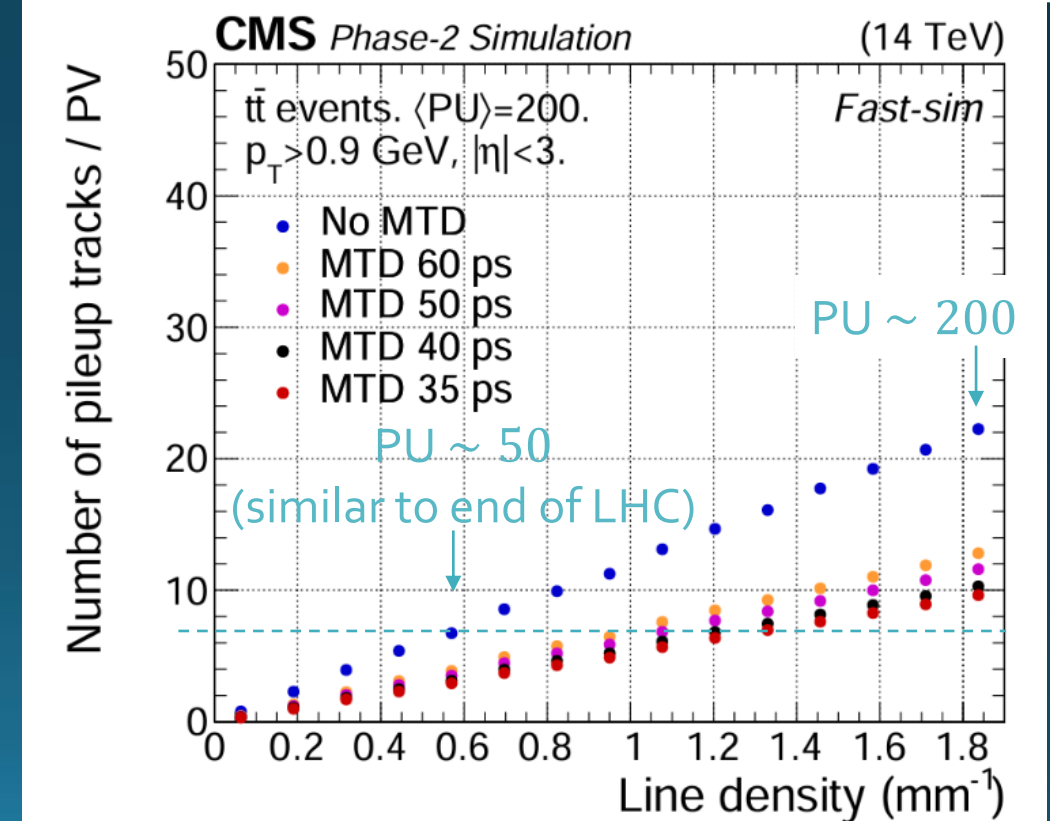
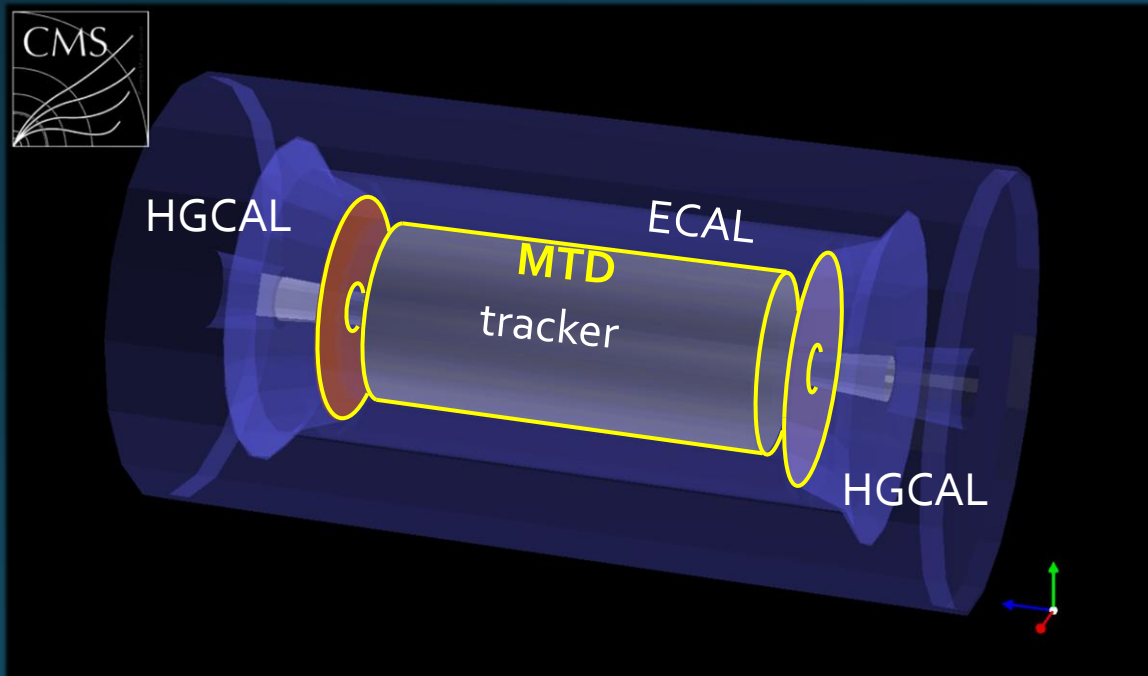
Timing information can resolve overlapping vertices

The MIP Timing Detector

New CMS layer for High-Luminosity LHC (HL-LHC):

- Time measurement of min.-ionizing (charged) particles (MIP) with resolution of 30-60 ps
- Reduce effective PU at HL-LHC using timing information
 - Time tagging MIPs: 3D $\rightarrow$ 4D vertex reconstruction
 - Reject $\sim 2x$ as many PU tracks on primary vertex

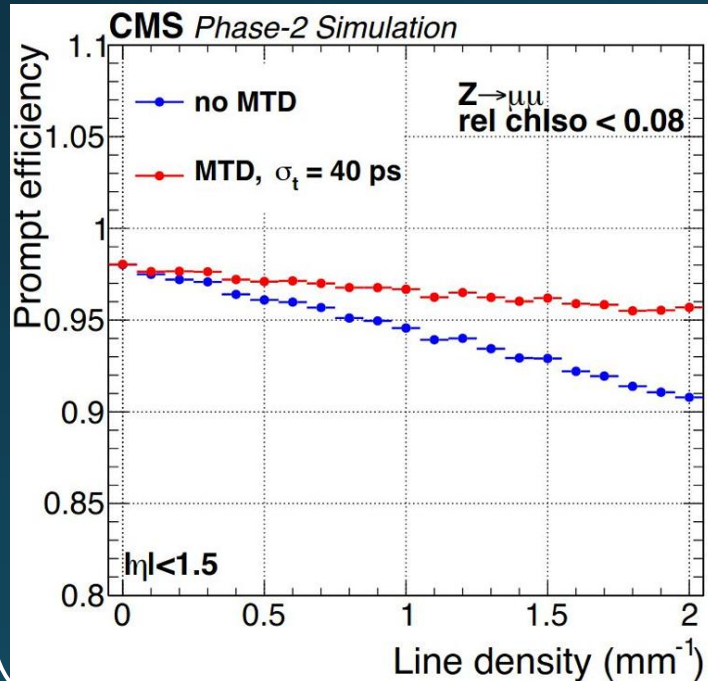
MTD Technical Design Report



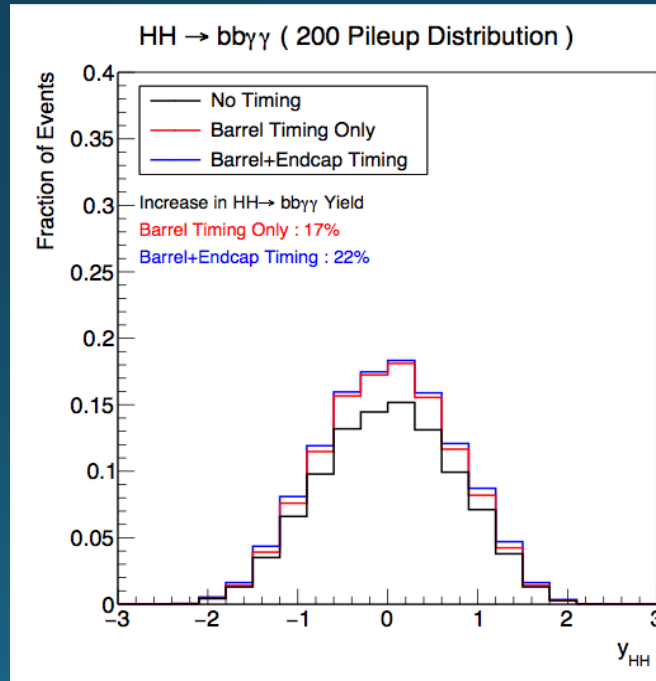
MTD impact on physics

- Improvement in identification, reconstruction and resolution of physics objects
- Higher sensitivity for rare processes
- Timing information to increase sensitivity to exotic time signatures or particle identification

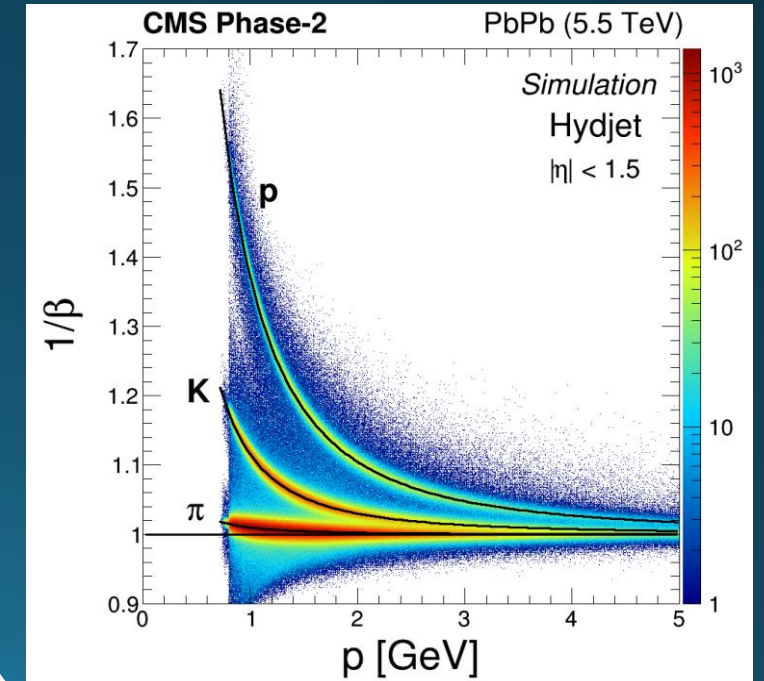
$Z \rightarrow \mu\mu$ efficiency increase



$HH \rightarrow b\bar{b}\gamma\gamma$ yield increase



Particle ID via time-of-flight



Barrel & Endcap Timing Layers

Different requirements on

- Radiation resistance
- Sensor granularity

Must Fit into

- Available space
- Different integration schedules
- Budget



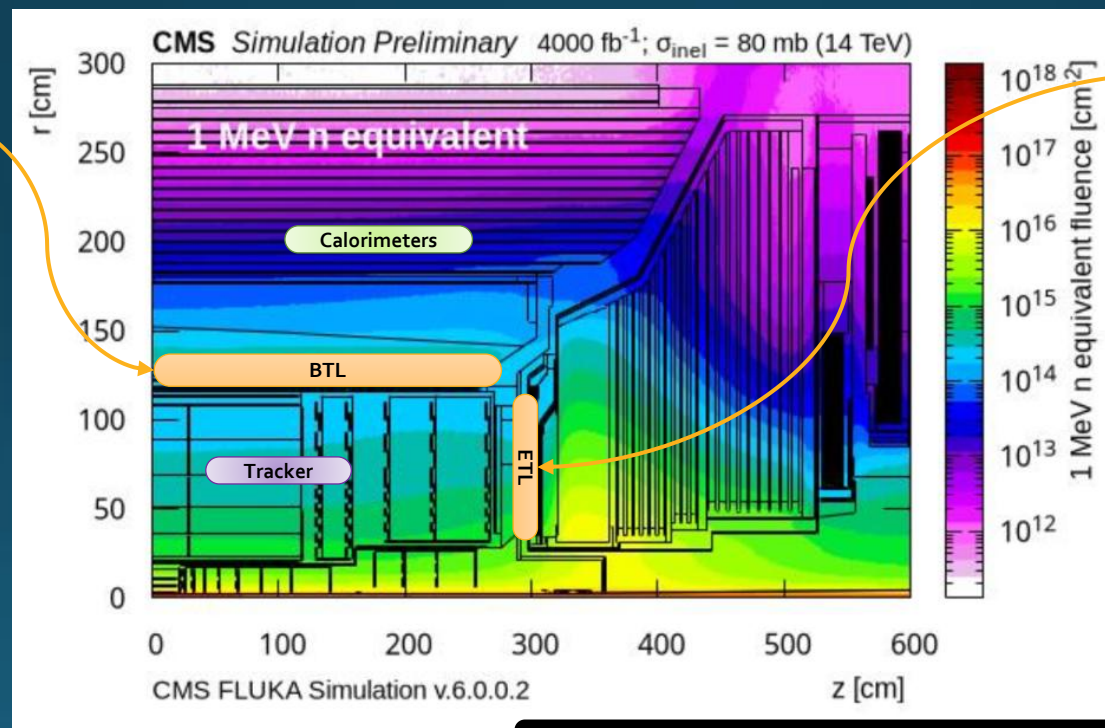
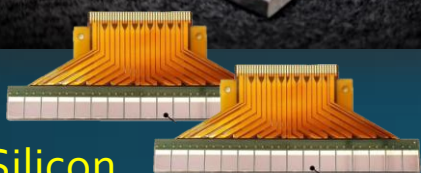
Different Detector Technologies

The Barrel Timing Layer

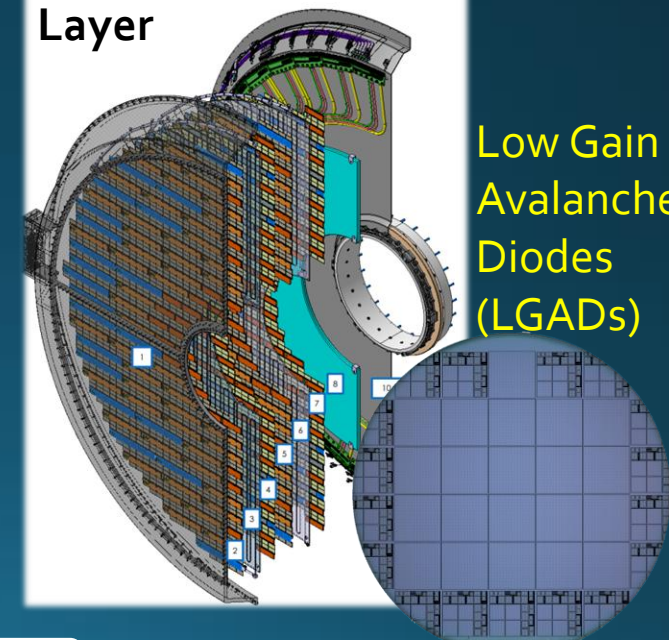
LYSO crystal array



Silicon photomultiplier (SiPM)



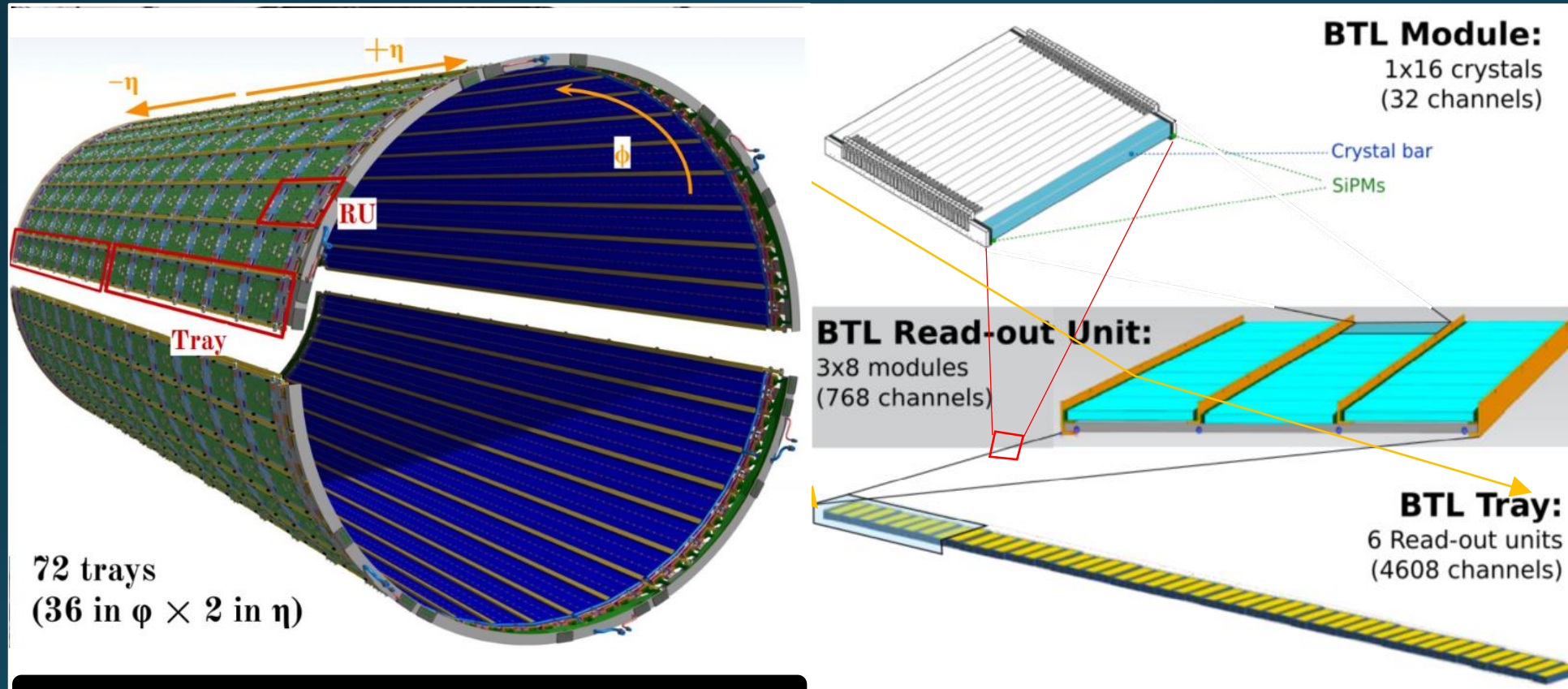
Endcap Timing Layer



[CMS public twiki - DP23087](#)

BTL Design

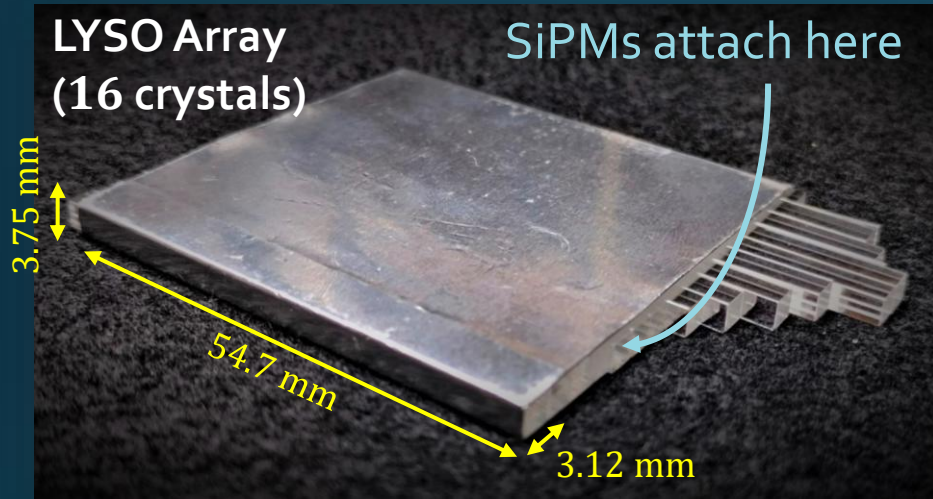
- Thin, cylindrical detector to be housed inside the BTL-Tracker Support Tube (BTST)
 - Covers region up to $|\eta| = 1.45$



[BTL-Tracker Support Tube \(BTST\) - CERN Document Server](#)

- 1.15 m radius
- 5.2 m length
- $\sim 38 \text{ m}^2$ surface
- 331k channels

BTL Sensors: LYSO

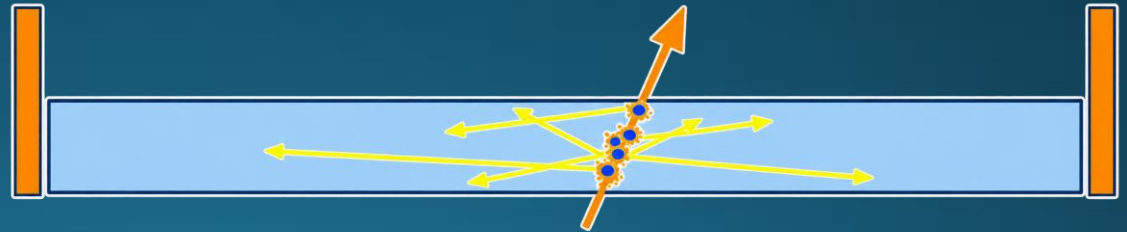


Cerium-doped Lutetium-Yttrium Oxyorthosilicate (LYSO:Ce)

- Rise time: $\tau_r \simeq 100$ ps
- Decay time: $\tau_d \simeq 40$ ns
- High Light Yield: $LY \simeq 40\,000$ ph/MeV
- High mass density (7 - 7.3 g/cm³)
- Radiation hardness
- Easy availability (used in medical applications such as PET)

Bar shaped geometry

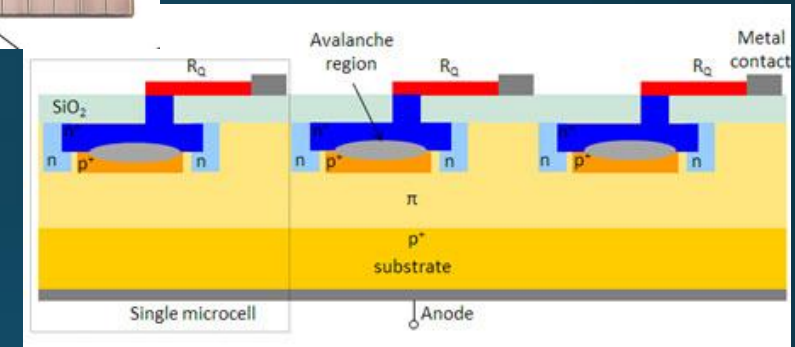
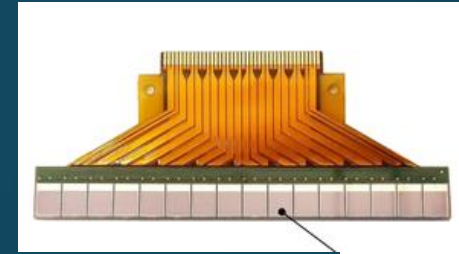
- Cover large surfaces with reduced amount of crystals
 - Reduced number of channels and power consumption
- LYSO array segmentation
 - ~ 3 mm (bar width) in transversal direction



BTL Sensors: SiPMs

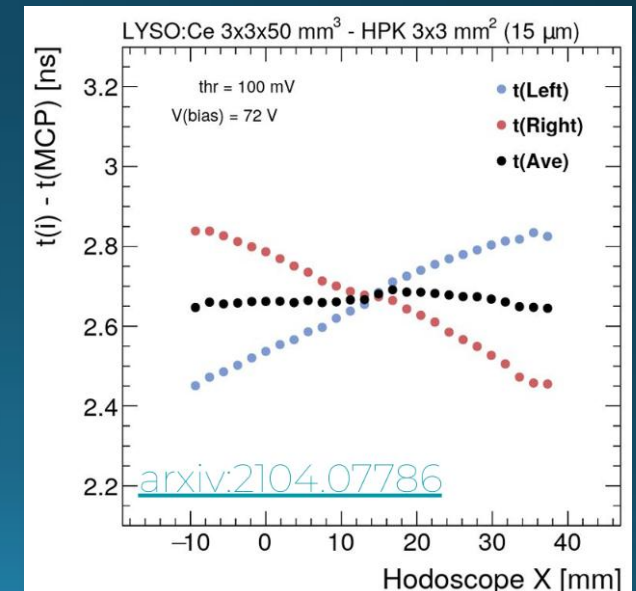
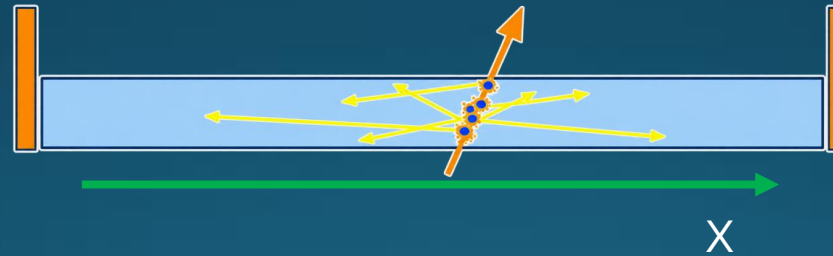
Silicon PhotoMultiplier (SiPM)

- Matrix of Avalanche PhotoDiodes (APD) in reverse bias
- Avalanche mechanism $\rightarrow$ Internal gain
- Compact and robust
- Insensitive to magnetic fields
- Operate at relatively low voltages with low power consumption
- Photo-Detection Efficiency, **PDE** up to 50%



Dual-readout

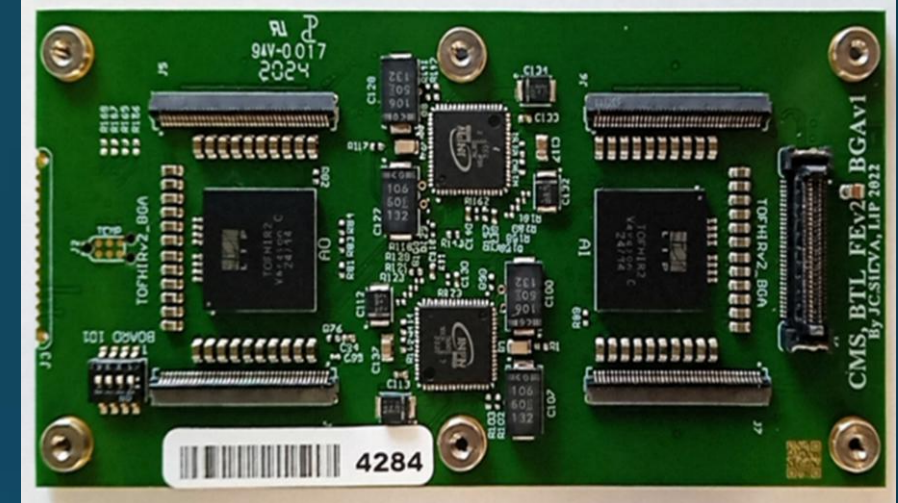
- Time average independent from impact point along the bar
- Time difference of left-right SiPMs can infer impact position along the bar
 - Spatial resolution of 2-4mm along X ([JINST 16 P07023](#)) measured since early test beams



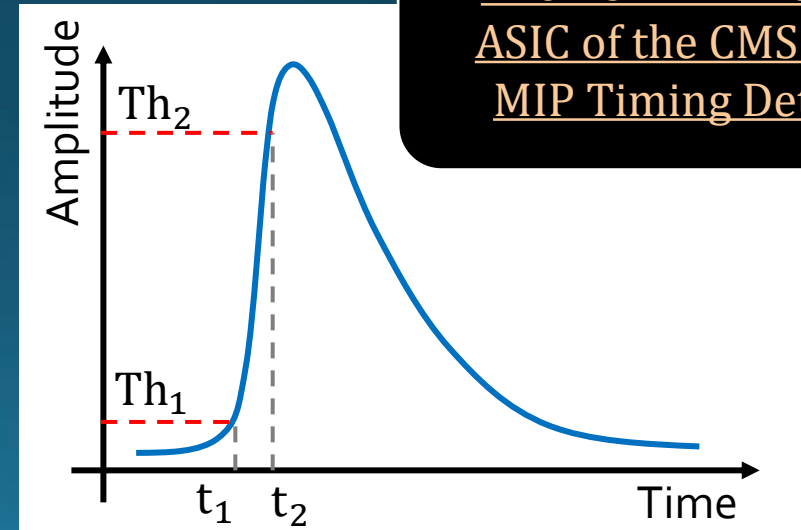
BTL Readout ASIC

TOFHIR2 ASIC for SiPMs read-out:

- 32 channels (1x BTL module)
- Radiation tolerant ($> 2 \cdot 10^{14}$ MeV neq/cm²)
- Filter for DCR reduction
- Two Time-to-Digital Converters per channel (10 ps resolution)
 - Two independent threshold for signal time measurement
- A Charge-to-Digital Converter for signal amplitude measurement → Time-walk corrections to time measurement
- Cope with MIP rate up to 2.5 MHz and a low energy signals rate up to 5 MHz



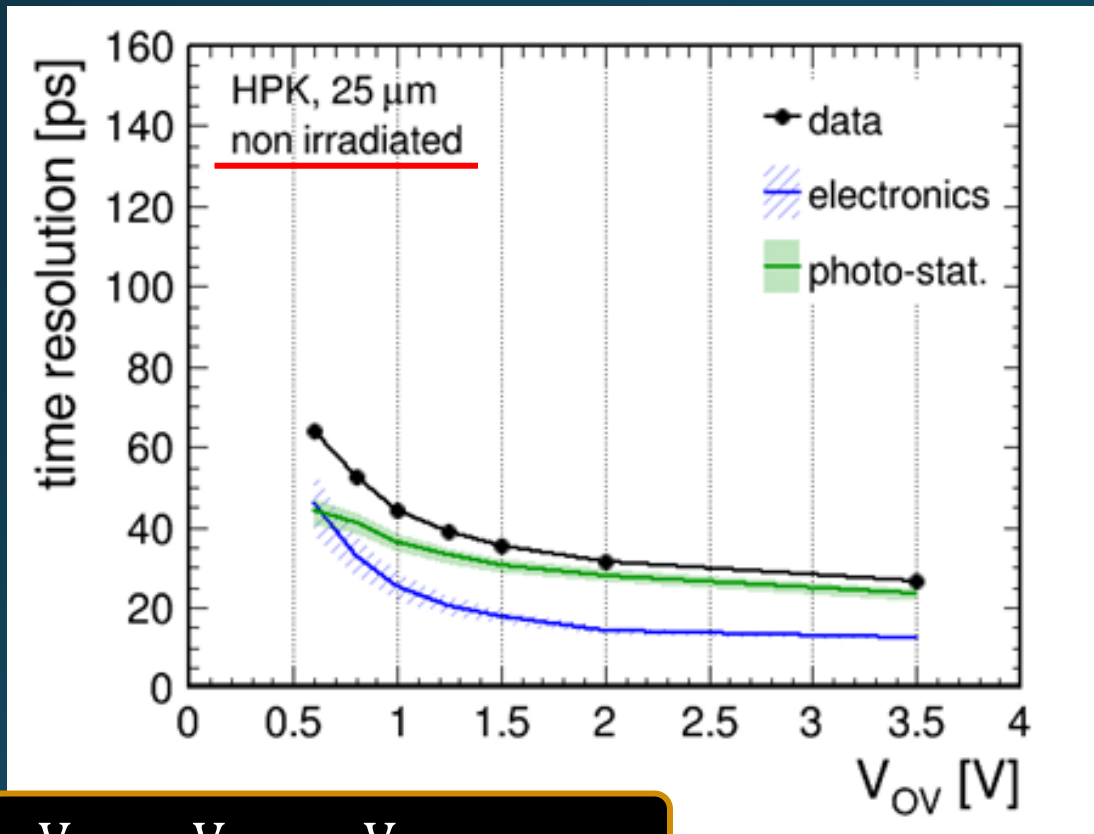
The TOFHIR2 readout ASIC of the CMS Barrel MIP Timing Detector



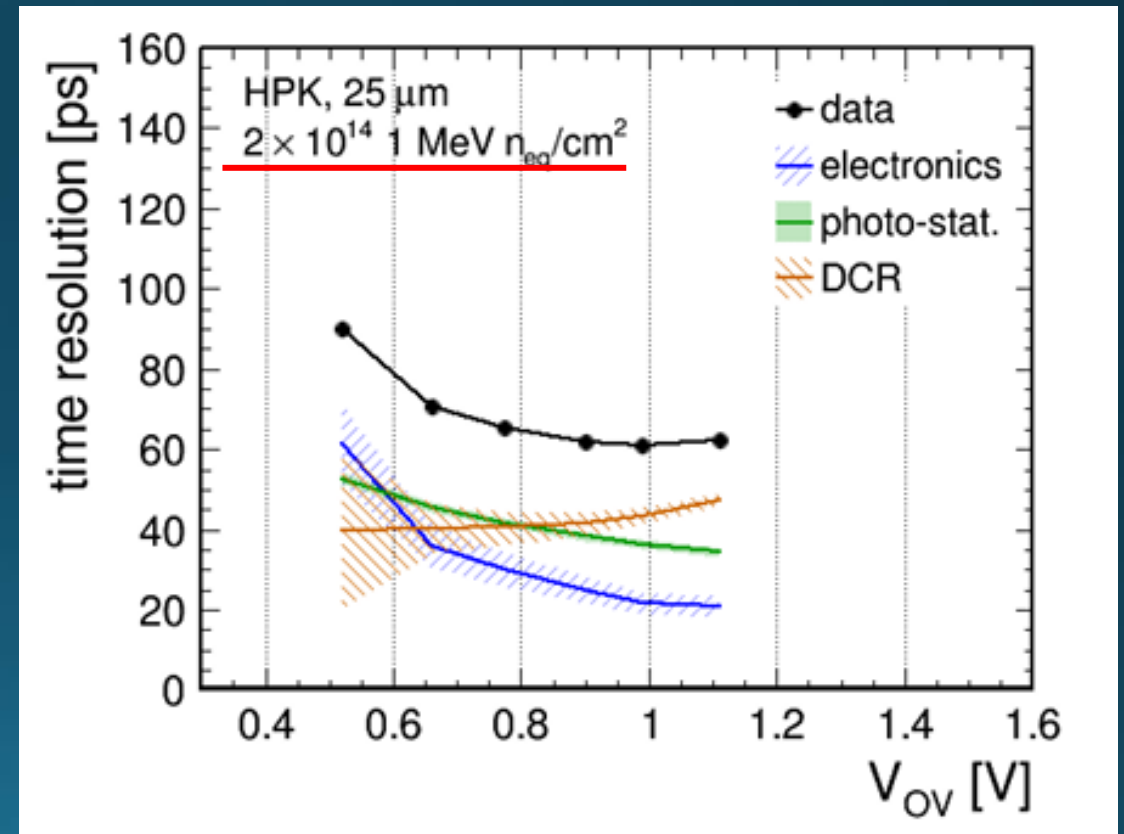
BTL Time Resolution

JINST 19 P12020 (Dec. 2024)

- SiPM Dark Count Rate will become the main time resolution driver, due to Irradiation damage,



$$V_{OV} = V_{bias} - V_{breakdown}$$



BTL Sensors Optimization

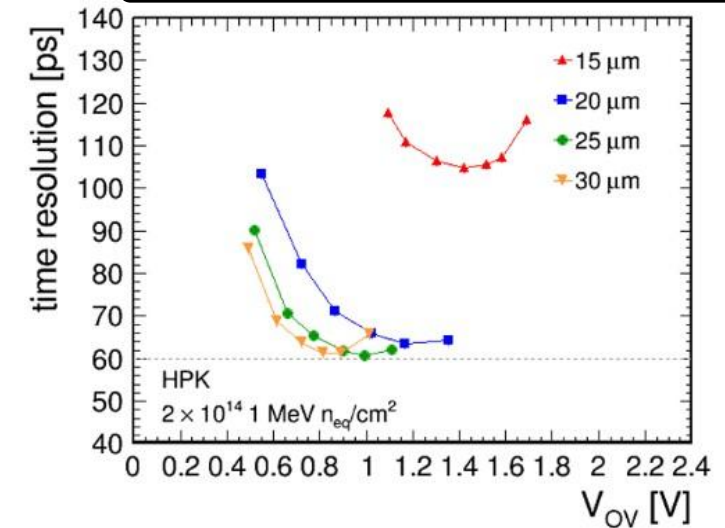
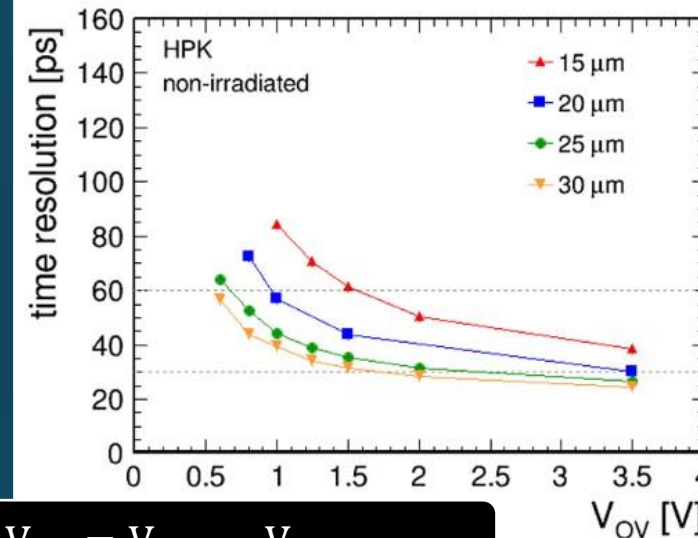
JINST 19 P12020 (Dec. 2024)

LYSO thickness

- Largest thickness allowed: 3.75mm

SiPMs cell size

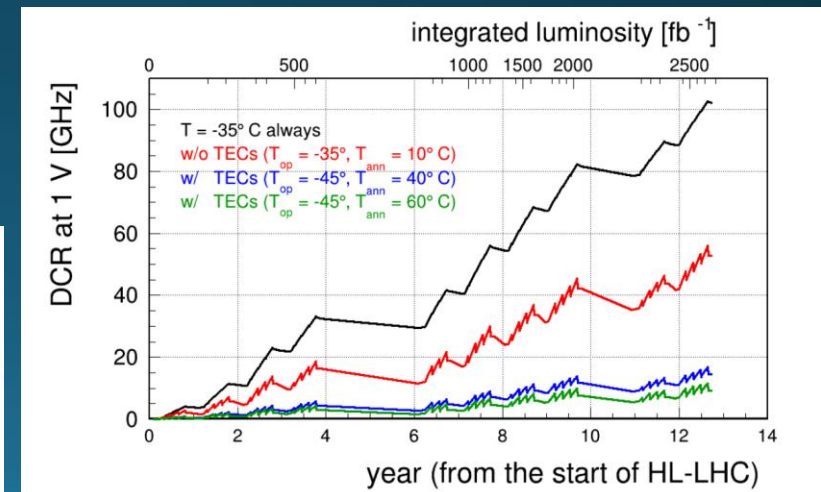
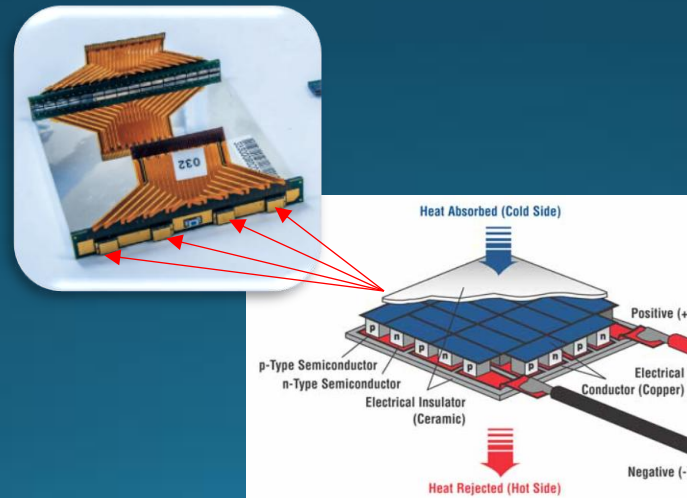
- 15 μ m, 20 μ m, 25 μ m, 30 μ m
- larger cells $\rightarrow$ higher Gain and PDE, but larger DCR for irradiated modules
- 25 μ m: best overall performances at test beams before/after irradiation



$$V_{OV} = V_{bias} - V_{breakdown}$$

DCR mitigation using Thermo Electric Coolers (TEC):

- Operating temperature from -35°C (original design) to -45°C
- SiPM radiation damage recovering (annealing) up to 60°C during LHC stops

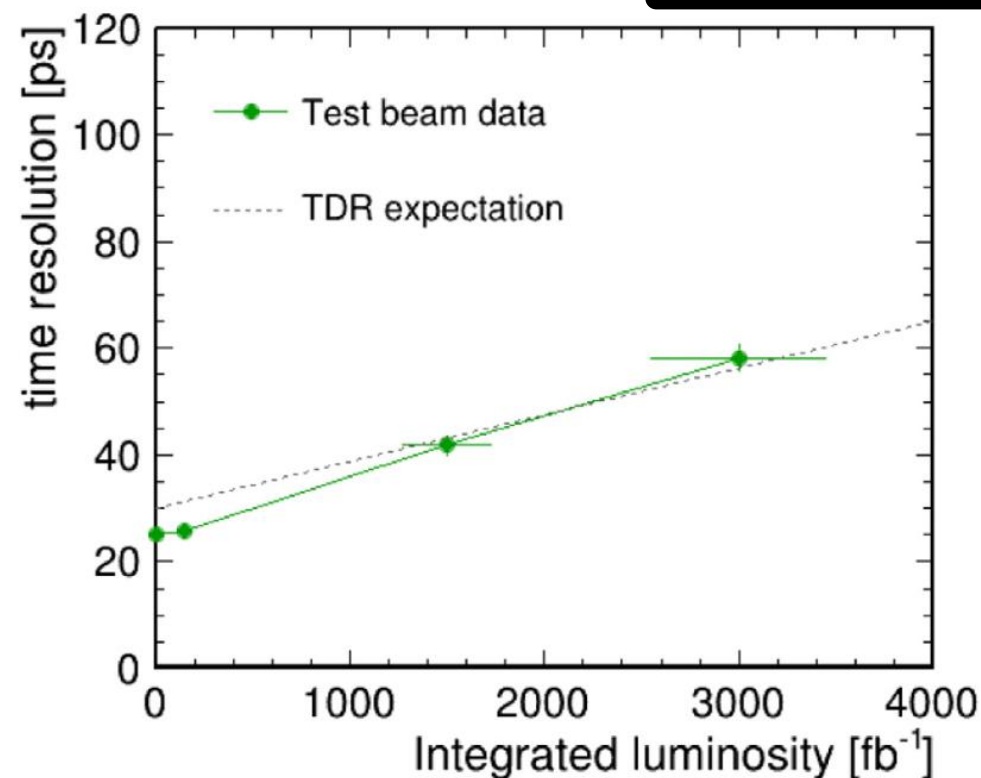
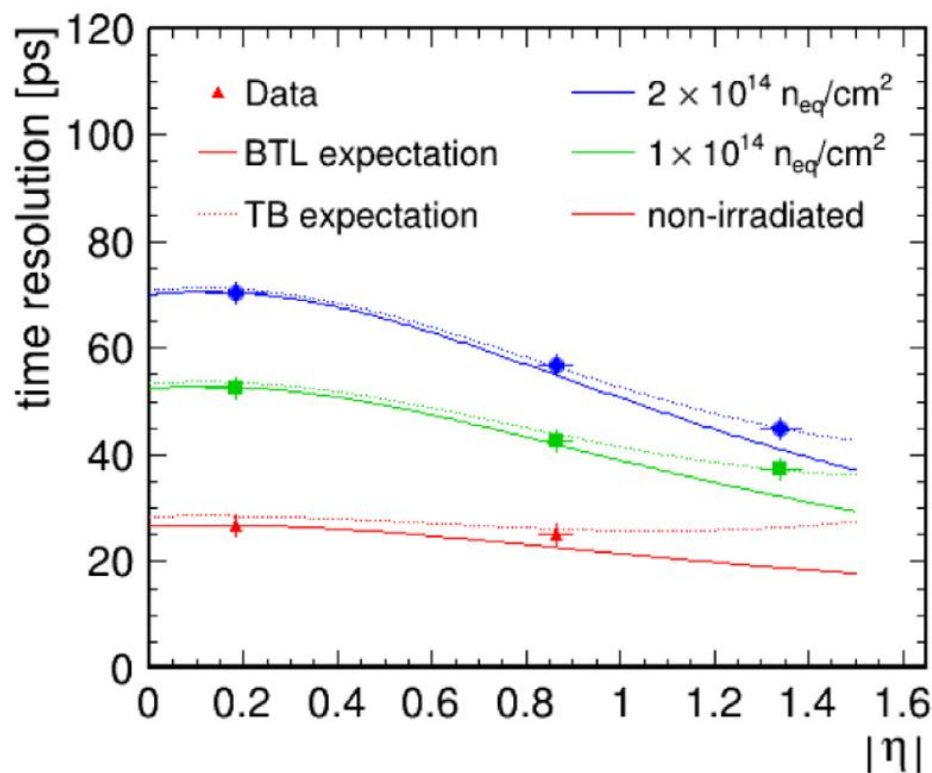


2023 JINST 18 P08020

Test-beam validation of BTL timing performance

Test-beam measurements **confirm that BTL meets the target timing performance** across the full detector acceptance and throughout the expected HL-LHC lifetime.

NIM A (2025) 170823

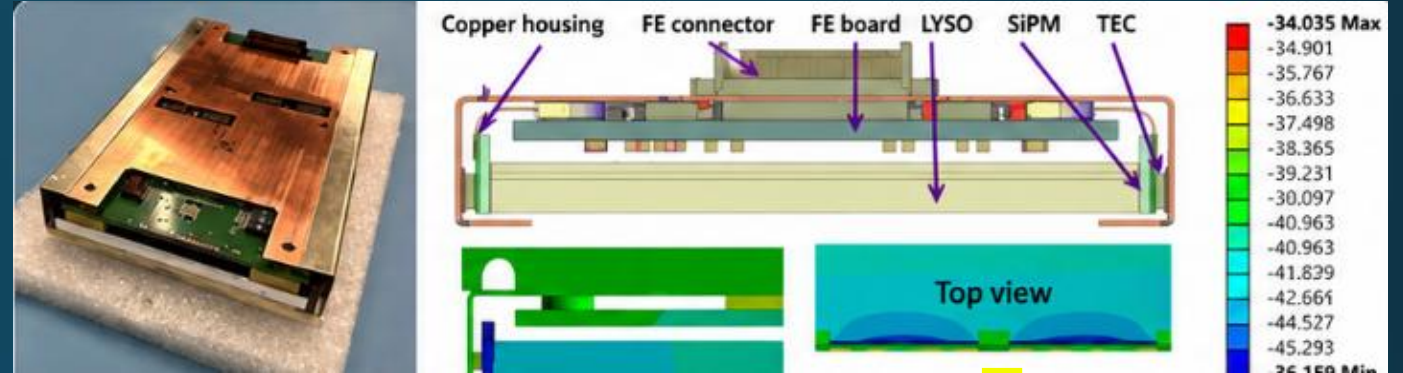


BTL Assembly

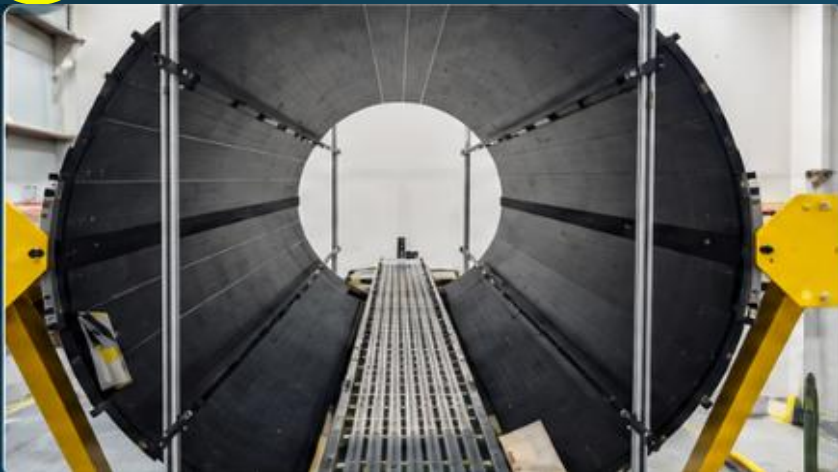
1 Sensor Module LYSO + SiPMs arrays



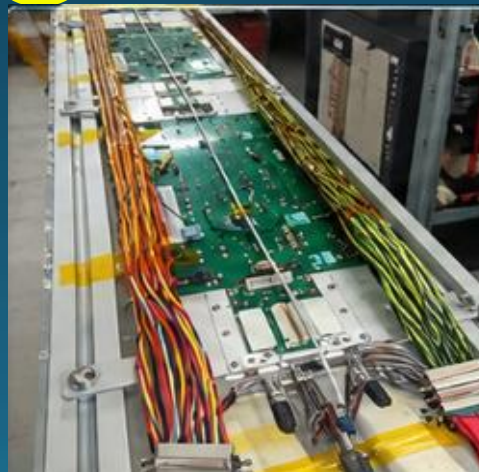
2 Detector Module (2 SMs + front-end board)



5 Integration in BTL-Tracker Support Tube



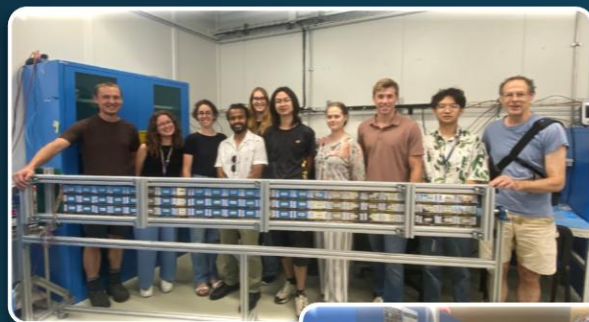
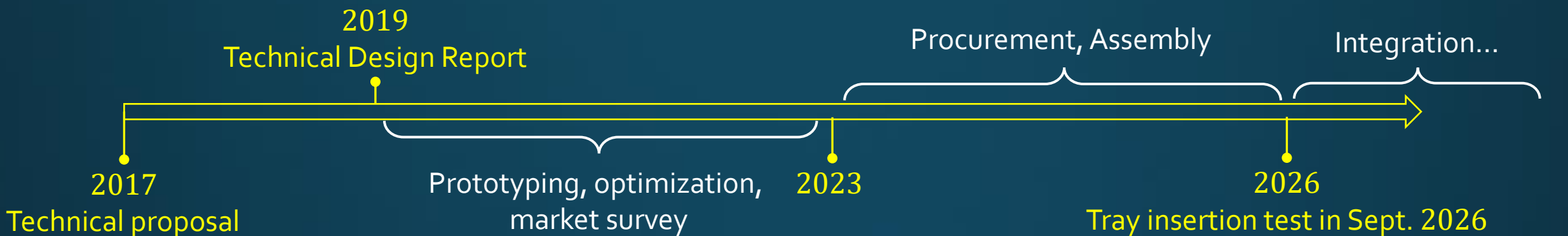
4 Tray (6 RUs)



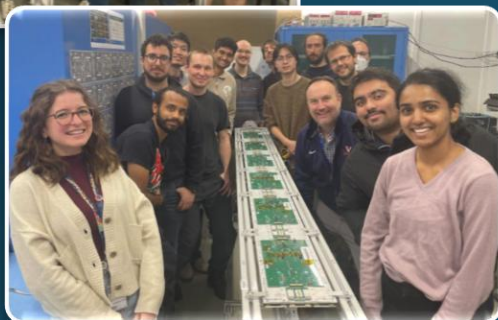
3 Readout Unit (3x12 DMs + Electronics)



BTL Status



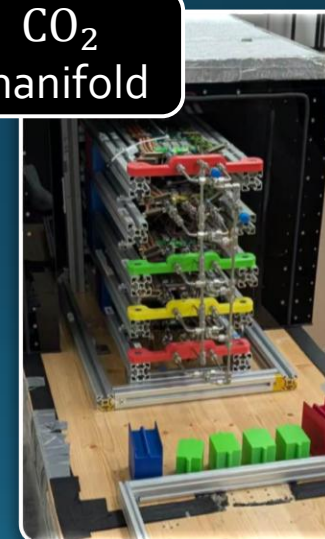
First 2 trays assembled at CERN (2024)



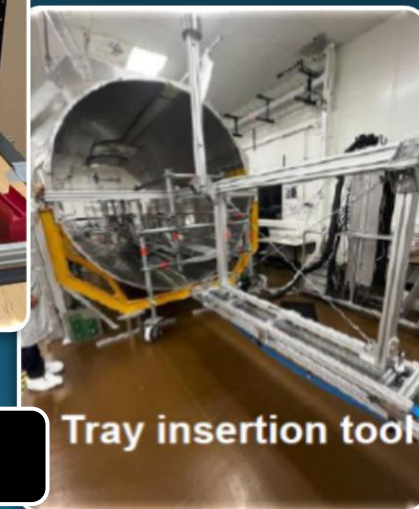
Each part assembled and QA/QC'd in 4 assembly centers worldwide



CO₂ manifold



Final cooling/annealing test at CERN

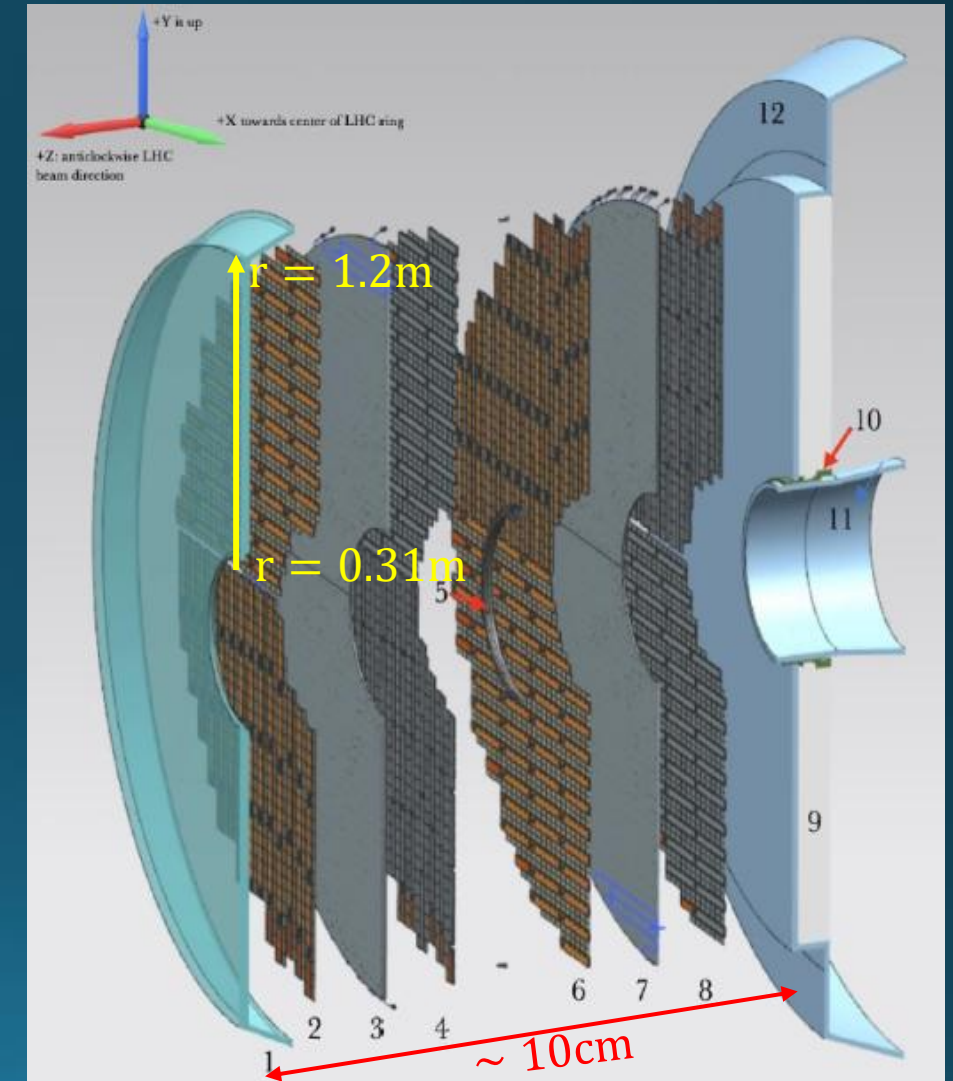
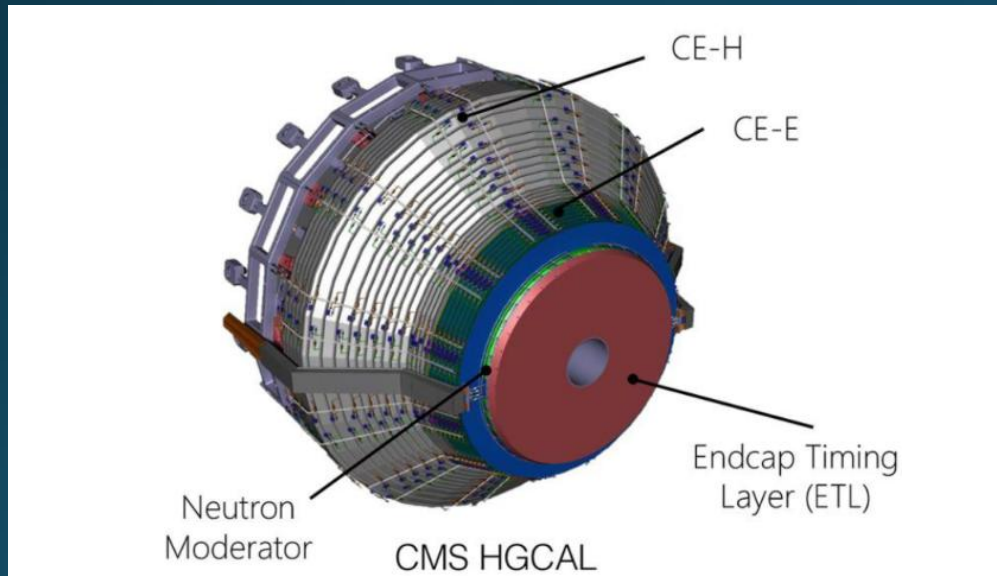


Integration!

Tray insertion tool

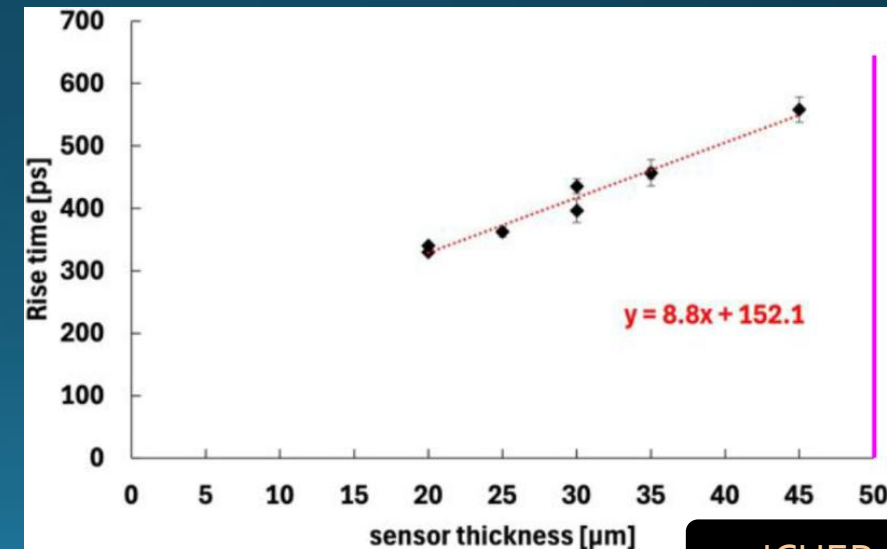
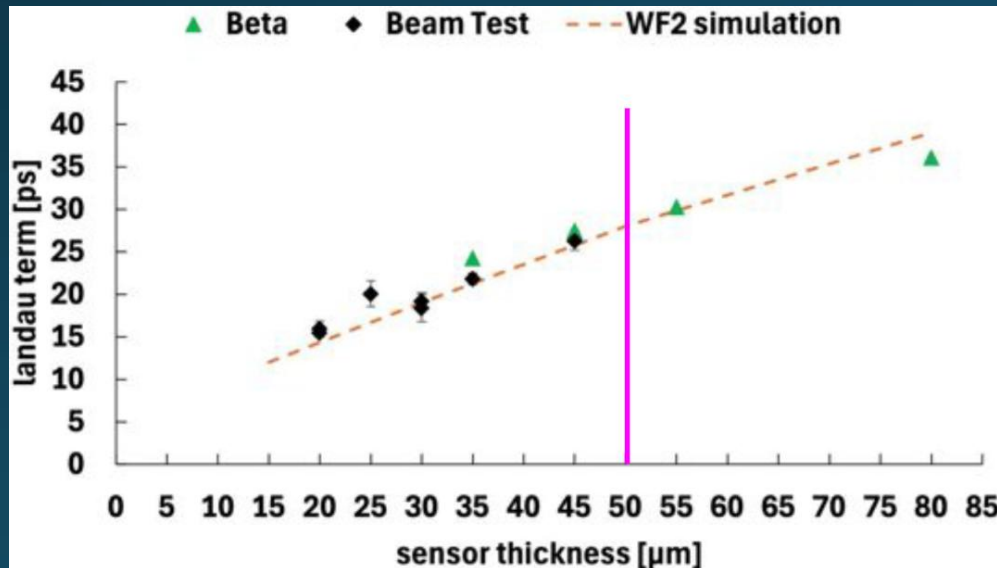
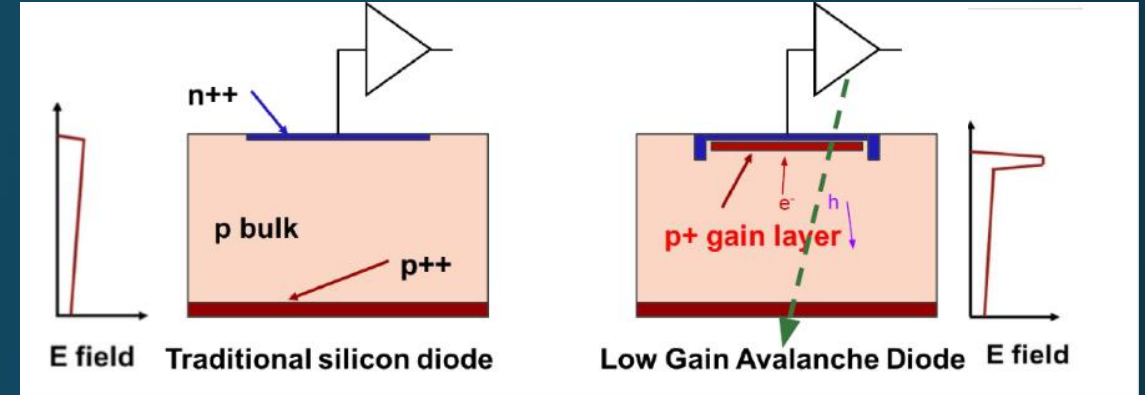
The ETL Design

- 2 disks per endcap, mounted on HGCal nose.
- **16x16 LGAD sensors**, bump-bonded to the **ETROC2 ASIC**
- Each disk has sensors on both sides:
 - ~85% geometrical acceptance. → Average 1.7 hits for clean MIPs with ~straight trajectory (muons)
 - Timing res. (end of lifetime): ~ 50ps per hit, ~ 35ps per track



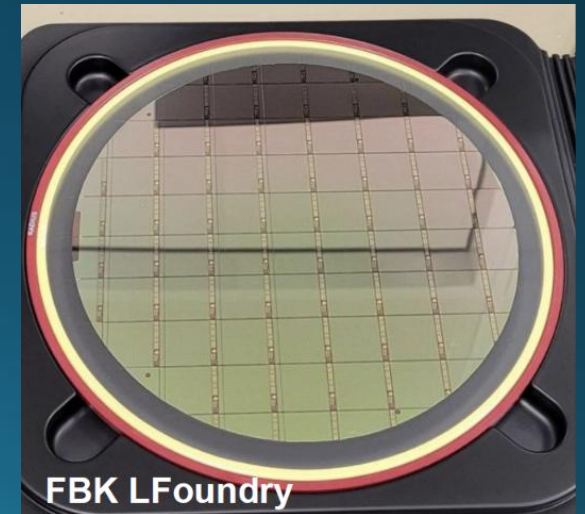
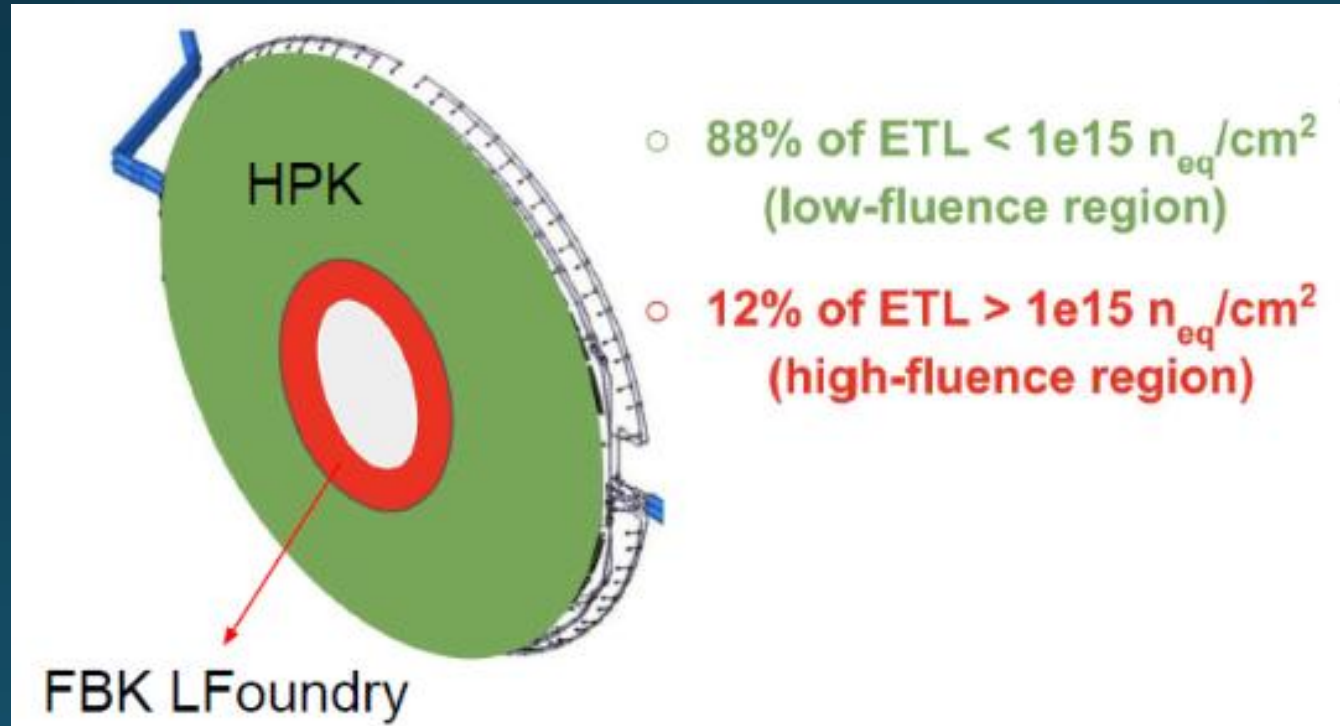
ETL Sensors

- n-in-p planar Si sensors based on Low-Gain Avalanche Diode (LGAD) technology
 - p-type implant in gain layer produces high electric field with internal gain: high S/N and low jitter.
 - Active thickness $\sim 50\text{ }\mu\text{m}$: low Landau fluctuation and fast signal rise time.



LGAD types and procurement

- Sensor characteristics:
 - 16x16 pixel matrix with 1.3 mm pitch and fill factor ~90%.
 - Specialized sensors for high and low fluence regions to cope with different radiation level
- May 2026: arrived 5% of ETL sensors - yield per wafer > 80% for both vendors

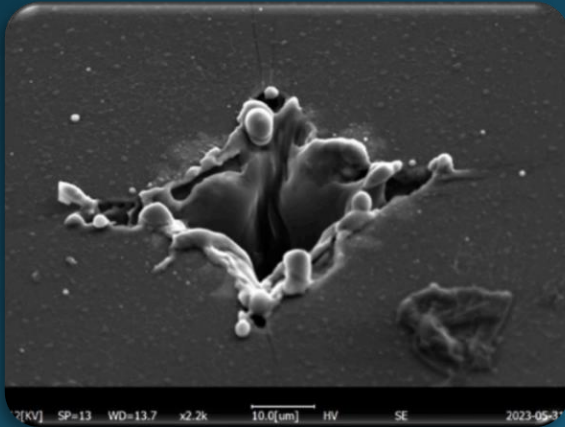


LGAD Radiation Damage Mitigation

Radiation Damage cause internal gain loss

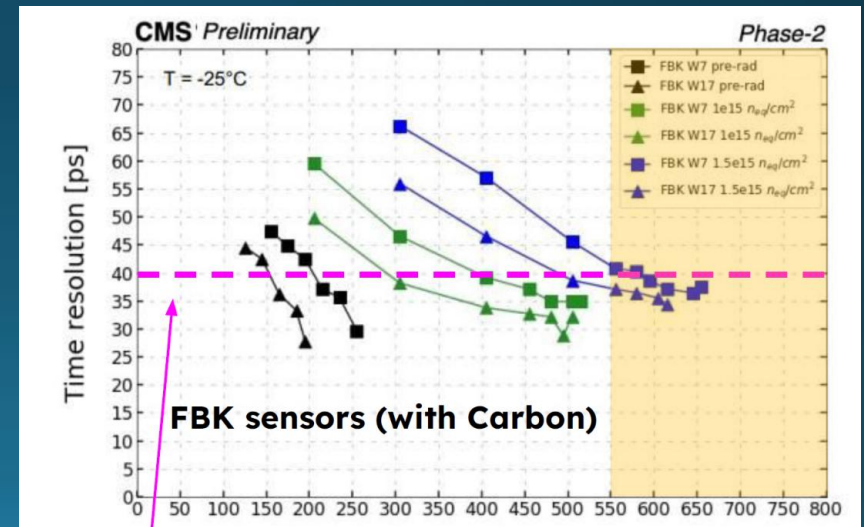
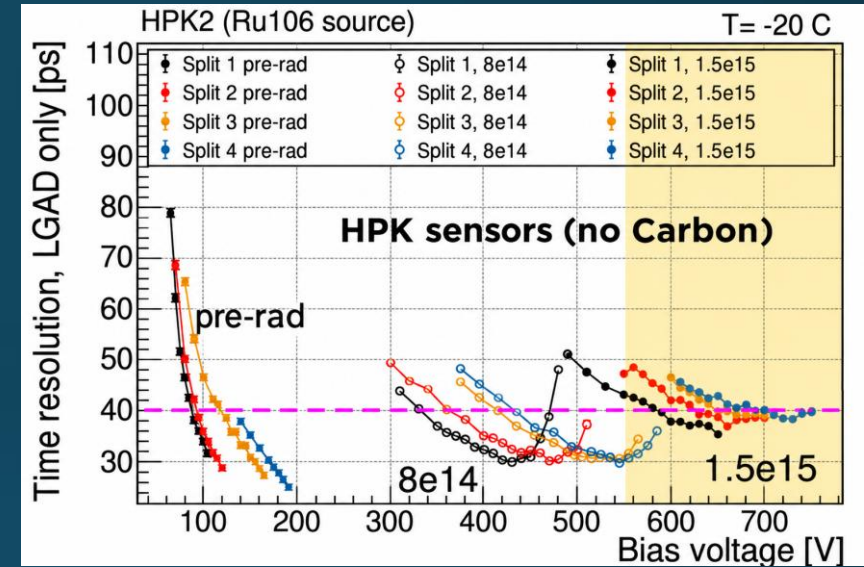


- Carbon co-implantation in p^+ layer in FBK-Lfoundry LGADs
 - Increased resistance to radiation
- Increase of Bias Voltage to compensate gain loss
 - Limited by Single Event Burnout (SEB) Events



Crossing of charged particle can cause SEB for an electric field $E > 11\text{V}/\mu\text{m}$

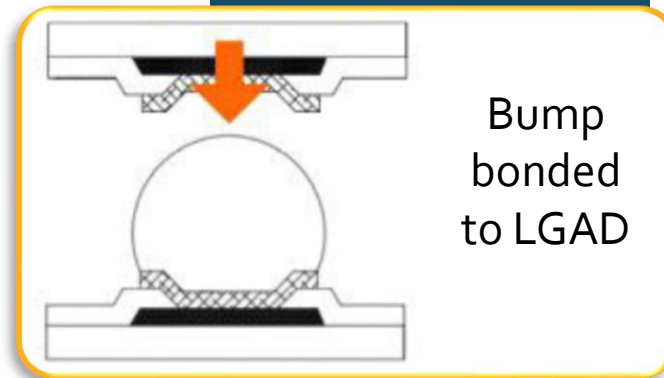
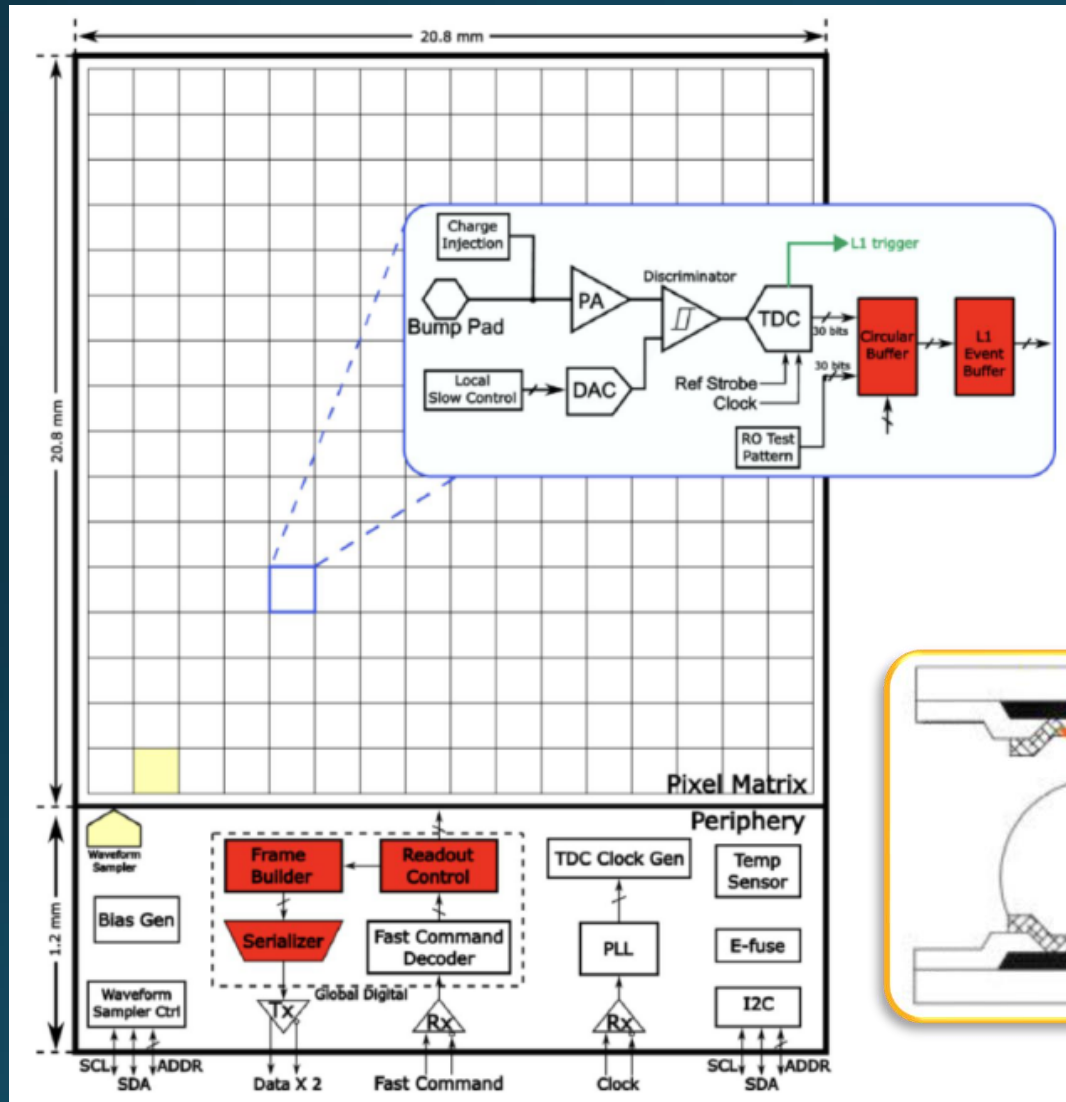
[Frontiers - 2025 - 1575672](#)



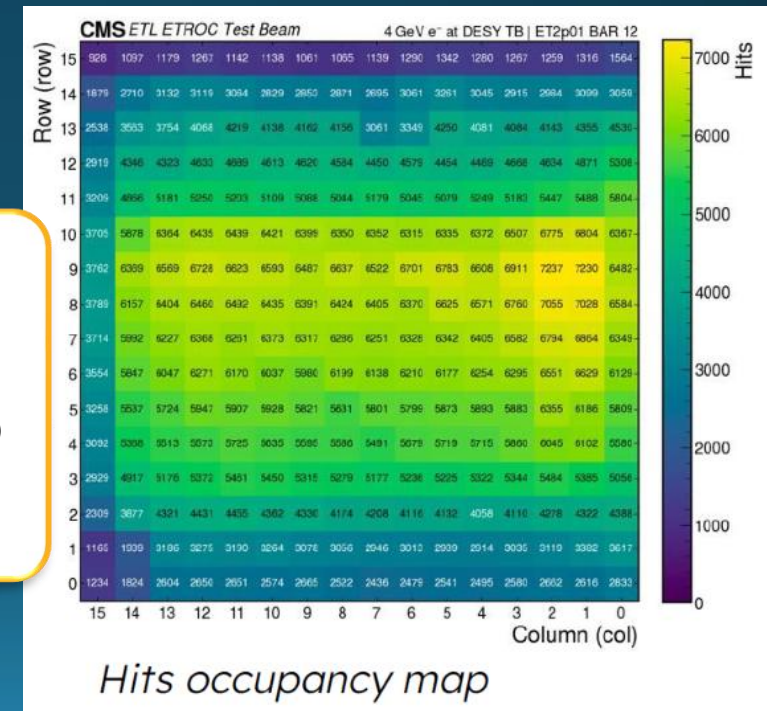
ETROC

Endcap Timing ReadOut Chip

- 16x16 array with 1.3 mm pitch in TSMC CMOS 65nm technology
- Pre-Amplifier + Discriminator + TDC
- High efficiency achieved in bump bonding (hybrids with all connected pixels at test beams)
- Thermal cycling studies performed: low number of disconnected bump bonds

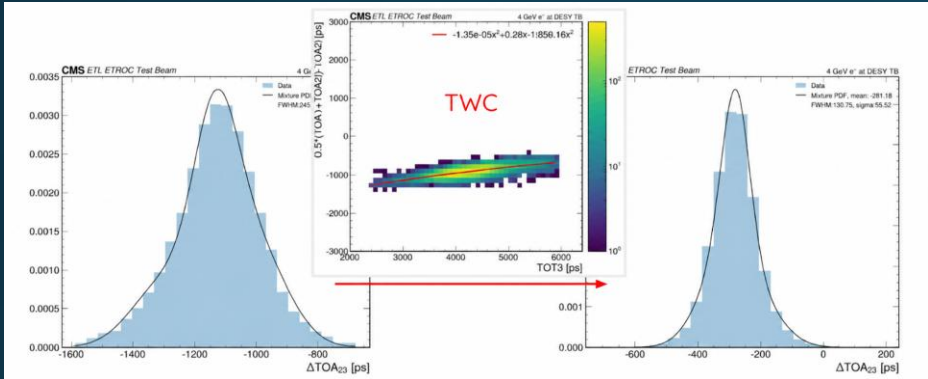


Bump
bonded
to LGAD



ETL performances at test beams

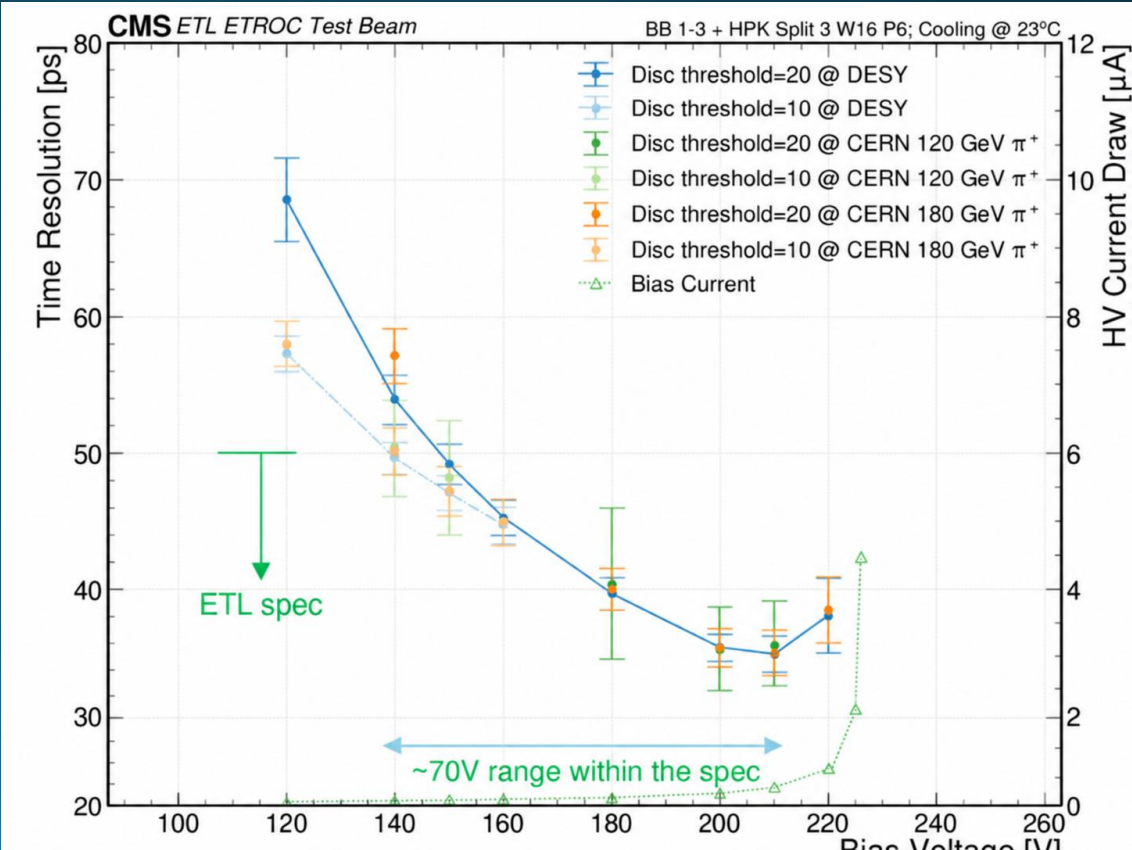
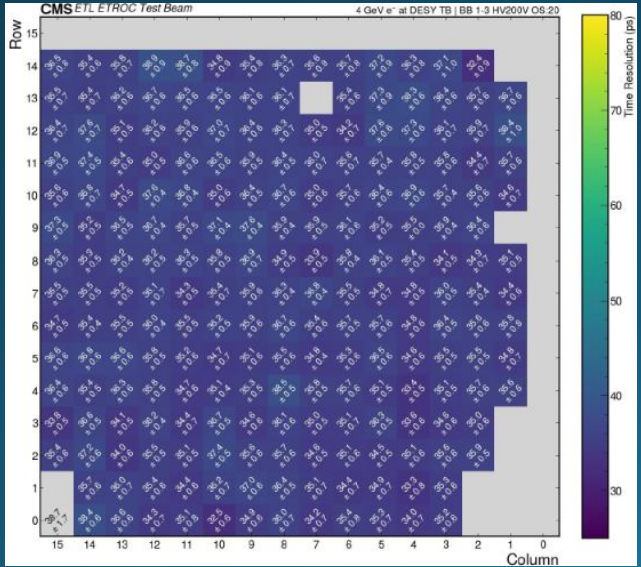
- Extensive test beam campaigns in last ~ 8 years
 - DESY, June 2024 (e^- , 4 GeV): ~ 35 ps time res., good uniformity in modules and over large V bias range



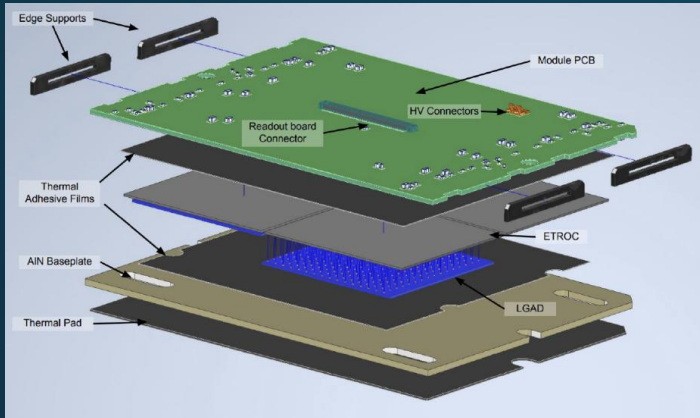
time-walk
corrections from
time-over-
threshold

Time resolution
uniformity in a
module

TWEPP – 2024
IEEE - 2024



ETL modules assembly and QA/QC



Modules

- 4 ETROC2 + LGAD hybrids
- Module PCB readout
- AlN substrate for thermal contact

Assembly centers

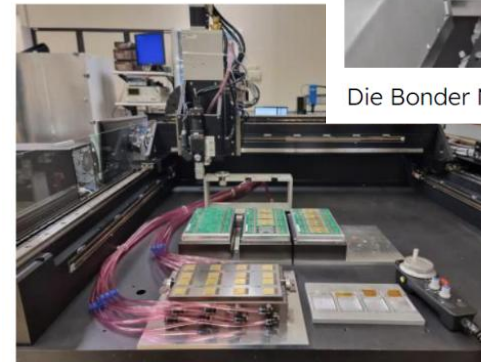
- FNAL, BU, INFN Turin and IFCA
- Recently KNU joined
- Procedures under development with versatile setup using cosmic / beta source/ laser



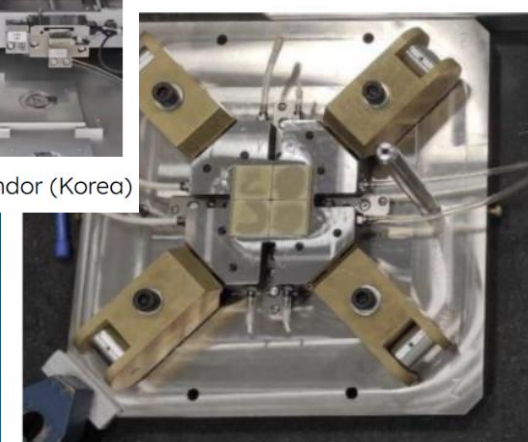
SCARA Robot: IFCA



Die Bonder Machine: KNU with vendor (Korea)



Robotic Gantry: FNAL and BU (US)

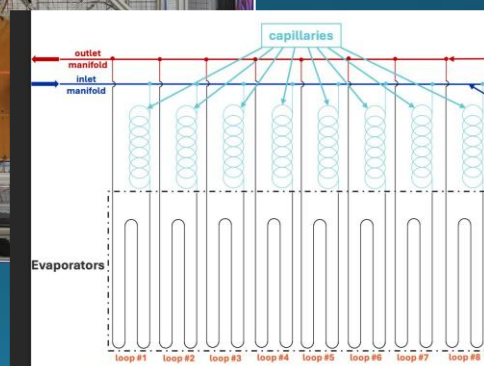
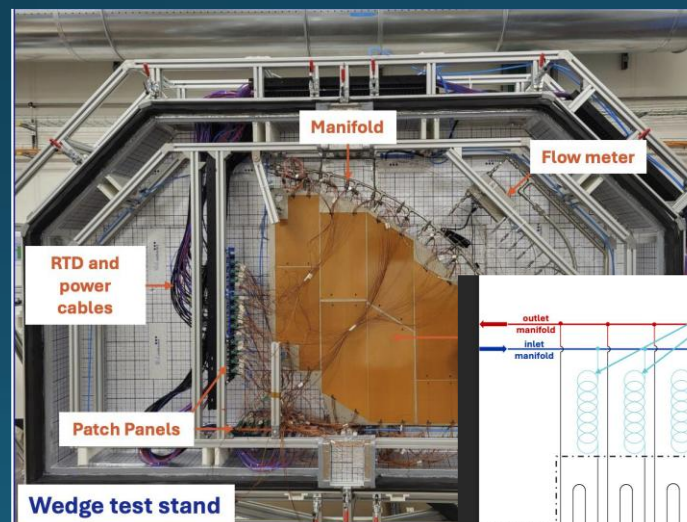
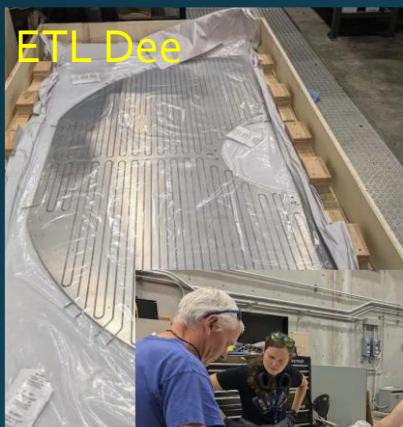
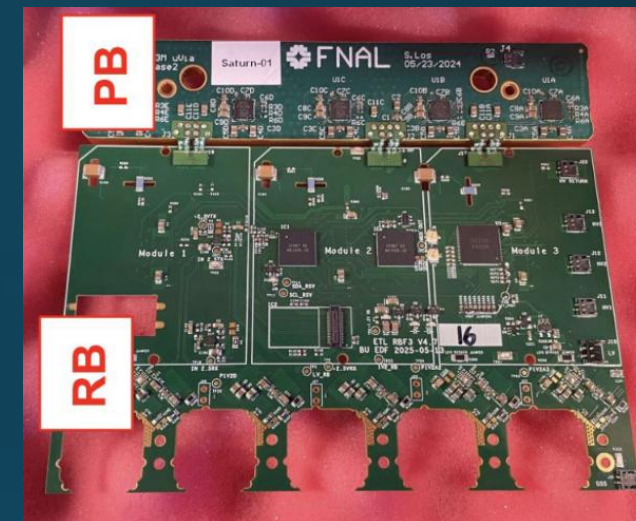
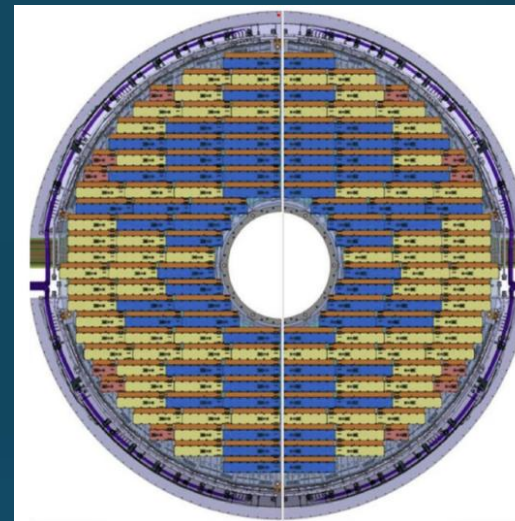


Mechanical Jig: INFN (Italy)

ETL system

Readout boards (RB) and power boards (PB)

- 3 different flavours (3, 6, 7) to optimize bias voltage lines maximizing coverage
- 3 RB+PB systems connected to modules tested on beam in June 2026, data analysis ongoing



Mechanics and cooling

- Dee: thin aluminum plate with steel pipes for evaporated CO₂ cooling
- First Dee in production at CERN
- Completed cooling test on a wedge (half dee), characterizing evaporators at -32°C

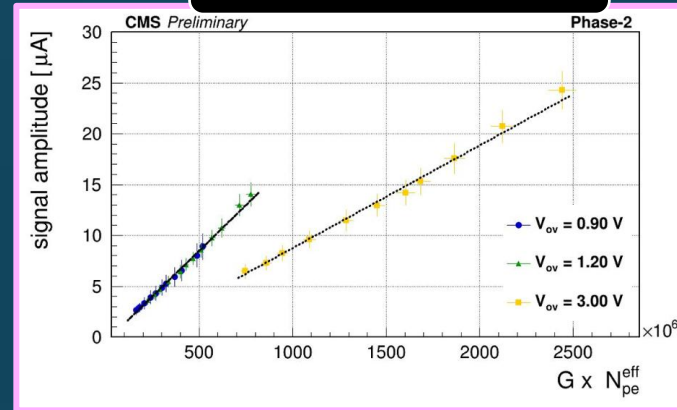
MTD Simulation and Reconstruction



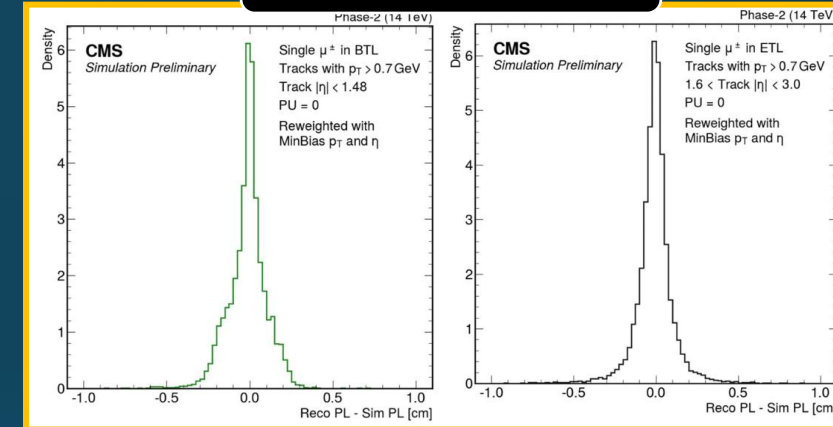
Improvement in detector knowledge

- Update of BTL digitization model from lab. measurement with UV-excited scintillation from laser
- Estimation of time uncertainties at the point of closest approach to beam line accounting for track propagation

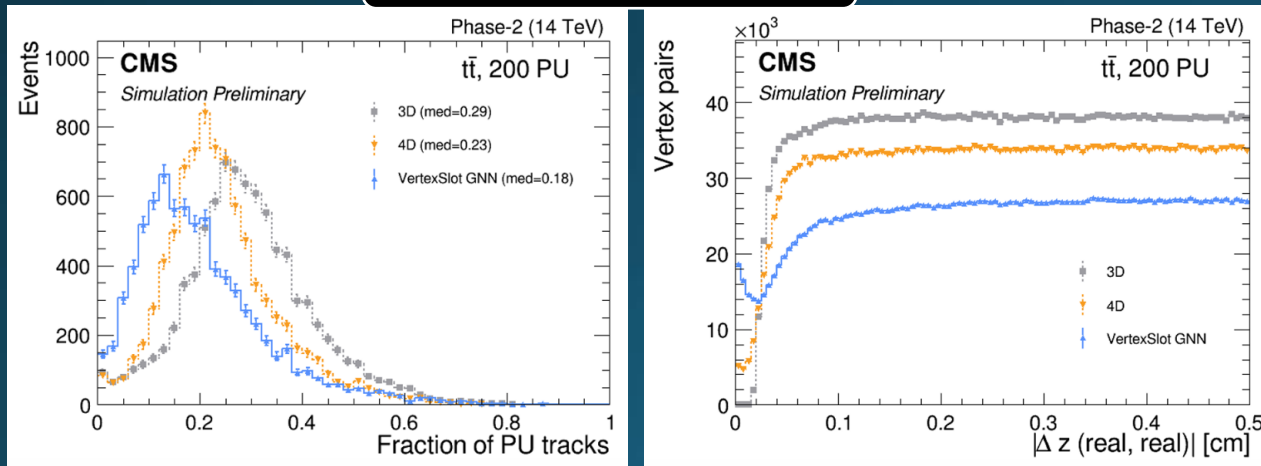
CMS-DP-2026-019



CMS-DP-2025-037



CMS-DP-2026-042



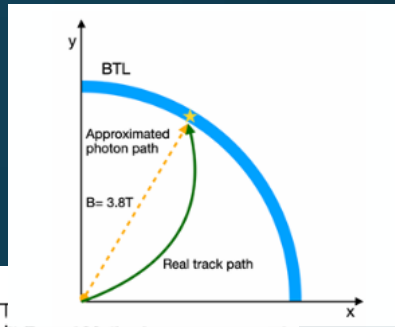
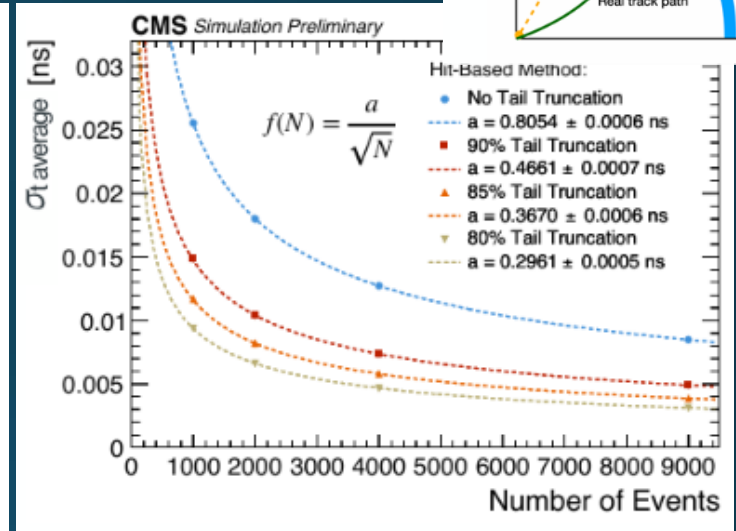
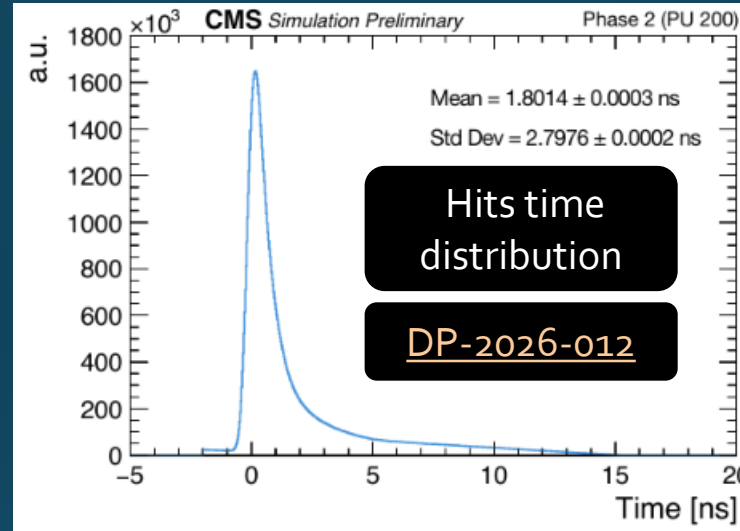
New primary vertex reconstruction algorithm

- Use of GNN with slot attention to cluster tracks into vertices
- reduces leading-vertex PU contamination, reconstructs comparable numbers of vertices, and retains closer vertex pairs than previous 4D algorithm
- Work ongoing to mitigate the increases in fake vertices rate from real vertex splitting

BTL Monitoring and Calibration

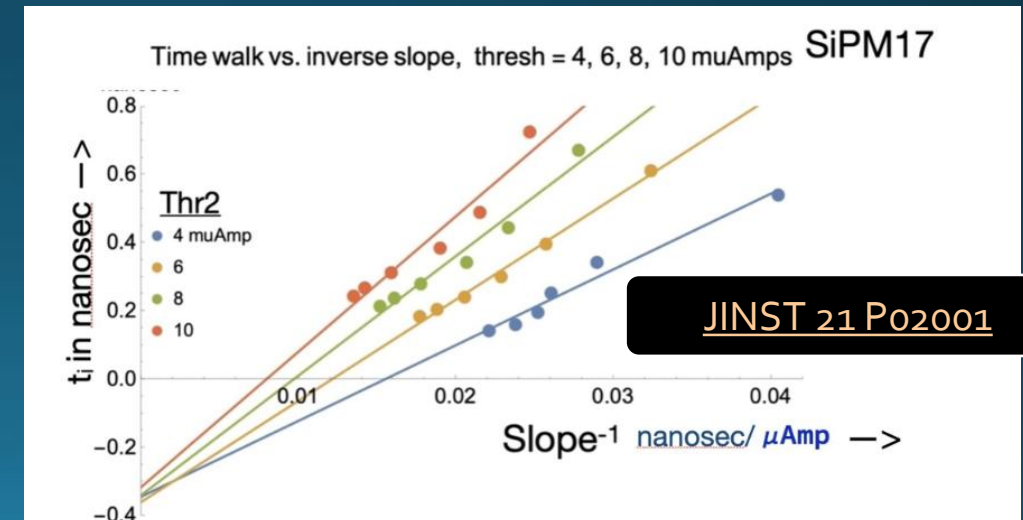
Approaches for in-situ time monitoring

- Only BTL hits time information (photon TOF hypothesis)
- With track info (pion TOF hypothesis, plots in backup)
- Monitoring median time measured by a RU in few sec. of data-taking



BTL Calibration

- Efforts ongoing on developing a framework for BTL Calibration in Phase 2
- Inputs from test beam experience and detector QA/QC useful to develop calibration approaches
- Investigating application of a method for time-walk correction using TOFHIR measurement of signal slope



Summary



- **MTD will provide 30– 60 ps timing for charged particles**, enabling 4D vertex reconstruction and reducing pile-up contamination to improve CMS physics sensitivity at the HL-LHC.
- **BTL test beams validate the target timing performance** across the full acceptance and expected HL-LHC lifetime. Optimized LYSO–SiPM modules and thermoelectric cooling mitigate radiation damage.
- **BTL assembly and QA/QC almost completed at four centers**, with integration activities at CERN ramping up and a tray insertion test in September
- **ETL test beams demonstrate ~35 ps timing resolution**, with < 50 ps after irradiation up to 10^{15} protons/cm². Sensor procurement and module assembly preparations are progressing.
- **ETL system integration is advancing**: complete readout and power chains underwent beam tests in June 2026, cooling tests are complete, and the first Dee is in production.
- **Software is developing** towards a more realistic simulation, with new approaches for reconstruction, monitoring and calibration under study

backup

The High-Luminosity LHC Schedule

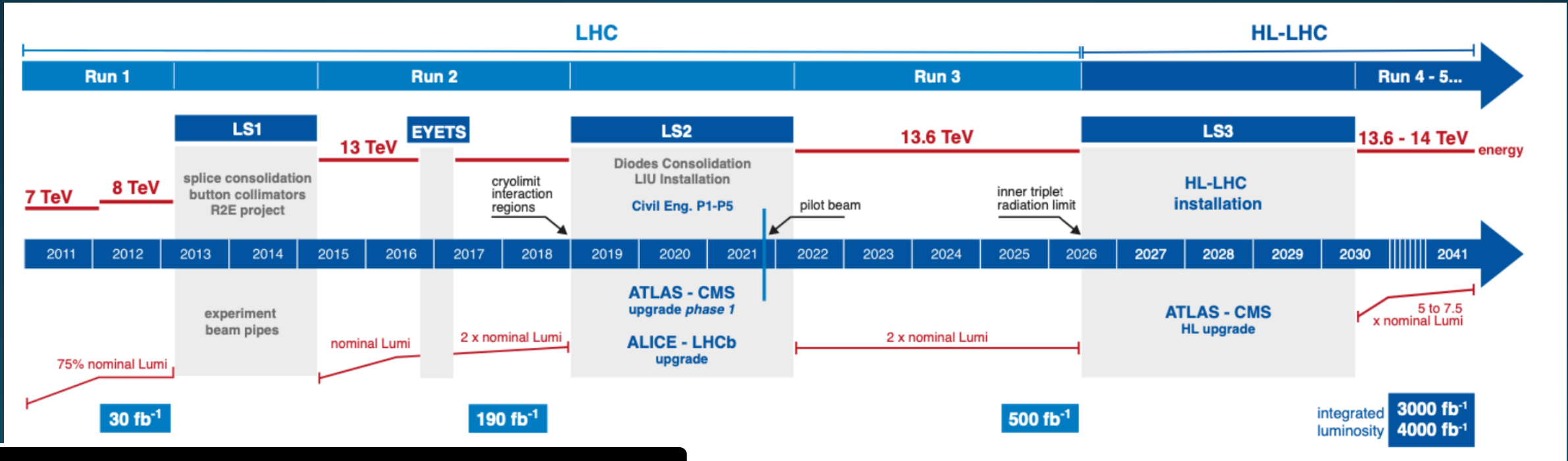


Performance Targets

- 3000 fb⁻¹ of data by early 2040s
- Peak lumi of 7.5×10^{34} cm⁻²s⁻¹, 3-4 times Run 3

Physics Goals

- Precision measurements of Higgs couplings
- Observation/study of rare processes
- Extend searches of physics beyond the Standard Model



[LHC upgrade project - arxiv.2505.03535v1](https://arxiv.org/abs/2505.03535v1) - May 2025

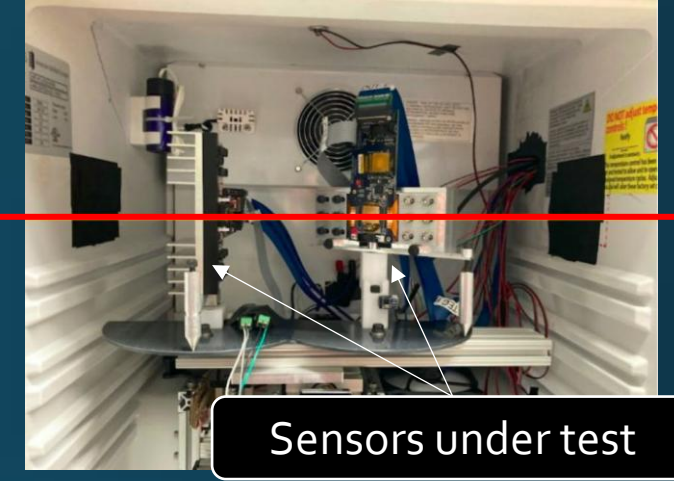
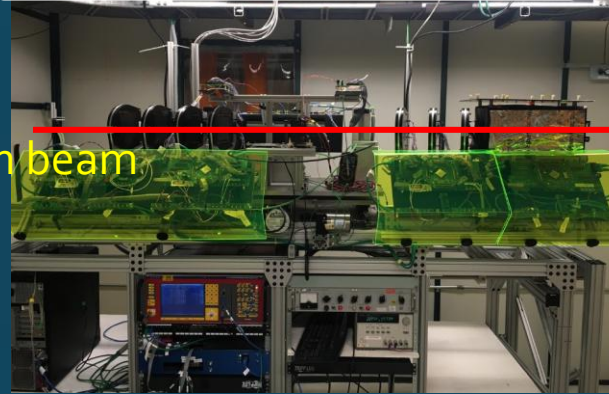
Latest BTL testbeam campainings

March 2023 @FNAL

- sensor modules with 10-15-25 μm cell-size SiPM and different LYSO thickness
- Only non-irradiated sensors

FNAL testbeam Telescope

proton beam

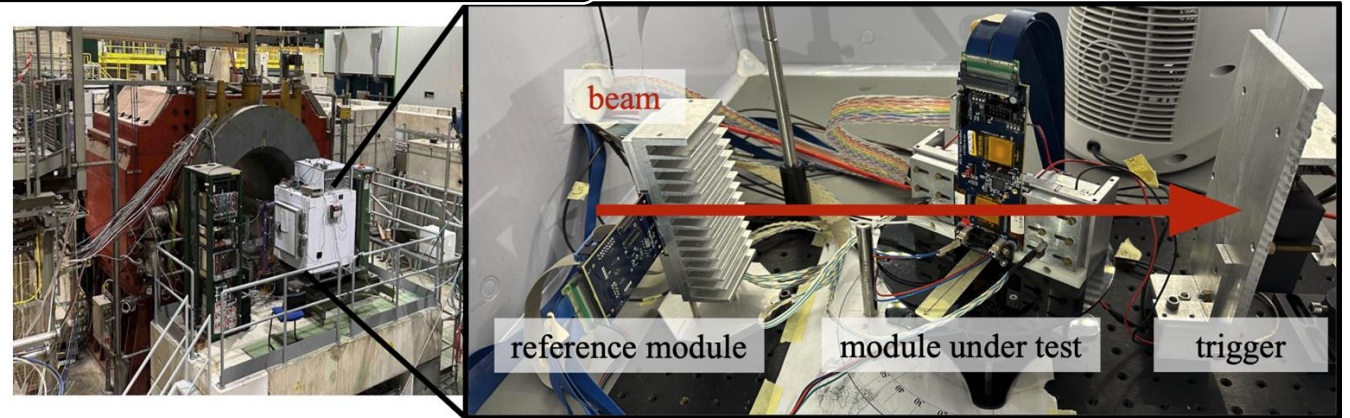


Sensors under test

June and Sep. 2023 @CERN North Area (H8)

- sensor modules with various SiPM cell size and different LYSO thickness
- both non-irradiated and irradiated sensors
- Temperature range from -45°C to 5°C emulating different ageing conditions

CERN North Area(pion beam)



tracking system
(wire chambers)

reference
module

module
under test

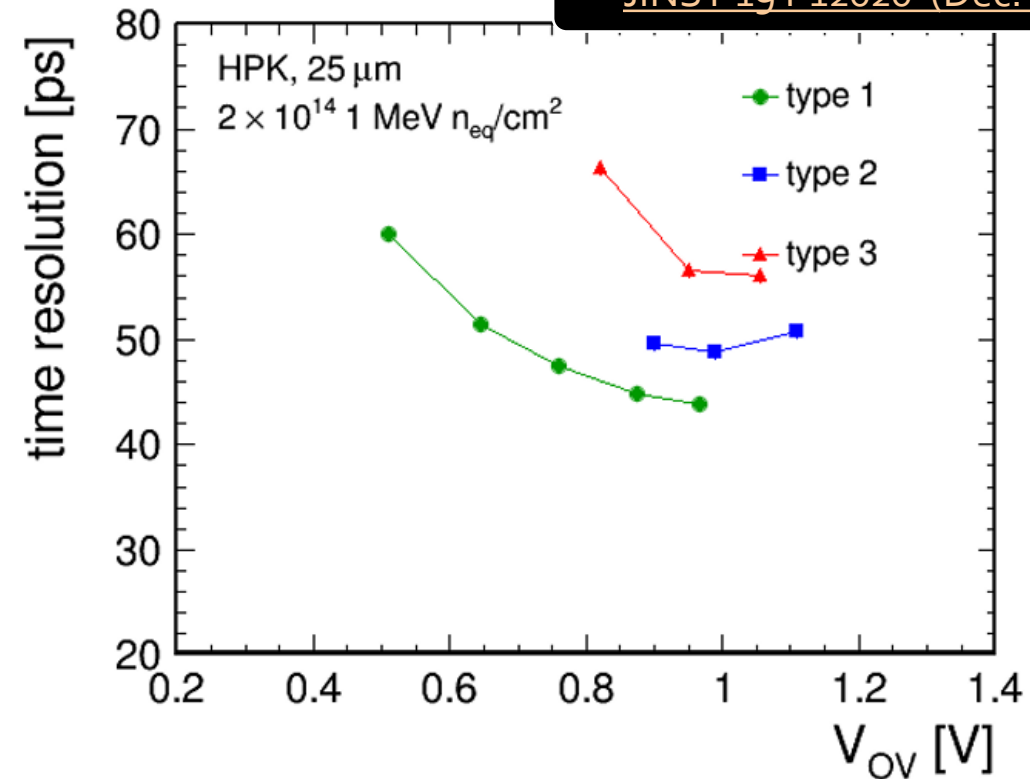
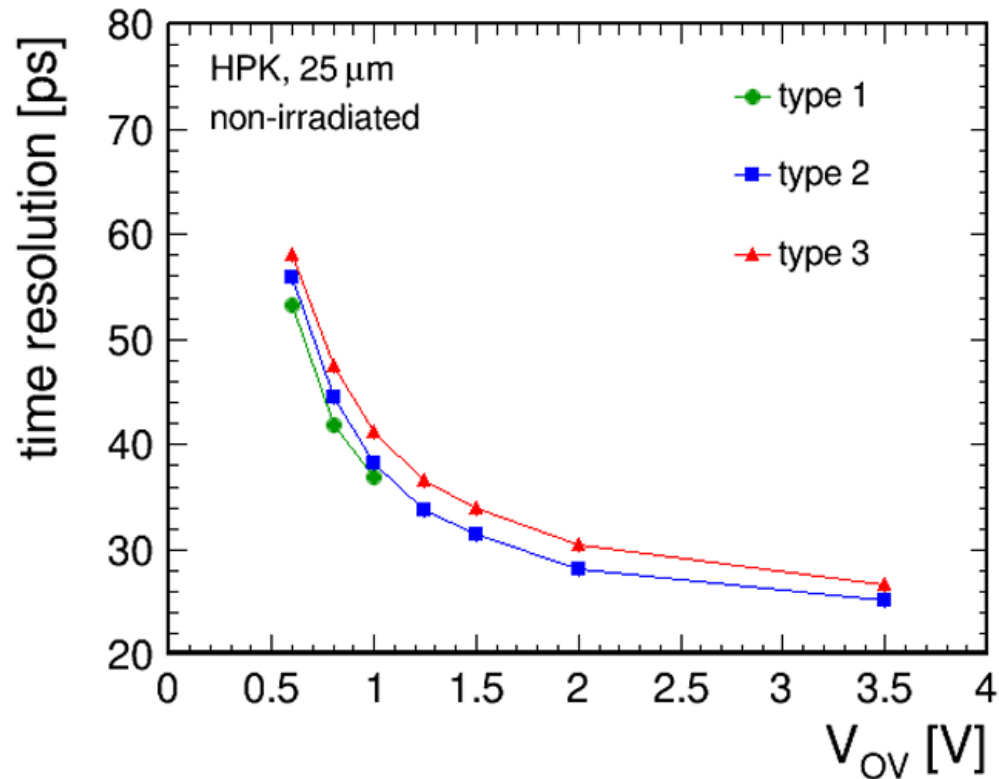
trigger
(plastic scintillator)

BTL Sensors Optimization: LYSO

LYSO crystals of thickness: 3.75mm (type 1), 3.00mm (type 2), 2.75mm (type 3)

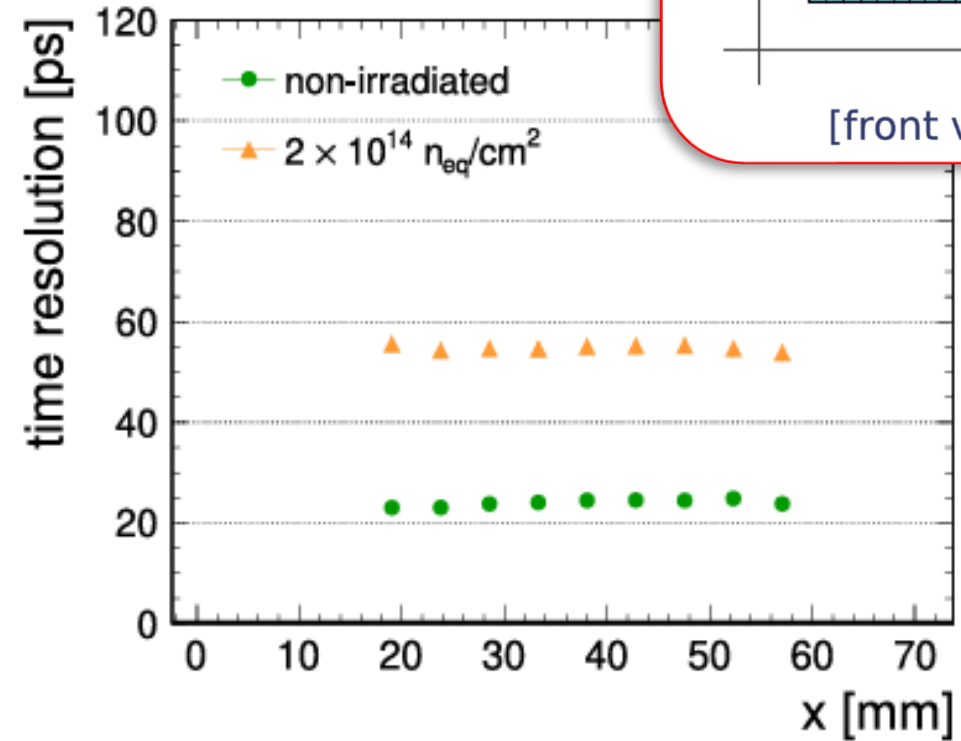
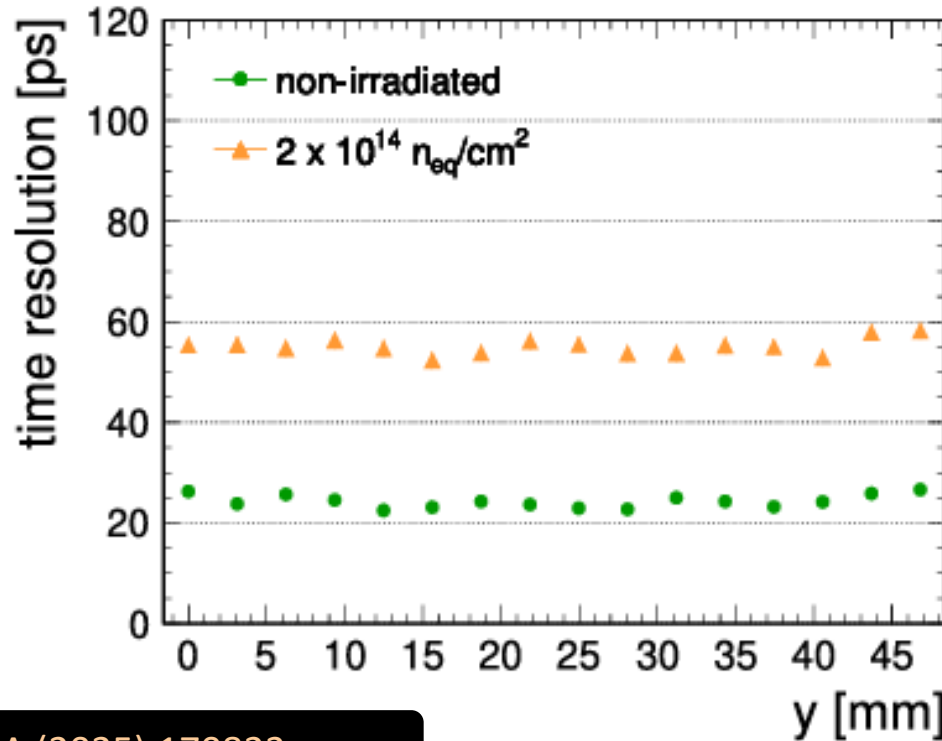
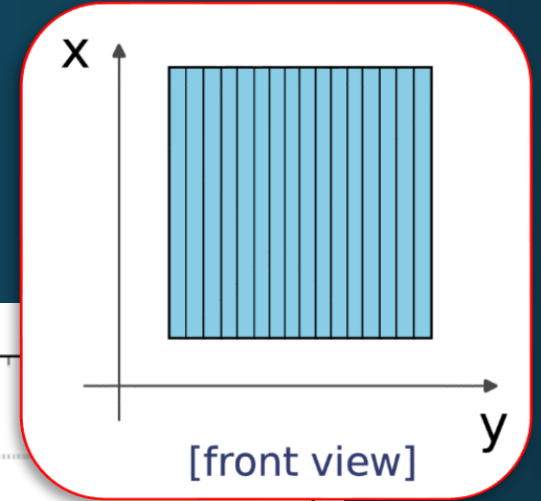
- Thicker crystals → larger energy deposit in LYSO
 - Limited by available space, material budget before calorimeters, and material cost

JINST 19 P12020 (Dec. 2024)



Time resolution uniformity

- The time resolution among crystals in a module is **uniform within 2ps RMS**, both along one bar (x) and across different bars (y)



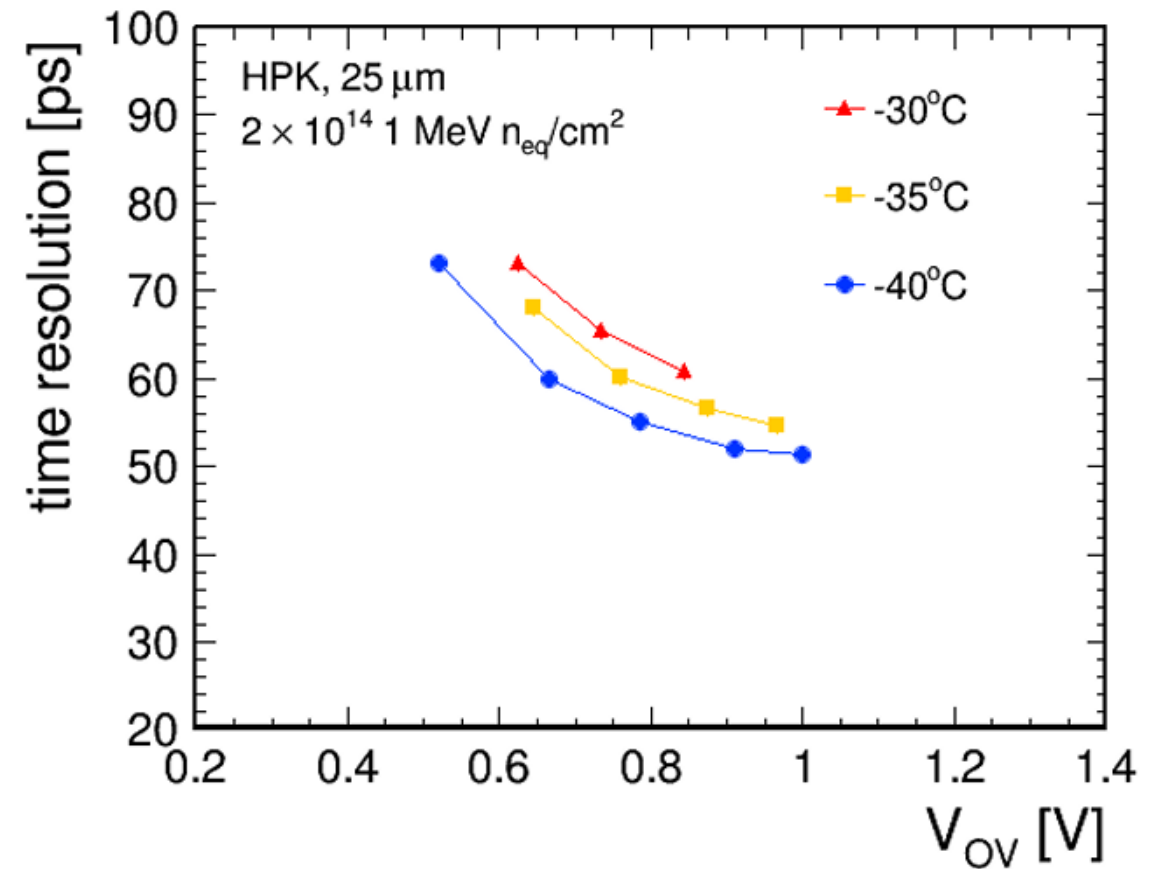
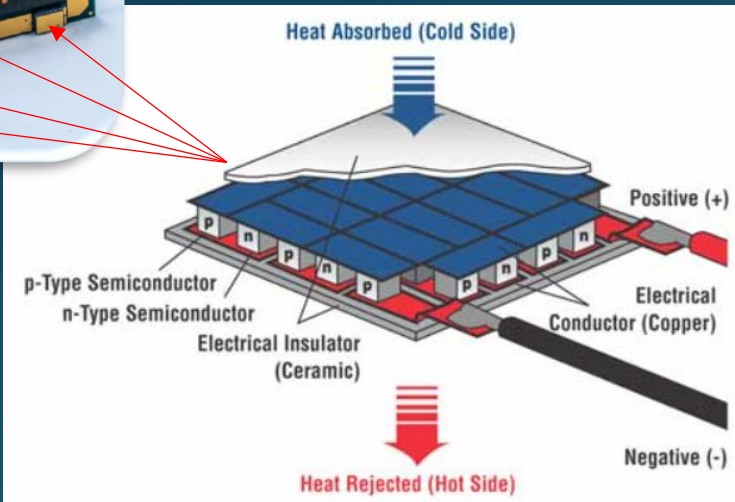
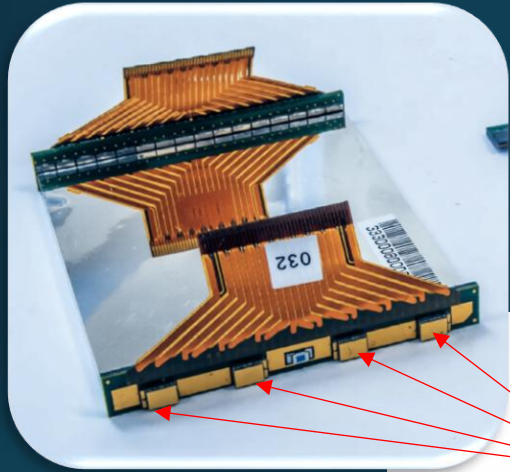
[NIM A \(2025\) 170823](#)

BTL Sensors Optimization: TECs

The DCR term is reduced at cold temperatures:

- Inserted Thermo-Electric coolers (TECs) on SiPMs to lower the operating temperature below -35°C
- Could also be used in HL-LHC stops for annealing at $+60^{\circ}\text{C}$

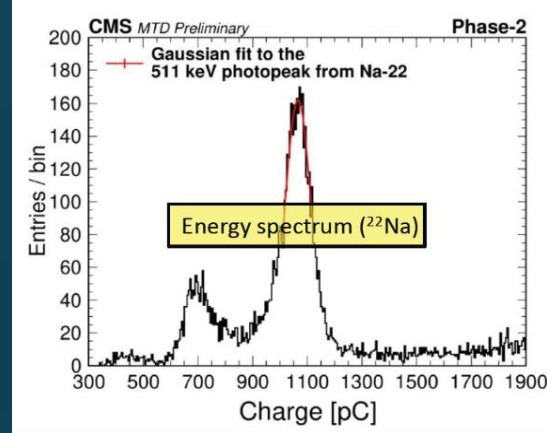
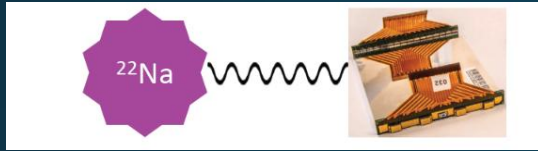
JINST 19 P12020 (Dec. 2024)



BTL Components QA/QC

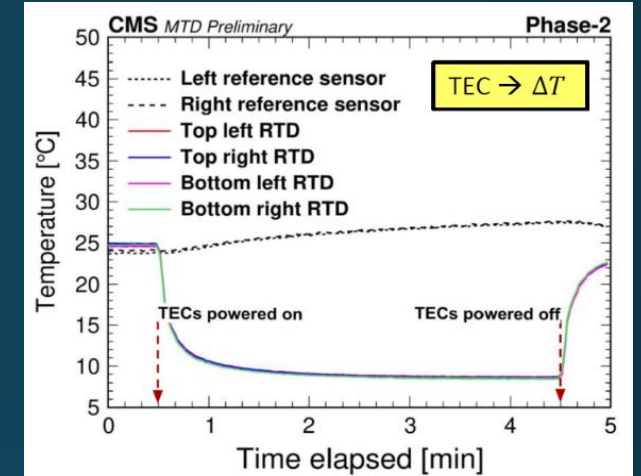
Sensor Modules

Na22 source
spectroscopy to check
the quality of gluing



Detector Modules

TEC thermal tests for
thermal contact
inspection



Tray Test

Connectivity
(electrical and
optical), calibration,
full readout using
LYSO intrinsic
radioactivity, and so
on

