Timing detectors at LHC with BTL/MTD

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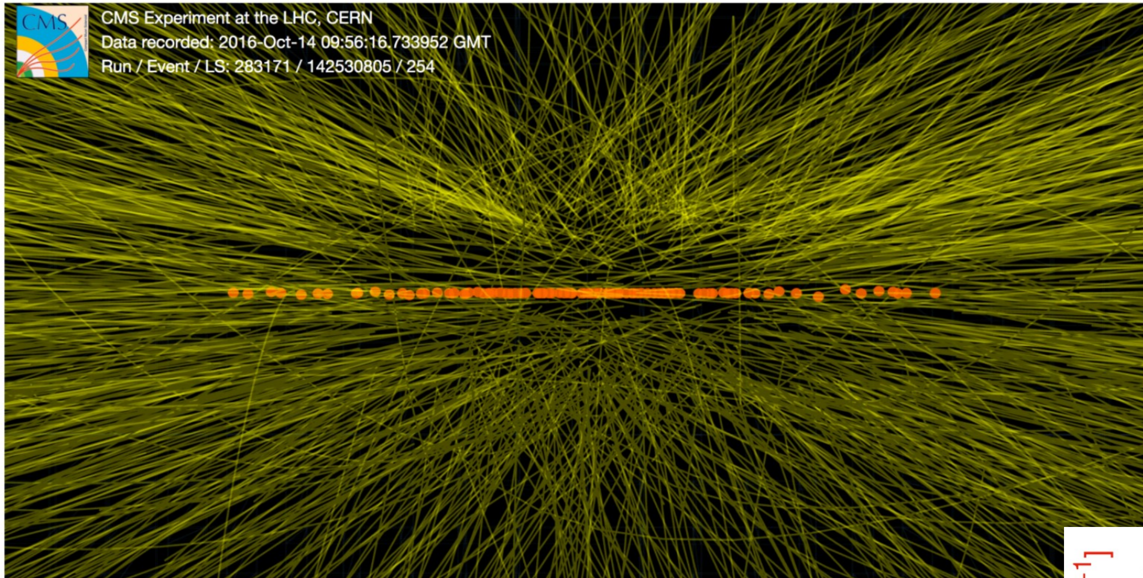
High-Luminosity LHC

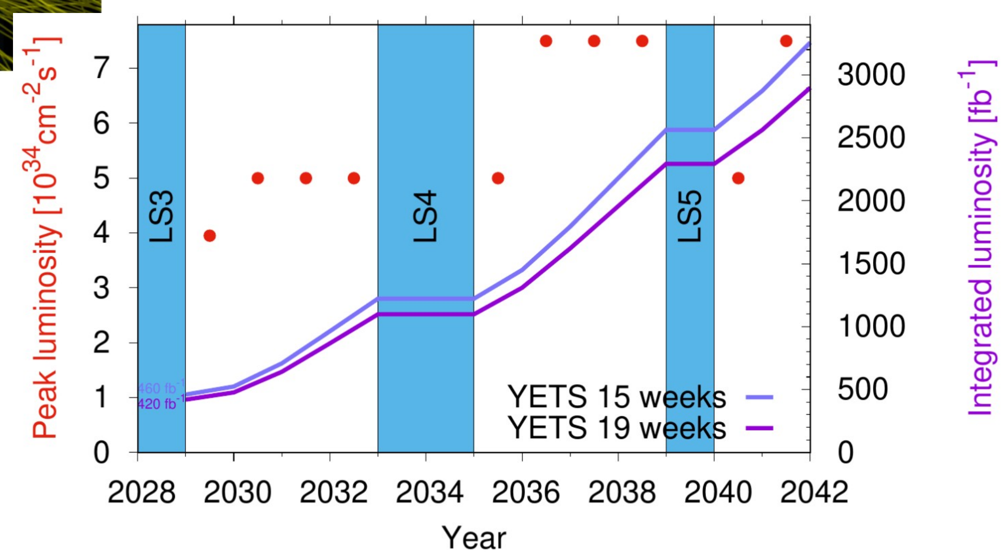


Upcoming High-Luminosity phase of LHC

- Instantaneous luminosity up to ~7.5 10^{34} cm^{-2} s^{-1}
- High density of vertices (x5 wrt LHC)
  - More challenging to associate tracks to correct vertex
- Large radiation damage

The CMS detector will undergo many upgrades

New detector to measure the time of charged particles: **MIP Timing Detector (MTD)**

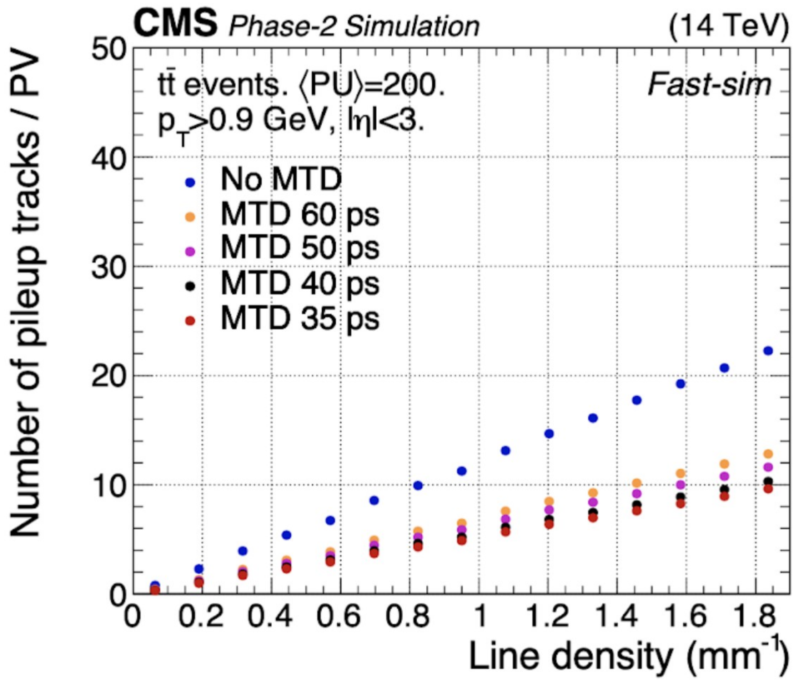


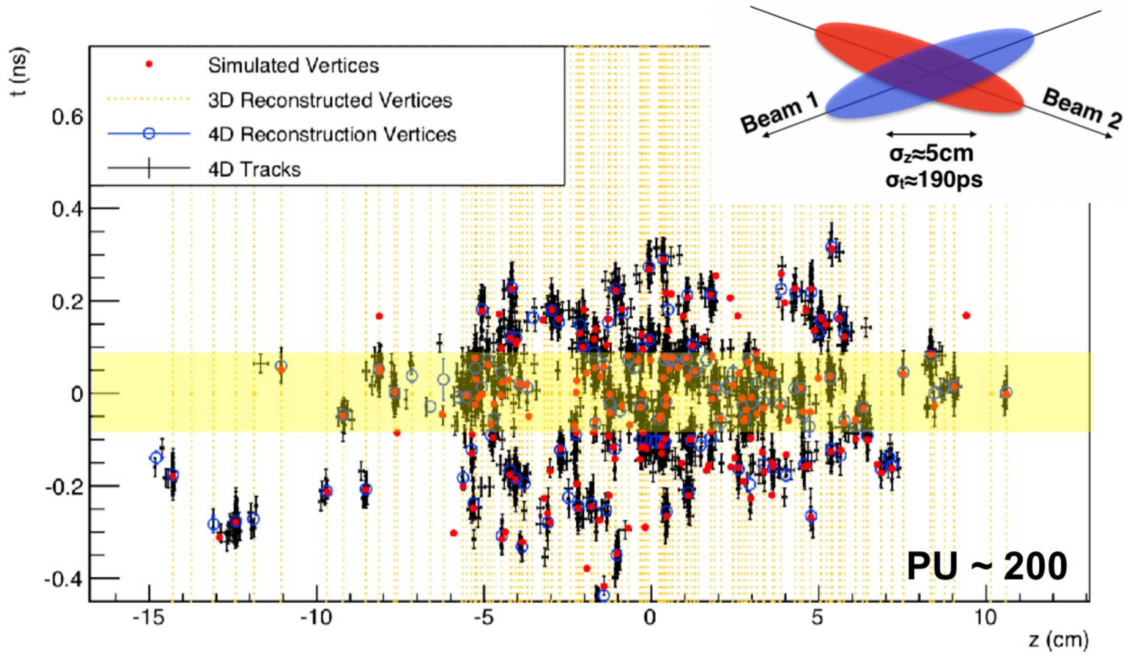
4D tracking

Addition of the timing information to the track reconstruction

Distinguishing the collision vertices using one additional dimension:

- spatial dispersion ~ 5 cm
- time dispersion ~190 ps





This will allow to reduce by ~50% the number of tracks mistakenly assigned to the hard interaction vertex

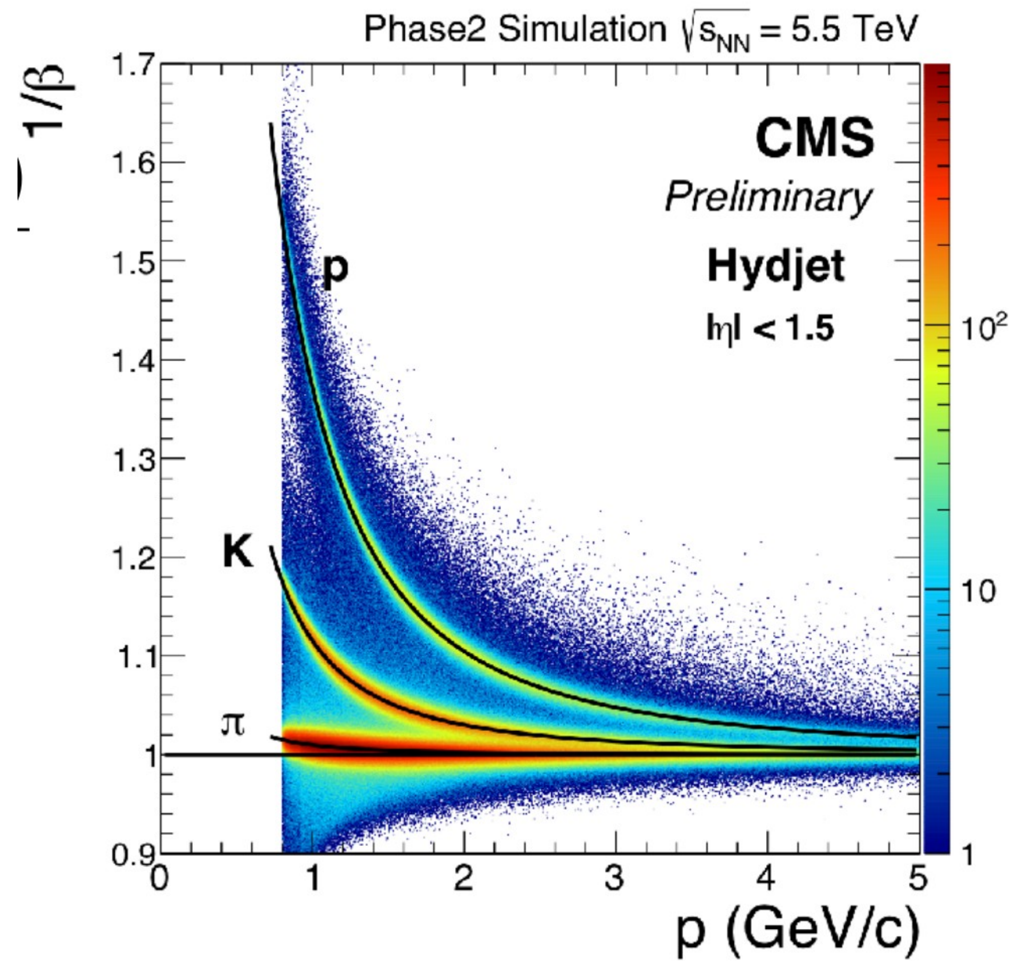
This leads to improved analysis techniques: lepton isolation, missing energy estimation, etc.

Particle identification

New tool for CMS:
time-of-flight particle identification

π/K separation up to momenta of 2-3 GeV
K/p separation up to 5 GeV

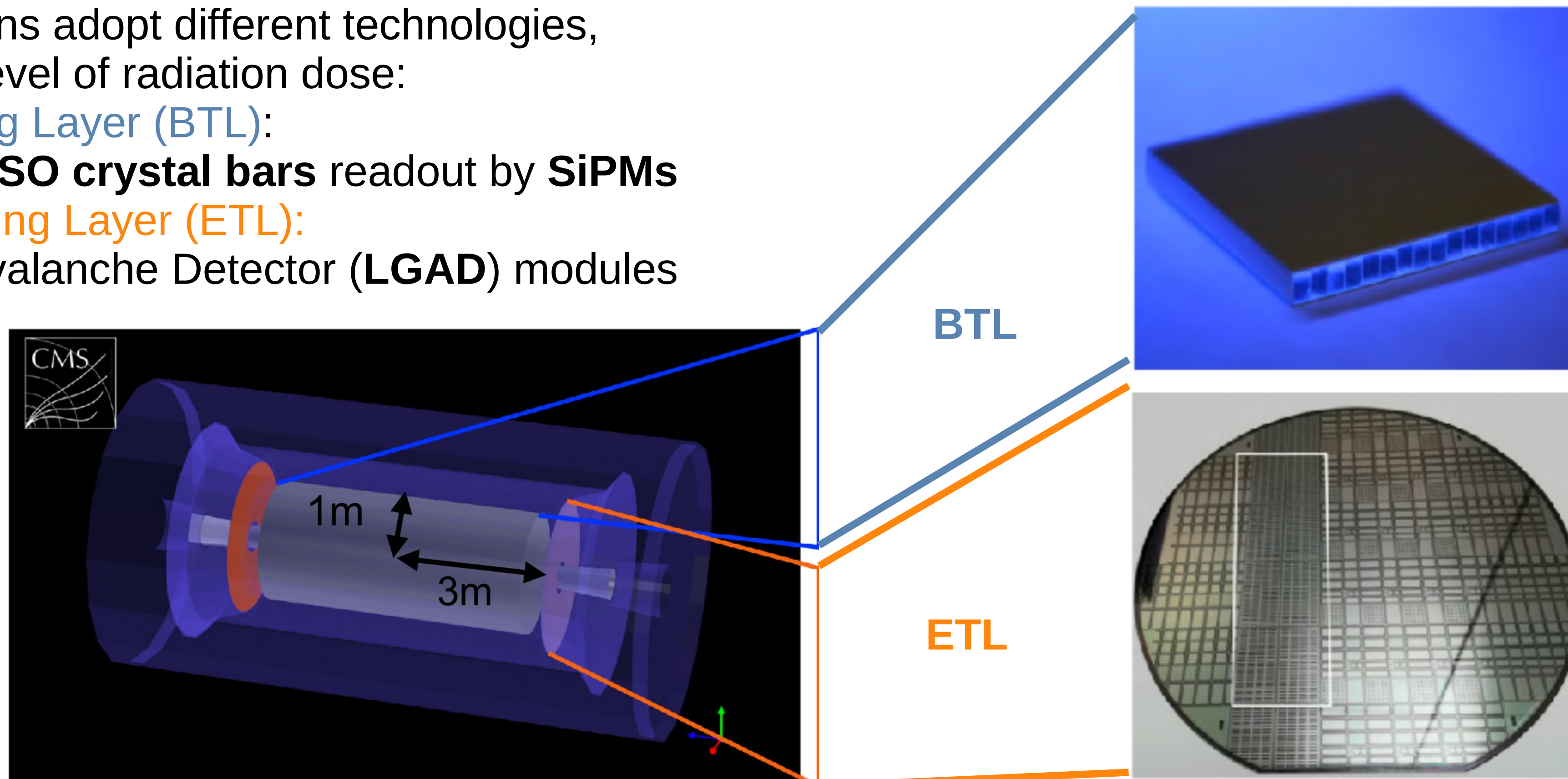
Useful tool for heavy-flavour analyses, both in **p-p and ion-ion collisions**, to explicitly reconstruct hadronic final states



CMS MIP Timing Detector

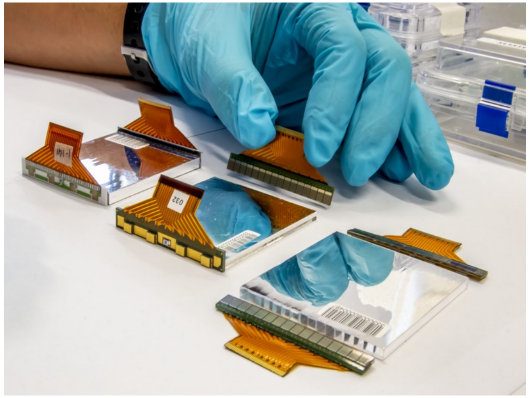
MTD detector
- Thin layer between tracker and calorimeters
- Almost hermetic (|η|<3)

Different regions adopt different technologies, suited to the level of radiation dose:
- Barrel Timing Layer (BTL):
  arrays of **LYSO crystal bars** readout by **SiPMs**
- Endcap Timing Layer (ETL):
  Low Gain Avalanche Detector (**LGAD**) modules

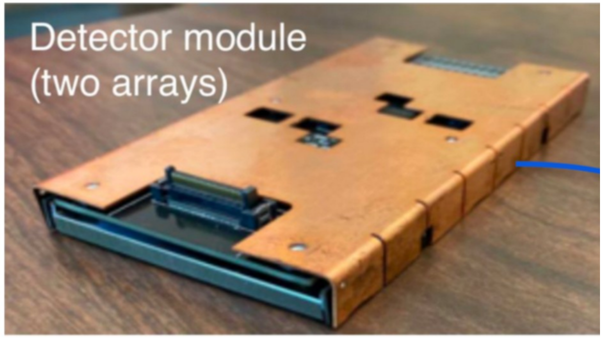


BTL design

Sensor module
- 16 LYSO bar + 2 arrays of SiPM
- Double-ended readout: time average position-independent and allow gaining factor of √2 on time reso.

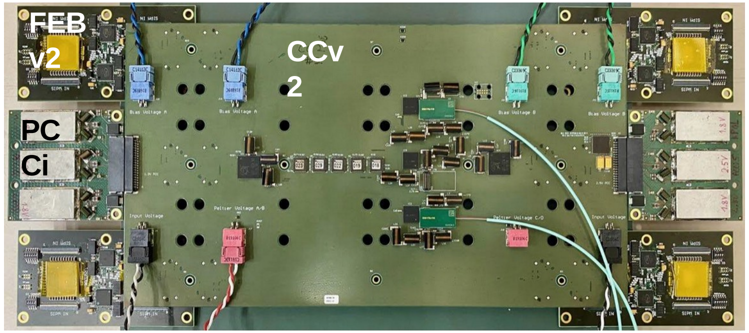


2x

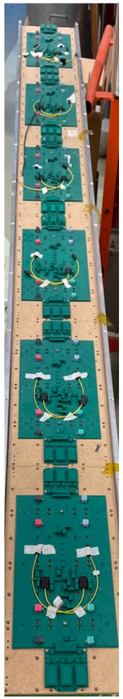


12x

Readout unit

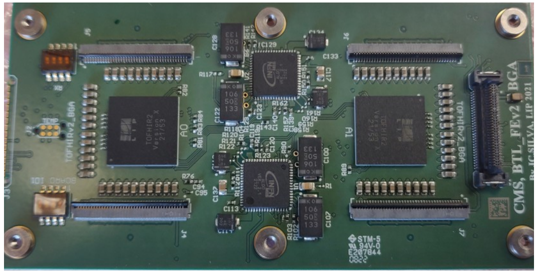


6x



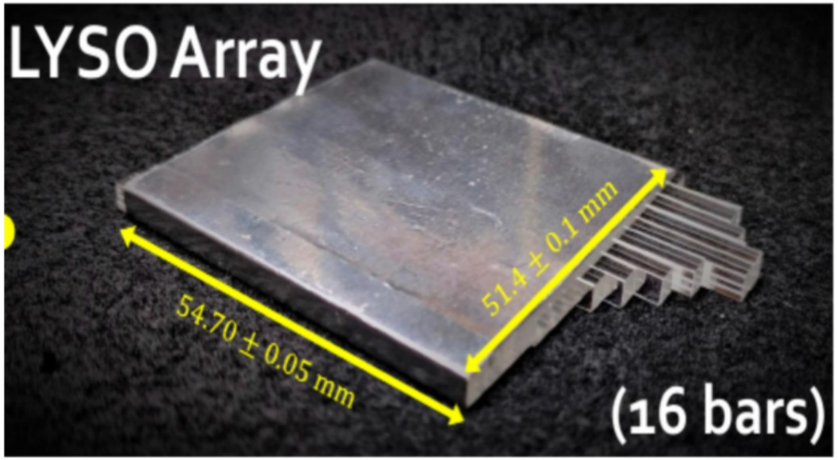
Tray

72x



Front-end board
- 2 TOFHIR ASICs
- 2 ALDO voltage regulators

BTL sensors



LYSO:Ce scintillating crystals
- fast scintillation rise time (<100 ps)
- short decay time (~40 ns)
- bar-like geometry (3x3x55 mm^3) [initial design]

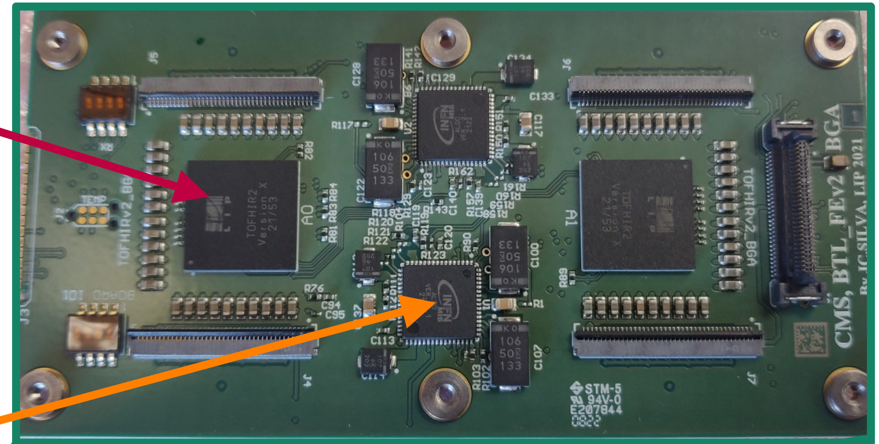
SiPM
- fast timing
- magnetic field tolerant
- compact
- 15 μm cell size [initial design]

Sensor module
- array of 16 LYSO bars
- two SiPM arrays glued to the extremities
- Thermo-Electric Coolers (TECs) integrated on SiPM packaging

Sensors will be exposed to fluence of 2*10^{14} n_{eq}/cm^2

BTL front-end electronics

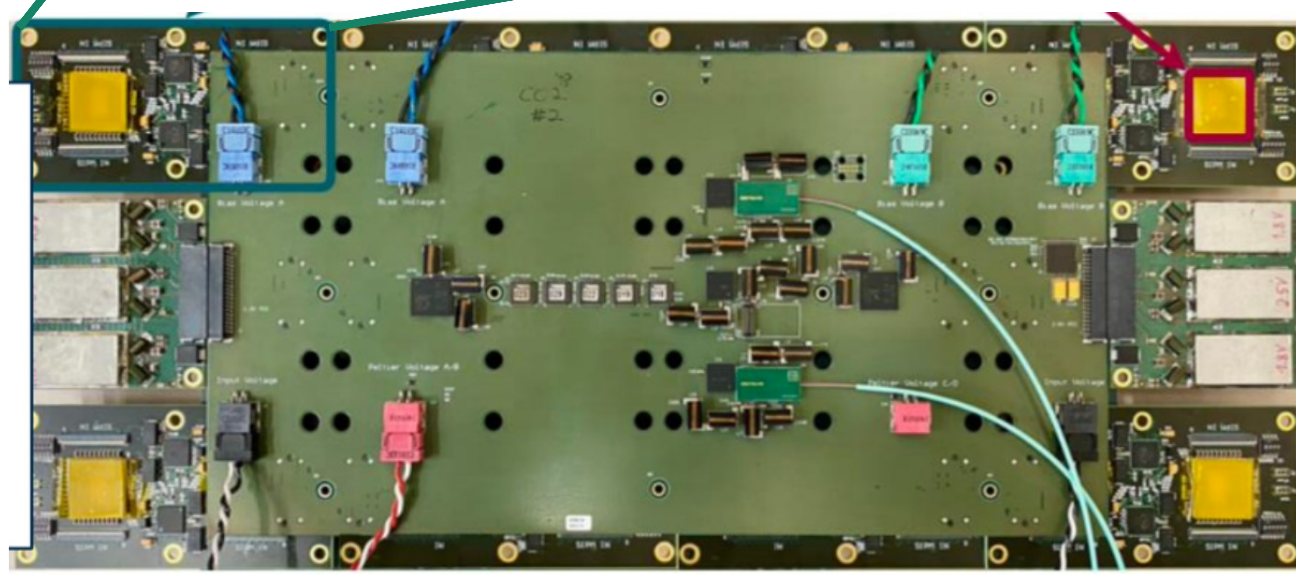
TOFHIR2 dedicated ASIC
- 32 channel
- Noise-cancellation module to deal with high DCR
- Three discriminators per channel (full corrent mode)
- 2 TDC and 1 QDC per channel



Front-end board

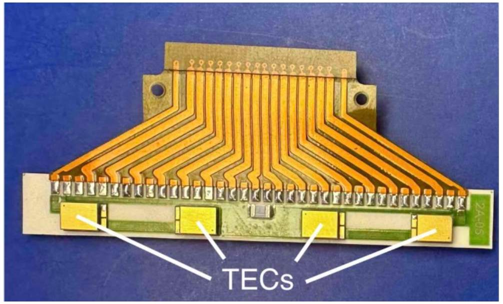
ALDO voltage regulator ASIC

Readout unit
- concentrator card to support communication of 12 front-end boards
- Two redundant optical links

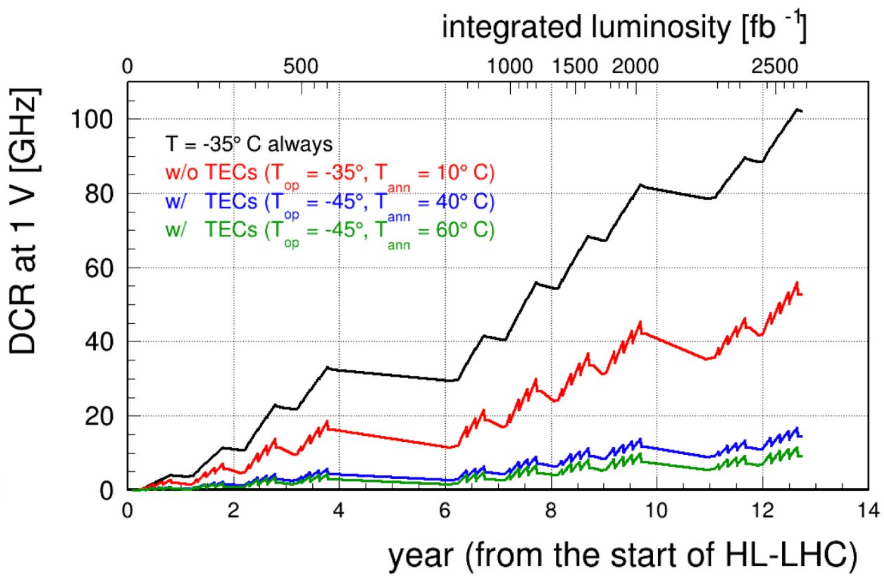


BTL challenges

High Dark Count Rate (DCR)
- Mitigated with TOFHIR DLED module and integration of TECs
- ~ 10°C lower operating temperatures, down to -45°C
- higher temperatures for in-situ annealing (~60°C)



- SiPM operated at low bias (~1 V above breakdown) at end-of-life, to keep DCR under control
- LYSO yield ~50% of the one preliminarily estimated
  → fewer photoelectrons and slower rise time



Amount of photoelectrons optimized in several ways:
- Higher pre-amplificator gain in TOFHIR
- Larger cell-size SiPM
- Thicker LYSO bars

$$\sigma_t^{BTL} = \sigma_t^{clock} \oplus \sigma_t^{digi} \oplus \sigma_t^{ele} \oplus \sigma_t^{phot} \oplus \sigma_t^{DCR}$$

dominates at EoO

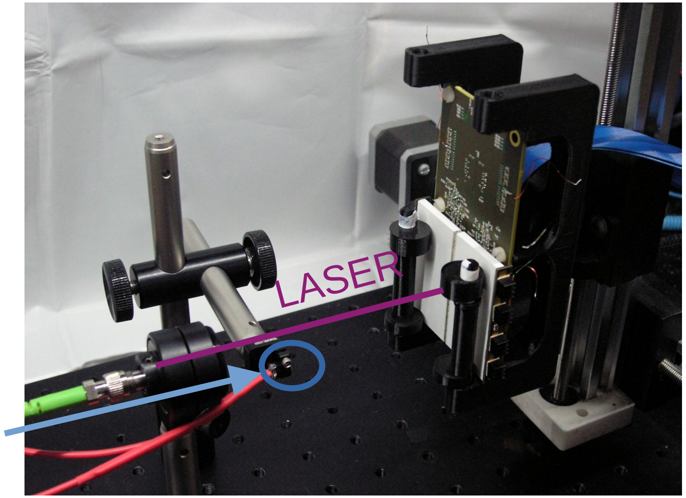
Intense lab and test-beam studies led to optimal specifications and operating conditions

Test facilities

Laser test setups installed in Lisbon, Milano and CERN
- Colling and light tight test boxes
- Blue (405nm) and UV (370nm) laser systems
- DAQ system based on FEB/D board (PETsys Electronics)

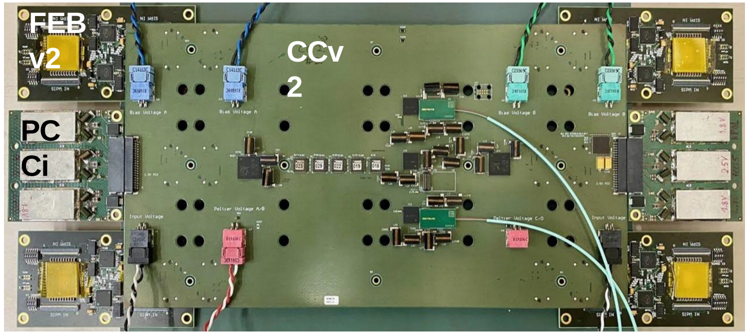
TOFHIR2 Test Board
- Two TOFHIR2 and ALDO2 (LV/BV regulator)
- SiPM input connectors
- Access to probing pads in TOFHIR2
- Access to data with DAQ system

Picosecond laser
- Blue light shinning directly on SiPMs
- UV light exciting scintillation in LYSO crystals

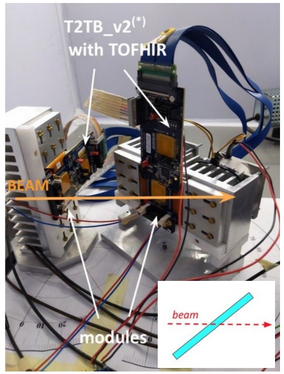


Blue LED emulating DCR noise

Integration test of Readout Unit:
- validate the full acquisition chain, assess the impact of the system noise, check the compatibility of the various components from the assembly point of view



Test beams at CERN
- CERN North Area H8 beam lines
- Detector modules with non-irradiated and irradiated (2e14 neq/cm2) SiPM arrays

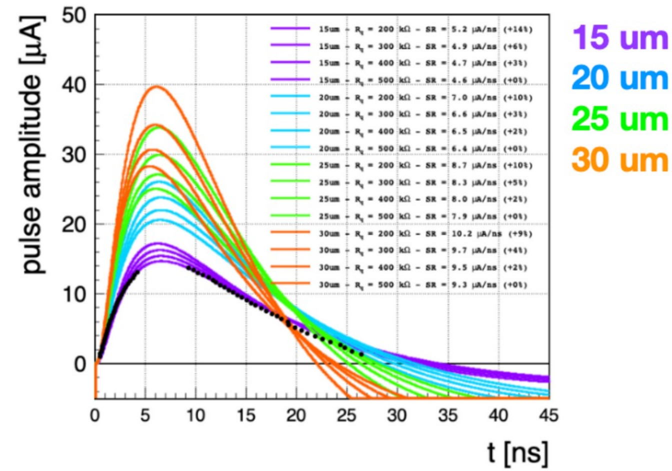


SiPM optimization

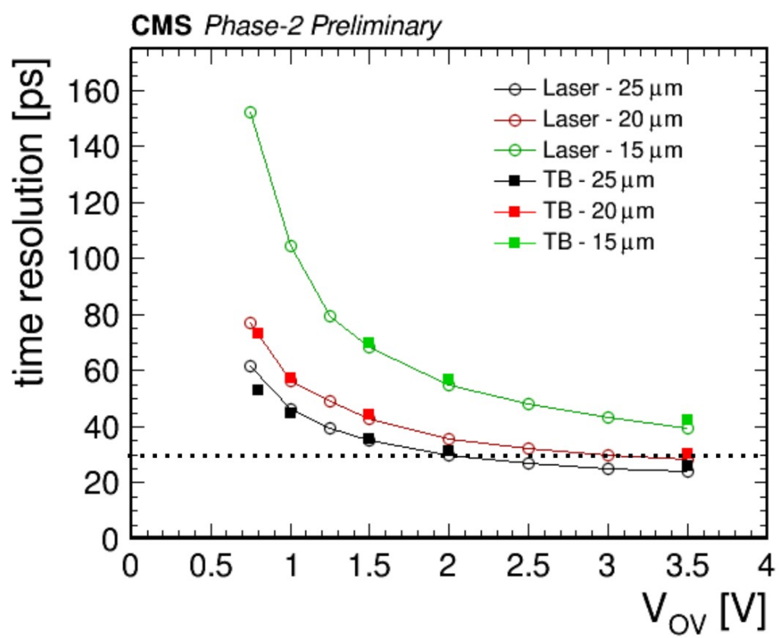
SiPM cell size optimized to achieve best performance

- In unirradiated sensors, clear improvement obtained from larger cell size, tested both in laser and test-beam measurements
- Larger-size irradiated sensors provide ~65 ps time resolution, compatible with TDR target

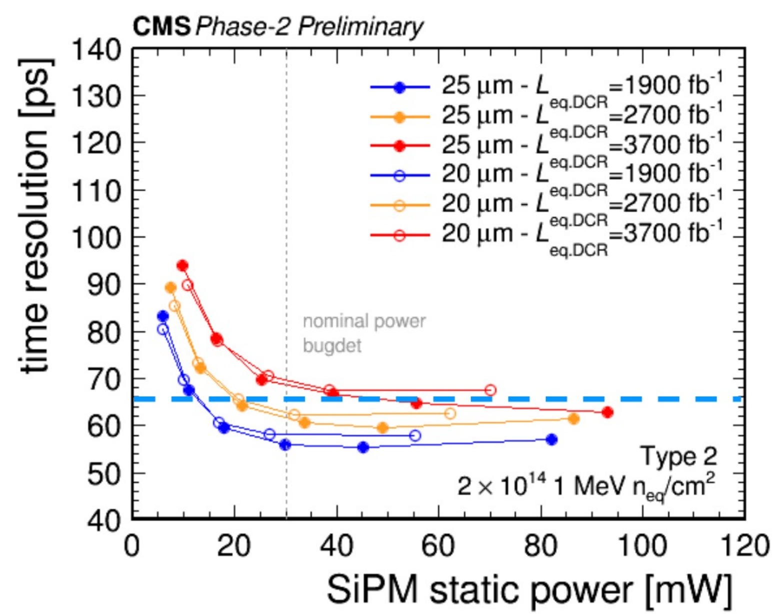
Model of SiPM+TOFHIR



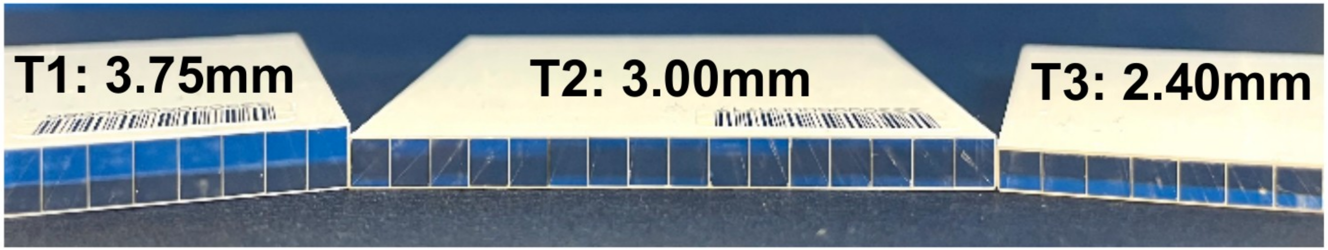
Unirradiated sensors

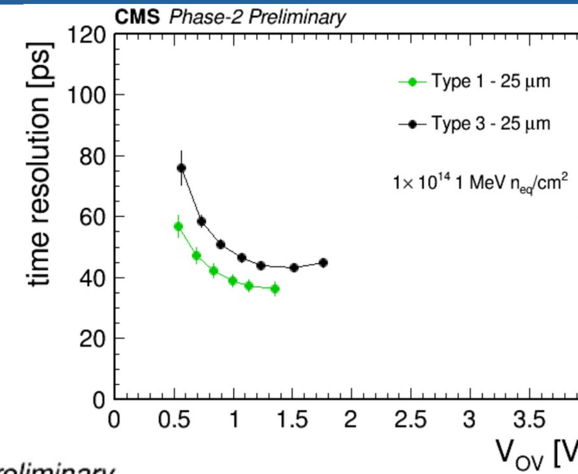


Irradiated sensors



LYSO thickness optimization



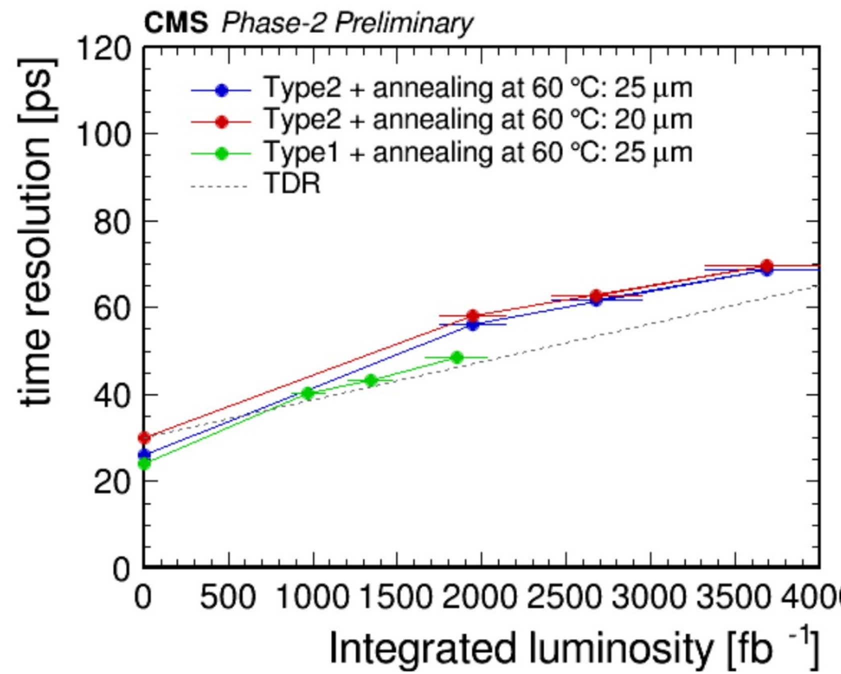


Three **thickness of crystal bars** tested:

- Light output and number of photoelectrons increase with thickness
- Drawback: irradiated SiPM with larger active area consume more power because of DCR

Crucial test of irradiated modules with different thickness

Results show improved performances for thicker option (T1)



Conclusions

- Prototyping phase successful
  - Intensive tests in lab and test-beam
  - Characteristics and operating conditions of sensors and electronics have been optimized
  - TDR performances achieved (30 – 60 ps time resolution)
- Production and assembly phase started
  - TOFHIR production and sensor pre-production ongoing now
  - Assembly will start in Q2/2024 (4 assembly centers)
  - Installation on tracker support in Q3/2025