Towards the validation and assembly of the CMS MTD Barrel Timing Layer

EPS-HEP 2023

European Physical Society Conference on High Energy Physics 2023

21-25 August, Hamburg (Germany)

22nd August 2023

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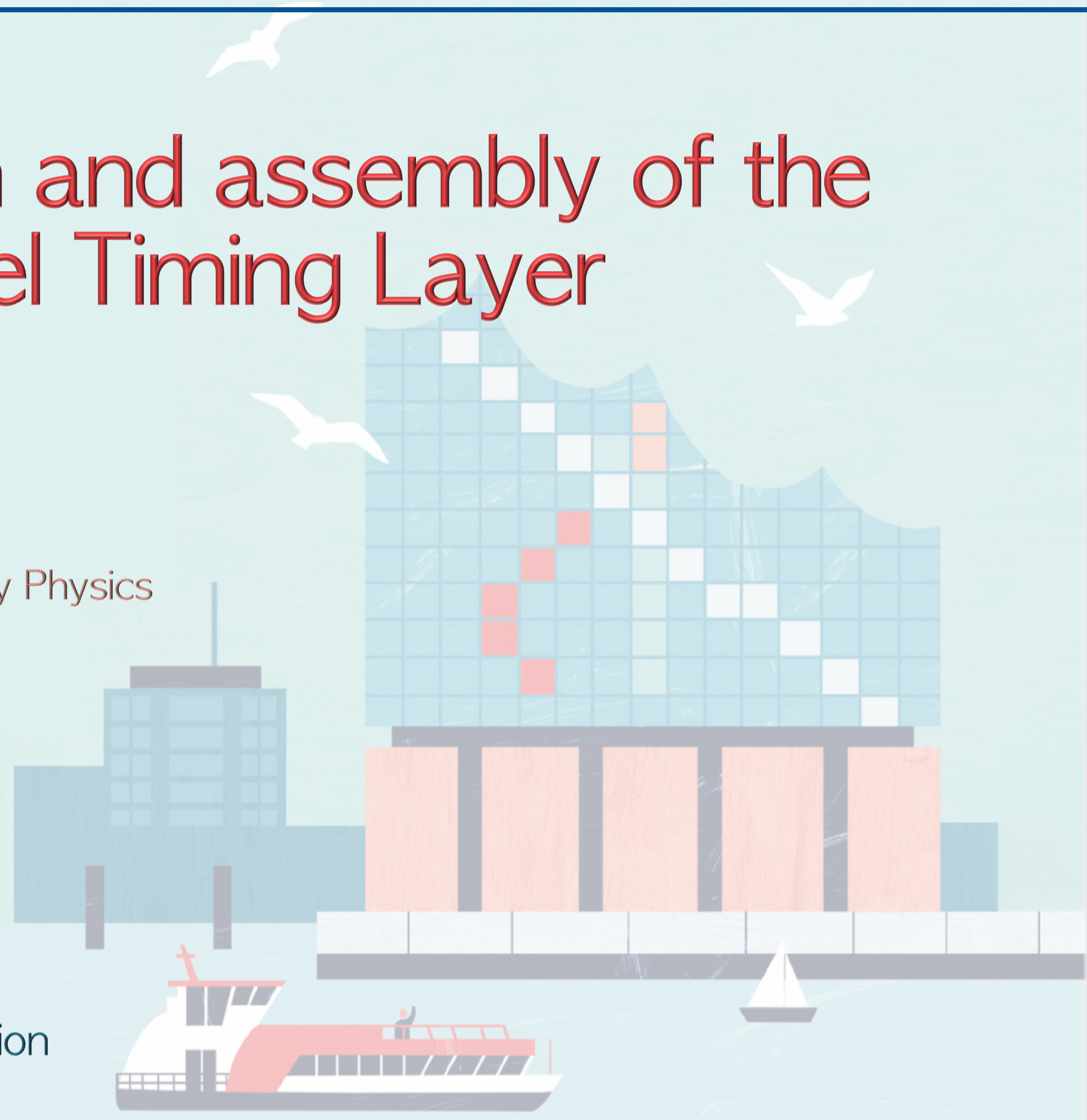

Illustration by Katinka Reinke

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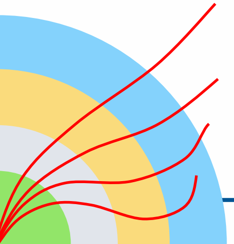
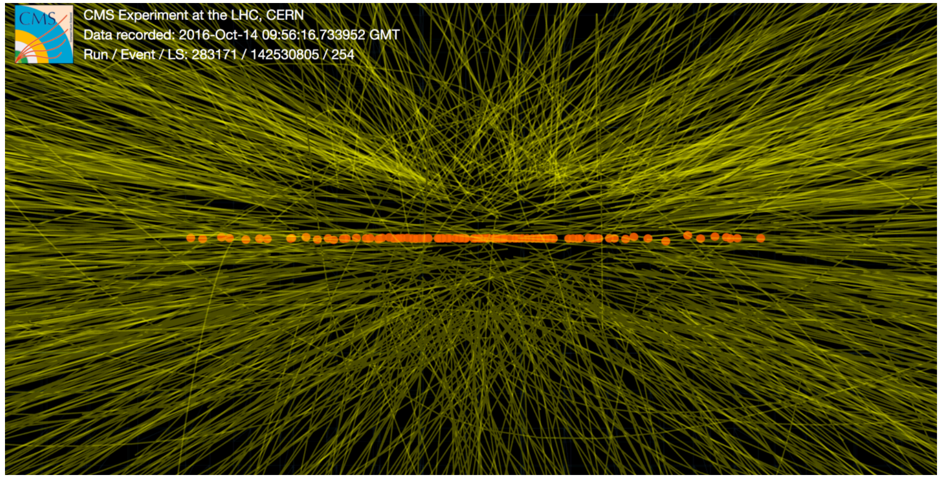


Precision timing in CMS for High Luminosity LHC



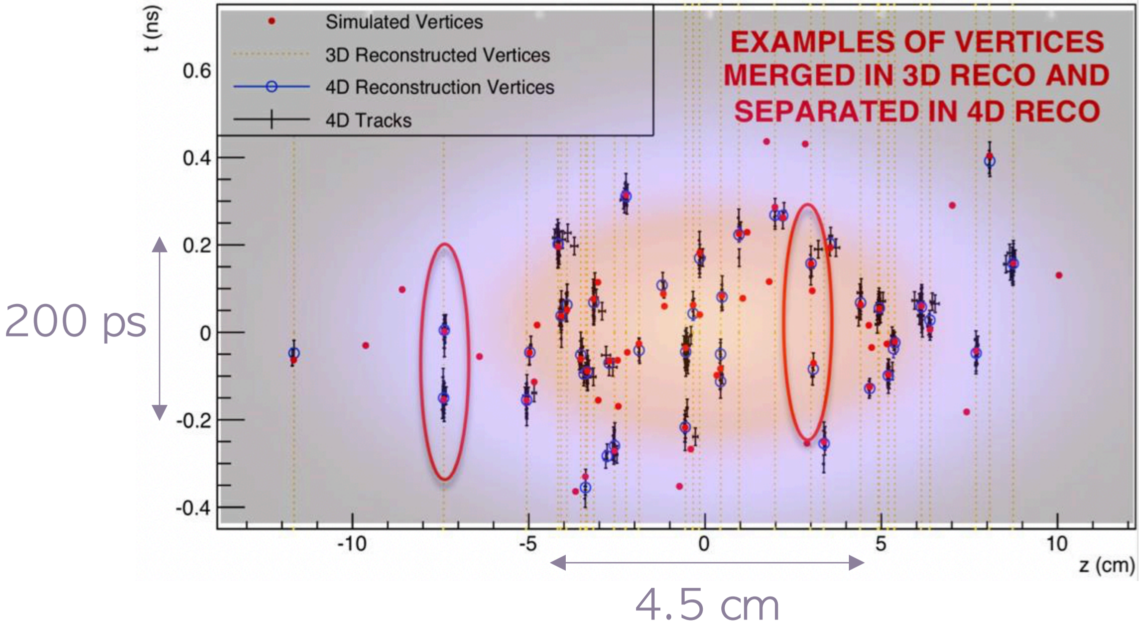
- New High Luminosity phase of LHC

→ $\mathcal{L}_{\text{ultimate}}$ up to ~ 7 x 10^{34} cm^{-2} s^{-1}

⇒ higher vertex density (up to x5) will lead to increases in:

○ Radiation damage

○ Pileup



- CMS is undergoing major upgrades to withstand such harsh conditions:

○ MIP Timing Detector will enable the measurement of the time of arrival of charged particles

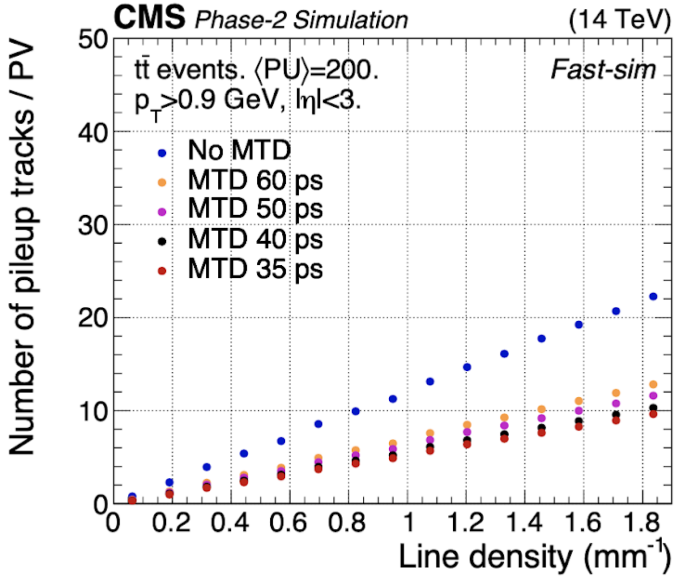
MTD impact on physics

The addition of track-timing information from MTD will:

- bring **new capabilities** to CMS

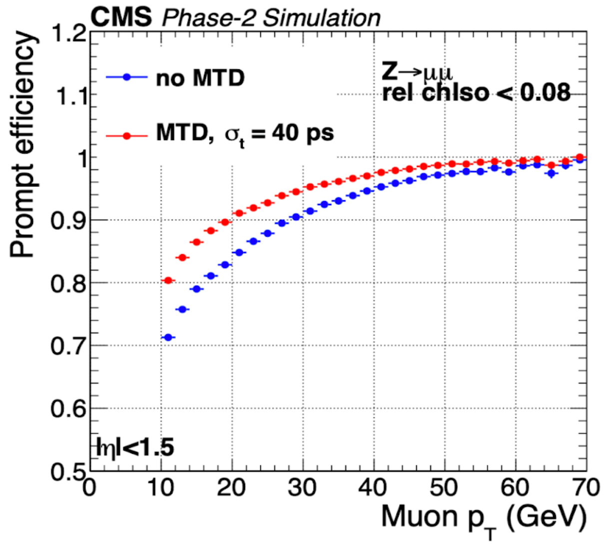
  e.g. identifying charged particles based on the time-of-flight, searching for long lived particles etc.

- **reduce tracks from pileup vertices** that are incorrectly associated with the hard interaction vertex →



Thus

- improving the efficiency in reconstructing the physics objects
  - better *lepton isolation* efficiency →
  - reduced *pileup jet* rate
  - improved *b-jet tagging* efficiency



- enhancing the significance of some benchmark cases

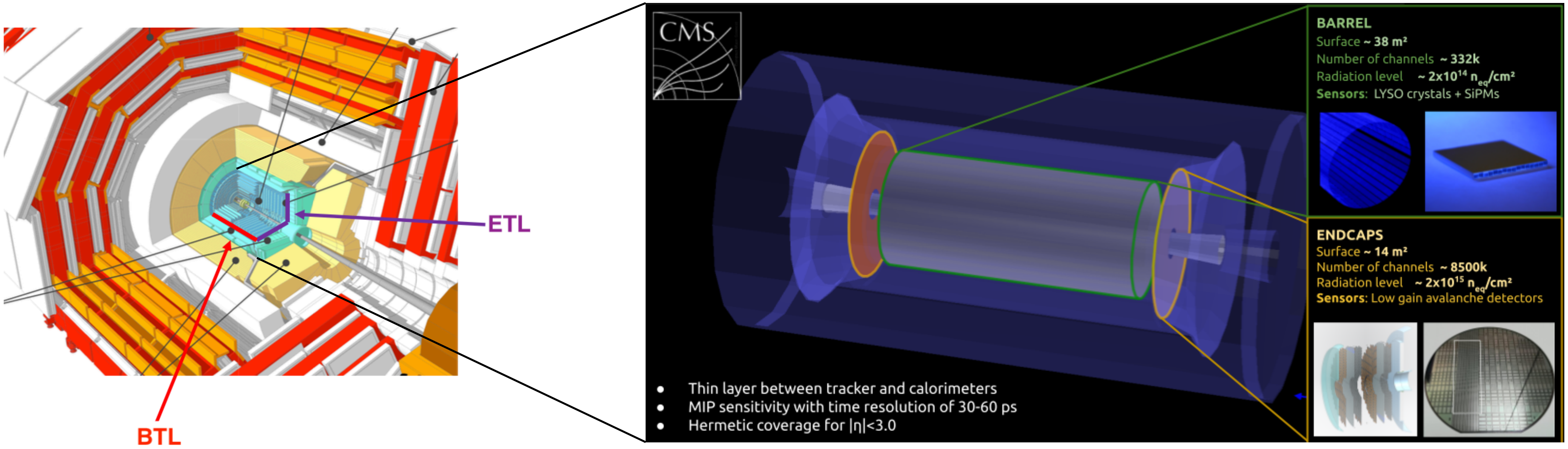
  e.g. measurement of **Higgs boson self coupling**

MTD design

Thin and hermetic detector ($|\eta|<3$) between the tracker and the calorimeter with different specifications contingent on radiation dose

⟶ employing diverse technologies to equip the barrel and the endcap areas of CMS:

- **Endcap Timing Layer** (ETL): modules of Low Gain Avalanche Detectors (LGADs)
- **Barrel Timing Layer** (BTL): arrays of LYSO crystal bars readout at both ends by SiPMs



BARREL
Surface ~ 38 m²
Number of channels ~ 332k
Radiation level ~ 2x10^{14} n$_{eq}$/cm²
Sensors: LYSO crystals + SiPMs

ENDCAPS
Surface ~ 14 m²
Number of channels ~ 8500k
Radiation level ~ 2x10^{15} n$_{eq}$/cm²
Sensors: Low gain avalanche detectors

- Thin layer between tracker and calorimeters
- MIP sensitivity with time resolution of 30-60 ps
- Hermetic coverage for |η|<3.0

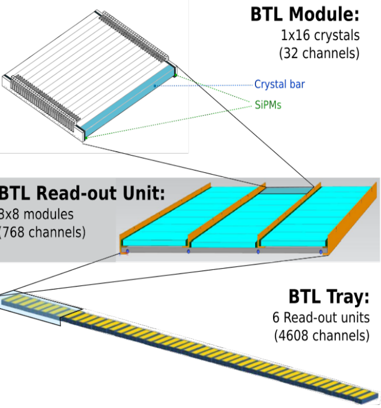
BTL design

Module

16 bars coupled at both ends to SiPMS

Detector module

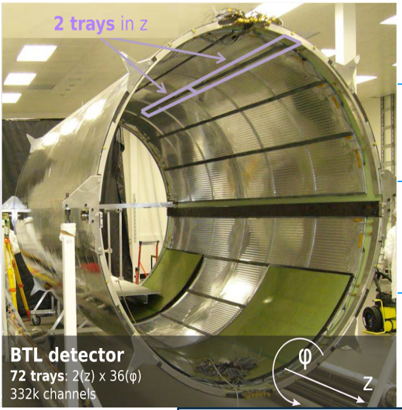
2 modules + TOFHIR ASIC (BTL Front End)



BTL Module:
1x16 crystals
(32 channels)

BTL Read-out Unit:
3x8 modules
768 channels)

BTL Tray:
6 Read-out units
(4608 channels)

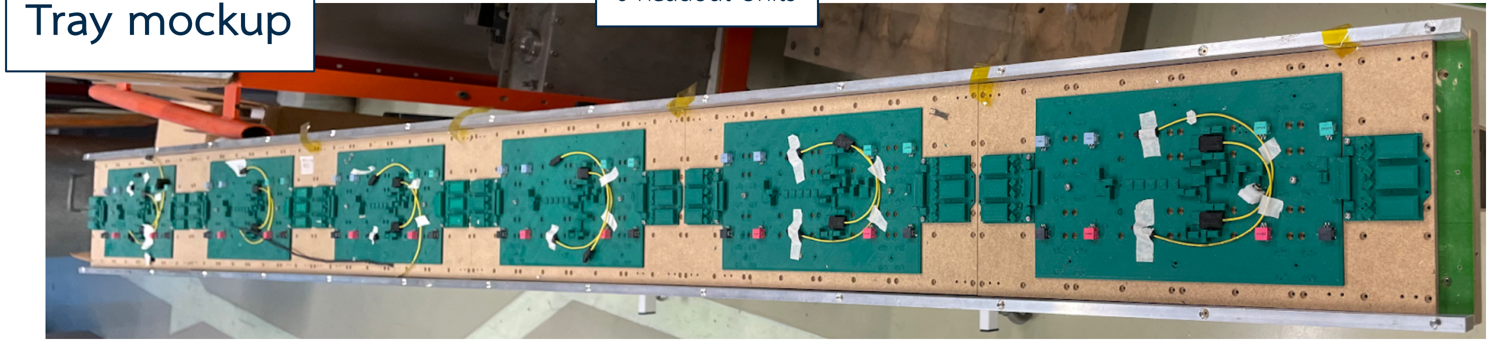


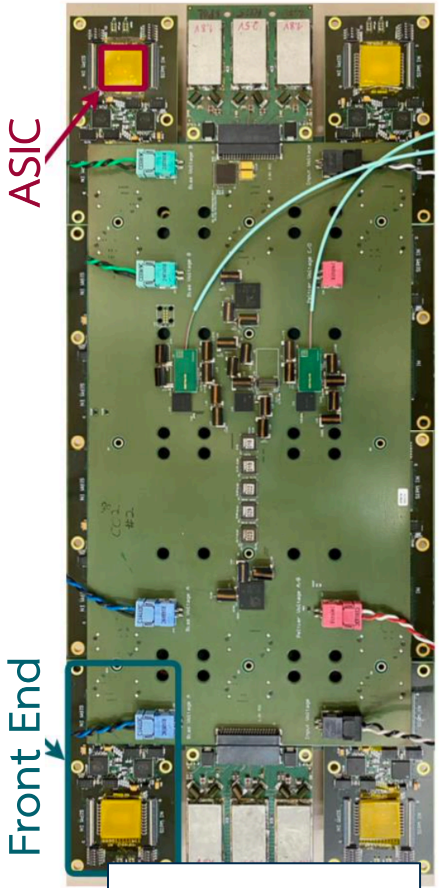
BTL detector
72 trays: 2(z) x 36(φ)
332k channels

12 Detector Modules

6 Readout Units

Tray mockup



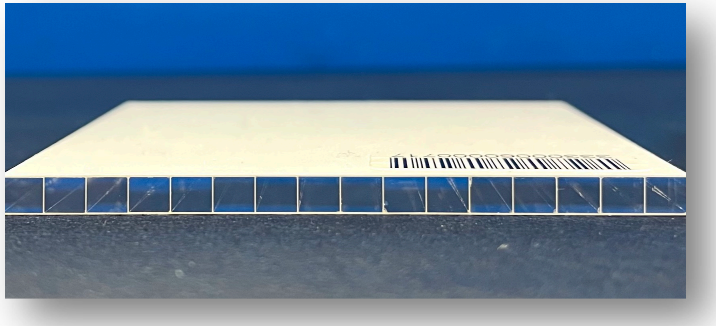


Readout Unit

BTL sensors

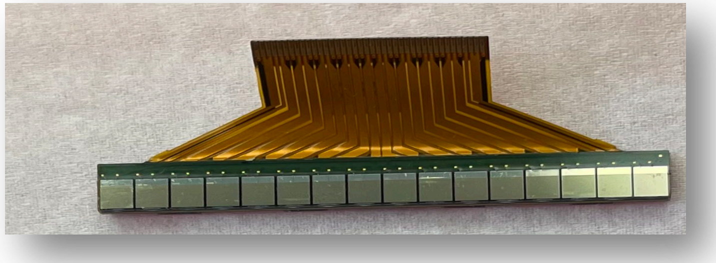
LYSO:Ce crystal

- large LY, fast scintillation rise time (<100 ps), short decay time (~40 ns)
- bar-like geometry: 3 x 3 x 52 mm^3



SiPM

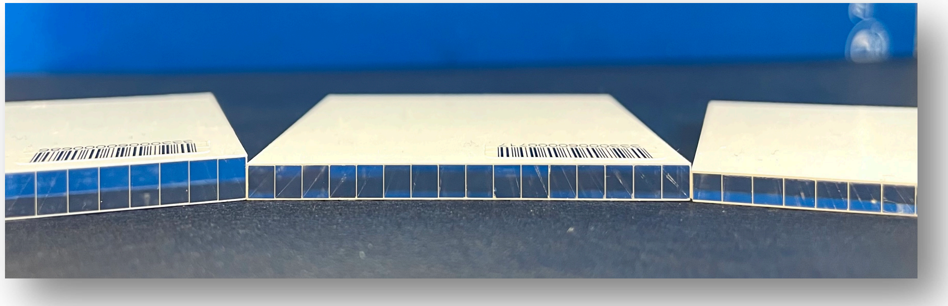
- fast timing properties, magnetic field tolerant, compact and robust
- 15 µm cell size (initial design)



Module

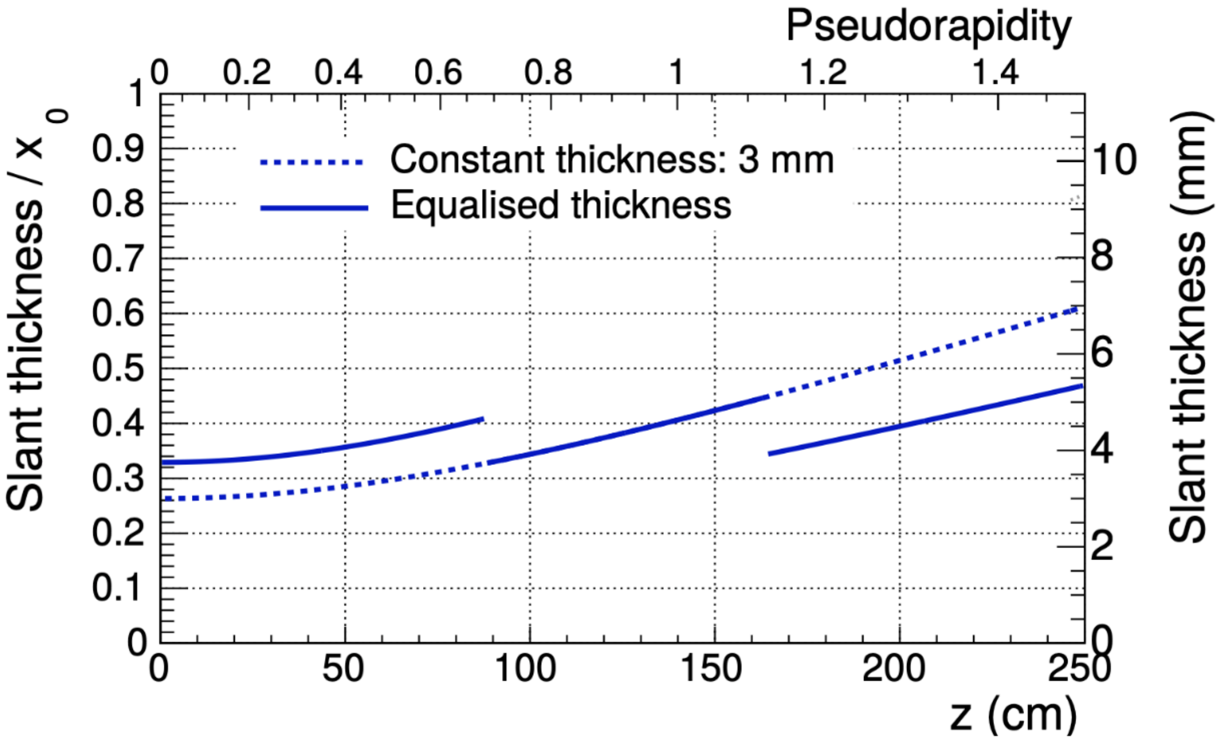
- array of 16 crystal bars coupled to a pair of SiPMs through optical glue
- modules will be exposed to an accumulated radiation levels of 50 kGy of ionizing dose and a neutron fluence of $2 \times 10^{14}\ n_{eq}/cm^2$
  - No other large area experiment has ever used SiPMs in such a harsh radiation environment

BTL sensor geometries



Modules exhibit different thicknesses depending on the η region: 3 sensor geometries featuring crystal thicknesses matching SiPM dimensions

- **type 1 (T1)**: 3.75 mm
- **type 2 (T2)**: 3.00 mm
- **type 3 (T3)**: 2.40 mm



BTL performance

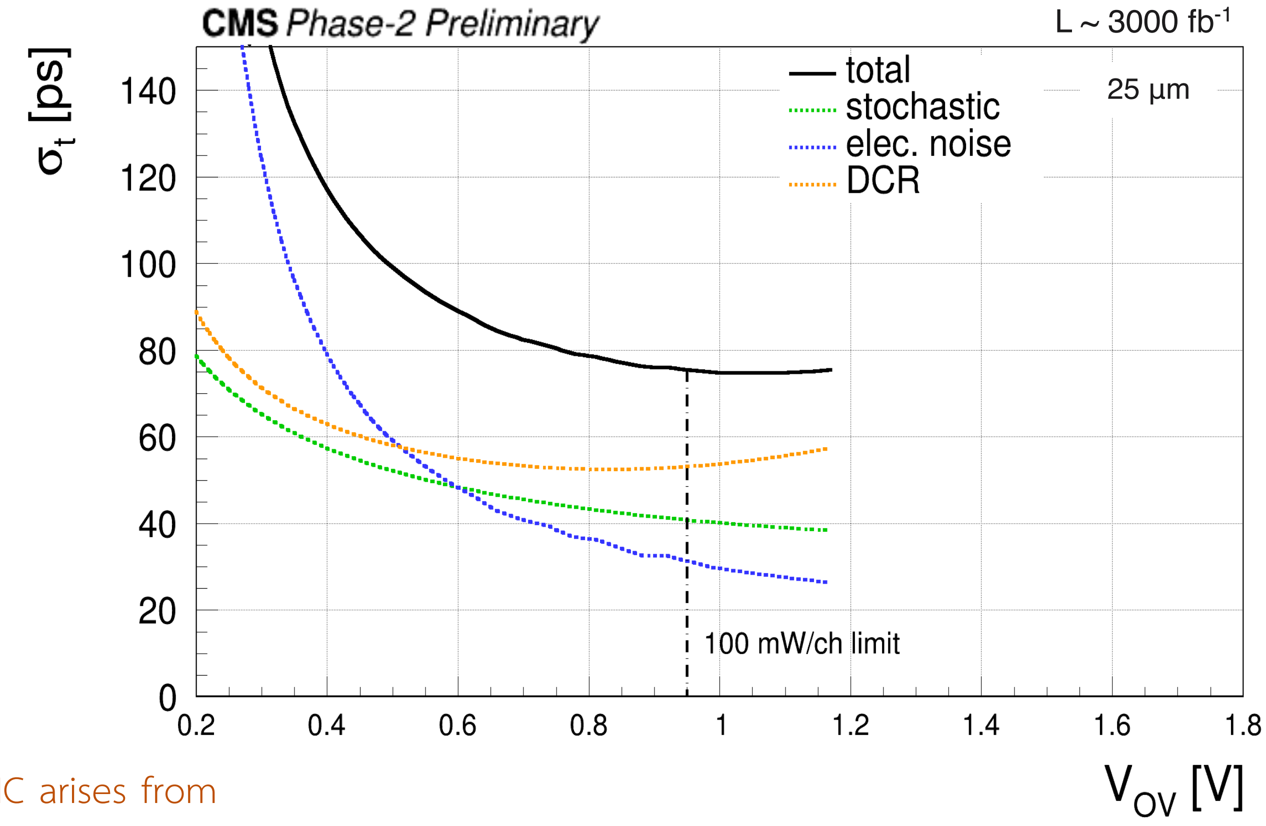
$$\sigma_{\mathrm{t}}^{\mathrm{BTL}} = \sigma_{\mathrm{t}}^{\mathrm{clock}} \oplus \sigma_{\mathrm{t}}^{\mathrm{digi}} \oplus \sigma_{\mathrm{t}}^{\mathrm{ele}} \oplus \sigma_{\mathrm{t}}^{\mathrm{phot}} \oplus \sigma_{\mathrm{t}}^{\mathrm{DCR}}$$

$$\sigma_t^{ele} \propto \frac{1}{dI/dt} \propto \frac{1}{N_{phe}}$$

$$\sigma_t^{phot} \propto \sqrt{\frac{\tau_d}{N_{phe}}}$$

$$\sigma_t^{DCR} \propto \frac{\sqrt{DCR}}{N_{phe}}$$

↓

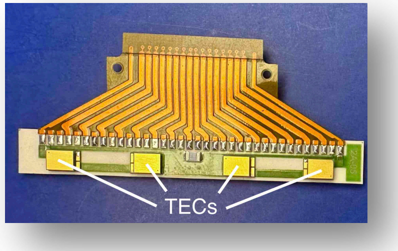


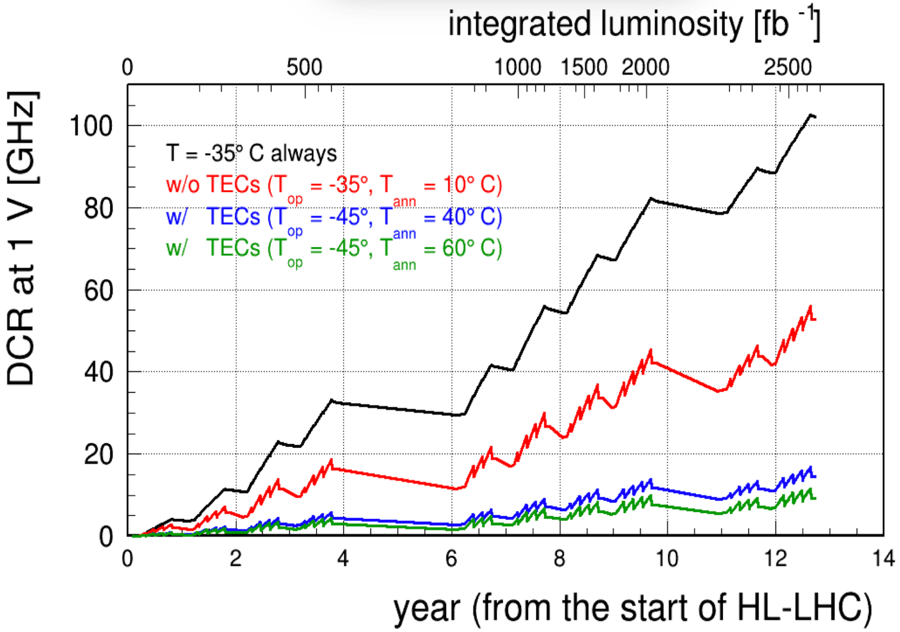
Significant impact towards the end of operations in HL-LHC arises from radiation-induced damage to SiPMs : Dark Count Rate ~ 10-30 GHz

Tackling Hi-Lumi challenges in BTL

Decreasing dark count rate

- *Thermo-Electric Coolers integration* on the SiPM packaging: lower operational temperature and higher annealing temperature





Reducing electronic noise contribution

- *SiPMs with a larger cell size*: increase in gain and PDE, faster rise time

Increase number of photoelectrons produced

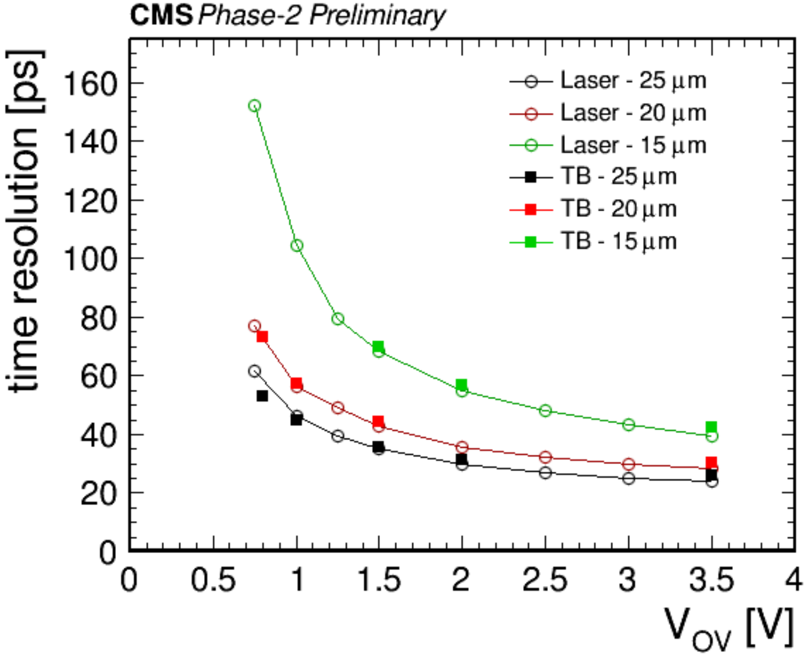
- *Increasing module thickness*: increase in energy deposit (~25%)

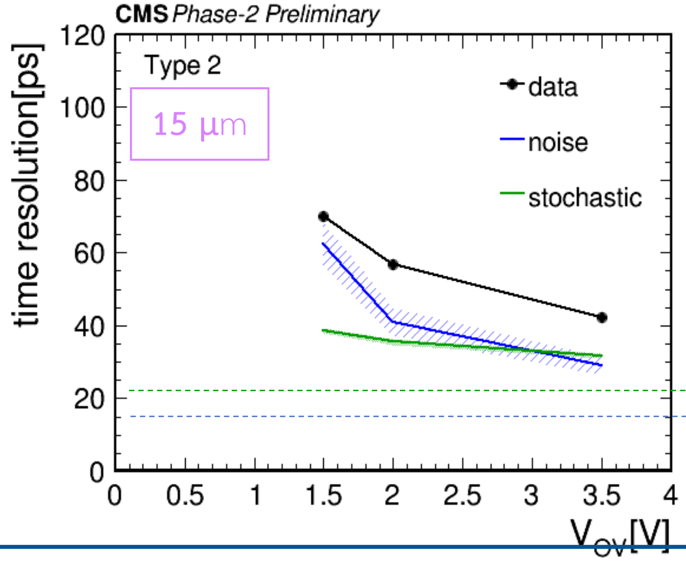
→ intense laboratory and test beam measurements focused on the validation of these studies

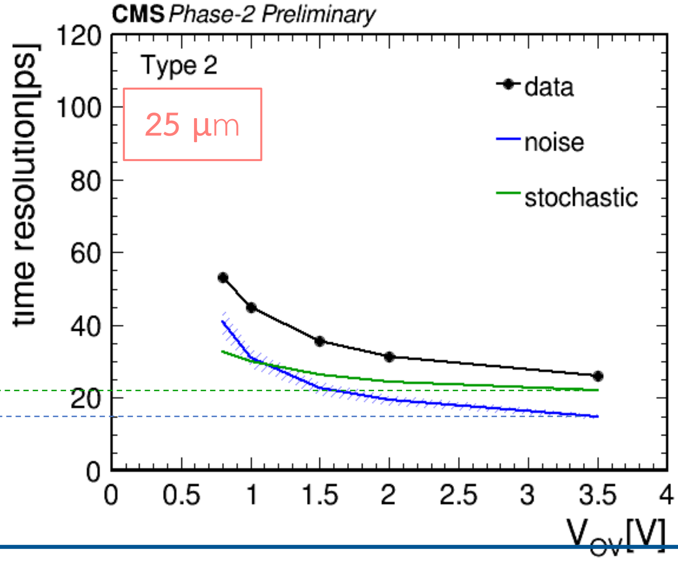
Larger cell size: non-irradiated sensors

- Modules with larger cell sizes confirmed to achieve the **best performance**
  - Good agreement between test beam and laboratory measurements

- Contributions to time resolution from electronic noise and stochastic term well understood using non-irradiated sensor modules





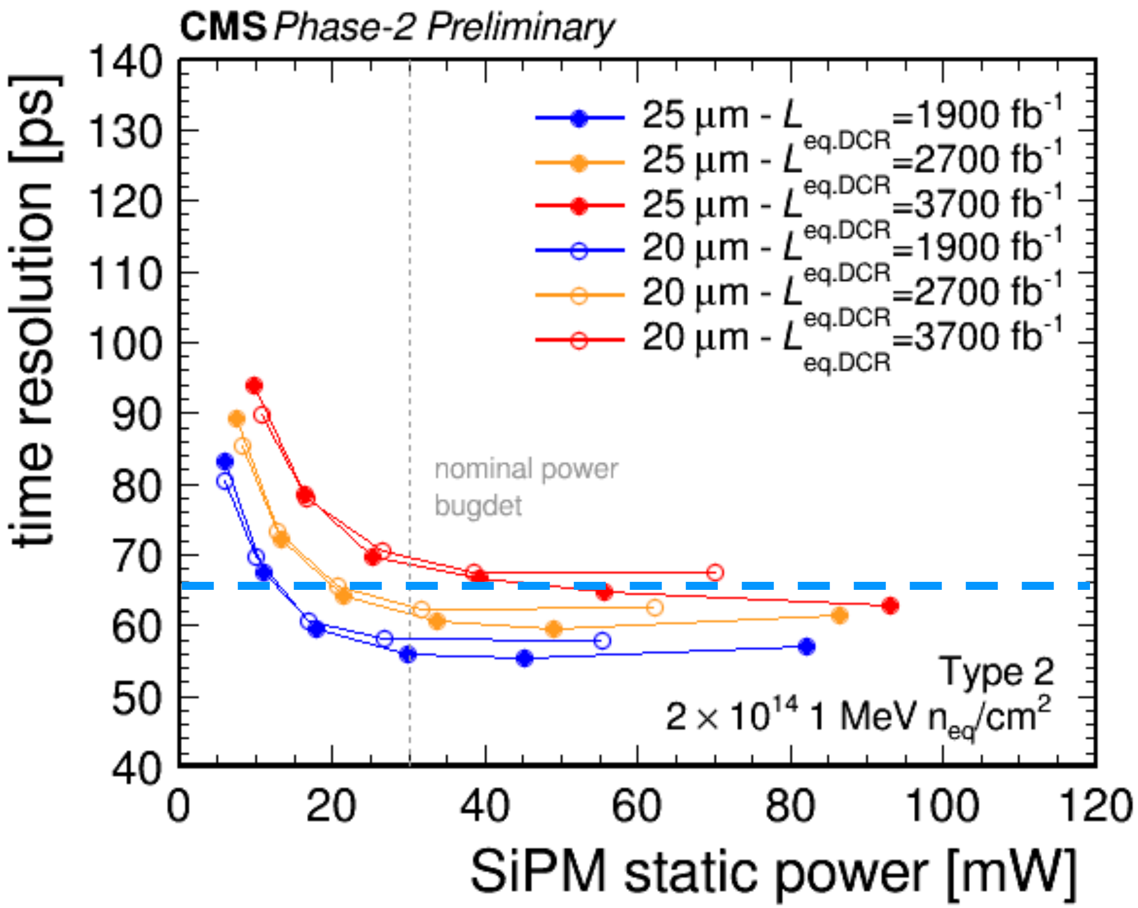


Larger cell size: irradiated sensors

- SiPMs featuring a cell size of 20 and 25 μm:

  - **irradiated to the total radiation level** expected at the end of HL-LHC operation (2×10^{14} n_{eq}/cm^{2})
  - assembled with LYSO arrays into sensor modules and tested at various temperatures to emulate different points of HL-LHC lifetime in terms of DCR

- Time resolution of **~ 65 ps** achieved with both modules, close to the design performance target

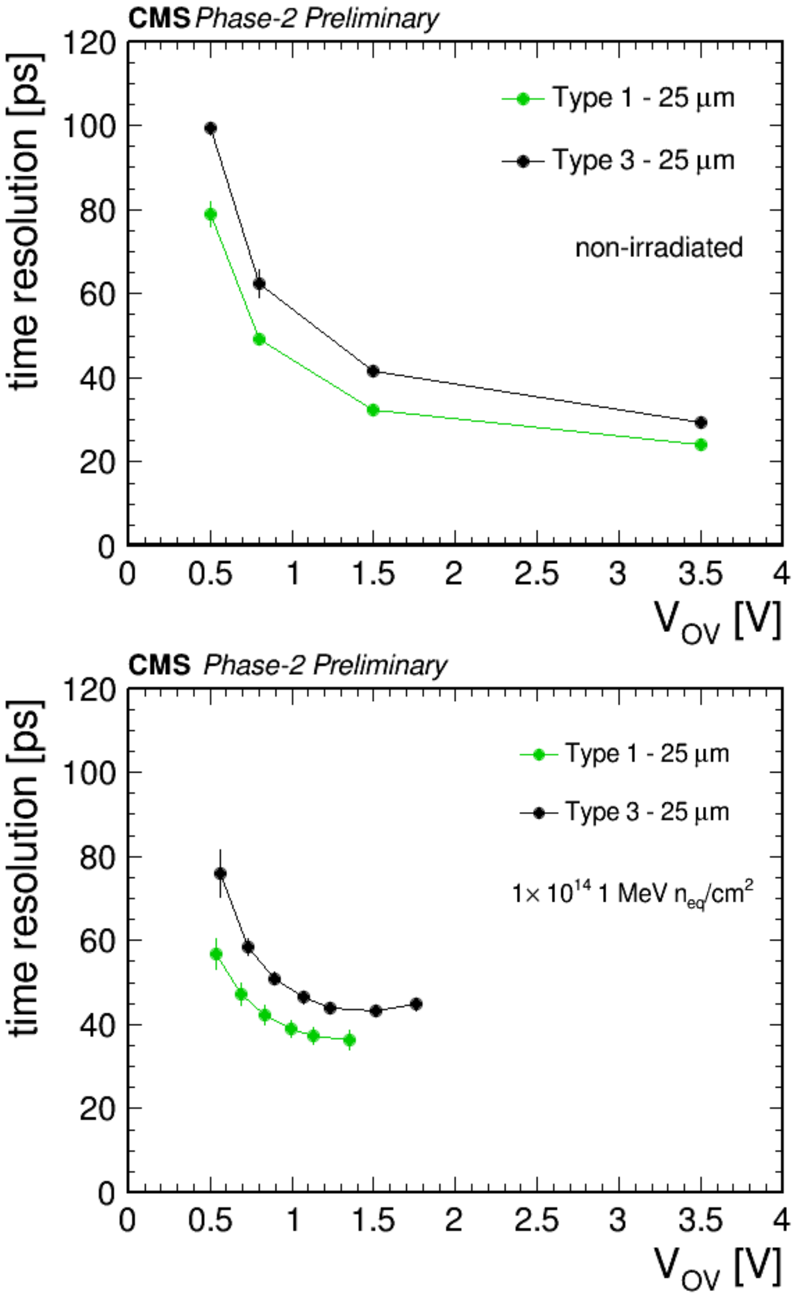


Thickening

- Non-irradiated SiPMs with a cell size of 25 μm were coupled to LYSO arrays
  - ○ **Significant enhancement** in time resolution observed from type 3 to **type 1**

- When subjected to irradiation, SiPMs with larger active area exhibit high DCR and increased power consumption ⟶ crucial to evaluate irradiated modules with different thicknesses

- Both T1 and T3 SiPMs, featuring a 25 μm cell size, underwent irradiation to half of the total radiation level (1 x 10^{14} n_{eq}/cm^2)
  - ○ **Enhanced performance of the thickest** modules was validated also in the case of **irradiated** SiPMs



Towards the assembly

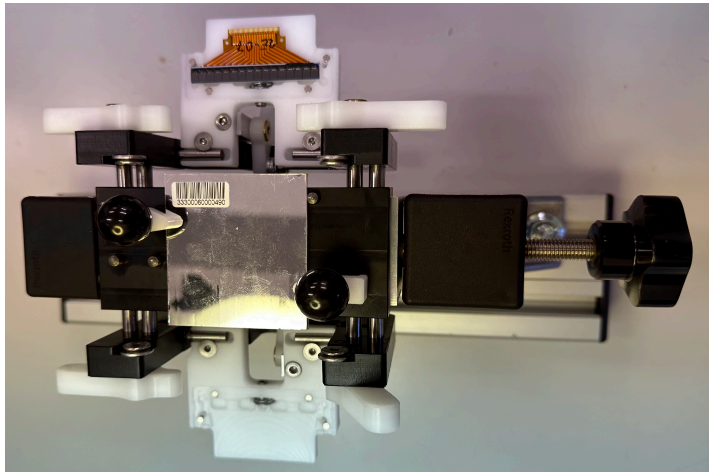
Prototyping phase concluded, ready for production!

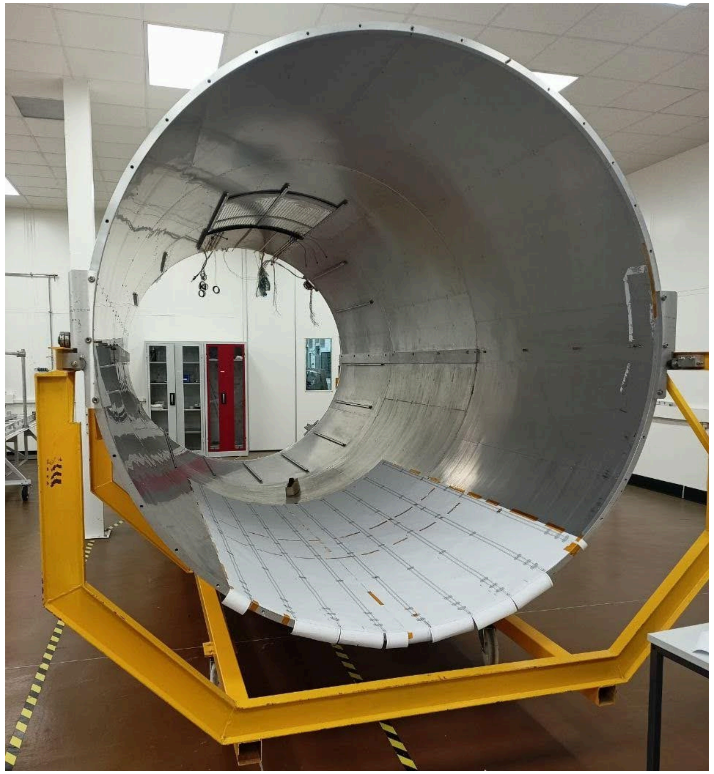
- ***4 BTL Assembly Centers*** (Milano-Bicocca, Caltech, U. Virginia and Peking U.)
- ***Common tools*** for module assembly (e.g. gluing tools and tester boards) are being finalized

- ***2 trays/month*** production and testing @ each BAC and sent to CERN
- ***Tray integration @ Tracker Integration Facility*** + tray test

- ***Final installation*** in the BTL Tracker Support Tube by May ***2025***

Commissioning in CMS starting in 2027





Conclusions

- BTL prototyping phase now concluded
- Innovations in sensors design:
  - ☐ TECs integration: reduced DCR ⟶ improved performance
  - ☐ 25 µm cell size SiPM: improved performance compared to 15 µm
  - ☐ Thickest module: better timing performance both at BoO and EoO

✓ Performance of the final prototypes aligned with the design target