Design validation of the CMS MTD Barrel Timing Layer

IPRD23 - Siena, 25-29 September 2023

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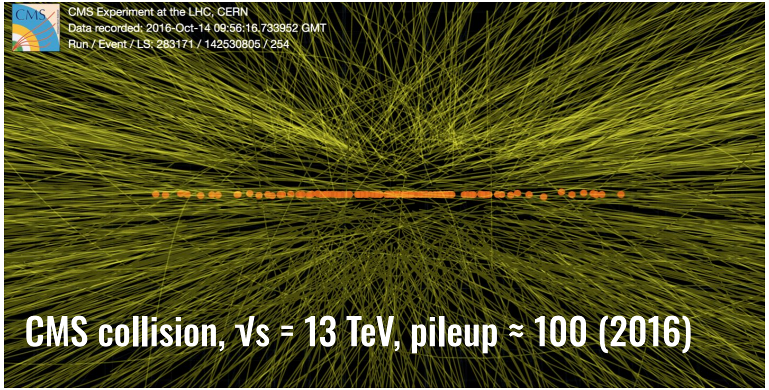
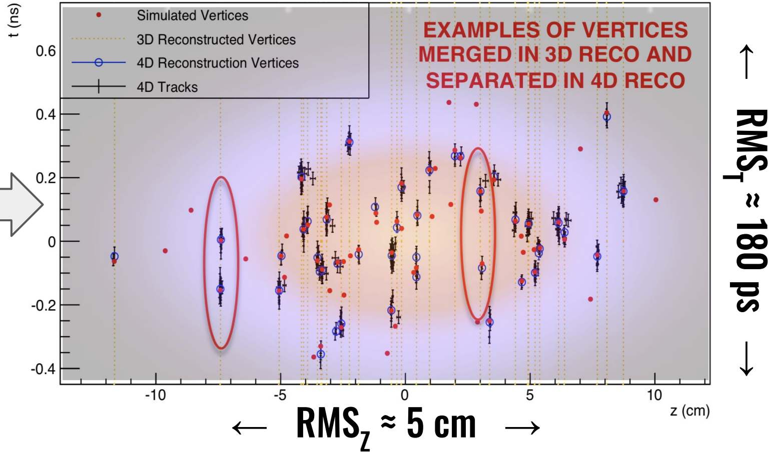
Outline:

- Introduction to MTD and BTL
- The challenges of BTL
- Performance validation
- Towards the assembly

Precision timing at CMS for HL-LHC

- At HL-LHC (2029 → 2042), instantaneous luminosity & pileup ≈ 4-6× higher than current LHC levels
  - **L_{inst} ≳ 5×10^{34} cm^{-2} s^{-1}**, up to **140-200** nearly-simultaneous collisions (**pileup**)
  - challenging radiation levels to withstand for all sub-detectors
- **Precision MIP timing with tens-of-ps resolution** allows recovering current LHC level of vertex merge rate & track purity

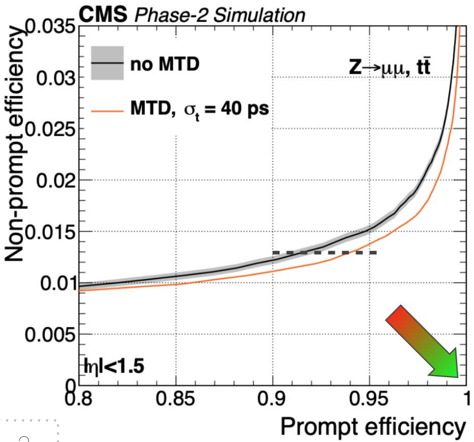




- **CMS strategy** for pileup mitigation: upgraded tracker + **a dedicated detector for precision timing**, the **MTD** (Mip Timing Detector)

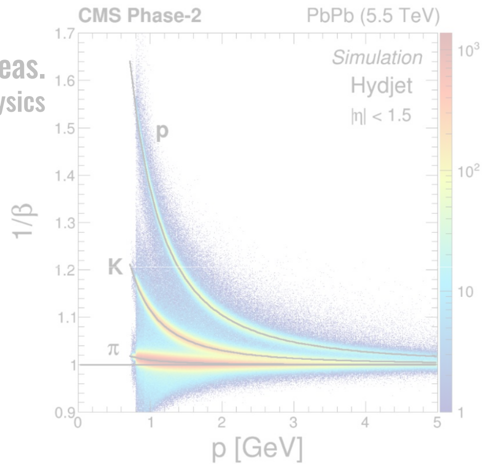
Impact of precision timing

- Precision timing brings an ample spectrum of downstream gains to the CMS physics programme at the HL-LHC:
  - ×2 **reduction of wrong track-vertex associations** → improved reconstruction performance of ~all physics objects and therefore ~all CMS analyses
    - e.g. improve expected HL-LHC HH significance as much as ~2-3 additional years of HL-LHC data taking

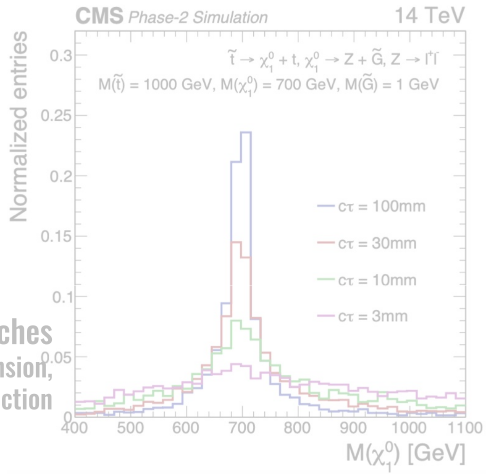


gains in object ID
~virtually all analyses

PID from β meas.
flavor / HI physics



LLP searches
acceptance extension,
mass reconstruction



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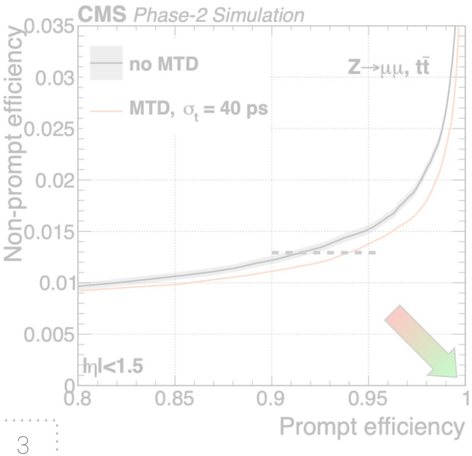
  - genuinely **new information** to the CMS event record (e.g. **PID**)
    - relevant for flavor / HI physics



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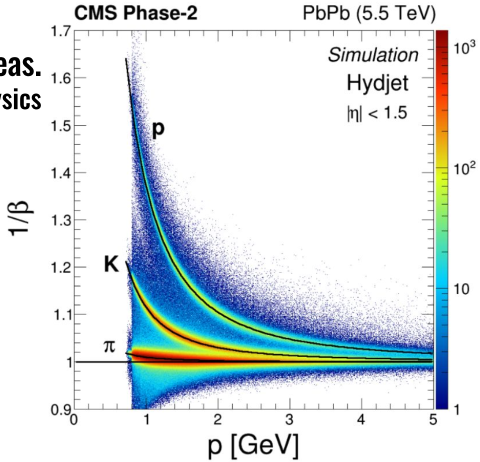

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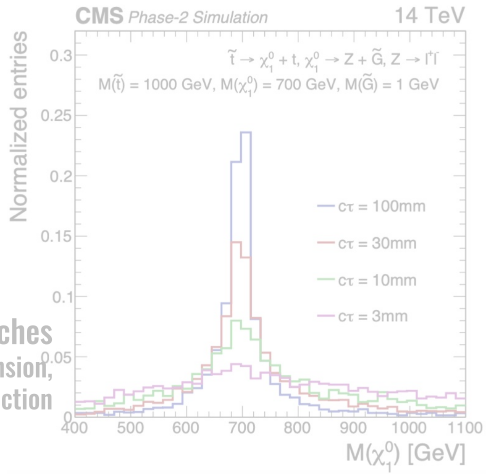

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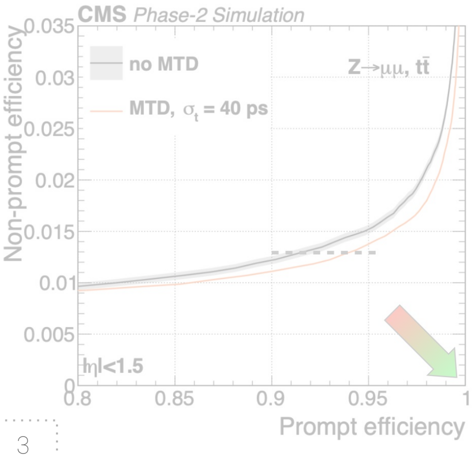
  - genuinely **new information** to the CMS event record (e.g. **PID**)
    - relevant for flavor / HI physics
  - new handle for long-lived particles (e.g. mass reconstruction from velocity measurements)



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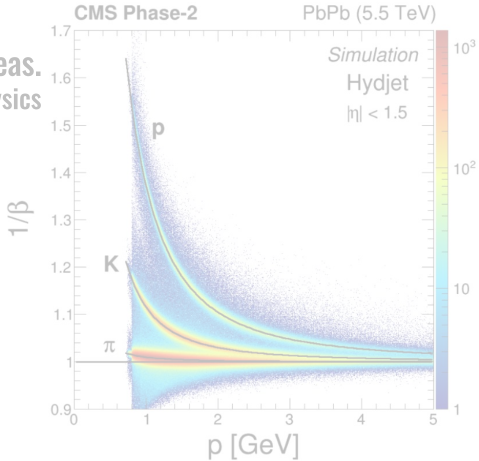

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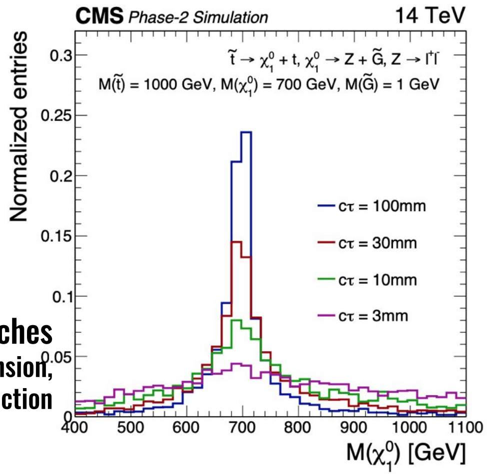
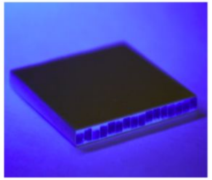


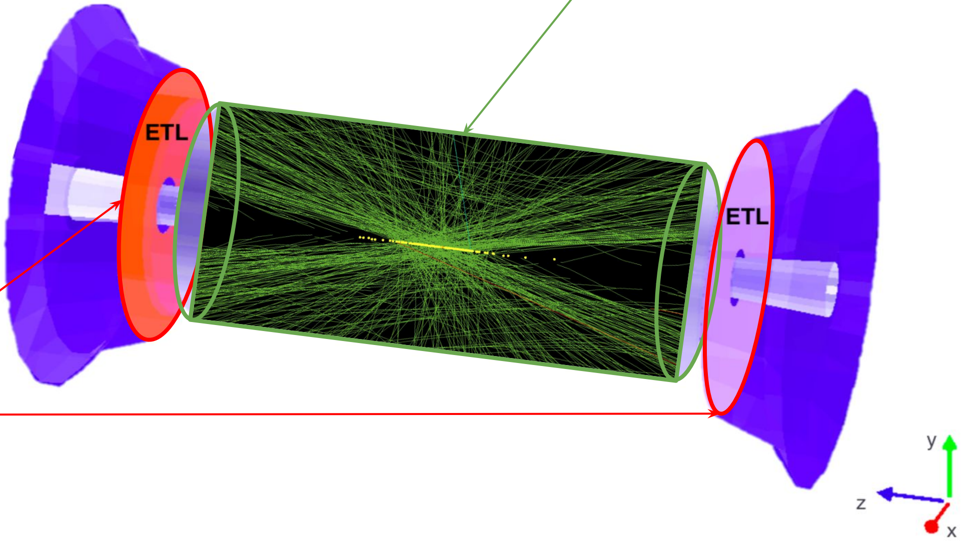
MTD design

- The MTD detector is a **thin, hermetic (|η| < 3) precision timing layer** for **MIP particles**, to be installed between the tracker and the calorimeter
- Different sensor technologies for barrel / endcap detectors, dictated by:
  - technology maturity / radiation tolerance
  - CMS integration and overall CMS Upgrade schedule
  - cost and power effectiveness

BTL: LYSO bars + SiPM readout:

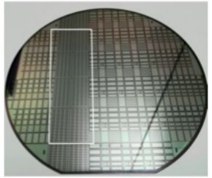
- TK / ECAL interface: |η| < 1.45
- Inner radius: 1148 mm (40 mm thick)
- Length: ±2.6 m along z
- Surface ~38 m^2; 332k channels
- Fluence at 4 ab^{-1}: 2×10^{14} n_{eq}/cm^2





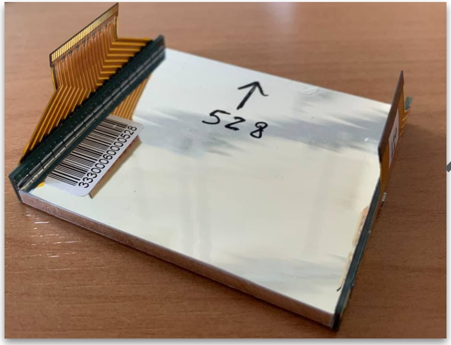
ETL: Si with internal gain (LGAD):

- On the CE nose: 1.6 < |η| < 3.0
- Radius: 315 < R < 1200 mm
- Position in z: ±3.0 m (45 mm thick)
- Surface ~14 m^2; ~8.5M channels
- Fluence at 4 ab^{-1}: up to 2×10^{15} n_{eq}/cm^2

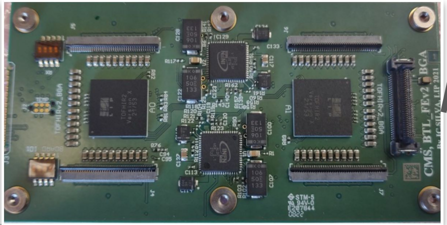


BTL design

sensor module
16 LYSO bars with double-ended SiPM readout



FE boards
2 TOFHIR ASICs +
2 ALDO LV/HV regulators



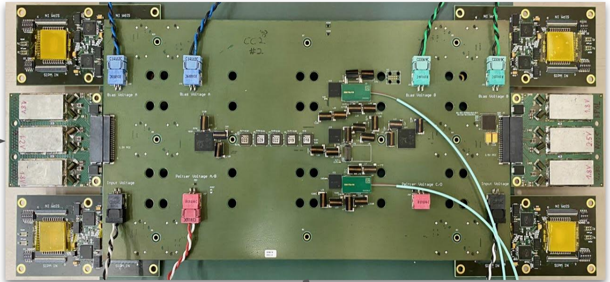
2×

1×

detector module
2 sensor modules + FE in a copper housing

12×

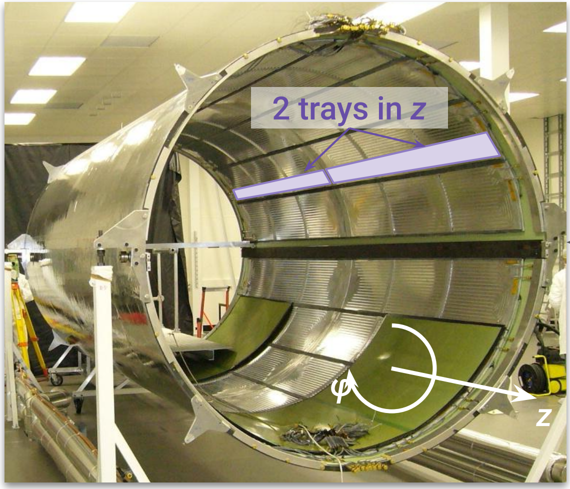
Readout unit
12 detector modules, optical readout + DC/DC converters



6×

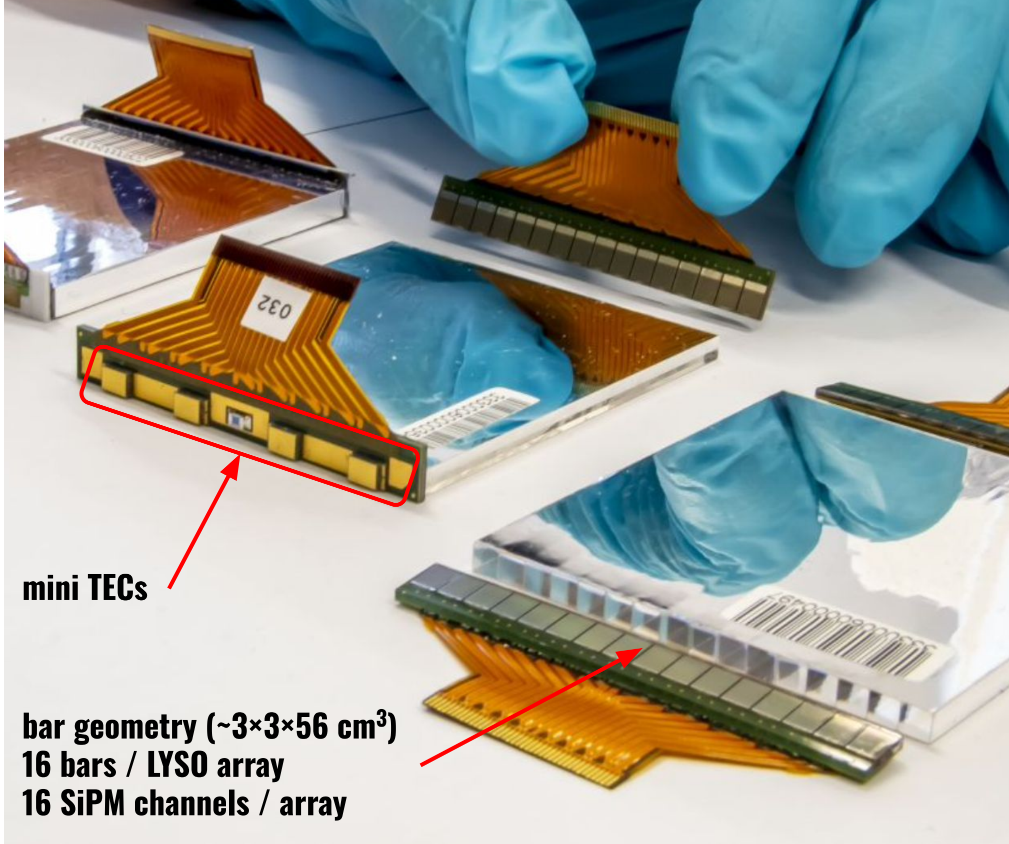
tray
2.5 m long, CO_2 cooling pipes

72×



BTL sensors

- **LYSO:Ce scintillating crystals**
  - fast scintillation rise time (< 100 ps)
  - short decay time (~40 ns)
  - high light yield (~40000 ph./MeV)
  - **tolerant to radiation**
    - light output loss < 10% for 50 kGy (end of HL-LHC + safety margin)
- **Silicon photomultipliers**
  - fast response, crucial for timing
  - compact & insensitive to magnetic field
  - **mini Thermo Electric Coolers (TECs)** integrated in the SiPM package
  - neutron **fluence of 2×10^{14} cm^{-2}** expected by the end of HL-LHC (3000 fb^{-1}) → high level of radiation-induced dark noise



- The **SiPM radiation damage** is the **biggest challenge** for the BTL performance & operations
  - it's the first time SiPMs will be used for a particle detector in such a harsh environment!

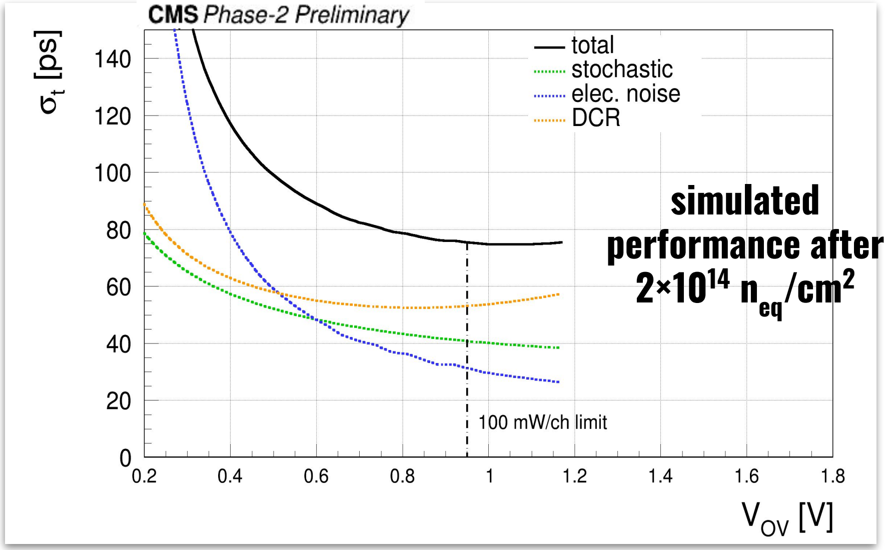
The BTL performance

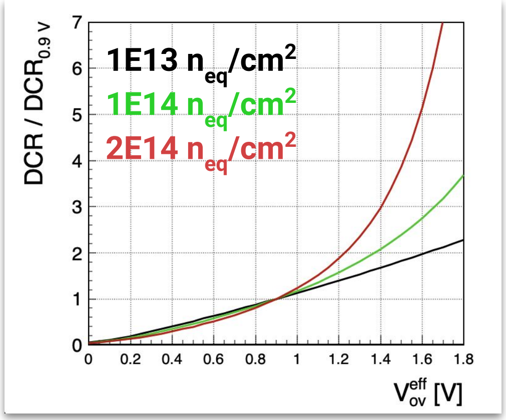
- The expected time resolution of the BTL detector can be described as $\sigma_t = \sigma_t^{stat.} \oplus \sigma_t^{elec.} \oplus \sigma_t^{DCR}$

- **photostatistics contribution**:
  - $\sigma_t^{stat.} \sim 1 / \sqrt{N_{pe}}$

- **electronics contribution**:
  - $\sigma_t^{elec.} \sim \sigma_{noise}$ / pulse slope $\sim \sigma_{noise} / N_{pe}$
    - benefits from large light output and fast SiPM response (e.g. high SiPM gain)

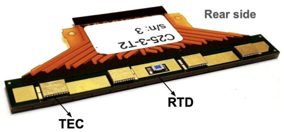
- **dark count rate (DCR) contribution**:
  - $\sigma_t^{DCR} \sim \sqrt{DCR} / N_{pe}$
    - **dominant contribution** for end-of-operation conditions (**EoO**)
    - expect **O(10-30 GHz)** of spurious DCR at EoO

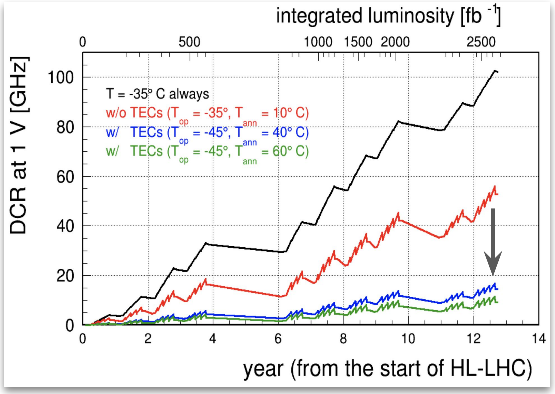




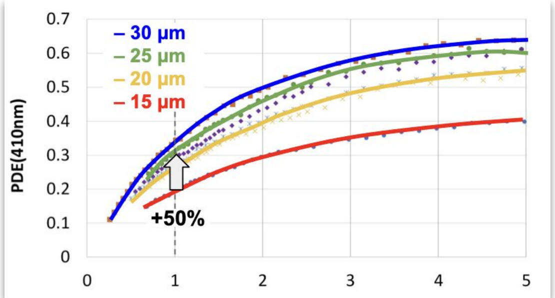
The BTL solution to high dark noise

- **Smart thermal management** thanks to the usage of **TECs**
  - lower local **SiPM temperature (ΔT = -10° C)** w.r.t. the CO_2 temperature during operations (from -35° C to -45° C) → **DCR reduction** of a factor of about 2
  - **high-temperature** cycles during technical stops / machine shutdowns to **anneal SiPM** radiation damage (**up to 60° C**, when the CO_2 runs at 10° C)
  - **~5× reduction in DCR** compared to the case of no TECs

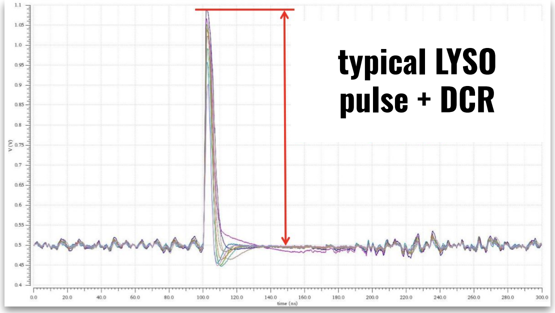




- **SiPM spad size optimized**
  - trade-off between PDE and gain (better for large spad area) and DCR / power dissipation
  - **25 μm² spad size** identified as the optimum for the BTL case

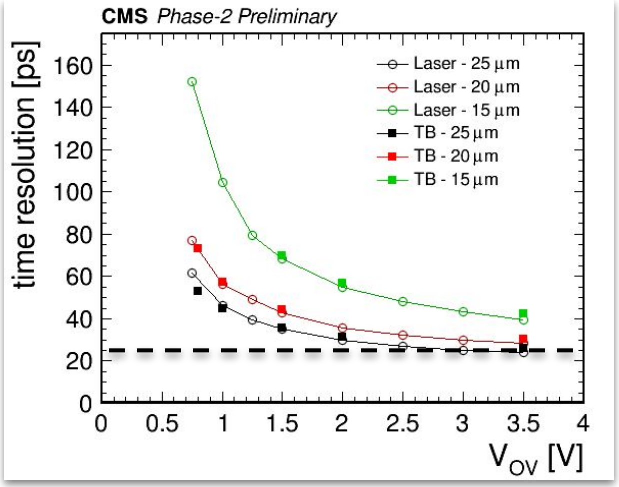


- **DCR mitigation** within the TOFHIR ASIC
  - inverted and delayed current pulse added to the original pulse (DLED)
  - mitigate noise / baseline fluctuations

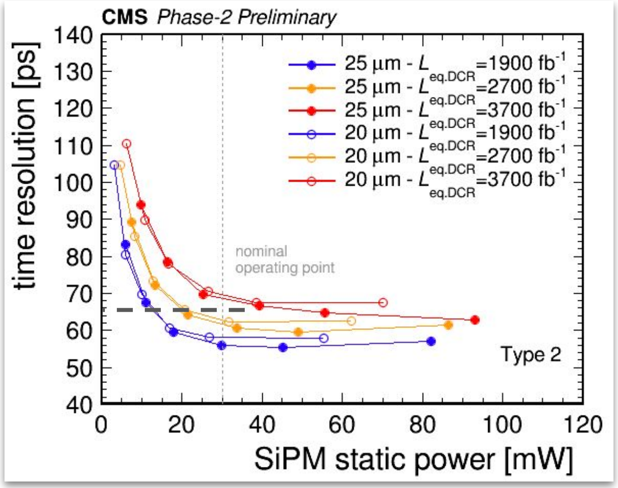


Performance validation

- The performance of **non-irradiated** BTL module prototypes was validated through beam and laboratory measurements
  - excellent agreement between beam and laboratory results
  - larger SiPM spad area beneficial for the performance
  - **≲ 30 ps achieved** for conditions representative of **HL-LHC startup**

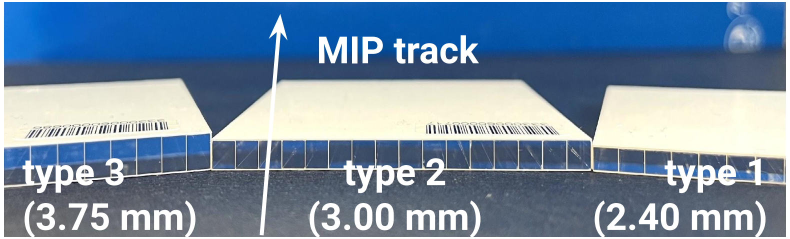


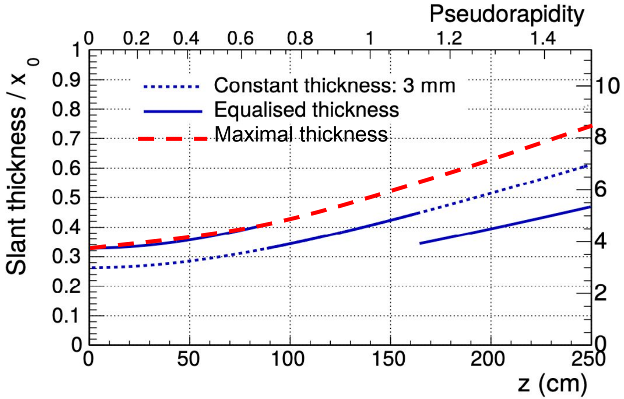
- Module prototypes with **SiPMs irradiated** to the full expected HL-LHC fluence were also tested on beam
  - SiPMs annealed and tested at a temperature that emulate the **expected conditions for end of HL-LHC operations** (3000 fb^{-1})
  - **~65 ps** measured for 25 µm SiPMs, within the available detector power budget

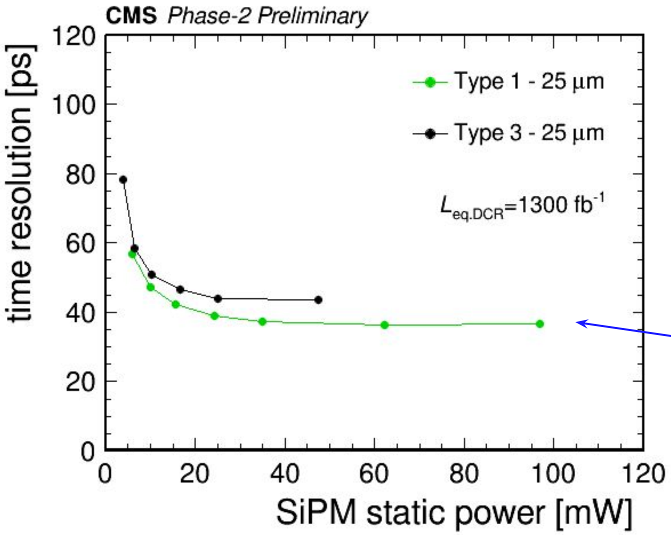


LYSO thickness optimization

- Variable LYSO thickness along the detector's pseudorapidity was assumed in the initial design
  - module prototypes were tested in three different thickness flavors [2.4, 3., 3.75 mm]
  - allowed for a ~uniform material budget in front of the electromagnetic calorimeter



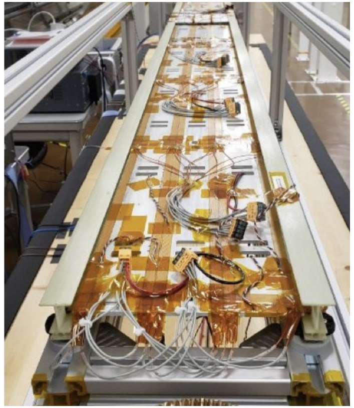




- Thanks to a larger energy deposit, modules with **thicker LYSO** exhibit a **better time resolution**, both before and after irradiation
  - downstream impact on ECAL still negligible
  - **maximal thickness scenario** now assumed as the **new baseline**, to gain performance margins

Towards assembly & integration

- 4 **BTL Assembly Centers** (Milano-Bicocca, Caltech, U. Virginia and Peking U.) are being set up for the detector assembly
- **Common tools** for module assembly (e.g. gluing tools and tester boards) are being finalized
- **2 trays/month** assembled and tested @ each assembly center, then shipped to CERN. Starting Summer 2024
- Tray integration at CERN @ Tracker Integration Facility
- **Final installation** in the BTL Tracker Support Tube by **Summer 2025**
- Commissioning in CMS starting in 2027




Summary

- The **BTL prototyping** phase is now **concluded**, now transitioning to production & assembly
  - major sensor procurements have started
  - detector module assembly at the Assembly Centers slated to begin in Summer 2024, integration at CERN by Fall 2024

- The **unprecedented challenges** posed by the operation of SiPMs in the harsh radiation environment of the BTL detector require smart solutions:
  - noise cancellation in the ASIC
  - SiPM spad size optimization
  - thicker LYSO for increased energy deposition
  - extreme temperature cycles [-45° C – 60° C] for DCR mitigation + annealing

- The **performance** of the final prototypes is **aligned with the design** (TDR) **target**