Test beam performance of sensor modules for the CMS Barrel Timing Layer

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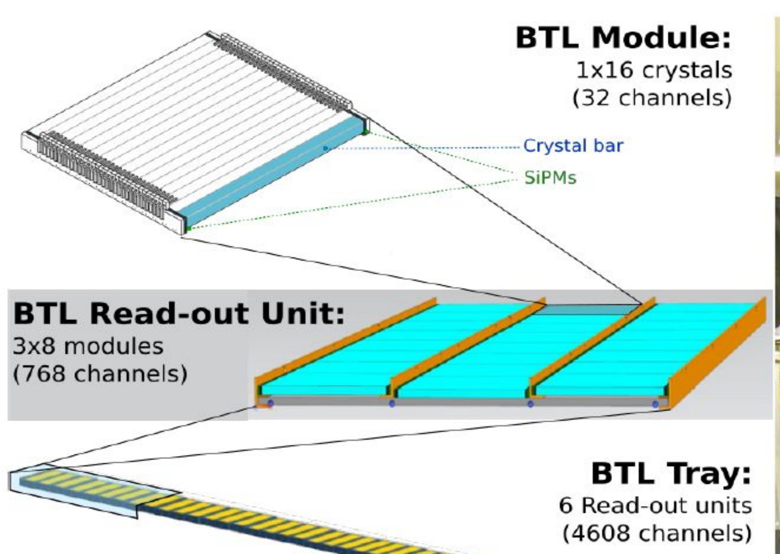
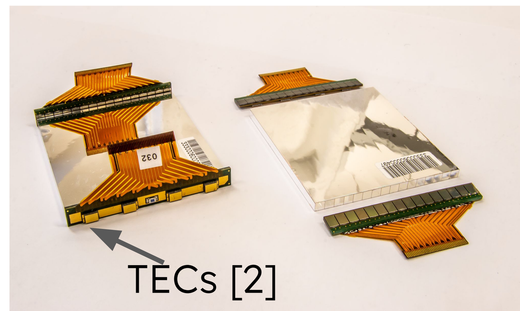
The Barrel Timing Layer for Phase II upgrade of CMS detector

The **Mip Timing Detector (MTD)** [1] is included in the **Phase II Upgrade** of the **Compact Muon Solenoid (CMS)** detector:

- Upgrade of the CMS detector needed to cope with harsh **High Luminosity (HL) LHC** conditions, such as:
  - **higher** amount of **interactions per bunch crossing** (~200)
  - **higher radiation damage** (integrated particle fluences of ~ 2 x 10^{14} 1 MeV n_{eq}/cm^2)
- MTD inserted between the tracker and the electromagnetic calorimeter:
  - Barrel Timing Layer : LYSO:Ce crystal bars readout at both ends by Silicon Photon Multipliers (SiPMs)
  - Endcap Timing Layer: LGADs
  - Time resolution: **30-60 ps** at the beginning of its operation (BoO) - end of operation (EoO) due to radiation damage
  - Perform **4D reconstruction** of vertices to maintain the actual CMS reconstruction performance

Barrel Timing Layer



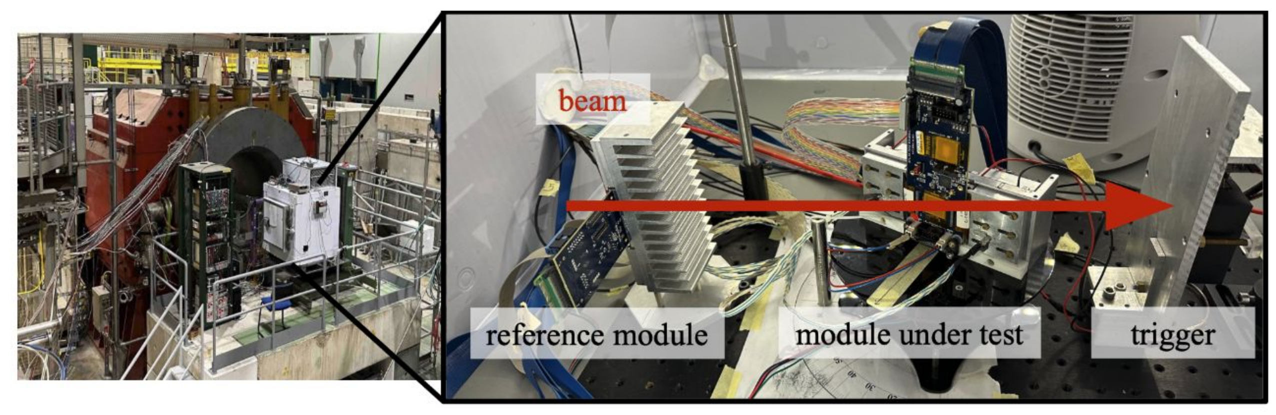


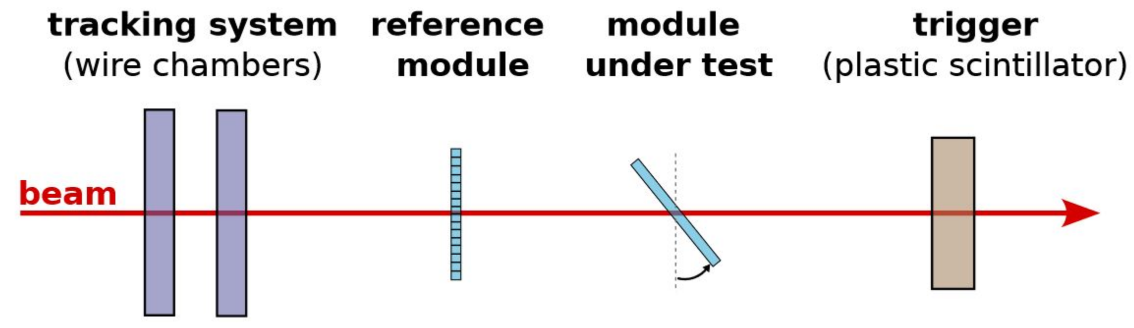
TECs [2]

Sensor modules
16 bars of LYSO:Ce
(3.75 x 3.12 x 55 mm^3)
+
Hamamatsu Photonics (HPK) SiPMs
+
dedicated readout chip TOFHIR2C [3]

Test beam campaigns

- Several **test beam campaigns** performed at CERN's test beam facility in the Prevessin Site with 180 GeV pions and at Fermilab Test Beam Facility with 120 GeV protons to evaluate optimal design





Time resolution main drivers

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

Electronics noise
Scaling with the steepness of the rising edge of signal pulses at the timing threshold

$1/(dI/dt) \propto 1/N_{pe}$

Photo-statistics
due to fluctuations in the time of arrival of photons detected by SiPMs

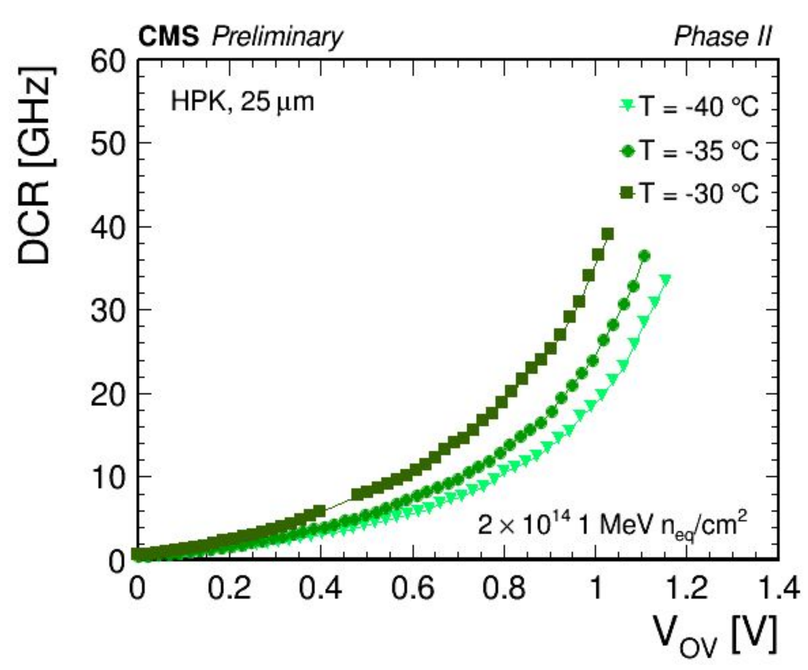
$1/\sqrt{N_{pe}}$

Dark Count Rate
Induced by radiation damage
Expected integrated fluence up to 2 x 10^{14} 1 MeV n_{eq}/cm^2

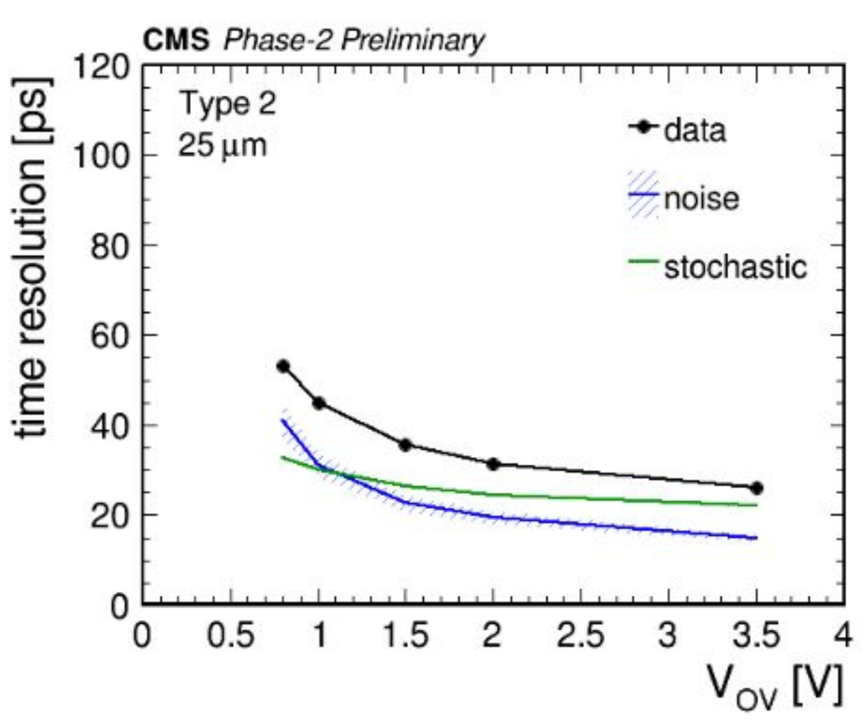
$\sigma_t^{DCR} \propto \sqrt{DCR}/N_{pe}$

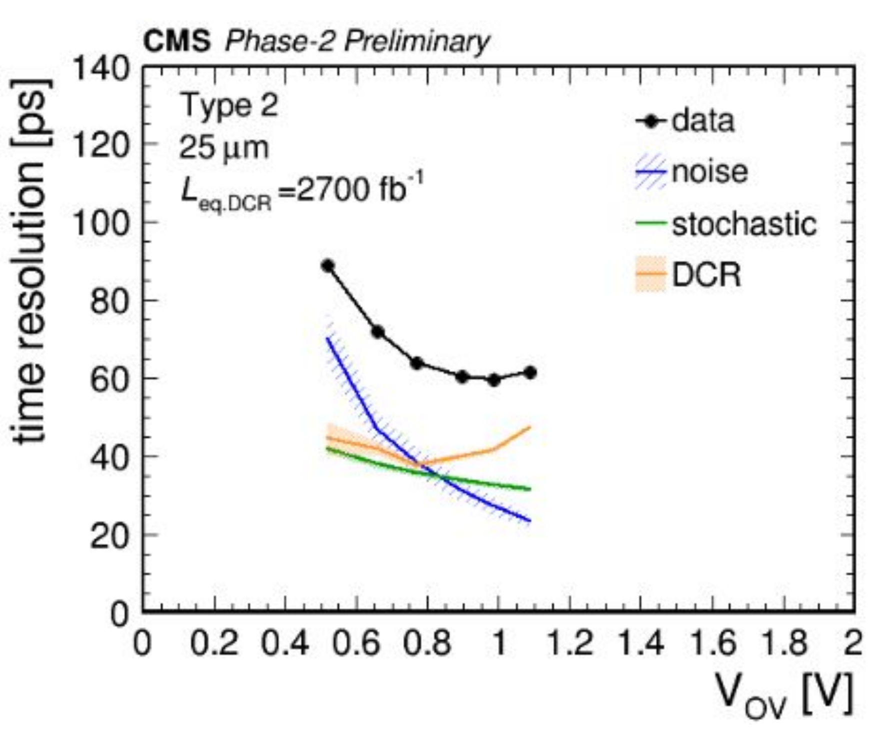
Addition of **mini thermoelectric coolers** (TECs) for DCR reduction [2]:

- operation of SiPMs at **-45 °C** (about a factor 2 reduction in DCR every 10 °C)
- annealing up to **60 °C** during shutdown/technical stops



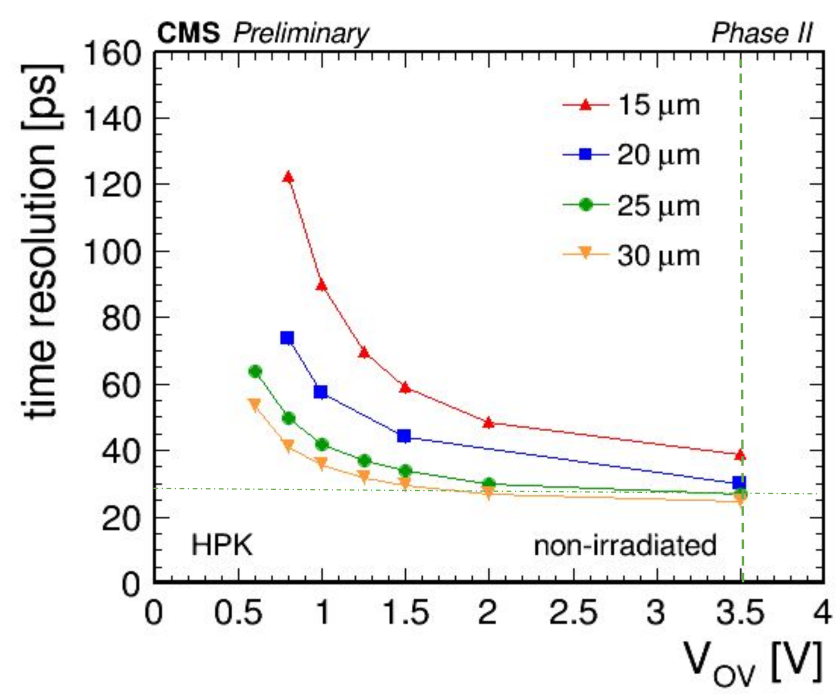
- **Photo-statistics** is dominant at BoO typical working point of 3.5 V
- **Electronics noise** has a large impact at low over-voltages (V_{ov})
- **DCR noise** becomes the main contribution at large V_{ov} in the time resolution for EoO SiPMs

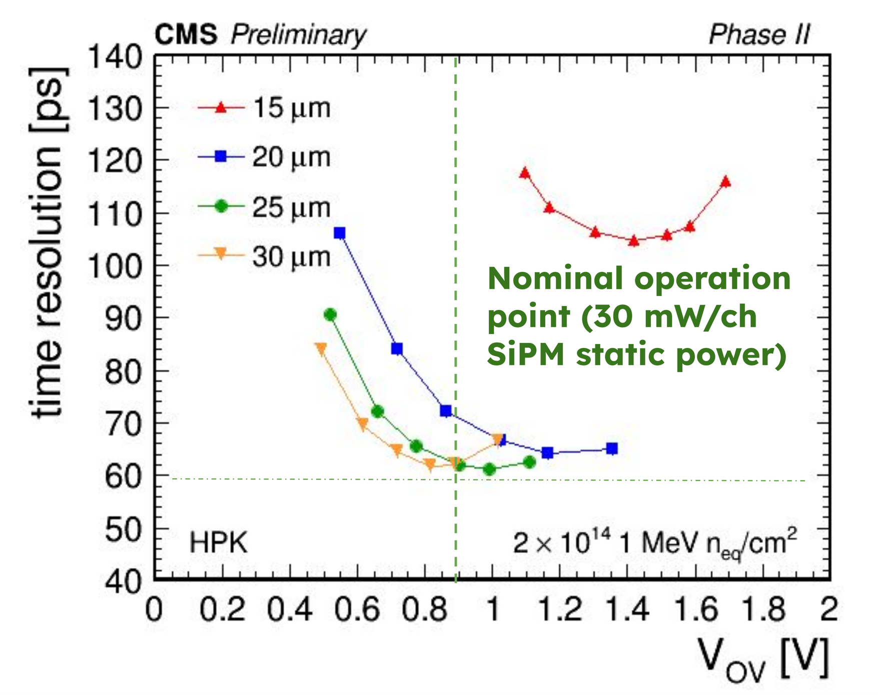




Optimization of the sensors

1. **SiPMs cell-size**:
   - SiPMs with larger cell-size feature **higher PDE and Gain,** which mean **higher number of photoelectrons (N_{pe}) and signal slope** → reduction of the photo-statistic and the electronics noise terms.
   - However, these SiPMs have **larger DCR** (due to larger effective active area of SiPMs). But since $\sigma_t^{DCR} \propto \sqrt{DCR}/N_{pe}$ → net improvement in **signal-to-noise ratio.**

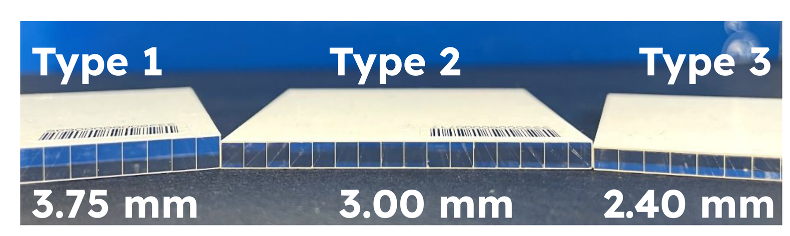




Non-irradiated SiPMs reproduce BoO performance. At typical working point of 3.5 V the target time resolution of **25-30 ps** is achieved.

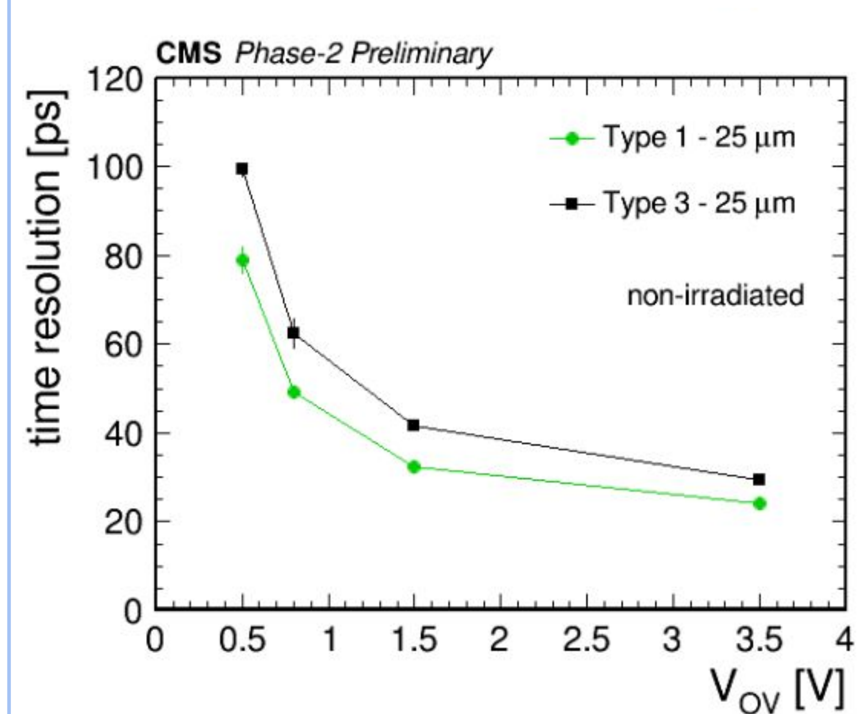
SiPMs irradiated to 2 x 10^{14} 1 MeV n_{eq}/cm^2 represent the performance expected at the EoO. A **60 ps** (nominal performance) time resolution is achieved with 25 um SiPMs within power budget constraints.

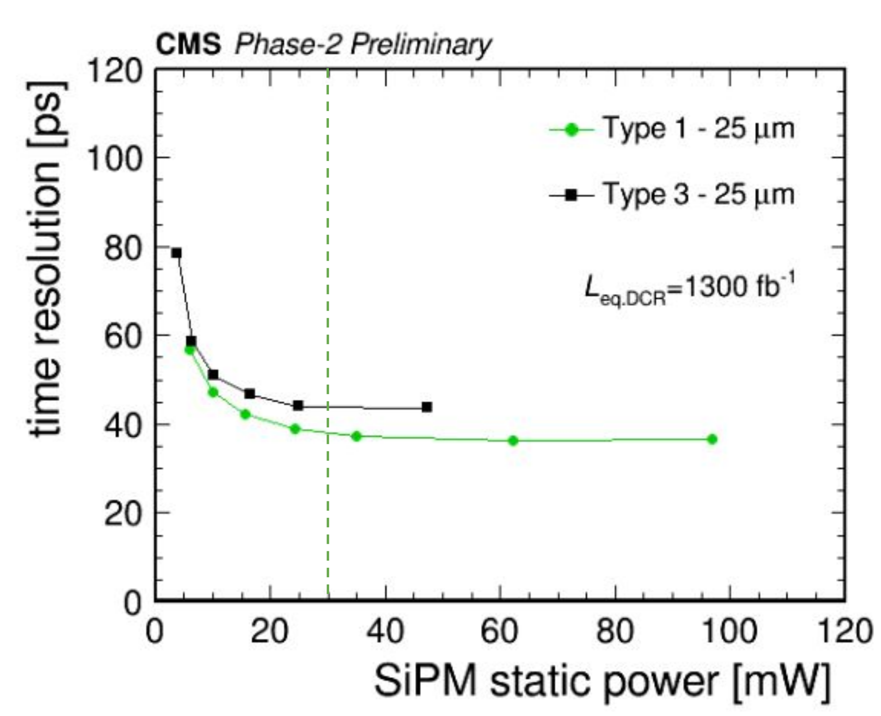
2. **Crystal thickness:**
   - Increasing the thickness (t) results in a **higher energy deposited** in the crystal by MIPs → $N_{pe} \propto t$



   - However, the need of SiPM with a larger active area to keep unaltered light collection efficiency increases **DCR** as well. Expected gain in $\sigma_t^{DCR} \propto 1/\sqrt{t}$

Type 1 crystals **perform better** in both BoO and after irradiation scenarios.

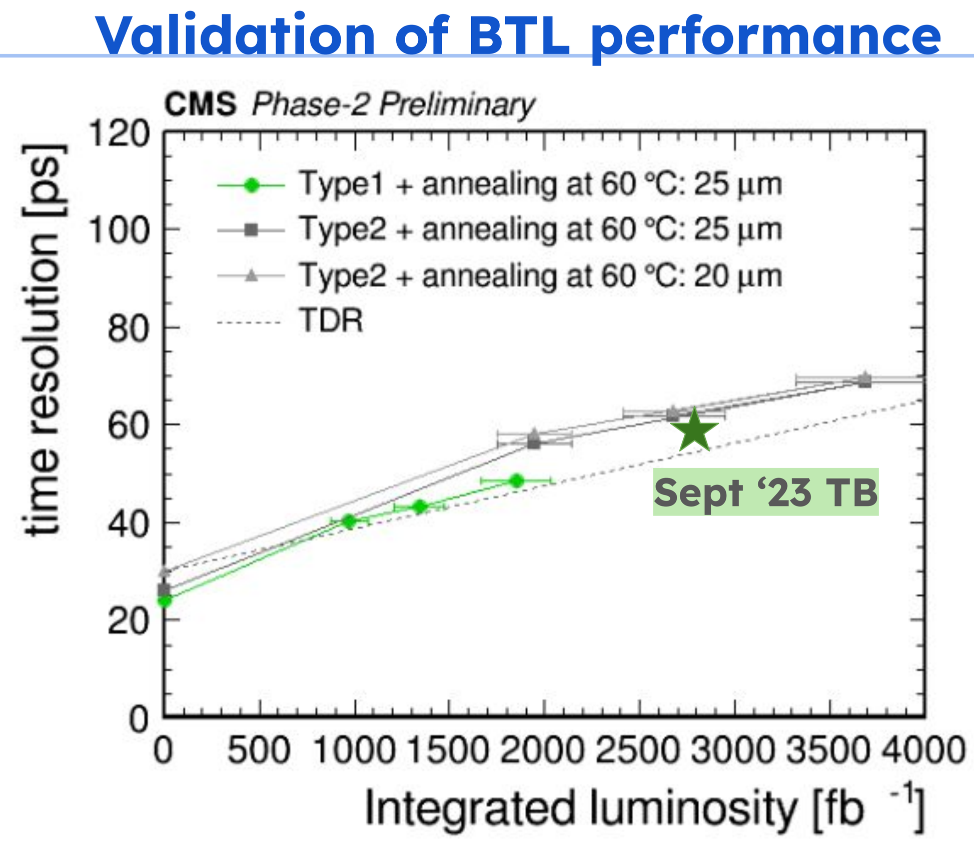




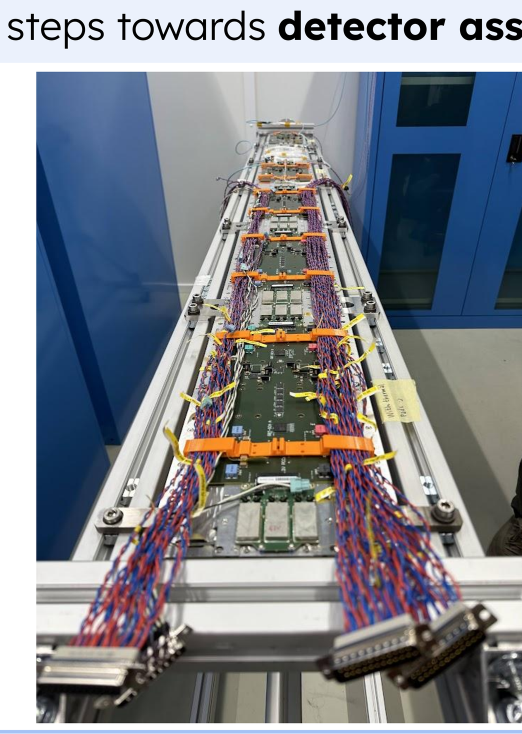
Validation of BTL performance

BTL timing resolution performance has been validated through a set of several test beam campaigns during 2023.

- ★ These campaigns led to the final choice of the sensor modules:
  - 25 um cell-size HPK SiPM with 3.75 mm thick crystals (type 1)
- ★ The chosen detector configuration achieves design requirements of **25-30 ps** at the BoO and **60 ps** after 3000 fb^{-1}.



Prototyping phase for BTL is closed, now into final preparation steps towards **detector assembly and integration**



References

[1] CMS Collaboration, *A MIP Timing Detector for the CMS Phase-2 Upgrade*, CERN-LHCC-2019-003; CMS-TDR-020
[2] A. Bornheim *et al.*, *Integration of thermo-electric coolers into the CMS MTD SiPMs arrays for operation under high neutron fluence*, JINST 18 (08) (2023) P08020. doi:10.1088/1748-0221/18/08/P08020.483
[3] E. Albuquerque *et al.* , *TOFHIR2: the readout ASIC of the CMS barrel MIP Timing Detector*, JINST 19 (05) (2024) P05048. doi:10.1088/1748-0221/19/05/P05048
[4] CMS Collaboration, *Barrel Timing Layer Performance Plots*, CERN-CMS-DP-2023-093
[5] CMS Collaboration, *Barrel Timing Layer Performance Plots*, CERN-CMS-DP-2024/049