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

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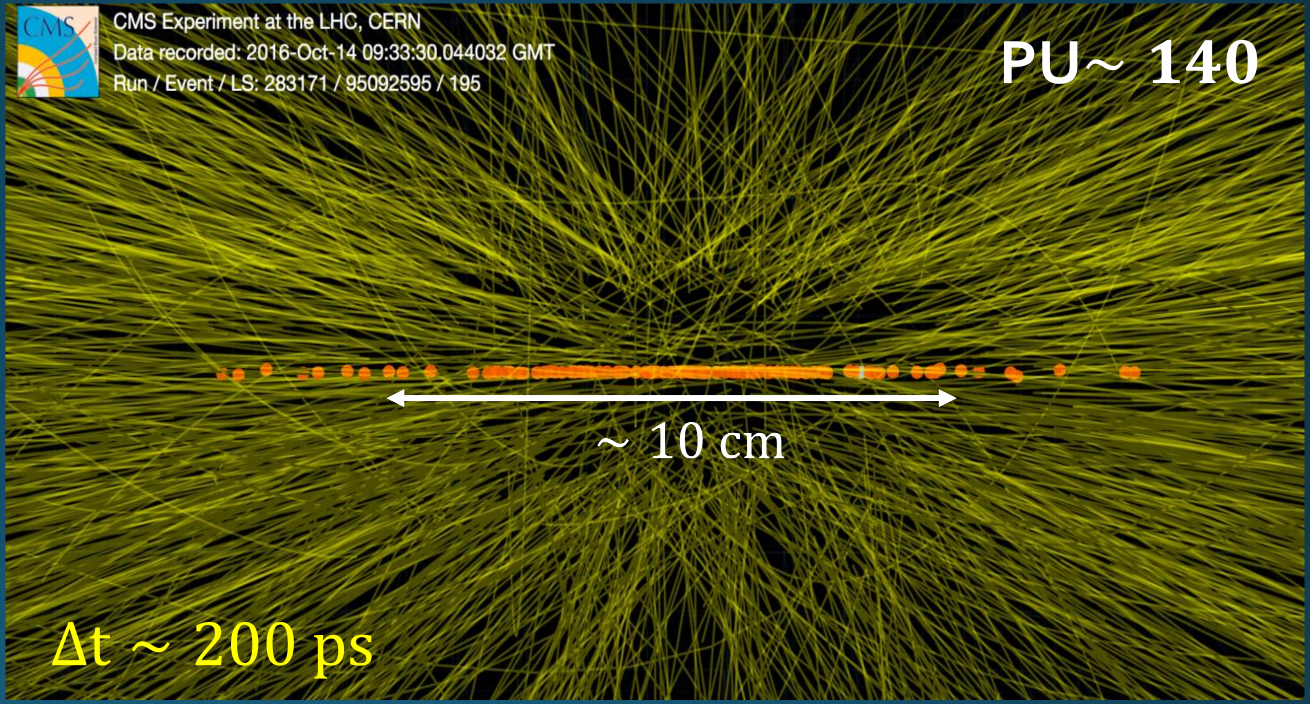
The High-Luminosity LHC challenge

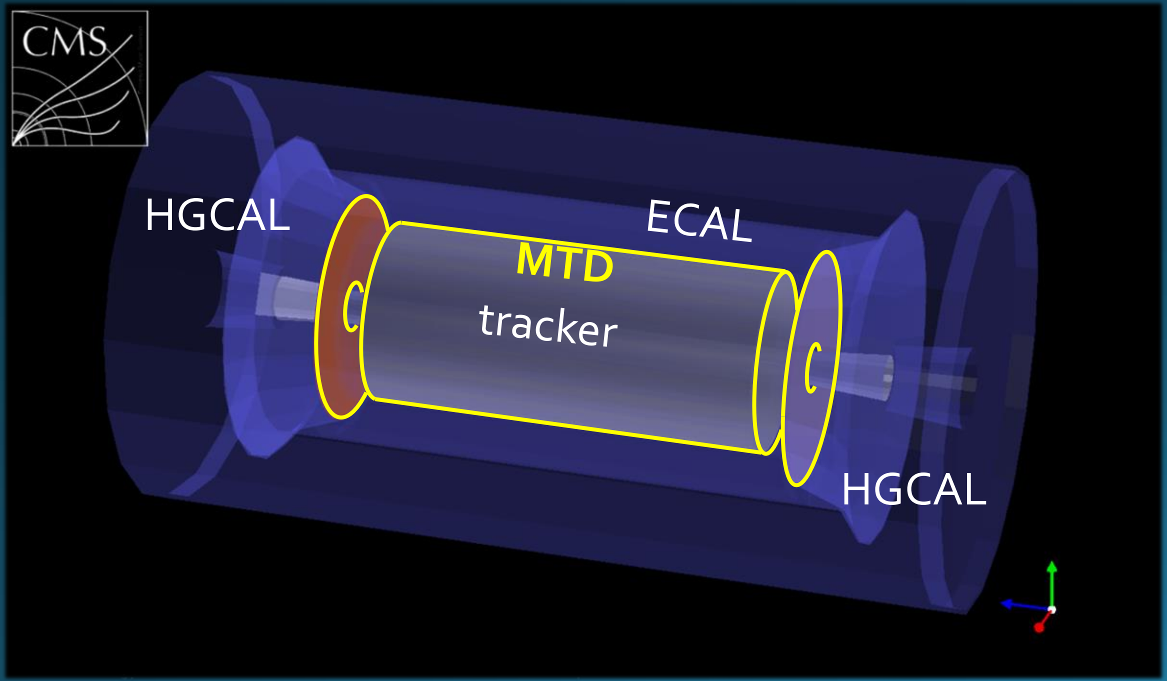
- HL-LHC scenario:
  - 3-4 times higher instantaneous luminosity
  - higher Pile-Up (40-60 $\rightarrow$ 140-200 events)
- Increased spatial overlap of vertexes
  - up to 5x higher vertex density
  - reduced efficiency of track-vertex association
  - event reconstruction degradation
  - Timing information useful to recover ~Run 2 performances in harsh HL-LHC condition



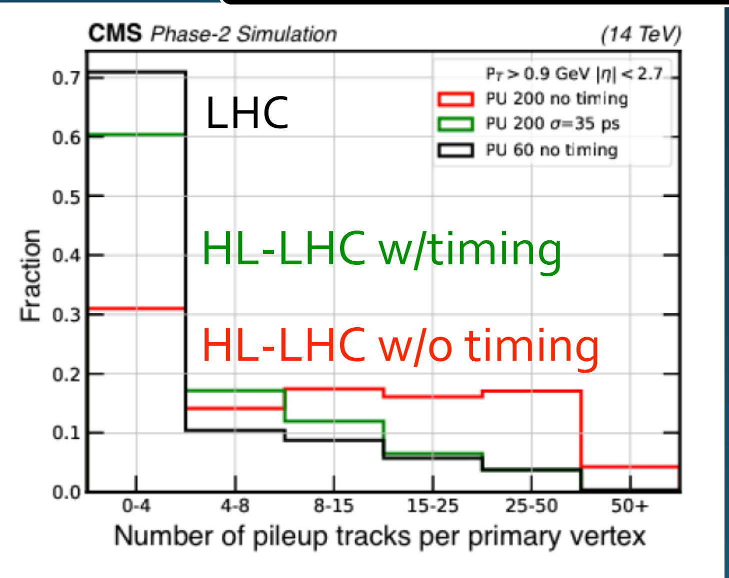
The MIP Timing Detector

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

- Time measurement of min.-ionizing (charged) particles (MIP) with resolution of 30-50 ps
- Reduce effective PU at HL-LHC using timing information
  - Time tagging MIPs: 3D → 4D vertex reconstruction
  - Restoring effective PU levels close to RUN 2 scenario (40 – 60 PU)



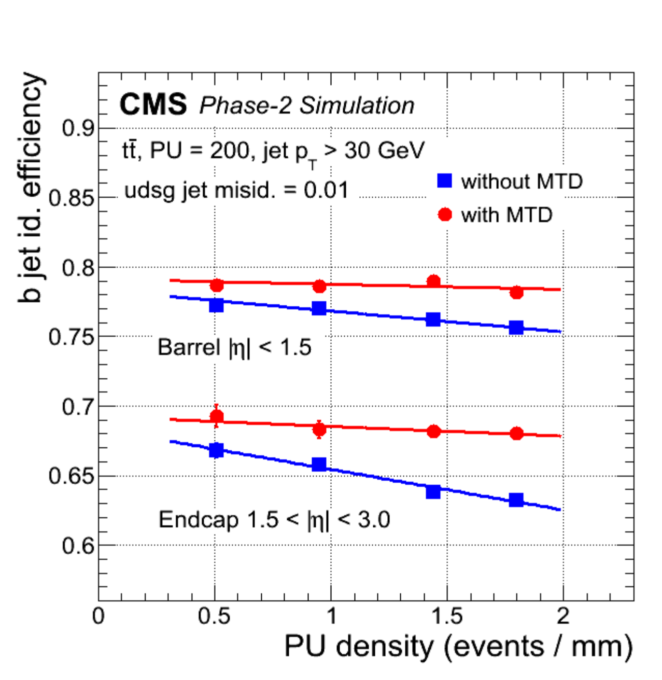
MTD Technical Design Report



MTD impact on physics

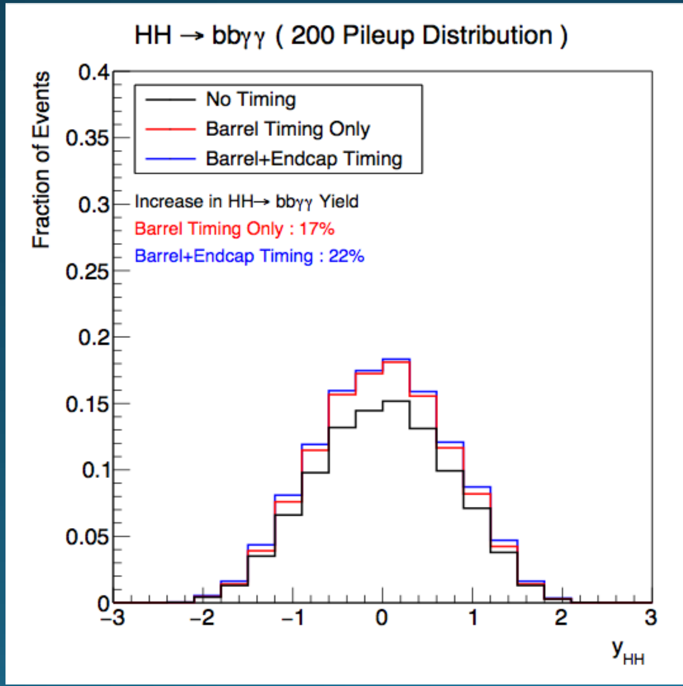
- Improvement in identification, reconstruction and resolution of physics objects

B-tagging efficiency increase



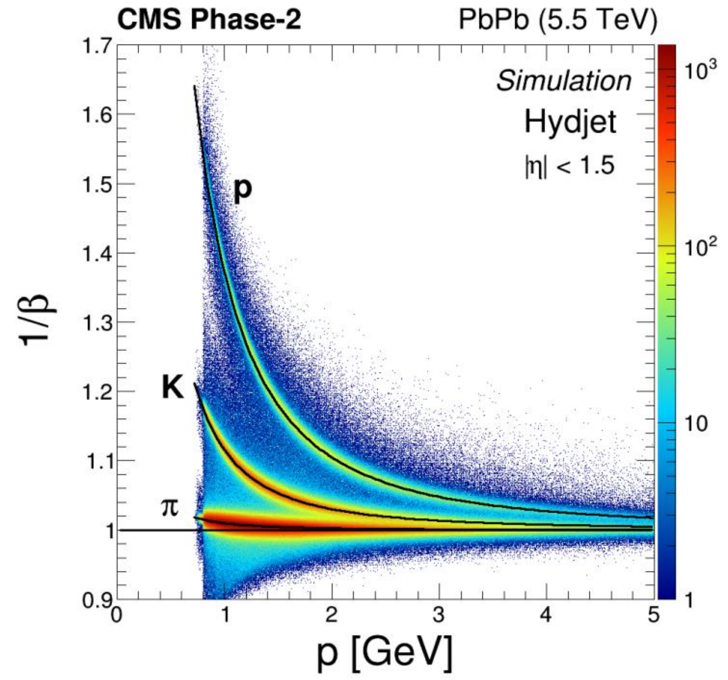
- Higher sensitivity for rare processes

HH → bbγγ yield inrease



- Provide new features to CMS
- New searches for exotic signatures (e.g. heavy charged stable particles)

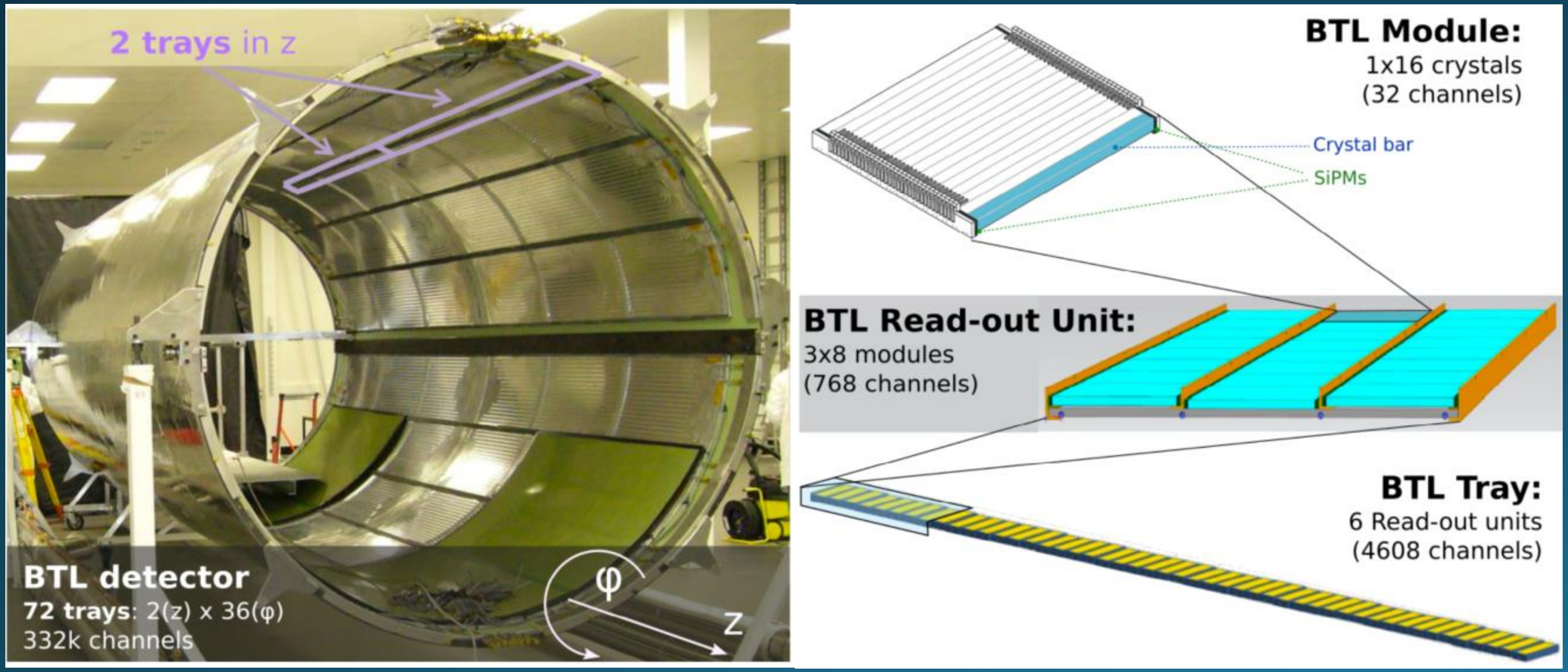
Particle ID via time-of-flight

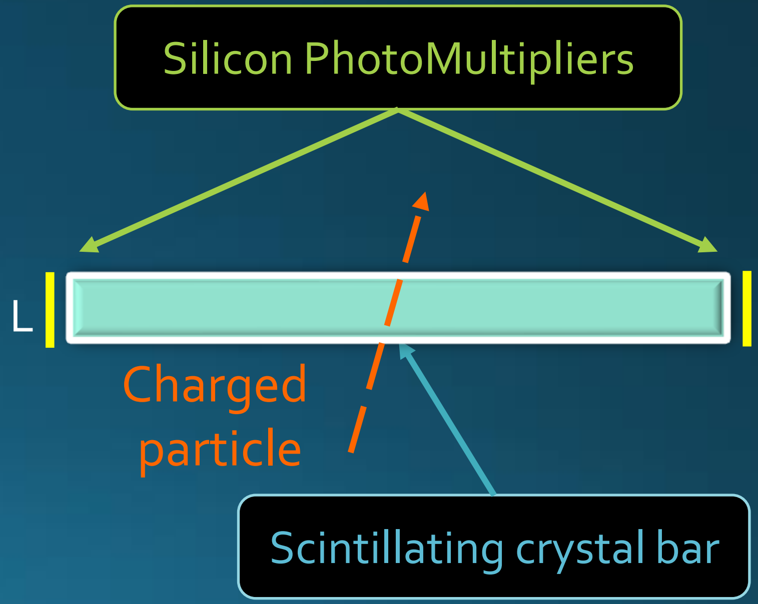


MTD Technical Design Report

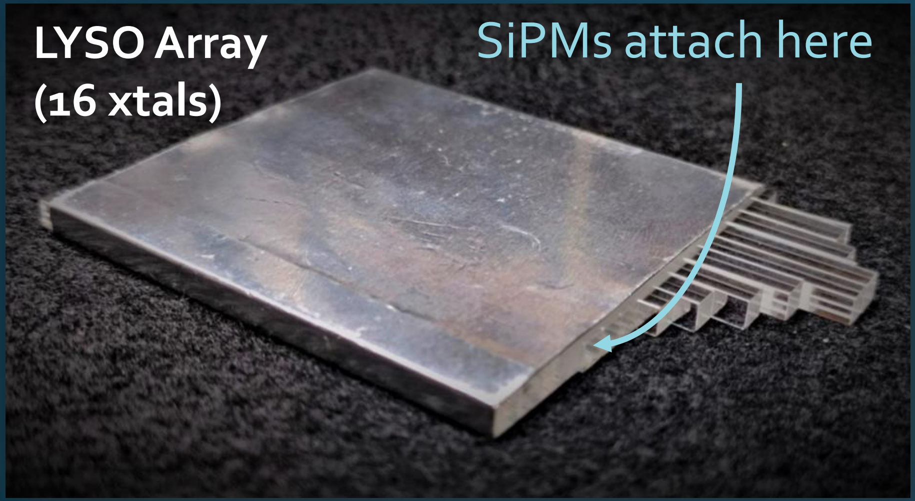
The MTD Barrel Timing Layer

- BTL requirements
  - Radiation hardness ($1.9 \cdot 10^{14}\ n_{eq}/cm^2$ end of HL-LHC)
  - Negligible impact on calorimeter performance (small energy absorption)
  - Mechanics, service, cost and schedule compatible with existing upgrades





BTL Sensors

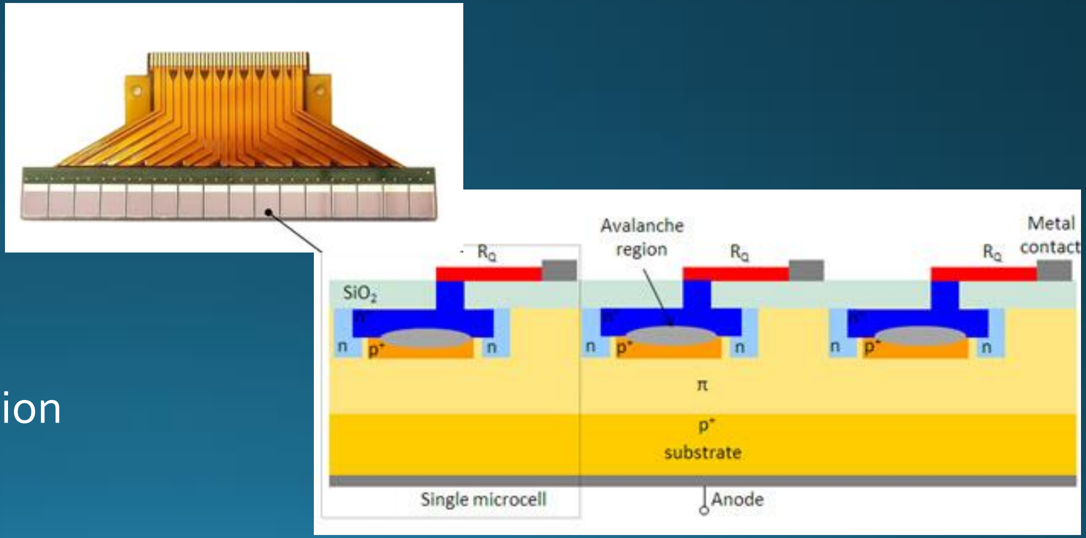


Cerium-doped Lutetium-Yttrium Oxyorthosilicate (LYSO:Ce)

- 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 $\mathrm{g/cm^3}$)
- Radiation hardness
- Easy availability (used in medical applications such as PET)

Silicon PhotoMultiplier (SiPM)

- Matrix of Avalanche PhotoDiodes (APD) in reverse bias
- Avalanche mechanism → 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%



BTL Time Resolution

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

$$\sigma_t^{ele} \propto \frac{\tau_r \tau_d}{\mathrm{Gain} \cdot N_{phe}}$$

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

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

Electronic noise

- scales with the steepness of the electronic signal
- $\sim 10 - 100$ ps for MIPs (highly dependent on SiPM bias voltage and cell size)

Photo-statistics term

- related to the stochastic fluctuations in the time-of-arrival of photons detected at the SiPM
- $\sim 25 - 30$ ps for MIPs

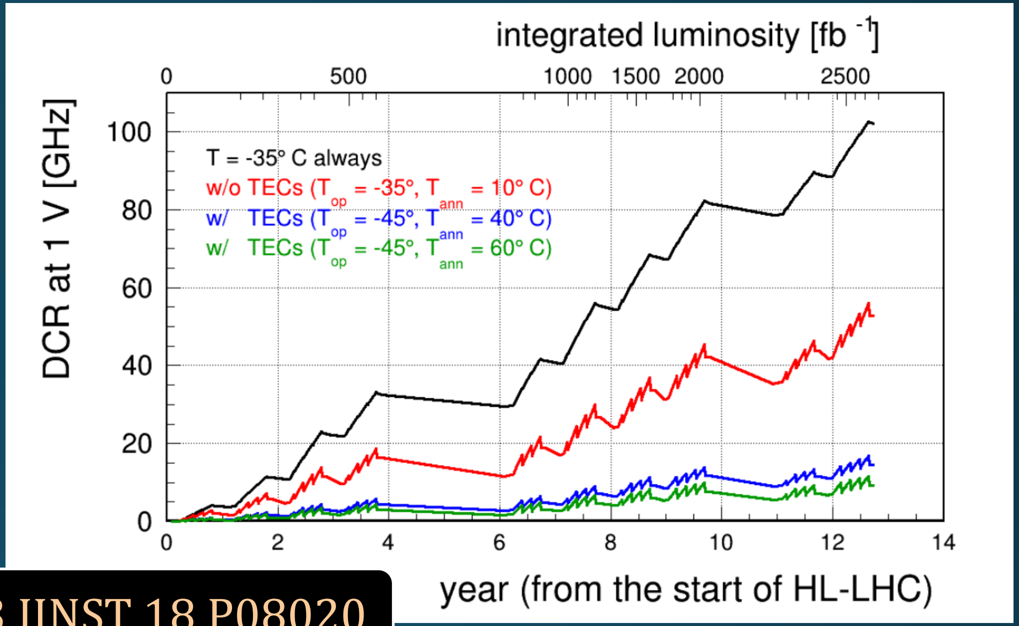
Dark Count Rate

- Induced by radiation damage
- Dominant term after first years of HL-LHC operation

BTL Sensors Optimization and DCR Mitigation

Sensors optimized to get higher $N_{phe} \propto E_{dep} \cdot LY \cdot PDE$:

- **Different crystal thickess (Type $1, 2, 3 = 3.75,\ 3.00, 2.4$ mm)**
  - thicker crystals → larger E_{dep}
  - limited by available space for BTL and costs
- **SiPMs with different cell size (15μm, 20μm, 25μm)**
  - larger cells → higher gain and PDE
  - increased sensitivity to radiation damage



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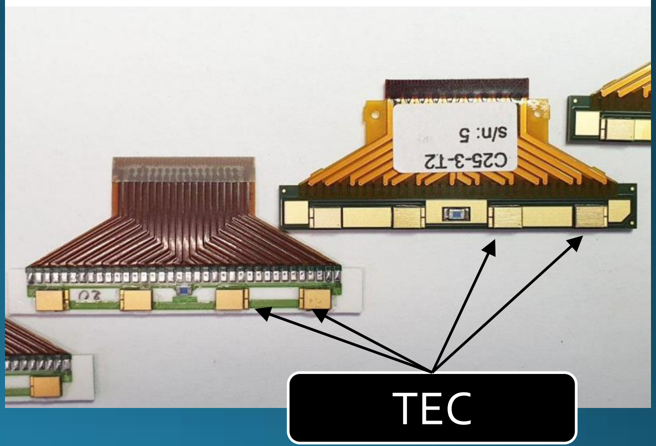
DCR mitigation using Termo Electric Coolers (TEC):

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

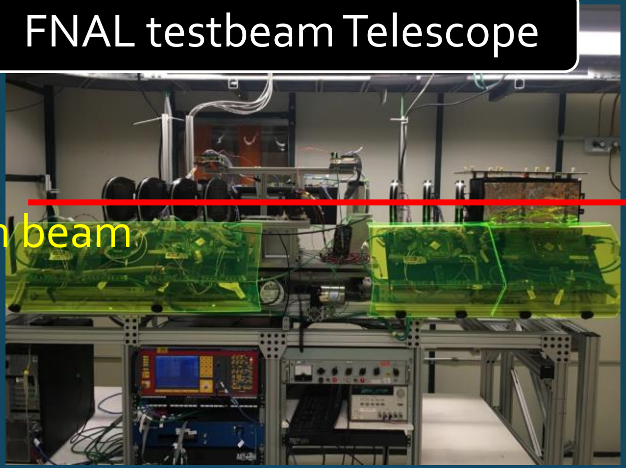


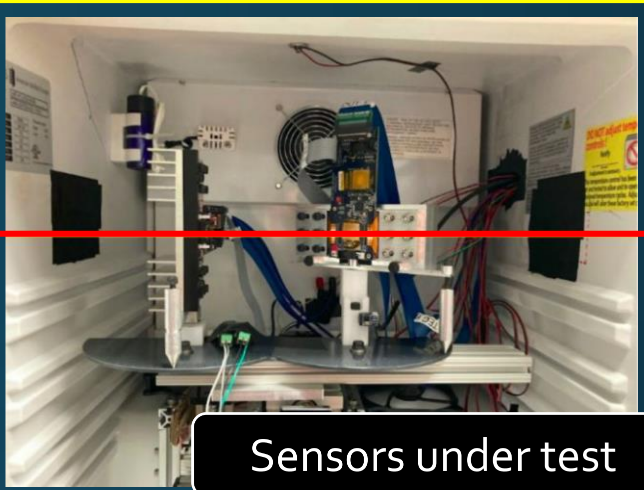
Latest testbeam campaings

March 2023 @FNAL

- sensor modules with 10-15-25 μm cell-size SiPM and different LYSO thickness
- Only non-irradiated sensors
- Operating temperature stabilized to 12°C with TECs, beginning of life performance

FNAL testbeam Telescope





Sensors under test

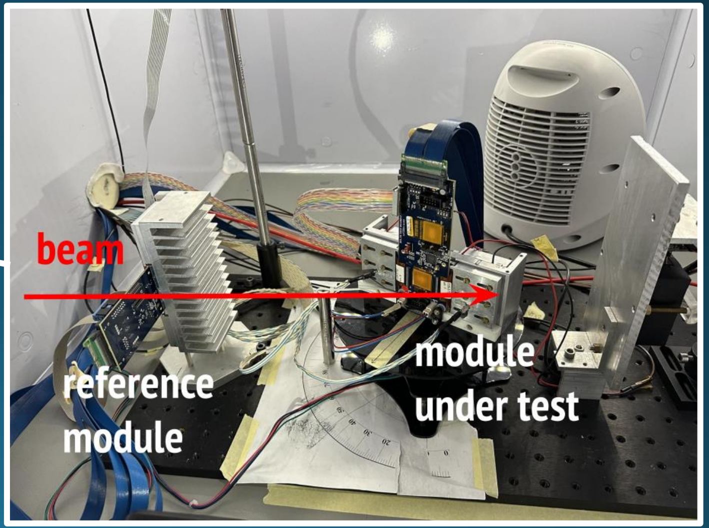
June 2023 @CERN North Area (H8)

- sensor modules with 10-15-25 μm 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

September 2023 @CERN North Area (H8)

- Similar as June + 30μm cell-size SiPMs → data analysis still ongoing…

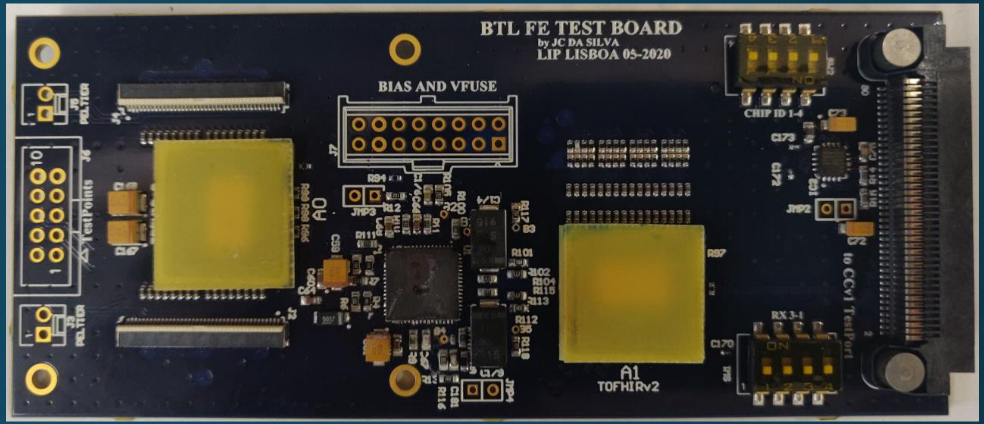
CERN North Area (pion beam)

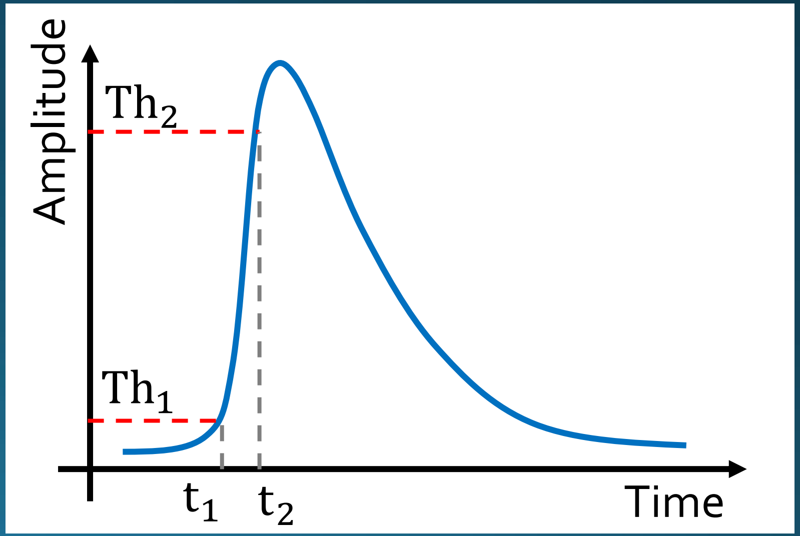


Testbeam readout electronics

TOFHIR2 ASIC for SiPMs read-out:

- 32 channels (1 BTL module)
- Radiation tolerant ($> 2 \cdot 10^{14}$ MeV neq/cm^2)
- Filter for DCR reduction
- Two Time-to-Digital Converters (10 ps resolution)
  - Two independent threshold for signal time measurement
  - Possibility to correct using signal slope
- 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





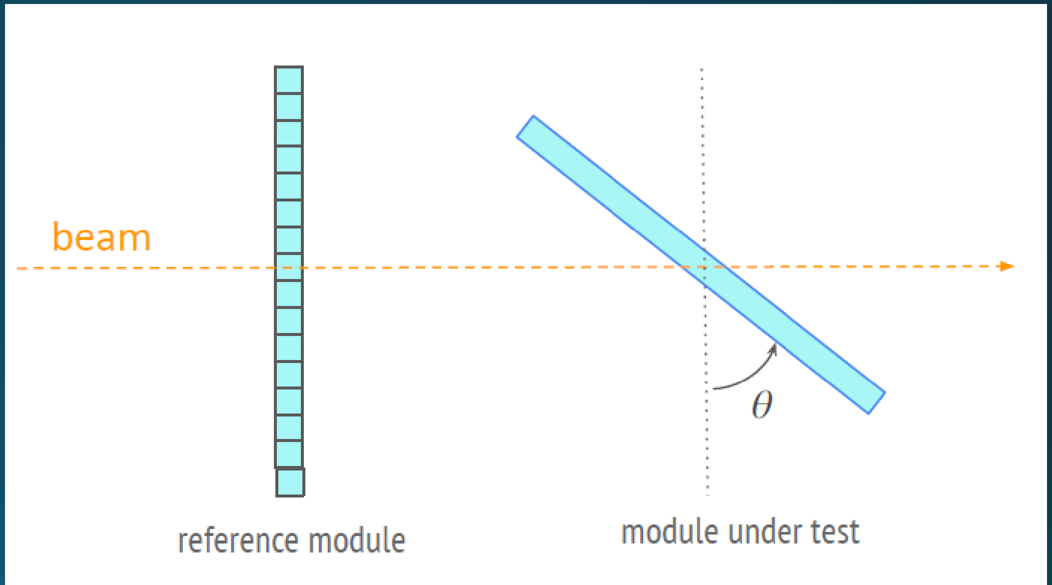
The TOFHIR2 readout ASIC of the CMS Barrel MIP Timing Detector

Time resolution measurement

$$t_{Average} = \frac{t_{left}+t_{right}}{2}; \qquad t_{Diff} = t_{left} - t_{right}$$

$$\sigma_{t_{Average}} = \frac{1}{2}\sqrt{\sigma^2_{t_{left}} + \sigma^2_{t_{right}}} = \frac{\sigma_{t_{Diff}}}{2}$$

- $t_{Average}$ is the BTL time estimator
- Need for an external reference to evaluate $\sigma_{t_{Average}}$
- $\sigma_{t_{Diff}}$ is indipendent from the time of arrival, no need for external reference
- t_{Diff} depends on impact position along crystal → select only a central area of few mm using reference module



Vertically oriented bars

Horizontally oriented bars

Comparison for different SiPM cell sizes

- **Scan in SiPMs over-voltage**

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

  - PDE increases with $\mathbf{V_{OV}}$ → better time res.
  - At high $\mathbf{V_{OV}}$ increased power consumption and DCR (for irradiated SiPMs)
- Used Type 2 LYSO arrays
- Data from proton beam and from UV-induced scintillation light (laser)
- Time resolution averaged across crystals within a module
- Achieved MTD target resolution at begin of operation. Best performance for 25 μm cell size @3.5 V_{OV}

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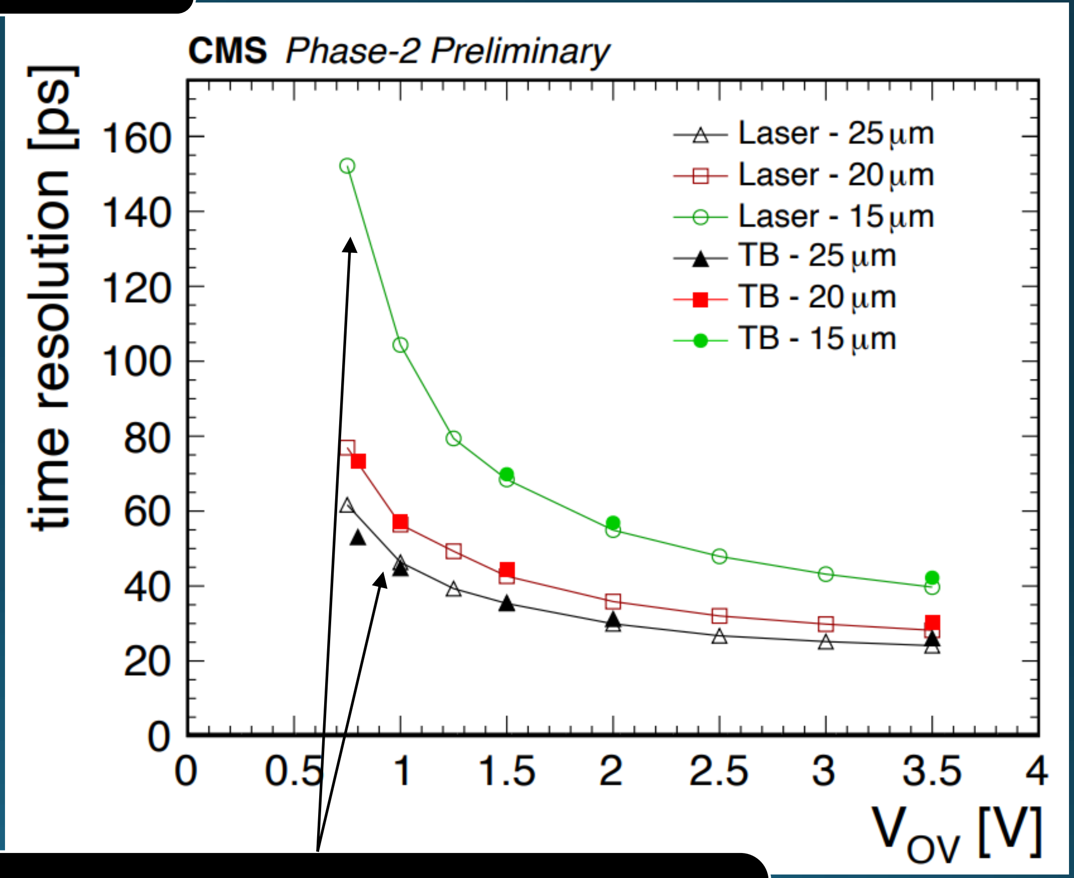
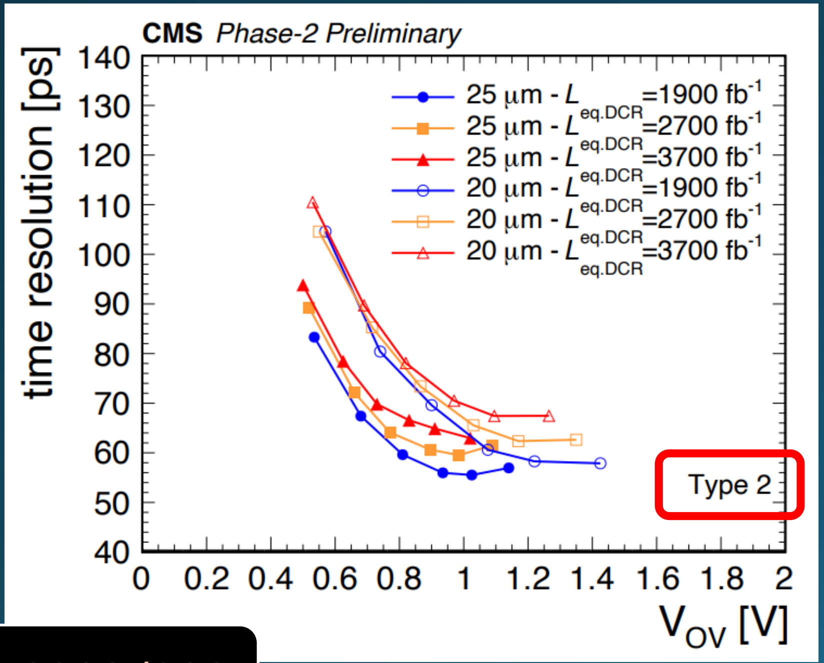
Non-irradiated modules

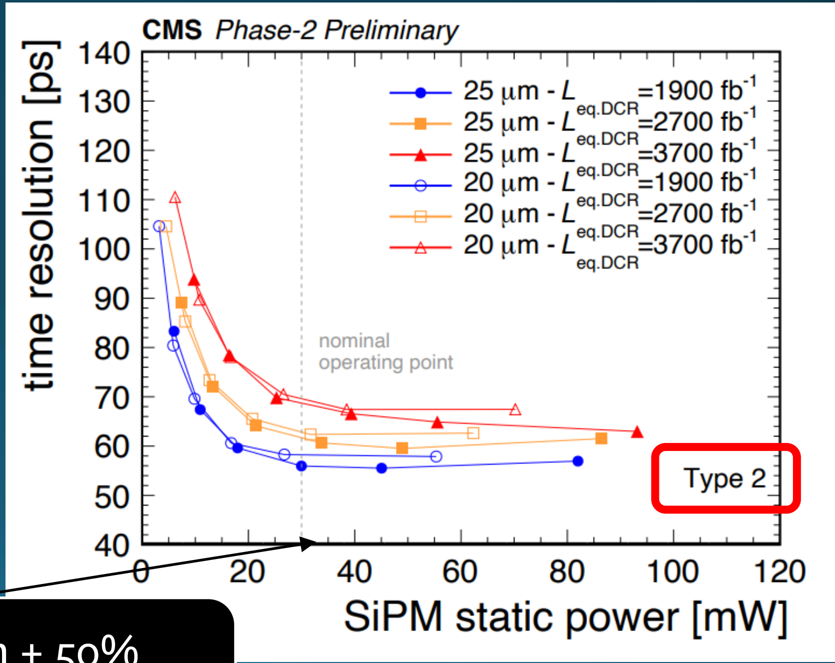


Electronic noise contribution reduced for large-cell SiPMs, as confirmed by lab tests

Performance after irradiation

- SiPMs irradiated to $2 \cdot 10^{14}$ MeV neq/cm^2, then accelerated annealing (40m @ 70°C, 3d @ 110° C, 4d @120°) to emulate end-of-operation conditions for BTL
- SiPMs operated at different temperatures to mimic different levels of DCR along the BTL lifetime
- For BTL end-of-operation (3000 fb^{-1}), a time resolution around 65 ps is achieved with 25 μm cell size SiPMs, assuming SiPM annealing at 60°C and operation in situ at −45°C.





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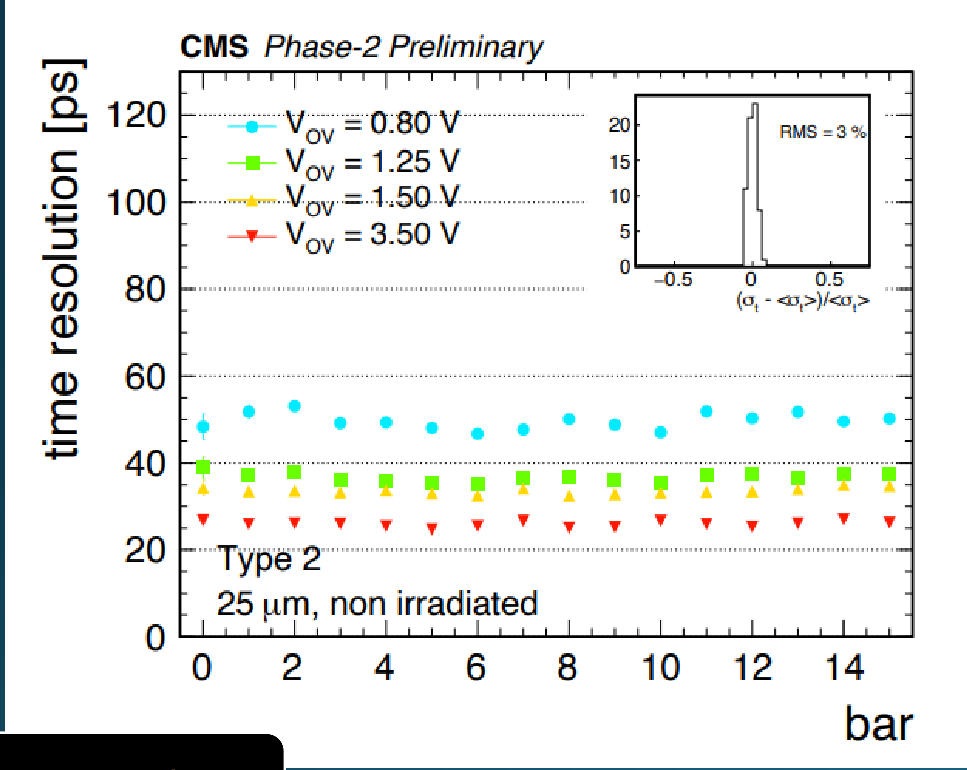
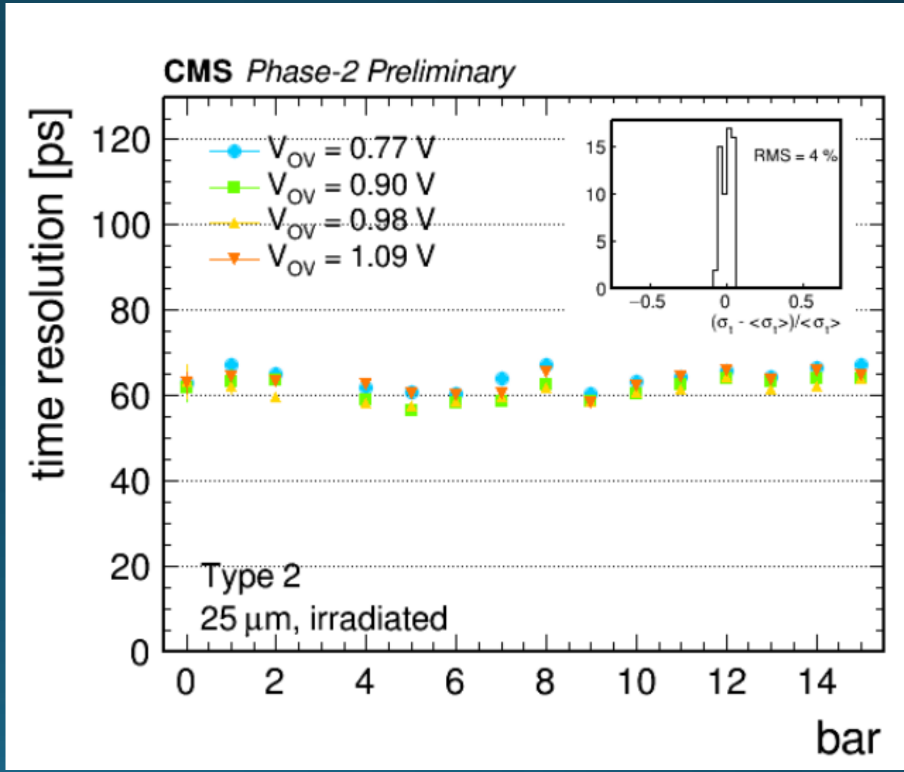
30 mW/ch + 50% contingency

Time resolution uniformity

- The time resolution among crystals in a module is uniform within 4%





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*Crystal #3 missing because of temporary issue with ASIC channel calibration during data-taking

Summary

- BTL optimized design finalized after 2023 test beam campaings
  - Type 1 (3.75 mm thick) crystals coupled with 25μm cell-size SiPMs
  - Sensors meet MTD time resolution target at Begin and End of Operation
- Preliminary results on September 2023 testbeam (not published yet) confirm good performance up to 3800 fb^{-1} for Type 1 modules
- BTL project is moving towards assembly and integration phases

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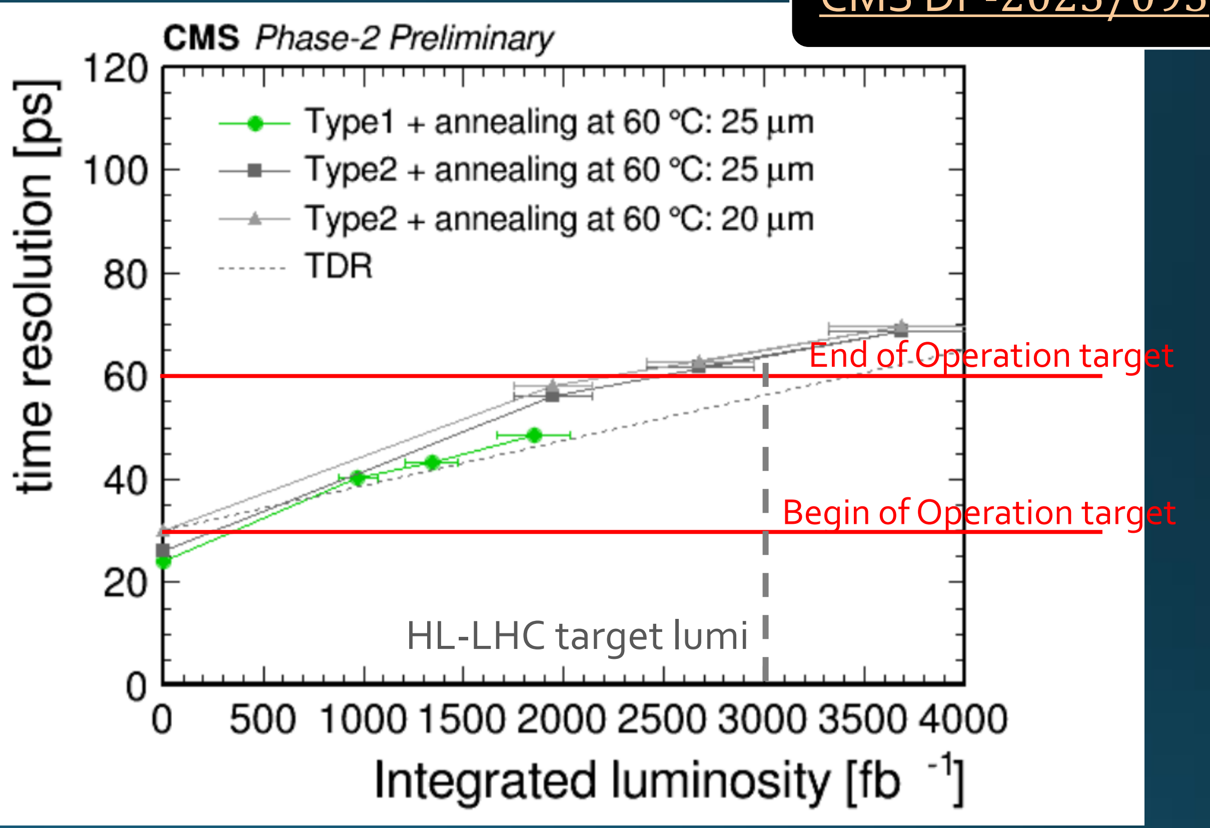
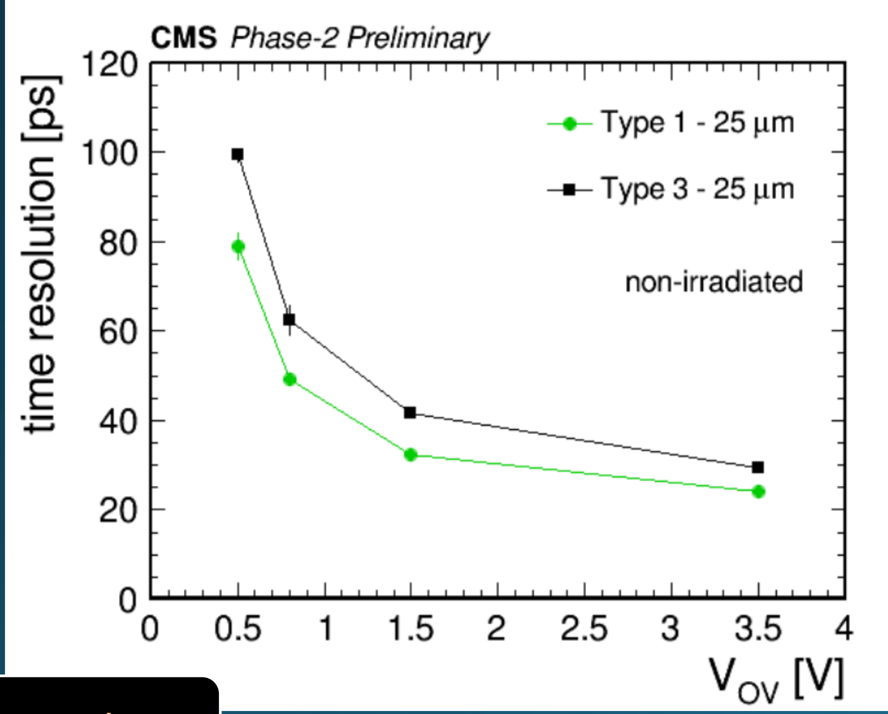


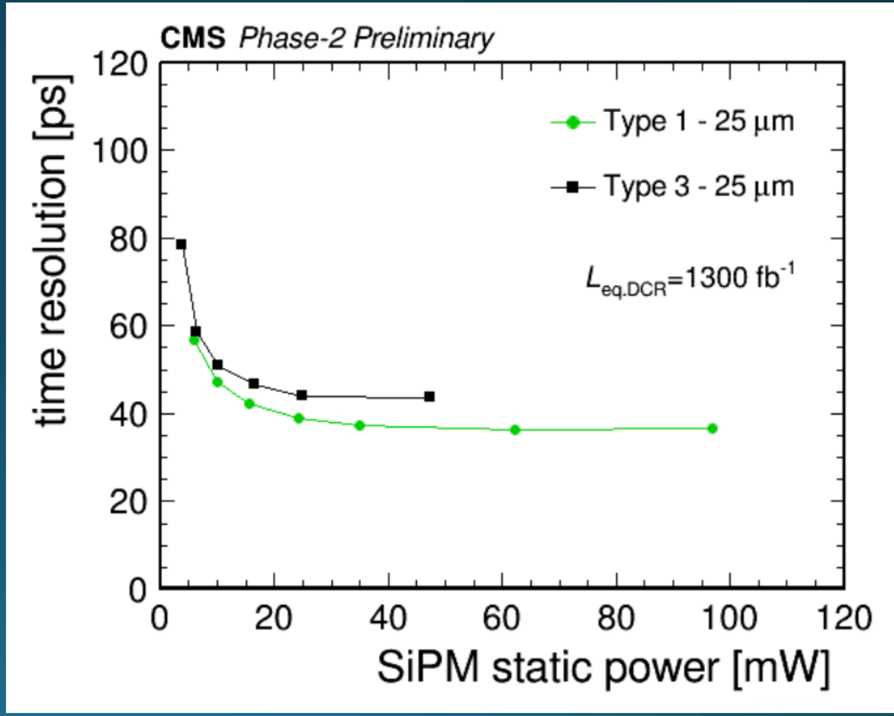
- New test beam campaigns planned for this year to test a BTL Readout Unit (24 modules) using the full readout chain of final design electronic

Backup

Comparison for different LYSO thickness

- Thicker LYSO crystals performs better independently on V_{OV} and radiation damage
- BTL final design will use only Type 1 crystals (3.75 mm thick), the thickest crystals feasible considering BTL constraints on costs, geometry, and impact on other CMS detectors





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