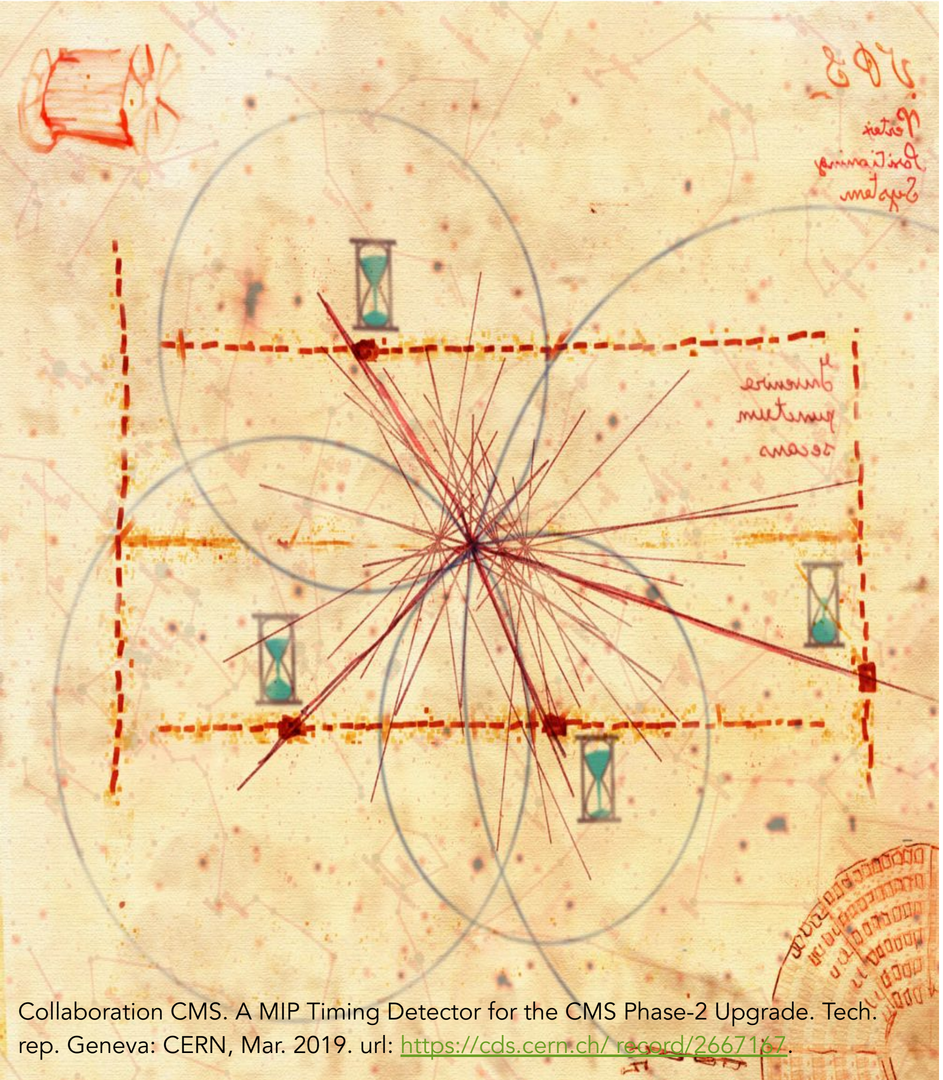


Collaboration CMS. A MIP Timing Detector for the CMS Phase-2 Upgrade. Tech. rep. Geneva: CERN, Mar. 2019. url: https://cds.cern.ch/ record/2667167.

Characterization of sensor modules for the CMS Barrel Timing Layer at HL-LHC

108° Congresso Nazionale - Società Italiana di Fisica

Milano, 12-16 Settembre 2022

Simona Palluotto

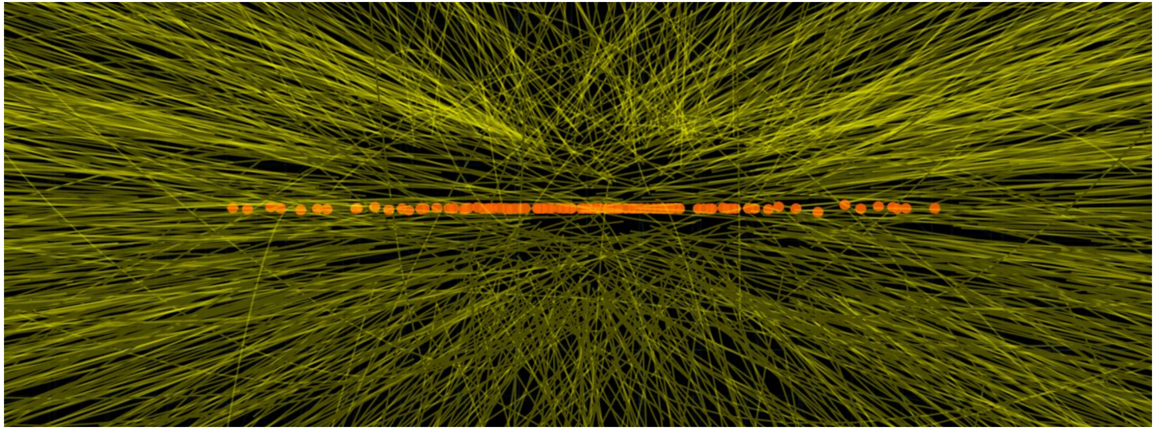
on behalf of the CMS Collaboration

The High Luminosity era of LHC

- New high luminosity phase of LHC $\rightarrow$ $\sqrt{s}$ ~ 14 TeV $\mathcal{L}_{ultimate}$ up to ~ 7 x 10^{34} cm^{-2} s^{-1}
- Increase in luminosity $\rightarrow$ increase in vertex density by a factor 5

$\Rightarrow$ radiation damage induced in detectors
$\Rightarrow$ spurious interactions per bunch crossing (pileup): from 40 (LHC) to 140-200 (HL-LHC)

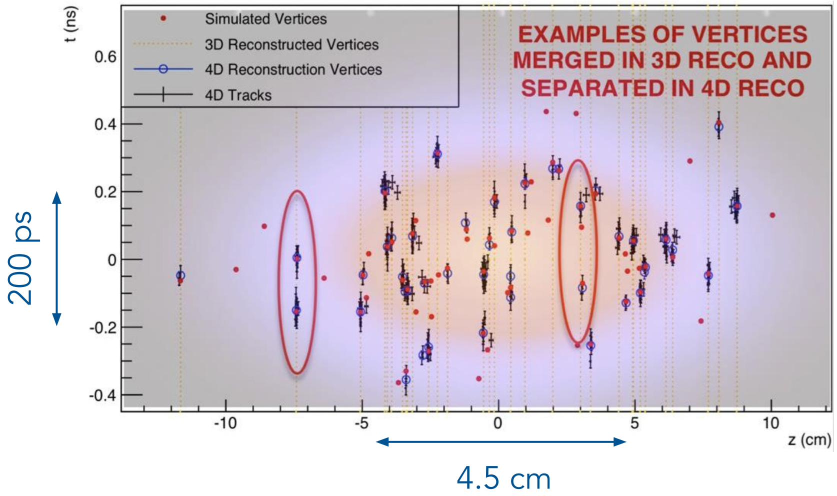
$\rightarrow$ upgrade required to maintain event reconstruction performance similar to LHC



Precision timing in CMS

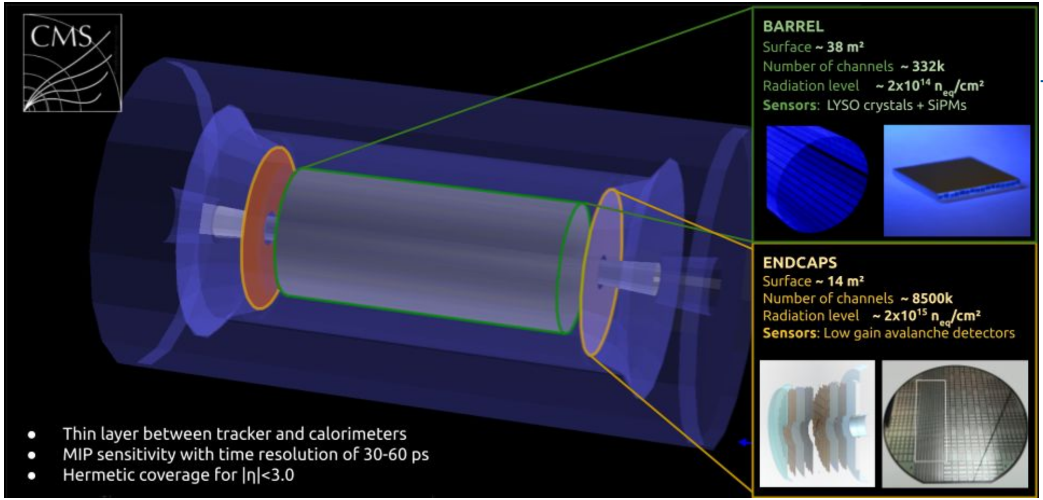
- To maintain the current excellent performance, substantial upgrades of the experiments are ongoing.
    - CMS: novel timing layer to mitigate pileup effect, track timing to provide 4D vertex reconstruction and a positive impact on physics analysis (see M. Malberti talk)

      → MIP Timing Detector (MTD) with σ_t ~ 30-60 ps will reduce the pileup at HL-LHC to the current LHC level



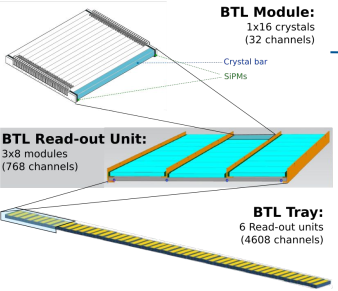
The MIP Timing Detector

- Hermetic detector ($|\eta|<3$) involving different technologies to equip both the barrel and the endcap regions of CMS:
    - Endcap Timing Layer (ETL): modules of LGADs
    - Barrel Timing Layer (BTL): arrays of LYSO crystal bars readout at both ends by SiPMs

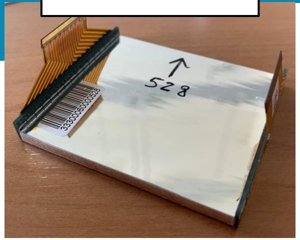


BTL will operate at -45°C to mitigate the radiation induced dark counts in the SiPMs at end of operation

BTL design

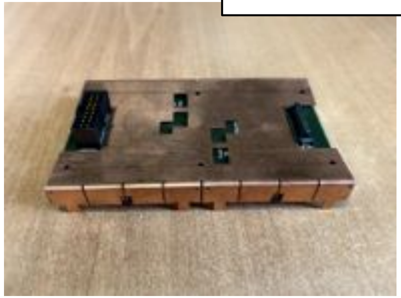


module prototype



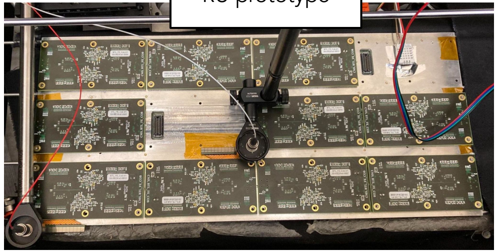
16 bars coupled at both ends to SiPMs
= 1 Module

detector module prototype



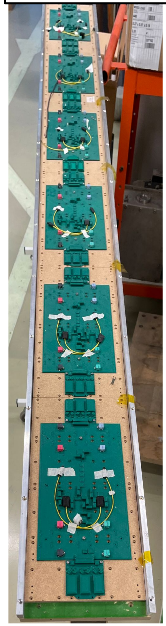
2 modules + TOFHIR ASIC (BTL Front End)
= 1 Detector Module (DM)

RU prototype



12 DM
= 1 Read Unit

tray mockup



6 RU
= 1 Tray

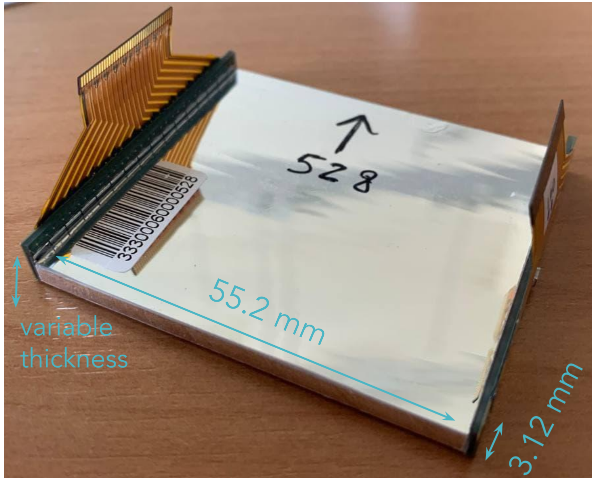
72 trays
= BTL

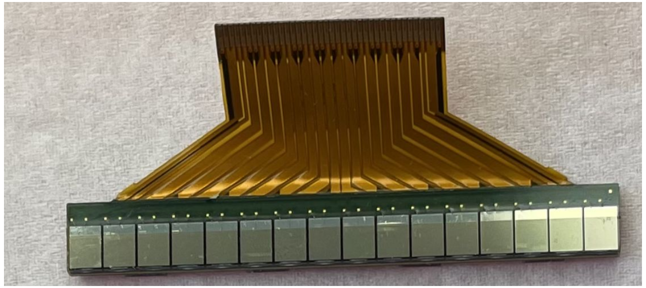
BTL sensor modules

- Arrays of 16 LYSO:Ce crystal bars wrapped with Enhanced Specular Reflector (ESR) attached with optical glue to a pair of SiPM arrays, one on each of the crystal open ends

- Crystal bar:
    - 55.2 mm in length,
    - 3.12 mm in width
    - variable thickness depending on the η region to maintain a uniform amount of material budget in front of ECAL

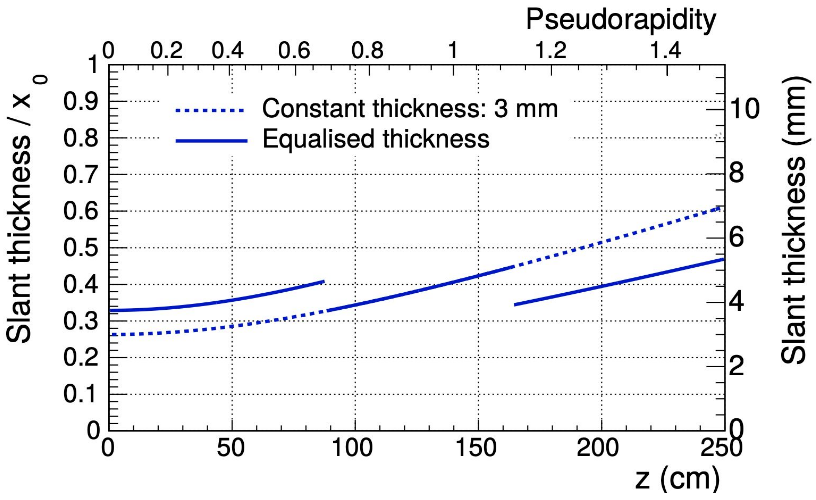
- SiPM:
    - 2.9 mm in width
    - variable height depending on the η region $\rightarrow$ dimensions as close as possible to crystal end face to enhance the light collection efficiency (LCE)

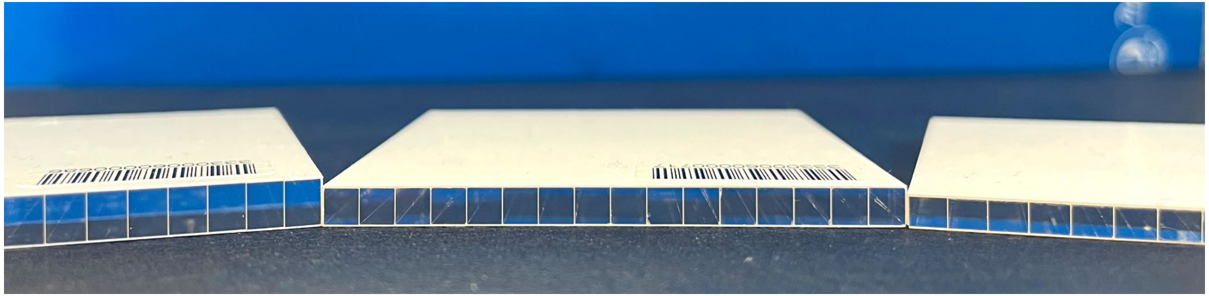




Different geometries

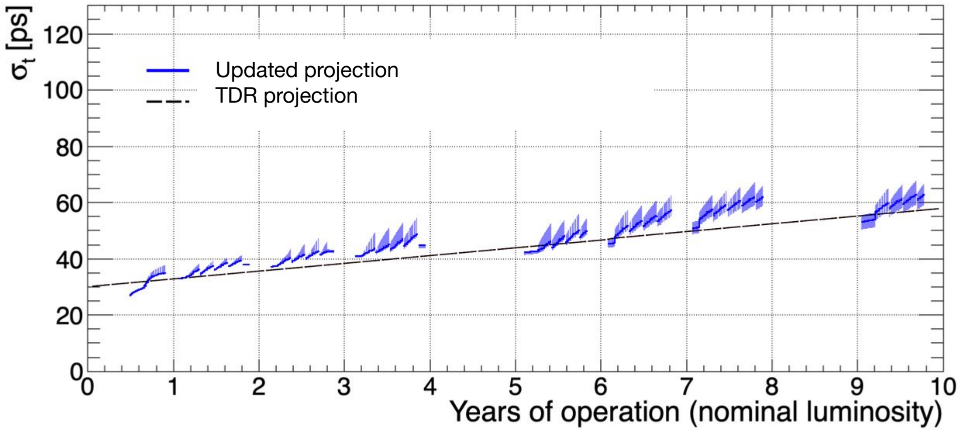
- Three different geometries of sensor modules:
  - type 1: 3.75 mm thick crystals matched to SiPM
  - type 2: 3.00 mm thick crystals matched to SiPM
  - type 3: 2.40 mm thick crystals matched to SiPM





type 1 type 2 type 3

Time resolution performance



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

Time resolution driven by:

- BoO: photo-statistics $\sigma_t^{phot} \propto \sqrt{\frac{\tau_r \tau_d}{N_{phe}}}$
- EoO: dark counts noise $\sigma_t^{DCR} \propto \frac{\sqrt{DCR}}{N_{phe}}$

- The number of photoelectrons produced depends on the Light Output (LO):

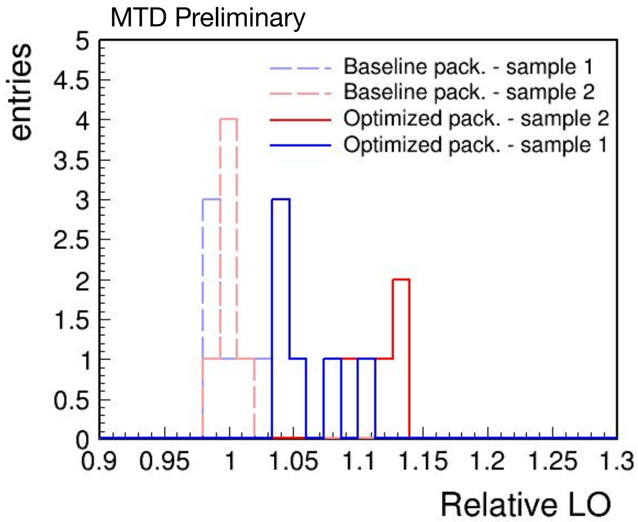
$$N_{phe} = LO \cdot PDE \cdot E_{dep} = LY \cdot LCE \cdot PDE \cdot E_{dep}$$

with LY: light yield of the crystal
LCE: light collection efficiency that is related to several factors affecting the amount of light detected by SiPMs
PDE: photon detection efficiency that is a property of the SiPM

⇒ A good comprehension and the optimisation of the LO is crucial for the BTL performance

Optimised packaging

- R&D activities: simulation studies predict an improvement of about 10% on the LO with a smaller amount of glue between the bars and the wrapping → enhancing total internal reflection



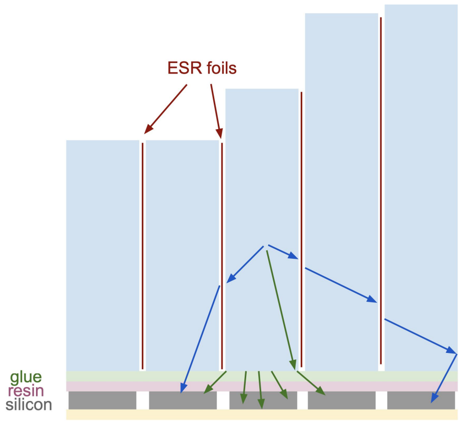
⇒ modules with the optimised packaging measured:

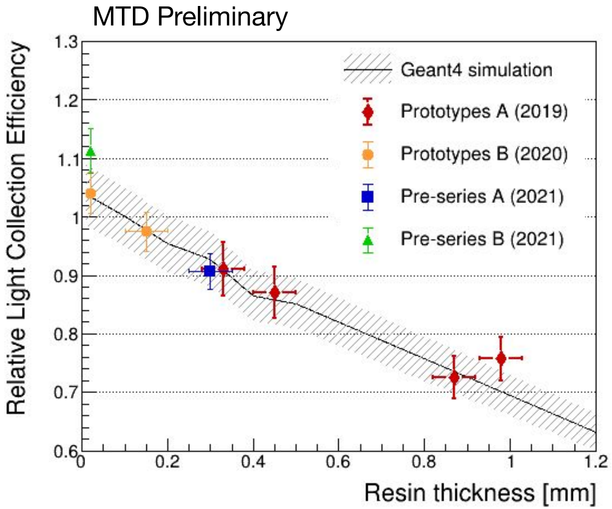
average improvement of 10%, confirming simulation

Impact of the protective window of SiPMs on LO

- Different SiPM protective windows having different thickness tested to assess the impact of the resin layer covering the SiPM on the LO

- Optimal LCE observed for thinner resin layer
    - Photons can be reflected at the resin-silicon interface and can bounce back inside the resin and be detected by a SiPM further away.

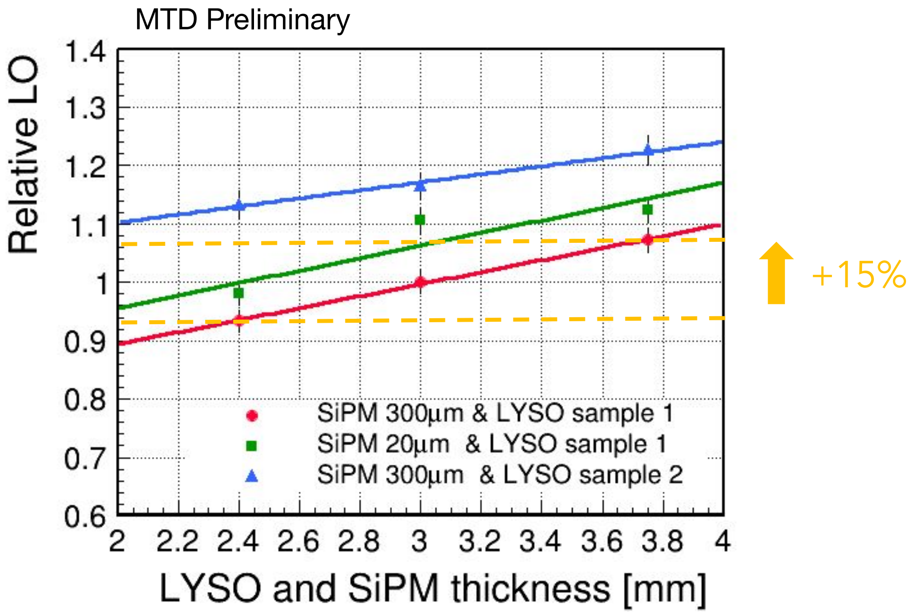




Impact of different module geometries on LO

- To evaluate potential differences in LO between different sensor module geometries:
  - different sizes of LYSO and SiPM matched measured

- Results:
  - Thicker crystals yield a higher LCE up to +15% (from type 3 to type 1)



Summary

- Characterisation and optimisation studies performed on BTL sensors to improve the performance in terms of light output ⇒ time resolution

    - Several characterisation studies:

        - Optimised packaging shows an improvement in light output on average of ~ 10%

        - Higher light collection efficiency observed with the thin coating technology compared to the full encapsulation technology

        - Thicker crystals yield a higher light collection efficiency up to +15%

- Modules with optimised packaging tested in a test beam in summer: analyses still ongoing

Backup

Light Output

Light output

- Stochastic fluctuations in the time of arrival of photons detected at the SiPM

➡ contribution from photo-stochastics

$$\sigma_t^{phot} \propto \sqrt{\frac{\tau_r \tau_d}{N_{phe}}} \propto \sqrt{\frac{\tau_r \tau_d}{E_{dep} \cdot \mathrm{LY} \cdot \mathrm{LCE} \cdot \mathrm{PDE}}}$$

where:

- τ_r: rise time of the scintillation pulse (~100 ps)
- τ_d: decay time of the scintillation pulse (~43 ns)
- N_{phe}: number of photoelectrons produced in the detecting system
- E_{dep}: energy deposited by a ionizing particles in the crystal
  $\rightarrow$ Landau distribution having MPV = 0.86 MeV/mm
- LY: intrinsic Light Yield of the crystal (photons produced per MeV of E_{dep})
- LCE: Light Collection Efficiency (photons impacting on SiPM / photons produced)
- PDE: Photon Detection Efficiency of the SiPM

Light Collection Efficiency

$$LO = LY \cdot LCE$$

- The LCE includes a set of inefficiency in light collection:

$$LCE = \epsilon_{coll} \cdot \epsilon_{ext} \cdot \epsilon_{det}$$

  - ε_{coll}: fraction of scintillation photons reaching the end of the crystal
    effects related to the propagation inside the scintillator (e.g. intrinsic absorption, reflection at the crystal surfaces, reflection at the reflective ESR layer etc.)

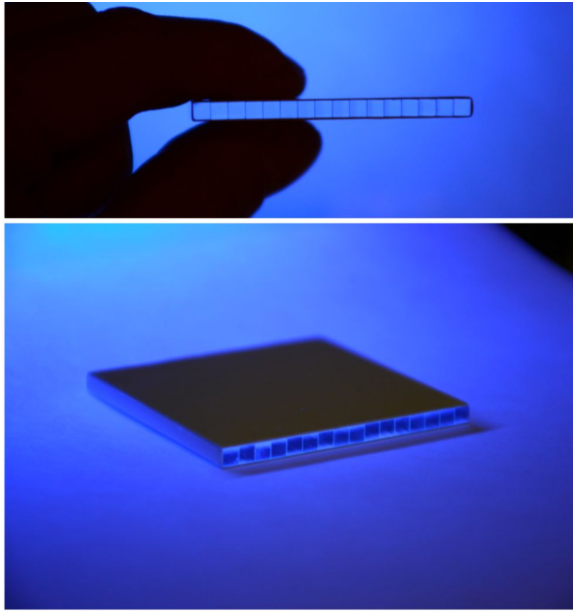
  - ε_{ext}: fraction of photons that manage to reach the SiPM
    effects related to the medium interposed at the interface between the crystal and the SiPM (e.g. air gap, grease, glue)

  - ε_{det}: fraction of photons reaching the SiPM active area
    effects related to the protective window of SiPM and the size of the crystal end face and SiPM active area

Light output measurements

BTL modules

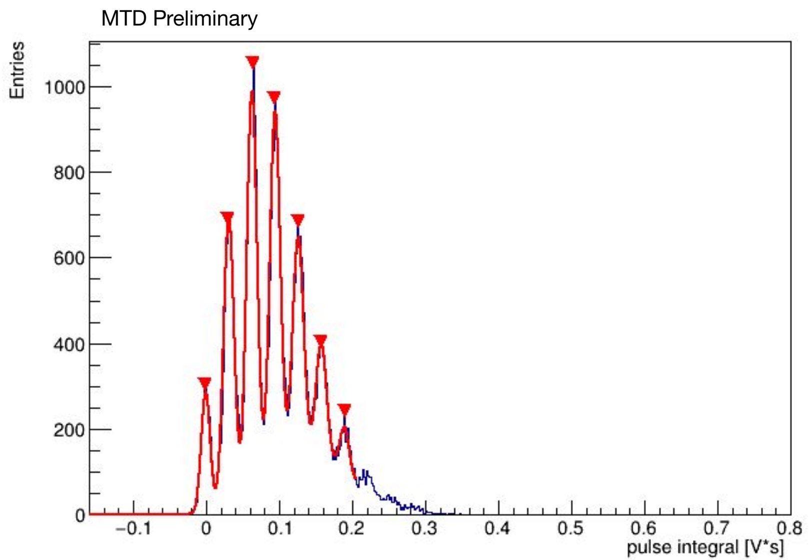
LYSO:Ce crystal array

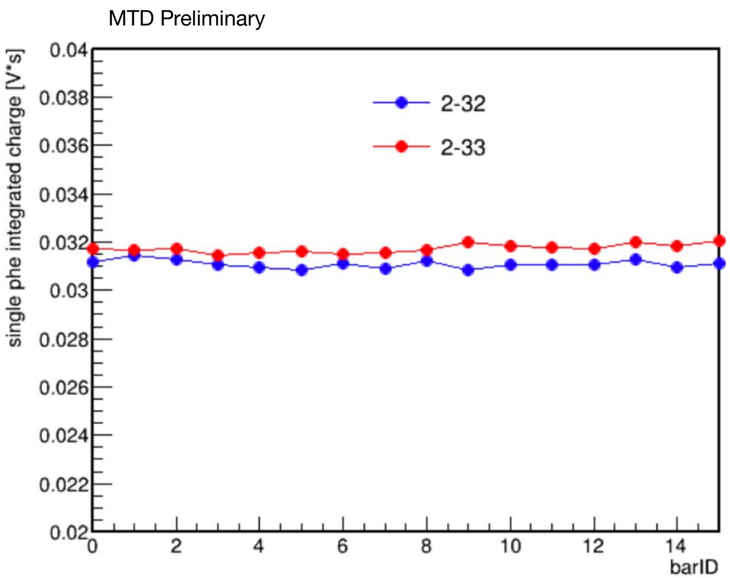


SiPM array

Single photoelectron calibration

- In order to extract N_{pe} values, the single photoelectron charge is needed
- The charge of a single photo-electron is extracted as the distance between two consecutive peaks
- A spread smaller than ~5% is usually observed along channels of a SiPM array



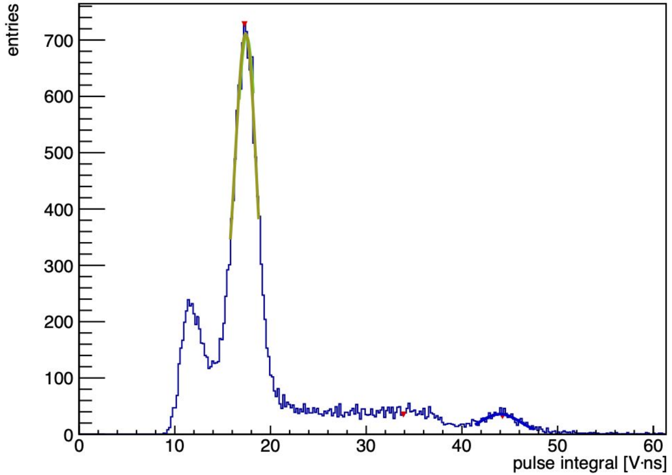


N_{pe} analysis

- A histogram was filled with the energy extracted from the waveform analysis and the ^{22}Na spectrum was obtained.

- The 511 keV and 1275 keV peaks were fitted with a gauss function and their positions were determined

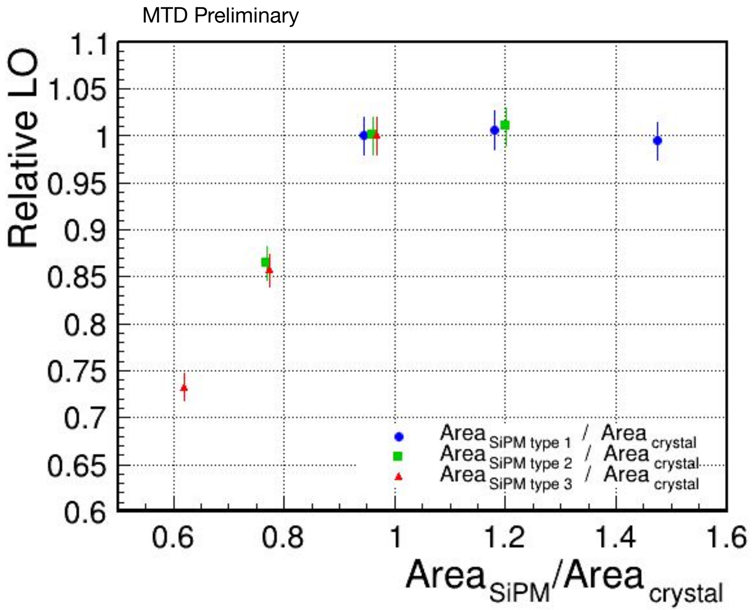
- The ratio between the charge of one peak and the single photoelectron gives the Npe value.



Impact of different module geometries on LO

- To evaluate potential differences in LO between different sensor module geometries:
  - different size of LYSO coupled with SiPMs having different dimensions measured

- Results:
  - LCE is proportional to the fraction of crystal end surface covered by SiPM active area until the area is fully covered



Time resolution performance

Contributing factors

photo-statistics

$$\sigma_{\mathrm{t}}^{\mathrm{phot}} \propto \sqrt{\frac{\tau_{\mathrm{r}}\tau_{\mathrm{d}}}{N_{\mathrm{phe}}}} \propto \sqrt{\frac{\tau_{\mathrm{r}}\tau_{\mathrm{d}}}{E_{\mathrm{dep}} \cdot \mathrm{LY} \cdot \mathrm{LCE} \cdot \mathrm{PDE}}}$$

dark counts

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

electronic noise

$$\sigma_t^{noise} = \frac{n}{slew\,rate} \oplus c$$