Beam-test evaluation of the precision timing capabilities of a CMS HGCAL prototype

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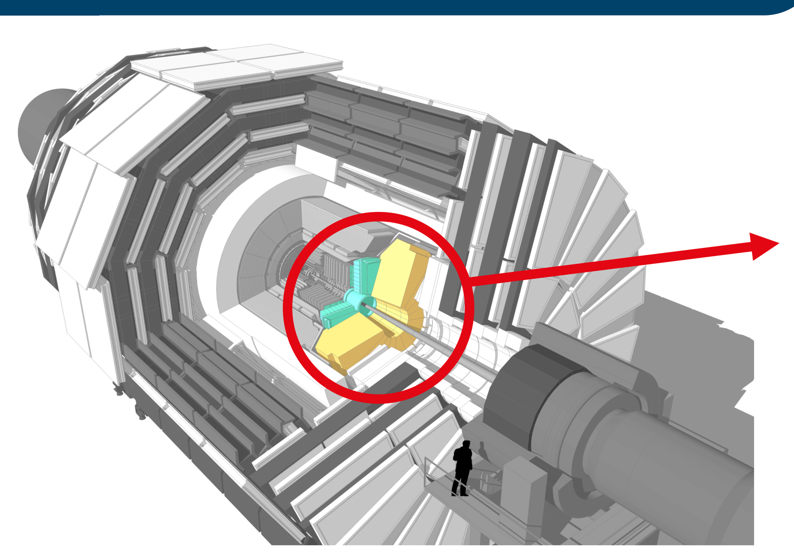
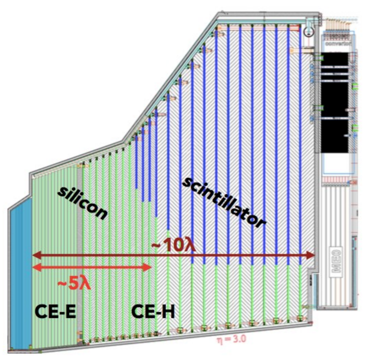
What is the context ?





The **HL-LHC** (starting in 2027) is the future phase of the LHC and aims to **accumulate 10 times more of luminosity**. But, this will lead to 5 times **more pile-up** and a **higher radiation dose** compared to current dose at LHC. The **High Granularity Calorimeter (HGCAL)** will replace the existing **endcap calorimeters of CMS**. It will be a sampling calorimeter measuring (x,y,z,t,E), composed of :

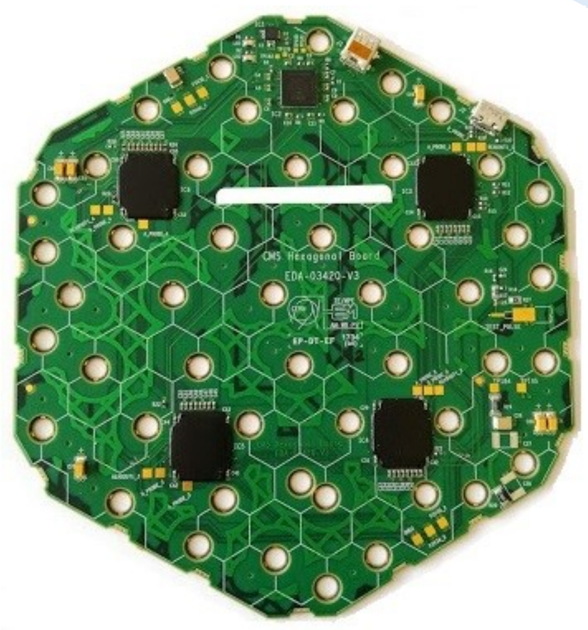
- Silicon-based modules (CE-E) for the electromagnetic part (≈ 25 X0 | 1.3 λ)
- Silicon-based modules (CE-H-Si) + Scintillator tiles for the hadronic part (≈ 8.5 λ)

In order to efficiently reject particles originating from pile-up, precision timing information of the order of 30 ps for a full shower will be of great benefit. Silicon module prototypes were tested in the SPS beam in order to validate the timing performance.

How were the prototypes tested ?

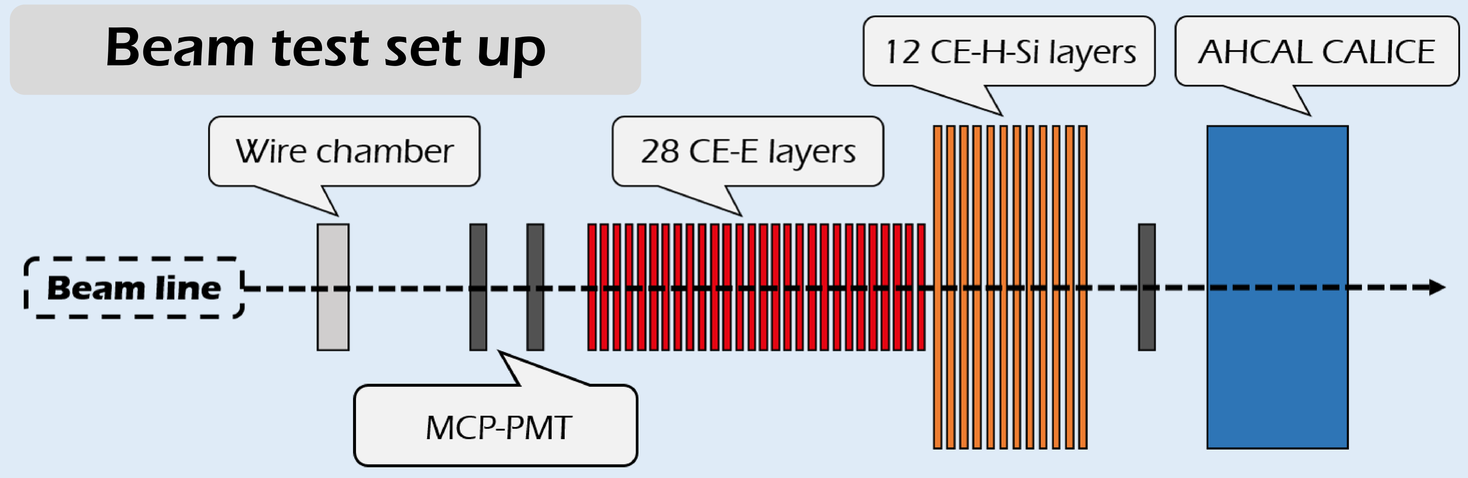
Prototype modules are hexagonal boards composed of a silicon sensor divided in 135 channels of hexagonal shape. On the boards, four chips read the signals from 32 cells. These modules are mounted on a copper-tungsten baseplate for the electromagnetic part and with a steel plate for the hadronic one.

In 2018, HGCAL prototype was exposed to beams of **electrons, pions and muons** with energy varying from **20 to 300 GeV**, produced at the CERN SPS.



HGCAL hexaboard prototype

Beam test set up

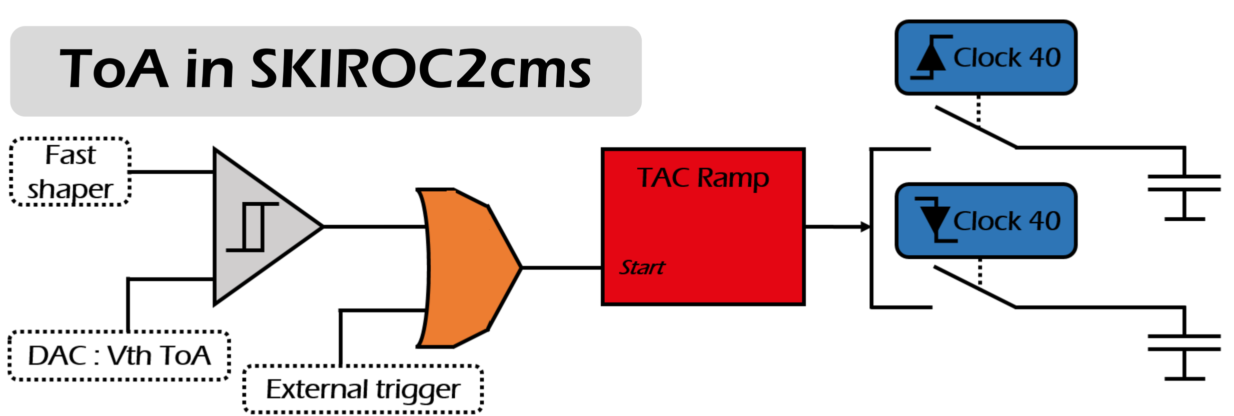


The experimental set up is composed of the following elements :

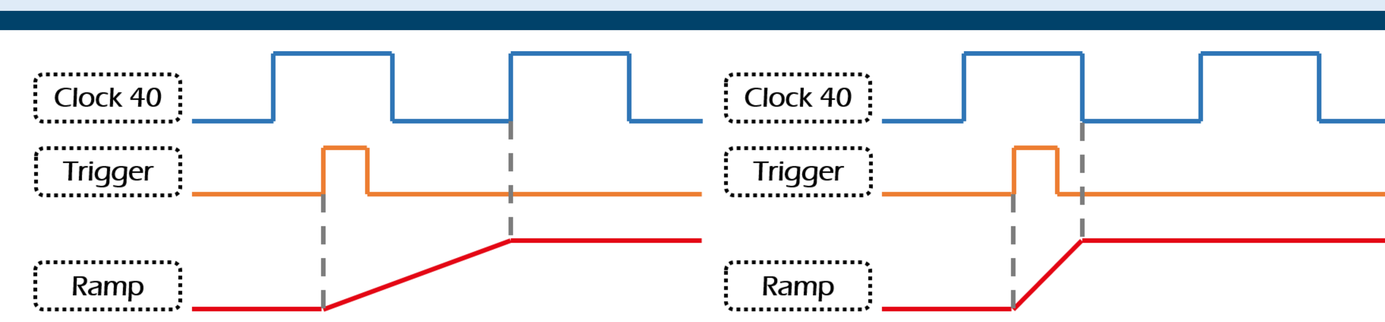
- Wire chamber ⟶ Tracking & position reference
- MCP-PMT ⟶ Timing reference
- 28 layers of 1 hexagonal module ⟶ Electromagnetic calorimeter (CE-E-Si)
- 12 layers of 7 hexagonal modules ⟶ Hadronic calorimeter (CE-H-Si)
- AHCAL CALICE scintillators tiles ⟶ Hadronic calorimeter (CE-H-Sci)

Where is the timing information from ?

ToA in SKIROC2cms



Time of Arrival (ToA) is measured from a fast shaper (5 ns). When the trigger is activated, ToA is measured with a Time to Amplitude Converter (TAC). The voltage ramp of the TAC is stopped by clock edge.



ToA is measured with respect to two reference points :

- **ToA Rise** ⟶ TAC ramp is stopped at the next **rising clock edge**
- **ToA Fall** ⟶ TAC ramp is stopped at the next **clock falling edge**

How is the timing information calibrated ?

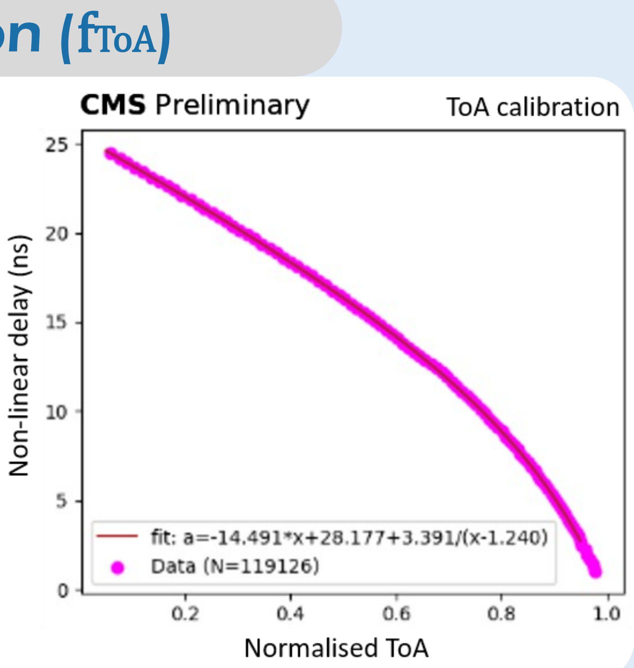
The individual channels need to be calibrated in order to harmonize their time-measurement response. Calibrated time is given by :

$$T(ToA, E, E_{layer}) = f_{ToA}\left(\frac{ToA - ToA_{min}}{ToA_{max} - ToA_{min}}\right) + f_{TW}(E) + f_{TW-Layer}(E_{layer})$$

- *ToA* is ToA from a single cell and *E* the assiociated energy
- *ToAmin* and *ToAmax* are the global extremal values of ToA
- *Elayer* is the energy sum per layer

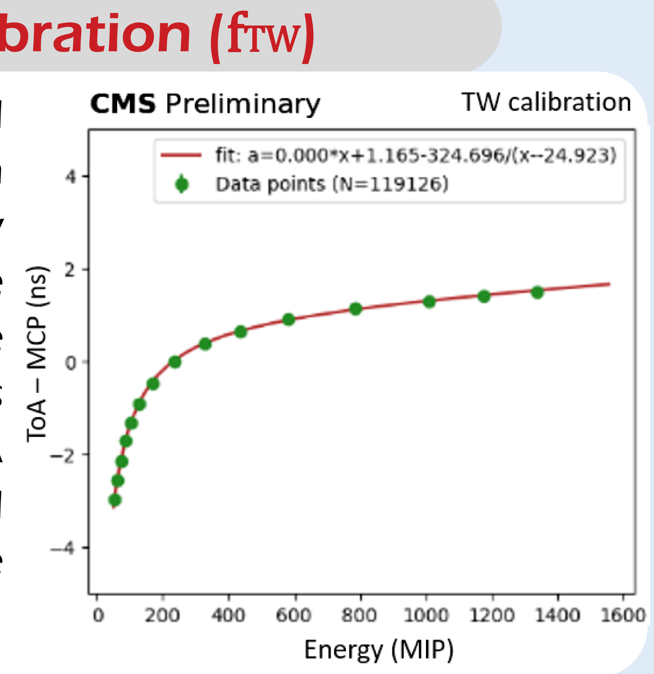
ToA calibration (f_{ToA})

ToA calibration allows to correct for the **non-linearity of the ToA** distribution due to the ramp saturation in the TAC. This plot shows the non-linear delay depending on the normalised ToA Rise from a single channel.



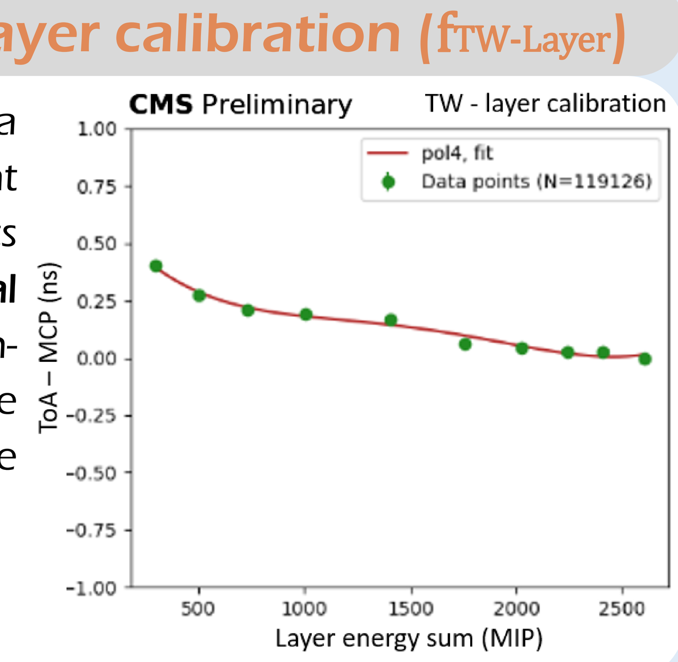
TW calibration (f_{TW})

Time Walk (TW) is measured as the difference between the time reference given by an **independent source (MCP)** and the ToA from the channels. This plot shows the difference between ToA Rise from a single channel and MCP, depending on the energy.



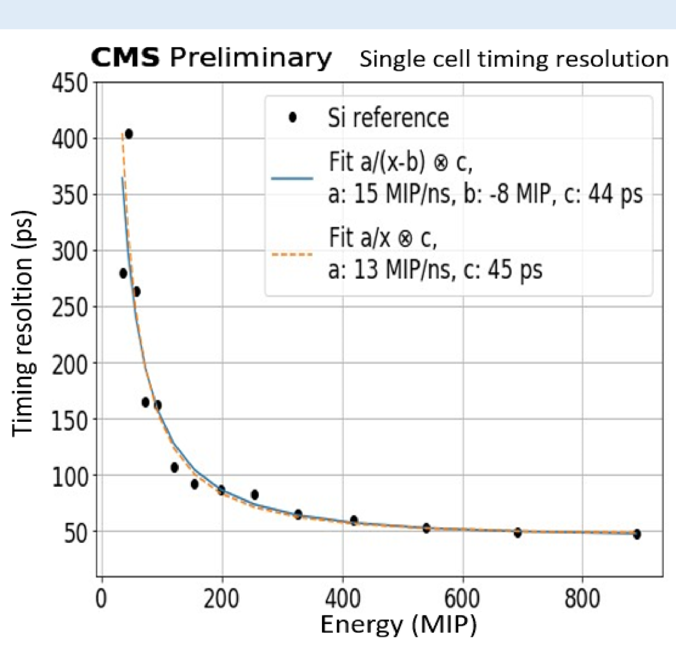
TW-layer calibration ($f_{TW-Layer}$)

This calibration step is a layer energy dependent TW calibration. It corrects **the systematic pedestal** shifts for high energy densities. This plot shows the TW depending on the energy sum of a layer.



What is the timing performance ?

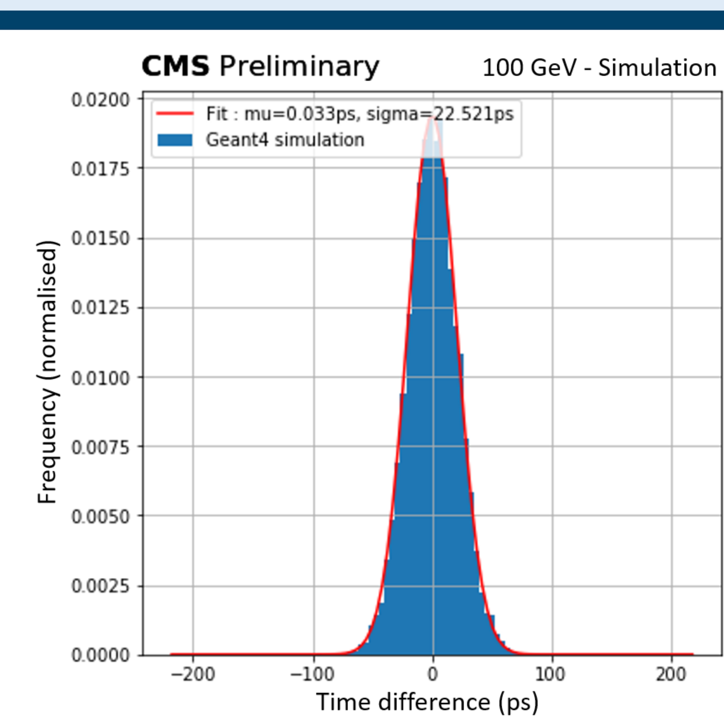
Single cell timing resolution as given below was measured in data. It has a stoch term of 10-20 ns.MIP and a constant term ~ 50 ps.

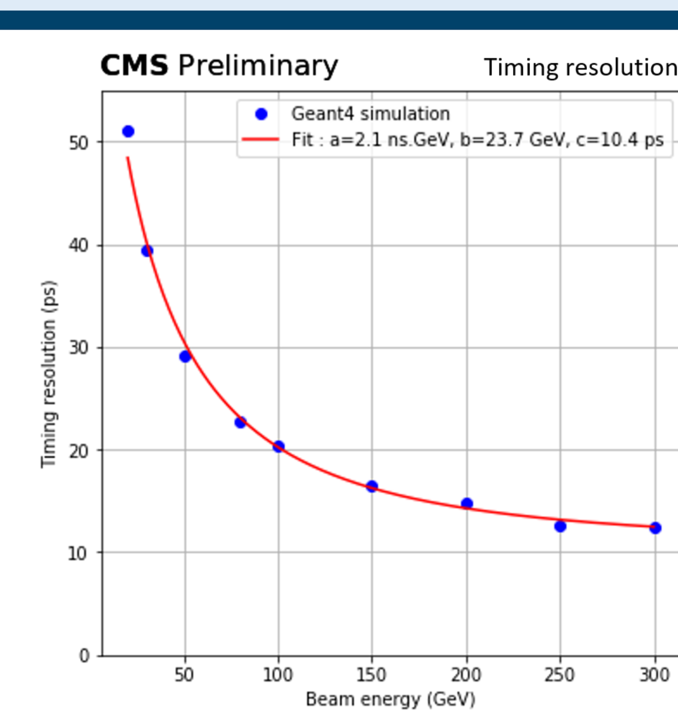


Shower timing determination

- Per channel combination of ToA Rise & Fall (12.5ns are added to ToA Fall to match ToA Rise)
- Outlier removal (keep only timing values within the shortest 68% interval of timing values per event)
- Energy weighting (for each event $t_{weighted} = \frac{\sum t_i E_i}{\sum E_i}$ where **i** is cell indice)

Timing resolution taken from a gaussian fit to the combined time distributions. Plots for 28 CE-E layers and electron beams.





Full shower resolution is currently done only with simulation.

Fit is done with : $y = \frac{a}{x-b} \oplus c$

It has a stoch term of 2.1 ns.GeV and a constant term of 10.4 ps which satisfies the specifications.

Conclusion

- Beam tests were performed at CERN of HGCAL prototypes silicon modules
- Time calibration was done for the ToA measurement of the prototype ASIC
- Resolution from the Geant4 simulation (~10 ps constant term) was achieved with assumption of ideal calibration and absence of systematic effects
- Constant term from data ~ 50 ps ⟶ Further understanding of systematic effects needed