Timing Layer at CMS

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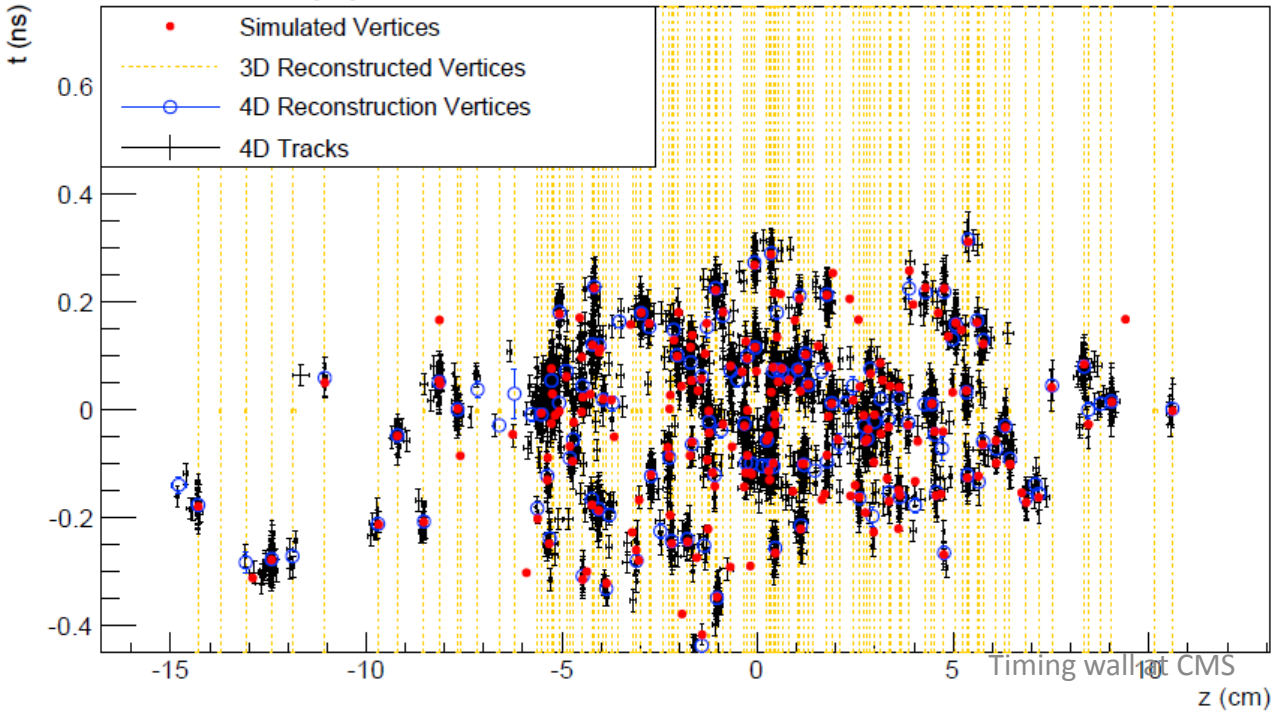
Motivation

- At the HL-LHC an average of **140–200 pileup** events will occur within 5 cm along the beam axis. This can degrade the identification and the reconstruction of the hard interaction, and can increase the rate of false triggers.



Red – true simulated position
Yellow – rec. without timing
Blue – how timing can help

What detector we need?

- In the time domain, pileup collisions at the HL-LHC will occur with an RMS spread of approximately 180–200 ps within the 25 ns bunch crossing structure of the colliding beams.
- If one imagines slicing the beam spot in consecutive time exposures of **30 ps**, the number of vertices per exposure drops down to current LHC pileup levels.
- At the hardware level, this approach requires a **dedicated detector for precision timing** of minimum ionizing particles (MIPs), **in addition to the enhanced timing capabilities of the calorimeters.**

What can we gain?

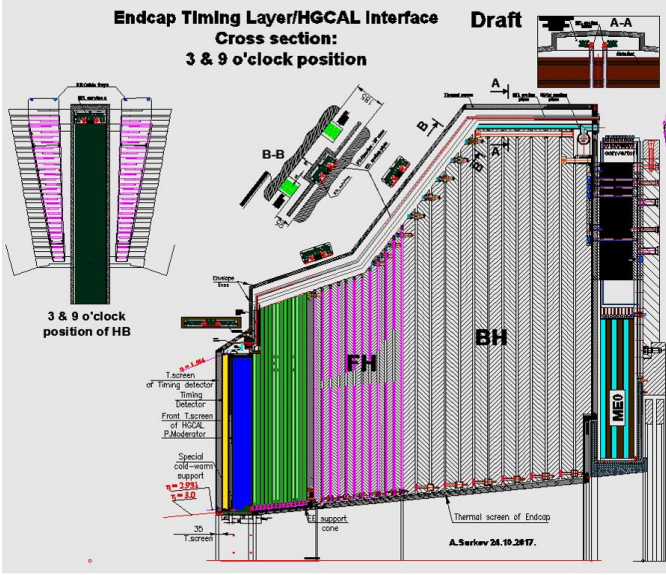
- Higgs: The quality of the isolation discriminant relies on the removal of pileup contributions close in angle to the candidate signal particle.

Signal	Detector requirement	Analysis impact	Physics impact
$H \to \gamma\gamma$	30 ps photon and track timing • barrel: central signal • endcap: improved time-zero and acceptance	$S/\sqrt{B}$: +20% - isolation efficiency +30% - diphoton vertex	+25% (statistical) precision on cross section
VBF+ $H \to \tau\tau$	30 ps track timing • barrel: central signature • endcap: forward jet tagging • hermetic coverage: optimal p_T^{miss} reconstruction	$S/\sqrt{B}$: +30% - isolation efficiency +30% - VBF tagging +10% - mass (p_T^{miss}) resolution	+20% (statistical) precision on cross section (upper limit or significance)
$\chi^{\pm}\chi^{0} \to W^{\pm}H + p_T^{miss}$	30 ps track timing • hermetic coverage: p_T^{miss}	$S/\sqrt{B}$: +40% - reduction of p_T^{miss} tails	+150 GeV mass reach
Long-lived particles	30 ps track timing • barrel: central signature	mass reconstruction of the decay particle	unique sensitivity to split-SUSY and SUSY with compressed spectra

ECAL upgrade

- In the barrel region (|eta| < 1.48), the **current ECAL** provides time information with a resolution of order **150 ps** for high energy showers (E > 30 GeV), limited mostly by time synchronisation and calibration.
- The **proposed upgrade** to the analog and digital readout electronics will enable the ECAL to achieve a time resolution of order **30 ps for photons of E_T > 30 GeV**

EndCap upgrade

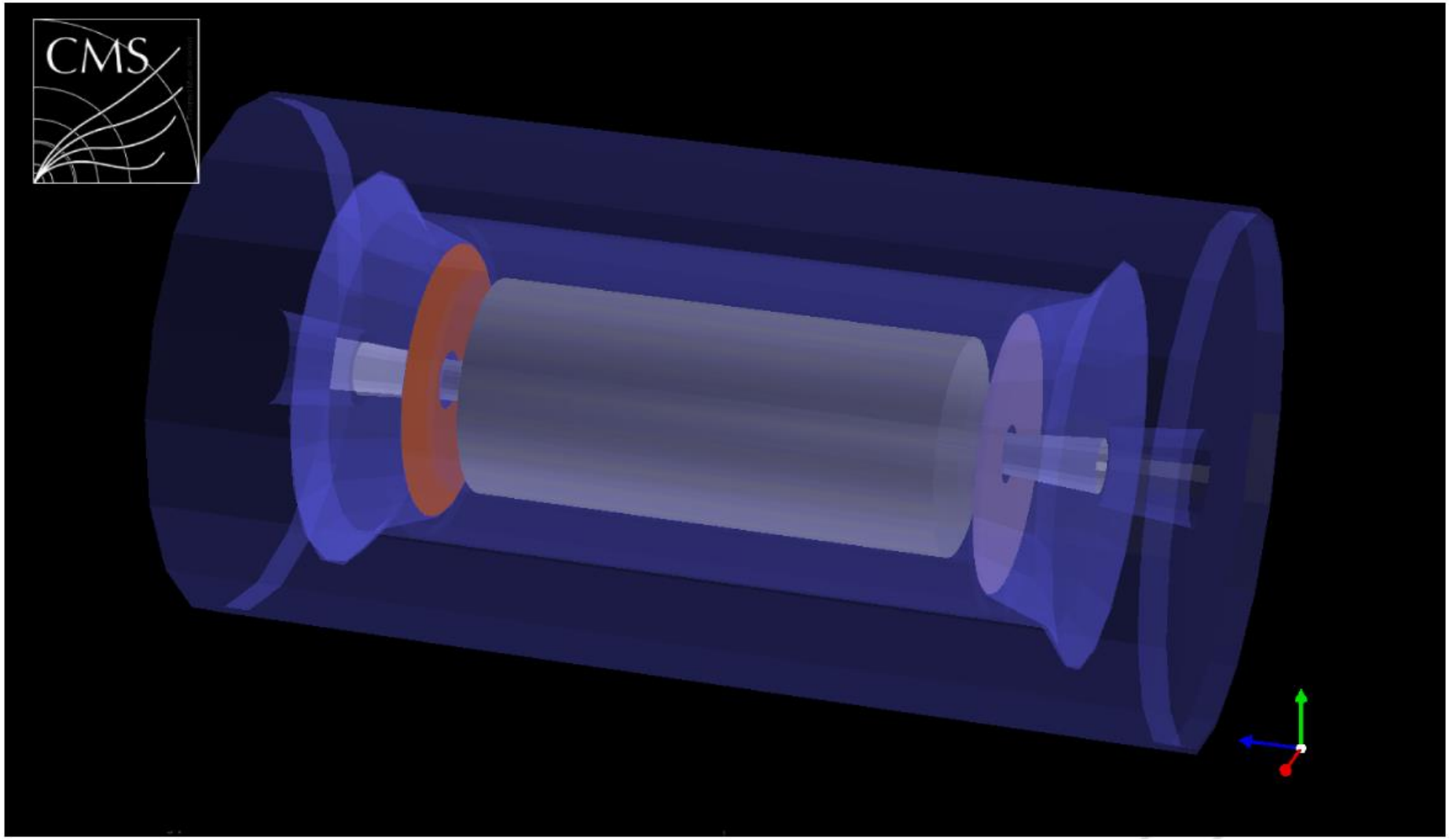


- HGCAL - highly segmented Si sensors
- The ToA system will provide a time measurement from each silicon pad (SiPAD) with a precision of 50–300 ps, depending on the energy deposited.
- The combination of multiple SiPAD hits in electromagnetic showers will provide time information for photons with high precision.
- A preliminary estimate indicates that the CE calorimeter could provide a time resolution of at least 30 ps with full efficiency for hadrons of $p_T > 10$ GeV.

Barrel and endcap

- A dedicated **hermetic** timing detector with high signal-to-noise for MIP depositions will provide efficient time vertex reconstruction.
- Thin layer between the Tracker and the calorimeters.
- The radial distance of these layers from the beam axis sets a threshold on the acceptance for charged particles at about $\mathbf{p_T = 0.7}$ GeV in the barrel and p = 0.7 GeV in the endcaps.

Barrel and endcap



Parameters

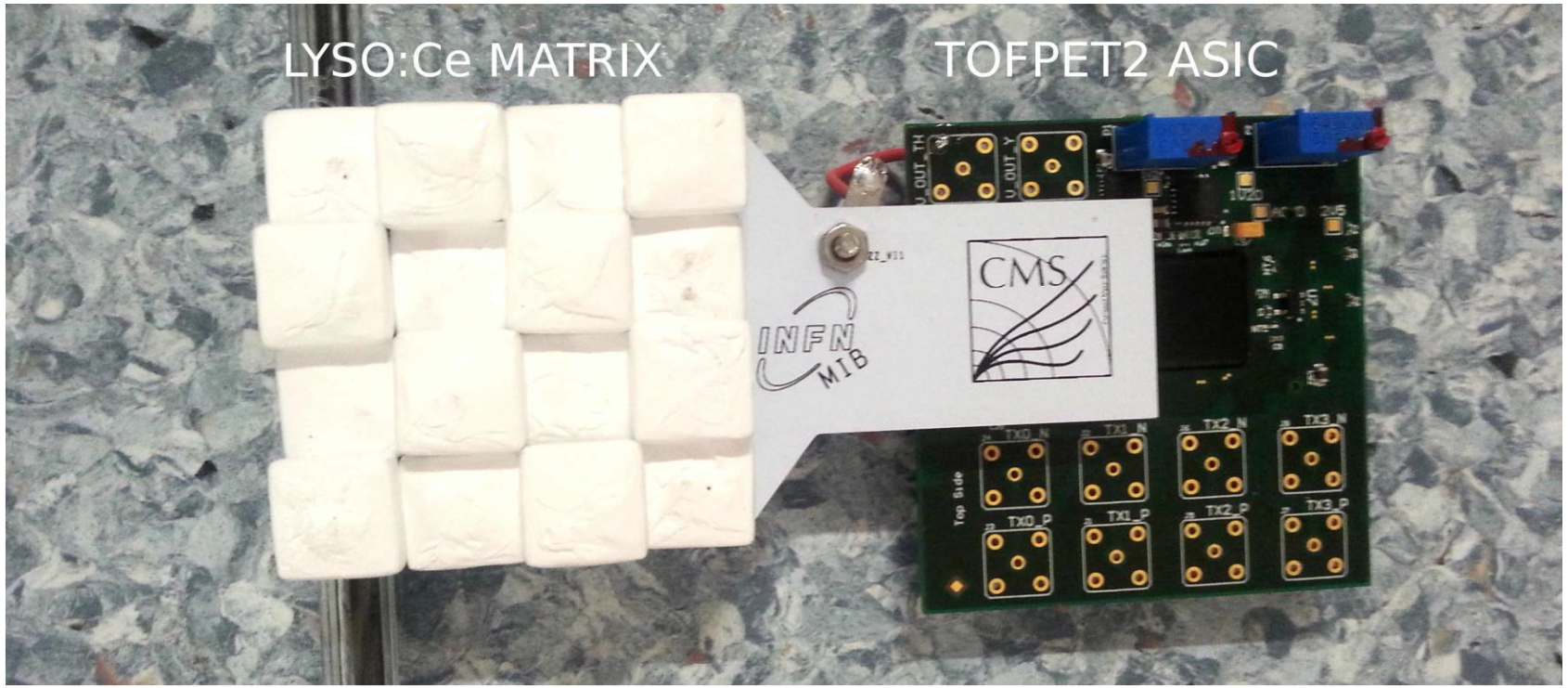
- Granularity: A channel area of order 1 cm2 in the barrel, and varying in the endcaps down to 3 mm^2
- Radiation tolerance: The devices must be able to operate efficiently up to an inte grated luminosity of 4000 fb^{-1}
- Marginal impact on the Tracker and calorimeters performance

Barrel

- The barrel timing layer (BTL) can be attached to the carbon fiber support tube of the Tracker as a thin standalone detector with minimal impact on the neighbouring sub-detectors. The fundamental detector unit consists of a LYSO:Ce crystal tile read outwith a SiPM.
- This type of sensor has been proven capable to achieve a time resolution better than 20 ps in test beam operation, when SiPMs and crystal tiles are of comparable surface, and to be radiation tolerant up to a neutron equivalent fluence of $2\ \ 10^{14}$ cm^{-2}.

BTL Module

- The fundamental detector cell consists of a thin LYSO:Ce crystal tile with an approximate cross section between 11*11 and 12*12 mm^2 coupled to SiPMs with a size of around 4*4 mm^2



Two layer configuration with 0.5 mm overlap
The read-out ASIC electronics will be connected directly to the SiPM

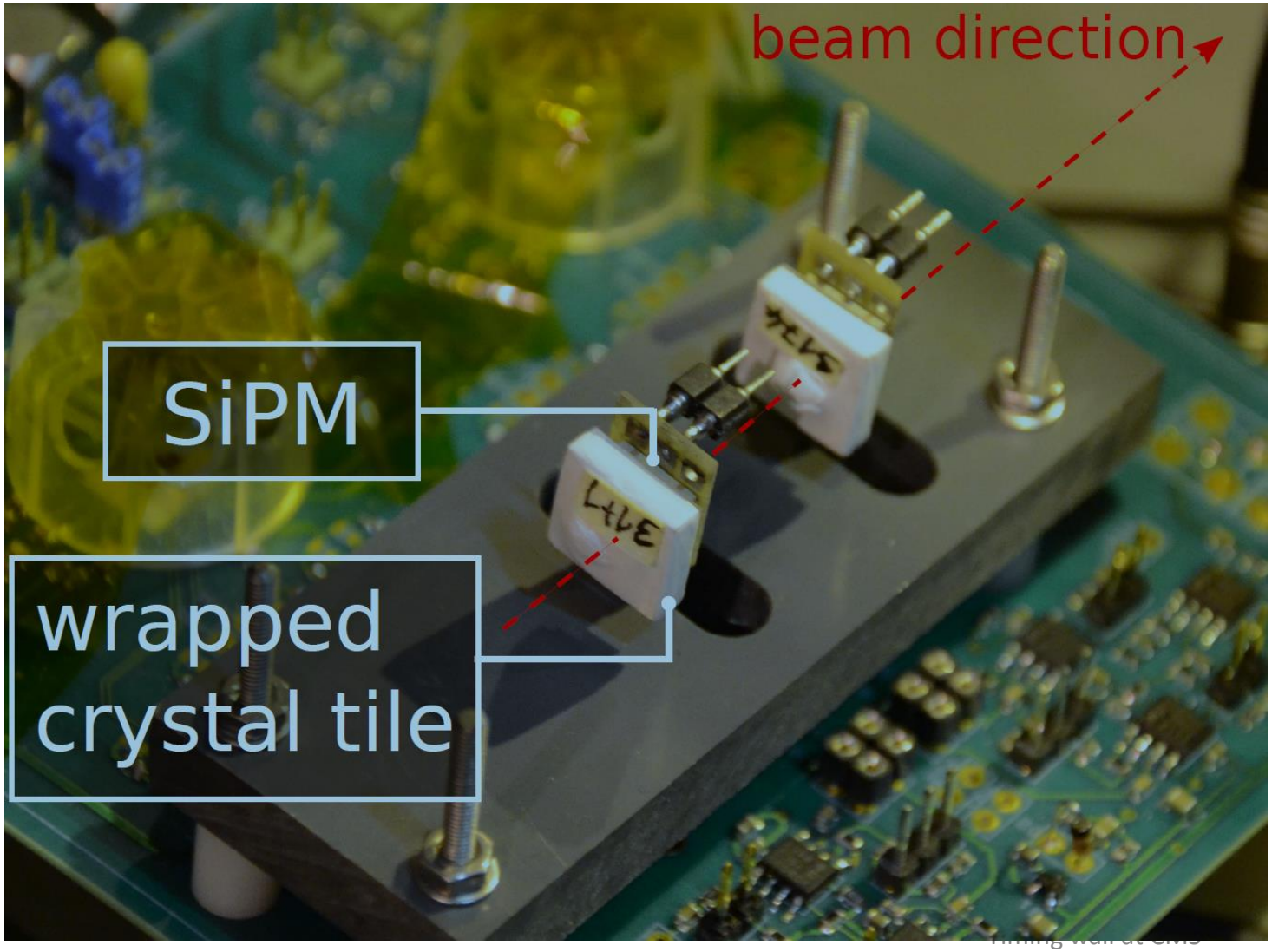
BTL sensor

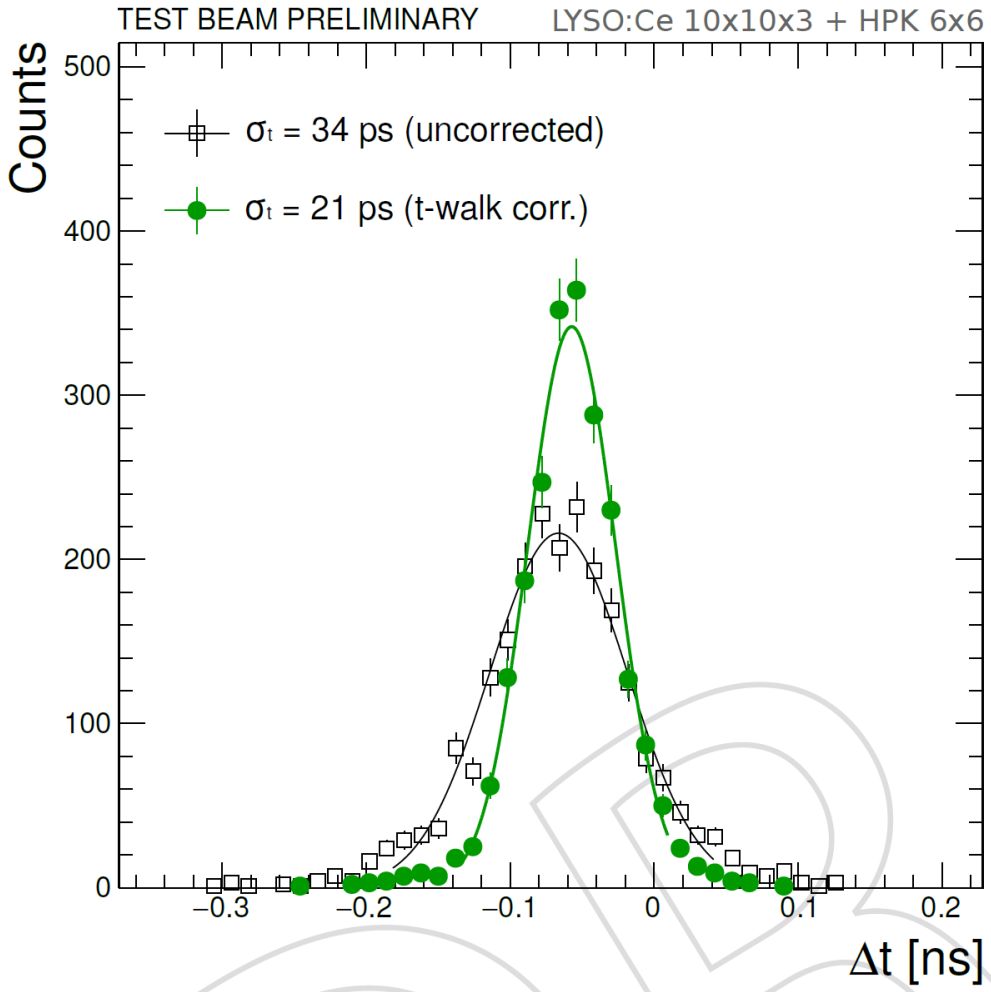
- The basic sensor used to instrument the barrel timing layer consists of a **LYSO:Ce** crystal tile read out with a **SiPM**.
- A trade off between sensor cost, timing performance and material budget in front of the ECAL lead to the choice of an optimal thickness of the crystal tile ranging from **3.75 to 2.4 mm**
- A signal of about 4500 photoelectrons is anticipated — the energy deposit of a MIP being about 1 MeV/mm in LYSO and the scintillation yield about 40 000 photons/MeV, photon detection efficiency (PDE) of about 15%.

Readout electronics

- Dedicated electronics based on a new ASIC derived from the TOFPET2 ASIC, developed for TOF-PET applications, will be used to read out the crystal+SiPM array contained in each module.
- The TOFPET2 chip will require some modifications in order to match the specifications of the barrel timing layer.

BTL single sensor test

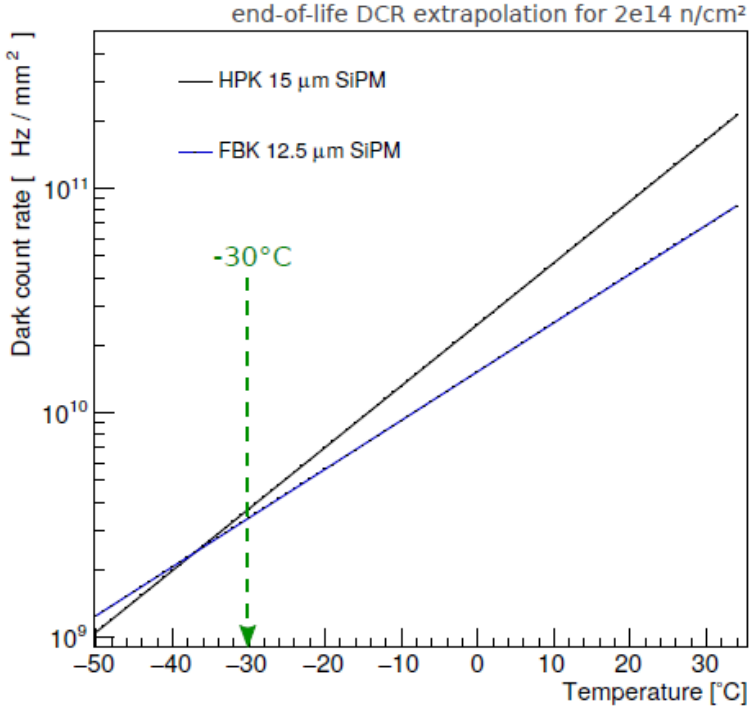


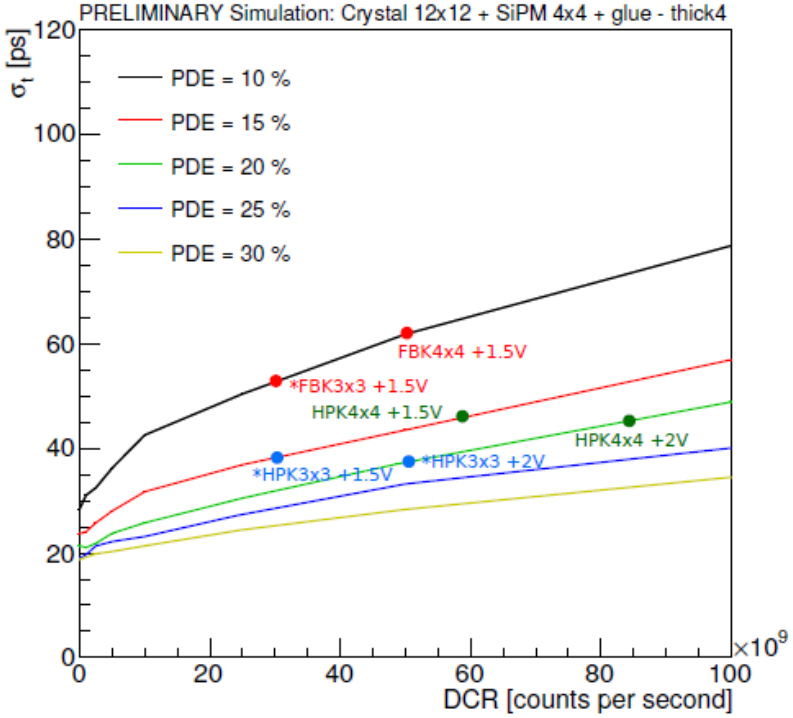


Irradiation

η	R [cm]	Z [cm]	1 MeV n_{eq} [cm^{-2}]	Charged hadrons [cm^{-2}]	Dose [kGy]
0	116.5	0	1.7×10^{14}	1.3×10^{13}	16
1.15	116.5	170	1.9×10^{14}	1.6×10^{13}	21
1.45	116.5	240	2.0×10^{14}	1.7×10^{13}	25

- Radiation tolerance of LYSO:Ce has been tested in the past years
- Radiation studies have been performed on several types of SiPMs in the context of the HCAL upgrade





Irradiation

- Under these conditions, the time resolution is predicted to vary from 25 ps (at the beginning of operation) to 35 ps after $1*10^{14}$ n_{eq}/cm^2 and to 40 ps after $2*$ 10^{14} n_{eq}/cm^2 at the end of detector operation
- More likely a long-termmonitoring using theMIP signal in the overlapping cells region and an adjustment of the optimal operational voltage of the SiPM will be performed to always operate at the best balance between PDE and dark current.

Clock

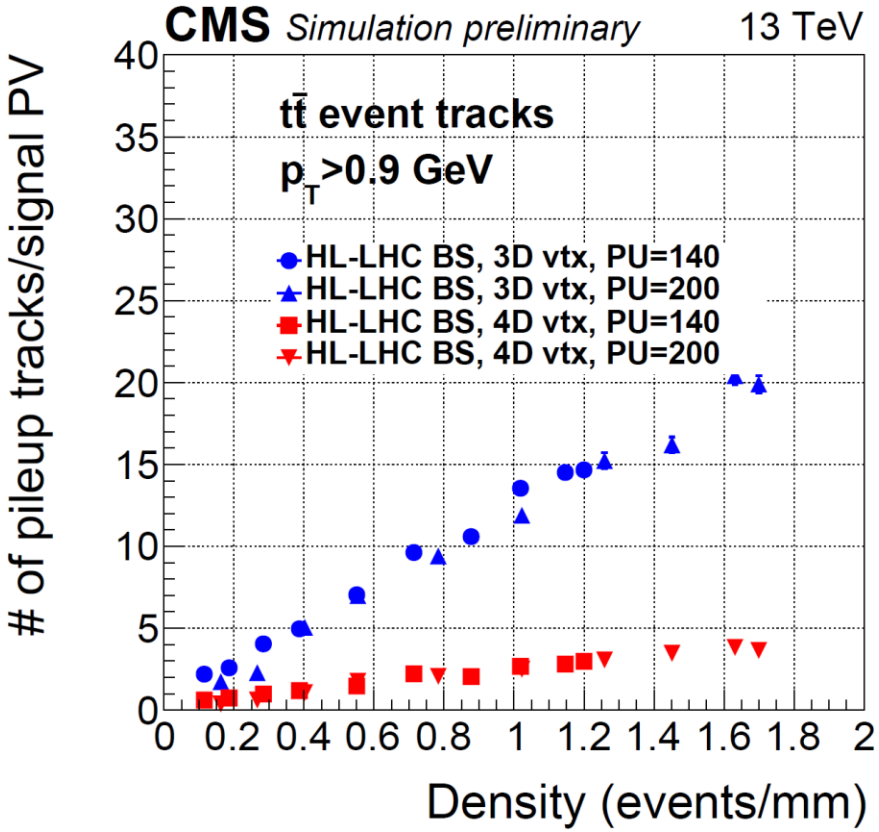
- The distribution of a precise clock to the front-end system is a major requirement for the BTL.
- A dedicated R&D effort across CMS sub-projects is being done to find the best solution for precise clock distribution at the level of the whole CMS detector.

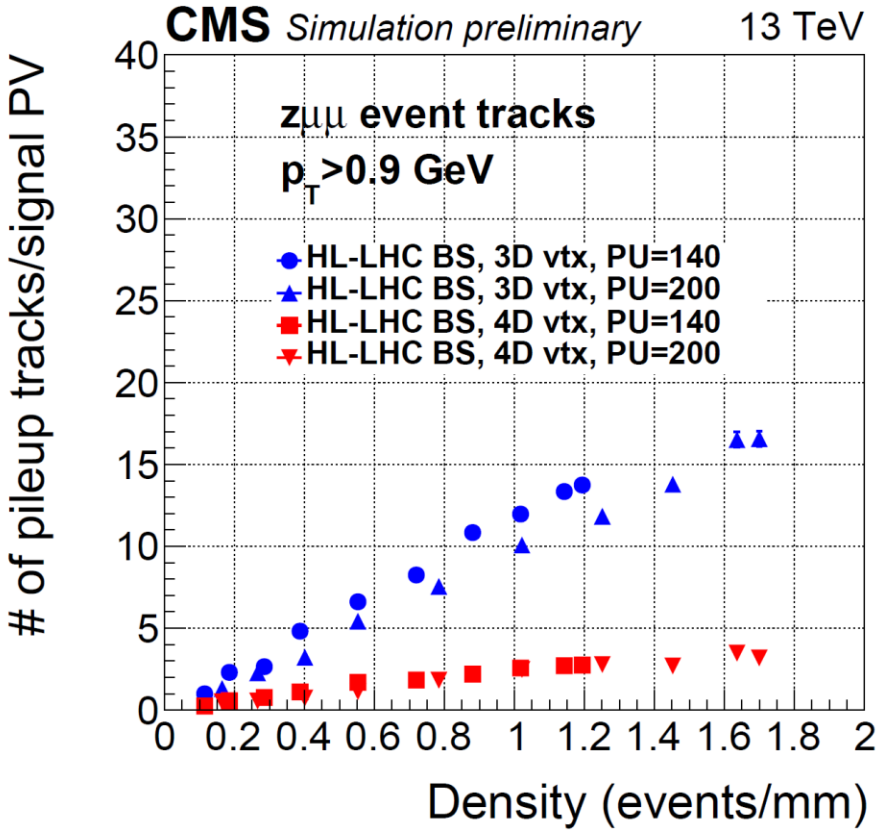
Occupancy

- The MIP most probable energy deposition corresponds to about 4 MeV for normal incidence. According to simulation, the channel occupancy at 200 pileup collisions remains below 3% across the entire BTL, for signals of amplitude higher than 50% of the MIP most probable energy deposition.
- At no threshold, there are many low energy hits, leading to an occupancy of order 10% or more, mostly due to out of time interactions originating from backscattered particles (e.g. low energy photons) from the ECAL.
- The double hit occupancy, which would cause an ambiguous assignment of the time information is below 0.1%.

Simulations - Reduction of pileup tracks

- with and without precision timing, as a function of the pileup density.



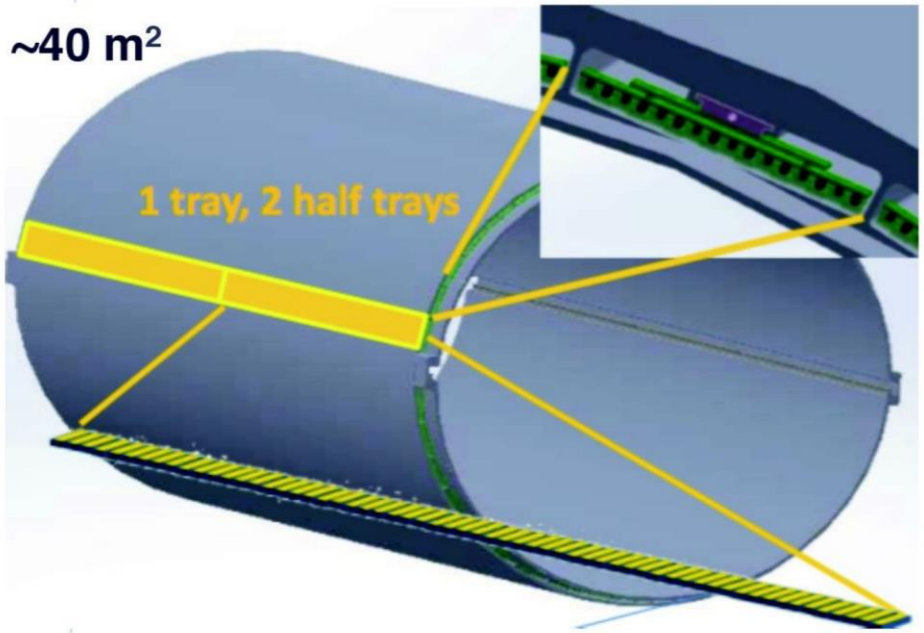


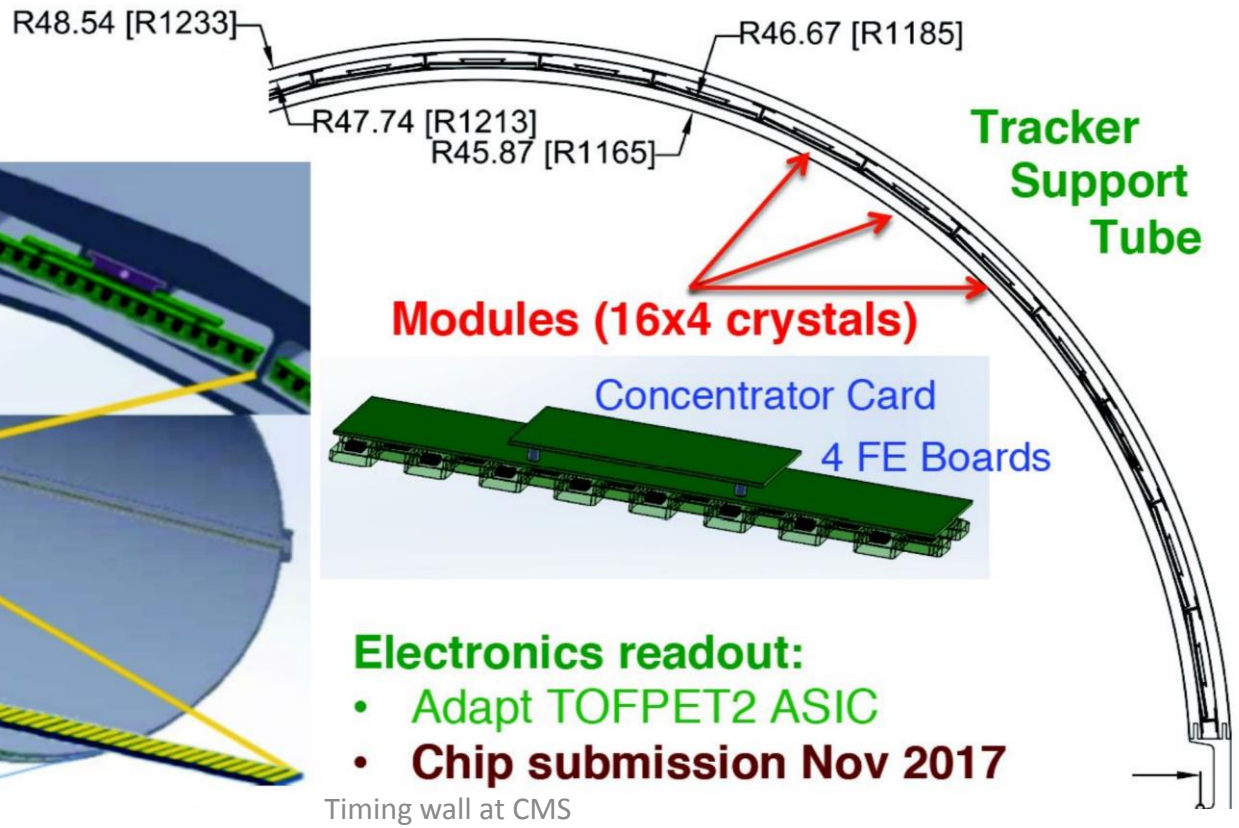
Simulations – Jets …

- In the presence of pileup, soft jets and underlying event activity from multiple pileup interactions may overlap and be clustered into a higher energy jet.
- Missing transverse momentum
- B-tagging and displaced vertices

From past presentations

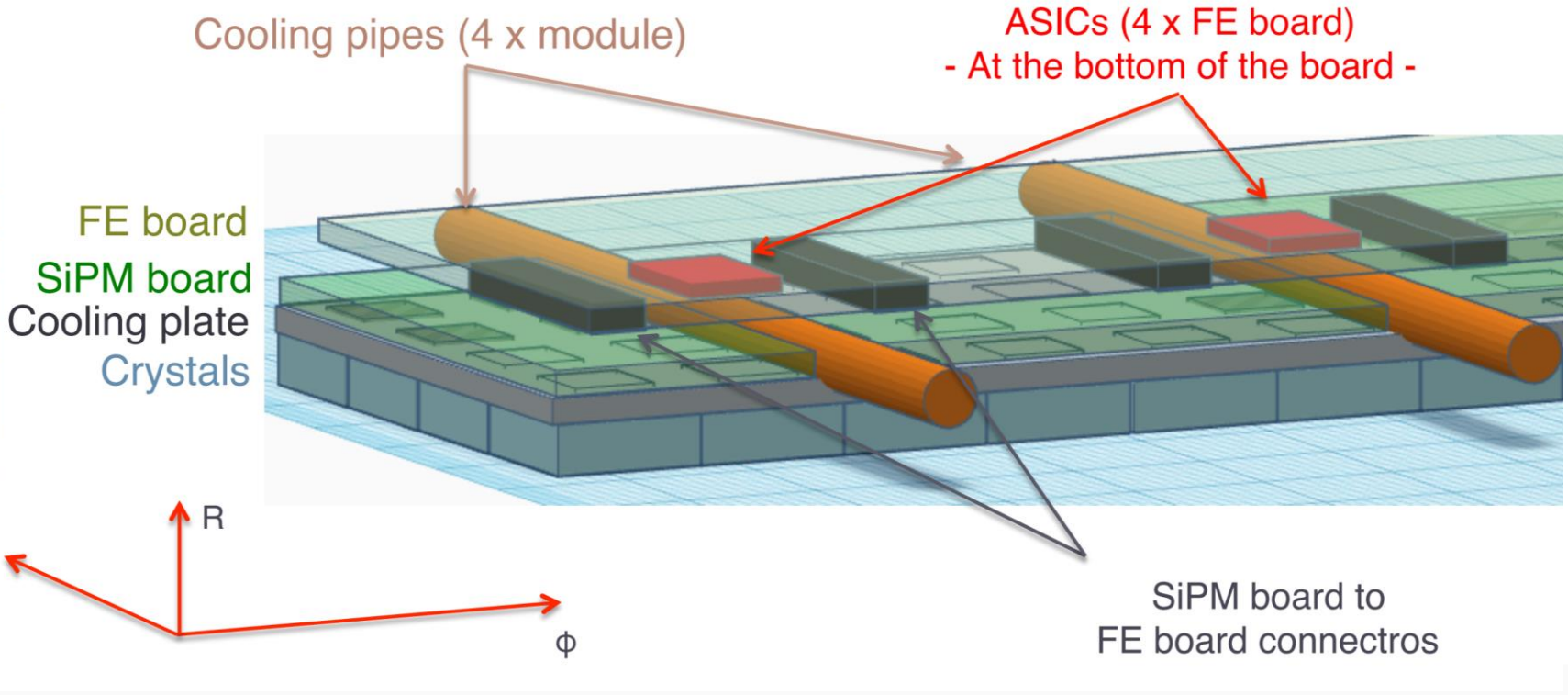
- **LYSO crystals + SiPM embedded in the Tracker tube**
  - Ready before TK integration (mid 2022)
  - Maintain performance at radiation level **$2x10^{14}$ n_{eq}/cm^2**

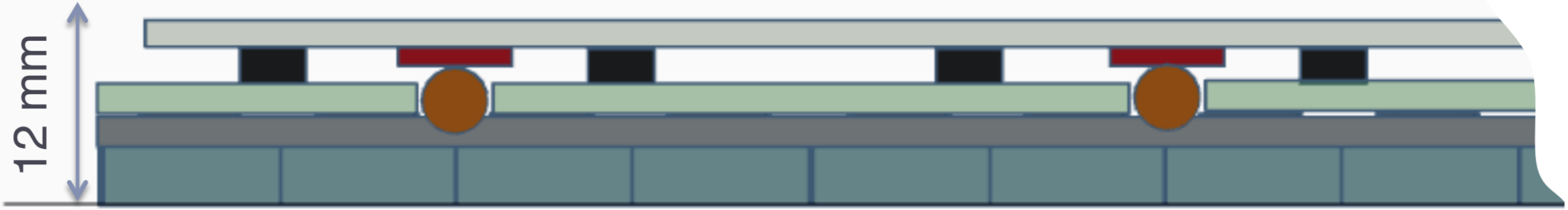




Electronics readout:
- Adapt TOFPET2 ASIC
- **Chip submission Nov 2017**

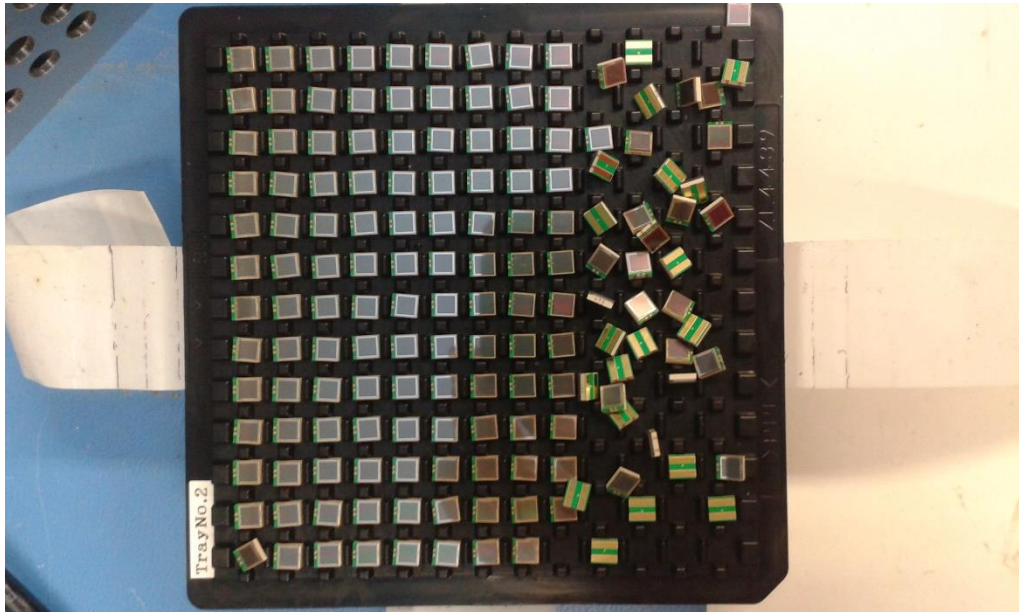
- ASIC and SiPMs largest sources of heat dissipation

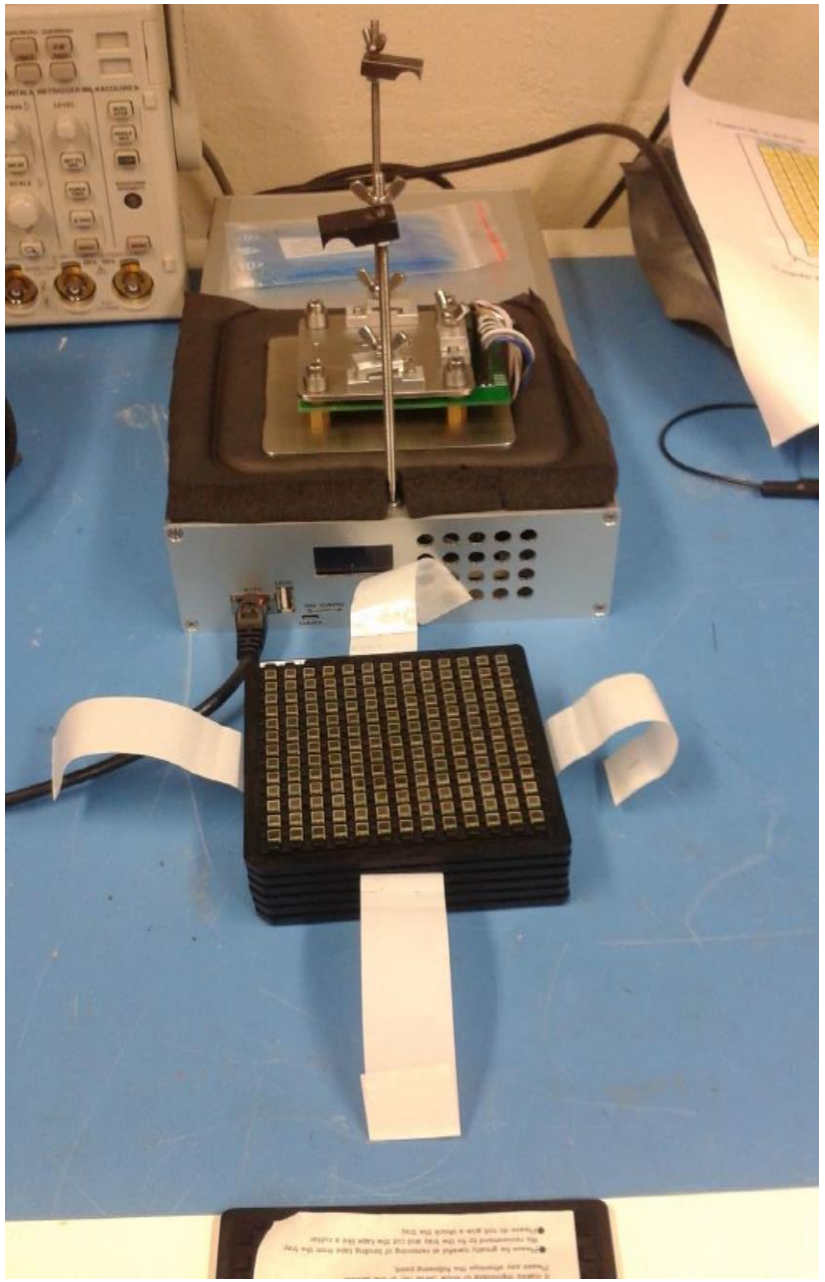




Our plans

- SiPM tester for CMS also
  - We are at the 3rd version for sPHENIX
  - 400 SiPMs were tested
  - 1500 SiPMs will be tested from 2nd of Dec





Irradiation, timing

- SiPM changes Vbr, PDE, gain … during irradiation, nobody measured with SPS (only IV) during it.
- With laser we can test the pixels