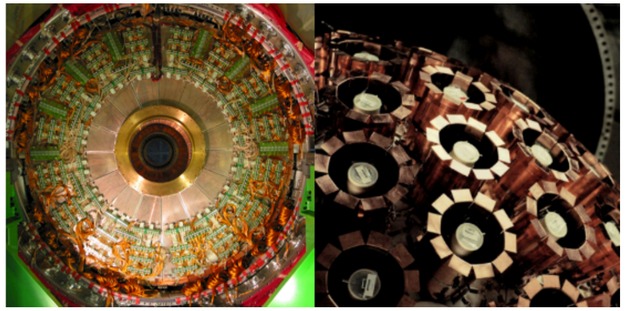
26th May 2021

Status and Plans for the CMS High Granularity Calorimeter Upgrade Project

International Conference on Technology and Instrumentation in Particle Physics

May 24-28, 2021 Online format

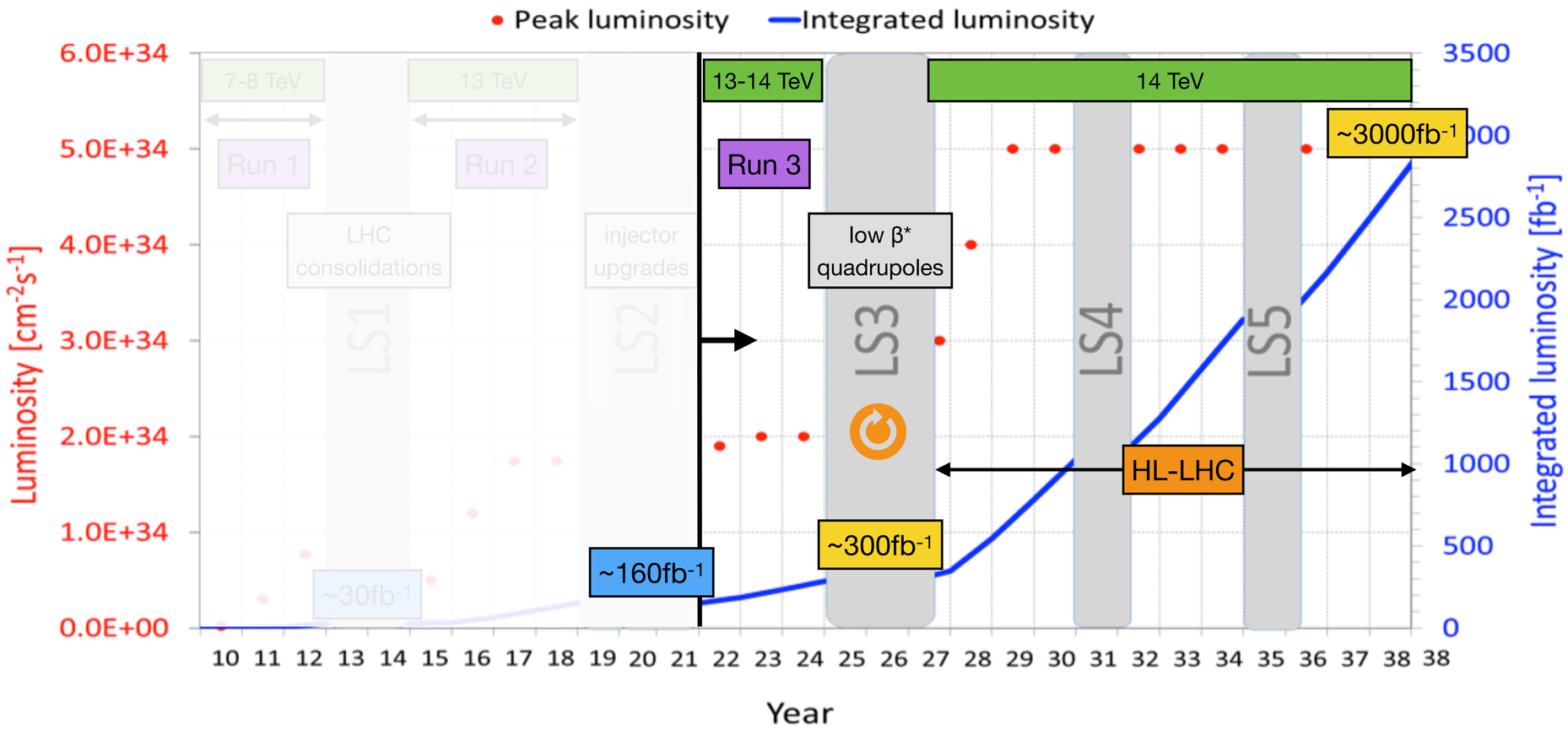


on behalf of the CMS collaboration

Thorben Quast (CERN)

The medium-term future at CERN: High Luminosity LHC

Experimental testing via high-energy particle collisions: **Large Hadron Collider (LHC)** @ CERN.



LHC upgrade to ~5x design luminosity = HL-LHC

cf. *Detector challenges from HL-LHC to FCC*,Werner Riegler

HL-LHC necessitates upgrades to the CMS detector

Experimental challenges	LHC		HL-LHC	General mitigation strategy
• inst. luminosity	$2 \times 10^{34}\ s^{-1}\ cm^{-2}$	→	up to $7.5 \times 10^{34}\ s^{-1}\ cm^{-2}$	‣ improved trigger & computing
• detector irradiation	$O(10^{14}\ neq/cm^2)$		$>O(10^{15}\ neq/cm^2)$	‣ radiation-tolerant sensors & electronics
• pile-up interactions	O(40)		140-200	‣ timing and increased granularity

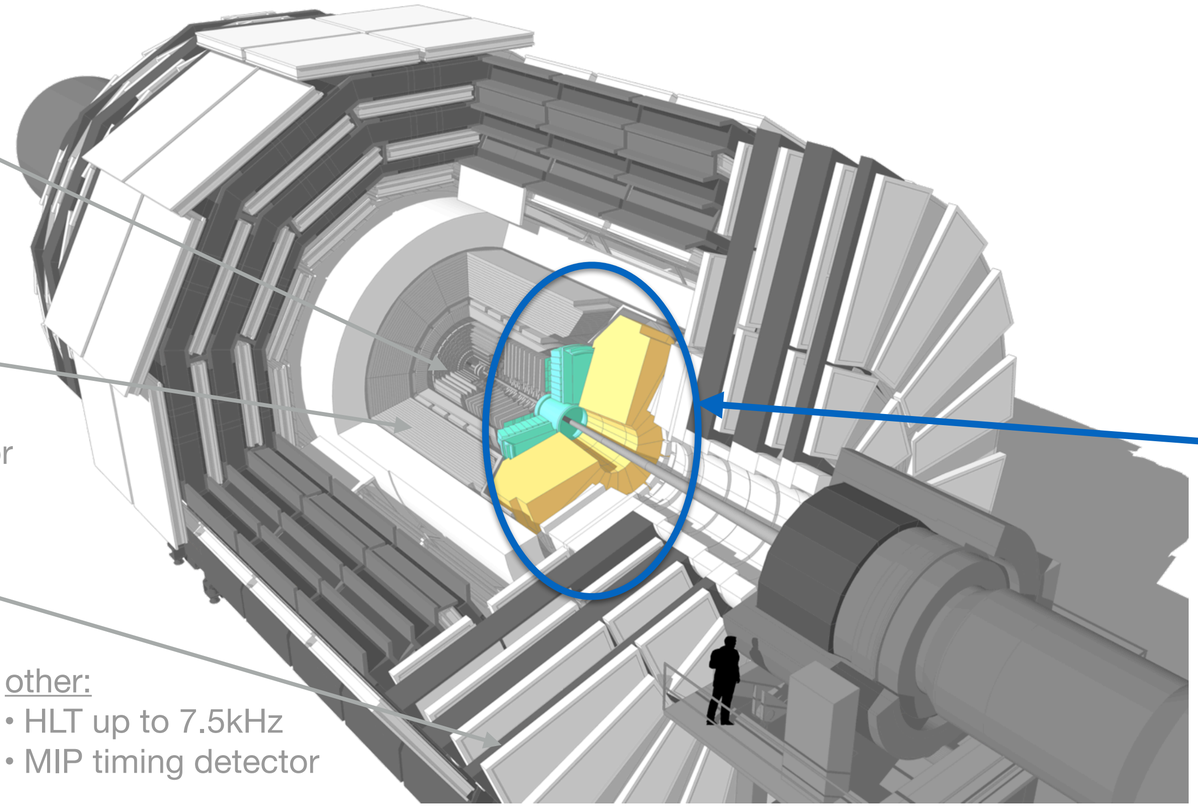
Compact Muon Solenoid (CMS)
HL-LHC Upgrades

Tracker:
Radiation tolerant,
high granularity,
less materials, tracks in
hardware trigger (L1),
coverage up to $|\eta| = 3.8$

Barrel Calorimeter:
New BE/FE electronics,
ECAL: lower temp.,
HCAL: partially new scintillator

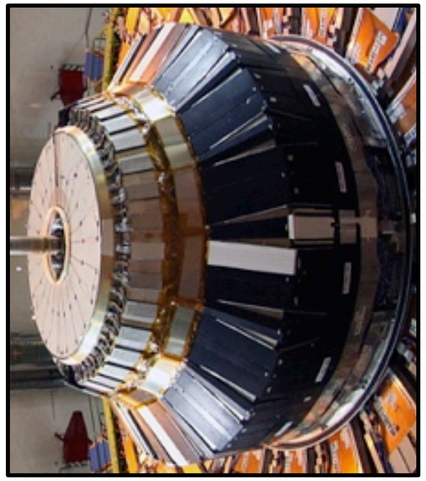
Muon system:
New electronics
GEM/RPC coverage in
$1.5 < |\eta| < 2.4$,
investigate muon tagging
at
higher η

other:
• HLT up to 7.5kHz
• MIP timing detector



To be replaced for HL-LHC

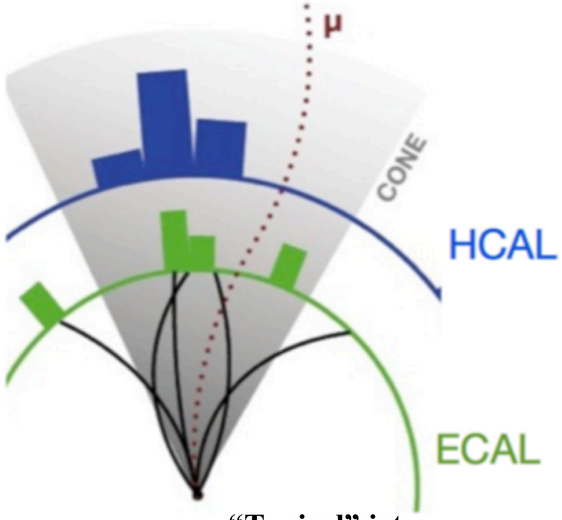
Endcap Calorimeters:
$1.5 < |\eta| < 3.0$



cf. *CMS Phase-2 Inner Tracker Upgrade*, Sudhir Malik
cf. ...

High granularity for particle flow

➡ Real need to improve ***jet energy resolution*** for the next generation of calorimeters @ HL-LHC

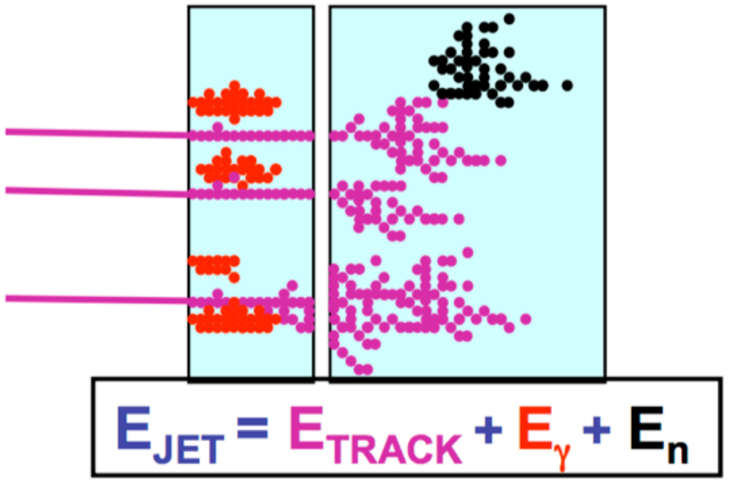


"Typical" jet:
~62% charged particles (mainly hadrons)
~27% photons
~10% neutral hadrons
~1% neutrinos

CMS follows the ***particle flow*** paradigm.

- Accurate reconstruction of ***each particle within a jet.***
- For each individual particle in a jet, use detector with best energy/ momentum resolution.
- Assignment of energy deposits to tracks: ***granularity in the energy measurement.***
- ***Granularity*** is more important than energy resolution.

cf. *Highly Granular Calorimeters for Particle Flow*, Katja Krüger



New calorimeter endcap: High-Granularity Calorimeter (HGCAL)

HGCAL = Sampling calorimeter

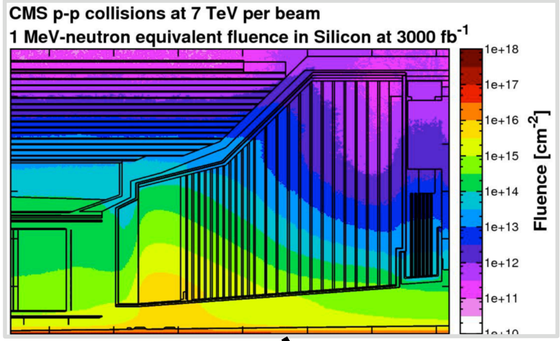
- Hexagonal **silicon sensor** based modules in CE-E and high radiation regions of CE-H.
- **Scintillating tiles** with on-tile SiPM readout in low-radiation regions of the CE-H.

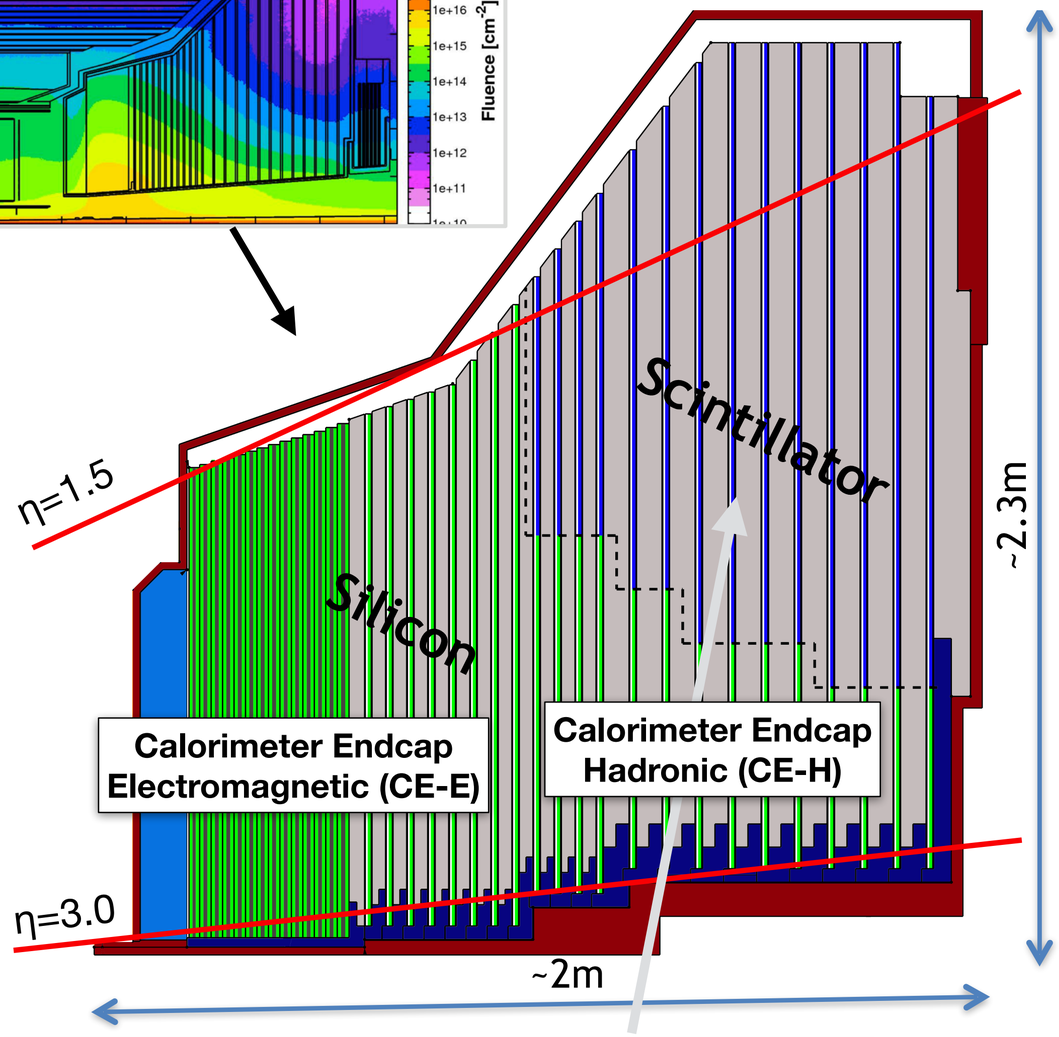
Active material

Both endcaps	Silicon	Scintillators
Area	**~620m²**	~370m²
#Modules	~27000	~4000
Channel size	**0.5 - 1 cm²**	4-30 cm²
#Channels	**~6 M**	~240k
Op. temp.	-30 ° C	-30 ° C

Passive material

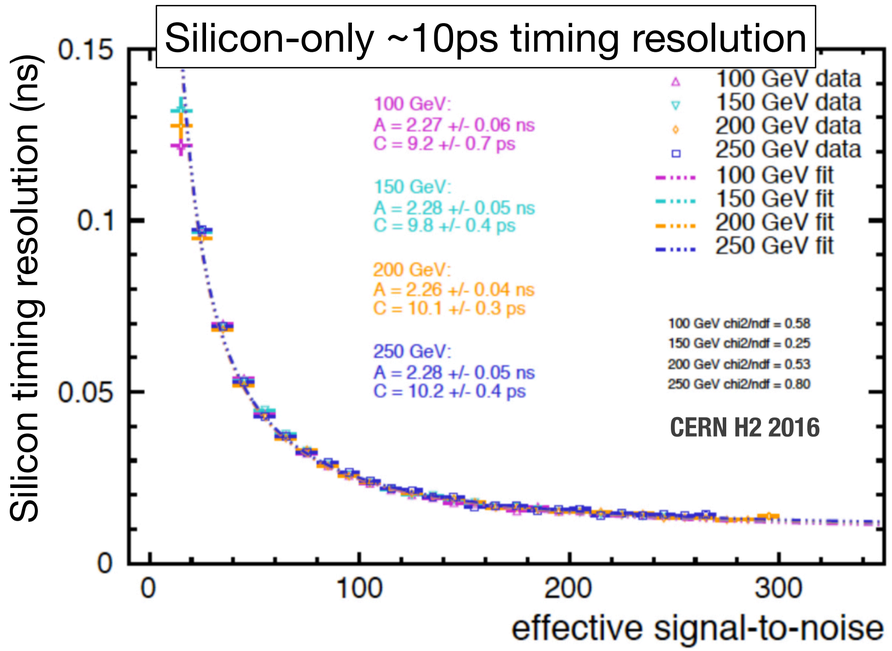
Per endcap	CE-E	CE-H (Si)	CE-H
Absorber	Pb, CuW, Cu	Stainless steel, Cu	
Depth	27.7 X_0	10.0 λ	
Layers	26	7	14
Weight	~230 t / endcap		

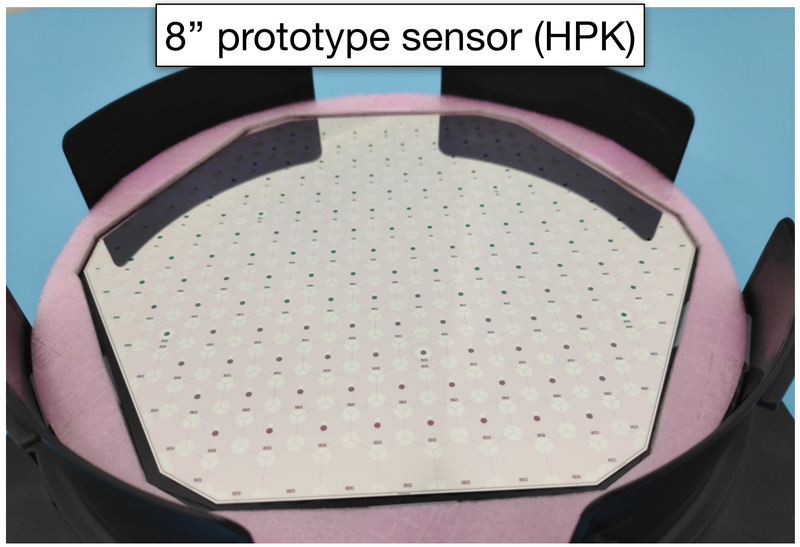




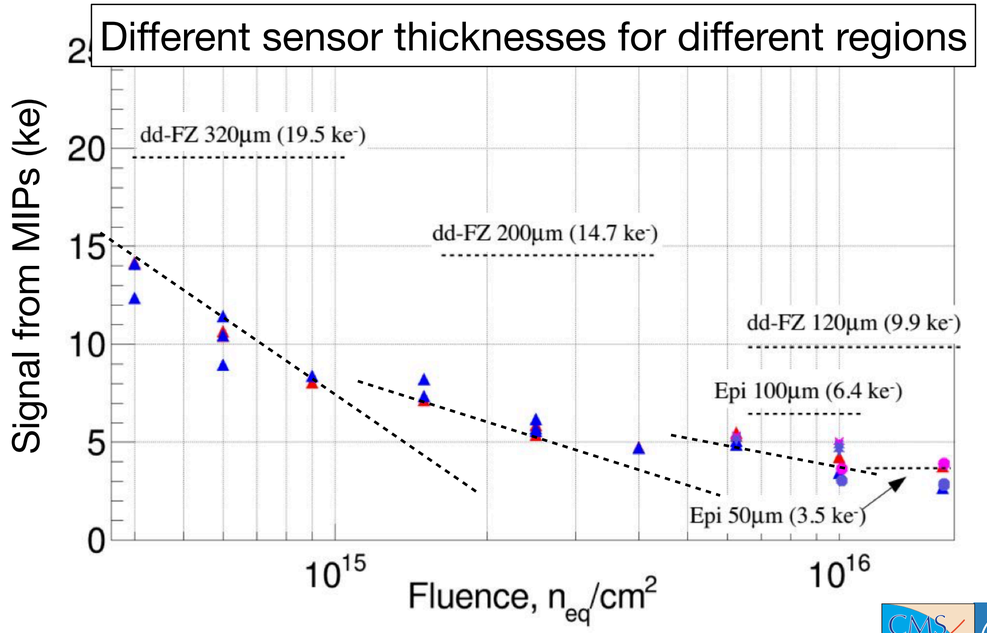
cf. The CMS High Granularity Calorimeter Scintillator/ SiPM Tileboards, Mathias Reinecke

620m² of 8” silicon sensors: Radiation-tolerant and fast signals





- ***8” hexagonal geometry***: most efficient use of Si area.
- Bulk: p-type, found to be more irradiation-tolerant than n-type.
- ***Sensor thickness and cell size vary*** with radiation levels:
  - 120, 200, 300 μm thickness.
  - 0.5 and 1cm² cell size.



Minimising degradation

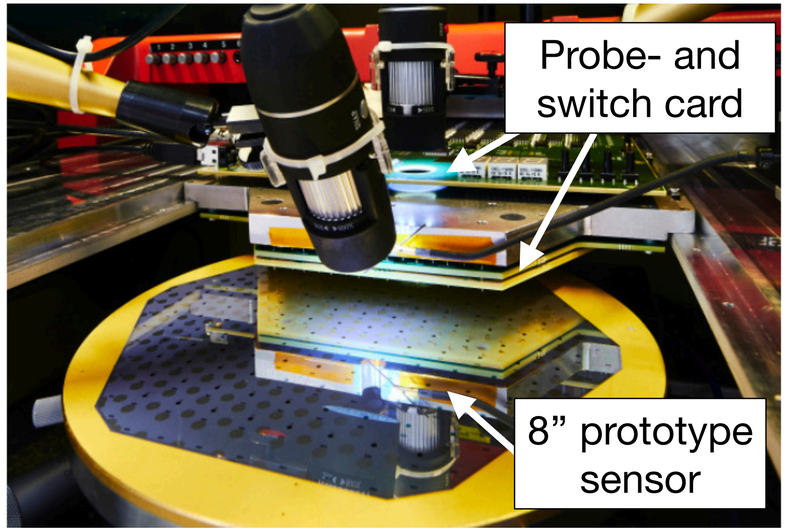
- Operation at -30° C: Reduce **increasing bulk leakage current**.
- Increasing the bias voltage up to -800V to reduce **signal loss**.

Electrical characterisation of silicon sensors is crucial

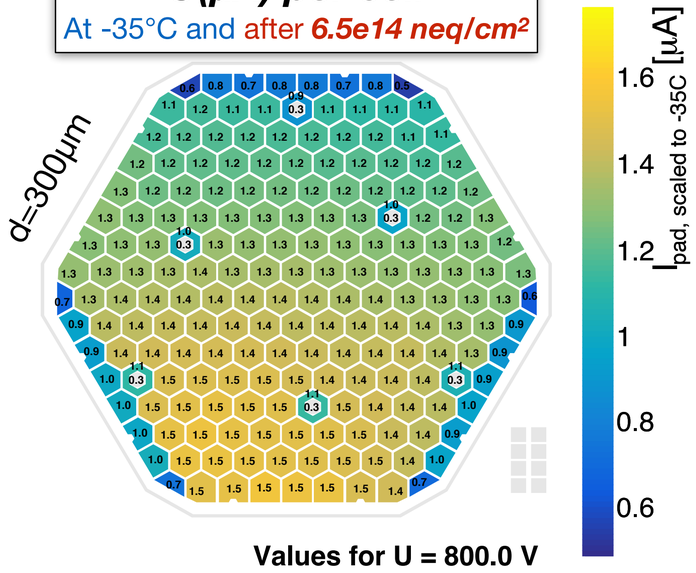
Important: **leakage current = power dissipation, capacitance ~ noise**

★ ***Switching and probe-card setup***

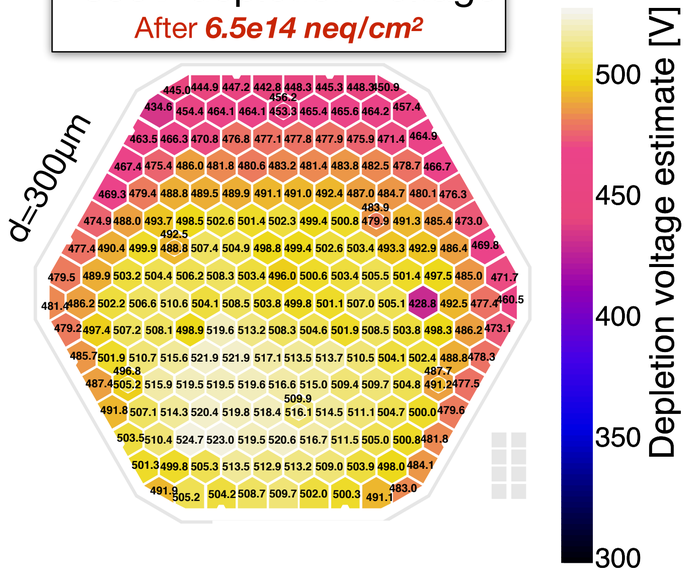
- Contact all cells via pogo-pin card, all pads biased while one is tested.
- Switch between channels using switching card.
- **Temperature control of the sensor**, important after irradiation to O(e14-e16) neq/cm².



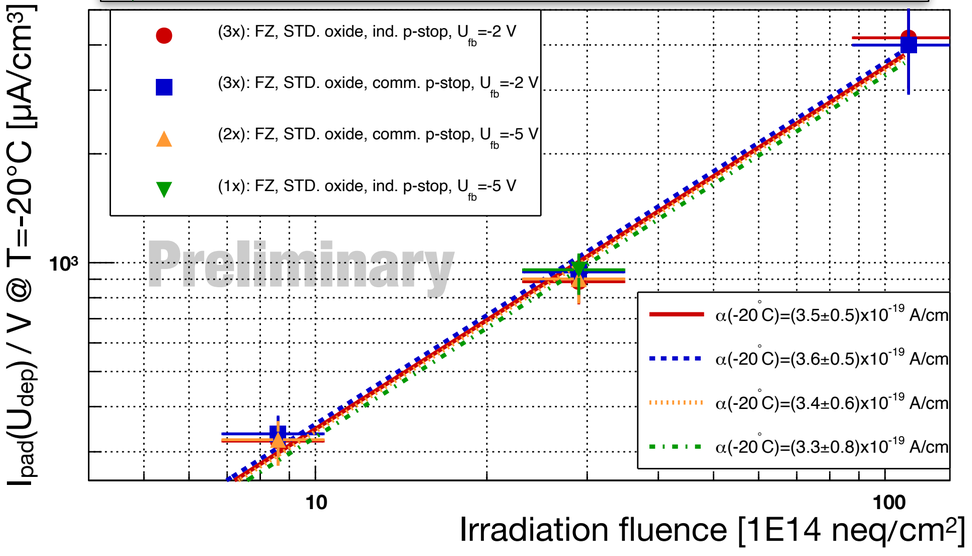
O(μA) per cell
At -35°C and after ***6.5e14 neq/cm²***



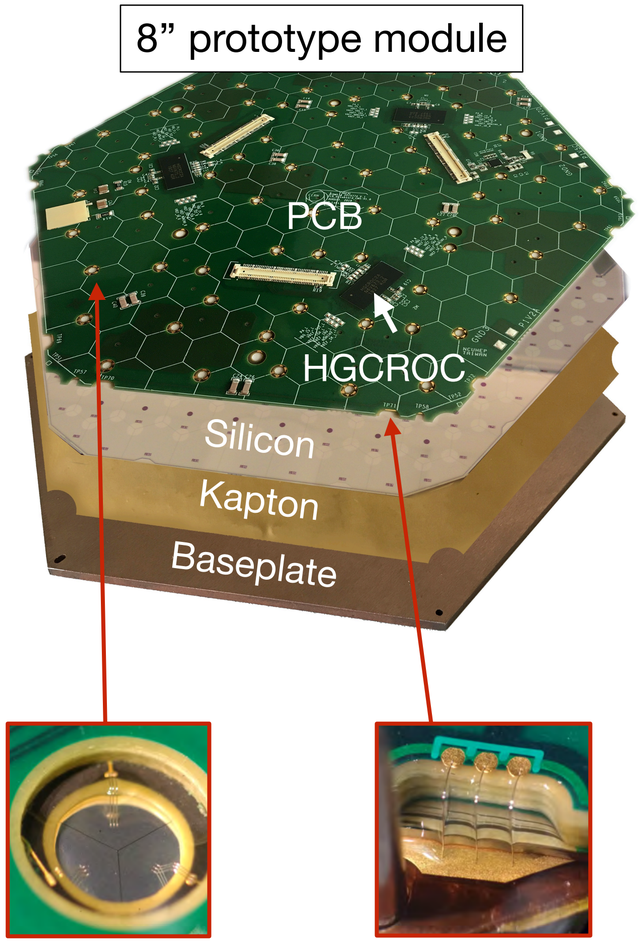
~500V depletion voltage
After ***6.5e14 neq/cm²***



✓ As expected: ***Leakage current ~ fluence***



Silicon modules



Silicon modules

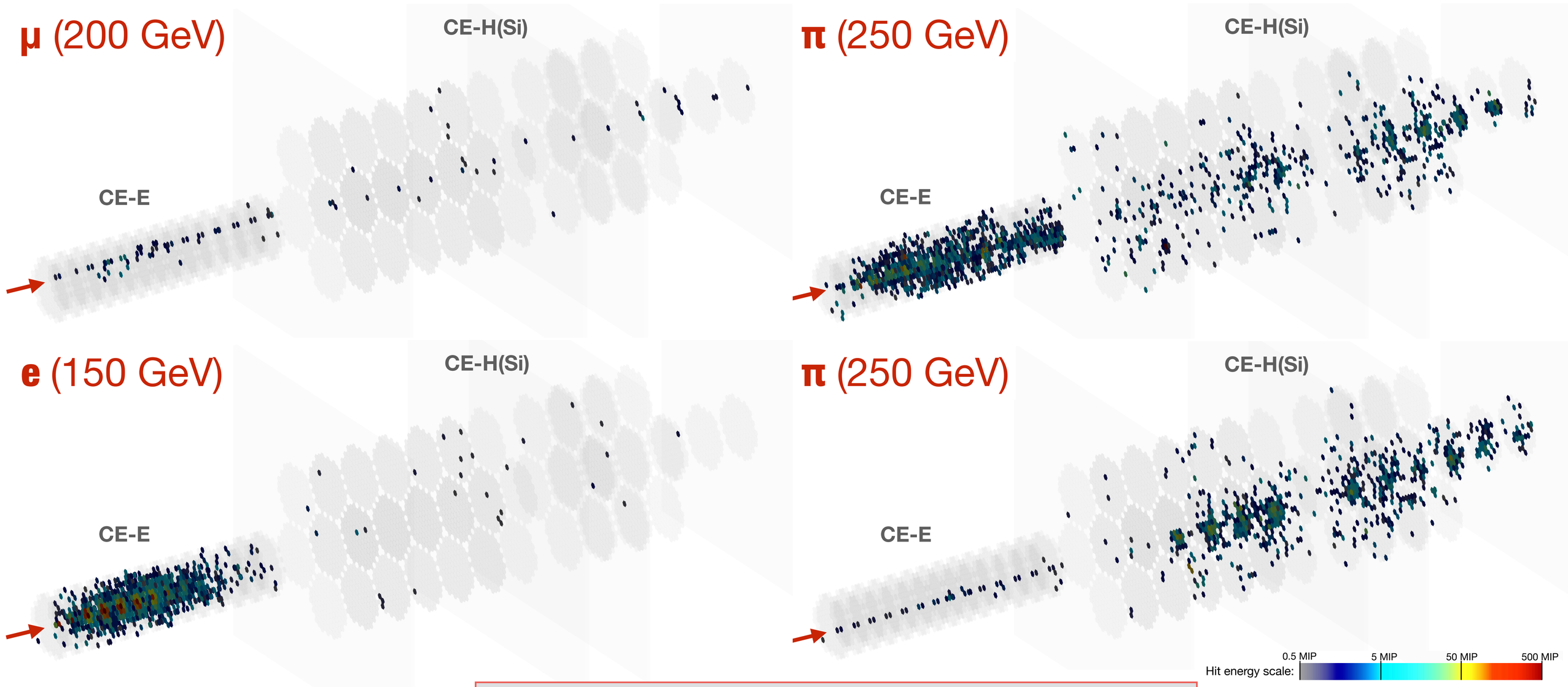
Sandwich of **PCB**, **sensor**, biasing/insulation layer and **baseplate** for rigidity/cooling.

- Wire-bonding from PCB onto the silicon.
- CE-E: CuW baseplates act as absorbers.
- CE-H: PCB baseplates (good thermal properties and cheaper).

5D calorimetry FE electronics requirements:

- ***Low noise*** (<2500e) and ***high dynamic range*** (0.2fC -10pC).
- Timing information to ***tens of picoseconds***.

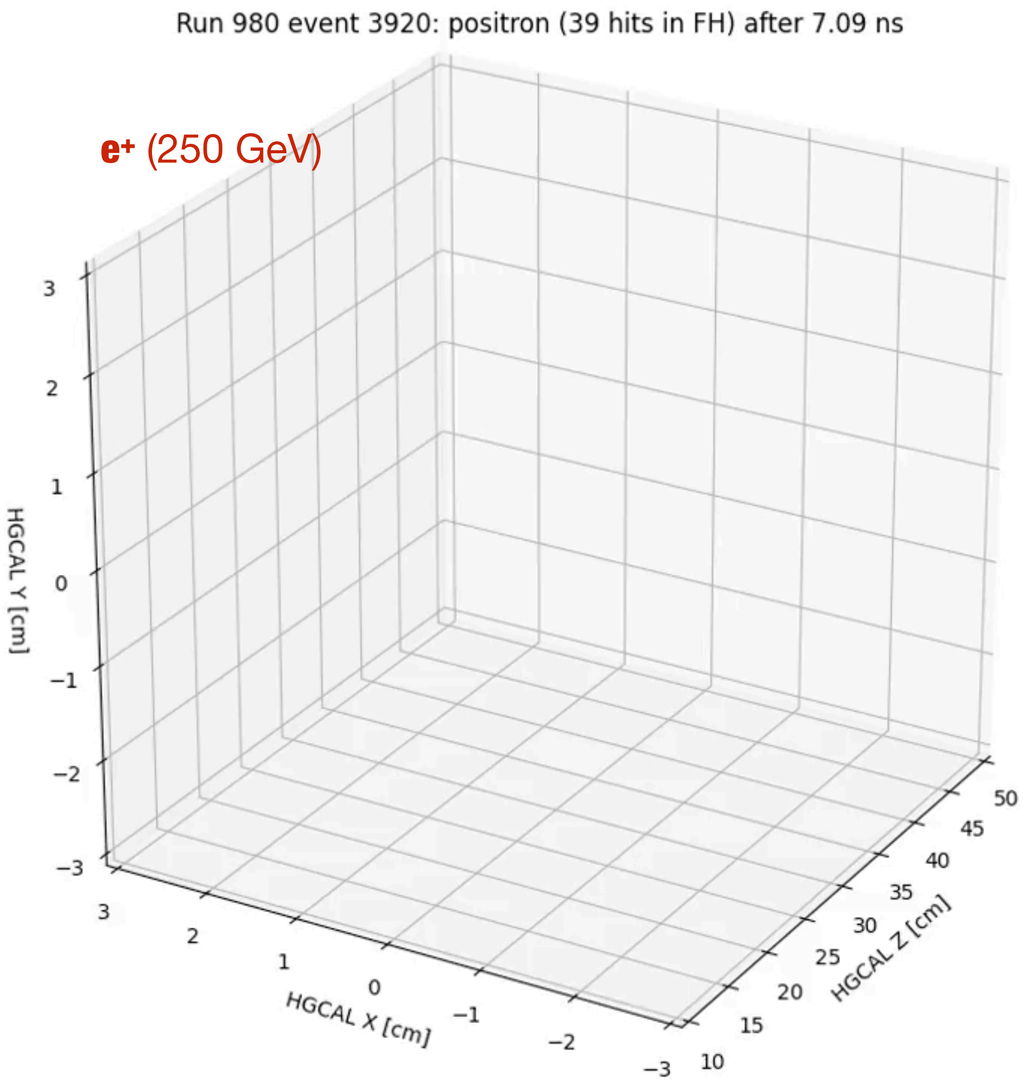
Demonstrated in test beam: HGCAL = Imaging calorimeter



cf. *Performance of CMS high granularity calorimeter prototypes in testbeam experiments*, Clemens Lange (poster)

Demonstrated in test beam: Timing resolutions down to ~70ps

➡**Resolve time evolution of real particle showers!**

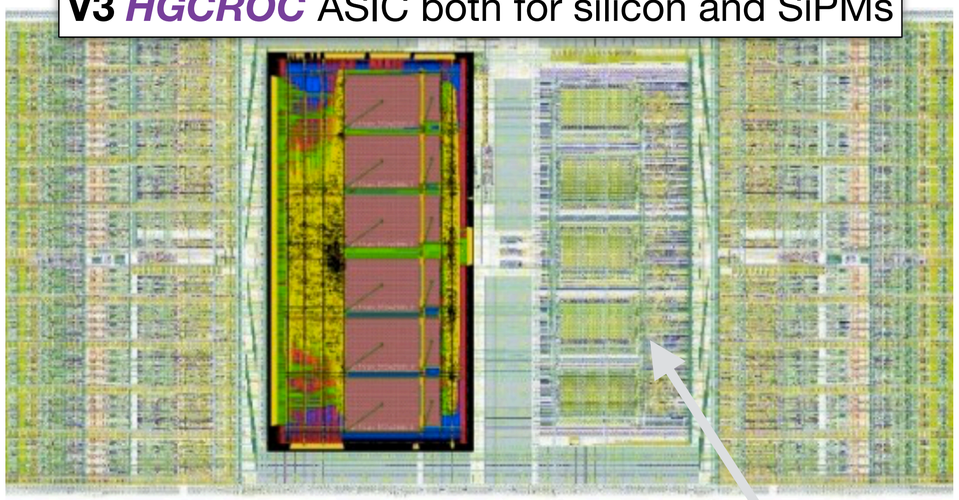


Electronics are challenging

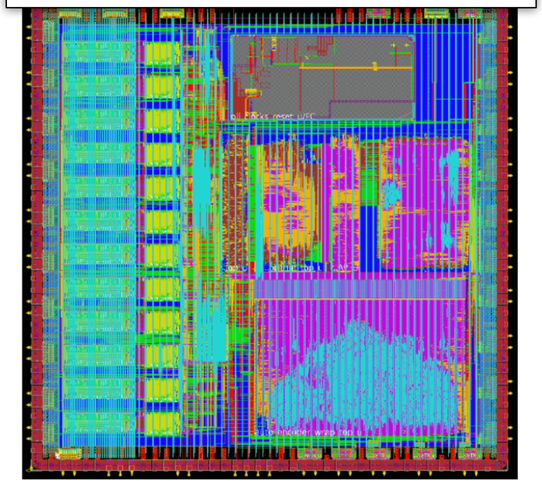
HGCAL FE electronics requirements:

- ✓***Low noise*** (<2500e) and ***high dynamic range*** (0.2fC -10pC).
- ✓Timing information to ***tens of picoseconds***.
- ***Radiation tolerant.***
- ***<20mW*** per channel (cooling limitation).
- ***Zero-suppression*** of data to transmit to DAQ.
- Computation of ***trigger sums*** for L1 trigger.

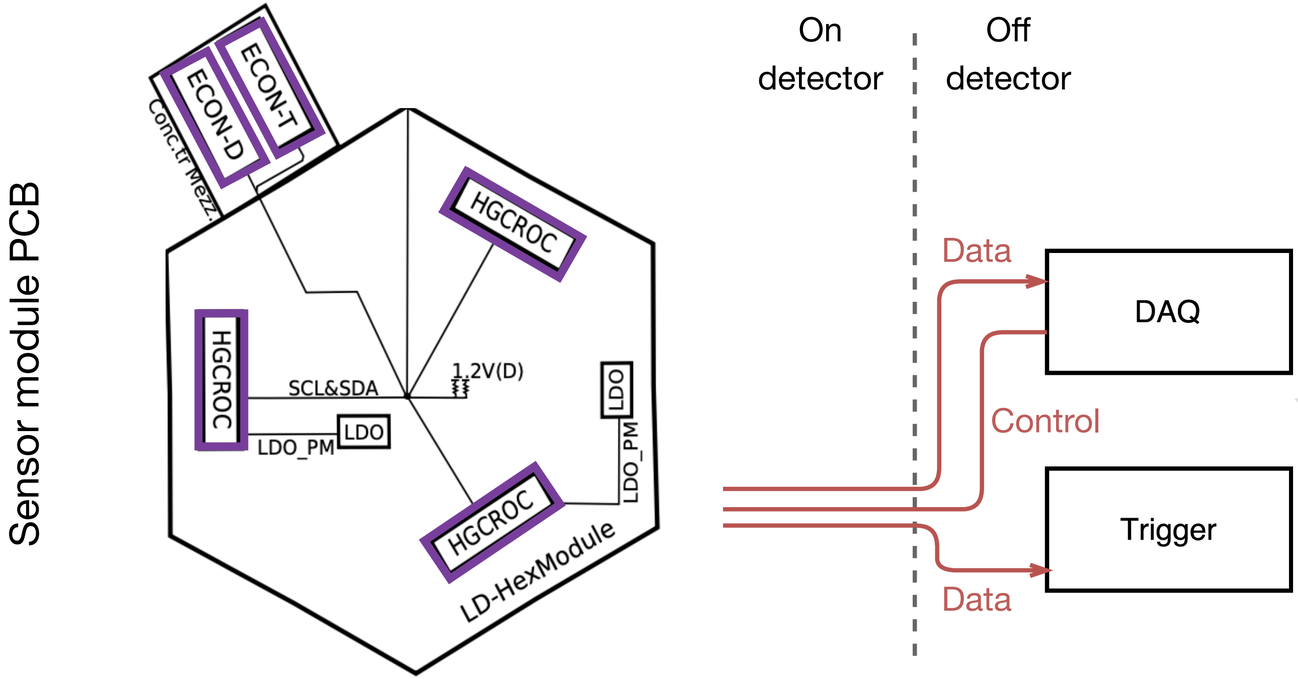
V3 *HGCROC* ASIC both for silicon and SiPMs



ECON as concentrator ASIC



cf. *HGCROC: the front-end readout ASIC for the CMS High Granularity Calorimeter*, Damien Thienpont

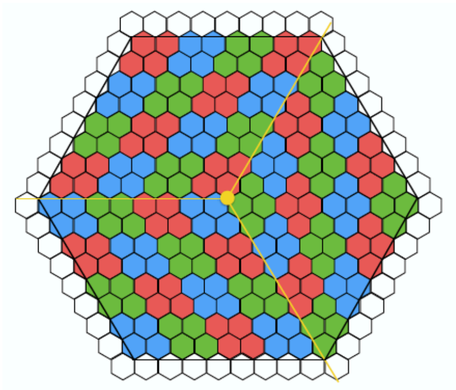


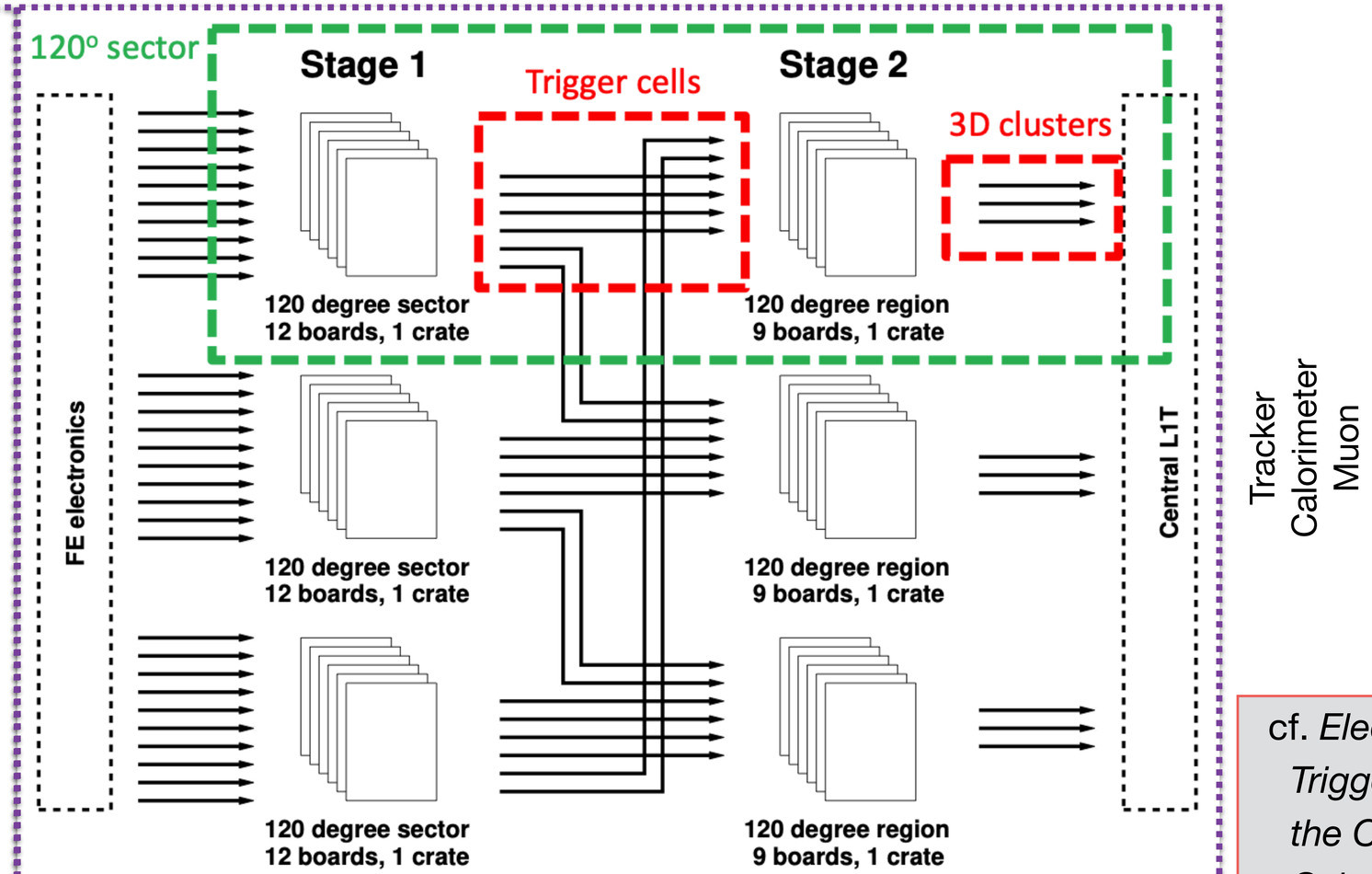
cf. *Electronics and Triggering Challenges for the CMS High-Granularity Calorimeter*, Matthew Noy

HGCAL trigger = 3D clustering

~300 TB/s → **Energy sums (compressed)** → 50 TB/s → **Trigger cells** → 60 TB/s → **3D clusters** → 4 TB/s

On-detector: 1.5μs



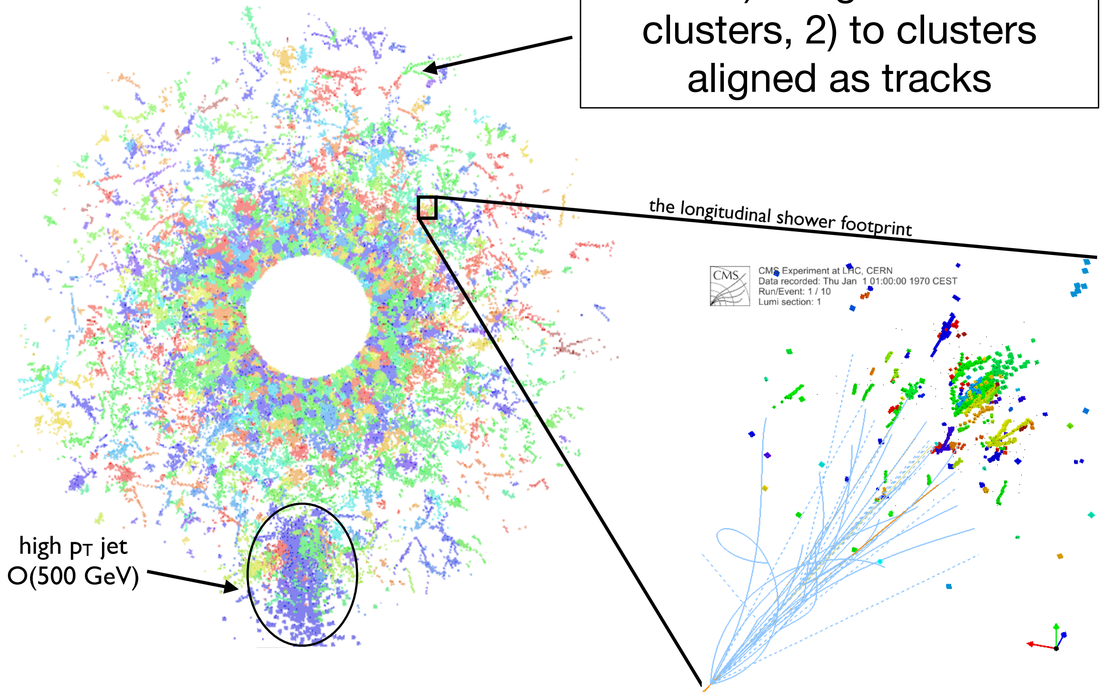


Off-detector: 3.5μs

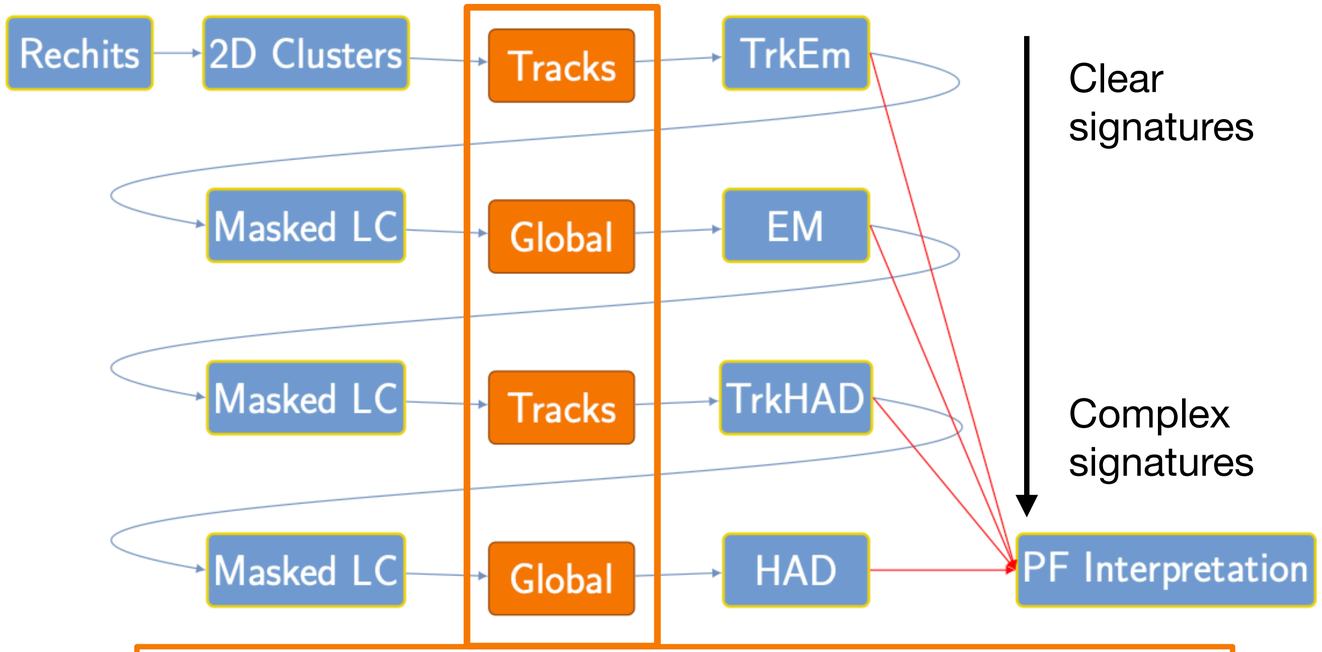
cf. *Electronics and Triggering Challenges for the CMS High-Granularity Calorimeter*, Matthew Noy

Sophisticated offline reconstruction = **T**he **I**terative **CL**ustering

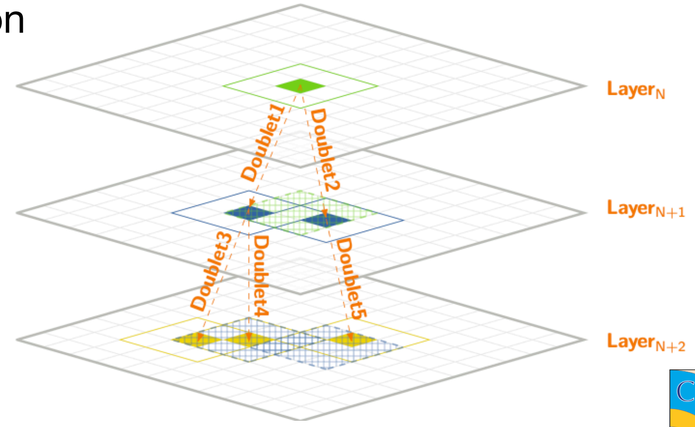
Goal: 1) merge hits to 2D clusters, 2) to clusters aligned as tracks



Iterative strategy: Reconstruct "easy stuff" first and work with what is left



Pattern recognition based on cellular automaton, e.g. doublet-search.



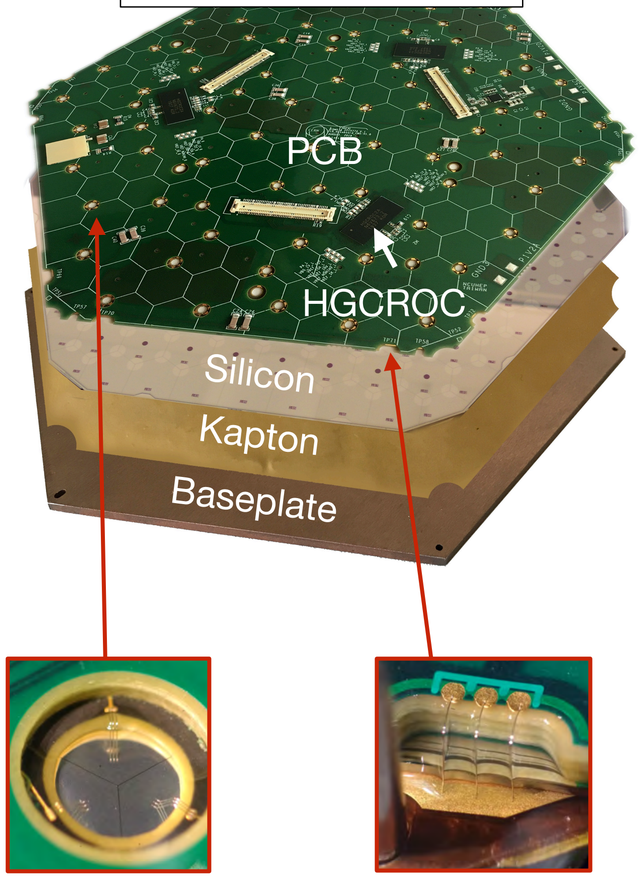
Current TICL highlights

- Modular framework, written in C++.
- Works well with single EM particles, validated with test beam.
- Pattern recognition for hadronic shower to be optimised.
- Competitive to end-to-end machine learning approaches.
- TICL reconstruction on tt+200PU = O(100ms) on CPU, only ~5% of CMS phase 2 reconstruction budget.

cf. vCHEP 2021

Silicon modules and cassettes

8” prototype module



Silicon modules

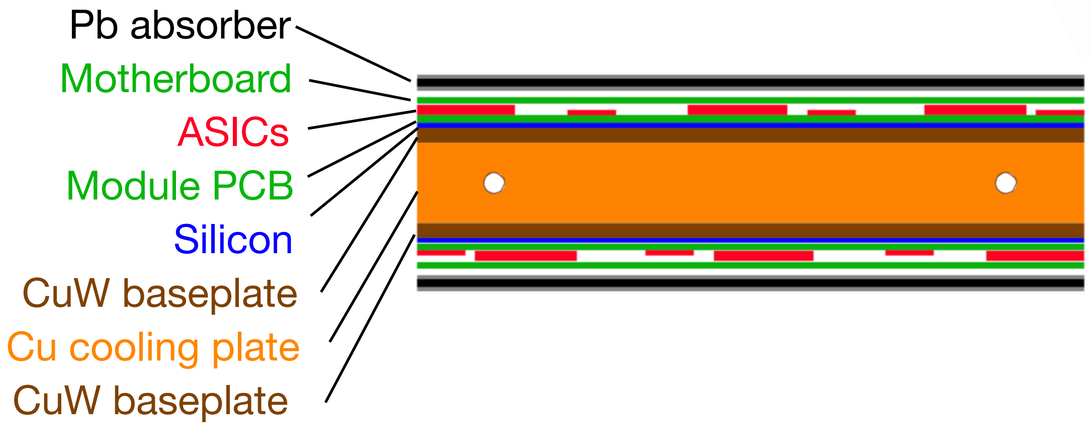
Sandwich of **PCB**, **sensor**, biasing/insulation layer and **baseplate** for rigidity/cooling.

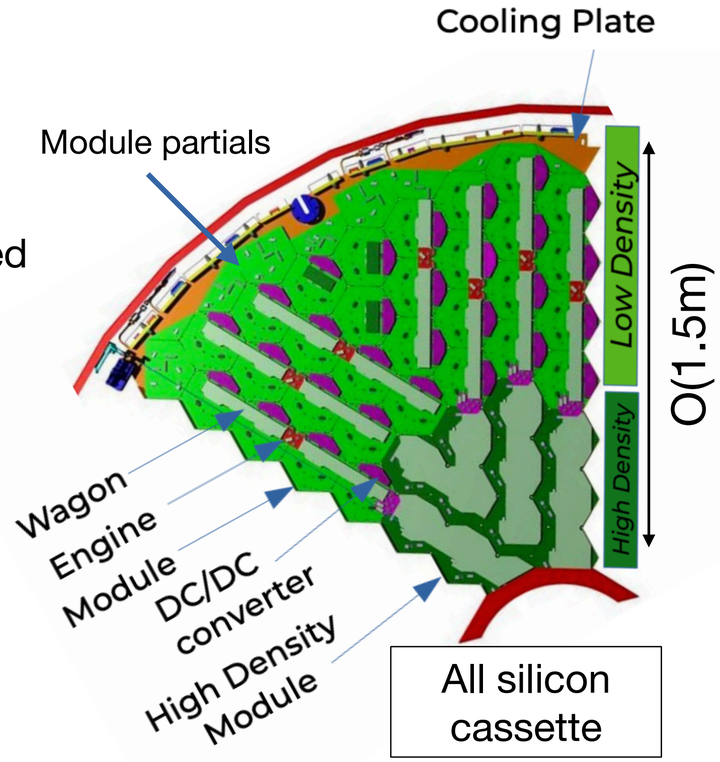
- Wire-bonding from PCB onto the silicon.
- CE-E: CuW baseplates act as absorbers.
- CE-H: PCB baseplates (good thermal properties and cheaper).

CE-E cassettes

Self-supporting sandwich structures (with absorbers).

- Modules placed on both sides of Cu cooling plate and closed with Pb plates.



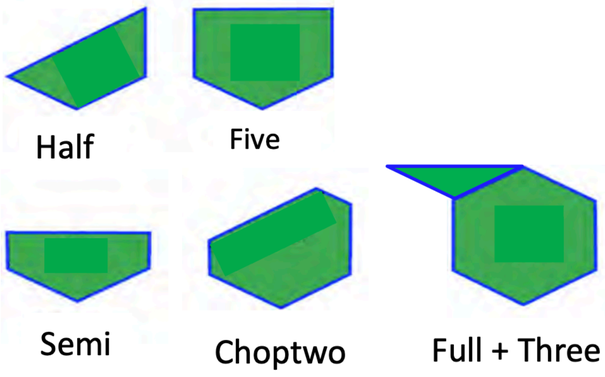


Towards mass production of silicon modules around the world

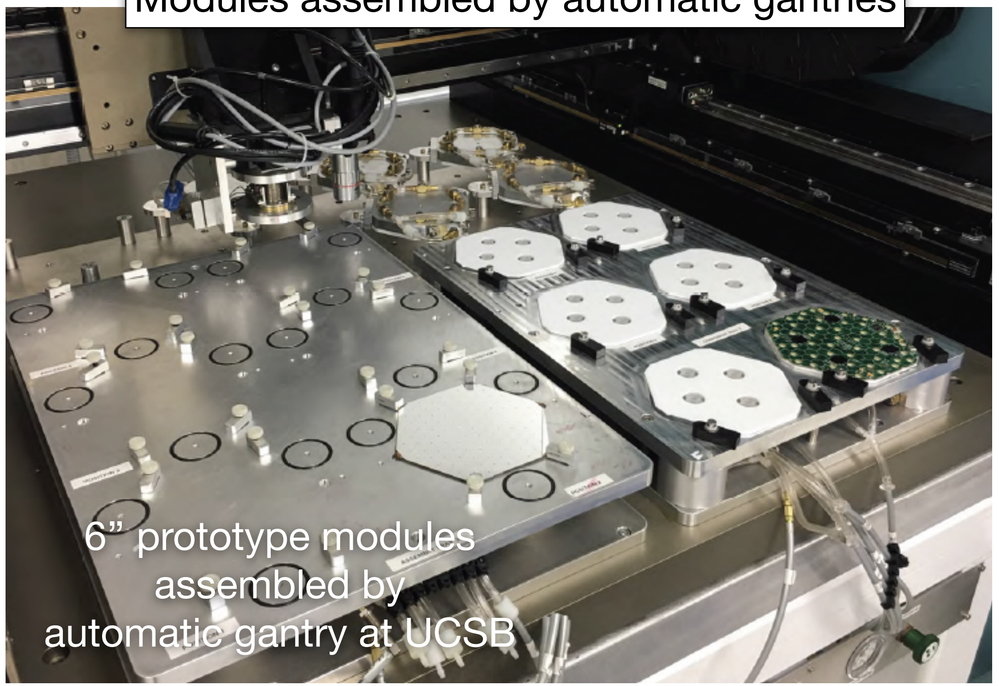
27k silicon modules to be produced

Module Type	300 µm	200 µm	120 µm	Sum
Full	8820	7740	4356	20916
Five	1158	144	0	1302
Choptwo	0	0	312	312
Semi	450	0	312	762
Half	1386	156	84	1626
Full+Three	1092	0	0	1092
Totals	13998	8040	5064	27102

Modules have different shapes



Modules assembled by automatic gantries

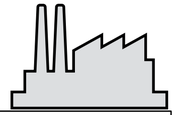


Tooling development and preparation for large scale production:

- ***Tooling*** for low density full modules ***ready***, soon also for high density full module.
- Design of gantry tooling for ***partial modules ramping up*** this year.

Module Assembly Centers (MACs) preparation is well advanced

- All **6** sites progressing on qualification of various module production steps.
- ***5 sites fully equipped*** and on track to be qualified for assembly in 2021.



Production plan

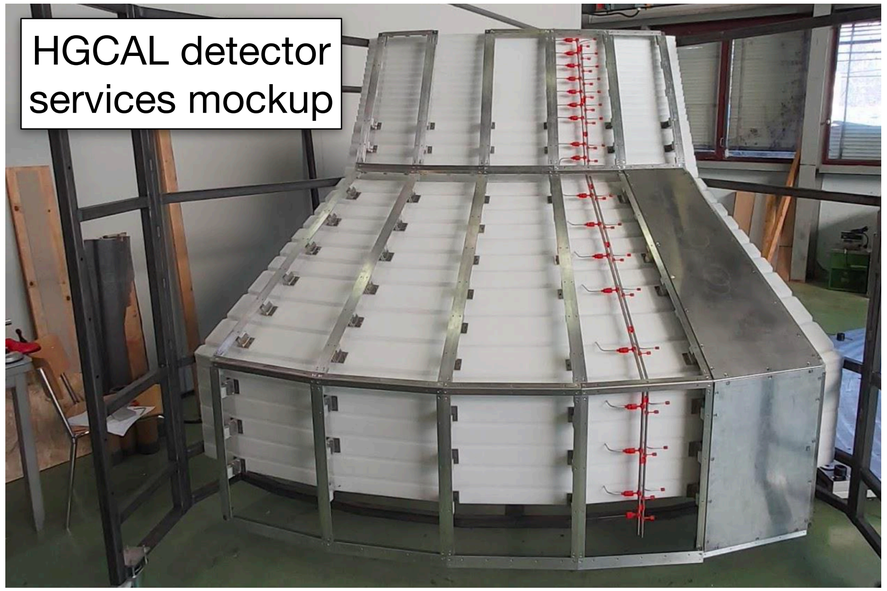
- 10 modules/day per MAC with 6 MACs.
- Could achieve up to 24 modules / day per MAC.

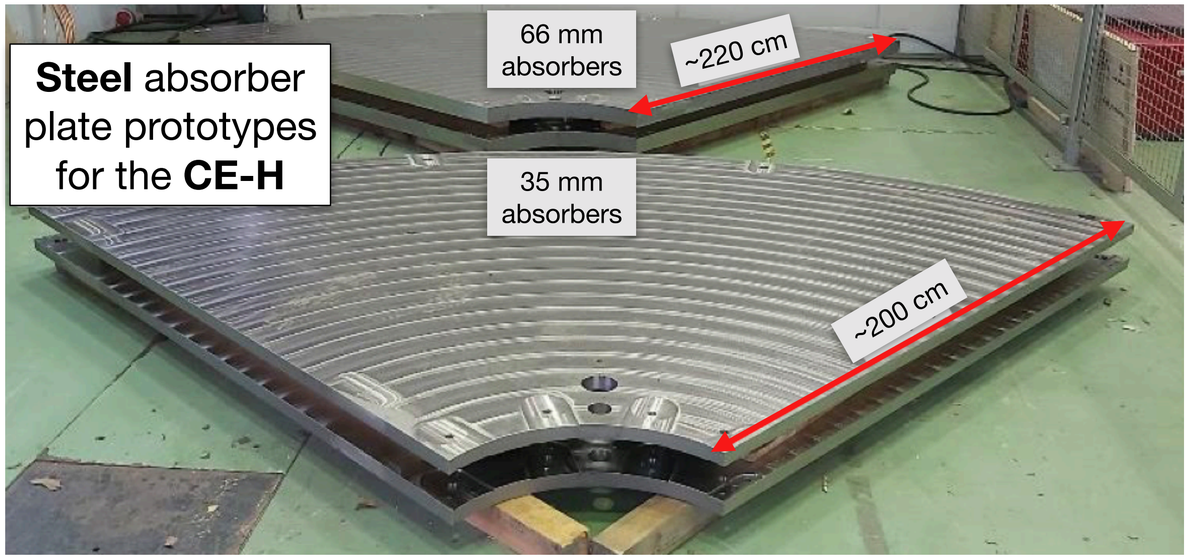
Prototyping of services and passive absorber plates advancing

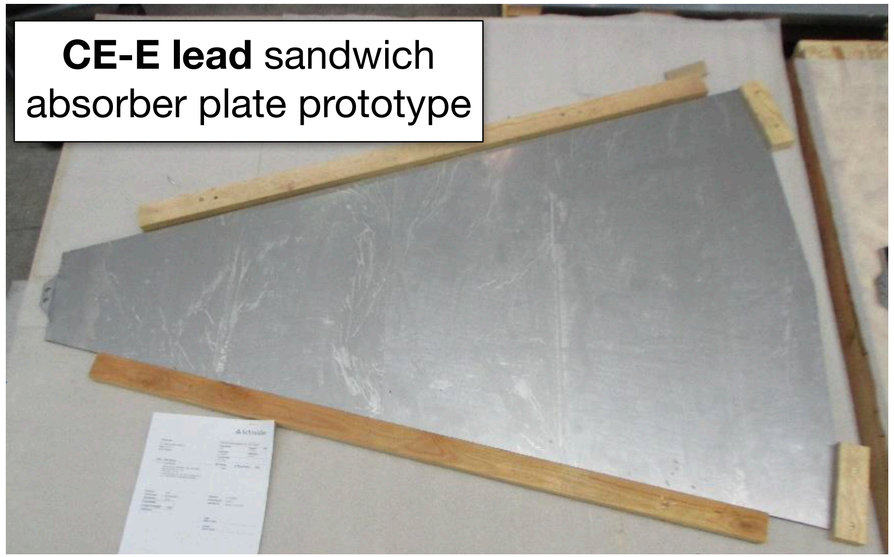
- ***Mockup structures*** to study installation steps and on-detector services locations.

- Procurement process of ***600 tons of stainless steel*** started.
- Achieved ***1 mm flatness*** for CE-H steel absorber plates.

- Lead sandwich absorber development challenging due to relative weakness and low workability.





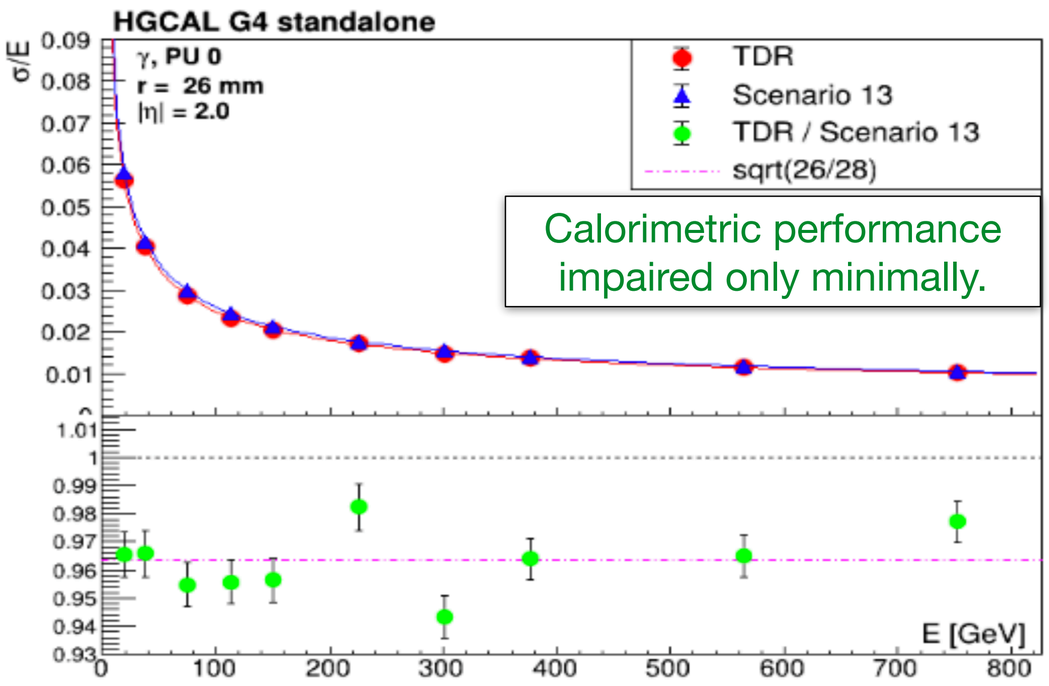


Recent re-optimisation of longitudinal sampling

- Mobile-phone-size front-end embedded in industrial-size absorbers.
  - **Absorber tolerances add up to ~height needed by front-end.**

- Absorber plates must be ordered soon.

➡ **Adapt to realistic absorber tolerances while preserving overall nuclear/radiation depths.**



Calorimetric performance impaired only minimally.

	Dec 2018	New: Scenario 13
# layers in CE-E, sampling layout	28, uniform	**26; last four thickened**
# layers in CE-H (all Si)	8	**7**
# layers in CE-H (mixed)	14	**14**
CE-H: thickness of thin/ thick absorbers	35.0mm / 66.0 mm	**41.5 mm / 60.7 mm**
Depth of CE-E	25.4 X_0	**27.7 X_0**
Total depth	9.85 λ	**9.97 λ**

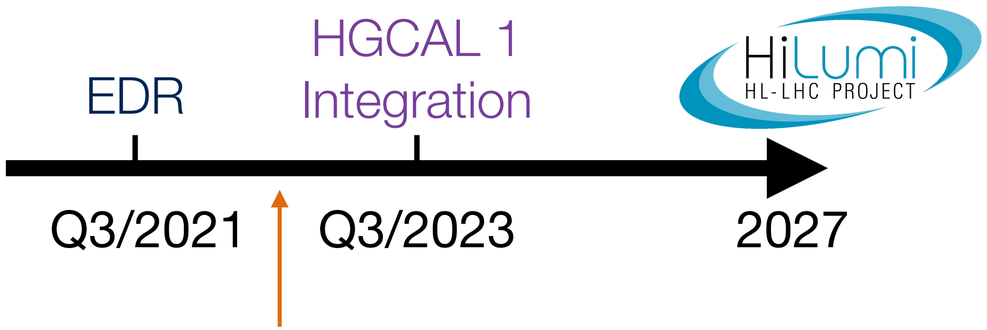
➡ **Number of layers reduced to minimise overall risk with minimal impact of performance.**

HGCAL upgrade project: Outlook

✓ Important progress since the Technical Proposal (2015) and ongoing developments since the Technical Design report (2018).

- Currently, the focus is on:
  - Finalisation of design, prototyping towards final systems.
  - Market surveys, orders.
  - Pre-productions, qualification of final components.

- Next major step: **Engineering Design Review due at the end of this year**

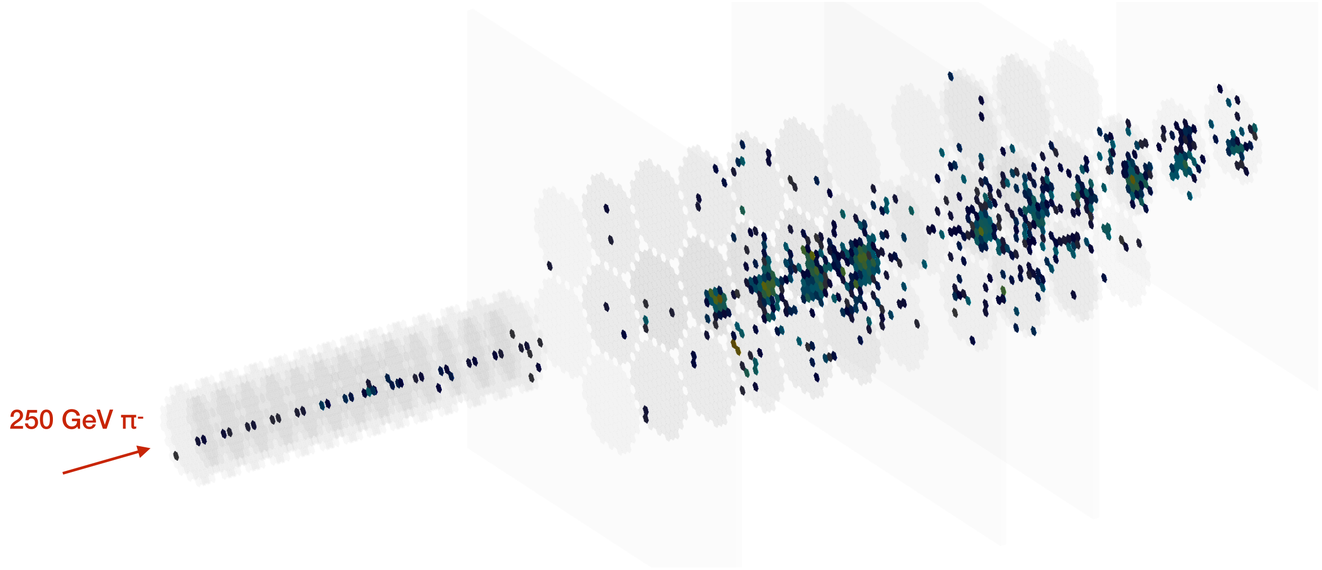


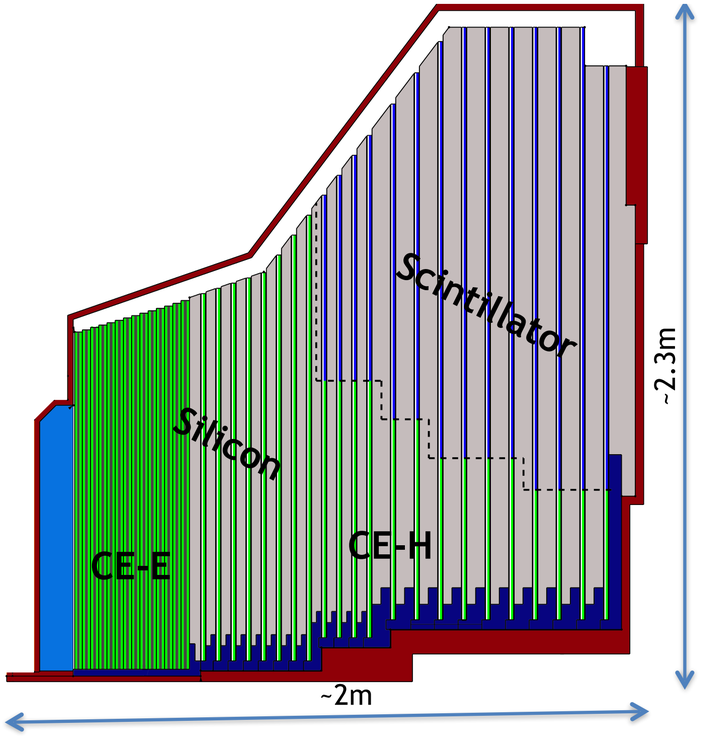
- **Production starting in 2022.**

Summary - not a conclusion

HGCAL: where highly granular calorimetry comes to life at the energy frontier

- Silicon as sensitive material in high radiation region, scintillator+SiPMs elsewhere.
- 3D energy & time measurement of particle showers.





Moving towards fully-engineered design in 2021

- e.g. silicon sensors close to being qualified.
- e.g. preparation for mass production of active modules. Prototyping of passive absorber plates.
- e.g. recent optimisation of longitudinal sampling to relax mechanical tolerances for metal plates and for air gaps.

Backup

CMS endcap calorimeter upgrade proposal

CALICE - inspired idea

An all-new 'imaging' calorimeter with unprecedented readout granularity that offers robustness and good performance through the full HL-LHC operational lifetime.

Requirements

Radiation tolerance

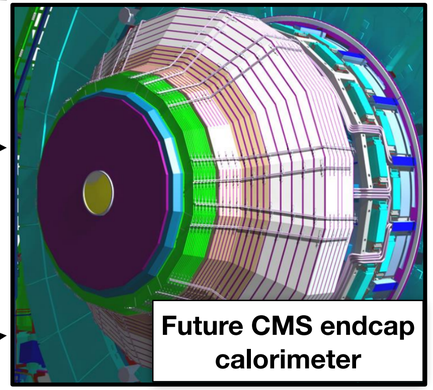
fully preserving the energy resolution after 3000 fb^{-1}

Dense calorimeter

preserve lateral compactness of showers

Fine lateral granularity

two shower separation + observation of narrow jets, minimise pileup contributions in energy & timing measurements



Fine longitudinal granularity

fine sampling of the shower: good energy resolution, pattern recognition, pile-up discrimination, …

Precision time measurement

high energy showers for pile-up rejection, primary vertex identification

Contribute to L1 (Hardware) trigger

~370m² of scintillator for regions of lower radiation

- ***Cheaper*** than silicon.

- Rely on experience from CALICE and past CMS HCAL upgrade.

➡Radiation hardness of scintillators & Si-PMs well understood.

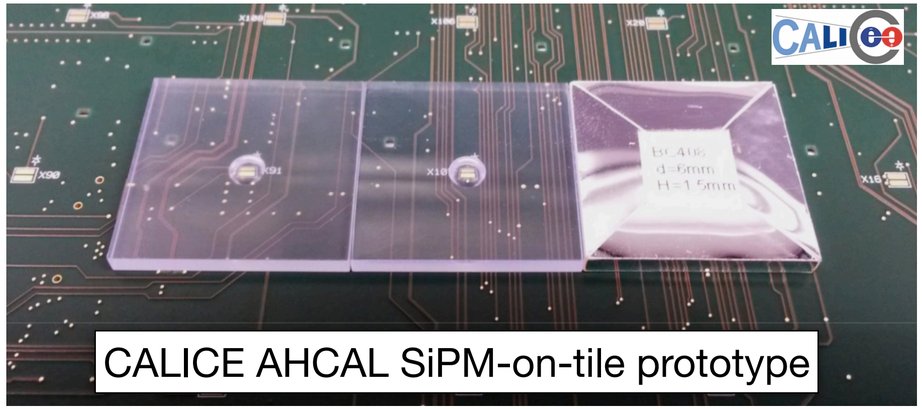
➡Overall ***S/N for MIP*** remains ***> 5*** after 3000 fb^{-1}.

SiPM-on-tile design

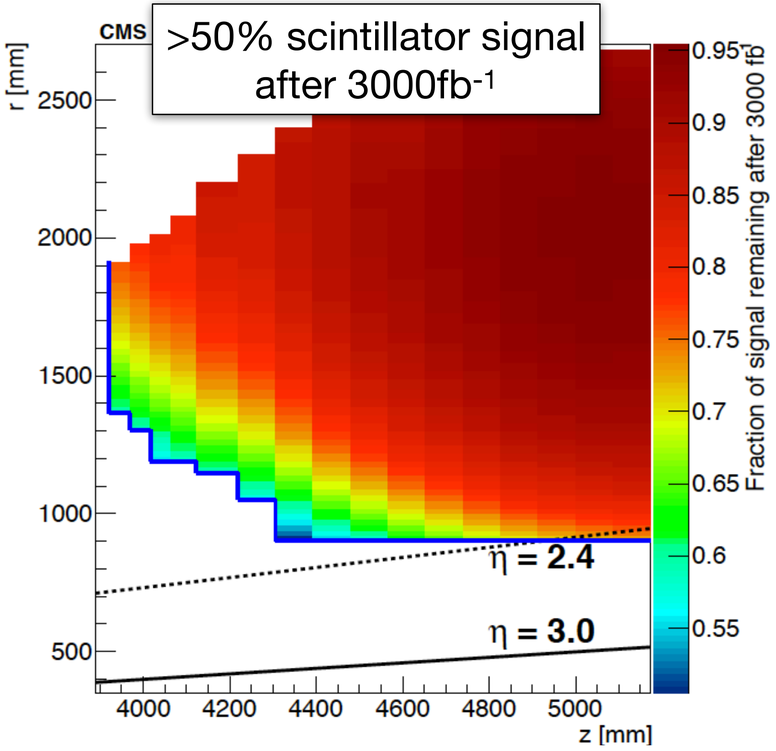
- 240k SiPMs integrated into the PCB, need to be cooled.
- Light ***readout*** directly on ***detector***.
- More compact and cost-effective.

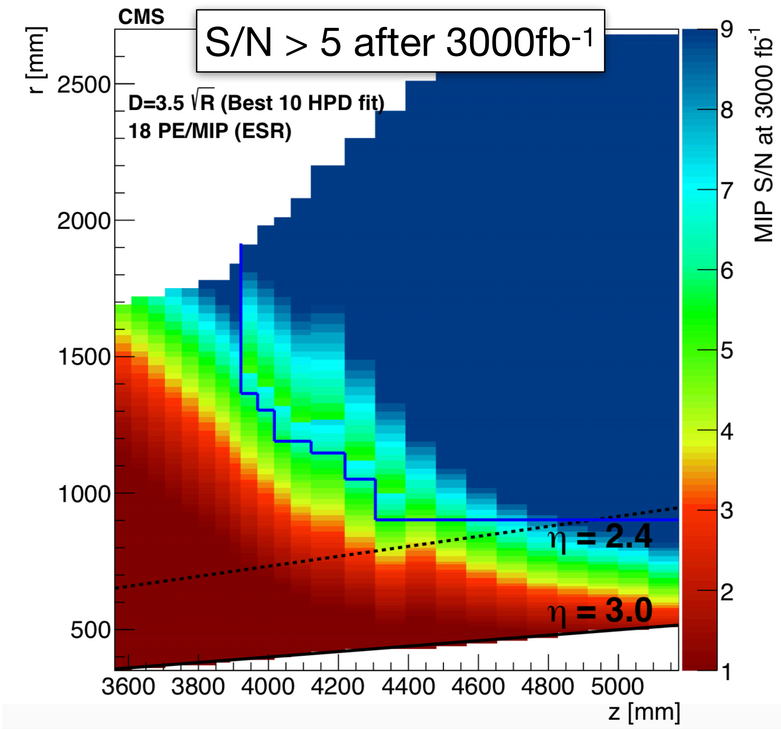
Ongoing R&D

- e.g. validate interplay SiPM - ROC.
- e.g. tile geometry and wrapping optimisation.
- …



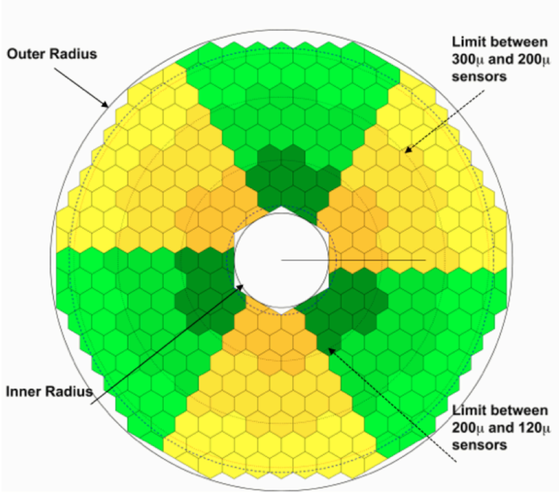
CALICE AHCAL SiPM-on-tile prototype

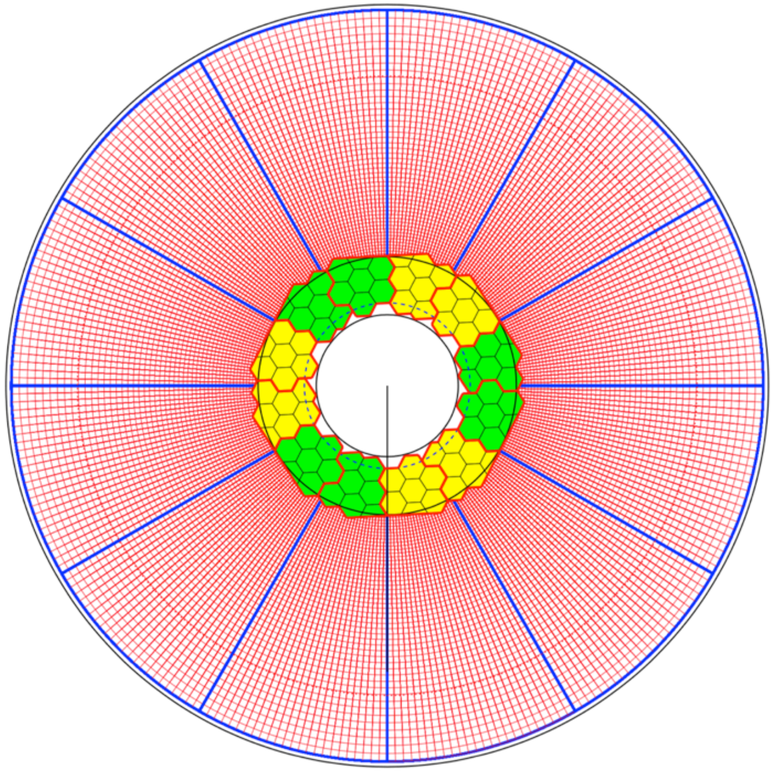




Arrangement of active modules

Silicon-only layer (in CE-E) showing “cassettes” and different sensor thicknesses.

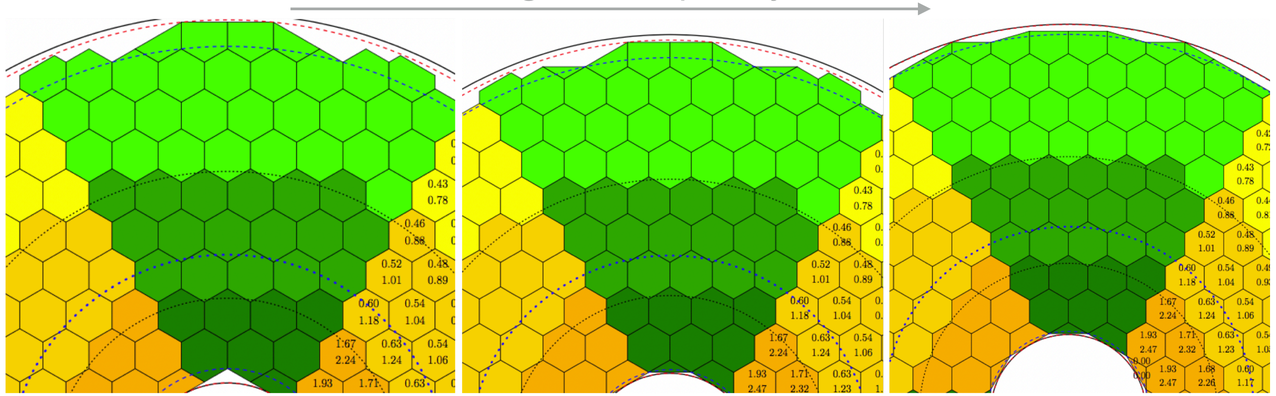




Mixed layer (in CE-H) with silicon at high η and scintillator+SiPM at low η.

Inner/Outer coverage:
Best coverage by O(10) variants of hexagonal modules.

coverage & complexity

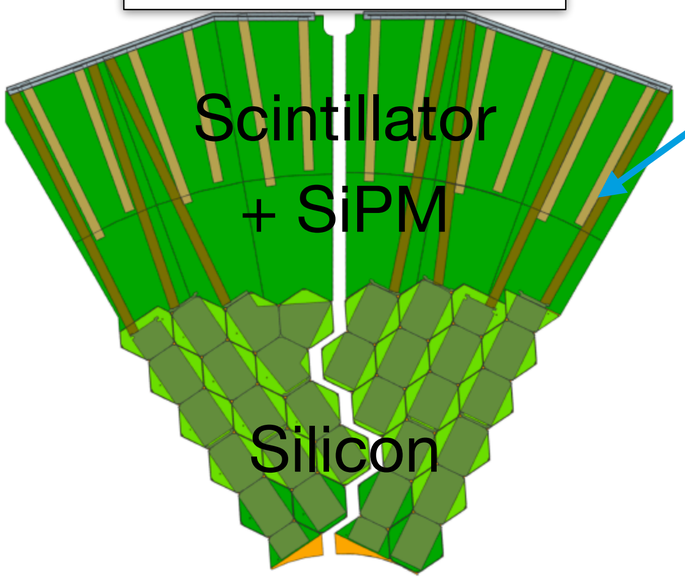


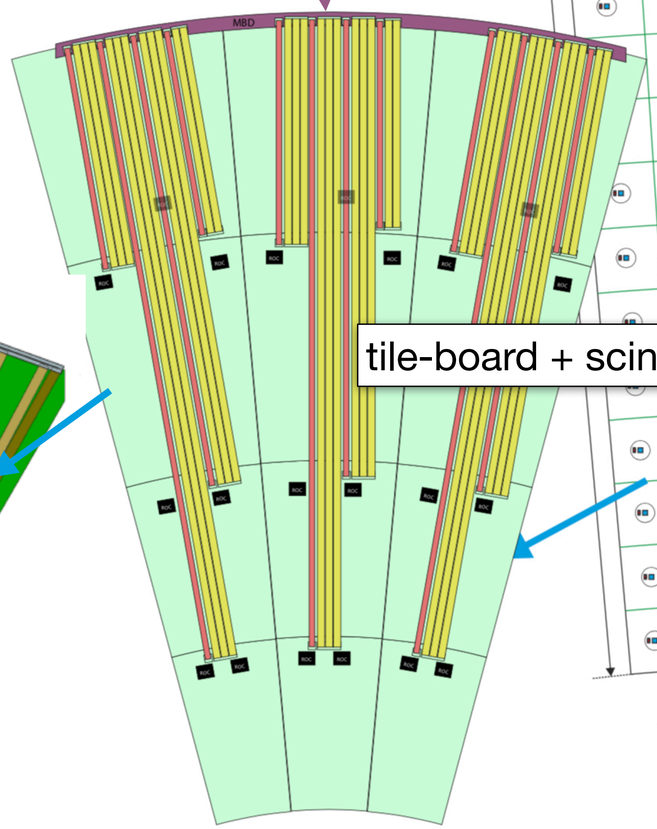
HGCAL tile-modules

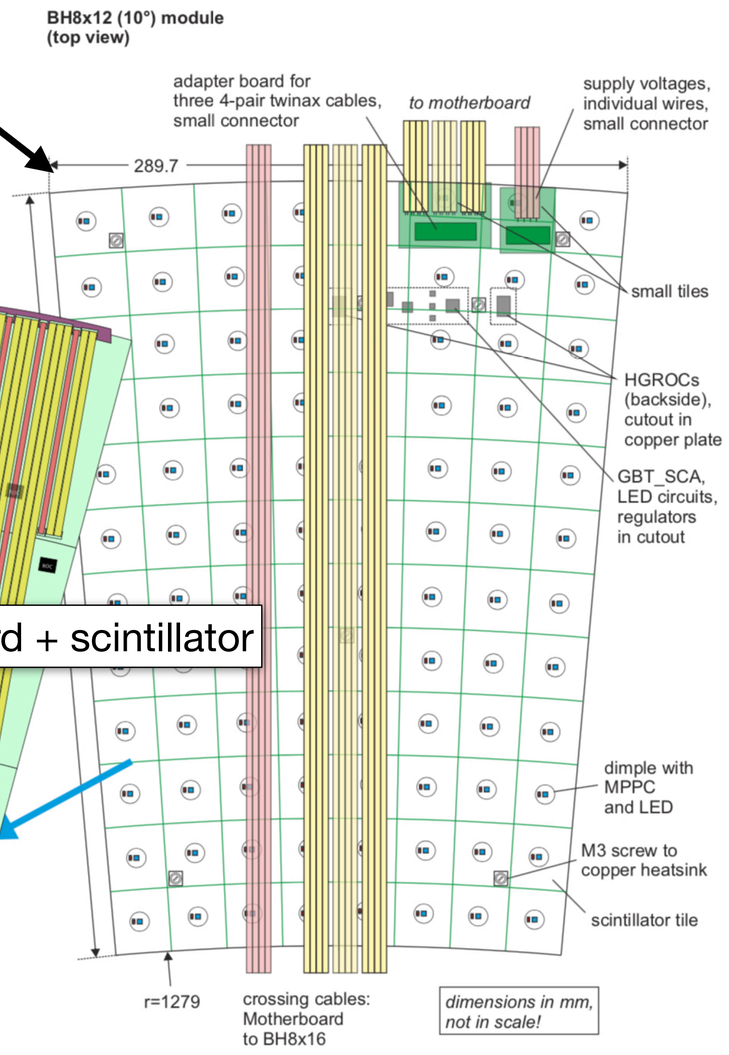
Tileboards

- Holds SiPMs, HGROCs, LEDs, …
- Complex layout.
- *Good:* alive and sending data.
- Ongoing R&D: tile-board characterisation (electronically, thermo-mechanically).
-

Arranging scintillator tiles in r-ϕ grid with constant azimuthal angle: 4 - 32 cm² area / tile





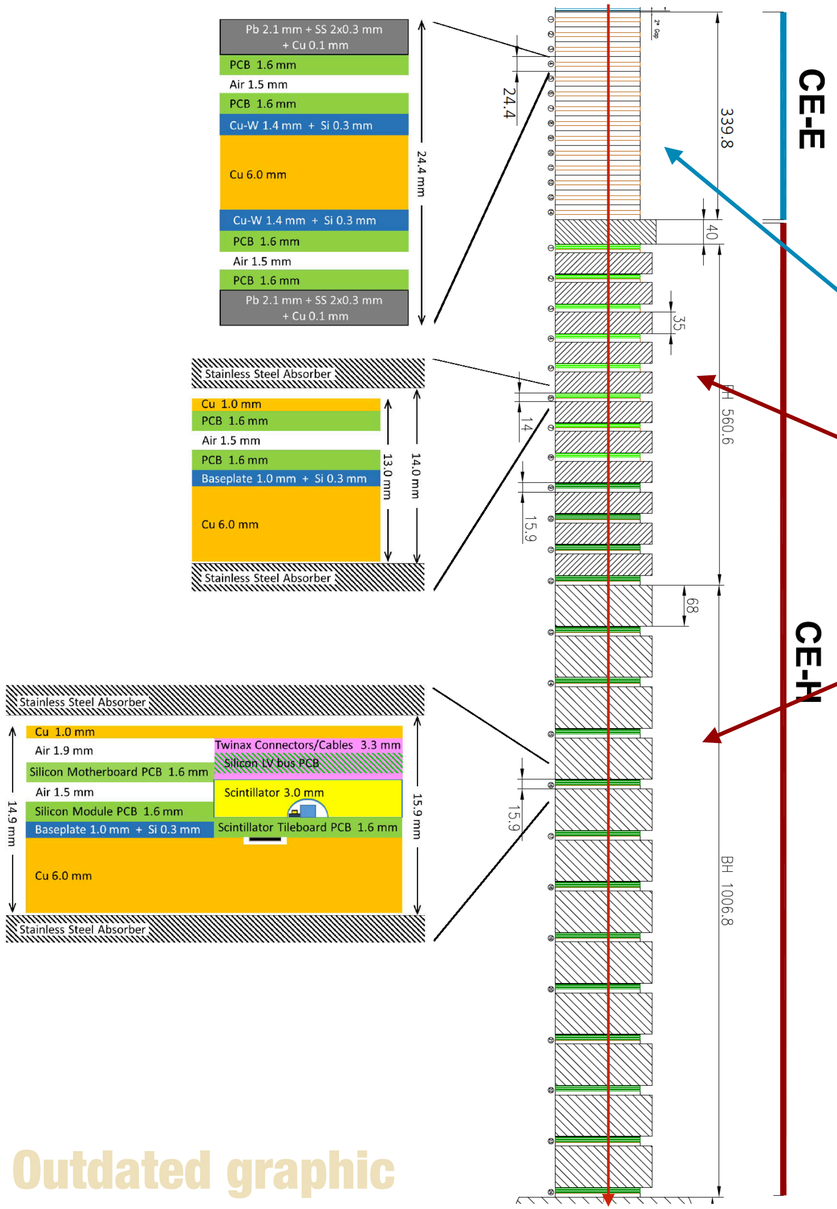


zoom out ⟷ zoom in

Technical challenges

- High-speed data transfer.
- Cooling of SiPMs through PCB.
- Thermo-mechanical rigidity +/- 40 °C.
- Radiation hardness.

Longitudinal structure and lateral coverage



Outdated graphic

Longitudinal sampling

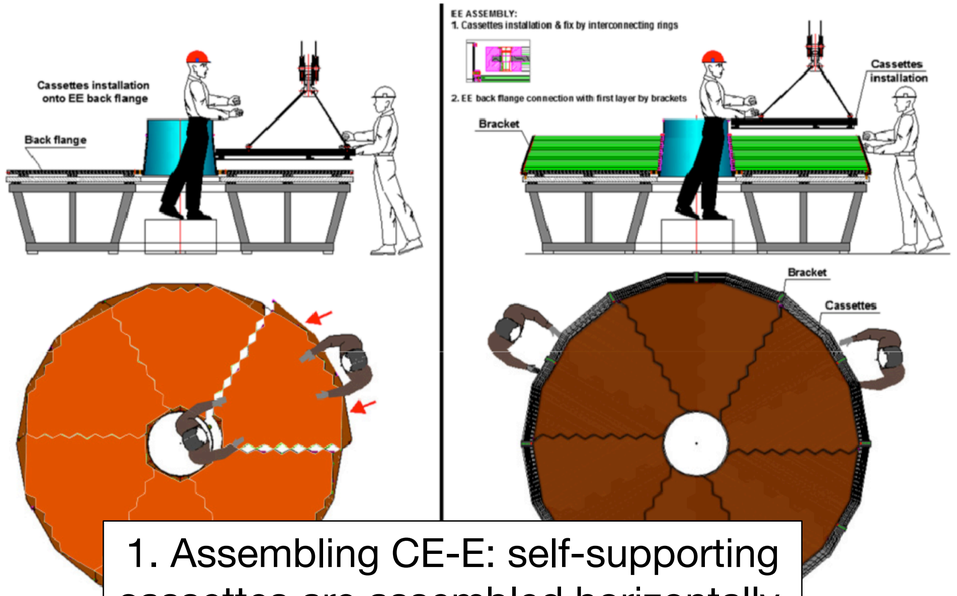
50 layers for total depth of ~9.8 λ

- CE-E: 28 fine samplings for 25 X_0 / 1.3 λ
- CE-H (1): 12 samplings in the first ~3.5 λ
- CE-H (2): 10 samplings in the last ~5 λ

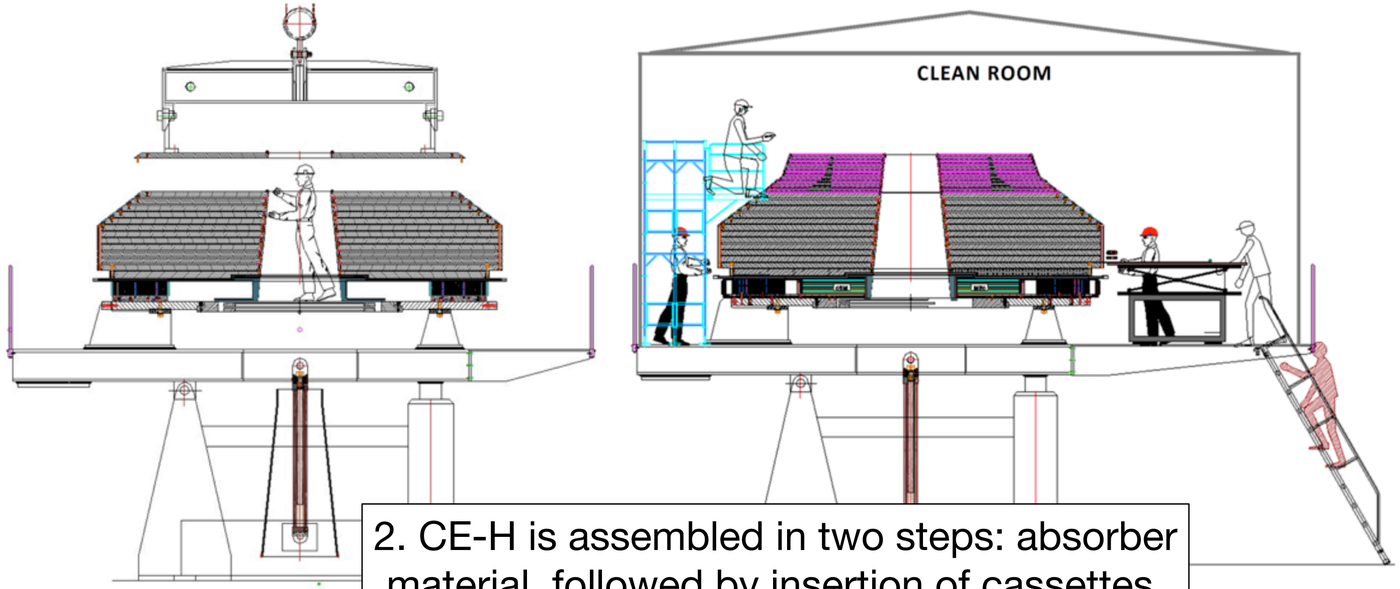
Main constraint: fit into existing detector endcap —> limited space.

- e.g. air gap in CE-E: limited space, very difficult for electrical components and connectors.

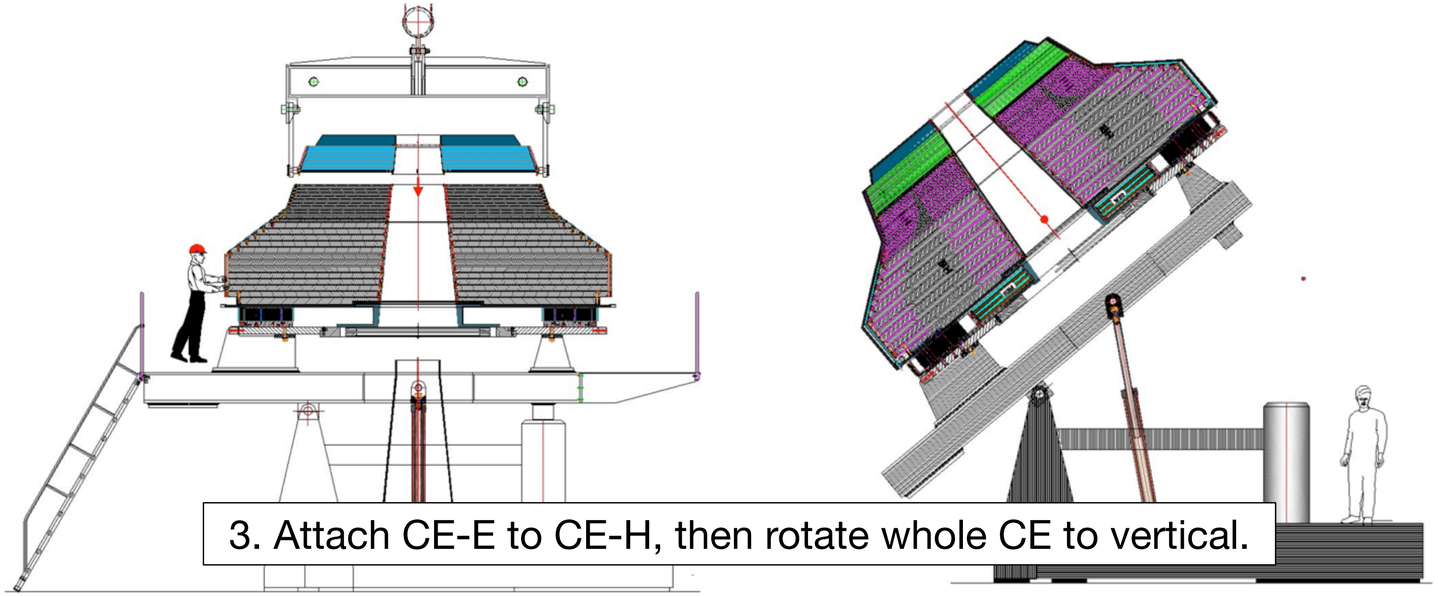
Planned calorimeter construction (x2)



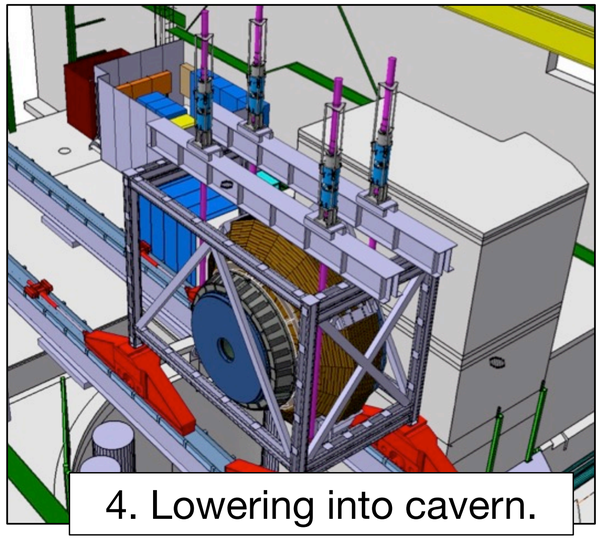
1. Assembling CE-E: self-supporting cassettes are assembled horizontally.



2. CE-H is assembled in two steps: absorber material, followed by insertion of cassettes.

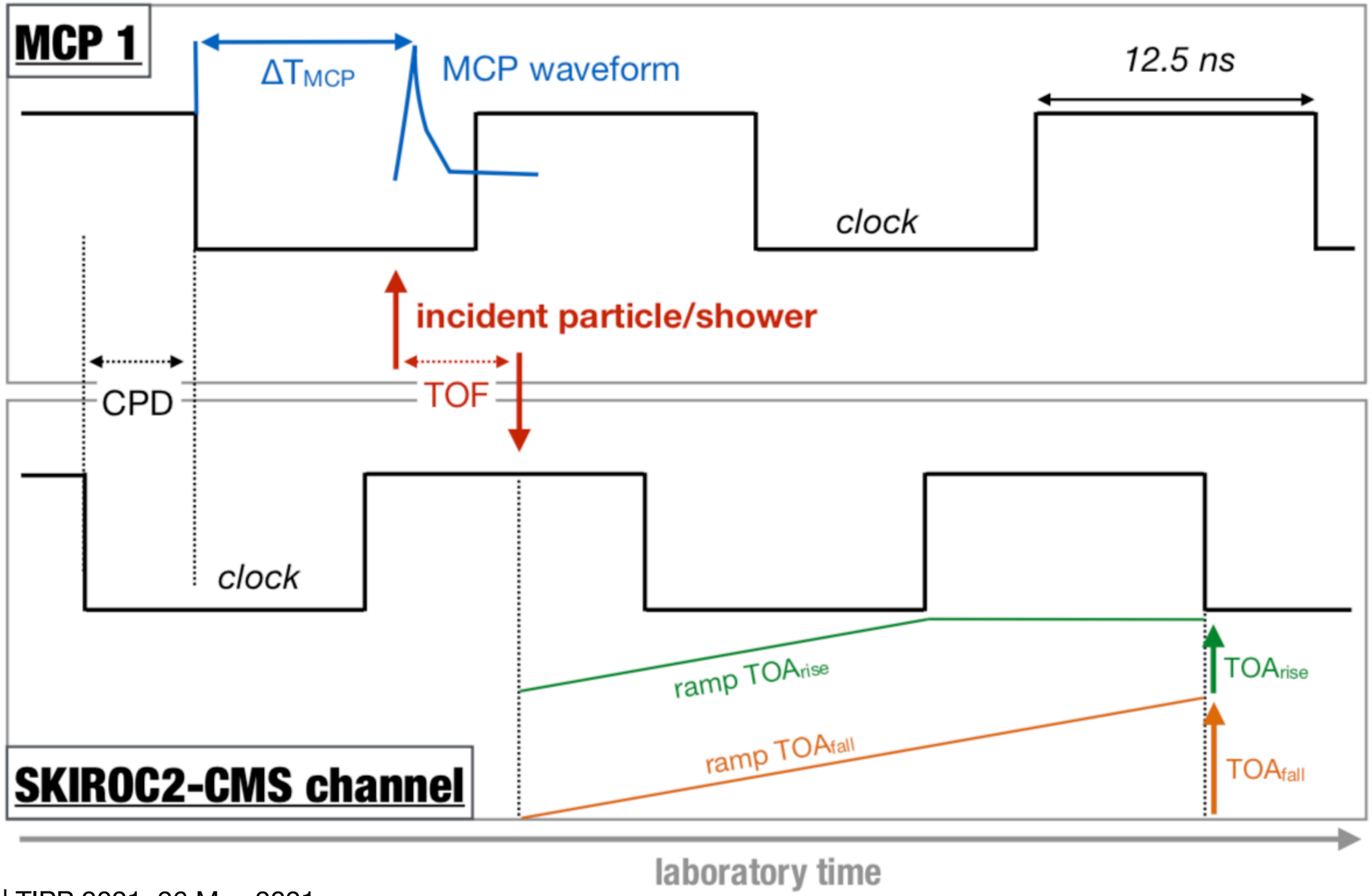


3. Attach CE-E to CE-H, then rotate whole CE to vertical.



4. Lowering into cavern.

Principle of the timing measurements in test beam



AHCAL + HGCAL prototype: Joint data taking October 2018

October 2018 run 517 - event 30:

250 GeV π^-