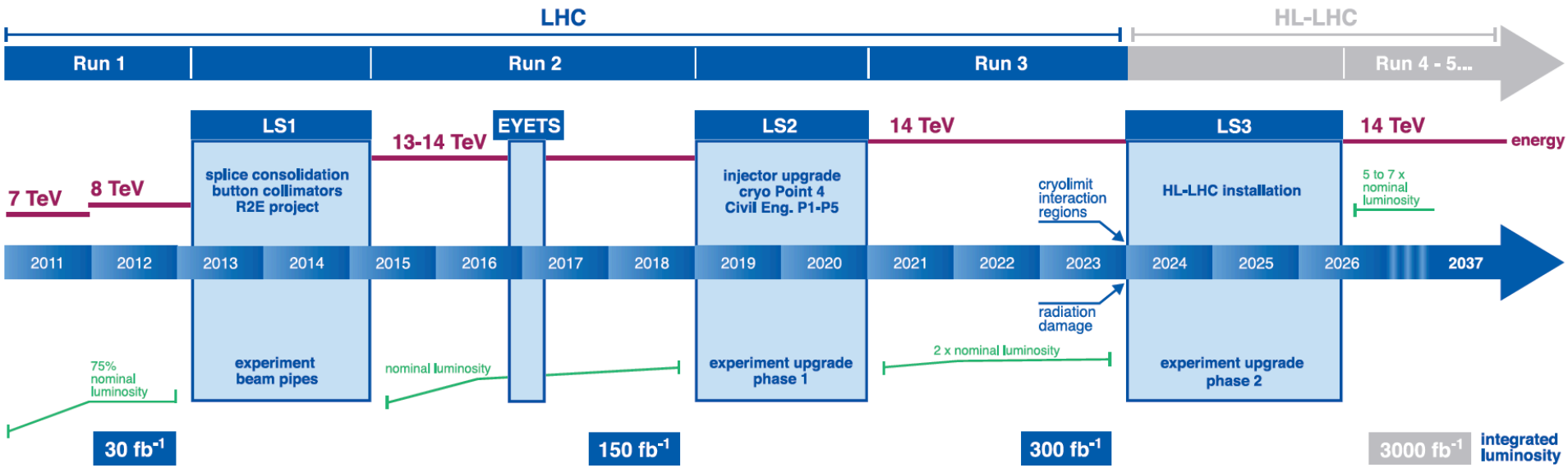
The CMS High-Granularity Calorimeter (HGCAL) upgrade project for HL-LHC

CEPC Workshop, Rome, 23-25 May, David Barney (CERN)

Motivation for upgrading CMS endcap calorimeters for HL-LHC

Luminosity provided by HL-LHC opens new doorways to physics



HL-LHC: levelled $\mathcal{L}$ = **5x10^{34}cm^{-2}s^{-1} and pileup 140**, with potential for 50% higher $\mathcal{L}$ & pileup

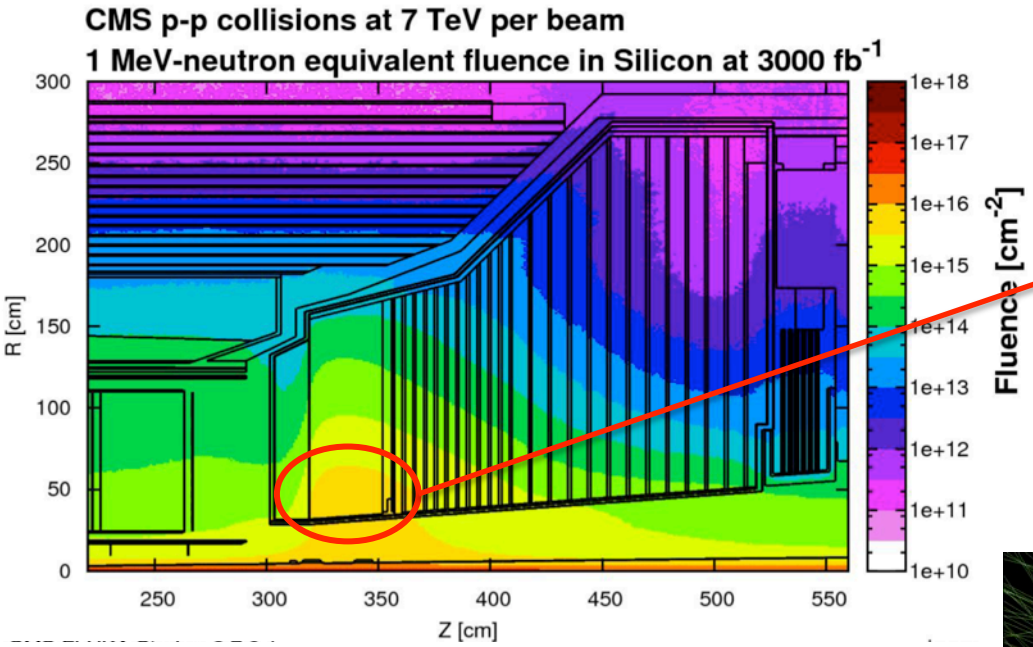
Physics reach will include SM & Higgs, with searches for BSM including reactions initiated by Vector Boson Fusion (**VBF**) and including **highly-boosted objects**

→ Narrow (τ) jets or merged (hadronic decays of W, Z) jets

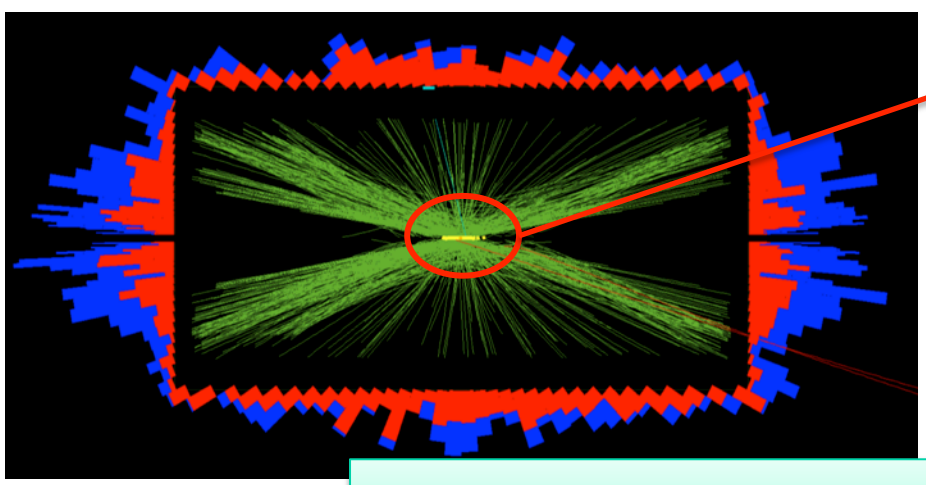
→ Ideally **want to trigger on these narrow VBF & merged jets**

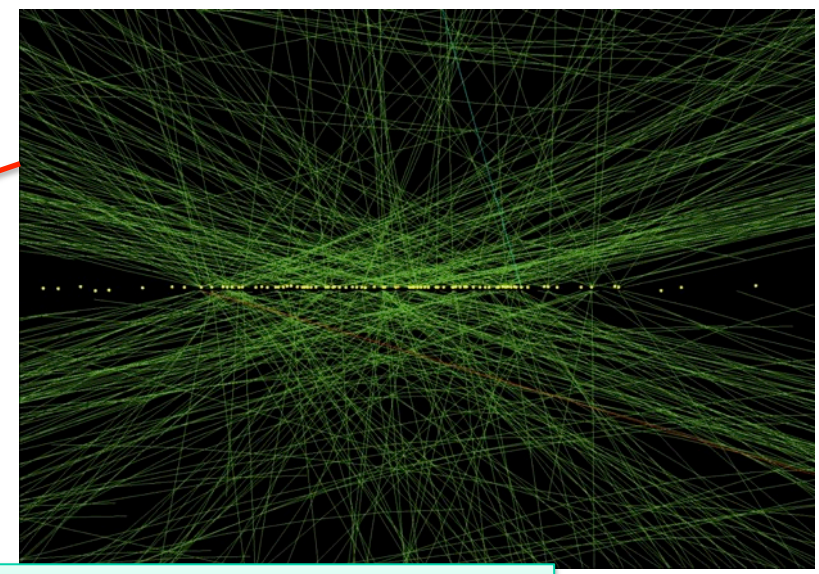
Good **jet identification and measurement**: crucial for HL-LHC

Existing CMS endcap calorimeters cannot cope with the expected radiation or pileup @ HL-LHC



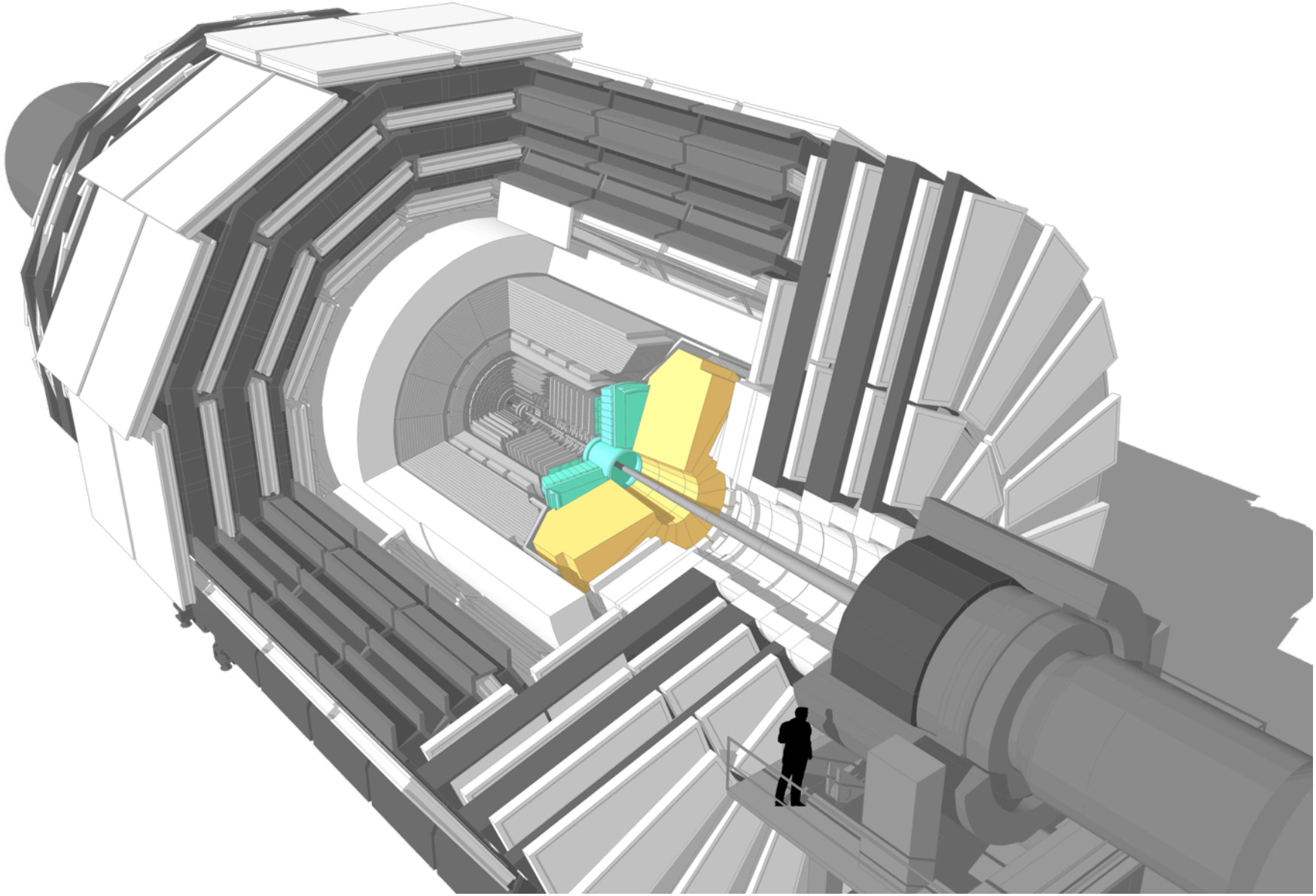
CMS @ HL-LHC:
~**1x10^{16}** 1 MeV n_{eq} cm^{-2} @ 3ab^{-1} and up to **2 MGy** absorbed dose in endcap calorimeters





78 pileup events in 2012. Expect **140-200 @ HL-LHC**

CMS will replace its endcap calorimeters for HL-LHC: the High Granularity Calorimeter



Replacement calorimeter must be radiation tolerant and able to deal with the expected pileup

At the same time, benefit from recent advances in technology to improve overall detector performance

One of the biggest challenges: improve jet energy resolution

Two main approaches for improving jet energy resolution

Substantial improvement of the energy resolution of hadronic calorimeters for single hadrons:

dual (or triple) readout, e.g. DREAM

- Cerenkov light for relativistic (EM) component
- Scintillation light for non-relativistic (hadronic)

Precise reconstruction of each particle within the jet
→ reduction of HCAL resolution impact:

particle flow algorithms and imaging calorimeters

e.g. **CALICE detectors for linear colliders (CLIC, ILC), CMS HGCAL**

Both techniques aim at separating charged/neutral & electromagnetic/hadronic components

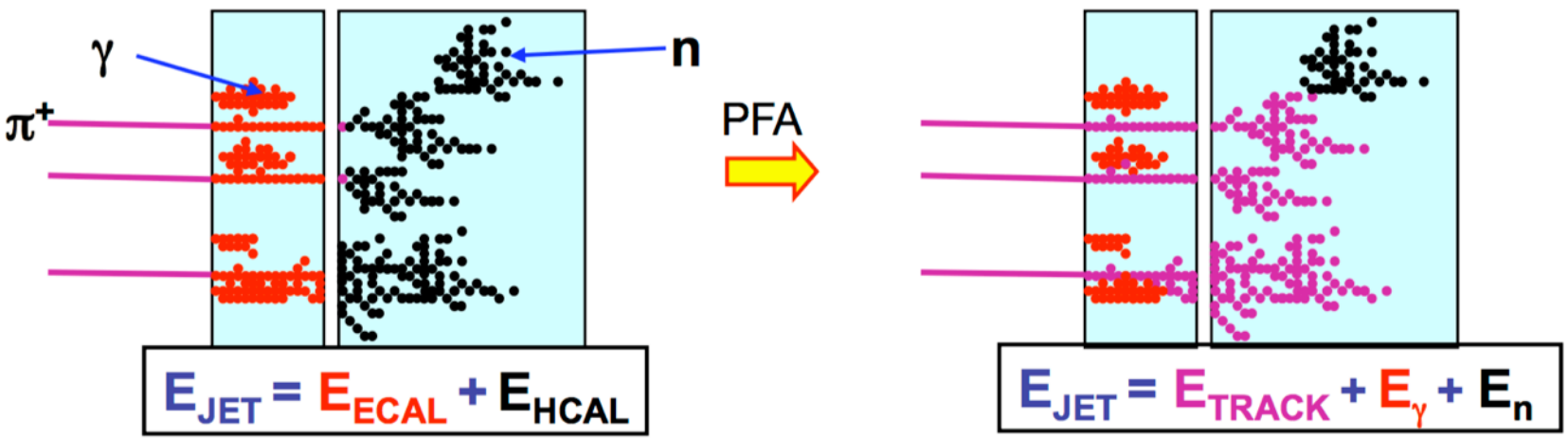
Particle flow technique: make best use of all detectors to measure jet energies

Idea: for each individual particle in a jet, use detector with best energy/momentum resolution

Charged tracks = Tracker

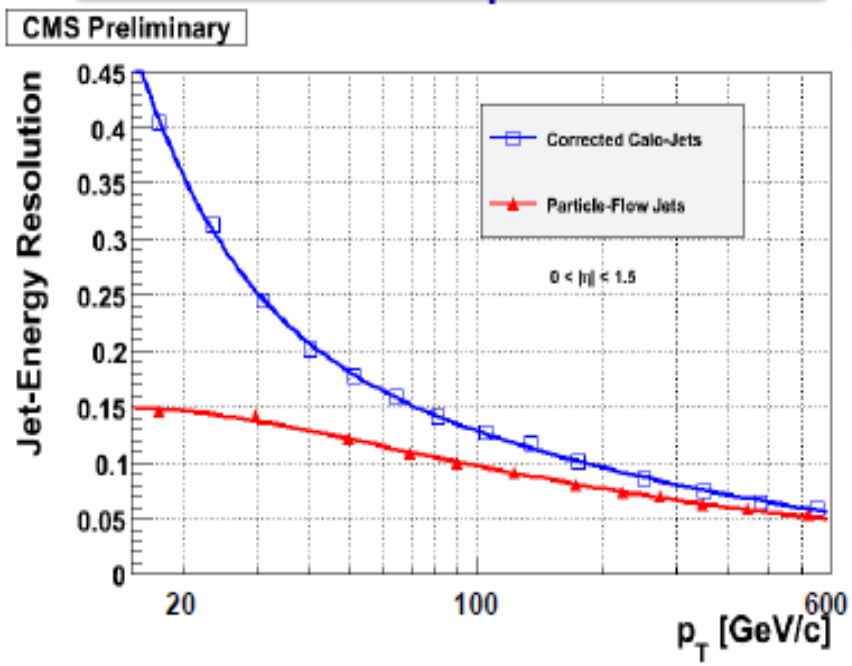
e/photons = ECAL

Neutral hadrons (only 10%) = HCAL

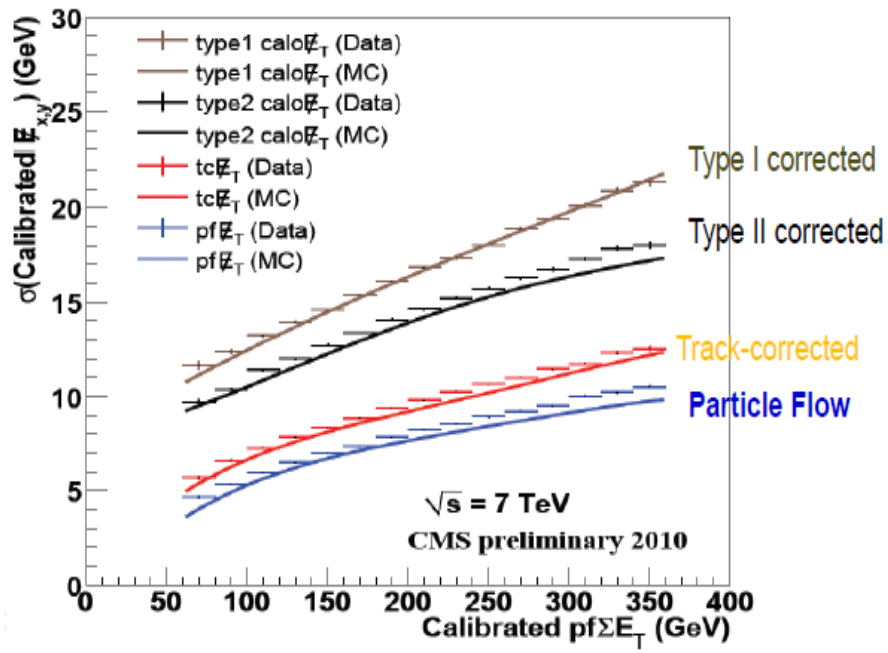


Particle flow already used in Aleph, Delphi & CMS (all had/have relatively low resolution HCALs)

Simulation: jet energy resolution



Data: Missing energy resolution

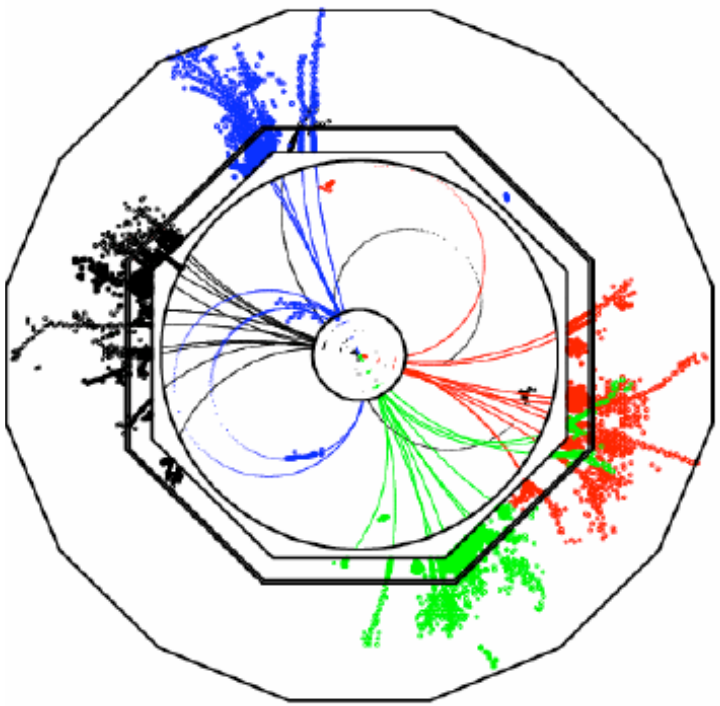


Measurement of jets in **CMS** is **enhanced greatly** by the use of particle flow techniques

For best results: high granularity in 3D – separation of individual particle showers

For a Particle-Flow Calorimeter:

- **Granularity** is more important than energy resolution
- Lateral granularity should be **below Molière radius** in ECAL and HCAL
- In particular in the ECAL: small Molière radius to provide **good two-shower separation** (particularly in high pileup environment)
  → dense absorbers and thin sensors
- **Sophisticated software** needed!



The CMS HGCAL design & prototyping

Overall design of HGCAL driven by need for radiation-hard segmented sensors

To realise a high-granularity calorimeter, we need:
low cost/area active material(s), radiation-tolerant on-detector electronics, high-bandwidth data transmission, powerful FPGAs for off-detector electronics

↓

Look for proven and adequately radiation-hard active materials
To build a dense e.m./hadronic calorimeter with a good energy resolution (for relevant e/γ energies in the endcaps), small R_M, good two-shower separation (e.m. and hadronic), with high lateral and longitudinal readout granularity

↓

A silicon-sensor-based sampling calorimeter
(absorber materials – W, Pb, Cu, Stainless Steel)
followed by **plastic scintillator tiles with direct SiPM readout**
for the lower radiation level region
(absorber materials Cu & SS)

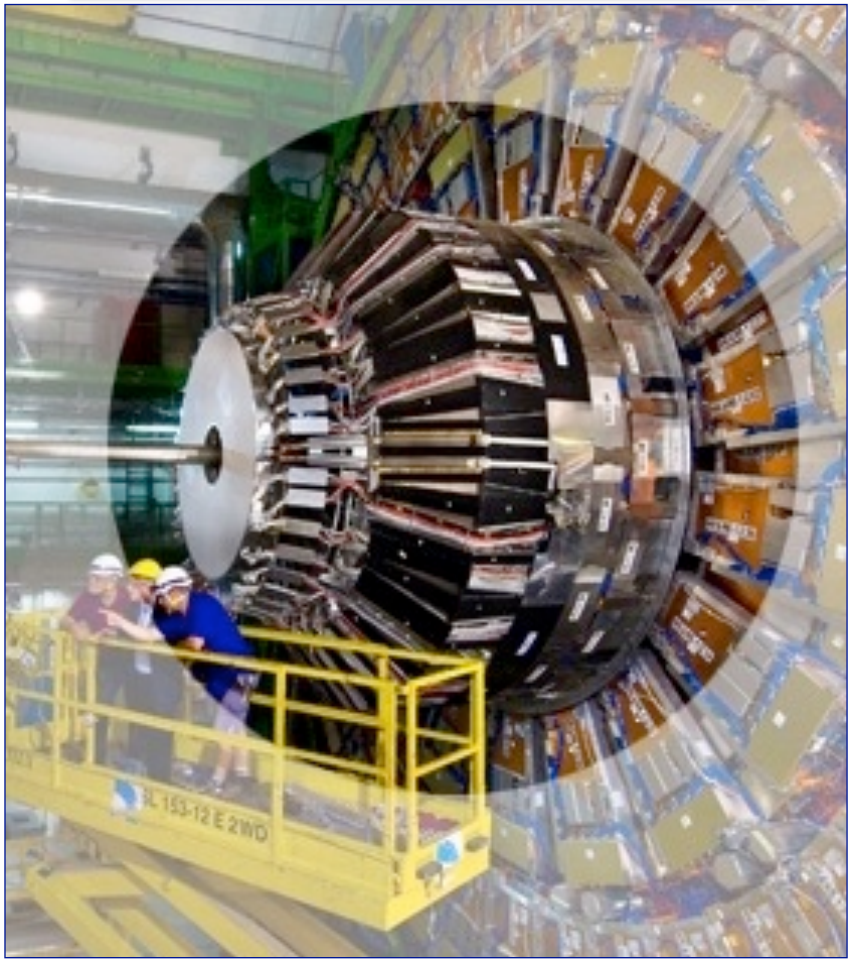
Granularity is driven by calibration requirements and energy resolution target

Calibration of Silicon sensors and scintillator tiles is **with MIPs**
→ need **good S/N for MIPs** after $3ab^{-1}$
→ low-capacitance **Si cells** → **small area** (0.5—$1.1cm^2$)
→ **Scint. cells with small area** for high-efficiency light collection

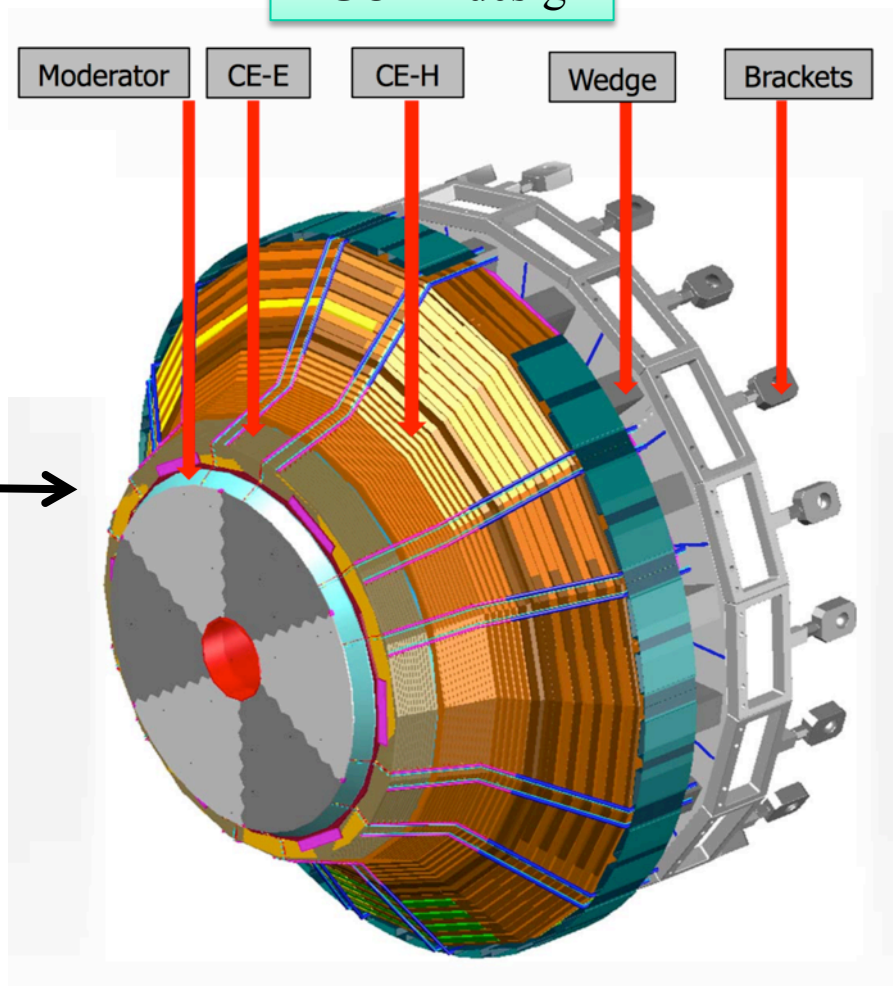
Fine longitudinal sampling needed to provide **good energy resolution** (minimize sampling term) especially with thin active layers (e.g. 100-300μm silicon sensors)

Overall mechanical design of HGCAL heavily constrained by present endcap calorimeters

Present CMS endcap calorimeters



HGCAL design



Concept: **remove** complete endcap calo. system and **replace** with HGCAL

CMS internal nomenclature: Calorimeter Endcap (CE), divided into CE-E and CE-H

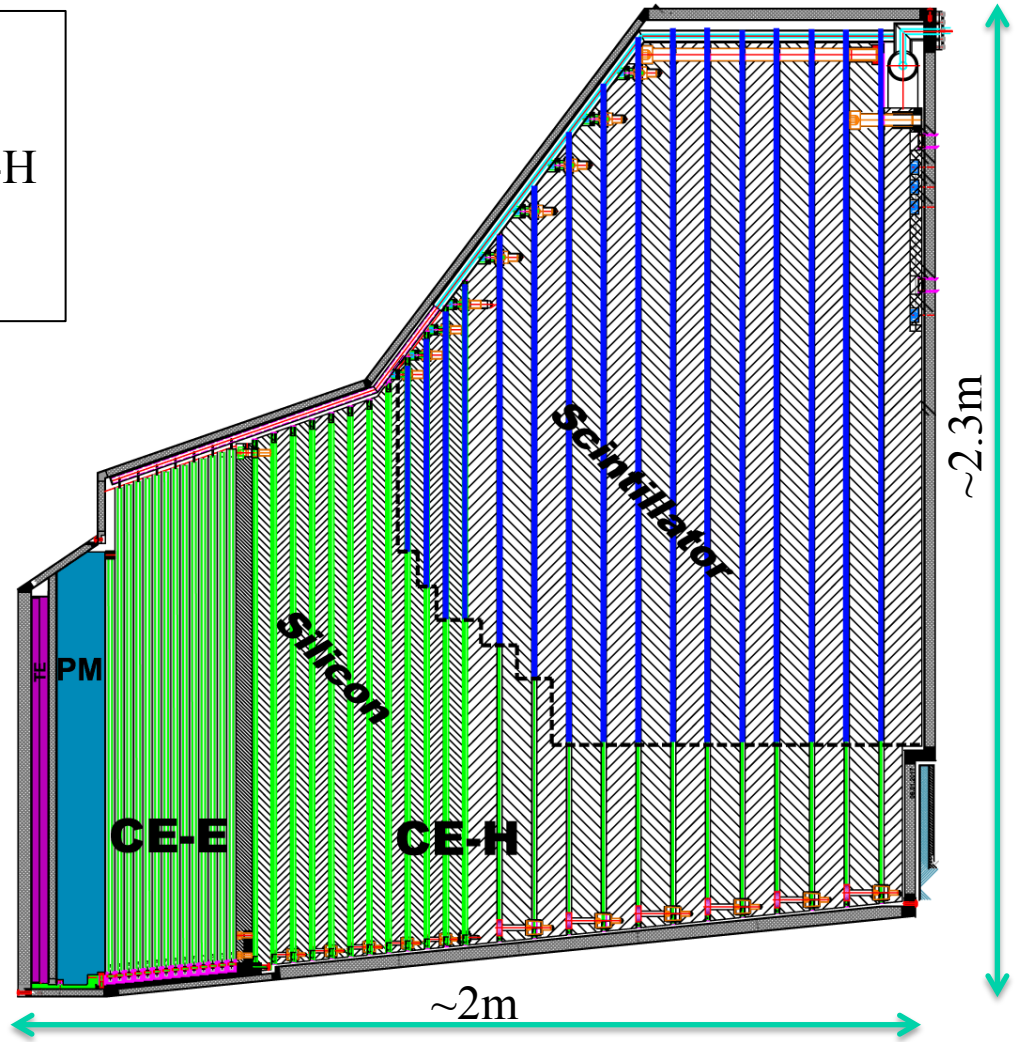
CMS HGCAL: a 52-layer sampling calorimeter with unprecedented number of readout channels

Active Elements:

- Hexagonal modules based on Si sensors in CE-E and high-radiation regions of CE-H
- Scintillating tiles with SiPM readout in low-radiation regions of CE-H

Key Parameters:

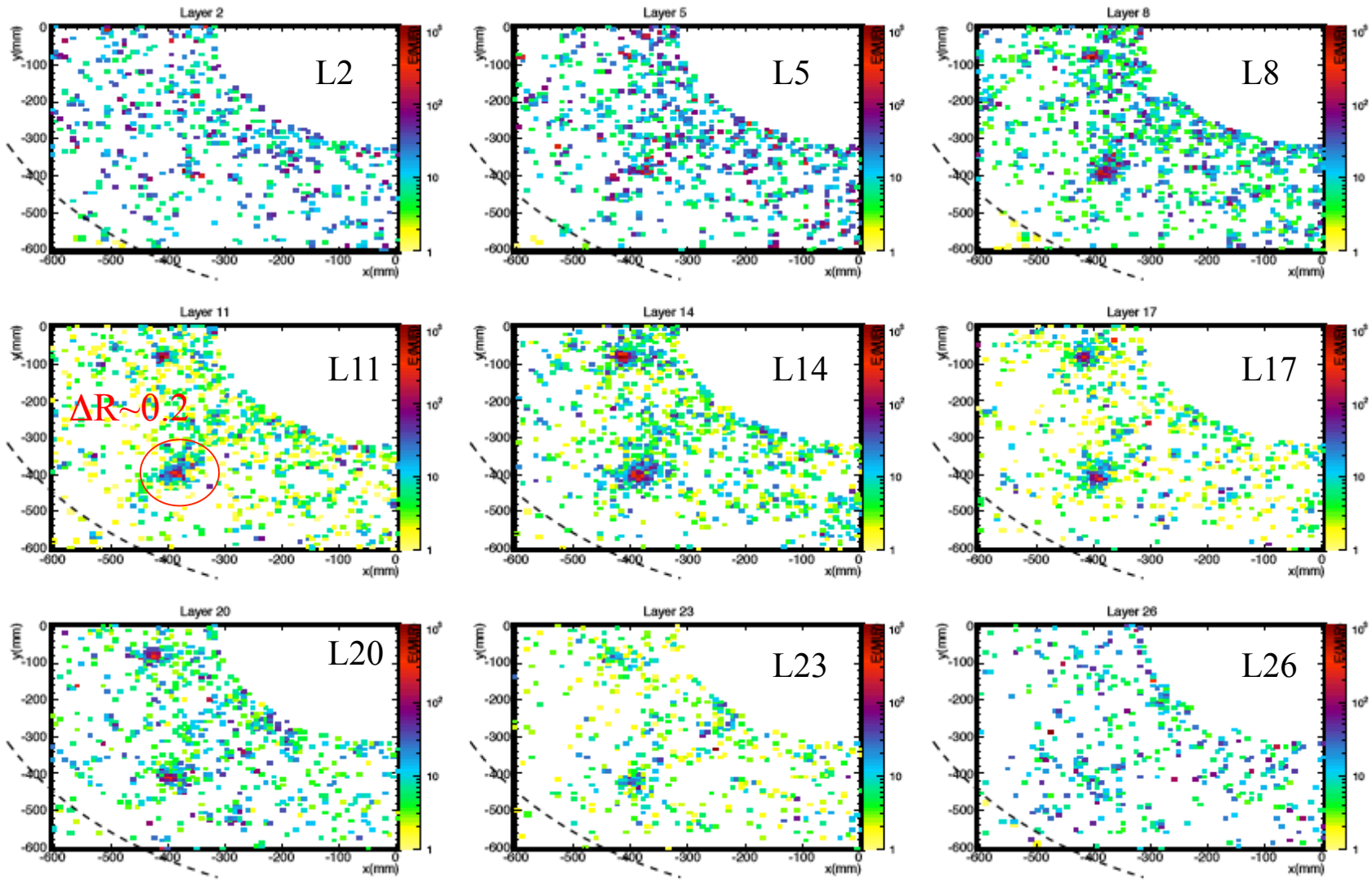
- HGCAL covers $1.5 < \eta < 3.0$
- **Full system maintained at -30°C**
- **~600m²** of silicon sensors
- **~500m²** of scintillators
- 6M Si channels, 0.5 or 1.1 cm² cell size
  - Data readout from all layers
  - Trigger readout from alternate layers in CE-E and all layers in CE-H
- ~27000 Si modules



Electromagnetic calorimeter (**CE-E**): **Si**, Cu/CuW/Pb absorbers, 28 layers, 26 X_0 & ~1.7λ
Hadronic calorimeter (**CE-H**): **Si** & **scintillator**, steel absorbers, 24 layers, ~9.0λ

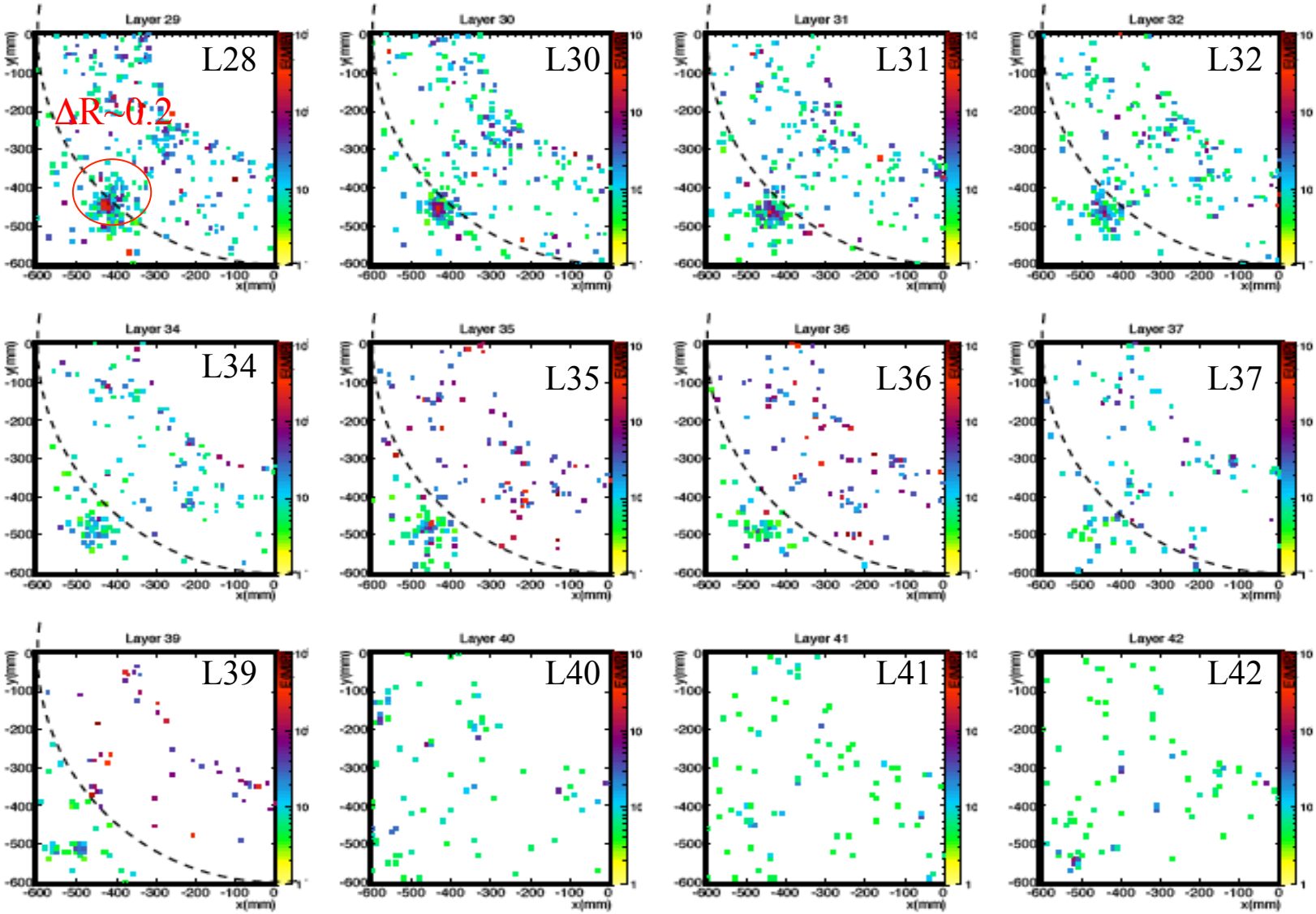
VBF H→γγ, with 720 GeV VBF jet (2 charged π + γ) & 175 GeV γ incident on CMS endcap; pileup 200

Showers from the **two photons** are visible in the layers of the electromagnetic part – CE-E

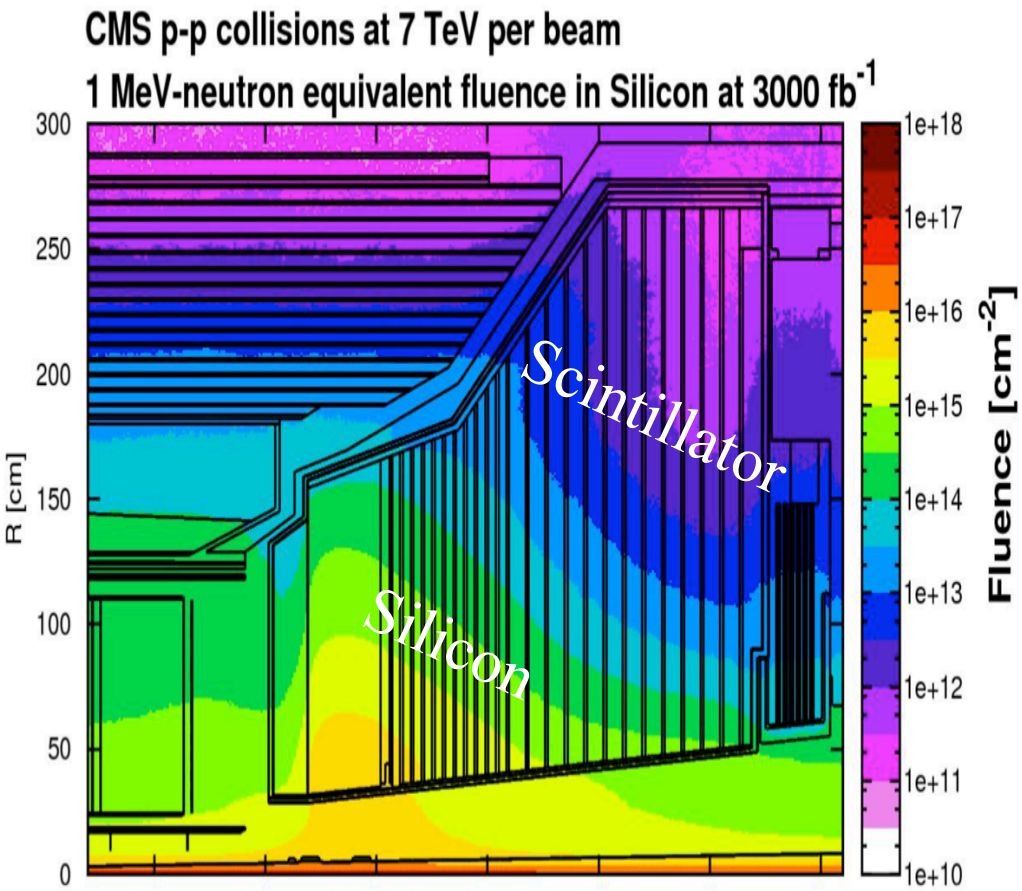


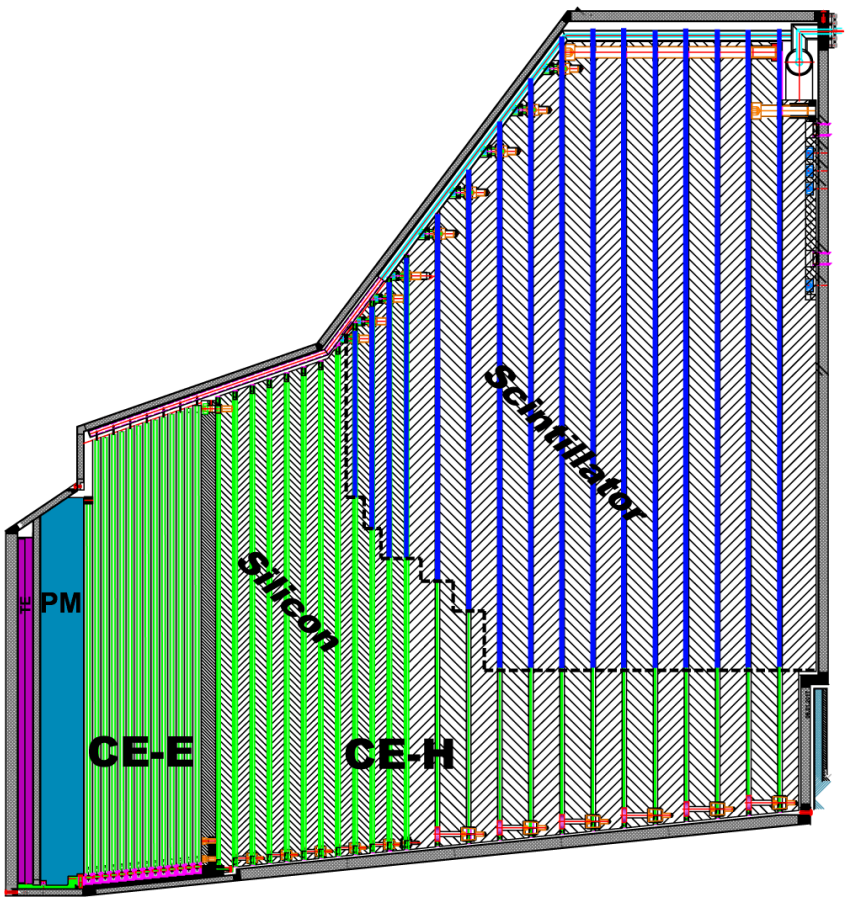
VBF H→γγ, with 720 GeV VBF jet (2 charged π + γ) & 175 GeV γ incident on CMS endcap; pileup 200

Showers from the **two pions become visible** in the layers of the hadronic part – CE-H



Regions of silicon or silicon + scintillator/SiPM governed by radiation field





Fluence in HGCAL spans **5 orders of magnitude**
Silicon in high-radiation regions; scint+SiPM in lower-radiation regions

~600m^2 of silicon sensors (3x CMS tracker) in radiation field peaking at ~10^{16}n/cm^2

Planar p-type DC-coupled sensor pads

- simplifies production technology; p-type more radiation tolerant than n-type
- (consider n-type for 300μm sensors in lower radiation region of HGCAL)

Hexagonal sensor geometry preferred to square

- makes most efficient use of circular sensor wafer
- reduces number of sensors produced & assembled into modules (factor ~ 1.3)

8” wafers preferable to 6”

- reduces number of sensors produced & assembled into modules (factor ~ 1.8)

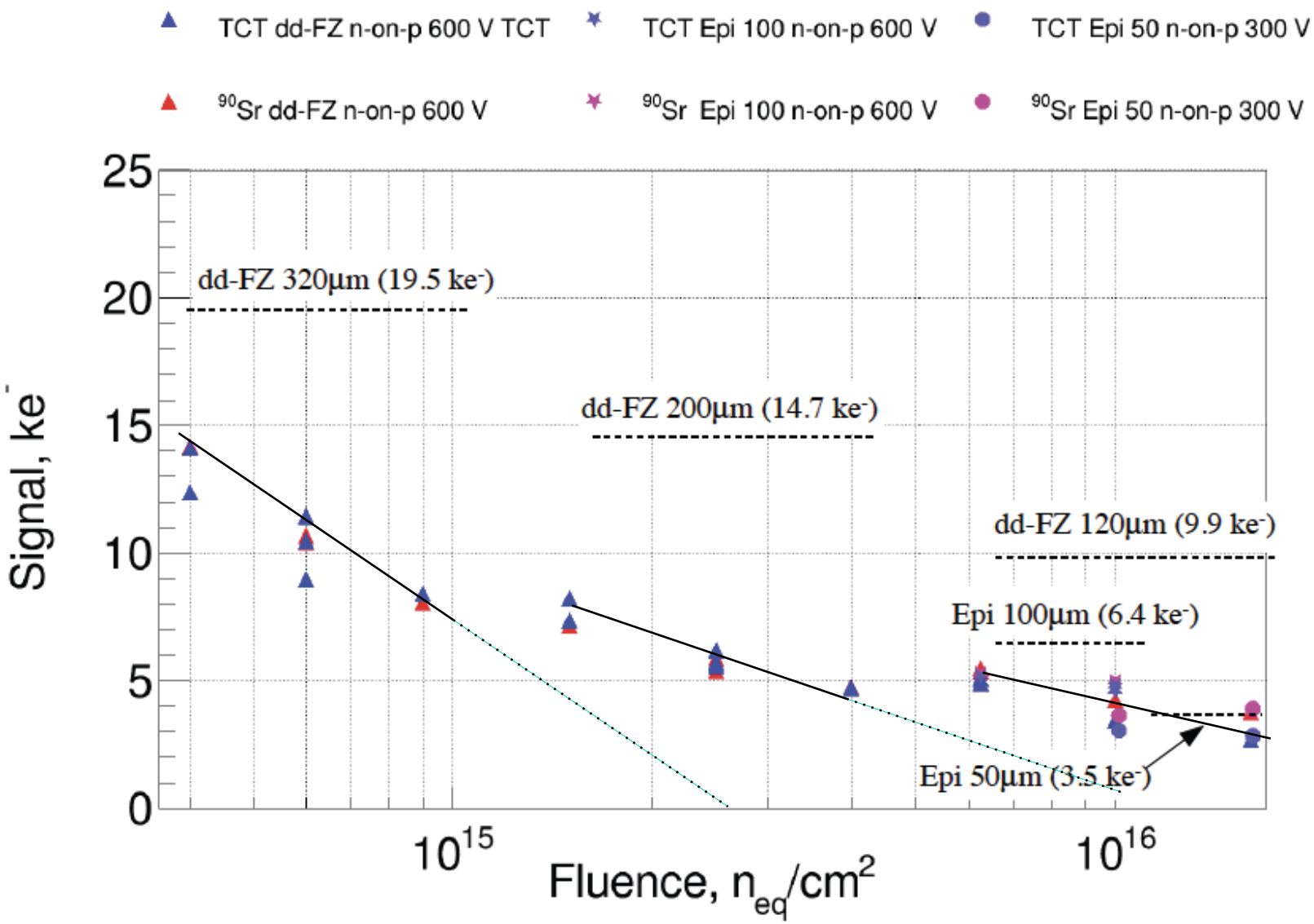
300μm, 200μm and 120μm active sensor thicknesses

- match sensor thickness (and granularity) to radiation field for optimal performance

Simple, rugged module design & automated module assembly

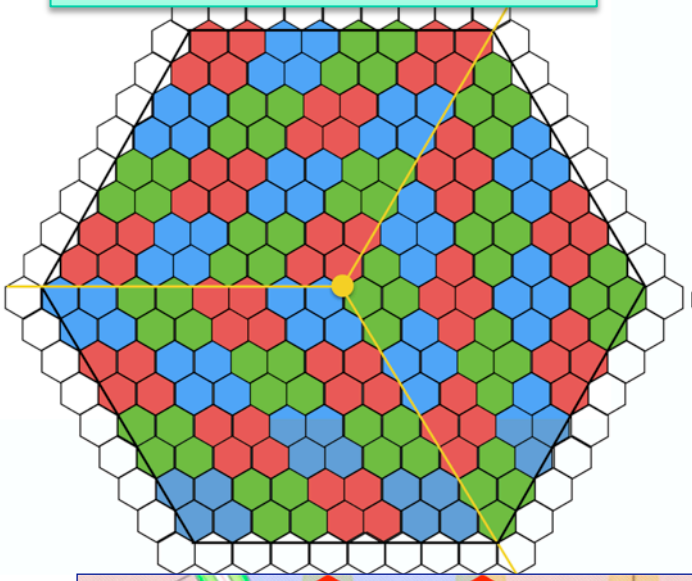
- provide high volume, high rate, reproducible module production & handling

Thinner sensors: less decrease in charge collection efficiency vs fluence than thicker sensors

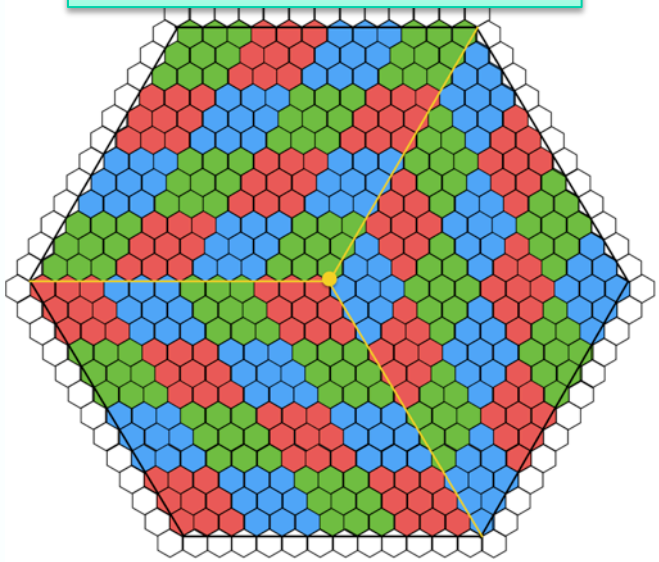


8” silicon sensors will be hexagonal, divided with 3-fold symmetry into hexagonal cells

300/200μm: 192 cells/sensor



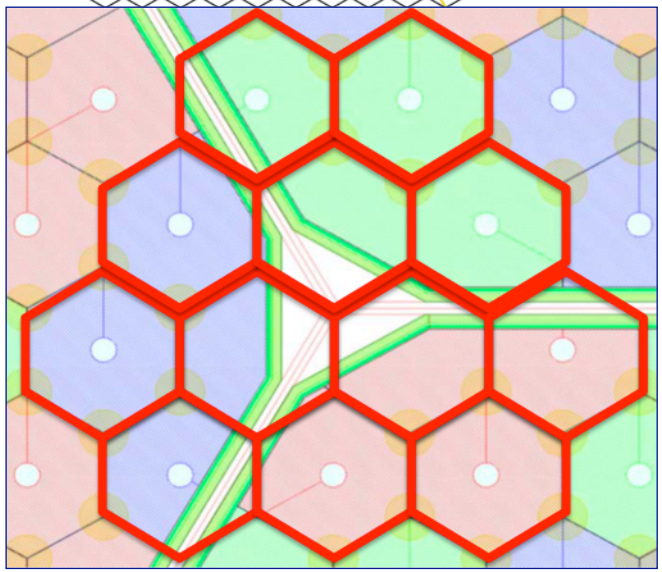
120μm: 432 cells/sensor

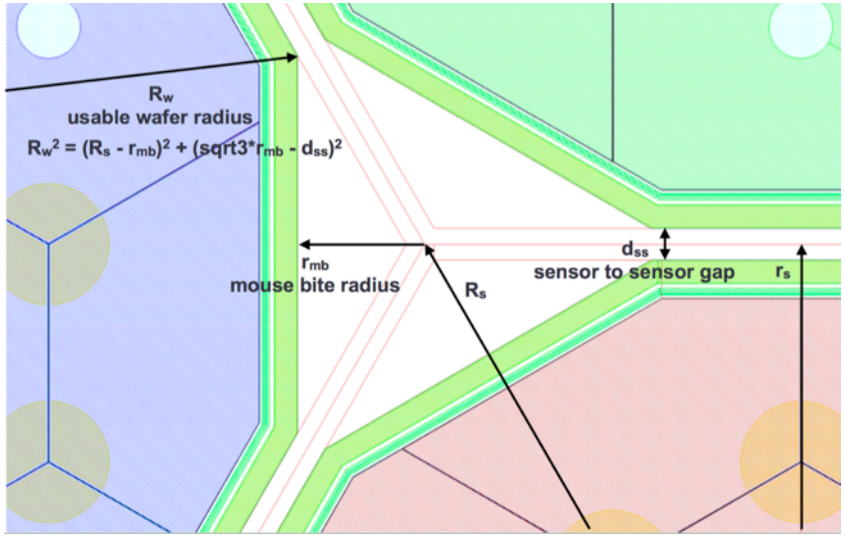


∅ ~ 190mm

All cells have C≤65pF

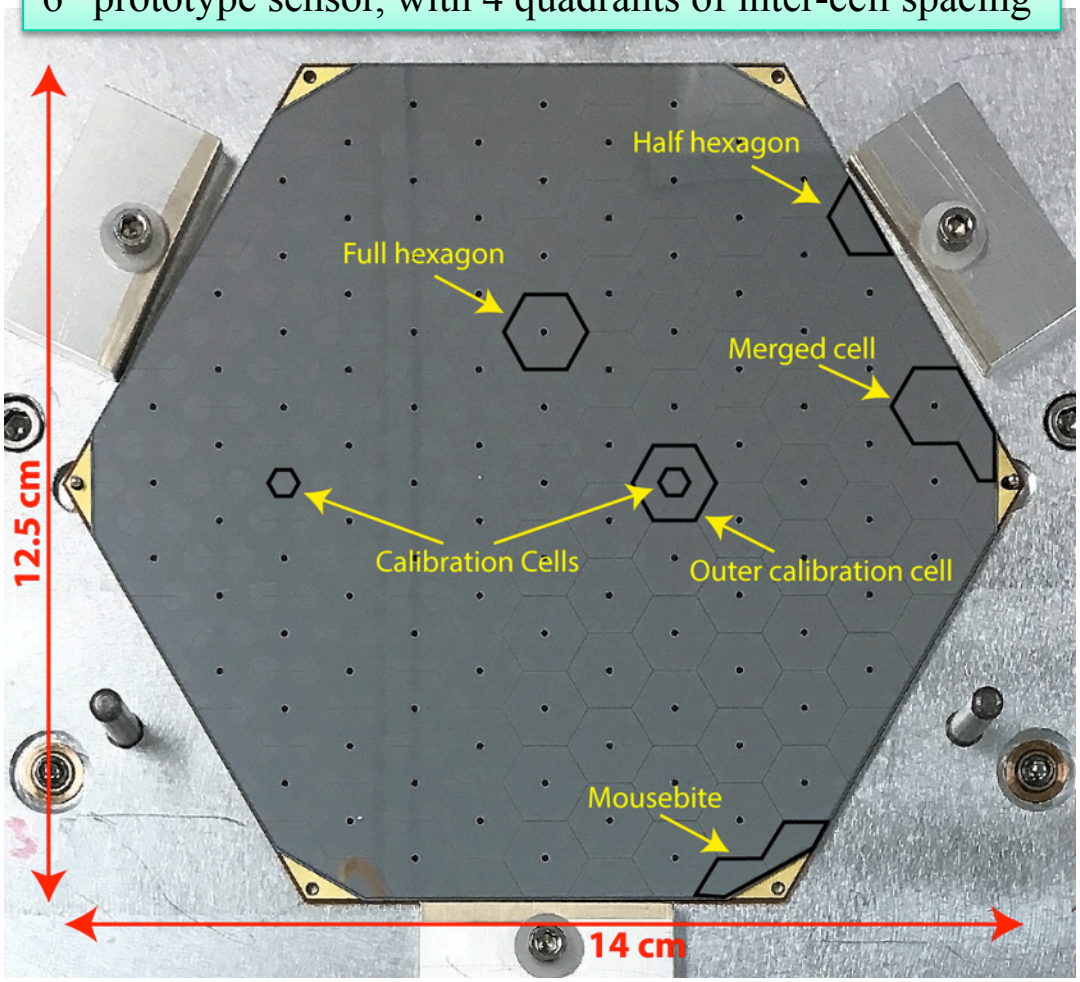
Coloured groupings of cells represent “trigger cells”



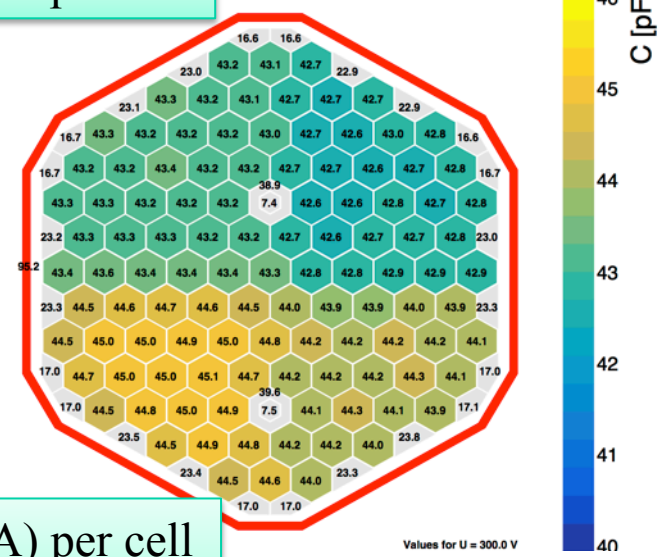


Hexagonal silicon sensors are divided (mostly) into hexagonal cells, with some special cells

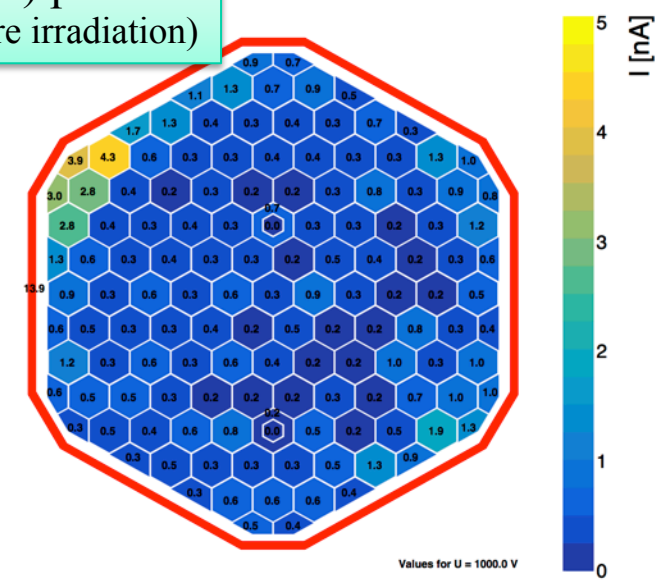
6” prototype sensor, with 4 quadrants of inter-cell spacing



~55pF per cell

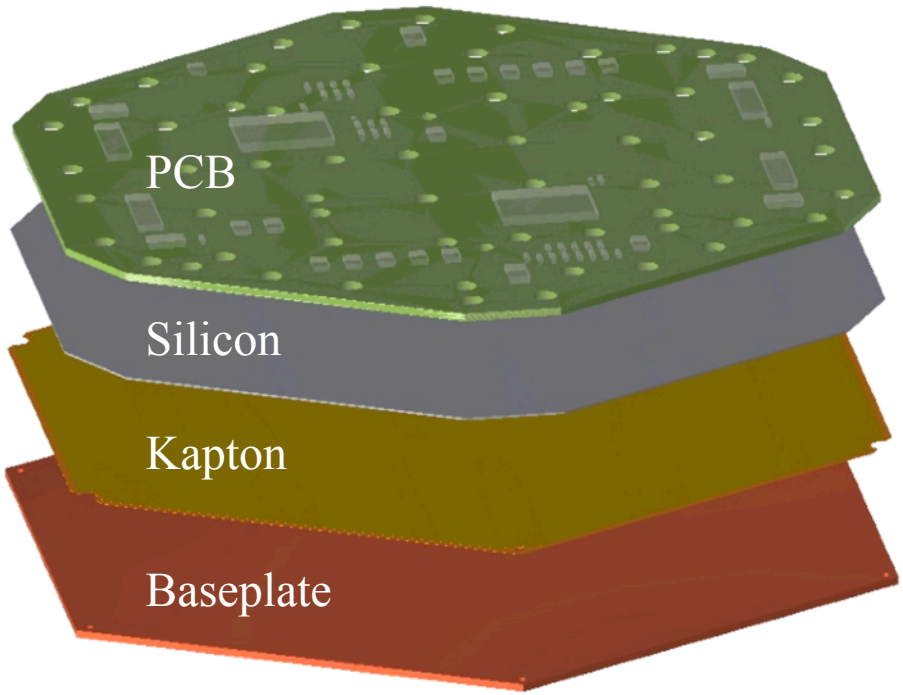


O(nA) per cell
(before irradiation)

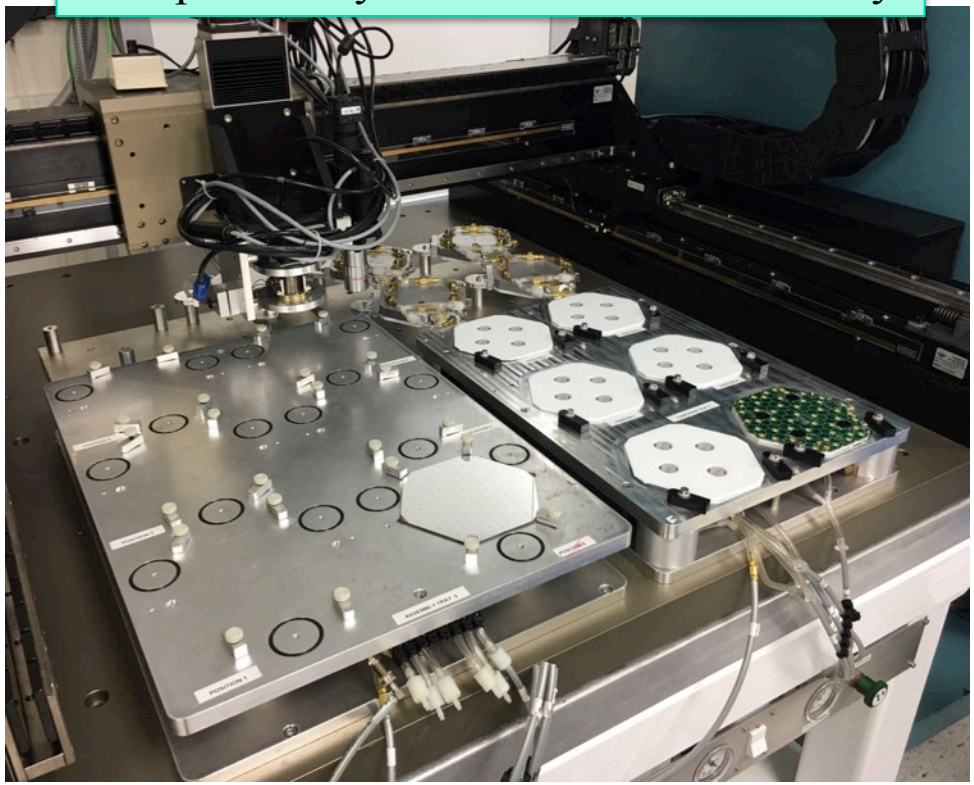


Prototype 6” and 8” sensors made by three producers

Silicon modules are glued assemblies, made with standardized gantry, wire-bonders etc.



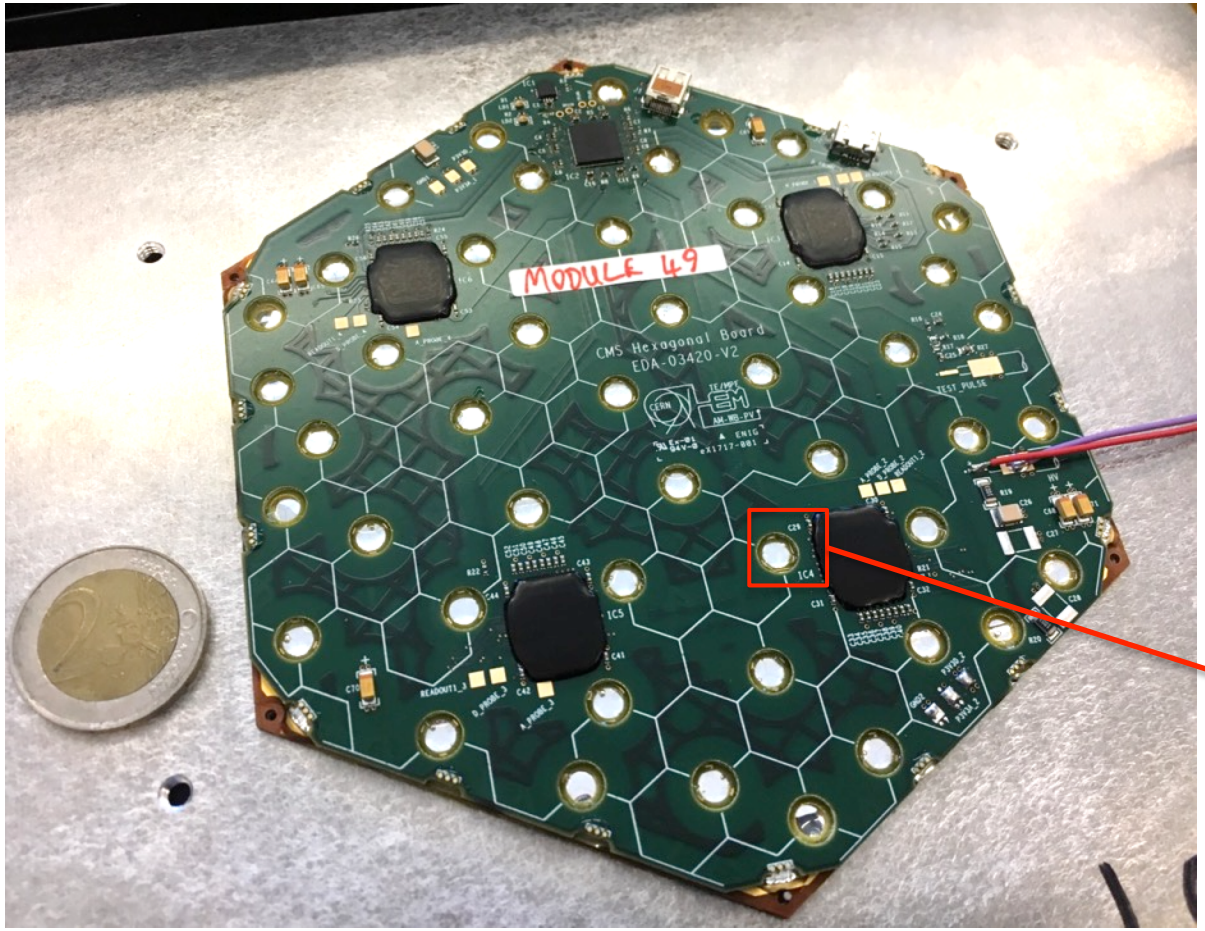
Automated gantry @ UCSB
used previously for CMS tracker assembly



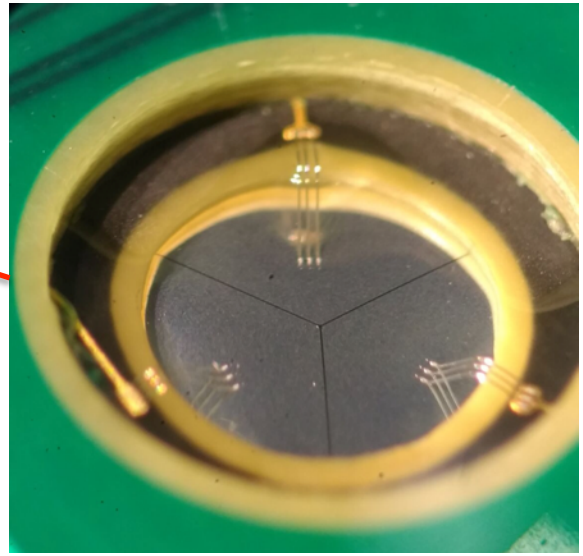
In CE-E, baseplate = 1.2mm CuW, to keep overall density high

HGCAL will include 27000 modules based on hexagonal silicon sensors with 0.5-1cm^2 cells

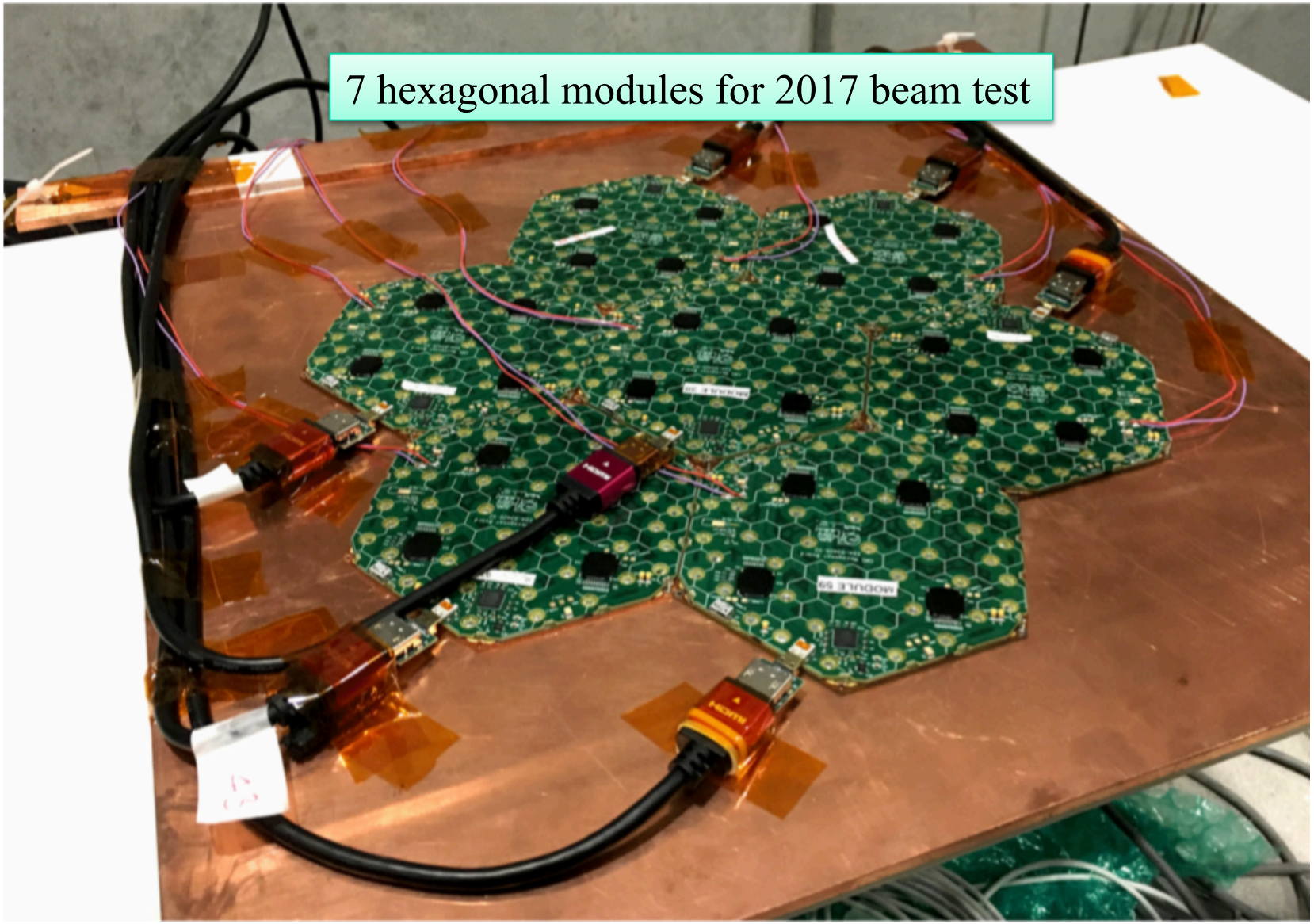
Silicon sensor glued to baseplate and PCB containing front-end electronics



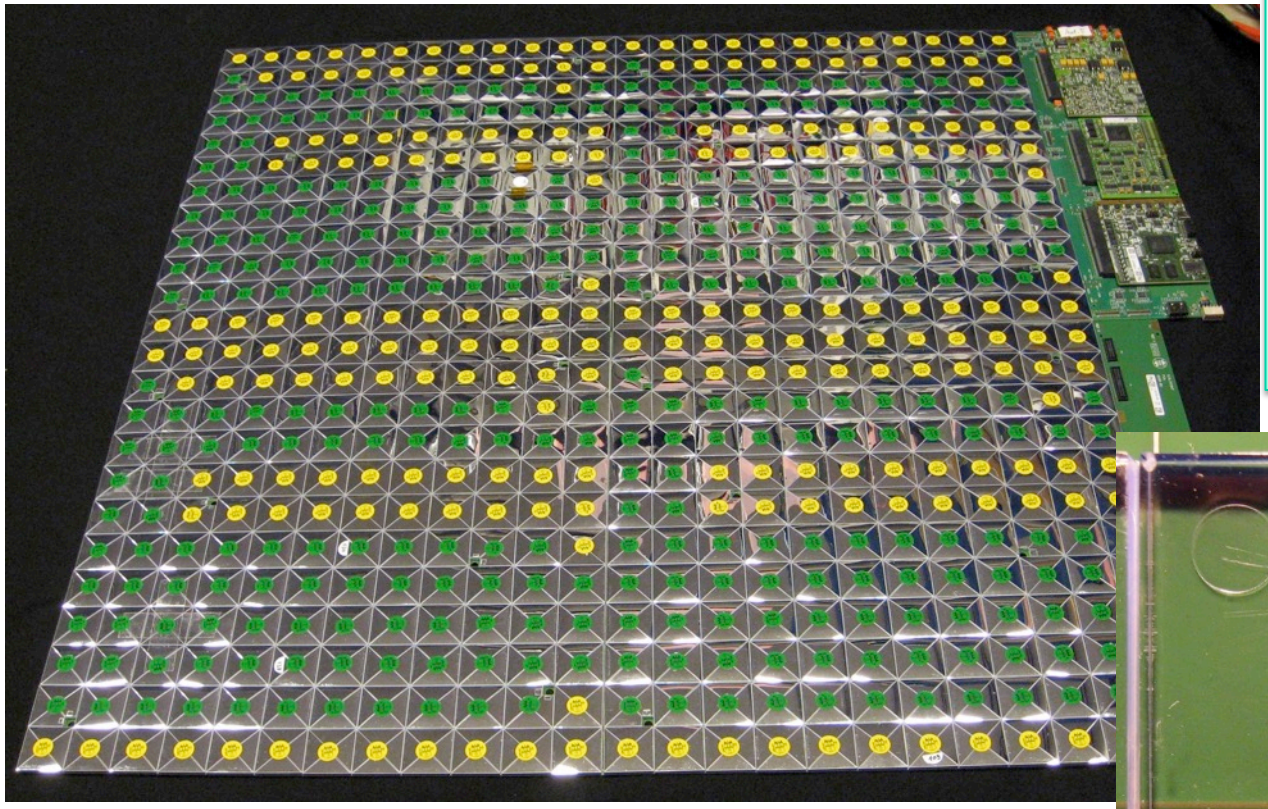
Wire bonding from PCB to silicon through holes



Silicon modules are arranged in hexagonal matrices to cover fiducial area of HGCAL

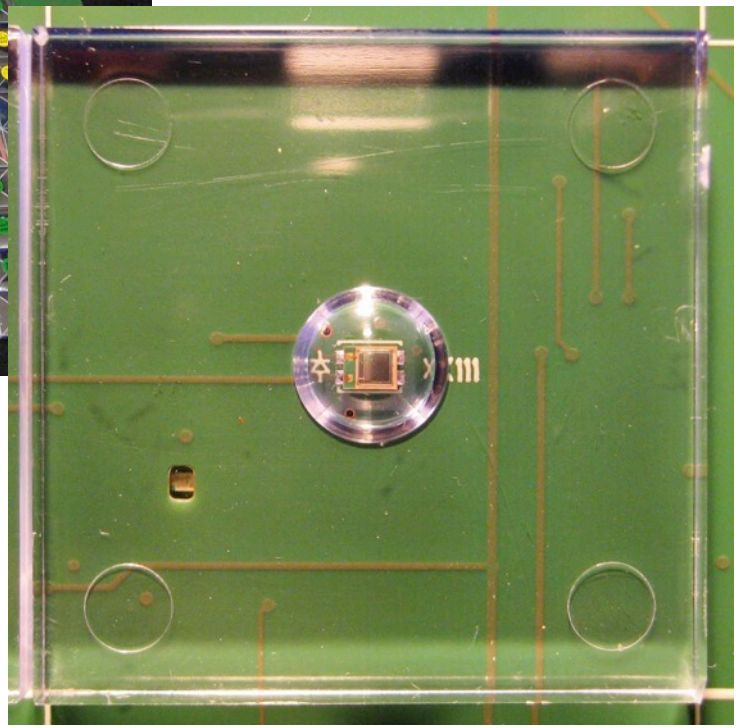


HGCAL will also include 500m^2 of scintillator tiles with on-tile SiPM readout



SiPMs already used successfully in e.g. CMS HCAL Phase 1 upgrade

Tile boards or "megatiles" limited in size by CTE of different components

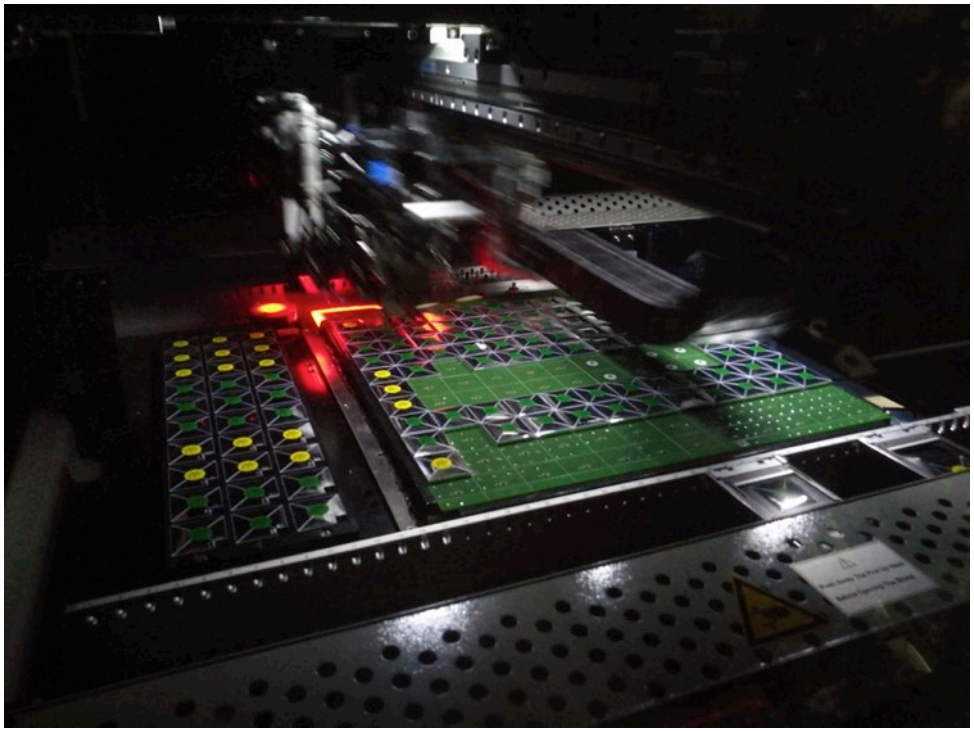


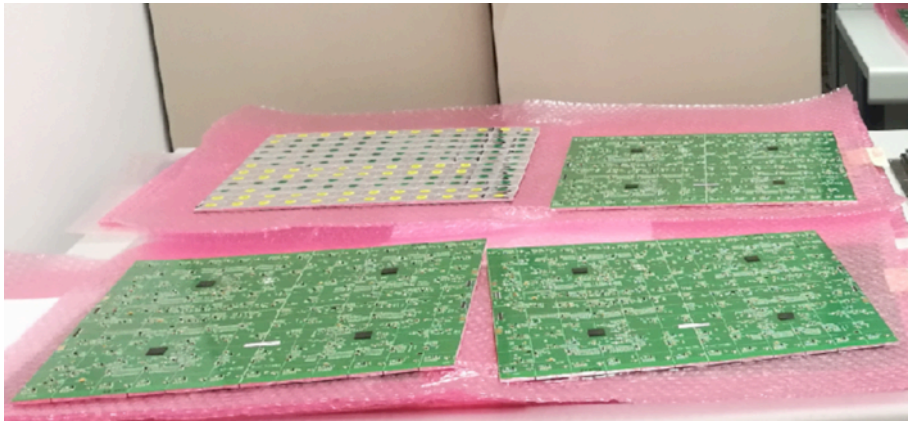
For first beam tests, modified CALICE AHCAL used for rear hadron calorimeter:
3x3cm^2 scintillator tiles + direct SiPM readout

Semi-automated assembly already used for CALICE prototypes: 28000 tiles on 158 boards

Glue dispensing With a screen printer → Placing tiles with a P&P machine → Curing over night → Installation in CR test stand → Calibration & MIP measurement

~ 1.5 h for 4 Boards | ~ 20 h | ~ 1 h | ~ 24 h





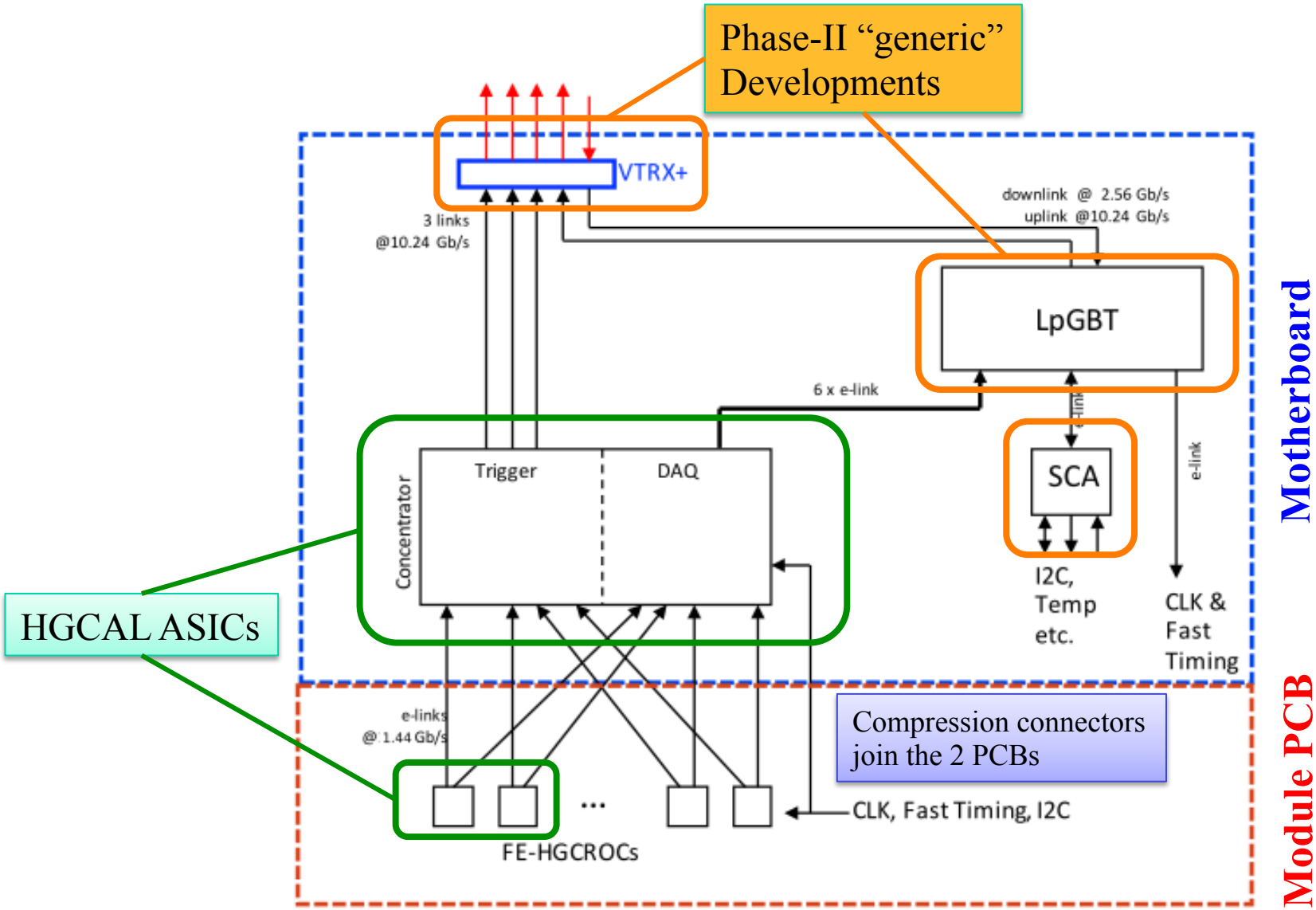
30 x 30 x 3 mm^3 tiles, automated wrapping, placed by automatic gantry

The front-end electronics are particularly challenging in the compact HGCAL

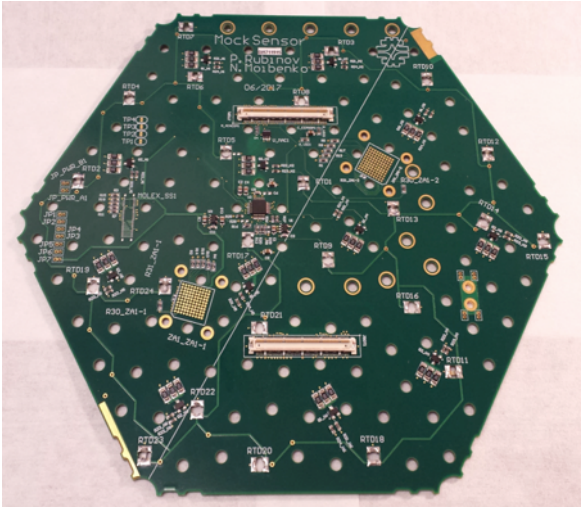
- **Low noise** (<2500e$^-$) and **high dynamic range** (~0.2fC → 10pC)*
  - See **MIPs** (~3.5fC in 300μm silicon) **with S/N > 2** for whole lifetime of HL-LHC
  - Use 130nm CMOS with 1.5V supply
- Provide timing information to **tens of picoseconds**
  - Need clock distribution jitter 10-15ps (same specs as for other CMS detector upgrades)
- Have **fast shaping time** (<20ns) to minimize out-of-time pileup
- On-detector **digitization, data concentration and zero suppression**
- On-detector creation of **trigger sums**
- Buffering of data to accommodate **12.5μs L1 latency**
- High-speed readout links to interface with 10 Gb/sec **lpGBT chipset**
- **<20mW per channel** (roughly limited by cooling power)
- High radiation resistance (**~2MGy and 10^{16} n_{eq}/cm^2**)
- And be in production ~2021

*want S/N >4 at beginning of HL-LHC for 1 MIP in 120μm silicon ~ 1.5fC; upper limit from 1.5 TeV photon shower producing ~6000 MIPs in a single cell

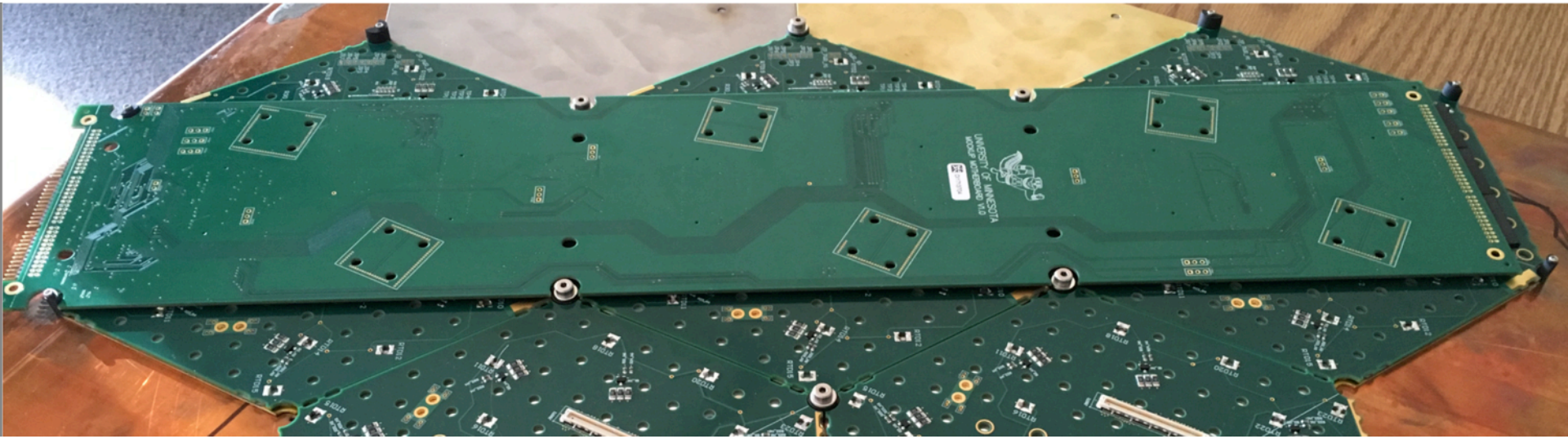
On-detector electronics are a mixture of HGCAL-specific ASICs and "generic" developments



“dummy” cassette being assembled with PCBs containing only connectors and heat loads

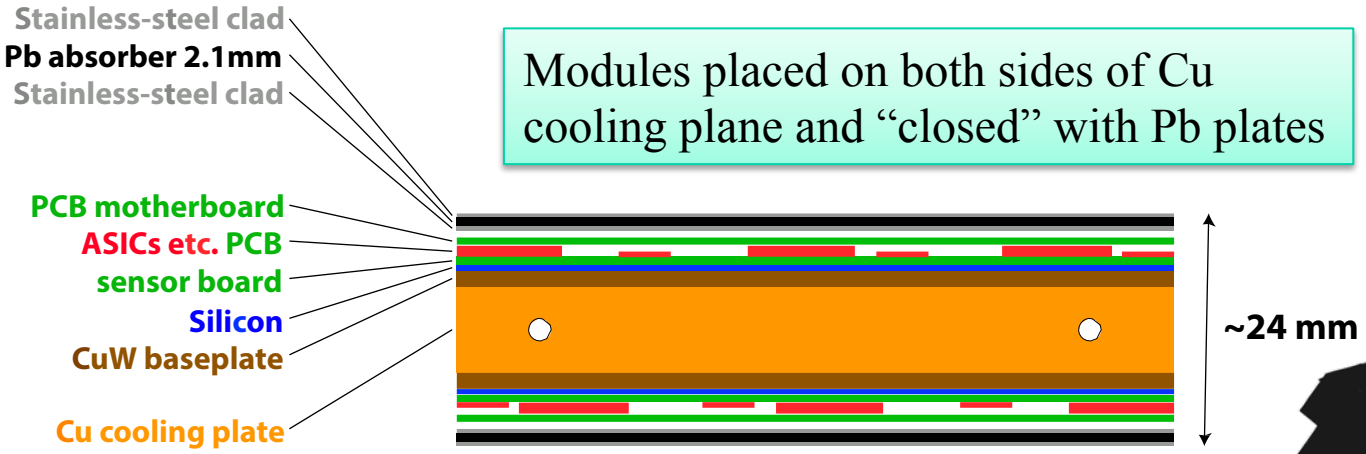


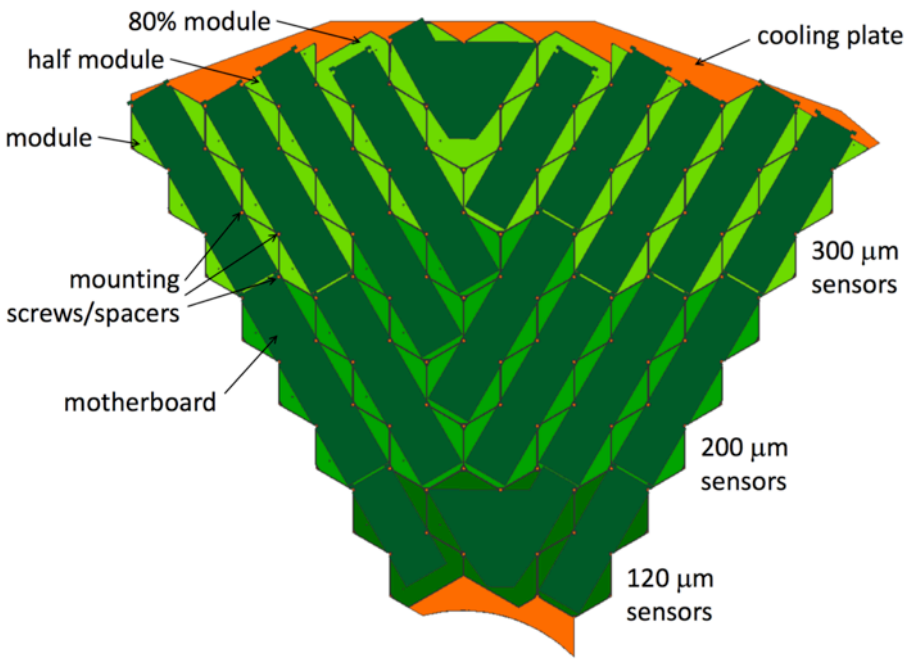
8” hexagonal PCBs glued to silicon and baseplates → **modules**
3 modules connected to a single “**motherboard**” providing power, data concentrator and optical links

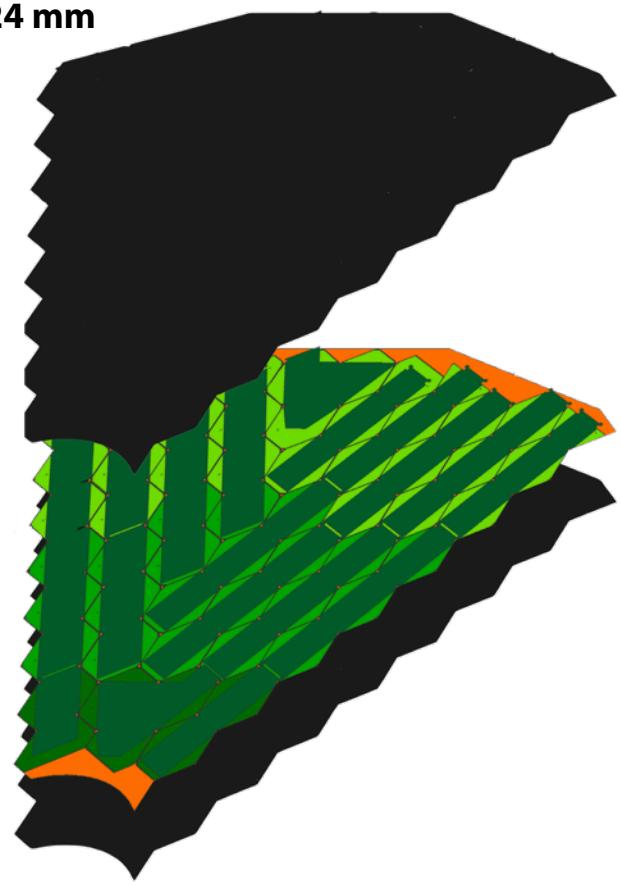


CE-E cassettes are self-supporting sandwich structures with Pb, Cu and Cu/W as absorbers

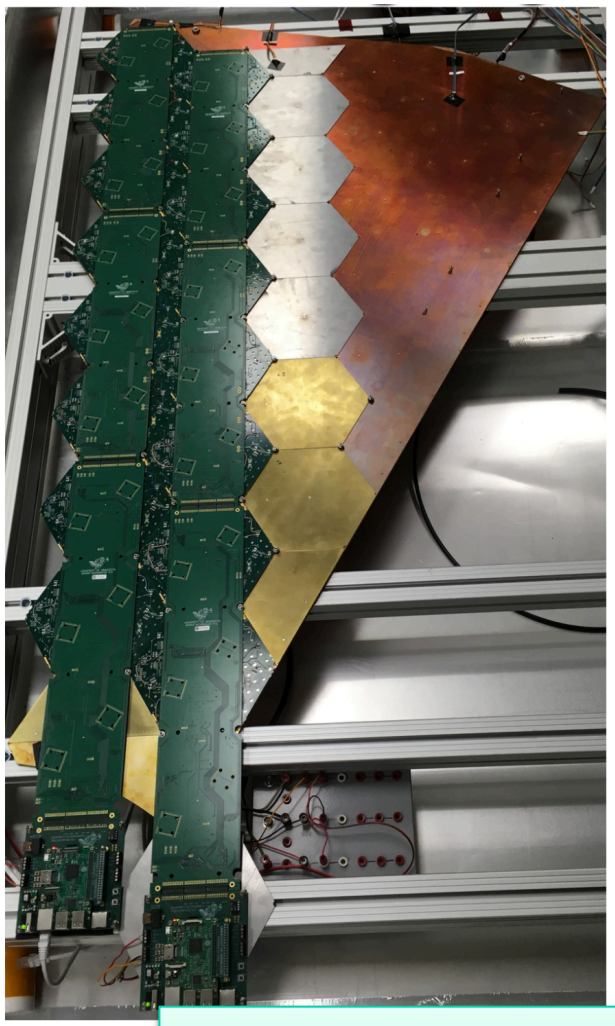
Modules placed on both sides of Cu cooling plane and "closed" with Pb plates

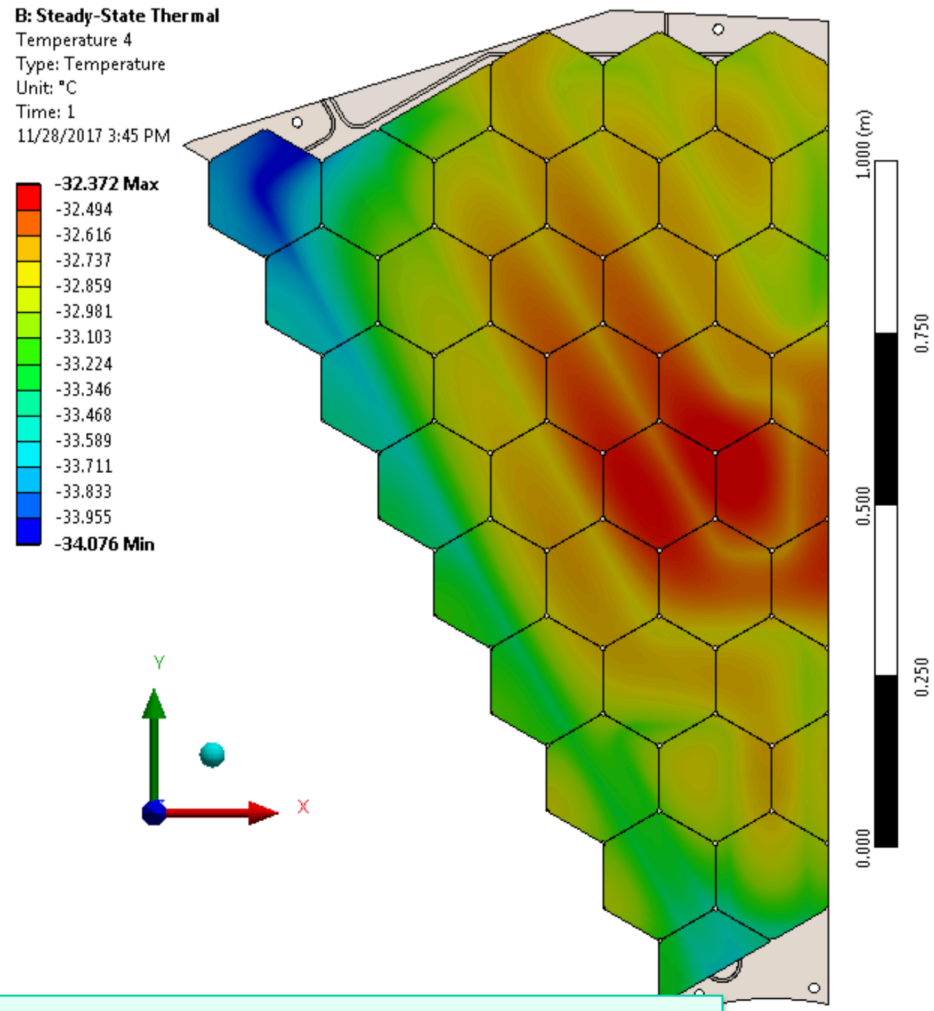






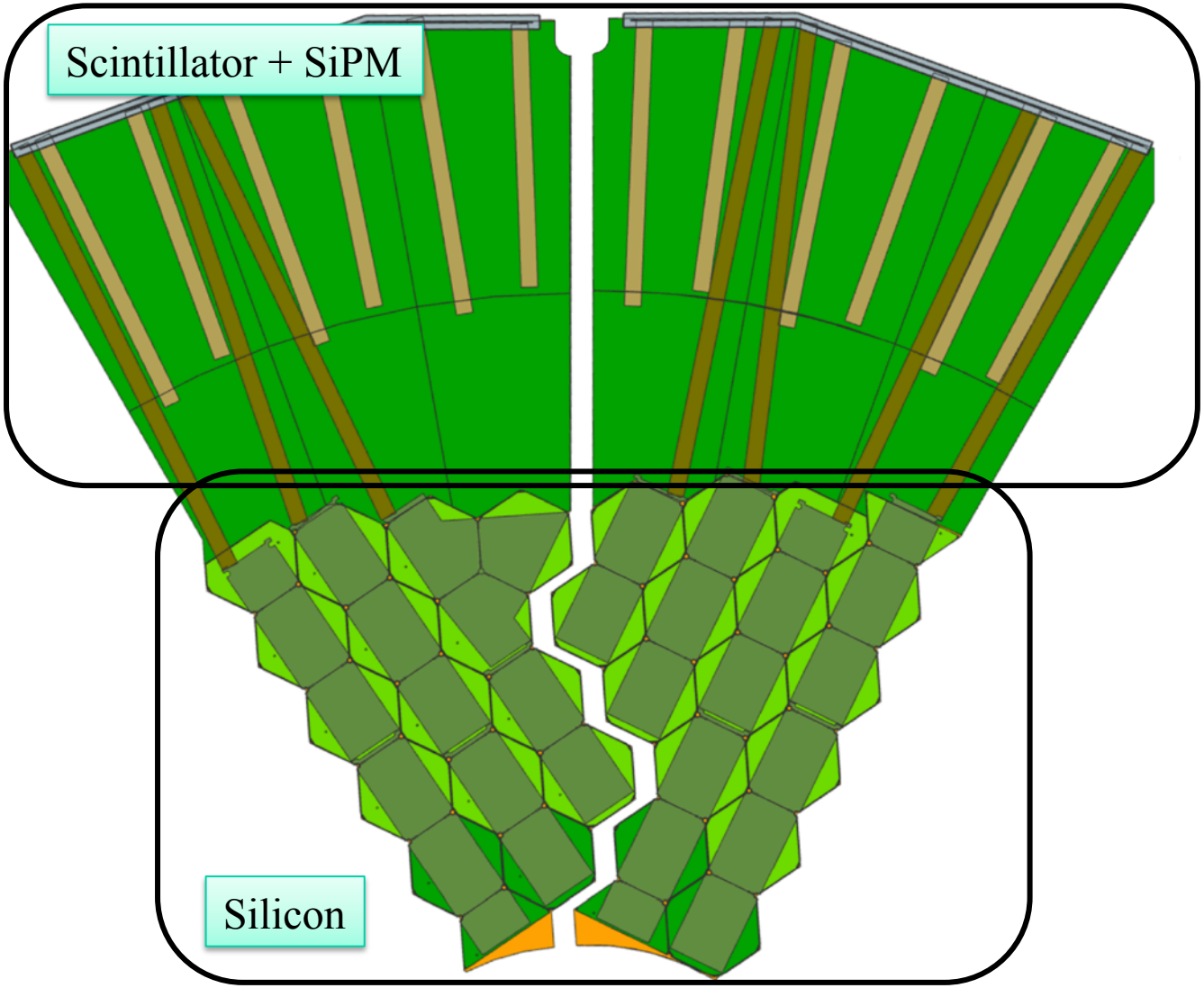
Dummy cassette is installed in a cold box to study heat-transfer characteristics – tests ongoing



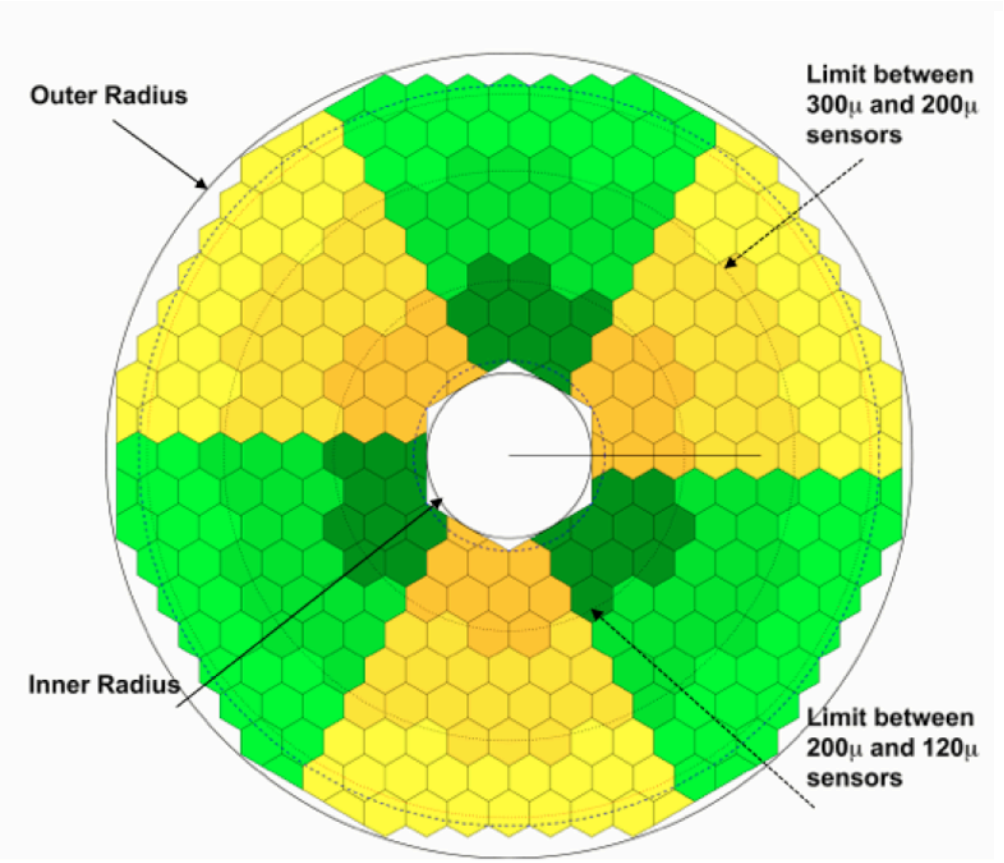


FEA calculations are made for nominal heat load *i.e.* 200 W
6.8 metre long tube, 2.197 gm/sec CO_2 flow
Maximum temperature of copper plate is below -30°C

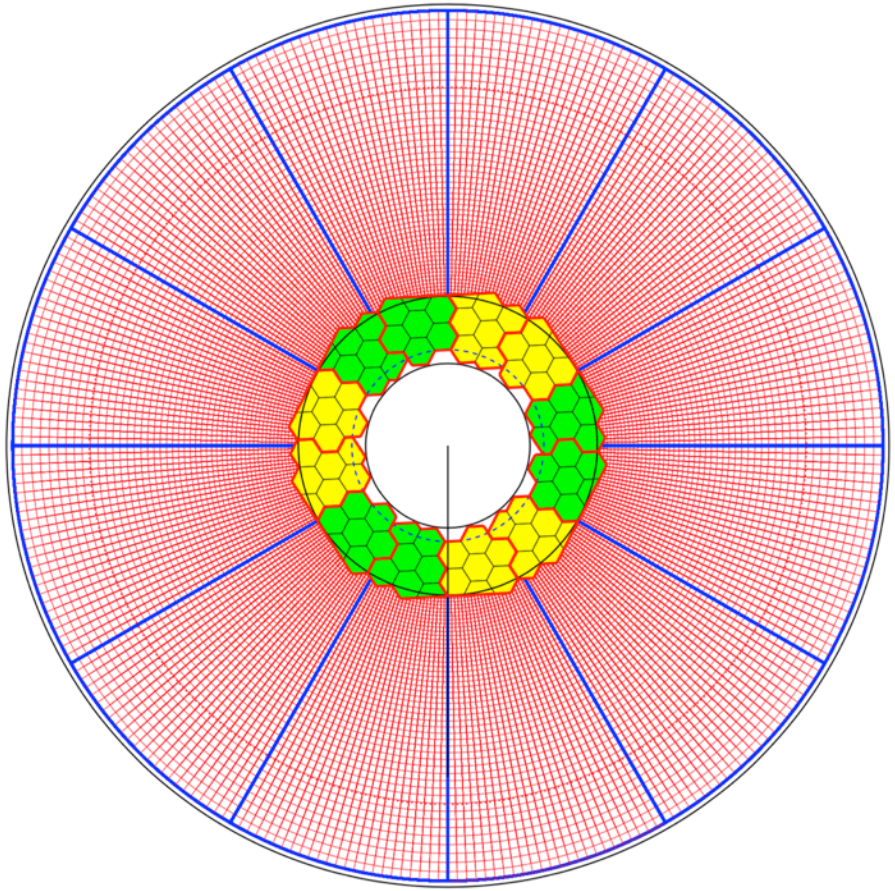
CE-H cassettes: some have all silicon (*a la* CE-E); some have mixture of Si and scint/SiPM



Wedge-shaped "Cassettes" containing arrays of silicon modules or silicon+scintillator/SiPM



Silicon-only layer (in CE-E) showing "cassettes" and different sensor thicknesses

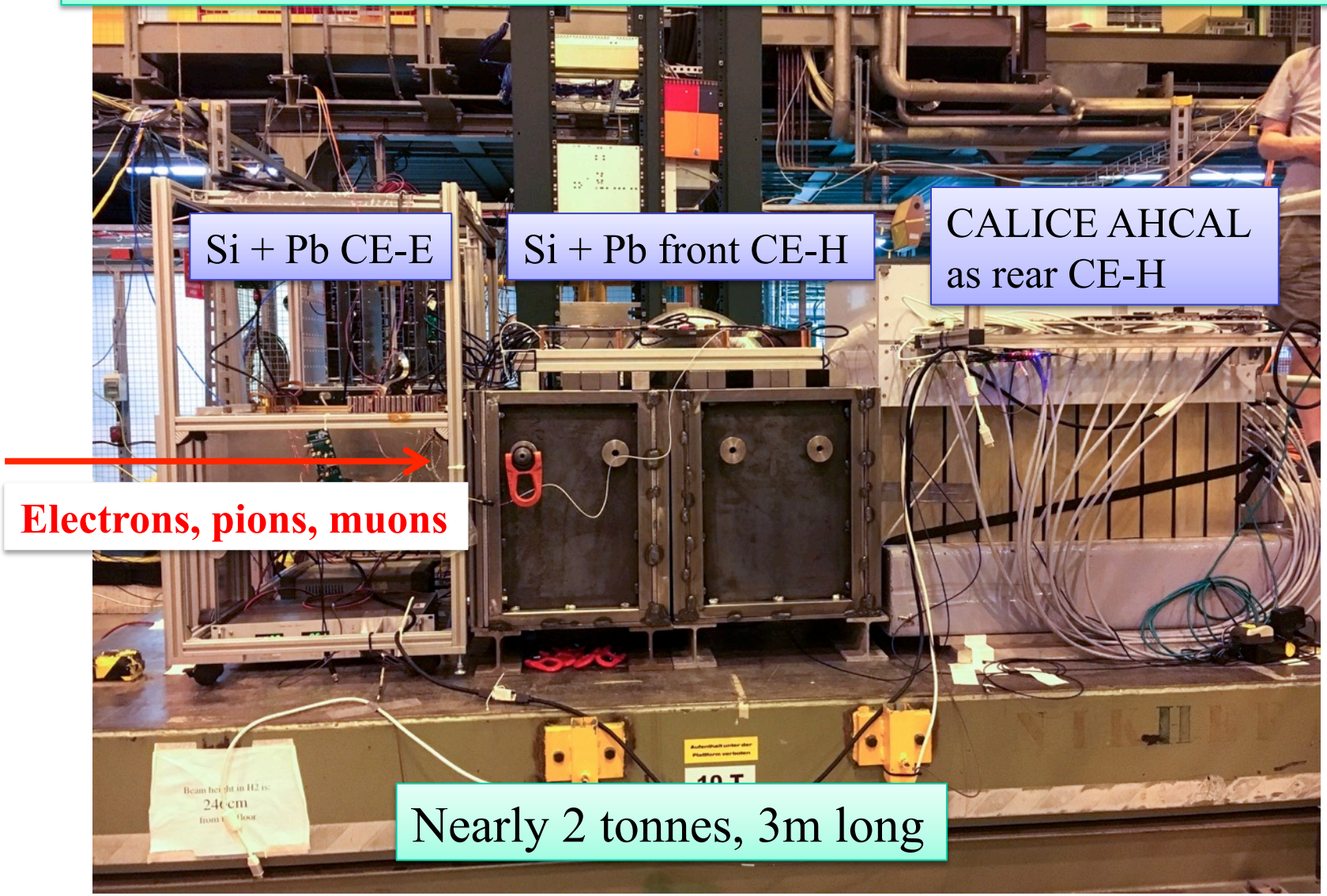


Mixed layer (in CE-H) with silicon at high η and scintillator+SiPM at low η

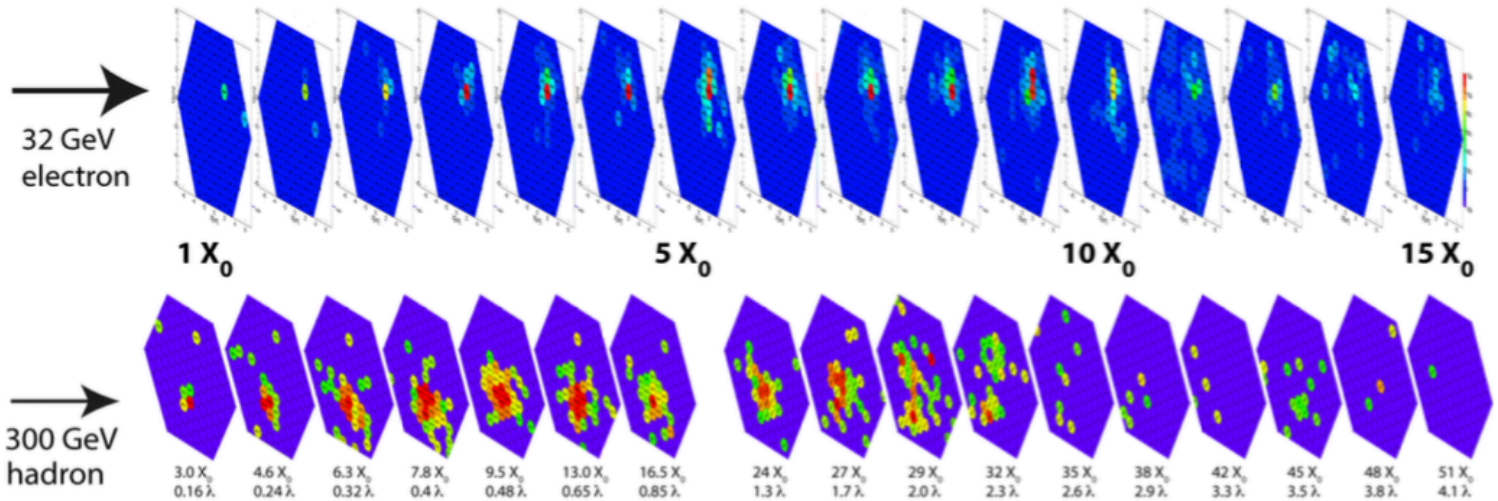
Measured and expected HGCAL performance

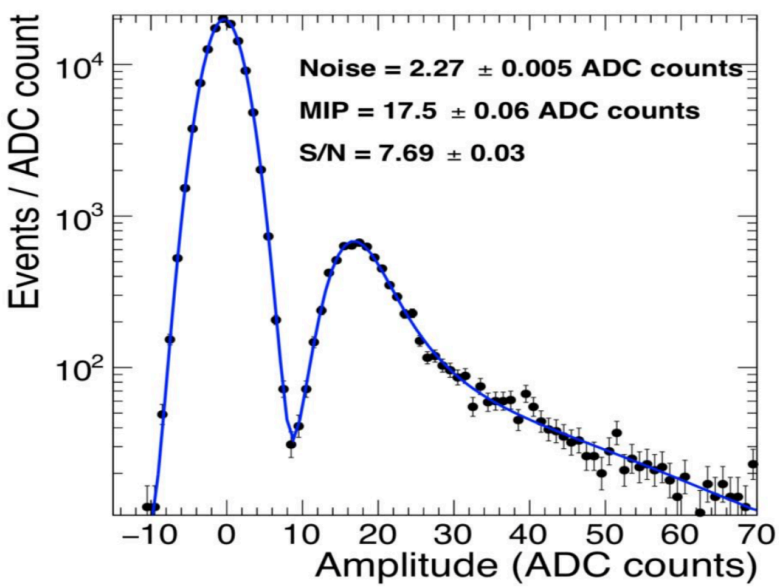
Prototype silicon modules + CALICE AHCAL tested at CERN in 2017; more in 2018

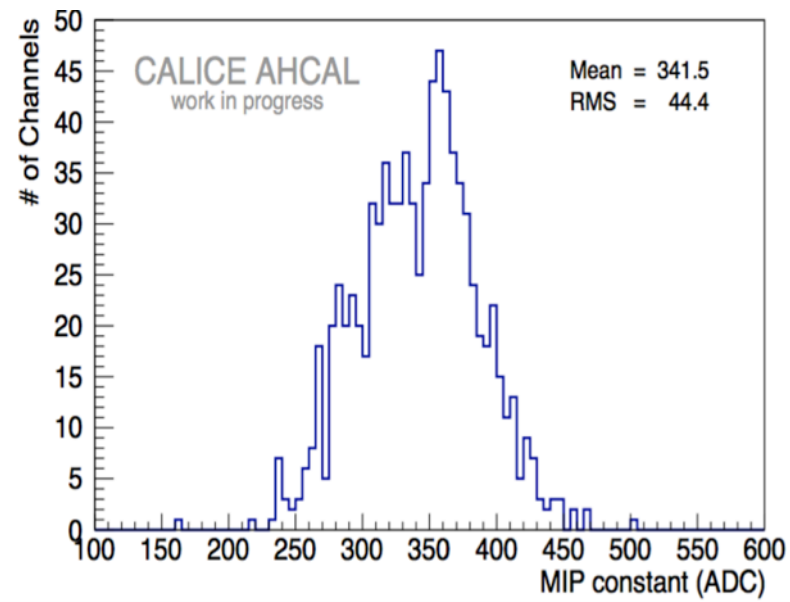
Existing ASIC (Skiroc2) used in 2016; evolution (Skiroc2-CMS) used in 2017/18



Beam tests in 2016 & 2017 validated basic design; good stability; MIPs seen in all parts

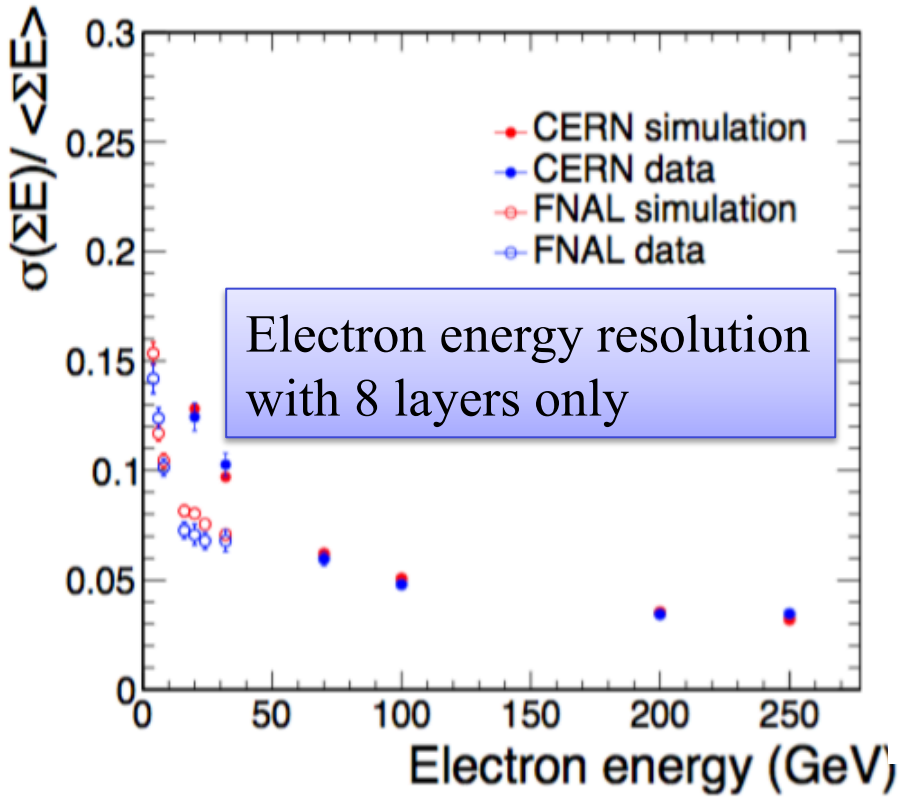


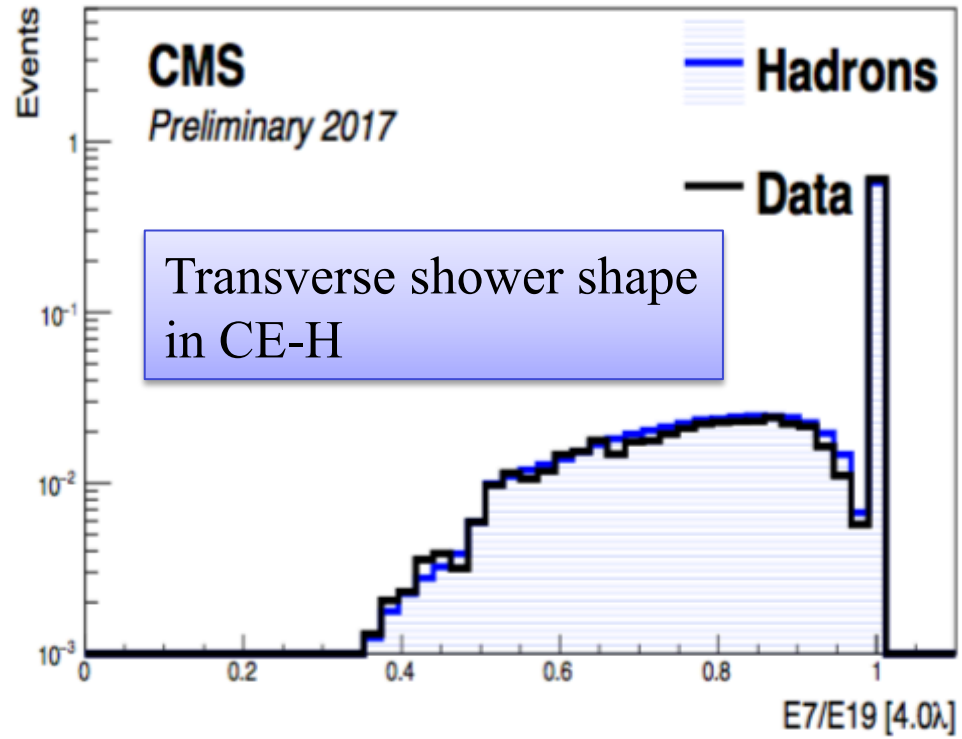




Mips (for calibration) seen from muons and also single particles within hadronic showers

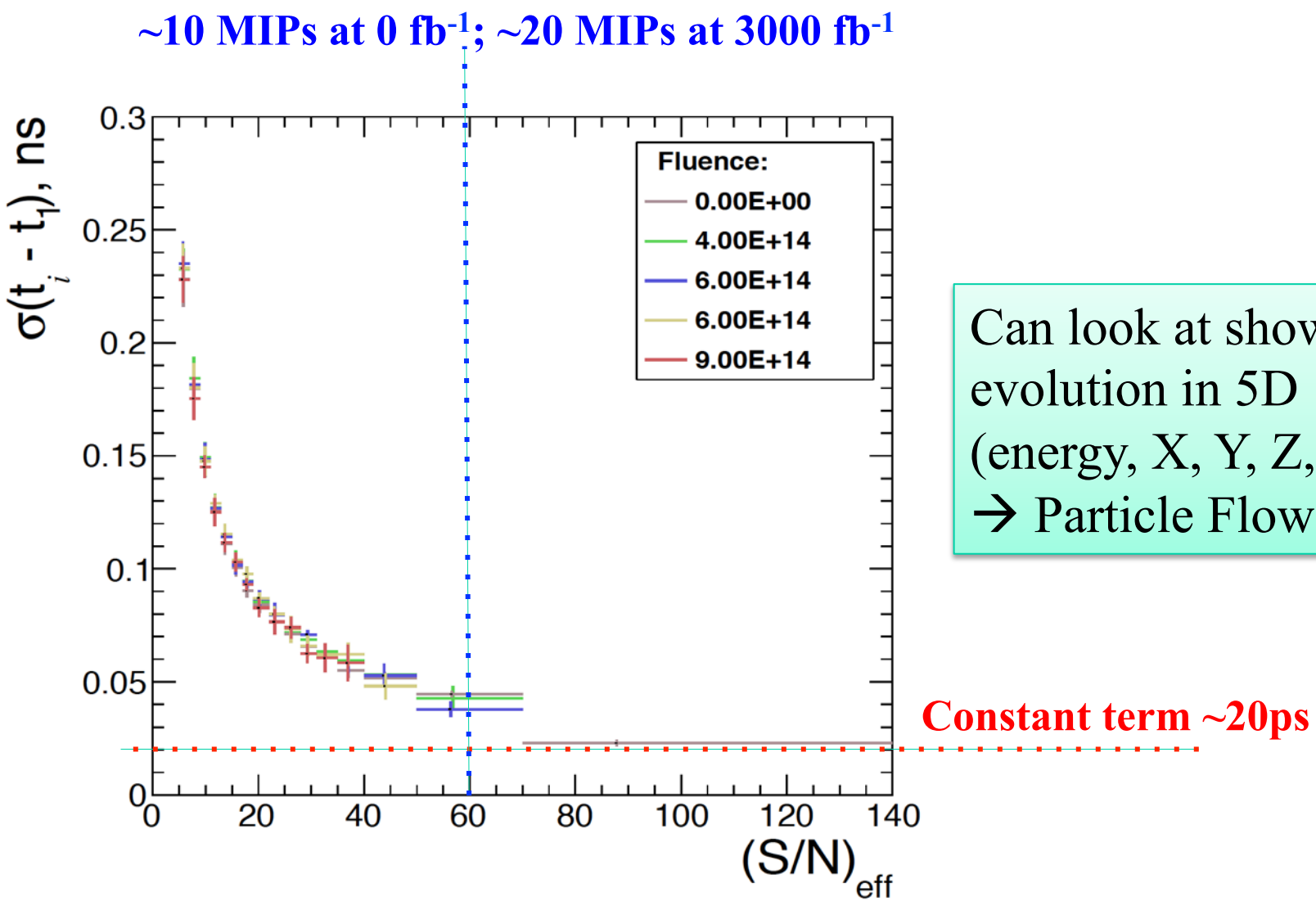
Beam tests in 2016 & 2017 with few layers validated basic design; good comparison to simulation





Distributions from electrons and pions match those predicted by simulation (to within 5%) demonstrating accuracy and scalability
First indications that HGCAL performance is as expected from simulation
More test-beam data will be taken in 2018

Silicon sensors also have good intrinsic timing resolution that does not degrade with radiation



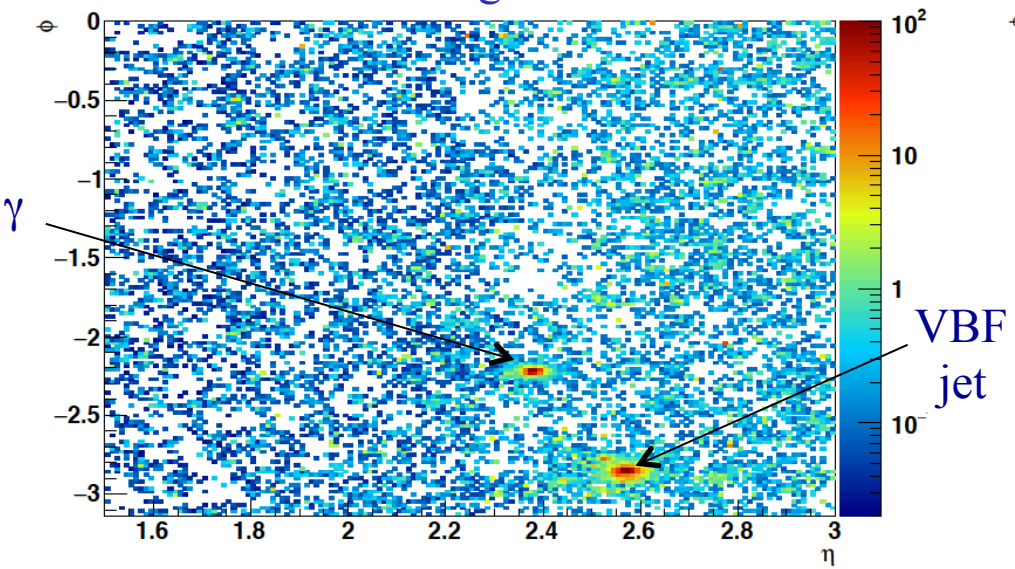
Can look at shower evolution in 5D (energy, X, Y, Z, t) → Particle Flow

As an illustration, granularity and timing can mitigate the effects of pileup → 5D detector!

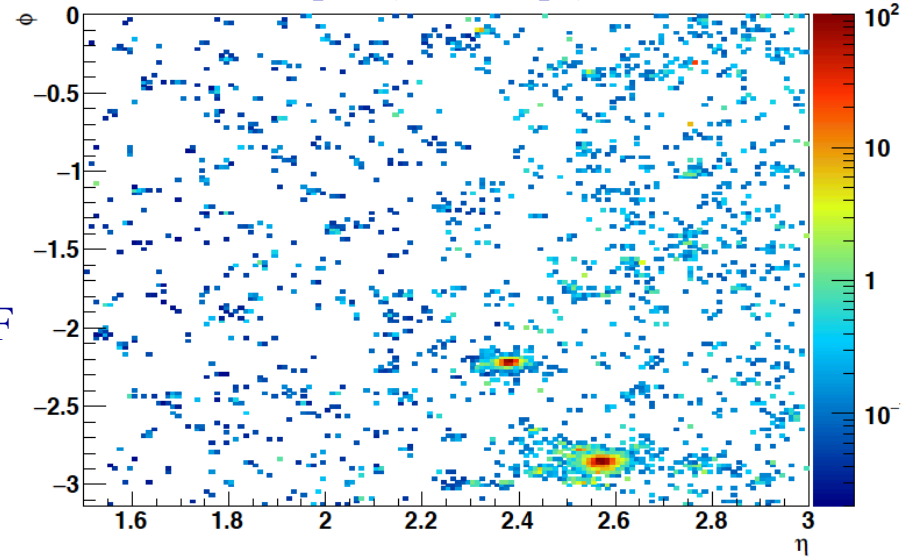
Possible due to the choice of CE sampling parameters and electronics

VBF (H→γγ) event with one photon and one VBF jet in the same quadrant,

No timing cut



Cut Δt < 90ps (3σ at 30ps)

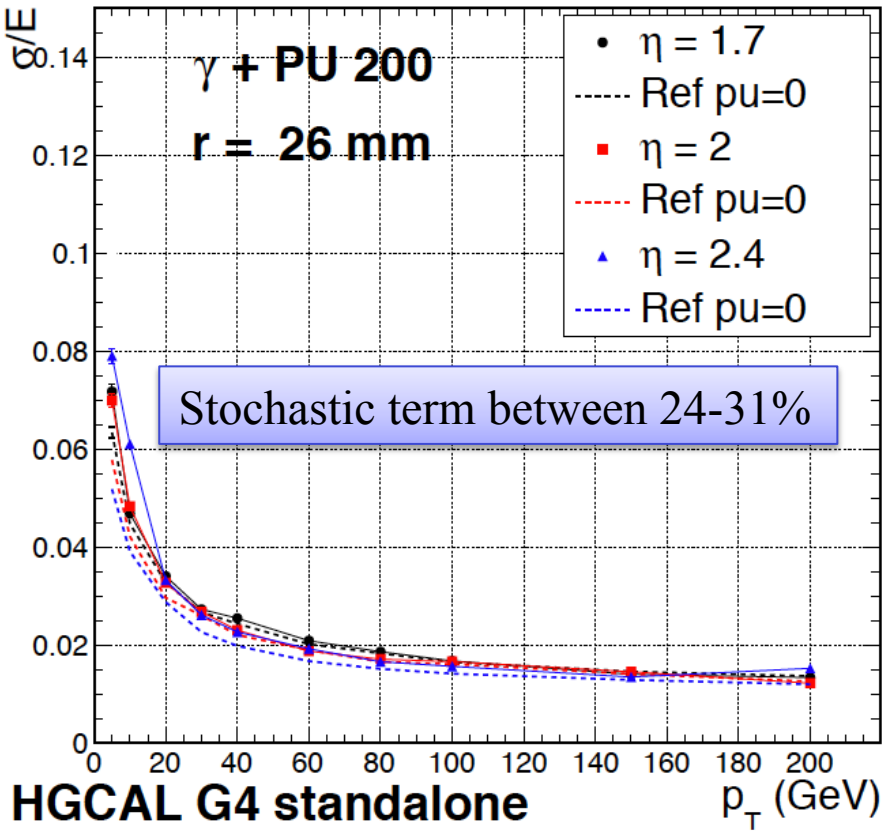


Plots show cells with Q > 12fC (~3.5 MIPs @300μm - threshold for timing measurement) projected to the front face of the endcap calorimeter.

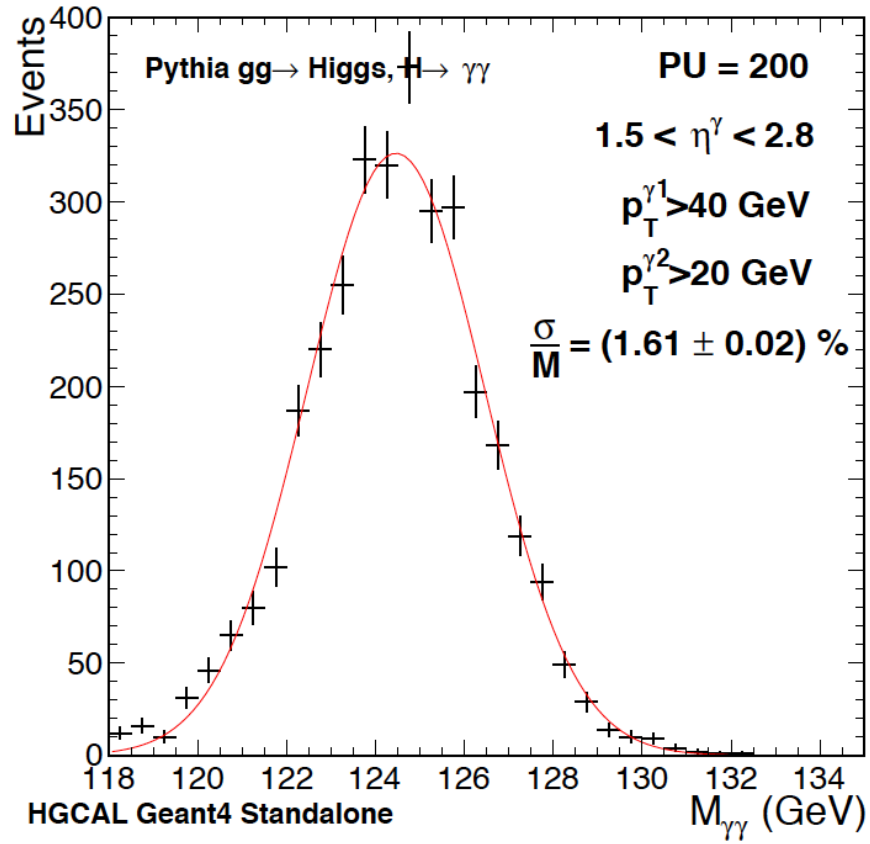
Concept: identify high-energy clusters, then make timing cut to retain hits of interest

G4 simulation used to predict performance of HGCAL in presence of pileup: e/γ resolution

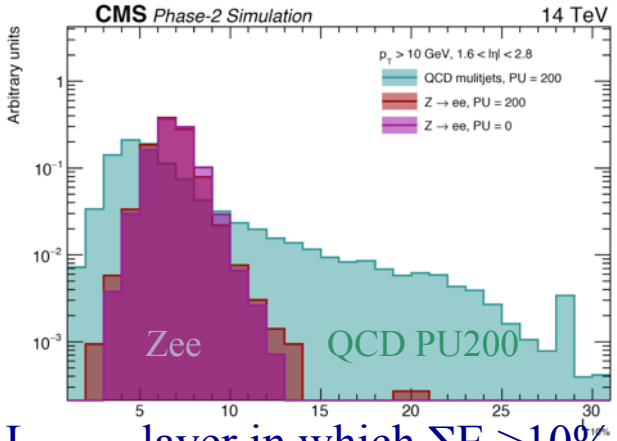
Single unconverted γ in CE-E reconstructed in r<2.6cm
→ **insensitive to pileup**



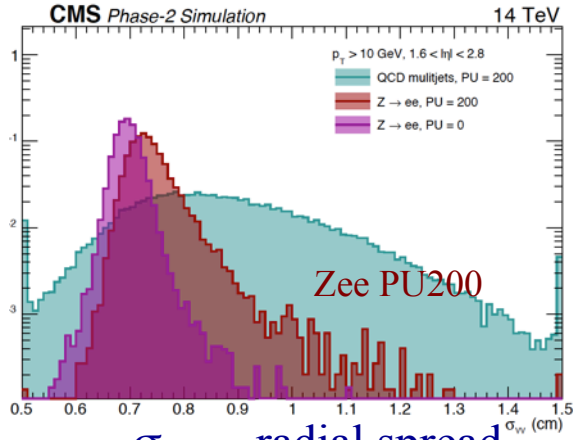
H-γγ, both γ in HGCAL (γ do not convert in TK) Pileup 200



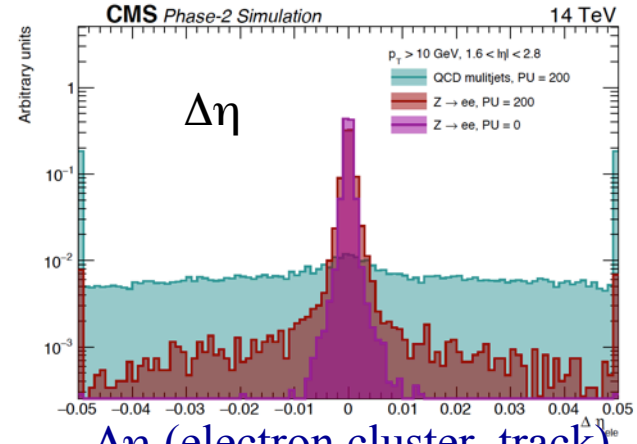
Longitudinal and transverse granularity provide excellent handles for electron/photon id



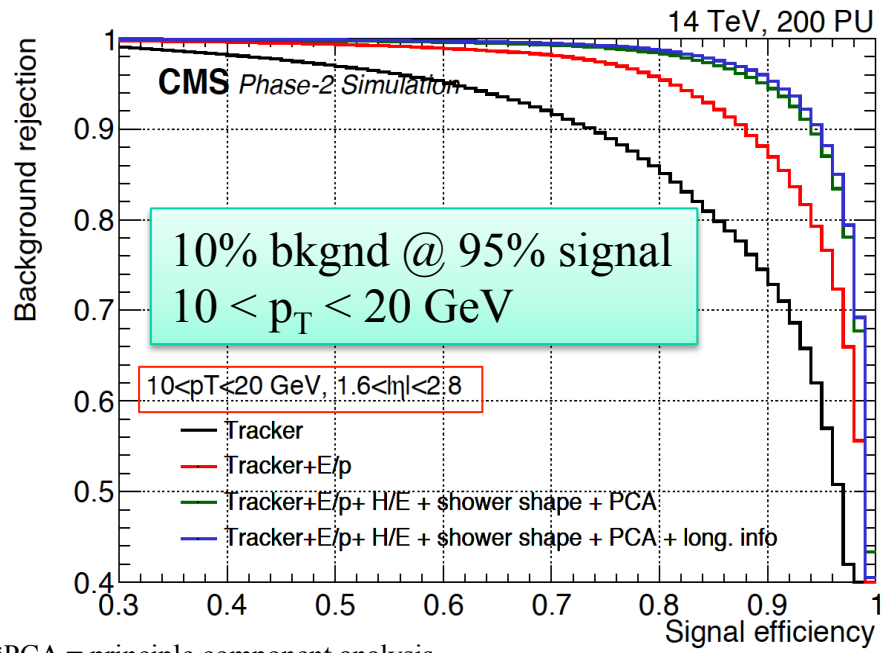
$L_{10\%}$ – layer in which ΣE >10%

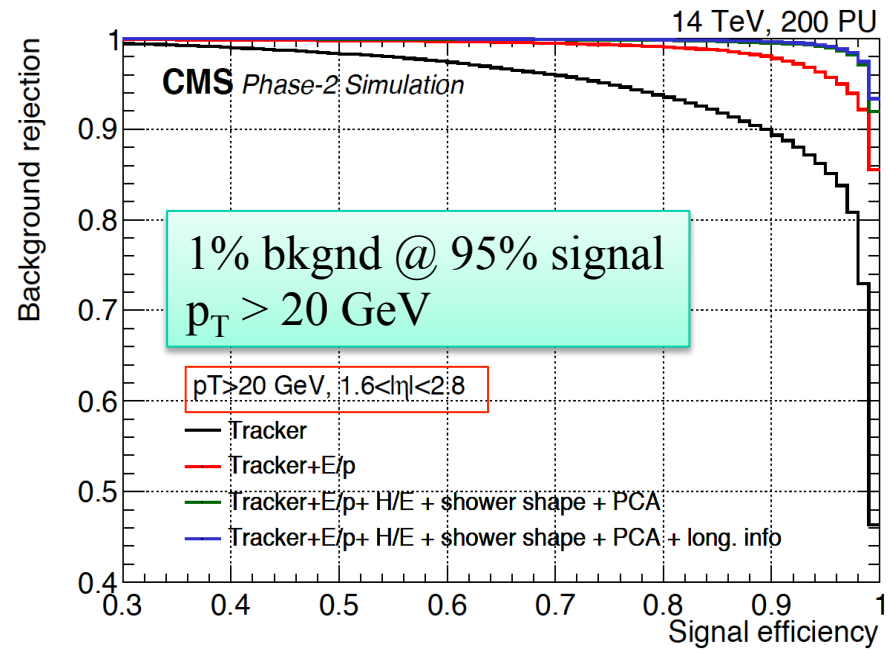


σ_{VV} – radial spread



Δη (electron cluster–track)

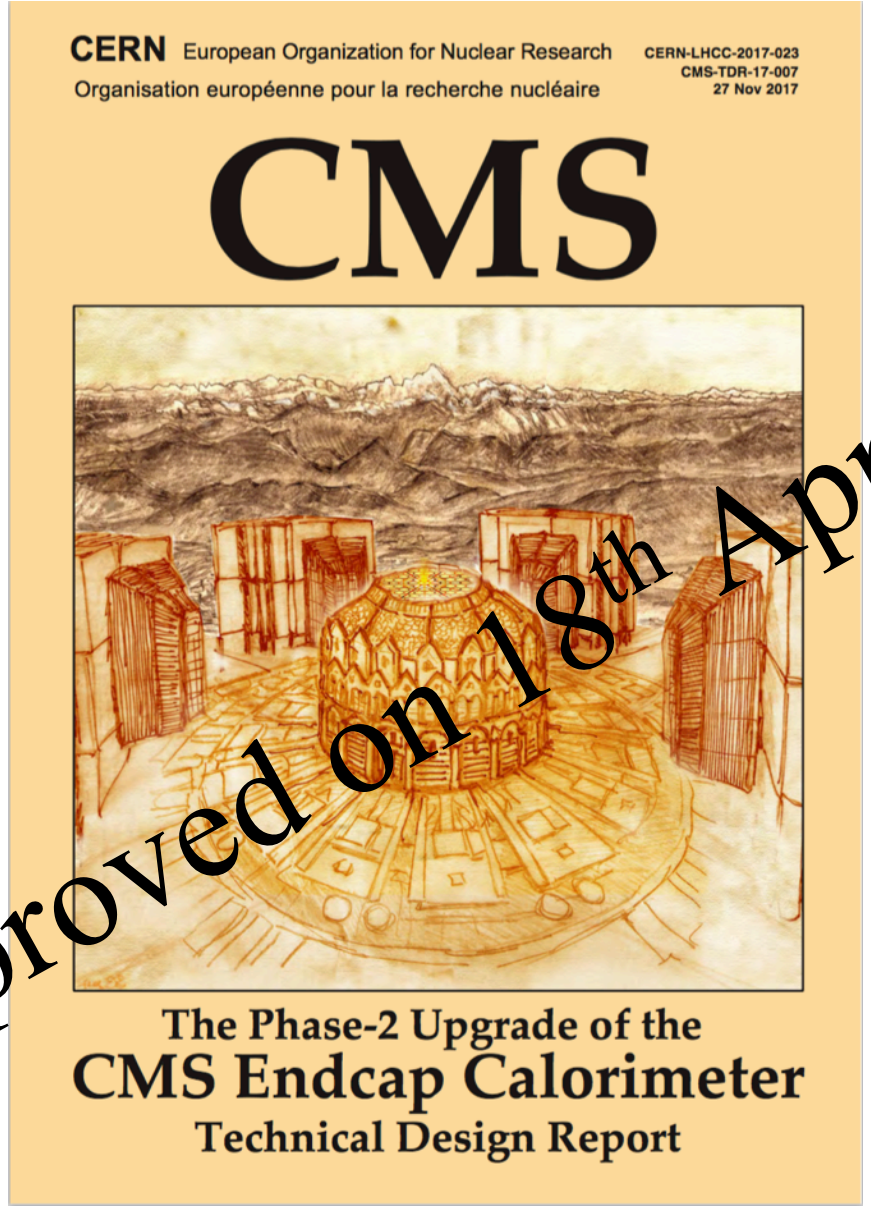




*PCA = principle component analysis

Challenges ahead

HGCAL TDR was submitted in Nov. 2017
R&D continues; construction starts in 2020



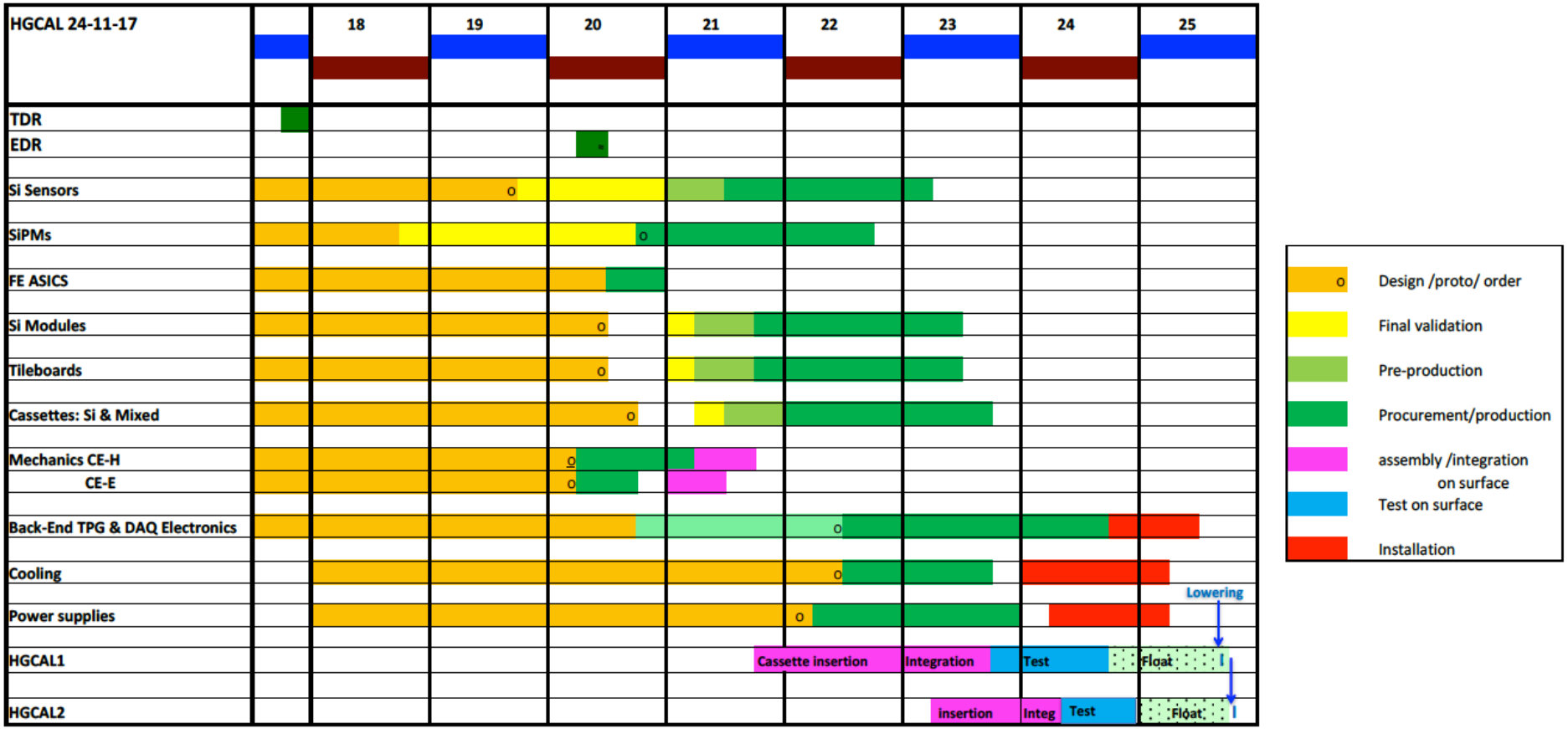
Approved on 18th April 2018!

CMS-TDR-17-007
http://cds.cern.ch/record/2293646

With the approval of the TDR (18th April 2018) we are entering a phase transition

- **Finalization of design, prototyping towards final systems (2 years)**
- **EDR (~May/June 2020) and ESRs**
  - This is a **much** faster timescale than the original LHC-experiment construction phase
- **Market Surveys, orders, preproduction, qualification of final components**
- **Production starts in <3 years !**

Synoptic view of HGCAL: ~5 years to finalize design, produce components, assemble, install



Highly-granular calorimeters, such as HGCAL, will provide much more information than any previous calorimeter.

Building and exploiting the HGCAL brings major technological challenges. An exciting time for detector and software development!