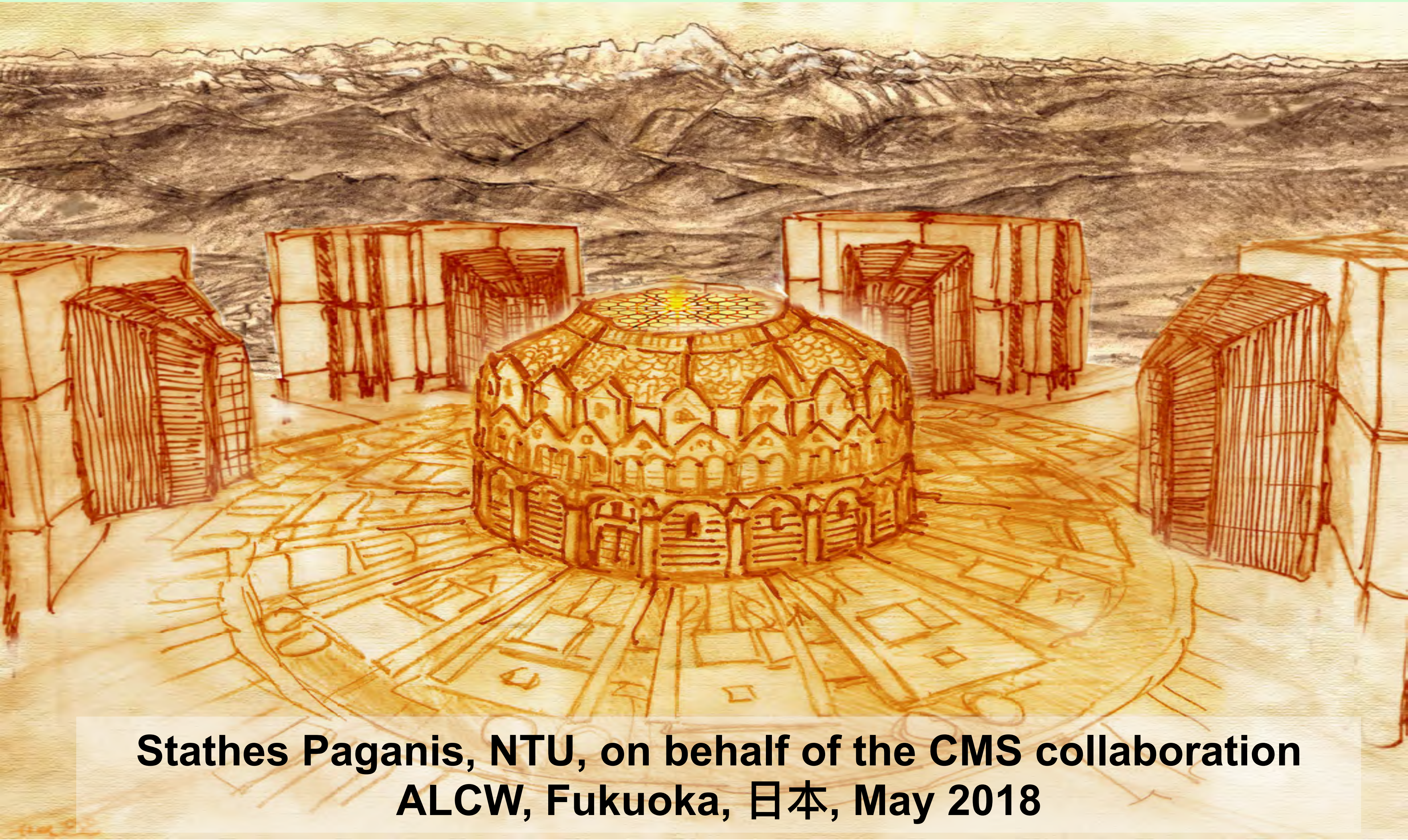
The CMS phase-2
High **G**ranularity **CAL**orimeter



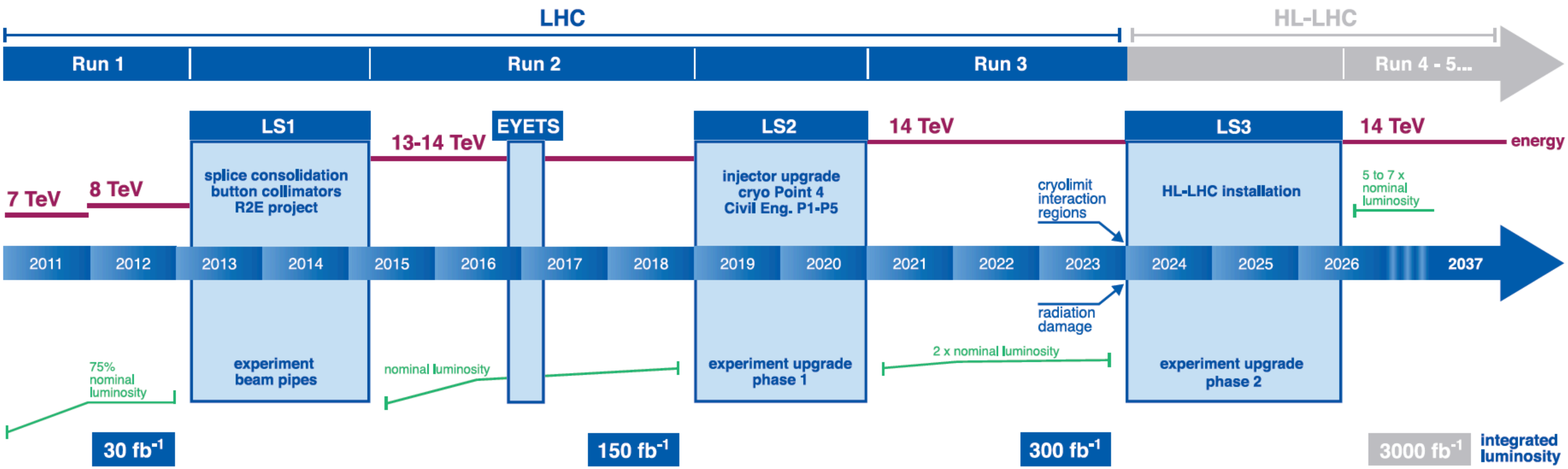
Stathes Paganis, NTU, on behalf of the CMS collaboration
ALCW, Fukuoka, 日本, May 2018

Outline

- Phase 2 requirements and the case for HGCAL
- Brief description of the detector design
  - Geometry, Sensors, Modules, Electronics.
- Reconstruction and Performance

- This presentation is based on the detailed review:
  Dave Barney, CERN EP Seminar, 20 April 2018.

High Luminosity LHC



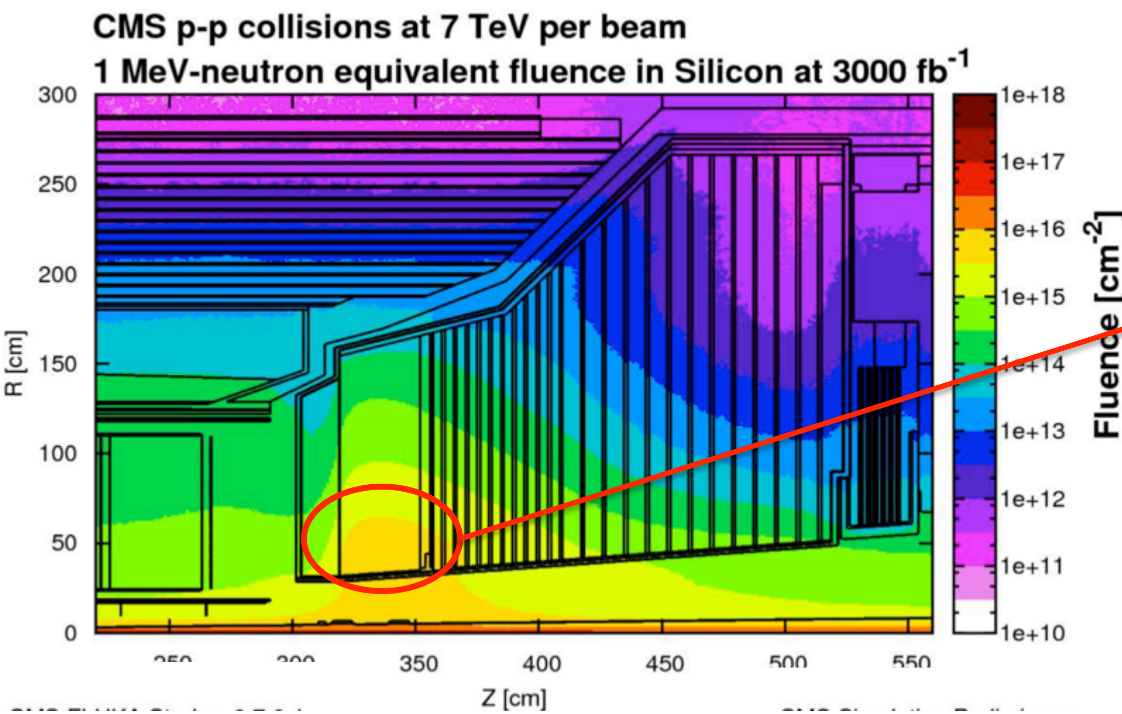
HL-LHC:
levelled $\mathcal{L}$ **= 5x10^{34}cm^{-2}s^{-1} and pileup 140**, with potential for 50% higher $\mathcal{L}$ & pileup

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

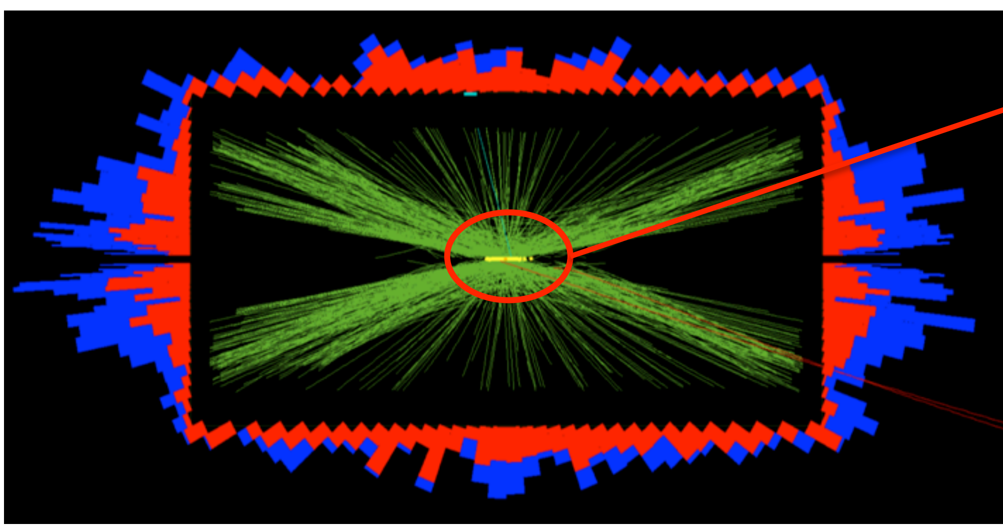
→ Ideally **want to trigger on these narrow VBF & merged jets**

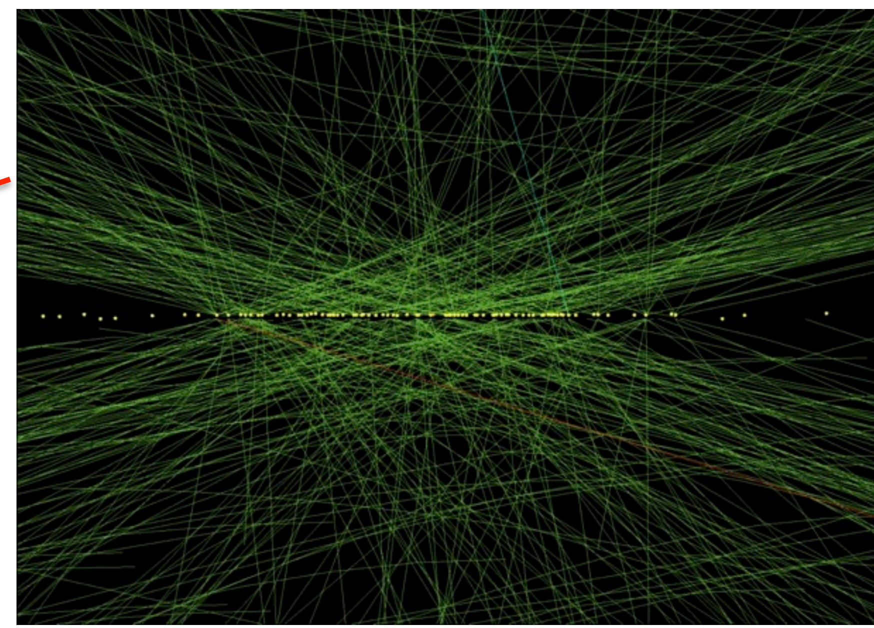
Existing CMS endcap calorimeters cannot cope with the expected radiation or pileup @ HL-LHC



CMS @ HL-LHC:

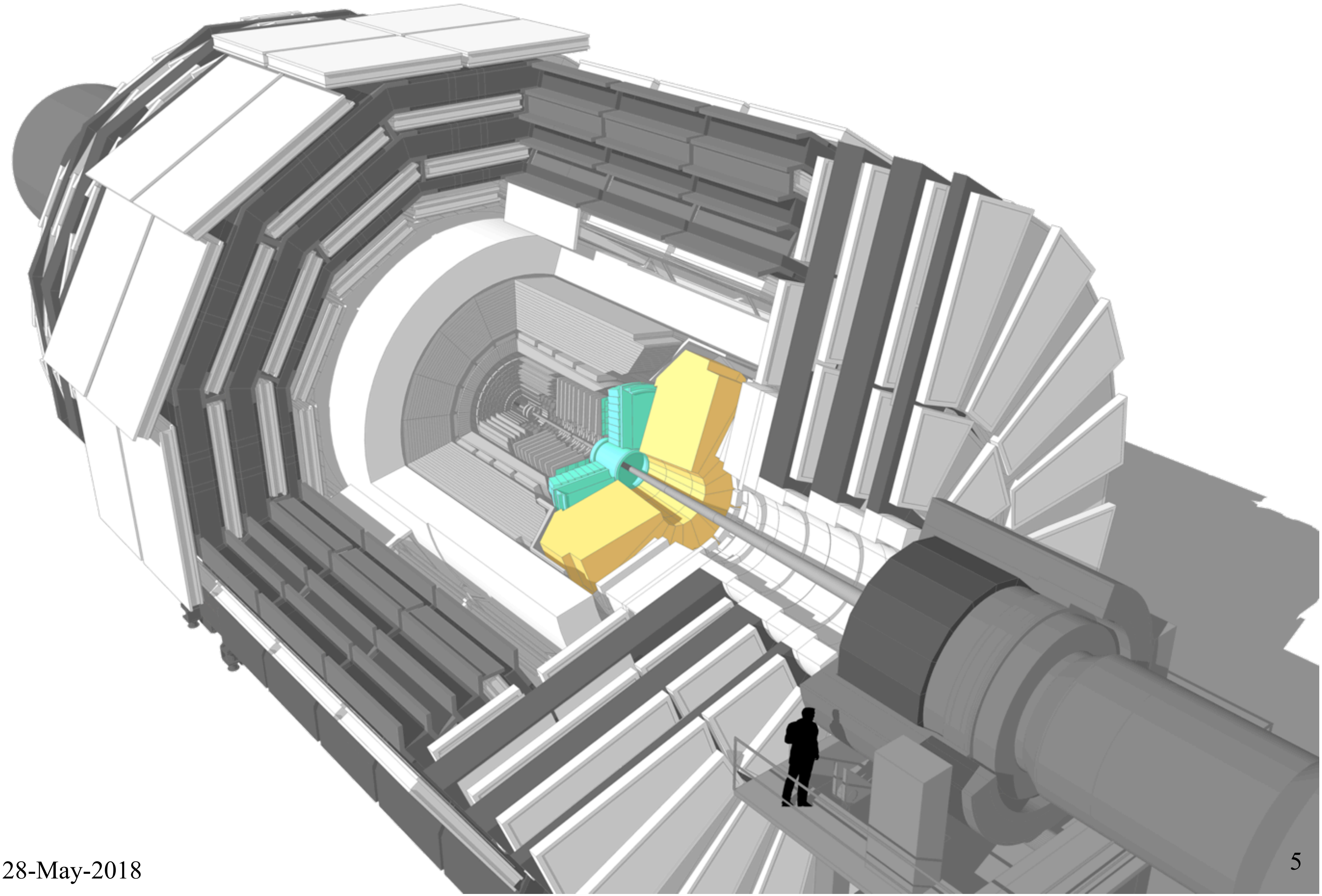
~1x10^{16} 1 MeV n_{eq} cm^{-2} @ 3ab^{-1} and up to **2 MGy** absorbed dose in endcap calorimeters





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

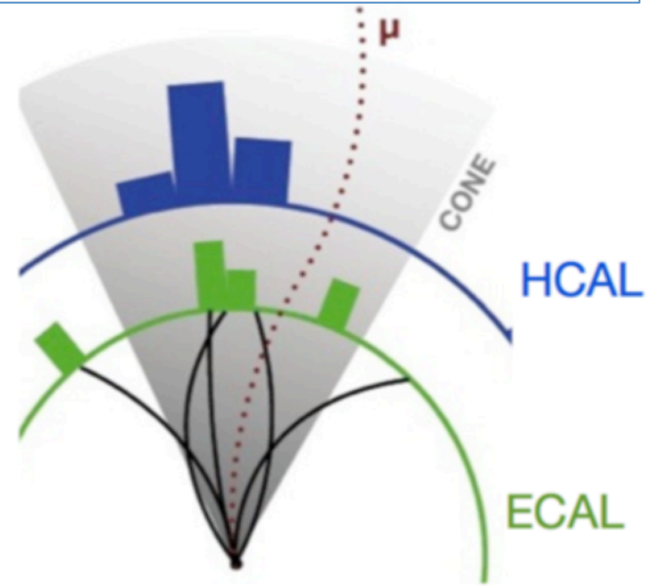
CMS will replace its endcap calos for HL-LHC: the **H**igh **G**ranularity **CAL**orimeter



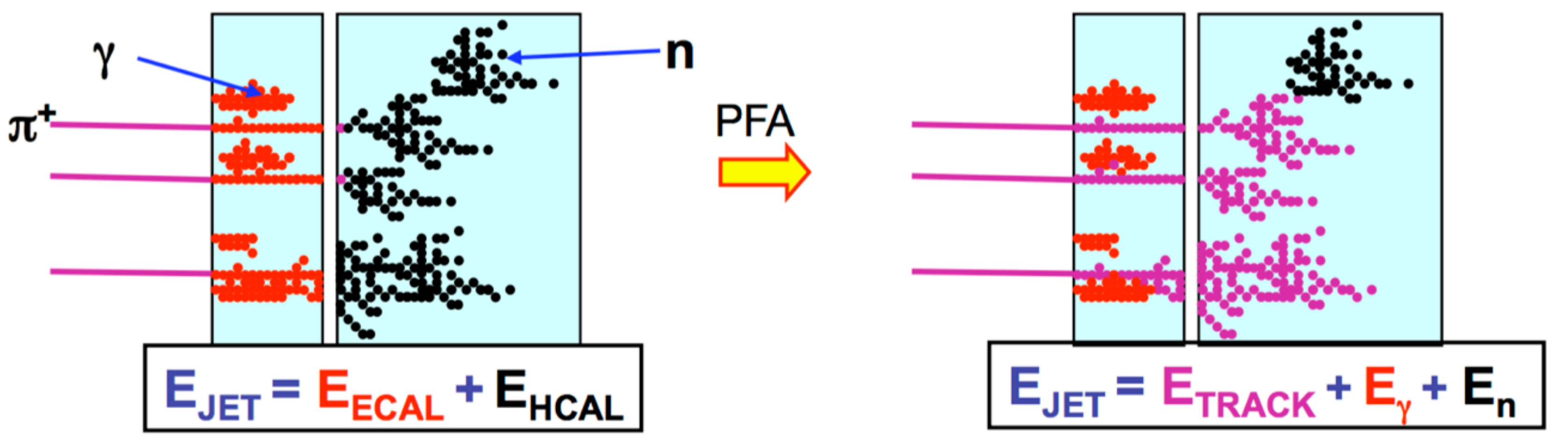
Need for good Jet Energy Resolution

Multi-jet final states (outgoing quarks, gluons)
Missing energy relies upon accurate jet energy measurements
Need to separate heavy bosons (W, Z, H) in hadronic decays

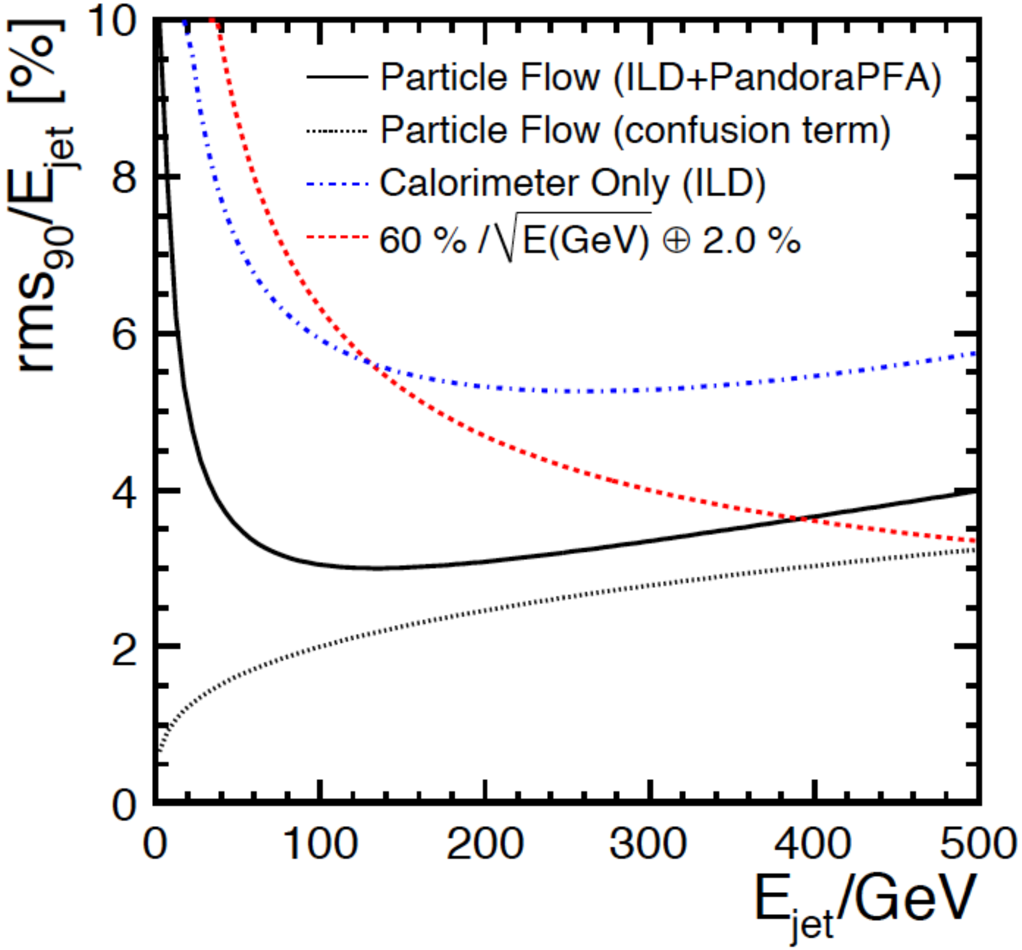
"Typical" jet:
- ~62% charged particles (mainly hadrons)
- ~27% photons
- ~10% neutral hadrons
- ~1% neutrinos



Particle Flow: use all available information for jet reconstruction



Particle Flow and HAD resolution



(from Katja Kruger's talk from BTTB5)

- PFA improves resolution.
- At high energies the correct track-cluster association becomes significant: need for high granularity
- At low energies dominated by calorimetric resolution: need for good energy resolution

Requirements ➔ Choice

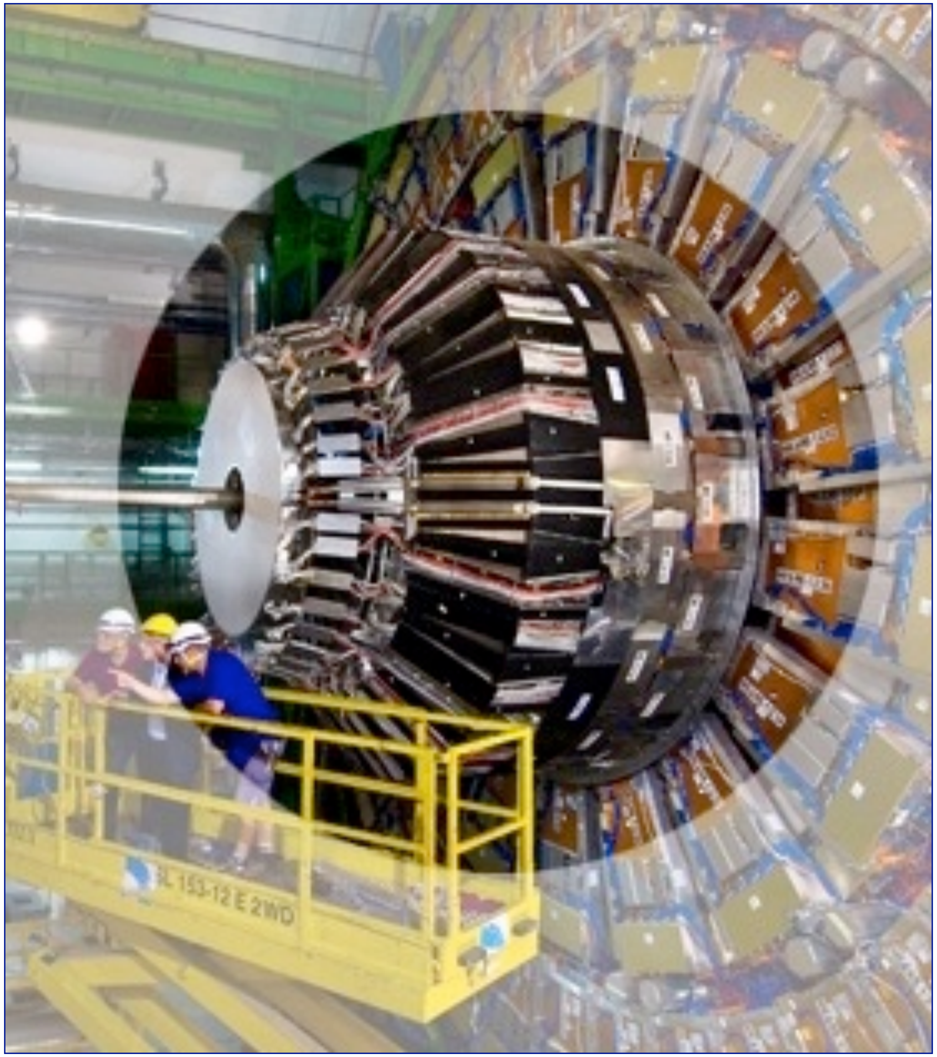
- Low cost/area active materials.
- Rad tolerant on-detector electronics
- High bandwidth data transmission, powerful FPGAs for off-detector electronics
- High transverse and longitudinal readout granularity for good PID, two-shower separation (EM and hadronic), good Energy resolution.
- Radiation hard active materials.

Inspired by the work of CALICE (many people from CALICE work in HGCAL)

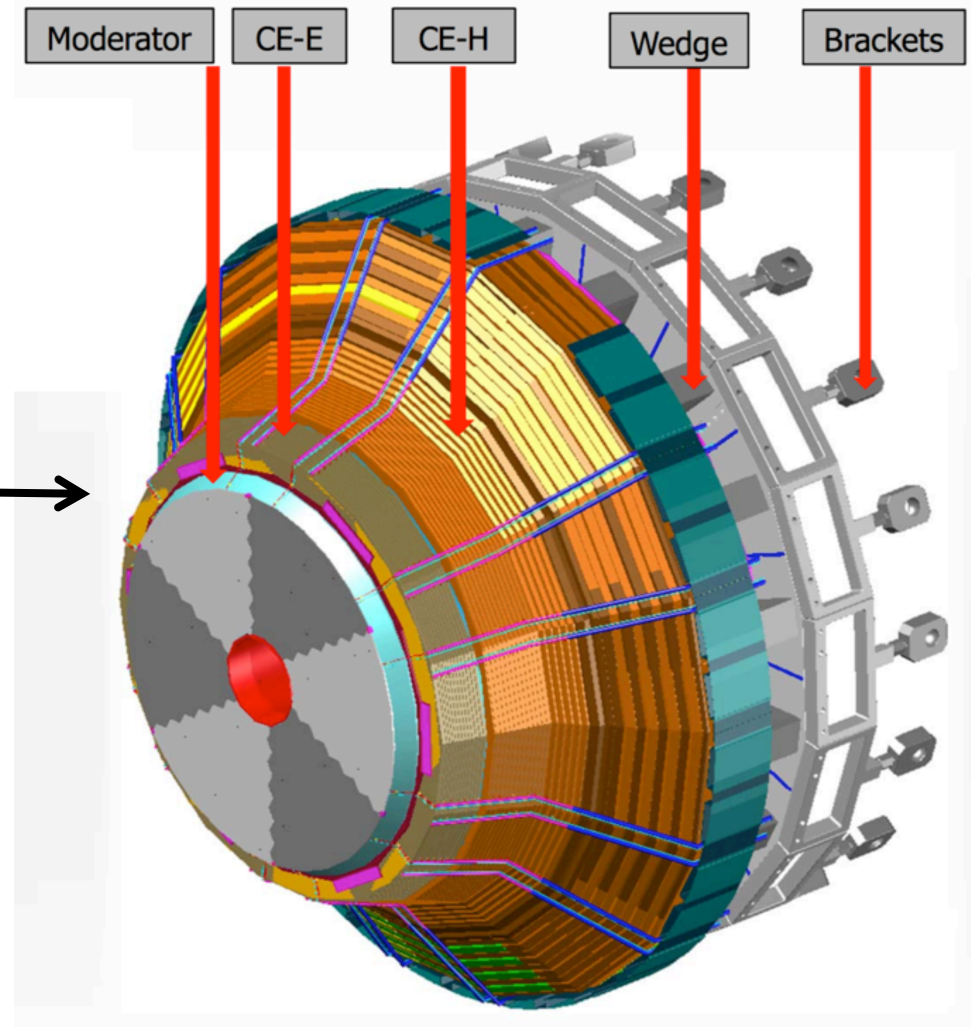
A silicon-sensor-based sampling calorimeter
(absorber materials – W, Pb, Cu, Stainless Steel)
followed by **plastic scintillator tiles with direct SiPM readout**
for the lower radiation level region
(absorber materials Cu & SS)

HGCAL Mechanical Design

Present CMS endcap calorimeters



HGCAL design

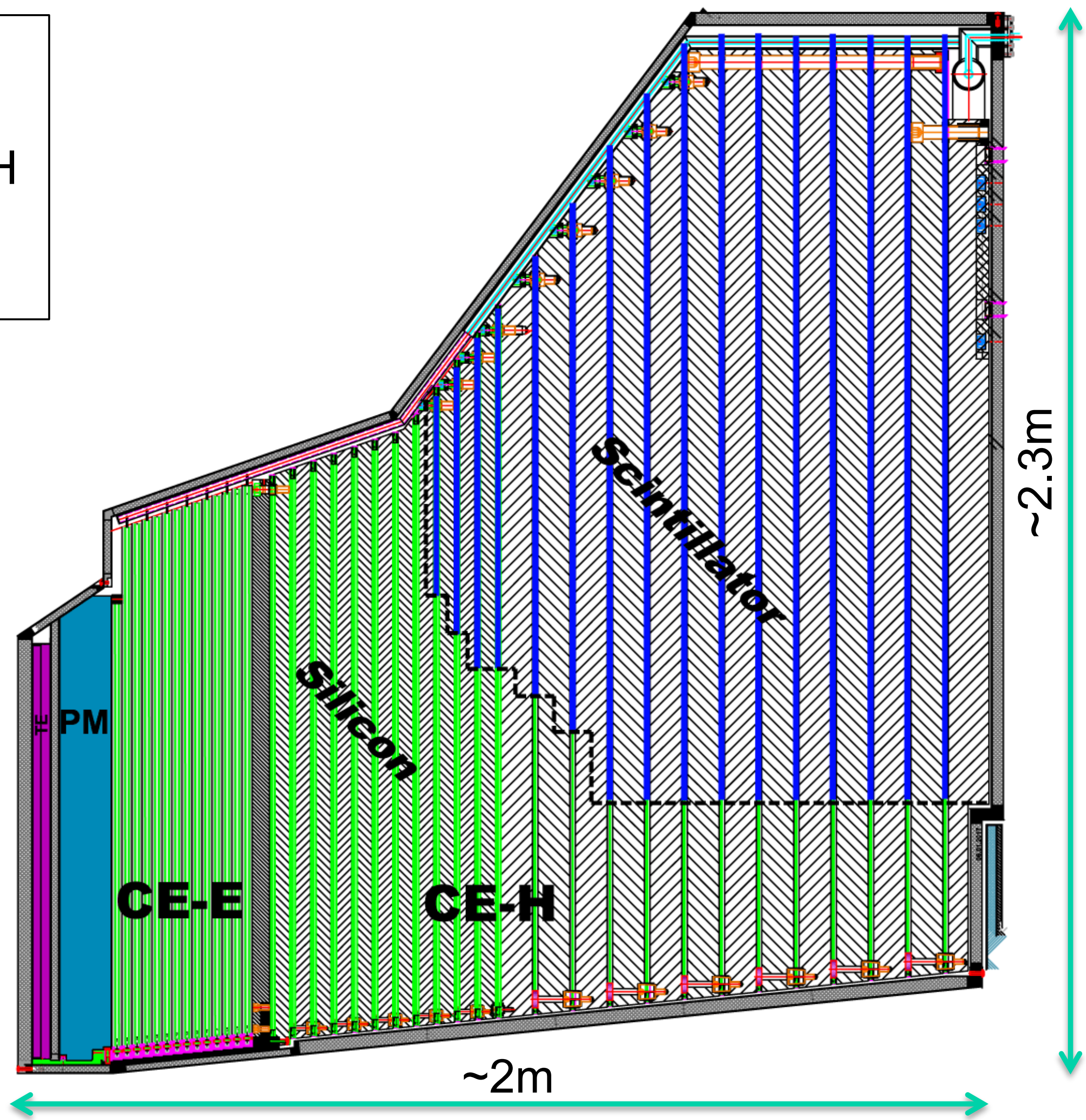


Remove complete endcap calo. system and **replace** with HGCAL
Calorimeter Endcap (CE), divided into CE-E and CE-H

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



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

~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)

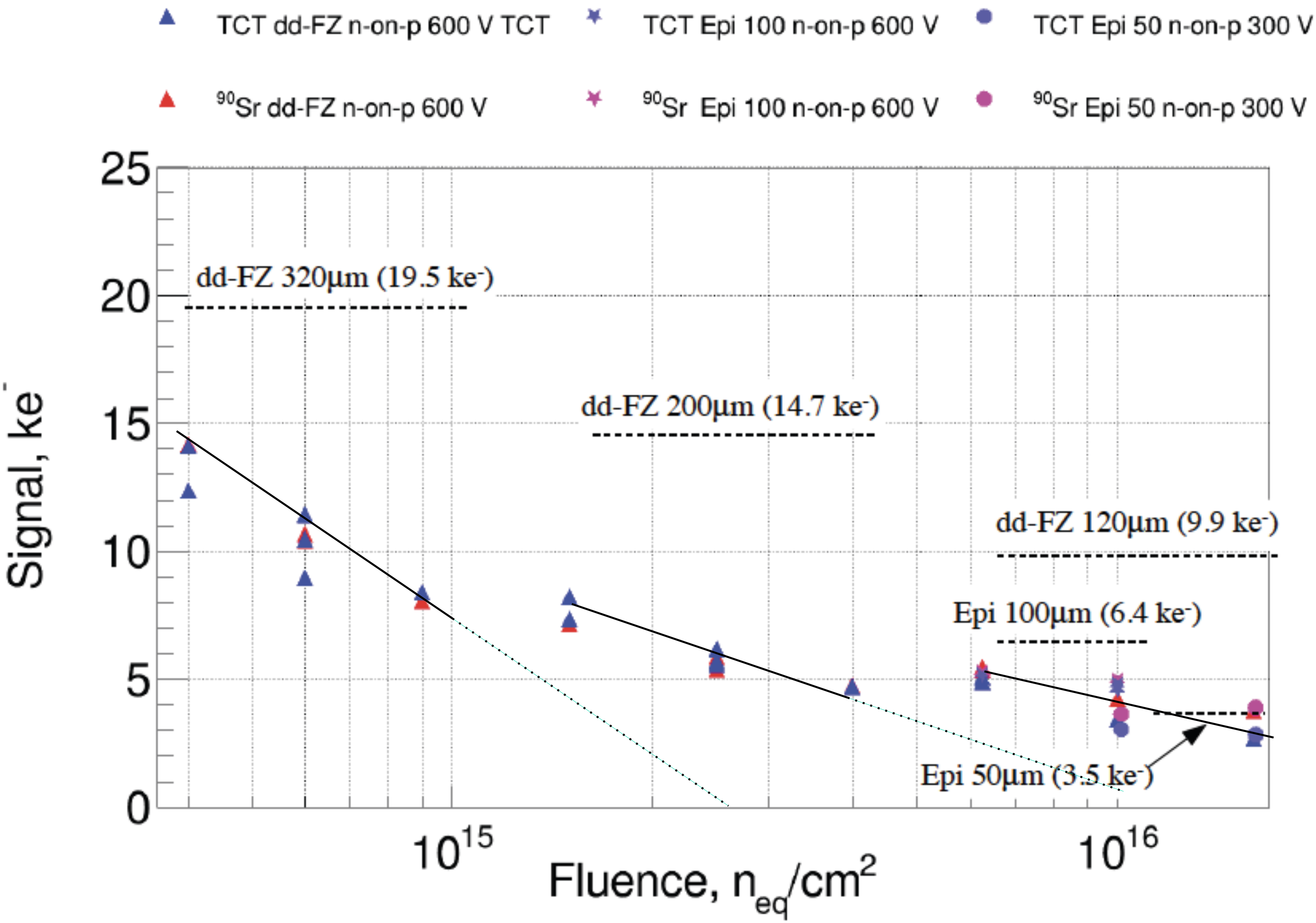
300μm, 200μm and 120μm active sensor thicknesses

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

Simple, rugged module design & automated module assembly

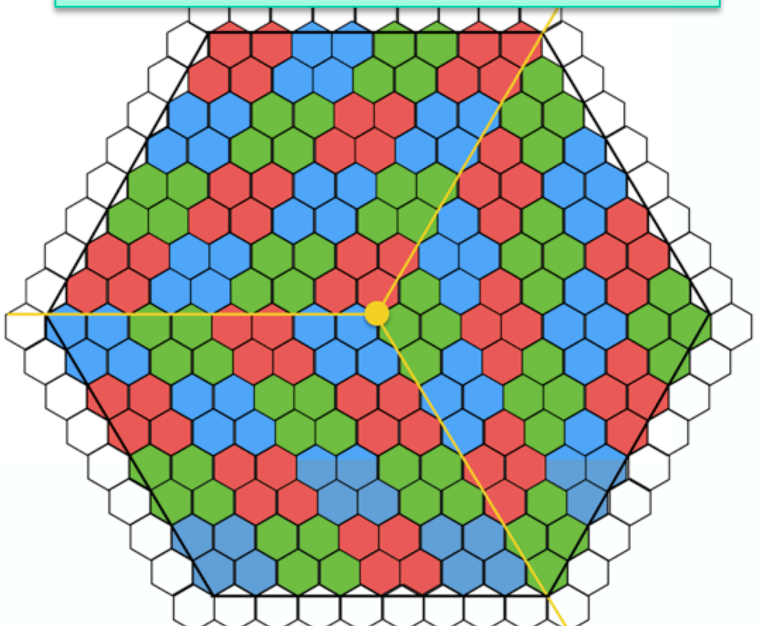
- provide high volume, high rate, reproducible module production & handling

Thinner sensors: less decrease in charge collection efficiency

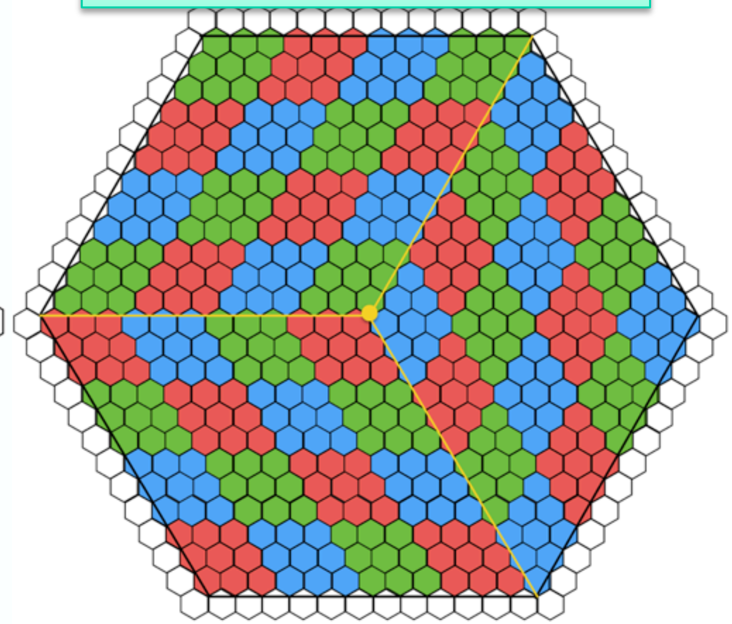


8” silicon sensors will be hexagonal, divided with 3-fold symmetry into hexagonal cells

300/200µm: 192 cells/sensor



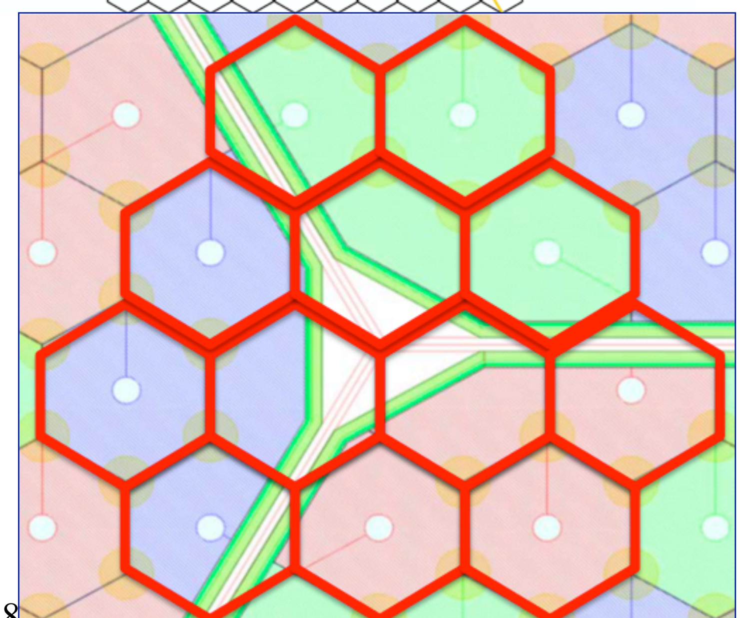
120µm: 432 cells/sensor

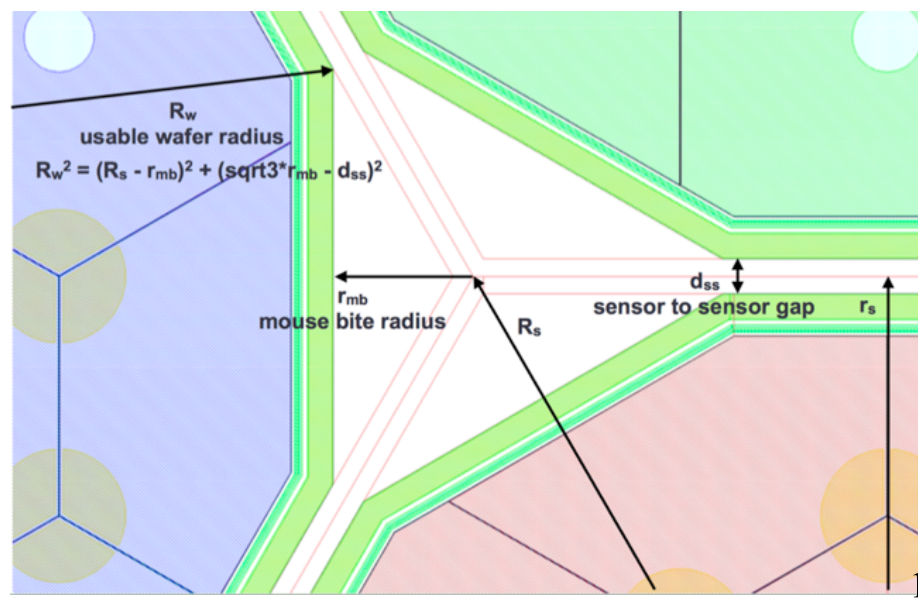


∅ ~ 190mm

All cells have C≤65pF

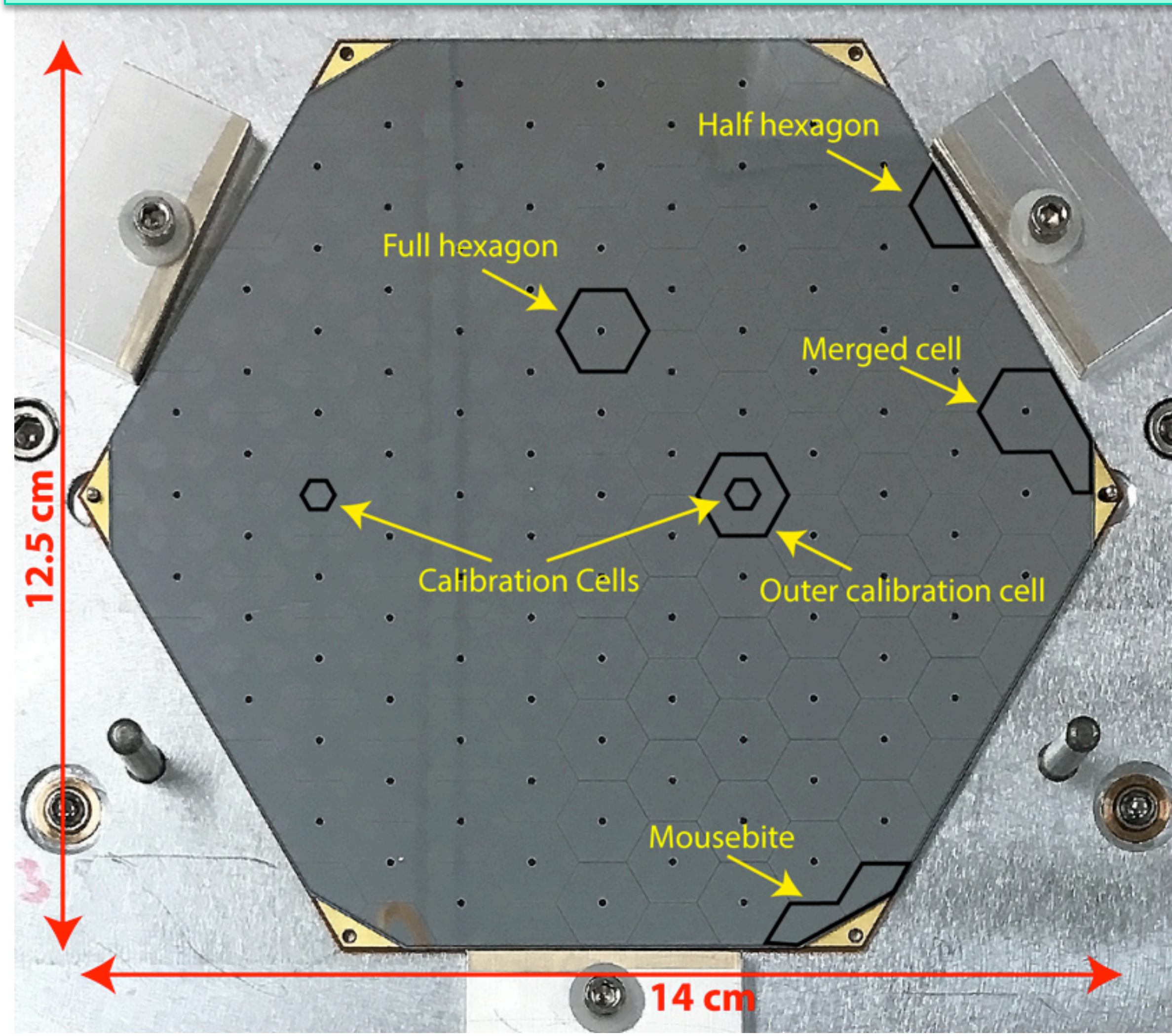
Coloured groupings of cells represent “trigger cells”



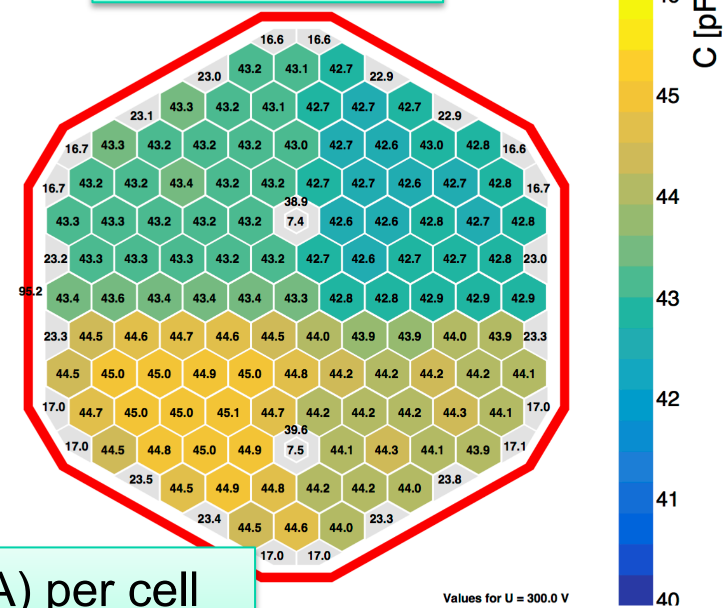


Sensors divided in hexagonal cells + some special cells

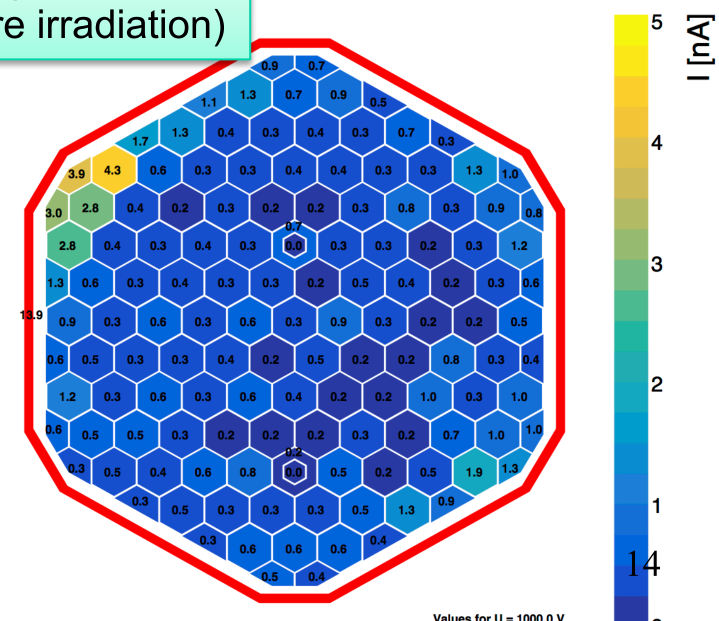
6” prototype sensor, with 4 quadrants of inter-cell spacing



~55pF per cell



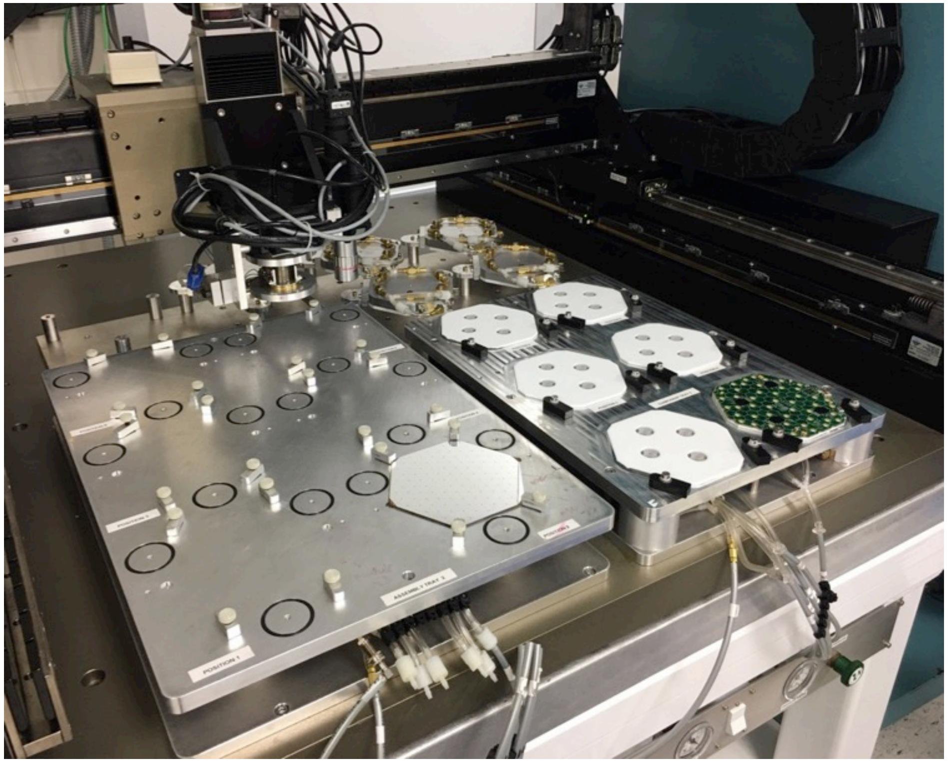
O(nA) per cell
(before irradiation)

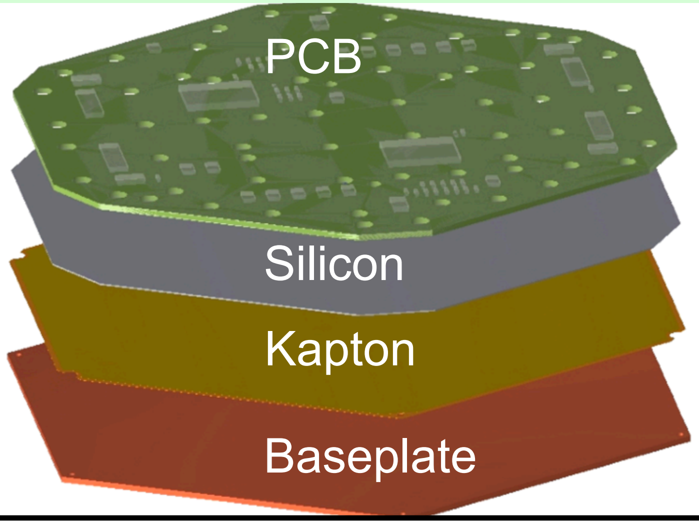


Prototype 6” and 8” sensors made by three producers

Si modules are glued assemblies

Automated gantry @ UCSB
used previously for CMS tracker assembly



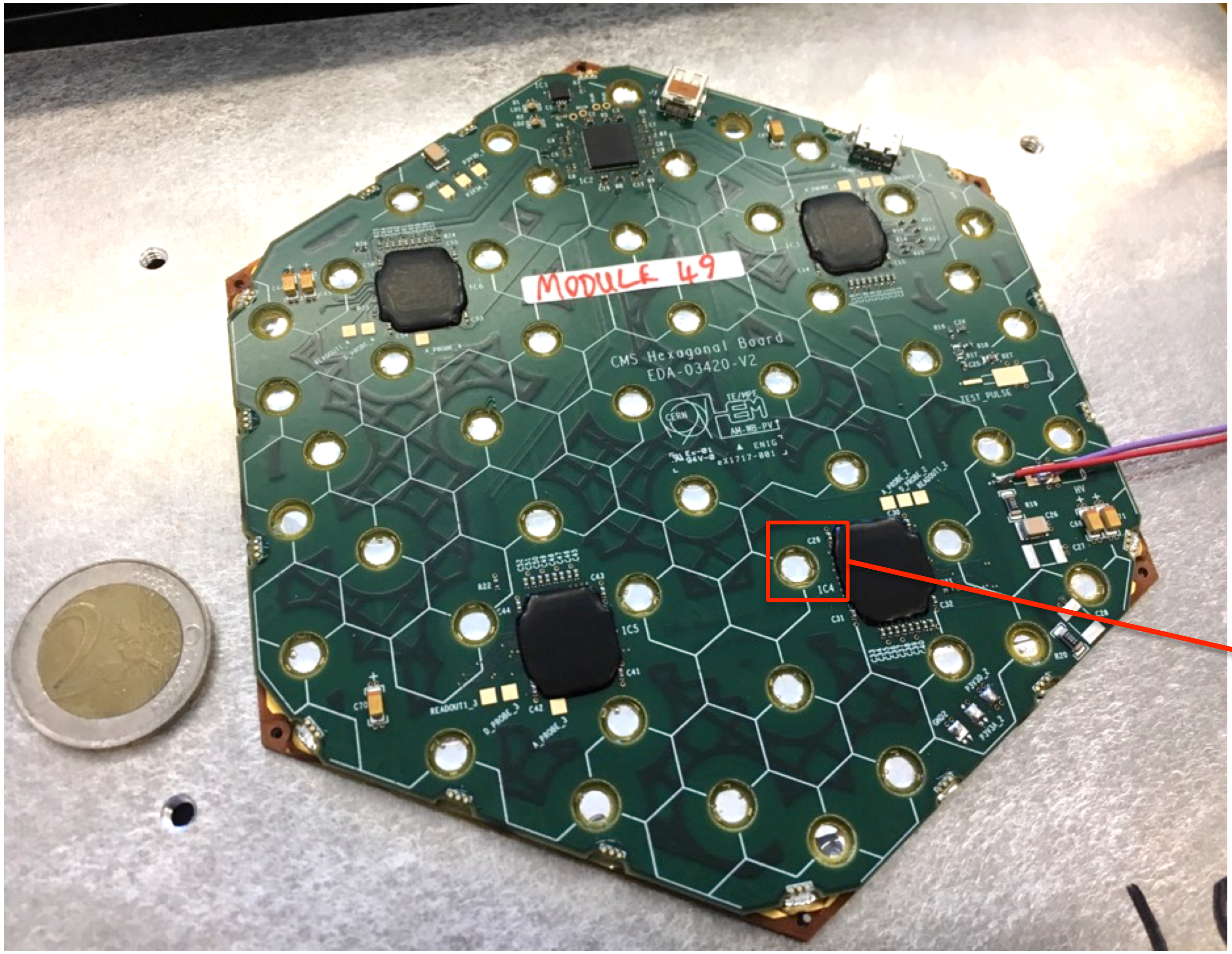


In CE-E, baseplate = 1.2mm CuW, to
keep overall density high

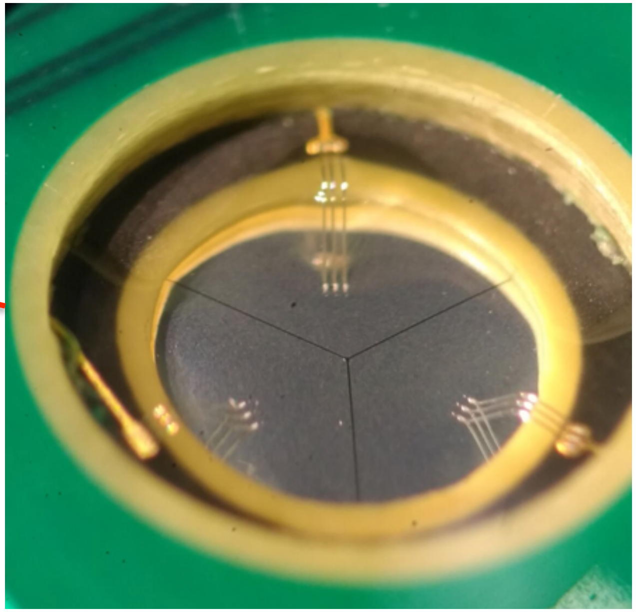
Three centers are being setup in Asia:
India, China (IHEP), **Taiwan (NCU/NTU)**

27000 modules with 0.5-1cm^2 pads

Silicon sensor glued to baseplate and PCB containing FEE

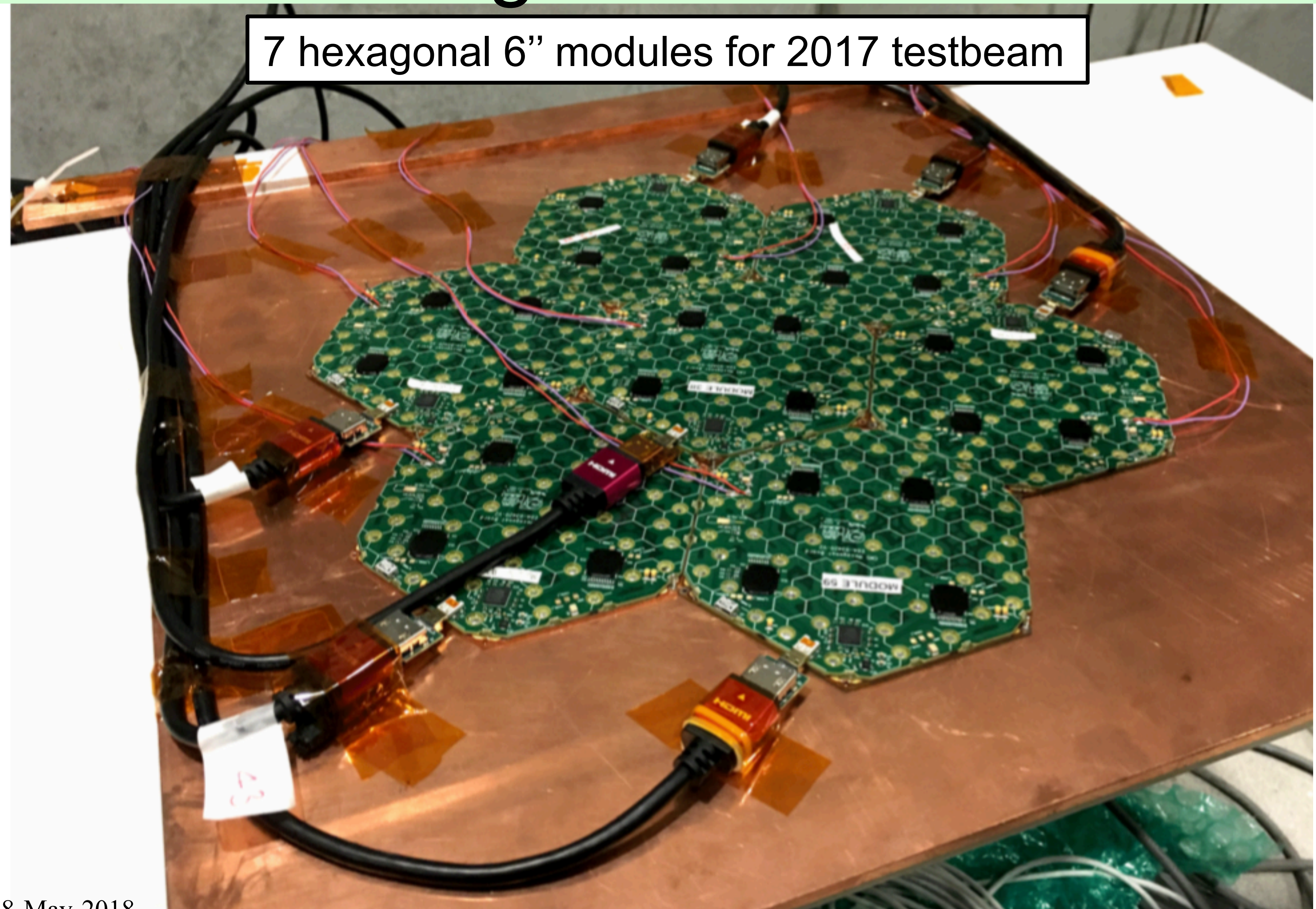


Wire bonding from PCB to silicon through holes

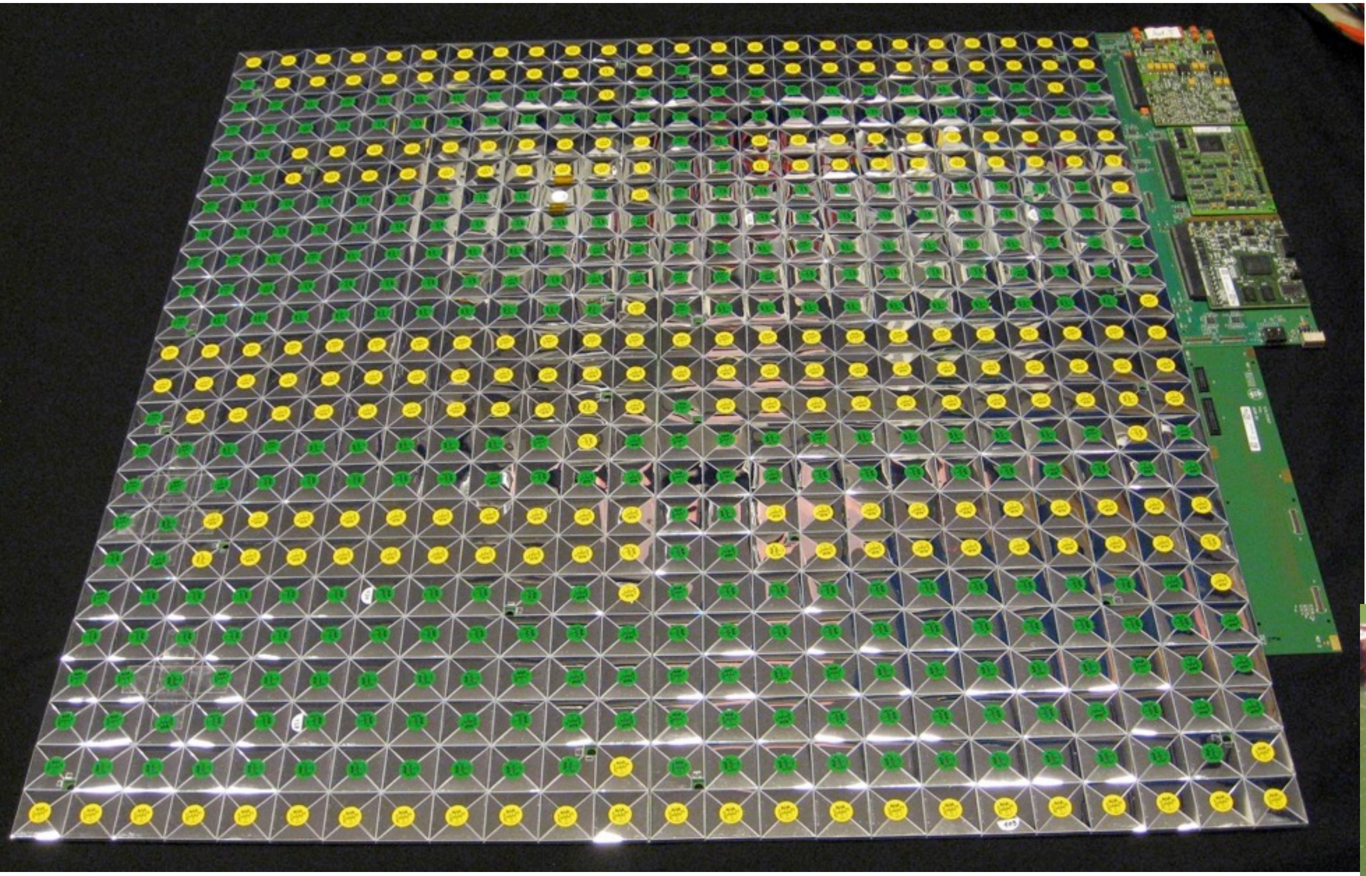


Si Modules arranged in hexagonal matrices

7 hexagonal 6” modules for 2017 testbeam

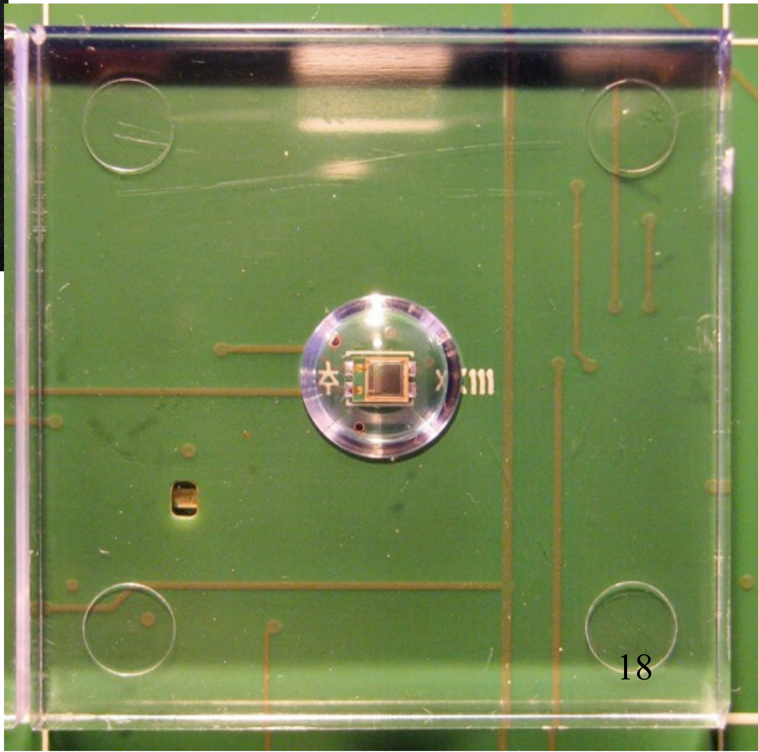


HGCAL will also include 500m^2 of scintillator tiles with on-tile SiPM readout



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

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



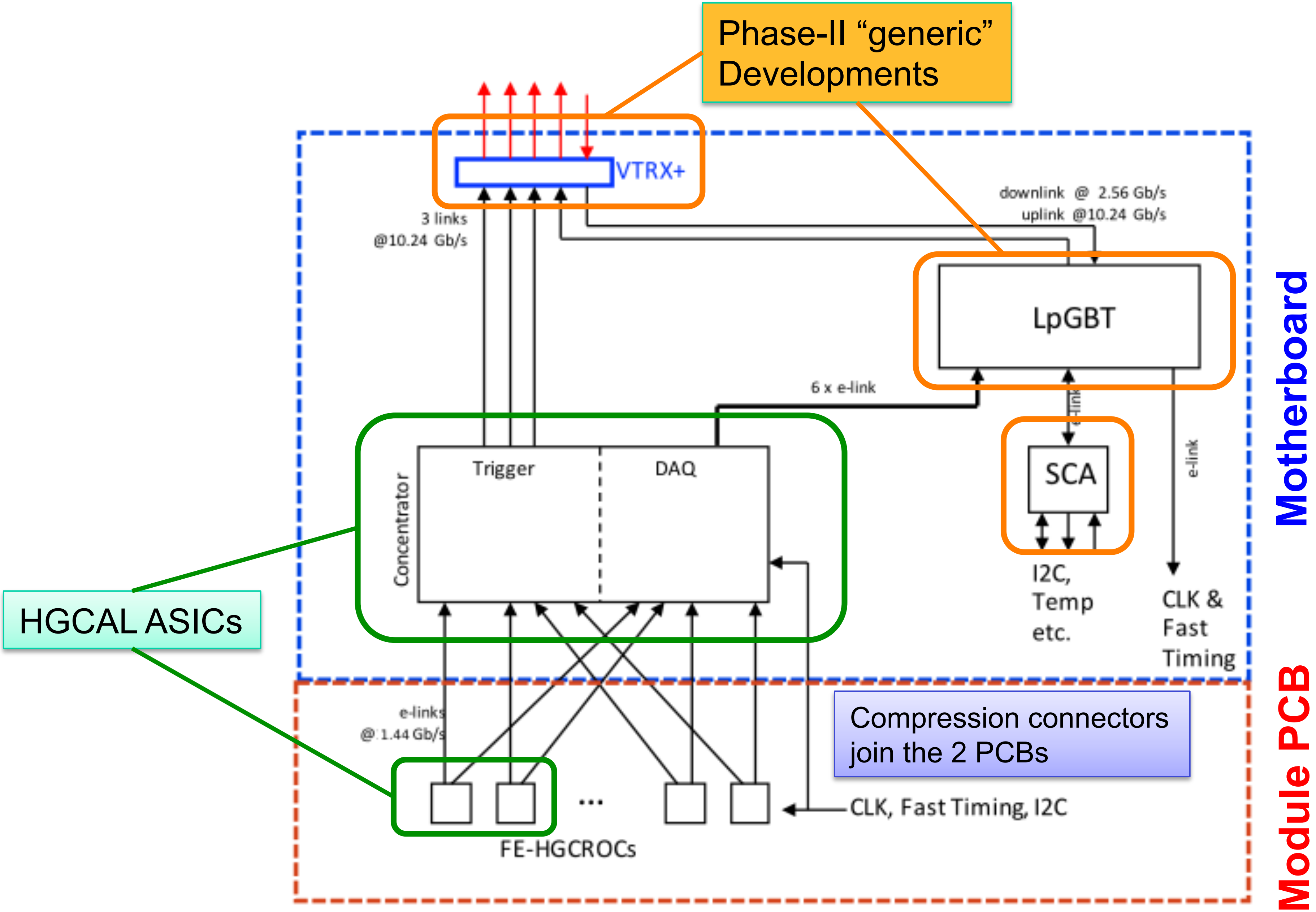
For first beam tests, modified CALICE AHCAL used for rear hadron calorimeter:
3x3cm^2 scintillator tiles + direct SiPM readout

The FE electronics are particularly challenging in the compact HGCAL

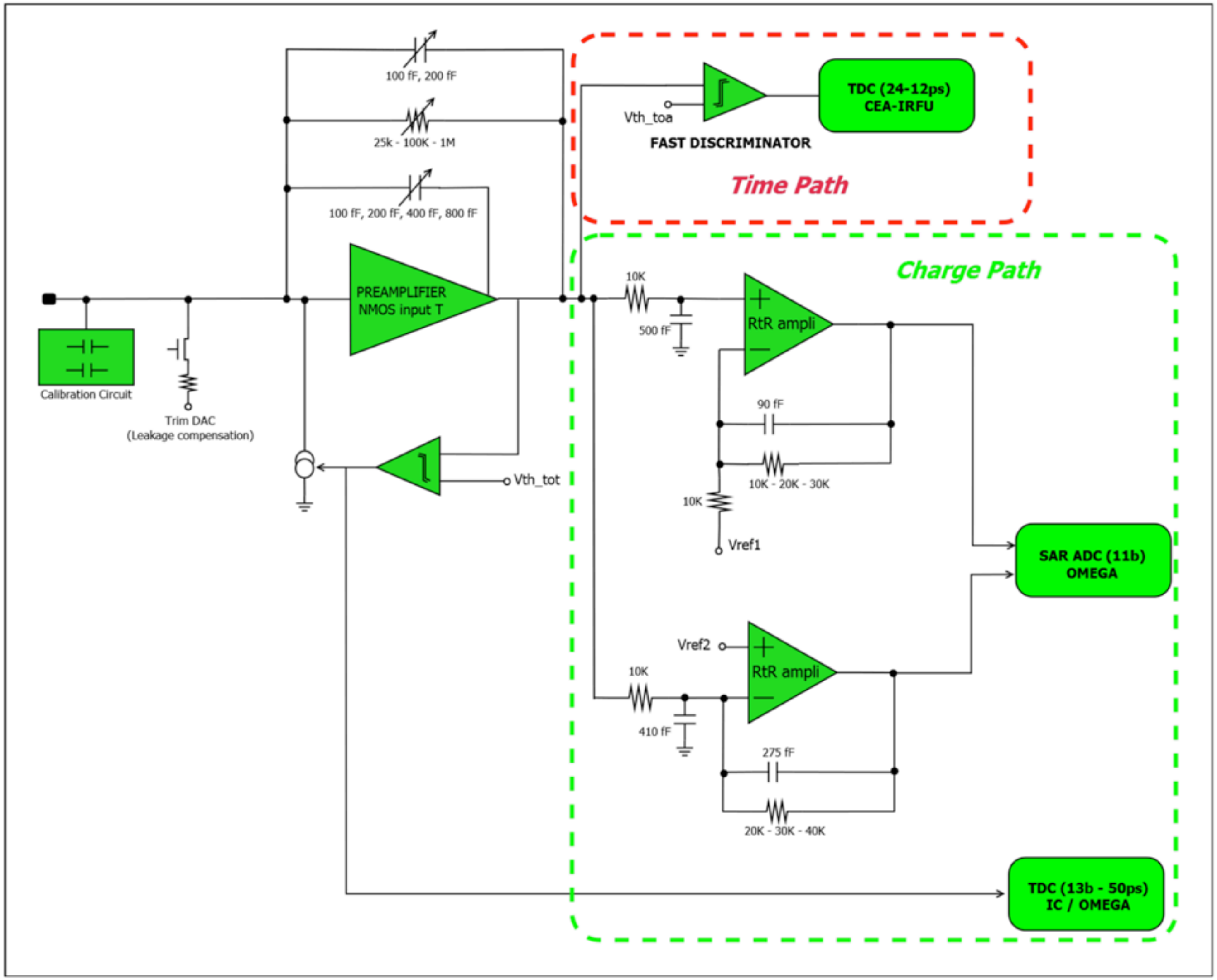
- Low noise (<2500e^-) and high dynamic range (~0.2fC → 10pC)*
  - See **MIPs** (~3.5fC in 300μm silicon) **with S/N > 2** for whole lifetime of HL-LHC
  - Use 130nm CMOS with 1.5V supply
- Provide timing information to tens of picoseconds
  - Need clock distribution jitter 10-15ps (same specs as for 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

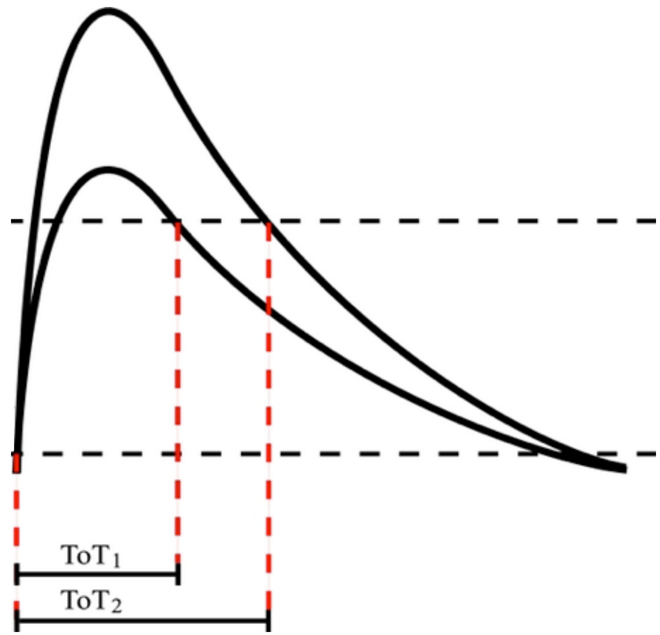
On-detector electronics are a mixture of HGCAL-specific ASICs and "generic" developments



HGCROC: includes ToT (low power high dynamic range), ToA (timing) and on-chip ADC/TDC

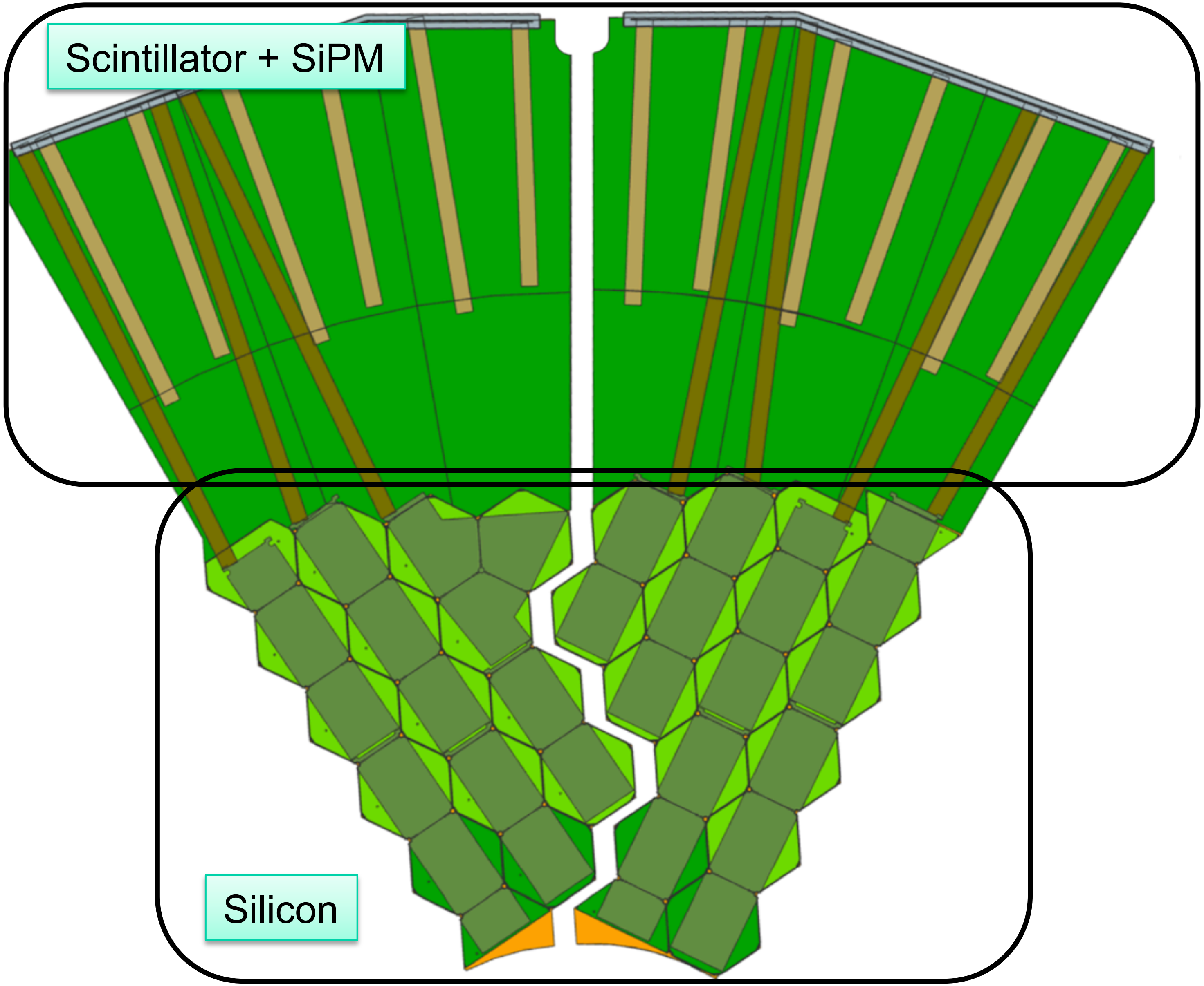


Time over threshold:
Proportional to pulse height

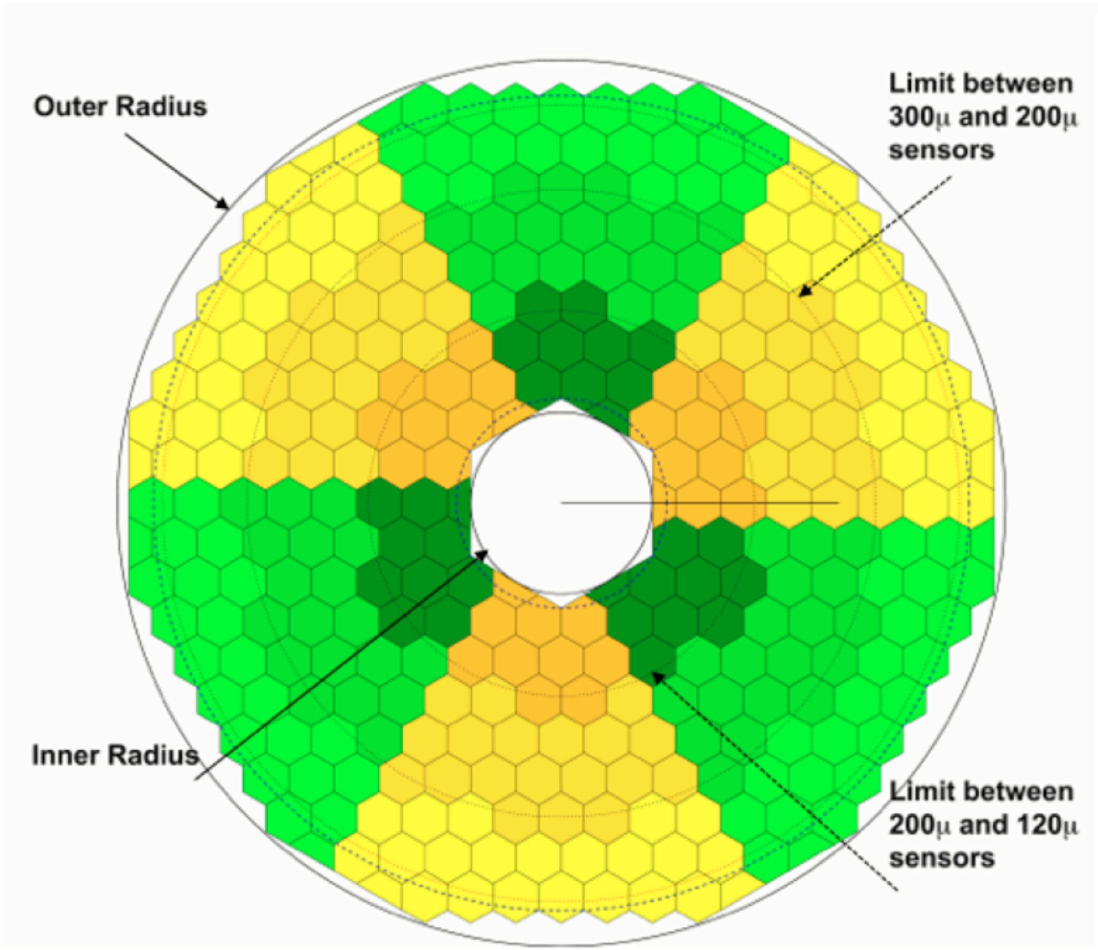


Skiroc2-CMS ASIC (2017) already had some of these features, inc. ToT
First simplified HGCAL ASIC (HGCROCV1) in 130nm CMOS being tested now

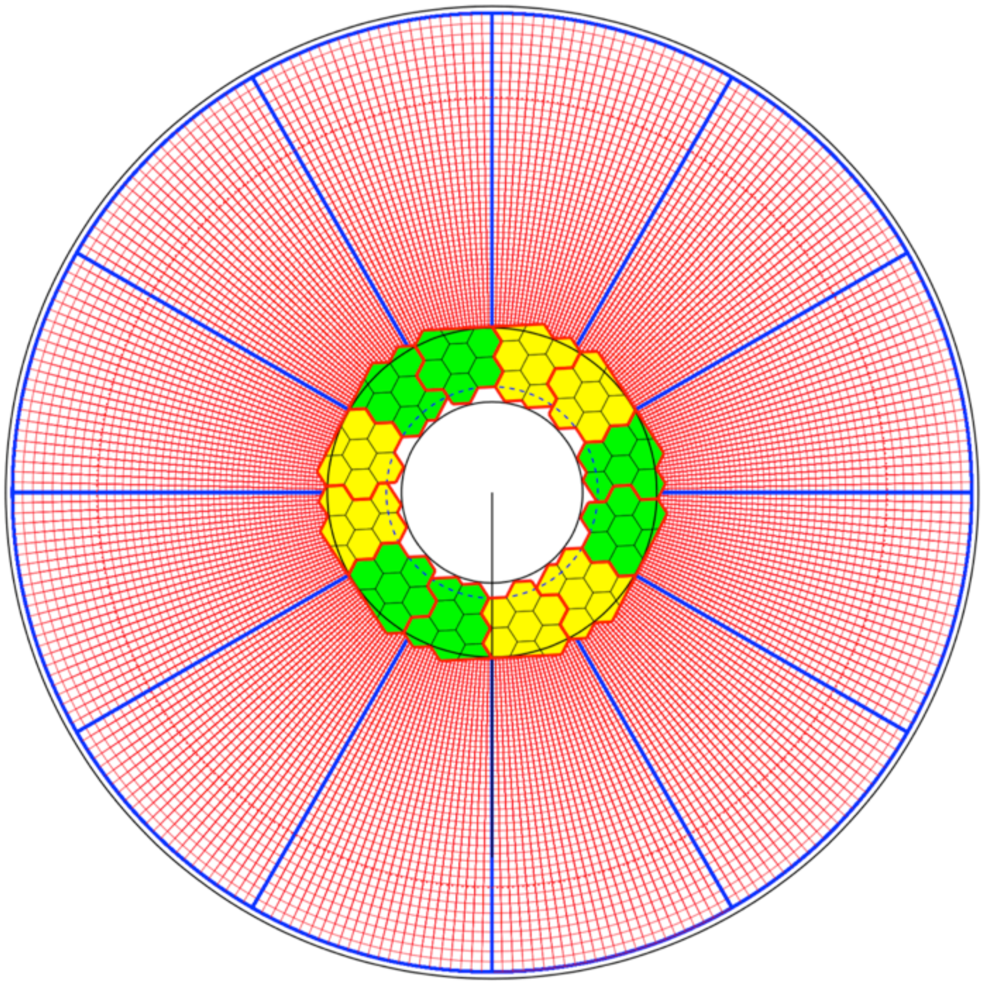
CE-H cassettes: some have all silicon (*a la* CE-E); some have mixture of Si and scint/SiPM



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



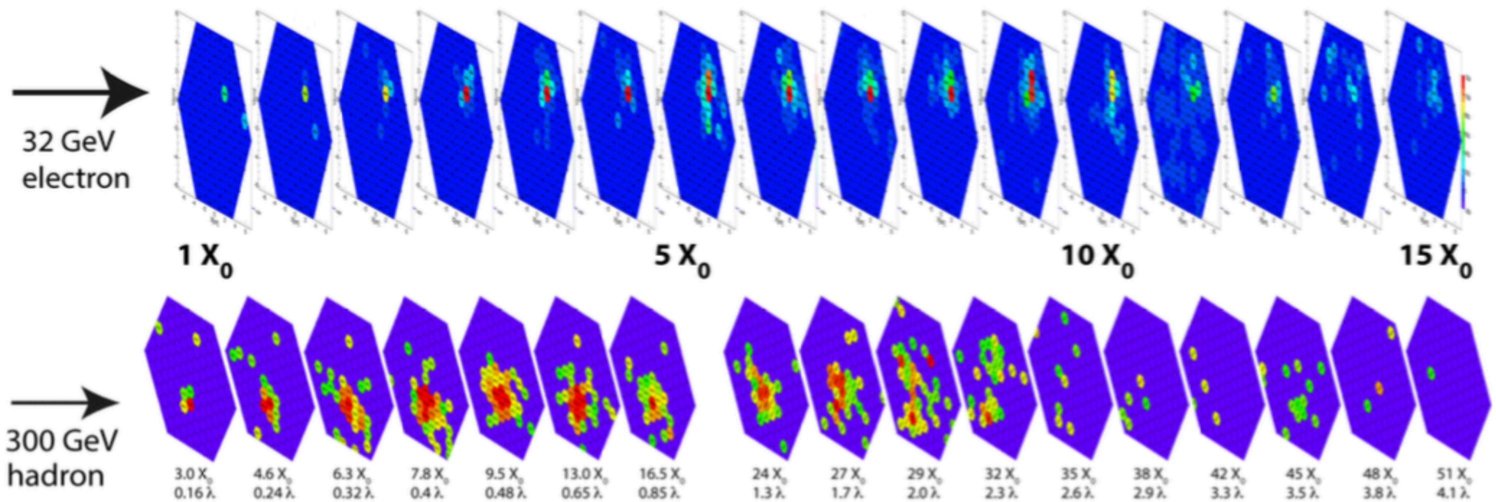
Silicon-only layer (in CE-E) showing "cassettes" and different sensor thicknesses

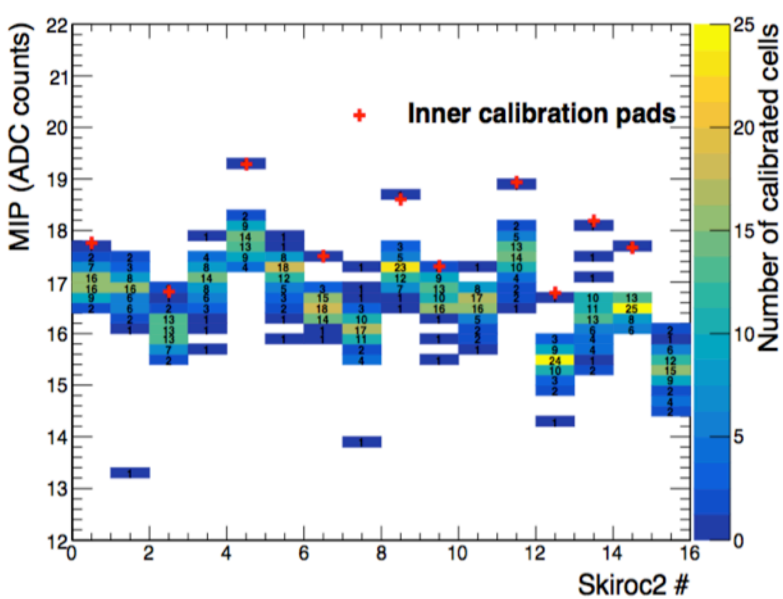


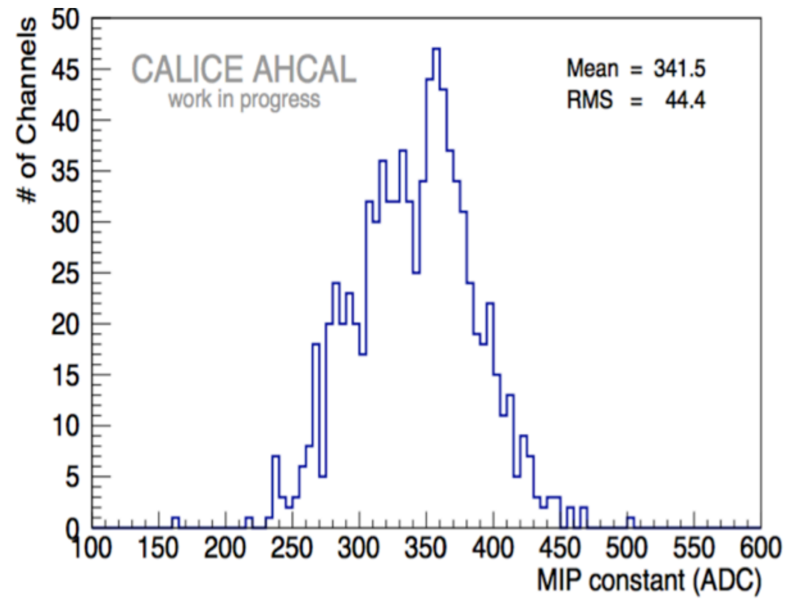
Mixed layer (in CE-H) with silicon at high η and scintillator+SiPM at low η

Prototypes tested in 2016-17 beam tests: validated basic design, good stability

Feng Wang's presentation





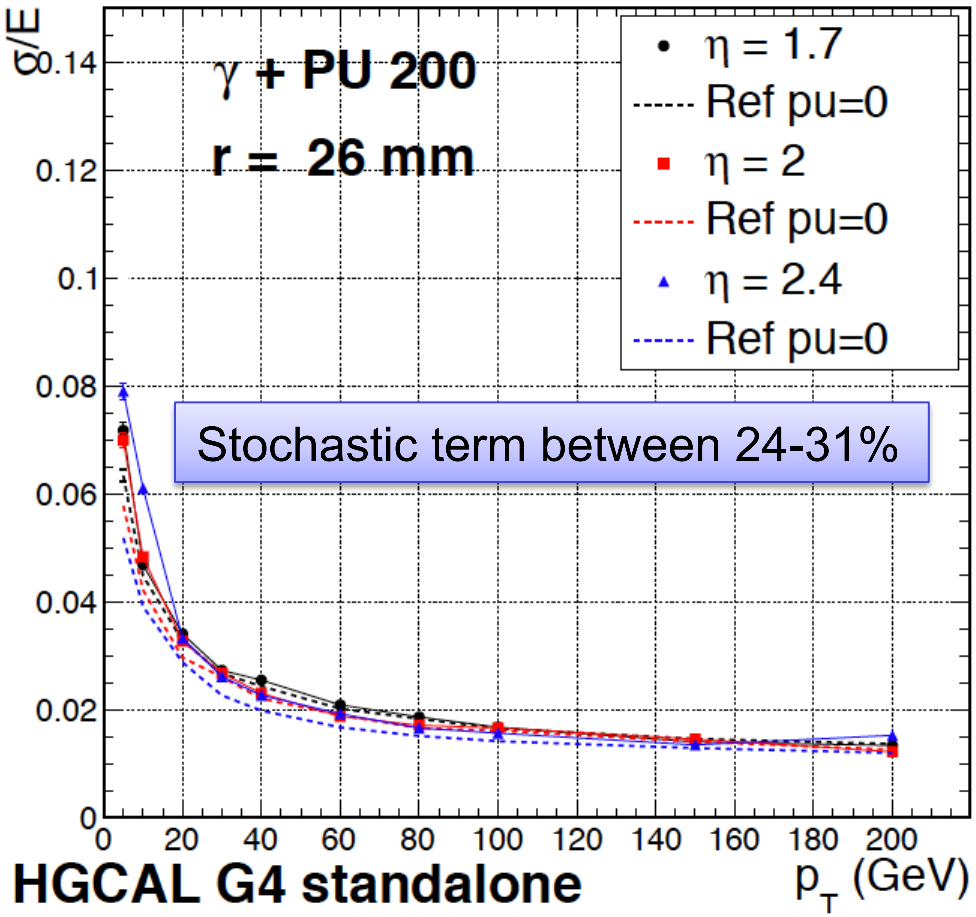


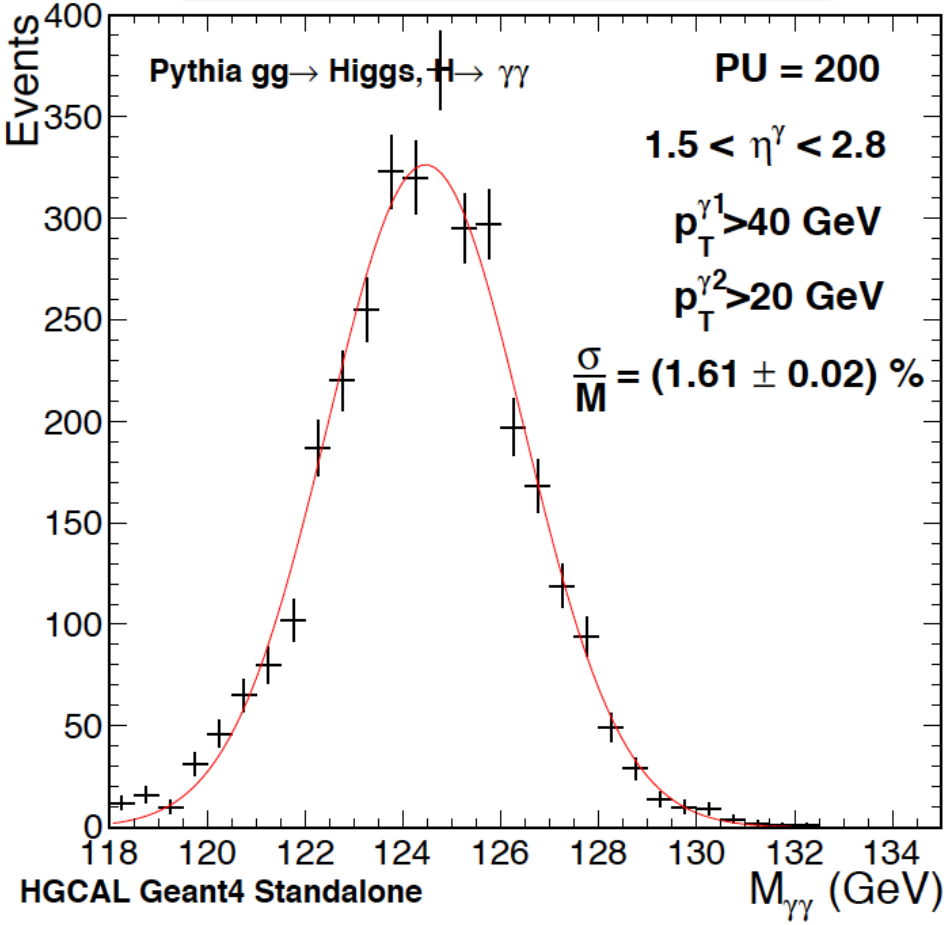
MIPs from muons seen in all parts, single particles seen within showers.

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

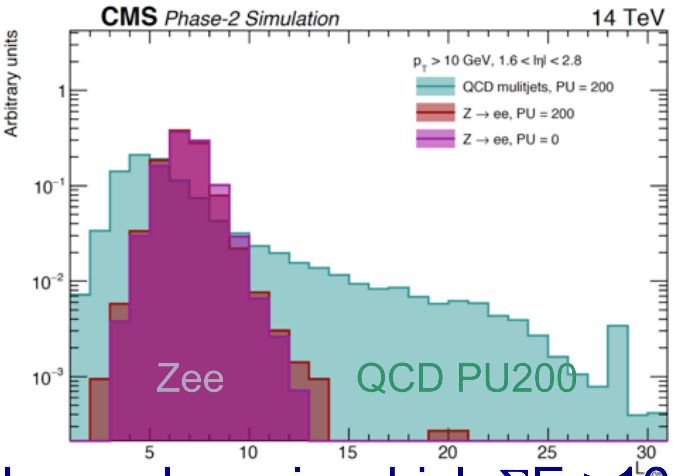
Single unconverted γ in CE-E reconstructed in r<2.6cm
→ **insensitive to pileup**

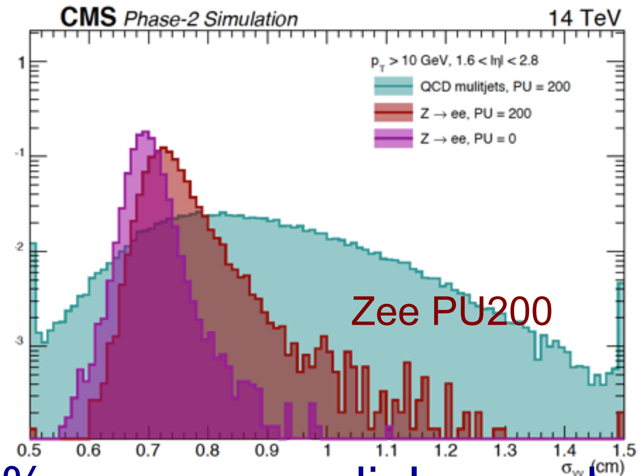
H-γγ, both γ in HGCAL
(γ do not convert in TK)
Pileup 200

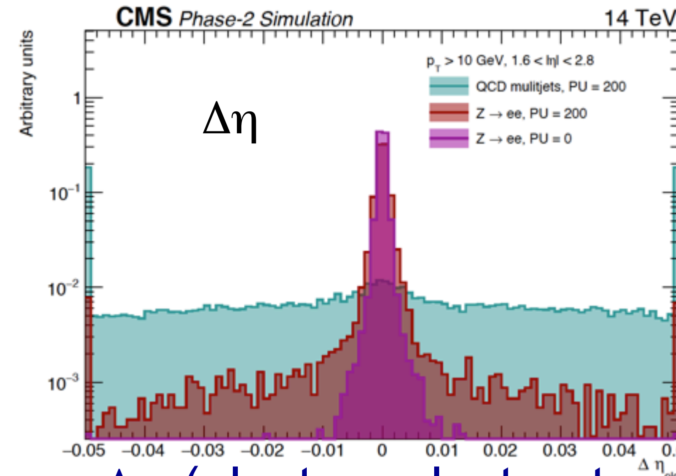




e-id greatly improved using shower-shape information from HGCAL



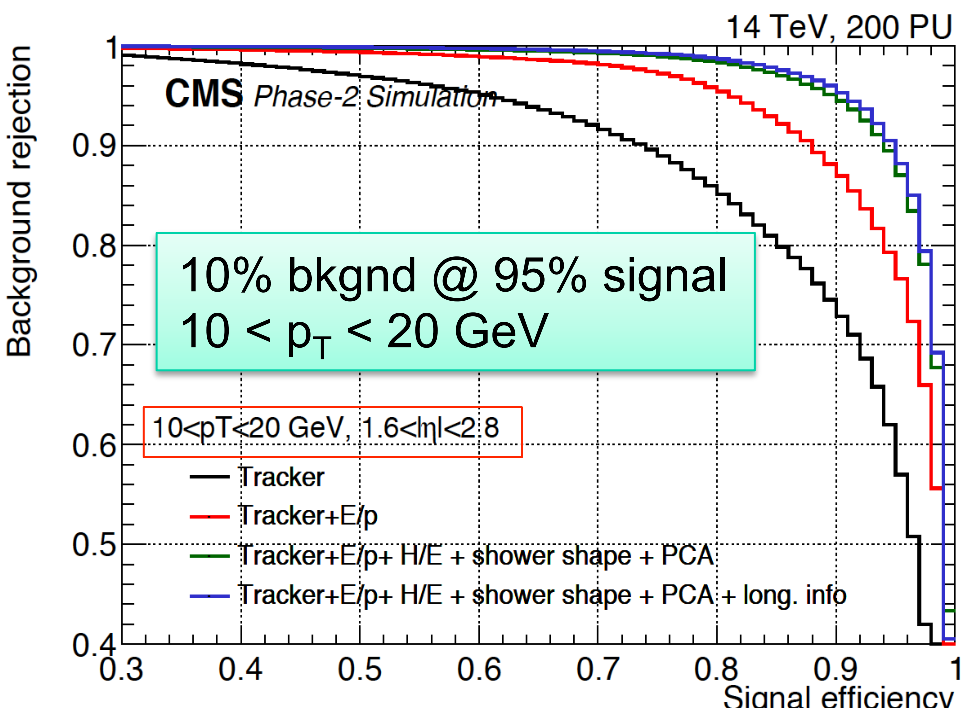


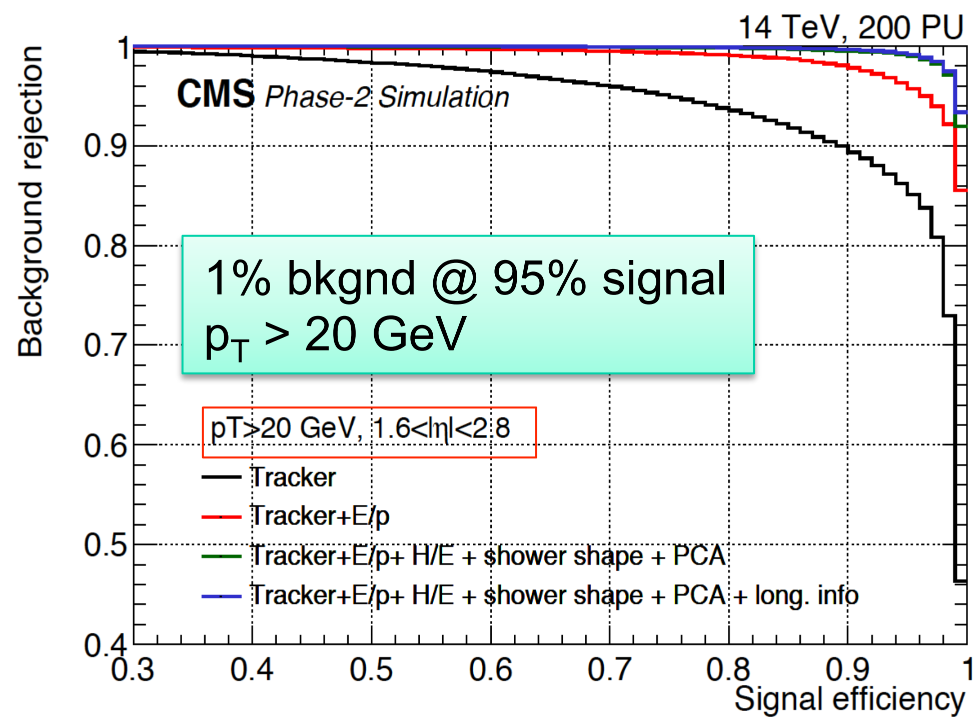


$L_{10\%}$ – layer in which ΣE >10%

σ_{VV} – radial spread

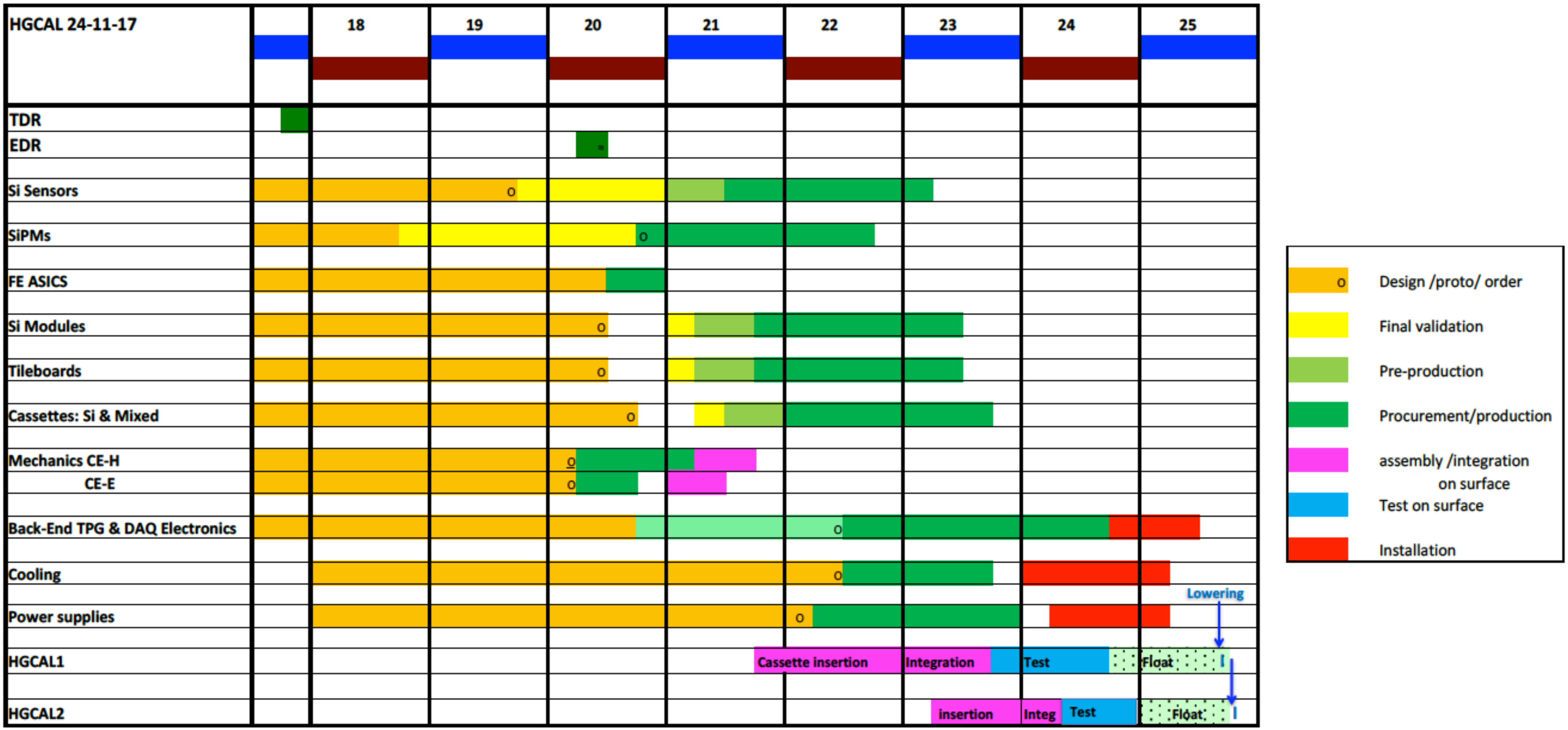
Δη (electron cluster–track)





*PCA = principle component analysis

HGCAL schedule: 5 years to complete



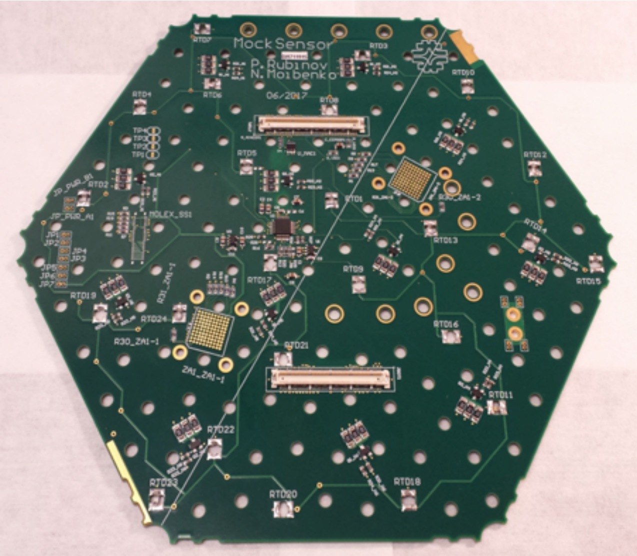
Challenging times ahead.

Summary

- The High Granularity CALorimeter is the CMS choice for the forward end-cap region.
- HGCAL will provide unprecedented number of readout/ trigger channels/layers, including timing, while capable of dealing with pileup and high radiation levels.
- The project comes with technological and engineering challenges: an experimentalist paradise.

Extra Slides

“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