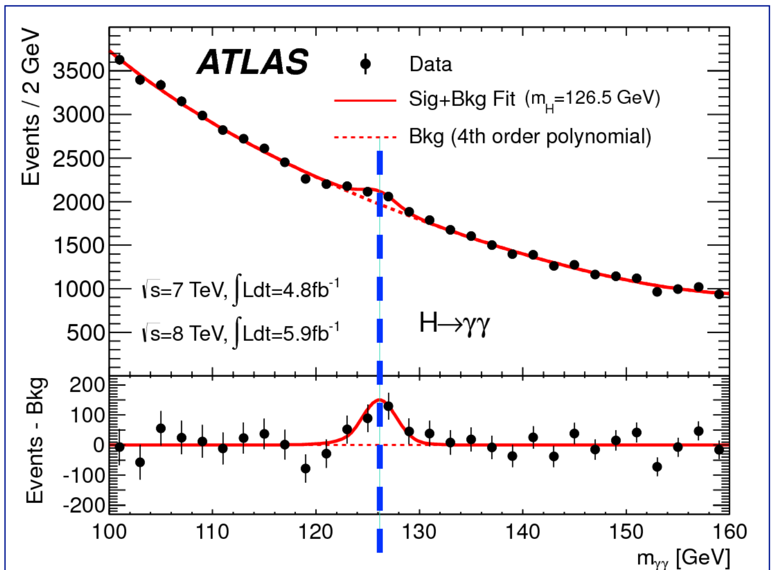
High-Granularity Calorimetry

1. Brief summary of **high-energy calorimetry**
2. The present **CMS electromagnetic** calorimeter
3. The main **challenge for future** calorimeters & possible solutions
4. High-granularity calorimetry
   1. **CALICE**
   2. CMS **HGCAL**

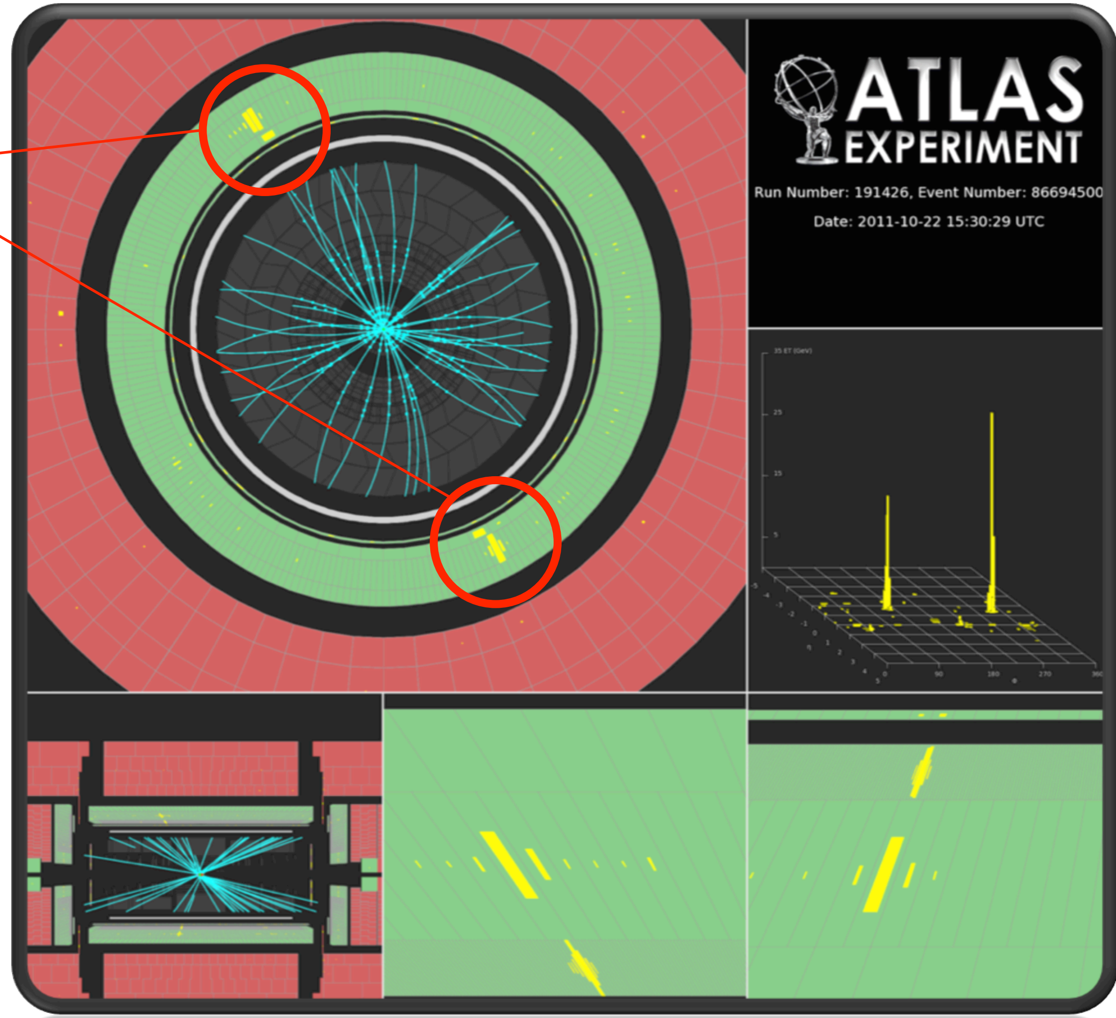
Frascati Detector School, 21-23 March 2018, David Barney (CERN)

Calorimeters played a crucial role in the discovery of the Higgs boson in 2012

Two high-energy photons observed in the ATLAS Liquid Argon (LAr) electromagnetic calorimeter in 2012
➔ Candidate $H \rightarrow \gamma\gamma$ event



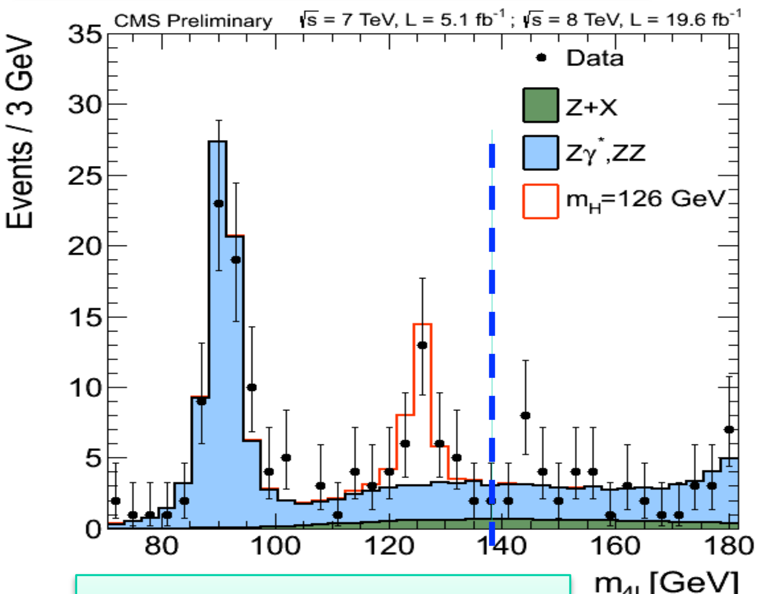
Diphoton invariant mass peak at 125.6 GeV/c^2



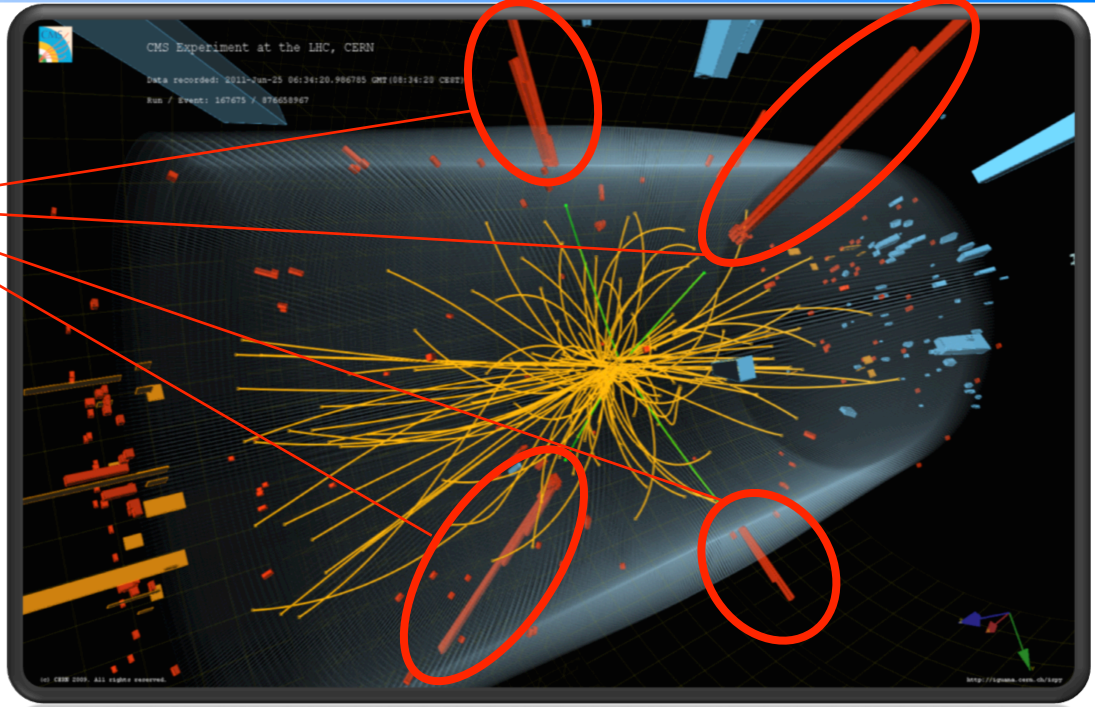
ATLAS $H \rightarrow \gamma\gamma$

Calorimeters played a crucial role in the discovery of the Higgs boson in 2012

Four high-energy electrons observed in the CMS crystal electromagnetic calorimeter in 2012
➔ Candidate H➔ZZ*➔4e



4-lepton invariant mass peak at 126 GeV/c²

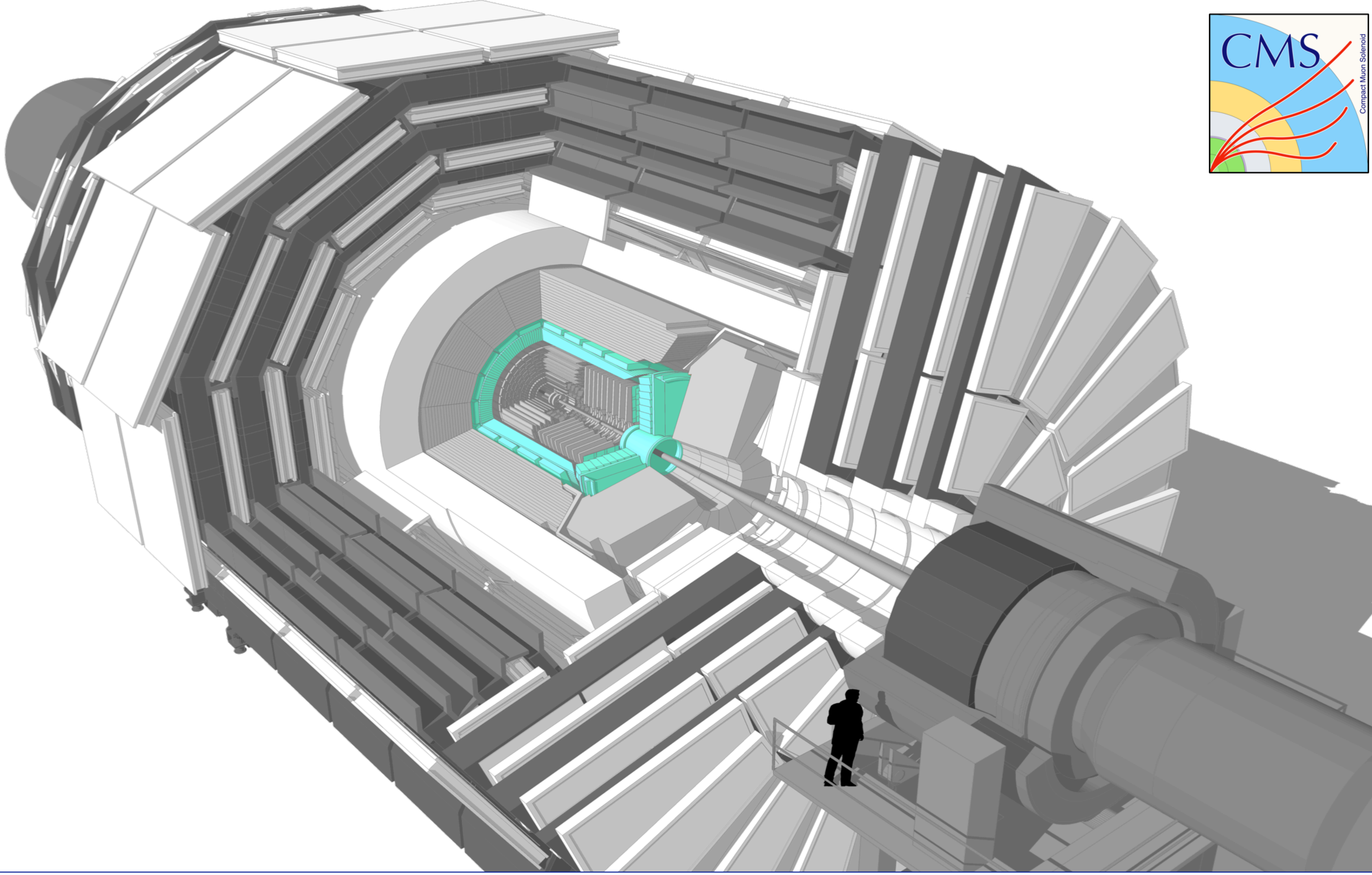


Channel	4e	4μ	$2e2\mu$	4ℓ
ZZ background	6.6 ±0.8	13.8 ±1.0	18.1 ±1.3	38.5 ±1.8
Z+ X	2.5 ± 1.0	1.6 ± 0.6	4.0 ± 1.6	8.1 ±2.0
All background expected	9.1 ± 1.3	15.4 ± 1.2	22.0 ± 2.0	46.5 ±2.7
m_H = 125 GeV	3.5 ±0.5	6.8 ±0.8	8.9 ±1.0	19.2 ±1.4
m_H = 126 GeV	3.9 ±0.6	7.4 ±0.9	9.8 ±1.1	21.1 ±1.5
Observed	16	23	32	71

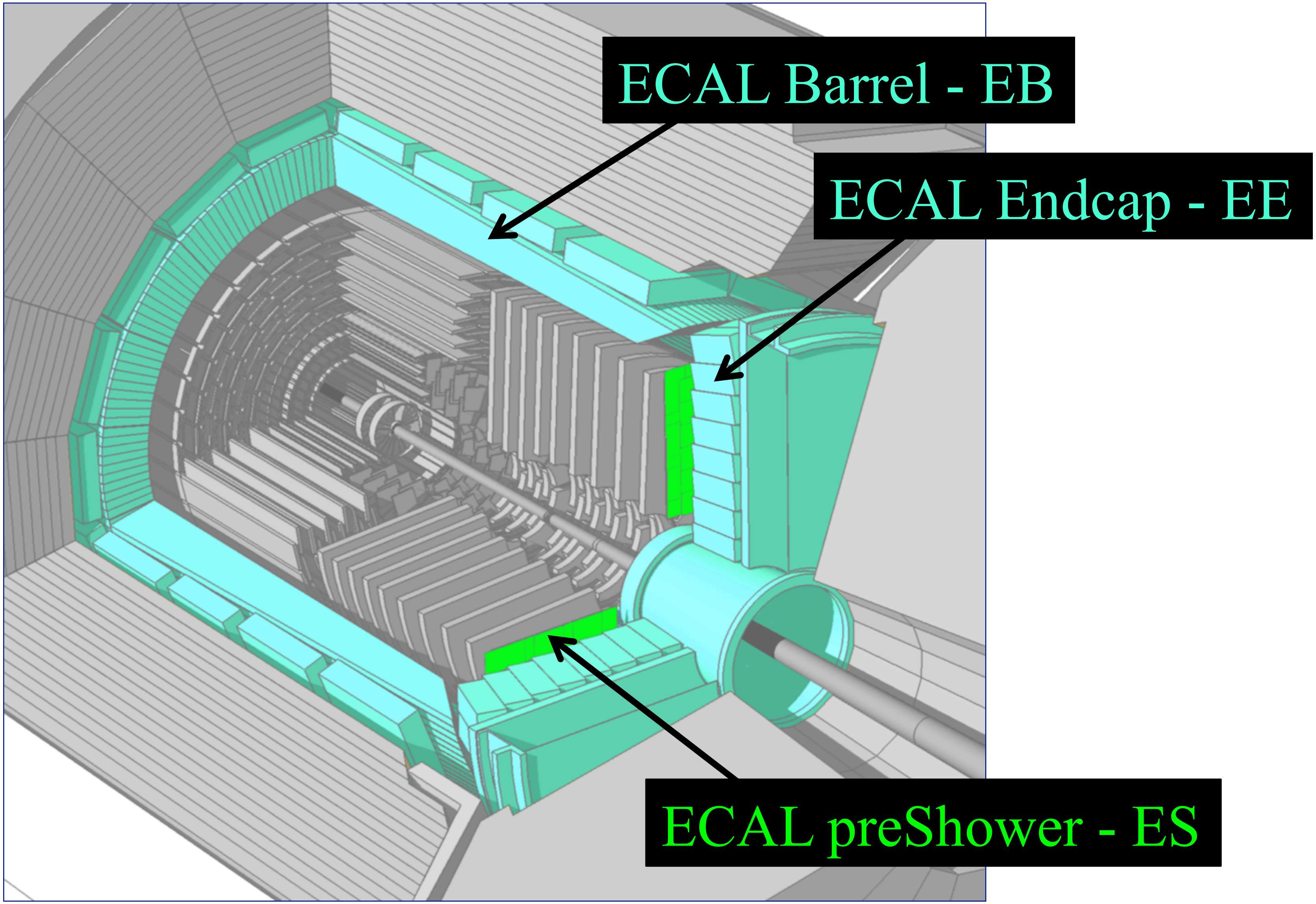
CMS H➔4 leptons

CMS LEAD-TUNGSTATE ECAL

CMS ECAL is just outside of the Tracker, and inside the HCAL and solenoid



All three parts of CMS ECAL are located within the solenoid



CMS ECAL: homogeneous calorimeter based on $PbWO_4$ scintillating crystals

- **Criteria for design of ECAL in CMS**
  - Hermetic, compact and granular, with **excellent energy resolution to |η|<2.5**
    ➔ **homogeneous** calorimeter (minimizes sampling fluctuations)
  - **Large dynamic range**, coupled with excellent linearity, to > 1 TeV
  - Provide **triggering** info. e.g. particle ID, energy, isolation
  - **Radiation tolerant** to expected dose rates and cumulative doses/fluences
- **Several options in the early days (early 1990s) of CMS, including:**

	Sampling	Homogeneous scintillators		
Property	Pb/plastic Shashlik	Liquid Xenon	CeF_3 crystals	**$PbWO_4$ crystals**
Density (g cm^{-3})	4.5	3.06	6.16	**8.28**
Radiation length X_0 (cm)	1.7	2.77	1.68	**0.85**
Molière radius R_M (cm)	3.4	4.1	3.39	**2.19**
Wavelength peak (nm)	500	175	300	**440**
Fast decay constant (ns)	<10	2.2	5	**<10**
Light yield (γ per MeV)	13	~5 x 10^4	4000	**100**

Selected by CMS in 1994

The CMS ECAL: ~75000 $PbWO_4$ scintillating crystals with APD/VPT light detection

Very compact:
- X_0 ~0.85cm, R_M ~ 2.2cm

Excellent energy resolution

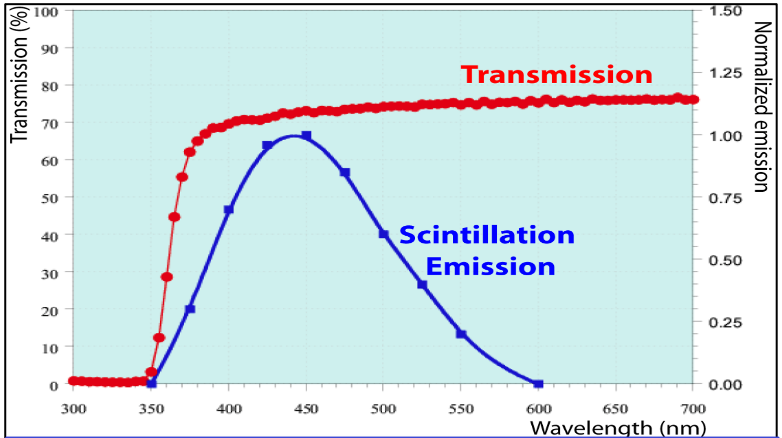
Fast << 100ns signals

High transverse granularity

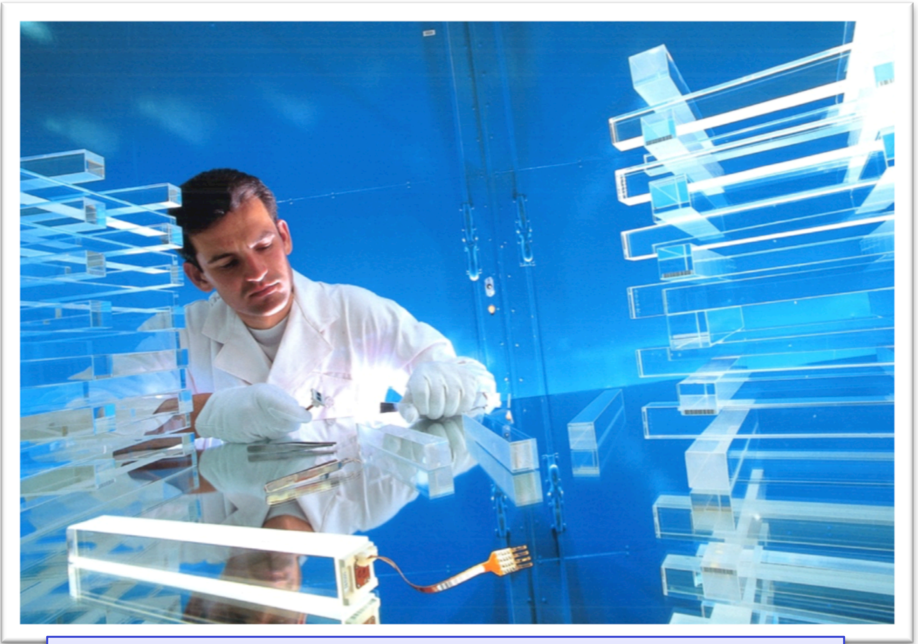
No longitudinal segmentation

→ No angular measurement

Time-dependent variations, due to:
- Temperature dependence
- Radiation damage



$PbWO_4$ crystals are transparent to the entire scintillation emission spectrum – before irradiation

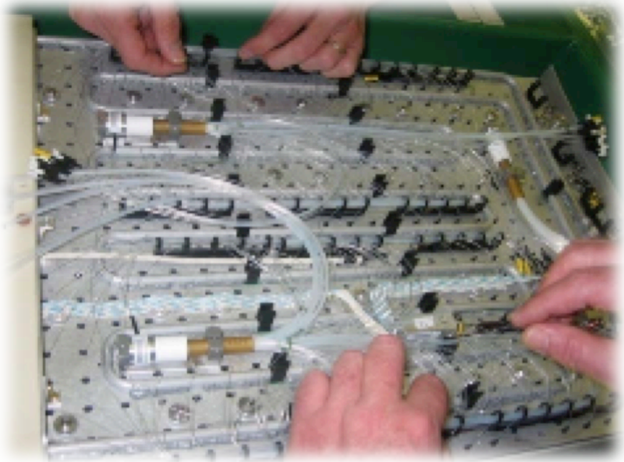


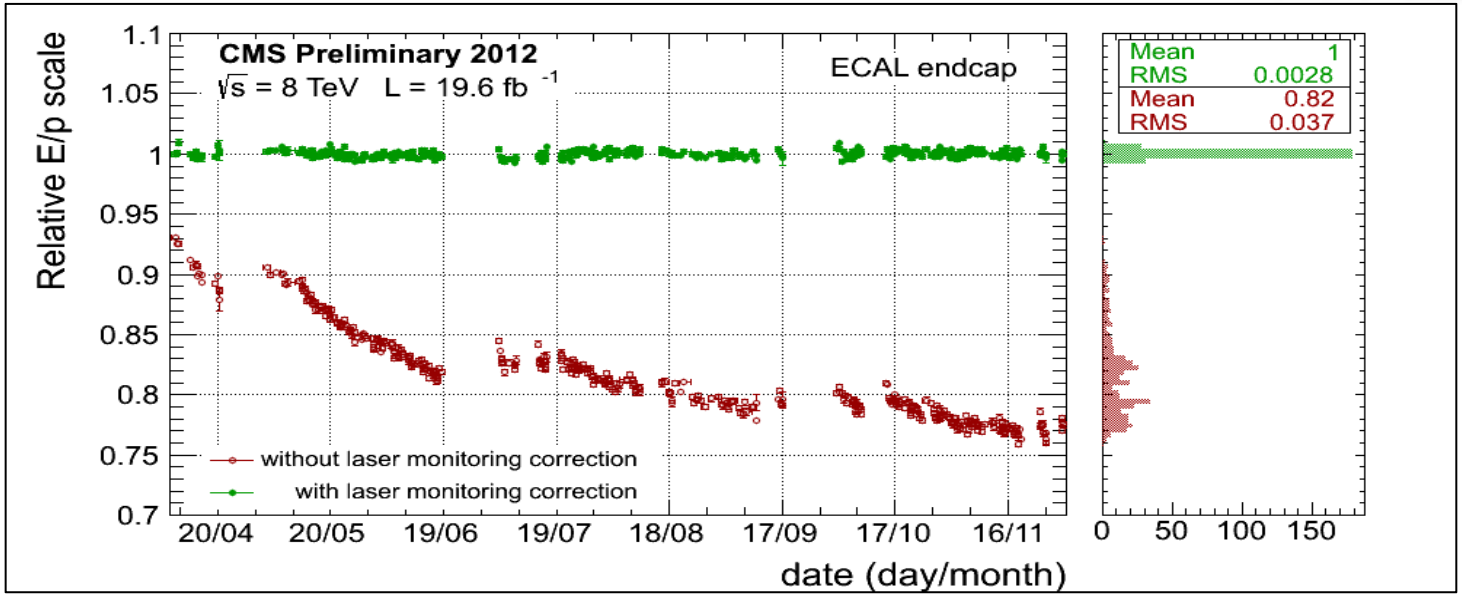
Avalanche PhotoDiodes (APDs, gain ~50) or Vacuum PhotoTriodes (VPTs, gain ~10) are glued to the lead tungstate ($PbWO_4$) crystals to detect the scintillation light in the barrel and endcaps of the CMS ECAL respectively

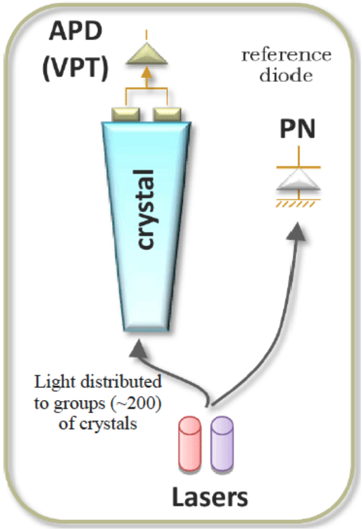
Crystal response stability is monitored and corrected through a laser system

Light from laser (447nm, ~peak emission) injected into each crystal

- One (averaged) measurement of the crystal transparency **every 40 minutes**
- Corrections ready for prompt reconstruction in **less than 48 hours**!
  - Validity checked using electrons from W decays





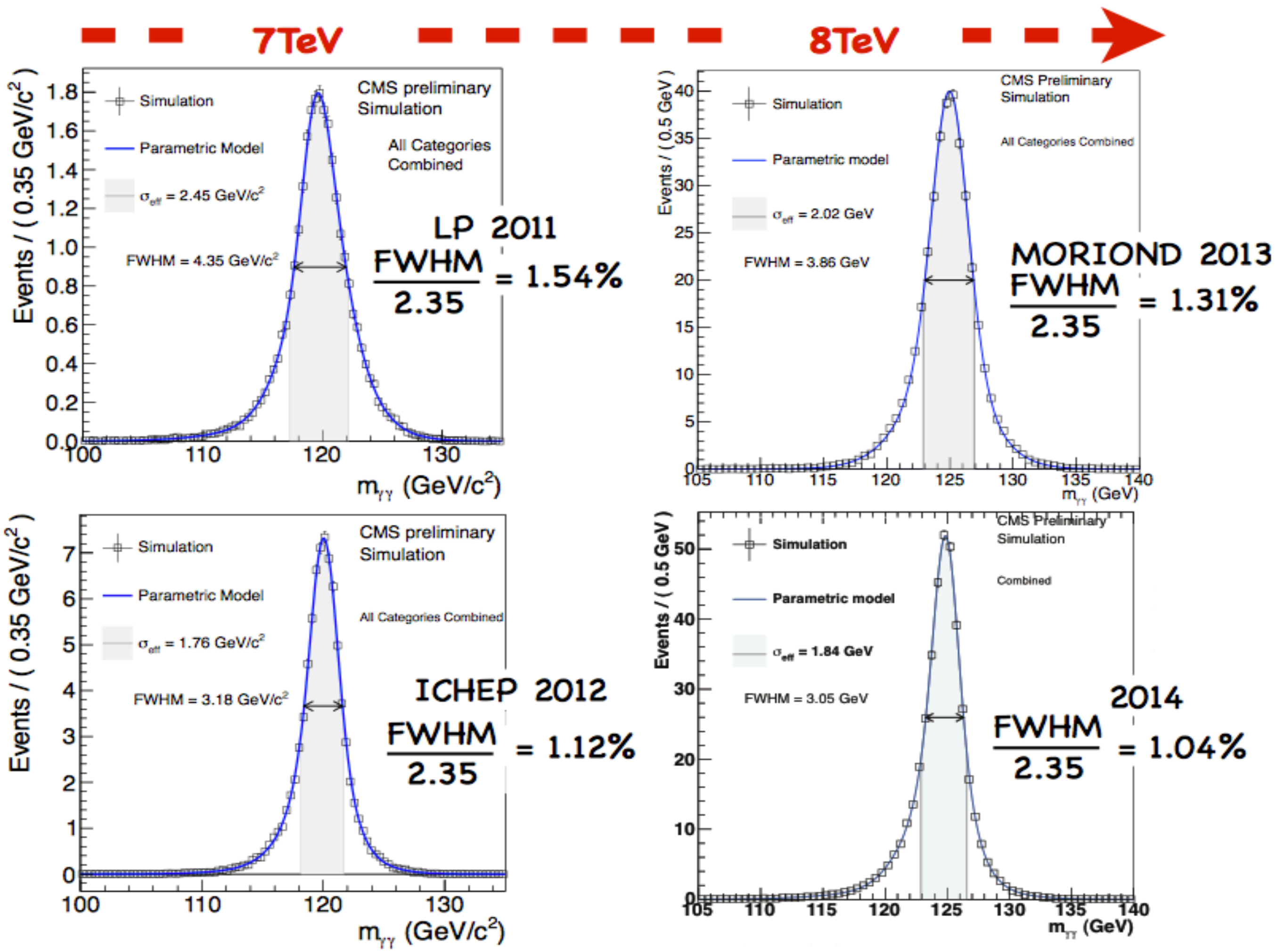


The CMS ECAL Benchmark: H→γγ

- The energy resolution measured in data with $Z \to ee$ is used to model the expected $H \to \gamma\gamma$ signal in the simulation
- **Steady progress and excellent results**

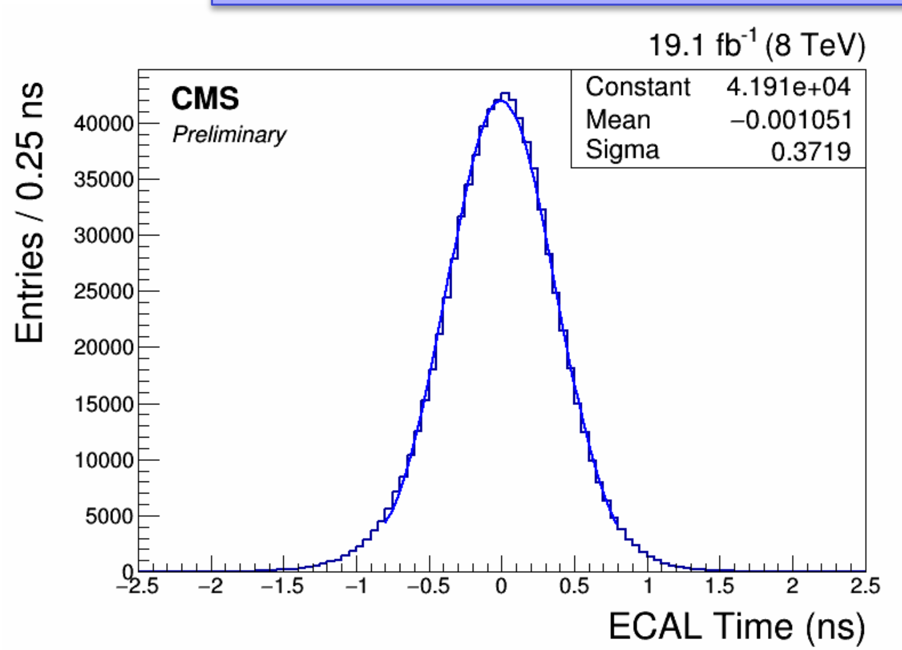
PROMPT reconstruction within 48h from data taking

RECONSTRUCTION with improved conditions



Intrinsic timing performance of ECAL (<200ps) can help in searches for exotic physics

CMS ECAL design requirements: ~1ns timing precision
Can easily achieve <400ps (including beamspread σ~300ps)



ECAL timing information used in direct searches for SUSY signatures. Limits could be far lower with even better timing performance

Available on the CERN CDS information server **CMS PAS EXO-12-035**

CMS Physics Analysis Summary

Contact: cms-pag-conveners-exotica@cern.ch 2015/10/29

Search for long-lived neutral particles in the final state of delayed photons and missing energy in proton-proton collisions at $\sqrt{s} = 8$ TeV

ELSEVIER

Physics Letters B

Volume 722, Issues 4–5, 24 May 2013, Pages 273-294

Search for long-lived particles in events with photons and missing energy in proton–proton collisions at $\sqrt{s} = 7$ TeV ☆

CMS Collaboration *

⊞ **Show more**

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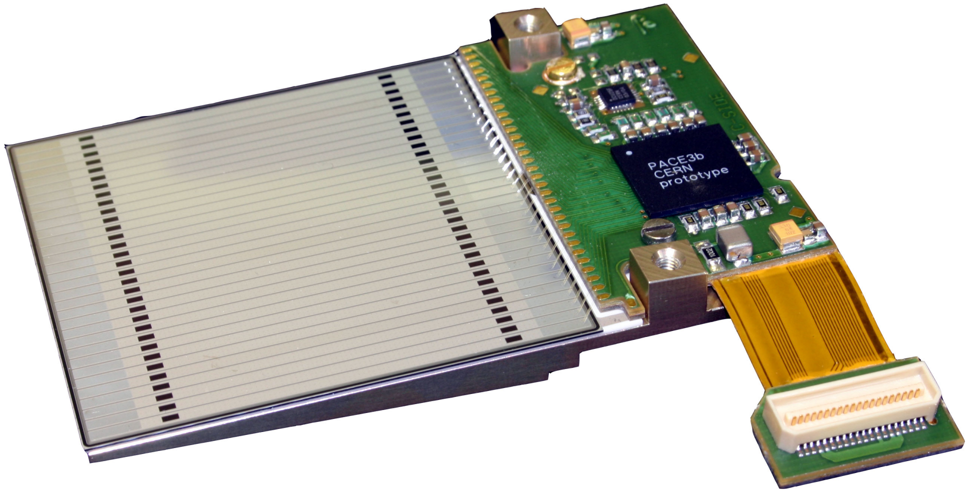
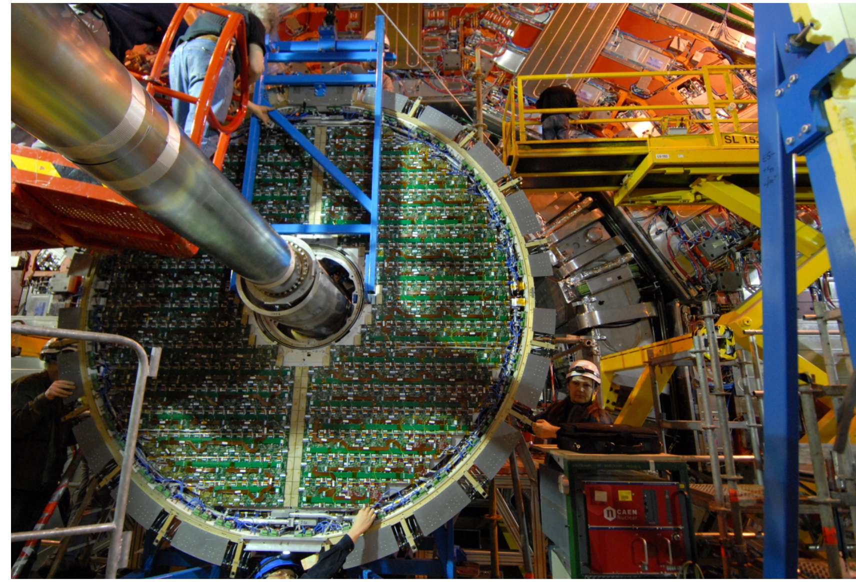
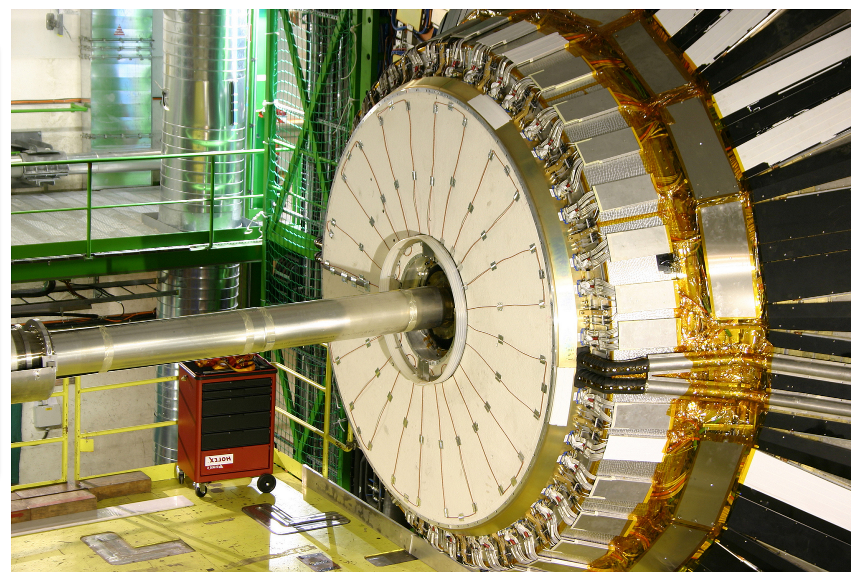
ECAL also includes a 2-layer silicon-strip-based "Preshower" in its endcaps, to aid particle ID



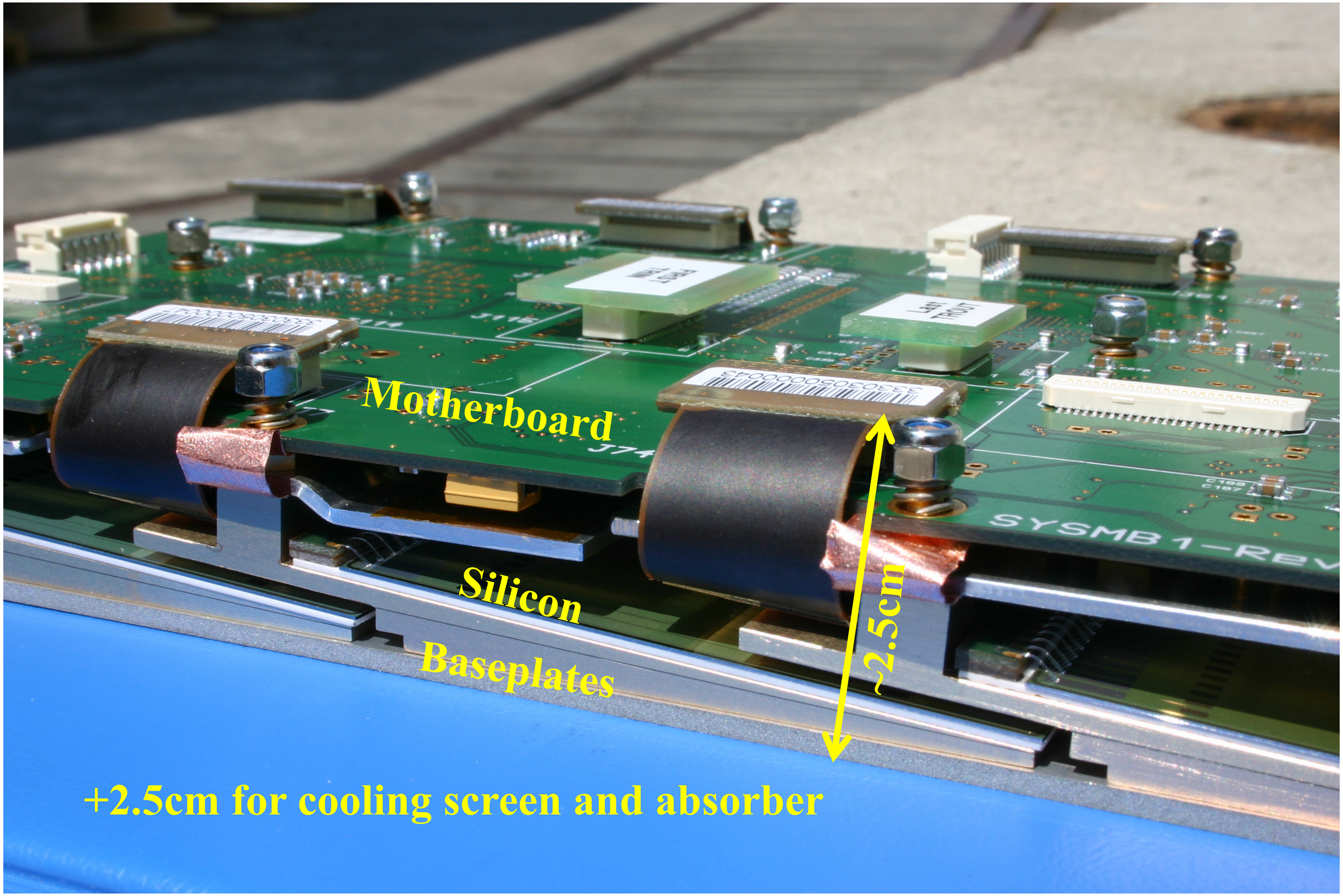




6 x 6cm^2 **silicon** sensor, 32 strips ~ 1cm^2/strip
4 planes of 1072 sensors = 137000 channels,
~16m^2 total (**largest silicon-based calorimeter!**)

Used mainly for π^0 identification, but ID power not as good as foreseen due to upstream TK material

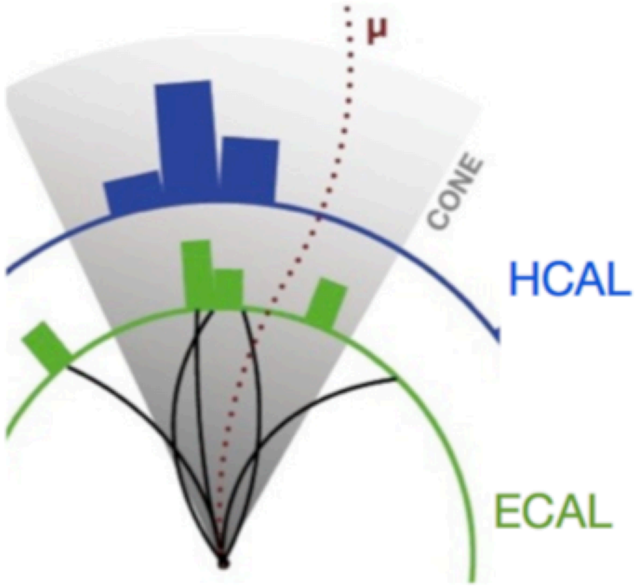
Preshower is a compact device, with one layer requiring ~5cm for absorber, cooling & modules



CURRENT FRONTIER IN HEP CALORIMETRY → IMPROVE JET MEASUREMENTS!

Real need to improve jet energy resolution for the next generation of calorimeters

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

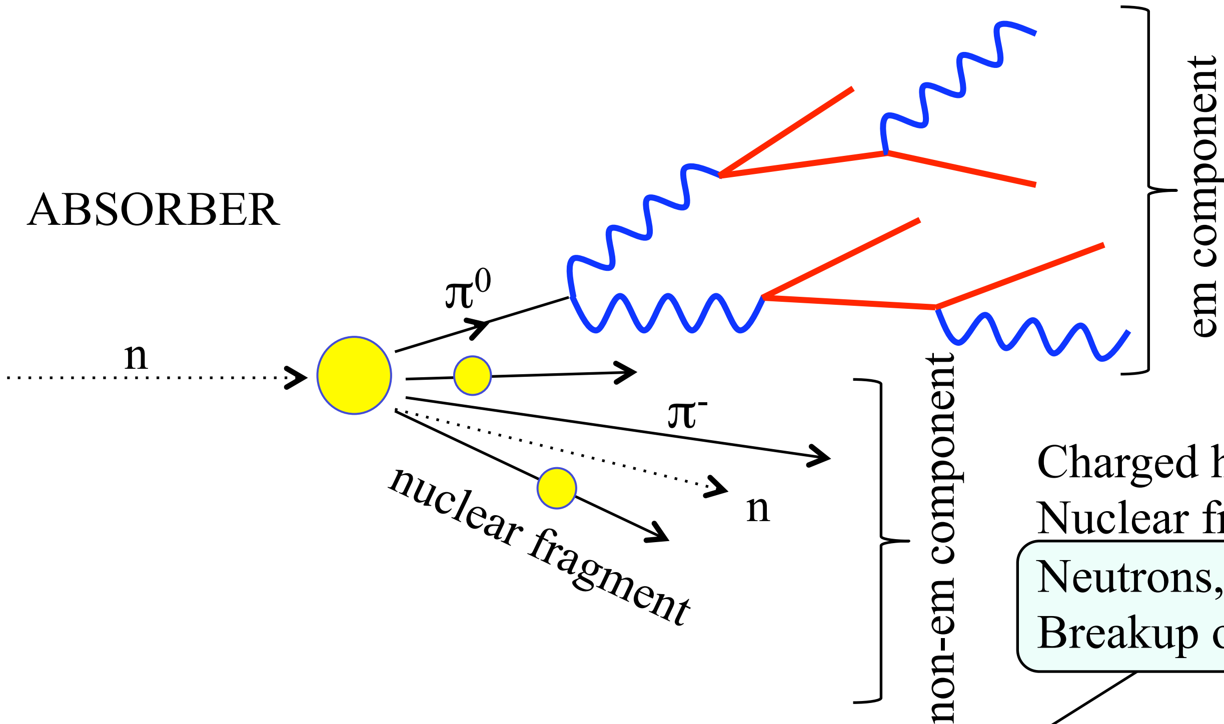


"Typical" jet:
- ~62% charged particles (mainly hadrons)
- ~27% photons
- ~10% neutral hadrons
- ~1% neutrinos

Jet reconstruction:
weighted sum of energies in a cone → energy of original parton

Resolution: driven by calorimeter with worst resolution (HCAL)

Hadron showers contain electromagnetic and hadronic components

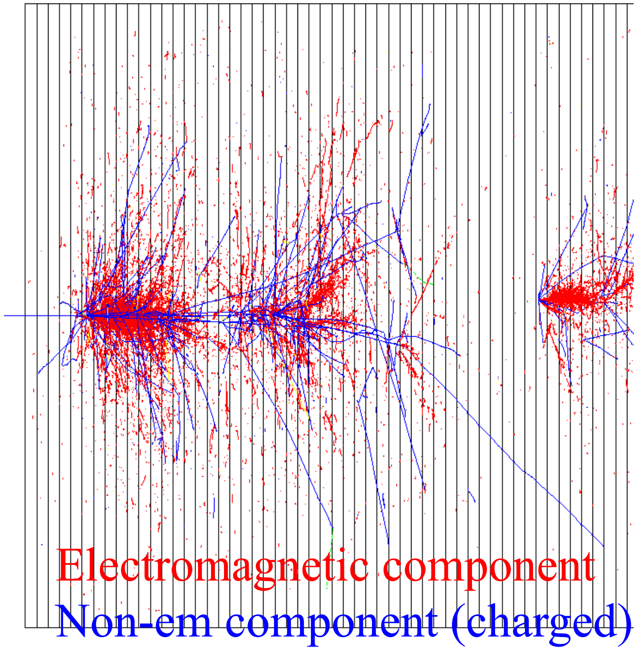


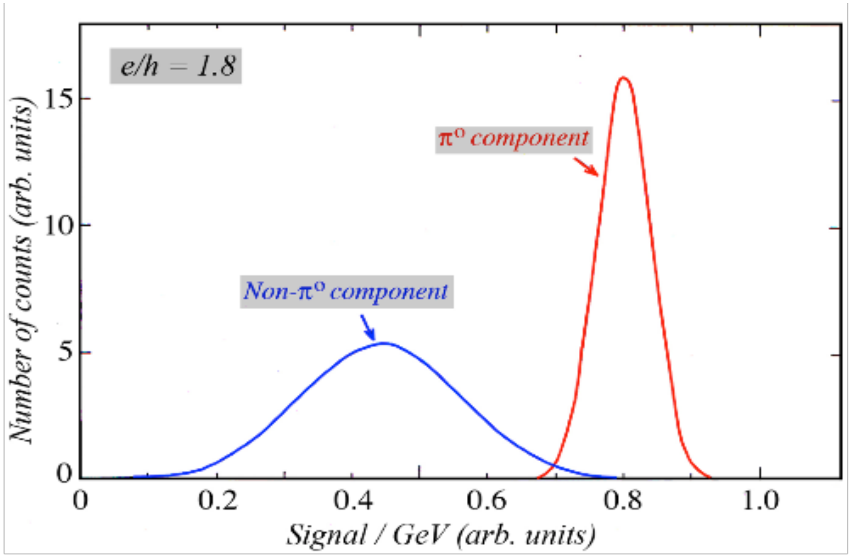
Electrons, photons
$\pi^0 \rightarrow 2\gamma$
➔ em sub-shower

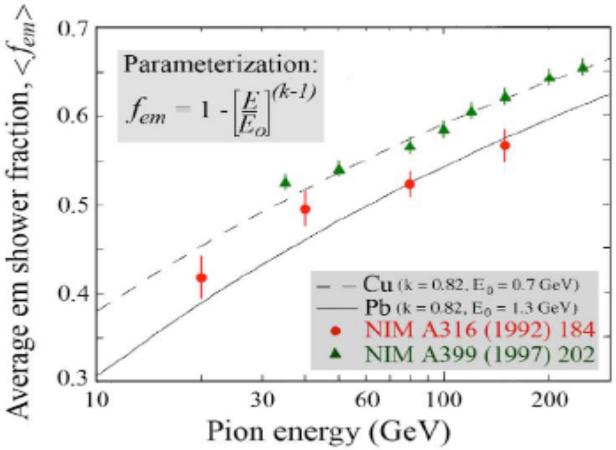
Charged hadrons	(20%)
Nuclear fragments, protons	(25%)
Neutrons, soft γs	(15%)
Breakup of nuclei	(40%)

Either not detected or often too slow to be within detector time window ➔ invisible energy

Efficiency of detecting hadronic & em components differs from unity: non-compensation







Fraction of non-em component ("h") detected is far lower than for the em-component ("e"): e/h > 1 for most detectors. This leads to:

- Non-linearities
- Non-Gaussian response
- Relatively poor energy resolution

em fraction is large & varies with energy & fluctuates with non-Gaussian tails

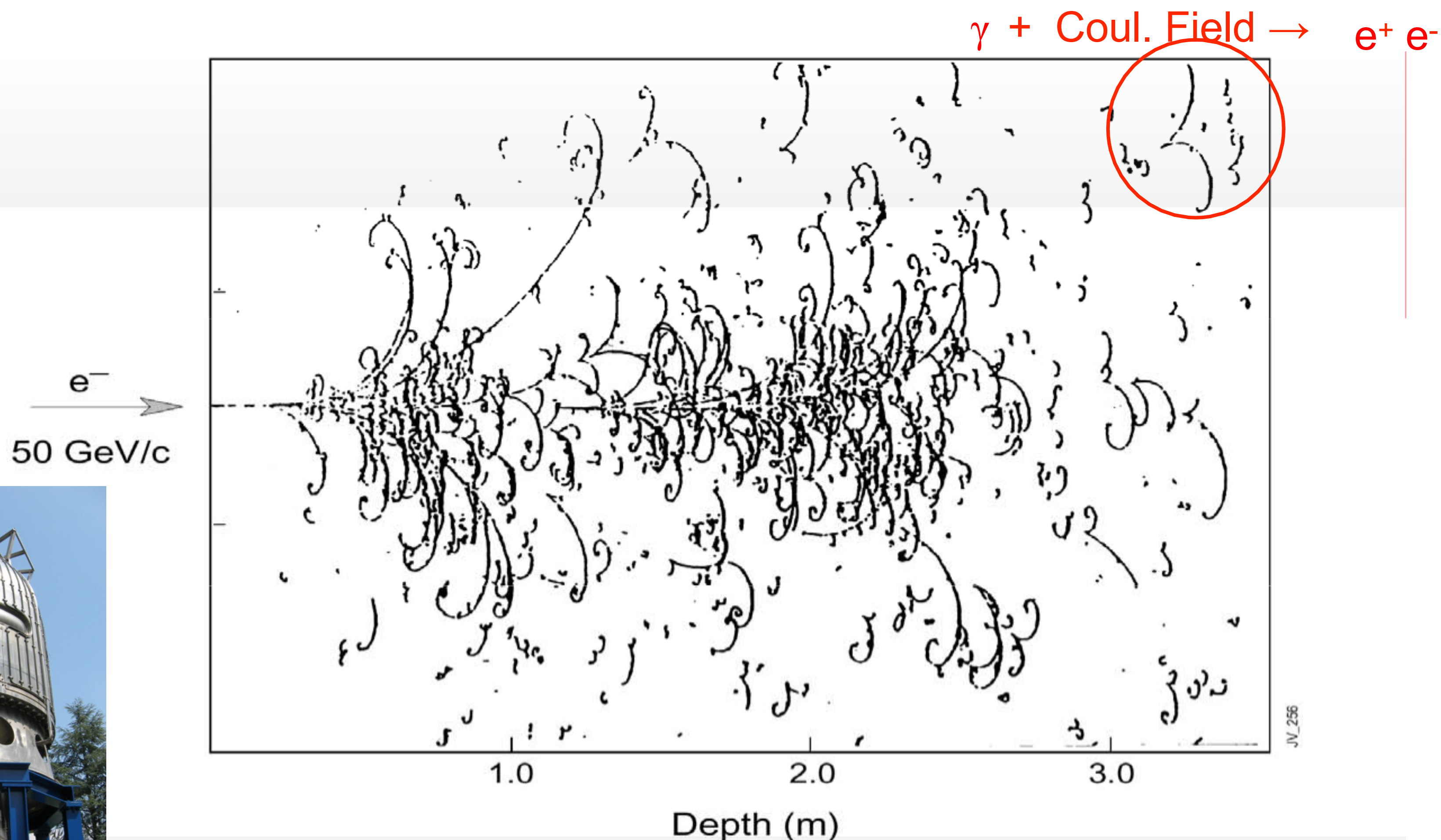
Two main approaches for improving jet energy resolution

Substantial improvement of the energy resolution of hadronic calorimeters for single hadrons:
dual (or triple!) readout, e.g. DREAM

Precise reconstruction of each particle within the jet
→ reduction of HCAL resolution impact:
particle flow algorithms and imaging calorimeters
e.g. **CALICE detectors, CMS HGCAL**

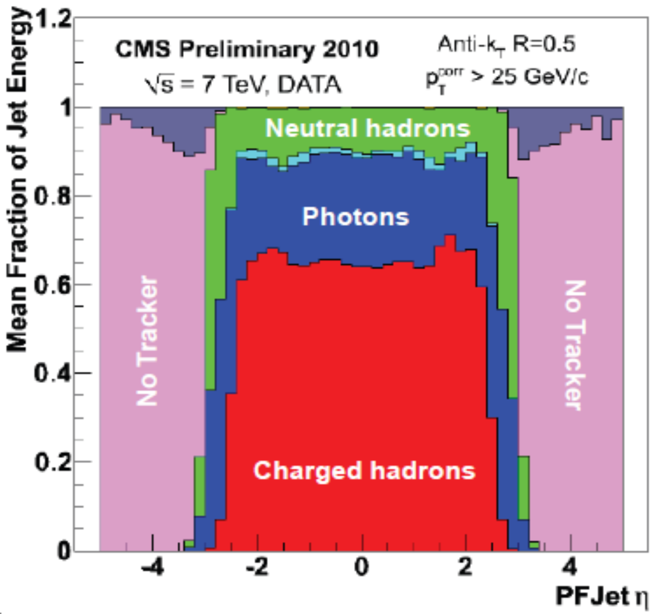
Both techniques aim at separating charged/neutral & electromagnetic/hadronic components

The previous generation of calorimeters could "see" showers! Can we do this again?



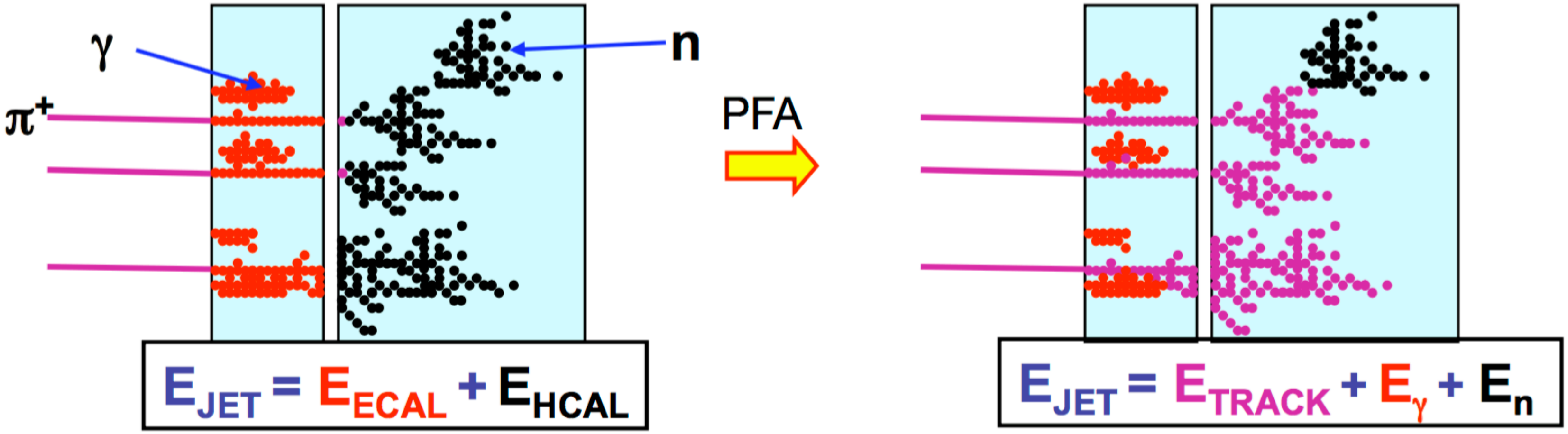
Big European Bubble Chamber filled with Ne:H_2 = 70%:30%, 3T Field, L=3.5 m, X_0≈34 cm, 50 GeV incident electron

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



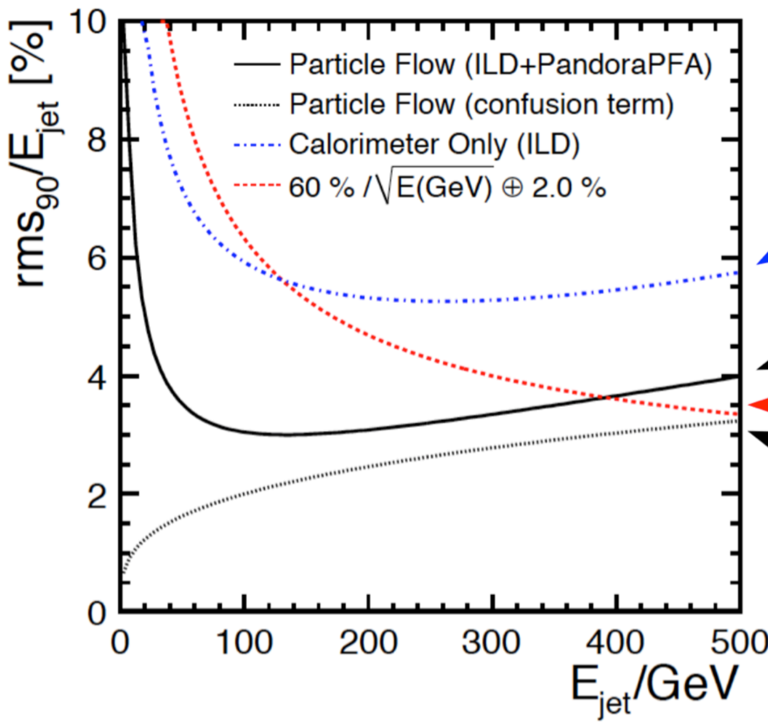
Idea: for each individual particle in a jet, use detector with best energy/momentum resolution

- Charged tracks = Tracker
- e/photons = ECAL
- Neutral hadrons (only 10%) = HCAL



Championed by CALICE (for ILC), CLIC and CMS HGCAL groups

Particle flow resolution is clearly better than calorimeter alone



Simulated ILD calorimeter/PF performance

realistic ILC calorimeter (ILD)

PFA

“ideal” traditional HAD calorimeter

„Confusion“: wrong association between tracks and calorimeter clusters

- at high jet energy: correct association between tracks and calorimeter clusters is very important ⇒ calorimeter with **very high granularity**
- at low jet energy: dominated by “classical” calorimeter energy resolution ⇒ hadronic calorimeter with **good energy resolution**

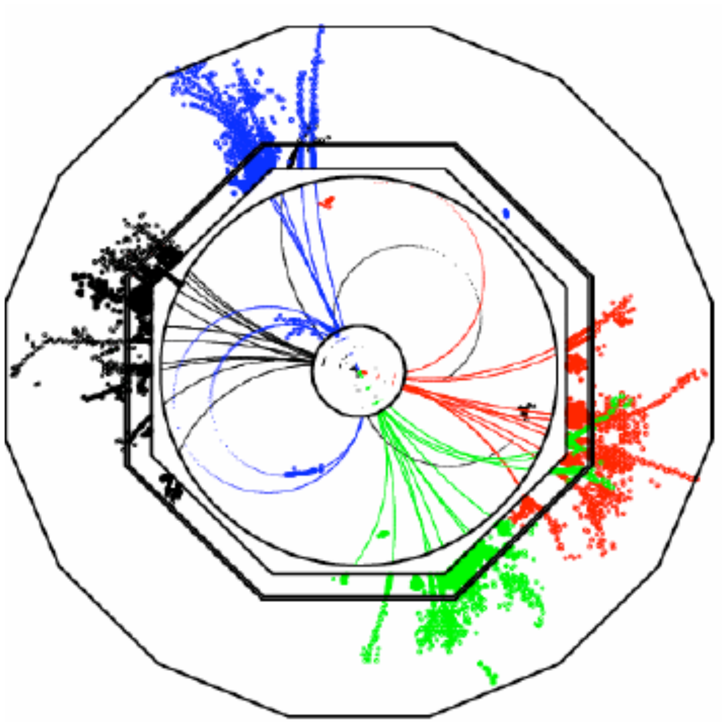
Katja Krüger | Basics of Calorimetry in Test Beams | 24 January 2017 | Page 10/46

(slide shamelessly stolen from Katja Kruger from BTTB5)

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

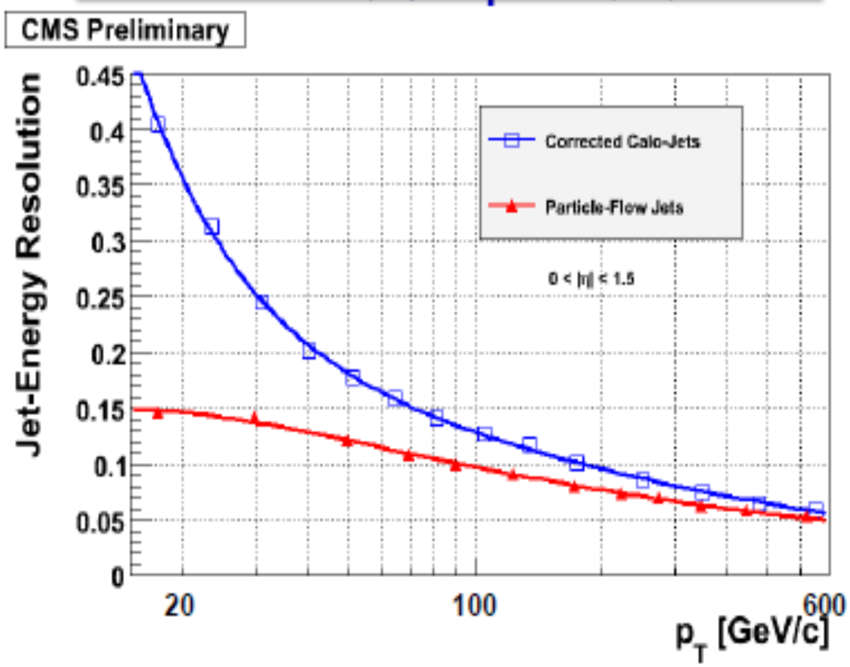
For a Particle-Flow Calorimeter:

- **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!

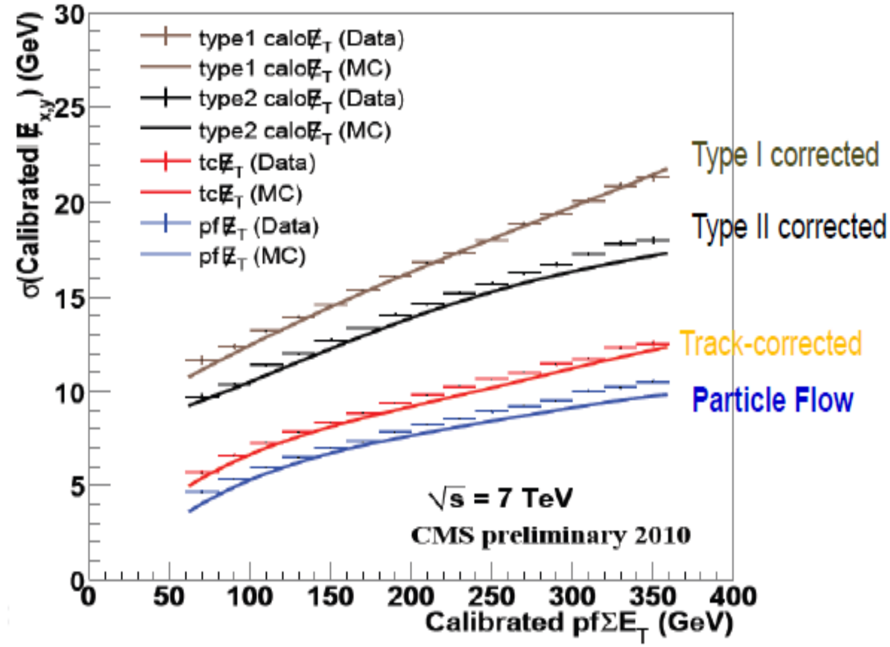


Particle flow already used in Aleph & CMS (both have relatively low resolution HCALs)

Simulation: jet energy resolution



Data: Missing energy resolution

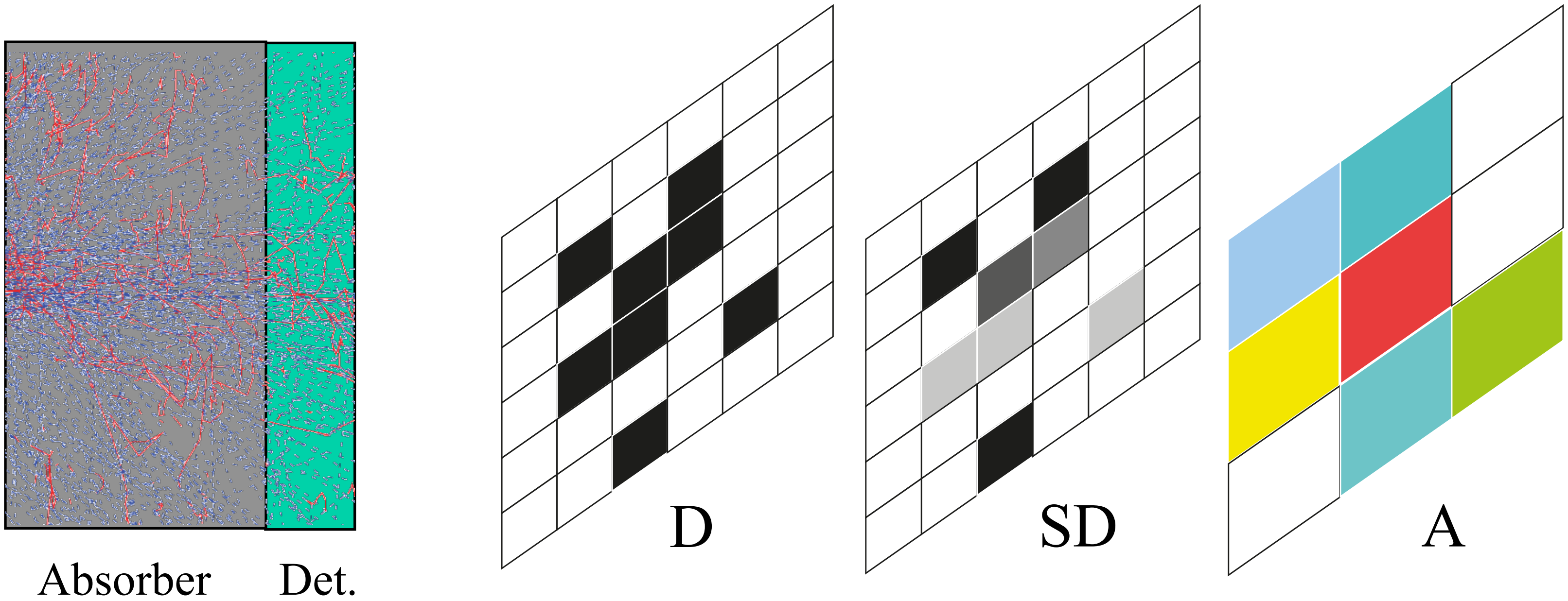


Measurement of jets in CMS is **enhanced greatly** by the use of particle flow techniques

CALICE: R&D COLLABORATION FOR HIGHLY-GRANULAR SAMPLING CALORIMETERS AT E^+E^- COLLIDERS

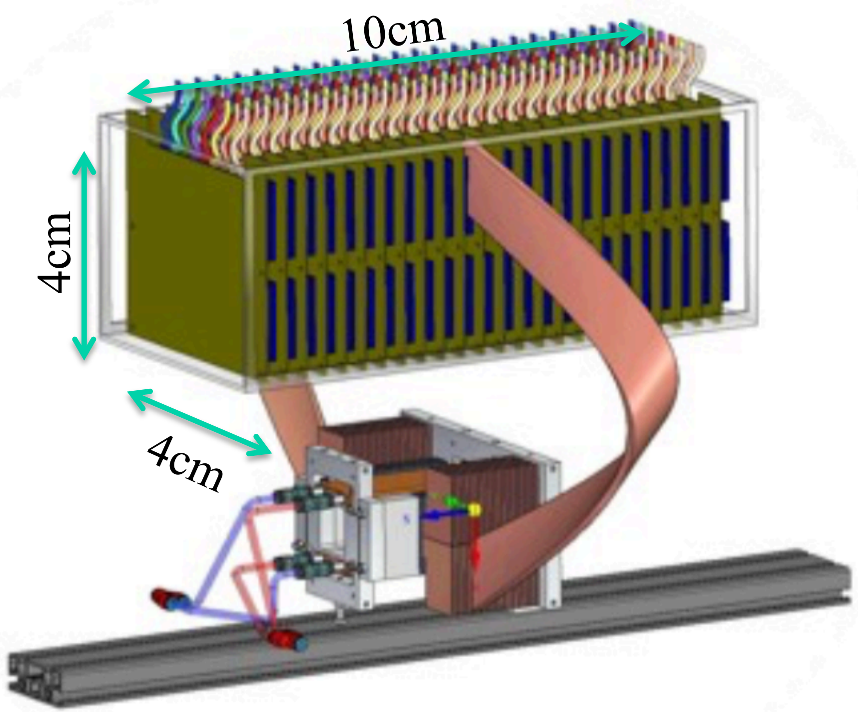
Various sampling layer types being explored

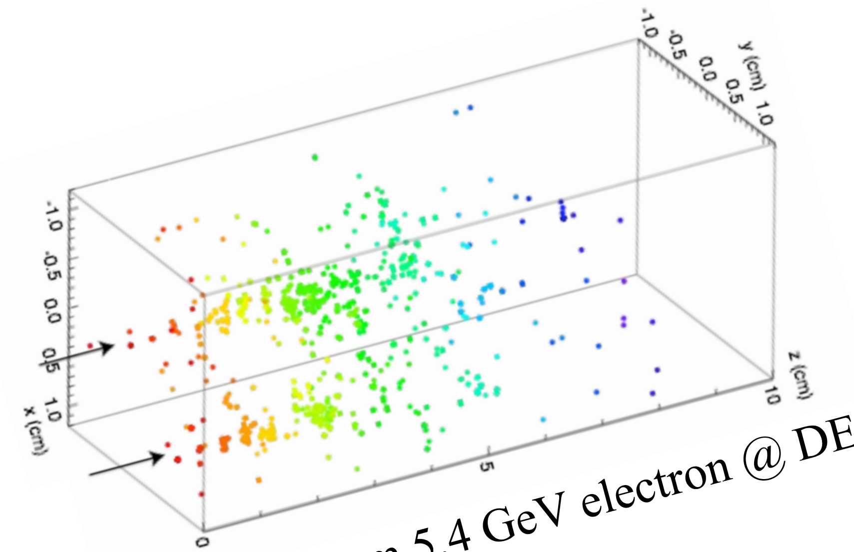
- **Digital (D):** count # pixels OFF/ON (e.g. MAPS)
- **Semi-digital (SD):** basic info of signal size in pixels – OFF/standard/ large/very large (e.g. RPCs or micromegas)
- **Analogue (A):** large dynamic range in (sometimes) larger pixels (e.g. silicon or scint+SiPM or GEM)



CALICE Digital 24-layer ECAL prototype is a potential upgrade for the ALICE FoCAL

39 M pixels in $4x4x10cm^3$ using silicon MAPS technology



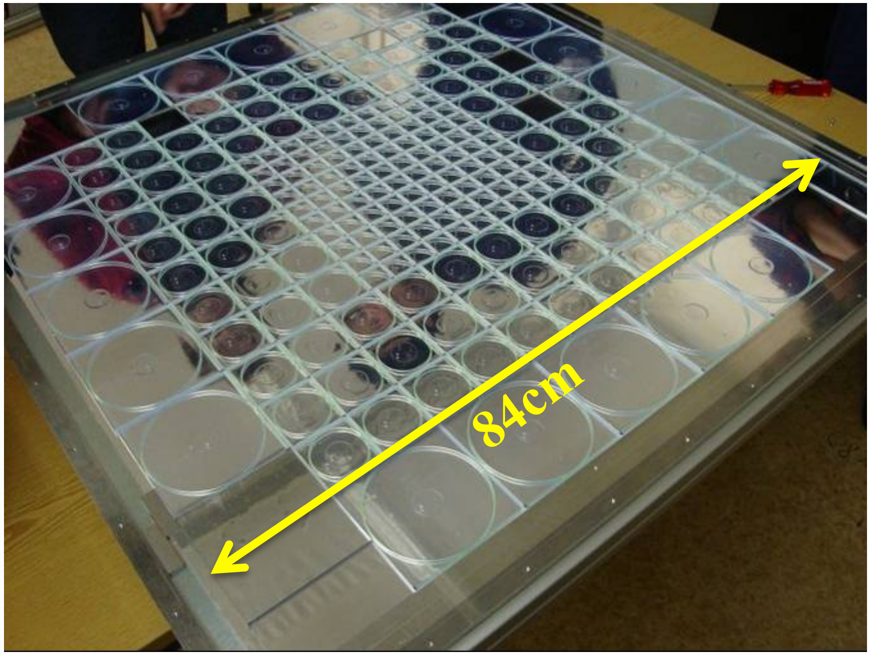


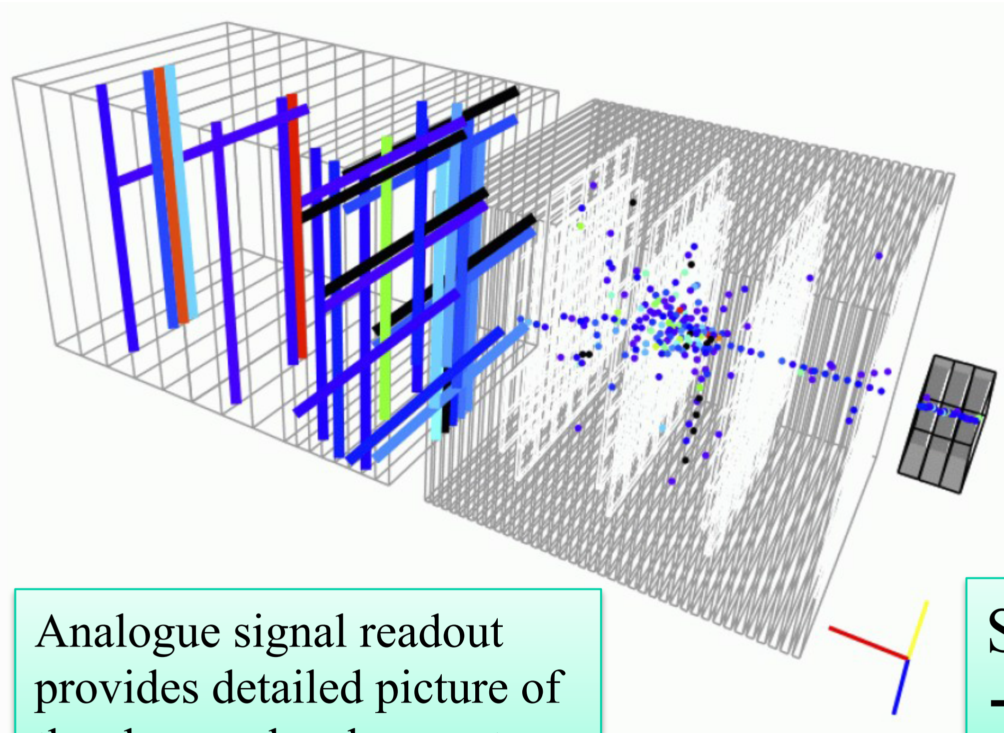
Signal in pixels from 5.4 GeV electron @ DESY

W absorbers, so small X_0 (~0.35cm) and R_M (~0.9cm)
→ relatively small transverse size prototype required

CALICE HCAL prototypes have included digital, semi-digital and analogue options

CALICE AHCAL: Scintillator tiles ($3x3cm^2$; $6x6cm^2$ and $12x12cm^2$) readout via wavelength-shifting fibres to on-tile SiPMs



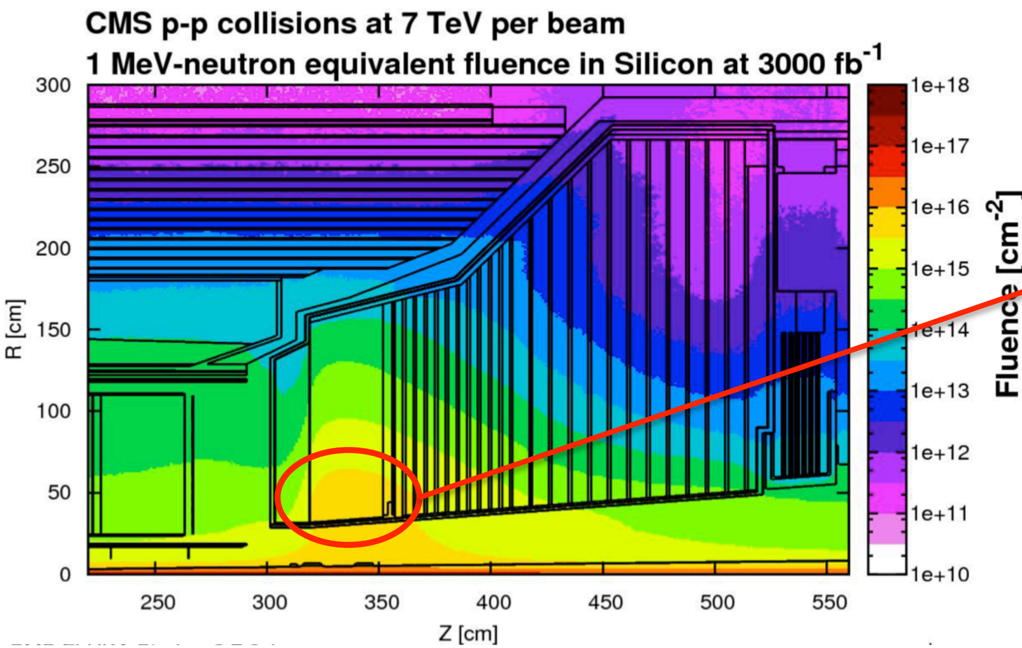


Analogue signal readout provides detailed picture of the shower development

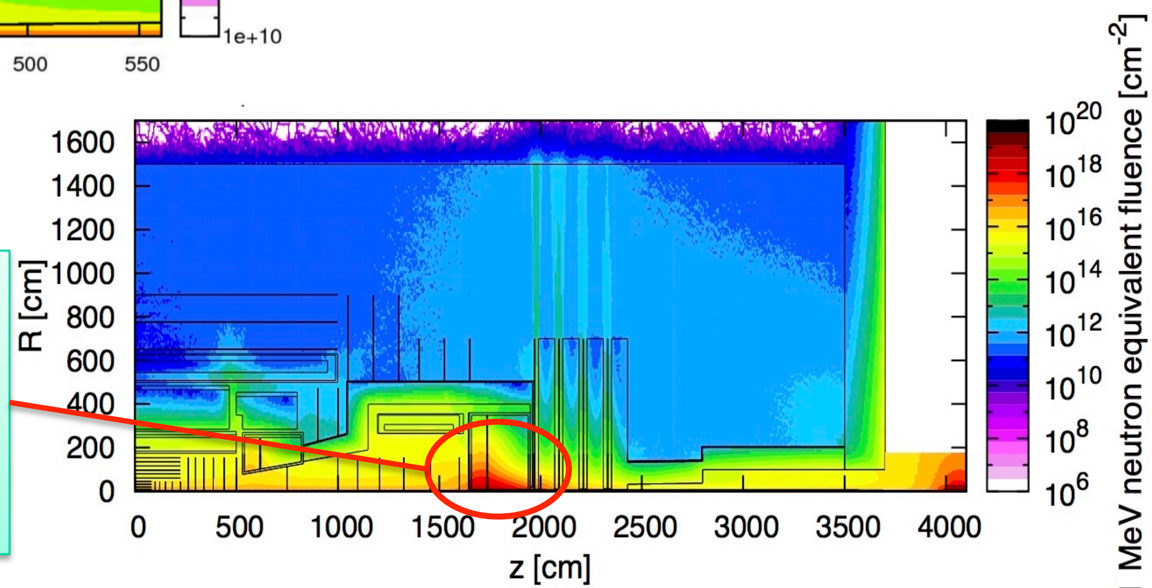
Steel absorbers with λ_{INT} ~17cm → need >40cm-wide calorimeter

HADRON COLLIDERS HAVE BIGGER CHALLENGES

Hadron colliders impose the tightest constraints on future calorimeters: radiation & pileup



CMS @ HL-LHC:
~**2x10^{16}** 1 MeV n_{eq} cm^{-2} @ 3ab^{-1}
in forward calorimeters,
with **pileup ~200**

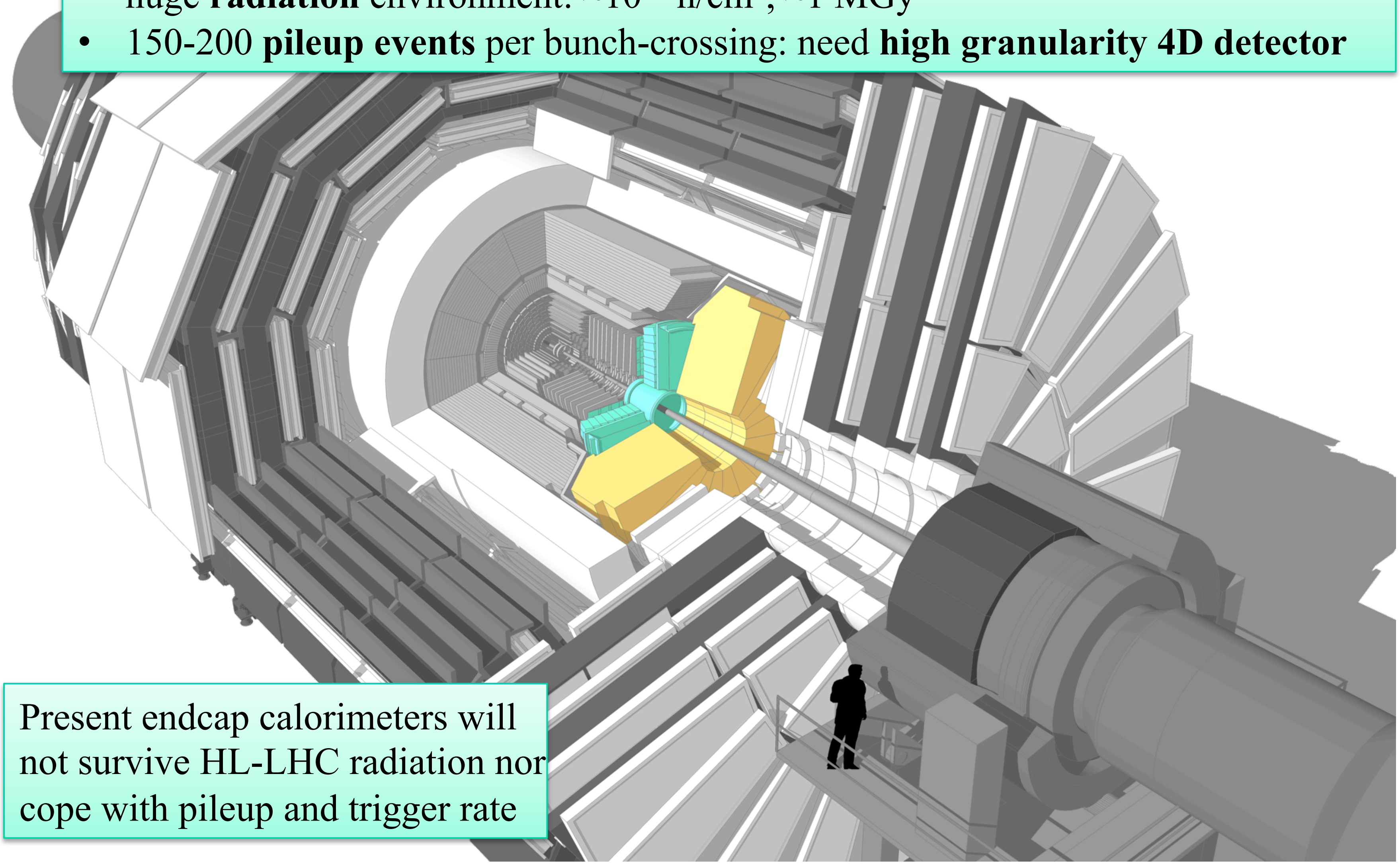


FCC-hh:
~**5x10^{18}** 1 MeV n_{eq} cm^{-2} @ 30ab^{-1}
in forward calorimeters,
with **pileup ~1000**

THE CMS HGCAL

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

Motivation for upgrade for HL-LHC:
- huge **radiation** environment: ~10^{16} n/cm^2, ~1 MGy
- 150-200 **pileup events** per bunch-crossing: need **high granularity 4D detector**



Present endcap calorimeters will not survive HL-LHC radiation nor cope with pileup and trigger rate

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

Look for proven and adequately radiation-hard active materials

To build a dense e.m./hadronic calorimeter with a good energy resolution, small R_M, good two-shower separation (e.m. and hadronic), with high lateral and longitudinal readout granularity

↓

A silicon-sensor-based sampling calorimeter

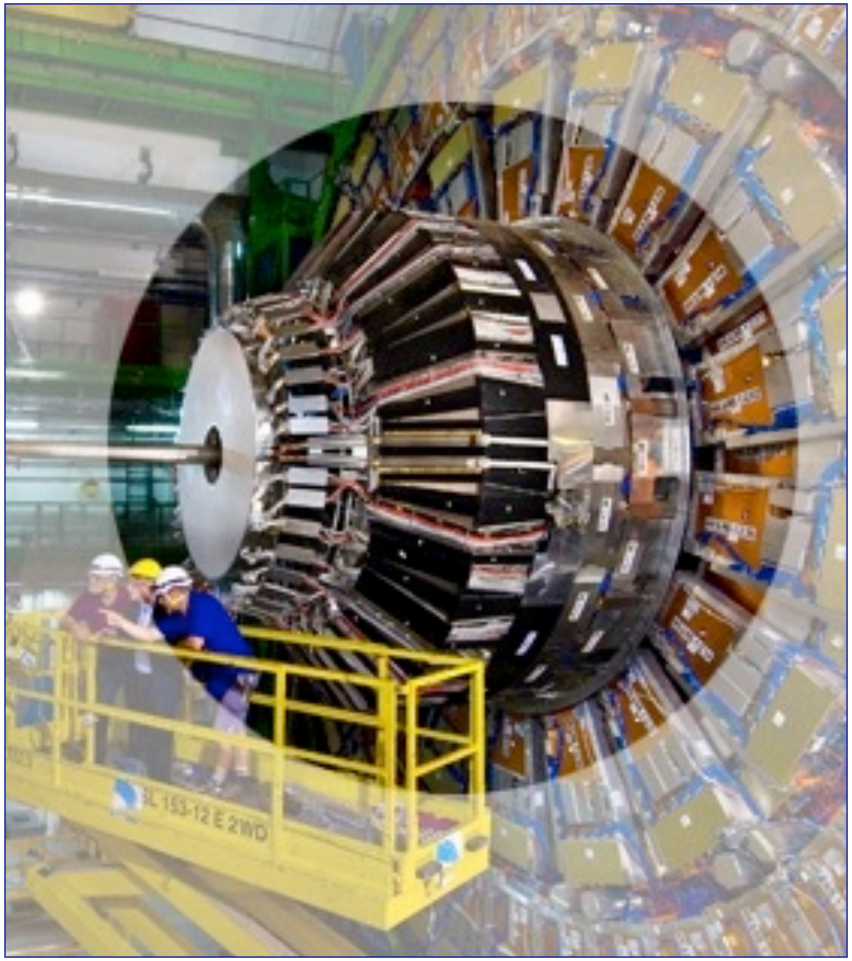
(absorber materials – W, Pb, Cu, Stainless Steel)

followed by **plastic scintillator tiles with direct SiPM** readout for the lower radiation level region

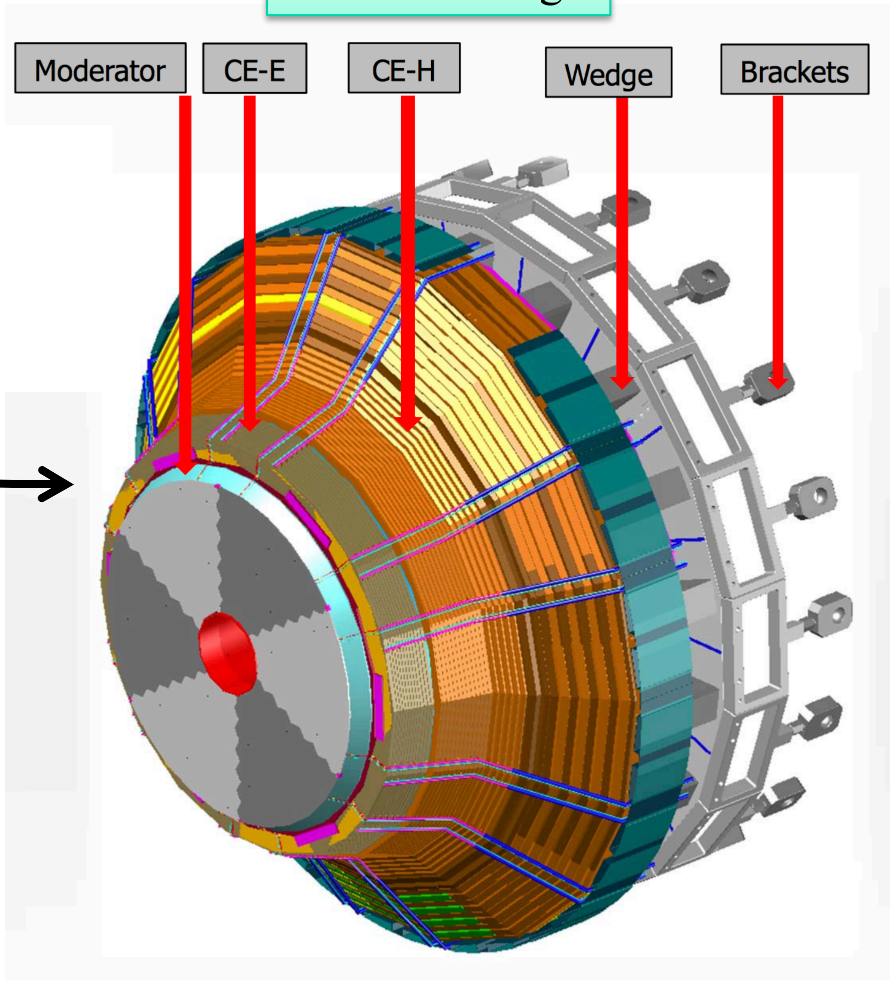
(absorber material SS)

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

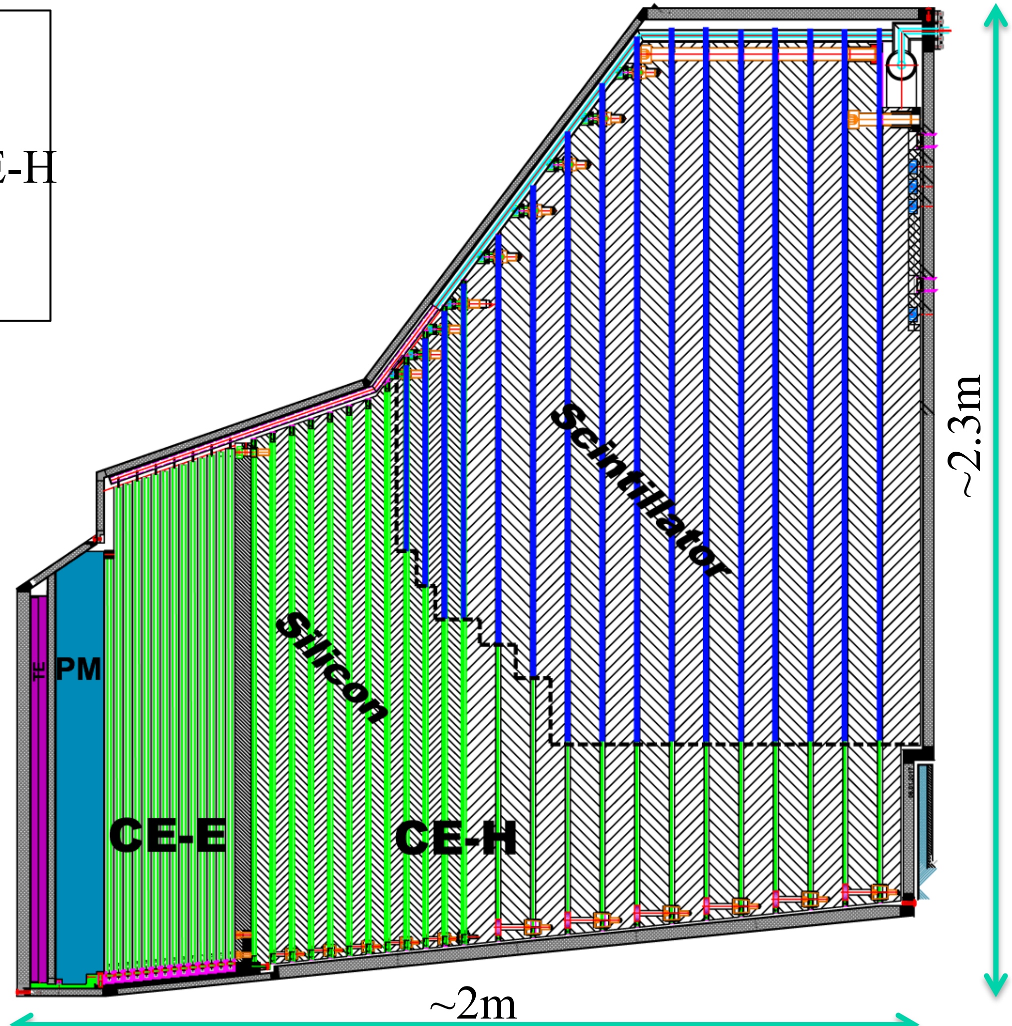
CMS HGCAL: a sampling calorimeter with unprecedented number of readout channels

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:

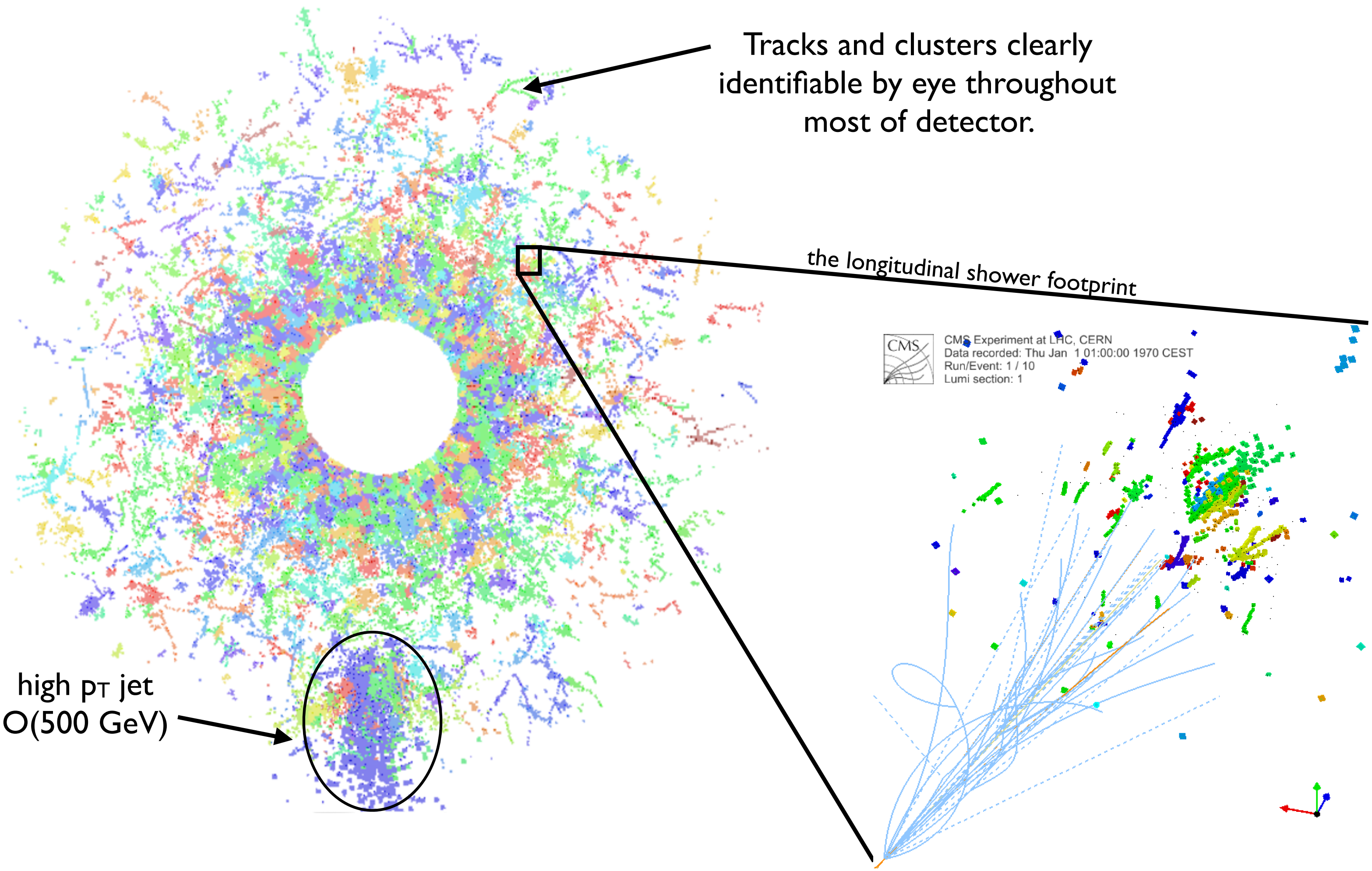
- HGCAL covers $1.5 < \eta < 3.0$
- **Full system maintained at -30°C**
- **~600m²** of silicon sensors
- **~500m²** of scintillators
- 6M si channels, 0.5 or 1 cm² cell size
- ~27000 si modules



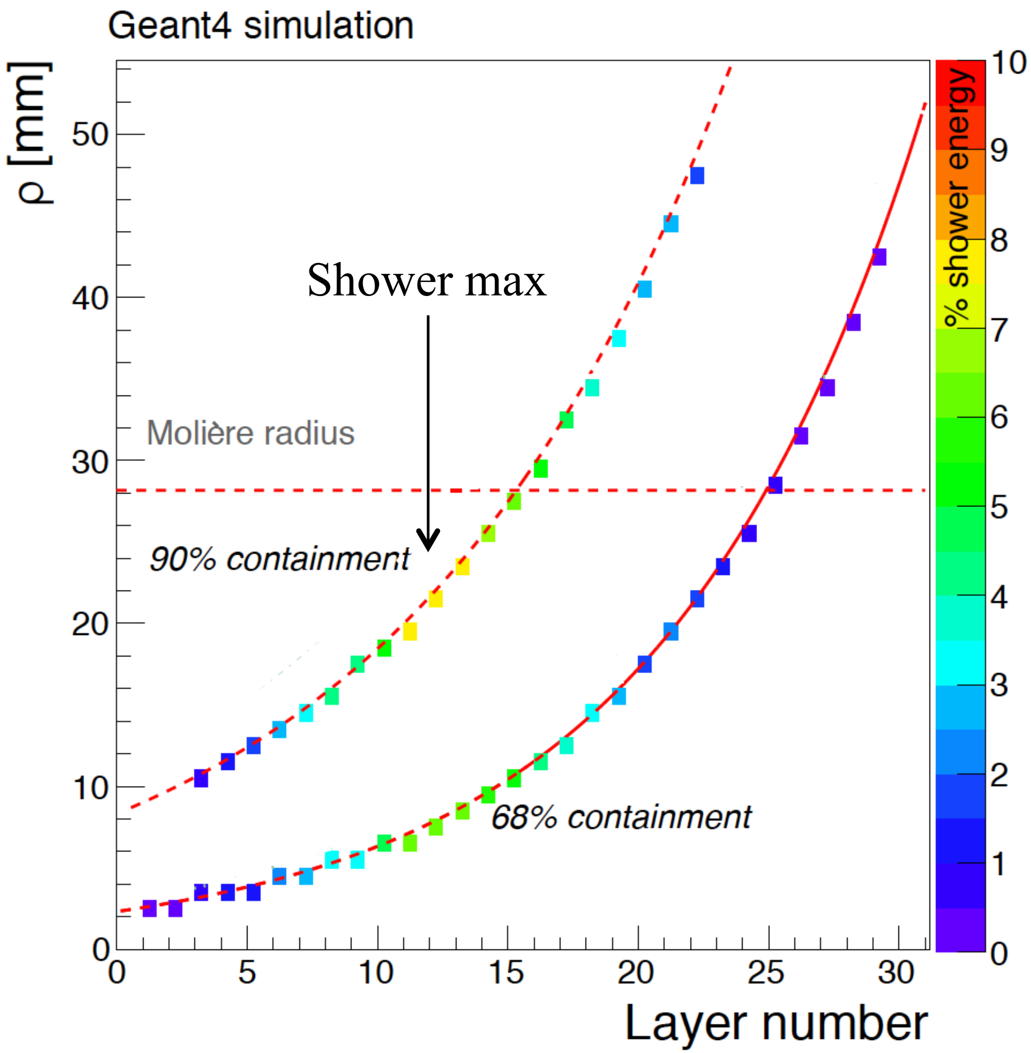
Electromagnetic calorimeter (C**E-E**): **Si**, Cu/CuW/Pb absorbers, 28 layers, 25 X_0 & ~1.3λ
Hadronic calorimeter (**CE-H**): **Si** & **scintillator**, steel absorbers, 24 layers, ~8.5λ

HGCAL has the potential to visualize individual components of showers

Simulation of 140 pileup events in CMS



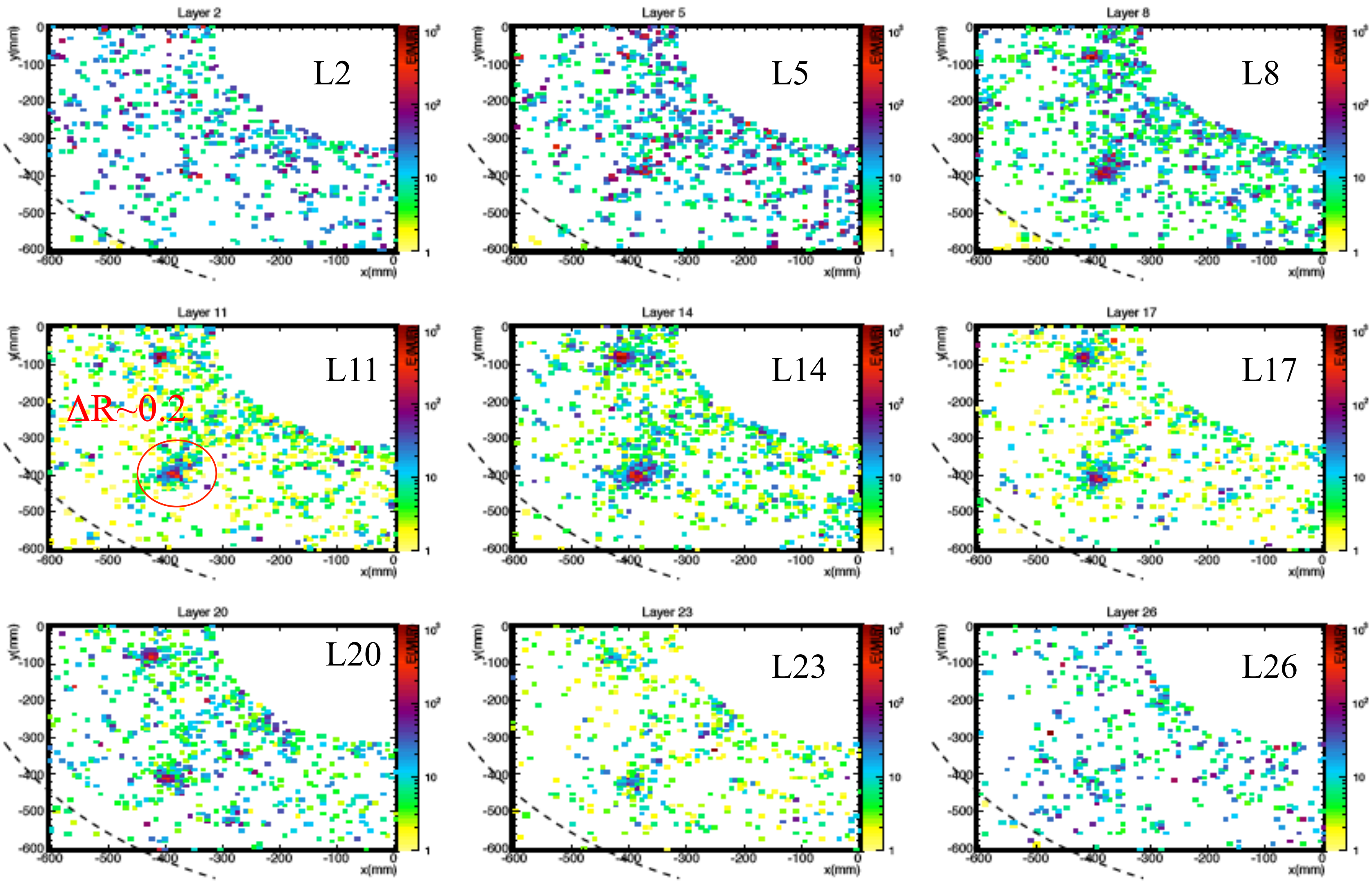
Moliere radius of HGCAL is ~28mm, but high granularity → much finer details can be resolved



Coloured rectangles:
= % shower energy deposited in that layer

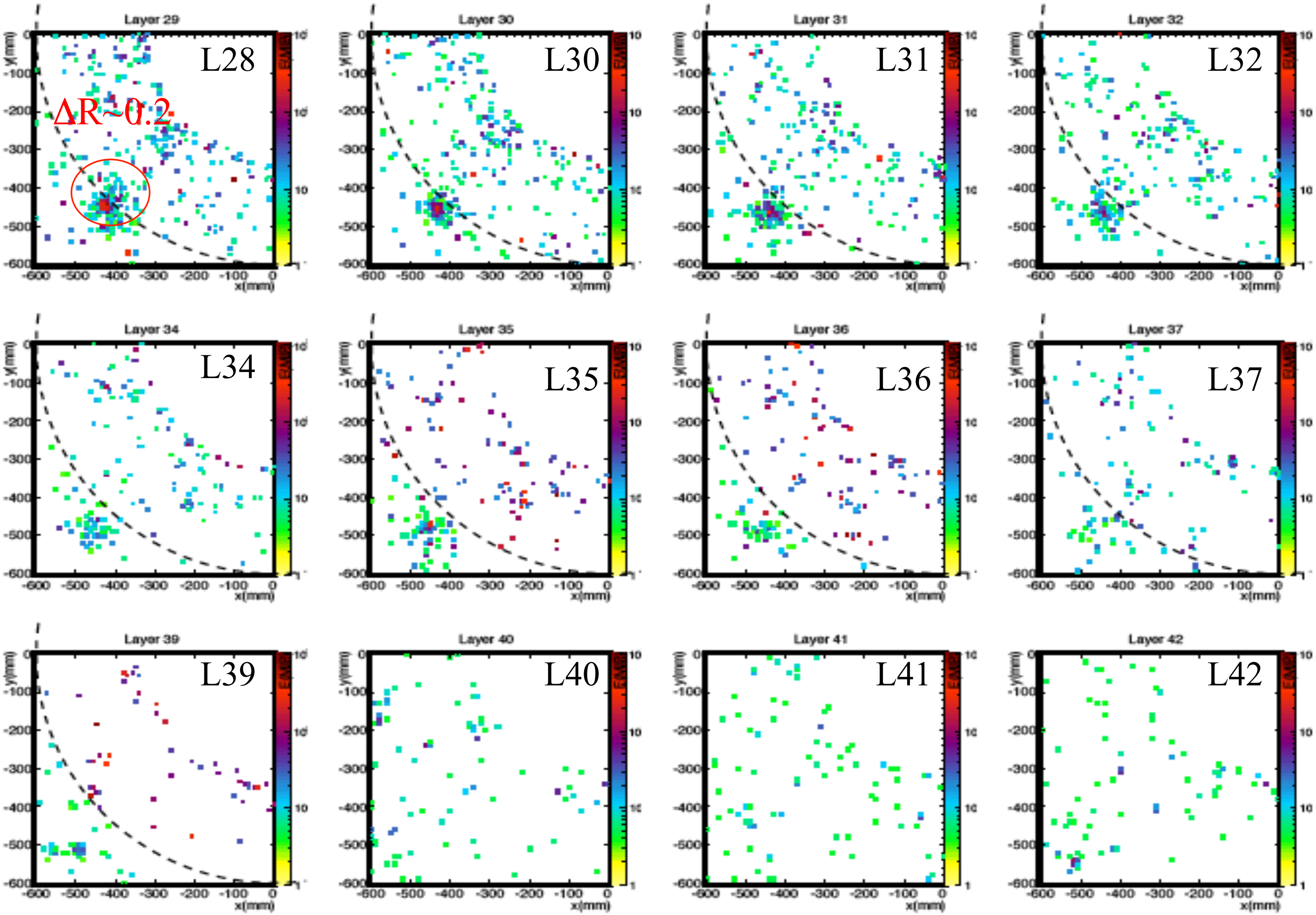
Example of VBF H→γγ, with the VBF jet (two pions + γ) and a γ incident on the CMS endcap

Showers from the two photons are visible in the layers of the electromagnetic part



Example of VBF H→γγ, with the VBF jet (two pions + γ) and a γ incident on the CMS endcap

Showers from the two pions become visible in the layers of the hadronic part



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

DC-coupled sensor pads

- simplify production technology
- (consider n-type sensors for 300μm sensors in lower radiation region of HGCAL)

Hexagonal vs square sensor geometry

- make most efficient use of sensor wafer
- reduce number of sensors produced & assembled into modules (factor ~ 1.3)

8” vs 6” wafer production

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

300μm, 200μm and 120μm active sensor thickness

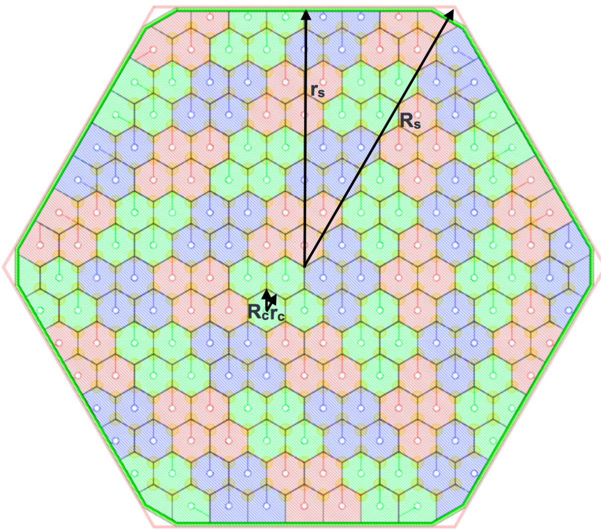
- match sensor thickness (and granularity) to radiation field for optimal performance

Simple, rugged module design & automated module assembly

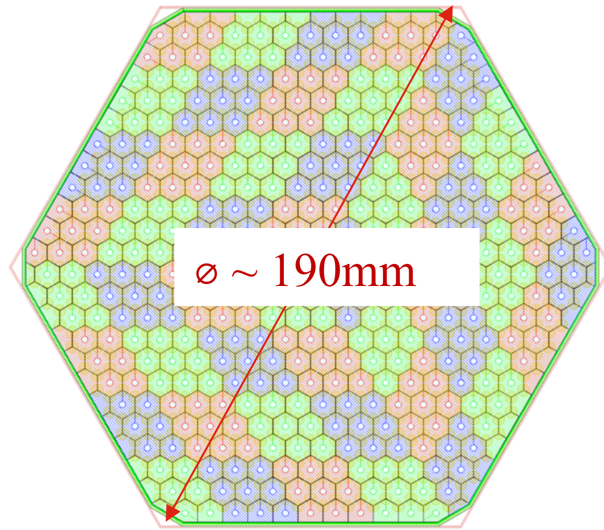
- provide high volume, high rate, reproducible module production & handling

8” silicon sensors will be hexagonal, divided into hexagonal cells (mostly)

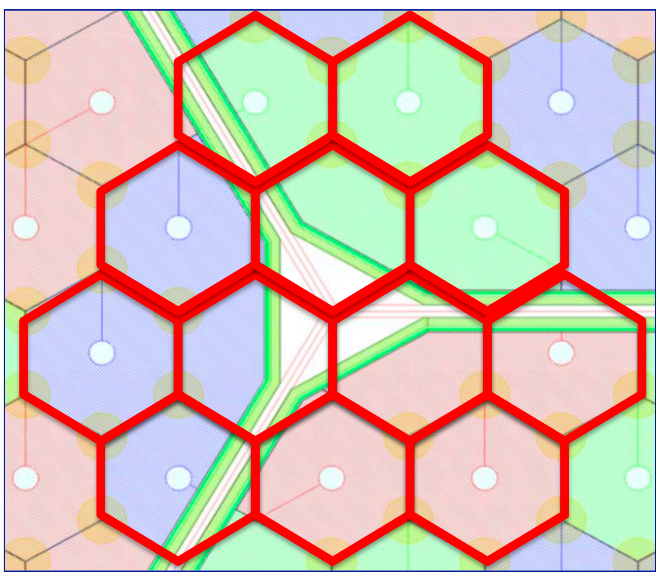
192 cells/sensor

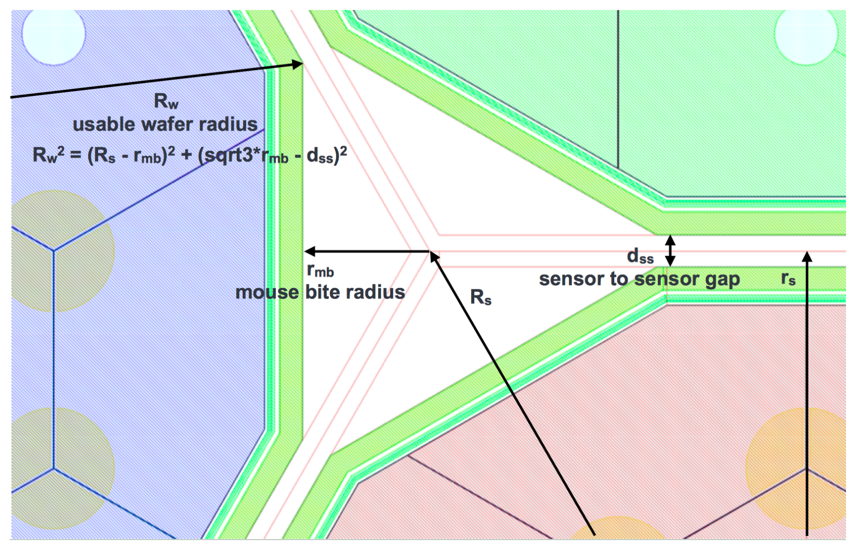


432 cells/sensor



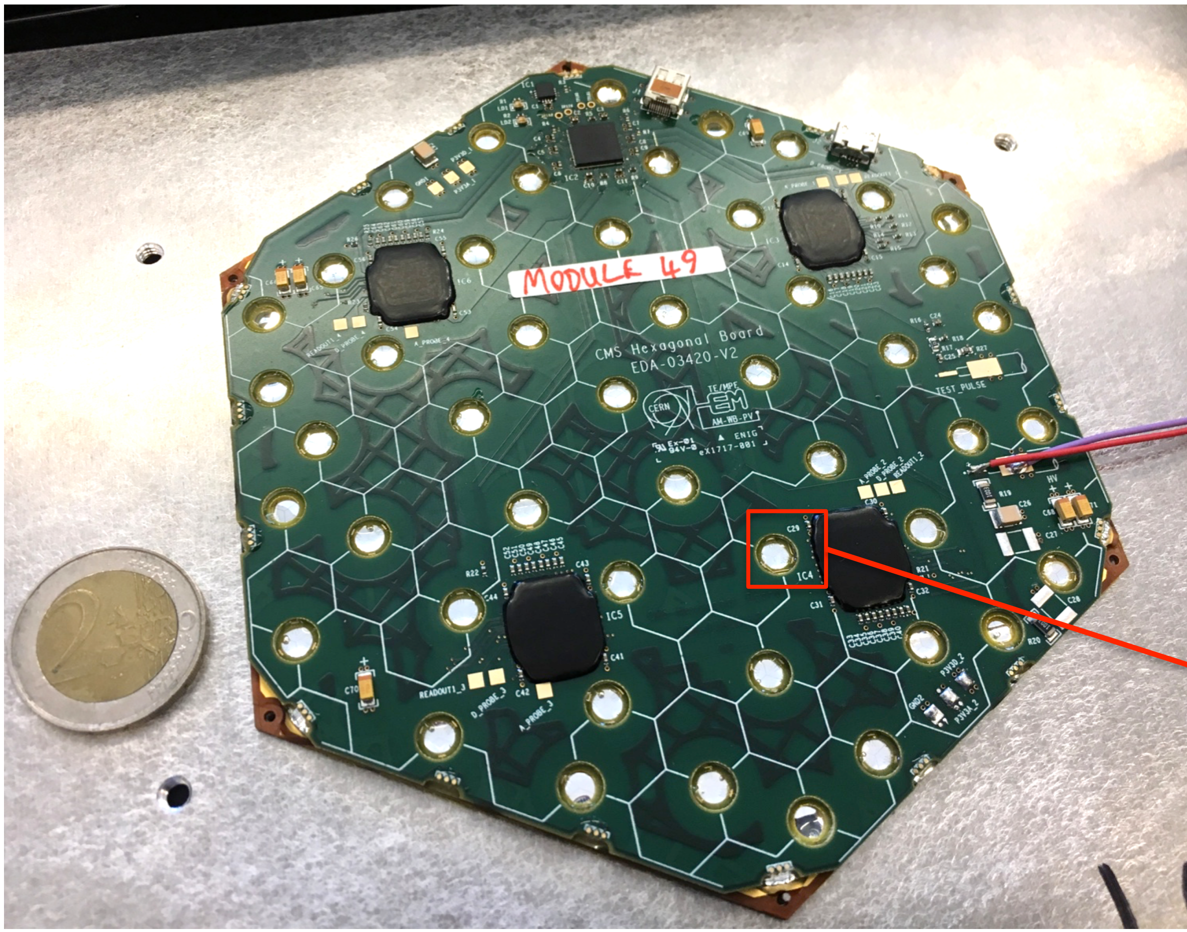
Coloured groupings of cells represent trigger readout units



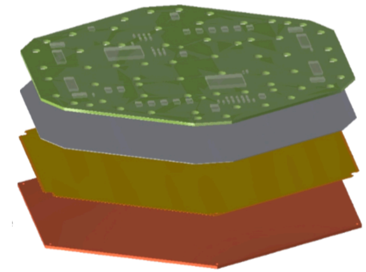


HGCAL will include 27000 modules based on hexagonal silicon sensors with 0.5-1cm^2 cells

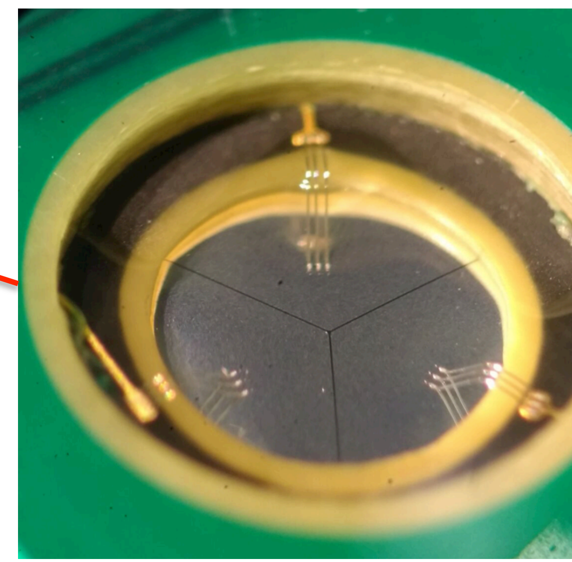
Silicon sensor glued to baseplate and PCB containing front-end electronics



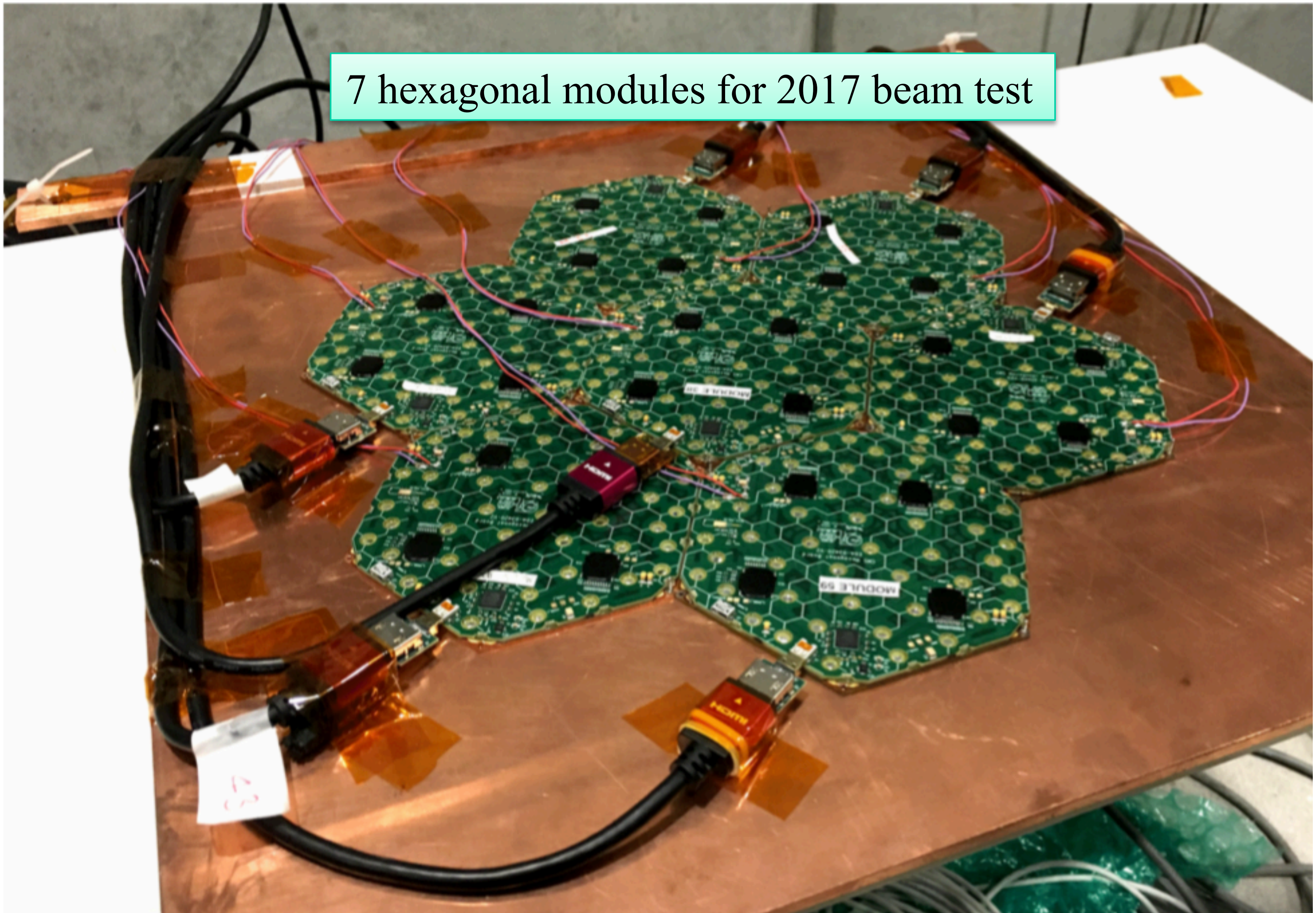
hexaboard
sensor
Kapton foil
Cu/W



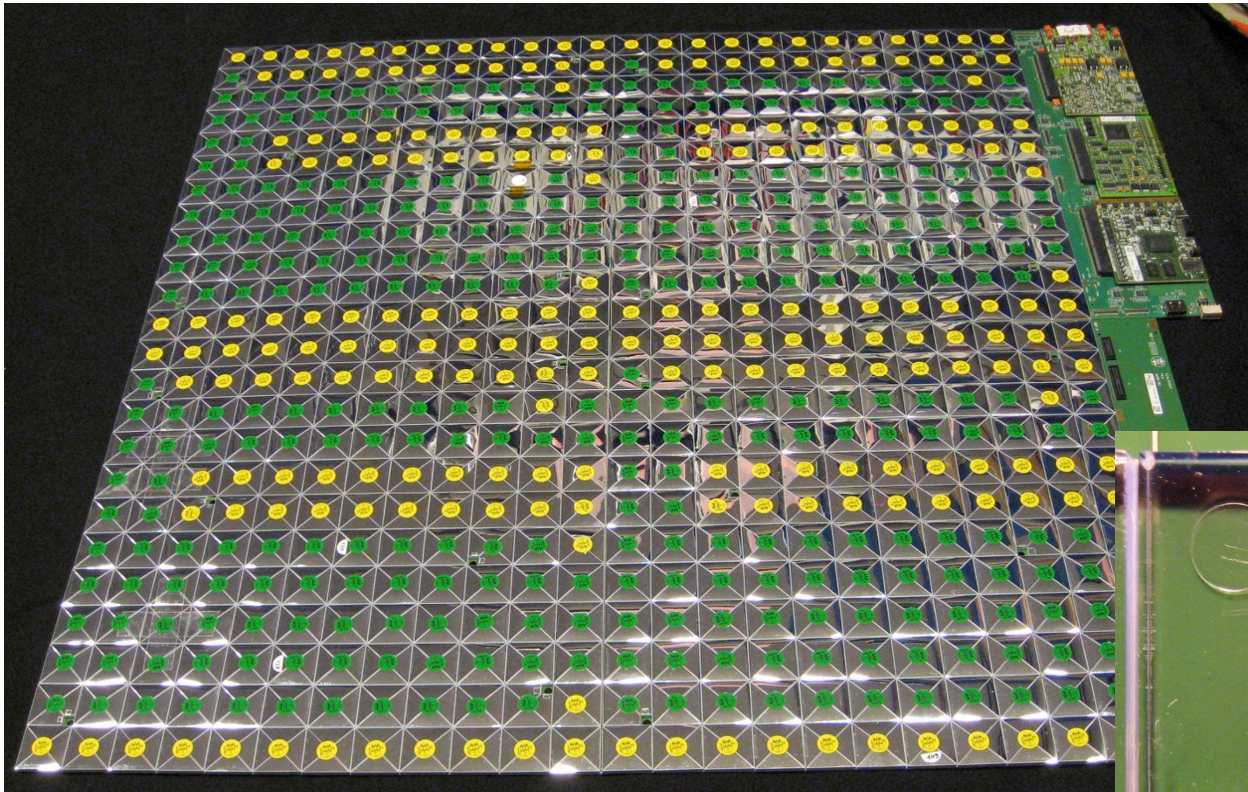
Wire bonding from PCB to silicon through holes

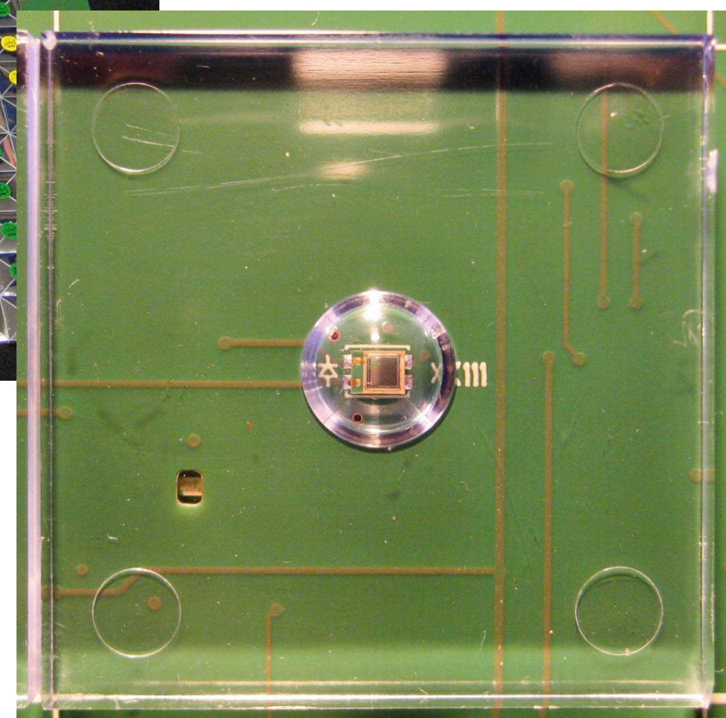


Silicon modules are arranged in hexagonal matrices to cover fiducial area of HGCAL



HGCAL will also include 500m² of scintillator tiles with on-tile SiPM readout

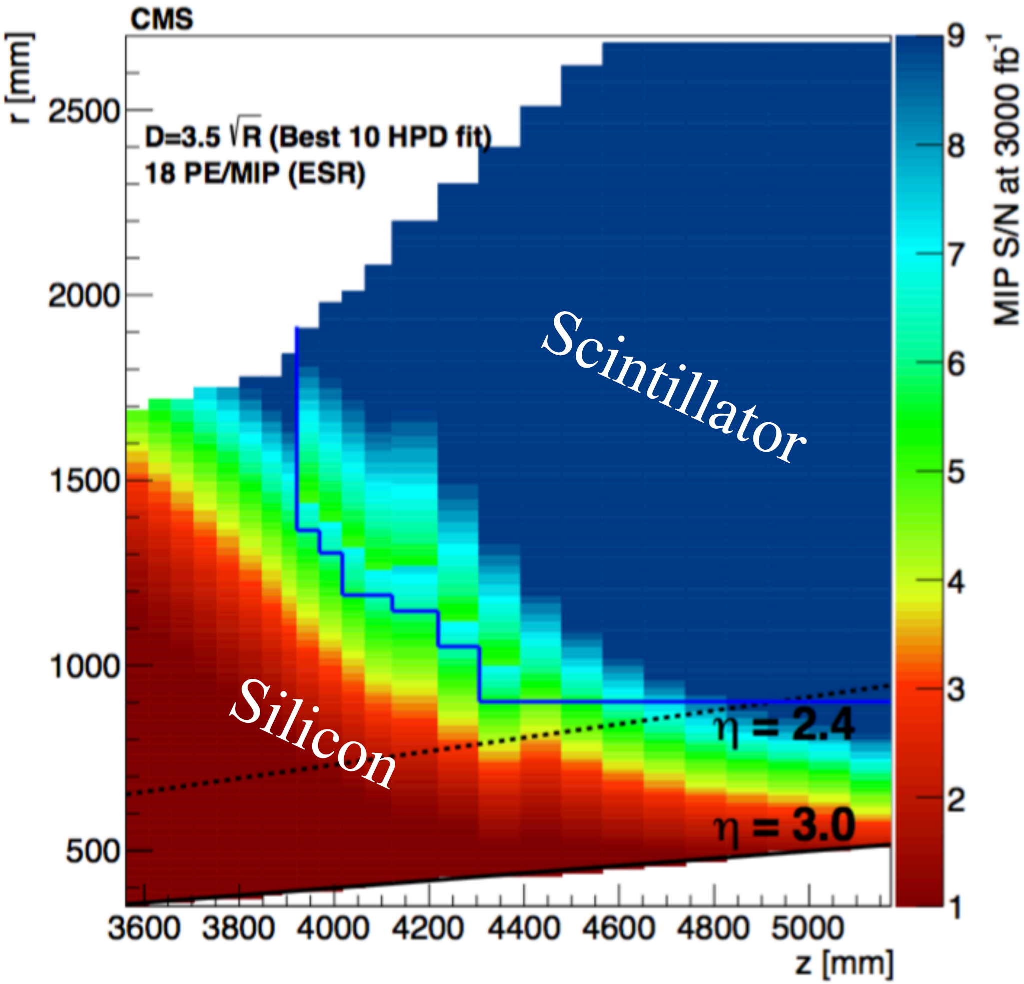


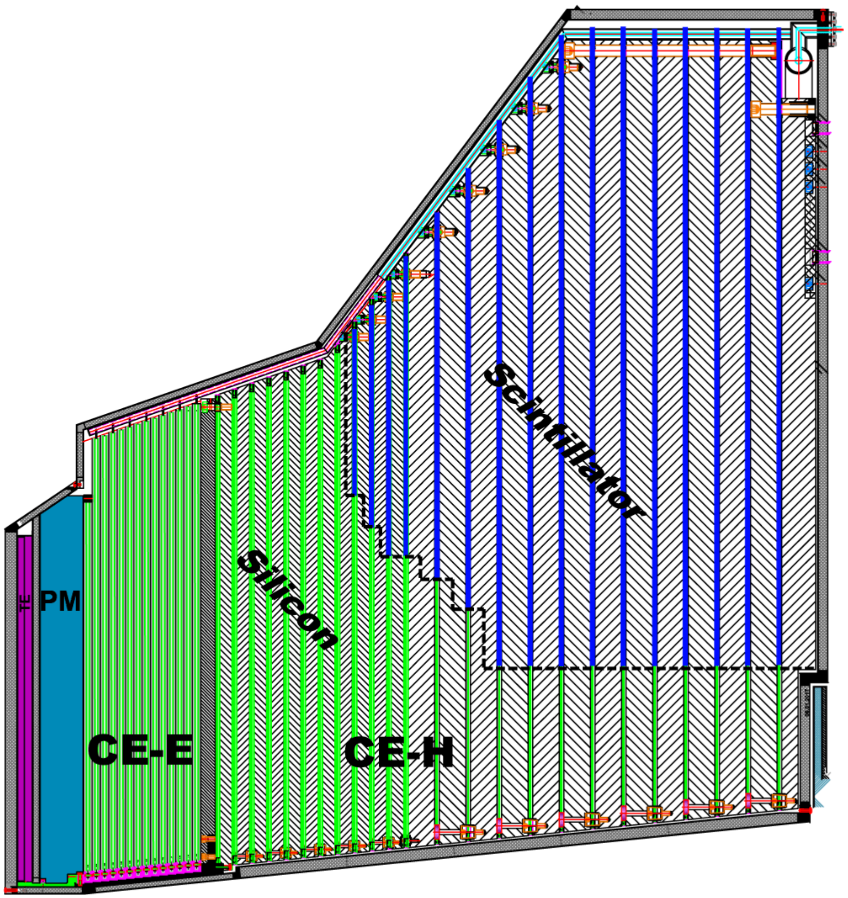


For first beam tests, modified CALICE AHCAL used for rear hadron calorimeter:
3x3cm² scintillator tiles + direct SiPM readout

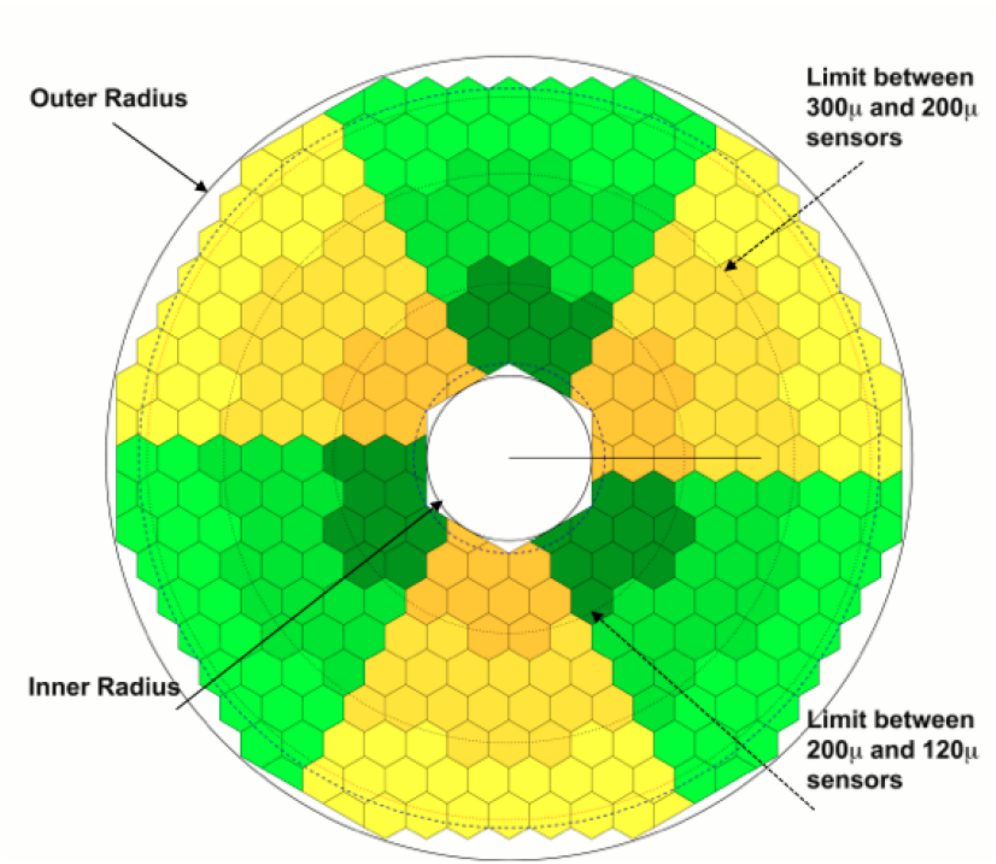
Regions of silicon or silicon + scintillator/SiPM governed by radiation field

Silicon in high-radiation regions

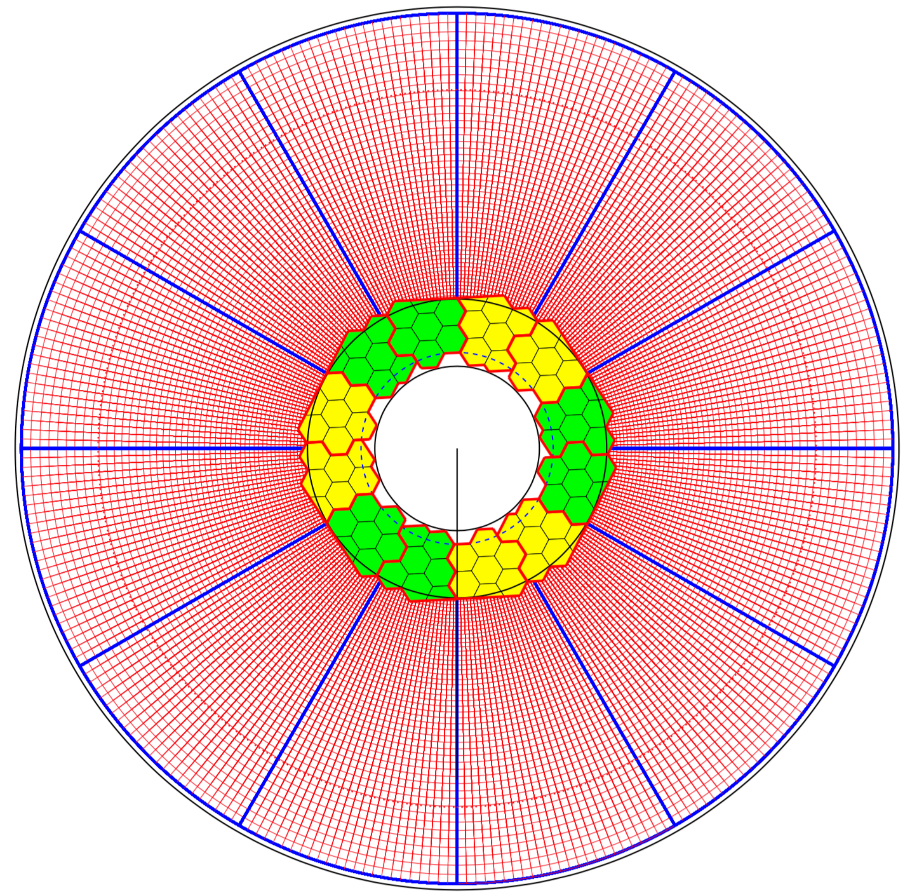




Wedge-shaped "Cassettes" containing arrays of silicon modules or silicon+scintillator/SiPM

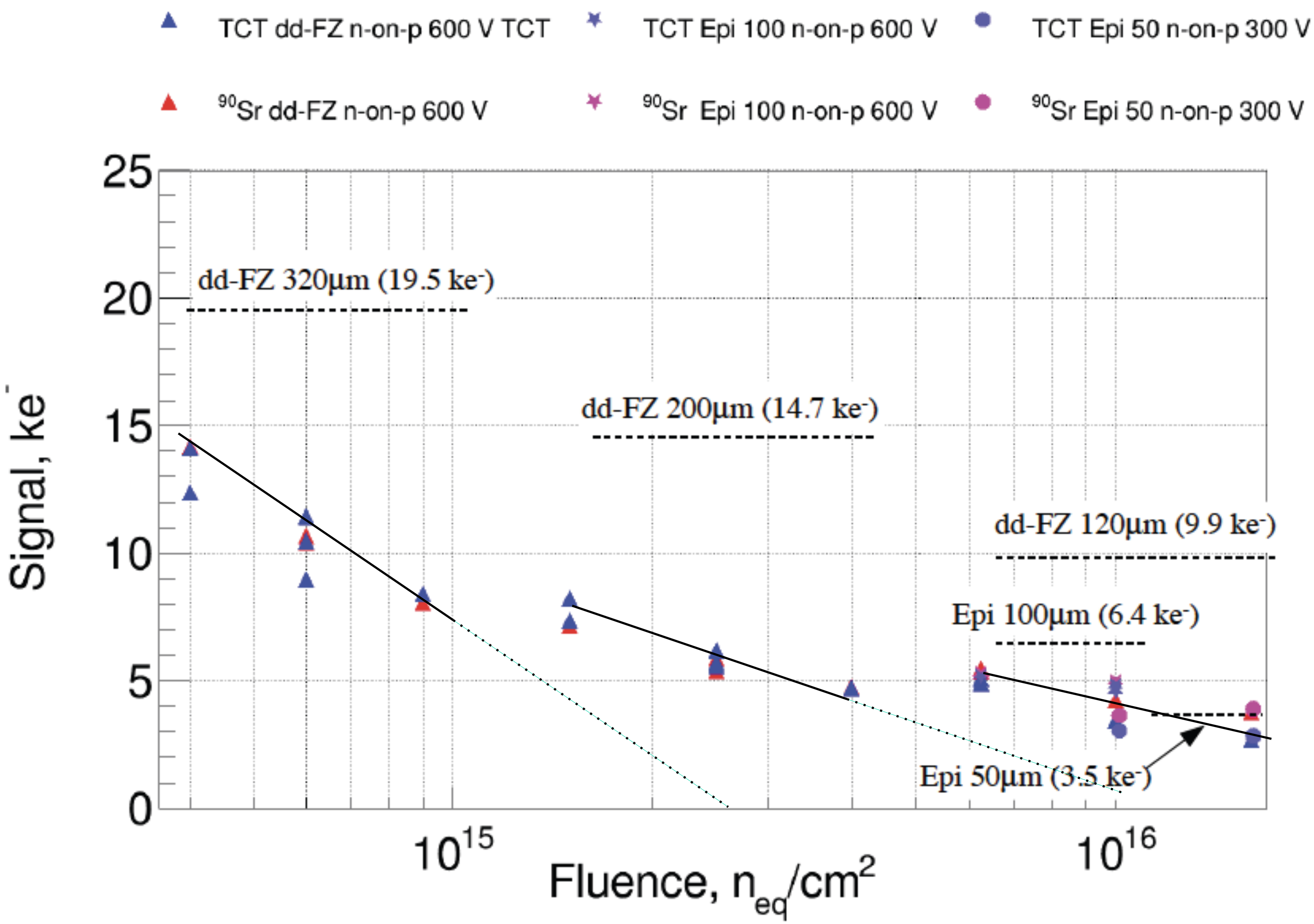


Silicon-only layer (in CE-E) showing "cassettes" and different sensor thicknesses



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

Thinner sensors show less change in CCE than thicker sensors vs fluence

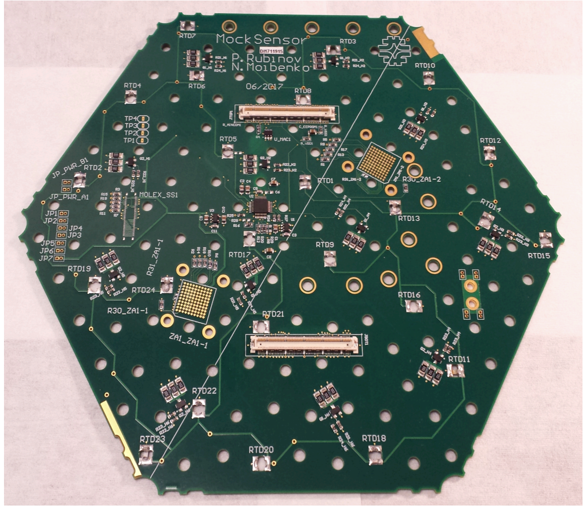


The front-end electronics are particularly challenging in the compact HGCAL

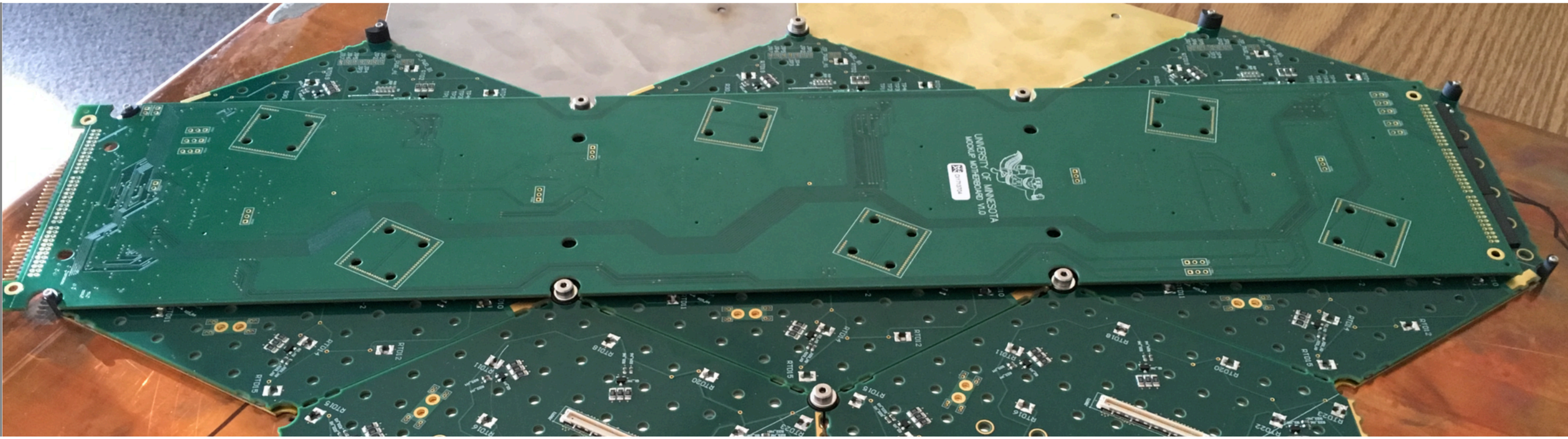
- **Low noise** (<2500e$^-$) and **high dynamic range** (~0.2fC → 10pC)*
  - See **MIPs** (~3.5fC in 300μm silicon) **with S/N > 3** for whole lifetime of HL-LHC
- Provide timing information to **tens of picoseconds**
- Have **fast shaping time** (<20ns) to minimize out-of-time pileup
- On-detector **digitization 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 (**>1.5 MGy and 10^{16} n_{eq}/cm^2**)
- And be in production ~2021

*want S/N ~8 at beginning of HL-LHC for 1 MIP in 120μm silicon ~ 1.5fC;
upper limit from 1.5TeV photon shower producing ~6000 MIPs in a single cell

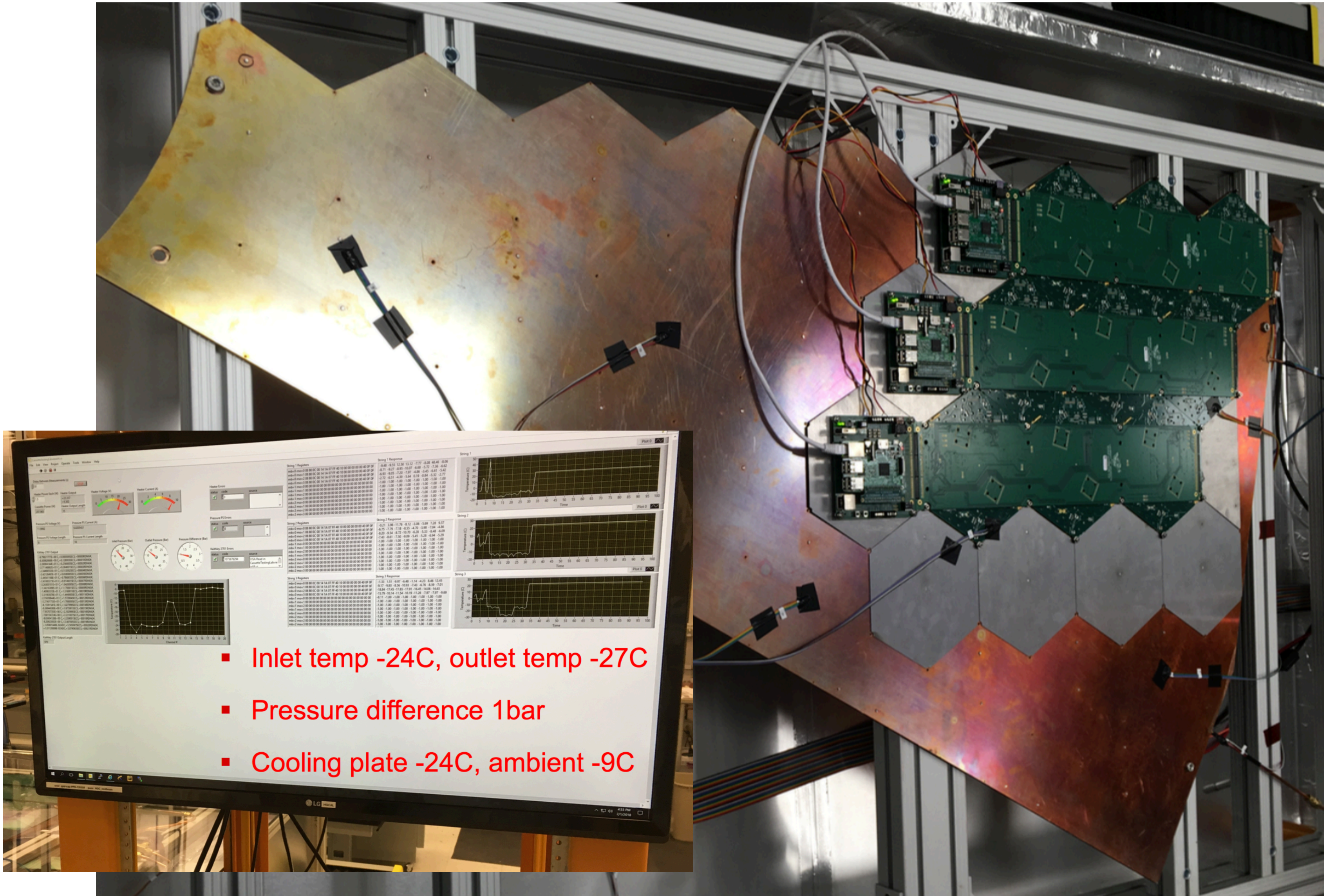
“dummy” cassette being assembled with PCBs containing only connectors and heat loads



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

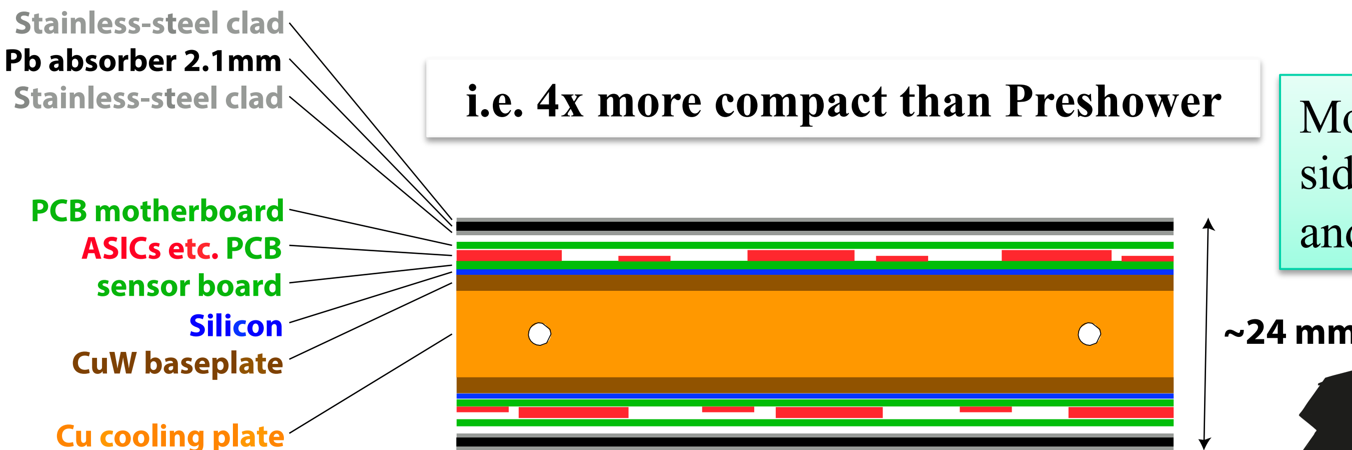


Dummy cassette is installed in a cold box to study heat-transfer characteristics – works well!

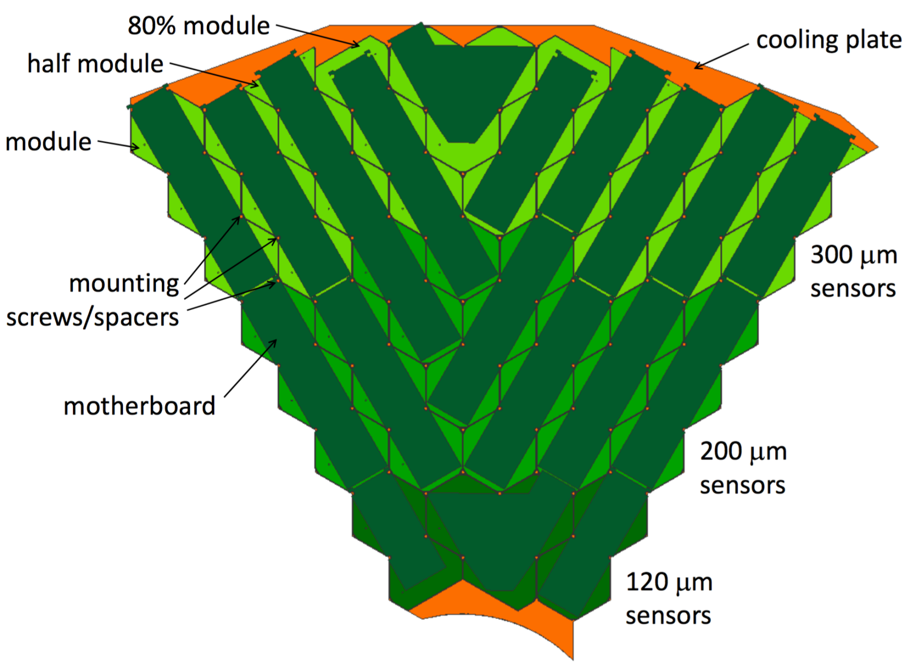


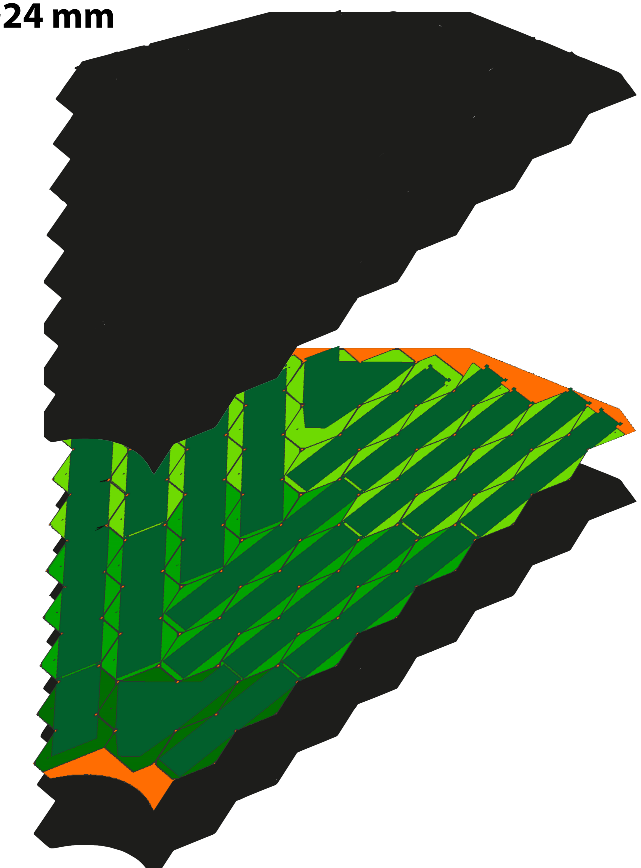
CE-E cassettes are self-supporting sandwich structures with Pb, Cu and Cu/W as absorbers

i.e. 4x more compact than Preshower

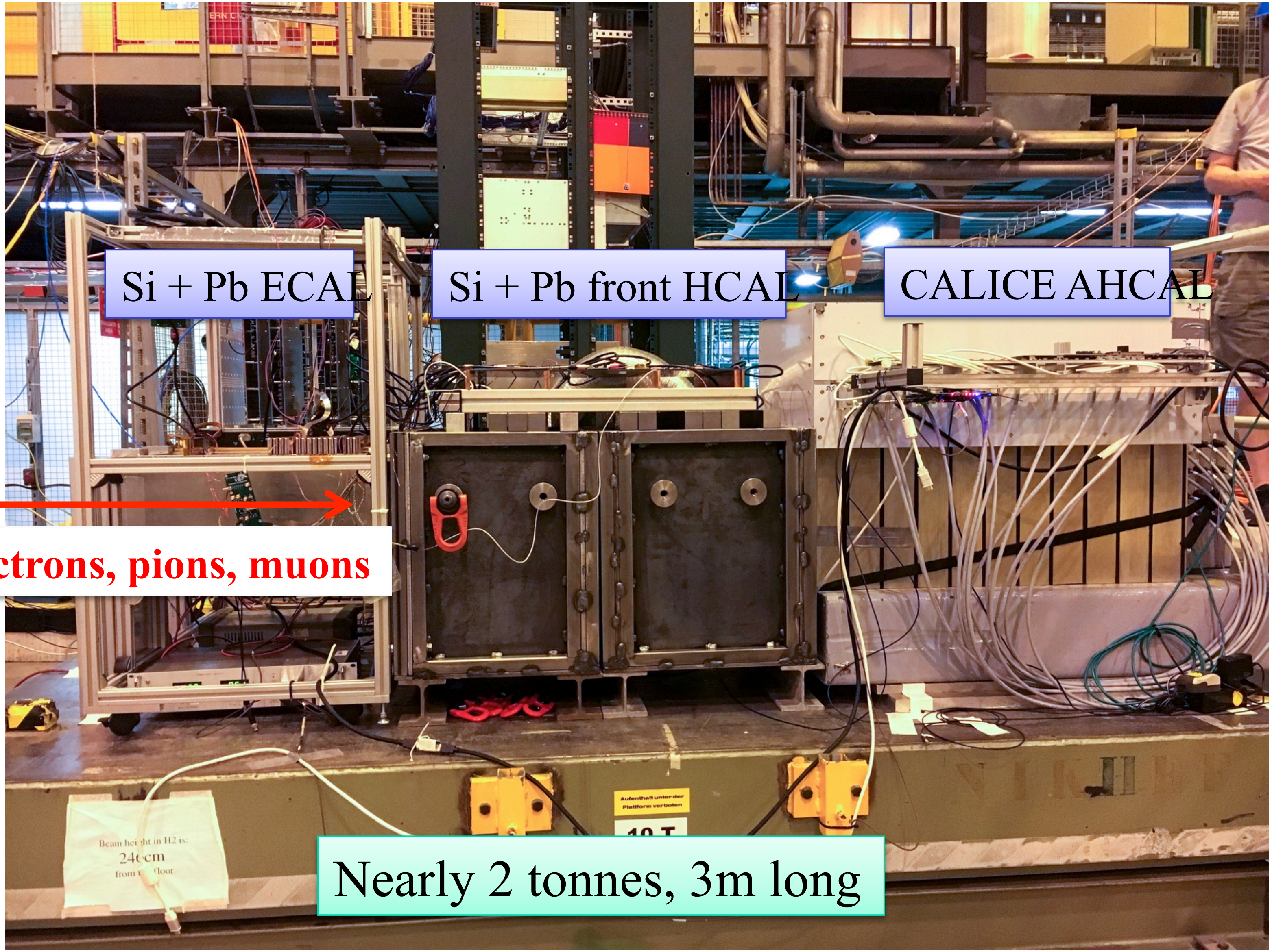


Modules placed on both sides of Cu cooling plate and “closed” with Pb plates

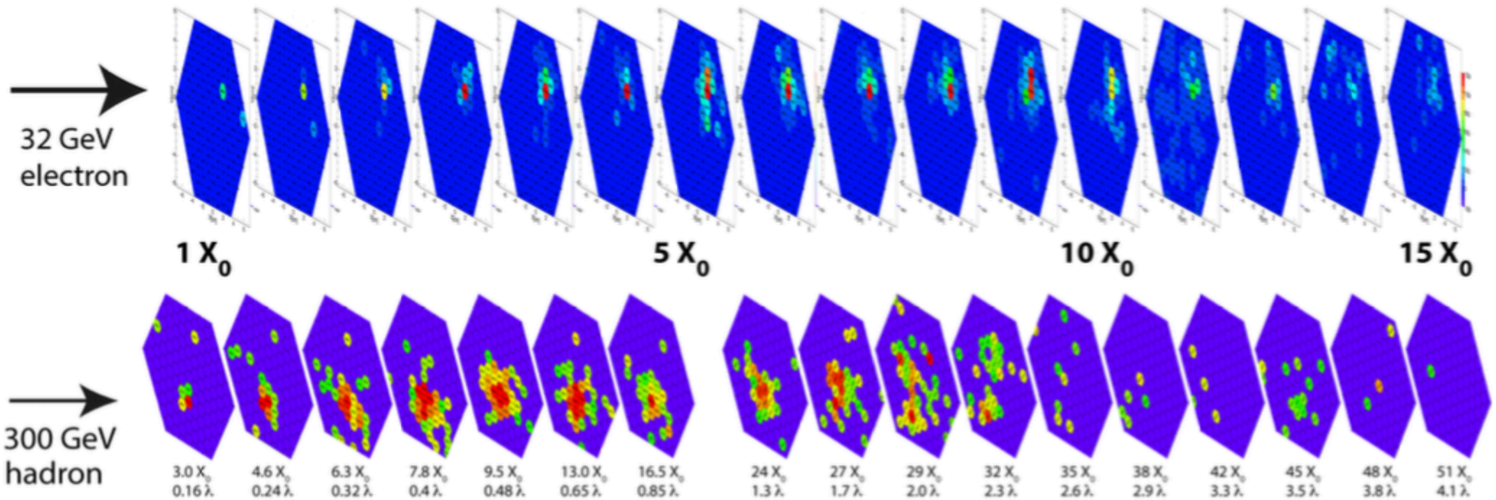


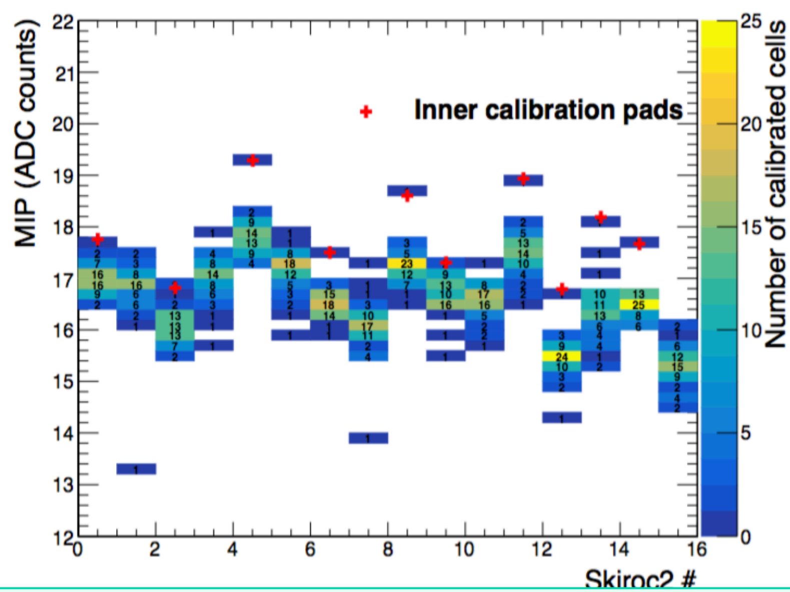


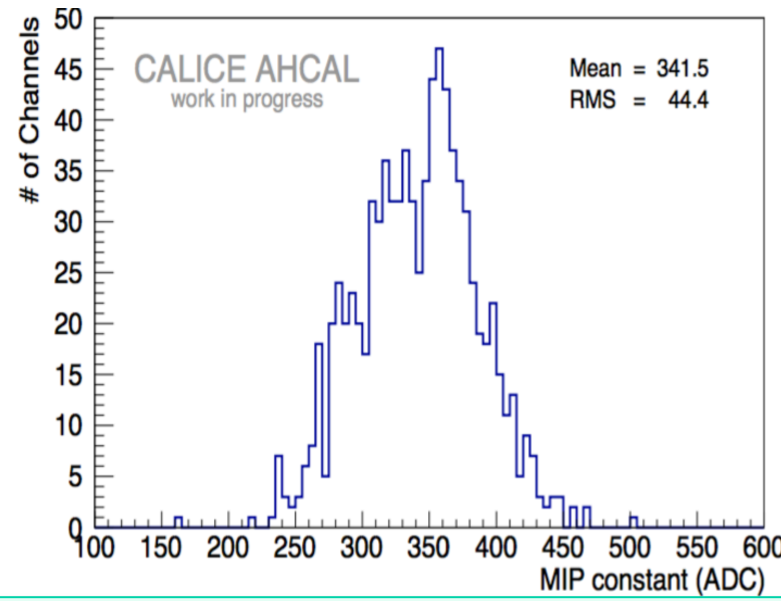
Prototype silicon modules + CALICE AHCAL tested at CERN in 2017; more in 2018



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

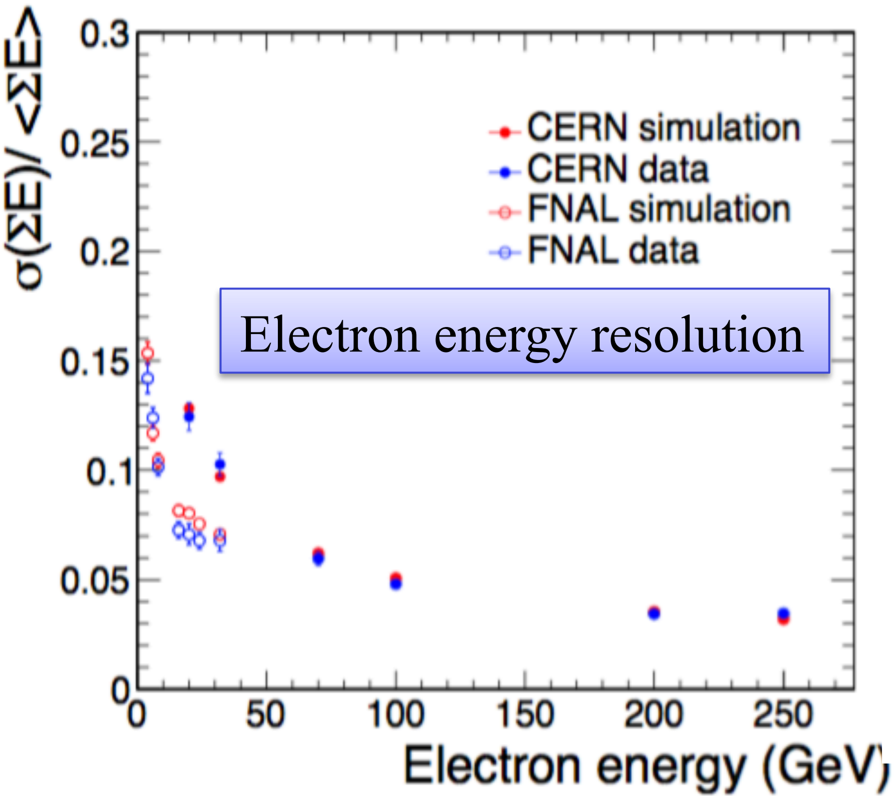


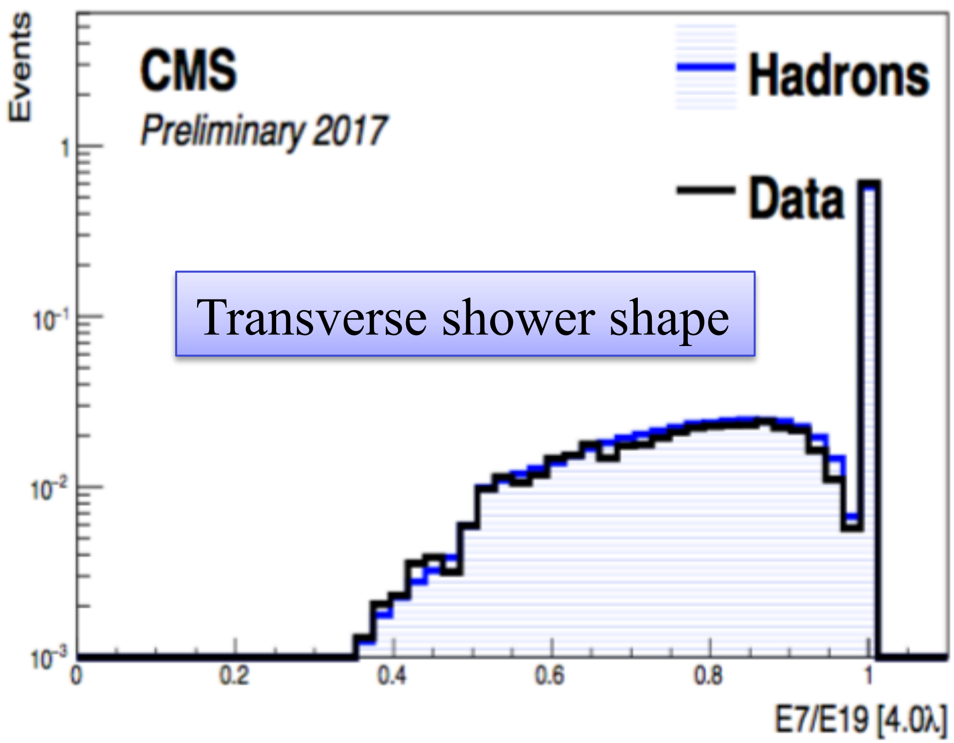




Mips (for calibration) seen from muons and also single particles within hadronic showers

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





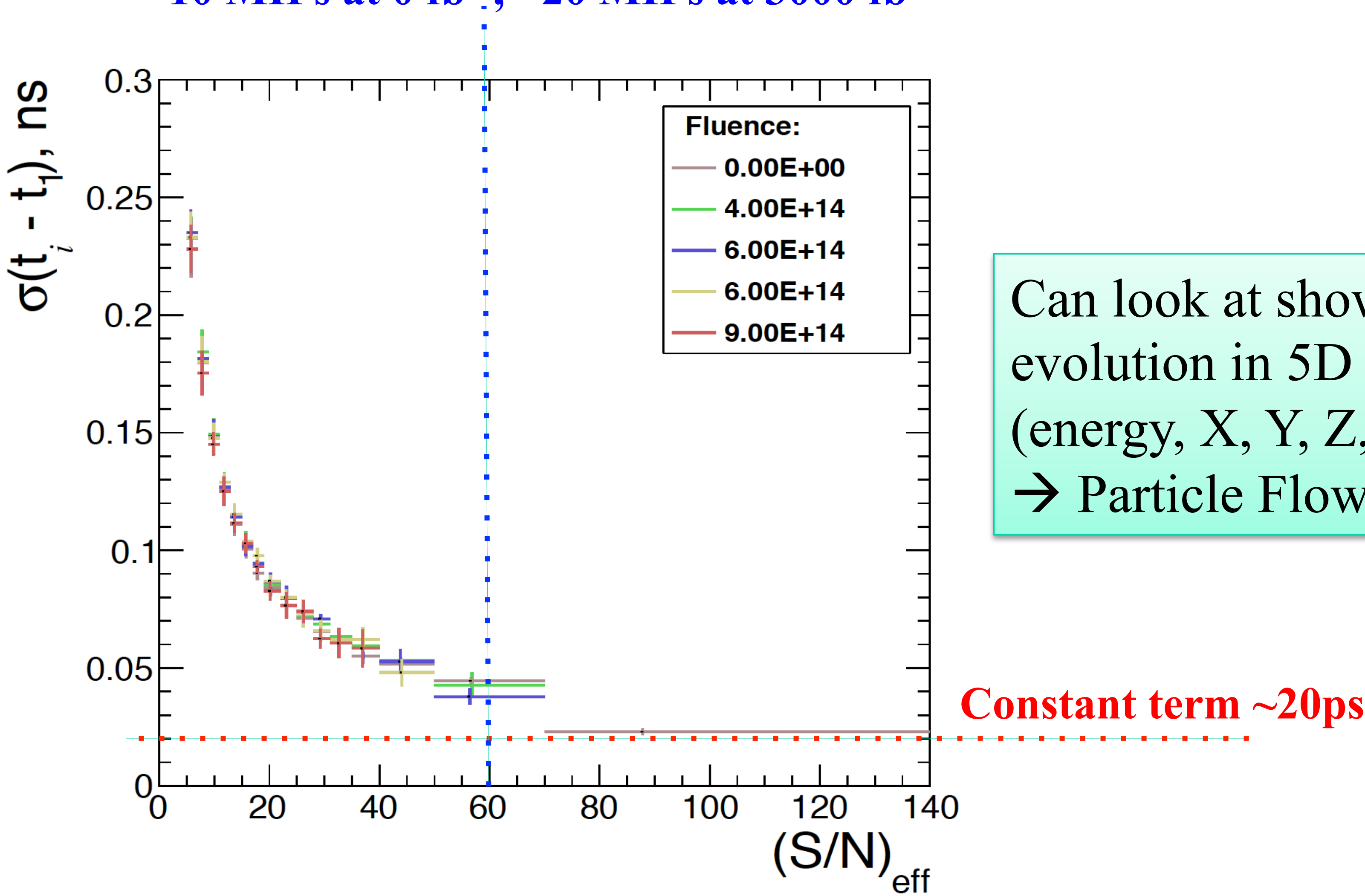
Distributions from electrons and pions match those predicted by simulation (to within 5%) demonstrating accuracy and scalability

First indications that HGCAL performance is as expected from simulation

More test beam data will be taken in 2018 (ongoing test in DESY now!)

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

~10 MIPs at 0 fb^{-1}; ~20 MIPs at 3000 fb^{-1}



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

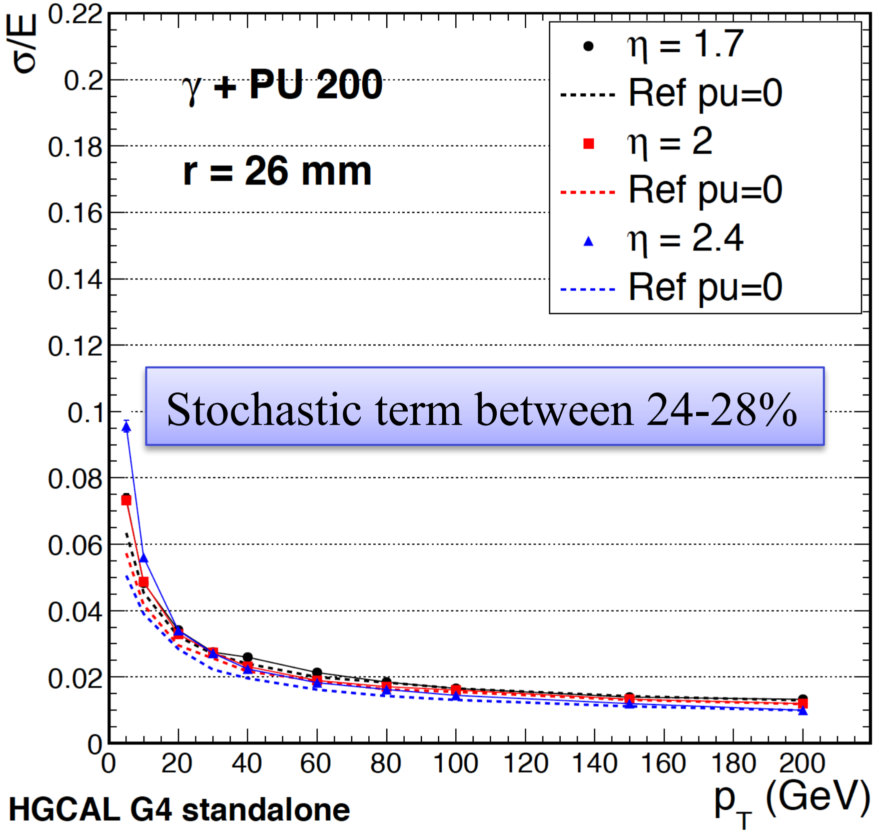
Full simulated reconstruction and performance of HGCAL is in its infancy

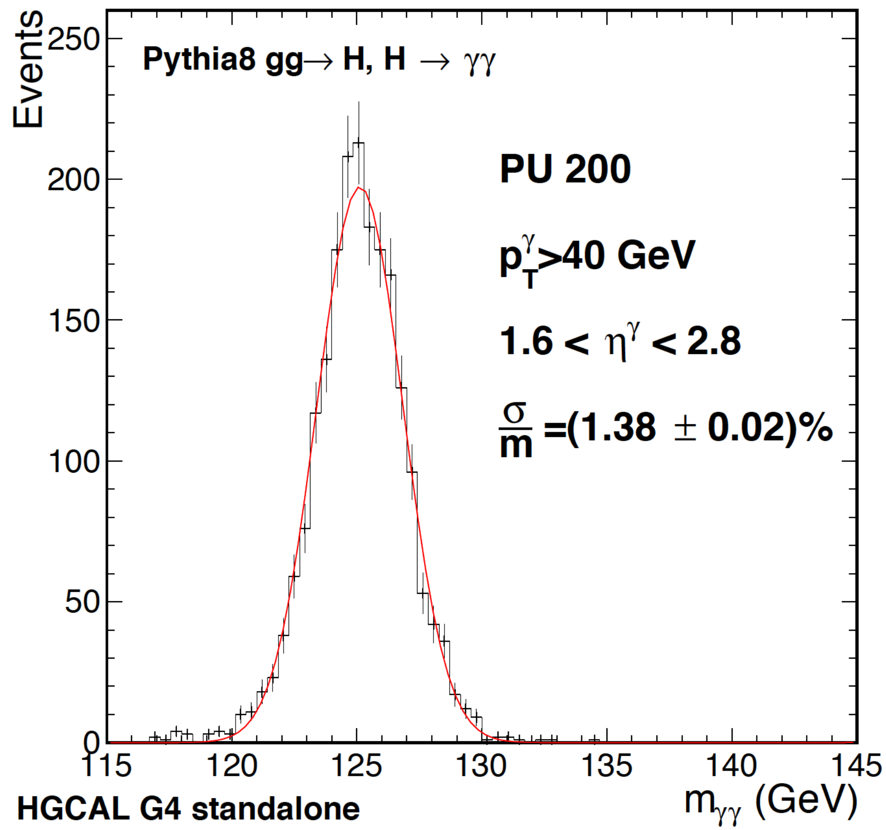
The detailed implementation of the detector geometry necessarily **lags behind technical design choices**. In autumn 2016, before the making of many of the important engineering decisions that are described in the TDR, the **HGCAL geometry implemented in** the CMS simulation and reconstruction software, **CMSSW**, **was frozen to allow simulation work to proceed**.

G4 simulation used to predict performance of HGCAL in presence of pileup: E/m resolution

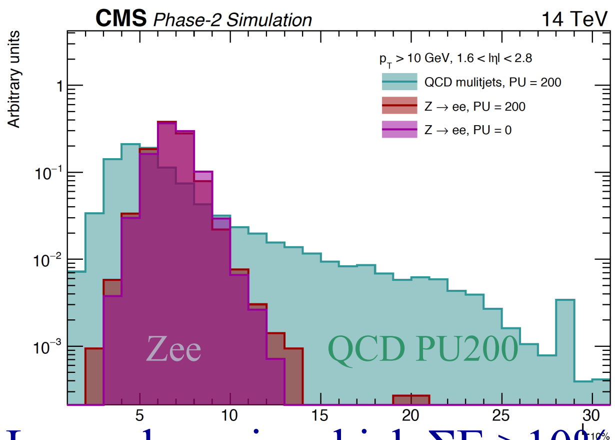
Single unconverted γ in CE-E reconstructed in r<2.6cm
→ **insensitive to pileup**

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

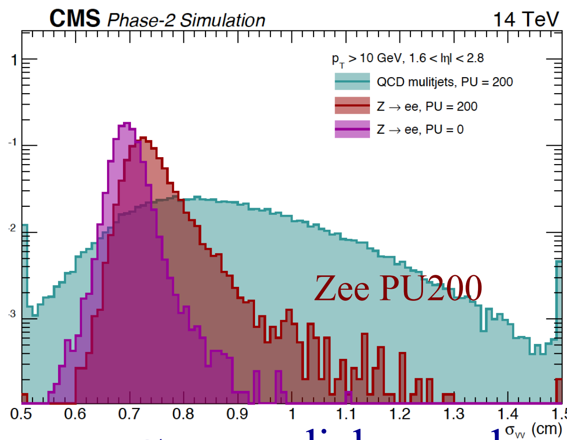




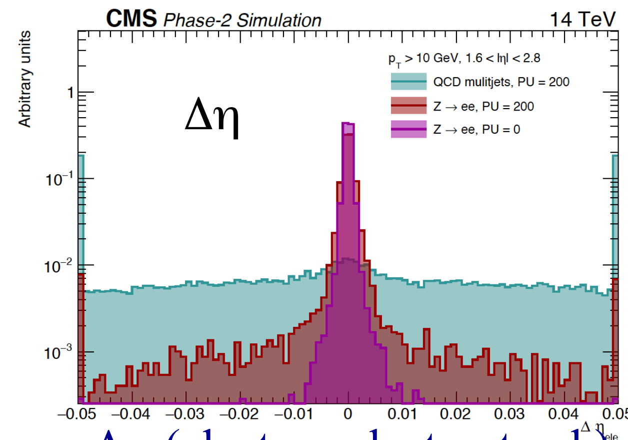
Jet identification greatly improved using shower-shape information from HGCAL



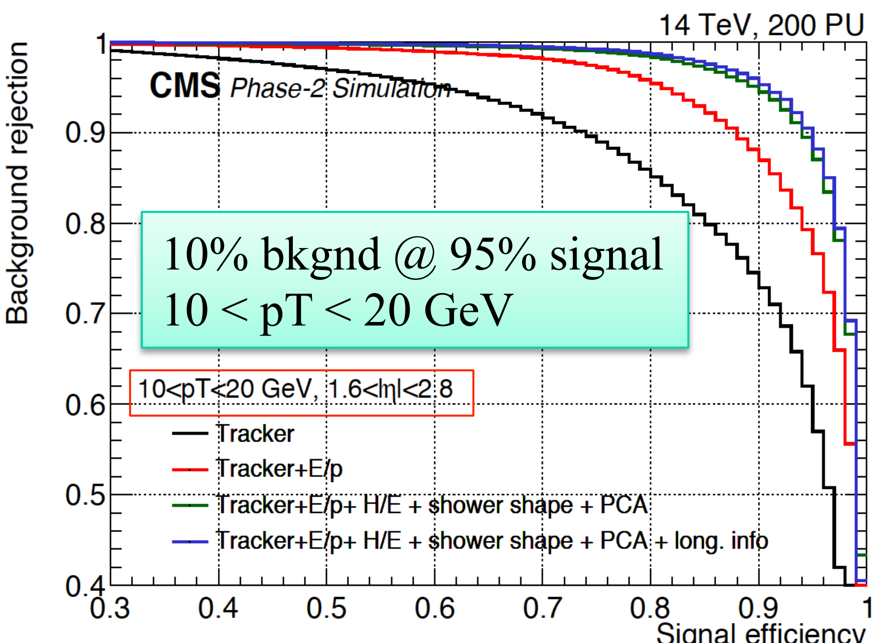
$L_{10\%}$ – layer in which ΣE >10%

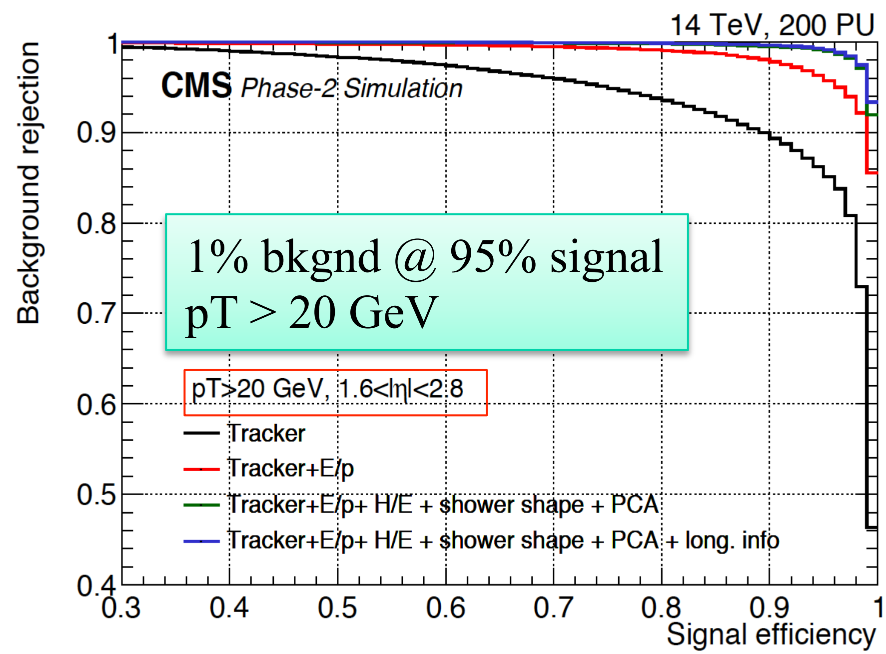


σ_{VV} – radial spread



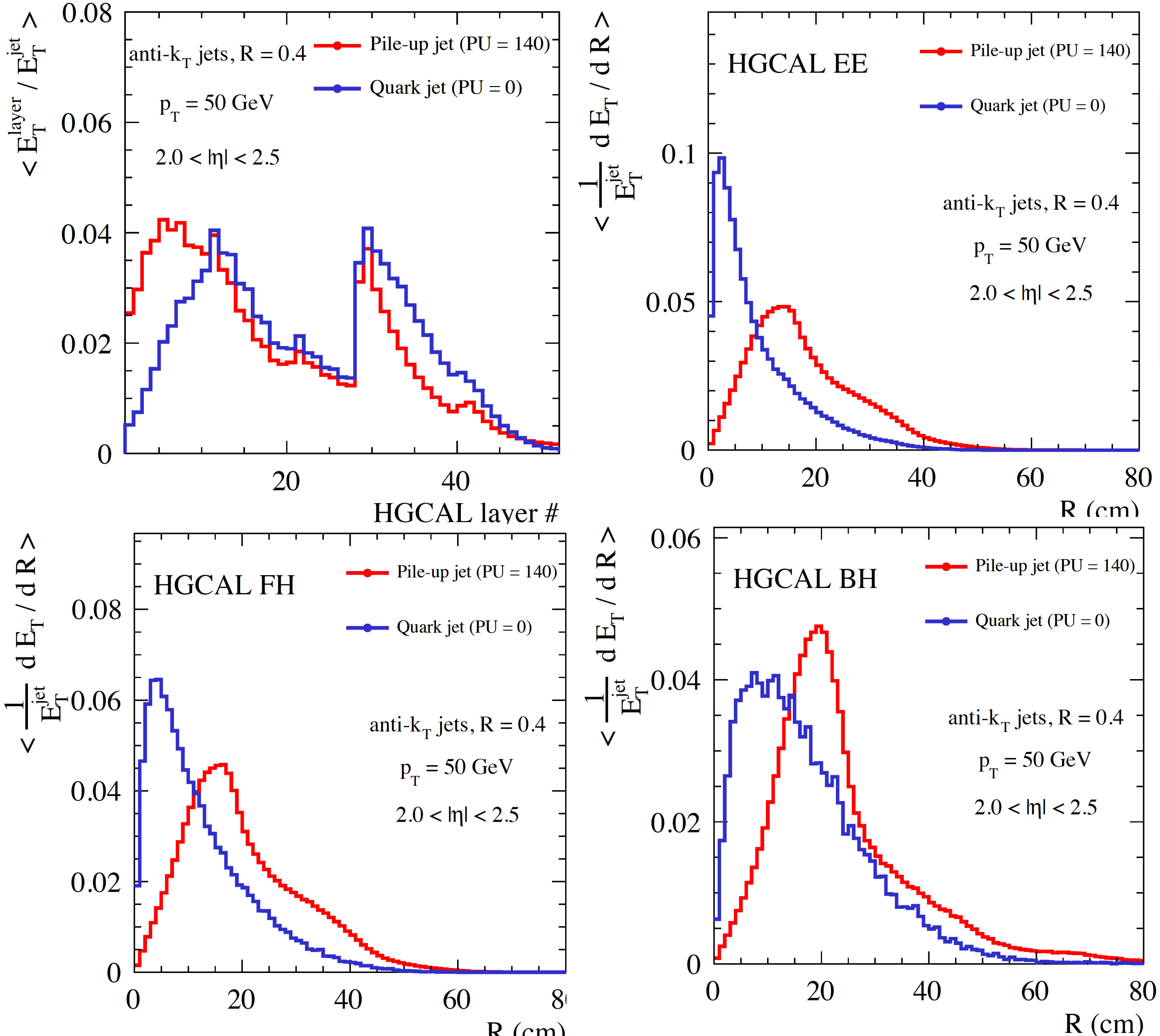
Δη (electron cluster–track)





*PCA = principle component analysis

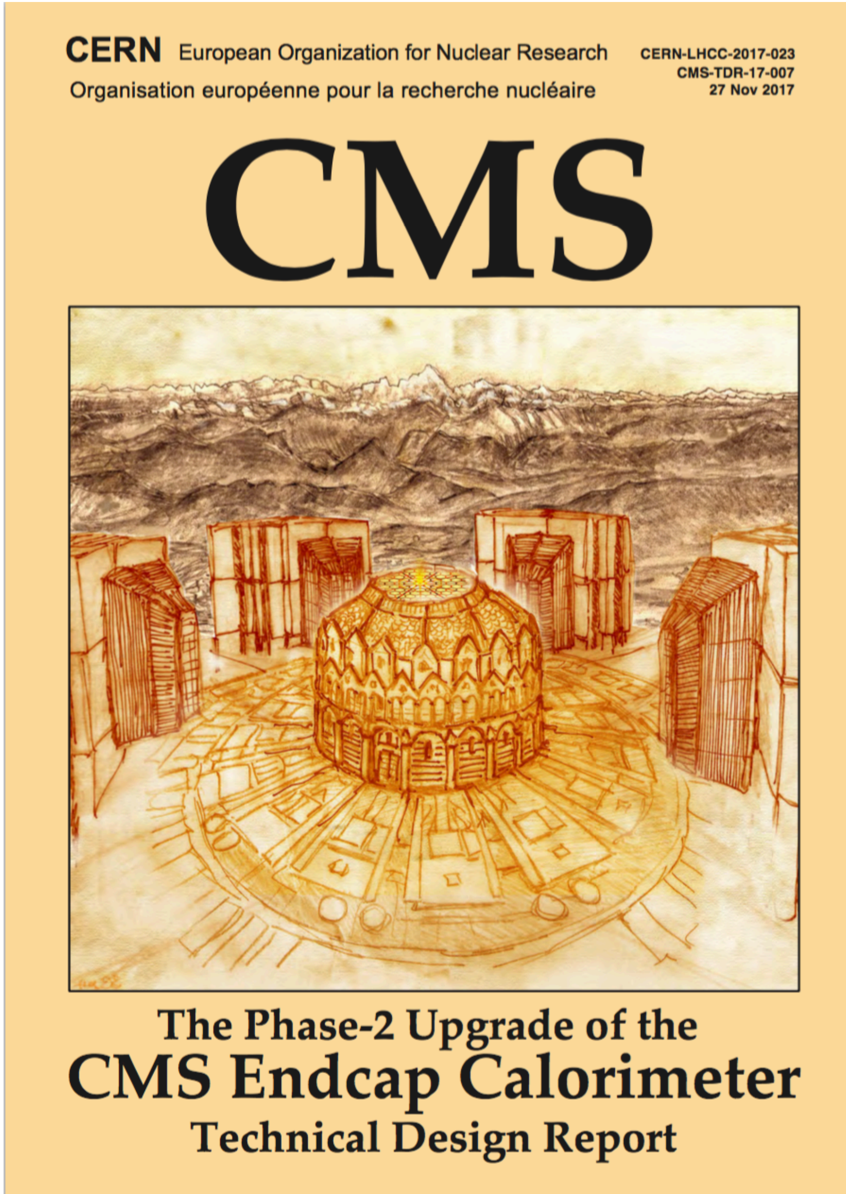
Longitudinal and transverse shower shapes can also distinguish VBF jets from pileup jets



EE/FH/BH refer to names of parts of HGCAL at time of TP (2016): simulation is based on this (not very different) geometry

Pileup jets tend to start earlier in the calorimeter and be less collimated than VBF jets

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



CMS-TDR-17-007

HIGHLY-GRANULAR CALORIMETERS, SUCH AS HGCAL, WILL PROVIDE MUCH MORE INFORMATION THAN ANY PREVIOUS CALORIMETER.

BUILDING AND EXPLOITING THEM BRING MAJOR CHALLENGES. AN EXCITING TIME FOR DETECTOR AND SOFTWARE DEVELOPMENT!

BACKUP

Calorimeters are perhaps the most versatile particle detectors

Primary objective is to measure the **energy** of incoming particles as **accurately as possible** – both charged and neutral (including neutrinos through missing E)

Can also measure:

- **Position**
- **Angle of incidence**
- **Arrival time**

Compact detectors: longitudinal shower spread increases only **logarithmically with E**

Unlike spectrometers, **E resolution improves with increasing E**

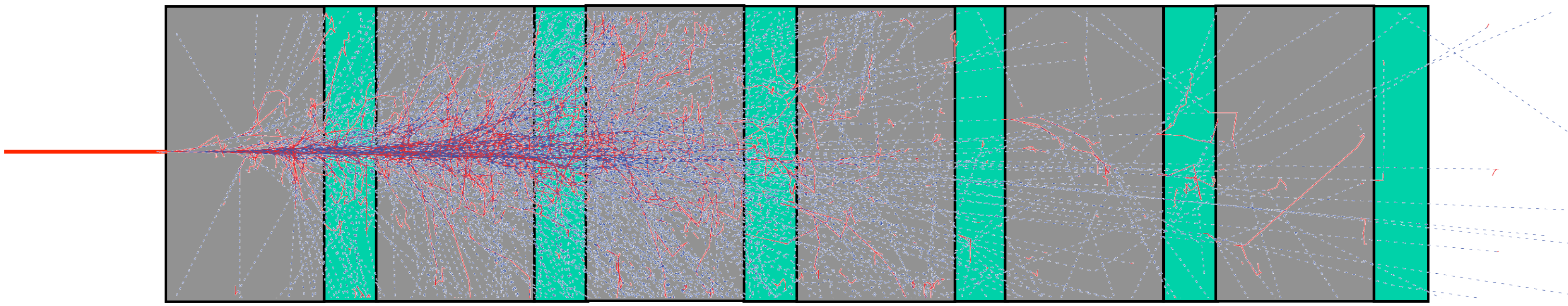
Calorimeter signals can be fast: **provide triggering information**

Two main types of calorimeter: Sampling and Homogeneous

Sampling Calorimeter

$\sigma/E \sim (10\text{-}30)\%/\sqrt{E}$

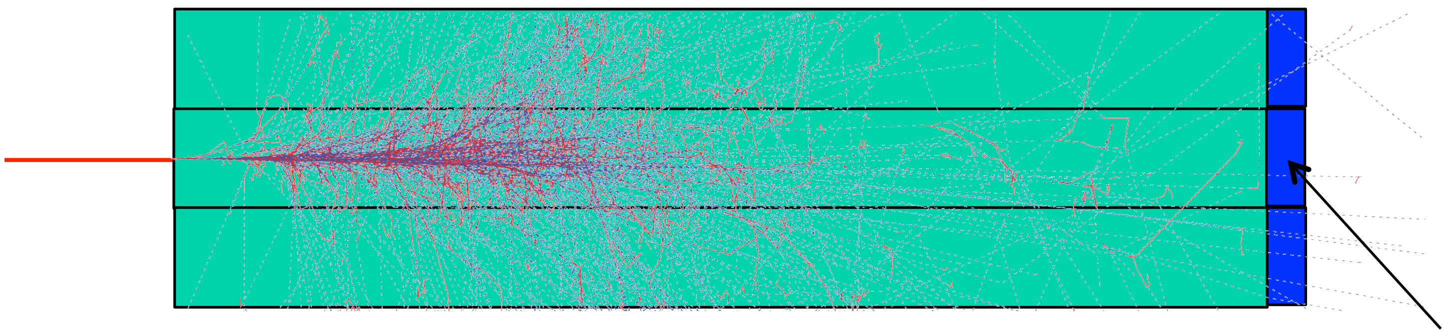
Layers of passive 'absorber' (e.g. Pb, Cu, W) alternate with active layers, such as Si, scintillator, liquid Argon (LAr)



Homogeneous Calorimeter

$\sigma/E \sim (1\text{-}3)\%/\sqrt{E}$

Single dense medium serves as both absorber and signal producer, e.g. liquid Xe or Kr (ionization), crystals such as BGO, $PbWO_4$ (scintillation)



Choice of homogeneous vs sampling calorimeter depends on application

Homogeneous

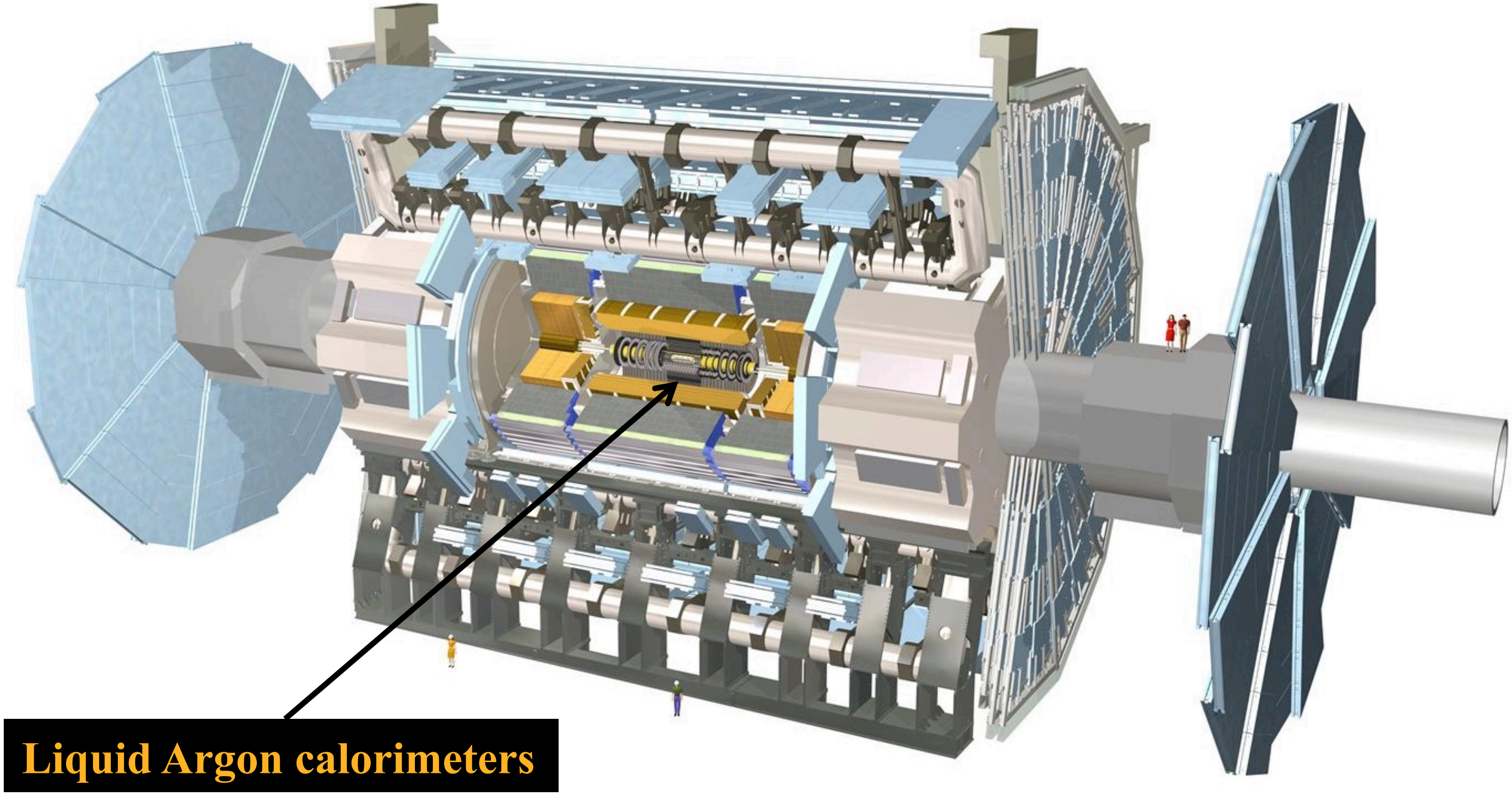
- **Advantages**
  - See all charged particles in the shower → best statistical precision (**lowest stochastic term**)
    ➔ minimizes detector contribution to measured particle widths
  - Same response from everywhere
    → **good linearity** (in principle)
- **Disadvantages**
  - Limited segmentation
  - Relatively high cost
- **Examples**
  - B-factories (small γ energies)
  - OPAL, Delphi, L3 (LEP)
  - ALICE PHOS & **CMS ECAL**

Sampling

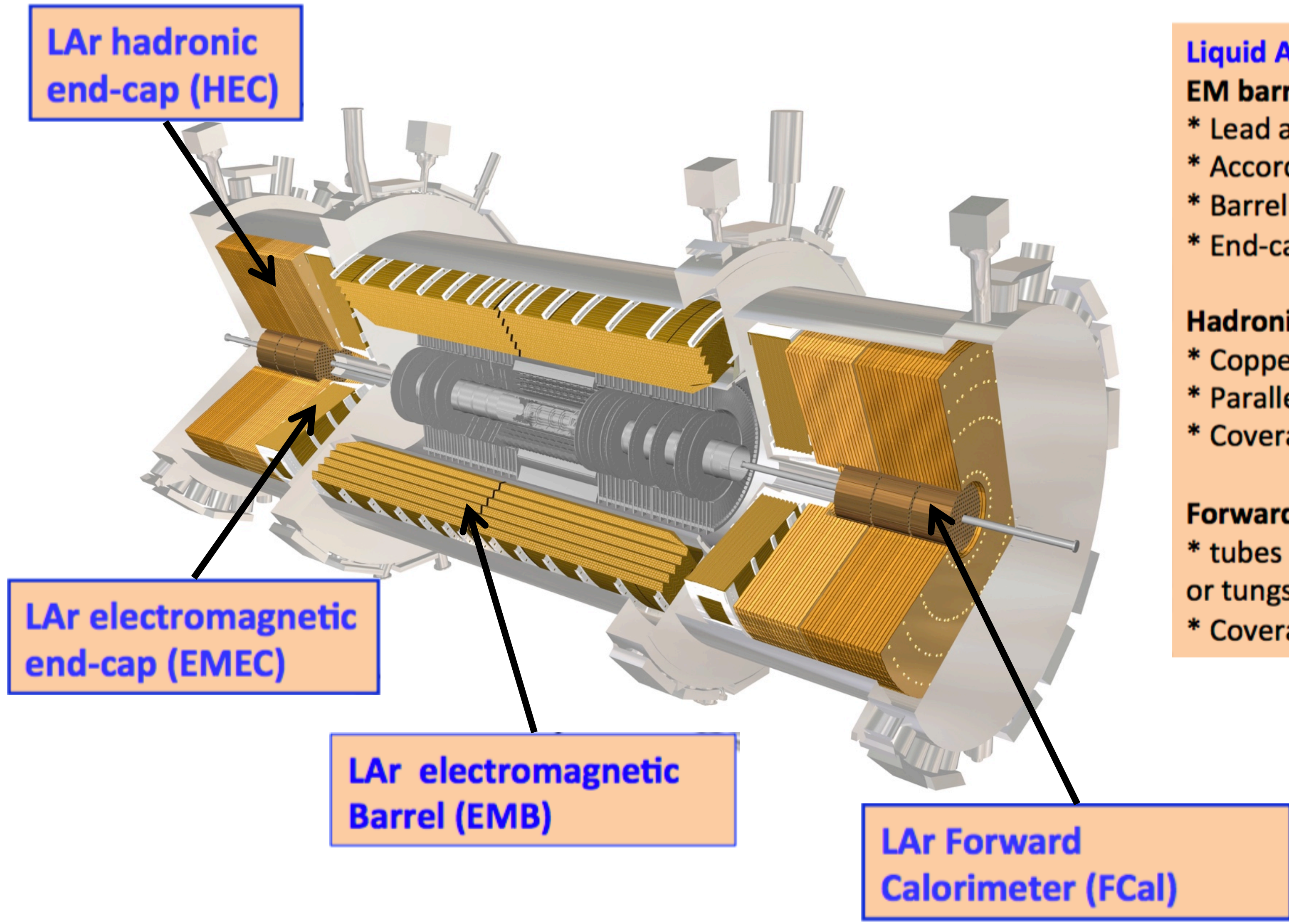
- **Advantages**
  - Relatively **low cost**
  - **Transverse & longitudinal segmentation** possibilities
    ➔ can significantly help to suppress background
- **Disadvantages**
  - Only part of the shower is seen → higher stochastic (sampling) term
- **Examples**
  - Aleph ECAL (LEP)
  - LHCb ECAL & ATLAS calorimeters
  - All HCALs (that I am aware of)

ATLAS LIQUID ARGON CALORIMETERS

ATLAS Liquid Argon Sampling Calorimeters



ATLAS Liquid Argon electromagnetic and endcap/forward hadronic calorimeters



Liquid Argon:

EM barrel and end-cap
* Lead absorber
* Accordion geometry
* Barrel: $|\eta| < 1.475$
* End-cap: $1.375 < |\eta| < 3.2$

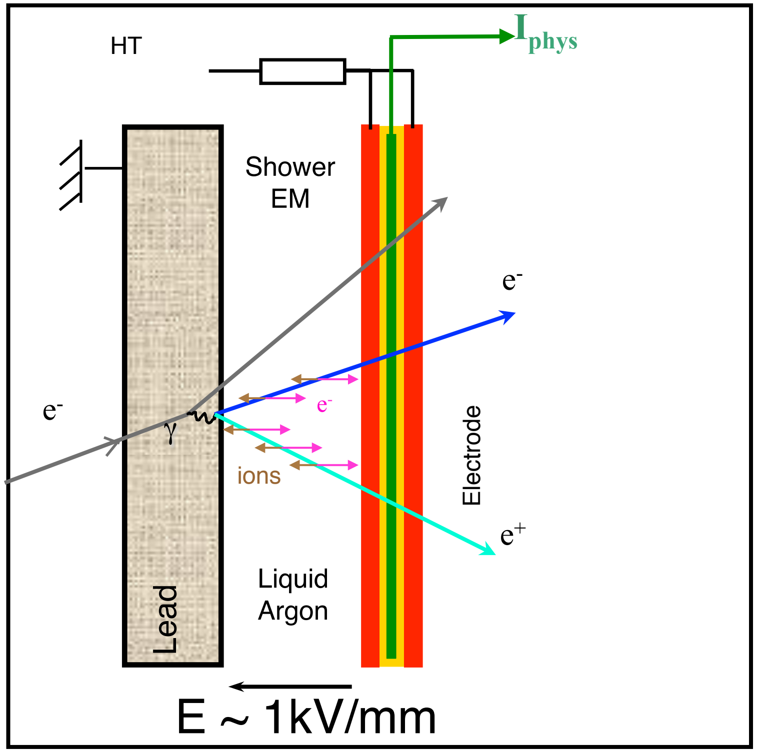
Hadronic end-cap
* Copper absorber
* Parallel plate electrodes
* Coverage: $1.5 < |\eta| < 3.2$

Forward Calorimeter
* tubes and rods in copper or tungsten matrix
* Coverage: $3.1 < |\eta| < 4.9$

ATLAS Liquid Argon calorimeter system

Sampling calorimeters using liquid argon as signal producer → ionization

- High # electron-ion pairs / MeV deposited **→ no amplification needed, small fluctuations**
- **Good energy resolution**
- Medium **granularity** (110000 channels)
- Longitudinally **segmented** → angle measurement; background suppression
- Intrinsically **uniform & radiation hard**
- Argon = liquid @ -183°C → cryogenic system
- Not so fast (~450ns)
- Temperature **sensitive** ~2%/°K
- Not too compact: 25 X_0 = 47cm



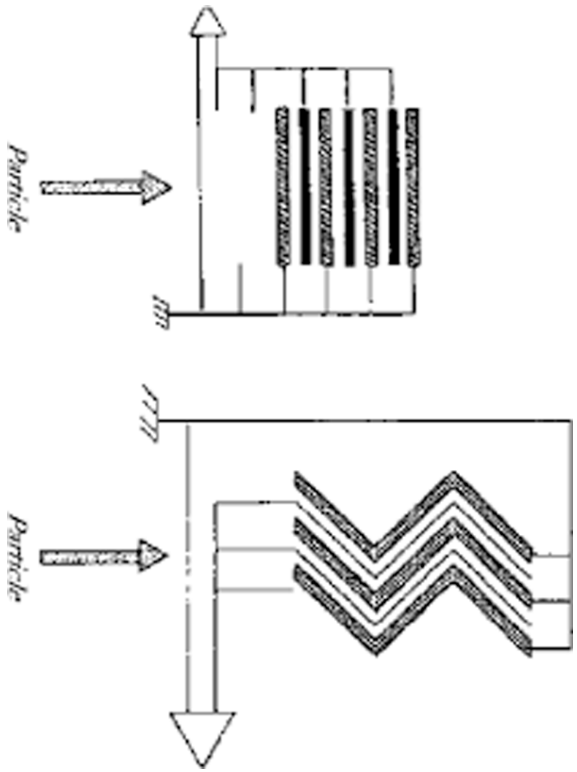
Signal is given from collection of released electrons

Drift velocity depends on electron mobility and applied field. In ATLAS :

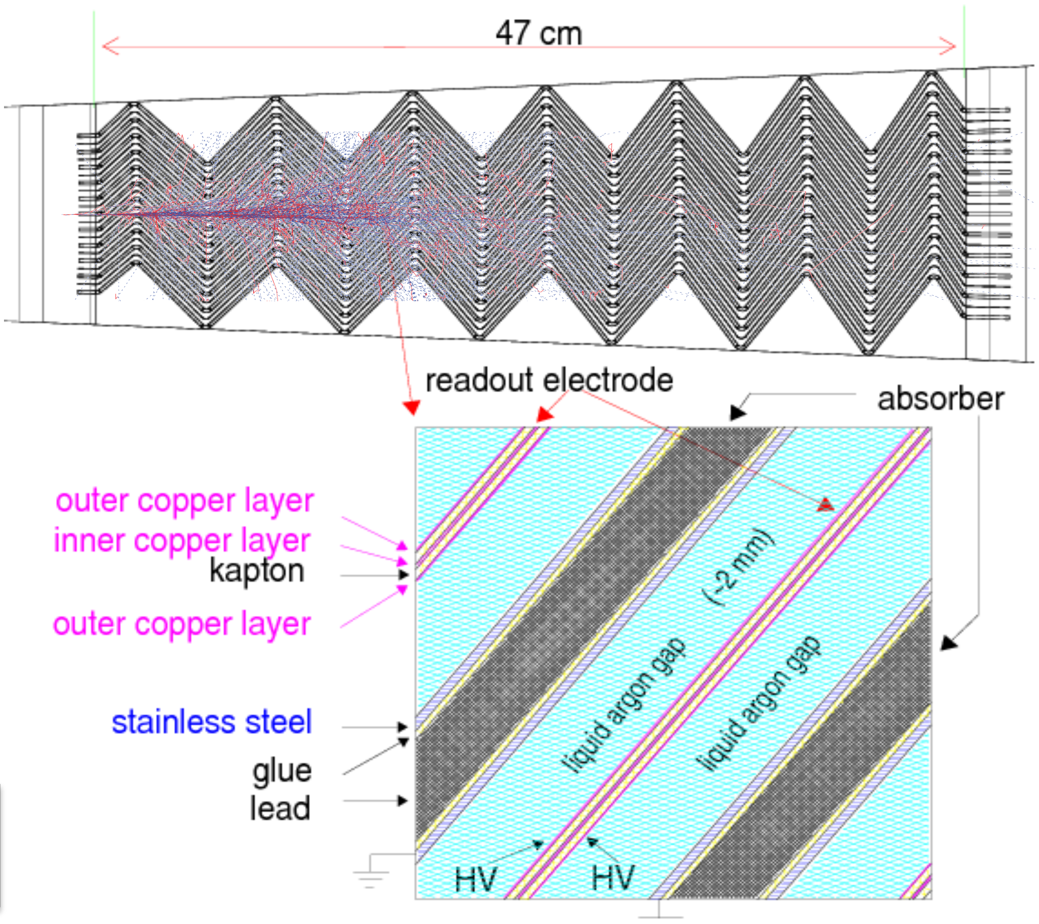
LAr gap 2 mm, ΔV = 2kV

ATLAS LAr calorimeter uses a novel "accordion" geometry to optimize performance

Absorber and gap layers in sampling calorimeters are normally perpendicular to the incoming particle direction → **gaps/cracks at boundaries**; long signal cables
Largely **avoided** in ATLAS by using novel "**accordion**" **geometry**



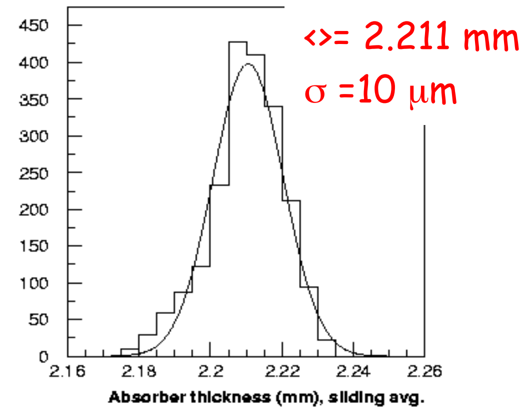
Traditional sampling calorimeter (top) and ATLAS accordion geometry (bottom)

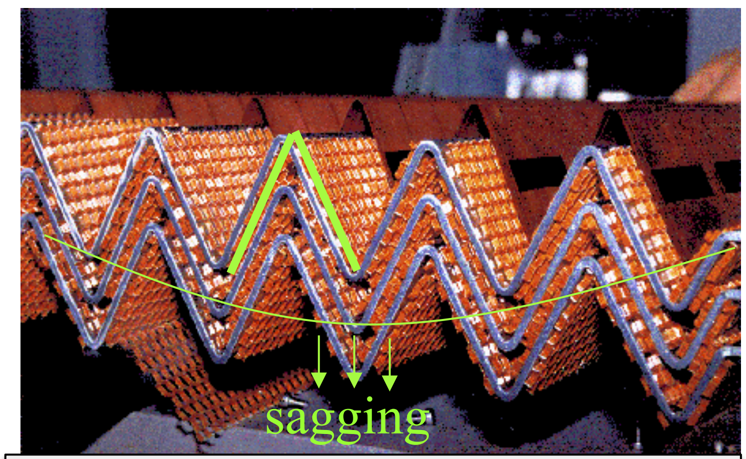


Keeping the constant term low was a major challenge for the ATLAS LAr

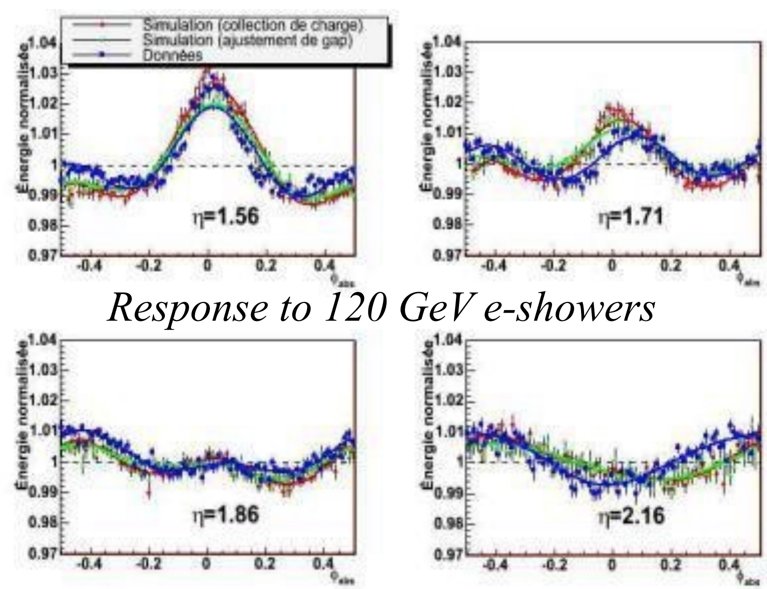
Mechanical non-uniformities can modify the electric field and detector response. Great care needed during construction; try to reproduce effects and apply corrections

1% variation in Pb (~200μm)
→ 0.6% change in response
Measured dispersion
σ = 10μm
Translates to
< 2‰ on constant term





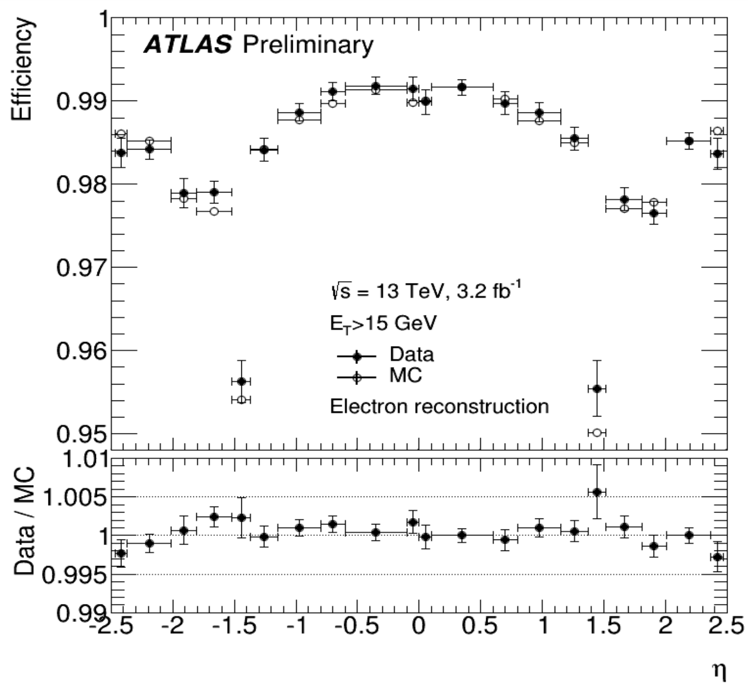
φ-modulations measured & simulated, and corrections applied



Response to 120 GeV e-showers

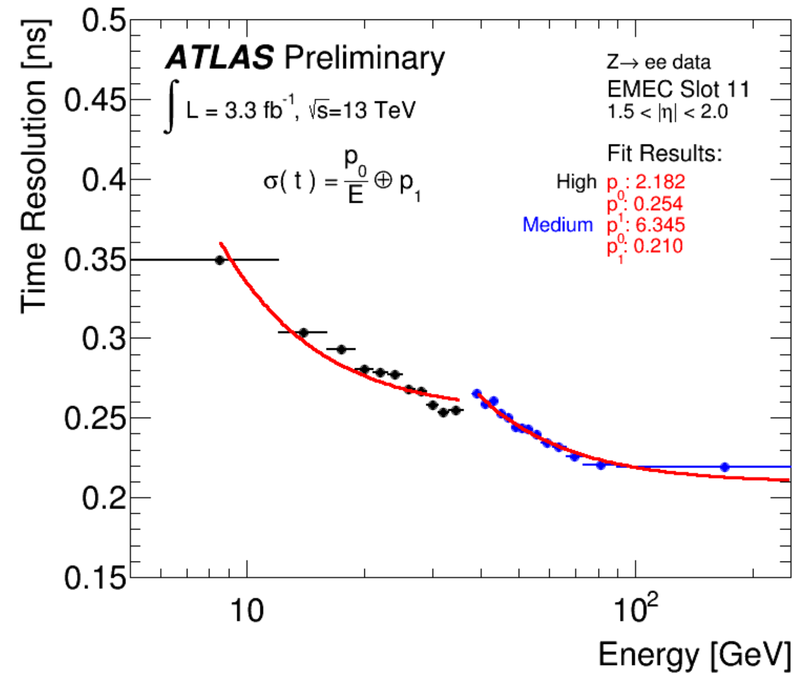
Calorimeters are not only for energy measurements!

Particle identification in ATLAS LAr



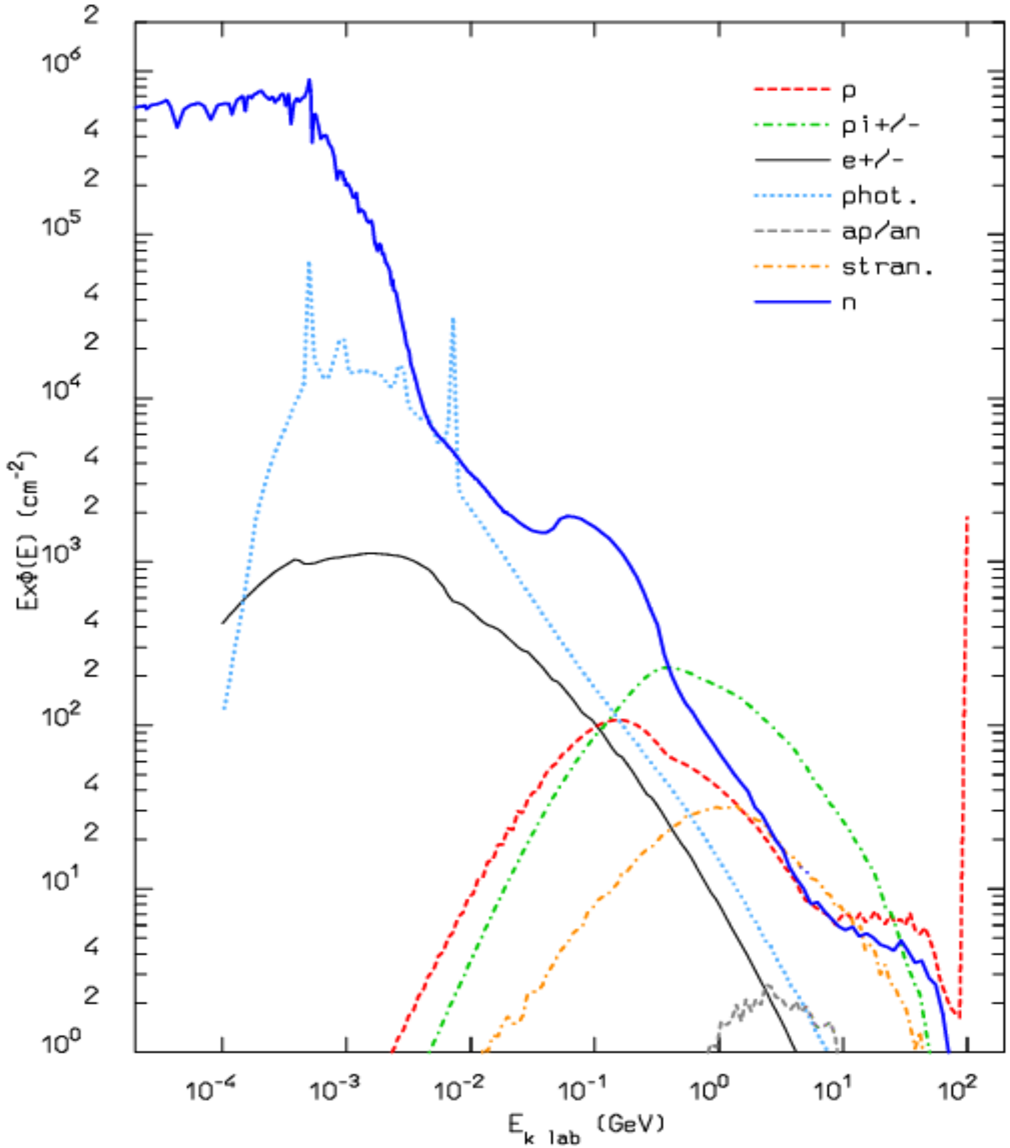
Electron identification efficiency as a function of η for the ATLAS LAr calorimeters. **Above 97%** except for barrel/endcap transition region

Timing performance in LAr endcaps



Timing measurements can help with pileup rejection. The above plot includes a contribution of ~200ps from the beamspread → intrinsic timing **precision approaches 65ps**! (about the **same as in CMS ECAL**)

Composition of hadronic showers is complex!



Hadron shower induced by a 100 GeV proton in Pb: energy spectra of the major shower components, weighted by their track length in the shower (*Ferrari, 2001*)

Fractions of particle types:

- Fluctuate in a non-Gaussian way
- Are energy dependent
- Depend on initial particle (p,π,n)

Simulation is very difficult as the number of physical processes and their fluctuations are large & span a large energy range: GeV → <MeV