Calorimetry

Fundamentals
Challenges for High Lumi LHC

Cogne School

Why calorimeters?

Neutral and **charged particles** incident on a block of material deposit their energy through generation of a shower of particles

The deposited energy is made measurable by ionization or excitations of the atoms of specific active medium(s)

The active medium can be the block itself (totally active or homogenous calorimeters) or sandwich of *dense absorbers* and *active planes* (sampling calorimeters)

The device is built such that the measurable signal is proportional to the incident particle energy

Besides estimating the energy of the incident particle, calorimeters are also used to identify the nature of particles (electron/photons vs hadrons)

Note: *calorimeter* is a misnomer (*Energy-meter* would be more appropriate)

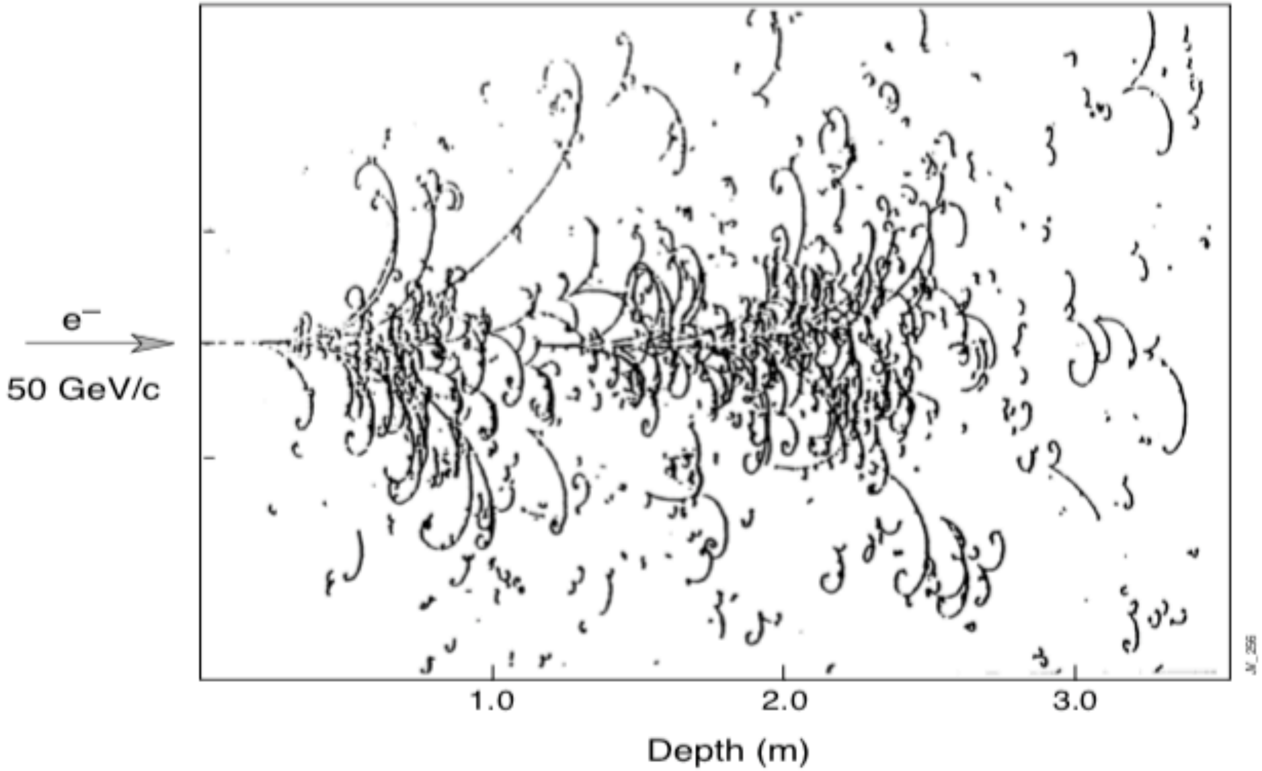
ΔT for 1 litre of water at 20^{o}C from energy deposition of:

- 1 GeV particle = 3.8×10^{-14} K
- All 13 TeV from 1 LHC pp collision = 5.5×10^{-10}K

The ideal calorimeter

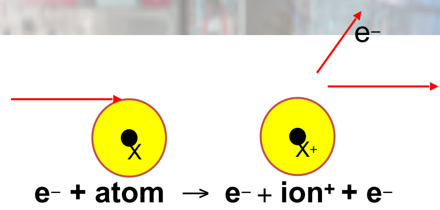
Ultimate granularity allowing to SEE the shower details

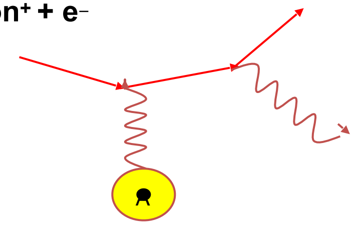
Big European Bubble Chamber filled with Ne:H_2 = 70%:30%,
3T Field, L=3.5 m, $X_0 \approx 34$ cm, 50 GeV incident electron

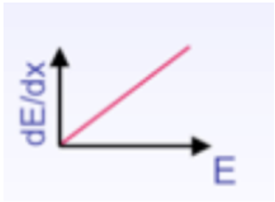


Electrons & Photons

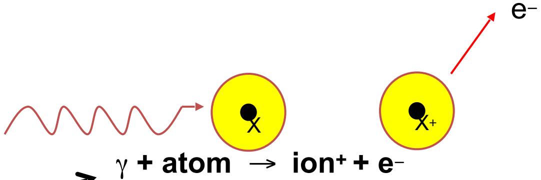
- Electrons
  - Ionization (atomic electrons)
  - Bremsstrahlung (nuclear)

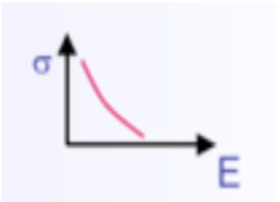




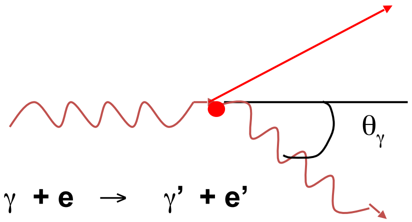


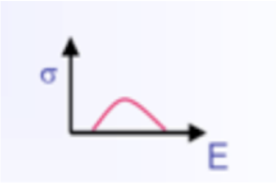
At high E, **bremsstrahlung dominates**





- Photons
  - Photoelectric effect (atomic electrons)
  - Compton scattering (atomic electrons)
  - Pair-production (nucleus + electrons)





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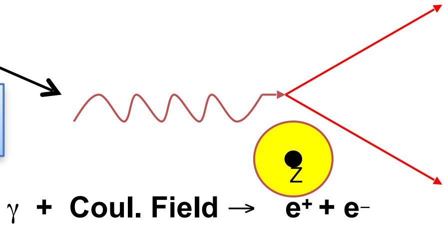
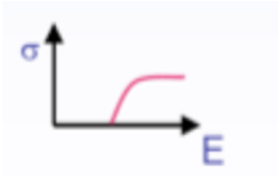
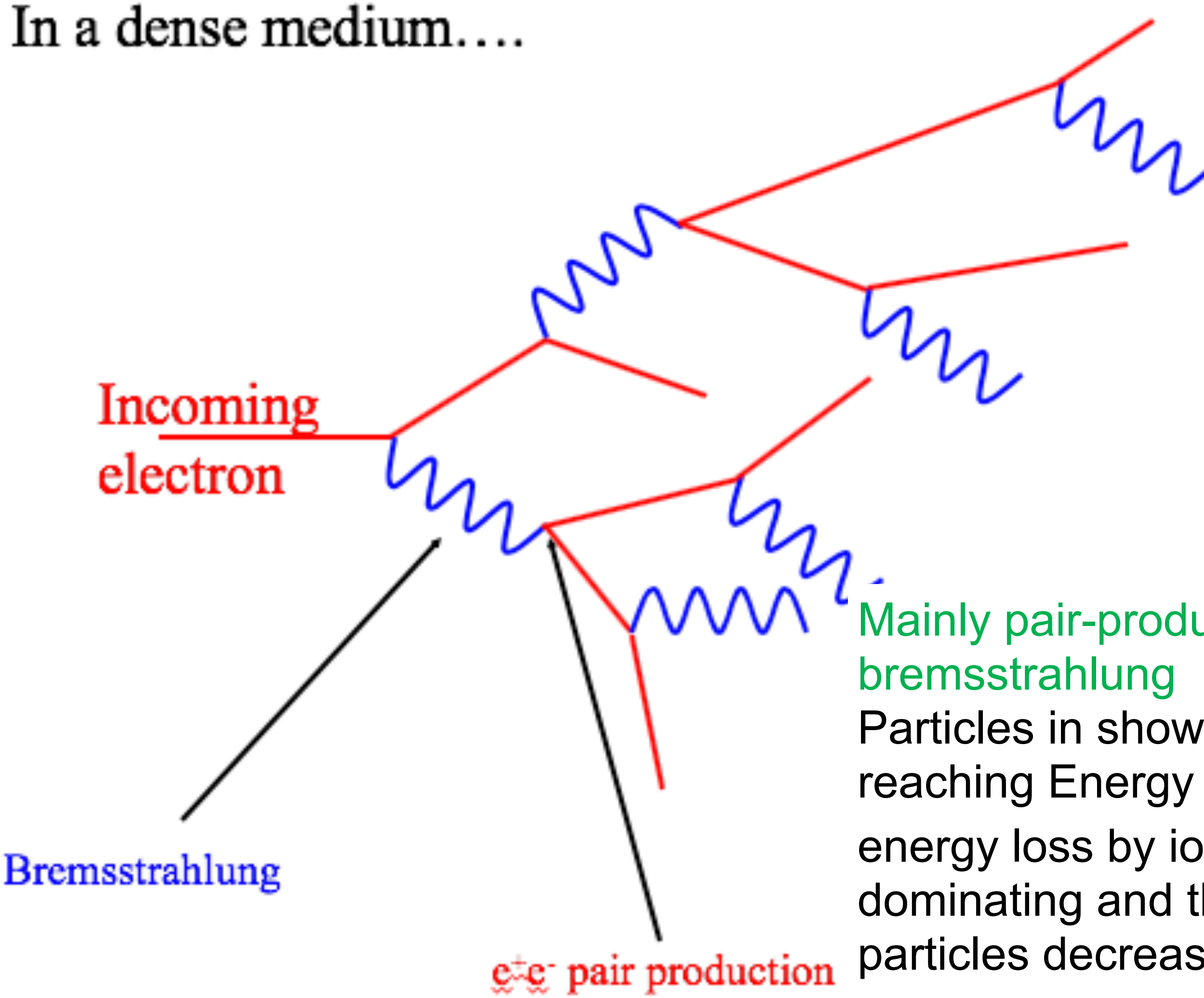




Electromagnetic shower

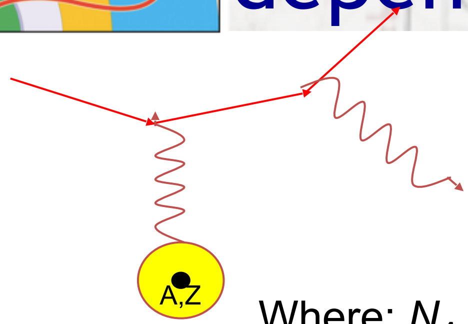
In a dense medium….



Mainly pair-production and bremsstrahlung

Particles in shower increase until reaching Energy E_c where energy loss by ionization starts dominating and the number of particles decreases

Energy loss through bremsstrahlung depends on particle, energy & material



$$-\frac{dE}{dx}\bigg|_{Brems} = 4\alpha N_A \left(\frac{e^2}{mc^2}\right)^2 ln \frac{183}{Z^{1/3}} \frac{Z(Z+1)}{A} Q^2 E$$

Where: N_A, α are Avogadro's number and the fine-structure constant
m, Q are the mass and charge of the particle (e.g. electron, muon)
A, Z = mass number and atomic number of the material

For electrons:

$$-\frac{dE}{dx}\bigg|_{Brems} = \frac{1}{X_0} E$$

$$E(x) = E_0 e^{-x/X_0}$$

X_0 = thickness of material that reduces the mean energy of an electron by a factor *e* (2.718)
→ **radiation length** of the material

$$\text{n.b.}: \frac{dE}{dx}\bigg|_{\mu} / \frac{dE}{dx}\bigg|_{e} = (m_e / m_\mu)^2 \sim 1/43000$$

Note about Radiation Length

- The radiation length of material is a critical parameter when dealing with interactions of high energy EM particles… it is less relevant if one deals with low energy
  - 15cm of Lead contain a 20 Gev γ shower
  - Needs more to ‘contain/shield’ a 1Curie CO^{60} source (1MeV γ)
- Low energy gammas can travel many radiation length in High Z material

EM Shower development: longitudinal

After t generations,

$$energy\ of\ particles\quad e(t) = \frac{E}{2^t}$$

$$number\ of\ particles\quad n(t) = 2^t$$

At shower max. where e ~ ε

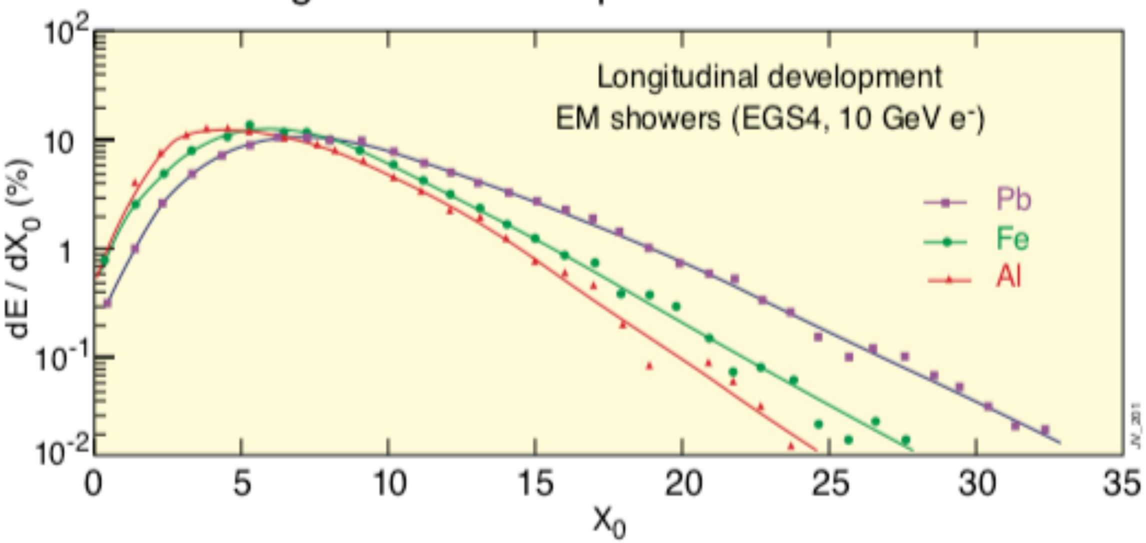
$$no.\ of\ particles\quad n(t_{max}) \approx \frac{E}{\varepsilon} = y$$

$$and\qquad t_{max} \approx \ln\frac{E}{\varepsilon} = \ln\ y$$

After shower maximum

remaining energy is carried forward by photons giving the typical exponential falloff

Longitudinal Development EM Shower



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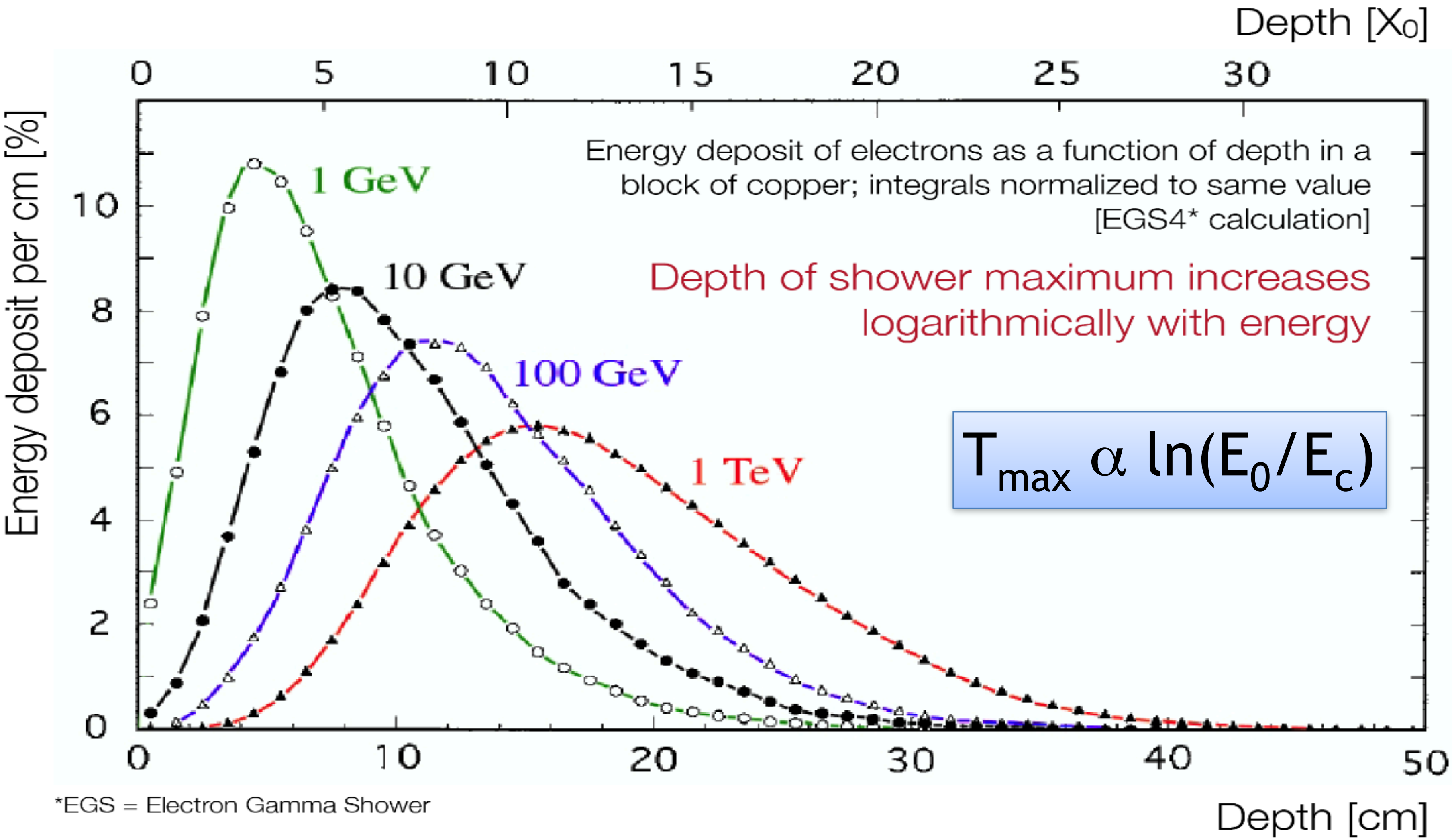
Need a depth of > 25 X_0 to contain high energy em showers

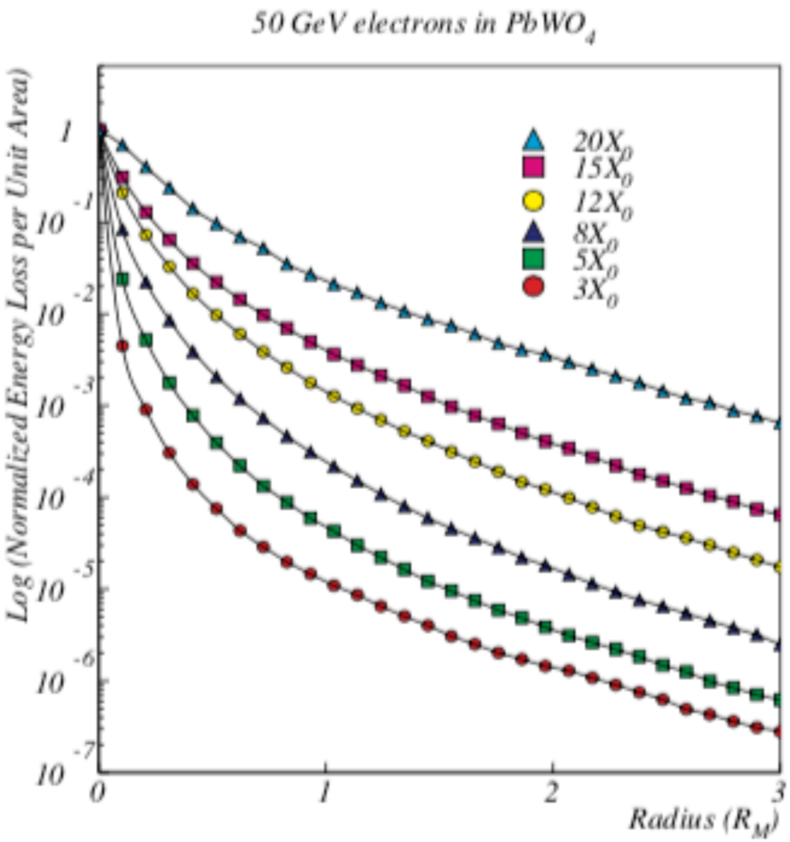
Length of EM calorimeter scales like logE

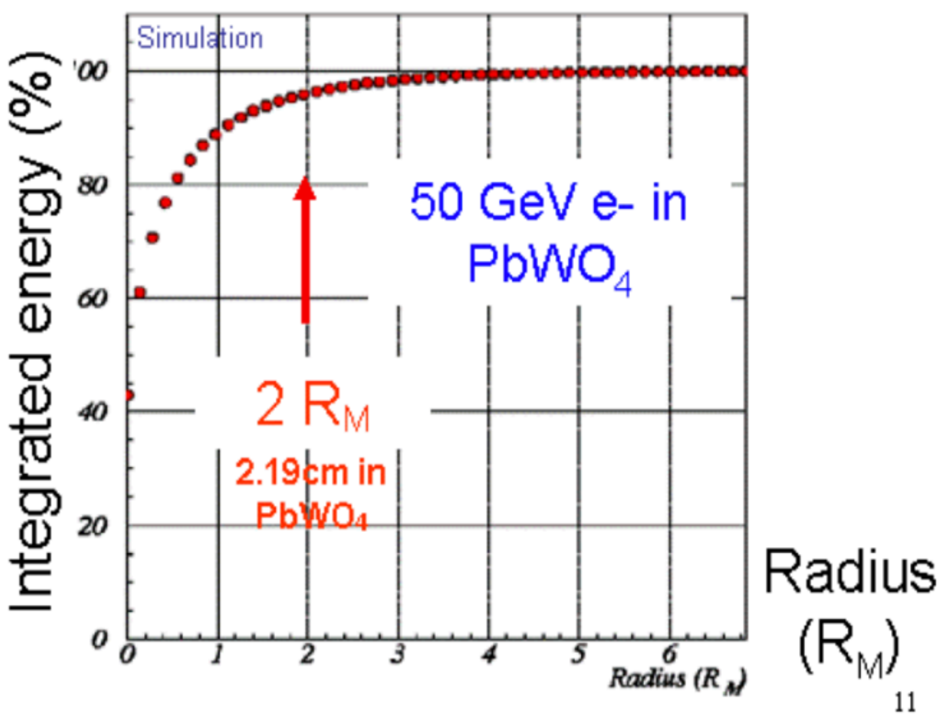


For good em shower containment, need about 25 X_0 of material

EM Shower development: lateral

The lateral spread of an e.m. shower is determined by multiple scattering of e± away from the shower axis and by minimally attenuated photons





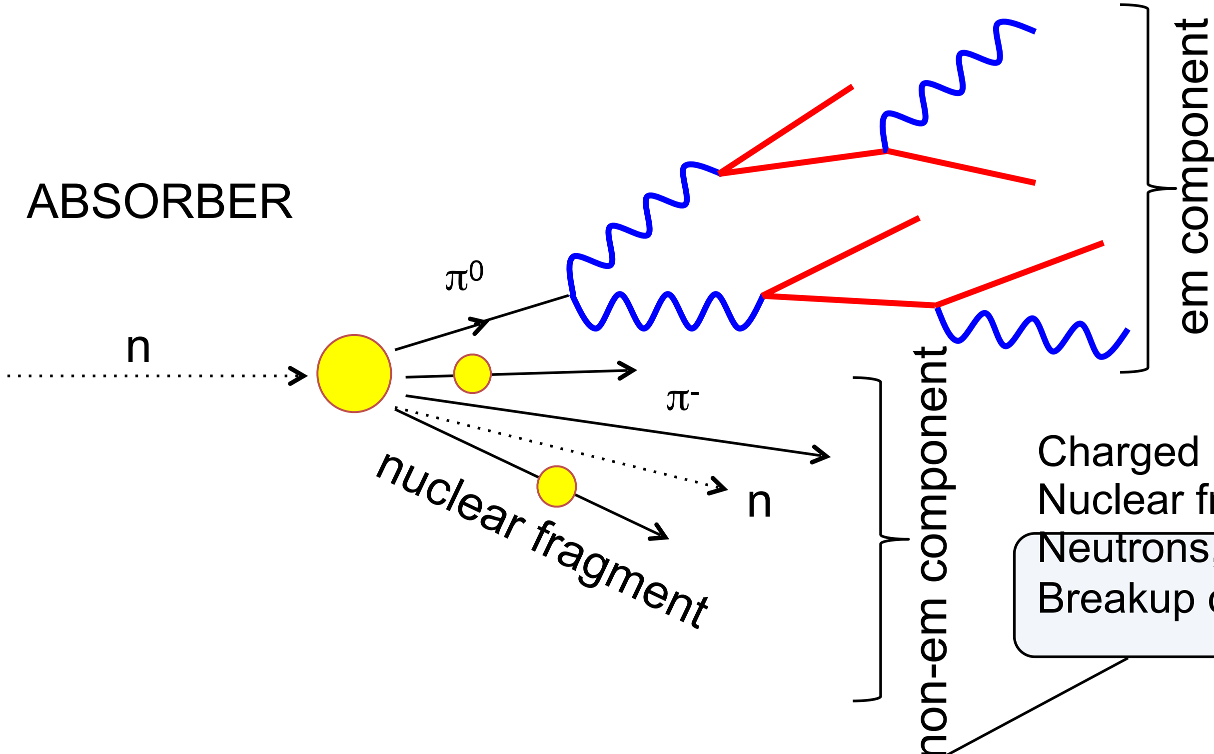
An infinite cylinder with a radius of $2R_M$ contains ≈ 95% of the shower energy.

Radiation length & Molière radius

Material	Z	A	Density (g/cm³)	X_0 (cm)	R_M (cm)
Carbon	6	12	2.27	18.8	5.01
Aluminium	13	27	2.7	8.9	4.42
Silicon	14	28	2.33	9.36	4.94
Iron	26	56	7.87	1.76	1.72
Copper	29	64	8.96	1.43	1.57
Tungsten	74	184	19.3	**0.35**	0.93
Lead	82	207	11.35	**0.56**	1.60
Uranium	92	238	18.95	**0.32**	1.00

Hadronic calorimeters

A complicated story: a shower of particles with quarks contains both Em and nuclear/hadron components



Electrons, photons
$\pi^0 \rightarrow 2\gamma$
$\rightarrow$ 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 $\rightarrow$ invisible energy

Features of an hadronic shower

Strong interactions are responsible of shower development: simulations are more difficult than for EM, a high energy hadron striking the calorimeter material provokes multiparticle production (e.g. $\pi^{\pm}$, π^0, K etc.)

Nuclei breakup lead to spallation Neutrons

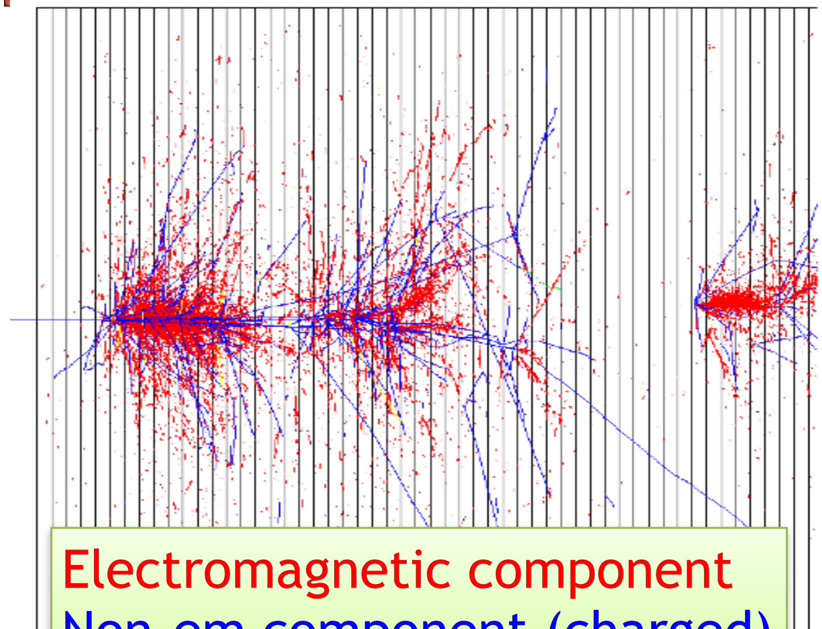
Multiplication continues until the pion production threshold $E_{th} = 2m\pi = 0.28GeV$

Simple model yields interaction cross section: $\sigma_{int} = \sigma_0 A^{2/3}$
Where σ_0 =35 mb and A is the material atomic number

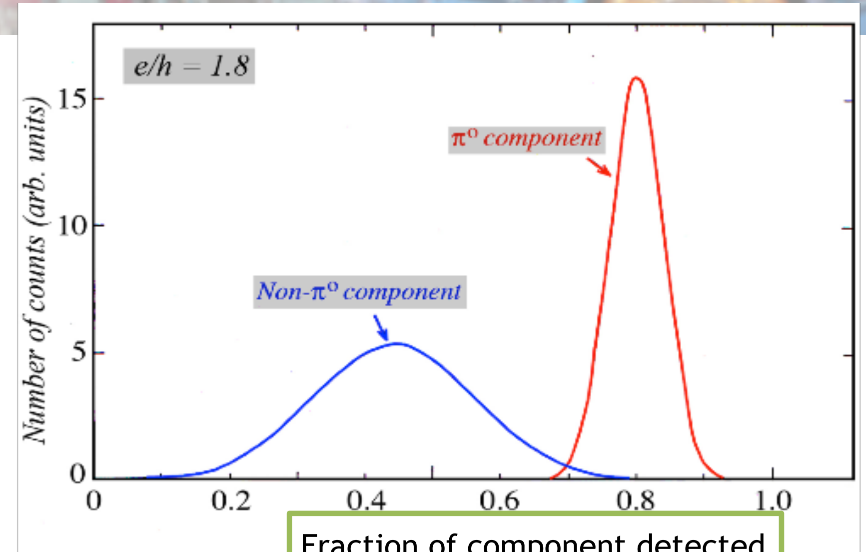
Define $$\lambda_{int} = \frac{A}{N_A \sigma_{int}} \propto A^{1/3} \quad \lambda \sim 35 \quad A^{1/3}\ gcm^2$$

Cascade particle have a limited transverse momentum $\langle p_T \rangle \sim$ 300-400 MeV

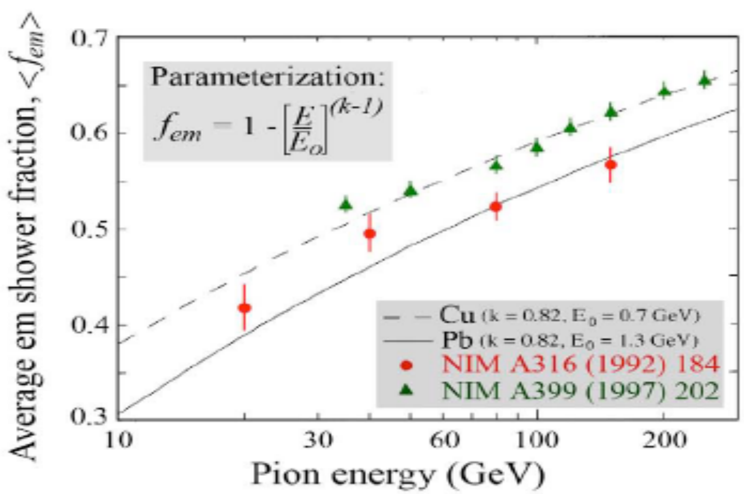
Response to EM and hadron component is different



Electromagnetic component
Non-em component (charged)



Fraction of component detected



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:

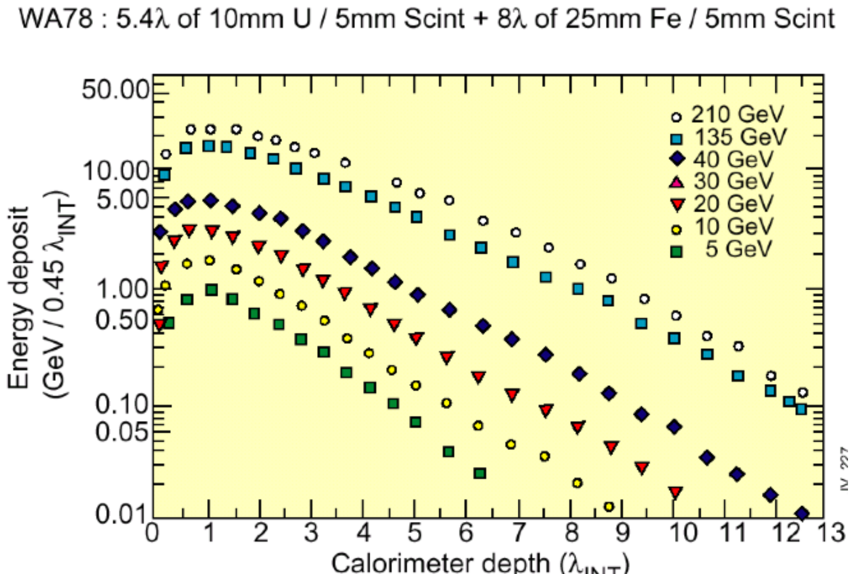
- Non-linearities
- Non-Gaussian response
- Relatively poor energy

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

Hadron calorimeter: containment

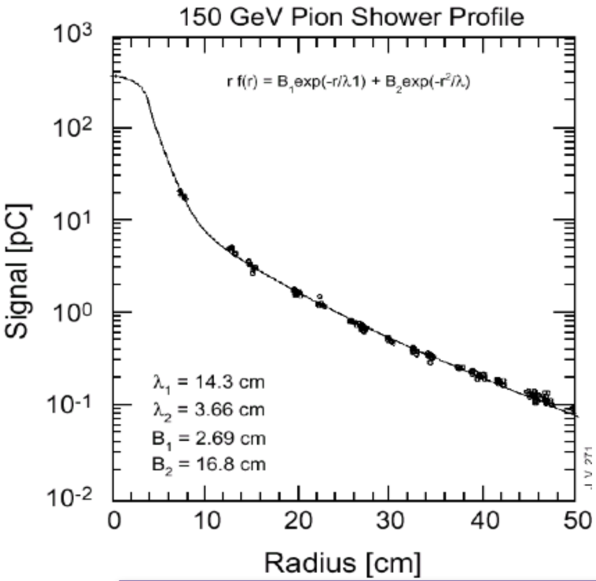
Sharp core due to π^0 in first λ_{int} then falloff with λ_{int} scale

Pronounced core due to π^0 Characteristic transverse scale 1 λ_{int}



Longitudinal development

10 λ_{int} needed to contain 99% of 200 GeV pion



Transverse development

Transverse radius to contain 95% of shower is ~ 1 λ_{int}

Interaction length and other characteristcs

Material	Z	A	Density (g/cm³)	X_0 (cm)	λ_{INT} (cm)
Carbon	6	12	2.27	18.8	38
Aluminium	13	27	2.7	8.9	39.4
Silicon	14	28	2.33	9.36	45.5
Iron	26	56	7.87	1.76	16.8
Copper	29	64	8.96	1.43	15.1
Tungsten	74	184	19.3	0.35	9.6
Lead	82	207	11.35	0.56	17.1
Uranium	92	238	18.95	0.32	10.5

As X_0 is smaller than λ_{INT}, electromagnetic calorimeters are placed in front of hadron calorimeters

The goods of calorimeters

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

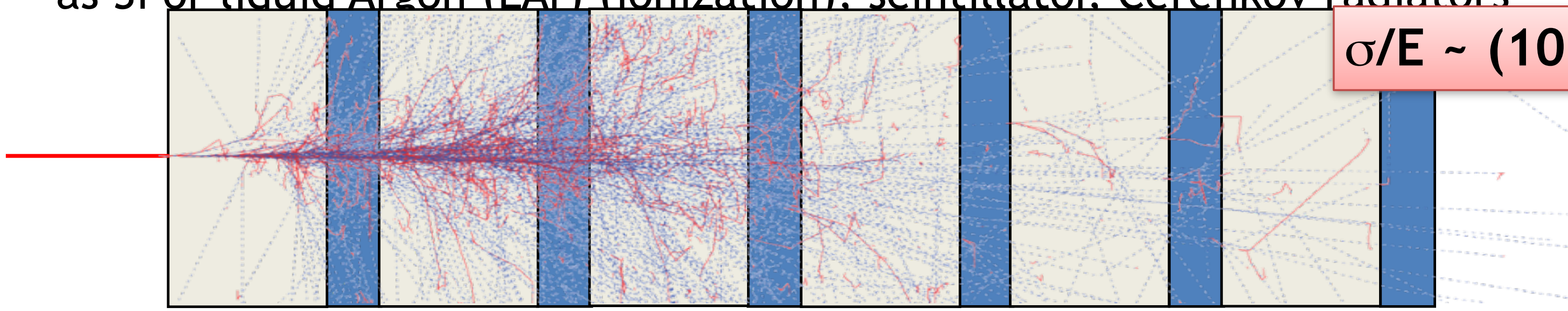
Unlike trackers, E resolution improves with increasing E

Calorimeter signals can be fast: provide triggering information

Two main types of calorimeter: Sampling and Homogeneous

Sampling Calorimeter (all hadron calo are sampling)

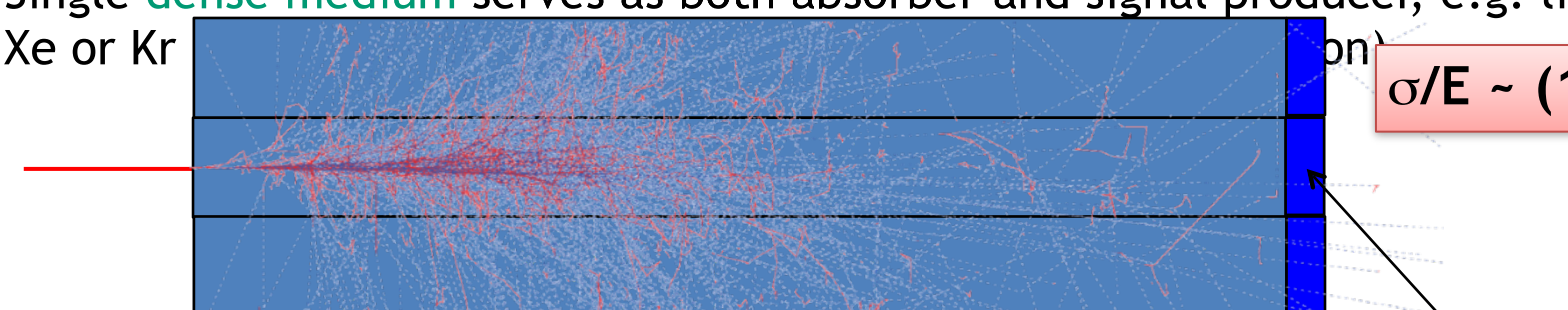
Layers of passive ‘absorber’ (e.g. Pb, Cu, W) alternate with active layers, such as Si or liquid Argon (LAr) (ionization), scintillator, Cerenkov radiators



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

Homogeneous Calorimeter

Single dense medium serves as both absorber and signal producer, e.g. liquid Xe or Kr ... on)



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

Energy resolution of calorimeters

Ideally, if all shower particles were counted: E~N, $\sigma \sim \sqrt{N} \sim \sqrt{E}$

In practice: other effects. For EM calorimeters:

$$\frac{\sigma(E)}{E} = \frac{a}{\sqrt{E}} \oplus \frac{b}{E} \oplus c$$

a: stochastic term

- intrinsic statistical shower fluctuations
- sampling fluctuations
- signal quantum fluctuations (e.g. photo-statistics)

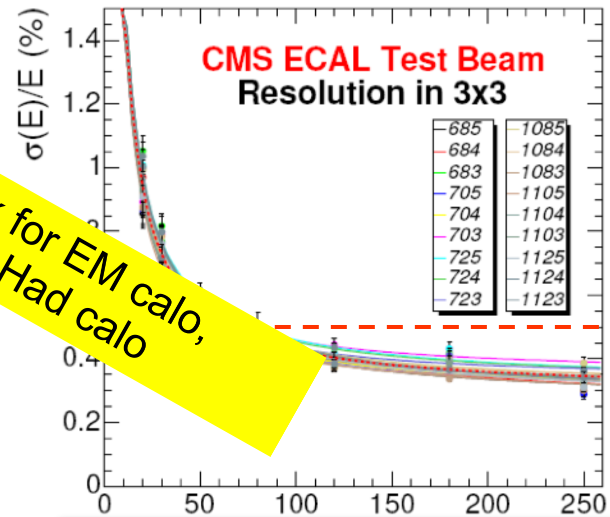
b: noise term

- readout electronics noise
- radioactivity, pileup fluctuations

c: constant term

- inhomogeneities (hardware or calibration)
- imperfections in calorimeter construction (gaps, dimensions variations etc.)
- non-linearity of readout electronics
- fluctuations in longitudinal energy containment
- fluctuations in energy lost in material upstream (or within) the calorimeter

This is ok for EM calo, approx for Had calo



For 9 $PbWO_4$ crystals tested @ CERN

The tolerable value of the 3 terms depends on the energy range of interest.
Such parametrisations allow the identification of the causes of resolution degradation.

Quadratic summation implies independent contributions which may not be the case.

Hadronic calo energy resolution

Response of a hadronic sampling calo $E = E_{em} + E_{ch} + E_n + E_{nucl}$

E_i - energy deposited by ith component

E_{em} - em component (π^0s)

E_{ch} - charged pions or protons

E_n - low energy neutrons

E_{nucl} -energy lost in breaking nuclei (binding energy)

$E_{vis} = eE_{em} + \pi E_{ch} + nE_n + NE_{nucl}$

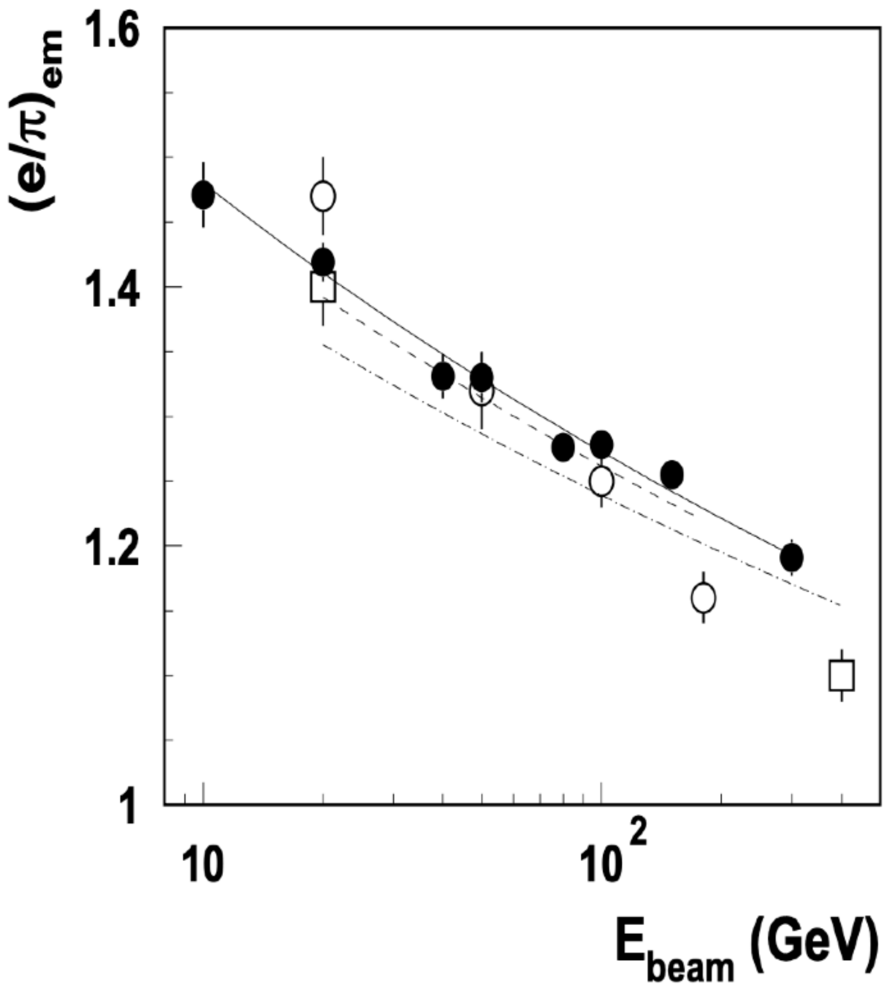
N is normally v. small but E_{nucl} can be large (~ 40 % in Pb)

Fluctuations in the visible energy have two sources

- *sampling fluctuation* as in em case
- *intrinsic fluctuation* in shower components (δE_{em}, δE_{ch} etc.)

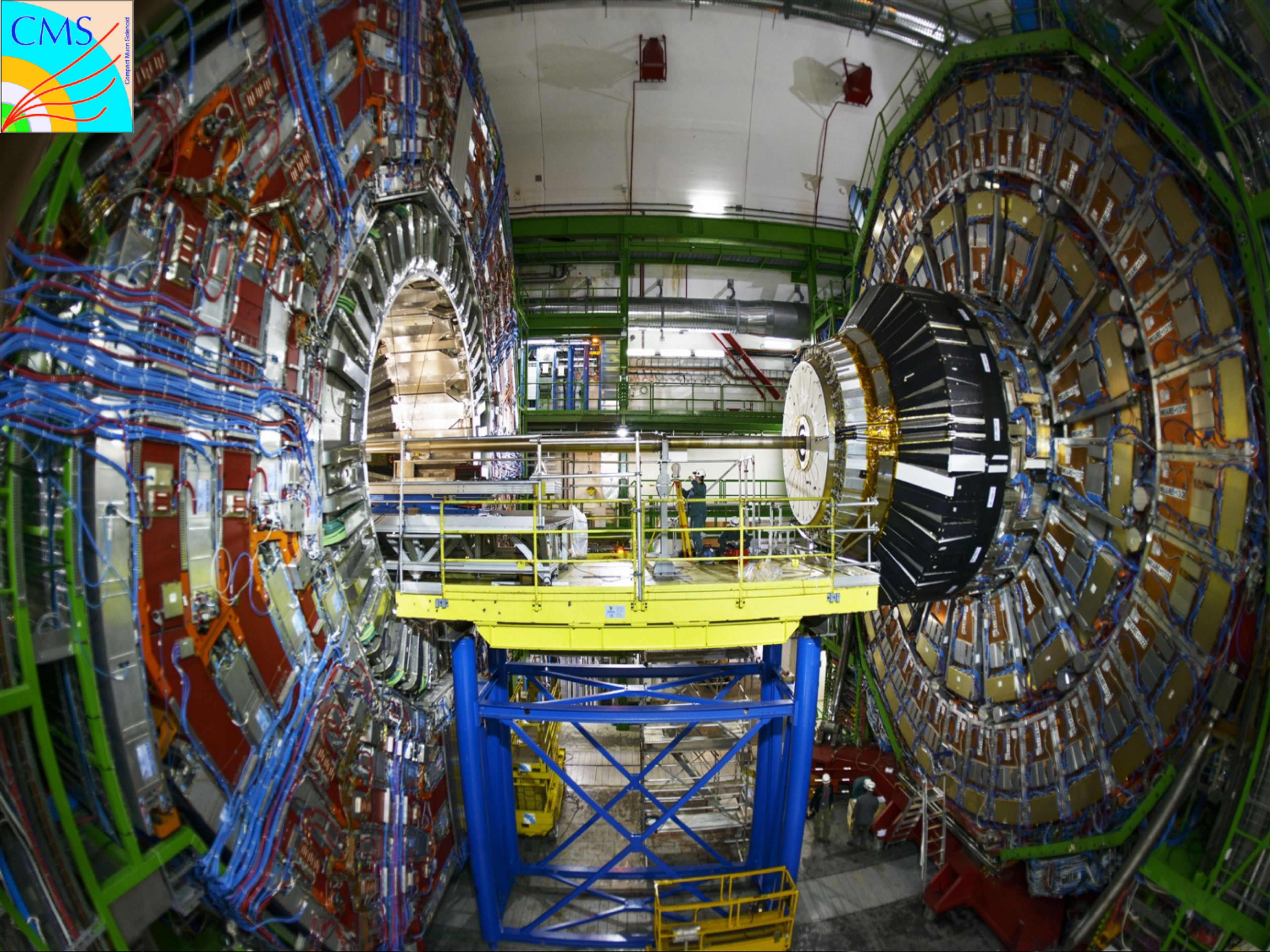
Effectively the 'constant' term of the resolution function typically depends on E , i.e. c(E) due to e/h≠1….
The 'art' of hadron calorimetry is to try to 'compensate' e/h

Example e/h (liquid argon)

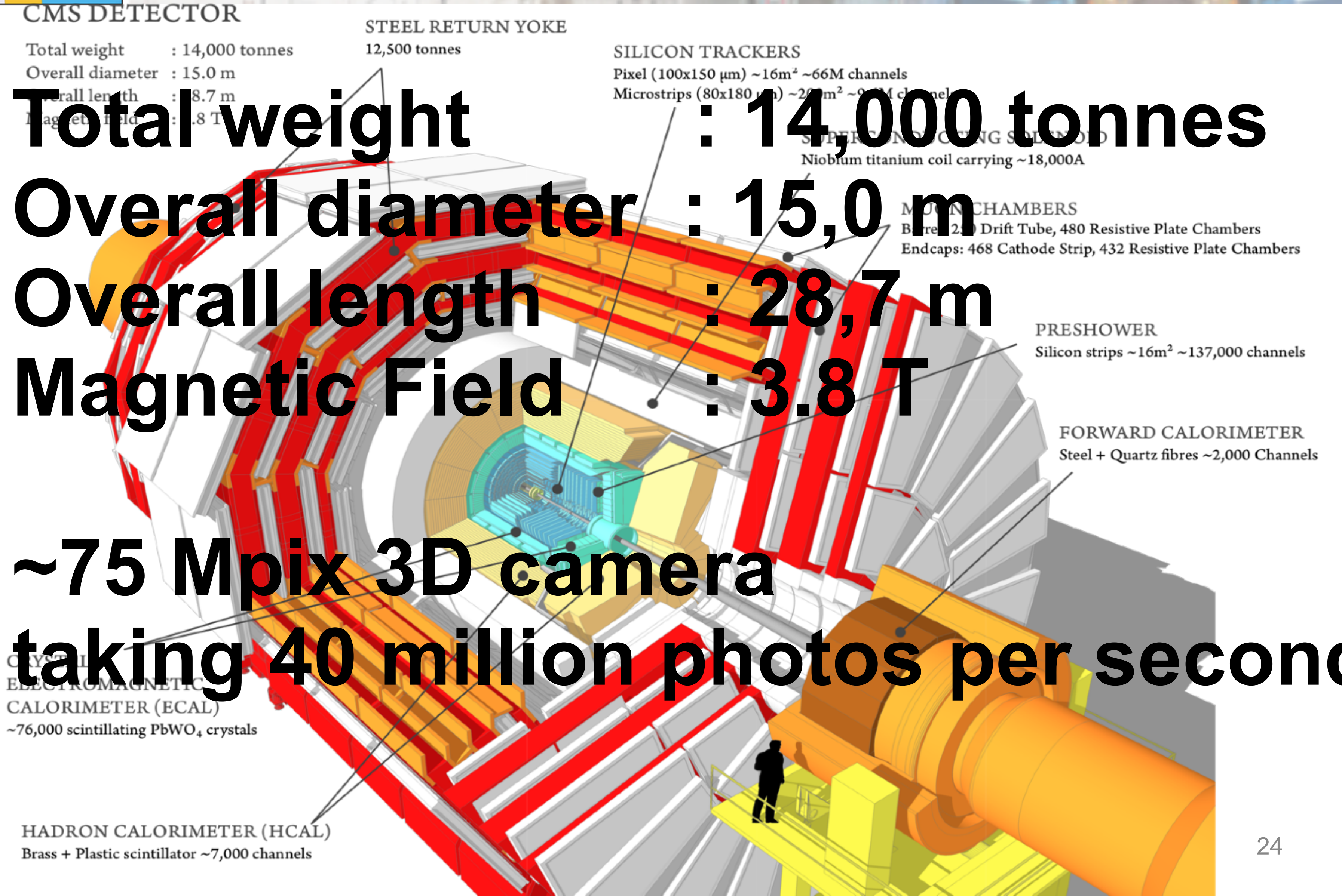


Atlas accordeon calo
(hep-ex/0005029)

How calorimeters are used
Ex: CMS at LHC

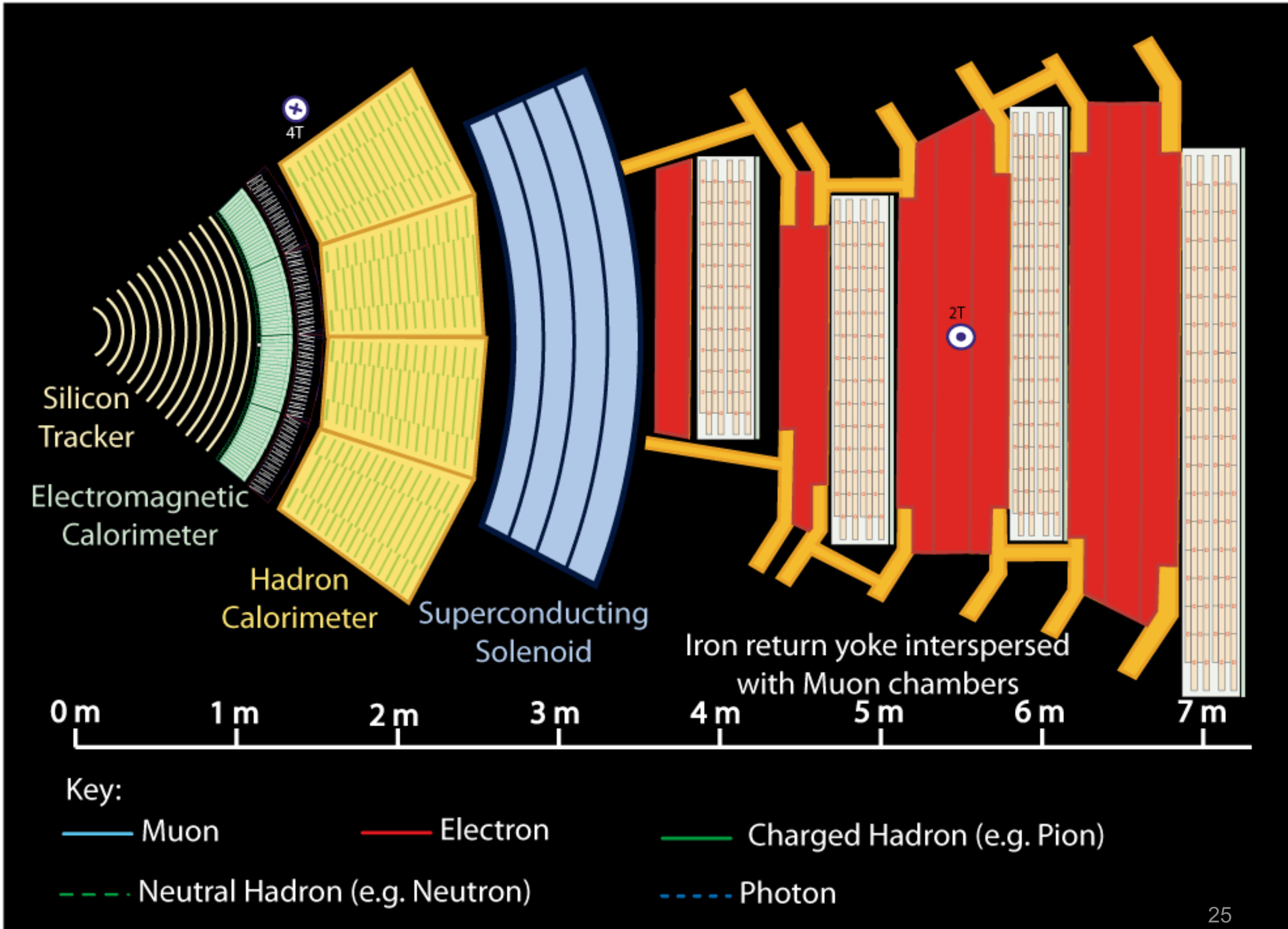

CMS

The Giant CMS Detector



Total weight : 14,000 tonnes
Overall diameter : 15,0 m
Overall length : 28,7 m
Magnetic Field : 3.8 T

~75 Mpix 3D camera
taking 40 million photos per second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2T
Silicon Tracker
Electromagnetic Calorimeter
Hadron Calorimeter
Superconducting Solenoid
Iron return yoke interspersed with Muon chambers
0 m
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2 m
3 m
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5 m
6 m
7 m
Key:
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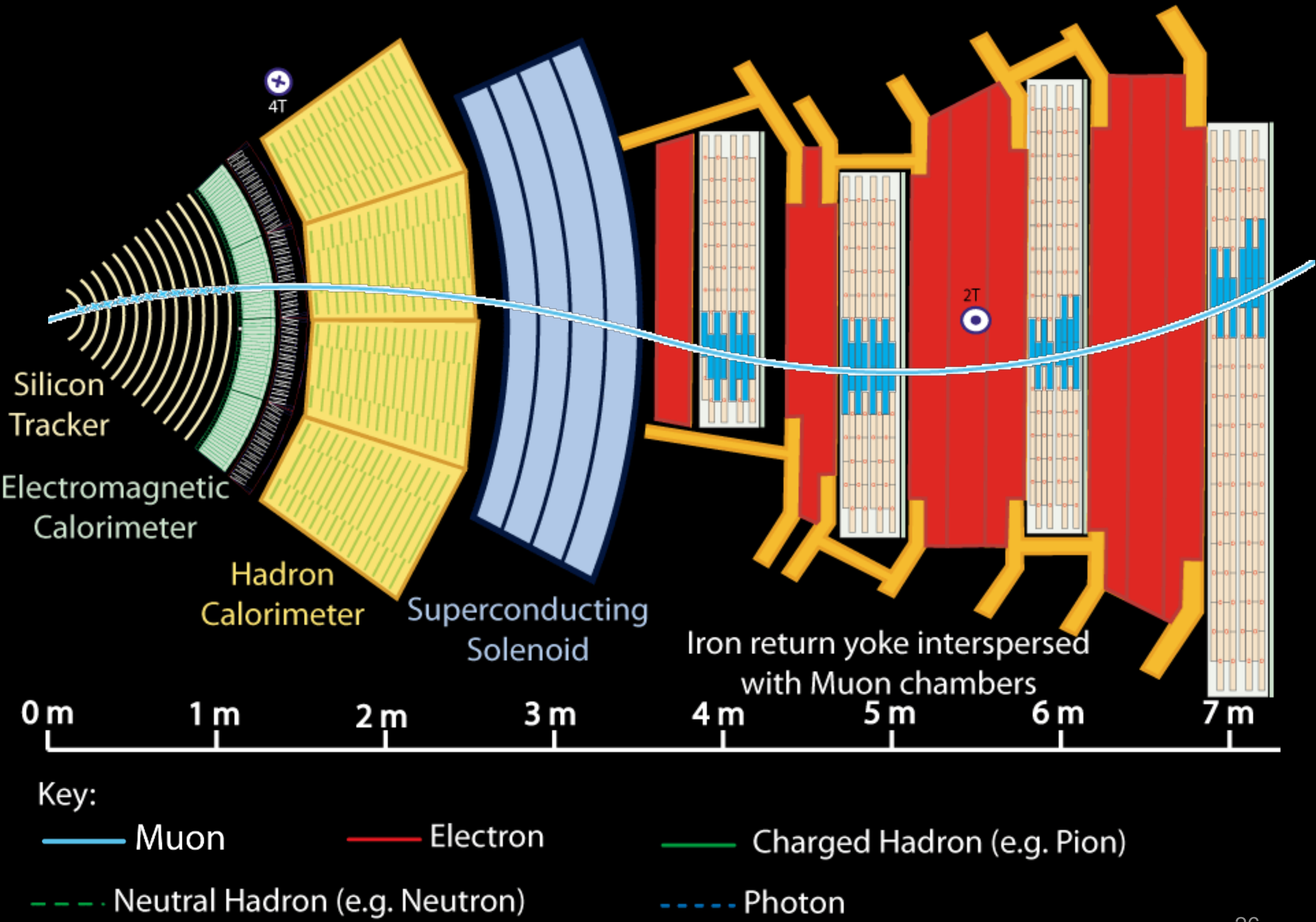
Electron
Charged Hadron (e.g. Pion)
Neutral Hadron (e.g. Neutron)
Photon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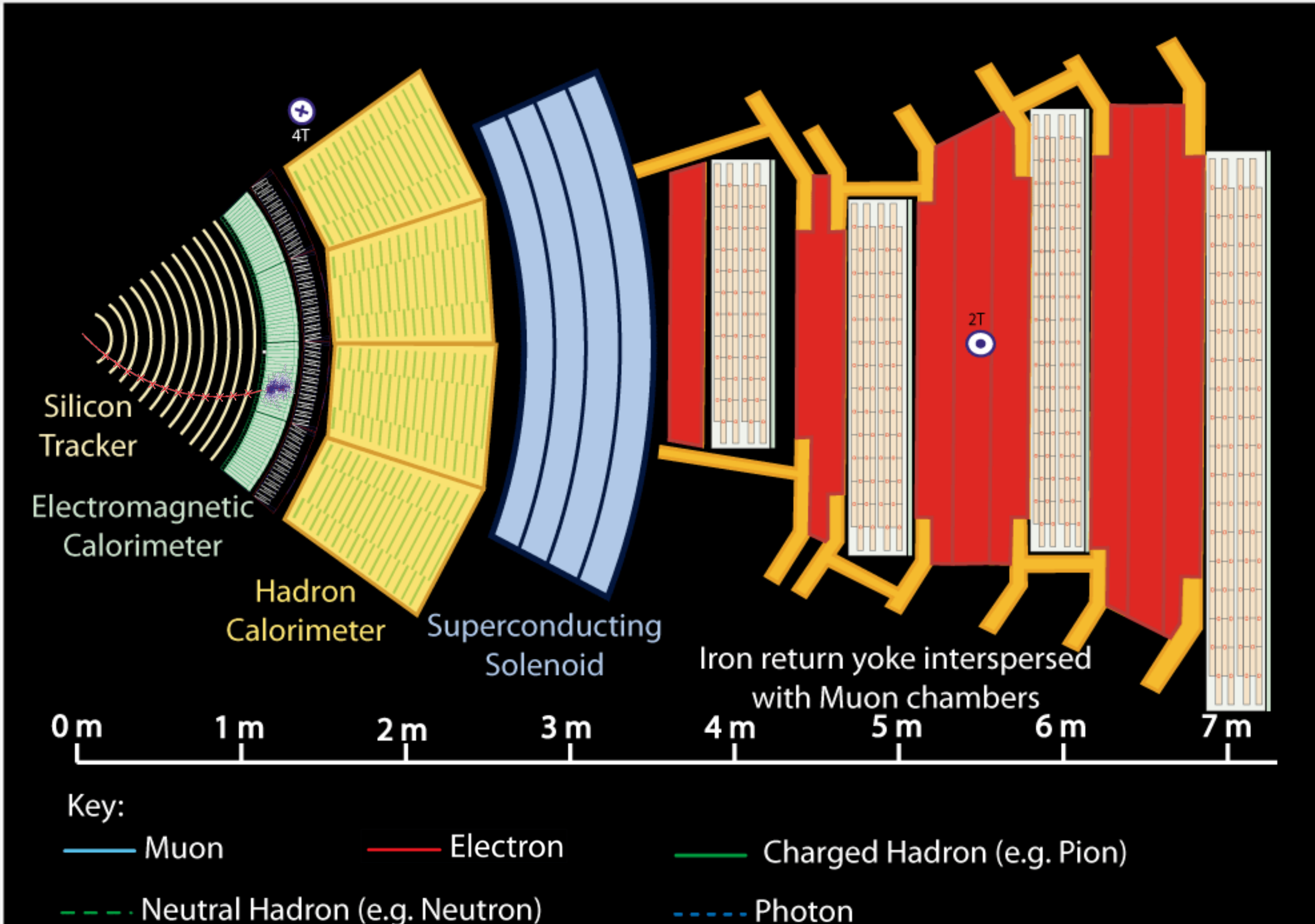
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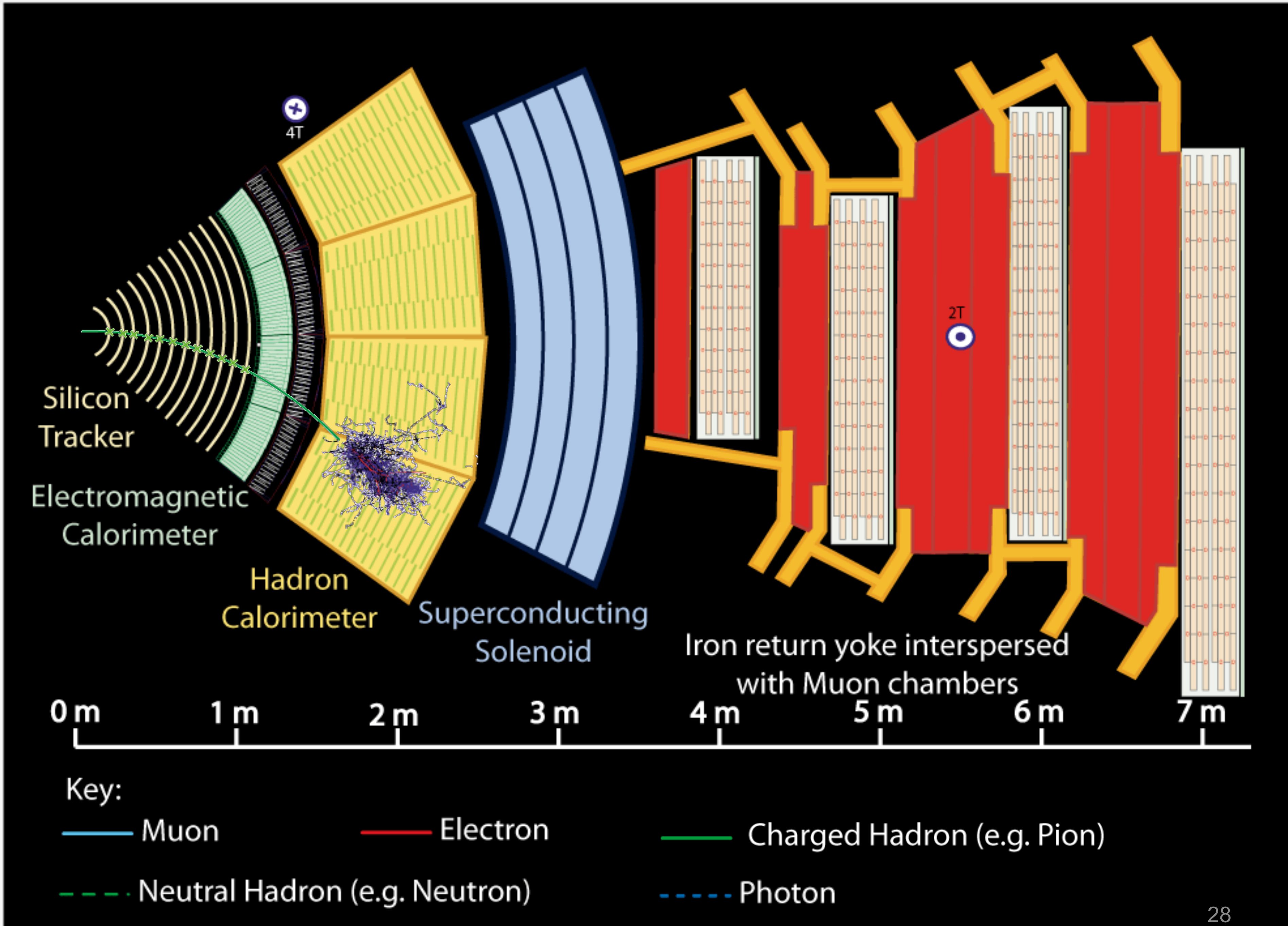
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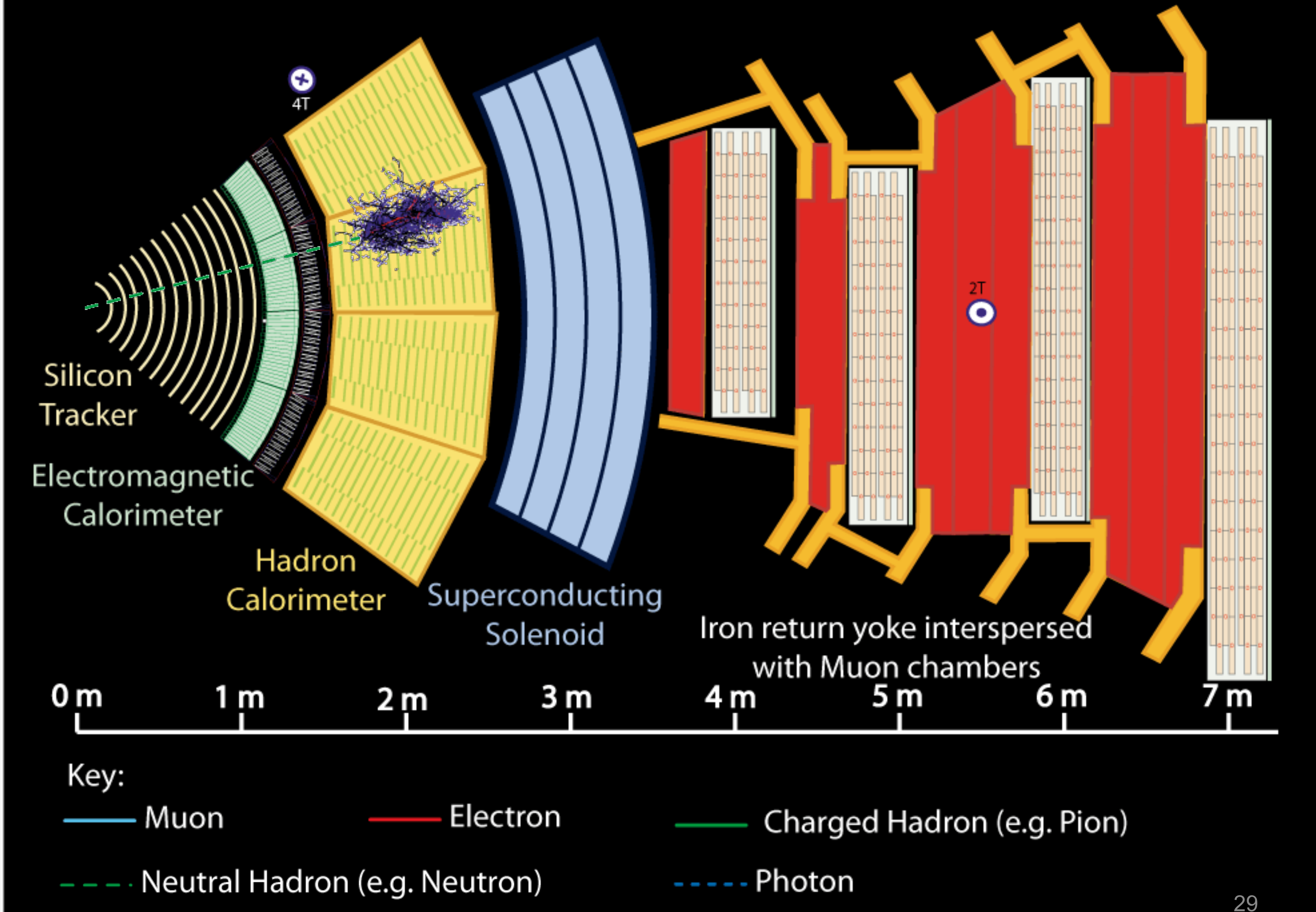
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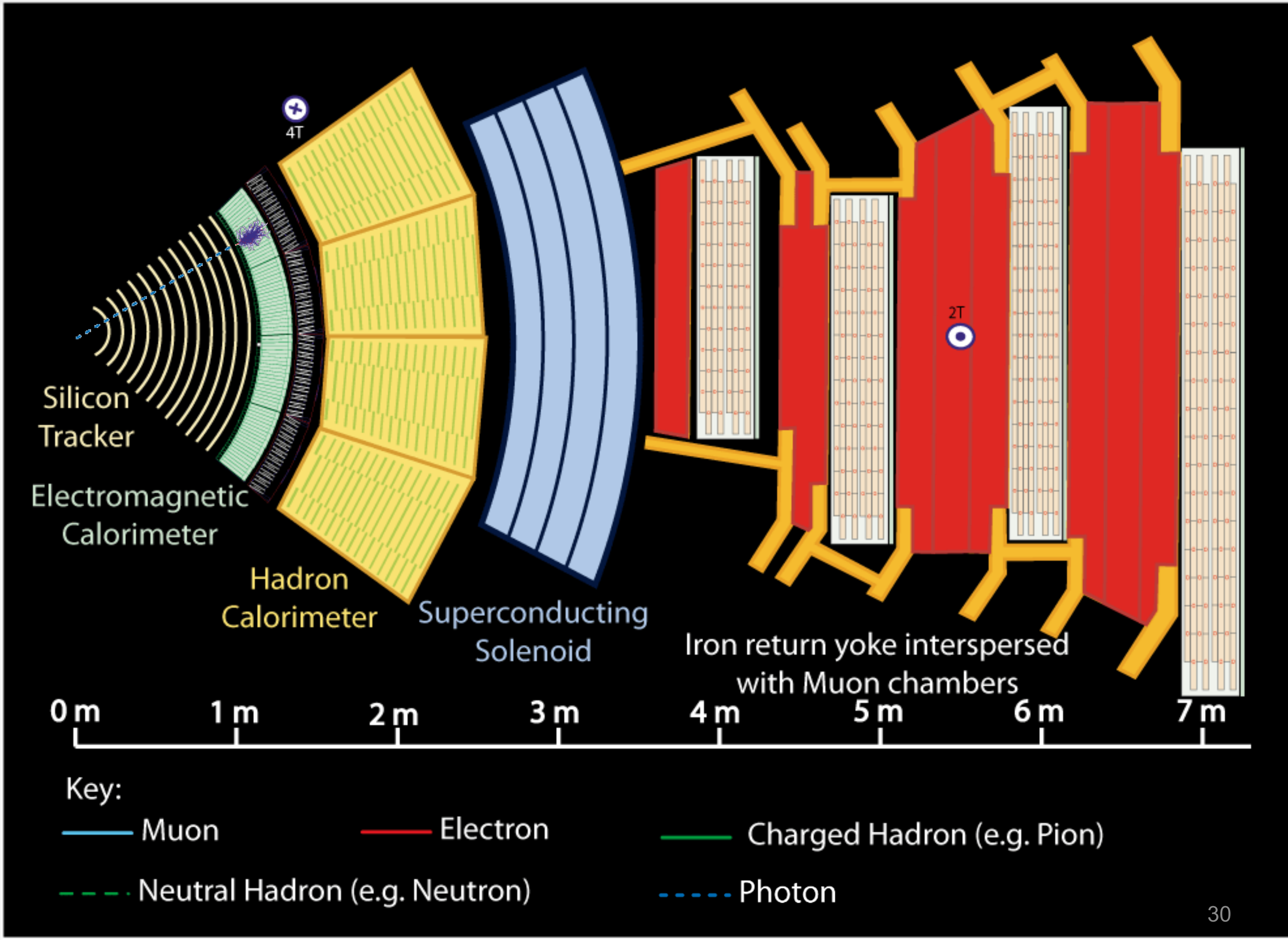
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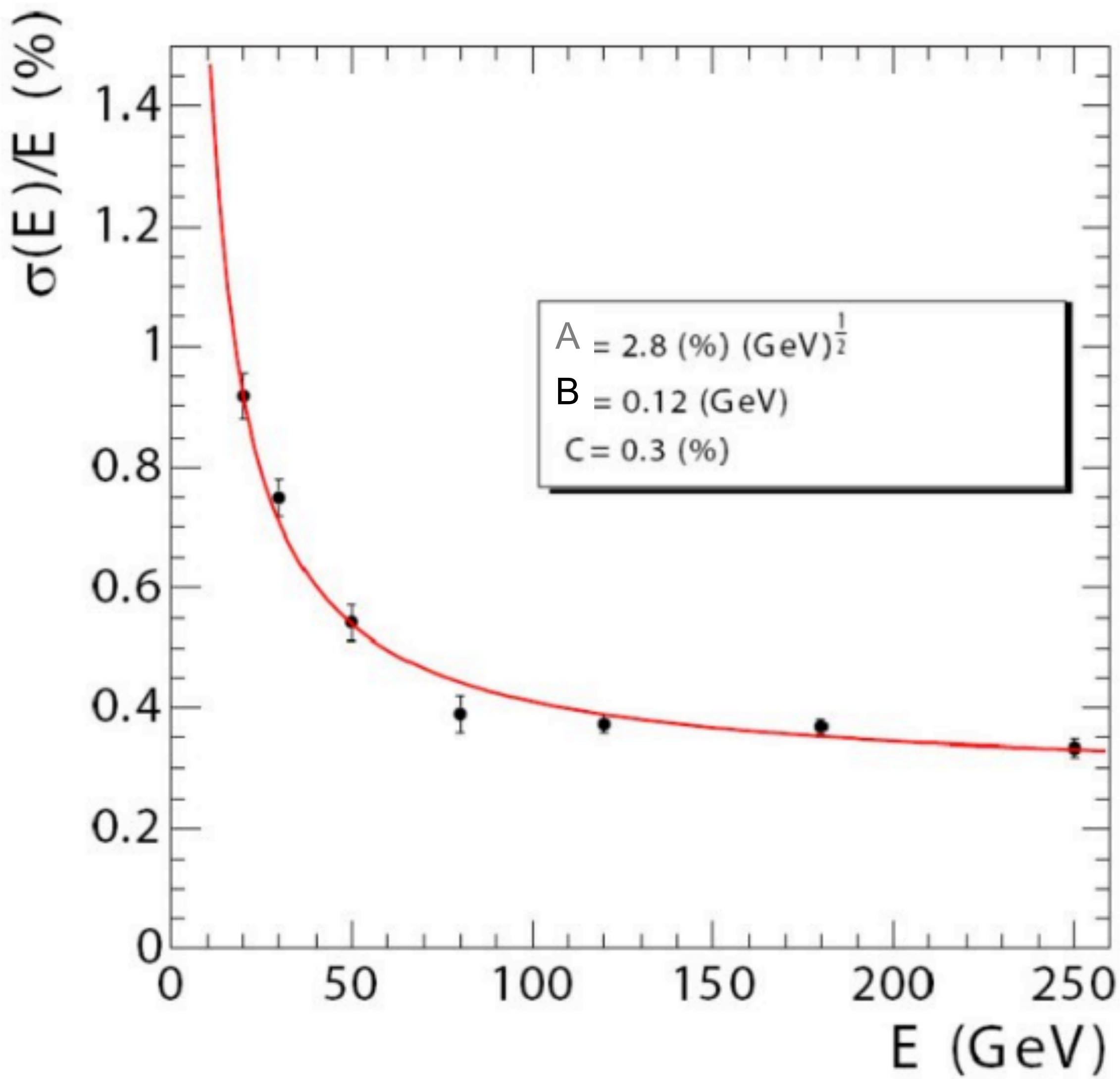
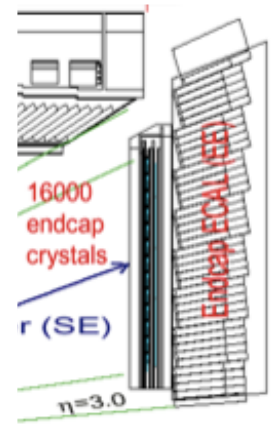
ECAL

- Benchmark
  Noise dete
  resolution
  narrow an
  order of m
- CMS choice





Pro

Crystal	X_0 (cm)	F
BaF_2	2.06	3
CeF_3	1.68	2
$PbWO_4$	0.89	

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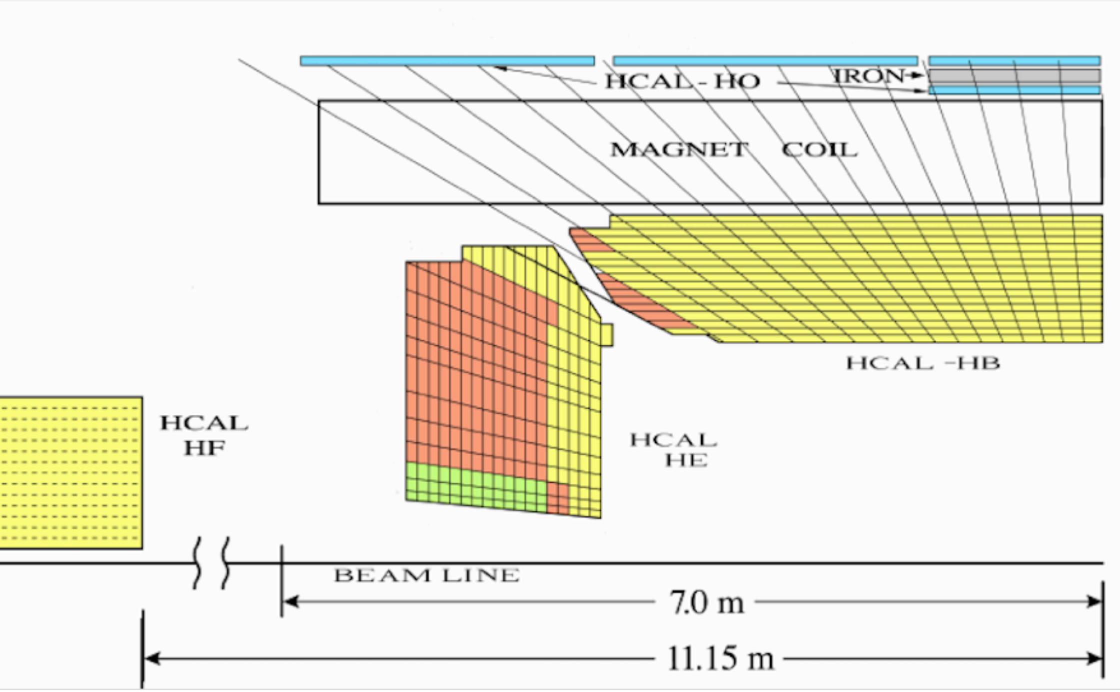
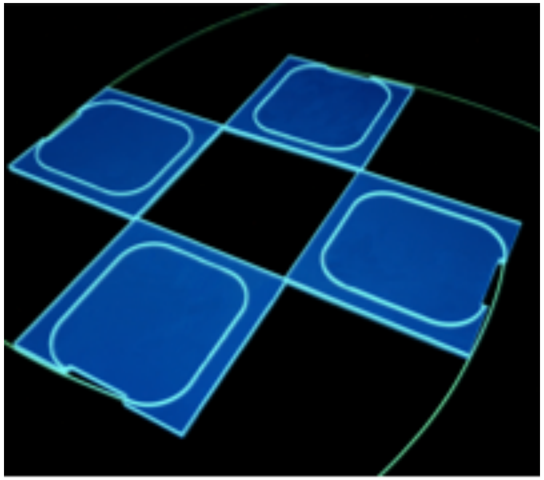
HCAL



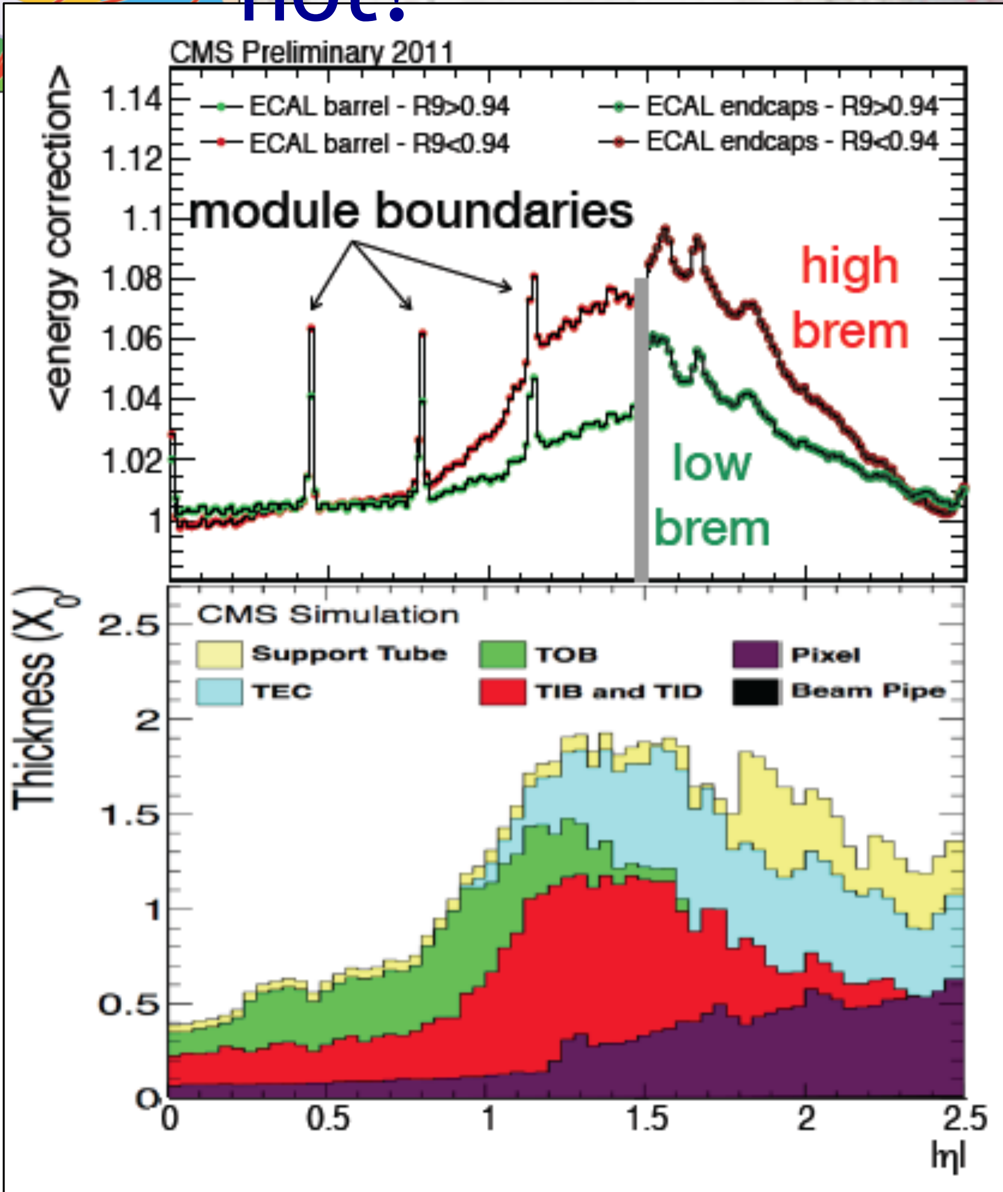
$$\frac{\sigma_E}{E}(\%) \sim \frac{100 - 150\%}{\sqrt{E}}$$

Scintillator tiles readout by Wave-Length-shifter fibers

B-field tolerant photo-detectors: HPDs



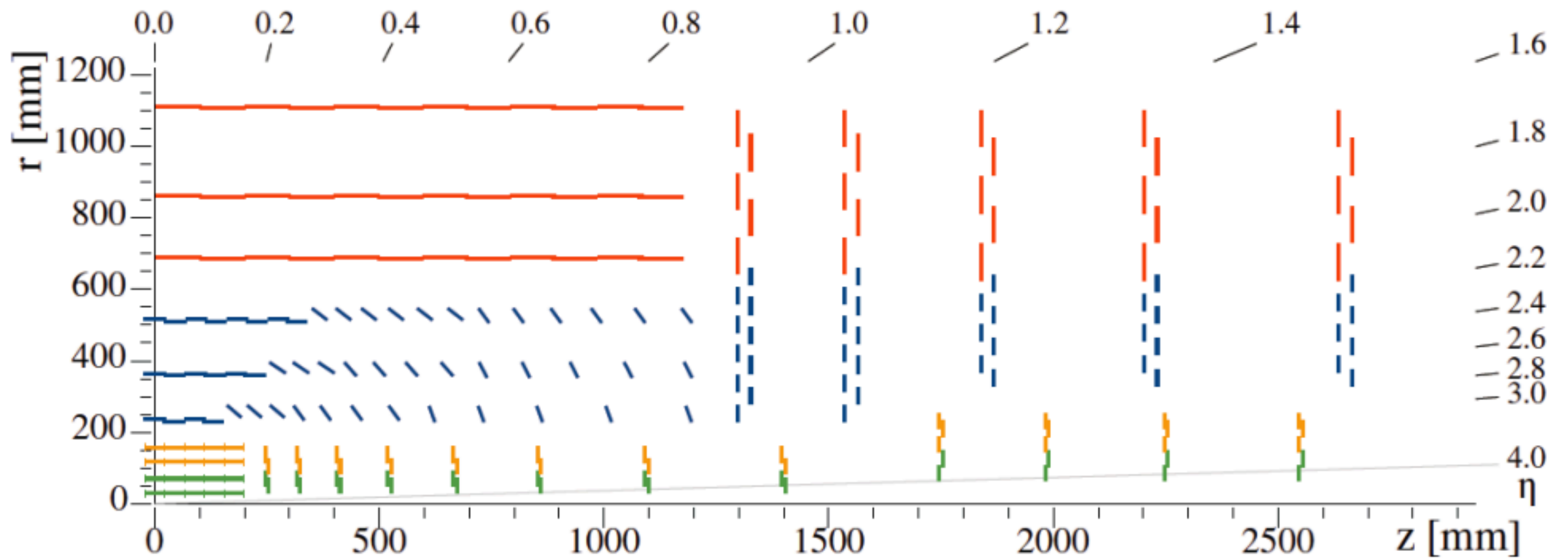
X^0 matters whether in the calo or not!



R9 = fraction of cluster energy contained in 9 crystals around max

- Correct energy clusters for:
  - Energy loss in **material upstream** of ECAL
    - e^+e^- bremsstrahlung and γ conversions
  - Local shower containment
  - Crystal geometry

…important:material in front of the calo



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  4.9
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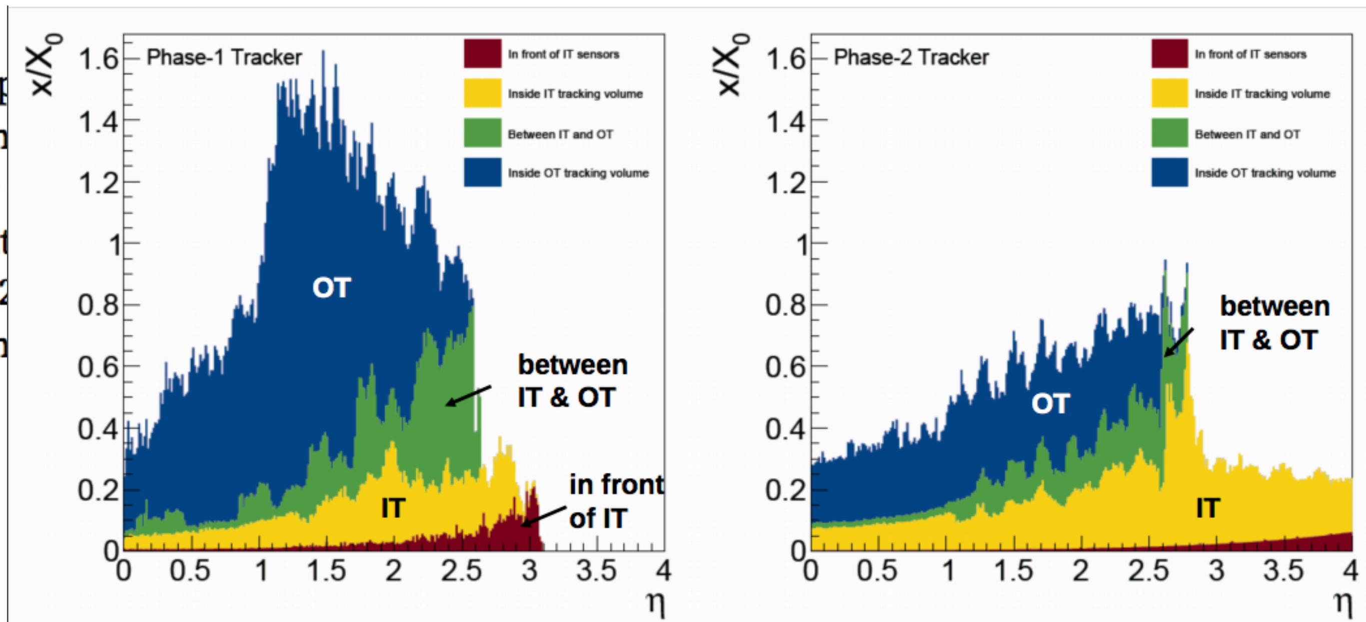
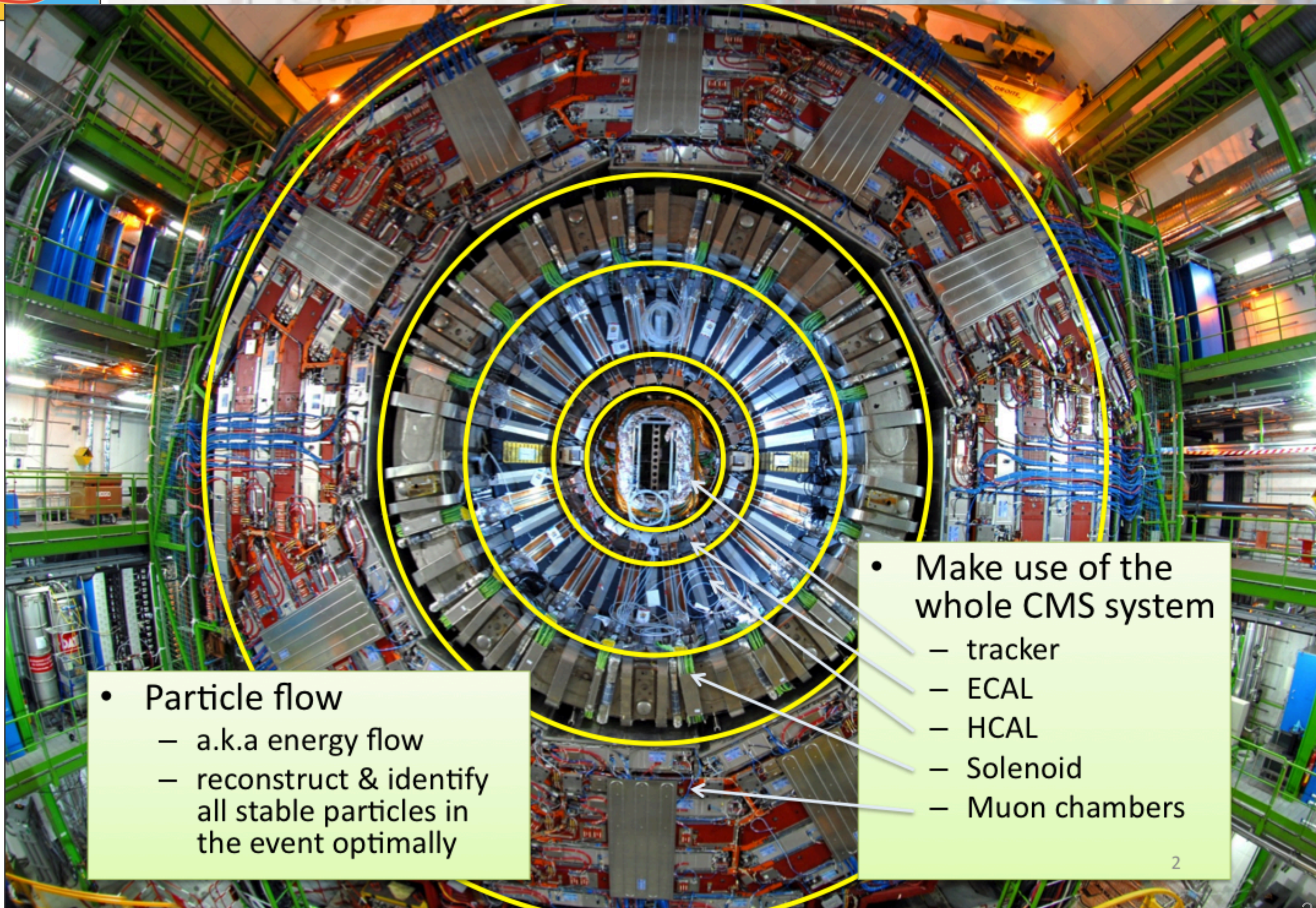
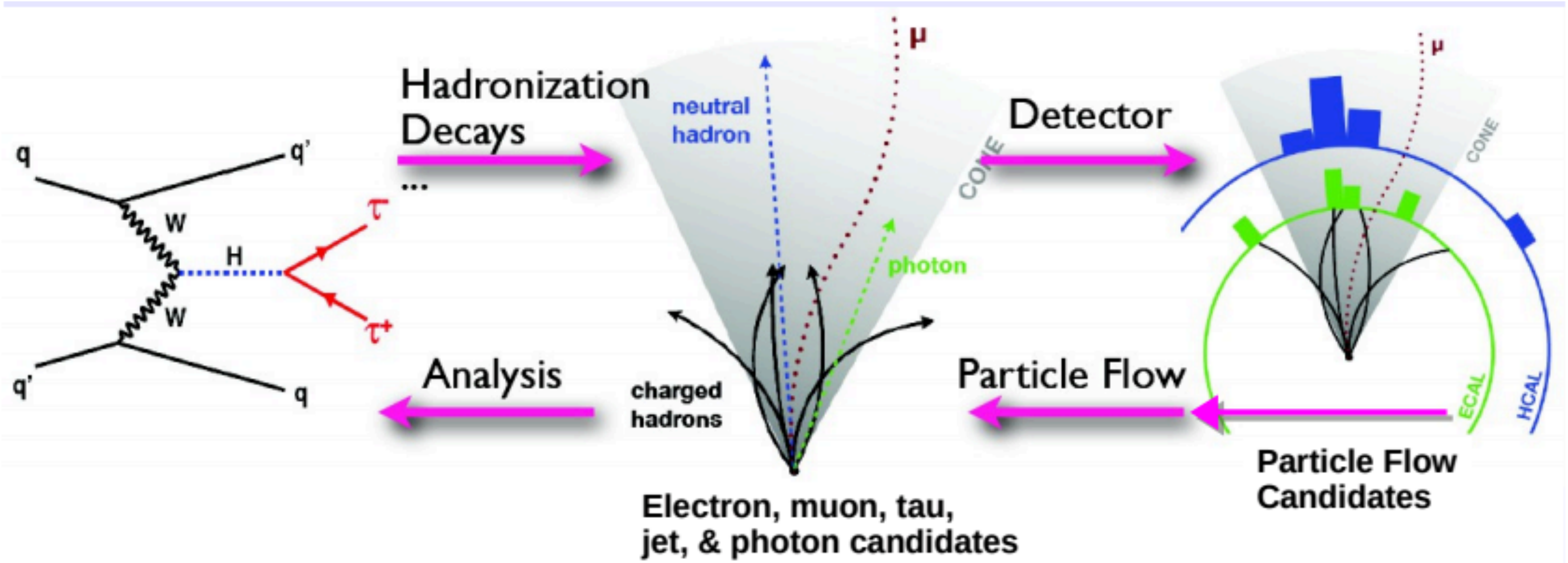
  13 2
  Inn



How to improve for e/h ≠ 1



Particle Flow

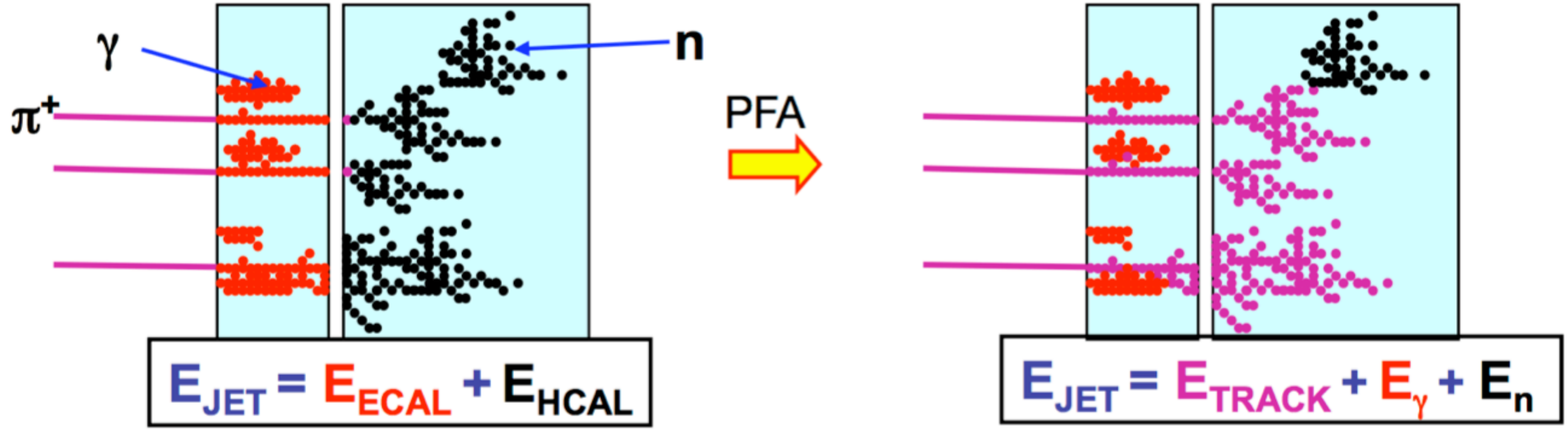


Why Particle Flow?

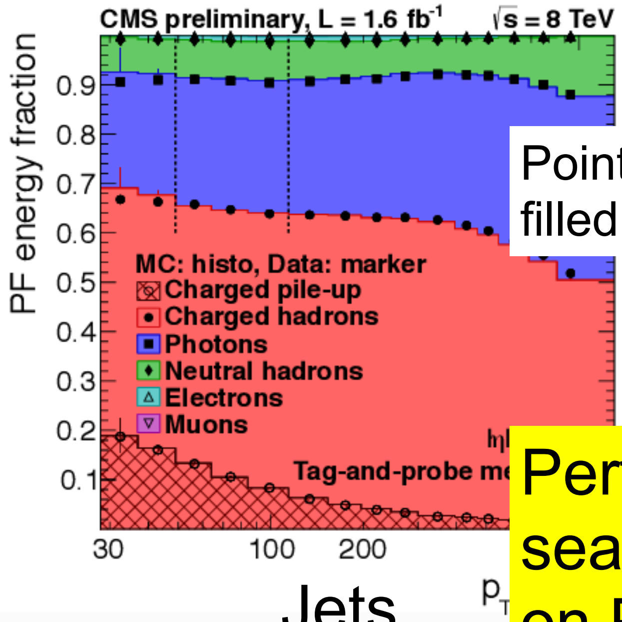
Idea: for each individual particle in a jet, use detector with best energy/momentum resolution

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

- Calorimeter jet:
  - $E = E_{HCAL} + E_{ECAL}$
  - σ(E) ~ calo resolution to hadron energy: 120 % / √E
  - direction biased (B = 3.8 T)
- Particle flow jet:
  - 65% charged hadrons
    - σ(pT)/pT ~ 1%
    - direction measured at vertex
  - 25% photons
    - σ(E)/E ~ 1% / √E
    - good direction resolution
  - 10% neutral hadrons
    - σ(E)/E ~ 120 % / √E

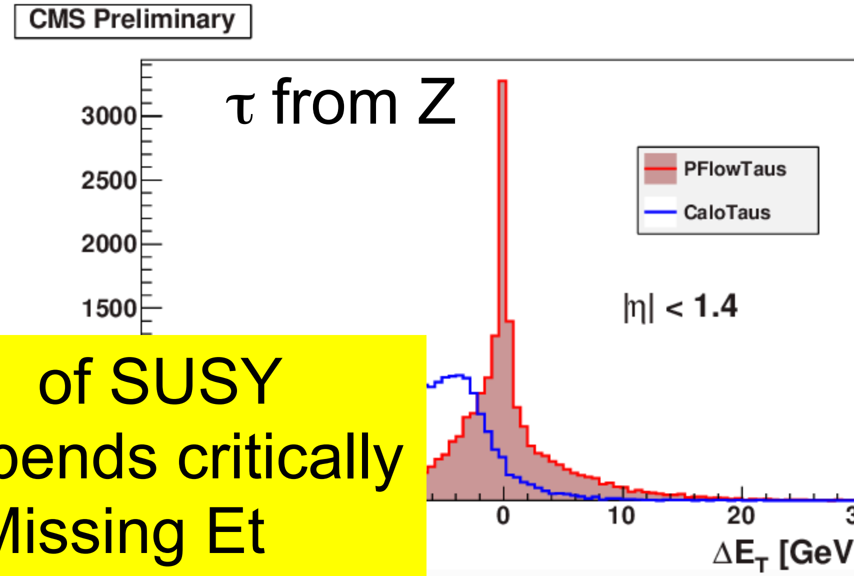


...and it worked ! (PFLOW)

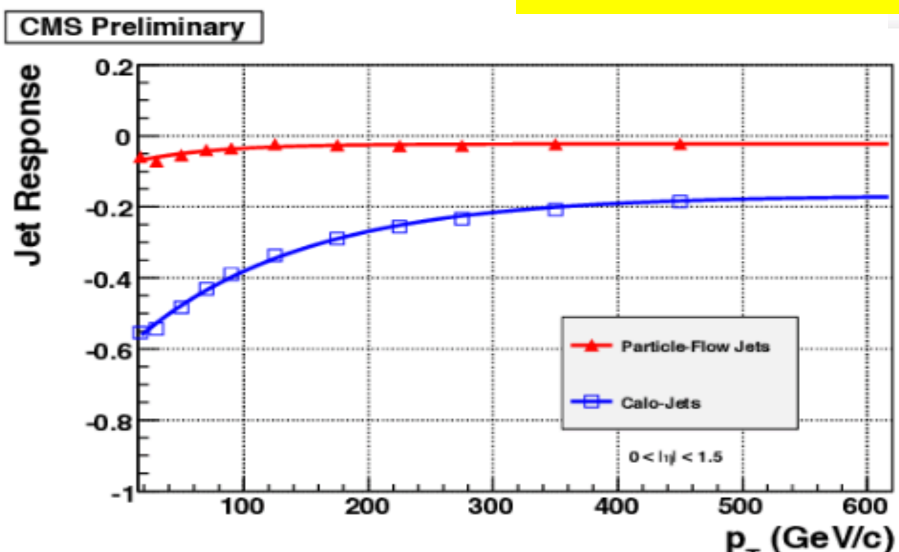


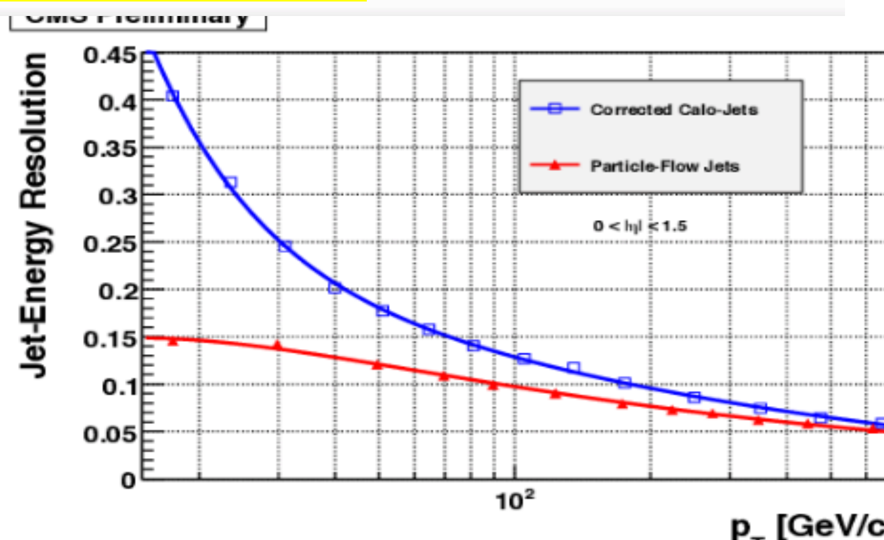
Points data, filled MC

Jets



Performance of SUSY searches depends critically on PFLOW Missing Et

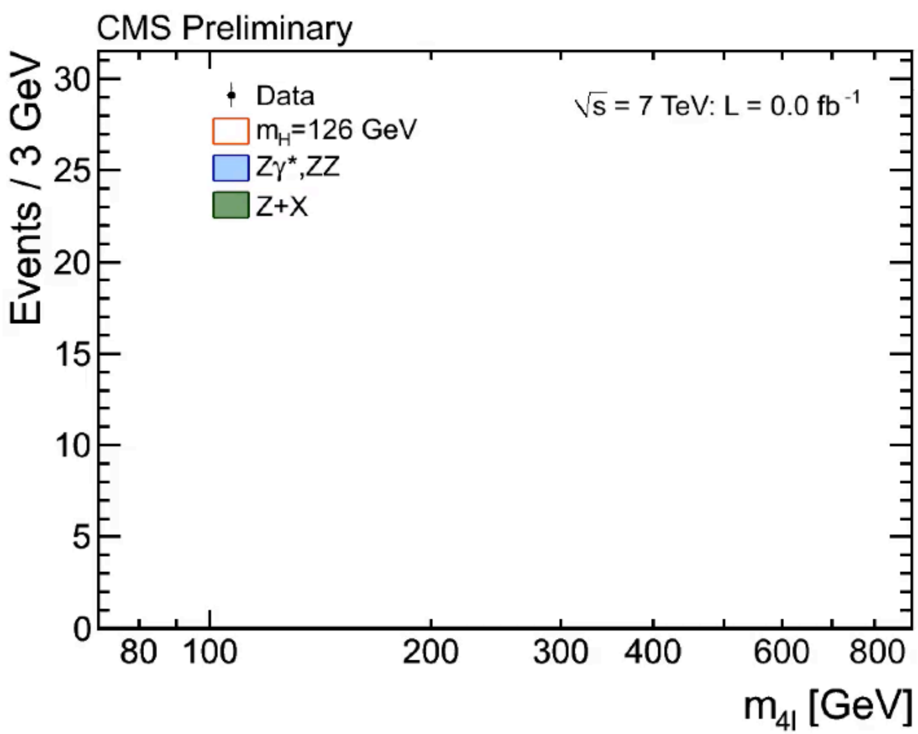


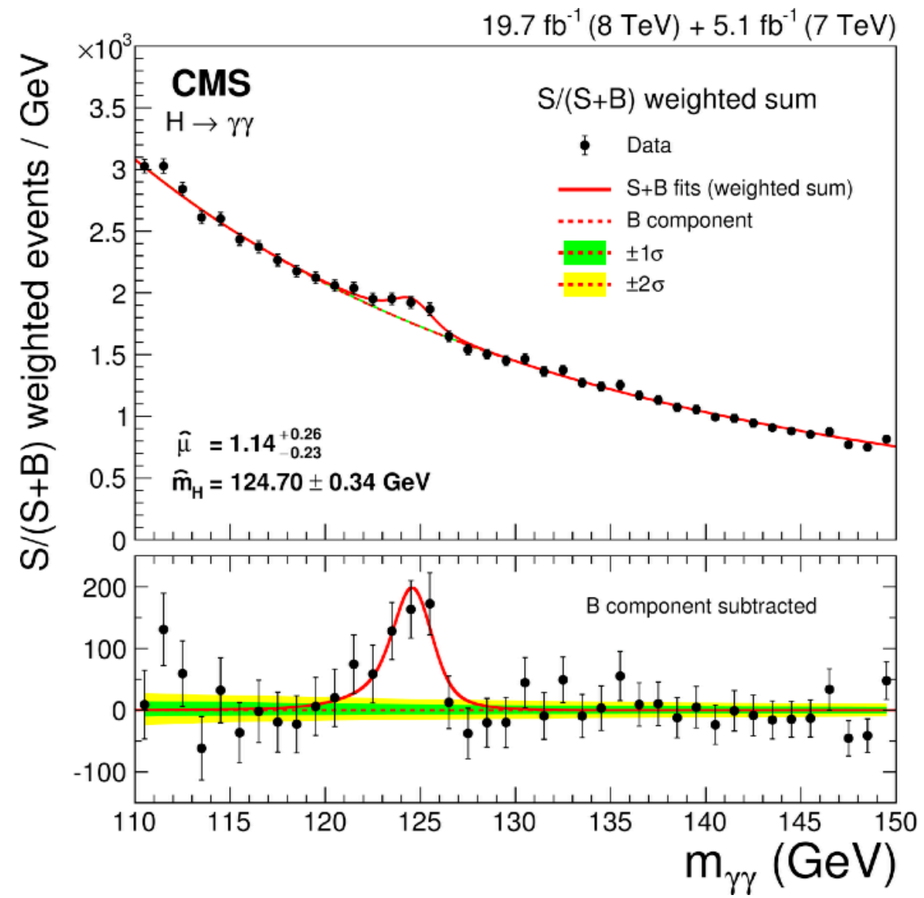


...and it worked ! (ECAL)

$H \to ZZ \to$ ee μμ

$H \to \gamma\gamma$

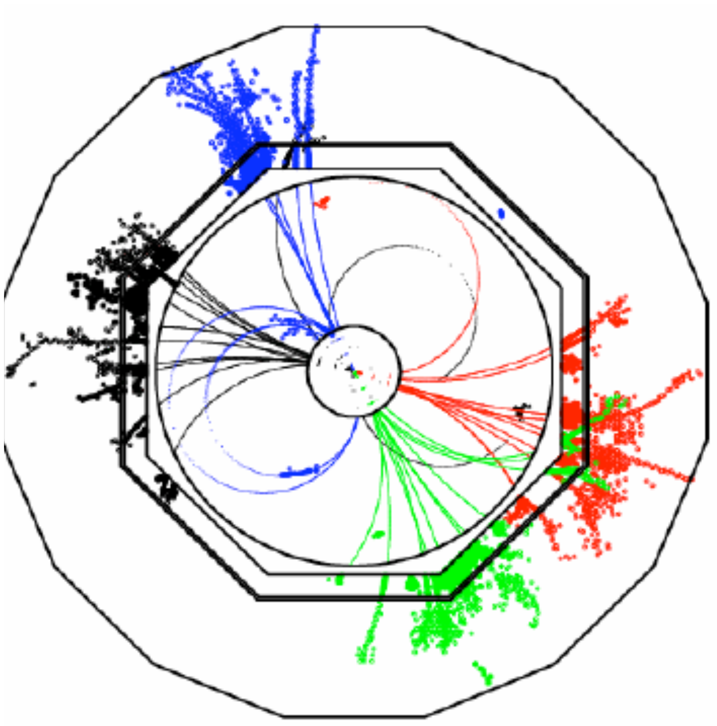




Calorimeter optimized for particle flow

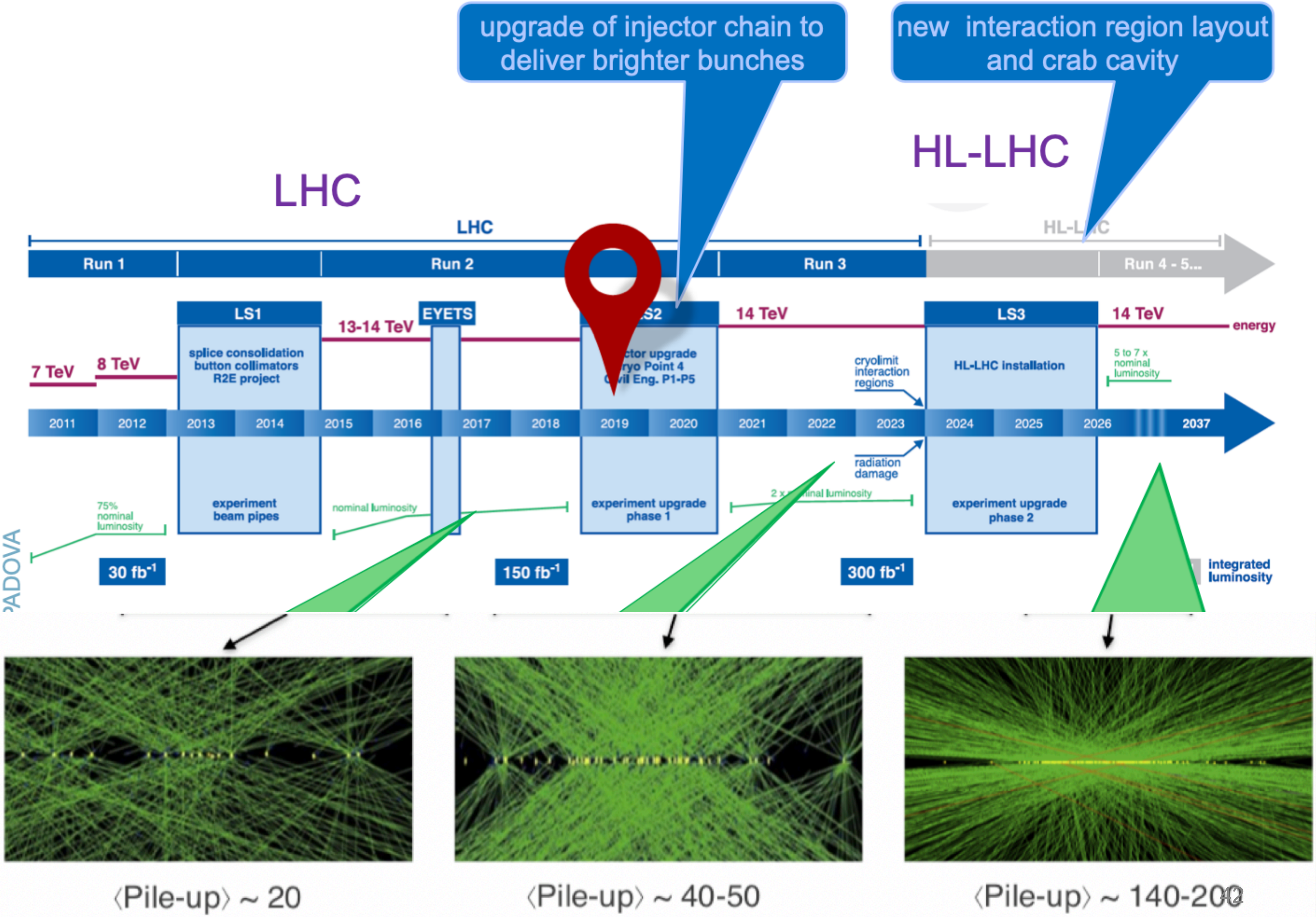
For a Particle-Flow Calorimeter:

- **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!



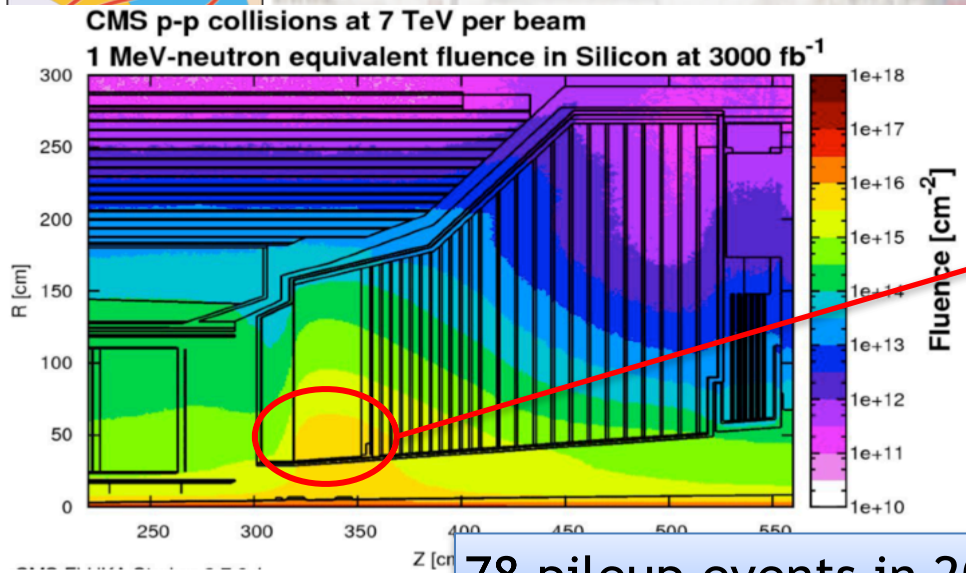
The future

- The original plan when LHC and the experiments were approved was to have a period of ~10 years of operation with ultimate luminosity at the end of the 10 years exceeding 10^{34} $cm^{2}s^{-1}$
- The performance of LHC has exceeded all expectations
- The success of the accelerator has led CERN to propose (and get approved) an ambitious upgrade program aiming to exploit the ultimate potential of LHC



upgrade of injector chain to deliver brighter bunches
new interaction region layout and crab cavity
HL-LHC
LHC
LHC
Run 1
Run 2
Run 3
Run 4 - 5...
LS1
EYETS
LS3
7 TeV
8 TeV
13-14 TeV
14 TeV
14 TeV
energy
splice consolidation
button collimators
R2E project
HL-LHC installation
cryolimit interaction regions
radiation damage
5 to 7 x nominal luminosity
2011
2012
2013
2014
2015
2016
2017
2018
2019
2020
2021
2022
2023
2024
2025
2026
2037
75% nominal luminosity
experiment beam pipes
nominal luminosity
experiment upgrade phase 1
experiment upgrade phase 2
30 fb^{-1}
150 fb^{-1}
300 fb^{-1}
integrated luminosity
⟨Pile-up⟩ ~ 20
⟨Pile-up⟩ ~ 40-50
⟨Pile-up⟩ ~ 140-200

Radiation and rate problems

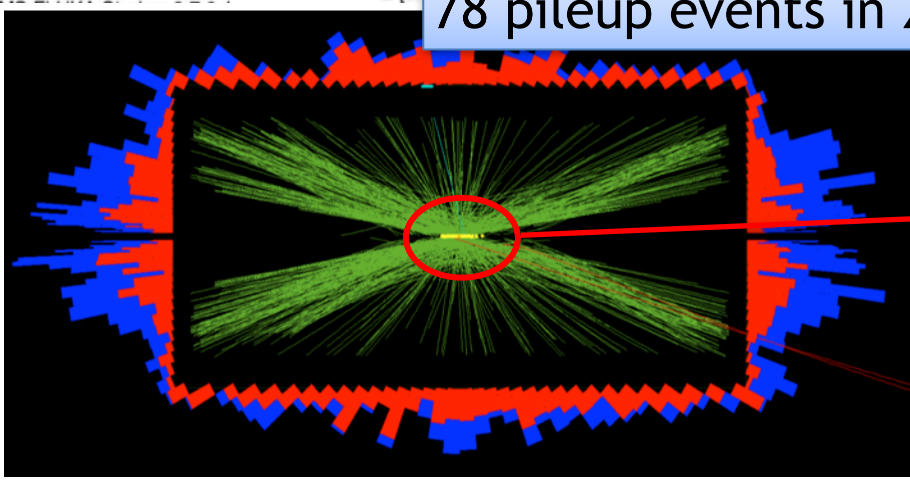


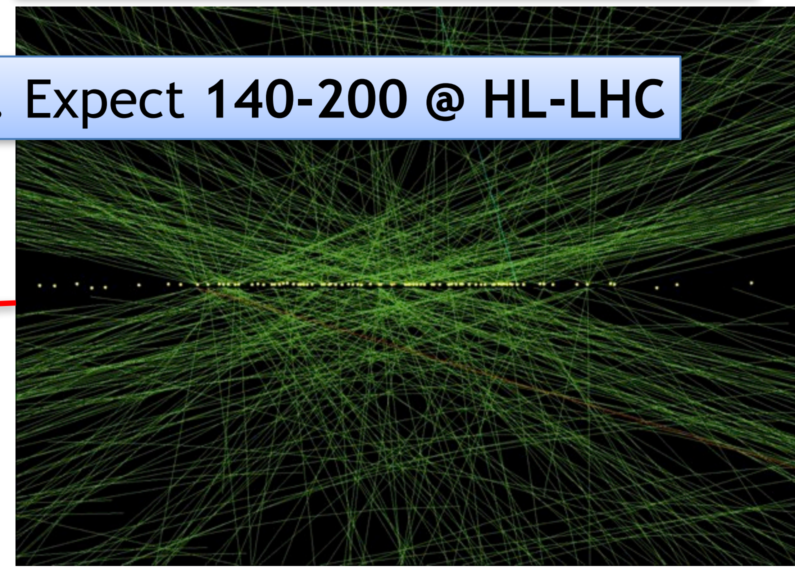
CMS @ HL-LHC:

~10^{16} 1 MeV n_{eq} cm^{-2} @ $3ab^{-1}$ in forward calorimeters, with **pileup ~200**

And up to **2 MGy** absorbed dose

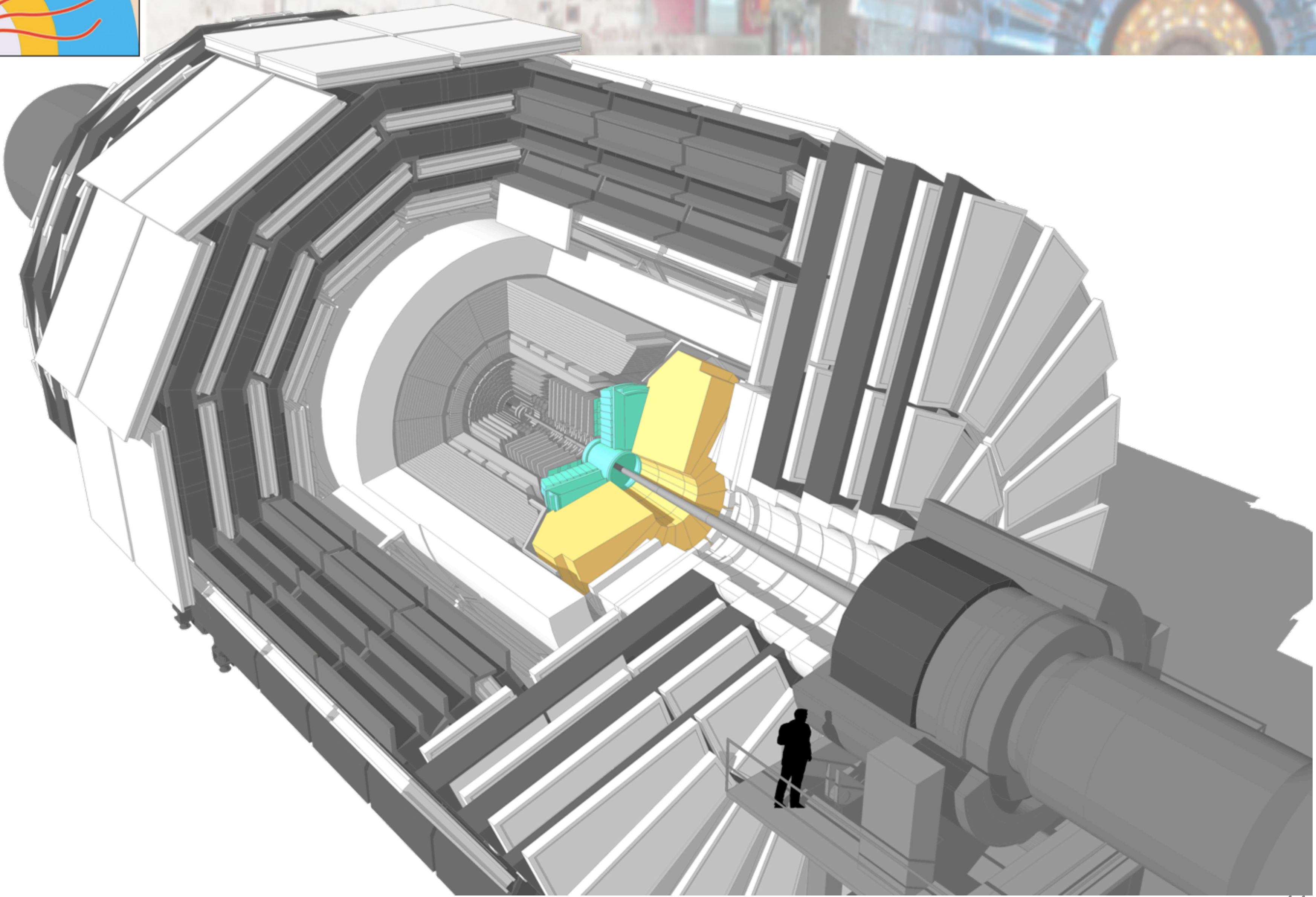
78 pileup events in 2012. Expect **140-200 @ HL-LHC**





All on-detector electronics will also be obsolete by LS3, due to necessary upgrades to the trigger and DAQ systems

CMS will replace its endcap calorimeters for HL-L

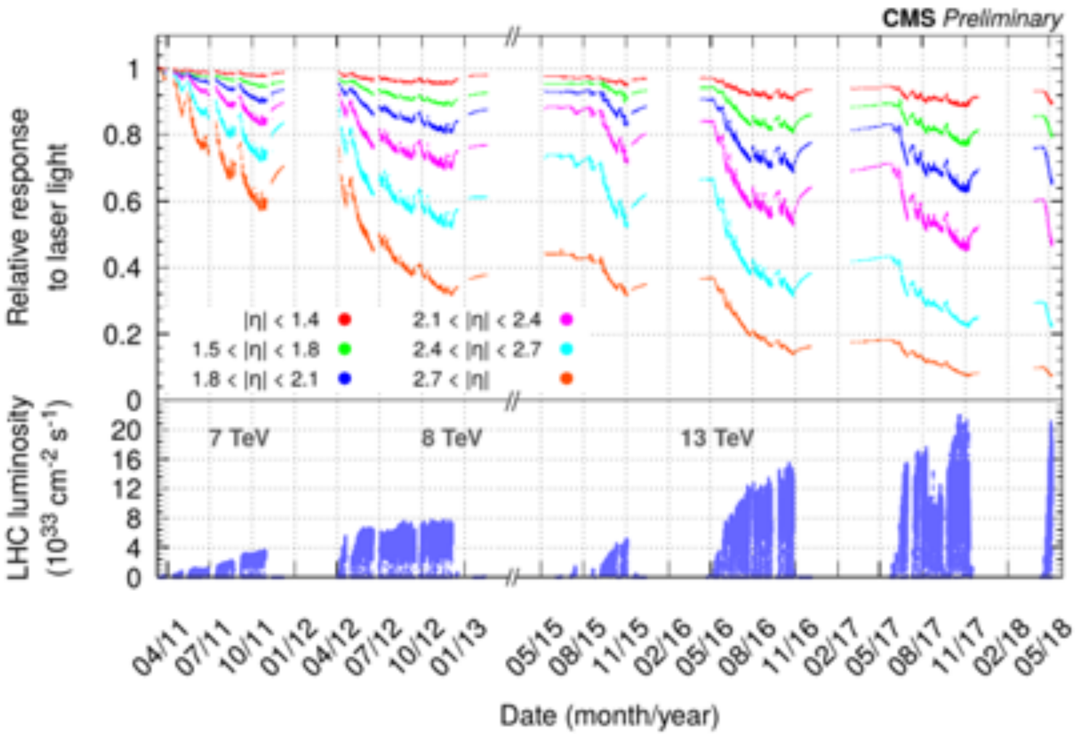


Why replace ?

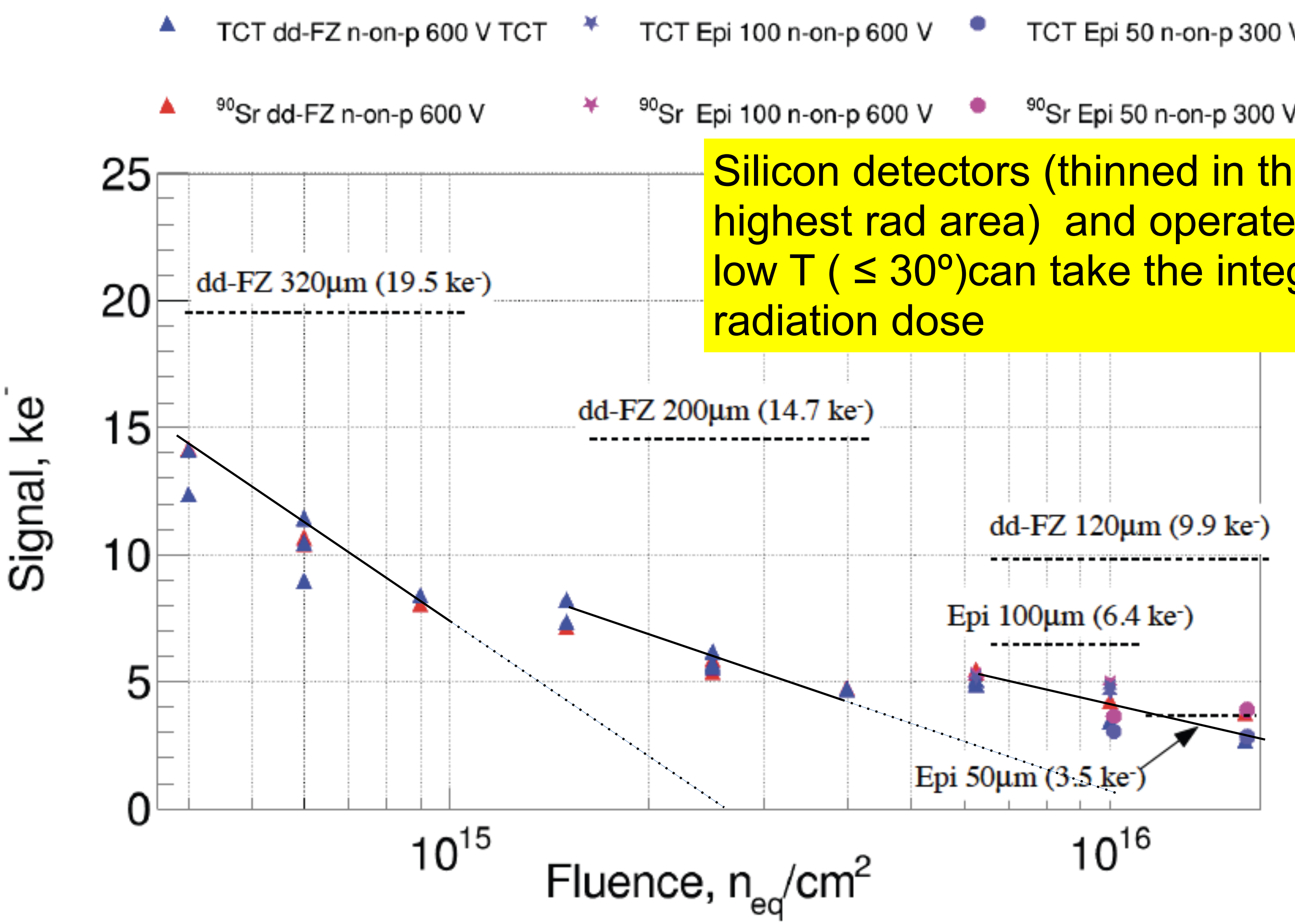
Original experiment was designed for an integrated lumi of < 300fb^{-1}

The radiation toll will impair performance beyond that !

Crystal calorimeter (in the forward region)



Silicon can do it

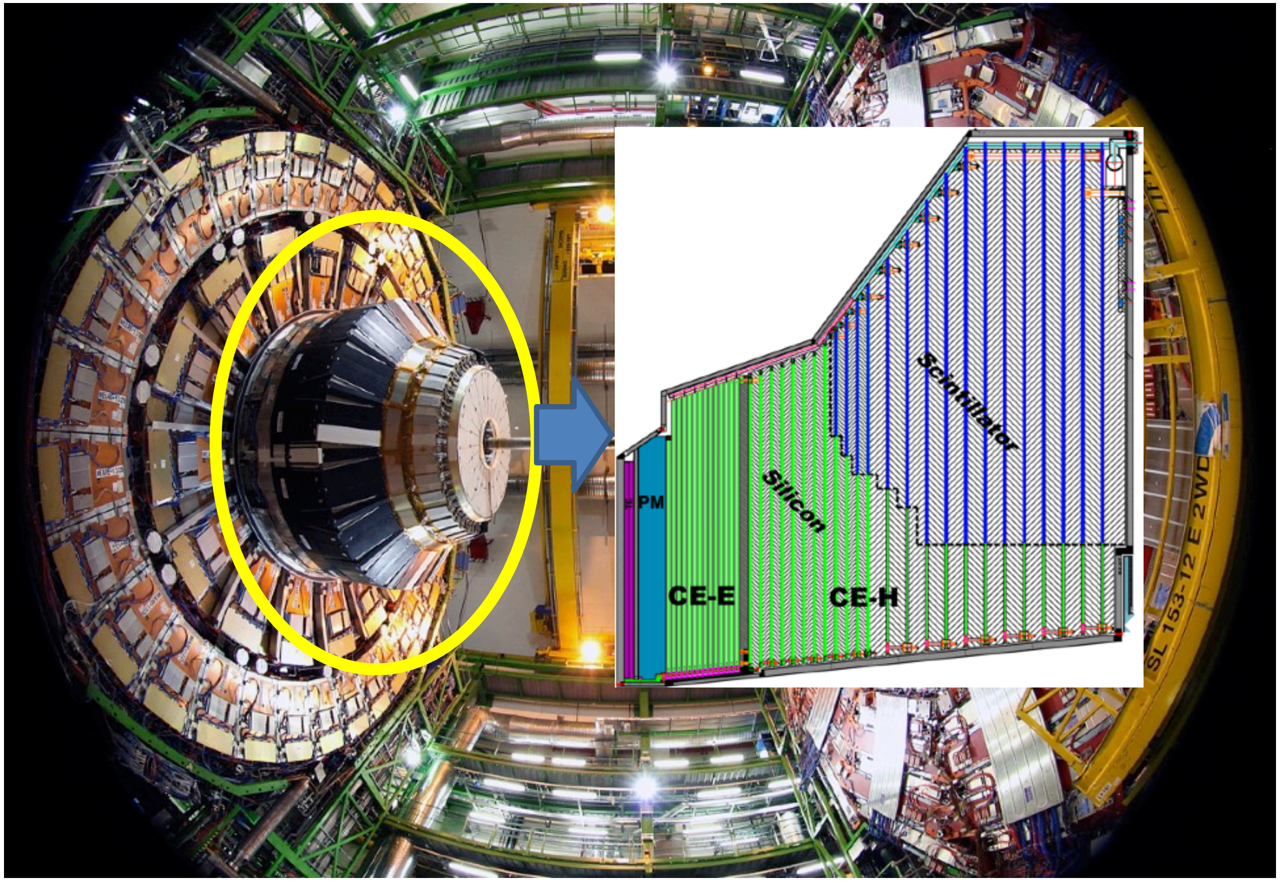


Silicon detectors (thinned in the highest rad area) and operated at low T (≤ 30º)can take the integrated radiation dose

Ultimate performance requirements

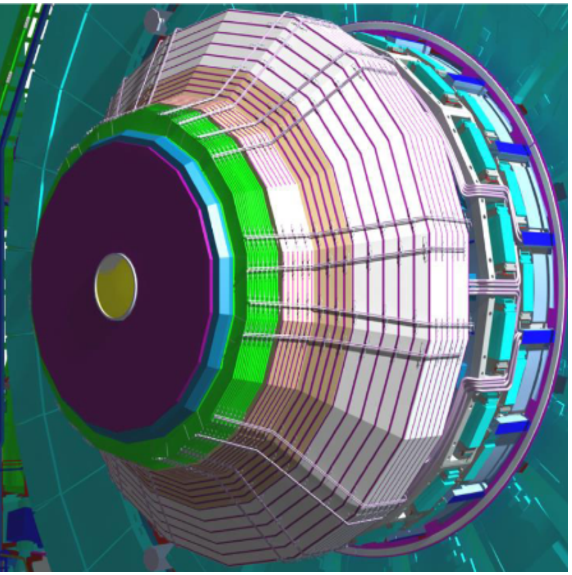
- The usual performance requirements for a calorimeter are pushed to the extremes
  - Energy Resolution
  - Signal Linearity
  - Electron/Pion sepration
  - Hermeticity
  - Rate Capability
  - Radiation resistance
  - Signal Uniformity
  - Electronic Stability + Calibration
  - Operation in Magnetic field
  - Compactness
  - ...last not least : cost! (Si affordable as price had decreased by > factor 3 since CMS construction)

Endcap calorimeter

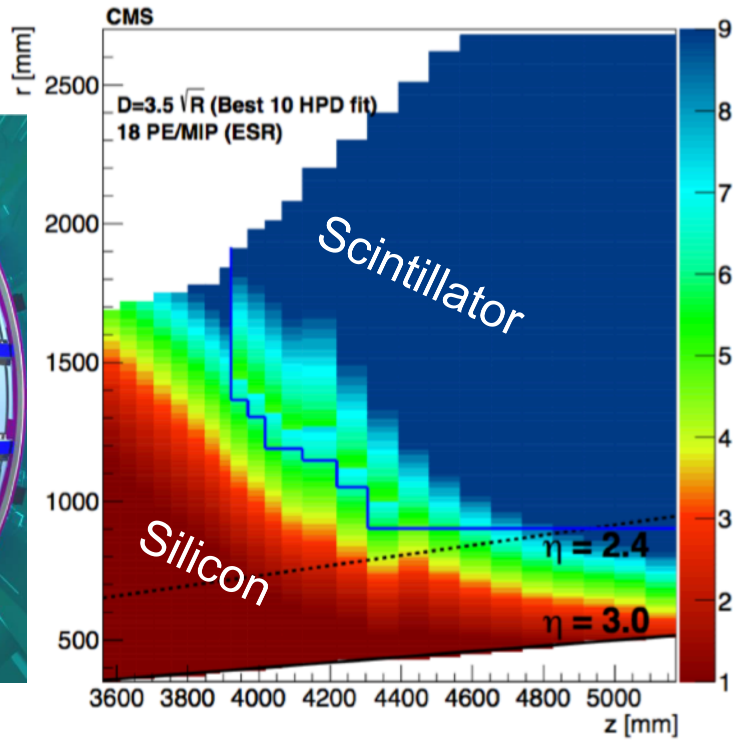


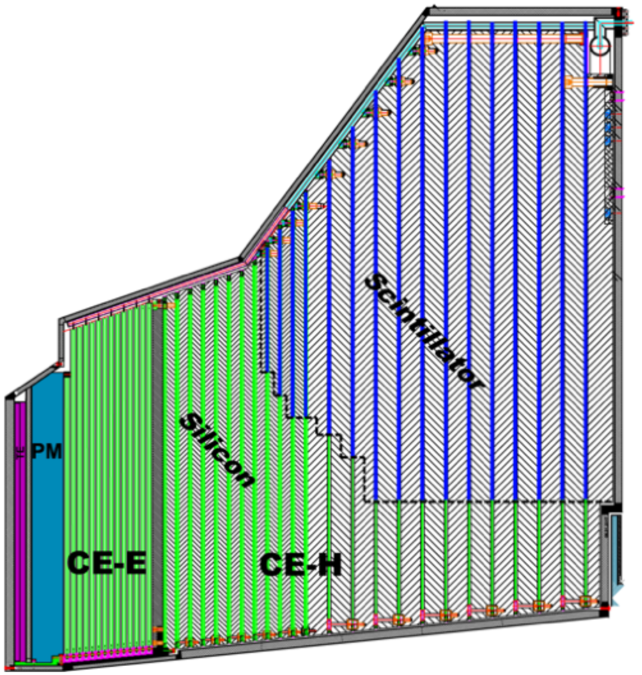
Be smart: use Silicon only where necessary

HGCAL design



Silicon in high-radiation regions





Need to be able to ‘use’ (sense) Minimum Ionising particles for calibration..Mip signal/noise ~3 even after maximum radiation exposure

The challenge

Mobile-phone technology on the scale of 4 tennis courts

That has to work efficiently for ~15 years without intervention

At -30 degrees C

In a radiation environment similar to being near the core of a nuclear reactor

Granularity driven by calibration needs

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

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

~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

Learned from Si-tracker experience

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 (new!) preferable to 6" (std for tracker)

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

300μm, 200μm and 120μm sensor thicknesses

- match sensor thickness (and granularity) to radiation field

Learned from Si-tracker experience

Simple, rugged module design & automated module assembly

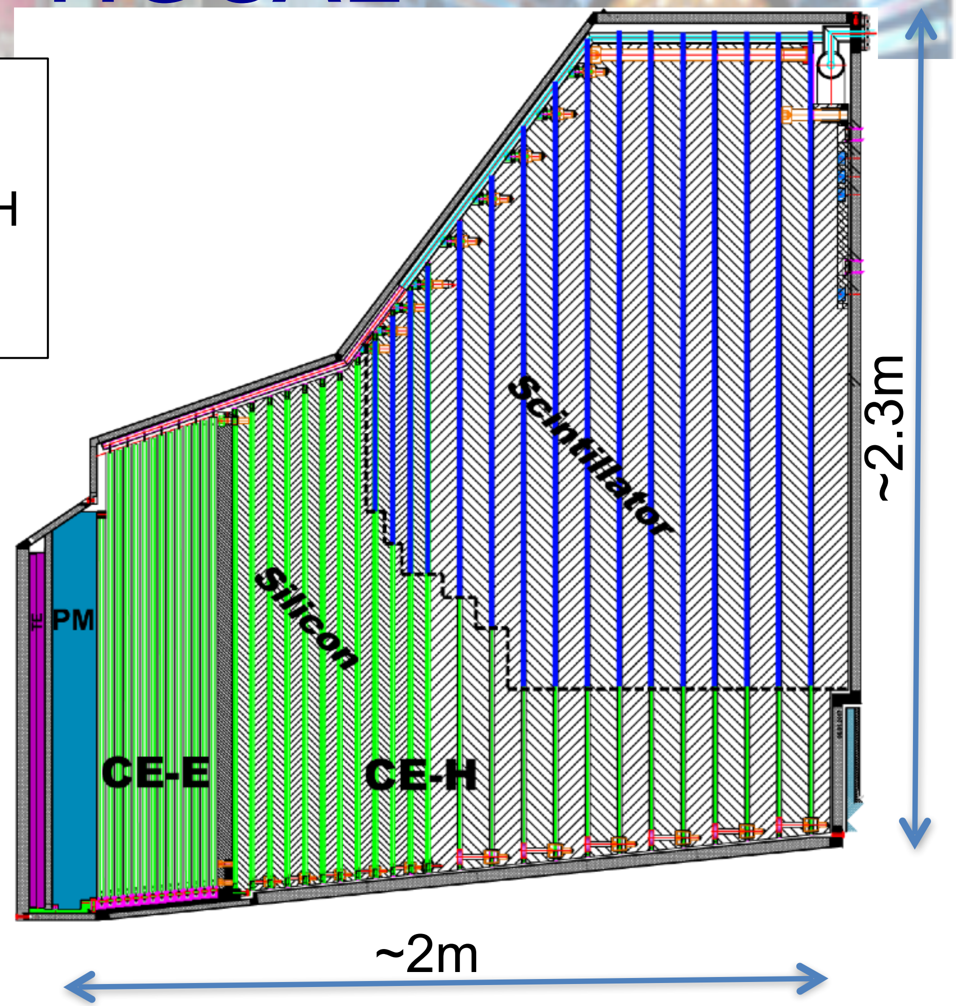
- provide high volume, high rate, module production & handling

Learned from Si-tracker experience

EM section of HGCAL

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



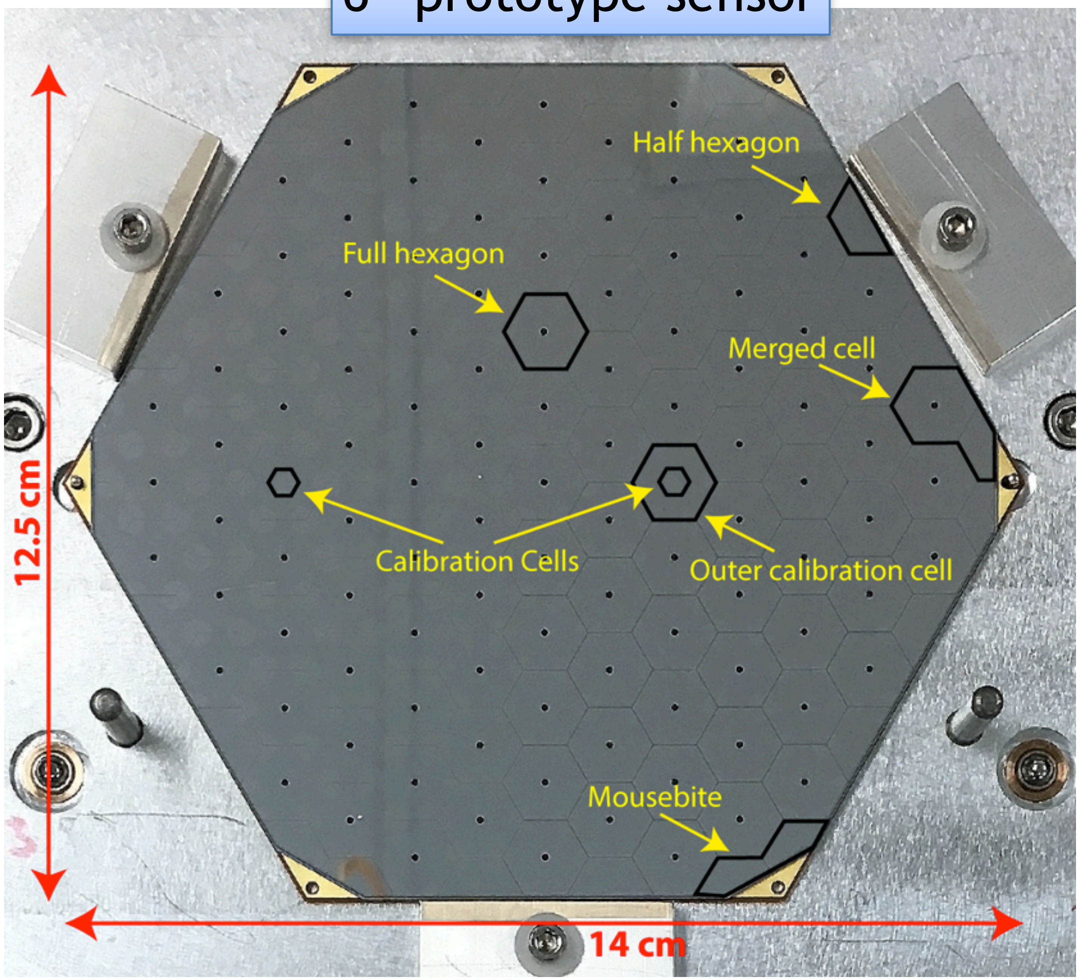
Key Parameters:

- 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
- ~140 kW per endcap

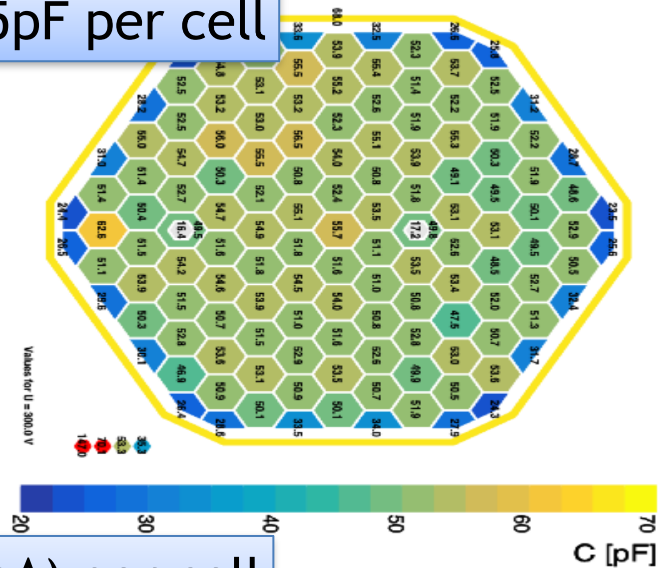
Electromagnetic calorimeter (**CE-E**): **Si**, Cu/CuW/Pb absorbers, 28 layers, 26 X_0 & ~1.7λ
Hadronic calorimeter (**CE-H**): **Si** & **scintillator**, steel absorbers, 22 layers, ~9.0λ

Hexagonal cells to fill optimally the SI wafer

6” prototype sensor

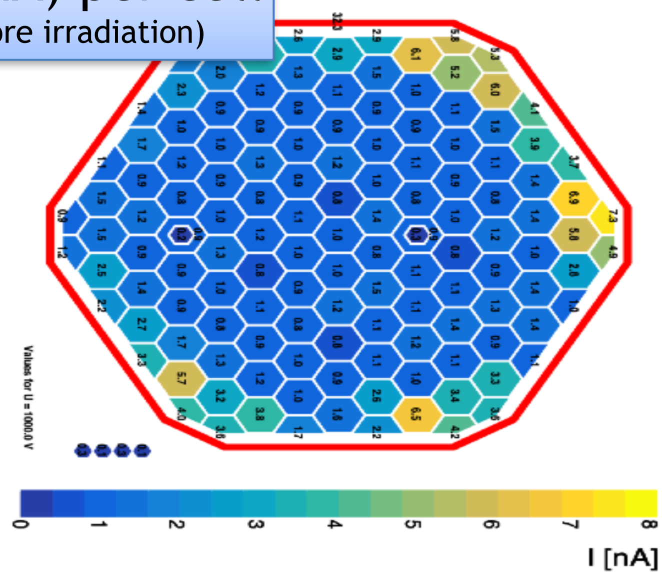


~55pF per cell



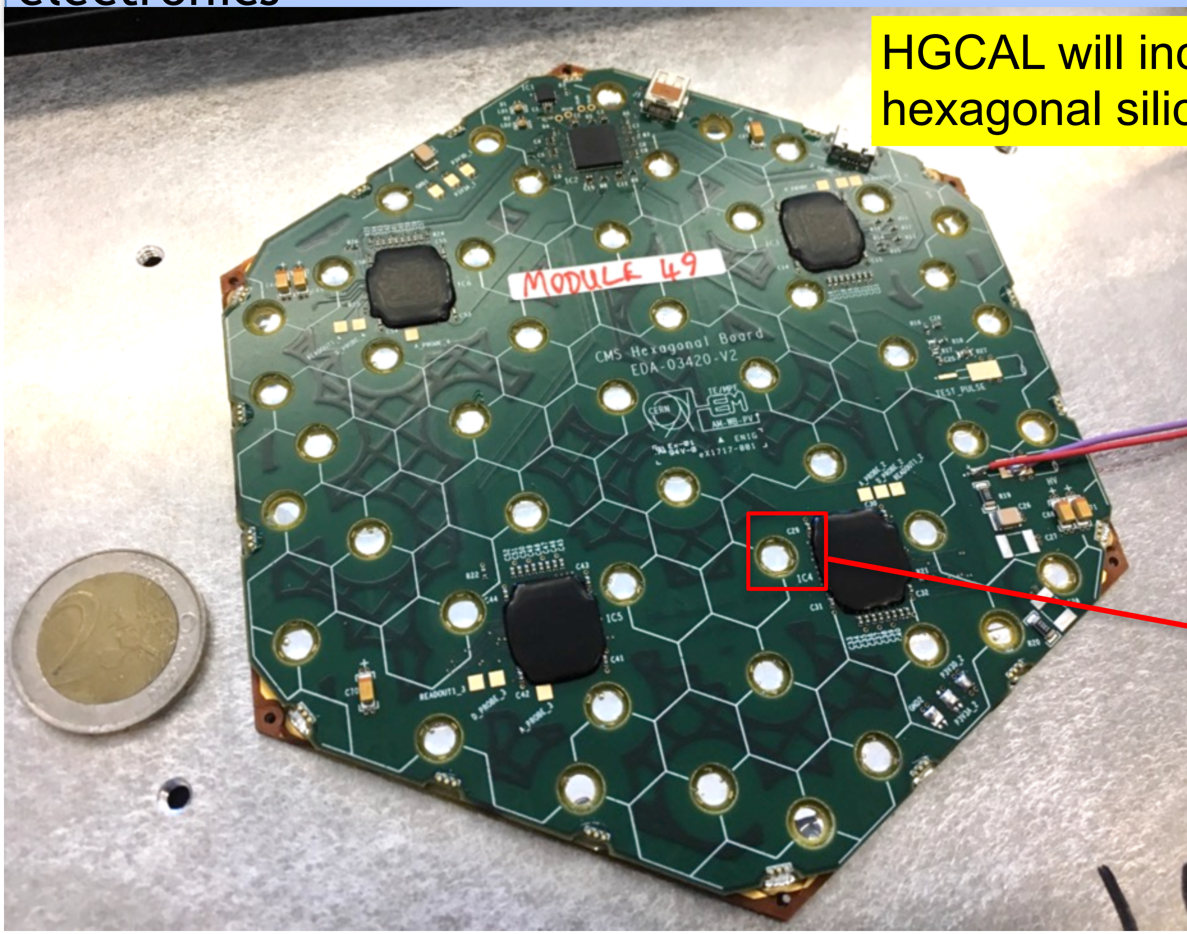
O(nA) per cell

(before irradiation)



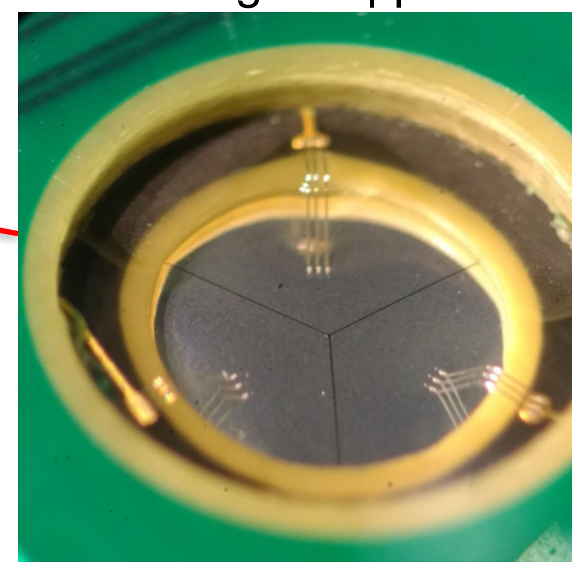
Modules

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

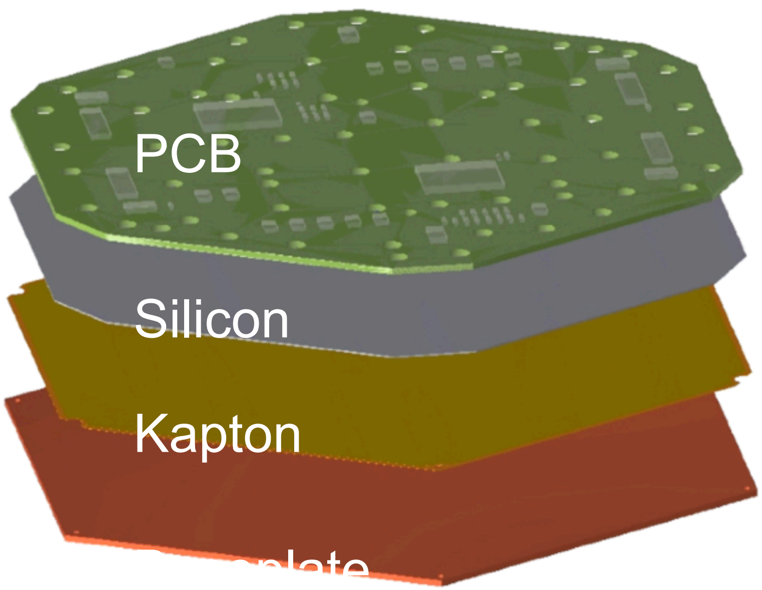


HGCAL will include 27000 modules based on hexagonal silicon sensors with 0.5-1cm^2 cells

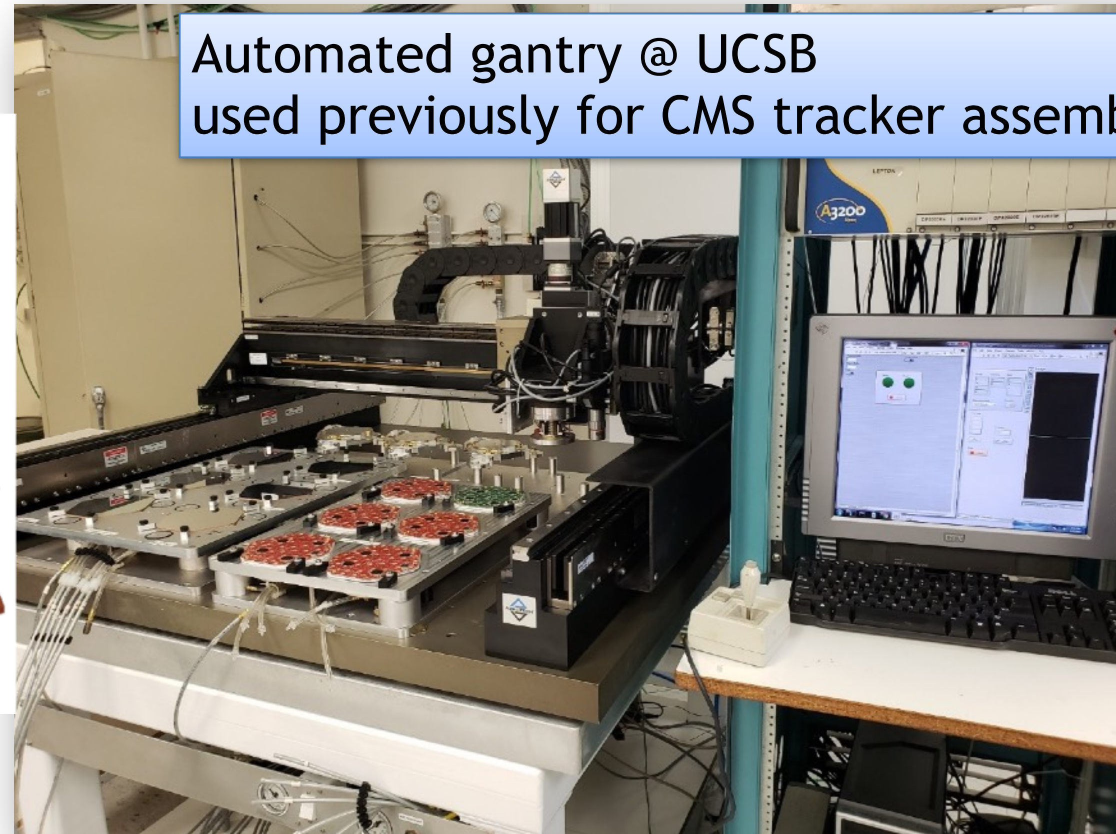
Wire bonding from PCB to silicon through stepped holes



Automated assembly

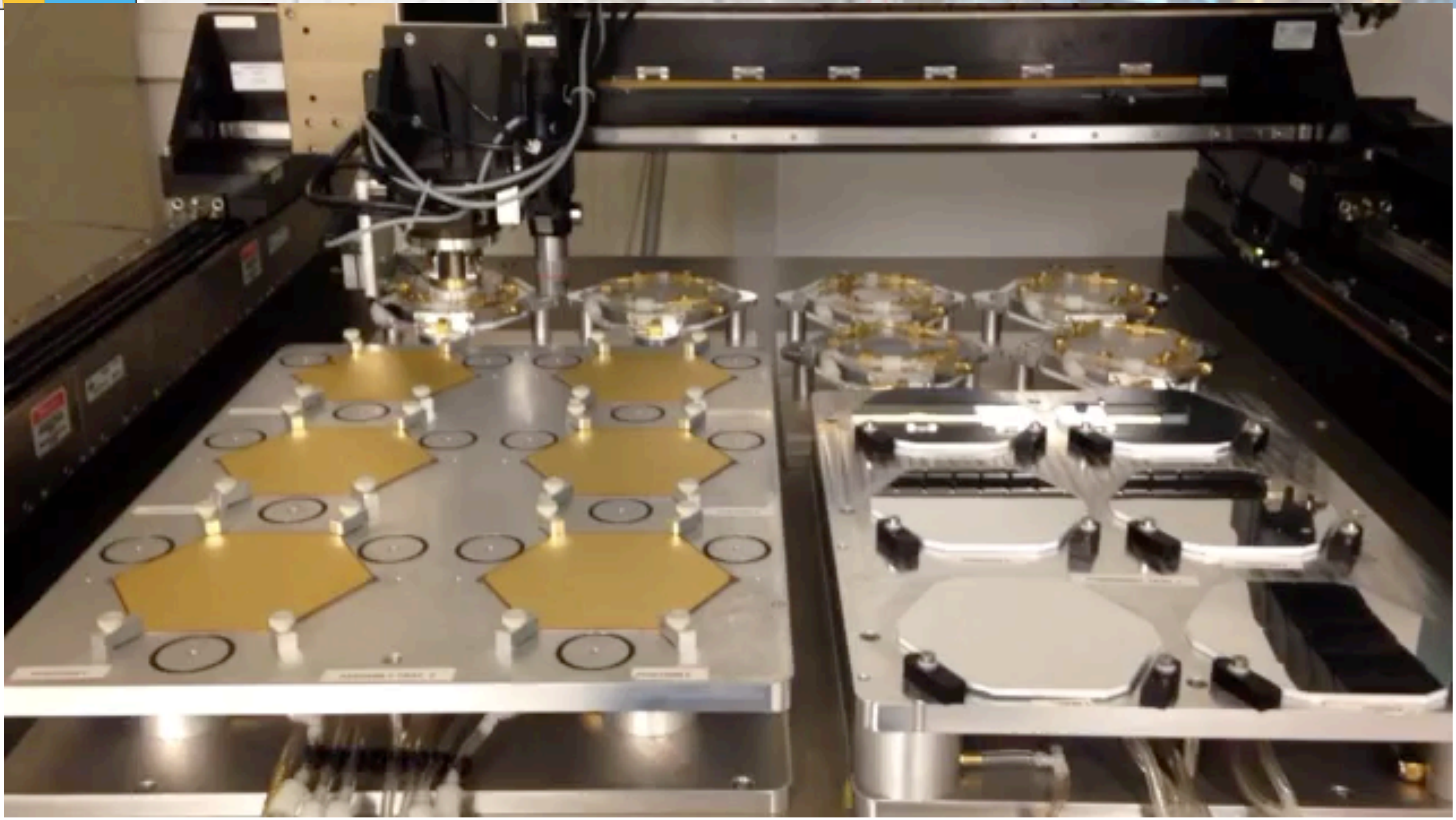


Automated gantry @ UCSB
used previously for CMS tracker assembl



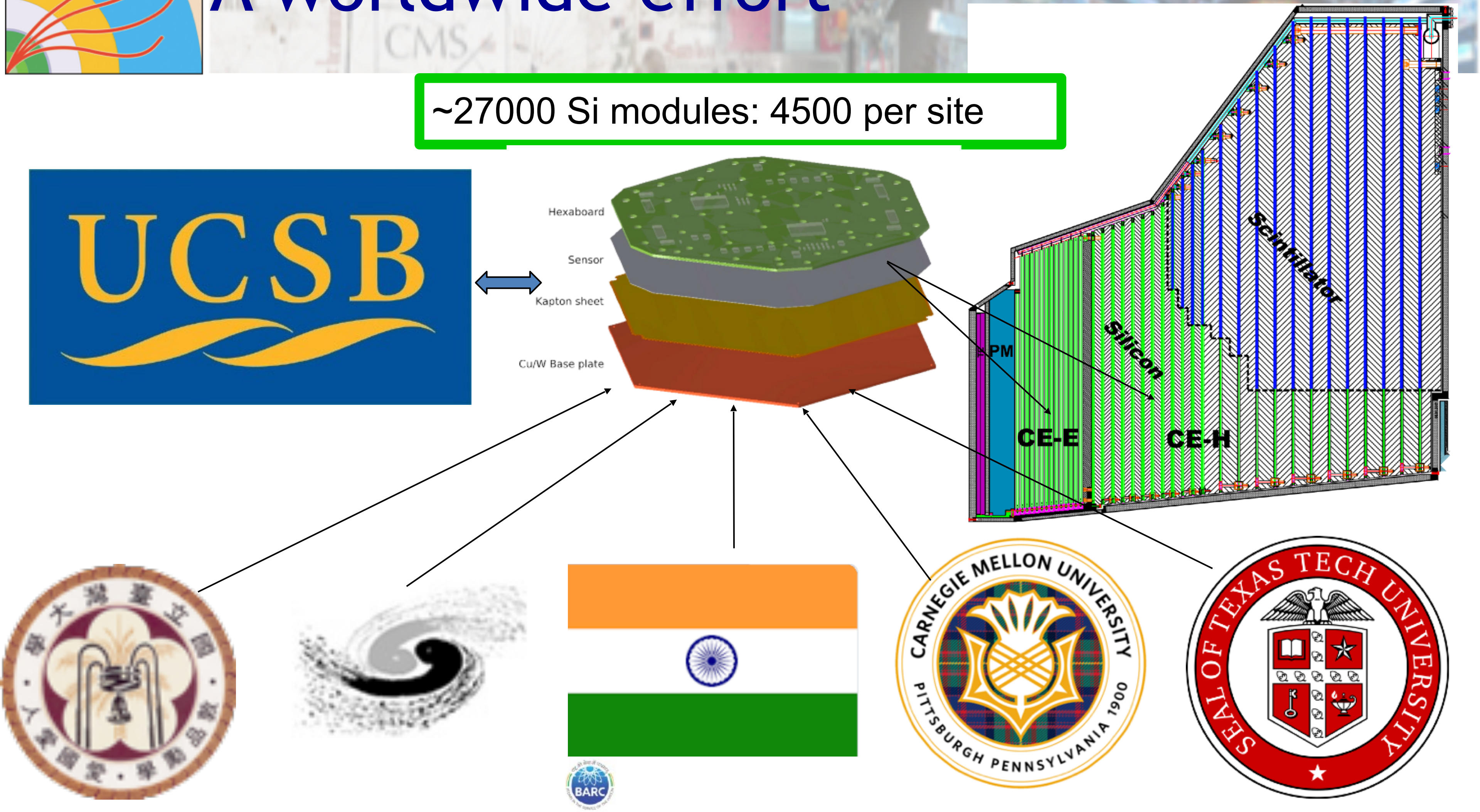
~100 modules already made and used for test purposes
Need to make ~27000 modules for HGCAL!
Other Module Assembly Centres (MACs) now being equipped

Gantry



A worldwide effort

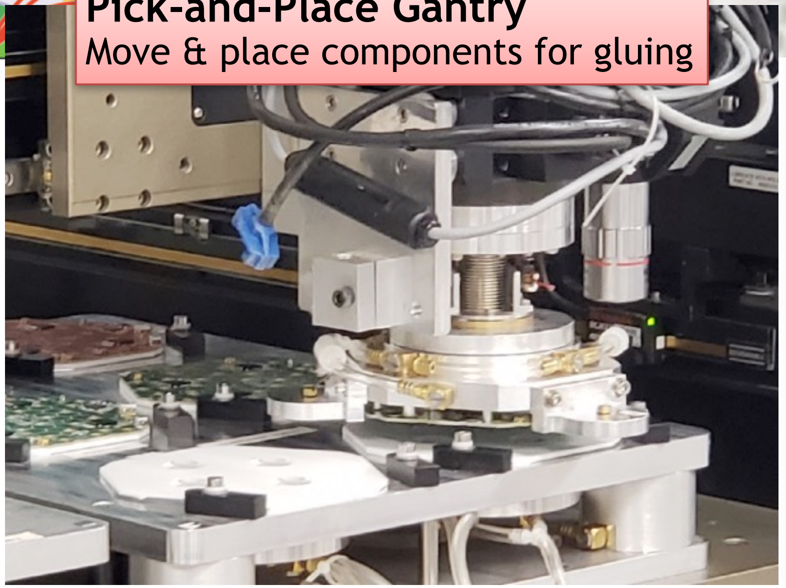
~27000 Si modules: 4500 per site



MAC Taiwan MAC Beijing MAC India MAC CMU MAC TTU

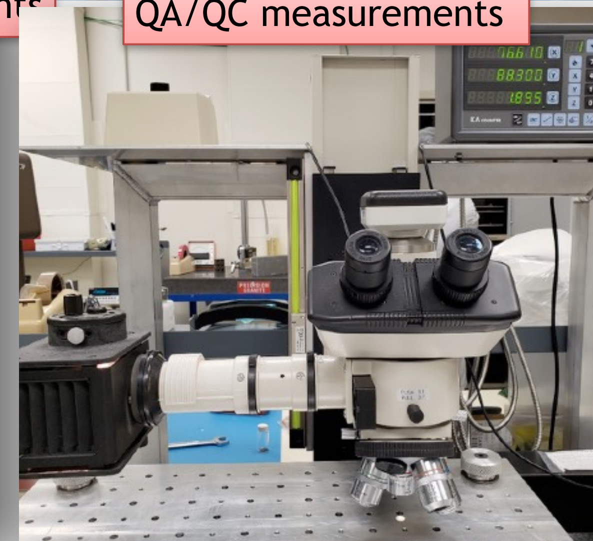
Assembly center equipment

Pick-and-Place Gantry
Move & place components for gluing

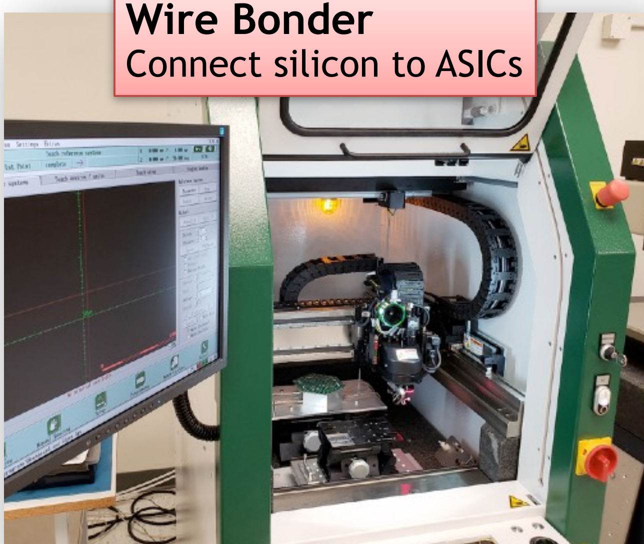


OGP microscope
Precise height measurements

Optical microscope
QA/QC measurements

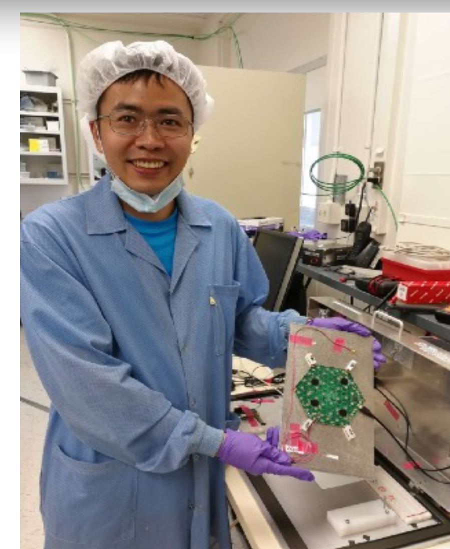


Wire Bonder
Connect silicon to ASICs

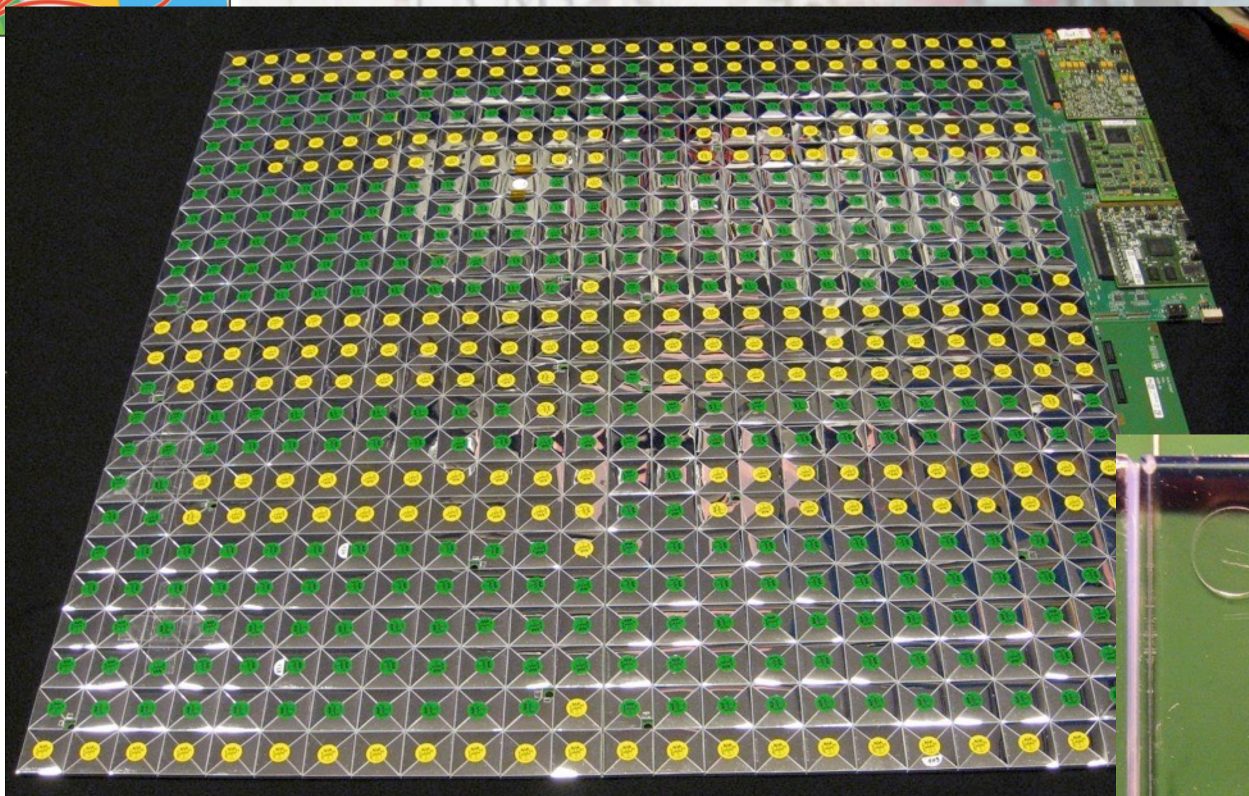


Pull Tester
Test strength of wire bonds

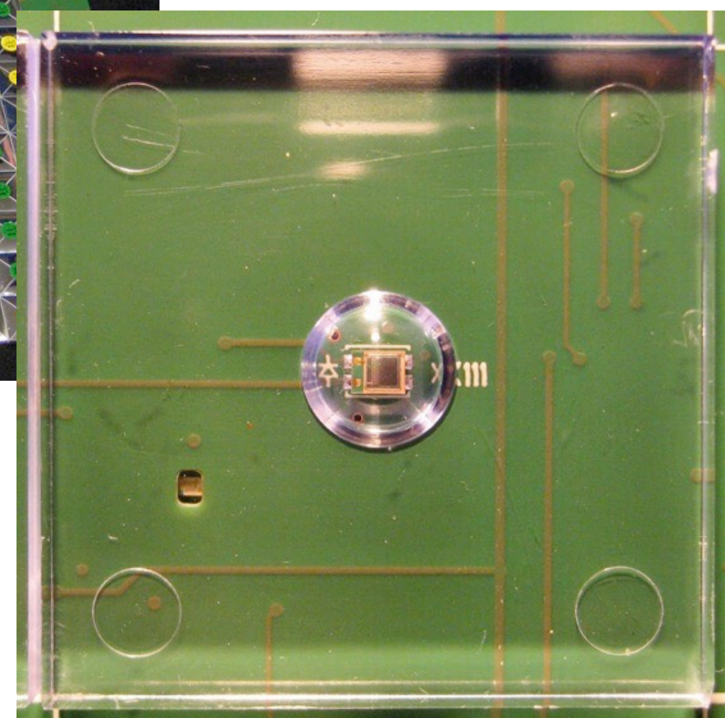
+



$500m^2$ of scintillator tiles with on-tile SiPM readout

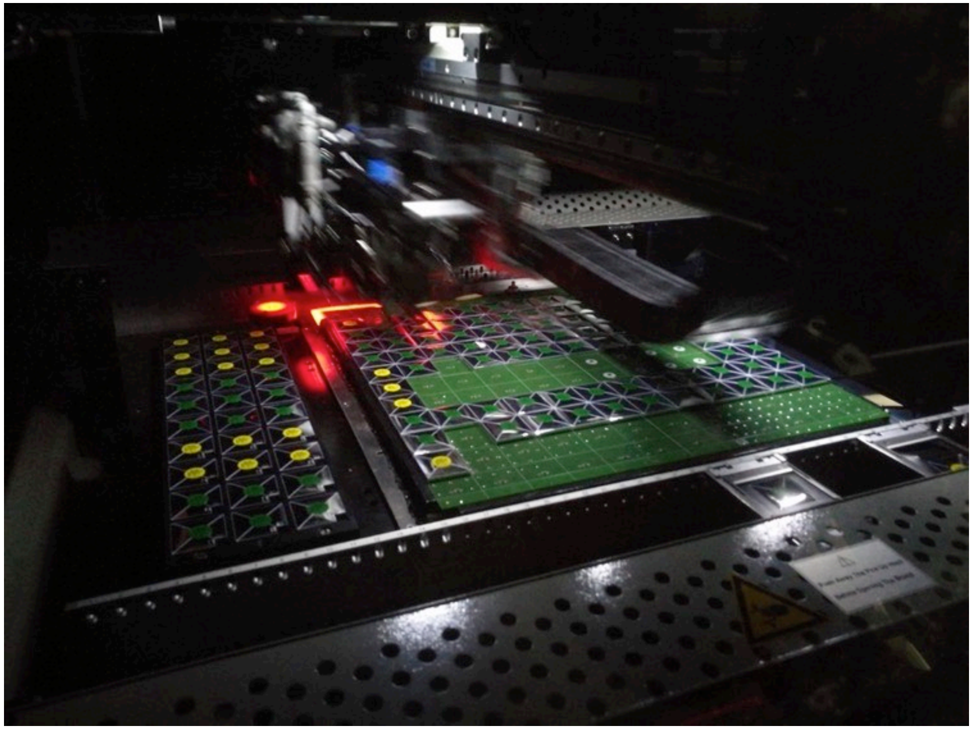


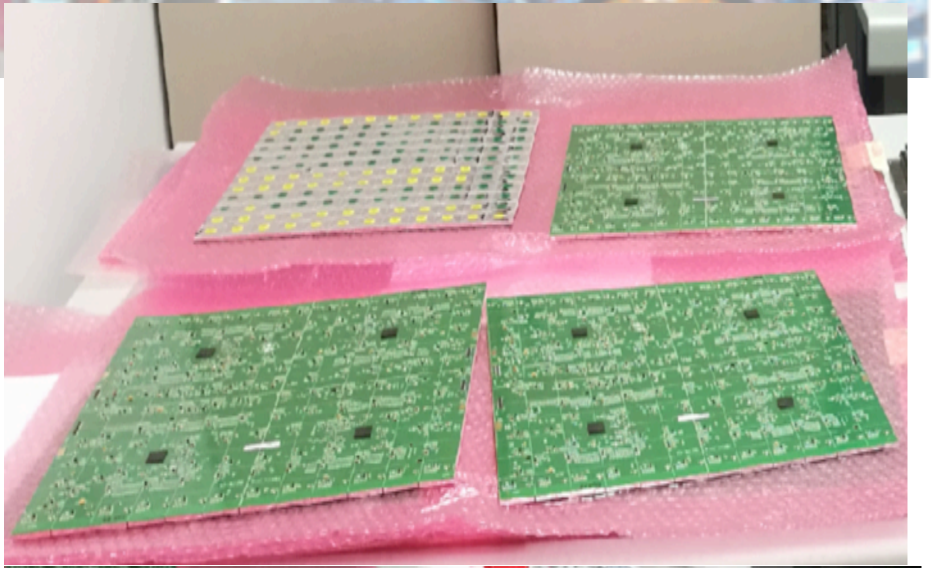
SiPMs already used successfully in e.g. CMS HCAL Phase 1 upgrade

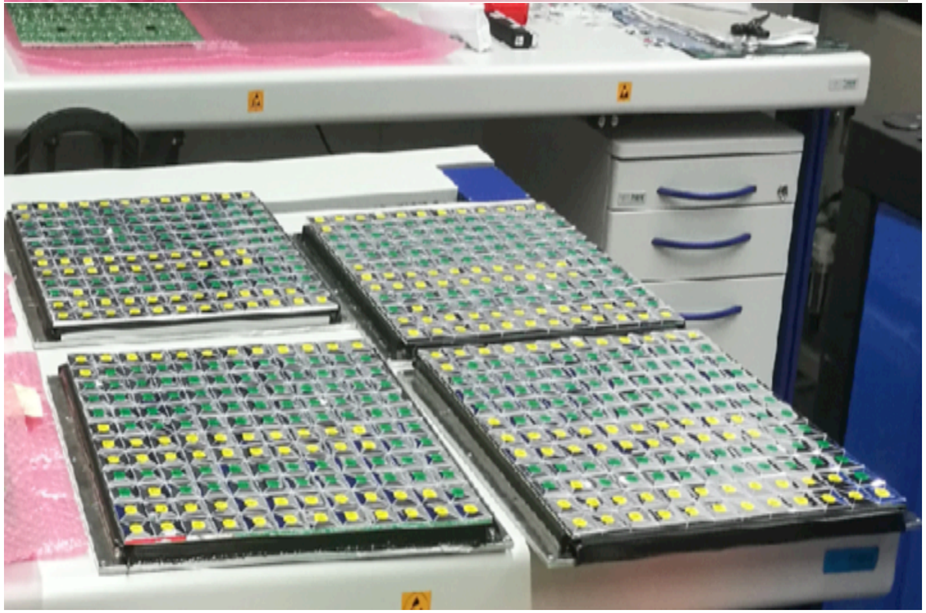


For first beam tests, modified CALICE AHCAL (ILC R&D effort) used for rear hadron calorimeter: $3x3cm^2$ scintillator tiles + direct SiPM readout

Reusing ILC CALICE tooling and experience

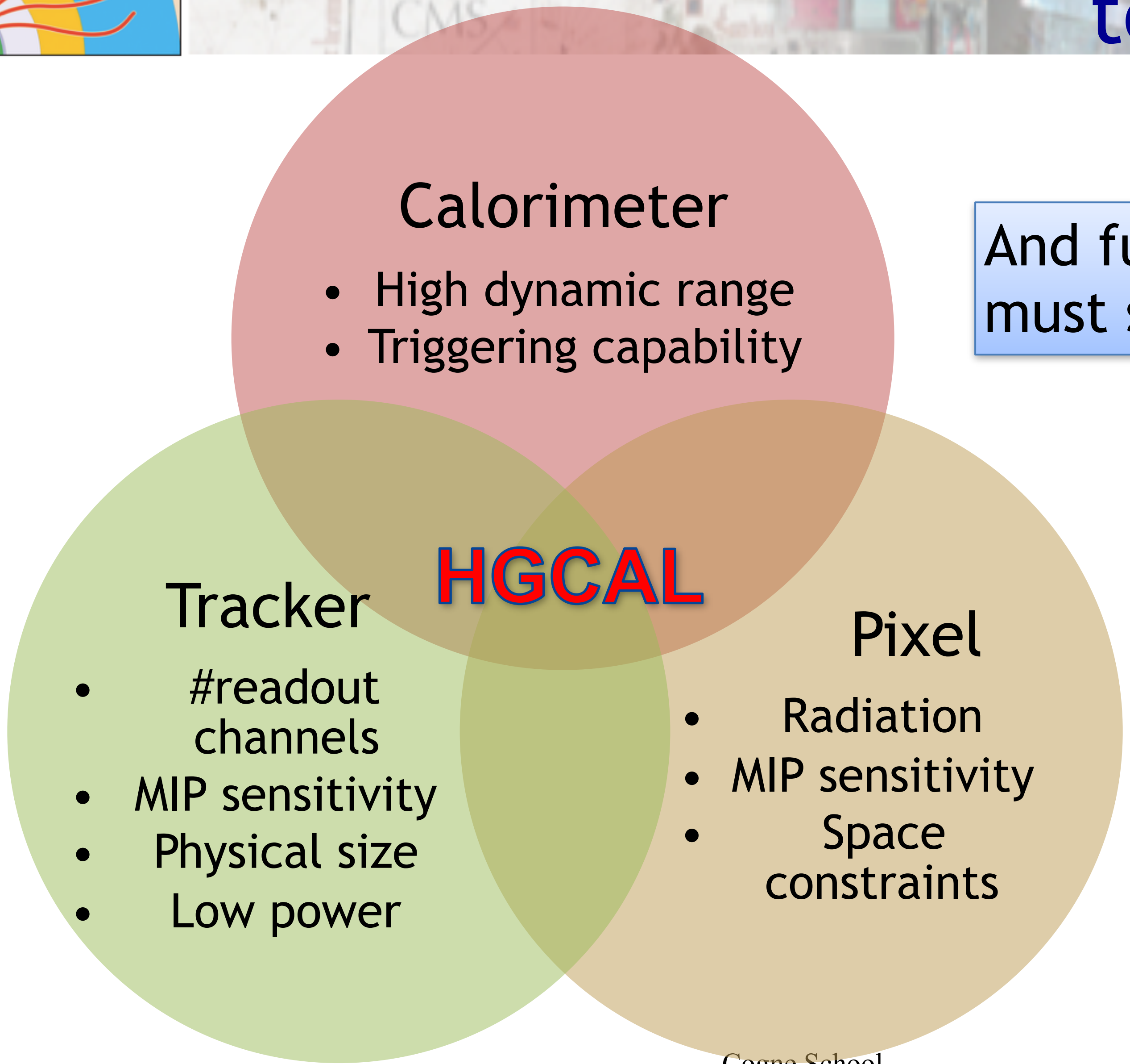






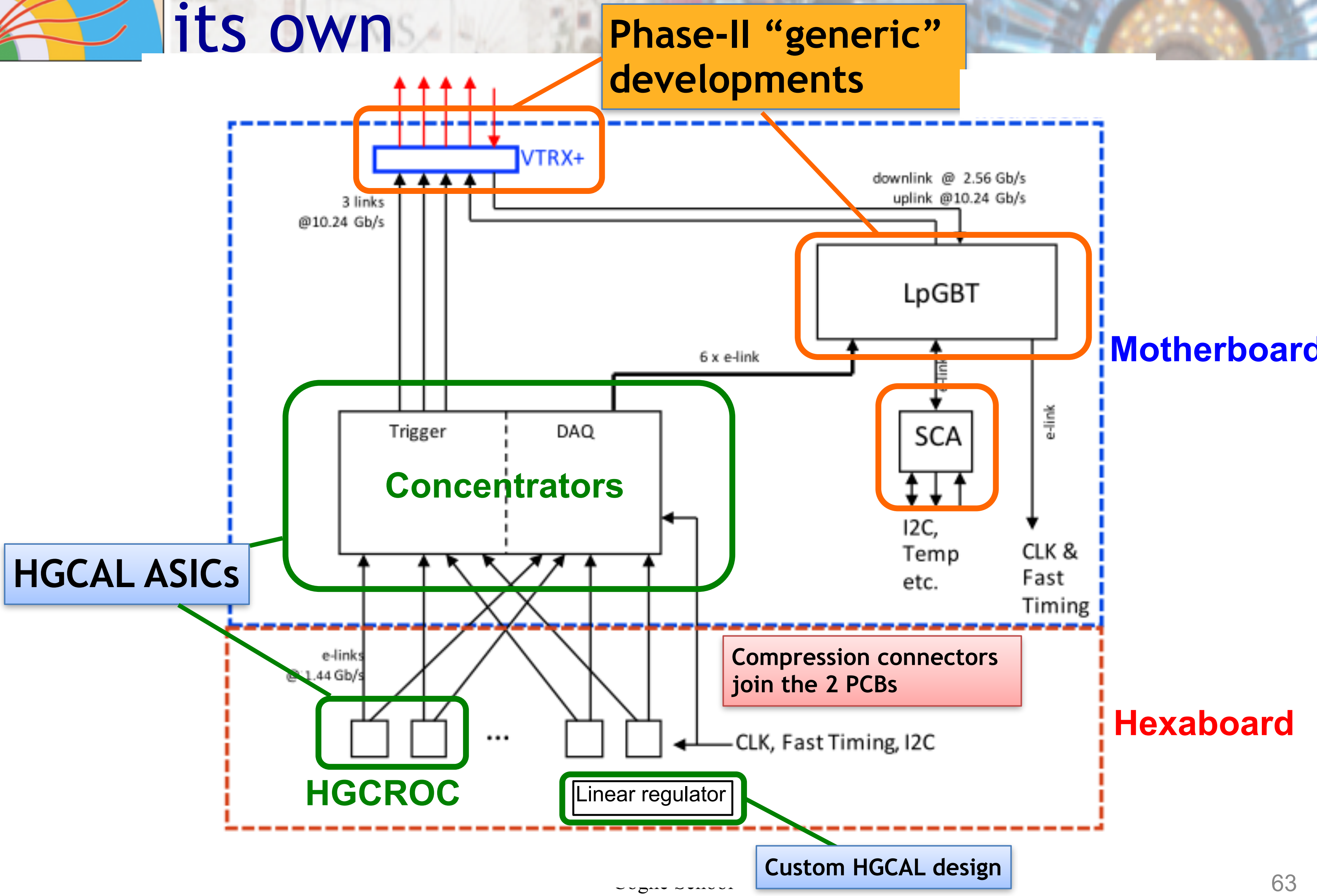
30 x 30 x 3 mm^3 tiles, automatically wrapped and placed by “gantry” machine

HGCAL: born out of several past technologies



And full-scale production must start in ~2021!

Electronic readout: a challenge on its own



The front-end ASIC is particularly challenging in the compact & mixed-technology HGCAL

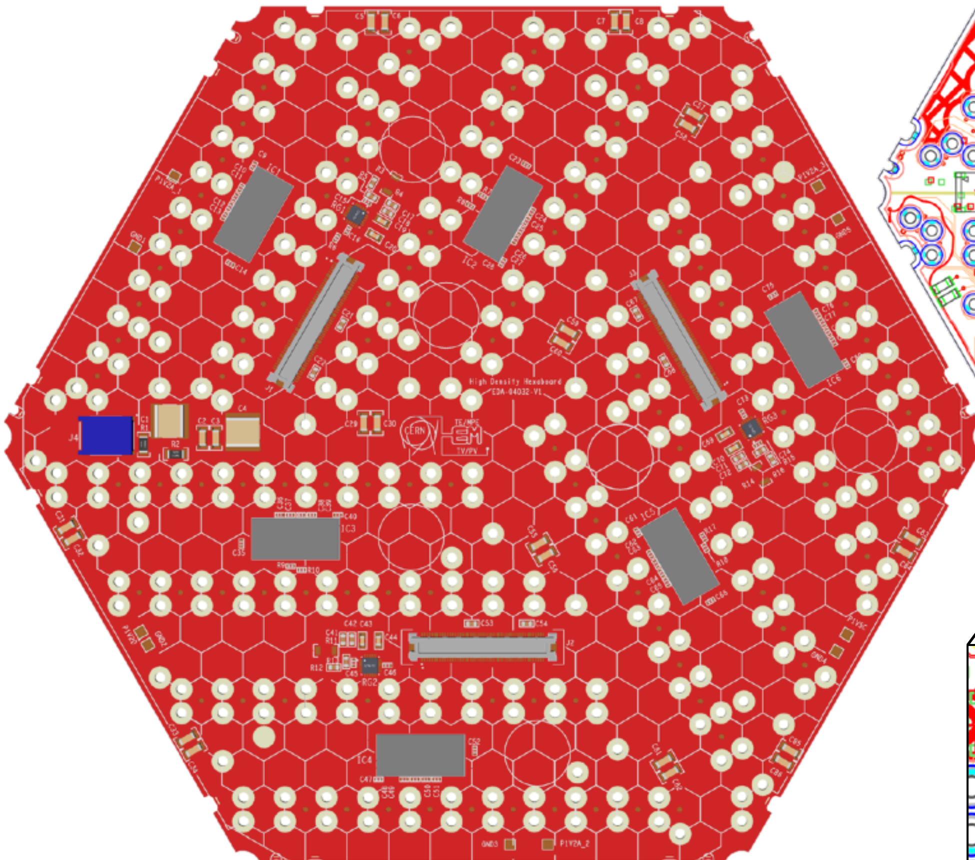
- Compatibility with –ve & +ve inputs for n-on-p and p-on-n silicon and SiPMs
- Low noise* (<2500e$^-$) despite ~65pF silicon cell capacitance
  - Measure **MIPs** (~3.5fC in 300μm silicon) **with S/N > 3** for whole lifetime of HL-LHC
- High dynamic range (~0.2fC → 10pC, i.e. 16-bits)

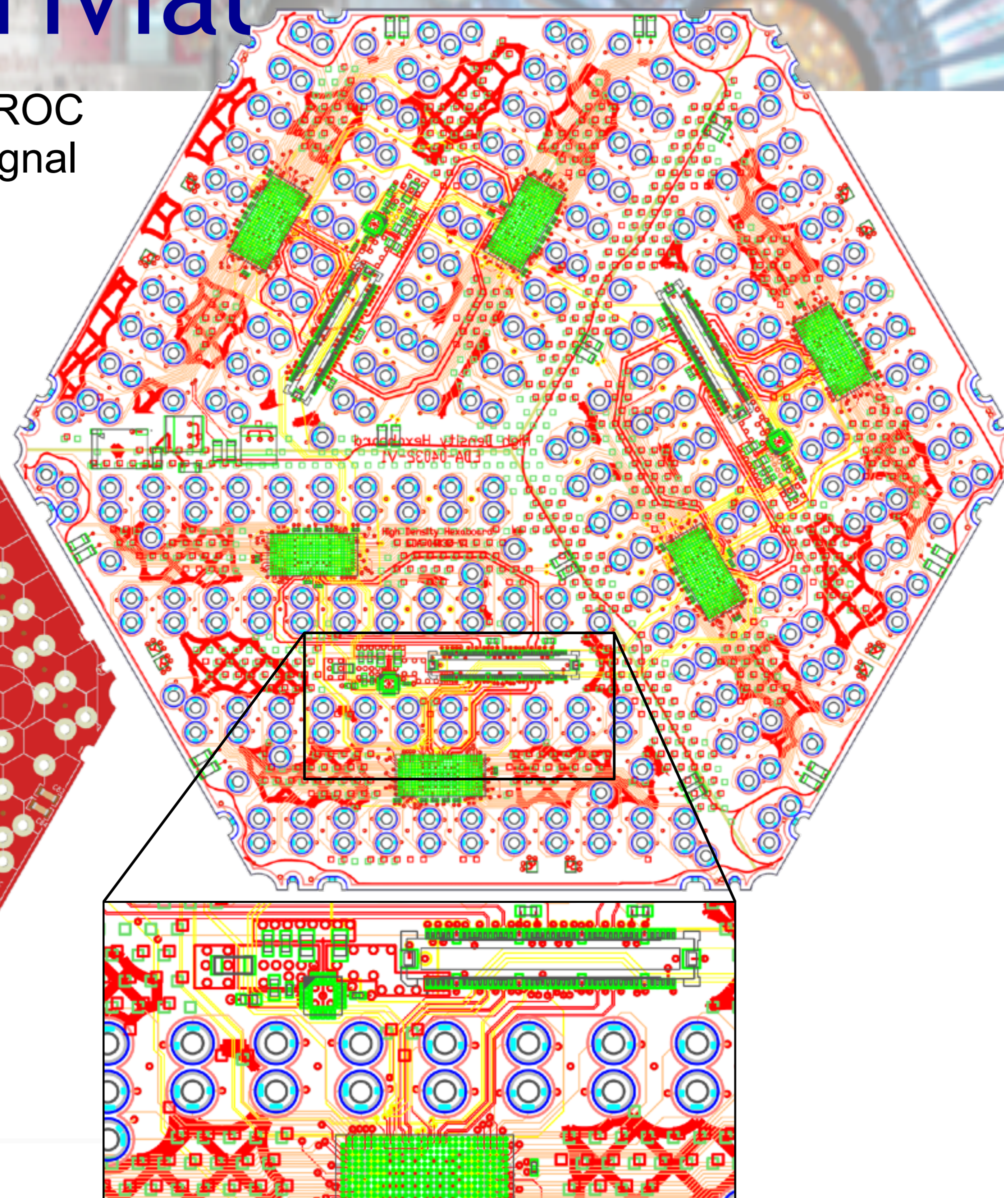
→ Use 130nm CMOS with 1.5V supply
  - Integral linearity better than 1% over full range
- Provide timing information to < 100ps for signals above tens of fC
  - Need clock distribution jitter 10-15ps (same specs as for other CMS detector upgrades)
- Fast shaping time (<20ns) to minimize out-of-time pileup
- On-detector digitization, linearization and zero suppression
- Creation of trigger sums
- Buffering of data to accommodate 12.5μs L1 latency
- <20mW per channel (~limited by cooling power) include $I_{leakage}$ compensation
- High radiation resistance (~2MGy and 10^{16} n_{eq}/cm^2 & SEU robustness)

*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

Nothing is trivial

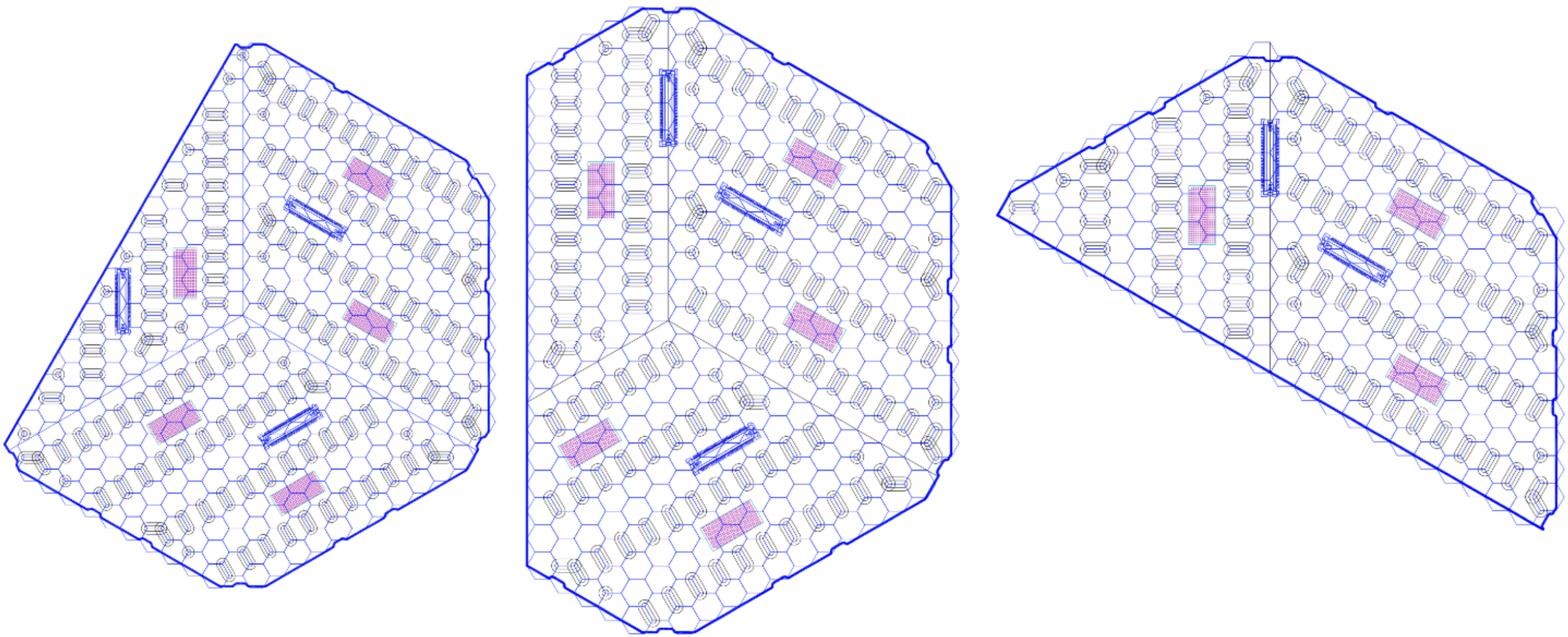
8” “High Density” Hexaboard with 6 x HGCROC ASICs to read 432 silicon cells and route signal to 3 FX11 low-profile connectors





Taking care of the edges

In parallel, started work on the design for partial sensors, needed to improve coverage on inner and outer radius

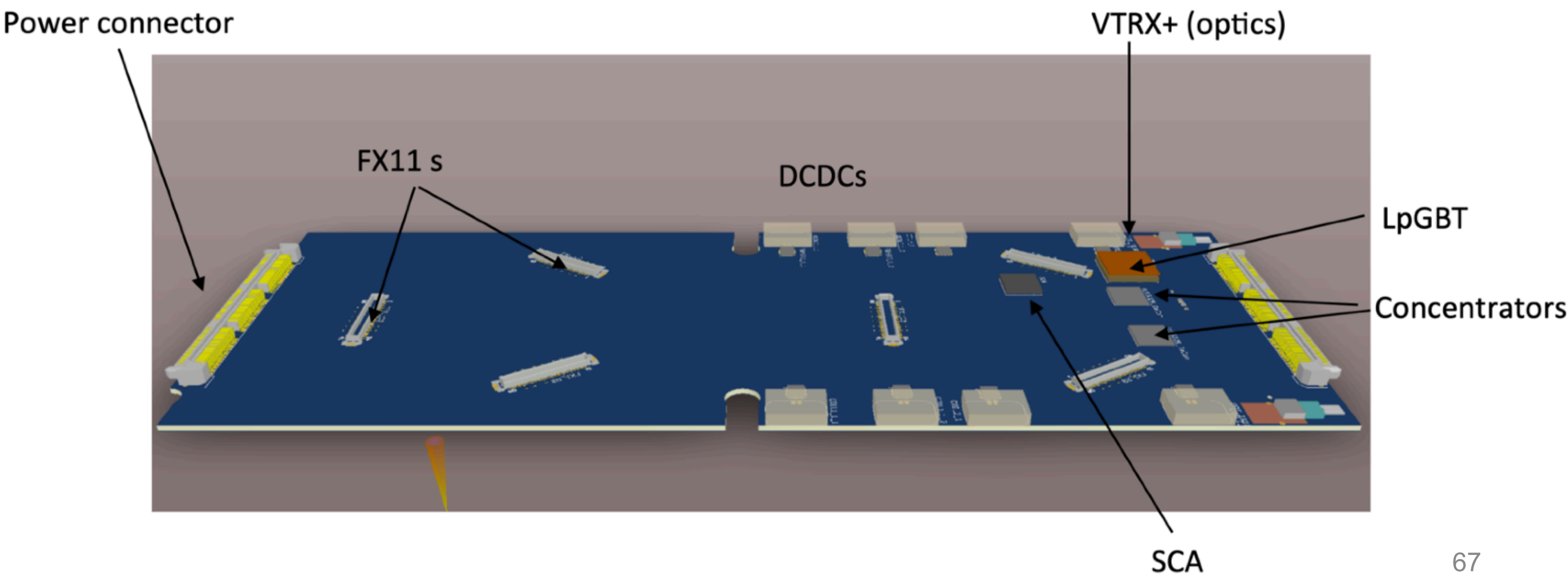


Five (83% of full area) Choptwo (79% of full area) Half(50% of full area)

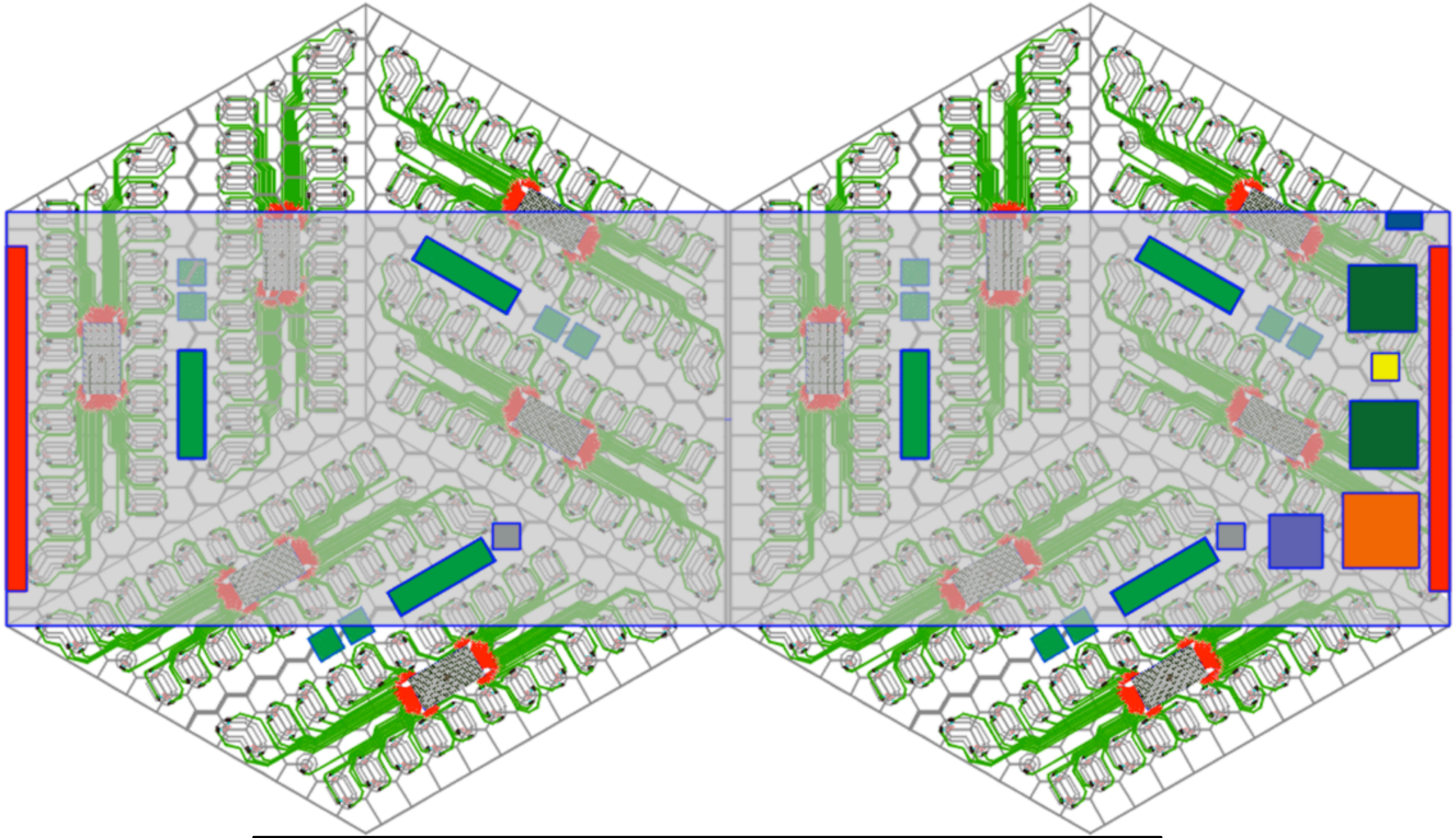
Motherboard connects to 2-5 hexaboards & contains electrical/optical interfaces

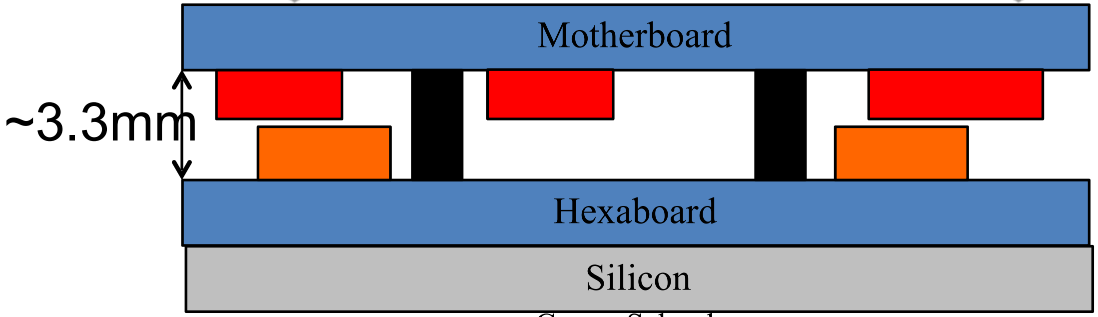
Motherboard functionality:

- Aggregates, formats & serializes the data (read at the L1 trigger frequency of up to 750kHz) in the **data concentrator ASIC**
- Selects trigger sums of interest, aggregates, formats and stores these data in a 12-bunch-crossing FIFO in the **trigger concentrator ASIC**
- Interfaces concentrators to **lpGBT → VTRX+** for data/trigger transmission
- Receives and distributes fast control signals
- Take input from on-detector environmental sensors and transmits outside
- Distributes power to detector modules – LV & bias



Motherboard connects to 2-5 hexaboards & contains electrical/optical interfaces



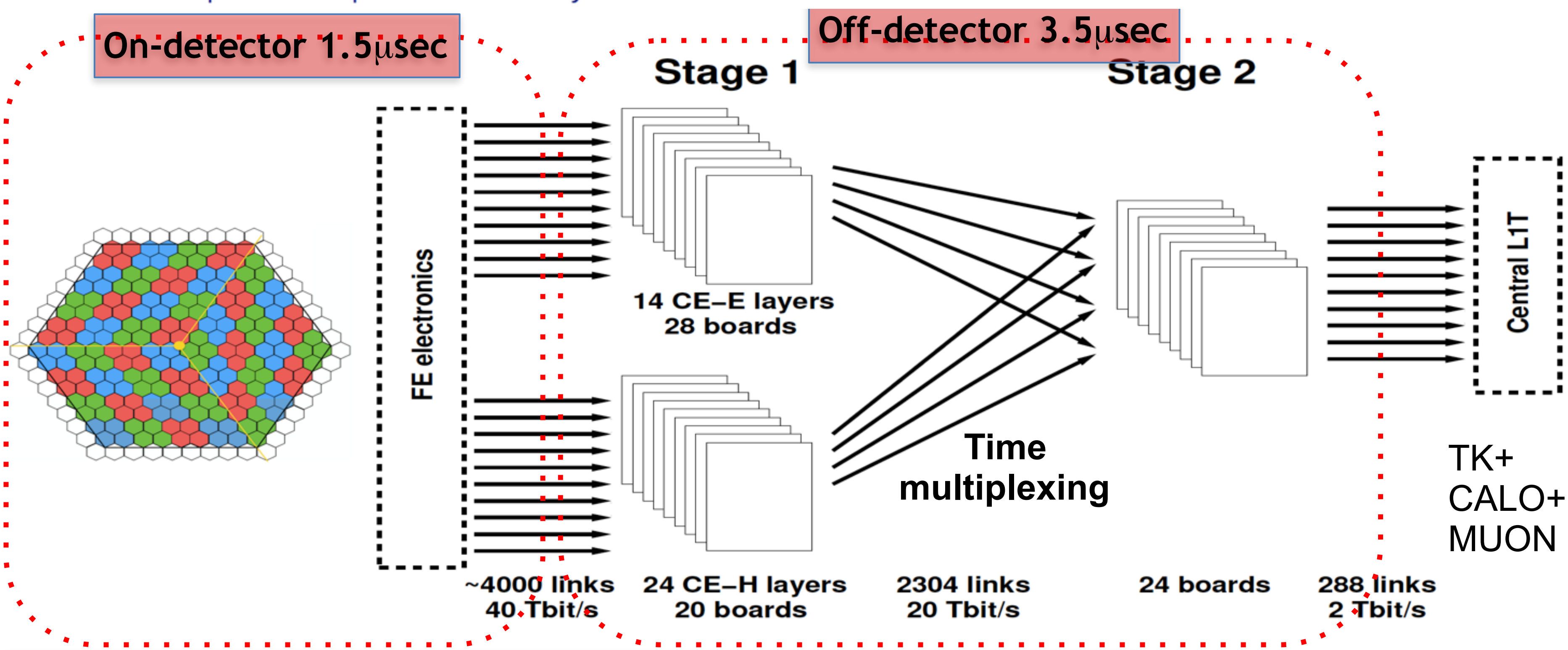


~1 million trigger cells (TC) in HGCAL,

Stage-1: Dynamical clustering techniques based on the Nearest Neighbour TCs to generate 2D-clusters in each HGCal trigger layer.

Stage-2: Generation of 3D-clusters relying on the longitudinal development of the shower, exploiting the projected position of each 2D-cluster to identify its direction.

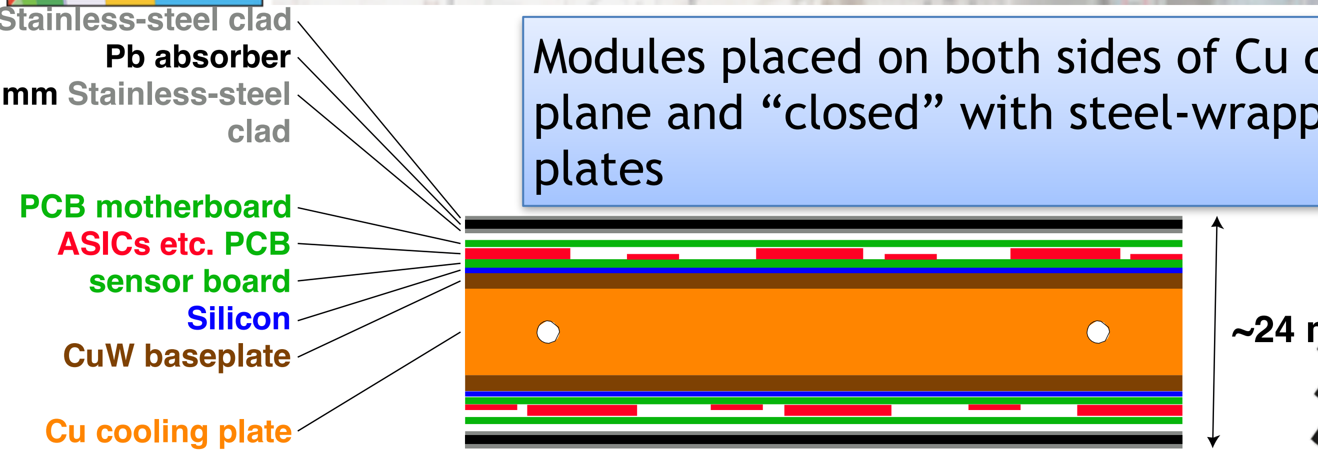
The Stage-1→Stage-2 data transmission is x24 time-multiplexed to allow all data from one endcap to be processed by one FPGA

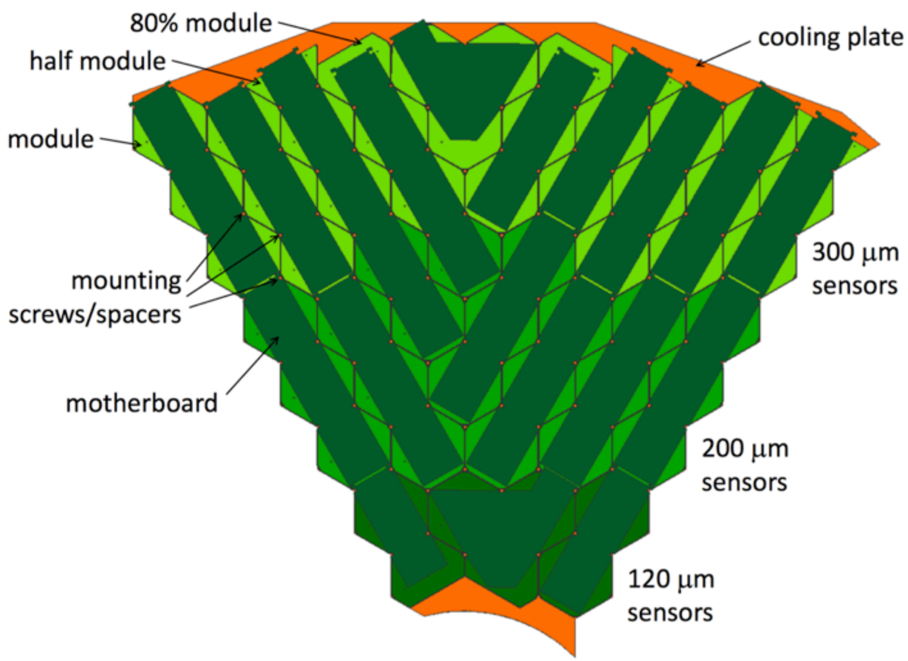


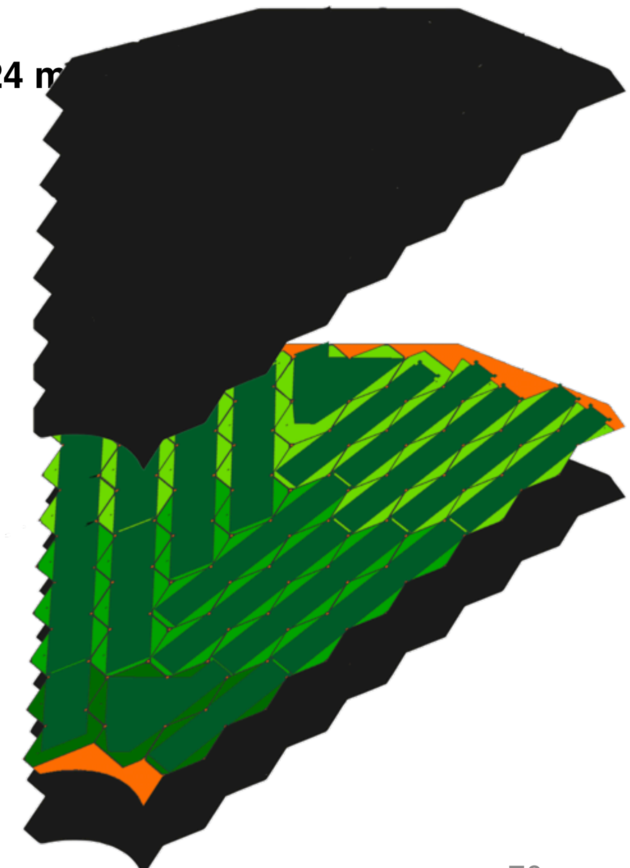
Presently exploring **Serenity ATCA board** for Trigger & DAQ back-end

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

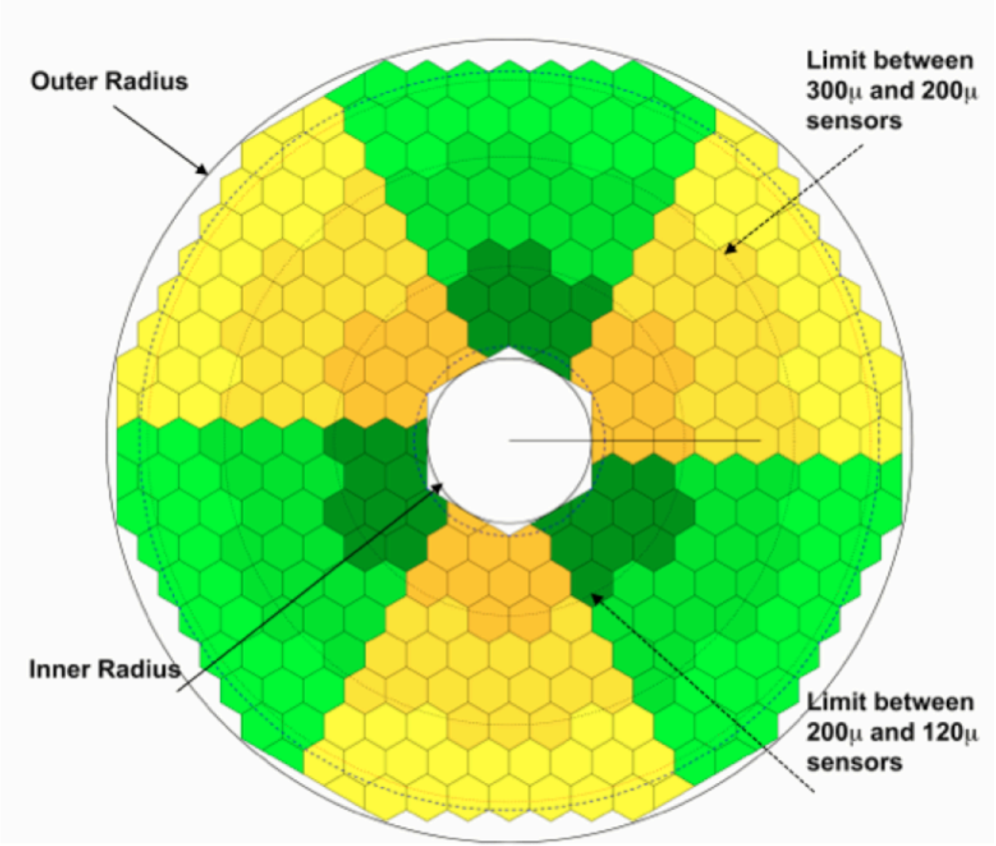
Modules placed on both sides of Cu cooling plane and “closed” with steel-wrapped Pb plates



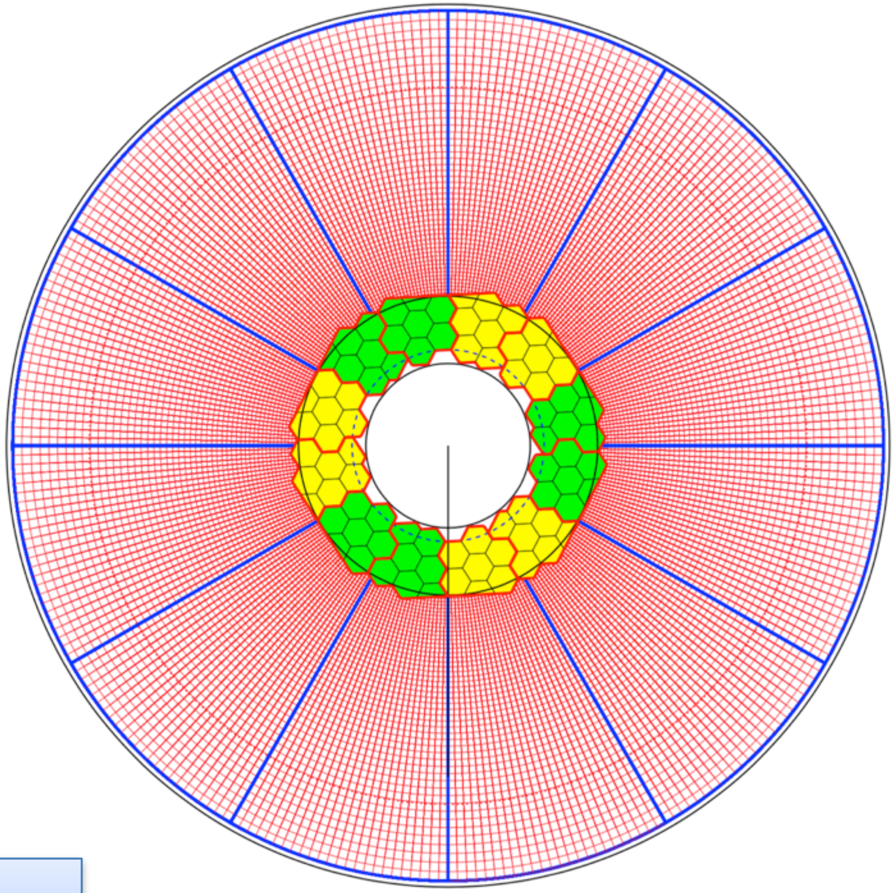




Wedge-shaped "Cassettes" containing arrays of silicon modules or silicon+scintillator/SiPM



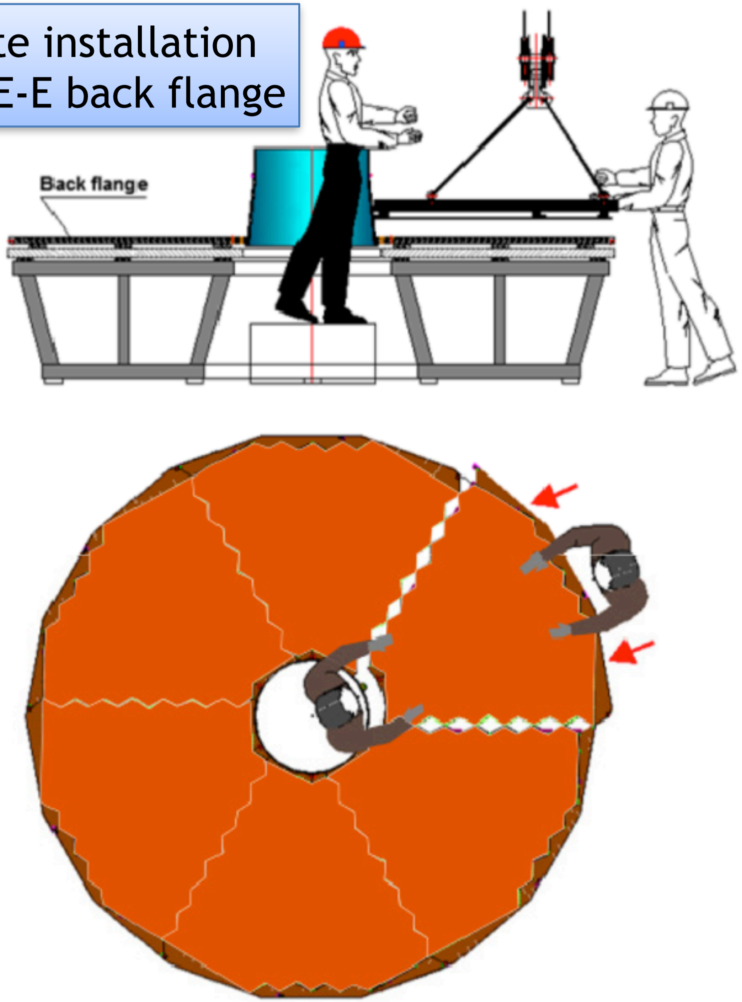
Silicon-only layer (in CE-E) showing "cassettes" and different sensor thicknesse

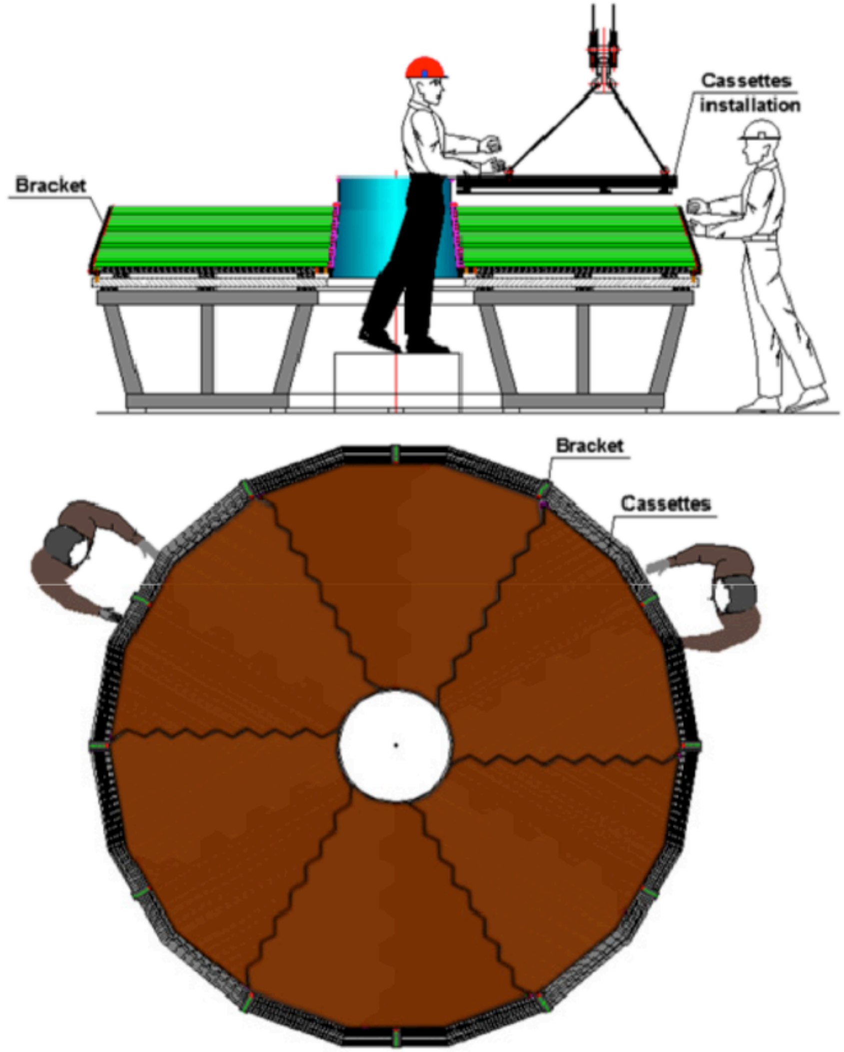


Mixed layer (in CE-H) with silicon at high η and scintillator+SiPM at low η

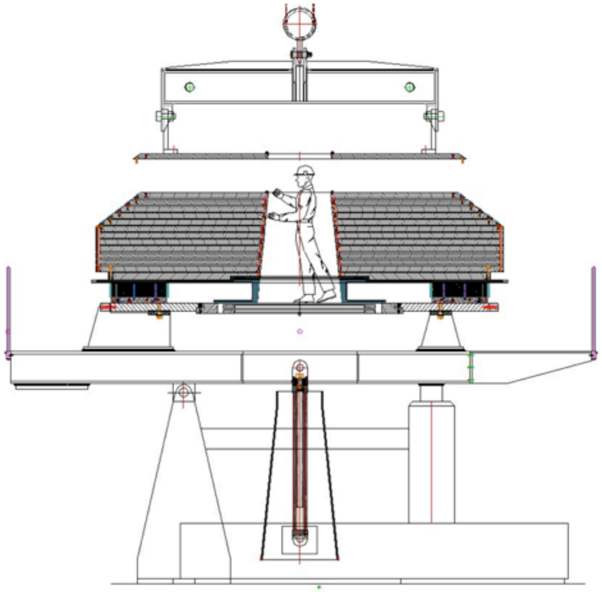
Assembling CE-E: self-supporting cassettes are assembled horizontally

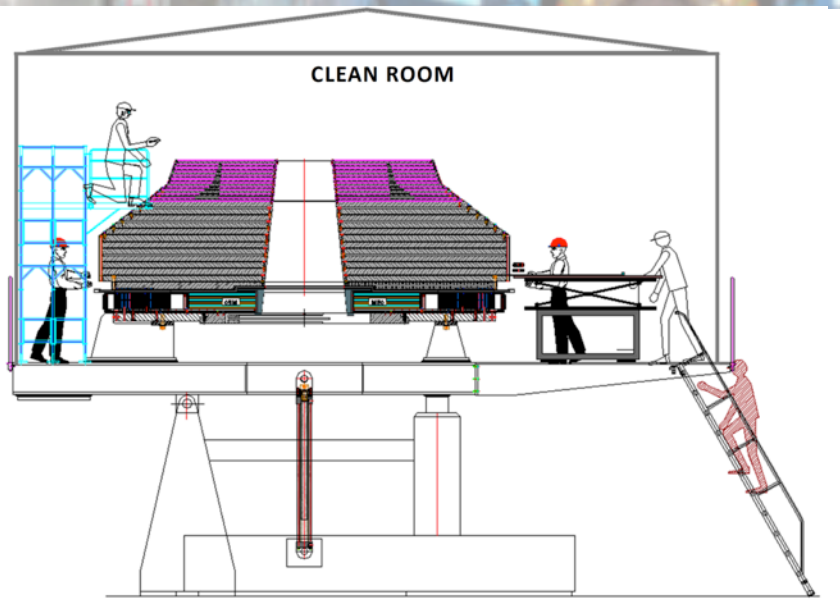
Cassette installation onto CE-E back flange

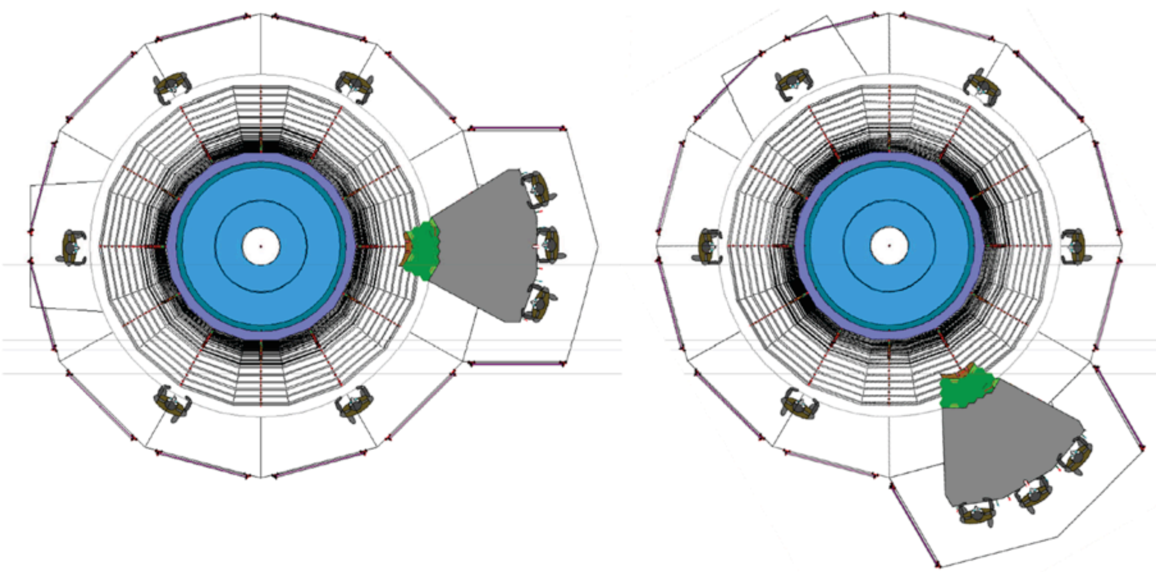




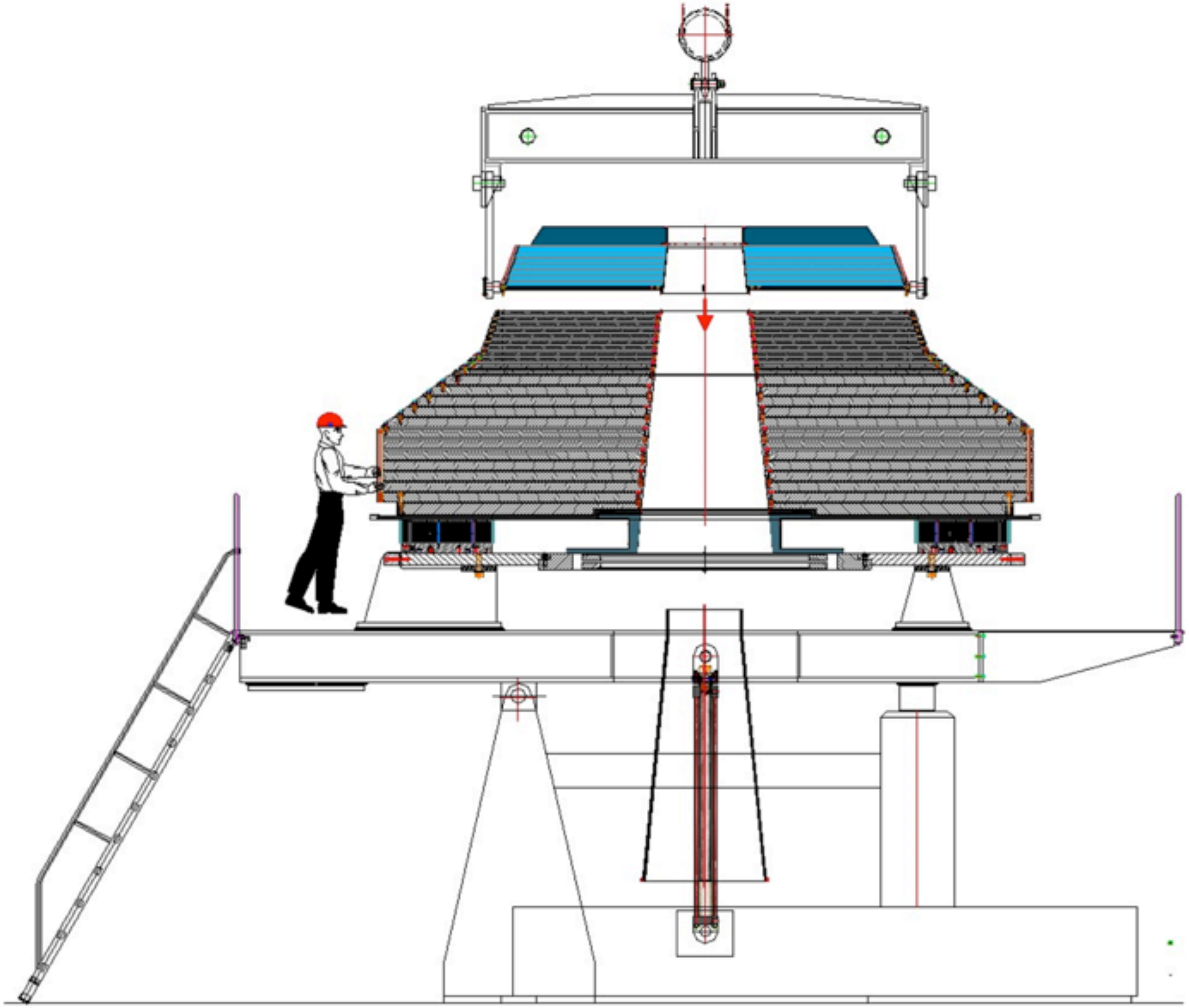
CE-H (Hadronic calo section) is assembled in two steps: absorber material, followed by insertion of cassettes



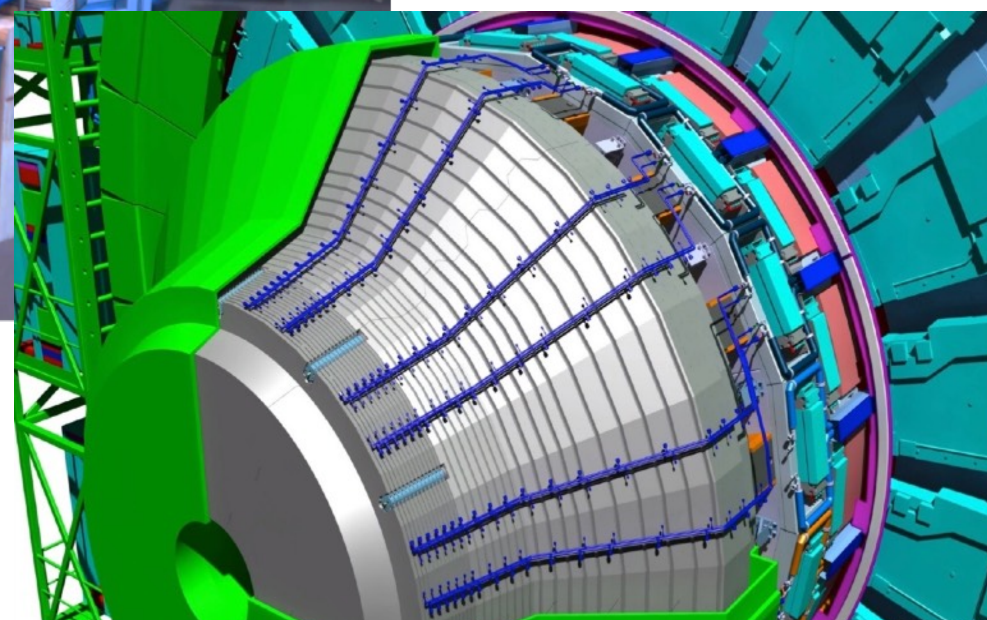




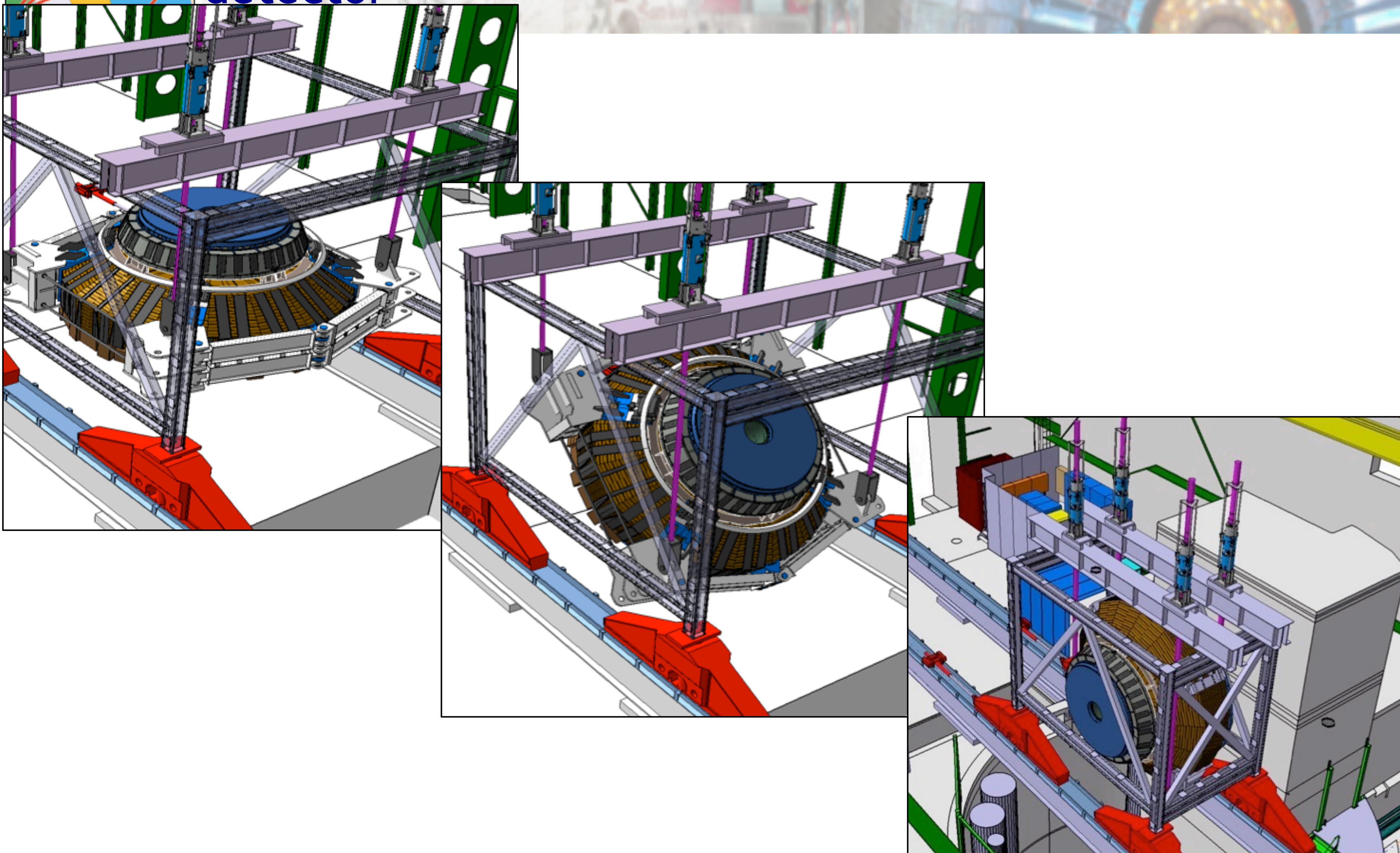
Final assembly step: attach CE-E to CE-H



The services (electrical, optical, cooling) feeding the cassettes is also a major challenge



Special tools needed to handle/transport/install detector

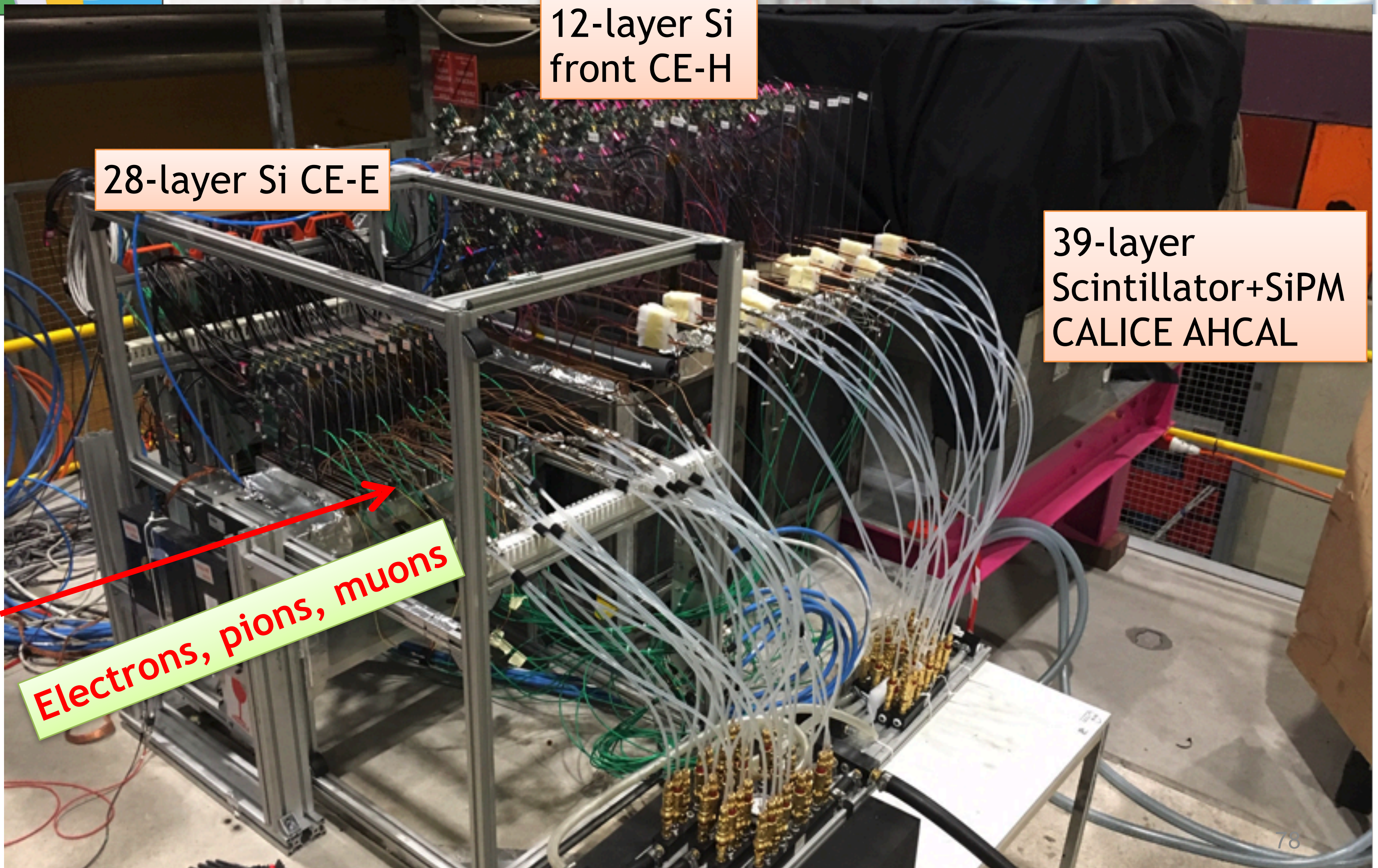


Performance

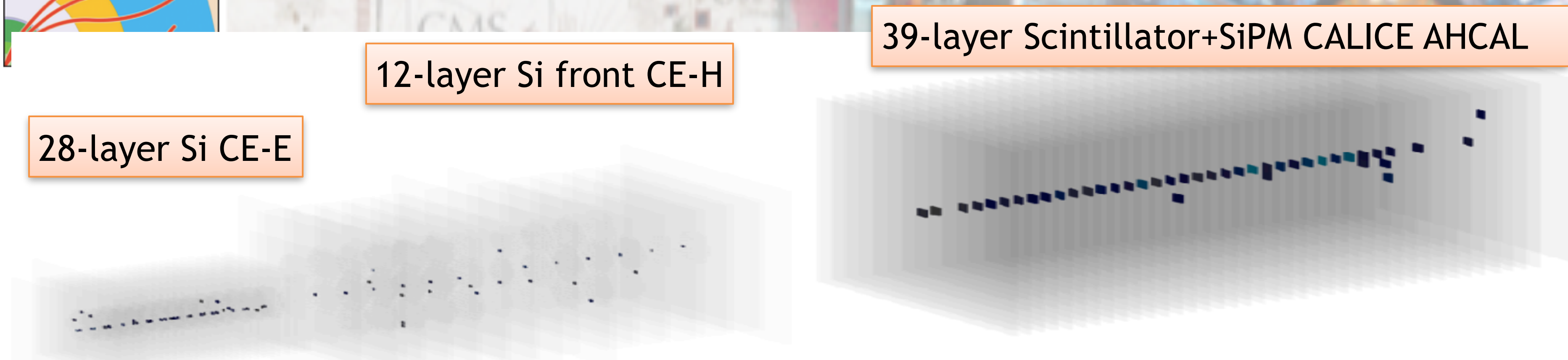
Test beam

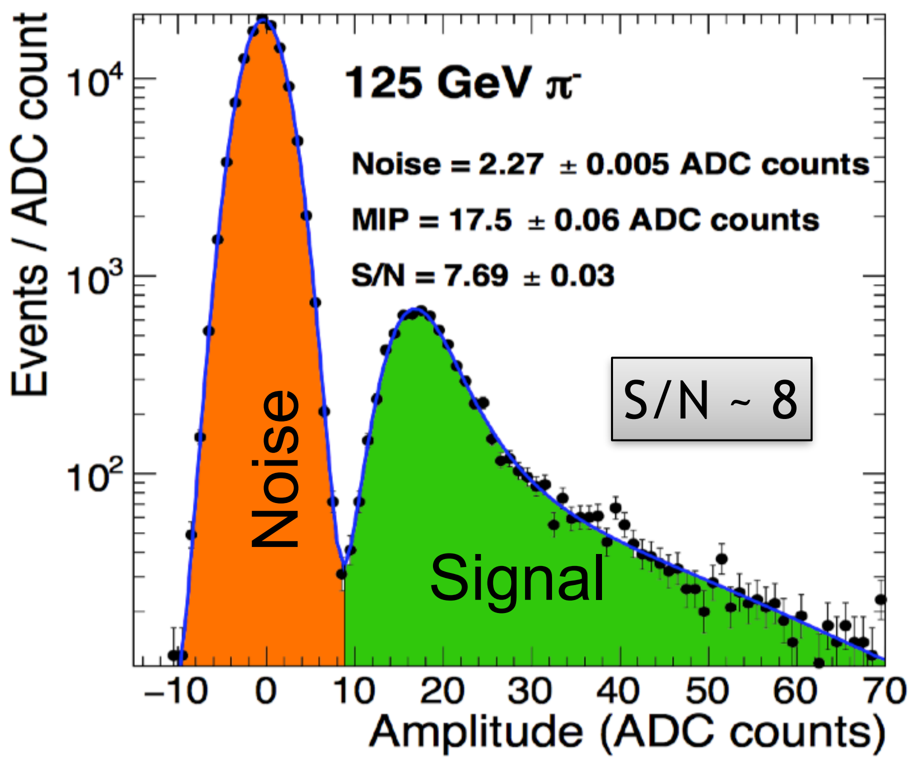
Simulation

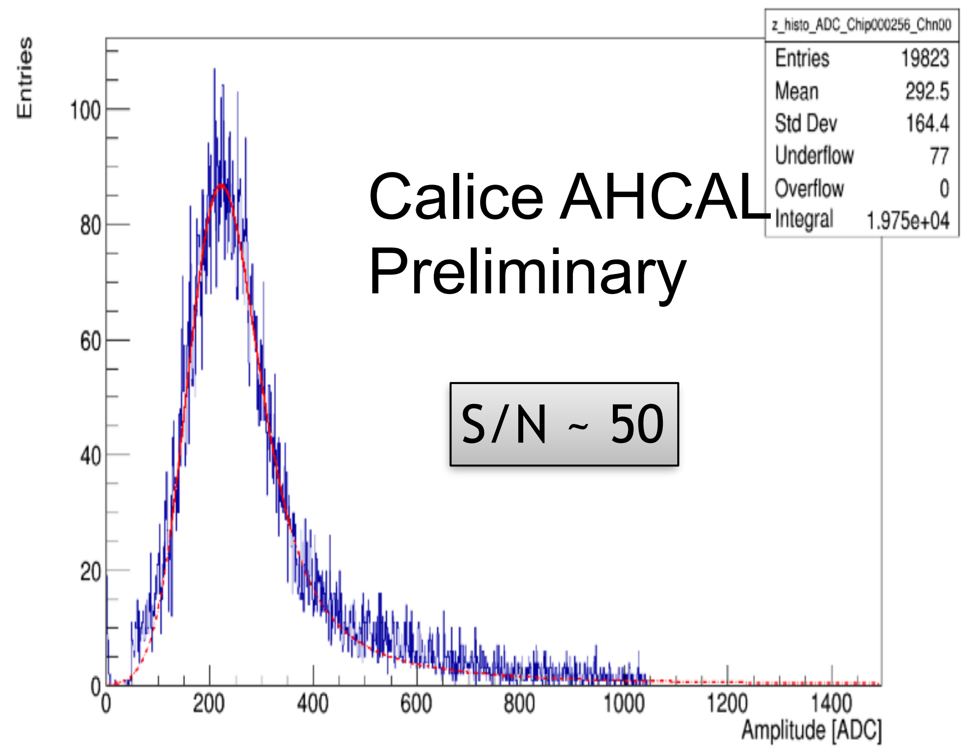
~100 Prototype silicon modules + CALICE AHCAL tested at CERN in 2018



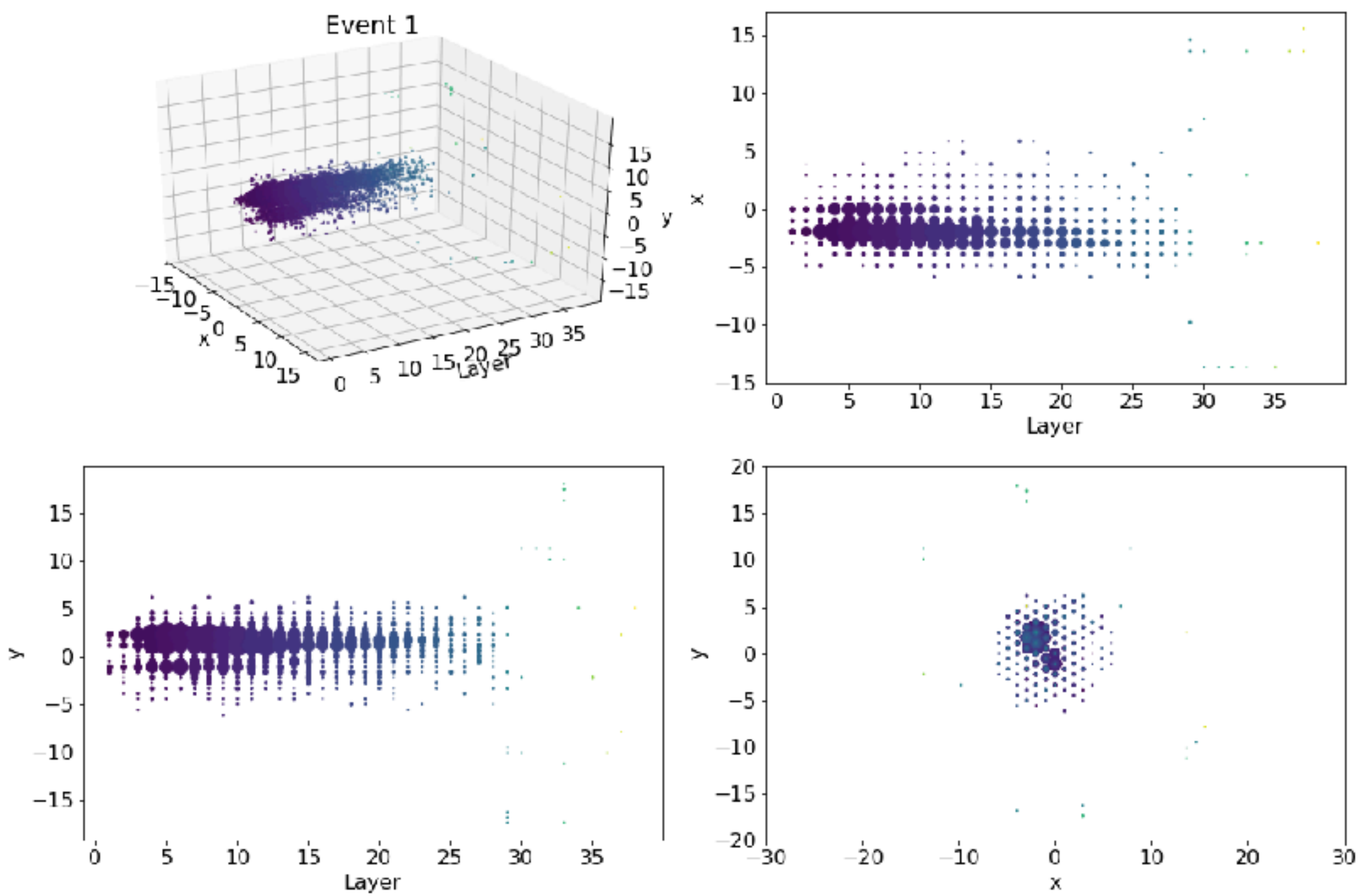
150 GeV muons: for MIP calibration





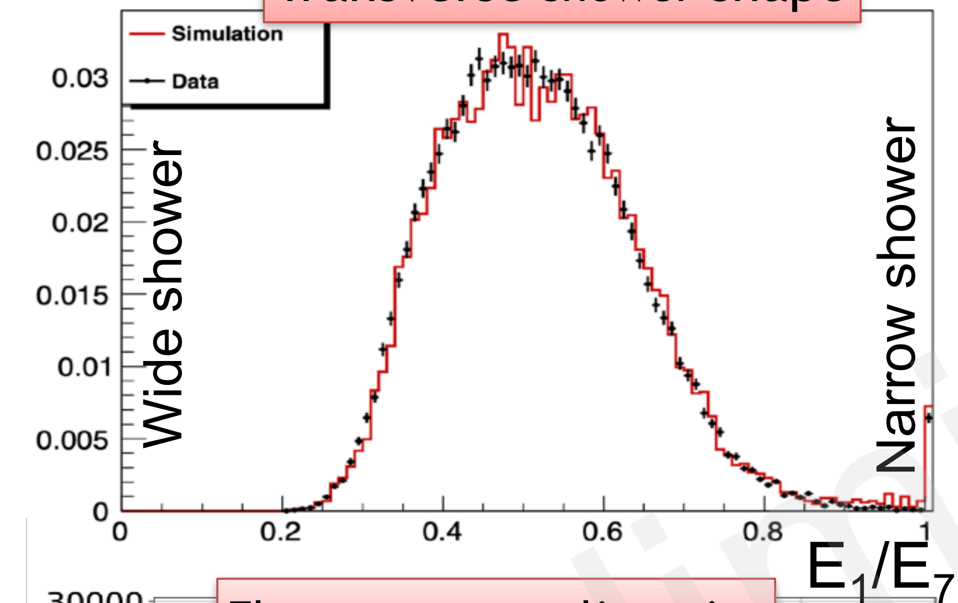


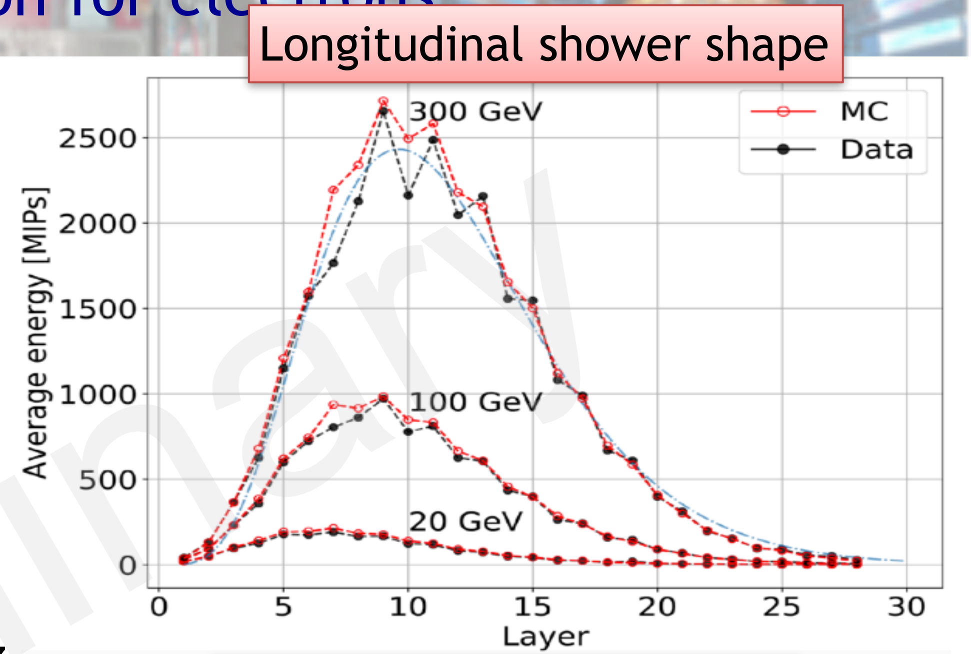
300 GeV electron shower: event

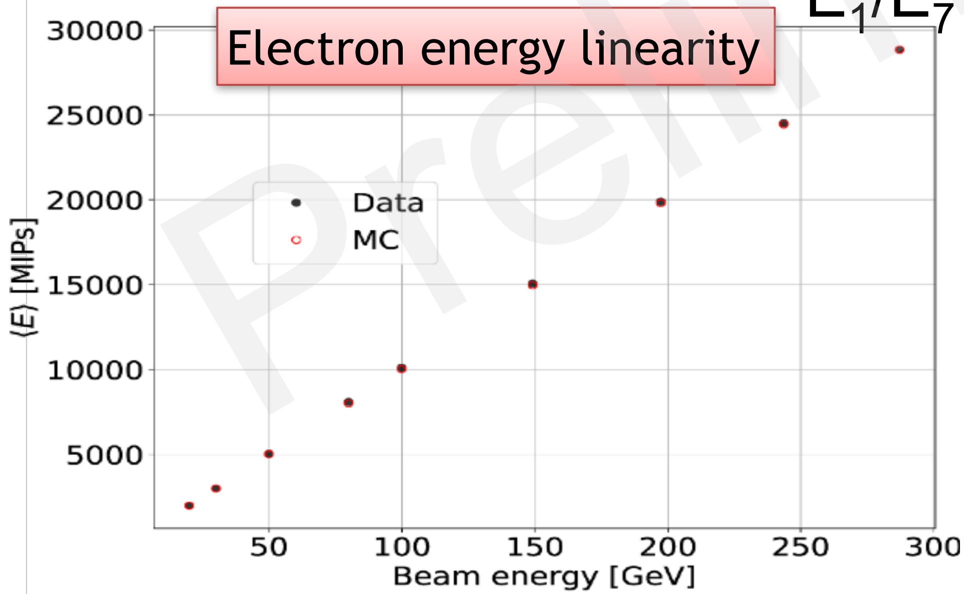


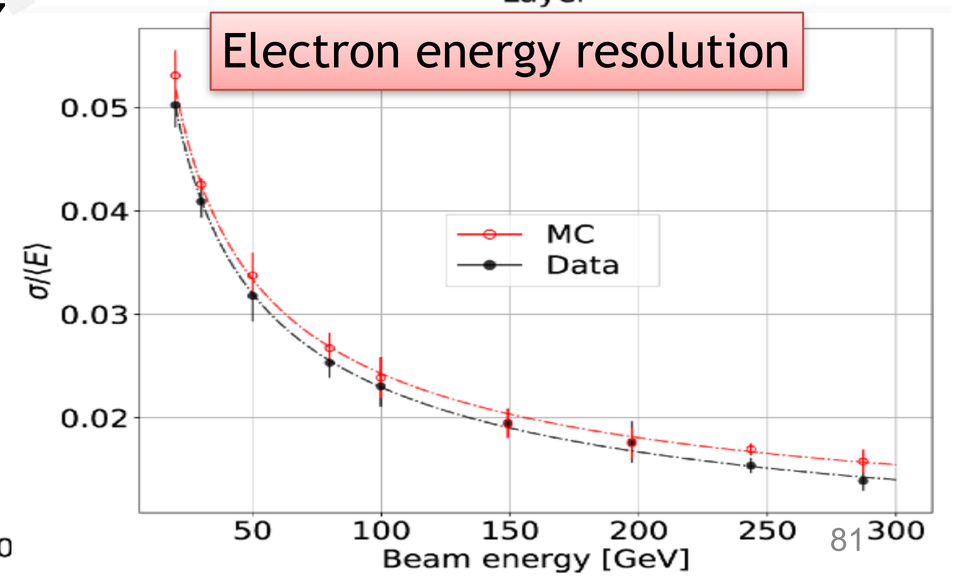
2 energy clusters seen due to **electron bremsstrahlung** upstream of HG

Beam tests 2016-2018: validated basic design; good comparison to simulation for electrons

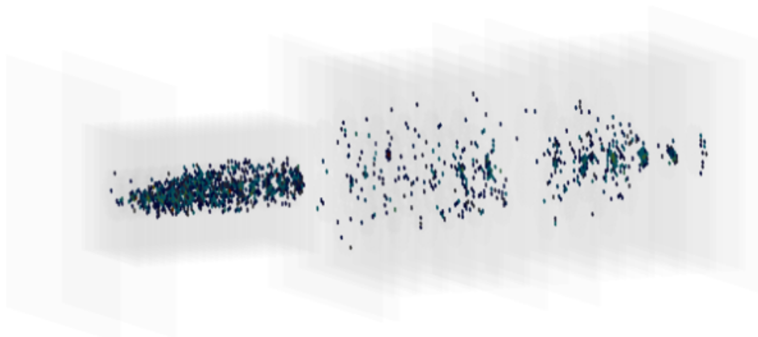


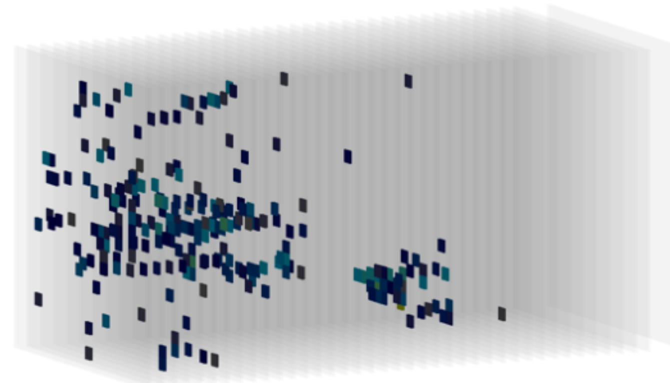






300 GeV hadron showers: event

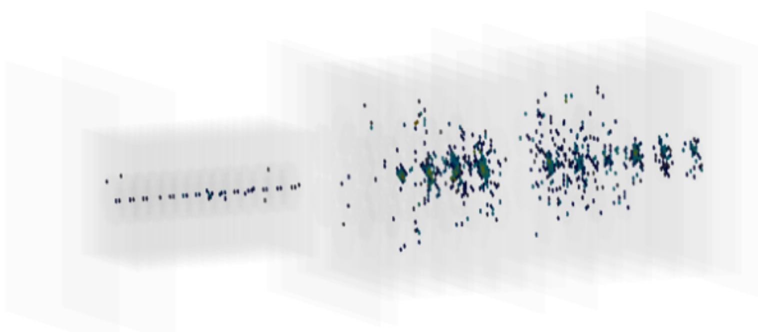


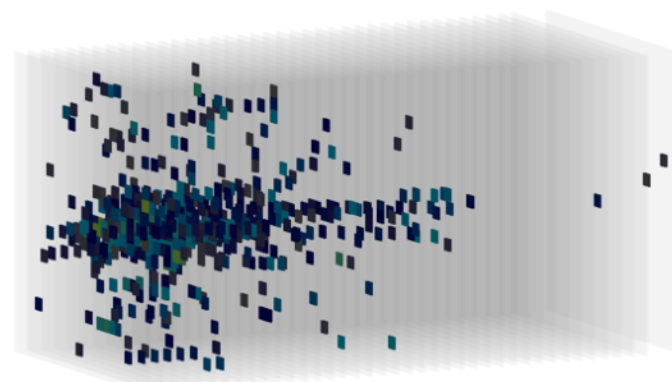


28-layer Si CE-E

12-layer Si front CE-H

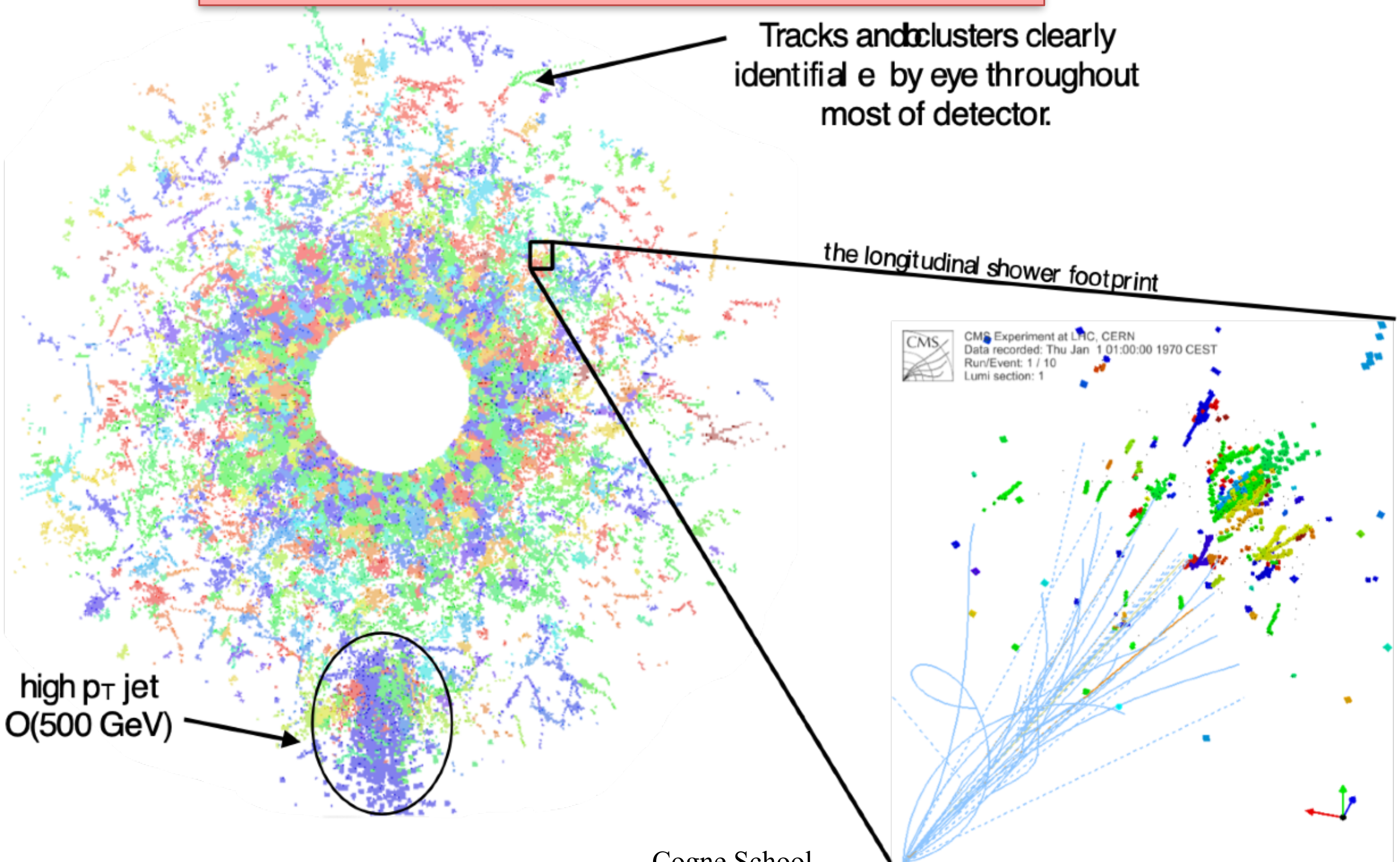
39-layer Scintillator+SiPM CALICE AHCAL





4D calorimeter

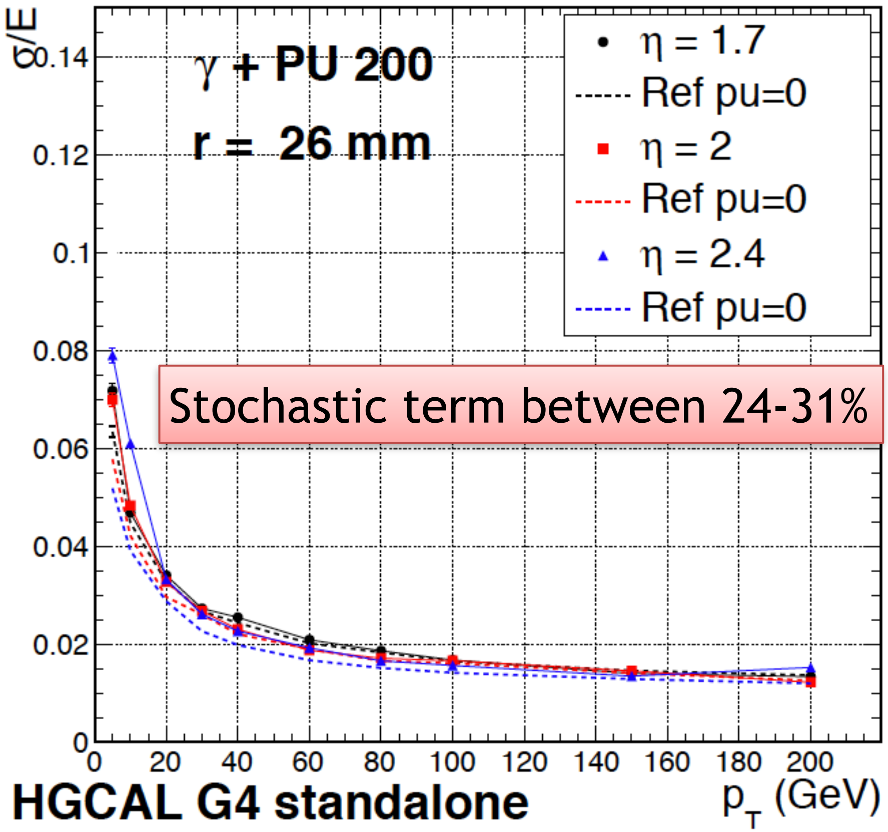
Simulation of 140 pileup events in CMS

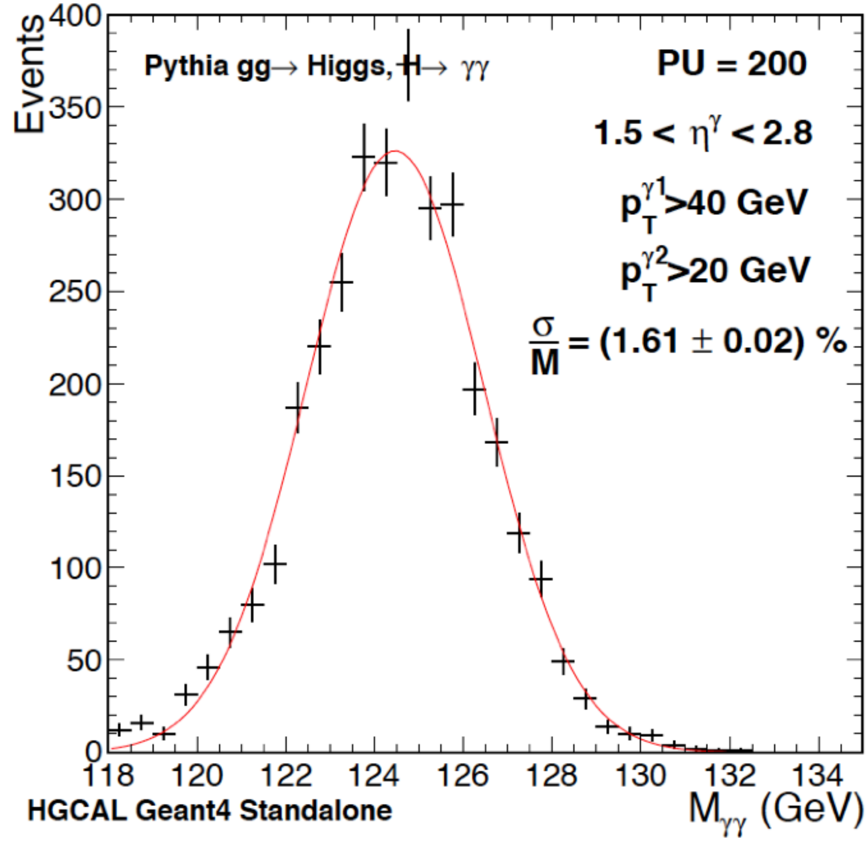


G4 simulation used to predict performance of HGCAL in presence of pileup: E/M resolution

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

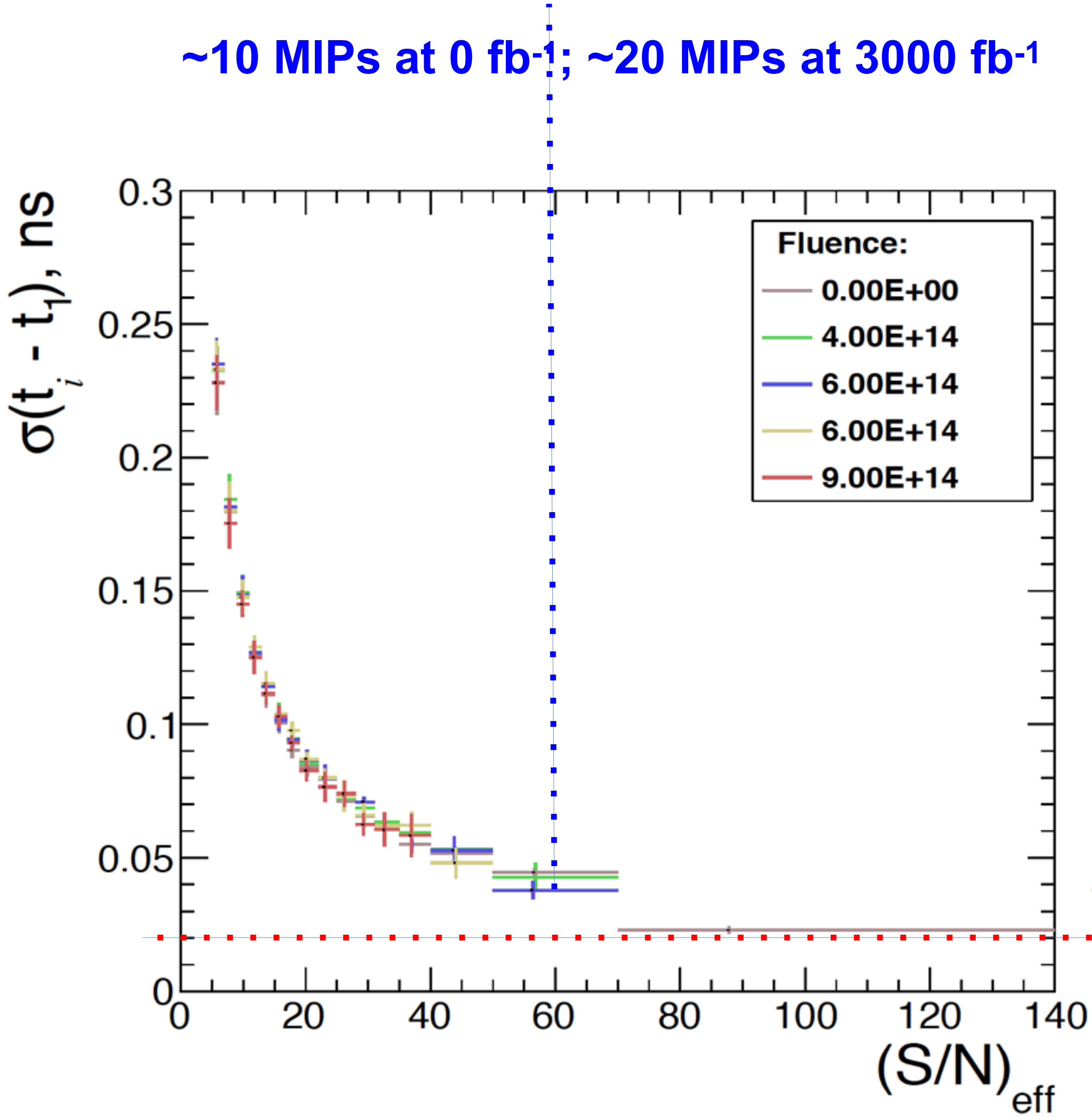
H-γγ, both γ in HGCAL (γ do not convert in TK)
Pileup 200





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}



Constant term ~20ps

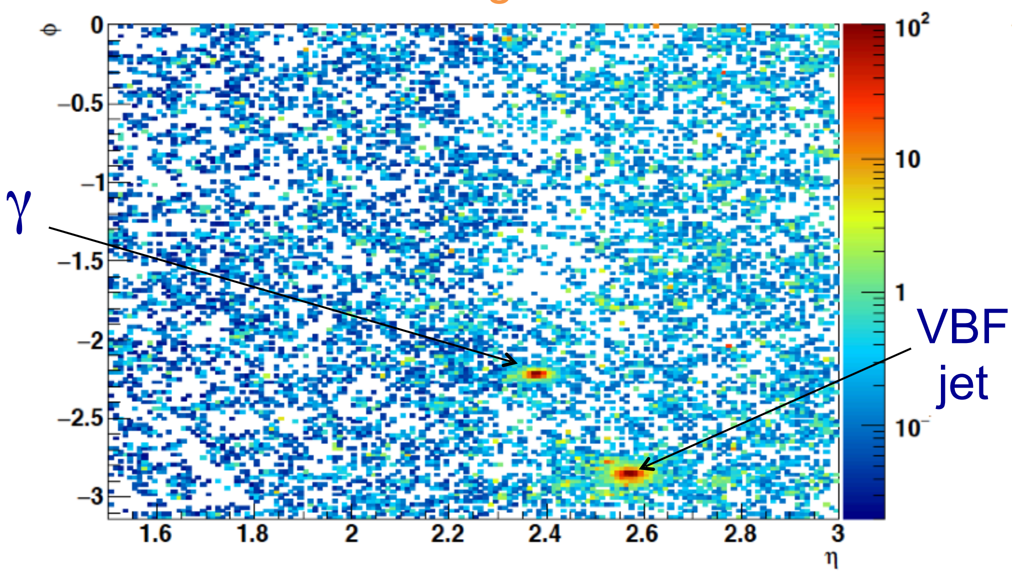
Can look at shower evolution in 5D (energy, X, Y, Z, t) → Particle Flow

5D calorimeter

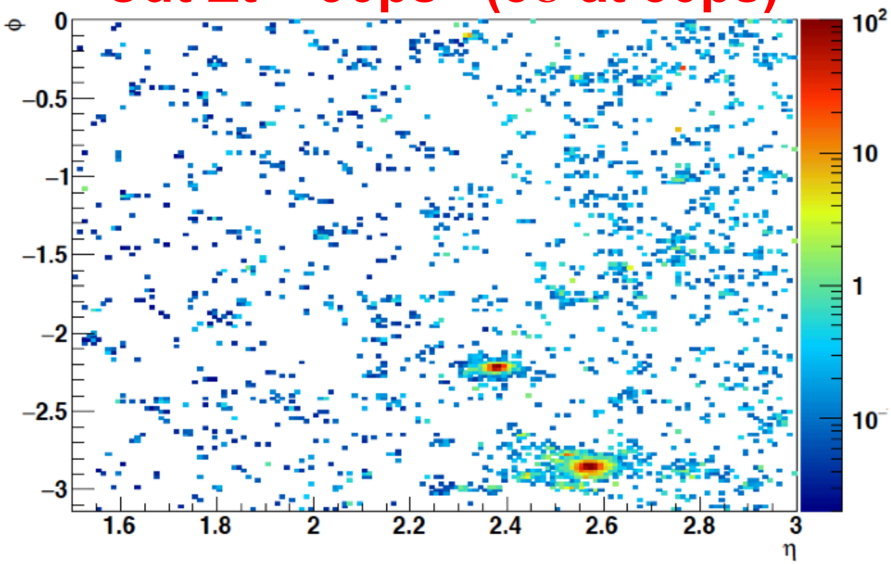
Possible due to the choice of HGCAL sampling parameters and electronics

VBF ($H \rightarrow \gamma\gamma$) 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 - threshold for timing measurement) projected to the front face of the endcap calorimeter.

Conclusions

- Calorimetry has always played a key role in High Energy Physics
- ..and it is continuing to be crucial for the research goals in accelerator based experiments
- A calorimeter like the HGCAL is providing more information than any previous calorimeter and is opening new possibilities
- ….and it comes with unprecedented challenges in detector, electronics, firmware and software developments

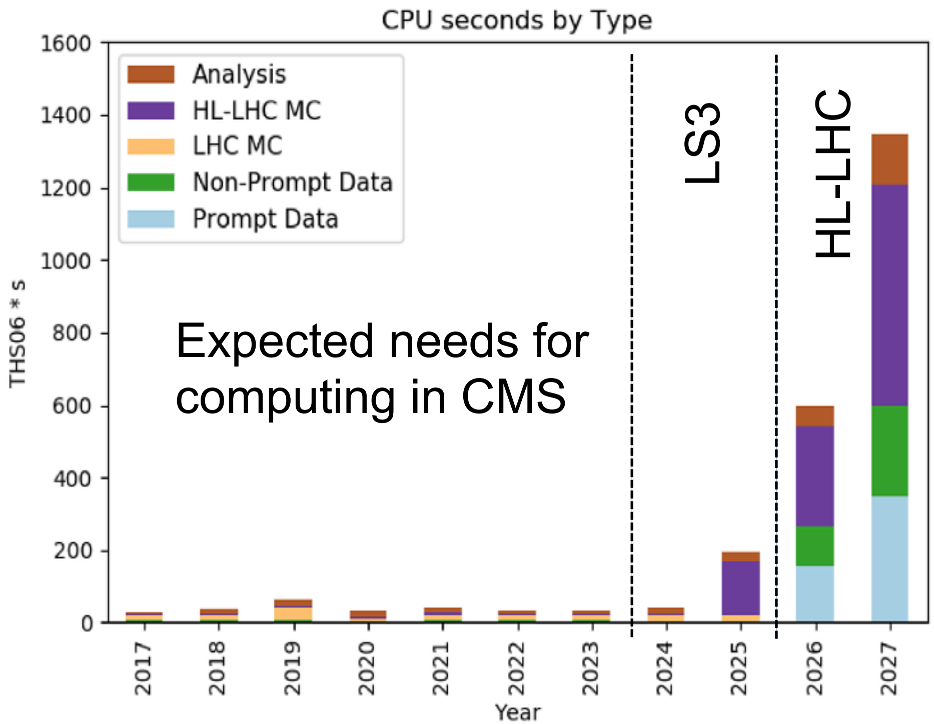
Backup

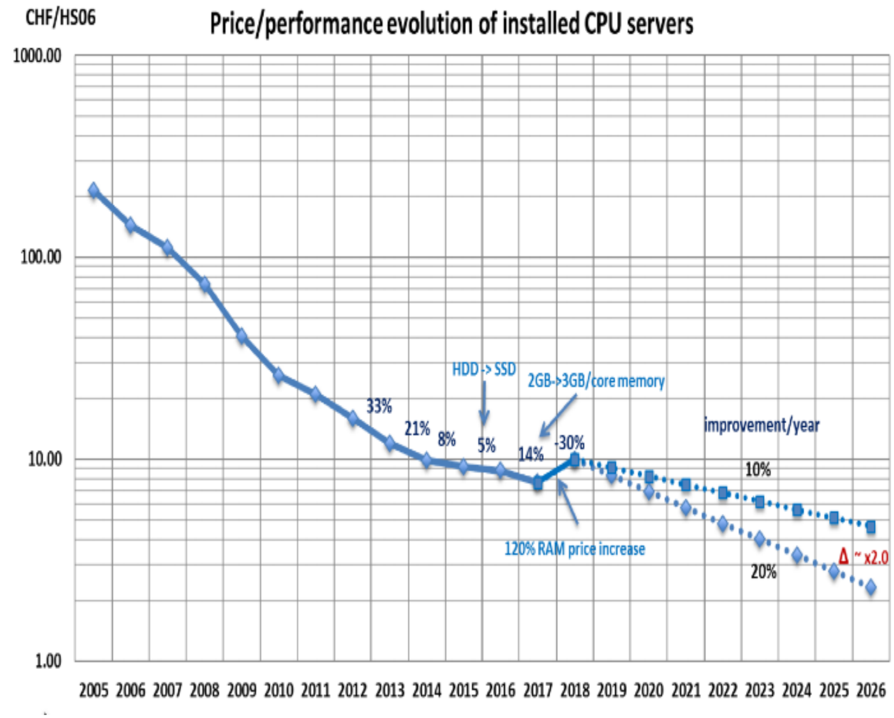
Achieving this performance in practice implies huge software challenges

HGCAL is a completely novel detector concept for a hadron collider environment and is an opportunity to consider new technologies and algorithms, e.g.:

- Heterogeneous computing (GPUs, FPGAs etc.)
- Machine learning
- Particle-flow reconstruction with pileup

Exploiting a 5D 6-million channel detector requires novel approaches to computing



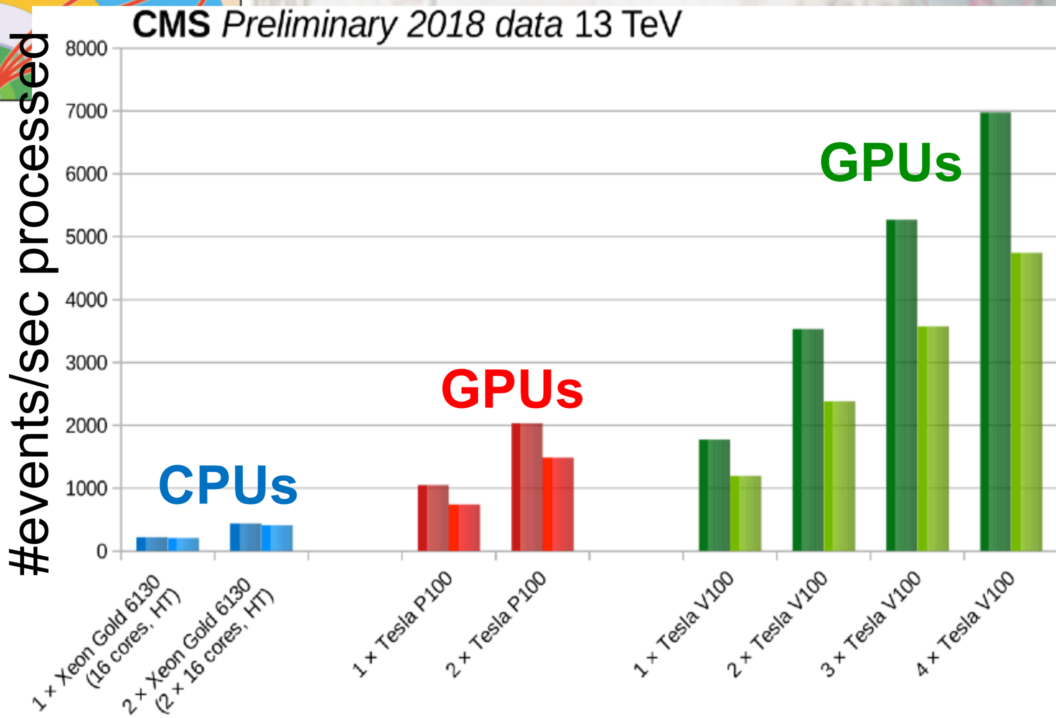


Computing needs increase by x30

May get a factor x2-3 from CPU developmen

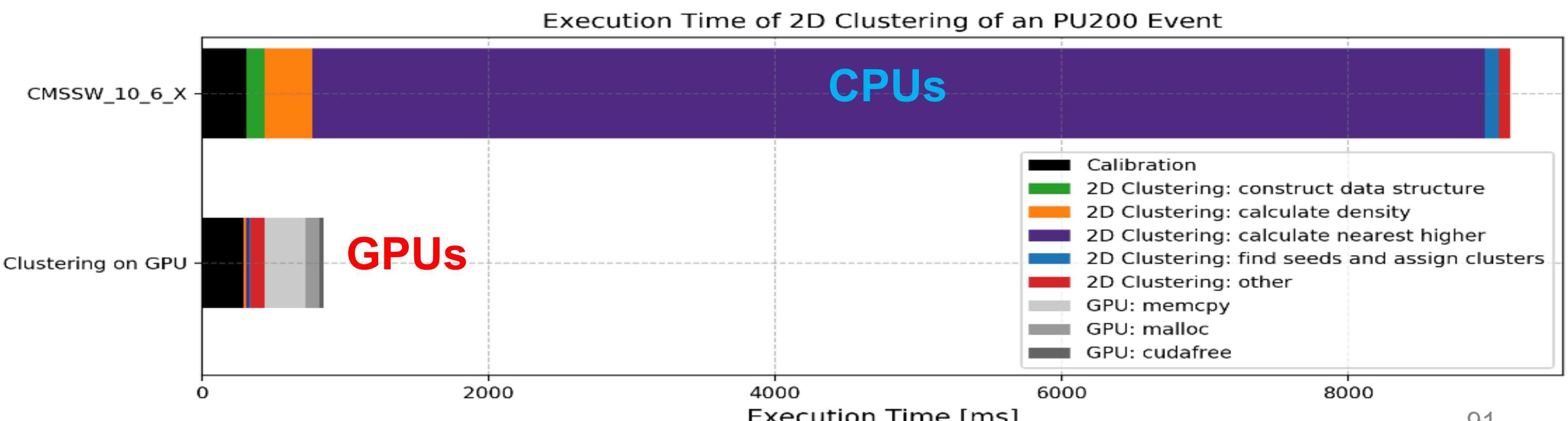
We are missing a factor 10 in computing power!

Heterogenous computing already being used in CMS
GCAL

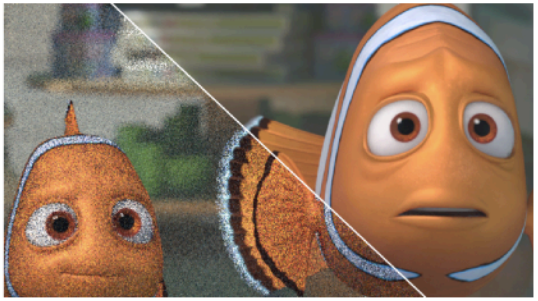


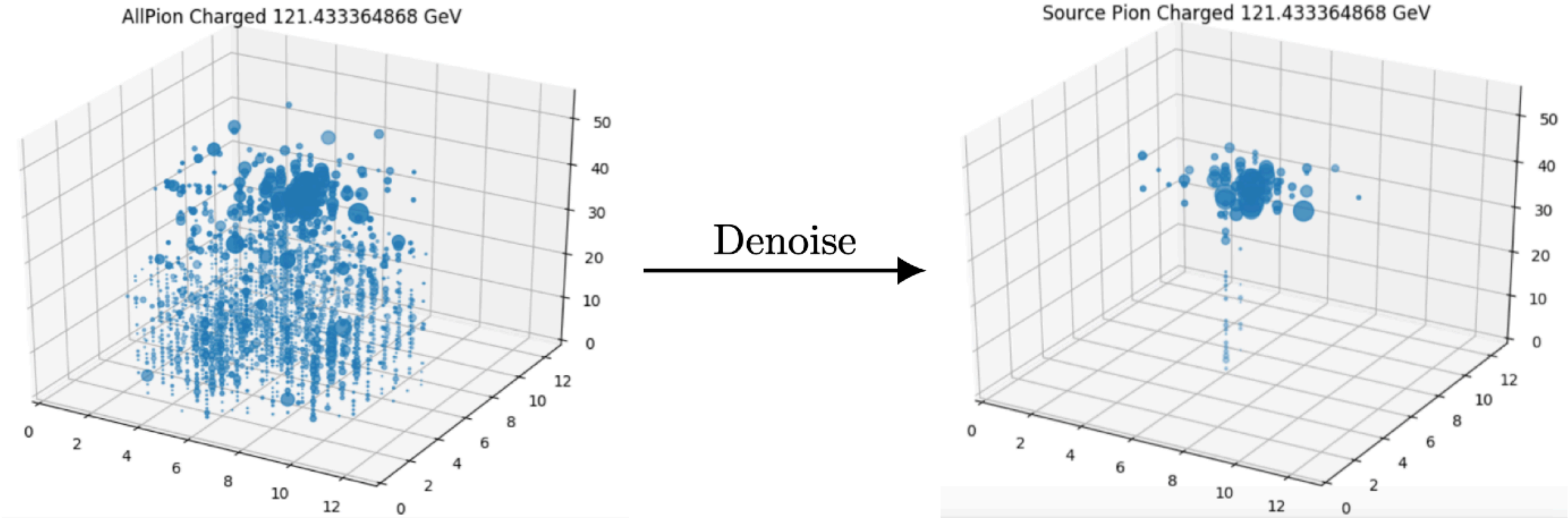
CMX Pixel tracking algorithms x8 faster with GPUs than CPUs and x10 more energy efficient

For HGCAL clustering, time spent on mathematical processing is almo negligible! Overall time is x10 faste than CPU, limited by data throughp



Machine learning techniques, such as de-noising, are very promising





- Very successful for image processing
- Interpret e.g. pileup as noise and filter it
- For this study: force energy deposits in a regular grid and use a set of convolutional DNN layers

We are in the final R&D phase, soon moving to production, assembly and commissioning

- Finalization of design, prototyping towards final systems (2 years)
- Engineering Design Review (March 2021) 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 !
- Installation of 1st endcap ~March 2025 and 2nd endcap 2 months later
- Ready for HL-LHC operation in 2026
- And operate for >10 years

Critical Energy

Critical Energy, ε

Defined to be the energy at which the energy loss due to ionisation* (at its minimum i.e. β≈0.96) and radiation are equal (over many trials)

$$i.e.\quad \frac{(dE/dx)_{rad}}{(dE/dx)_{ion}} = 1$$

$$\Rightarrow \quad \varepsilon = \frac{560}{Z} \quad (E \ \ in \ \ MeV)$$

$$-\frac{dE}{dx}\Big|_{ion} = N_A \frac{Z}{A}\frac{4\pi\alpha^2(\hbar c)^2}{m_e c^2}\frac{Z_i^2}{\beta^2}\left[\ln\frac{2m_e c^2\gamma^2\beta^2}{I} - \beta^2 - \frac{\delta}{2}\right]$$

$$-\frac{dE}{dx}\Big|_{Brems} = 4\alpha N_A\left(\frac{e^2}{mc^2}\right)^2 ln\frac{183}{Z^{1/3}}\frac{Z(Z+1)}{A}Q^2E$$

Fractional Energy Loss by Electrons