Calorimetry

"everything not tracking" (in CMS)

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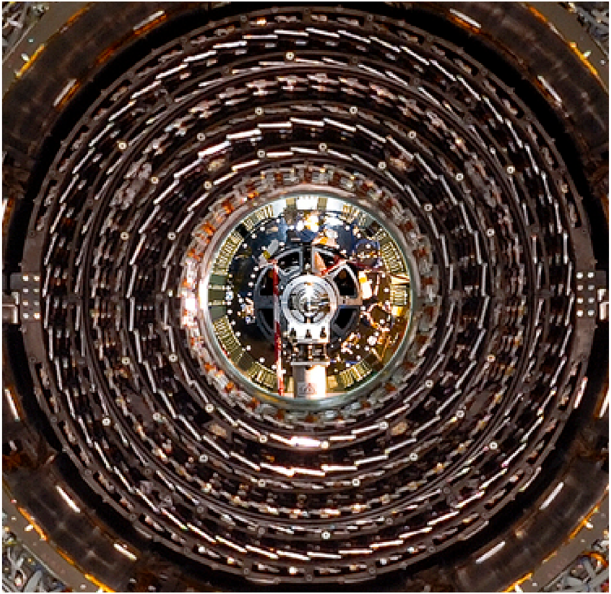
on behalf of the ECAL and HCAL groups

with thanks to F. Ferri, F. Cavallari, P. de Barbaro, J. Dittmann, T. Laird
and the previous induction speakers

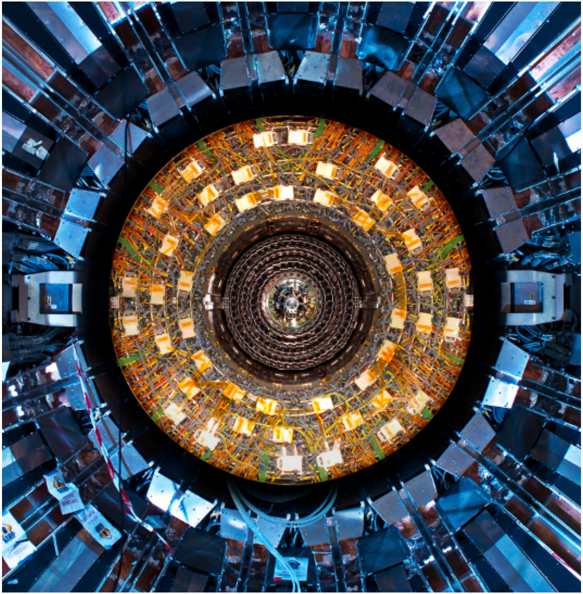
CMS Induction Course, September 20, 2021

What you have just heard about...

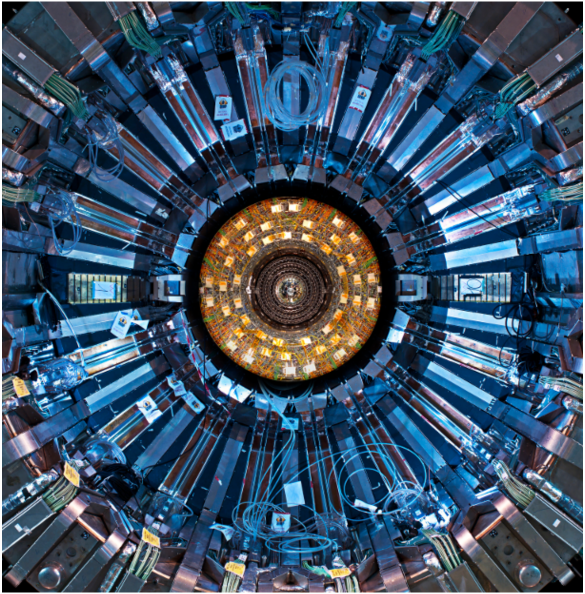


What you have just heard about...

What you can't wait to hear about!

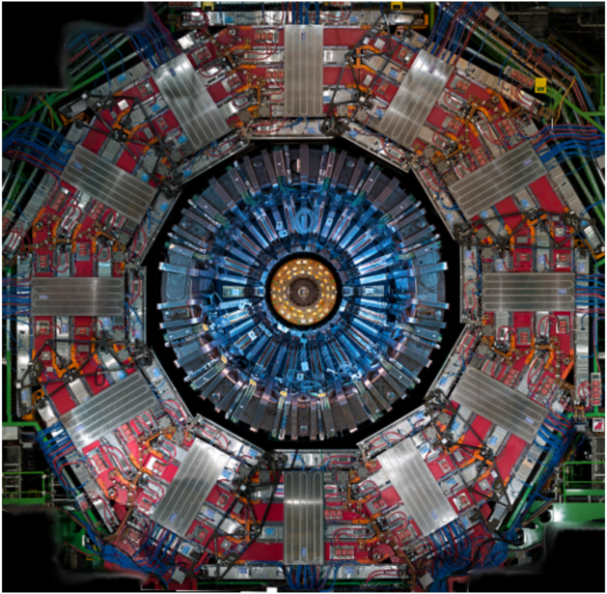


What you can't wait to hear about!



What no one ever talks about (but everything depends upon!)

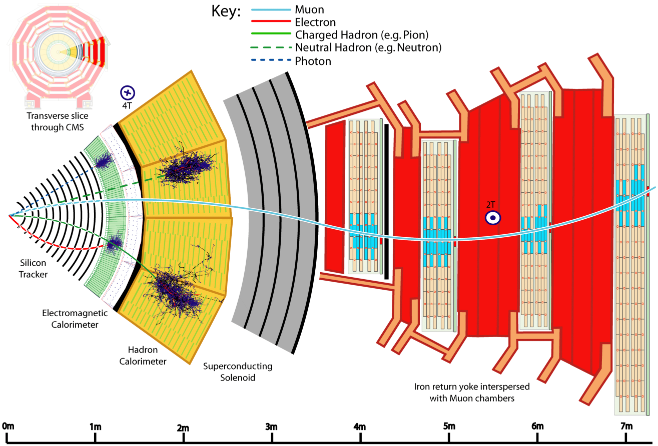
The whole CMS in one sli~~d~~ce



What does a calorimeter do?

It converts the energy of incident particles into a detector response, in a destructive way

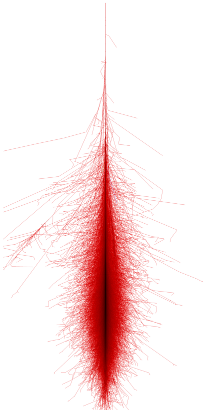
- **E**lectromagnetic **CAL**orimeter: electrons and photons
- **H**adronic **CAL**orimeter: charged and neutral hadrons



Particle interaction with matter (oversimplified^n)

- **Electrons and photons**, a "self-contained" case:
  - above 1 GeV: bremsstrahlung ($1e^\pm \to 1\gamma$) and pair production ($1\gamma \to 1e^+ + 1e^-$)
  - below 1 GeV: ionization, photoelectric, Compton
  - critical energy, $E_c \approx 610\ \text{MeV}/(Z + 1.24)$: energy at which the average energy losses by radiations equal those by ionization

e.m. example



- **Hadrons**, a complex case:
  - multi-particle production, typically mesons ($\pi^\pm$, π^0, K, ...)

  N.B. $\pi^0 \to \gamma\gamma \Rightarrow$ electromagnetic component!
  - nuclei breakup leading to spallation neutrons/protons

A cascade process ("shower") develops until the energy of charged secondaries is degraded to the regime dominated by ionization loss (i.e. no production of new particles)

Compensation (oversimplified^n)

- The response of a calorimeter to electromagnetic objects and to hadrons is generally not the same, because of undetected energy:
  - energy to release nucleons from nuclei
  - + smaller contributions from ν and μ from π and K decay in flight

  $\Rightarrow$ hadrons have lower response than e/γ

- **Compensation:** selectively increase the hadron energy deposition, or decrease the e.m. one, to eliminate differences in the average response
  - not an easy task at all
  - can be attempted by a suitable choice of the hardware
  - and/or by being clever at analysis level
  - fluctuations in the average e.m. component of an hadronic shower makes it challenging to keep a good resolution
  - many ingredients come into play at this stage: design strategies, costs, physics goals, collision type, etc.

CMS approach: clearly separate e.m. and hadron calorimeters, and be clever at analysis level (Global Event Description, i.e. team spirit, keep this in mind for later)

Showers: minimal quantities and names

$$\frac{dE}{dx} = -\frac{E}{X_0}$$

longitudinal development

$$\frac{dE}{dt} \propto E_0 t^{\alpha} e^{\beta t}$$

e.m case, E. Longo (active CMS member! Rome group), I. Sestili, NIM 128 (1975)

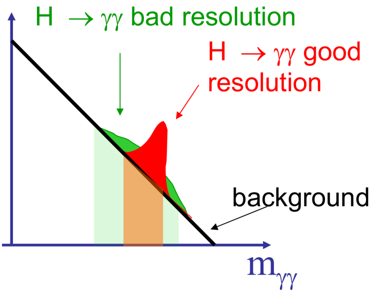
Radiation length (X_0): thickness of material that reduces the mean energy of a beam of high energy electrons by a factor e

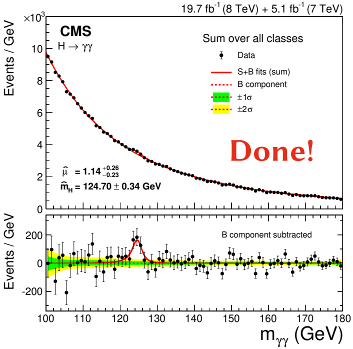
Molière radius (R_M): average lateral deflection of electrons of critical energy E_c after traversing $1X_0$; 90% E_0 within $1R_M$, 95% within $3R_M$

Interaction length (λ_{int}): average distance a high energy hadron has to travel inside a medium before a nuclear interaction occurs, $\lambda_{int} = A/N_A\sigma_{int} \propto A^{1/3}$

What are we aiming at?

Best possible energy resolution σ_{calo} (compatible with the LHC environment).





Signal $S = \text{constant}$

Background $B \propto \sigma_{\gamma\gamma}$

$$\Downarrow$$

$$\frac{S}{\sqrt{B}} \propto \frac{1}{\sqrt{\sigma_{\gamma\gamma}}} = \frac{1}{f(\sigma_{\text{calo}})}$$

But also:

- jet resolution (analogous reasons)
- small fluctuations in the transverse missing energy: large MET sign of new physics!

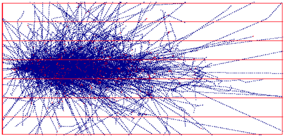
Thumbmetry of a calorimeter

- Detection of both **charged and neutral** particles
  - only muons escape
- Detection based on **stochastic** processes
  - precision increases with energy
- Dimensions necessary to **containment** scale with $\log E$
  - allow compactness
- **Granularity** plays a fundamental role
  - transverse: impact position measurement, particle ID on topological basis
  - longitudinal: direction measurement
- **Fast** response
  - high rate capability, trigger

HOWTO build a calorimeter

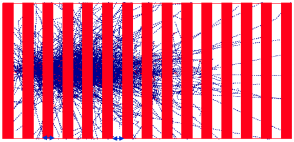
Two main possibilities (oversimplified[1]):

Homogeneous calorimeters: all the energy is deposited in the active medium



- Excellent energy resolution
- No information on longitudinal shower shape
- Cost

Sampling calorimeters: the shower is sampled by layers of active medium (low-Z) alternated with dense radiator (high-Z)



- Limited energy resolution
- Longitudinal segmentation: detailed shower shape information
- Cost

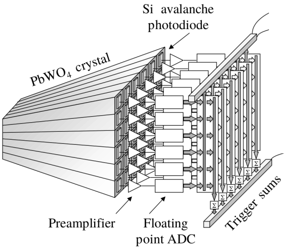
HOWTO build a calorimeter

Two main possibilities (oversimplified[1]):

Homogeneous calorimeters: all the energy is deposited in the active medium

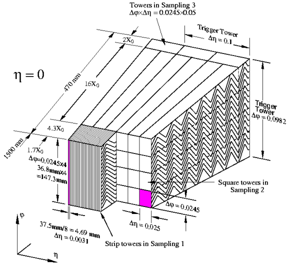
Sampling calorimeters: the shower is sampled by layers of active medium (low-Z) alternated with dense radiator (high-Z)

CMS ECAL choice



- Excellent energy resolution

ATLAS ECAL choice



- Longitudinally segmented

HOWTO build a calorimeter

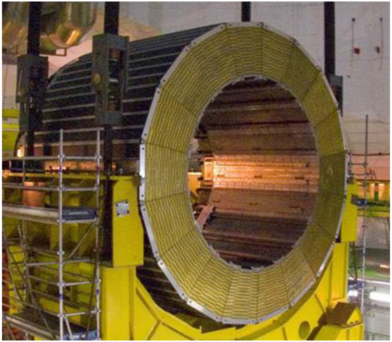
Two main possibilities (oversimplified[1]):

Homogeneous calorimeters: all the energy is deposited in the active medium

Sampling calorimeters: the shower is sampled by layers of active medium (low-Z) alternated with dense radiator (high-Z)

CMS ECAL choice

CMS HCAL choice



HOWTO build a calorimeter in few steps

- **Particle interaction** with matter
  $\rightarrow$ depends on the impinging particle and on the kind of material

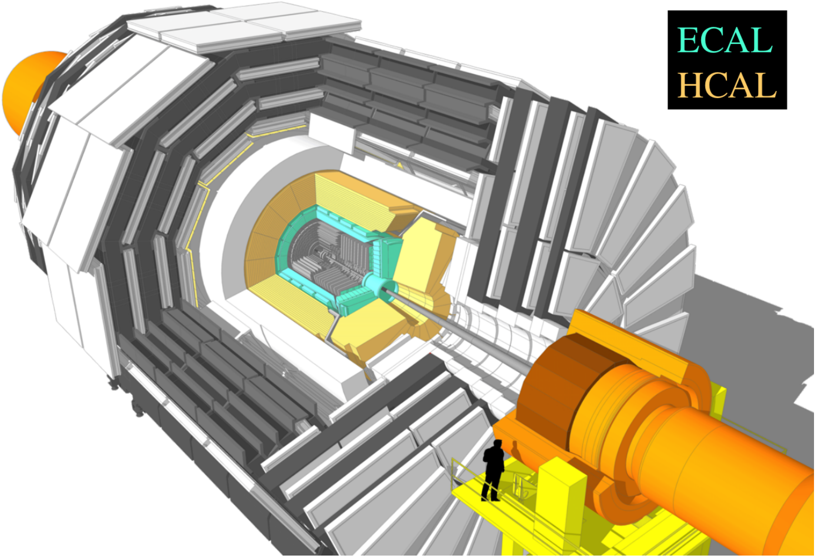
- **Energy** loss transferred to a detectable signal
  $\rightarrow$ depends on the material, typically light (or charges, e.g. ATLAS)

- **Signal** collection
  $\rightarrow$ depends on the signal, many techniques of collection

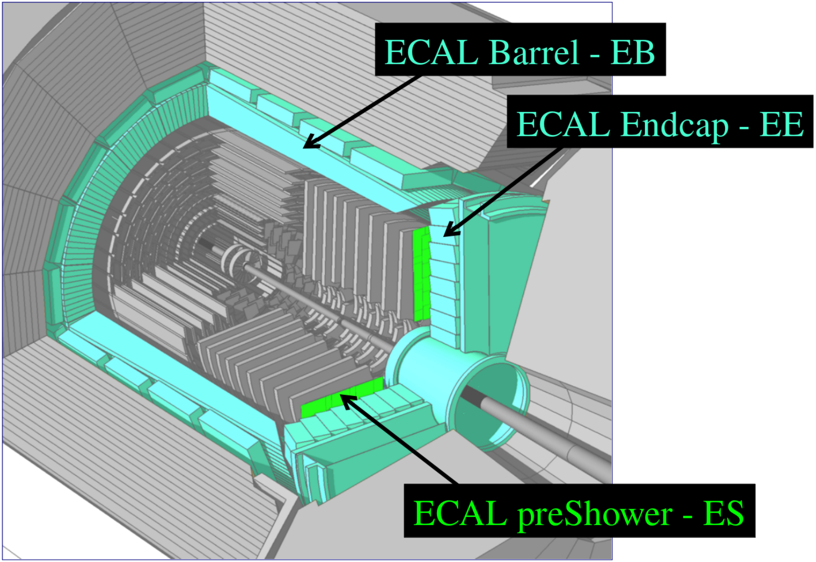
- Conversion to **electrical signal** and digitization
  $\rightarrow$ depends on the signal and granularity, also many techniques

- Do it for a unit of detector, then repeat to cover as much **solid angle** as possible
  $\rightarrow$ build a hermetic system

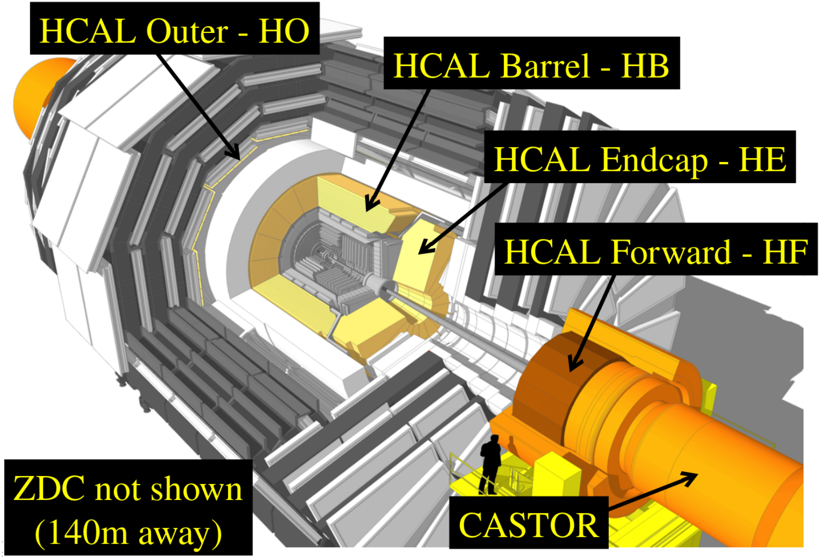
The CMS calorimeters



The CMS calorimeters



The CMS calorimeters



The CMS calorimeters

Em Barrel : EB

Em Endcap : EE

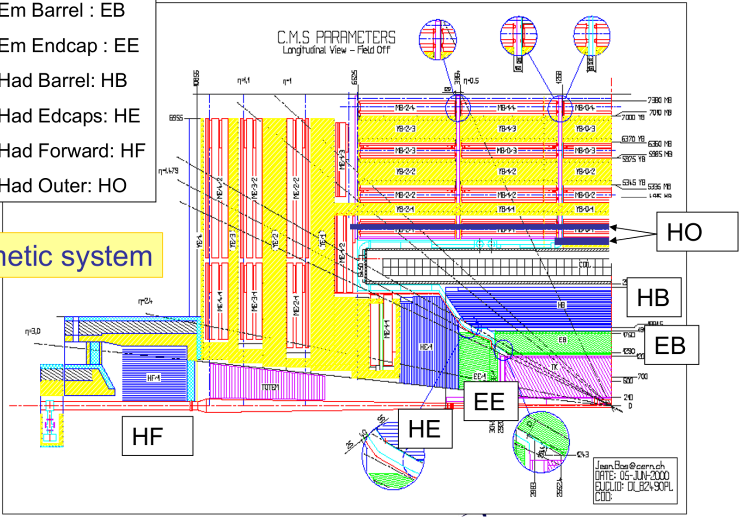
Had Barrel: HB

Had Edcaps: HE

Had Forward: HF

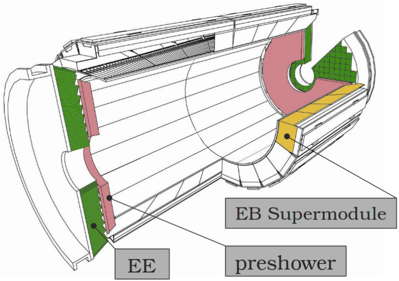
Had Outer: HO

Hermetic system



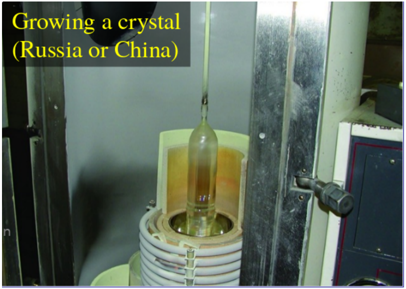
The CMS ECAL

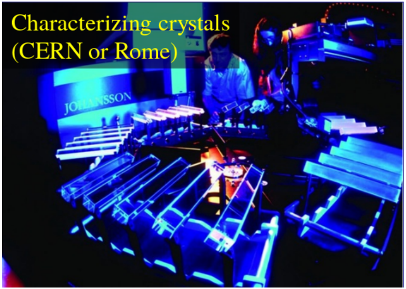
- **Homogeneous, hermetic, high granularity $PbWO_4$ crystal calorimeter**
  - density of 8.3 g/cm^3, radiation length 0.89 cm, Molière radius 2.2 cm, $\approx$ 80% of scintillating light in $\approx$ 25 ns, refractive index 2.2, light yield spread among crystals $\approx$ 10%
- **Barrel**: 61200 crystals in 36 super-modules, $|\eta| < 1.48$,
  Avalanche Photo-Diode (APD) readout
- **Endcaps**: 14648 crystals in 4-Dees, $1.48 < |\eta| < 3.0$,
  Vacuum Photo-Triode (VPT) readout
- **Preshower** (endcaps only): $3X_0$ of Pb/Si strips, $1.65 < |\eta| < 2.6$

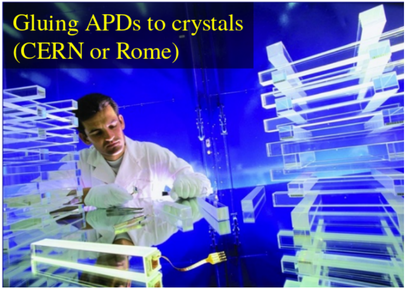


- Solenoidal magnetic field: 3.8 T
  ECAL fully contained in the coil
- CMS tracker coverage: $|\eta| < 2.5$

Production of the ECAL crystals (75848)







The CMS HCAL

Barrel (HB)

- 36 brass/scintillator wedges
- 17 longitudinal layers, 5 cm brass, 3.7 mm scintillator
- $|\eta| < 1.3$

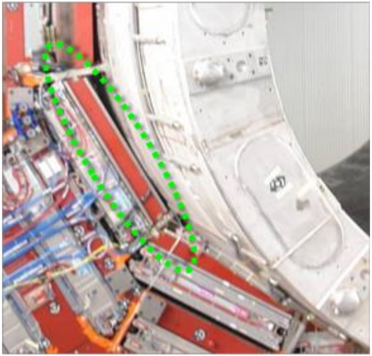
Endcap (HE)

- Two brass/scintillator discs
- 19 longitudinal layers, 8 cm brass, 3.7 mm scintillator
- $1.3 < |\eta| < 3.0$

The CMS HCAL

Outer (HO)

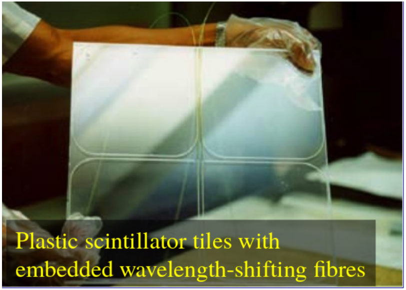
- Scintillator tiles (outside yoke)
- 1 or 2 longitudinal layers, 10 mm scintillator
- $|\eta| < 1.3$

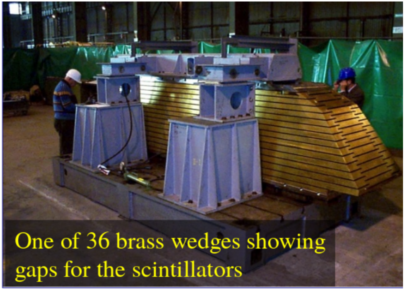


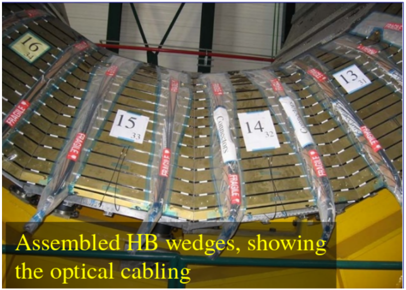
Forward (HF)

- Steel absorber/quartz fiber
- 20 deg wedges, $\approx$ 1000 km fibers
- $3 < |\eta| < 5$

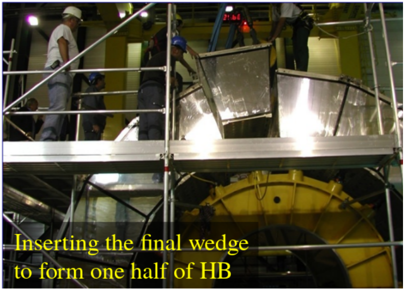
Assembly of HCAL barrel (wedges + megatiles)


Plastic scintillator tiles with embedded wavelength-shifting fibres


One of 36 brass wedges showing gaps for the scintillators



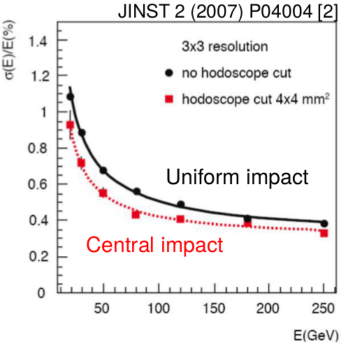
Assembled HB wedges, showing the optical cabling


Inserting the final wedge to form one half of HB

Detector parts (modules) produced. Then? Happy?

ECAL performance at Test Beams: text book

- Perfect calibration, no magnetic field, no material upstream, negligible irradiation, controlled environment



Energy resolution

central impact, 3×3 barrel crystals [?][?]:

$$\frac{\sigma(E)}{E} = \frac{2.8\%}{\sqrt{E}} \oplus \frac{0.128}{E(GeV)} \oplus 0.3\%$$

- constant term to be kept $\ll 1\%$
- stochastic term also affected by the material upstream

Time resolution: constant term ≈ 200 ps

- from time difference of crystals in the same e.m. shower

A success of 20 years of R&D

In situ operations: from ideal to real

Light yield variations:

- ECAL scintillation light $\rightarrow$ temperature dependence: $\Delta S/S \sim -2\%/^{\circ}\mathrm{C}$ @ $18\ ^{\circ}\mathrm{C}$
- ECAL crystal transparency $\rightarrow$ radiation dose-rate dependence
- HCAL scintillator response $\rightarrow$ radiation dose dependence

Photo-detector response:

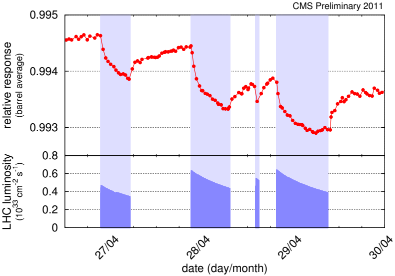
- APD $\rightarrow$
  - gain temperature dependence: $\Delta G/G \sim -2\%/^{\circ}\mathrm{C}$
  - gain High-Voltage dependence: $\Delta G/G \sim 3\%/\mathrm{V}$
  - direct ionization effects, a.k.a. “spikes”
- VPT, HPD, PMT $\rightarrow$ response dependence on the incremental charge at the cathode
- HPD $\rightarrow$ discharges, noise effects

$\longrightarrow$ **Excellent environmental stability** ($\times 2$ to $\times 3$ better than required) [?]

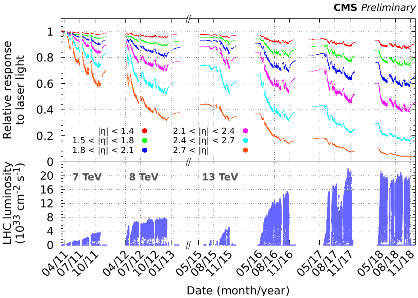
$\longrightarrow$ **Dedicated monitoring system and calibration techniques** [?, ?]

A glimpse of the challenges

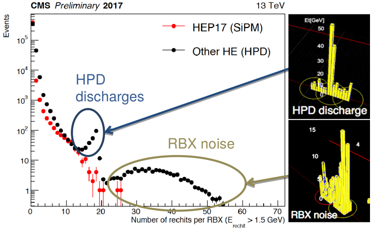
ECAL response: dose-rate variation...

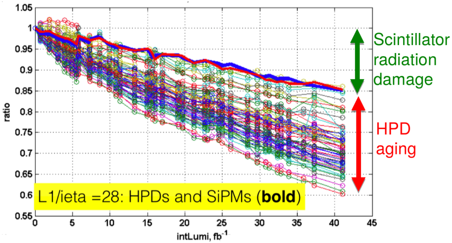


...over 6+ years



HCAL: selected features





ECAL APD spikes analogous to HPD discharges

Not only calorimetry-induced fun

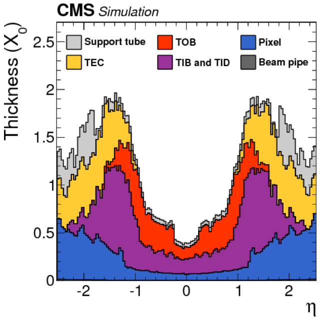
Tracker material in front of ECAL:

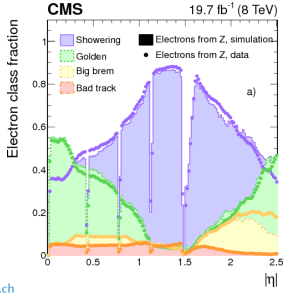
- photon conversions
- bremsstrahlung losses for electrons

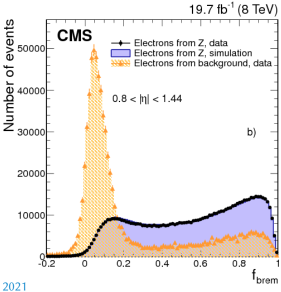
3.8 T solenoidal magnetic field:

- spread of the e, γ energy along φ, at $\approx$ constant η

$\longrightarrow$ Specific energy reconstruction algorithms and corrections

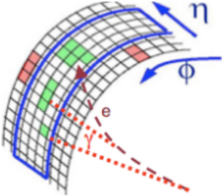






Ingredients for precision physics (ECAL example)

Electrons and photons deposit energy over several crystals (70% in one 97% in a 3×3 array), spread in φ, collected by "clustering" algorithms



$$E_{e,\gamma} = \mathcal{G}\, \mathcal{F}_{e,\gamma} \sum_i c_i s_i(t) \mathcal{A}_i$$

$\mathcal{A}_i$: single channel amplitude, pulse fit in the time domain

$s_i(t)$: single-channel time-dependent response corrections, via a dedicated laser monitoring system

c_i: inter-calibration of the single channel response, using physics: φ- and time-invariance of the energy flow in minimum-bias events, $\pi^0, \eta \to \gamma\gamma$ and $Z \to ee$ invariant mass peak, electron E/p

$\mathcal{F}_{e,\gamma}$: particle energy correction (geometry, clustering, ...)

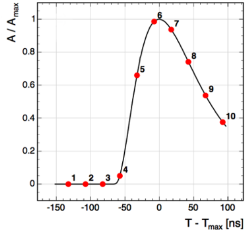
$\mathcal{G}$: global scale calibration, with $Z \to ee$ events

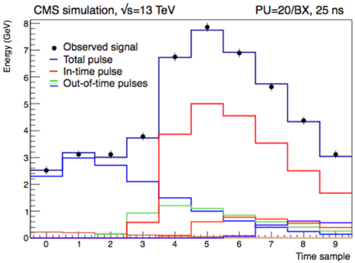
Resolution, efficiency and particle ID: $Z \to ee$

Amplitude reconstruction

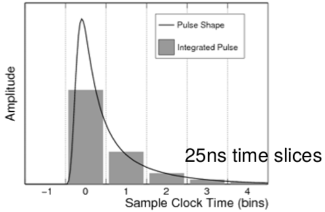
$$E_{e,\gamma} = \mathcal{G}\ \mathcal{F}_{e,\gamma} \sum_i c_i s_i(t) \mathcal{A}_i$$

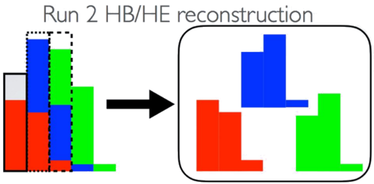
ECAL algorithm





HCAL algorithm





- Fit for **in-time pulse, previous** and **next** bunch crossings
  - Chi2 minimization for amplitude and timing

$$\chi^2 = \sum_{i=0}^{9} \frac{(\mathrm{TS}_i - A_i)^2}{\sigma_{p,i}^2} + \sum_{j=0}^{3} \frac{(t_j - \langle t \rangle)^2}{\sigma_t^2} + \frac{(\mathrm{ped} - \langle \mathrm{ped} \rangle)^2}{\sigma_{\mathrm{ped}}^2}$$

$c_i$alibration

$$E_{e,\gamma} = \mathcal{G}\ \mathcal{F}_{e,\gamma} \sum_i c_i s_i(t) \mathcal{A}_i$$

Main principle: use **well know physics as reference** signal (e.g. a resonance, exploit symmetry features, etc.)

ECAL

- Light monitoring system
- azimuthal symmetry of the energy flow
- $\pi^0, \eta \to \gamma\gamma$
- Electron E over tracker p
- Z$\to$ ee invariant mass

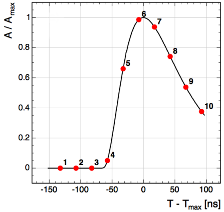
HCAL

- Light monitoring system
- azimuthal symmetry of the energy flow
- m.i.p. deposits (HE)
- pi^+ (HCAL E - ECAL E) over tracker p
- Z$\to$ ee invariant mass for HF

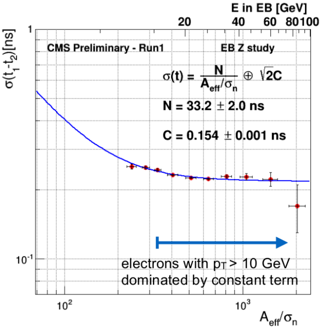
Many more subleties and challenges, **calibrating a detector is an art ;-)**

Gift: time resolution performance (ECAL)

- **Better than $\mathcal{O}(1\ \text{ns})$ stability required** for precise energy determination $\rightarrow$ **regular calibrations**
- Fast scintillation response ($\approx$ 80% of light within 25 ns), shaping time ($\approx$ 40 ns), and sampling rate (40 MHz) allows for excellent time-resolution

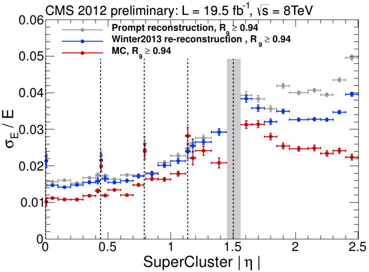


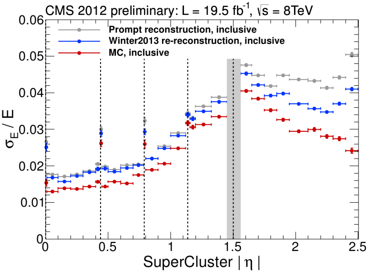
- From the time difference between the highest energy crystal of each of the two electrons from a $Z \rightarrow ee$
- **Noise term consistent** with Test-Beam
- **Constant term of $\approx$ 150 ps, much better than design**, uniform and stable in time
  - residual differences with Test-Beam qualifications ascribed to the clock distribution system



Energy resolution performance (ECAL)

With electrons from Z

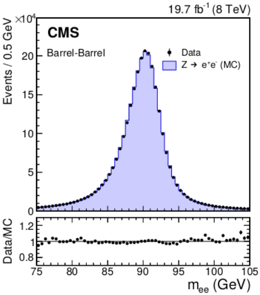


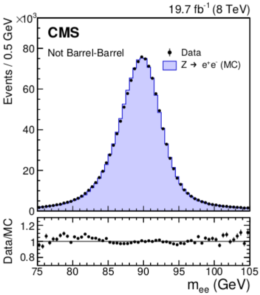


↑ Fit to $Z \to ee$ of a Breit-Wigner convolved with a Gaussian function [?]

→ Simulation tuned to match performance observed *in situ* with $Z \to ee$ events

- scale: data → simulation
- resolution: sim. → data





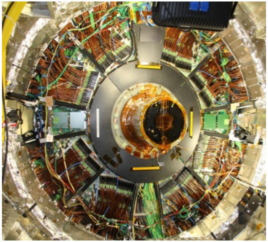
Parenthesis on simulation: quite detailed!

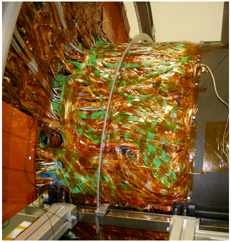
Noise model:

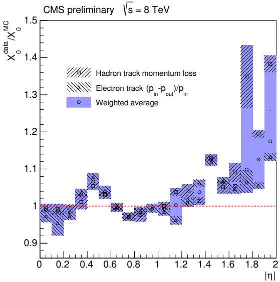
- realistic noise with sample-correlations and channel-to-channel variations
- increase of the readout noise, e.g. APD and SiPM dark currents
- transparency variations for realistic light-yield (and corresponding photo-statistics)

Material description:

- including in-homogeneities in φ of services in front of the endcaps





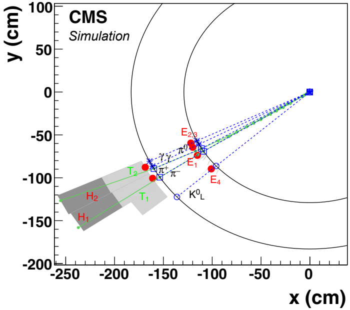


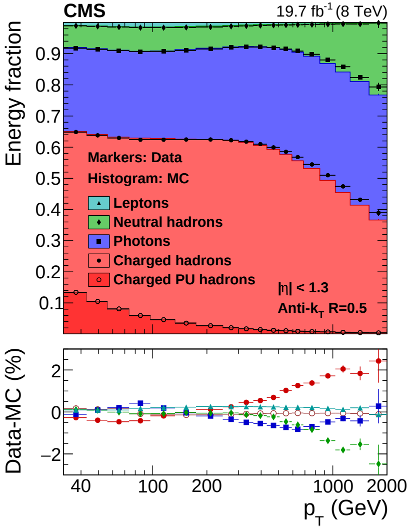
Light propagation effects in the crystals (only relevant for upgrade studies)

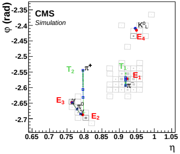
Varying conditions can be used for a "run-dependent" simulation

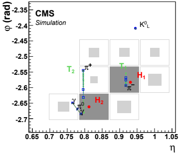
Team spirit: combine information

Particle Flow, or Global Event Description, in pictures



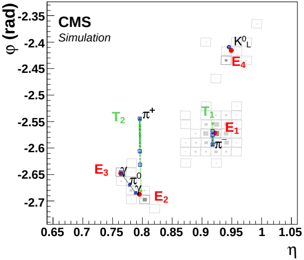


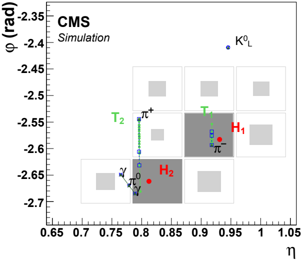


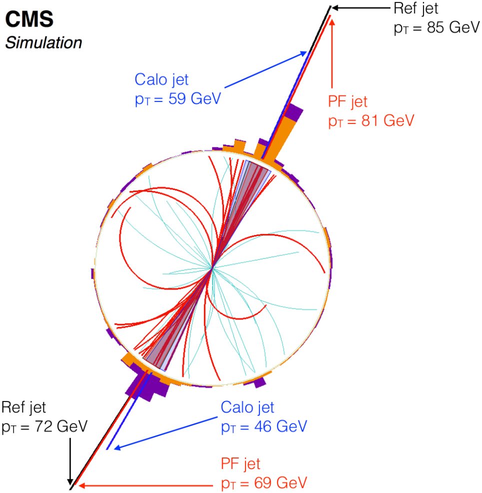


Team spirit: combine information

Particle Flow, or Global Event Description, in pictures



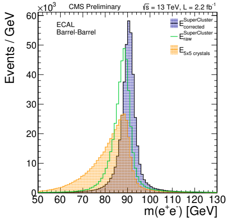


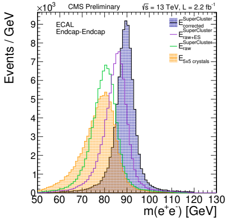


Satisfied? Can improve further...

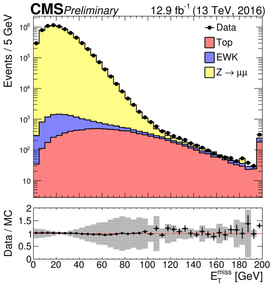
...with multivariate techniques (MVA, BDT, NN, etc.)

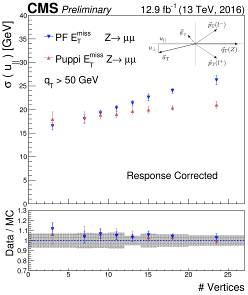
- Reconstructed Z mass in data with different levels of energy reconstruction and corrections (regression)





- From Z→ $\mu\mu$ events: missing distribution for PF MET and resolution for PF MET and regression-treated MET for PU mitigation (PUPPI)





But remember: Spe melioris amittitur bonum

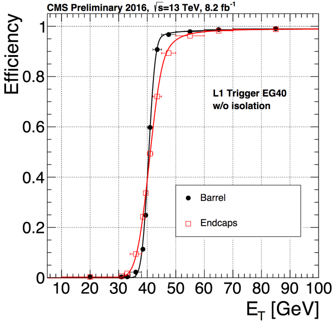
i.e. With the hope for the better, the good is lost

Trigger: another combined effort...

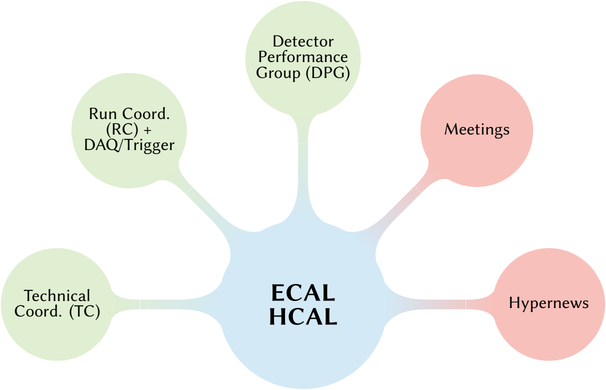
...which I leave to the data taking talk (speaker's team spirit ;-))

- At **L1** custom hardware processors 40 MHz → 100 kHz
  - from calorimetry and muons only, no pixel, no tracker
  - with coarse granularity (oversimplified^n: $\mathcal{O}(10)$ less)
- At **HLT** the whole detector information is used 100 kHz → 1 kHz

- Low rate AND high **efficiency**
- Sharpest possible **turnon**, i.e. best possible agreement "online" (HLT) and "offline" (full reco)
  - implies correcting both at L1 and HLT for detector changes (e.g. ECAL response)
  - and remove fake triggers from e.g. APD direct ionization, HPD discharges



General modus operandi (oversimplified[3])



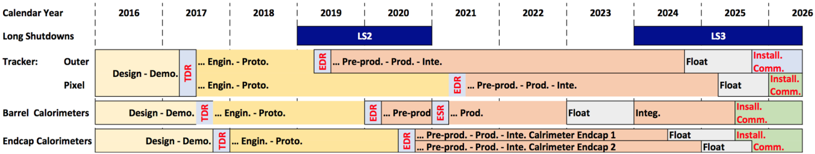
+ 2 experts on call 24/7
+ a team of prompt feedback and data certification

- both "+" get central shift points and are an excellent starting activity to be involved and feel the group

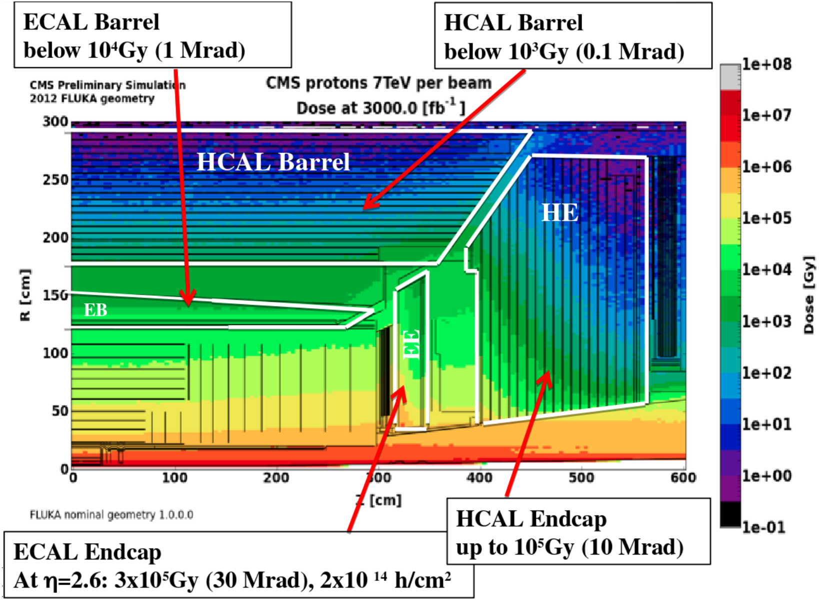
All done, cruise ON for the rest of the LHC life?

Maintain the current Phase 1 performance in High-Luminosity LHC

- $\times 5$ higher instantaneous luminosity w.r.t. Phase 1
- 150-200 PU events per BX
- new regime for detectors, trigger, DAQ…



Radiation levels



Upgrades of the central calorimetry (mostly)

ECAL: extract and refurbish the 36 EB supermodules during LS3

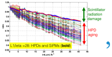
- retain crystals + APDs
- replace Front-End (FE) and Very-Front-End (VFE) readout (12.5 μs trigger latency): shorter shaping and full ECAL granularity at L1
- run colder to mitigate increase in radiation-induced APD dark current (noise)
- new off-detector electronics to cope with higher output bandwidth from FE

HCAL: mandatory replacement of the HB off-detector electronics

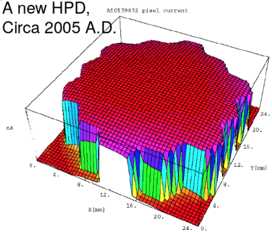
- already in 2016-17 year-end stop: replace PMTs of HF
- already in 2017-18 year-end stop: refurbish HE readout, HPD $\rightarrow$ SiPM
- transition HB in LS2

MTD: m.i.p. timing detector - not a calorimeter, but worth mentioning

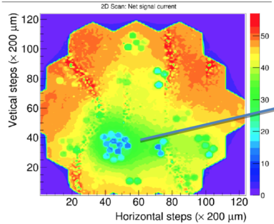
- new device between the tracker and the calorimetry, both in barrel and endcap, providing the arrival time of charged particles with a $\approx 30\,\mathrm{ps}$ resolution

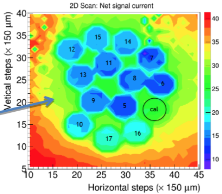
HPD damage (remember  , slide 28)

A new HPD,
Circa 2005 A.D.



HPD from HEP17/RM4, Dec 2017





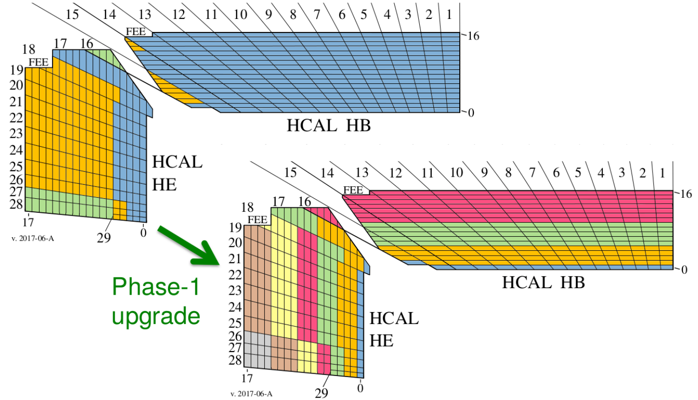
Numbers on "fiber imprints" indicate layer# of tile

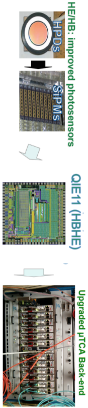
- Scan of most damaged HPD extracted from HEP17 last EYETS – performed at TIFR, Mumbai
  - HPD photocathode illuminated with λ=520 nm laser while output current is measured, 200 µm steps Z-axis: measured current proportional to HPD response to incident light
- Each HPD reads out 18 channels
  - each channel is an hexagonal area on the photocathode
- Very localized damage: imprints of fibers - damage proportional to integrated amount of light incident on photocathode
- More distributed effect: possibly migration of photosensitive material on photocathode
- Results of scan consistent with observations from HE laser/LED/Co60 monitoring over the past years

Longitudinal segmentation in the readout

Phase 0 vs. Phase 1 (vs. Phase 2)

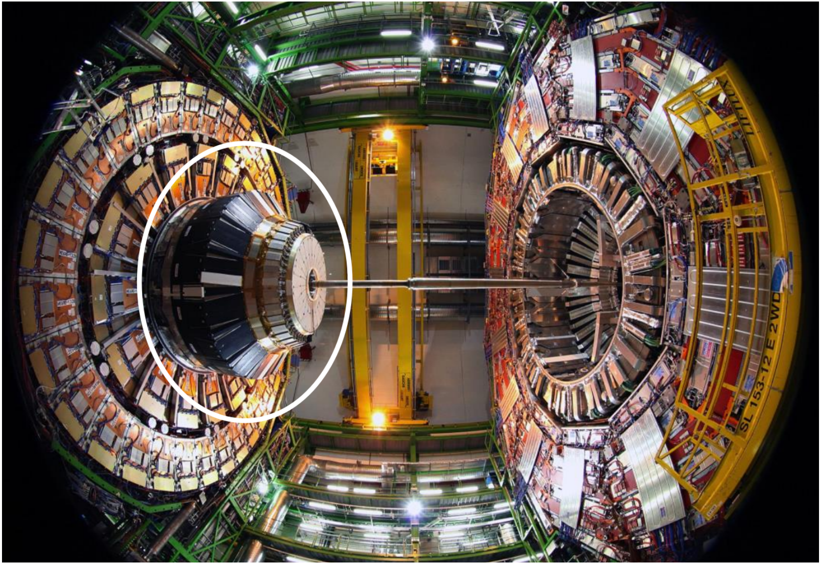
- Occurs with the photodetector transition HPD $\rightarrow$ SiPM
  - Phase 1 done (winter stop 2017/18): endcap segmentation fully exploited
  - Phase 2 during LS2 (just done!): barrel segmentation fully exploited
  - new opportunities to improve the offline reconstruction!
- and with an improved front-end electronics (from 7 bits to 8 bits) and μTCA technology for the electronic backhand





Forward calorimetry (for Phase 2)

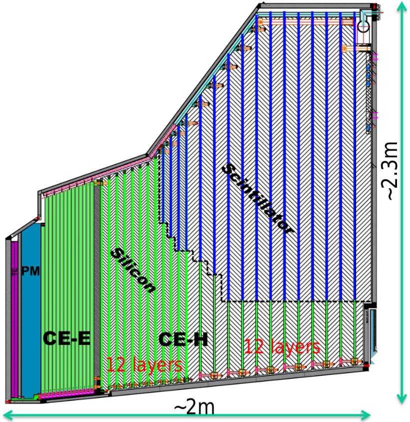
EC (Endcap Calorimeter), a.k.a. **H**igh **G**ranularity **CAL**orimetry (HGCAL)



Forward calorimetry (for Phase 2)

EC (Endcap Calorimeter), a.k.a. **H**igh **G**ranularity **CAL**orimetry (HGCAL)

- Complete replacement for EE and HE in LS3
- Sampling calorimeter with fine transverse granunlarity
- Silicon sensors in EE + FE and inner BH region: intrinsically rad-hard
- Hexagonal Si-sensors built-in into modules
- Modules with a W/Cu backing plate and PCB readout board

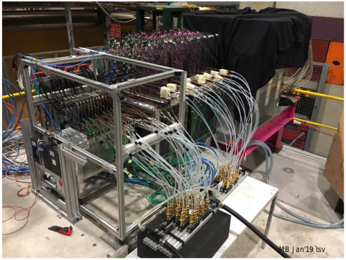


593 m^3 of silicon, 6 M channels (0.5 or 1 cm^2 cells size), 21660 modules, 92000 Front-End ASICS, **a new paradigm for calorimetry (3D-4D shower reconstruction)**

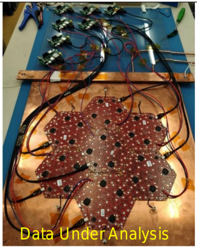
CE: not just designing!

Quite some activity ongoing to test the different parts of the future detector

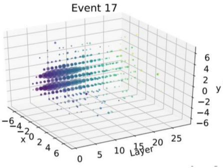
- Test beams in 2018 (CERN, DESY)
- 28 layers CE-E, 12 layers CE-H-Si
- Testing noise, mip calibration, electron and pion reconstruction

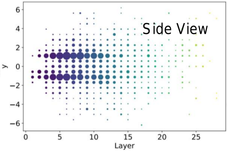


7 hexagonal Si modules in 1 plane

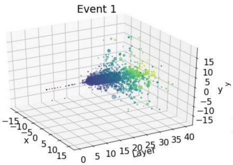


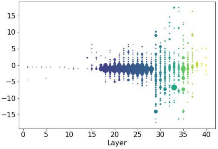
Electron(s? ;))





Pion





Wrapup

- **ECAL and HCAL are fundamental** ingredients to achieve new physics discoveries as well as excellent measurement
- While electrons and photon reconstruction is dominated by the ECAL, the intrinsic challenging nature of jets (and missing energy) requires a **combined effort** of HCAL, ECAL, and tracking to achieve the best performance
- Techniques for maintaining and improving the current detector performance are continuously being developed, **new ideas from new people are the fuel** for this

Welcome to CMS!

- Each year we have about 3-4 months, 6 when starting, to invest in “Experimental Physics Responsibilities” (EPR). My 2 cents:
  - working on and understanding **detectors** is what makes us do **better analyses**
  - choose something you would **really like** to learn and you feel comfortable working with for several months
  - **do not be afraid of the unknown**: in few weeks anyone well motivated can give significant contributions

- CMS is a wonderful detector that keeps producing excellent results and offers golden opportunities for involvement

And also remember: the **best advances in physics are made talking to people** in corridors and over coffees, not (just) at meetings. **Do not be shy!**