Calorimetry

"everything not tracking" (in CMS)

David Yu (LPC/Nebraska)

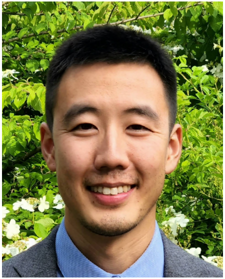
on behalf of the ECAL and HCAL groups

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

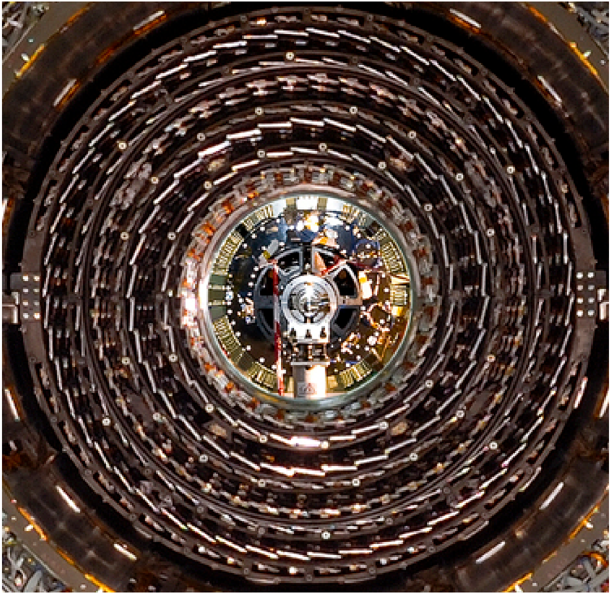
CMS Induction Course, July 19, 2023

Me

- Physics interests:
  - Direct searches for new particles (especially dark matter), Higgs measurements, calorimetry, remote shifts at the LPC
- Eyes on:
  - Phase-II upgrade detectors, especially HGCAL
  - The Next Collider (muon collider?)
- Outside of work:
  - Running, cycling, photography



What you've already learned...



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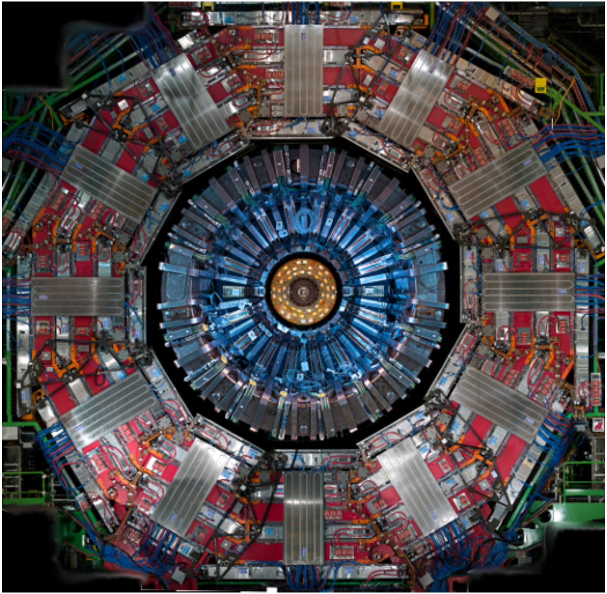
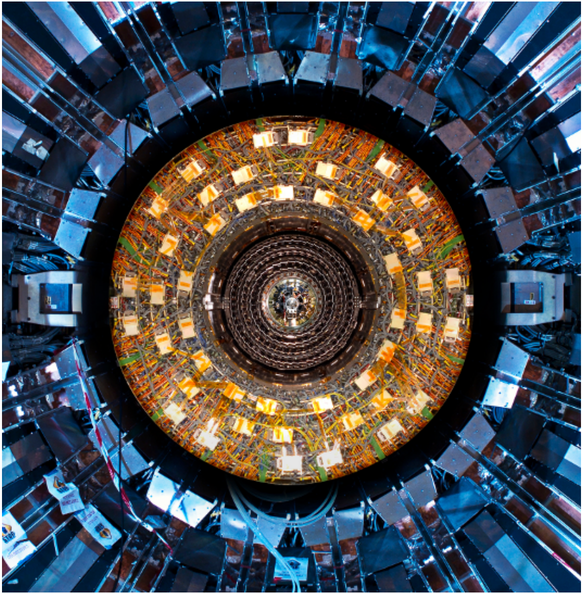


What you can't wait to hear about!



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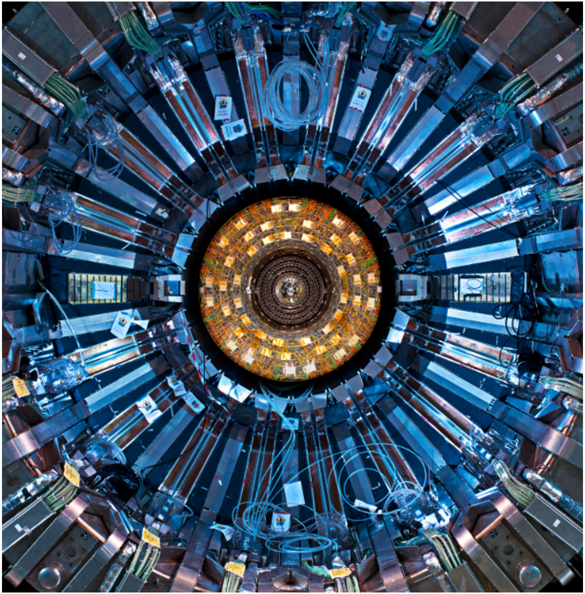
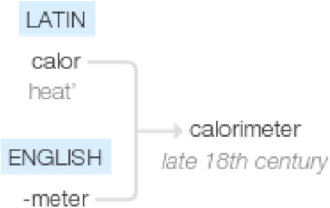


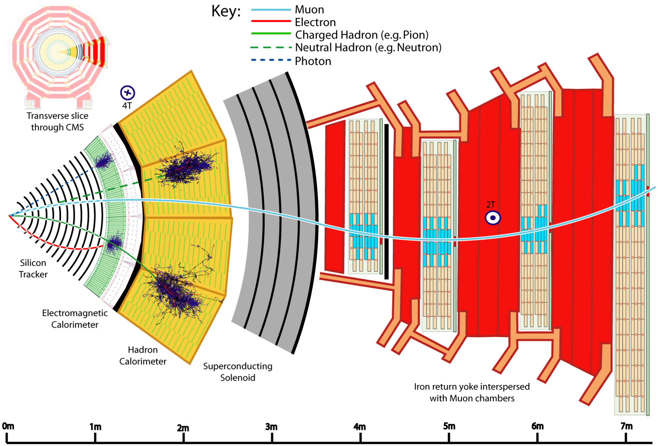
What is a calorimeter?



What is a *particle physics* calorimeter?

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

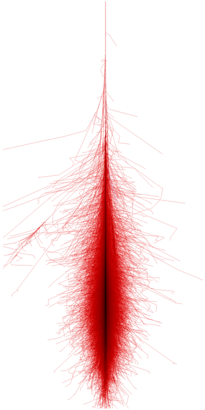


Particle interaction with matter (oversimplified^n)

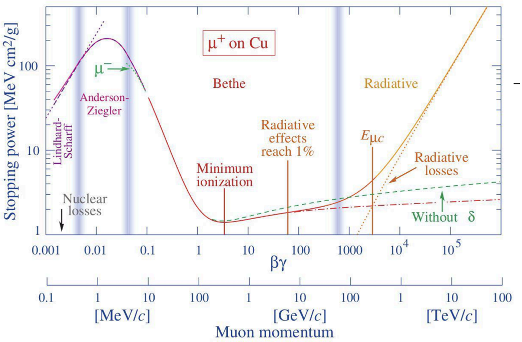
- **Electrons and photons**, a simple story:
  - above 1 GeV: **bremsstrahlung** ($1e^{\pm} \rightarrow 1\gamma$) and **pair production** ($1\gamma \rightarrow 1e^{+} + 1e^{-}$)
  - below 1 GeV: ionization, photoelectric, Compton
  - critical energy, $E_c \approx 610\ \text{MeV}/(Z + 1.24)$: energy at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

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)

e.m. shower example



Electrons vs. photons vs. muons



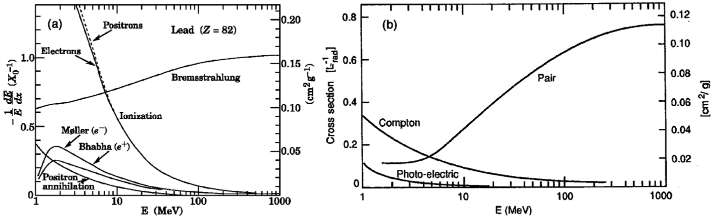
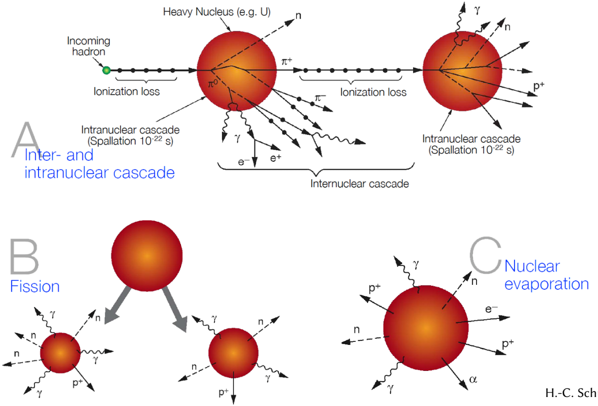


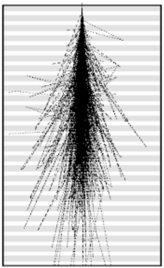
FIG. 1. (a) Fractional energy lost in lead by electrons and positrons as a function of energy (Particle Data Group, 2002). (b) Photon interaction cross section in lead as a function of energy (Fabjan, 1987).

Particle interaction with matter (oversimplified^n)

- **Hadrons**, a complex story:
  - multi-particle production, typically mesons ($\pi^{\pm}$, π^0, K, ...)
  - Important: $\sim \frac{1}{3}$ of secondaries are π^0s, which decay immediately via $\pi^0 \to \gamma\gamma$. $\Rightarrow$ EM shower inside hadronic shower!
  - This happens every interaction $\Rightarrow$ EM fraction increases w/energy
  - Nuclei breakup leading to spallation neutrons/protons



had. shower



H.-C. Schultz-Coulon

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, $X_0 \sim A/Z^2$

Photon mean distance $= \frac{9}{7} X_0$

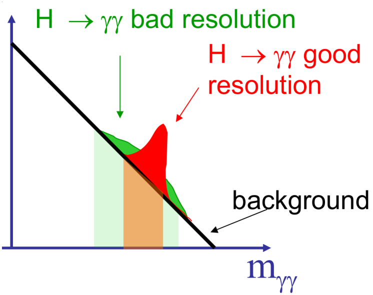
Molière radius (R_M): average lateral deflection of electrons of critical energy E_c after traversing $1X_0$; 90% E_0 within $1R_M$, 95% within $3R_M$

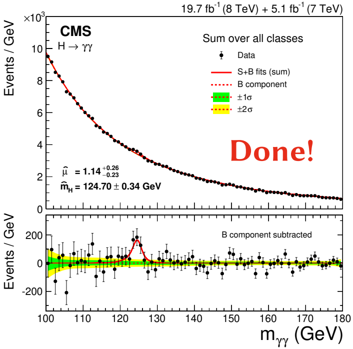
Interaction length (λ_{int}): average distance a high energy hadron has to travel inside a medium before a nuclear interaction occurs, $\lambda_{int} = A/N_A\sigma_{int} \propto A^{1/3} \gg X_0$

	LAr	Fe	Pb	U	C
λ_{int} [cm]	83.7	16.8	17.1	10.5	38.1
X_0 [cm]	14.0	1.76	0.56	0.32	18.8

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!

Designing a calorimeter - a HOW TO guide

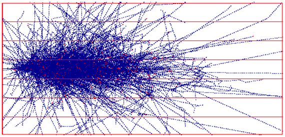
Design goals:

- Detection of both **charged and neutral** particles
  - only muons escape (and ν)
- 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

Designing a calorimeter - a HOW TO guide

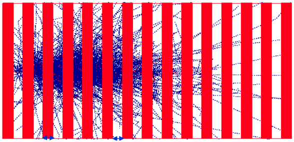
Two main possibilities (oversimplified[1]):

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

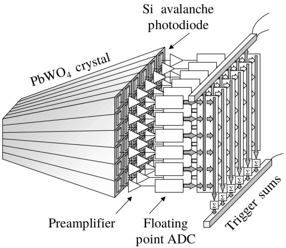
Designing a calorimeter - a HOW TO guide

Two main possibilities (oversimplified[1]):

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

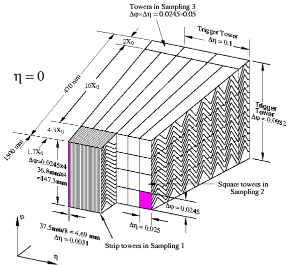
Sampling calorimeters: the shower is sampled by layers of active medium (low-Z) alternated with dense radiator (high-Z)

CMS ECAL choice



- Excellent energy resolution

ATLAS ECAL choice



- Longitudinally segmented

Designing a calorimeter - a HOW TO guide

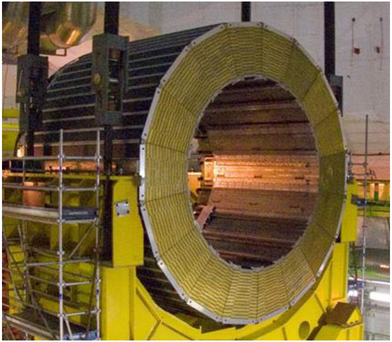
Two main possibilities (oversimplified[1]):

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



Building a calorimeter - a HOW TO guide

- **Particle interaction** with matter
  → depends on the impinging particle and on the kind of material

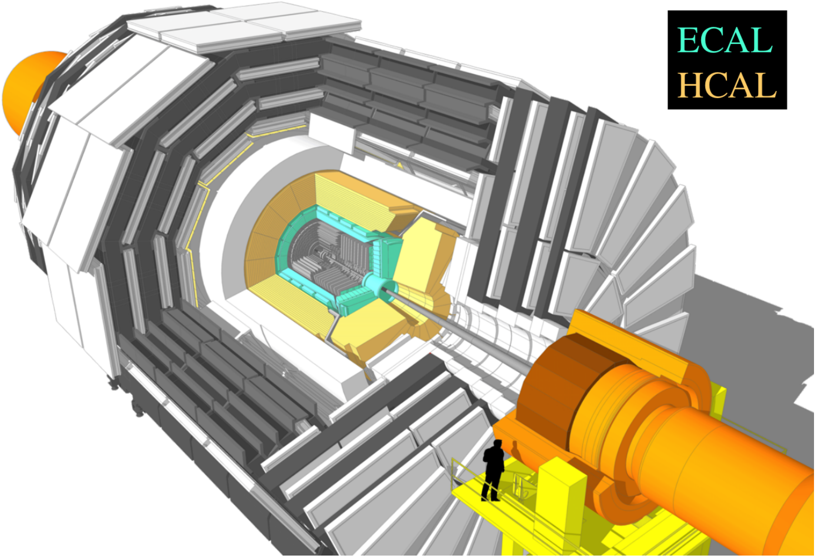
- **Energy** loss transferred to a detectable signal
  → depends on the material, typically light (or charges, e.g. ATLAS)

- **Signal** collection
  → depends on the signal, many techniques of collection

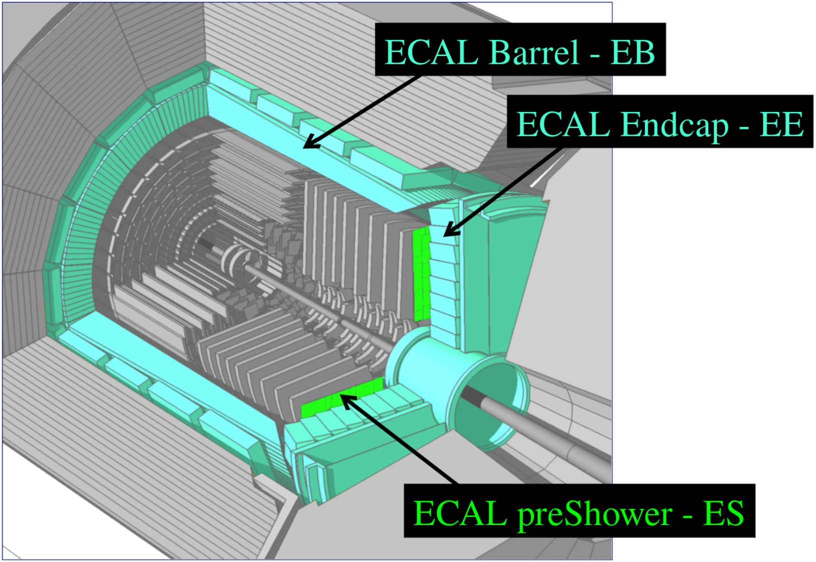
- Conversion to **electrical signal** and digitization
  → depends on the signal and granularity, also many techniques

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

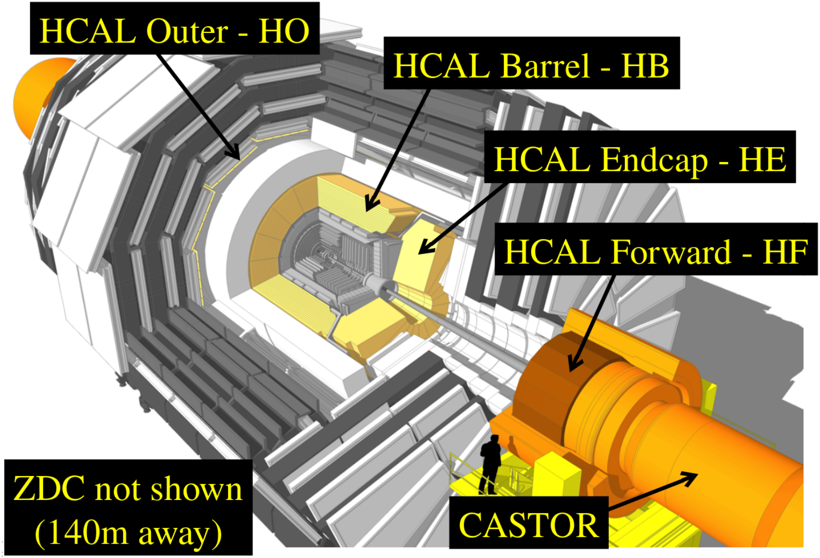
The CMS calorimeters



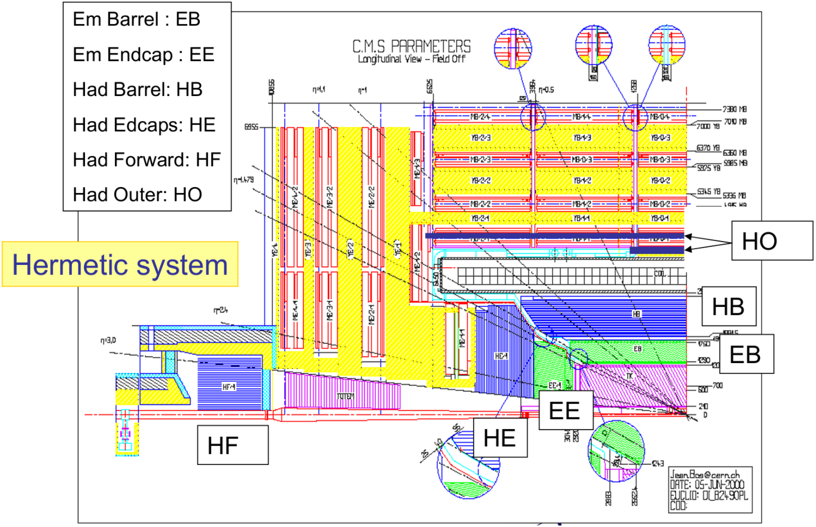
The CMS calorimeters



The CMS calorimeters

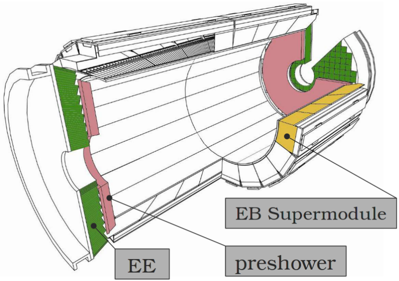


The CMS calorimeters



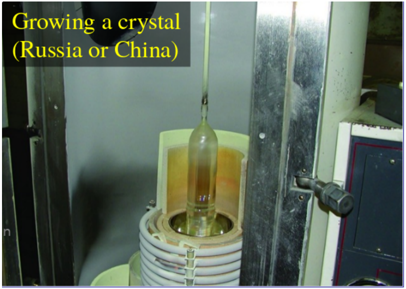
The CMS ECAL

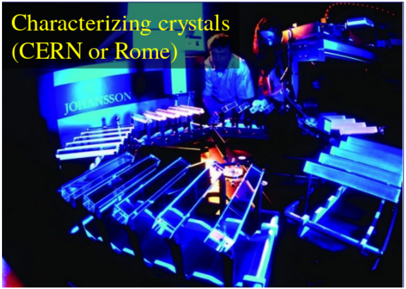
- **Homogeneous, hermetic, high granularity $PbWO_4$ crystal calorimeter**
  - density of 8.3 g/cm^3, radiation length 0.89 cm, Molière radius 2.2 cm, $\approx 80\%$ of scintillating light in ≈ 25 ns, refractive index 2.2, light yield spread among crystals $\approx 10\%$
- **Barrel**: 61200 crystals 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, $1.65 < |\eta| < 2.6$

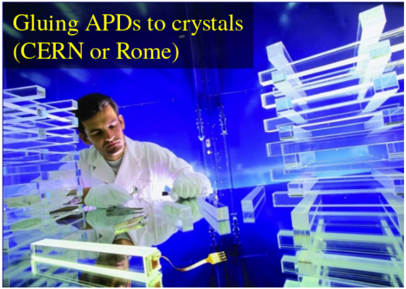


- Solenoidal magnetic field: 3.8 T
  ECAL fully contained in the coil
- CMS tracker coverage: $|\eta| < 2.5$

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
- $|\eta| < 1.3$

Fun fact: much of the brass came from old WWII shells from the Russian Navy!

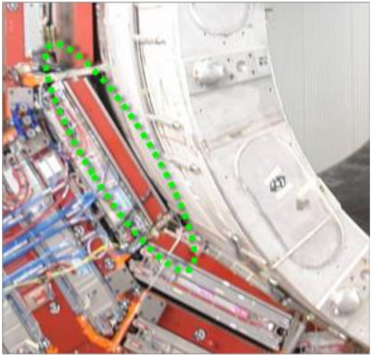
Endcap (HE)

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

The CMS HCAL

Outer (HO)

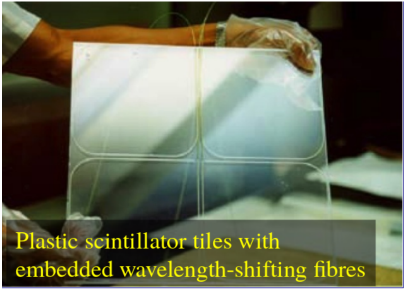
- Scintillator tiles (outside magnet yoke)
- 1 or 2 longitudinal layers, 10 mm scintillator
- $|\eta| < 1.3$



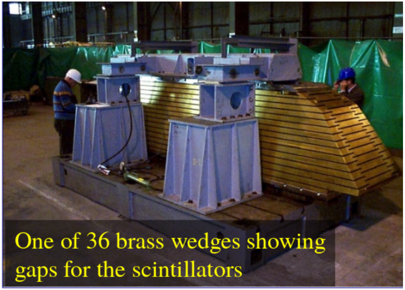
Forward (HF)

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

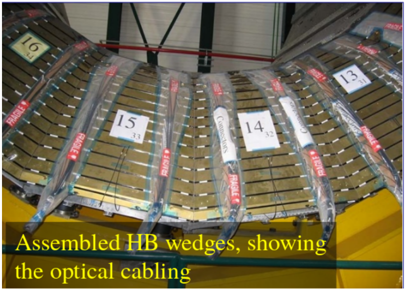
Assembly of HCAL barrel (wedges + megatiles)



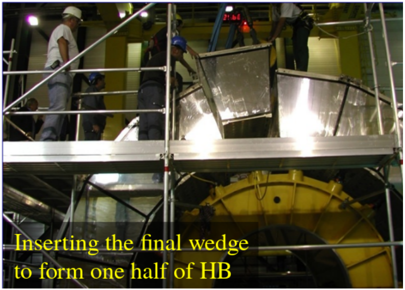
Plastic scintillator tiles with embedded wavelength-shifting fibres



One of 36 brass wedges showing gaps for the scintillators



Assembled HB wedges, showing the optical cabling

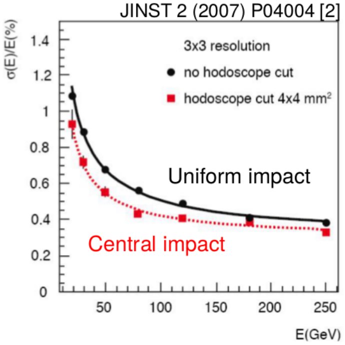


Inserting the final wedge to form one half of HB

Detector parts (modules) produced. Then? Happy?

Performance at Test Beams: text book

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



Energy resolution

$e^{\pm}$, 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

$\pi^{\pm}$ w/ECAL+HCAL:

$$\frac{\sigma(E)}{E} = \frac{84.7\%}{\sqrt{E}} \oplus \frac{7.6\%}{E(GeV)}$$

Time resolution: constant term ≈ 20 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 → temperature dependence: $\Delta S/S \sim -2\%/^{\circ}\mathrm{C}$ @ $18\ ^{\circ}\mathrm{C}$
- ECAL crystal transparency → radiation dose-rate dependence
- HCAL scintillator response → radiation dose dependence

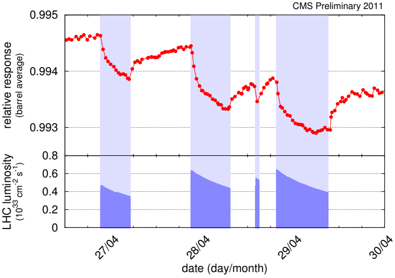
Photo-detector response:

- APD → 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 → response dependence on the incremental charge at the cathode
- HPD → discharges, noise effects, radiation damage
- SiPM → dark current, temperature/voltage dependence

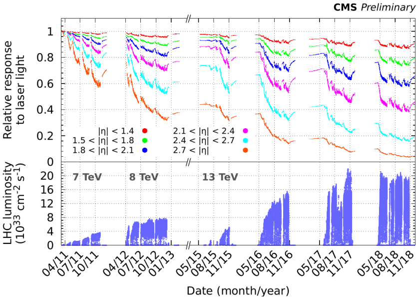
→ **Excellent environmental stability** ($\times 2$ to $\times 3$ better than required) [?]
→ **Dedicated monitoring system and calibration techniques** [?, ?]

A glimpse of the challenges

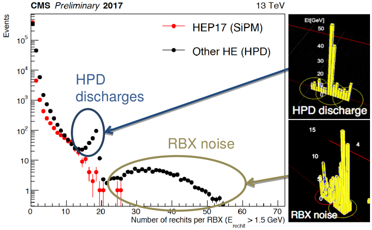
ECAL response: dose-rate variation...

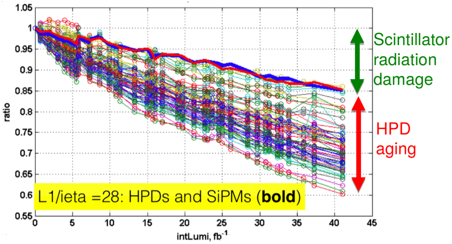


...over 6+ years



HCAL: selected features





ECAL APD spikes analogous to HPD discharges

Not only calorimetry-induced fun

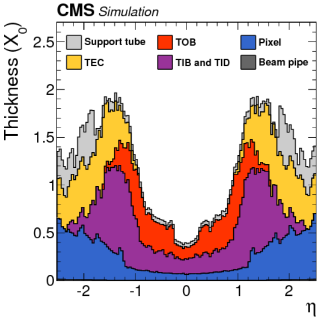
Tracker material in front of ECAL:

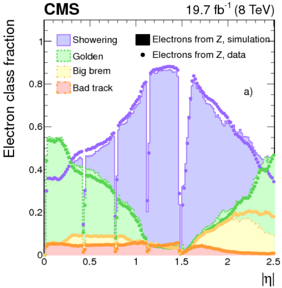
- photon conversions
- bremsstrahlung losses for electrons

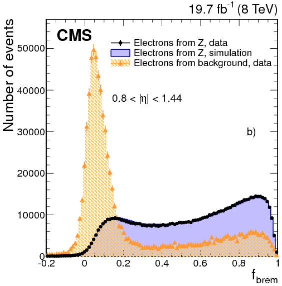
3.8 T solenoidal magnetic field:

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

$\longrightarrow$ Specific energy reconstruction algorithms and corrections

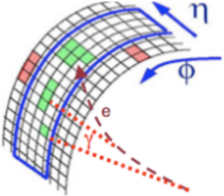






Ingredients for precision physics (ECAL example)

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



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

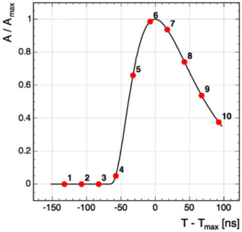
- $\mathcal{A}_i$: single channel amplitude, pulse fit in the time domain
- $s_i(t)$: single-channel time-dependent response corrections, via a dedicated laser monitoring system
- c_i: inter-calibration of the single channel response, using physics: φ- and time-invariance of the energy flow in minimum-bias 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

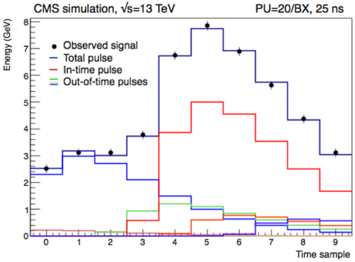
Resolution, efficiency and particle ID: $Z \to ee$

Amplitude reconstruction

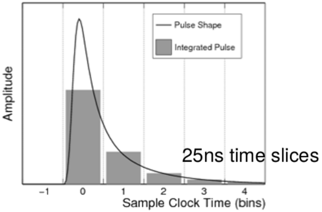
$$E_{e,\gamma} = \mathcal{G}\ \mathcal{F}_{e,\gamma} \sum_i c_i s_i(t) \mathcal{A}_i$$

ECAL algorithm

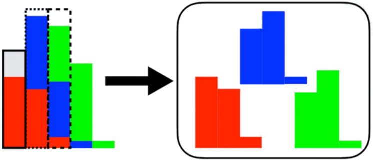




HCAL algorithm



Run 2 HB/HE reconstruction



- 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

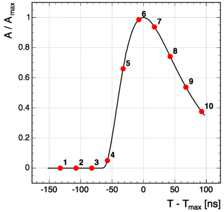
HCAL

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

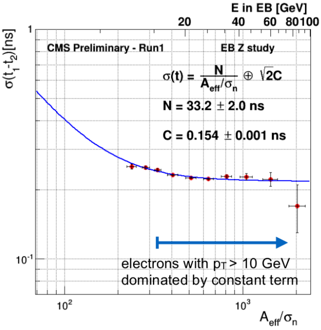
Many more subleties and challenges, **calibrating a detector is an art ;-)**

Gift: time resolution performance (ECAL)

- **Better than $\mathcal{O}(1\ \mathrm{ns})$ 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

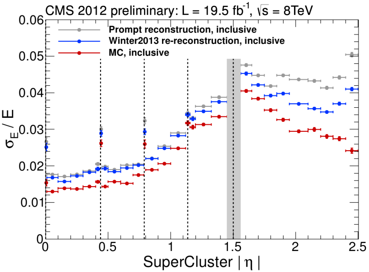


- From the time difference between the highest energy crystal of each of the two electrons from a $Z \rightarrow ee$
- **Noise term consistent** with Test-Beam
- **Constant term of ≈ 150 ps, much better than design**, uniform and stable in time
  - residual differences with Test-Beam qualifications ascribed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



Energy resolution performance (ECAL)

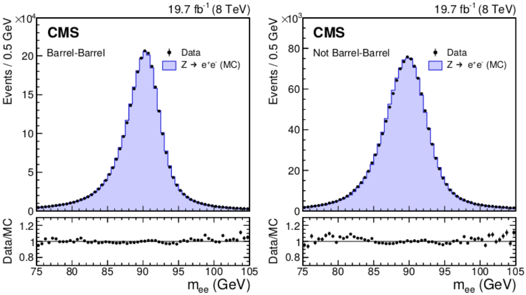
With electrons from Z



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

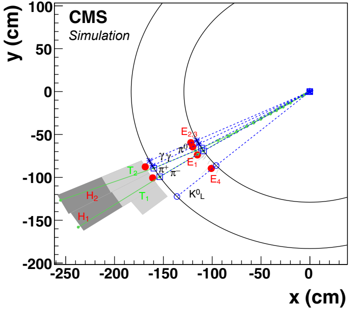
→ Simulation tuned to match performance observed *in situ* with $Z \to ee$ events

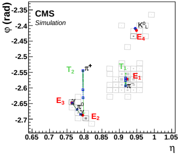
- scale: data → simulation
- resolution: sim. → data

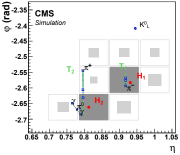


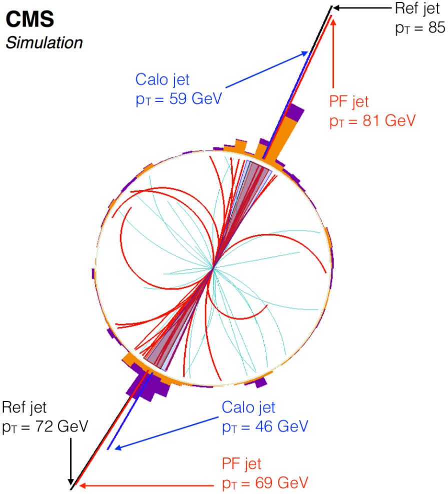
Team spirit: combine information

Particle Flow, or Global Event Description, in pictures

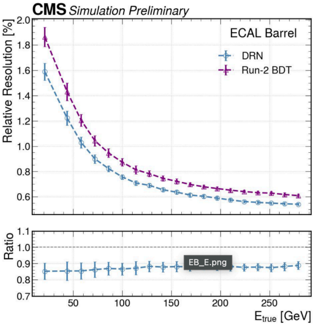




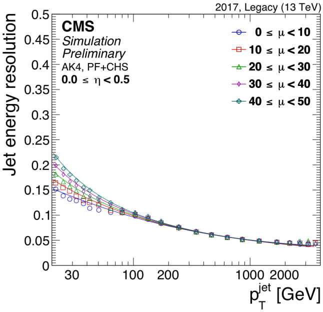




Final results: energy resolution



(a) $e^{\pm}, \gamma$

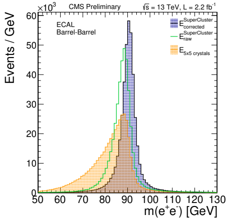


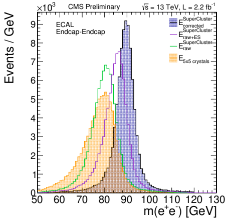
(b) Jets

Satisfied? Can improve further...

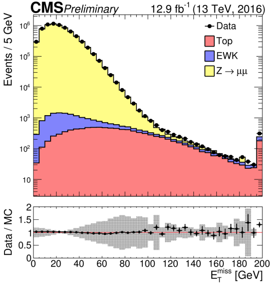
...with multivariate techniques (MVA, BDT, NN, etc.)

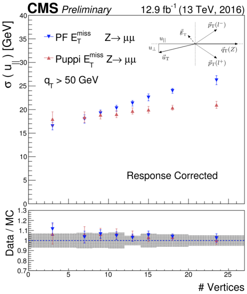
- Reconstructed Z mass in data with different levels of energy reconstruction and corrections (regression)





- From $Z \to \mu\mu$ 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

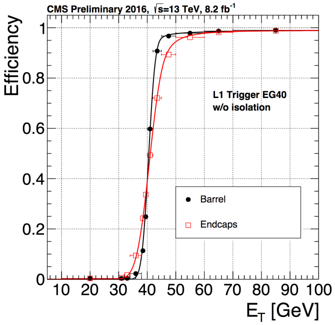
i.e. With the hope for the better, the good is lost

Trigger: another combined effort...

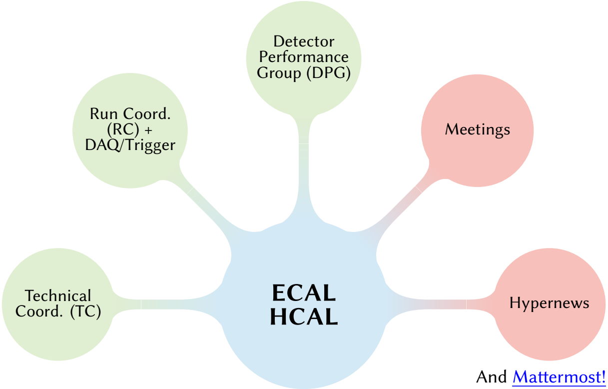
...which I leave to the data taking talk (speaker's team spirit ;-))

- 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



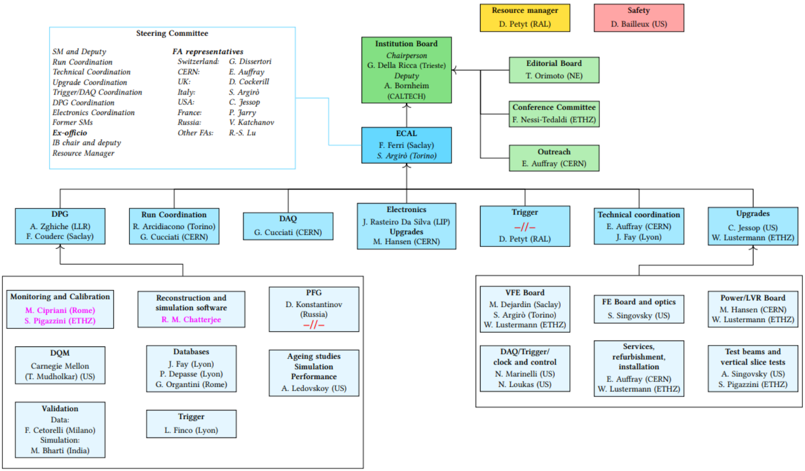
General modus operandi (oversimplified[3])



+ 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

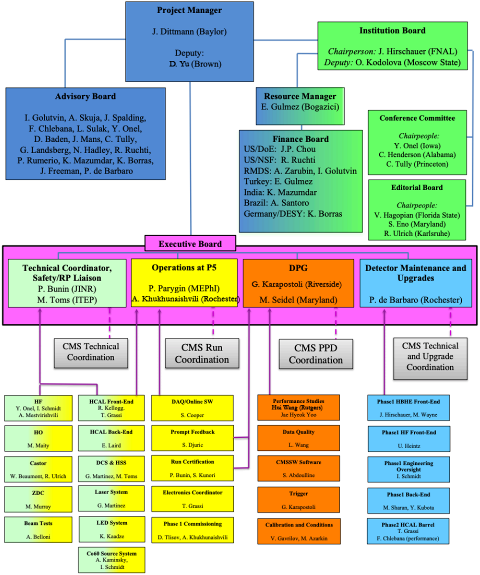
Main suspects for ECAL



- Organigram + DoC & DGL (2020; see twiki)

Main suspects for HCAL

To give you the feeling of the organization (2020; see twiki).



Already convicted

ECAL

Project manager

Stefano Argirò
(Torino U.)

Deputy

Toyoko Orimoto
(Northeastern)

HCAL

Project manager

Alberto Belloni
(U. Maryland)

Deputy

David Yu
(Nebraska/LPC)

CE (or HGCAL)

Project manager

Karl Gill
(CERN)

Deputy

Marcello Mannelli
(CERN)

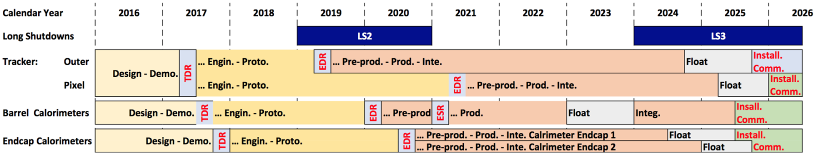
Deputy

Jim Strait
(Fermilab)

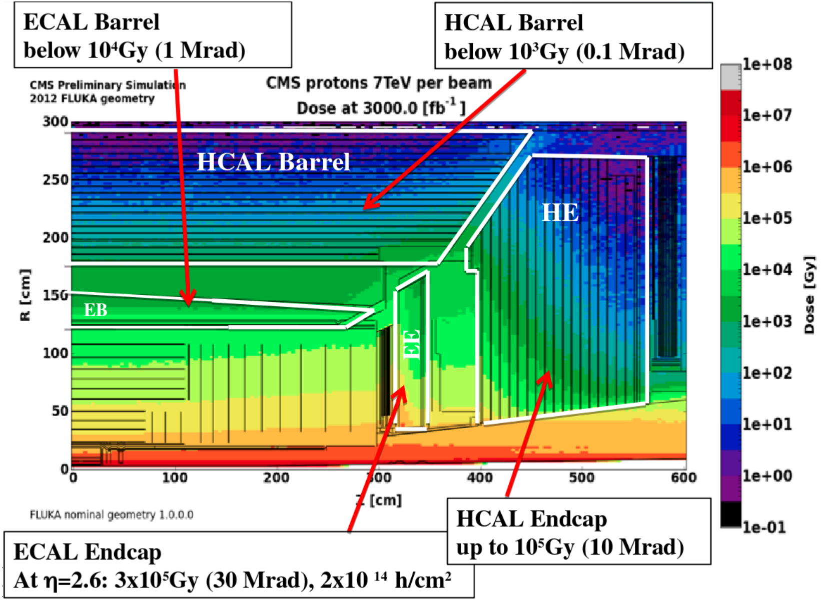
The future...

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

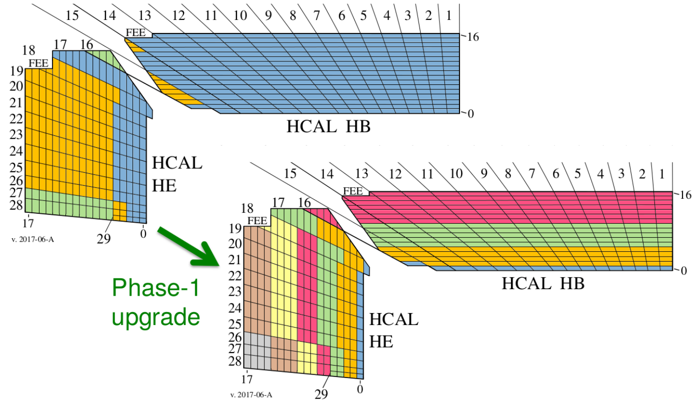
MTD: m.i.p. timing detector - not a calorimeter, but worth mentioning

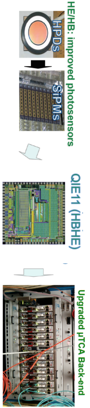
- new device between the tracker and the calorimetry, both in barrel and endcap, providing the arrival time of charged particles with a $\approx 30\,\mathrm{ps}$ resolution

Longitudinal segmentation in the readout

Phase 0 vs. Phase 1

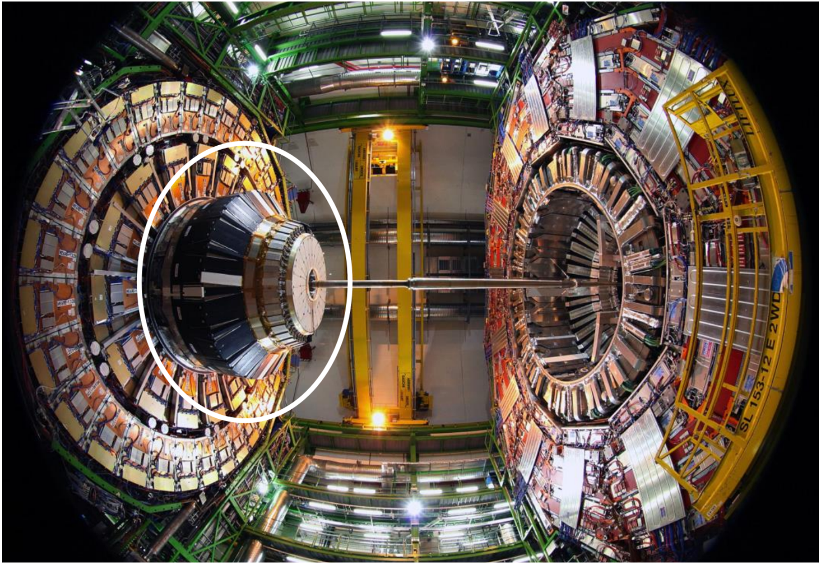
- Occurs with the photodetector transition HPD $\rightarrow$ SiPM
  - Phase 1 done (winter stop 2017/18): endcap segmentation fully exploited
  - Phase 2 during LS2 (just done!): barrel segmentation fully exploited
  - new opportunities to improve the offline reconstruction!
- and with an improved front-end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





Forward calorimetry (for Phase 2)

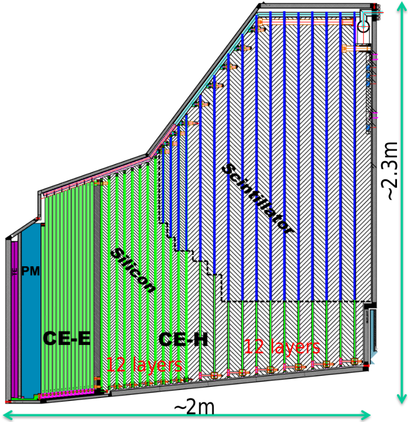
EC (Endcap Calorimeter), a.k.a. **H**igh **G**ranularity **CAL**orimetry (HGCAL)



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

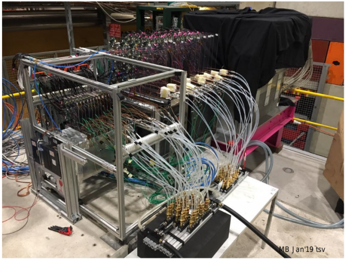


593 m^3 of silicon, 6 M channels (0.5 or 1 cm^2 cells size), 21660 modules, 92000 Front-End ASICS, **a new paradigm for calorimetry (3D-4D shower reconstruction)**

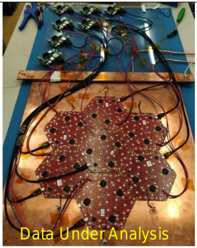
CE: not just designing!

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

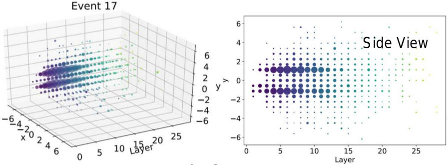
- Test beams in 2018 (CERN, DESY)
- 28 layers CE-E, 12 layers CE-H-Si
- Testing noise, mip calibration, electron and pion reconstruction



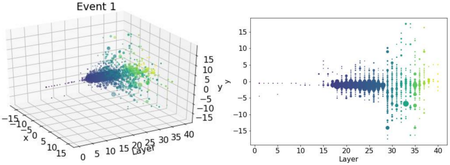
7 hexagonal Si modules in 1 plane



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

- This was a fast and practical introduction to calorimetry at CMS. Many other, more in-depth resources are available!
  - E.g., R. Rusack's ongoing detector lectures at the FNAL LPC, review by Fabiola (CERN director general!)

Welcome to CMS!

- Each year, CMS members have about 3-4 months, 6 when starting, to invest in “Experimental Physics Responsibilities” (EPR). Our advice:
  - 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!